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SEA LEVEL RISE IN EUROPE

1st Assessment Report of the Knowledge Hub on Sea Level Rise

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2021 2030 United Nations Decade of Ocean Science for Sustainable Development

About the Knowledge Hub on Sea Level Rise

The Knowledge Hub on Sea Level Rise (KH-SLR) is a joint initiative by the Joint Programming Initiatives Connecting Climate Knowledge for Europe (JPI Climate) and Healthy and Productive Seas and Oceans (JPI Oceans) supported by member countries **Belgium, Germany, France, Ireland, Italy, the Netherlands, Norway, Sweden,** and **Spain** and endorsed as a UN Ocean Decade project. The KH-SLR aims to provide essential information through frequent, detailed, and region-specific assessments of sea level changes to better inform policymaking.

About this Report

Conceived through a stakeholder co-design process and implemented by a network of over 60 experts, the 1st Assessment Report addresses sea level rise projections, impacts, adaptation options, policy needs, and knowledge gaps. It aims to inform sound and effective policymaking and coastal planning with region-specific analyses. The report was made possible through the financial support of **Belgium, Ireland, Spain, Germany,** and **Italy,** with additional in-kind contributions from all member countries of the KH-SLR.

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Sea Level Rise in Europe: Summary for Policymakers

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Abstract. Sea level rise (SLR) is a global concern for low-lying coastal areas, including many European coasts. The European Knowledge Hub on Sea Level Rise (KH-SLR), a collaborative effort by the Joint Programming Initiatives for "Connecting Climate Knowledge for Europe" (JPI Climate) and for "Healthy and Productive Seas and Oceans" (JPI Oceans), has developed the 1st Assessment Report (SLRE1) to address the challenges posed by SLR in Europe. The report's target audience includes national and subnational bodies focused on research and policy advice for coastal management and climate adaptation, as well as European experts who contribute to shaping policy frameworks and collecting information at a pan-European scale. This report, preceded by a series of targeted surveys and workshops with researchers and stakeholders (e.g. coastal decision-makers), has synthesized the current scientific knowledge on SLR drivers, impacts, and policies at local, national, and European basin scales. It provides in-depth and basin-specific analyses on local sea level changes, compared with relevant global assessments of the Intergovernmental Panel on Climate Change (IPCC). In addition, it identified critical knowledge gaps needed to support the development of actionable information. The Summary for Policymakers (SPM) distils the key findings of the SLRE1, presenting information specific to the six European basins: Mediterranean Sea, Black Sea, North Sea, Baltic Sea, Atlantic, and Arctic. The SPM highlights basin-specific trends, vulnerabilities, and potential impacts, while also orienting future requirements.

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Key statements from the 1st Assessment Report of the Knowledge Hub on Sea Level Rise

- Sea level rise is a chronic hazard that is addressed in the governance of environmental and economic development of European coastal regions in all surrounding sea basins (Sect. 5, 5.1, 5.2, 5.3, 5.4, 5.5).
- The mean rate of European absolute sea level rise slightly exceeds the global mean trend and is accelerating. Regional variability is large, with lower (or negative) relative sea level rise in some Baltic regions due to vertical land movements and the effects of loss of land ice masses. Future sea level rise rates are very uncertain and depend greatly on emission scenarios. Higher relative rates of sea level rise are expected in the southern areas (Sect. 2, 2.3, 2.4, 2.5).
- Sea level rise has several coastal impacts (such as the increased likelihood of floods, shoreline retreat via coastal erosion, and freshwater shortages due to saltwater intrusion). Other human interventions can exacerbate these impacts, such as reduced sediment supplies due to streamflow obstructions, urbanization, and habitat loss in exposed coastal areas; lack of sustainable groundwater strategies; or ageing coastal infrastructure (Sect. 3.1, 3.2).
- Values of sea level rise considered in the management of coastal developments vary across countries and depend on socioeconomic developments in coastal areas, environmental constraints, and options to take measures against negative sea level rise impacts. Many countries have mainstreamed sea level rise in national and regional policies for climate adaptation as well as in (marine) spatial planning and environmental conservation (Sects. 4.3, 5.1)
- Selection of options against adverse sea level rise impacts must usually strike a balance between multiple objectives, available time windows, and long-term implications. Uncertainty in future sea level rise and socioeconomic developments require long-term flexibility by adopting an iterative decision process and monitoring progress in reaching policy objectives (Sect. 4.2, 4.3).
- Many measures to reduce adverse sea level rise impacts exist, classified in broad categories (accommodate, protect, advance, and retreat). They include hard (engineering) and soft (nature-based) infrastructure measures, upgrading or restoring existing coastal assets (such as dikes) or resources (such as aquifer recharge), preventive (such as early warnings) or recovery (such as insurance) measures, and changes in land occupation (such as managed retreat) (Sect. 4.1, 4.3).

1 Assessment scope and stakeholder needs for European sea level rise information

1.1 Scope of the assessment

Despite the global threat of sea level rise (SLR), Europe faces disparities in understanding and applying sea level science, evaluating its impacts, and devising effective adaptation strategies. The European Knowledge Hub on Sea Level Rise (KH-SLR), a joint effort between "Connecting Climate Knowledge for Europe" (JPI Climate) and " Healthy and Productive Seas and Oceans" (JPI Oceans), has compiled the 1st Assessment Report (SLRE1) based on an extensive scoping process defining its outline and identifying critical knowledge gaps. It aims to provide easy access to usable knowledge on regional–local sea level change in Europe and enable policymakers to make well-informed decisions regarding protective and adaptive measures. The assessment of SLR for the six European basins is intended to provide additional value that complements global (e.g. the Intergovernmental Panel on Climate Change – IPCC) and national assessments (also see Pinardi et al., 2024, in this report).

1.2 Stakeholder consultation

1.2.1 Online survey

An online survey targeting stakeholders involved in coastal planning and in research was conducted to assess the availability and use of SLR information, impacts of SLR, and adaptation strategies and policy implications of SLR. Responses were received from 200 stakeholder participants, with 94 % from 23 European countries and 6 % from 8 non-European countries, and participants were separated into two groups based on their professional backgrounds. The first group (labelled "government") consisted of potential users of SLR information for policy design and implementation, usually professionals in public regional and national governance and in private industry with advisory roles, and was represented by about one-third of the respondents. The second group (labelled "research") consisted of information providers and was primarily comprised of academic research staff (about two-third of the respondents) (see Fig. 2 of Jiménez et al., 2024, in this report). Major outcomes of the survey are summarized in the text below (also see Sect. 3.1 in Jiménez et al., 2024, in this report).

Availability of SLR information

Approximately 32 % of respondents indicated a lack of essential regional–local data and information on SLR, with disparities across different sea basins and stakeholder groups. Overall, global sea level projections were most accessible and most widely used. Information gaps primarily revolve around regional SLR projections, uncertainties, and ice sheet mass loss contributions, highlighting the need for better projections related to long-term SLR and comprehensive understanding. Government and scientist respondents identified gaps with slight variations in perspectives and priorities. Government respondents prioritized precise regional projections as the ultimate product, crucial for fulfilling their responsibilities, with uncertainty estimation being a significant concern. Scientists, however, prioritized a comprehensive understanding of factors influencing regional projections, considering these insights as the final goal, with a strong focus on the factors contributing to uncertainty. Improving local SLR projections, understanding the impact on extreme water levels, and addressing coastal erosion were all deemed important.

Impacts of SLR

Shoreline erosion emerged as a dominant concern in all basins except the Arctic, highlighting the critical role of beaches in regional economies. Due to this, other significant impacts are outlined, such as increased flooding, damage to infrastructure, and groundwater salinization, with notable disparities across sea basins. Challenges persist due to the absence of high-quality impact assessments, particularly in the Black Sea and Arctic basins.

Adaptation to SLR

The survey results show that many stakeholders deem existing adaptation plans to be inadequate, with scientists being more critical than government respondents. Flexibility of existing adaptation strategies in the face of SLR-induced impacts is considered insufficient, highlighting the need for adaptive planning approaches. SLR impacts that were mostly neglected by stakeholders include those on coastal ecosystems, coastal urban planning frameworks, river discharge characteristics, and freshwater management.

Respondents unanimously agree on the usefulness of IPCC reports for informing policy and decision-making. Identified needs encompass periodic updates to SLR projections, comprehensive impact assessments, and enhanced exploration of adaptation strategies to mitigate SLR impacts on coastal communities (people living, working, and residing in coastal zones) and ecosystems. Additionally, allocating resources for research and data collection to improve evidence-based and adaptive policymaking was deemed necessary. Collaboration among government agencies, research institutions, and stakeholders to develop and implement effective adaptation measures was emphasized.

Policy implications include the recognition of the value of incorporating nature-based solutions (NBSs) in coastal adaptation plans, although their implementation requires rigorous evaluation and evidence of long-term sustainability under site-specific circumstances.

1.2.2 Online workshops

The SLRE1 also reports on four online scoping workshops focusing on specific European sea basins that gathered insights from stakeholders, policymakers, and experts, furthering the understandings from the survey. Major outcomes of the workshops are summarized in the text below (also see Sect. 3.2 in Jiménez et al., 2024, in this report).

For all European sea basins, the workshops identified significant data and information gaps, particularly in climate projections that capture local processes and coastline details. Notably, there is insufficient resolution in estuaries and a lack of data on human activities, alongside the need for a robust data delivery and quality control system. The workshops also highlighted the need for a solid methodology to assess the effectiveness of coastal adaptation measures and to develop integrated coastal zone management and/or maritime spatial planning that incorporates sea level rise policies. Additionally, both scientists and policymakers emphasized the importance of community engagement and effective communication strategies. More details on the specific needs for each European basin are given in Jiménez et al. (2024, in this report).

2 Past, present, and future sea level

The SLRE1 delves into observed and projected SLR and extreme sea levels (ESLs) in European basins. Despite some variability in SLR trends between European basins, satellite altimetry shows a consistent upward trend in the basin-averaged sea level for the past 30 years, slightly above the global mean SLR. Relative sea level rise (RSLR), which considers human-induced subsidence, and vertical land motion, due to past and contemporary land ice mass loss, present more contrasting trends across European seas, including a relative sea level fall in the uplifting northern Baltic Sea.

Relative sea level will rise throughout the 21st century over European seas, except in the northern Baltic Sea and parts of the European Arctic. Under a very high emission scenario, a 1 m SLR is projected to occur over most European coasts south of 60° N during the first half of the 22nd century. Because of the large inertia of ice sheets and of the deep ocean, sea level is committed to rise for centuries to millennia in European seas. A major uncertainty for SLR projections relates to the Greenland and Antarctic ice mass loss and related tipping points.

The frequency at which historical centennial water levels are reached is projected to amplify along most European coasts in the coming decades, especially in the southern European seas, implying the need for more adaptation measures. Higher-resolution sea level projections are needed, along with information on local drivers of extreme sea levels (including tides, waves, and storm surges). Europe-wide drivers of past mean and extreme sea level as well as future projections of these are provided for each of the assessed basins.

2.1 Eastern Atlantic

2.1.1 Drivers of past mean and extreme sea level

The north-eastern Atlantic Ocean basin, concerning Portugal, Spain, France, the UK, and Ireland, features strong bathymetric gradients, energetic tides, waves, and storm surges, notably due to the North Atlantic mid-latitude storm track. Rates of SLR have accelerated over the past century. Regional patterns of relative SLR are mostly explained by ocean current changes and mass loss from the Greenland ice sheet and mountain glaciers. Climate variability, such as the North Atlantic Oscillation (NAO), significantly affects storminess and atmospheric-pressure patterns, thereby impacting the frequency and intensity of extreme sea level events, particularly storm surges. The highest extreme water levels (50-year return period) of European seas are reached in the north-eastern Atlantic.

2.1.2 Projections of mean and extreme sea level

Projections for the 21st century suggest that relative sea level over European seas will rise (close to) the fastest along the coasts of the north-eastern Atlantic (see Table 3 in Melet et al., 2024, in this report). Relative SLR in this region will closely track the global mean, with some variations in rates across sea basins. SLR, driven by global mean thermal expansion, salinity, and ocean circulation changes, remains the primary contributor to relative SLR along the European Atlantic coast. Changes in ocean circulation patterns, such as the intensification of currents, are projected to influence mean and extreme wave conditions, affecting coastal flooding and erosion. Projections indicate a decrease in significant wave height and period along European coasts, leading to a reduction in wave set-up and run-up, with the potential exception of the Baltic Sea. Non-linear interactions between SLR, tides, and storm surges can be substantial in the north-eastern Atlantic and are anticipated to have substantial impacts on coastal water levels, with implications for coastal resilience and adaptation measures (see Sect. 6.1 in Melet et al., 2024, in this report).

2.2 North Sea

2.2.1 Drivers of past mean and extreme sea level

The North Sea, bordered by several European countries, experiences a predominant cyclonic ocean circulation due to prevailing westerly winds. It receives warm, saline water from the North Atlantic and cooler, fresher water from the Baltic Sea, resulting in complex dynamics. Relative SLR in the North Sea is largely driven by temperature, salinity, and current changes. Spatially varying rates of relative SLR are also substantially influenced by factors such as ice mass loss and subsidence, with the highest rates of relative SLR found in the south-eastern North Sea. Interannual variations in sea level are mostly driven by variability in local winds and surface atmospheric pressure. Sea levels in the North Sea are known to experience large changes over time. Astronomical tides significantly influence water levels, with the largest tidal ranges observed along the UK east coast. Large, non-linear interactions between the tidal and non-tidal components of water level are especially important in the southern North Sea. Changes in waves, tides, and storm surges have been observed, influenced by historical trends in mean sea level, changes in ocean stratification, and non-linear interactions between water level components.

2.2.2 Projections of mean and extreme sea level

Projections suggest that relative SLR in the North Sea will vary spatially in the 21st century, with higher rates in the southern parts of the basin and spatial differences influenced by factors like past and present terrestrial ice mass loss. Changes in SLR, due to temperature, salinity, and currents, are projected to be relatively uniform across the North Sea. However, uncertainty stemming from factors like the resolution of global climate models (GCMs) and local dynamics are still large. There are likely to be more ESL events due to SLR, which will affect coastal communities, but the increase in frequency of ESLs is smaller than in other European seas. The impact of SLR on storm surges, tides, and waves is significant, particularly in shallow areas, necessitating adaptive coastal management strategies. While the effect of changes in storminess on ESLs remains uncertain, studies agree that mean SLR itself is the primary driver of change in the North Sea (see Sect. 6.2 in Melet et al., 2024, in this report).

2.3 European Arctic

2.3.1 Drivers of past mean and extreme sea level

Vertical land motion (VLM) is a significant driver of relative sea level change in the European Arctic, bordering Iceland and parts of Norway, attributed to past ice mass loss. Ongoing ice mass loss in Iceland and on Svalbard also contributes to local land uplift. Recent studies highlight widespread VLM in the European Arctic due to ice mass loss from Greenland, and an overall rising trend in sea level. Sea level observations are challenging due to the remote location of the European Arctic, the limited number of tide gauges, and hampered satellite measurements.

2.3.2 Projections of mean and extreme sea level

Projections suggest that the European Arctic will experience a below-global-average SLR, mainly due to land uplift effects, particularly from Arctic glaciers and the Greenland ice sheet melting. Consequently, a 0.5 or 1.0 m SLR will be reached later in the future in the European Arctic than in other European seas (see Fig. 11, in Melet et al., 2024, in this report). However, temperature-, salinity-, and current-driven SLR in the Arctic is expected to be larger than the global average, primarily due to ocean freshening. Projections indicate uncertainties regarding changes in storm surges and waves, but future wave climate projections generally indicate a lower mean significant wave height in the north-eastern Atlantic sector. Receding sea ice cover will result in higher waves in the north-western part of the Norwegian and Barents seas (see Sect. 6.3 in Melet et al., 2024, in this report).

2.4 Mediterranean Sea and Black Sea

2.4.1 Drivers of past mean and extreme sea level

The Mediterranean Sea, connected to the Atlantic Ocean via the Strait of Gibraltar, experiences sea level changes driven primarily by mass contributions at basin scale, while the temperature and salinity components explains a significant portion of variance at the subbasin scale. Interannual to decadal basin-averaged sea level variability correlates with the nearby Atlantic, while regional deviations result from ocean circulation, heat redistribution, and air–sea momentum fluxes. Storm surges, due to North Atlantic atmospheric cyclones and to medicanes, and seiches are especially important for ESLs in the microtidal Mediterranean Sea. VLM can be locally important.

The Black Sea, primarily receiving freshwater from the Danube, Dnieper, and Don basins, presents much lower salinity than the Mediterranean. Most of the SLR in this basin appears to be primarily related to salinity reduction, rather than temperature increases. Coastal VLM is a relatively minor contributor to relative SLR in the Black Sea compared with other basins.

2.4.2 Projections of mean and extreme sea level

Multi-model ensemble projections for the Mediterranean Sea suggest basin-averaged rates of SLR by 2100 that are amongst the highest for European seas (see Table 3, in Melet et al., 2024, in this report). The Black Sea's projected relative SLR has been scarcely assessed, but it is expected to be within a range of ±20 % of global mean SLR. Mean SLR will be the dominant driver of increasing coastal ESLs during the 21st century. Storm surges and wind waves are projected to undergo small and mostly negative changes in southern Europe by 2100. Additionally, future changes in medicanes (extratropical cyclones) and meteotsunamis (high-frequency oceanic waves due to rapid atmospheric-pressure changes) are anticipated due to increased sea surface temperatures and altered atmospheric-circulation patterns, with potential implications for coastal hazards. The projected increase in the frequency and amplitude of ESLs is the largest in the Mediterranean Sea among the European seas (see Fig. 12 in Melet et al., 2024, and Sect. 6.4 in Melet et al., 2024, in this report).

2.5 Baltic Sea

2.5.1 Drivers of past mean and extreme sea level

The Baltic Sea is characterized by its semi-enclosed and shallow nature. The NAO plays a significant role in the climate variability in the basin, impacting wind patterns and sea level fluctuations. The Baltic Sea experiences pronounced seasonal variations in sea level. At timescales longer than a month, the mean sea level in the Baltic Sea approximately follows the sea level in Kattegat, outside the Baltic Sea, but with larger variance at the northernmost and easternmost bays. SLR in the southern Baltic Sea approximately follows the projected global mean SLR (or is slightly lower), but land uplift due to ice mass loss is particularly significant in northern subbasins, leading to a relative mean sea level fall there. Storm surges, amplified by westerly winds, pose threats to low-lying coastal areas. Tides have relatively low amplitudes, and ESLs in the Baltic Sea are caused by pronounced atmospheric cyclones that sometimes interact with seiches on daily timescales and with volume changes on weekly timescales.

2.5.2 Projections of mean and extreme sea level

Projections of 21st-century sea levels in the Baltic Sea require high-resolution regional climate models due to the complex coastline and topography of the basin. Available projections suggest continued basin mean SLR in the Baltic Sea under medium- and high-emission scenarios, slightly below the global mean SLR. Relative sea level will continue to exhibit a clear north–south gradient during the 21st century, with a relative sea level fall in the northernmost Baltic Sea due to the effects of ice mass loss (see Fig. 10 in Melet et al., 2024, in this report). Future changes in ESLs will depend on mean SLR; atmospheric-circulation patterns, which remain uncertain; and wind changes. Sea ice loss due to warming is expected to increase sea level extremes in previously ice-covered regions, leading to higher wave heights, coastal erosion, and sediment resuspension. While some studies suggest a rise in ESLs beyond the mean sea level due to changes in atmospheric circulation, confidence in these projections remains limited due to inconsistencies between global climate model projections. Due to land uplift, the lowest amplification factors of the frequencies of ESLs in European seas are found in the northern Baltic Sea (see Sect. 6.5 in Melet et al., 2024, in this report).

3 Coastal flooding, erosion, and saltwater intrusion in Europe

The analysis of the primary impacts of SLR on Europe employs the Source–Pathway–Receptor–Consequence framework and focuses on coastal flooding, coastal erosion, and saltwater intrusion.

3.1 Impacts

3.1.1 Flooding

Coastal flooding, influenced by rising sea levels and various factors like storms, has profound impacts across Europe, causing social, economic, and environmental consequences. Despite high flood-defence standards, significant populations and assets remain vulnerable, especially on low-lying coastal flood plains. The risks are further escalated by ageing infrastructure, urbanization in these areas, and habitat loss. Compound flooding, resulting from combined factors, like heavy rainfall, river overflow, and storm surge, exacerbates these challenges. The interplay of drivers like extreme coastal water levels, tides, storm surges, and waves is receiving increasing attention in development of early-warning and decision support tools.

Climate change intensifies coastal flooding, primarily through SLR, altering flood dynamics and increasing the likelihood of compound events. Efforts to address flooding involve a multi-faceted approach, including coastal defences, habitat restoration, and enhanced flood forecasting.

Policy directives incorporating SLR risk assessments can help to improve flood management strategies. While extensive flood management infrastructure exists, challenges persist, especially with accelerating SLR. Effective adaptation measures and investments in flood resilience are essential to mitigate the growing risks posed by coastal and compound flooding in Europe (see Sect. 4 in van de Wal et al., 2024, in this report).

3.1.2 Erosion

Extreme waves, storm surges, and human activities influence coastal erosion, which governs over 8200 km of European sandy beaches, causing shoreline change. SLR and the reduction of river sediment supply due to human developments and dams are main drivers of erosion.

While local sediment budgets and climate patterns (winds and atmospheric-pressure changes) determine the specific sign and magnitude of shoreline changes, rising sea levels will negatively impact all coastlines by adding a background erosion rate to existing trends. Coastal erosion poses significant challenges for coastal communities, leading to habitat loss, infrastructure damage, and increased flood risk as well as compromising the sustainability of recreational beach use and, thus, impacting the tourism sector.

Europe's coastline is heavily influenced by human activities and infrastructure. Human development along coastlines exacerbates erosion. Effective coastal management strategies must consider the complex interplay of drivers contributing to erosion and shoreline change (see Sect. 5 in van de Wal et al., 2024, in this report).

3.1.3 Saltwater intrusion

Saltwater intrusion (SWI) is the encroachment of saltwater into freshwater resources, affecting both surface waters and groundwater. It poses significant challenges to agriculture, freshwater availability, and coastal communities' livelihoods due to salt damage to crops and health risks associated with saline drinking water. SWI reduces freshwater storage and impacts soil fertility, vegetation, freshwater species, and ecosystem services, especially in deltaic regions and estuaries.

Human activities, including reduced river flows and urbanization, exacerbate SWI. Climate change intensifies SWI drivers, including SLR and reduced freshwater supply, affecting hydrogeological interactions between groundwater, surface water, and marine water. SWI's consequences encompass social, economic, and environmental aspects, including reduced drinking water reserves, agricultural losses, habitat degradation, and land subsidence. Anthropogenic interventions, such as flood barriers and managed aquifer recharge schemes, aim to mitigate SWI impacts by limiting saltwater intrusion and enhancing freshwater resources. However, challenges persist, including the effectiveness of engineered solutions during extreme events and the need for sustainable groundwater management strategies. Future projections indicate increasing groundwater salinization and drinking water loss, underscoring the importance of integrated coastal management and adaptation measures to address SWI's multifaceted impacts on Europe's coastal regions (see Sect. 6 in van de Wal et al., 2024, in this report).

3.2 Regional impact

While not all SLR impacts have been systematically assessed for each basin, an inventory of the main impacts covered within the report are summarized in the text below. The reader is advised not to consider that any impacts not covered for a specific basin are not experienced; rather, these impacts are a possible scope for future assessments to fill these gaps.

3.2.1 Eastern Atlantic

The following SLR impacts are reported for the eastern Atlantic:

- *Flooding*. The eastern Atlantic coastline is affected by coastal flooding due to SLR. Flood-defence standards in many European countries along the eastern Atlantic are among the highest in the world, indicating the high importance of protection measures in this basin.

- *Coastal erosion*. Projections under different emission scenarios indicate a shoreline retreat along the Basque coast of 10–66 m by the year 2100.

- *Saltwater intrusion*. Along the Atlantic coasts, various cases of increased saltwater intrusion in the groundwater system have been reported. Specifically, the Minho and Lima estuaries on the northern coast of Portugal have been affected by SLR, leading to a transgression of the saltier front over several kilometres.

3.2.2 North Sea

The following SLR impacts are reported for the North Sea:

- *Flooding*. The North Sea coastline is significantly affected by coastal flooding due to SLR. Coastal cities, such as Rotterdam, Hamburg, and London, are vulnerable to compound flood events arising from storm surges, waves, river discharge, and heavy precipitation. Port operations may also be negatively affected by SLR.

- *Saltwater intrusion*. Enhanced salinization is projected to be induced by SLR and climate change in several coastal locations in the North Sea. The text cites examples such as the Netherlands and Belgium, where coastal locations are facing increased saltwater intrusion due to SLR.

3.2.3 Mediterranean Sea and Black Sea

The following SLR impacts are reported for the Mediterranean Sea and Black Sea:

- *Flooding*. The Mediterranean Sea coastline is highly vulnerable to SLR-induced coastal flooding. Specific locations such as the Gulf of Valencia, north-west Algeria, the Gulf of Lion, and the Adriatic coast of the Balkan Peninsula present an increased flood risk due to compounding features characterizing hydrometeorological hazards and coastlines.

- *Coastal erosion*. Mediterranean beaches are particularly susceptible to the negative effects of SLR due to their relatively narrow width. Studies project significant erosion impacts on Mediterranean beaches, such as those in the Balearic Islands, with projections of at least 20 % of beaches losing more than 50 % of their surface area by the end of the 21st century.

- *Saltwater intrusion*. There are significant impacts of saltwater intrusion on the Mediterranean Basin, including through increased seawater infiltration in coastal aquifers. This has pronounced consequences for agricultural productivity and poses a threat to coastal ecosystems, including the potential loss of subtidal seagrass meadows.

3.2.4 Baltic Sea

The following SLR impact is reported for the Baltic Sea:

- *Flooding*. The vulnerability of coastal subtidal seagrass meadows and intertidal salt marshes to SLR is particularly high in microtidal areas in parts of the Baltic Sea coast.

Despite prior infrastructure investments, increased flood risk and losses are expected, particularly with higher SLR rates.

4 Adaptation measures and decision-making principles

4.1 Key adaptation strategies

A wide range of adaptation measures and decision-making principles related to sea level rise and coastal hazards exist. Interventions and measures can be classified in four main adaptation strategies (see Sect. 2.1.1 in Galluccio et al., 2024, in this report):

- *Accommodation* refers to measures that enable coping with the consequences of sea level rise, such as flood-proofing buildings and increasing resilience of critical infrastructure, which reduce the vulnerability of coastal communities to SLR impacts. These measures encompass a range of approaches, from flood-proofed materials to early-warning systems and climate risk insurance schemes.

- *Protect* measures aim to reduce coastal hazards through hard and soft defence mechanisms, as well as the restoration and management of coastal ecosystems. Examples include dams and seawalls, artificial reefs, restoring marshes, and other forms of NBSs.

- *Advance* measures involve creating or advancing new land to address coastal flooding and erosion, often through conservation and restoration efforts.

- *Retreat* measures focus on reducing exposure to coastal hazards by relocating human activities, infrastructure, or cities from high-risk to less-exposed areas. This may involve planned relocation or managed realignment programmes. Relocation strategies involve complex trade-offs between effective risk reduction and societal and economic costs.

The reader is refer to Table 1 of Galluccio et al. (2024, in this report) listing the relevant adaptation measures, in response to SLR impacts, for different basins.

4.2 Approaches for decision-making

Coastal adaptation decision-making is complex, demanding thoughtful approaches to address uncertainties about future climate and societal developments. Coastal adaptation decisions involve the selection of various options planned for implementation at different moments in the future. Policy analysis methods exist that systematically examine the sequential ordering and timing of adaptation decisions in the future, including their potential triggers, alternatives, and long-term implications. A combination of participatory and analytical methods is crucial in this process, fostering stakeholder cooperation and identifying suitable options.

Coastal adaptation decision processes usually have to strike a balance between multiple objectives, available measures, and uncertainties about future conditions and policy implications. Methods such as multi-criteria decision analysis (MCA) help manage this complex balance by organizing decisions and highlighting preferences and priorities. Potential low-regret measures can be identified that offer immediate benefits with minimal costs, including awareness campaigns and preservation of landscapes with high societal support.

Inherent SLR uncertainties require the flexibility and adaptability of strategies. Keeping future options open involves postponing long-term decisions where possible and implementing flexible measures that can be adjusted to changing conditions and available information. SLR affects current decisions with long-term consequences, particularly in the domains of critical infrastructure and urban planning. Iterative revision of decisions and monitoring progress enable timely adjustments as well as the adoption of new policies as needed. Adopting a systematic approach to coastal adaptation decision-making ensures resilient and sustainable outcomes amidst evolving challenges. Methods like economic analyses, robust decision-making, and adaptive policy planning aid in evaluating decision timing and strategic prioritization (see Sect. 2.2 in Galluccio et al., 2024, in this report).

4.3 Assessment of regional adaptation

In Europe, adaptation to SLR varies across different sea basins and often includes a combination of accommodate, protect, advance, and/or retreat strategies. All basins display examples of the integration of traditional (hard) engineering solutions with ecosystem-based (soft) measures, community involvement in decision-making processes, and continuous monitoring and flexible management strategies through coastal and marine planning instruments (see Table 1 in Galluccio et al., 2024, and Sect. 2.3 in Galluccio et al., 2024, in this report).

4.3.1 Eastern Atlantic

Across the Atlantic Ocean basin, countries are implementing a variety of adaptation measures, including NBSs and improved spatial planning. Ecosystem-based protection measures, such as cliff strengthening and sand nourishment, are prominent, alongside advance strategies like the regeneration of beaches and artificial-dune systems. Retreat measures, including the removal of constructions in flood-critical areas, are also being considered at various locations.

4.3.2 North Sea

In the North Sea basin, most countries have integrated SLR information into coastal planning, employing a combination of hard and soft protection measures, such as dike upgrades, sand nourishment, and managed retreat. Comprehensive strategies combine flood protection with the maintenance of a healthy freshwater system, while also enhancing societal and ecological values.

4.3.3 Mediterranean Sea

Countries in the Mediterranean Sea basin have advanced the mainstreaming of SLR information into national adaptation planning, e.g. in Spain and Italy. Soft protection measures, including sand nourishment, coastal reforestation, and the restoration of dunes and marshes, are emphasized along with large-scale adaptation initiatives in major urban areas like Venice (Italy) and Barcelona (Spain). Furthermore, insurance is emerging as an accommodation measure to address SLR, e.g. in Spain and France.

4.3.4 Black Sea

In the Black Sea basin, efforts are being directed towards developing monitoring and early-warning systems, alongside upgrading coastal infrastructure to manage SLR and associated flood risks. Initiatives combining sand nourishment, cliff stabilization, and artificial reef building are being implemented with the aim of reducing erosion risks and enhancing resilience in the tourism sector.

4.3.5 Baltic Sea

In the Baltic Sea basin, several nations have integrated SLR projections into spatial planning and land use regulations. Protection measures, including upgrading coastal defences and implementing NBSs, are being implemented and are contributing to marine environment conservation and the enhancement of living marine resources.

5 Governance context and challenges

The governance of coastal adaptation policies includes institutional organization, stakeholder engagement, and the practice of decision-making, including the management of scientific knowledge, conflicting objectives and interests, and the incorporation of a diversity of perspectives and views. Assessment of coastal adaptation governance does require the incorporation of the socioeconomic and political contexts. In the SLRE1, this is carried out by reviewing relevant European coastal adaptation policy frameworks in place at regional and national levels and their contexts within each of the selected sea basins (see Sect. 5.2 in Bisaro et al., 2024, in this report).

5.1 Eastern Atlantic

The eastern Atlantic Basin encompasses several vital economic sectors, such as maritime tourism, shipping, and blue-economy sectors (including renewable energy and green-port infrastructure). However, the basin also faces militarization and competition over natural resources and trade routes. This necessitates strategic engagement and cooperation from the European Union (EU) and its Member States. With the rise in maritime activities, challenges related to sustainable development and resource management emerge. Policy interventions are necessary to balance economic growth with environmental conservation. Atlantic Ocean basin countries have adopted adaptation policy strategies, but challenges persist in addressing uncertainty in SLR and the associated risks. Some countries incorporate SLR into their maritime spatial planning, whereas others lack specific measures.

5.2 North Sea

The North Sea basin hosts significant economic sectors like shipping, oil, and gas and is witnessing heightened attention due to its vast energy reserves and potential for renewable energy, notably offshore wind. The EU aims to leverage these resources for its energy transition to enhance economic growth and stability.

Countries in the North Sea basin have reported SLR as a chronic hazard and have adopted adaptation policy strategies. Coastal adaptation measures vary and funding approaches differ substantially among countries. Governance challenges include maintaining environmental sustainability amidst economic growth while ensuring safe maritime activities and transitioning towards renewable energy sources.

5.3 European Arctic

The Arctic Ocean has become a geopolitical hotspot due to its rich energy resources and strategic positioning to face the growing territorial competition. The EU is actively engaged in Arctic policy, focusing on sustainable development, climate resilience, and cooperation with indigenous populations amidst growing global competition.

The European Arctic faces economic opportunities in traditional sectors, like oil and gas and fishing, and in emerging sectors, including data centres and raw-material extraction. Governance challenges include balancing economic development with environmental conservation and addressing demographic shifts and indigenous peoples' rights alongside industrial growth. In the Arctic Ocean basin, Norway considers mid-range SLR scenarios in planning approaches, highlighting a proactive stance towards coastal adaptation.

5.4 Mediterranean Sea and Black Sea

The Mediterranean and Black Sea regions host crucial traditional economic sectors, like tourism, fisheries, and mariculture, and emerging sectors, like offshore energy. In addition, complex challenges are present, including migration, territorial disputes, and energy security concerns. In its policies and recommendations, the EU emphasizes partnership and cooperation to address conflicts, promote stability, and mitigate environmental degradation in these critical basins.

Governance challenges include sustainable tourism management, ensuring seafood security, and transitioning towards renewable energy sources to mitigate environmental degradation. The Mediterranean Basin has regional instruments addressing coastal adaptation, albeit with limited effectiveness due to the absence of specific measures for SLR. In the Black Sea, regional instruments lack provisions for SLR and coastal adaptation.

5.5 Baltic Sea

The Baltic Sea basin features significant traditional sectors, such as shipping and fishing, and emerging sectors, like offshore wind energy. However, the region also faces security challenges exacerbated by the Russia–Ukraine conflict and aggravated by its energy dependence. Efforts focus on diversifying energy sources, enhancing maritime security, and promoting sustainable development through innovation and cooperation.

Other governance challenges involve addressing pollution concerns, sustainable resource management, and promoting green technologies to reduce environmental impact. Countries in the Baltic Sea basin show varying levels of adoption of adaptation policies and measures addressing SLR. Maritime spatial planning is enforced across the basin, with some countries incorporating SLR into their plans.

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STATE OF THE PLANET

Sea Level Rise in Europe: A knowledge hub at the ocean–climate nexus

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1 Scope of the Knowledge Hub on Sea Level Rise and Knowledge Hub Assessment Report

The Knowledge Hub on Sea Level Rise (KH-SLR) is a joint effort by JPI Climate (http://www.jpi-climate.eu, last access: 28 July 2024) and JPI Oceans (http://www.jpi-oceans.eu, last access: 28 July 2024), focusing on regional to local sea level changes in Europe, as well as the need for science-based information of European policy-making and coastal planning communities. The establishment of the KH-SLR was endorsed by two consultation meetings with the European science and policy community at large in the summer of 2021. The KH-SLR governing structure was established in October 2021.

Even the lower-end projections for sea level rise are expected to impact the livelihoods of residents in the ever-growing coastal populations worldwide. Beyond the obvious threat of permanent inundation of low-lying areas, sea level rise induces numerous other coastal impacts. Key societal and ecological effects include coastal erosion; saltwater intrusion into surface water, groundwater, and agricultural soils; changes in coastal habitats and ecosystems; and damage to cultural heritage sites. It is crucial to continue monitoring current sea level rise and its drivers, develop localized SLR impact projections, and provide an evidence base to support coastal defence strategies.

The KH-SLR identifies scientific knowledge status and gaps and strives to engage coastal planners, managers, and European policymakers in providing up-to-date, accessible information at local and basin scales. Constructing this interface and responding to information needs requires active involvement from professionals in coastal management and policy development. A significant part of KH-SLR activities involves organizing scoping workshops and conferences, which facilitate discussions among scientists, coastal managers, practitioners, and policymakers. These events explore the scientific evidence of sea level rise, its impacts, adaptation planning, and the essential policy frameworks required for informed decision-making.

Actionable knowledge and user engagement (Mach et al., 2020) are the dual pillars of the KH-SLR mission, supporting the development and implementation of policies for the protection and sustainable use of coastal resources at local, national, and European levels. Since the establishment of the KH-SLR, the initial focus of KH-SLR activities has been the production of an assessment report, known as the KH-AR, which is presented in this volume.

The long-term objective of the joint JPI Climate and JPI Oceans KH-SLR could be to ensure a periodic update of the KH-ARs and the creation of a networking platform to facilitate the exchange, synthesis, integration, and generation of knowledge on regional and global historical and future sea level rise characteristics. This might involve creating a customized platform to present the outcomes of the assessment reports in a format that is accessible to various stakeholders. The platform would convey recent scientific and socio-economic developments in an aggregated manner, tailored to current themes and debates in policy and public discussions.

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1.1 Goal of the assessment report

The goal of the KH-AR is to document the state of knowledge of sea level rise topics at the local, national, and European basin scales using an interdisciplinary and integrated approach; elucidate gaps in available information; and outline the present European landscape of policies, governance, and adaptation planning.

The KH-AR is designed to support policymakers in obtaining comprehensive information for informed decisions on protective and adaptive measures against sea level rise impacts. Compared to the IPCC assessment reports (e.g. IPCC, 2023), the KH-AR offers more detailed and region-specific analyses. A collaborative, interdisciplinary approach is adopted to facilitate knowledge and expertise transfer among European member states, fostering solutions for this global challenge and addressing its regional and local nuances.

This first KH-AR is prototyping a potential future program of periodically updated regional SLR assessments. An analysis of its uptake and feedback from stakeholders conducted by JPI Climate and JPI Oceans will determine the feasibility of the format, frequency, and governance of future releases.

1.2 Target audience

The intended audience for this report can be categorized into distinct levels.

1. *National and sub-national level*. This includes research, policy advice, and service organizations. These intermediate stakeholders are responsible for preparing information for policymakers in areas such as coastal planning, climate change adaptation, and infrastructure management, operating across various spatial scales (coastal management units).

2. *European level*. This encompasses experts from various operational, research, and policy services, including the European Environment Agency (EEA), Copernicus Services, the European Center for Medium Weather Forecast (ECMWF), the European Climate Research Alliance (ECRA), the European Marine Observation and Data Network (EMODnet), and the Joint Research Center and the European Commission. These experts contribute to the collection and dissemination of pan-European information and play a crucial role in shaping European policy frameworks.

2 Report's place in the assessment landscape

The existing assessment reports on sea level rise drivers and impacts span a wide range of focus areas, time windows, spatial scales, scenarios, and institutional settings.

In 2019, a Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) was released by the IPCC as part of the sixth assessment cycle (IPCC, 2019). By assessing the new scientific literature, the SROCC responds to government and observer organizations that require specific and updated information at a higher level of topical detail than the regular IPCC assessment reports. SROCC addresses the multidisciplinary and concurrent impacts of sea level rise (specifically in Chap. 8) while primarily focusing at large spatial scales exceeding those of the European coastal areas. The release of the IPCC AR6, in particular the Working Group 1 report (IPCC, 2021), has generated a comprehensive body of literature assessing the Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2014), the Coupled Model Intercomparison Program Phase 6 CMIP6 (Eyring et al., 2016) projections, and the corresponding SLR scenarios. The KH-AR uses CMIP6 and SSP scenarios as a general reference.

The COordinated Regional climate Downscaling EXperiment (CORDEX) under the coordination of the World Climate Research Program (WCRP) has established common protocols for climate downscaling studies from projections of global climate models. For Europe, two main downscaling regions were considered: the EURO-CORDEX (Jacob et al., 2014) and Med-CORDEX (Somot et al., 2018) regions. At the moment of constructing the KH-AR the available downscaled data make use of older global climate simulations than CMIP6 (such as the projections assessed in the IPCC Fifth Assessment Report), although a first white paper on CMIP6-driven downscaling has been recently published (Sobolowski et al., 2023). However, CMIP6-based regional downscaling datasets are not yet widely available and have not been used extensively in this KH-AR.

Several international assessment reports dedicated to European sea basins have recently been produced. For the Baltic Sea Meier et al. (2022) provided an update of the second release of the Baltic Climate Change Assessment, addressing atmospheric, oceanic, cryospheric, and ecologic topics affecting the Baltic Sea region. A special journal issue dedicated to assessing physical, ecological, and socio-economic climate trends and sea level rise (SLR) in the Mediterranean Sea has been published (Somot et al., 2018).

A range of data platforms and portals to display analyses of observational data and CMIP experiments has recently become available. Data and projections on SLR and its impacts are primarily derived from the following portals:

1. the IPCC/NASA sea level projection tool (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool, last access: 28 July 2024) – a repository of all sea level rise products published in AR6 (Fox-Kemper et al., 2021);

2. the IPCC Interactive Atlas (https://interactive-atlas.ipcc.ch/, last access: 28 July 2024) published in AR6 (Gutiérrez et al., 2021);

3. the Copernicus Marine Service operated by Mercator Ocean International (https://data.marine.copernicus.eu/, last access: 28 July 2024);
4. the Copernicus Climate Change Service (C3S) operated by ECMWF (https://climate.copernicus.eu/, last access: 28 July 2024).

In addition, knowledge and experience on marine and coastal spatial planning are retrieved from the European Maritime Spatial Planning Platform (https://maritime-spatial-planning.ec.europa.eu/, last access: 28 July 2024). The EEA operates several online platforms assessing a range of climate indicators including sea level rise and building on an analysis of global and local observations and projections (https://www.eea.europa.eu/ims/global-and-european-sea-level-rise, last access: 28 July 2024). The EEA Climate Adapt portal (https://climate-adapt.eea.europa.eu/, last access: 28 July 2024) collects data, use cases, and adaptation support tools to support decision makers and practitioners with knowledge, information, and experience.

At the global and European scale, the Copernicus Marine Service publishes annually the Ocean State Report that is a reference report of the European Union where both observations and model-based sea level reconstructions and extreme events are published (von Schuckmann et al., 2023). The Copernicus Climate Change Service publishes sea level trend climate indicators, updating the information every year. It publishes annually the interactive European State of the Climate (ESOTC) report.

3 Knowledge Hub on Sea Level Rise's operational processes

The knowledge hub process has applied approaches for user consultation to build bridges between research and key stakeholders. These include JPI Climate and JPI Oceans country representatives as well as the European coastal management and research communities at large.

The consultation activities resulted in setting up a governance structure for the KH-SLR management under the auspices of both joint programming initiatives, the implementation of an ad hoc consultation with five European basin-scale communities via workshops, and the organization of a science-policy conference enabling topical discussions between policymakers from different European regions. Those combined efforts finally led to the compilation of the present assessment report. In the following we will describe these collaborative activities and their outcomes.

3.1 The KH-SLR governing structure

To establish the KH-SLR governance structure in 2021, members of the JPI Climate and JPI Oceans governing boards appointed national contact points (NCPs) forming a KH-SLR governing council (GC). Nine countries contribute to this structure: Belgium, France, Germany, Ireland, Italy, Norway, Spain, Sweden, and The Netherlands.

The GC appointed a management committee (MC) which is directed by two co-chairs with the support of the secretariats of the two JPIs. The MC is composed of experts in various disciplines regarding SLR drivers and impacts. Several task groups (TGs) were established:

- TG-1 – co-design and user engagement, responsible for the survey, scoping workshops, and a dedicated KH-SLR conference (delivered in 2022; see Sect. 3.2);
- TG-2 – topical science experts on adaptation policies and governance;
- TG-3 – topical experts on physical science addressing SLR and its impacts;
- TG-4 – outreach and communication.

Membership of these TGs was formed by experts from all countries that actively support the KH-SLR, supplemented by experts from non-supporting countries for larger representativity and sharing of workload. The TG experts were primarily involved in the discussion and writing of the KH-AR as well as the preparation of the scoping workshops and the conference. Every TG is directed by two co-chairs, and the collection of co-chairs forms the MC that oversees the scientific development and process management supporting the KH-AR. The overall governance structure is visualized in Box 1.

3.2 The user consultation process

For the various ocean basins in Europe, scoping workshops were organized to make an inventory of the requested knowledge on SLR and its impacts, the governance arrangements, and adaptation strategies. During these workshops, interaction between scientists and policy practitioners took place, leading to comparative discussions on challenges and options for regional SLR management. All workshops followed a similar format, and each workshop was held online and spread over two consecutive days. The European ocean basins considered are the Arctic, the Baltic Sea, the North Sea, the eastern Atlantic, the Mediterranean, and the Black Sea.

The final step of the user consultation was achieved by a European SLR conference held in Venice on 17–18 October 2022. Aims and outcomes of the conference are outlined in Box 2.

3.3 The review process

The AR papers were initially structured by the coordinating authors (being the co-chairs of the task groups) and co-authors (members of the task groups). A first review was carried out by members of the KH-SLR governing council and management committee. Based on the feedback from this internal review, revisions were made to produce a second-order draft, which was submitted as a series of chapter papers to the scientific journal *State of the Planet*. An open discussion stage was initiated, during which all five papers were posted as preprints for public commenting by invited referees, authors, and the scientific community following the review procedures of the journal. This ensured comprehensive evaluation and transparency, and after a number of review iterations it resulted in five accepted manuscripts. The “Summary for Policymakers” (SPM) was drafted as a stand-alone document and was subjected to a similar review process.

Box 1: KH-SLR governance structure

Box 2: The Venice Sea Level Rise Conference

A KH-SLR pan-European conference took place on 17–18 October 2022 at the Scuola Grande San Giovanni Evangelista of Venice, Italy. The conference convened researchers, stakeholders, and policy professionals to evaluate existing and needed scientific knowledge regarding regional–local sea level change in Europe. Discussions also focused on policy development and implementation, incorporating the latest geographical and contextual details. The outcome of the conference was the scope and rough outline of the first assessment report. Through a diverse set of keynotes, panels, and other sessions, the conference has put the needs and involvement of policy-making and coastal planning at the centre of exchanges on regional to local sea level changes in Europe. The conference endorsed the following recommendations:

1. The KH-SLR Assessment Report (KH-AR) is a valuable repository of actionable science in climate change adaptation and mitigation.

2. The KH-AR provides regional specificity, assessing projections and drivers of SLR impacts, utilizing common benchmarks, datasets, and analysis tools.

3. Beyond rising waters, the KH-AR explores compound floods, flood-erosion patterns, and shoreline changes, proposing solutions such as nature-based approaches and addressing groundwater salinization.

4. The KH-AR goes beyond physics, encompassing marine spatial planning options, methodologies for finalizing and assessing risk, and considerations of risk perception and learning scenarios.

4 Structure of the assessment report

The KH-AR is composed of five scientific peer-reviewed papers published in the Journal *State of the Planet*, each addressing major conceptual milestones of the KH-SLR mission. It is concluded with a stand-alone “Summary for Policymakers” compiled from the paper’s findings.

The first paper (Jiménez et al., 2024) reports the results of the external stakeholder consultation, consisting of basin workshops organized during 2022, the European Sea Level Rise Conference, and a web survey. During this consultation actionable knowledge needs were collected, which shaped the contents of the KH-AR.

The second and third papers offer an overview of research results from observational and modelling data sets for Europe, synthesizing SLR (Melet et al., 2024) and its impacts (van de Wal et al., 2024) in the European regional seas.

The fourth paper presents an inventory of adaptation principles and activities undertaken in Europe (Galluccio et al., 2024), while the fifth paper discusses governance aspects connected to adaptation plans (Bisaro et al., 2024). A summary for policymakers concludes the assessment report (van den Hurk et al., 2024).

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Sea Level Rise in Europe: Knowledge gaps identified through a participatory approach

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Abstract. The Intergovernmental Panel on Climate Change (IPCC) plays a pivotal role in delivering information and knowledge on sea level rise (SLR), a global threat impacting coastlines worldwide. However, considerable disparities still persist in Europe in understanding and applying sea level science, evaluating its repercussions, and devising effective adaptation strategies. These are influenced by local factors such as diverse environments, socioeconomic conditions, policy contexts, and diversity in stakeholder involvement, producing, in turn, varying knowledge gaps and information needs across European sea basins. In this context, this chapter presents the findings of a comprehensive scoping process carried out by the European Knowledge Hub on Sea Level Rise (KH SLR) to define the outline of the first KH SLR Assessment Report. It consists of the analysis of stakeholder responses to an online survey and insights shared during four regional workshops, aiming to pinpoint critical gaps in available information on SLR and its potential consequences in European sea basins. It considers viewpoints from both scientific and policy perspectives, engaging stakeholders from academia and research and government sectors. The analysis is divided into three categories: (i) SLR science and information, (ii) SLR impacts, and (iii) SLR adaptation policies and decision-making. Regarding SLR science and information, many respondents found that relevant gaps exist in regional SLR projections and uncertainties, particularly related to long-term (from multidecadal to end of century) SLR induced by potential melting of large ice sheets. Interestingly, the perspective on information gaps is different for scientists (emphasizing the need to increase regional projection capabilities) and government users (stressing the availability of accurate projections for their regions). Regarding impacts and hazards, shoreline erosion stands out as a dominant concern in all sea basins except the Arctic, while emerging issues like saltwater intrusion and the role of SLR in compound risks associated with extreme water levels and river flow were also given significant regional relevance. With regard to policy and decision-making, existing adaptation plans are perceived as ineffective and lacking adaptability, with gaps related to underestimated impacts and urban planning. Participants, especially end-users of sea level knowledge, emphasized the relevance of improved information dissemination and communication to support informed decision-making.

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1 Introduction

Despite the global threat posed by sea level rise (SLR) to coastlines worldwide and the crucial role played by the Intergovernmental Panel on Climate Change (IPCC) in providing assessments based on the existing literature (IPCC, 2021, 2022), there remains an uneven distribution in both the knowledge and application of sea level science, the assessment of its impacts, and the formulation of adaptation plans (Magnan et al., 2023; McEvoy et al., 2021). This may be associated with local factors such as the diversity of environments, socioeconomic conditions, policy contexts, and stakeholders which cause local needs and knowledge gaps to vary from one site to another. As decisions regarding the response to SLR need to be made at a national, regional, or local scale, it is necessary to assess knowledge gaps and needs at the same scale. This is the ambition of the European Knowledge Hub on Sea Level Rise (KH SLR) which was initiated with the objective of providing easily accessible and practical knowledge on regional and local sea level changes and their consequences. For each of the ocean and sea basins surrounding Europe (Fig. 1; Table 1), characteristics on drivers of sea level variability, coastal occupation, SLR impacts, and approaches to SLR adaptation are recognized.

To achieve its long-term goals (see Chap. 2 in this report), the initial implementation phase of the KH SLR centred on a scoping process. This process consisted of four key components that collectively contributed to identifying the primary issues pertinent in European seas. The approach followed a bottom-up methodology, which integrated the viewpoints and contributions of representative stakeholders from European seas. As suggested by Fraussen et al. (2020), an effective stakeholder consultation approach involves a hybrid array of tools, encompassing open surveys, workshops, conferences, and closed consultations with specific interest groups. This comprehensive approach enhances engagement with a diverse range of stakeholders and ensures a rich inflow of information.

The KH SLR scoping process adopted this hybrid approach through four key components: (i) an online survey, designed to collect insights and perceptions on SLR in European sea basins from a diverse range of stakeholders; (ii) four dedicated workshops on SLR, tailored to each basin, which provided focused discussions and knowledge exchange, enabling a deeper understanding of regional challenges; (iii) a pan-European conference on SLR, serving as a platform for experts and stakeholders from across Europe to share their expertise, experiences, and perspectives on SLR; and (iv) a closed consultation with member-country representatives involved in the Joint Programming Initiatives (JPI), JPI Climate and JPI Oceans.

The Sea Level Conference 2022, promoted by the KH SLR, focused on evaluating and exchanging scientific knowledge and policy development regarding SLR in European coastal regions. Rooted in findings from the survey and scoping workshops, it featured insights from experts from the Knowledge Hub, as well as invited experts and policymakers from each basin, through a combination of keynote speeches, panels, and posters. The outcomes aimed to provide accessible and updated knowledge tailored to users across European basins, addressing the needs of policymakers, coastal planners, and stakeholders.

This work provides a comprehensive summary of the scoping process undertaken in the survey and sea-basin-specific workshops and presents the key findings from each. The primary objective of this process is to identify critical gaps in available information on regional SLR and its potential impacts in European sea basins and to discern the knowledge requirements and areas necessitating further research for both experts and stakeholders. These findings form the basis for this assessment report and are expected to inform future research endeavours and policy decisions.

2 Methods

2.1 Survey design and data collection

The KH SLR conducted an online survey targeting stakeholders involved in coastal planning and research, especially those whose work is related to or influenced by SLR. The online questionnaire was hosted on the EU Survey platform (https://ec.europa.eu/eusurvey/runner/KH-SLRsurvey2022, last access: 19 July 2024). Invitations to participate were distributed through various channels, including the JPI Climate and JPI Oceans websites and social media channels, direct outreach to individuals within government offices, and distribution via mailing lists. Invited participants were also encouraged to share the survey with others who fell within the target audience. The first round of invitations was dispatched in January 2022, followed by multiple reminders in the first half of 2022. The data presented here reflect responses received until July 2022 in anticipation of the Sea Level Rise Conference 2022 held by the KH SLR in October 2022 in Venice, Italy.

In total, we received responses from 200 participants across 23 European countries (94 % of the participants) and 8 non-European countries (6 % of participants) who provided information and perceptions about the covered sea basins according to the distribution shown in Fig. 2. The participants were broadly categorised in two professional groups (Fig. 2): (i) government, encompassing individuals working within regional or central government agencies and international organizations (about 35 % of the total); and (ii) research, including those affiliated with universities, research institutes, private companies, and non-governmental organizations (NGOs) (about 65 % of the total).

Table 1. Basic indicators for European sea basins (data sources and methodology are shown in the Supplement) (LECZ is the low-elevation coastal zone between 0 and +10 m a.m.s.l.; GIA is the glacial isostatic adjustment). Rates of SLR per European regional sea for 1950–2014 are based on Dangendorf et al. (2019). Coastal archetypes are as defined in Haasnoot et al. (2019). Methods to derive extension of archetypes and population are shown in the Supplement.

Basin name and countries*	Mean SLR 1950–2014 (mm yr^{-1})	Coastal archetypes (%)	Population in LECZ (2020)
North Sea (Denmark, UK, Germany, Norway, the Netherlands, Belgium)	1.5 ± 0.1	Urban: 6.44 % Rural: 62.62 % Urban delta: 0.49 % Rural delta: 2.73 % Urban estuary: 0.72 % Rural estuary: 23.91 % Urban delta/estuary: 0.41 % Rural delta/estuary: 1.82 % Cliff: 0.87 %	24.88 million people
Arctic seas (Norway, Iceland)	1.5 ± 0.1 1.4 ± 0.1 (GIA corrected)	Urban: 4.29 % Rural: 84.39 % Urban estuary: 0.44 % Rural estuary: 5.90 % Cliff: 4.97 %	9.02 million people
Atlantic coast (France, Spain, Ireland, UK, Portugal)	1.2 ± 0.1		
Baltic Sea (Sweden, Denmark, Finland, Latvia, Estonia, Lithuania, Poland, Germany)	−1.1 ± 0.4 1.8 ± 0.4 (GIA corrected)	Urban: 6.26 % Rural: 77.09 % Urban delta: 0.11 % Rural delta: 0.66 % Urban estuary: 1.03 % Rural estuary: 14.19 % Urban delta/estuary: 0.01 % Rural delta/estuary: 0.46 % Cliff: 0.18 %	6.90 million people
Mediterranean Sea (Spain, France, Italy, Croatia, Montenegro, Albania, Greece, Malta, Türkiye)	1.2 ± 0.1	Urban: 6.55 % Rural: 73.95 % Urban delta: 0.07 % Rural delta: 1.00 % Urban estuary: 0.38 % Rural estuary: 17.31 % Urban delta/estuary: 0.05 % Rural delta/estuary: 0.60 % Cliff: 0.54 %	12.38 million people
Black Sea (Romania, Bulgaria, Türkiye)	1.2 ± 0.1	Urban: 7.45 % Rural: 78.57 % Urban delta: 0.03 % Rural delta: 2.11 % Urban estuary: 0.90 % Rural estuary: 1.55 % Urban delta/estuary: 0.02 % Rural delta/estuary: 9.34 % Cliff: 0.05 %	1.31 million people

* The extension of the coastal zone along the European sea basins used to measure archetypes and population in LECZ is shown in Fig. S2 in the Supplement.

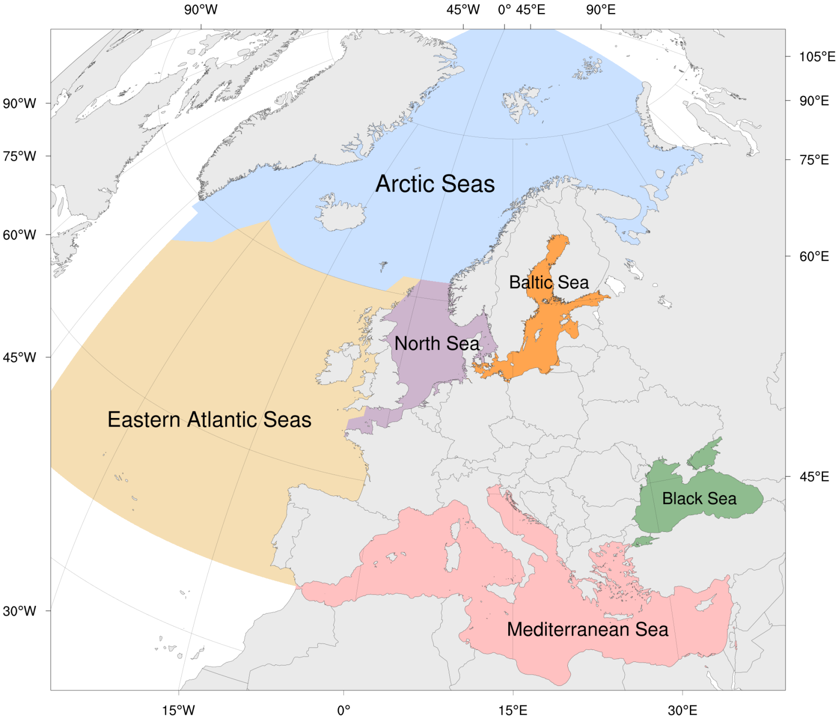

Figure 1. KH categorization of sea and ocean basins across Europe into regional seas, which serves to organize the consultation process.

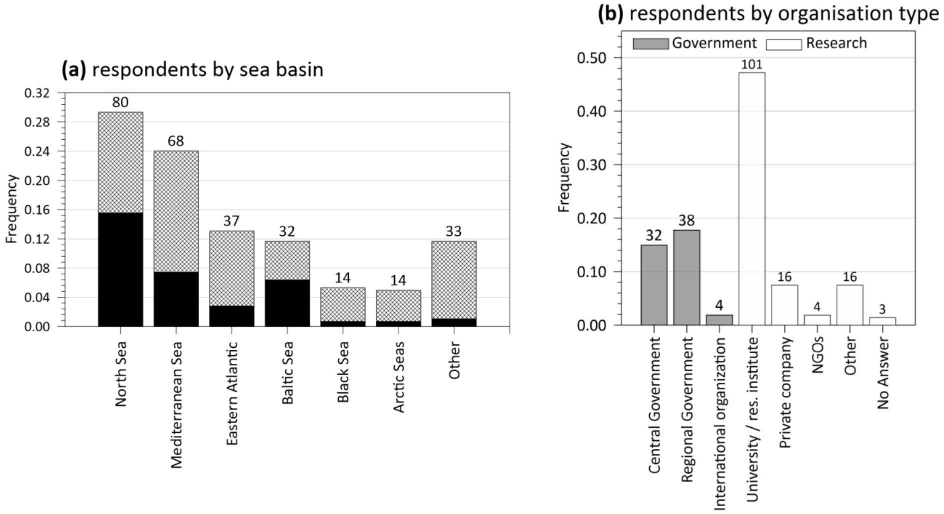

Figure 2. **(a)** Breakdown of respondents by sea basin (solid black bars show the percent of government respondents; cross-hatched bar shows the percent of percent research respondents). "Other" refers to areas of interest other than the European sea basins, such as the global ocean or the Pacific (only 10 respondents declared an area of interest outside the European sea basins). **(b)** Distribution of respondents by organization type. The numbers above each bar indicate the total number of respondents for each category (sea basin and organization type). Note that respondents can be representative of more than one basin and may belong to two different institutions.

The survey questionnaire commenced with a concise introduction, outlining its purpose. It was structured in four sections. The first section sought information about the respondents, including the type of institution/organization they were affiliated with and the specific sea basin that best aligned with their work. For both questions, participants had the option to select multiple responses when applicable. The second section consisted of five closed-ended questions and one open-ended question with the aim of assessing the need for, availability of, requirements for, and usage of SLR information. The third section featured three closed-ended questions, serving the purpose of identifying the most relevant impacts associated with SLR. It also assessed the availability and importance of impact assessments. The final section included three closed-ended questions and two open-ended questions focused on policy decisions and adaptation strategies related to SLR. The survey concluded with a general question about the perceived usefulness of SLR information in IPCC Assessment Reports. A comprehensive list of all survey questions can be found in the Supplement.

To assess the closed-ended questions related to specific topical statements, a Likert-type scale with five response categories was employed, spanning from “strongly disagree (1)” to “strongly agree (5).” Likewise, a similar scale was utilized to gauge the perceived significance of the impact assessment, offering choices from “not important (1)” to “very important (5).” Similarly, when evaluating the effectiveness of adaptation strategies, the scale ranged from “nonexistent (1)” to “very effective (5).”

To determine the overall relevance of multiple answers, a total score was calculated that considered responses from all surveyed sea basins. This score was computed by summing the percentages of respondents who selected each answer across all basins. The resulting score ranges from 0, which signifies that no respondents selected the answer across any sea basin, to 600, indicating unanimous selection of the answer across all six sea basins, with each basin contributing a maximum of 100 to the total score.

Regarding open-ended questions, we categorised the responses by keywords that encapsulated their content. These keywords were then visualized using a word cloud chart to highlight the most pertinent topics while estimating the percentage of times they were identified by participants.

2.2 Scoping workshops

The scoping workshops conducted in 2022 played a pivotal role in the process of identifying the requirements of policymakers, coastal planners, and stakeholders at large. The insights gathered from these workshops were instrumental in shaping and collaboratively designing the key themes related to SLR drivers, impacts, and policy options for each of Europe’s major sea basins to be addressed in the Assessment Report.

Four scoping workshops were run online between March and May 2022. Each workshop had a specific focus on one or two European sea basins and was organized by one or more partner institutes within the respective region, with support from the Secretariat to the KH SLR (Table 2).

The agenda of the workshops mirrored the structure of the survey, although each specific workshop adapted it slightly. This approach ensured that results would be comparable and allowed for a cohesive discussion of the three main sections: (i) SLR physical science and data, (ii) SLR hazards and impacts, and (iii) SLR adaptation policies and decision-making. The agenda was further divided into distinct segments, including keynote speeches, stakeholder contributions, and expert presentations from the scientific community. In addition to these, interactive breakout sessions were incorporated and moderated by the workshop conveners. These interactive sessions were facilitated using the remote collaboration tool, Mural. The detailed agendas of the scoping workshops can be seen in the Supplement.

Each online workshop spanned 2 d, totalling 8 h of engagement, and attracted a diverse range of participants, with attendance ranging from 42 to 70 registered individuals (Table 2). Participants ranged from stakeholders from each European sea basin who participated in the survey to others who responded to either personalized or public invitations. Upon approval of their registration, participants received comprehensive materials, including the agenda, meeting link, detailed instructions, and expectations from their active involvement in the workshop.

3 Results

3.1 Survey

3.1.1 Sea level rise information

When asked about the availability of essential information and data on SLR required for their work, approximately 32 % of the respondents expressed that a substantial portion of this information is missing. This observation holds true across different respondent profiles (government 33 %; research 32 %) (see Table S1 in the Supplement). The highest percentage reporting a lack of information was identified in the Arctic (43 %) and Mediterranean (40 %) sea basins. Notably, there was a significant difference between science (34 %) and government (57 %) respondents in these regions, emphasizing the disparity in access to information. In contrast, the lowest percentages of respondents indicating information deficits were associated with the Baltic Sea (25 %) and North Sea (26 %) basins (Fig. 3).

Among the various types of available information, global sea level projections received the highest accessibility and utilization scores (total score of 455 out of 600). Regional sea level projections followed closely (total score of 367 out of 600), as depicted in Fig. 3. Importantly, there were no significant disparities observed across different sea basins, with the differences remaining under 15 %. However, it is worth noting that the Black Sea and Arctic basins exhibited the largest deviations from the prevailing trend regarding information accessibility (global and regional projections as information types). Nevertheless, these findings show the disparity in the use of SLR information among stakeholders across different sea basins. Hirschfeld et al. (2023) previously pointed to this inconsistency in the use of SLR information by coastal planners in their adaptation efforts.

All respondents unanimously concurred on the necessity for periodic updates to SLR projections and the importance of comprehending the associated uncertainties in these pro-

Table 2. List of scoping workshops.

Region	Organizers	Dates	Attendees
North Sea and Arctic Ocean	Deltares, NL, and Nansen Environmental and Remote Sensing Center, NO	21–22 March 2022	65
Eastern Atlantic	French Research Institute for Exploitation of the Sea, FR	28–29 April 2022	42
Mediterranean and Black seas	Universitat Politècnica de Catalunya, BarcelonaTech, ES; University of Bologna, IT, and Euro-Mediterranean Centre on Climate Change, IT.	5–6 May 2022	70
Baltic Sea	Leibniz Institute for Baltic Sea Research Warnemünde, DE; Federal Maritime and Hydrographic Agency of Germany, DE, and Tallinn University of Technology, EE.	9–10 May 2022	70

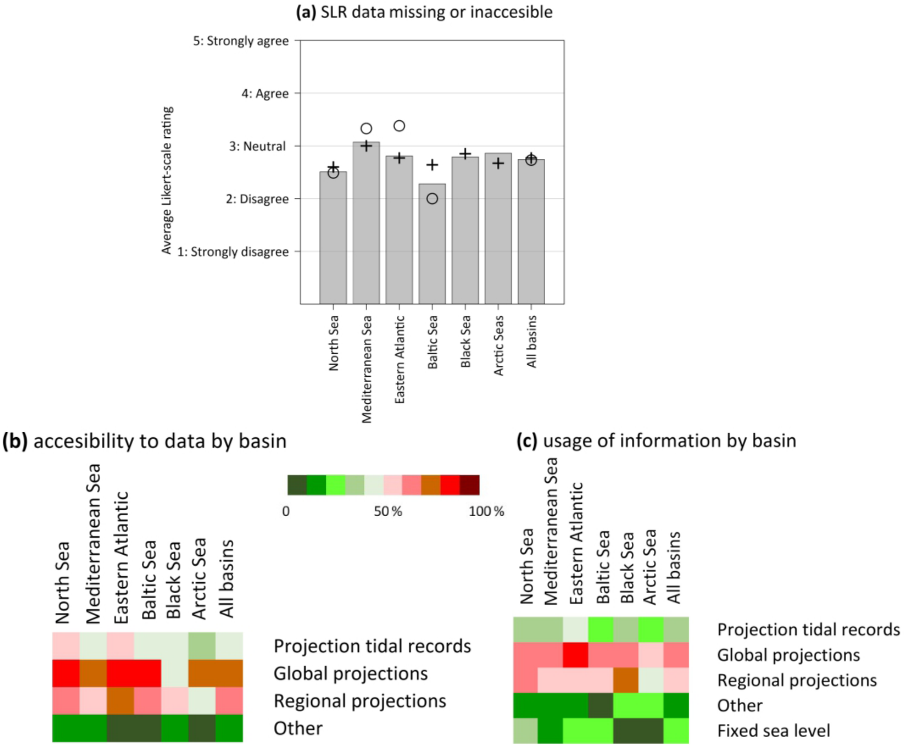

Figure 3. **(a)** Average rating on the Likert-scale to the statement “For my work, crucial information and data on SLR are missing and/or not accessible” (o is for government; + is for scientists; the grey bar shows the total). **(b)** Percentage of respondents who reported having access to specific types of SLR data/information (the original question was “What type of SLR data and/or information do you have access to?”). **(c)** Percentage of respondents who reported the use of the mentioned type of SLR data/information (the original question was “What type of SLR data and/or information do you use?”).

jections (see Table S1). Over the years, SLR projections and their uncertainty have undergone notable evolution, as evidenced by Garner et al. (2018) and Bamber et al. (2022), among others, emphasizing the need for regular updates.

Figure 4 shows the word clouds generated from responses to an open-ended question seeking to identify the most relevant knowledge gaps in SLR among respondents from both science and government. The percentage of responses identifying each keyword-related issue per respondent category is shown in Table 3. The identified gaps are notable in three topics: regional and local SLR projections, the overall level of uncertainty associated with these projections, and, most significantly, the uncertainty related to contributions from ice sheet melting. Both government and scientist respondents identified the same gaps, although with slight variations in their perspectives and relative importance (Table 3). For instance, government respondents emphasized the need for precise regional projections, viewing them as the ultimate

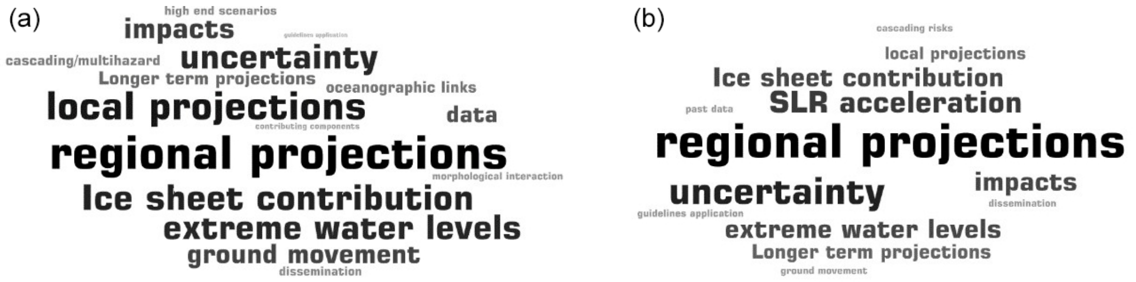

Figure 4. Word cloud representation of responses to the open-ended question “From the perspective of your work, what are the largest knowledge gaps in SLR?” from scientist **(a)** and government **(b)** respondents (generated using the WordArt Generator at http://wordart.com, last access: 3 November 2023) (see Table 3 for their quantitative representativity).

Table 3. List of keywords and percentages of responses within the type of respondents who identify a keyword-related issue to the open-ended question “From the perspective of your work, what are the largest knowledge gaps in SLR?” (only issues with a response rate larger than 5 % are shown). Examples of different responses associated with the same keyword indicate a different view/interest in the issue.

Respondents’ profile	Scientists	Government
Keywords and percent of responses identifying a keyword-related issue over the total of responses	Regional projections: 19 % Local projections: 13 % Ice sheet contribution: 11 % Extreme sea levels: 10 % Uncertainty: 10 % Impacts: 7 % Ground motion: 6 %	Regional projections: 29 % Uncertainty: 18 % SLR acceleration: 11 % Extreme sea levels: 9 % Ice sheet contribution: 9 % Impacts: 9 % Longer-term projections: 5 %
Example of different views on the same topic (regional projections)	Determining relative importance of different regional contributions (land subsidence, isostatic adjustment, glacier melting, and sediment compaction).	Regional mean sea level projections for the inner German Bight for different IPCC scenarios.
Example of different views on the same topic (uncertainty)	Refining uncertainty in future sea level projections associated with deep ocean contribution, Arctic contribution, and ice sheet mass change.	The largest gap is not the question of understanding how uncertain any given SLR scenario is but rather dealing with the fact that all SLR scenarios are uncertain.

product. From their perspective, these projections play a crucial role in fulfilling their responsibilities, and in relation to this, uncertainty emerges as the second most identified issue; in this case, these stakeholders are concerned about how to address it. On the other hand, scientists prioritize a more comprehensive understanding of the various factors influencing regional projections, considering these insights as the final goal to be achieved. Uncertainty is frequently mentioned, especially with regard to the factors contributing to it. In addition to these commonly recognized gaps, scientists expressed heightened concern regarding other common issues. These include improving local SLR projections, which requires a more accurate understanding of ground level movements. Surprisingly, government respondents appear to be less concerned about this matter. Furthermore, both types of respondents acknowledge the necessity of comprehending the impact of SLR on extreme water levels, as well as its influence on compound/cascading events and multihazard risks, although the latter is given lower priority.

3.1.2 Impacts

The experts assessed the most relevant impacts of SLR for each of the sea basins by selecting from a list of the most common impacts along the European coast (Fig. 5). Among these impacts, coastal/beach erosion emerged as the most critical concern, with a total score of 537 out of 600, prevailing in all basins except the Arctic Sea. The prominence of this issue can be attributed to the essential role played by beaches not only in supporting coastal tourism and the regional economy but also in providing a natural defence for inland areas. Furthermore, this is a widely recognized SLR-induced impact (e.g. Nicholls and Cazenave, 2010), the importance of which has been documented along the European coastline (e.g. Vousdoukas et al., 2020a). The reduced significance of this impact in the Arctic seas can be attributed to the fact that this region has the lowest percentage of sandy shoreline (e.g. Luijendijk et al., 2018) and the largest representation of cliffs among the analysed sea basins (Table 1).

The second most pertinent impact identified was the influence of SLR in increasing storm impacts, a concern uniformly acknowledged across all sea basins (total score of 480 out of 600). This impact is well-documented and widely acknowledged, involving the projected rise in extreme water levels due to SLR, thereby increasing the likelihood of present-day storm surges and inundation events (e.g. Vousdoukas et al., 2018). Conversely, permanent inundation due to SLR is generally perceived as a less significant impact (361 out of 600). It will primarily affect very low-lying and unprotected areas, with relatively limited extent, mainly concentrated in natural areas (e.g. Antonioli et al., 2020).

Damage or loss to public infrastructure (471 out of 600) and, in a slightly smaller proportion, private properties (417 out of 600) was identified as a relevant impact. This is highly related to the large exposure of these assets along the European coasts and with an expected increase in damage under SLR (e.g. Vousdoukas et al., 2020b).

Groundwater salinization (338 out of 600) is a lesser concern in the eastern Atlantic, Black Sea, and Arctic basins. In contrast, it holds substantial importance in the remaining sea basins. This significance is grounded in the presence of pre-existing soil salinization issues (Daliakopoulos et al., 2016) and the anticipation of potential salinity challenges exacerbated by climate-related factors (e.g. Falloon and Betts, 2010; Oude Essink et al., 2010). The relatively limited attention given to this impact can be linked to the predominant role played by other natural and anthropogenic variables that affect groundwater salinity (e.g. Taylor et al., 2013).

The relevance of these impacts for the European sea basins is underscored by the nearly unanimous consensus among respondents (mean value of 4.55 on the Likert scale) on the need to employ impact assessments in shaping planning decisions amidst SLR (see Table S2). Despite this consensus, approximately 39 % of all respondents faced challenges due to the absence of up-to-date and high-quality assessments of SLR-induced impacts. This perception was consistent across all sea basins, with the Black Sea and Arctic Sea facing the most pronounced gaps in the available assessments (Fig. 5). Government respondents conveyed a more positive outlook compared to those from the research sector (see Table S2). Specifically, 44 % of research respondents disagreed or strongly disagreed with the statement "high-quality and up-to-date assessments of SLR-induced impacts are available for making decisions on planning", whereas only 32 % of government respondents held this view.

3.1.3 Adaptation

Last, respondents were queried on the performance of adaptation plans and strategies aimed at addressing the impacts of SLR in their respective regions (see Table S3). Regarding the effectiveness of the current adaptation plans, a noteworthy 51 % of respondents assessed them as either insufficient or inexistent (Fig. 6). Significantly, scientists exhibited a more critical perception in this regard, with an additional 18 % deeming the plans as insufficient, compared to government respondents. Nevertheless, a relatively low proportion of respondents (7.5 %) indicated the complete absence of adaptation plans, aligning with the findings of a recent survey of McEvoy et al. (2021) on the planning approaches of European countries in response to SLR. Notably, the Black Sea basin emerged as the region where the absence of plans was most conspicuous.

Regarding the perceived flexibility of the existing adaptation strategies and plans in the face of future SLR-induced impacts (or conversely, the ability to cope with the inherent uncertainty in their assessment), 40 % of respondents expressed the view that existing plans lack sufficient flexibility (see Table S3). This perception remained relatively consistent across different sea basins, with the Arctic and Black seas exhibiting the lowest perceived lack of flexibility. In general, there were no significant differences in perception based on respondent type, except in the North Sea, where government respondents were notably less positive about flexibility, with a 15 % difference compared to scientists. It is important to note that flexible adaptation allows for plan adjustments in response to future changes. Unless plans are designed with an adaptation-pathway-like approach (Haasnoot et al., 2013), achieving this flexibility can be challenging. In this context, Kim et al. (2022) introduced a framework for assessing the flexibility in adaptation plans.

Participants were asked to identify areas where considerations related to SLR are often neglected but should be incorporated into decisions and policy objectives. Figure 7 shows word clouds generated from responses to this open-ended question, while Table 4 provides the distribution of the most frequent responses according to the type of respondents. A significant proportion of respondents (68 % and 65 % for scientist and government, respectively) either did not respond to this question or indicated that there were no relevant decision requiring the inclusion of SLR considerations that did not include it. Notably, scientists identified a greater number of issues in comparison to government respondents (Fig. 7). Those who identified such omissions emphasized key gaps primarily related to management issues in the coastal zone or, directly, SLR-induced impacts such as saltwater intrusion or damage to infrastructure (previously prioritized in Fig. 5). A prominent emerging issue is the interaction of SLR with coastal ecosystems, which is mentioned in different ways, including its impact on existing ecosystems, disruptions of ecosystem services, and ecosystem management. This aligns with the growing concerns about the anticipated impact of SLR on coastal habitats, particularly in areas such as coastal wetlands (e.g. Schuerch et al., 2018), and the projected decline in services provided by coastal ecosystems (e.g. Pa-

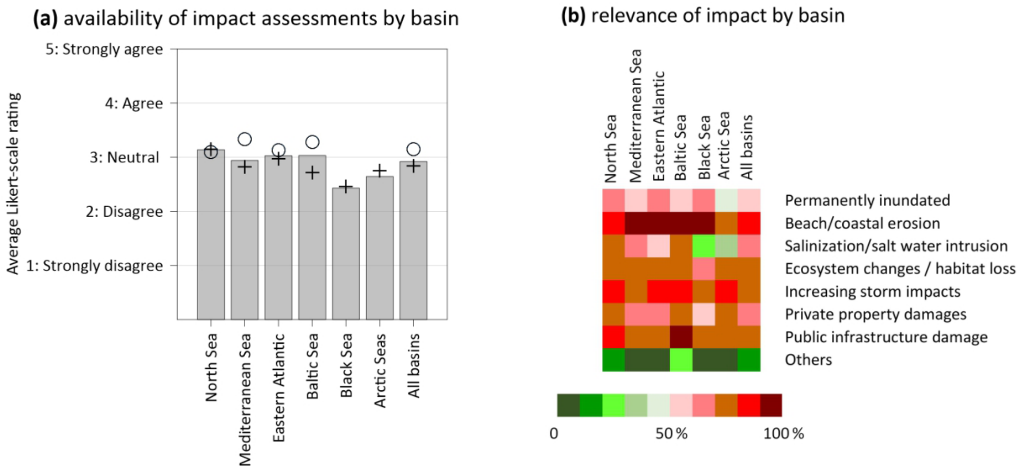

Figure 5. **(a)** Average rating on the Likert-scale to the statement "High-quality and up-to-date assessments of SLR-induced impacts are available for making decisions on planning" (o is for government; + is for scientists; the grey bar shows the total; the values for government representatives from the Black and Arctic seas are excluded due to their low representation with only two respondents each). **(b)** Relevance of specific SLR-induced impacts in each sea basin indicated by the percentage of respondents who identified these impacts.

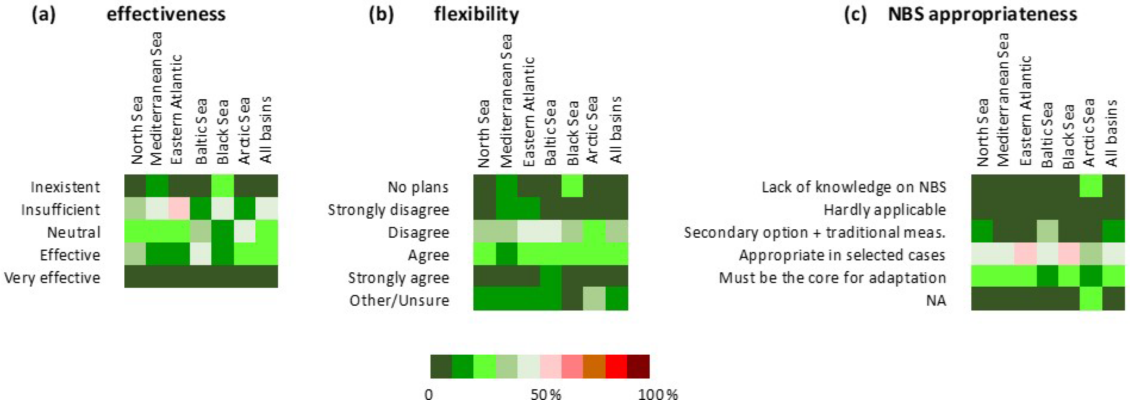

Figure 6. Percentage of responses by sea basin for the following questions/statements. **(a)** "How effective do you consider the present adaptation strategy to SLR in your country/region?" **(b)** "Existing adaptation strategies/plans are flexible enough to adapt to future updates in SLR-induced impacts or to cope with the inherent uncertainty in their assessment." **(c)** "Nature-based solutions (NBSs) are appropriate as adaptation measures to SLR in your country/region."

protny et al., 2021). Furthermore, urban planning is a notable concern, in line with the expected impacts of SLR on coastal cities (e.g. Abadie et al., 2019). This indicates that the legal competence of cities in managing coastal issues is often insufficient and underlines the necessity of integrating SLR considerations in urban planning frameworks. Other identified concerns include the influence of SLR on river flow and flood management, a topic gaining increased attention in the context of compound risks (e.g. Bermúdez et al., 2021), and the effects of SLR on seawater intrusion and, consequently, in freshwater management (e.g. Ketabchi et al., 2016) and agriculture (e.g. Gopalakrishnan et al., 2019).

Last, in response to the increasing recognition of nature-based solutions (NBSs) (e.g. European Environment Agency, 2021), we included a specific question about their suitability as adaptation measure to address SLR-induced impacts. While all respondents recognized the value of incorporating NBSs in coastal adaptation plans, the majority viewed their effectiveness as conditional and dependent on site-specific circumstances (Fig. 6c) (see Table S3). This perspective emphasizes the importance of providing a more comprehensive account of the co-benefits and lessons learnt from prior implementations of NBS measures (e.g. Moraes et al., 2022). Furthermore, it calls for a rigorous evaluation of their effectiveness when compared to artificial protection structures (e.g. Morris et al., 2018) and substantiated evidence of their long-term cost-effectiveness and self-sustainability (e.g. Toimil et al., 2020).

Finally, it is worth noting that all respondents quasi-unanimously acknowledged the high level of usefulness of

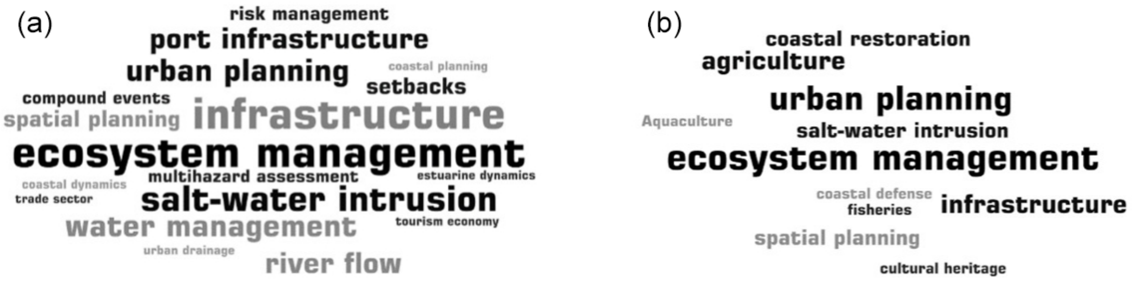

Figure 7. Word cloud representation of responses to the open-ended question "Are there other decisions/purposes for which you currently do not consider SLR but for which you think it would be important to do so?" from scientist **(a)** and government **(b)** respondents (generated using the WordArt Generator at http://wordart.com) (see Table 4 for their quantitative representativity).

Table 4. List of keywords and percentage of responses within the type of respondents who identify a keyword-related issue to the open-ended question "Are there other decisions/purposes for which you currently do not consider SLR but for which you think it would be important to do so?" (only issues with a response rate larger than 5 % are shown).

Respondents' profile	Scientists	Government
Keywords and percent of responses identifying a keyword-related issue over the total number of responses	Infrastructures: 13 % Ecosystem management: 13 % Saltwater intrusion: 9 % Water management: 7 % Urban planning: 7 % River flow: 7 % Port infrastructure: 7 %	Ecosystem management: 23 % Urban planning: 19 % Infrastructures: 12 % Agriculture: 12 % Spatial planning: 8 % Saltwater intrusion: 8 %

IPCC reports for their work, as evidenced by an average rating of 4.4 on the Likert scale (see Table S3). This consensus is consistent across different sea basins and respondent types.

3.2 Workshops

In this section, key points derived from the workshop discussions are presented. While the discussions were extensive and covered a wide range of issues, we focus on points that complement the survey results presented in the previous section or are considered relevant for further specification. Results are presented following the three main themes: SLR information, hazards and impacts, and adaptation.

3.2.1 North Sea and Arctic basins

Sea level rise information

Recurrent themes in the sessions focusing on the physical science of SLR included the need for locally specific reconstructions and projections of extreme sea levels. It was recommended to incorporate local observations when studying historical extreme events, as this forms the foundation for precise impact assessments and statistical analysis. Additionally, research-oriented attendees expressed their desire for comprehensive guidance regarding existing models, recent developments, their limitations, and how to interpret model outputs. This is particularly crucial when dealing with low probability, high-impact scenarios and associated sea level projections.

Hazards and impacts

With respect to hazards and impacts, regional assessments should encompass a comprehensive understanding of the interplay of various processes that contribute to the magnitude of sea level extremes. This includes accounting for vertical land movements, shifts in wind patterns, and the spatial extent of compound flooding events in coastal areas. While it is true that the consequences of SLR, such as erosion, salt intrusion, and flooding, may differ among regions, there is the potential for mutual learning and information exchange. This includes sharing data, tools, and the development of a European catalogue of relevant historical events.

Adaptation and decision-making

During the sessions focused on policy and adaptation, a clear consensus emerged regarding the need for a comprehensive overview of adaptation options. Such an overview should encompass details on the suitability of individual options in specific environments, the scalability of pilot initiatives, an evaluation of the co-benefits and drawbacks associated with each measure, and real-world examples of successful applications. Policy-makers demonstrated a particular interest in exploring NBSs and sought guidance on structuring the adaptation planning process, for example, through Dynamic Adaptive Policy Pathways (Haasnoot et al., 2020). The participants also expressed a desire for a comparative assessment of policies across different countries to facilitate shared learning and to evaluate and compare the progress in adaptation across countries. To encourage community and stakeholder engagement, attendees stressed the importance of transparent communication and the use of clear visualizations. Policy-makers specifically emphasized the need for geo-visualization tools that support decision-making and communication. They also requested scientists to provide clear explanations of how global SLR data are downscaled and how these data are interpreted within a local context.

3.2.2 Eastern Atlantic basin

Sea level rise information

The discussions highlighted several knowledge gaps that have relevant implications for future SLR management. These gaps encompass the need for comprehensive SLR scenarios tailored to estuaries, as well as the necessity of conducting local-scale assessments to bridge geographic information disparities. Furthermore, the discussions underscored the importance of enhancing the spatial resolution of climate models and projections, as well as incorporating low-likelihood scenarios. The monitoring of ice sheets and other key processes was actively discussed in the context of the set-up of early-warning systems. Key areas for advancement were identified, including the imperative to improve ice sheet modelling, to gain a deeper understanding of climate system tipping points, especially in the context of ice sheets, and to update sea level budgets (e.g. WCRP Global Sea Level Budget Group, 2018) along coastlines.

Hazards and impacts

A strong consensus emerged regarding the pivotal need to better assess the combined impact of waves, surges, tides, and mean SLR. Ideally, future planning should consider the potential for internal variability in compound flood hazards, such as the combination of storm surges with river discharges and SLR, including changing trends in storminess. Cascading impacts involving SLR and human activities, such as salt intrusion affecting agriculture, was widely acknowledged but often overlooked in planning. The protection of cultural heritage requires specific actions, yet the implementation of informed preservation strategies seems to face obstacles due to the absence of systematic and localized assessments.

Adaptation and decision-making

Throughout this session, it became evident that the adequate identification and improved engagement of stakeholders are fundamental prerequisites for the adaptation process that require additional efforts. Participants stressed the importance of enhancing the language used in communication, particularly when reaching out to the general public and policy-makers. National debates on SLR adaptation were also deemed crucial. A key focus was on clearly presenting the co-benefits of adaptation and delineating the costs of taking action and, just as crucially, the cost of inaction. The need to increase confidence in SLR projections was also highlighted. Related to this, there was an unanimous consensus on the necessity of developing multiple SLR scenarios tailored to different stakeholder groups. Governmental agencies, already actively involved in political measures against sea level impacts, require a different level of information than local communities, who may not fully grasp the urgency of SLR due to perceiving it as similar to present-day floods.

3.2.3 Mediterranean and Black Sea basins

Sea level rise information

The gaps and needs raised by stakeholders during the sessions related to SLR information can be grouped in four main categories. An integrative data management approach was recommended to facilitate the integration of different data types, to establish standards for defining metadata and quality control, and to endorse a data policy promoting the free and open exchange of sea level data at the European level. Regarding sea level data gaps, key objectives should focus on sustaining the current tidal station network (see Pérez Gómez et al., 2022), improving data distribution, and expanding spatial coverage, especially along the northern African coast. This includes the establishment of "open-sea" tidal stations to enhance large-scale sea level monitoring. Standardized quality control procedures and data processing methods are essential (e.g. IOC/UNESCO, 2020).

There is a need for robust, local sea level projections with quantified uncertainties, as well as examining low-probability, high-impact scenarios, and comprehensive numerical modelling of extreme water levels that considers various contributing factors like meteo-tsunamis and river discharge–sea level interaction. Digital twins could be considered for testing coastal adaptation options (e.g. Pillai et al., 2022). To comprehensively address SLR impacts and risks, there is a need for multidisciplinary data and model simulations. While the European Marine Observation and Data Network (EMODnet) provides human activity data, their potential for SLR risk assessment remains untapped. Coastal vulnerability data are scarce and lack standardization. Considering factors like sediment balance is crucial for long-term coastal erosion estimates, yet accurate data on sediment balance are often lacking. It is strongly recommended to establish requirements for high-resolution bathymetry and digital terrain models tailored for SLR and inundation analysis.

Hazards and impacts

In relation to SLR impacts, attendees confirmed impacts identified in the survey, specifically erosion and flooding. Erosion was recognized as a critical factor that diminishes the coastal resilience to SLR and heightens its vulnerability. Additionally, discussions highlighted the significance of compound flooding, especially taking into account its occurrence along the sea basin. Participants also underscored the importance of addressing the impact of saltwater intrusion on freshwater resources due to SLR, especially in light of the expected increase in desertification in these sea basins (e.g. Gao and Giorgi, 2008). In the context of assessing risks and impacts, it was deemed essential to consider "what-if" scenarios for SLR, including extreme SLR scenarios. Given the prevalence of low-lying sedimentary features like deltas and coastal plains in the region, controlling and measuring local vertical land movements was considered crucial. Also, an accurate estimation of the vulnerability of the densely populated coastal zones and their exposure and values was considered a top priority.

The second part of the session was dedicated to eliciting crucial information required for assessing hazards, risks, and impacts. Notably, inputs often mirrored the participants' local experiences, emphasizing the significance of accessing specific data that might already be available and accessible in other locations. This highlights a key characteristic of the region: stakeholders from various countries and institutions exhibit a diverse spectrum of profiles in terms of data accessibility, assessment methodologies, and their commitment to conducting assessments at different scales. Significant knowledge gaps related to hazards and vulnerability were particularly evident in the southern Mediterranean Sea and non-European coastal areas.

Adaptation and decision-making

Several key themes emerged as relevant areas requiring attention in the forthcoming assessment report with regard to SLR adaptation strategies and policies. Foremost among these was the imperative of incorporating the needs and challenges of future generations into the frameworks. The second priority highlighted the necessity to bridge the knowledge gap by standardizing the information derived from observations and models, with the aim of informing and prioritizing action. Integrated coastal zone management was underlined as a foundational paradigm for the development of new policy instruments aimed at bolstering coastal resilience and as an integral component of marine spatial planning strategies. Additionally, any adaptation policy should take into account social factors and community engagement, ensuring a participatory decision-making process in which diverse stakeholders have a voice. This approach also requires the implementation of effective outreach and communication strategies.

3.2.4 Baltic Sea basin

Sea level rise information

Participants highlighted that there is a need to constrain the uncertainty in SLR along the Baltic coast, primarily arising from various sources, including the relative contributions of melting from the Greenland and Antarctic ice sheets and regional differences in the response of sea levels to atmospheric forcing, among others (e.g. Weisse et al., 2021). It was considered necessary to have high-resolution projections of future total water level extremes, including wind contribution, to properly reflect the spatial variability in the sea level variations across the basin. The need to separate the effects of natural variability and anthropogenic global warming on long-term sea level changes was also emphasized. In addition, participants highlighted the need for progress in the characterization of drivers involving sea level variations triggering natural hazards, which might be amplified under SLR, including meteo-tsunamis and storm surges.

Hazards and impacts

In addition to well-documented erosion and flooding risks along the Baltic coast, other often-overlooked impacts of SLR, such as saltwater intrusion and freshwater salinization, will be equally important for some areas. Compound events, such as the combined effects of extreme sea levels and high river discharges, pose a threat to coastal communities like Stockholm, Pärnu, and Klaipėda, among others, especially in scenarios of rising sea levels and increased precipitation.

In the Baltic Sea, key locations such as St Petersburg, Stockholm, and the Kiel Canal have already experienced or are projected to face substantial impacts from extreme sea levels and SLR. A recurring theme across these locations is the utilization of locks and water control infrastructure as a means to mitigate and adjust to elevated water levels. These critical infrastructures play a vital role in safeguarding coastal cities, preventing saltwater intrusion, and regulating levels for shipping across the region. Consequently, the challenge lies in effectively adapting to SLR while preserving the functionality of these vital systems.

Adaptation and decision-making

Several topics related to adaptation were raised and were often applicable to any sea basin. Enhancing the response to SLR involves integrating SLR-related policy and marine spatial planning that are traditionally more focused on marine ecosystems. Identifying and addressing conflicts of interest, such as conservation versus economic development, is essential. Identifying the obstacles hindering implementation and devising workable solutions can help ensure the success of these initiatives.

Striking a balance between communicating scientific uncertainty and providing specific policy-compliant data is challenging but crucial. Overemphasis on uncertainty can potentially hinder adaptation efforts. It is recommended to combine short-term and long-term planning with a focus on adaptive planning approaches. Assessing the outcomes of SLR-related adaptation measures and policies, particularly for innovative measures like nature-based approaches, is critical. This includes an examination of their scalability and applicability across different contexts.

Recognizing the role of insurance and banking sectors in SLR policy and planning is pivotal for future coastal development. Effective communication with these influential stakeholders is vital due to their potential influence on future coastal development.

4 Discussion

The presented results encapsulate the perceptions and interpretations of survey and workshop participants regarding questions and discussions on SLR within three pivotal themes across European sea basins: SLR information, hazards, impacts, and adaptation. The varying percentage of participation among different participant profiles in each basin may contribute to the spatial differences observed in responses. However, considering the number of completed surveys, workshop attendance, and the interactive dynamics established during these events, the results are considered to provide representative insight into the topics investigated across European sea basins. It is, however, essential to note that, from a quantitative perspective, the participation of stakeholders and, in particular, government representatives from the Arctic seas and Black Sea basins were notably lower than other regions, reducing the significance of the findings for these areas.

While the distinctive characteristics of each sea basin affect specific elements there, some shared issues highlight their importance in understanding sea level requirements for the key themes under discussion.

During almost all scoping workshops, there was a common consensus regarding the importance of local sea level data to accurately assess spatial sea level variations within basins, especially concerning extreme water levels. In addition to expanding existing tidal networks, it was suggested to encourage sea level monitoring through citizen science sensors such as low-cost global navigation satellite system (GNSS) receivers and pressure sensors (Ahmed et al., 2023). This approach not only has the potential to raise awareness among coastal communities about (extreme) sea level conditions but also leads to a more extensive and high-resolution network of coastal sea level data, addressing spatial variability effectively (e.g. Spicer et al., 2021). In addition to incorporating new data, it was acknowledged that there is an urgent need for harmonization among existing data portals providing tide gauge information, such as the Global Sea Level Observing System (GLOSS) and European data portals (e.g. Pérez Gómez et al., 2022). This also includes updating metadata related to tidal gauges, which are indispensable for accurately reconstructing and interpreting the observed sea level related to, for instance, vertical land movement (e.g. Latapy et al., 2023).

Uncertainty emerged as a recurring theme in both survey and workshops, independent of the respondent's sea basin of origin. Striking the right balance between effectively conveying uncertainty while providing specific data crucial for policy compliance remains a relevant challenge. In this regard, Kopp et al. (2023) identify the communication of uncertainty and ambiguity as a key challenge in translating sea level science to inform long-term coastal planning. During the workshops, some stakeholders acknowledged that an excessive emphasis on uncertainty could lead to delays or hinder progress in the planning or implementation of adaptation measures. However, it is essential to recognize that the tolerance for uncertainty varies based on its intended use (e.g. long- and short-term applications) and the risk perceptions of individuals and groups. There tends to be a higher tolerance for uncertainty when the potential value at risk is relatively low (e.g. Hinkel et al., 2019).

In connection with this prevailing uncertainty, respondents also emphasized the importance of investigating low-probability, high-impact SLR scenarios. While these scenarios may be unlikely to materialize, they hold significance from a risk management standpoint (e.g. Hinkel et al., 2015). Research sector stakeholders underscored the need for advancing our understanding of the contributions of ice sheets to future SLR (e.g. Bamber et al., 2022; van De Wal et al., 2022). Management professionals emphasize the need for regional projections that facilitate impact analysis (e.g. Dayan et al., 2021). One highlighted concern pertains to the necessity for enhanced information and data to improve current and future regional and local sea level change estimations. Specifically, they emphasized the importance of assessing the local impact of vertical land movements on relative SLR. This assessment should encompass both natural and human-induced factors to accurately gauge relative SLR and, in turn, enhance assessments of SLR-induced hazards (e.g. Nicholls et al., 2021).

Participants recognized the importance of integrating comprehensive multidisciplinary data for assessing risks, including both exposure and vulnerability characteristics in susceptible areas, particularly in the low-elevation coastal zone (LECZ). In many instances, these factors significantly influence the estimated risk (e.g. Neumann et al., 2015).

In terms of hazards and their impacts, scoping workshops consistently highlighted the need for multihazard risk assessments. Specifically, the workshops brought attention to compound coastal floods in which elevated sea levels coincide with high river flow or heavy rainfall events. This was also identified as an impact to be considered in the open-ended questions of the survey (Fig. 7). From a risk management perspective, the significance of such occurrences lies in their potential to amplify the impact of the individual hazards and/or accumulate them within a specific region (Zscheischler et al., 2020). Within the context of this scoping process, it is crucial to recognize that SLR may influence the likelihood of the occurrence and intensity of these events through anticipated changes in local extreme sea levels (e.g. Moftakhari et al., 2017), which may also affect the spatial distribution of high-risk locations (see, e.g., Bevacqua et al., 2019).

To enhance the assessment of the primary SLR-induced hazard identified by stakeholders in the global survey (Fig. 5), i.e., long-term coastal erosion, there was an emphasis on considering additional factors influencing the sediment budget, such as sediment supplies from rivers, where the impact of river damming plays a relevant role in modulating the expected erosion, especially in deltas (e.g. Ericson et al., 2006).

It is interesting to note that, while saltwater intrusion received one of the lowest overall relevance scores in the survey (Fig. 5), it was consistently brought up by participants in all scoping workshops. This emphasis is justifiable when we consider that coastal aquifers serve as critical freshwater sources for many coastal areas, and these resources face threats from both groundwater extraction and rising sea levels (e.g. Ferguson and Gleeson, 2012). The growing concern regarding SLR and its impact on seawater intrusion is evident in the recent metaanalysis of seawater intrusion research by Cao et al. (2021), which identified the impact of SLR as the most widely discussed topic. In this regard, Ketabchi et al. (2016) identified key knowledge gaps on the impacts of SLR on seawater intrusion and recommended the main aspects for future research. The relevance of this impact also aligns with the findings from open-ended survey questions, where participants highlighted water management and agriculture issues (Fig. 7).

Regarding adaptation topics, the survey responses showed slight differences in responses across sea basins, albeit within a relatively narrow range (Fig. 6). This variability aligns with findings from McEvoy et al. (2021), who observed regional differences in adaption planning in their analysis of European countries and their approaches to SLR planning. One key aspect was the necessity of tailoring SLR information to different application domains, involving different stakeholders, institutions, and their specific information needs (see also, e.g., Hinkel et al., 2019; Durand et al., 2022). The relevance of taking social factors into account when formulating adaptation strategies was also noted, since barriers and limits to adaptation often stem from social aspects rather than purely technical factors (e.g. Adger et al., 2009; Hinkel et al., 2018; Galluccio et al., 2024). Additionally, there was a consensus on the importance of the effective communication of this information to stakeholders and the enhancement of visualization techniques to engage local communities (e.g. Calil et al., 2021).

When comparing responses from government and research participants in the survey, both groups generally exhibited similar behaviour in responding to various questions. However, a significant divergence emerged regarding their views on two practice-oriented issues: the availability of impact assessments and the effectiveness of adaptation plans. Government respondents tended to be more positive than their research counterparts, expressing greater confidence in the availability of high-quality and up-to-date impact assessments, as well as in the effectiveness of adaptation plans. An exception to this was found in the North Sea basin, where government respondents were less confident on the flexibility of adaptation strategies than researchers. Finally, it has to be considered that while the availability of impact assessments is a quantifiable matter, the effectiveness of the adaptation plans is arguably a matter of perception for most part. In practice, the true effectiveness of these plans remains unverified until they are implemented and operational under the projected scenarios.

Last, it is important to acknowledge that the results presented herein represent the prevailing perceptions of stakeholders across European sea basins regarding various aspects regarding SLR. These findings should be interpreted with the other chapters of this report, where detailed analyses are provided on the current state of data/information availability on SLR (Melet et al., 2024), the resulting impacts (van de Wal et al., 2024), adaptation policies (Galluccio et al., 2024), and the governance landscape (Bisaro et al., 2024) throughout European sea basins.

5 Conclusions

The combination of survey and regional workshops has effectively revealed shared knowledge gaps and needs concerning SLR across European sea basins. This assessment spans both scientific and governmental perspectives classified into three main SLR-related themes: information on SLR, its impacts, and adaptation policies and decision-making.

In terms of SLR information, notable gaps involve regional SLR projections and uncertainties, particularly related to long-term SLR induced by large-scale ice sheet melting. Scientists view these gaps as objectives, seeking to refine regional projections and reduce uncertainty. In contrast, government users see these gaps as barriers to achieving their specific goals and for which they need accurate SLR projections for their regions and advice on how to deal with uncertainty.

Concerning hazards and impacts, shoreline erosion emerged as a prominent issue across sea basins (except in the Arctic), with emerging issues like saltwater intrusion being recognized as undervalued and necessitating additional attention due to potential impacts on agriculture, freshwater resources, and coastal ecosystems. Among these emerging issues, the role of SLR in compounding risks events, such as those related to extreme water levels and river flow, was underscored. Participants also emphasized the necessity for high-quality and updated impact assessments to inform adaptation planning to SLR.

Concerns were raised about existing adaptation plans, revealing a common perception of inefficient and inflexible strategies to address SLR impacts. Some gaps were identified, particularly related to undervalued impacts, with urban planning being a prominent aspect needing attention. Furthermore, participants, particularly end-users, expressed the need for enhanced information dissemination and more effective communication of relevant data and information to support decision-making.

Stakeholders emphasized the crucial role of transnational collaboration in sharing experiences and expertise regarding various aspects of sea level rise. They noted the disparities in the responses among different regions, along with shared concerns and interests, highlighting the importance of knowledge exchange to foster harmonization across European sea basins. Initiatives like the Knowledge Hub on Sea Level Rise and the development of a European Assessment Report serve as prime examples of such exchanges. These efforts aim to harmonize knowledge pertinent to SLR, facilitating more accurate impact assessments and more informed decision-making processes regarding coastal adaptation to SLR.

Data availability. The collected data are not publicly available as the participants of this study did not give written consent for their data to be shared publicly. Anonymized data can be provided by the corresponding author upon request.

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Sea Level Rise in Europe: Observations and projections

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Abstract. Sea level rise (SLR) is a major concern for Europe, where 30 million people live in the historical 1-in-100-year event flood coastal plains. The latest IPCC assessment reports provide a literature review on past and projected SLR, and their key findings are synthesized here with a focus on Europe. The present paper complements IPCC reports and contributes to the Knowledge Hub on SLR European Assessment Report. Here, the state of knowledge of observed and 21st century projected SLR and changes in extreme sea levels (ESLs) are documented with more regional information for European basins as scoped with stakeholders. In Europe, satellite altimetry shows that geocentric sea level trends are on average slightly above the global mean rate, with only a few areas showing no change or a slight decrease such as central parts of the Mediterranean Sea. The spatial pattern of geocentric SLR in European Seas is largely influenced by internal climate modes, especially

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the North Atlantic Oscillation, which varies on year-to-year to decadal timescales. In terms of relative sea level rise (RSLR), vertical land motions due to human-induced subsidence and glacial isostatic adjustment (GIA) are important for many coastal European regions, leading to lower or even negative RSLR in the Baltic Sea and to large rates of RSLR for subsiding coastlines. Projected 21st century local SLR for Europe is broadly in line with projections of global mean sea level rise (GMSLR) in most places. Some European coasts are projected to experience a RSLR by 2100 below the projected GMSLR, such as the Norwegian coast, the southern Baltic Sea, the northern part of the UK, and Ireland. A relative sea level fall is projected for the northern Baltic Sea. RSLR along other European coasts is projected to be slightly above the GMSLR, for instance the Atlantic coasts of Portugal, Spain, France, Belgium, and the Netherlands. Higher-resolution regionalized projections are needed to better resolve dynamic sea level changes especially in semi-enclosed basins, such as the Mediterranean Sea, North Sea, Baltic Sea, and Black Sea. In addition to ocean dynamics, GIA and Greenland ice mass loss and associated Earth gravity, rotation, and deformation effects are important drivers of spatial variations of projected European RSLR. High-end estimates of SLR in Europe are particularly sensitive to uncertainties arising from the estimates of the Antarctic ice mass loss. Regarding ESLs, the frequency of occurrence of the historical centennial-event level is projected to be amplified for most European coasts, except along the northern Baltic Sea coasts where a decreasing probability is projected because of relative sea level fall induced by GIA. The largest historical centennial-event amplification factors are projected for the southern European seas (Mediterranean and Iberian Peninsula coasts), while the smallest amplification factors are projected in macro-tidal regions exposed to storms and induced large surges such as the southeastern North Sea. Finally, emphasis is given to processes that are especially important for specific regions, such as waves and tides in the northeastern Atlantic; vertical land motion for the European Arctic and Baltic Sea; seiches, meteotsunamis, and medicanes in the Mediterranean Sea; and non-linear interactions between drivers of coastal sea level extremes in the shallow North Sea.

1 Introduction

Sea level rise (SLR) is a major concern for Europe, where more than 50 million people live in low-elevation ($\leq 10\,\mathrm{m}$) coastal zones and 30 million in the 100-year-event marine coastal flood plains (Neumann et al., 2015).

Sea level (SL) changes at the coast result from processes acting at various spatial scales and timescales, from extreme events to long-term SLR, with the superposition of global, regional, and local variations. SLR is a direct consequence of climate change, which is due to the current energy imbalance of our planet at the top of its atmosphere induced by anthropogenic emissions of greenhouse gases (e.g. Forster et al., 2021). As our planet reemits less energy to space than it receives from the Sun, an excess of energy, mostly in the form of heat, accumulates in the climate system. About 91 % of the excess heat stored in the climate system has been absorbed in the oceans (Cheng et al., 2017; Von Schuckmann et al., 2020), causing a thermal expansion of the ocean, leading to global mean sea level rise (GMSLR). The remainder of the excess heat has been absorbed by the atmosphere, land ice, sea ice, and land surface. As land ice (glaciers, ice sheets) melts and is discharged to the ocean, water is added to the ocean, increasing its mass and volume and thereby rising SL. Changes in land water storage due to natural hydrological cycle and human interventions also lead to ocean mass and SL changes.

SLR has not been and will not be uniform over the ocean (Fox-Kemper et al., 2021). At a regional scale, mean SLR can deviate substantially from GMSLR due to a number of processes, with three key drivers. First, ocean circulations redistribute the seawater mass, heat, and salinity, leading to regional dynamic SL changes. Changes in ocean circulations are mostly driven by surface wind stress but also by air–sea heat and freshwater fluxes (Forget and Ponte, 2015; Meyssignac et al., 2017; Todd et al., 2020) and by intrinsic ocean variability (Llovel et al., 2018; Sérazin et al., 2015). Regional dynamic SL changes are mostly steric (ocean density changes), with a predominance of its thermosteric component. When combined together, the global mean steric SL change and ocean dynamic SL changes are called sterodynamic SL change (Gregory et al., 2019). Second, geographical redistribution of mass over the Earth, including contemporary or past transfers between land and ocean, such as glacier and ice sheet mass loss or land water storage changes, induce changes in Earth gravity and rotation as well as viscoelastic solid Earth deformations (called GRD effects). GRD effects induce SL changes through changes in the geoid and vertical land motion (VLM; Tamisiea, 2011). Glacial isostatic adjustment (GIA; Peltier, 2004) causes contemporary relative SL change due to GRD effects through ongoing viscous changes in the solid Earth caused by past changes in land ice, mostly through the deglaciation following the Last Glacial Maximum (∼ 20 000 years ago). Third, regional changes in atmospheric pressure loading over the ocean (due to changes in atmospheric circulations and moisture content) induce regional changes in the inverted barometer effect at scales longer than about a month (Wunsch and

Stammer, 1997). The inverted barometer effect is a relatively minor driver of regional SL changes at seasonal and longer timescales.

At more coastal scales, relative SL changes can be due to VLM of natural and anthropogenic origins (e.g. sediment compaction in deltas, Earth tectonics, GIA and solid Earth deformation due to contemporary land ice mass loss, pumping of groundwater, and weight of the built environment). In many coastal megacities, including European ones, VLM can induce relative SL trends similar to or larger than trends induced by oceanic and climate factors causing geocentric SL changes (Gregory et al., 2019, also known as absolute sea level changes) (e.g. Nicholls et al., 2021; Wu et al., 2022). In addition, several other processes lead to substantial SL deviations from the open ocean and should be considered when estimating local SL changes at the coast (Woodworth et al., 2019). Among these processes are tides, atmospheric surges, wind wave setup and swash, seiches, coastal waves, and effects of river discharges. Coastal SL variability spans a wide range of temporal and spatial scales (Hughes et al., 2019; Woodworth et al., 2019). Processes driving coastal SL change can also interact (e.g. Idier et al., 2019) due to their effects and their dependence on water depth for instance.

European regional seas (see Jiménez et al., 2024, in this report) and their bordering coasts along Europe present contrasting environments, from open-ocean environments (northeastern Atlantic, European Arctic) to semi-enclosed (North Sea) and quasi-enclosed seas (Baltic Sea, Mediterranean Sea, and Black Sea), microtidal (Mediterranean, Baltic and Black Seas) to mesotidal (European Arctic) and macrotidal environments (northeastern Atlantic, North Sea), deep to shallow seas on the continental shelf (North Sea, Baltic Sea), regions exposed to large swells or storms under the North Atlantic storm track, and regions experiencing different VLM. These contrasted atmospheric and ocean environments induce different past and projected SL changes over European seas. Here, the state of knowledge of observed and 21st century projected changes in mean and extreme SL is documented for European basins as part of the Knowledge Hub on Sea Level Rise Assessment Report.

First, a synthesis of the key findings of recent Intergovernmental Panel on Climate Change (IPCC) assessment reports on past and future SLR is provided in Sect. 2.1, with a European perspective in Sect. 2.2. The following Sects. 3–6 complement the IPCC assessment reports and provide extensive regional information on European observed and projected SL changes, as requested by stakeholders (see Jiménez et al., 2024, in this report). Observations of SLR in Europe from tide gauges (Sect. 3.1) and satellite altimetry (Sect. 3.2) are discussed, together with available SL tools and data portals (Box 1). As VLM due to human-induced subsidence and GIA is important for many coastal European regions, observations of this component of relative sea level rise (RSLR) are discussed in Sect. 3.3. Observed changes in extreme sea levels (ESLs, Sect. 3.4) and a selection of iconic historical storms causing coastal flooding in Europe and their consequences are reported (Box 2). In Sect. 4, drivers of SLR and ESLs are discussed, with a focus on Europe. Projected changes in European SL are presented in Sect. 5, with a focus on projected 21st century changes in mean SL and extremes. A discussion on tipping points, irreversibility, and commitment of SLR is also provided. Finally, a regional focus per European regional sea (northeastern Atlantic, North Sea, Arctic Ocean, Baltic Sea, and Mediterranean and Black seas) with key developments per region is provided in Sect. 6.

2 Summary of previous assessments

2.1 Synthesis of recent IPCC assessment reports

Here we present a synthesis of the key findings of the two most recent assessment reports that provided comprehensive information on past and future SLR: (1) the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC; IPCC, 2019; Oppenheimer et al., 2019) and (2) the IPCC Sixth Assessment Report of Working Group I (Fox-Kemper et al., 2021; IPCC, 2021a). The text in this Section is based primarily on the AR6 WG1 and SROCC Summaries for Policy Makers (IPCC, 2019, 2021b), which have been endorsed by international government delegations during the IPCC approval sessions. The IPCC reports synthesize a huge body of literature, and we refer the reader to the above assessment reports and references therein for further discussion on the topics summarized in this section. Recent progress and additional regional information are provided in subsequent Sections.

During the 20th century, global mean SL has risen faster than during any preceding century in at least the last 3000 years. SLR has accelerated since the late 1960s. The average rate was about 1.3 $\mathrm{mm\,yr^{-1}}$ during 1901–1971, increasing to about 1.9 $\mathrm{mm\,yr^{-1}}$ during 1971–2006 and further increasing to about 3.7 $\mathrm{mm\,yr^{-1}}$ during 2006–2018. Our understanding of the physical mechanisms of these past changes has increased through demonstrated closure of the observed GMSL budget, in particular after 1970 (Oppenheimer et al., 2019; Fox-Kemper et al., 2021). For example, the acceleration of GMSLR in recent decades is driven primarily by a 4-fold increase in the rate of ice sheet mass loss since the 1990s. For the period since 2006, ice mass input to the ocean from ice sheets and glaciers exceeds all other contributions to GMSLR. It is now understood that anthropogenic forcing was the main driver of the observed GMSLR since at least 1971 (Slangen et al., 2016). There is also scientific evidence for changes in the drivers of ESL events. There is high confidence that anthropogenic climate change has increased some cyclone-driven ESL events. Extreme wave heights have increased in the Southern Ocean and North Atlantic since the 1980s, and loss of sea ice has been linked to increased wave heights in the Arctic Ocean since the 1990s (Oppenheimer et al., 2019).

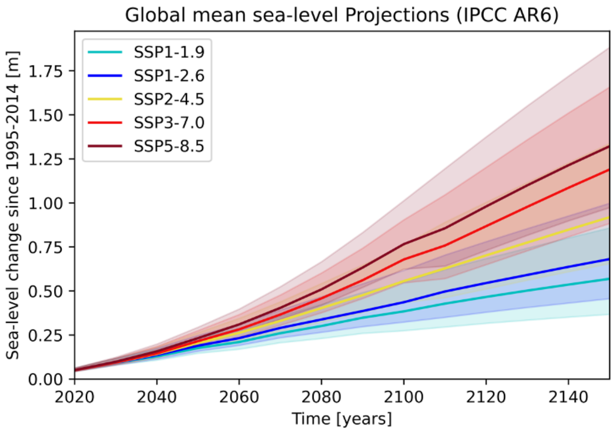

Figure 1. Projected GMSLR from the sixth assessment report of the IPCC relative to 1995–2014. Median (50th percentile) projections for all scenarios are indicated by the solid lines as shown in the figure legend. For each scenario, the shading shows the likely range (17th–83rd percentiles) (Fox-Kemper et al., 2021).

One of the main innovations in AR6 was the use of emulators with multi-model ensembles and observational constraints to develop SL projections that were consistent with the assessment of climate sensitivity (Forster et al., 2021; Fox-Kemper et al., 2021; IPCC, 2021a). Another important innovation was the explicit treatment of the potential for accelerated future SLR associated with deeply uncertain ice sheet instability processes through illustrative high-end storylines, intended to aid decision-making. While these high-end storylines yielded much higher multi-century SLR projections than seen in previous IPCC reports, the likely range (i.e. the central two-thirds of the distribution) of the projections has remained relatively stable since the publication of the IPCC Fifth Assessment Report (Church et al., 2013) despite major advancements in the models and methods used in AR6 (Slangen et al., 2023).

The latest IPCC likely range projections of GMSL yield values at 2100 of 0.32–0.62 m (low GHG emissions, SSP1-2.6) and 0.63–1.01 m (very high GHG emissions, SSP5-8.5), relative to the 1995–2014 average (Fig. 1). Furthermore, GMSLR approaching 2 m by 2100 and 5 m by 2150 cannot be ruled out for a very high GHG emissions scenario, due to deep uncertainty in ice sheet processes. On longer timescales, GMSLR will continue for centuries to millennia due to continued deep-ocean warming and ice sheet melt, as these elements of the Earth system slowly adjust to the anthropogenic warming. Over the next 2000 years AR6 assessed that GMSLR will reach about 2–3 m if surface warming is limited to 1.5 °C relative to pre-industrial values. This rise increases to about 2–6 m with a peak warming of 2 °C and about 19–22 m with a peak warming of 5 °C.

At regional scales, it is virtually certain (99 %–100 % probability) that mean RSLR will continue throughout the 21st century, except in a few regions with large vertical land uplift rates. By 2100 it is projected that ESL events that occurred once per century in the recent past will occur at least annually at more than half of all tide gauge locations around the world due to local mean SLR (Fox-Kemper et al., 2021). SLR will increase the frequency and severity of coastal flooding in low-lying areas and coastal erosion along most sandy coasts. The combination of more frequent ESLs and increased extreme rainfall and river flow events associated with an intensified hydrological cycle will make flooding more probable in coastal cities and settlements by the sea (IPCC, 2021a).

Despite the inevitability of SLR in the coming centuries, the science also shows the benefit of reduced GHG emissions in terms of avoiding the worst future risks and buying more time to adapt to the changes. By the end of the 21st century, scenarios with very low and low GHG emissions would strongly limit the rate of increase in the frequency of ESL events relative to higher GHG emissions scenarios. Excluding uncertain ice sheet processes, the assessed ranges of projected GMSLR at 2300 under a low GHG emissions are substantially lower (0.6–1.0 m in SROCC; 0.3–2.9 m in AR6) than for the very high GHG emissions scenario (2.2–5.3 m in SROCC; 1.7–6.8 m in AR6), implying that strong mitigation is needed to prevent large SLR in 2300.

2.2 The European perspective

Most coastal regions in Europe are currently experiencing a local SLR of a few millimetres per year, but there are large spatial variations across the continent. A key driver of these spatial variations is GIA: the ongoing GRD response to past ice mass changes. The spatial pattern of this land motion is characterized by vertical land uplift in areas covered by ice sheets during the last glacial period and land subsidence in other areas (Sect. 3.3). As a result, much of the northern Scandinavian coastline is currently experiencing a local SL fall, since the long-term rate of land uplift following the last deglaciation exceeds the global-warming-driven contemporary SLR.

Projected local SLR for Europe is broadly in line with projections of GMSL rise in most places (Sect. 5.1). GIA will continue to be an important driver of spatial variations across the continent, with additional spatial differences also arising from the effect of Greenland ice sheet mass loss on Earth's gravity field and also by local oceanographic processes (Fox-Kemper et al., 2021). There may also be highly localized VLM processes active either now or in the future, such as subsidence associated with groundwater and hydrocarbon extraction or tectonic activity (Sect. 3.3). Risk-based decision-making should account for these additional non-climatic processes when assessing potential magnitudes or rates of future SLR.

The scientific consensus is that changes in future coastal flood hazard will be dominated by SLR, rather than changes in the drivers of ESLs such as waves, tides, and surges (e.g.

Fox-Kemper et al., 2021; Howard et al., 2019; Vousdoukas et al., 2018; see van de Wal et al., 2024, in this report for more details). However, systematic changes in these drivers could exacerbate local SLR, and internal variability is expected to play a large role in shaping the evolution of wave and storm surge extremes on decadal timescales (Sects. 3.4 and 5.3). In addition, there is a growing body of scientific evidence that suggests SLR could have substantive effects on local tidal characteristics (Haigh et al., 2020). Combined 21st century projections of SLR, tides, surges, and waves for European coasts found the largest absolute increases in ESLs in the North Sea, followed by the Baltic Sea and Atlantic coasts of the UK and Ireland (Vousdoukas et al., 2017), but in the Mediterranean the relative increase is larger, implying a more urgent need to improve adaptation strategies. Changes in waves and storm surges were found to exacerbate SLR for most coasts with contributions of up to 40 % of the change in ESLs. However, the response of waves and surges under climate change remains a key uncertainty (e.g. Howard et al., 2019). IPCC AR6 concluded that “relative SLR is extremely likely to continue around Europe (except in the northern Baltic Sea), contributing to increased coastal flooding in low-lying areas and shoreline retreat along most sandy coasts (high confidence)” (Ranasinghe et al., 2021).

Box 1: Common practices and available sea level tools and data portals

As the impact of SL change is a local issue, it is important to communicate SL projections in a form that can be used by local decision makers. In this Box, we will provide a non-exhaustive overview of online visualization tools and data portals that provide information on past and projected SL change.

The IPCC AR5 Chap. 13 (Church et al., 2013) made the SL projections available online, through the Integrated Climate Data Centre from the University of Hamburg (Table 1), but this was not actively communicated or referred to in the report, and the online tool was more science-focused than public-oriented. The focus on accessible regional information has increased in the recent IPCC AR6 report, which produced an interactive atlas (https://interactive-atlas.ipcc.ch/, last access: 2 July 2024, Table 1), showing observations and projections of a wide range of climate variables for all IPCC working group 1 reference regions (Gutiérrez et al., 2021). For SL change, this atlas includes the SL projections for the different future climate scenarios. However, the atlas only shows SLR for three time periods for large regions. Therefore, in collaboration with NASA, the IPCC Chap. 9 authors built an additional tool which specifically focuses on SL projections (Table 1). This tool allows the user to select and visualize the projected changes for different time periods (by decade), scenarios, and contributions. It also provides projections at specific tide gauge locations using an interactive map. In addition, all the IPCC AR6 SL projections (global and gridded 1 by 1° regional) can be downloaded by the user from the NASA website and from a Zenodo archive (Table 1).

There are also several other online interactive SL tools. For instance, the INSeaPTION project (an ERA4CS European research consortium) has made a tool which includes IPCC AR5 and SROCC projections but also allows for investigating different scenarios using sliders and high- and low-end scenarios (Table 1). The UK Met Office has made a “sea level dashboard”, where global mean projections (total and individual contributions) are connected to observations (Table 1). Focusing on local or national changes, there are also various online tools available. For instance, the Norwegian Mapping Authority has developed a tool that provides users with information on observed and forecasted water levels, predicted tides, extreme still water levels, VLM, and past and future SL for Norway (Table 1). Users can find information on vertical datums (various tidal datums and Norway’s national height system NN2000) which are relevant for planning decisions and on SL impacts (more in van de Wal et al., 2024, in this report, Sect. 5).

Several online data portals provide information on past and projected SL changes. The Permanent Service for Mean Sea Level (PSMSL), for instance, provides an overview of tide gauge measurements around the world (Table 1). Regarding coastal ESLs, return levels and simulated time series since 1979 from a global hydrodynamic model forced with atmospheric pressure, wind and tides are available in the Climate Data Store of the Copernicus Climate Change Service (C3S), which also hosts various other SL observation and projection-related datasets (Table 1). The Joint Research Centre hosts a number of datasets as part of the Large Scale Integrated Sea Level and Coastal Assessment Tool, including historical and projected ESLs along the European coasts. A global database of daily maxima storm surges obtained with a data-driven model (Tadesse and Wahl, 2021) is also available at tide gauge sites using five different atmospheric reanalyses as forcing fields (Table 1). The European Marine Observation and Data Network (EMODnet) also provides via its unified Portal, open and free access to integrated and harmonized data from tide gauges (including EuroGOOS platforms), together with specific data products for SLR, including SL trends (relative and geocentric) and relative SL anomalies. Such societally relevant data layers are also made publicly available via the European Atlas of the Seas, a European Commission Communication tool to support public awareness and ocean literacy.

European Copernicus Services also provide SL data, with a free and open access policy (Melet et al., 2021). Altimeter SL products are operationally produced and distributed by the Copernicus Marine Service and by the Copernicus Climate Change Service (C3S) (Legeais et al., 2021), and used to produce Ocean Monitoring Indicators (https://marine.copernicus.eu/access-data/ocean-monitoring-indicators?f%5B0%5D=omi_family:438, last access: 2 July 2024), such as observed mean SLR for the global ocean and regional European seas, as well as regional SL trends. In addition, the Copernicus Marine Service provides tide gauge data and ocean and wave forecasts and reanalyses (Irazoqui Apecechea et al., 2023).

Table 1. Overview of publicly available data portals and online visualization tools of SL data. Please note that this is a non-exhaustive overview, providing entry points to data, with a focus on the IPCC and European-based organizations.

Data source or organization	Access link (last access: 2 July 2024)	Contents
IPCC AR5 WG1 Chap. 13 (Church et al., 2013)	https://www.cen.uni-hamburg.de/en/icdc/data/ocean/ar5-slr.html	IPCC AR5 SL projections viewer and data portal (global)
IPCC AR6 WG1 report	https://interactive-atlas.ipcc.ch	IPCC AR6 climate observations and projections viewer and data portal (global)
IPCC AR6 WG1 Chap. 9 (Fox-Kemper et al., 2021)	https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool	IPCC AR6 SL projections viewer and data portal (global)
PSMSL	https://psmsl.org/	SL observations (tide gauges) data portal (global)
INSeaPTION	http://www.inseaption.eu/index.php/news/23-web-map-of-sea-level-projections	SL projections viewer (global)
UK Met Office	https://climate.metoffice.cloud/sea_level.html	SL observations viewer (global)
Global storm surge reconstruction database (Tadesse and Wahl, 2021)	http://gssr.info/	Observed daily maxima storm surges (global)
Copernicus Climate Data Store	https://cds.climate.copernicus.eu/#!/home	Various datasets on observed and projected sea levels and extreme sea levels (Europe)
Copernicus Marine	https://marine.copernicus.eu/	Satellite altimetry, tide gauge records, ocean and wave reanalyses, ocean and wave forecasts (including for sea level); visualization tool (global and Europe)
EMODnet	https://emodnet.ec.europa.eu/en	SL observations data portal (Europe)
European Atlas of the Seas	https://emodnet.ec.europa.eu/en/eu_atlas_of_the_seas	SL observations data portal (Europe)
Norwegian Mapping Authority	https://www.kartverket.no/en/at-sea/se-havniva/se-havniva-i-kart	Observed and projected sea level change viewer (Norway)
Joint Research Centre	Joint Research Centre Data Catalogue – Large Scale Integrated Sea-level and Coastal Assessment Tool – European Commission (https://data.jrc.ec.europa.eu/collection/liscoast)	Modelled historical and projected extreme sea levels
SONEL	Système d’Observation du Niveau des Eaux Littorales (SONEL, https://www.sonel.org/?lang=en)	Observed sea level trends from tide gauges and VLM trends derived from GNSS at tide gauge sites.

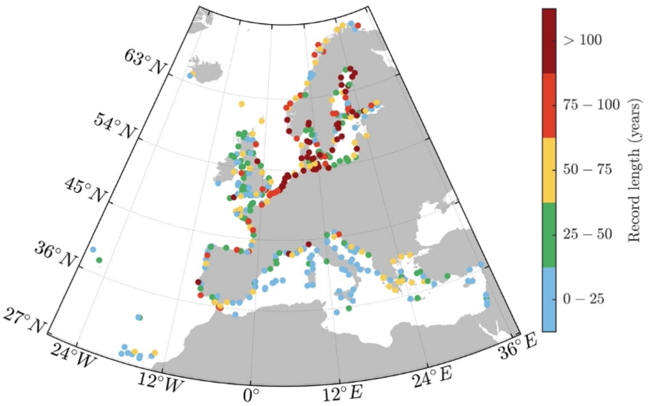

Figure 2. Location of tide gauges in Europe from the PSMSL database with the length of records in years.

3 Regional observations: past mean trends and extreme value intensification

3.1 Tide gauge record

Centennial changes in SL are largely based on tide gauge observations. The European coastlines are home to many of the longest tide gauge records worldwide (Marcos et al., 2021; Raicich, 2020; Woodworth and Blackman, 2004; Wöppelmann et al., 2014; Wöppelmann and Marcos, 2016; Fig. 2). Tide gauges measure SL changes relative to the coastal point where they are installed. This implies that they observe the oceanic component of SL together with VLM driven by a variety of mechanisms (Sect. 3.3). To account for VLM, tide gauge measurements are often complemented with VLM measurements (Global Navigation Satellite System, GNSS) to separate the ocean-related and solid Earth processes from SL records (Wöppelmann and Marcos, 2016).

Tide gauges are installed and operated by national and subnational agencies and also by research institutions, each of which provide access to SL records with a variety of formats, sampling frequencies and quality checks. User access is facilitated by original data providers or data assembly centres and initiatives, including those in the framework of the Global Sea Level Observing System (GLOSS), the Copernicus Marine Service or EMODnet Physics, among others (Table 1). Monthly and annual mean SL records from tide gauges are obtained by national providers and compiled and distributed by the Permanent Service for Mean Sea Level (http://www.psmsl.org, last access: 2 July 2024) (Holgate et al., 2013). A total of 595 tide gauge records are available along the European coasts on the PSMSL website, of which 55 span a period longer than 100 years (Fig. 2). In addition to homogenized tide gauge datasets, the database contains other historical records that provide valuable information on long-term SL changes, such as Amsterdam or Stockholm (see https://psmsl.org/data/longrecords/, last access: 2 July 2024) (Fig. 3a). For studies related to extreme events or storminess, high-frequency SL observations are required. The Global Extreme Sea Level Analysis dataset (http://www.gesla.org, last access: 2 July 2024; Haigh et al., 2022; Woodworth et al., 2016; Caldwell et al., 2001), currently in its version 3, contains a global set of hourly and higher sampling tide gauge observations (Fig. 3b). High-frequency records are needed for ESLs and to capture high-frequency processes contributing to SL changes at the coast such as seiches, meteotsunamis, and infragravity waves (Vilibić and Šepić, 2017).

In Europe, these observations can be obtained from the Copernicus Marine Service (https://marine.copernicus.eu/, last access: 2 July 2024), from EMODnet Physics (https://emodnet.ec.europa.eu/en/physics, last access: 2 July 2024), and from national and subnational agencies (see the GESLA website for more details on data providers). Different data portals may distribute repeated stations, albeit with different metadata, convention names, or ID and distinct levels of processing. An intercomparison of available tide gauge portals is provided by SONEL (https://www.sonel.org/tgcat/, last access: 2 July 2024). As an example of the database contents, there are a total of 1072 tide gauge stations of at least hourly sampling along the European coasts in the GESLA database with a median length of 15 years and of which 48 span a period longer than 100 years, providing essential information (Fig. 2).

3.2 Satellite record

While tide gauges provide point-wise, long-term relative SL (relative to the local land surface to which they are grounded), altimetry measurements provide shorter but spatially coherent and quasi-global measurements of geocentric SL (relative to a reference ellipsoid). Satellite altimetry measures sea level from space with a radar emitter to measure the distance between the satellite and the sea surface and precise positioning instruments to measure the position of the spacecraft. Satellite altimeters allow us to measure the geocentric SL, which is the SL with respect to the centre of mass of the Earth. Since 1993, SL has been monitored routinely on a daily basis with a resolution of $1/4° \times 1/4°$ from 82° S to 82° N (e.g. Legeais et al., 2021). Although SL dynamics are highly heterogeneous, the time and space samplings are enough to effectively resolve the global mean SL dynamics on a weekly basis (Fox-Kemper et al., 2021; Henry et al., 2014; Scharffenberg and Stammer, 2019).

Since 1993, global mean SL has risen by $3.3 \pm 0.3\,\mathrm{mm\,yr^{-1}}$, which represents a total increase in SL of 10 cm (Fig. 5). Over 1993–2018, 46 % of GMSLR is attributed to the ocean thermal expansion, 19 % to melting mountain glaciers, 15 % to land ice mass loss from the Greenland ice sheet, and 9 % from the Antarctic ice sheet (Fox-Kemper et al., 2021). The remaining 11 % is attributed to changes in land water storage such as dam building, groundwater pumping, and aquifer recharge and discharge (Cazenave and Moreira, 2022; WCRP Global Sea Level

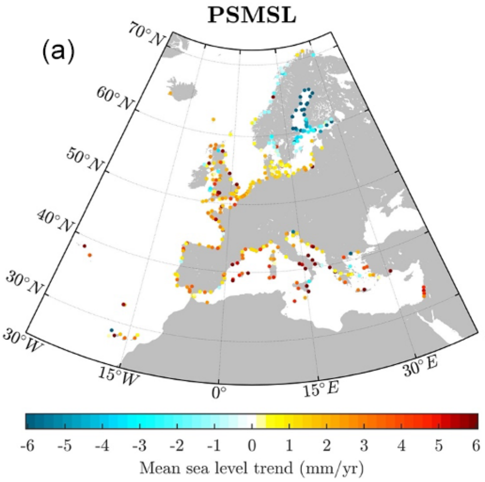

Figure 3. **(a)** Relative SL trends at PSMSL European tide gauges. Note that the tide gauge records are covering different periods (Fig. 2). **(b)** Location of GESLA European tide gauges. Coloured dots indicate the location for which return level curves of storm surges are shown in Fig. 4: blue for Oslo, green for Cuxhaven, purple for Brest, and orange for Alicante.

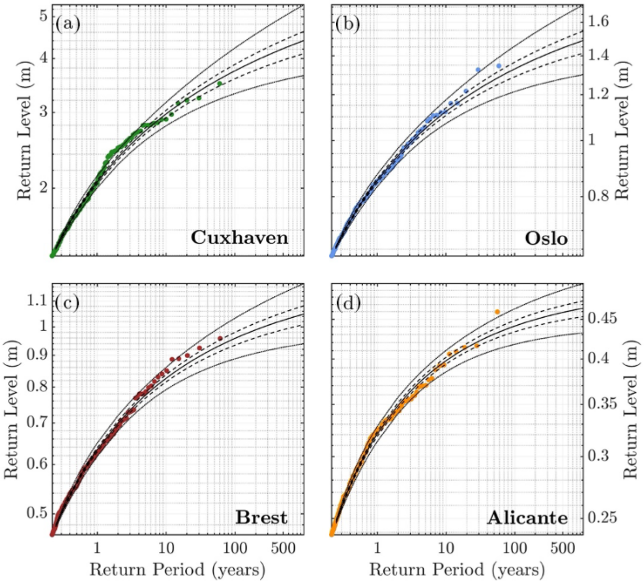

Figure 4. Return level curves of storm surges at four selected GESLA tide gauges from different European basins shown in Fig. 3b. Tide gauge records were de-tided (using Utide MATLAB software; Codiga, 2024), and extremes were selected as peaks over the 95th percentile of each time series, with events separated by at least 3 d to ensure independence. Return levels have then been calculated fitting a generalized Pareto distribution to each record. Uncertainties indicate 30th–70th (dashed lines) and 5th–95th (dotted lines) confidence levels.

Budget Group, 2018). The satellite altimetry SL record also shows an acceleration of $0.11 \pm 0.6\,\mathrm{mm\,yr^{-2}}$ (Guérou et al., 2023). This acceleration since 1993 has mostly been due to an acceleration of ice mass loss from Greenland and to a lesser extent to an acceleration of the contribution from glacier melting and ocean warming (Frederikse et al., 2020b). Studies have shown that present-day GMSLR cannot be explained by internal climate variability and mostly results from anthropogenic forcing (Fasullo and Nerem, 2018; Marcos et al., 2015a, 2017; Richter et al., 2020; Slangen et al., 2016). In Europe, geocentric SL trends since 1993 have been contrasted with high SLR in the Baltic Sea (see Sect. 6.5 and Fig. 7 for RSLR in the Baltic), low SLR in the Mediterranean Sea, and a SLR close to the global mean rate in the Atlantic sector (Fig. 6). Only a few areas, such as central parts of the Mediterranean Sea, show no change or a slight decrease in geocentric SL. On interannual timescales, the global mean SL record shows significant variations, which are mostly generated by El Niño–Southern Oscillation events and its influence on the ocean heat content and global hydrological cycle. During El Niño events, the global mean SL is temporarily increased due to both an increase in ocean mass and in ocean thermal expansion (e.g. Cazenave and Le Cozannet, 2014; Piecuch and Quinn, 2016; Hamlington et al., 2020). Indeed, during El Niño events, more precipitation occurs over the ocean (mostly in the tropics), resulting in a temporary increase in the barystatic component of global mean SL. In addition, the ocean heat content temporarily increases during El Niño, with a dominance of the tropical Pacific Ocean, leading to sizeable increases in global mean steric SL.

To analyse sea level changes at regional scales, gridded altimetric products can be used. Although such products are provided as daily maps on a 1/4° × 1/4° grid, the dynamical content of these maps does not have full 1/4° spatial and 1-D temporal resolutions due to the filtering properties of the optimal interpolation. The effective resolution corresponds to the spatiotemporal scales of the features that can be properly resolved in the maps. The temporal effective temporal

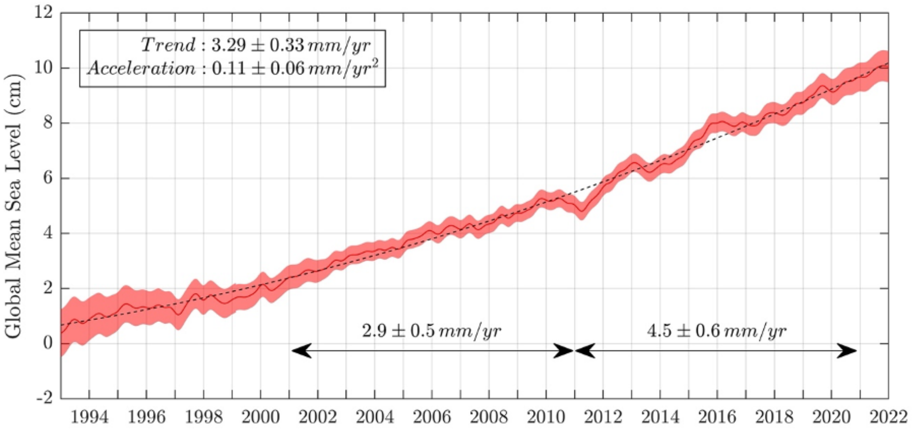

Figure 5. Global mean SL measured by satellite altimetry since 1993 (red curve), shaded area represents the uncertainty and the dotted line shows a trend line with an acceleration. The annual and semi-annual periodic signals are removed and the time series is low-pass filtered (175 d cut-off). The time series is corrected for GIA using the ICE5G-VM2 GIA model (Peltier, 2004) to consider the ongoing movement of land. Over 1993–1998, global mean sea level is corrected for the TOPEX-A instrumental drift, based on comparisons between altimeter and tide gauge measurements (Ablain et al., 2019; Legeais et al., 2020). Over 1993–2022, the GMSLR trend is 3.29 ± 0.33 mm yr^{-1} (uncertainty at 90 % confidence level) and the GMSLR acceleration is 0.11 ± 0.06 mm yr^{-2}. Trends are also reported for the period 2001–2011 and 2011–2021 to highlight the changing decadal trend of global mean sea level. The shaded envelope indicates uncertainties (17th–83rd percentiles). Data source: EU Copernicus Marine Service product (2019b) Ocean Monitoring Indicator based on the C3S altimetric SL product. Credit: C3S/ECMWF/Copernicus Marine.

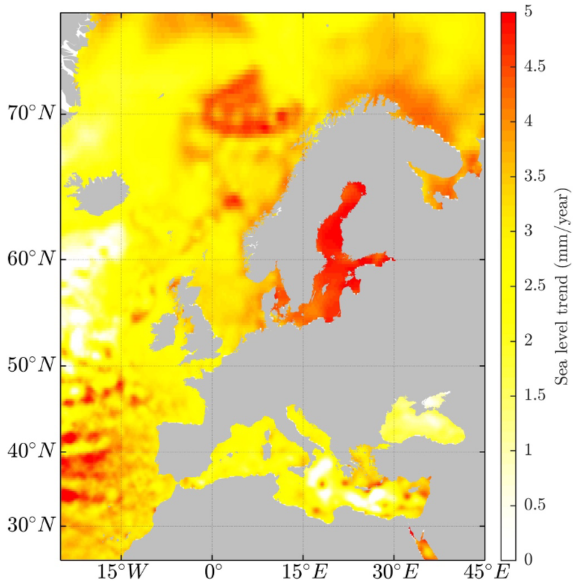

Figure 6. Geocentric SL trends (mm per year) from January 1993 to July 2021. The data have not been adjusted for GIA or for the TOPEX-A instrumental drift. Data source: Copernicus Marine Ocean Monitoring Indicator based on the C3S SL product. Credit: C3S/ECMWF/Copernicus Marine. Geocentric SL does not account for VLM, which is described in Sect. 3.3. The trend of GMSLR observed by altimetry over the same period, with no GIA correction and with the seasonal cycle removed, is 3.20 mm yr^{-1} (Source: AVISO).

resolution has been estimated to around 34 d (spatially varying), and the effective spatial resolution has been estimated to range from 100 to 200 km in the northeastern Atlantic and from 90 to 160 km in the Mediterranean and Black seas (Ballarotta et al., 2019). Satellite altimetry shows that the rate of SL change is spatially highly heterogeneous. The dominant contribution to the regional SL trend patterns is the non-uniform thermal expansion caused by the redistribution of heat within the ocean in response to the wind-forced ocean circulation, and direct exchange of heat between the lower atmosphere and the upper ocean (Forget and Ponte, 2015; Meyssignac et al., 2017). The spatial trend patterns in SL are not stationary, in particular in the North Atlantic, where positive trends shift to negative trends from the first to the second decade of the spatial altimetry SL record and vice versa (e.g. Chafik et al., 2019). This is because spatial trend patterns in SL remain so far mostly driven by the internal climate modes. Several climate modes of variability are influencing sea levels in European seas, such as the North Atlantic Oscillation (NAO) in the Atlantic (see Sect. 6.1), the Arctic Oscillation, and the East Atlantic pattern and the Scandinavian pattern (see Roberts et al., 2016, for an analysis of the climate modes signature on sea level; Boucharel et al., 2023; Wakelin et al., 2003; Jevrejeva et al., 2005; Chafik et al., 2017). Strong differences in SL trends at the sub-basin scale are also recognized in the Mediterranean (Bonaduce et al., 2016; Mohamed et al., 2019; Skliris et al., 2018), in which variability and complexity arise from changes in ocean circulations (Mauri et al., 2019; Meli et al., 2023; Menna et al., 2019, 2021, see Sect. 6.4.1). Near the coast, the altimeter-

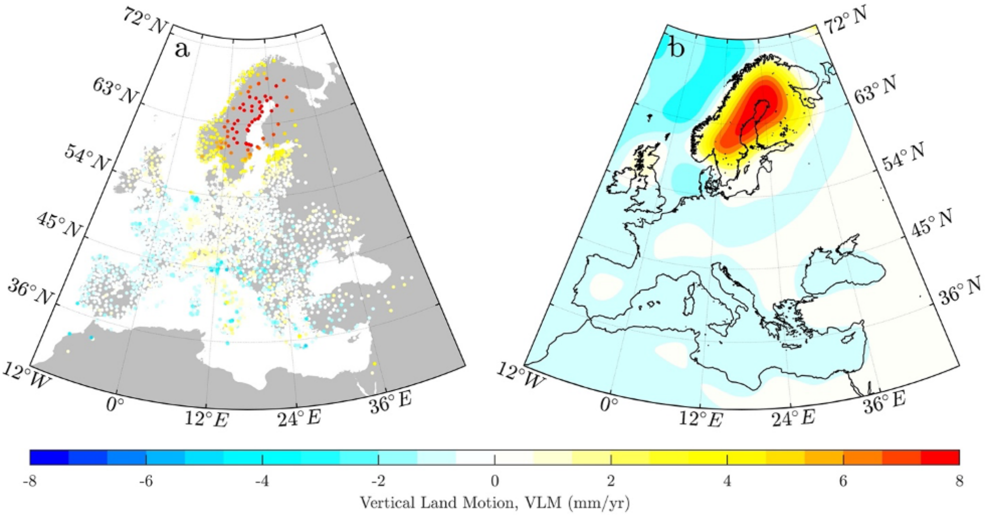

Figure 7. **(a)** Preferred filtered and smoothed present-day VLM field from Piña-Valdés et al. (2022) and based on data from ∼ 4000 GNSS stations in Europe. **(b)** The present-day VLM from the GIA inversion model from Caron et al. (2018). Values are given in units of millimetres per year.

based SL variations and associated trends are more uncertain than the measurements retrieved in the open ocean (e.g. Birol et al., 2017; Cipollini et al., 2017; Vignudelli et al., 2019). This is due to local factors, such as the distortion of the altimeter radar echo by coastal features, the higher uncertainties of some altimeter corrections (e.g. ocean tides), other local processes that are not captured by satellites (e.g. how far waves wash up the shore), and the spatial resolution of the satellite data. Although more uncertain, recent estimates of the SL at the coast (e.g. Birol et al., 2021) show a general agreement between SLR on European coast and closest SLR in the open ocean in terms of trends and interannual variability, at least when getting as close as a few kilometres from the coast (The Climate Change Initiative Coastal Sea Level Team et al., 2020).

Satellite altimetry has also been used to study the annual, semiannual, and interannual cycles in SL (e.g. Fernández-Montblanc et al., 2020), including in relative SL changes (Ray et al., 2021), which is of relevance for coastal flooding. Along the coasts of Europe, the annual cycle of geocentric SL is characterized by annual maxima during the autumn (except for the Black Sea, where the annual maxima are reached in spring). The annual cycle amplitude ranges from around 5 to 12 cm with the largest amplitude found in the North Sea, Baltic Sea, along the Arctic coast of Norway, and in the western Mediterranean Sea (Fernández-Montblanc et al., 2020; Ray et al., 2021), going up to 20 cm in the German Bight (Dangendorf et al., 2013). Based on altimetric data, it has been shown that the monthly mean SL (including SLR) contribution to ESLs at the coast is mostly larger than that of tides and of the same order of magnitude as that of storm surges in microtidal areas (Black Sea, Baltic and Mediterranean Sea) (Fernández-Montblanc et al., 2020).

3.3 Vertical land motion

VLM is an important component of relative SL change along Europe's coasts as measured by tide gauges. It encompasses all processes leading to a vertical change in the land surface such as GIA due to short- and long-term ice mass loss, tectonics, volcanism, and subsidence owing to groundwater or hydrocarbon withdrawal or sediment compaction. These physical processes operate on different spatial and temporal scales and can be related to climate change, human activities, or natural processes. Several techniques can be used to measure VLM. Historically, repeat levelling has been the main technique. It determines changes in elevation across a network of points and gives a measure of VLM across the levelling network. The repetition of levelling also provides VLM measurements relative to past ones. Repeat levelling has been extensively used in parts of Europe to help constrain VLM, for example, in Scandinavia and the Baltic countries where uplift rates are large (Vestøl et al., 2019). Levelling is also used to measure differences in VLM between global navigation satellite system (GNSS) stations and tide gauges.

Permanent GNSS stations provide a continuous and very accurate (uncertainties smaller than 1 mm yr^{-1}) measure of VLM in the terrestrial reference frame. GNSS thereby gives a high-quality pointwise measurement of VLM but lacks information in areas between stations, where station spacing is typically of several 10s of kilometres. There are several thousand GNSS stations in Europe which are operated in national or regional networks, and are owned by, e.g. national agencies, research institutions, and private companies (Fig. 7a). Efforts to bring together GNSS data and products from across Europe are available from the EUREF (International Association of Geodesy Reference Frame Sub-Commission for Europe) permanent network (http://www.epncb.oma.be, last access: 2 July 2024), and from the European Plate Observing System (http://www.epos-eu.org, last access: 2 July 2024) research infrastructure. Several analyses have focused on combining European GNSS data (e.g. Kenyeres et al., 2019) with some of those interpolating VLM values for potential use along the coast (e.g. Hammond et al., 2021; Piña-Valdés et al., 2022). For users interested in tide gauges, the International GNSS Service has a programme for analysing GNSS data from stations near or co-located with tide gauges. These data are currently hosted at Système d'Observation du Niveau des Eaux Littorales (http://www.sonel.org, last access: 2 July 2024) (GLOSS data portal for GNSS data at tide gauges). GNSS stations co-located at tide gauges are important for understanding the contribution of VLM to relative SL (Woodworth et al., 2017).

Finally, a more recent technique is interferometric synthetic aperture radar (InSAR), which uses satellite radar to measure VLM with millimetre accuracy. InSAR can image the spatial pattern of VLM and has very good spatial coverage, allowing users to detect local areas of land movement. For example, InSAR has been used in Venice to measure land subsidence (e.g. Teatini et al., 2012). Integrating InSAR and GNSS data can maximize the advantages of both techniques. InSAR data products are newly available from the European Ground Motion Service (https://egms.land.copernicus.eu/, last access: 12 July 2024), which uses Copernicus Sentinel-1 radar images.

The broad pattern of land motion in Europe can be seen from GNSS measurements (Fig. 7). Note that on local scales VLM can deviate significantly from this picture. In European cities like Antwerp, Rotterdam, and Venice, for example, there are complex patterns of localized subsidence (see, e.g. https://egms.land.copernicus.eu/ and Wu et al., 2022). As discussed, subsidence can be natural or human induced. Gas production at the Groningen field, for example, situated in the northeastern Netherlands, has caused measurable subsidence since the 1960s. Understanding the processes causing subsidence and their respective timescales is crucial for sea level studies. This can be particularly challenging in areas where subsidence has multiple causes and requires us to try and disentangle the individual contributions to VLM (Candela and Koster, 2022).

There are several distinct features in the broad VLM field. In northern Europe a dome pattern of uplift due to GIA is clearly visible related to the long-term contribution of unloading since the last ice age. On century timescales we assume this as a constant rate. GNSS observations show a maximum uplift of $\sim 10\,\mathrm{mm\,yr^{-1}}$ in northern Sweden and rates of subsidence exceeding $1\,\mathrm{mm\,yr^{-1}}$ in northern central Europe. Rates of highest uplift correspond to where ice was thickest during the past glacial. Note that GIA also causes gravity and Earth rotation effects on SL, which are around 5 %–10 % of the VLM signal. GIA is the dominant driver of regional VLM in many parts of northern Europe (notably the North Sea, European Arctic, and Baltic basins) (e.g. Kierulf et al., 2021; Milne et al., 2001; Teferle et al., 2009). In those regions VLM can be almost an order of magnitude larger than the climate-driven increase in SL. GIA also largely explains the broad pattern of differences in RSLR in this region.

Land areas adjacent to the Atlantic basin (France and Spain) have generally low rates of VLM. In southern Europe, the GNSS VLM field shows uplift in the Alps. Around the Mediterranean and Black Sea basin there are (volcano)-tectonic deformations in Italy, the Balkans, and Greece, causing a large variability in VLM that is reflected in different relative SL trends.

3.4 Past changes in coastal extreme sea levels

Observations of coastal ESLs rely on high-frequency tide gauge records. In Europe there is a relatively large number of high-quality, long-term tide gauge records with hourly or higher sampling (Haigh et al., 2022, Sect. 3.1, Figs. 2, 3) that have been used to extensively characterize the magnitude and frequency of ESLs as well as their temporal variability (e.g. Marcos and Woodworth, 2017; Fig. 4). Long tide gauge records demonstrate that mean SL change is a major driver of changes in ESLs (Ferrarin et al., 2022; Weisse et al., 2014; Woodworth et al., 2011). However, variability in storm surges unrelated to mean SL has also been identified from observations at interannual and decadal timescales (Dangendorf et al., 2013; Marcos et al., 2015a; Mudersbach et al., 2013; Weisse et al., 2014). In addition, Calafat et al. (2022) determined that long-term trends in storm surges due to a combination of forced changes and internal variability along the European Atlantic coasts have had a contribution comparable to that of mean SLR on changes of ESLs since 1960. Changes in tides have also been evidenced. Although generally small, contemporary past changes in tides were substantial in, e.g. the German Bight (e.g. Haigh et al., 2020). There is also evidence for changes in wave regimes over the past decades notably related to changes in the surface winds in response to climate modes of variability and climate change (e.g. Dodet et al., 2019; for a review, see also Sect. 6 for European seas), but past trends in wind wave characteristics are associated with uncertainties due to the sensitivity of processing techniques, inadequate spatial distribution of observations, and homogeneity issues in available records (Fox-Kemper et al., 2021). Past changes in wind wave regimes imply changes in wave setup and runup (e.g. Melet et al., 2018).

4 Drivers of sea level rise and extremes

4.1 The role of Antarctica and Greenland

Ice loss from the Antarctic and Greenland ice sheets contributes to SLR (e.g. The IMBIE team, 2018, 2020). There is high agreement that for both Antarctica and Greenland, the rates of mass loss and relative contributions to SLR have increased substantially since the 1990s (Otosaka et al., 2023; Fig. 8a). As a consequence, the total mass loss of glaciers and ice sheets has become the dominant term in the SL budget since 2006 (Fox-Kemper et al., 2021). Ice loss reduces the mass of the ice sheets, thereby reducing their gravitational pull, which causes a relative lowering of ambient SL (within ∼ 2000 km of ice mass loss) and a relative heightening of far-away SL (further than ∼ 7000 km from the ice mass loss). This contemporary GRD effect is sometimes referred to as a SL fingerprint. This means that ice loss in Antarctica raises SL in Europe proportionally more than GMSLR (around 1.25 times the global mean), while ice loss in Greenland raises SL proportionally less than GMSLR over Europe (from around −0.4 to −0.2 times the global mean along the coast of Norway to 0.6–0.8 times the global mean in the eastern Mediterranean Sea and Black Sea, e.g. Tamisiea et al., 2014). Because of higher proximity, the Greenland fingerprint effect is more pronounced in northern European coasts (Bamber and Riva, 2010; Grinsted et al., 2015).

The contribution of the Greenland ice sheet comes from dynamic changes at the margins (Smith et al., 2020), likely caused by changes in the ocean (Holland et al., 2008; Straneo and Heimbach, 2013), as well as a reduction in the surface mass balance due to atmospheric warming (Hanna et al., 2021) which causes increasing surface melt and runoff (Slater et al., 2021), see Fig. 8b. The latter was estimated to account for about 60 % of the mass loss (Van Den Broeke et al., 2016) and both processes are expected to remain relevant over the coming decades (Choi et al., 2021). Projections of mass loss of the Greenland ice sheet until 2100 show a clear greenhouse gas-emission dependency with higher levels of warming leading to higher SL contributions (Goelzer et al., 2020). Uncertainties in atmospheric changes are directly reflected in Greenland projections: higher warming in CMIP6 models in comparison to CMIP5 yield higher mass loss in Greenland due to surface melt (Payne et al., 2021). Ocean-driven processes in Greenland projections are still highly parameterized (Slater et al., 2020). The role of atmospheric dynamics is also uncertain. Increased surface melt was found during atmospheric blocking events (e.g. Fettweis et al., 2013), which are, however, not captured in CMIP5 models (Hanna et al., 2018) and CMIP6 models (Delhasse et al., 2021). As such, van de Wal et al. (2022) added a factor of 2 to the possibility that the current CMIP models underestimate the change in the atmospheric dynamics in their estimate of the high-end contribution to SL change caused by loss of ice in Greenland. Along a similar line of reasoning, Beckmann and Winkelmann (2023) argued for a substantial increase of mass loss in Greenland if extreme warm summers are added to the projections. Other sources of uncertainty in the contribution from Greenland to SLR are related to the sensitivity of regional climate models used for downscaling global climate models results and the calculation of the surface albedo. Finally, there is an uncertainty related to the downscaling of global climate models results with regional climate models. The chain of processes causing mass loss in Greenland is outlined in Fig. 8b.

Antarctica's current mass loss (Rignot et al., 2019; Smith et al., 2020) can be linked to the thinning and enhanced calving of its surrounding ice shelves (Greene et al., 2022; Gudmundsson et al., 2019) driven by warmer ocean water masses; see Fig. 8c. In near-future projections, a further mass loss due to ocean-driven melting is expected to be counteracted by increased surface accumulation (Seroussi et al., 2020). Both processes were found to increase with increasing global forcing, suppressing a scenario dependence of the Antarctic future SL contribution until 2100 (Edwards et al., 2021). The climate forcing of this century will cause SLR over the longer term, and the contrast between lower and higher scenarios will emerge increasingly clearly at longer timescales. Fox-Kemper et al. (2021) assess the Antarctic contribution to global mean SLR in 2300 (without Marine Ice Cliff Instability possible contribution; see Sect. 5.2) to range between −0.14 and +0.78 m (17th–83th percentiles) for a low-emission scenario (SSP1-2.6) and between −0.28 and +3.13 m for a very high-emission scenario (SSP5-8.5). Critical for the timing of the accelerated mass loss of the Antarctic ice sheet is the timing of the collapse or weakening of ice shelves. As long as the major ice shelves are in place, ice mass loss is limited, but the rate of mass loss can increase strongly if ice shelves lose their buttressing force as enhanced ice discharge will then lead to an acceleration of SLR. For these reasons the Antarctic projections constitute the largest source of uncertainty in SL projections (e.g. Fox-Kemper et al., 2021). The loss of ice shelves is controlled by atmospheric, oceanographic, and glaciological conditions.

Currently, global circulation models that are used to provide the ocean and atmosphere forcing for the ice sheet models in projections do not include the processes on the continental shelf and in ice shelf cavities, which are ultimately determining the changes in sub-shelf melting below the ice shelves and thereby the dynamic mass loss of Antarctica. The sensitivity of melt rates to ocean temperature changes are highly uncertain but explain differences between LARMIP-2 (Levermann et al., 2020) and ISMIP6 projections (Reese et al., 2020; Seroussi et al., 2020). Recent projections with coupled atmosphere–ocean–ice sheet models for Antarctica also show a wide range of results (Park et al., 2023; Siahaan et al., 2022). In the future, ice shelves might also become increasingly vulnerable to atmosphere-driven melting (e.g. van Wessem et al., 2023). It may induce hydrofracturing of the ice shelves. For some shelves, atmospheric process will dominate, while for other shelves oceanographic controlled processes will dominate.

In addition, ice shelf collapse with subsequent self-sustaining ice cliff collapse has been suggested in DeConto and Pollard (2016). This instability is not yet convincingly demonstrated at present, and the importance of this process is debated. A recent paper discussed for example that the presence of ice mélange (a mix of icebergs and sea ice) could

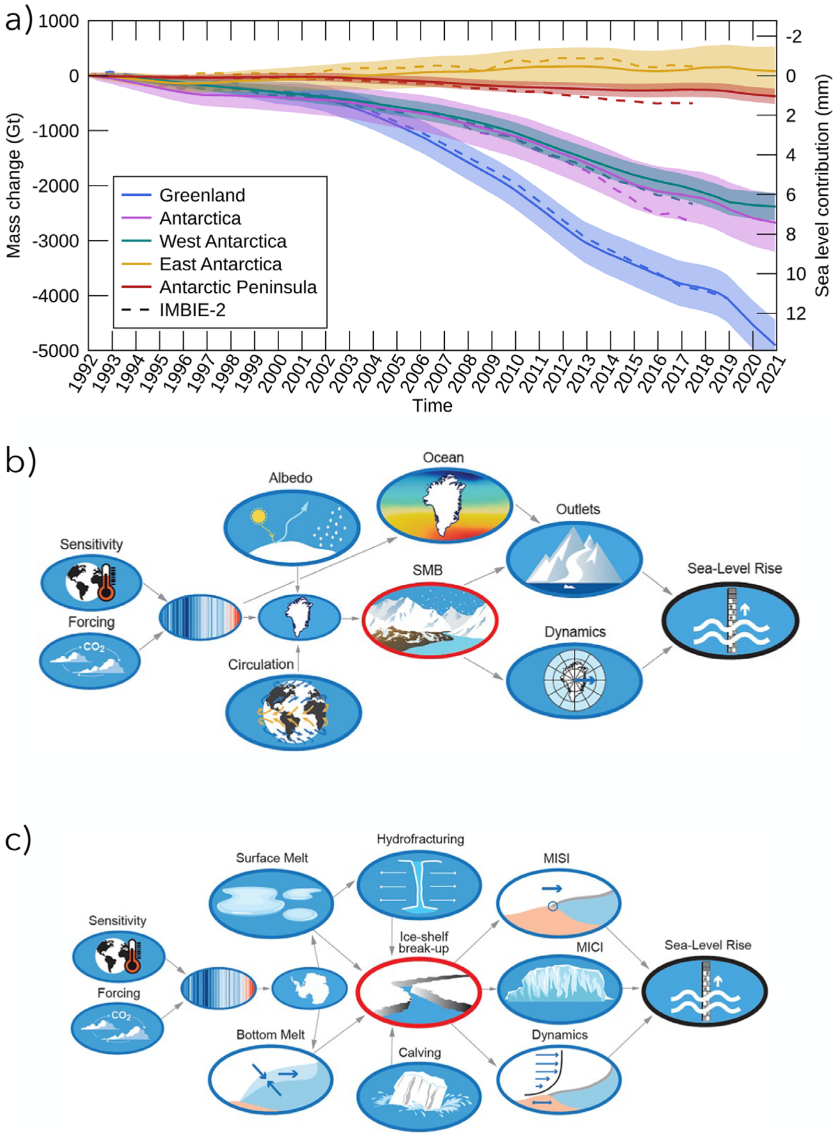

Figure 8. **(a)** Greenland and Antarctic ice sheet mass changes. Credit: reproduced from Fig. 4 of Otosaka et al. (2023). **(b)** Processes that influence Greenland's contribution to SLR and its future uncertainty. Credit: reproduced from Fig. 2 of Van De Wal et al. (2022). **(c)** Processes that influence Antarctica's contribution to SLR and its future uncertainty. Credit: reproduced from Fig. 3 of Van De Wal et al. (2022).

suppress this instability (Bassis et al., 2021; Schlemm et al., 2022). In the recent IPCC, it is treated as "deep uncertainty" (Kopp et al., 2023). The representation of ice shelf calving and damage in the ice constitutes a further uncertainty. Furthermore, uncertainty in processes related to basal sliding may also lead to large rates of ice mass loss (Sun et al., 2020). Hill et al. (2021) report that for the Filchner–Ronne Ice Shelf the range of possible parameters for atmospheric and oceanic changes yield a larger uncertainty than numerical model parameters. An unrealistic upper bound on the ice sheet response due to complete loss of ice shelves is provided by Sun et al. (2020). Problematic in projections for the ice sheets is that the initial state of the ice sheet is poorly constrained (e.g. Aschwanden et al., 2021) and that the Antarctic ice sheet has the potential to cross critical thresholds, which cause irreversible ice loss (see Sect. 5.2) and amplify uncertainty in SL projections (Robel et al., 2019). For this reason, the low-confidence (Fox-Kemper et al., 2021; Kopp et al., 2023) or high-end scenarios (Van De Wal et al., 2022) were developed.

4.2 Sea level budget

On decadal to multi-millennial timescales, global mean SL changes are essentially caused by changes in the Earth energy budget. Since the end of the 19th century, the increase of greenhouse gas concentrations from anthropogenic emissions modified the Earth energy budget such that the amount of outgoing radiation is less than the amount of incoming solar radiation, leading to global warming. Oceans absorbed 90 % of global warming leading to seawater expansion and SLR. A total of 3 % of the excess heat is absorbed by the cryosphere, causing the melting of land ice, such as glaciers and ice sheets, which contributes to SLR. Changes in terrestrial water storage, such as groundwater or water stored in lakes and rivers, also contribute to SLR. Part of the changes in terrestrial water storage are related to the energy budget and the climate variability through the changes in rain patterns that change the amount of water stored in areas such as lakes and rivers. Part of the changes in terrestrial water storage are related to direct anthropogenic activity (such as groundwater depletion and dam building) and thus are independent of the global energy budget.

SL budget analysis over the past century, based on development and application of new statistical methodologies for reconstructing global mean SL (e.g. Dangendorf et al., 2019; Frederikse et al., 2020a) and its contributions (e.g. Bagnell and DeVries, 2020; Frederikse et al., 2020b; Zanna et al., 2019), suggests that the primary factors contributing to GMSLR over 1901–2018 are the mass loss of glaciers (41 ± 15 %), the thermal expansion of seawater due to global warming (38 ± 10 %), and the Greenland ice sheet mass loss (25 ± 8 %). The contribution of Antarctic ice sheets mass loss is relatively small (4 ± 6 %) over this period. The contribution of land water storage is largely uncertain, but it is likely to contribute to a SL fall over 1901–2018 up to −8 ± 20 % (Fox-Kemper et al., 2021). Recent studies show that GMSLR started to accelerate in the 1960s and 1970s, initiated by an acceleration of thermosteric SLR due to an intensification and a basin-scale equatorward shift of Southern Hemispheric westerlies and induced increased ocean heat uptake (Dangendorf et al., 2019). Since the 1990s, accelerated ice mass loss, mostly from the Greenland ice sheet, has also contributed to the GMSLR acceleration (Dangendorf et al., 2019; Frederikse et al., 2020b). Over the period 1971–2018 the SL budget is consistent with the global energy inventory of the climate system, which gives high confidence to the global mean SL budget over this period (Fox-Kemper et al., 2021).

Over a more recent period, since 2006, global mean SL has been monitored by satellite altimetry, thermal expansion of the ocean by Argo floats, and the change in ocean mass by space gravimetry. Consequently, the SL budget is significantly more precise and the closure more accurate. Over 2006–2018, the SL budget is closed with an uncertainty of a few millimetres (Fig. 9). Over 2006–2018, the primary factors contributing to SLR are the thermal expansion of seawater due to global warming (39 %) and the Greenland ice sheet mass loss (17 %). The melting of glaciers represents 17 % of GMSLR over this period, while the Antarctica contribution rose to 10 %. Land water storage changes explain the remaining 17 % (Fox-Kemper et al., 2021, Table 9.5). Percentages are based on central estimate contributions compared to the central estimate of the sum of contributions.

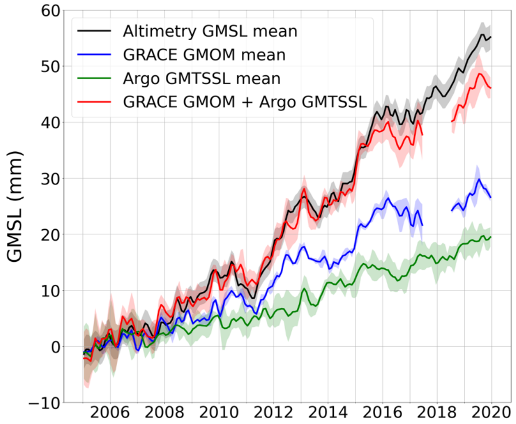

Figure 9. Global mean SL (GMSL) budget from 2006 to 2021. Global mean SL is estimated by satellite altimetry (black curve, data from the Copernicus Marine Environment Monitoring Service). Global mean ocean mass (GMOM) change (sum of ice sheet mass loss, glaciers ice melt, and land water storage changes) is estimated from GRACE and GRACE-FO (blue curve, data taken from the JPL, CSR, and GSFC mascon solutions). Global mean thermosteric sea level (GMTSSL) change is estimated from Argo (green curve, data taken from an ensemble of the NOAA, EN4, SCRIPPS, and JAMSTEC Argo products). From Fig. 2b in Barnoud et al. (2021).

Since 2018, the global mean SL budget derived from altimeter data has not closed anymore within conventional uncertainty thresholds (Barnoud et al., 2021, Fig. 9). A cause for this non-closure is a drift in the wet tropospheric correction (which is the correction for the path delay in the radar altimeter due to the water vapour content in the atmospheric column) of the Jason-3 altimeter and a drift in Argo salinity sensors. After correction of the spurious Jason-3 drift and after using only thermosteric SLR (and not steric SLR), the non-closure is reduced by 40 % but remains larger than the uncertainty in the components of the SL budget from 2019 on (Barnoud et al., 2023). More research is needed to understand the causes of the residual non-closure of the SL budget over the past few years.

At regional scale, closing the SL budget is more challenging due to the higher variance of the signal, although there have been some attempts to explore the closure from local (Royston et al., 2020) to large basin-wide scales (Purkey et al., 2014). Instead, Camargo et al. (2023) used unsupervised machine learning techniques to identify regions of coherent SL variability. Compared to previous studies, which looked at the regional budget on entire ocean basins, this study identified more and smaller domains. These domains reflect large-scale climate patterns, such as El Niño–Southern Oscillation in the Pacific and NAO in the Atlantic, and highlight which ocean regions are connected through physical processes, such as propagating coastally trapped waves from

Iberia to the northwestern European shelf (Calafat et al., 2012, 2014; Hughes et al., 2019). While in gridded data (for instance a 1 × 1 rectangular grid) the SL budget cannot be closed everywhere, the budget can be closed in almost all domains identified by self-organizing maps when all contributions, including estimates for deep steric changes, are accounted for and with a residual error of only 0.6 mm yr^{-1} for the period 1993–2016. The regional SL budget has also been closed along coastal regions of coherent variability (Dangendorf et al., 2021), also showing that most of the interannual changes are linked to dynamic SL variability. For example, in the North Sea, observations corrected for VLM display a linear trend of 2.01 mm yr^{-1} (95 % confidence intervals of 1.30–2.76 mm yr^{-1}) over 1960–2012, while the sum of the sterodynamic and barystatic contributions is 2.09 mm yr^{-1} (1.58–2.52 mm yr^{-1}) (Dangendorf et al., 2021). Despite the good agreement in this region, there are uncertainties in VLM that may result in slightly different rates of SL change (e.g. Frederikse et al., 2016, who reported around 1.3 mm yr^{-1} for the same period).

4.3 Drivers of extreme sea levels

Coastal ESLs result from the combined action of mean SL changes, astronomical tides, atmospheric pressure, and surface winds that generate storm surges and wind waves. Higher-frequency processes such as coastal waves, meteotsunamis and seiches (in semi-enclosed basins such as the Adriatic Sea) can also contribute to ESLs at the coast. Thus, ESLs are short-term phenomena (timescale of minutes or hours to a day) triggered by atmospheric perturbations and tides, but they are also modulated by long-term changes in mean SL and by low-frequency variability in storminess (associated with changes in frequency, tracks, and/or severity of weather systems; Woodworth et al., 2019). Return levels for extreme storm surges are shown in Fig. 4 for selected European locations.

Changes in mean SL affect ESLs in several ways: variations in water levels modify the baseline level upon which extremes reach the coastline, and at the same time changes in mean SL interact with other coastal SL contributors like tides, surges, and waves (Idier et al., 2019), for instance through velocity and friction effects over tides and storm surges due to depth changes in coastal shallow waters. Along many European coastlines, astronomical tides are an important component of ESLs and in some regions tide–surge interactions take place, such as in the English Channel (Haigh et al., 2010; Idier et al., 2012), the UK coastline (Horsburgh and Wilson, 2007), and the North Sea (Arns et al., 2020; Wolf, 1981). Changes in mean SL also affect tidal propagation in the same way as storm surges. As these processes take place at subregional spatial scales, further research is needed to explore future changes and the resulting impacts on the coasts (see Sect. 5.3).

Changes in tides (Sect. 3.4) and storminess can also drive changes in ESLs at the coast. Besides storm surges, wind waves are also a driver of coastal hazards, especially when they co-occur with storm surge extremes. Wind waves in the nearshore contribute to coastal ESLs through transfer of momentum due to wave breaking (the so-called wave setup effect) and the wave uprush on a beach or structure (the so-called wave run-up) (Dodet et al., 2019). The magnitude of the wave contribution is locally variable and often difficult to assess from observations, as tide gauges are placed in sheltered areas to avoid instrumental failures. The effect of wind waves on ESLs over broad spatial scales has therefore been assessed mostly using parametric approaches (Melet et al., 2018; Vousdoukas et al., 2017). Coupled hydrodynamic and wind wave models are available, but they need a very high spatial resolution in coastal areas to properly represent wave setup, thus limiting their applicability (Roland et al., 2009).

Despite the relatively good coverage of tide gauges along European coastlines (Sect. 3.1, Figs. 2, 3), their location is sparse and SL records are often incomplete, thus providing only a partial picture of the spatial and temporal footprints of coastal ESLs. One way to overcome the limitation of the observational network is to simulate ESLs using either numerical models or data-driven approaches. Hydrodynamic models, the most common to simulate storm surges, use the shallow water equations to simulate the response of the ocean to atmospheric pressure and surface winds. Ocean general circulation models can also be used for this purpose (e.g. as in Copernicus Marine regional forecasting systems; Irazoqui Apecechea et al., 2023), as they explicitly resolve tides and storm surges, although at higher computational expenses. Model accuracy depends essentially on the available forcing fields and on the model setup, including the spatial resolution of the coastal bathymetry and the coastline. Computational needs and data availability of this type of models are currently one of the main limitations to increase the spatial resolution. For example, available bathymetric data in the German Bight is coarse and inconsistent, and affected by morphodynamic changes at interannual timescales. Hydrodynamic model runs are available at global and European scales spanning several decades, thus allowing us to explore seasonal variability and long-term trends in storm surges (e.g. Fernández-Montblanc et al., 2020; Muis et al., 2020). Alternatively, data-driven approaches rely on establishing a statistical relationship between observed ESLs and a set of predictors from atmospheric and/or oceanic variables. These data-driven approaches can be, in some places, more accurate than hydrodynamic models and require less computational resources (Tadesse et al., 2020). These alternative methods, however, are site dependent and may not be reliable to reproduce an event that is beyond the observational records. Quantitative information on coastal ESLs derived from data-driven approaches or models, in the form of simulated or reconstructed time series, are available online along all European coastlines (see Sects. 3, 5.3, 6).

5 Projections of sea level rise and extremes on global and regional scale

5.1 21st century projections

Projections of future SL change can be computed using global climate model information for the ocean density and dynamics, in combination with dedicated model simulations for the contributions from ice sheets (Sect. 5.1), glaciers, land water storage change, and VLM (Sect. 3.3). The latest IPCC AR6 report provided 21st century SL projections for five different emission scenarios (Fox-Kemper et al., 2021: SSP1-1.9 (“very low”), SSP1-2.6 (“low”), SSP2-4.5 (“intermediate”), SSP3-7.0 (“high”) and SSP5-8.5 (“very high”); Fig. 1). These projections include all processes that could be assessed with at least medium confidence, thereby excluding ice sheet processes associated with deep uncertainty as discussed in Sect. 4.1 (see also Sect. 5.2). In addition, low-confidence projections (Fox-Kemper et al., 2021) and high-end projections (Van De Wal et al., 2022) were developed, reflecting the deep uncertainty associated with the contribution of the Antarctic and Greenland ice sheets.

The medium-confidence regional IPCC AR6 projections (Fig. 10) show that some European coasts are projected to experience a RSLR by 2100 below the projected GMSLR, such as the Norwegian coast, the Baltic Sea, the northern part of the UK and Ireland, and the northern coasts in the Mediterranean basin. Other coasts also show projected RSLR above the global mean, for instance the Atlantic coasts of Portugal, Spain, France, Belgium, and the Netherlands. For semi-enclosed basins, the projections can be improved by replacing the ocean density and dynamics component from the IPCC projections by high-resolution regional model results that capture the local dynamics and exchange with the ocean basins in much more detail. More regional information on SLR projections is provided in Sect. 6 per European sea basin.

A new addition to the AR6 report, compared to previous IPCC reports, is the inclusion of SL projections stratified by warming level (Fox-Kemper et al., 2021; their Sect. 9.6.3.4). As SLR is mostly a product of time-integrated warming, rather than instantaneous warming (e.g. Bouttes et al., 2013; Hermans et al., 2021; Kuhlbrodt and Gregory, 2012; Melet and Meyssignac, 2015), it is important to specify the timing of the peak warming. The AR6 projections (Table 2) are based on a global mean surface air temperature increase of 1.5, 2, 3, 4, and 5° by 2081–2100 but do not specify the route to this temperature increase. The differences in the pathways and their effect on the projected SLR are reflected in the uncertainties in the temperature level projections (Table 2).

For decision making around SLR, it may be useful to ask “when” a certain SLR threshold will be crossed (Slangen et al., 2022), as this provides an indication of the time left to prepare adaptive and protective measures for that specific threshold. Figure 11 indicates the first decade in which the median projected regional SL change over European seas has crossed a certain threshold (0.5, 0.75, 1.0 m above the 1995–2014 baseline) under two emissions scenarios. A lower-emission scenario (Fig. 11, left column) typically leads to slower SLR, which in turn leads to a later crossing of thresholds, whereas high-emission scenarios (Fig. 11, right column) have a faster SLR and therefore earlier crossing of thresholds. For thresholds crossed before 2050 there is little dependence on the emission scenario used.

5.2 Tipping points, irreversibility, and commitment

Greenland and the West and East Antarctic ice sheets are considered tipping elements in the climate system (Armstrong McKay et al., 2022; Lenton et al., 2008). In this case, tipping is understood as crossing a critical threshold beyond which ice loss becomes irreversible on human timescales, i.e. the relevant climate forcing (regional oceanic and atmospheric conditions) would need to be reduced substantially below the pre-tipping value to halt or reverse the retreat of the ice sheet.

The tipping behaviour of the Greenland ice sheet is linked to the melt–elevation feedback, where the ice sheet surface lowering brings the ice surface into regions of higher surface air temperatures which causes more melting and thereby further surface lowering (Levermann and Winkelmann, 2016; Weertman, 1961). The Greenland ice sheet was confirmed to exert a tipping behaviour in Robinson et al. (2012); however, in other model simulations, e.g. of a coupled ice and atmosphere general circulation model (Gregory et al., 2020), only the northern part of the ice sheet, corresponding to 2 m of SL equivalent, was found to behave irreversibly. In some cases, examining statistical properties indicate whether the system is close to a tipping point. Boers and Rypdal (2021) suggest that based on surface melt reconstructions the central western Greenland ice sheet is close to a critical transition. Importantly, the timescale of tipping depends on the strength of the forcing scenario. A nearly complete disappearance of the Greenland ice sheet might still take millennia if the threshold is marginally crossed (Robinson et al., 2012), which would imply that rates of SLR are still modest.

A widely accepted mechanism for tipping in Antarctica is the marine ice sheet instability (MISI; Schoof, 2007; Weertman, 1974), where the ice sheet retreats rapidly in marine parts of the ice sheet because of a positive feedback between the seawards ice flux and ice retreat. Since stability conditions for MISI are more complicated than only a retrograde slope for realistic Antarctic conditions (Gudmundsson, 2013; Haseloff and Sergienko, 2018; Pegler, 2018; Sergienko and Wingham, 2022), numerical modelling is required to identify these tipping points. Studies suggest tipping behaviour for the glaciers (e.g. Thwaites and Pine Island) in the Amundsen Sea (Favier et al., 2014; Rosier et al., 2021) and West Antarctica (3 m of SL equivalent; Feldmann and Levermann, 2015). The East Antarctic ice sheet contains marine basins that can

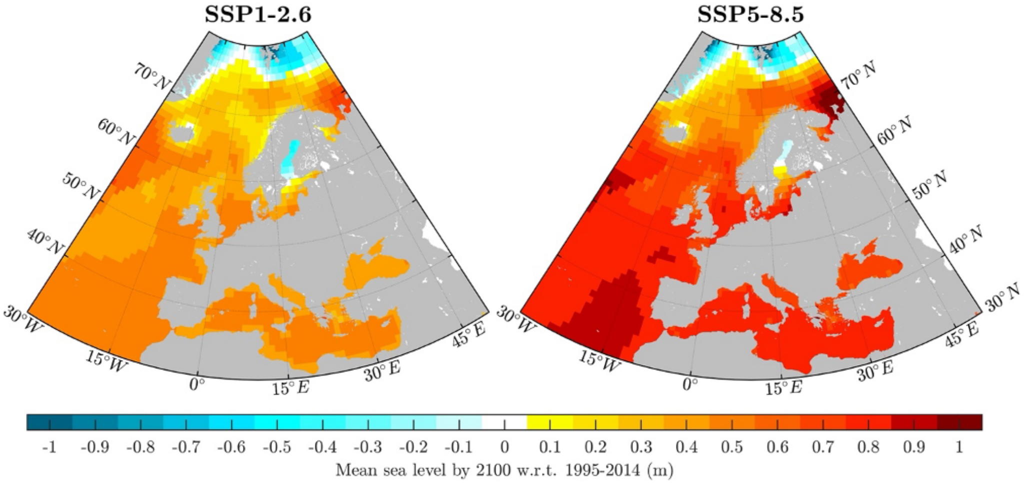

Figure 10. Median relative SL regional projections (medium confidence, i.e. excluding ice sheet processes associated with deep uncertainty) from the IPCC AR6 report around Europe under (left) SSP1-2.6 and (right) SSP5-8.5 in 2100 with respect to 1995–2014 (m) (IPCC AR6 projection data available from https://doi.org/10.5281/zenodo.5914709, Garner et al., 2021).

Table 2. GMSLR projections (*m*) for exceedance of five global warming levels, defined by sorting global mean surface air temperature in 2081–2100 with respect to 1850–1900. Median values and likely range in 2050 and 2100 relative to a 1995–2014 baseline are given (Fox-Kemper et al., 2021). Data for the temperature pathways are available at https://doi.org/10.5281/zenodo.5914709 (Garner et al., 2021).

GMSLR (m)	1.5°	2.0°	3.0°	4.0°	5.0°
Total (2050)	0.18 (0.16–0.24)	0.20 (0.17–0.26)	0.21 (0.18–0.27)	0.22 (0.19–0.28)	0.25 (0.22–0.31)
Total (2100)	0.44 (0.34–0.59)	0.51 (0.40–0.69)	0.61 (0.50–0.81)	0.70 (0.58–0.92)	0.81 (0.69–1.05)

also show tipping, such as the Wilkes basin (19 m sea level equivalent; Mengel and Levermann, 2014). In addition, the Aurora basin (3.5 m sea level equivalent), which is a large marine-based area, has been suggested to have the potential of tipping. Observations and modelling of continued grounding line retreat in the Amundsen Sea has raised the question whether MISI is already ongoing (Favier et al., 2014; Joughin et al., 2014; Rignot et al., 2014). A recent study by Hill et al. (2023) finds that MISI-driven grounding line retreat is likely not yet underway in Antarctica. However, a collapse of the West Antarctic ice sheet on millennial timescales is possible already under current climate conditions (Reese et al., 2023). This is consistent with Garbe et al. (2020) reporting that retreat of West Antarctic grounding lines could be initiated by around 1–2 °C of global warming above pre-industrial levels. Golledge et al. (2021) also find that in a simulation coming from the last interglacial, the West Antarctic ice sheet starts retreating after 1500 years with constant current climate conditions. Oceanic forcing of the Amundsen Sea region is expected to increase, which would push the system faster towards tipping (Naughten et al., 2023). Thus, the general idea is that West Antarctica is unstable for high-forcing scenarios (Oppenheimer et al., 2019), but our insights are not detailed enough to indicate where the threshold is in detail. Importantly, the timescales of tipping also depend on the strength of the forcing scenario, parameter choices, and physical choices made in model set up. Feldmann and Levermann (2015) and Golledge et al. (2019) find that a collapse of the Antarctic ice sheet takes millennia for temperature values close to the threshold, while the unrealistic ice shelf removal in the Antarctic Buttressing Model Intercomparison Project (ABUMIP; Sun et al., 2020) causes the West Antarctic ice sheet to collapse within a few centuries.

An alternative tipping mechanism has been suggested by DeConto and Pollard (2016) based on ice shelf disintegration followed by the collapse of the newly formed vertical ice cliffs is called marine ice cliff instability (MICI), yielding even more rapid rates of mass loss. MICI would be caused by the feedback between ice cliff height and calving. The importance, timescales, and mechanism of this process are debated (e.g. Bassis et al., 2021), and it is for this reason classified as “deep uncertainty” in the latest IPCC report (Fox-Kemper et al., 2021). The importance of both MISI and MICI strongly depends on the extent to which the ice shelves retain their buttressing force to keep the ice sheet in place. Timing of collapse or thinning of the major ice shelves is not foreseen in the 21st century, but DeConto et al. (2021) suggest that increased mass loss due to shelf collapse starts to play a role around 2100 with consequences for enhanced SLR in the early 22nd century.

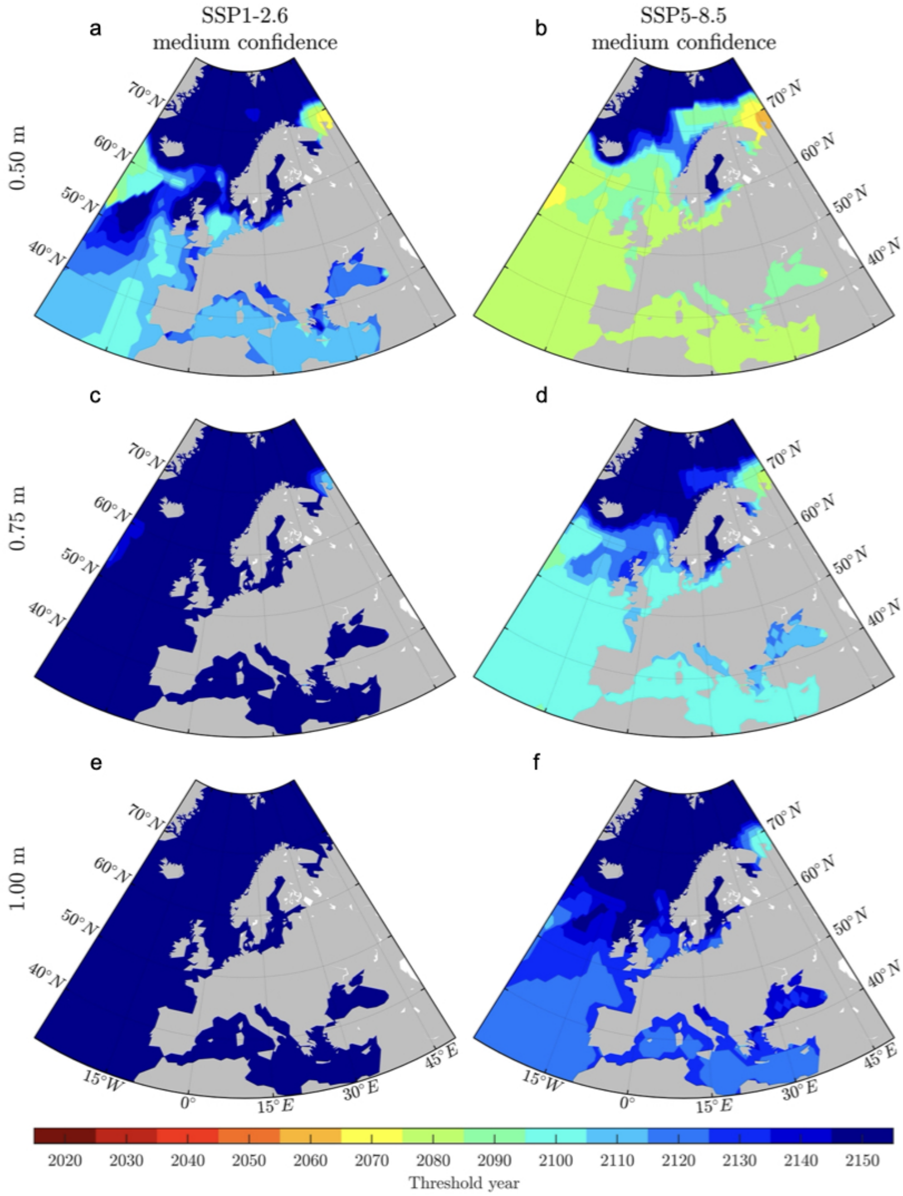

Figure 11. The first year of the decade (between 2020 and 2150) when the median regional SL projections around Europe have crossed a threshold since 1995–2014 of 0.5 m **(a, b)**, 0.75 m **(c, d)**, and 1.0 m **(e, f)** under SSP1-2.6 emissions **(a, c, e)** and SSP5-8.5 **(b, d, f)**. Dark blue indicates no crossing before 2150. Results are based on the medium-confidence IPCC AR6 SL projections (Fox-Kemper et al., 2021; IPCC AR6 projection data available from https://doi.org/10.5281/zenodo.5914709, Garner et al., 2021).

Crossing tipping points would mean an irreversible commitment to SLR unless a rapid temperature decrease is materialized (Bochow et al., 2023). SL commitment is, however, not only due to crossing of tipping points but also because ice sheets respond on long timescales and climate forcing might be hard to reverse. The contribution of the Greenland ice sheet in 2100 that has already been committed through past climate change has been estimated to be around 3.3 cm SLR (Nias et al., 2023). Climate change during this century will commit ice loss over the coming centuries to millennia even without further climate change.

Furthermore, there is a long-term SLR commitment from the ocean, through the key role it plays for uptaking heat from the atmosphere and the consequently induced thermal expansion (e.g. Bouttes et al., 2013). The efficiency of ocean heat uptake (the temporal rate of change of the ocean heat content) depends on how quickly heat gained at the ocean surface is transported to depth. The faster heat is mixed to the deep ocean, the less the surface air temperature warms as more excess heat is taken up by the ocean and the lower the transient climate response (Krasting et al., 2018; Marshall and Zanna, 2014). If emissions of GHG were to stop, the radiative forcing of GHG that was previously released in the atmosphere would remain quasi-constant with a slow decay over centuries (e.g. Ehlert et al., 2017; Zickfeld et al., 2017). As a result, the global mean surface air temperature would remain quasi-constant. The upper-ocean temperature, which exchanges heat with the atmosphere, tracks the radiative forcing and would thus equilibrate. On the other hand, the deep ocean, which is coupled to the upper ocean through mixing, would continue to warm and to export heat to deeper layers (e.g. Bouttes et al., 2013; Dalan et al., 2005; Ehlert et al., 2017; Melet et al., 2022). Although the ocean heat uptake would decline over time, the large thermal inertia of the deep ocean and the long timescales of its adjustment would result in a net warming of the ocean and related steric SLR that is largely irreversible for at least a millennium after emissions stop (e.g. Zickfeld et al., 2017). Only on very long timescales the deep ocean may release this energy again.

5.3 Projected changes in extremes

Projections of future changes in ESLs generally either only include the effect of an increase in the mean SLR on the baseline height of extremes, assuming that the distribution of ESLs is stationary, or also include non-stationarity in extremes due to changes in storm surges, tides, and/or waves based on numerical modelling (Sect. 4.3).

5.3.1 Projected changes in extremes

Projections of future changes in ESLs due to SLR are often reported through so-called amplification factors, which correspond to the change in the expected frequency of a given contemporary ESL height under climate change scenarios (Buchanan et al., 2016; Fox-Kemper et al., 2021; Frederikse et al., 2020b; Hermans et al., 2023; Jevrejeva et al., 2023; Lambert et al., 2020; Oppenheimer et al., 2019; Rasmussen et al., 2018; Tebaldi et al., 2021; Wahl et al., 2017) or as the height by which coastal defences need to be raised to restore the historical flood probability (called allowances; Hunter, 2012; Hunter et al., 2013; Slangen et al., 2017; Woodworth et al., 2021). For instance, the IPCC AR6 (Fox-Kemper et al., 2021) projected that the SL associated with the historical centennial event, which is the event that historically had a 1 % chance of occurring each year (once per century on average), will be exceeded at least annually (i.e. corresponding to an amplification factor of 100) at 19 %–31 % of 634 tide gauges worldwide in 2050 and at 60 %–82 % in 2100. In Europe, the largest amplification factors of the frequency of ESLs are projected for the south (Mediterranean and Iberian Peninsula coasts), whereas in the northeast of the United Kingdom and in the southeastern North Sea, amplifications are generally smaller because the current variability of ESLs is larger (Fig. 12). Amplifications of the historical centennial event are below 1, implying a decreasing probability of the historical centennial event in the northern Baltic Sea because of the land uplift anticipated for that region associated with GIA (Sects. 3.3 and 6.5). The spatial pattern in Fig. 12 is a robust feature across different studies (e.g. Fox-Kemper et al., 2021; Frederikse et al., 2020b; Oppenheimer et al., 2019).

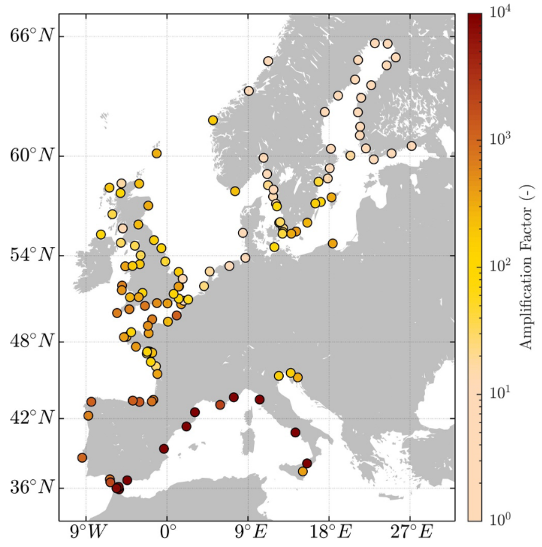

Figure 12. Amplification factors showing the expected change in frequency of the historical centennial SL event in 2100 projected by the IPCC AR6 for Europe under the SSP2-4.5 middle-of-the-road emission scenario (obtained from Fig. 9.32 of Fox-Kemper et al., 2021). Here, an amplification factor of 10 means that the historical centennial SL event will become a decennial event in 2100, while an amplification factor of 100 means that the historical centennial SL event will become an annual event in 2100.

Projected amplification factors in most of the studies mentioned above are derived by combining inferences of the historical ESL distribution with projected relative SLR, incorporating the uncertainty in both and assuming that the historical extremes distribution remains the same (so-called static or mean SL offset method). Projections of amplification factors are therefore sensitive to the type of extreme value distribution used and to the threshold above which events are defined as extreme (Buchanan et al., 2016; Wahl et al., 2017). A generalized Pareto distribution with the 99th percentile as a threshold was identified to be the preferred approach to assess ESLs at a global scale (Wahl et al., 2017). Acknowledging that the same threshold is not appropriate at all locations, two recent studies implemented an automatic threshold selection (Hermans et al., 2023; Lambert et al., 2020), which substantially affected their results in specific locations. To characterize the events below the threshold, different approximations have been used such as a Gumbel distribution between mean higher high water and the extremes threshold (Buchanan et al., 2016; Fox-Kemper et al., 2021; Rasmussen et al., 2018) or a simple extrapolation (Hermans et al., 2023; Sweet et al., 2022). Rasmussen et al. (2022) applied an extreme value mixture model instead, but the extent to which declustering the data below the threshold is appropriate is unclear. Furthermore, since wave-sheltered tide gauge measurements are typically used to infer the extreme SL distributions, the effect of waves is not (fully) incorporated in the type of projections in this Section. Incorporating waves generally increases the historical range of extremes at a given location, which leads to smaller projected amplification factors (Lambert et al., 2020).

Most studies have projected the amplification of the historical centennial event. However, information on changes in the probability of a single extreme SL can be of limited salience locally (Rasmussen et al., 2022). For instance, the design height of local protective infrastructure may differ from the height of the historical centennial event, and large amplifications of the historical centennial event do not necessarily affect a large fraction of the local population (Rasmussen et al., 2022). Projections of the population affected by changes in extremes (e.g. Haasnoot et al., 2021; Kirezci et al., 2020, 2023; Rasmussen et al., 2022) or projections of the amplification factors of specifically those ESLs that local coastal protection is designed to withstand (Hermans et al., 2023), help to add context to projections of amplification factors that facilitates translating hazards into impacts (Rasmussen et al., 2022; van de Wal et al., 2024, in this report). Policy-relevant information may also be provided by projecting when certain critical increases in the probability of ESLs may be reached instead of how much that probability will increase in 2100 (Rasmussen et al., 2022), akin to the timing of mean SLR milestones (Cooley et al., 2022; Fox-Kemper et al., 2021; Haasnoot et al., 2019; Slangen et al., 2022). Recent projections of the timing of amplification factors due to SLR indicate that the probability of ESLs that coastal flood defences are designed to withstand will increase substantially within the time it may take to implement large adaptation measures in Europe as well (Hermans et al., 2023).

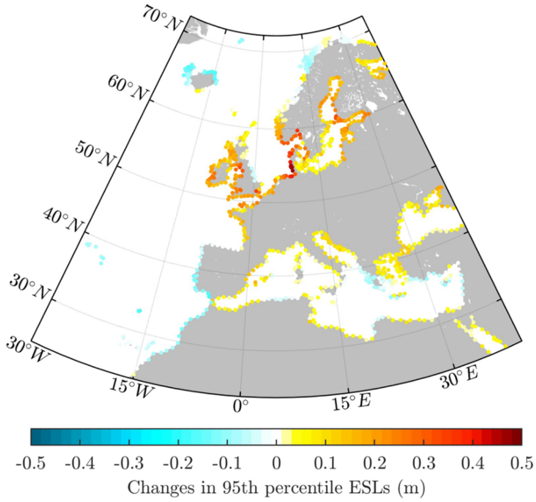

Figure 13. Projected changes in the height of ESLs associated with storm surges and waves only under a worst-case scenario (95th percentile of the centennial event, corresponding to a return period of 0.01 yr^{-1}) by 2100 relative to 1980–2014 along the European coastline (adapted from Fig. 3 of Jevrejeva et al., 2023, using data from Vousdoukas et al., 2018).

5.3.2 Projections of dynamic changes in extremes

To account for changes in the distribution of extremes, numerical models can be used to simulate changes in storm surges, tides, and waves due to changes in atmospheric conditions and water depth (e.g. Fig. 13). Barotropic hydrodynamic models (Sect. 4.3) have been used to simulate storm surges, tides, and their future changes, either only as a function of atmospheric changes simulated by regional or global climate models (Palmer et al., 2018; Vousdoukas et al., 2017, 2018; Jevrejeva et al., 2023) or also due to projected mean SLR, imposed in the model as a change in water depth (Muis et al., 2020, 2023). High-resolution baroclinic ocean models, which can simulate both changes in mean SLR and in storm surges, tides and their non-linear interactions, can provide more consistent simulations of dynamic changes in extremes. As these models are computationally more expensive than hydrodynamic models, they are often limited to a specific region (e.g. Northern Atlantic and North Sea in Chaigneau et al., 2022; Chinese Seas in Kim et al., 2021; and Jin et al., 2021). As explained in Sect. 4.3, wave contributions to ESLs and their projections can be evaluated using parameterizations based on numerical wave models outputs (Dodet et al., 2019; Kirezci et al., 2020; Lambert et al., 2020; Melet et al., 2018), but these parameterizations are limited as they are restricted to specific coastal environments, rely on the specification of a local beach slope, and are calibrated with relatively sparse historical field data (Lambert et al., 2020, 2021; Melet et al., 2020).

Using the models described above, substantial dynamic changes in each contribution to ESLs have been projected for the European coasts, especially under the SSP5-8.5 scenario. The results are presented here for the SSP5-8.5 scenario, since this is the scenario that shows the largest projected changes and that has been the focus in most dynamic approaches in the past years. Forcing a hydrodynamic model with atmospheric simulations from high-resolution climate models (Haarsma et al., 2016), Muis et al. (2023) projected a decrease in storm surges of up to 15 % in southern Europe by mid-21st century. Around the UK, Palmer et al. (2018) and Howard et al. (2019) concluded no projected changes in storm surges due to the spread of the global climate forcing models. For the same region a strong decrease of around −10 % in mean and extreme wave heights and periods (Aarnes et al., 2017; Lobeto et al., 2021b; Mentaschi et al., 2017; Meucci et al., 2020; Morim et al., 2018, 2021), resulting in a decrease in wave setup and runup (Melet et al., 2020), is also expected by the end of the century. In the southern North Sea, Jevrejeva et al. (2023) showed an increase of +50 cm in extreme storm surges and waves under a low-probability high-impact scenario (Fig. 13), in line with early attempts to account for dynamic changes in storm surges (Woth, 2005; Woth et al., 2006). In addition, non-linear interactions between SL, surges, waves, and tides, for instance through changes in water depth, can impact ESLs and their future changes in Europe (Idier et al., 2019). For example, tidal ranges may change by several tens of centimetres in Europe depending on the spatial variability of SLR, considered SL drivers, and the inclusion of flooding of low-lying topography (Haigh et al., 2020; Idier et al., 2017; Pickering et al., 2017). Extreme significant wave heights are projected to be significantly larger (up to +40 %) at the end of the century under the SSP5-8.5 scenario due to the consideration of mean SLR and tides (Arns et al., 2017; Chaigneau et al., 2023) with implications on wave setup and runup and thus on projections of ESLs. In addition, recent studies have shown, on a global scale and more specifically for Europe, that historical trends in storm surges (Calafat et al., 2022; Reinert et al., 2021; Roustan et al., 2022; Tadesse et al., 2022) and tides (Pineau-Guillou et al., 2021; Jänicke et al., 2021) have been comparable in magnitude to the historical mean SLR trend.

The historical and projected dynamic changes in extremes and their non-linear interactions in Europe suggest that studies using a static approach may miss an important aspect of changes in ESLs (e.g. Boumis et al., 2023). However, recent studies using dynamic approaches concluded that generally mean SLR is the dominating driver of the projected changes in ESLs (Howard et al., 2019; Jevrejeva et al., 2023; Muis et al., 2020; Vousdoukas et al., 2018). For instance, Jevrejeva et al. (2023) concluded that projected changes associated with storm surges and waves contribute less than 10 % to the total increase in ESLs by 2100 in Europe and elsewhere. Nevertheless, these studies typically do not include projected changes in all the coastal SL components (tides, storm surges, waves) nor their non-linear interactions and may therefore underestimate the importance of dynamic changes in extremes. Moreover, most studies projecting dynamic changes in extremes are based on small ensembles of model simulations, often for a single emissions scenario, due to the high computational cost of high-resolution hydrodynamic or 3D ocean and wave models and the limited availability of appropriate forcing data (Jevrejeva et al., 2023; Muis et al., 2020, 2023; Vousdoukas et al., 2017, 2018). The projections may therefore not be robust due to structural differences between the different driving climate models and internal climate variability, as also suggested by Calafat et al. (2022). Furthermore, the driving global climate models often have a relatively low atmospheric resolution, so they cannot resolve historical and future cyclones very well.

In summary, while several studies have concluded that mean SLR is the dominant driver of changes in ESLs at most locations, including in Europe, further research is required to better quantify dynamic changes in extremes.

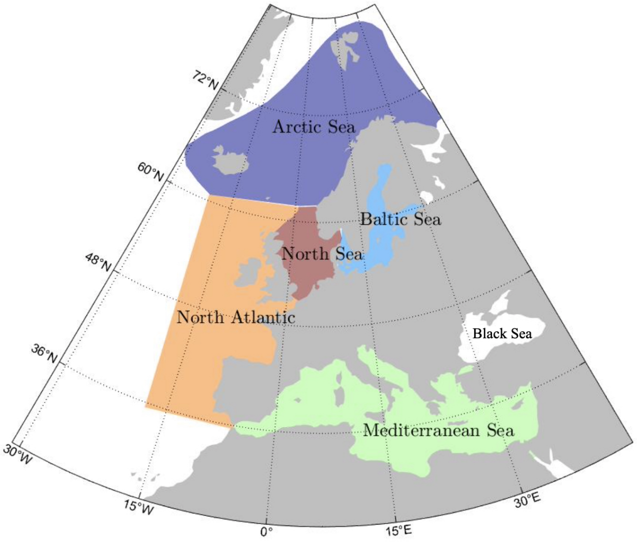

Figure 14. European regional seas domains used in this section, Table 3 and Figs. 15 to 19.

6 Key developments per region

In this section, we provide a regional focus per European regional sea: northeastern Atlantic, North Sea, European Arctic Ocean, Baltic Sea, and Mediterranean and Black seas (Fig. 14). Key developments per region are provided, with first the general context for each regional sea, then past mean and extreme sea level changes, and finally future mean and extreme sea level changes. As key processes can differ across European regional seas, specific discussions are provided in each section.

Rates of RSLR over the recent past (1950–2014) and end of the 21st century under different climate change scenarios are provided in Table 3 for each European regional sea.

In addition, Figs. 15 to 19 provide, for each regional sea, basin-averaged relative SL (with GIA and GRD effects being included) over 1900–2014, basin-averaged projected multi-model ensemble mean relative SL until 2100, linear trends of vertical land motion, and 50-year return levels of extreme still water levels representative of the recent past. For that purpose, different datasets were used in addition to IPCC AR6 projections.

For SL changes over 1900–2014, the global reconstruction of mean sea level changes by Dangendorf et al. (2019) is used. This dataset uses long-tide gauge records, altimetric observations, SL fields from climate models and spatial fingerprints of land-based ice melting (including GIA) to generate a hybrid monthly mean SL reconstruction that accounts for both observed trends and variability on a global $1^\circ \times 1^\circ$ grid. Relative SL with and without the effect of GIA are provided in Dangendorf et al. (2019) and are used to provide RSLR for the European Arctic and Baltic Sea in Table 3, as these regional seas are largely impacted by GIA. In Figs. 15–

Table 3. Rates of RSLR (in mm yr^{-1}) per European regional seas for 1950–2014 (based on Dangendorf et al., 2019), and 2080–2100 under the SSP1-2.6 low-emission, high-mitigation scenario; SSP2-4.5 middle-of-the-road scenario; and SSP5-8.5 very high-emission, low-mitigation scenario from IPCC AR6. Corresponding time series are shown in Fig. 15a for the northeastern Atlantic Ocean, Fig. 16a for the North Sea, Fig. 17a for the European Arctic, Fig. 18a for the Mediterranean Sea and Black Sea, and Fig. 19a for the Baltic Sea. Note that for the European Arctic and the Baltic Sea, rates are also presented over 1950–2014 without GIA contribution (i.e. GIA corrected), as provided by Dangendorf et al. (2019). Reported uncertainties for the 1950–2014 rates correspond to the standard error of the time series only. For 2080–2100, the rate of the median RSLR is reported, together with the trends of the RSLR 17th–83th percentiles in brackets.

mm yr^{-1}	Reconstruction (1950–2014)	SSP1-2.6 (2080–2100)	SSP2-4.5 (2080–2100)	SSP5-8.5 (2080–2100)
Arctic	1.5 ± 0.1	1.6 [−0.7–4.5]	3.4 [1.1–6.8]	5.9 [2.7–10.9]
Arctic (no GIA)	1.4 ± 0.1			
Baltic	-1.1 ± 0.4	0.6 [−1.5–3.2]	4.5 [3.1–7.1]	9.2 [5.0–14.7]
Baltic (no GIA)	1.8 ± 0.4			
Mediterranean	1.2 ± 0.1	4.3 [1.8–7.2]	6.8 [4.4–10.4]	12.6 [9.7–17.2]
NE Atlantic	1.2 ± 0.1	4.4 [1.9–7.3]	7.3 [5.1–10.7]	12.3 [9.5–17.1]
North Sea	1.5 ± 0.1	3.7 [1.6–6.3]	6.7 [5.2–9.5]	11.8 [8.7–16.5]

19, reconstructed relative SL with the effect of GIA (and GRD from contemporary mass loss of land-based ice) are shown. In addition, the vertical reference of the reconstructed relative SL time series has been adjusted to match projected mean sea level records, as it is arbitrary.

Regarding trends of VLM in Figs. 15 to 19, the dataset provided by Oelsmann et al. (2024) is used. This dataset is based on point-wise observations (time series from 11 000 GNSS and from differences between altimetry and 713 tide gauges). Time series were first adjusted or corrected for offsets and outliers. Following this, VLM was reconstructed over 1995–2020 using Bayesian principal component analysis and was finally spatially interpolated along the world's coastlines.

The 50-year return levels of extreme still water levels (still water levels represent coastal sea level including relative mean sea level, tides and surges, as observed by tide gauges) representative of the recent past are provided by different datasets, depending on regional seas. In the northeastern Atlantic, a high-resolution, 3D ocean model including tides and surges is used (IBI-CCS; Chaigneau et al., 2022). In the North Sea and Baltic Sea, the barotropic Global Tide and Surge Model (GTSM) dataset is used (Yan et al., 2020). In the European Arctic, estimates provided by the Norwegian Mapping Authority (Table 1) are used. Finally, for the Mediterranean Sea, computed using a 72-year ocean simulation of coupled hydrodynamic and wave model (Toomey et al., 2022b).

6.1 Atlantic Ocean

6.1.1 General context

The northeastern Atlantic Ocean basin bordering western Europe (Portugal, Spain, France, the UK, Ireland, Fig. 14) is characterized by strong bathymetric gradients, with a deep ocean basin and a continental shelf that is narrow along the Iberian Peninsula and that widens northward up to Ireland. This region includes parts of the North Atlantic subtropical and subpolar gyres, separated by the North Atlantic Current. A slope current flows northward along the continental slope separating the deep ocean from the continental shelf (Clark et al., 2022; Huthnance and Gould, 1989). Strong summer upwellings of deeper, colder water occur along the coasts of Portugal (Fiúza, 1983). On the continental shelf, higher-frequency processes have a more leading role on sea level variability (e.g. Woodworth et al., 2019) and can lead to sea level variability of larger amplitude (due to, for example, tides and storm surges). Although spatial scales of ocean mesoscale dynamics are smaller on continental shelves than in the deep ocean (e.g. Chelton et al., 1998; Hallberg, 2013; LaCasce and Groeskamp, 2020), sea level along the northeastern Atlantic European coast northward of 25° N can also be coherent over thousands of kilometres at decadal timescales (e.g. Calafat et al., 2014) related to coastally trapped waves (Hughes et al., 2019). Along-shore wind forcing is a major contributor to such coastal sea level variability (Calafat et al., 2012).

Tides on the northeastern Atlantic continental shelf are amongst the most energetic ones worldwide, with the principal lunar semidiurnal tidal constituent (M2) dominating. The coasts of Portugal, Spain, the Bay of Biscay, Ireland, and the northern UK experience a lower macrotidal regime (3.5 to 5.0 m tidal range). An upper macrotidal regime along the coasts of the English Channel, Brittany, and southern UK reaches from 5.0 to 10 m of amplitude (e.g. Flemming, 2005).

The North Atlantic mid-latitude storm track induces large waves, swells, and storm surges due to surface winds and low atmospheric pressure that directly impact western Europe. Extreme storm surges along the northeastern Atlantic coasts are therefore directly related to the track location and intensity of extra-tropical cyclones. In addition, swells generated by North Atlantic extratropical storms are reaching western

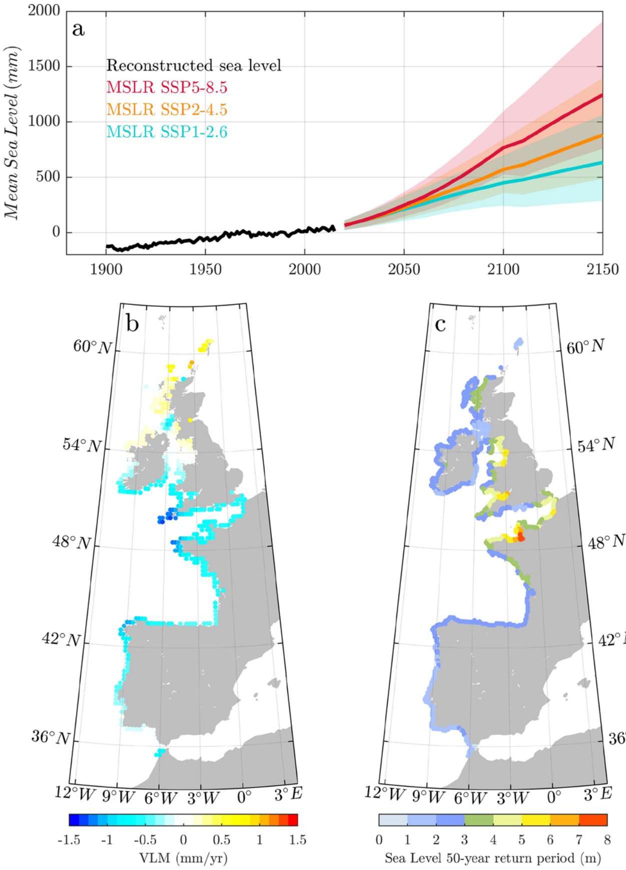

Figure 15. **(a)** Yearly reconstructed basin-average (Fig. 14) mean relative SL over 1900–2014 from Dangendorf et al. (2019) with the effect of GIA and GRD from contemporary mass loss of land-based ice, together with basin-average projected multi-model ensemble mean relative SL until 2100 and relative to 1995–2014 under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shading indicates the 17th–83rd percentile uncertainties under SSP2-4.5 and SSP5-8.5 obtained from AR6 IPCC. Projections were obtained from AR6 IPCC accounting for VLM (including GIA) effects. **(b)** Linear trends of VLM over 1995–2020 (Oelsmann et al., 2024). **(c)** The 50-year return levels of extreme still water levels that are representative of the recent past computed using a historical regional ocean model forced by a climate model (Chaigneau et al., 2022).

European coasts (e.g. Amores and Marcos, 2020; Bricheno and Wolf, 2018). Under the present climate, the world's highest 50-year return period significant wave heights are found in the northeastern Atlantic (Morim et al., 2023).

VLM in the northeastern Atlantic is rather small, with rates over 1995–2020 ranging from $-1.5\,\mathrm{mm\,yr^{-1}}$ (Brittany in France, Cornwall in the UK) to close to $1.0\,\mathrm{mm\,yr^{-1}}$ (Shetland Islands, UK) (Fig. 15b).

6.1.2 Past sea level changes

SL changes along the coastline of the northeastern Atlantic have been monitored through a rather dense network of tide gauges for decades and up to centuries at specific locations (e.g. at Brest, France, or Newlyn, UK, Fig. 2). Over 1950–2014, the mean RSLR for the northeastern Atlantic was $1.2\,\mathrm{mm\,yr^{-1}}$ (Table 3). Since 1993 and the advent of precise satellite altimetry to monitor SL changes from space, SLR over the coasts of western Europe in the northeastern Atlantic has not largely deviated from the global mean, with most places exhibiting rates ranging between 2 and $4\,\mathrm{mm\,yr^{-1}}$ (Sect. 3.2).

Regional RSLR patterns in this region are mostly explained by ocean dynamics and by GRD effects related to mass loss of the Greenland ice sheet and of mountain glaciers.

The regional pattern of SLR in this region can differ from one decade to another (Sect. 3.2), due to the large influence of the North Atlantic Oscillation (NAO) and other climate modes of variability and teleconnection patterns (e.g. Roberts et al., 2016). The NAO is the most prominent and recurrent pattern of large-scale atmospheric circulation variability over the mid- and high-latitudes of the Northern Hemisphere (e.g. Hurrell et al., 2003). Its strength and phase can be characterized by the difference in surface atmospheric pressure between the Icelandic low-pressure system and the Azores high-pressure system. In addition to its influence on the regional pattern of SL trends, the NAO also influences the year-to-year (or interannual) variability as well as ESLs in the northeastern Atlantic as the variation in pressure patterns influences the strength and location of the jet stream and the path of storms across the North Atlantic. At interannual to decadal timescales, coastal SLs (as recorded by tide gauges) are highly correlated to the NAO (Calafat et al., 2012).

Regarding extremes, storm surges along the coasts of western Europe are related to extra-tropical storms under the storm track and hitting the coasts. The 50-year return period extreme still water levels over the recent past range from 1–2 m for the coast of Portugal to 7–8 m in the macrotidal Mont Saint-Michel Bay (France) (Fig. 15c). During positive NAO phases, the North Atlantic westerlies and storm tracks are shifted northwards. This results in increased (decreased) storminess, storm surges, and precipitation over northern (southern) Europe (e.g. Hurrell and Deser, 2010). The maximum amplitude of surges increases from the coasts of Portugal and Spain to France and the UK in the Atlantic. The 50-year return period level of surges characteristics of the past decades is close to 0.5 m along the coast of Portugal (Cid et al., 2016) and reaches between 1 (e.g. at Brest, France) and 2 m (e.g. at Liverpool, UK) along the Atlantic coasts of northern Europe (Marcos and Woodworth, 2017). The median number of extreme skew surges per year also tends to be larger around the coasts of the UK and in the English Channel than in the Bay of Biscay or the Iberian Peninsula (Marcos and Woodworth, 2017). A skew surge is the difference between the maximum observed SL and the maximum predicted tide regardless of their timing during the tidal cycle – there is one skew surge value per tidal cycle (Pugh and

Woodworth, 2014). The median duration of extreme skew surge events is less than 5 h in most places along the northeastern Atlantic coasts (Marcos and Woodworth, 2017).

In many places, changes in mean SL have been the dominant driver of changes in ESLs since at least 1960 (Sect. 4.3). As such, both mean sea level changes and ESLs are modulated by the NAO in the northeastern Atlantic at interannual timescales. The extreme value distribution of skew surges has been shown to evolve over time along the Atlantic European coasts, even when mean SL changes are discarded (Marcos and Woodworth, 2017). According to a review of storminess over northwestern Europe (Feser et al., 2015), trends in storminess vary with the analysed time period (see also Sect. 5.3). An analysis of tide gauges with at least 25 years of data since 1960 indicates that the amplitude of extreme skew surges tend to have decreased along the northeastern Atlantic coast (Marcos and Woodworth, 2017). In Europe, it has recently been reported that changes in storm surge activity, related to the NAO, have contributed just as much as MSLR to the overall change in ESLs in Europe since 1960 (Calafat et al., 2022). The probability of extreme storm surges since 1960 has been suggested to have increased north of 52° N and decreased south of 52° N (especially so along the coasts of Brittany and the English Channel). This is due to the compounding effect (north of 52° N) or cancelling effect (south of 52° N) of trends in both the storm surge extremes and of regional MSL, which make comparable contributions to the overall change in ESLs in Europe (Calafat et al., 2022).

Along the European Atlantic coast, the timing of the storm surge season is highly correlated with the NAO and the timing of the storm atmospheric events. Extreme storm surges tend to occur earlier in the year in the south (Portugal and Spain) than in the north (English Channel, UK). A consistent spatio-temporal shift in the timing of the storm surge season over the second half of the 20th century has recently been reported (Roustan et al., 2022). The storm surge season has tended to occur earlier along the Atlantic coasts of Europe south of 50° N, at an average pace of around 5 d per decade (e.g. a 25 d shift over 1950–2000).

6.1.3 21st century projections

Projections indicate that 21st century SLR along the coasts of the northeastern Atlantic is expected to be close to GMSLR south of 55° N and lower for northern UK and Ireland (Fig. 10), notably due to VLM (Figs. 7, 15). For instance, under the high-emission, low-mitigation SSP5-8.5 scenario, total mean SL is projected to increase by 0.77 m on global mean, 0.85 m in Cádiz (SP), 0.73 m in Brest (FR), and 0.56 m in Tobermory (UK) in 2100 compared to 1995–2014 (Fox-Kemper et al., 2021; Garner et al., 2021; see also Table 3).

Sterodynamic SLR, which includes global mean thermal expansion of the warming ocean and steric and dynamic SL changes induced by ocean circulations (Gregory et al., 2019), remains the dominant contributor to total SLR along the European Atlantic coast. Regionally downscaled projections of SL changes over parts of the northeastern Atlantic have been produced (Chaigneau et al., 2022; Gomis et al., 2016; Hermans et al., 2022). Hermans et al. (2020) and Chaigneau et al. (2022) have demonstrated the influence of dynamical downscaling on projections of dynamic SL over the 21st century for the northwestern European region. Hermans et al. (2020) have found that projected changes in dynamic SL in the downscaled simulations are up to 15 cm lower than in the GCM simulations for the RCP8.5 scenario. These differences are notably observed in the Celtic Sea, which is poorly resolved in the coarse-resolution GCMs. In Chaigneau et al. (2022), the impact of the regionalization on ocean dynamic SL projections is weaker due to forcings from a higher-resolution GCM, including more spatial details. In the same study, the impact of bias correcting the GCM ocean and atmospheric forcings on the regionally downscaled ocean dynamic SL projections is also highlighted.

The amplitude of the historical centennial climate extreme event (as defined in Sect. 5.3.1) (including storm surges and wave setup) is estimated to range from 1.5 m in the Gulf of Cádiz, increasing northward along the Atlantic European coast to up to 3.0–3.5 m on the western UK coast (Vousdoukas et al., 2017). The 21st century projections indicate a decrease in the overall wave and storm surge contribution to extreme total SL along the Atlantic coast of the Iberian Peninsula and a general increase northward, with values ranging between ±0.3 m by 2100 under a high-emission scenario (Vousdoukas et al., 2017). Along the coast of Portugal and in the Gulf of Cádiz, the projected reduction in surge and wave extremes correspond to an offset of relative SLR by 20 %–30 %.

Future changes in North Atlantic storm positions and intensities will induce changes in mean and extreme wave conditions along the western coasts of Europe. Changes in significant wave height, period, and energy flux in turn contribute to changes in coastal flooding through overflowing or overtopping and in coastal erosion (van de Wal et al., 2024).

Global and regional projections of the wave climate indicate a robust decrease in annual and seasonal mean significant wave height, together with a decrease in the mean wave period over the northeastern Atlantic (e.g. Bricheno and Wolf, 2018; Lobeto et al., 2021a; Morim et al., 2018). This leads to a decreased wave setup contribution to 20-year mean SLR at the coast by the end of the 21st century in this region. Along the Atlantic coast of the Iberian Peninsula, a projected lower wave setup contributes substantially to the regional departure of 20-year mean coastal SL changes from GMSLR (Melet et al., 2020). Changes in wave direction are also relevant for wave impacts at the coast and yet understudied. Indeed, impacts of waves on the coast depend on the wave direction relative to the orientation of the shoreline. For instance, wave setup is largest when wave direction is shore normal. A robust clockwise change in mean wave direction is projected for the Atlantic Iberian coast (e.g. Lobeto et al., 2022; Morim et al., 2019). Extreme significant wave heights are also consistently projected to decrease over the northeastern Atlantic, with the largest decrease found along the Iberian coasts (Aarnes et al., 2017; Chaigneau et al., 2023; Meucci et al., 2020; Morim et al., 2018, 2021). In an analysis of 14 stations distributed worldwide, Lobeto et al. (2021b) indicate that the stations located along the Atlantic coasts of Europe are the ones exhibiting the strongest projected decrease in wave energy by the end of the 21st century under a high-emission scenario.

Non-linear interactions between the different components of extreme coastal water levels can be substantial in the northeastern Atlantic (e.g. Idier et al., 2019). Tides are sensitive to SLR as increased water depths will alter tidal dynamics (e.g. Haigh et al., 2020; Idier et al., 2017; Sect. 4.3). The English Channel and the Irish Sea are amongst the world regions where tides would change the most substantially in response to SLR (Haigh et al., 2020) and induced shifts in amphidromic points (Idier et al., 2017; Pickering et al., 2017). Changes in M2 amplitude would be spatially heterogenous and might be up to 10 % of the MSLR within the next century (e.g. Palmer et al., 2018; Pickering et al., 2017; Schindelegger et al., 2018).

Wave–SL interactions can lead to a substantial increase in significant wave heights and water levels in macro-tidal areas of the northeastern Atlantic during extreme events (e.g. Calvino et al., 2023; Chaigneau et al., 2023; Staneva et al., 2017). In terms of coastal impacts, accounting for wave–water level interactions can increase the centennial wave setup event by +10 % at some locations and the wave energy flux by up to +40 % in 2100 under a high-emission, low-mitigation scenario (Chaigneau et al., 2023). Sea-state-induced processes also modulate ESLs in the northeastern Atlantic (Bonaduce et al., 2023).

6.2 North Sea

6.2.1 General context

The North Sea is a shallow continental shelf sea bordering France, Belgium, The Netherlands, Denmark, Norway, and the United Kingdom. Due to the prevailing westerly winds over the North Sea, the ocean circulation in the North Sea is predominantly cyclonic (Sündermann and Pohlmann, 2011). The North Sea receives relatively saline and warm water from the North Atlantic Ocean from the south, through the English Channel, and from the north, through the Orkney–Shetland section, the Shetland shelf area, and the Norwegian Trench. In the east it is also connected to the Baltic Sea, from which it receives relatively cool and fresh water. Water exits the North Sea mainly along the Norwegian coast.

Astronomical tides significantly influence the dynamics of the North Sea (Sündermann and Pohlmann, 2011) and contribute to the height of extreme water levels. The semidiurnal tides of the North Sea are driven by co-oscillation with northern Atlantic tides and travel anticlockwise through the North Sea. As the tidal wave propagates from the deep ocean towards the shallower shelf, it is deformed by shallow water and frictional effects, resulting in overtides (having multiple periods of the fundamental constituents) and compound tides (as linear combinations of multiple constituents). The largest tidal ranges are observed along UK east coast (Pugh, 2004), reaching spring tidal ranges of up to 3.60 m at Aberdeen and 6.20 m at Immingham (Horsburgh and Wilson, 2007). Mean tidal ranges amount to 3.40 m in the UK, 1.98 m along the Dutch west coast, 2.33 m along the northern Dutch coast, and 2.82 m along the German coast (Jänicke et al., 2021). The northern and central North Sea are stratified from early summer to early autumn, but the southern North Sea has no thermocline throughout the year due to strong tidal mixing (Sündermann and Pohlmann, 2011). Large non-linear interactions between the tidal and non-tidal components of water level have been recognized and studied for a long time, particularly in the southern North Sea. For example, Doodson (1929) noticed a tendency for surge maxima in the Thames Estuary in the UK to occur most frequently on the rising tide; this phenomenon has been studied in depth by many authors (e.g. Horsburgh and Wilson, 2007; Prandle and Wolf, 1978; Proudman, 1955, 1957; Williams et al., 2016; Wolf, 1981). Large historic changes in tides have been observed in the North Sea (Haigh et al., 2020; Jänicke et al., 2021; Woodworth et al., 1991).

The North Sea has a long history of severe coastal flooding, which accelerated the development in coastal flood risk management such as the 1953 flood that killed more than 2000 people around the coastlines of the southern North Sea (Baxter, 2005; Gerritsen, 2005; McRobie et al., 2005) and the 1962 flood in the German Bight, in which more than 300 people lost their lives (Von Storch and Woth, 2008). Today, settlements along the North Sea coast are much better protected against the impacts of ESLs, relying on ongoing improvements in flood warnings and defences (van den Hurk et al., 2022).

6.2.2 Past sea level changes

Based on tide gauge records, relative SL averaged over the North Sea rose at a rate of $1.4 \pm 0.3\,\mathrm{mm\,yr^{-1}}$ during 1958–2014 (Frederikse et al., 2016). Reconstructed RSLR indicates rates of $1.5 \pm 0.1\,\mathrm{mm\,yr^{-1}}$ over 1950–2014 (Dangendorf et al., 2019, Table 3). Observed trends over the 20th and early parts of the 21st century vary by one to three tenths of a millimetre per year between different parts of the North Sea region (Wahl et al., 2013). Several assessments of sea level trends around the British Isles (e.g. Woodworth et al., 1999, 2009; Haigh et al., 2009; Woodworth et al., 2017; Hogarth et al., 2020, 2021) include tide gauge sites in the North Sea and again observed trends typically range between one to three tenths of a millimetre per year over the last century. The rates over this period match well with the sum of the rates of ob-

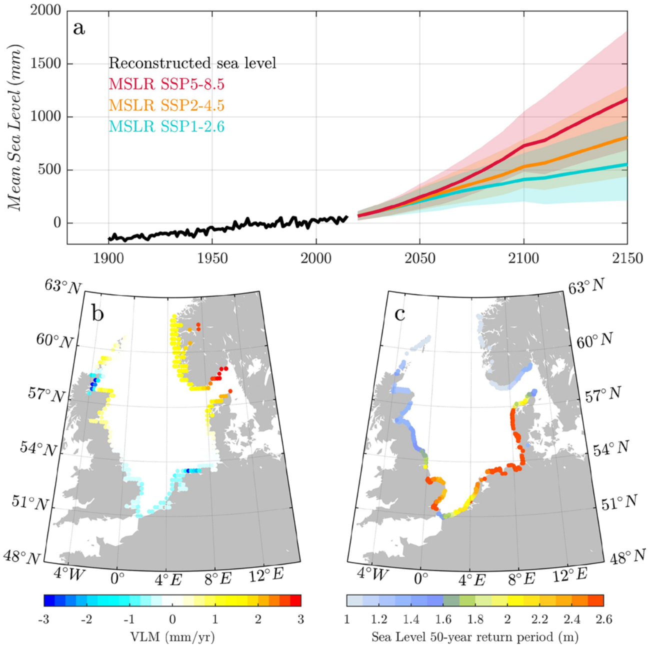

Figure 16. **(a)** Yearly reconstructed basin-average (Fig. 14) mean relative SL over 1900–2014 from Dangendorf et al. (2019) with the effect of GIA and GRD from contemporary mass loss of land-based ice, together with basin-average projected multi-model ensemble mean relative SL until 2100 and relative to 1995–2014 under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shading indicates the 17th–83rd percentile uncertainties under SSP2-4.5 and SSP5-8.5 obtained from AR6 IPCC. Projections were obtained from AR6 IPCC accounting for VLM (including GIA) effects. **(b)** Linear trends of VLM over 1995–2020 (Oelsmann et al., 2024). **(c)** The 50-year return levels of extreme still water levels representative of the recent past from GTSM dataset (Yan et al., 2020).

served individual components, with the sterodynamic component contributing the most (both to the observed trend and temporal variability) (Dangendorf et al., 2021; Frederikse et al., 2016). The relative SL change measured at tide gauges in the North Sea is also influenced by VLM due to glacial isostatic adjustment, present-day ice mass loss, and other processes such as tectonic activity and naturally or anthropogenically driven subsidence (Fig. 16b). Near regions that were covered by ice sheets during the last glacial maximum, such as Scandinavia and the UK, GIA causes relatively large land uplift contributing to a relative SL fall, whereas further away, in the southeastern North Sea, the land is gradually subsiding due to a collapse of the forebulge, contributing to relative SLR (Frederikse et al., 2016; Peltier et al., 2015). Estimates of the contributions of GIA and other sources of VLM to relative sea level rise rates, however, are relatively uncertain (Wahl et al., 2013). An estimate over 1995–2020 shows VLM rates ranging from $-3\,\mathrm{mm\,yr^{-1}}$ in the northeastern UK to $3\,\mathrm{mm\,yr^{-1}}$ in southern Norway in the Skagerrak Strait (Fig. 16b, Oelsmann et al., 2024).

Based on satellite altimetry, which measures geocentric sea level change, linear SL trends estimated for 1993–2014 vary spatially over the North Sea from 1.3 to $3.9\,\mathrm{mm\,yr^{-1}}$, with the highest rates found in the southeastern North Sea (Sterlini et al., 2017). Averaged over the wider northwestern European Shelf, the SL trend seen by satellites during 1993–2022 was $3.1\,\mathrm{mm\,yr^{-1}}$ (Copernicus Marine Service, Ocean Monitoring Indicator; Box 1). However, interannual to decadal SL variability has a large impact on the estimated SLR trends in the North Sea when evaluated over periods of only a few decades, especially in the southeastern North Sea where the variability is largest (Calafat and Chambers, 2013; Dangendorf et al., 2014; Gerkema and Duran-Matute, 2017; Tinker et al., 2020). Consequently, temporal SL variability is projected to continue to be the dominant source of uncertainty in SL change in the North Sea for the coming decades (Palmer et al., 2018).

Observational and model studies have shown that seasonal (Frederikse and Gerkema, 2018) and interannual to decadal SL variability (Dangendorf et al., 2014; Frederikse et al., 2016; Hermans et al., 2020; Tinker et al., 2020) in the North Sea is primarily caused by the variability in local wind and SL pressure and to a lesser extent also by variability in buoyancy fluxes (Hermans et al., 2020). After removing part of the SL variability driven by local wind and SL pressure variability from tide gauge records, recent studies have found statistically significant accelerations of SLR in the southeastern North Sea (Dutch coast) (Keizer et al., 2023; Steffelbauer et al., 2022). At timescales of years to decades, a spatially coherent SL variability can be found along the eastern boundary of the North Atlantic Ocean, extending from the Canary Islands all the way up to the Norwegian Sea, which is thought to also affect the North Sea (Dangendorf et al., 2014, 2021; Frederikse et al., 2016). This signal is thought to be caused by remote along-shore winds and the subsequent northward propagation of coastally trapped waves (Calafat et al., 2012, 2013; Dangendorf et al., 2014; Frederikse et al., 2016; Hermans et al., 2020; Hughes et al., 2019), but it may also be caused by open-ocean steric anomalies that follow from decadal variability in the strength of the Subpolar North Atlantic Gyre (Chafik et al., 2019).

In terms of extreme still water levels, the 50-year return levels of the recent past range from 1 m (coast of Norway) to less than 3 m in parts of the southern North Sea such as the German Bight (Fig. 16c).

Trends and variability in mean SL influence the baseline height of ESLs (Sect. 5.3). Furthermore, storm surges, waves, and tides, which constitute ESLs in the North Sea, have also been observed to change. For instance, Calafat et al. (2022) concluded that historical trends in the height of storm surges are similar in magnitude to trends in mean SL. They found positive trends in storm surges mainly along the northwestern North Sea coastline (northeastern UK), and negative trends along the southern and southeastern North Sea coasts. The changes along the English North Sea coast were mainly attributed to internal climate variability and partly to forced change associated with the strengthening and eastward extension of the North Atlantic storm track that is also projected for the 21st century (Calafat et al., 2022). Besides changes in storminess, the historically increasing water depth (due to SLR) has been shown to affect storm surges, wave height, and tides non-linearly in the German Bight, with the largest changes found in the Wadden Sea due to spatially variable changes in tidal constituents (Arns et al., 2015).

Changes in water depth and other non-astronomical factors, such as changes in stratification and large construction measures, affect tides along the North Sea coast (e.g. Jänicke et al., 2021; Jensen, 1984; Jensen and Mudersbach, 2007; Mudersbach et al., 2013; Woodworth et al., 2017), including in estuaries (e.g. Amin, 1983; Keller, 1901; Jiang et al., 2020) and harbours (e.g. Doodsen, 1924; Marmer, 1935; Schureman, 1934; Vellinga et al., 2014). However, a comprehensive and generalized analysis is still missing.

6.2.3 21st century projections

Recent SL projections (Fox-Kemper et al., 2021; Palmer et al., 2018; KlimaatScenario's 2023, https://www.knmi.nl/klimaatscenarios23-toolkit, last access: 12 July 2024) suggest that 21st century SLR in the North Sea will be close to or slightly higher than GMSLR at southern North Sea coasts, whereas at the more northern North Sea coasts, projected SLR is lower than the global mean (Sect. 5.1, Table 3). For example, for the emissions scenario SSP5-8.5, the IPCC AR6 projects a SLR of 76–85 cm at the southeastern UK, Belgian, Dutch, and German coasts for 2100, whereas at the northern UK and southern Norwegian coastlines, the projected rise is typically below 70 cm for the same period (Fox-Kemper et al., 2021; Garner et al., 2021). This gradient is predominantly caused by GIA (Sect. 3.3) and the gravitational imprint of the melt of the Greenland ice sheet (Fox-Kemper et al., 2021; Palmer et al., 2018). In contrast, the projected sterodynamic SLR is spatially relatively uniform over the North Sea and slightly higher than elsewhere on the northwestern European continental shelf (Fox-Kemper et al., 2021; Hermans et al., 2022, their Supplementary Fig. 1).

The sterodynamic SLR in the North Sea is typically projected using simulations of global climate models, several of which have a too coarse resolution to capture important bathymetric and topographic features influencing the North Sea circulation such as the Norwegian Trench and the English Channel. Downscaling the simulations of global climate models with a high-resolution regional ocean model can have large effects on the projected ocean dynamic SL change for the North Sea depending on the global climate model (up to 30 % of the total sterodynamic sea-level rise simulated for the 21st century; Hermans et al., 2020), but downscaling has not been applied to large ensembles of global climate models yet. Besides changes in annual mean ocean dynamic SL, CMIP6 global climate models also simulate changes in the amplitude and phase of the seasonal SL cycle (Hermans et al., 2022; Widlansky et al., 2020). The projected changes are largest in the southeastern and eastern parts of the North Sea and may have implications for intertidal ecosystems.

Several studies have projected changes in the frequency of ESLs in the North Sea due to future SLR using the static approach described in Sect. 5.3.1. Compared to other regions, the projected frequency amplification factors of the historical centennial event and other return heights are small in most of the North Sea (see Fig. 12), because the current variability of extremes is large (Fox-Kemper et al., 2021; Frederikse et al., 2020a; Hermans et al., 2023; Oppenheimer et al., 2019). These studies did not consider changes in ESLs due to dynamic changes such as changes in storminess or the effect of an increasing water depth (due to SLR) on surges, tides, and waves.

The impact of changes in water depth induced by SLR on surges, tides, and waves is more important in the North Sea than elsewhere in Europe since the North Sea is a shallow sea, especially near the southern coasts. Haigh et al. (2020) and Idier et al. (2017) both demonstrated a +10 cm and +10 % increase in the semi-diurnal component of the tide along the southeastern North Sea coast, respectively, for a hypothetical increase of +2 m and + 80 cm. Arns et al. (2017) used fine-scale (1 km) numerical modelling in the German Bight to highlight that the long-term SLR would generate waves of greater amplitude (around +48 %–56 % depending on the scenario). Chaigneau et al. (2023) showed with regional climate modelling (6 km resolution) that future mean significant wave heights could become up to +8 % higher in the southern North Sea than at present if SL would rise by 80 cm. These important future changes will also impact the interactions between processes (e.g. tide–surge interactions; Arns et al., 2020; Bonaduce et al., 2020; Staneva et al., 2021) and lead to further changes in ESLs in the North Sea.

The potential contribution of changes in atmospheric storminess to changes in ESLs in the North Sea is uncertain and strongly depends on the (large-scale) atmospheric forcing used to project such changes (Howard et al., 2019; Palmer et al., 2018; Vousdoukas et al., 2016; Woth et al., 2006). For instance, based on a small ensemble of high-resolution regional model simulations forced with downscaled atmospheric changes from CMIP5 models, Palmer et al. (2018) and Howard et al. (2019) find that storm surges around the UK may change by -1 to 1 mm yr^{-1} depending on the model but that the ensemble mean change is close to 0. Under a high-emission scenario, Vousdoukas et al. (2016) project increases in the height of storm surge events with return periods of 5 to 100 years of several percent but report that the disagreement between models is large elsewhere in the region. In conclusion, the amount by which changes in storminess affect ESLs in the North Sea is uncertain, but studies agree that these changes are small compared to the effect of mean SLR itself. In Lobeto et al. (2021a), Chaigneau et al. (2023), and Aarnes et al. (2017), mean and extreme wave characteristics slightly decrease in the north of the North Sea under the SSP5-8.5 scenario. The amplitude of storm surges does not appear to be significantly modified by mid-century in Muis et al. (2023) under a very high-emission scenario. In contrast, Jevrejeva et al. (2023) showed an increase of +50 cm in extreme storm surges and waves under a low-probability, high-impact scenario in the southern North Sea, in line with early attempts providing future changes in storm surges (Woth, 2005; Woth et al., 2006).

6.3 European Arctic

6.3.1 General context

The European Arctic basin is defined here as the area covering the Nordic Seas, i.e. the Norwegian Sea, Icelandic Sea, and Greenland Sea (Fig. 14). European countries considered in this report and within the European Arctic basin are Iceland and the middle to northern coast of Norway, including Svalbard.

An important component of SL change in the European Arctic is VLM. The broad pattern of VLM in the region can generally be ascribed to past ice mass loss and GIA (e.g. Kierulf et al., 2021; Milne et al., 2001; Vestøl et al., 2019). A regional semi-empirical model of VLM and gravity changes (Vestøl et al., 2019) has been applied in several regional SL studies. Over 1995–2020, rates of VLM were estimated to range between 1 and 6 mm yr^{-1} along the coast of Norway (Oelsmann et al., 2024, Fig. 17b).

There are important contributions to VLM from ongoing ice mass loss on Iceland (Compton et al., 2015) and Svalbard (e.g. Kierulf et al., 2022) driving high rates of local elastic land uplift and variability. GIA on Iceland, where there is a low-viscosity Earth structure that deforms on short timescales, is thought to be dominated by ice mass changes over the past ∼ 100 years (Auriac et al., 2013). VLM on Iceland is further complicated by significant tectonic and volcanic movements. Recent studies have also shown that ice mass loss in the Arctic and from Greenland produces widespread non-negligible elastic VLM in the European Arctic (e.g. Coulson et al., 2021; Frederikse et al., 2016; Kierulf et al., 2021; Richter et al., 2012). These show that during years of high mass loss from Greenland rates of uplift in Scandinavia reach ∼ 0.7 mm yr^{-1}.

6.3.2 Past sea level changes

Measuring SL in the European Arctic is challenging due to (1) its remote location and lack of land masses, limiting the number of tide gauges in this region, and (2) hampered measurements from satellites by, e.g. sea ice and limited satellite coverage at high latitudes. In a recent analysis of the Arctic Ocean SL record from altimetry, Rose et al. (2019) found a rate of 3.19 mm yr^{-1} (3.10–3.37 95 % confidence interval) between 1991 and 2018 for the sector covering the European Arctic. Reconstructed RSLR indicate rates of 1.5 ± 0.1 mm yr^{-1} in the European Arctic over 1950–2014 (or 1.4 ± 0.1 mm yr^{-1} after removal of GIA effects, Dangendorf et al., 2019, Table 3, Fig. 17a).

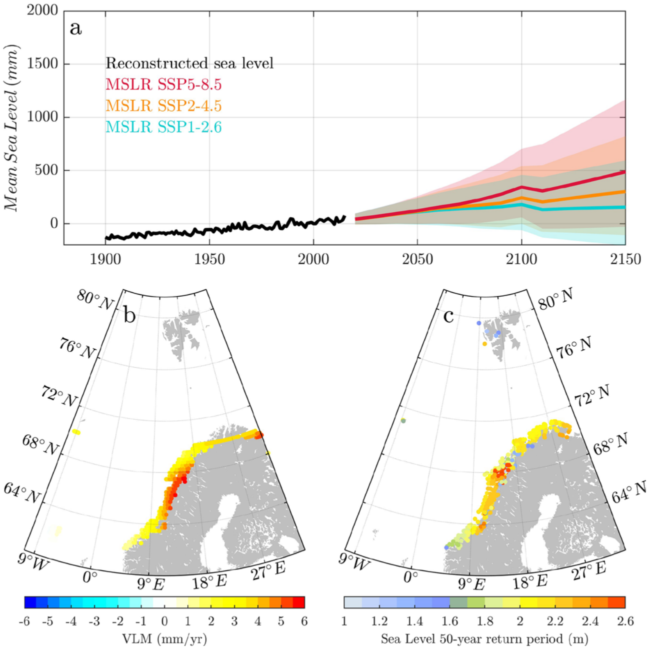

Figure 17. **(a)** Yearly reconstructed basin-average (Fig. 14) mean relative SL over 1900–2014 from Dangendorf et al. (2019) with the effect of GIA and GRD from contemporary mass loss of land-based ice, together with basin-average projected multi-model ensemble mean relative SL until 2100 and relative to 1995–2014 under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shading indicates the 17th–83rd percentile uncertainties under SSP2-4.5 and SSP5-8.5 obtained from AR6 IPCC. Projections were obtained from AR6 IPCC accounting for VLM (including GIA) effects. **(b)** Linear trends of VLM over 1995–2020 (Oelsmann et al., 2024). **(c)** The 50-year return levels of extreme still water levels representative of the recent past computed using the average conditional exceedance rate method (Skjong et al., 2013; https://www.kartverket.no/til-sjos/se-havniva, last access: 9 June 2023).

A number of studies in the region have looked at coastal SL variability and trends with particular focus on Norway (e.g. Breili, 2022; Breili et al., 2017; Frederikse et al., 2016; Henry et al., 2012; Mangini et al., 2022; Richter et al., 2012). Interannual SL variability can be largely explained by atmospheric forcing on wind and the inverse barometer effect. Decadal variability appears to largely reflect steric changes that have been linked to a remote forcing and wind-driven coastally trapped waves that can travel over long distances and reach up to the Arctic (e.g. Calafat et al., 2013; Dangendorf et al., 2014; Frederikse et al., 2016). Studies have shown that the long-term trends and regional SL budgets can be explained by mass, steric, and VLM changes (e.g. Frederikse et al., 2016; Richter et al., 2012).

In terms of extreme still levels, the 50-year return levels of the recent past range from 1 to 2.6 m, with a large spatial variability along the coast of Norway (Fig. 17c).

6.3.3 21st century projections

Projections for the European Arctic indicate the region will experience a SL change somewhat below GMSLR (e.g. Simpson et al., 2017; Table 3, Fig. 17a).

Apart from GIA, several components of projected SL changes are relevant for the European Arctic. (1) Owing to its relatively close proximity to Arctic glaciers and the Greenland ice sheet, GRD effects cause a negative or less than average SLR in the region. Compared to other basins the European Arctic is particularly sensitive to the pattern of ice melt on Greenland (e.g. Mitrovica et al., 2018), inducing a below average regional SLR. (2) At the same time, projections generally indicate that steric dynamic SLR in the Arctic will be larger than the global average. Here the halosteric term is positive and dominates due to ocean freshening (e.g. Pardaens et al., 2011). We note that the large projected steric dynamic SLR in this region also has a large model spread.

As discussed in Sect. 5.3, there is considerable uncertainty attached to projections of changes to storm surges and waves. However, these changes tend to be smaller than the projected mean SL change (e.g. Howard et al., 2019). Projections of future wave climate in the period 2070–2100 generally indicate a lower mean significant wave height in the northeastern Atlantic (e.g. Aarnes et al., 2017). The RCP8.5 scenario yields the strongest reduction in wave height. The exception to this is the northwestern part of the Norwegian Sea and the Barents Sea, where receding ice cover gives longer fetch and higher waves.

6.4 Mediterranean Sea and Black Sea

6.4.1 General context

The Mediterranean Sea is a semi-enclosed basin connected to the Atlantic Ocean, to which it exports around 1 Sv (1 Sverdrup = $10^6\,\mathrm{m^3\,s^{-1}}$) of Mediterranean waters through the narrow Strait of Gibraltar. The mass component is considered the dominant contributor to the mean SL trend in the Mediterranean Sea (Calafat et al., 2010; Pinardi et al., 2014), while the steric component accounts for approximately 20 % of the total variance (Calafat et al., 2012). At the sub-basin scale, however, there are large differences, and the steric component can explain a substantial part of the total SL variance, such as in the Aegean, southern central Mediterranean, and Levantine basin (Mohamed and Skiliris, 2022). The southeastern Mediterranean is affected by warm and salty waters flowing through the Suez Canal from the Red Sea, also altering the steric signal, especially since the early 1990s. Mean SL variability at long timescales (interannual to decadal) averaged over the basin has been shown to be consistent with the nearby Atlantic (Calafat et al., 2012). At the regional scale, however, SL changes within the basin deviate from the mean value, due to ocean circulation, heat redistribution, and atmospheric–ocean momentum fluxes. Storm surges are particularly relevant due to the microtidal nature of the basin and are generated both by incoming atmospheric perturbations from the North Atlantic and by regional cyclogenesis, which occasionally generates tropical-like cyclones in the basin (see Sect. 6.4.7). The Mediterranean Sea is also a hotspot for atmospherically induced high-frequency SL oscillations known as meteorological tsunamis (see Sect. 6.4.8) that affect various locations in the basin.

Coastal VLM is a significant contributor to changes in relative SL in the Mediterranean Sea (Wöppelmann and Marcos, 2012). GIA-related subsidence (Sect. 3.3) is small in comparison to northern European regions and is estimated to be, on average, $0.5\,\mathrm{mm\,yr^{-1}}$ over the last millennia, albeit spatially varying (Vacchi et al., 2018). In situ VLM observations from GNSS and from the combination of altimetry and tide gauges used in Oelsmann et al. (2024) are concentrated over the European coast and around the southern Black Sea, with very little information in northern Africa. Linear trends obtained from these observations are mapped in Fig. 18b. The results display regional variability of VLM in the Mediterranean basin with a median value of $-0.4\,\mathrm{mm\,yr^{-1}}$ and highlight areas with differential VLM, as is the case of Venice. However, local variability in VLM is much larger, due to active neo-tectonics and volcano-tectonics affecting large part of the Mediterranean coasts.

The Black Sea is an enclosed basin connected to the Mediterranean Sea through the Marmara Sea and the Turkish straits: the Bosphorus and Dardanelles straits. The Mediterranean and Black seas are microtidal basins. The Black Sea receives freshwater from the Danube, Dnieper, and Don rivers especially. The salinity of the Black Sea (~ 18 psu at the surface) is much lower than that of the Mediterranean Sea (~ 38 psu at the surface). In the Black Sea, most of the steric SLR appears to be related to salinity reduction (implying a SLR), rather than to an increase in temperature (Tsimplis et al., 2004).

6.4.2 Past sea level changes

In the Mediterranean and Black seas there is a geographical bias in coastal SL monitoring, with most tide gauge stations located along the northern coasts of the basin and the Black Sea (see Pérez Gómez et al., 2022, for a recent summary of all stations and operators). Although most tide gauges have been deployed since the 1980s, some records date back to the 19th century. This is the case of Marseille and Genoa, which indicate a centennial mean SL trend of 1.3–1.4 $\mathrm{mm\,yr^{-1}}$ since the late 19th century. Over 1950–2014, reconstructed RSLR rates were estimated to be $1.2 \pm 0.1\,\mathrm{mm\,yr^{-1}}$ on average in the Mediterranean Sea (Table 3, Fig. 18a, Dangendorf et al., 2019). Linear mean SL trends from satellite altimetry since 1993, with a GIA correction applied, display

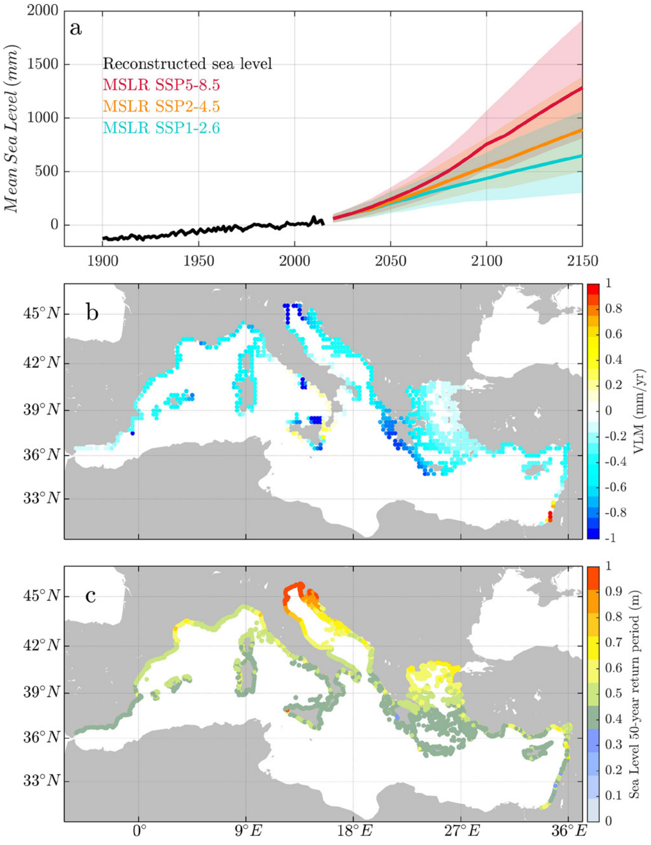

Figure 18. **(a)** Yearly reconstructed basin-average (Fig. 14) mean relative SL over 1900–2014 from Dangendorf et al. (2019) with the effect of GIA and GRD from contemporary mass loss of land-based ice, together with basin-average projected multi-model ensemble mean relative SL until 2100 and relative to 1995–2014 under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shading indicates the 17th–83rd percentile uncertainties under SSP2-4.5 and SSP5-8.5 obtained from AR6 IPCC. Projections were obtained from AR6 IPCC accounting for VLM (including GIA) effects. **(b)** Linear trends of VLM over 1995–2020 (Oelsmann et al., 2024). Note that North African coasts have not been represented due to lack of data. **(c)** The 50-year return levels of coastal extreme SLs computed using a 72-year ocean simulation of coupled hydrodynamic and wave model (Toomey et al., 2022a).

positive values among most of the Mediterranean and Black Sea basins (Fig. 6) with an average rate of 2.5 mm yr^{-1} over 1993–2022 for the Mediterranean Sea and 1.4 mm yr^{-1} for the Black Sea (EU Copernicus Marine Service, 2019c, a). SL trends as observed by altimetry over 1993–2020 are lower than the global mean (and the European Seas mean) in the eastern Mediterranean Sea and Black Sea (Prandi et al., 2021, Fig. 6). In addition, a slight deceleration of SLR has also been observed in the eastern Mediterranean Sea and more substantially in the Black Sea (Prandi et al., 2021).

The combination of in situ and remote measurements allows reconstructing SL changes over the basin for long periods of time. Temporal variability at multidecadal to interannual timescales is evidenced by tide gauge records (e.g. Marcos and Tsimplis, 2008). At decadal and multi-decadal timescales, the basin-average SL rates range between -5 and $+7$ mm yr^{-1} and respond, to a large extent, to variations in the nearby northeastern Atlantic Ocean. Part of this variability is coherent along all the European coasts and is driven by along-shore winds propagating northwards along the European continental shelves (Calafat et al., 2012; Hughes et al., 2019). At interannual timescales, nearby records are very coherent. At these timescales, mean SL is largely correlated to large-scale atmospheric circulation patterns, particularly the North Atlantic Oscillation that has been shown to force Mediterranean SL through different mechanisms (Martínez-Asensio et al., 2014; Masina et al., 2022; Volkov and Landerer, 2015). Temporal and spatial variability also results from satellite altimetry data, where non-linearity in SL trend occurs due to oceanographic processes at the sub-basin scale, being also reflected at the basin scale. Main changes in SL trend occur around 1997, 2006, 2010, and 2016, driven by variations in thermohaline circulation and mass redistribution in the Ionian Sea and other sub-basins (Meli et al., 2023). Subannual SL fluctuations in the Aegean Sea, the Mediterranean basin, and the Black Sea are correlated, with the Black Sea lagging behind the Aegean Sea (Volkov and Landerer, 2015). The time lag between the Aegean Sea–Sea of Marmara SL and the Black Sea SL increases from approximately 10 d for monthly averages, to nearly 40 d for 9-months averages. The response of the Black Sea SL is due to barotropic flow anomalies through the Bosphorus Strait, constrained mainly by friction and the strait geometry (Volkov et al., 2016). Black Sea elevation changes are also forced by SL pressure, wind stress along the Bosphorus, and the net freshwater flux into the Black Sea. In their study on the Thrace Peninsula in Türkiye, a vulnerable area to SLR bordered by the Sea of Marmara, Aegean Sea, and Black Sea (Ozsahin et al., 2023) recommend using local mean SL measurements. As highlighted by Kopp et al. (2014), this reflects the need for specific SLR information to generate more accurate projections of SLR.

Coastal ESLs generated by storm surges can be assessed using high-frequency tide gauge records or model hindcasts. Largest values of storm surges are observed at tide gauges located in the northern Adriatic Sea (Marcos et al., 2009) and along the Tunisian and Aegean coasts (Cid et al., 2016). Wind waves, when co-occurring with storm surges, exacerbate the coastal hazard (Lionello et al., 2017). The 50-year return levels of coastal SL extremes obtained with a 72-year run of a hydrodynamic model coupled with wind waves (Toomey et al., 2022b) are mapped in Fig. 18c, showing a consistent picture with observations. Values exceeding 1 m are found in the northern Adriatic and the Gulf of Lions and along the Tunisian and Libyan coasts. Along the rest of the coasts, 50-year return levels are smaller than 50 cm. Besides changes linked to mean SL variations, storm surges also display long-term to interannual variability unrelated to mean

SL and associated with changes in storminess. Decadal variations, such as those observed in the tide gauge records from Trieste (Raicich, 2003) and Marseille (Marcos et al., 2015b), are geographically consistent and related to large-scale atmospheric patterns (Lionello et al., 2021b; Marcos et al., 2015b). The same applies to changes in storm surges at interannual timescales (Masina and Lamberti, 2013).

The wave climate of the Mediterranean Sea is characterized by two well-defined seasons (winter and summer, with spring and autumn having mixed characteristics). In winter, mean and extreme waves are highest in the western Mediterranean, mostly caused by the dominant northwesterly mistral wind. In summer, waves are lower, with a mean wave maximum in the Levantine basin, caused by the Etesian winds and extreme wave maximum in the western basin (Barbariol et al., 2021; Lionello and Sanna, 2005). Along the coastal regions, the largest waves are found in areas with longer fetch distance, such as the Balearic Islands, the west coast of Sardinia, and the northern Algerian coast, with 100-year return levels exceeding 4 m (Toomey et al., 2022b). In contrast, values smaller than 1 m are typical of continental coasts protected by small islands, as on the Dalmatian coast and in parts of the Aegean Sea (Toomey et al., 2022b).

Multidecadal trends from wave gauges have been computed only in the northern Adriatic Sea (Pomaro et al., 2017), while in other locations time series are too short (e.g. Amarouche et al., 2022). Multidecadal trends based on satellite data are still associated with large uncertainties (e.g. Dodet et al., 2020). Therefore, analyses of trends have commonly been based on hindcasts with no overall consensus on trends, possibly associated with the selected period. Trends in the mean wave height are negative or non-significant during the second part of the 20th century (Lionello and Sanna, 2005; Musić and Nicković, 2008; Ratsimandresy et al., 2008), and become positive, particularly in winter, in the western Mediterranean since the 1980s (Amarouche and Akpinar, 2021; Barbariol et al., 2021).

6.4.3 21st century projections

Mean SL projections of the Mediterranean Sea were explored by Sannino et al. (2022) under the RCP8.5 climate scenario, using a high-resolution ocean model capable of resolving the water exchanges through the Strait of Gibraltar. The increase in model resolution together with improved SL information at the Atlantic lateral boundary and the adequate treatment of the complex, hydraulically driven dynamics across the Gibraltar Strait resulted in an improved description of the subregional SL patterns. They concluded that the resulting basin-average mean SL change was within the uncertainties of the multi-model ensemble of global coarser-resolution models from CMIP5 (excluding models without an open connection between the basin and the Atlantic Ocean). This study is in line with Adloff et al. (2018), who pointed at the mean SL in the nearby Atlantic Ocean as a major driver of projected mean SL changes in the Mediterranean. Therefore, projected regional mean SL time series averaged over the Mediterranean Sea are nowadays obtained from multi-model ensemble from CMIP6 (Fig. 18a, Table 3). It is worth mentioning that available climate models have a relatively coarse spatial resolution over the oceans, of around 1 ° in latitude and longitude, that misrepresent water exchanges through the Strait of Gibraltar, which are a major component of SL changes in this semi-enclosed basin. Thus, caution must be taken using the sterodynamic contribution from such models in the Mediterranean Sea. Projected mean SL values reach, under the SSP5-8.5 climate change scenario, 0.79 m (0.64–1.06 m likely ranges 17 %–83 %) by 2100 and 1.22 m (0.91–1.78 m) by 2150 with respect to the period 1995–2014 (Ali et al., 2022). Under SSP2-4.5, projected mean SL by 2100 is 0.57 m (0.44–0.79 m). Few studies assessed projected SL changes in the enclosed Black Sea. According to Görmüs and Ayat (2019), relative SLR for the Black Sea would be within ±20 % of GMSLR.

Projections of storm surges based on hydrodynamic runs forced with climate models show small and mostly negative changes in southern Europe during the 21st century (Conte and Lionello, 2013; Muis et al., 2020; Vousdoukas et al., 2017). Considering the small changes of marine storminess in climate projections, mean SLR will be the dominant driver of increasing coastal ESLs also in the future, but the overall decrease in meteorological surges and storm wave severity is expected in the Adriatic Sea (Benetazzo et al., 2022; Lionello et al., 2021b).

Regarding wind waves, 21st century projections tend to agree that mean significant wave height will decrease as a consequence of anthropogenic climate change (Lionello et al., 2008; Casas-Prat and Sierra, 2013; De Leo et al., 2020).

6.4.4 Medicanes: past and future projections

Medicanes are mesoscale maritime extratropical cyclones developing over the Mediterranean, whose structure resembles tropical cyclones. Analysis of their past trends has not been possible until now, but evidence is for a future decrease in their frequency and an increase of intensity, as a consequence of future sea surface temperature increase (González-Alemán et al., 2019; Koseki et al., 2021; Romero and Emanuel, 2013, 2017). Projected changes in medicane-induced coastal hazards do not exceed 20 % of present-day values in terms of storm surges and wind waves, although there is poor agreement among model projections (Toomey et al., 2022a).

6.4.5 Meteotsunamis: past, present, and future

Meteotsunamis are atmospherically induced high-frequency (< 2 h) oceanic waves generated by travelling atmospheric perturbations (Monserrat et al., 2006). There are different mechanisms by which an atmospheric disturbance can generate a meteotsunami wave in the open sea, such as Proudman resonance (Proudman, 1929), Greenspan resonance (Greenspan, 1956), front-line passages, and even atmospheric Lamb waves (Villalonga et al., 2023). Analogously to seismically generated tsunamis, meteotsunami waves can travel long distances across the ocean, being amplified when they reach the coastline under specific bathymetric and morphological conditions. The Mediterranean Sea is a hotspot for meteotsunami events. These have been observed at various locations within the basin and sometimes have reached heights of several metres along the coast of Croatia (Orlić, 2015), the Balearic Islands (Rabinovich and Monserrat, 1998; Vilibić et al., 2021), Algeria (Okal, 2021), and the Black Sea (Šepić et al., 2018). In addition, meteotsunamis can also significantly contribute to ESLs generated by other mechanisms (Ruić et al., 2023; Vilibić and Šepić, 2017). For example, recently a meteotsunami has been identified as a contributor to an extreme SL event in Venice (Ferrarin et al., 2023).

Forecasting meteotsunami events is challenging due to the high-computational load required to simulate all high-resolution processes involved. Some examples have recently been implemented in the Balearic Islands (Mourre et al., 2021; Romero et al., 2019). Alternatively, other proxy-based methods use the relationship between observed high-frequency SL oscillations and synoptic atmospheric patterns, which is validated using reported meteotsunami events and atmospheric reanalyses (Vilibić et al., 2018; Zemunik et al., 2022). As it is plausible that the effects of climate change will affect atmospheric circulation and synoptic patterns, it will also imply an effect on the frequency and intensity of meteotsunamis (Vilibić et al., 2018). Therefore, these proxy-based methods have also been applied to explore projected changes in meteotsunamis (Denamiel et al., 2023; Vilibić et al., 2018). An analysis of selected events suggests that the intensity of meteotsunamis could increase under the higher-emission climate scenario (Denamiel et al., 2022).

6.5 Baltic Sea

6.5.1 General context

The semi-enclosed and shallow Baltic Sea (mean depth < 54 m; see Seifert and Kayser, 1995) is located in northern Europe in the highly variable transition zone between the maritime North Atlantic region (warm and wet) and the continental Siberian climates (cold and dry). During winter, about 50 % of the climate variability is explained by the North Atlantic Oscillation (Hurrell, 1995; Weisse et al., 2021; see also Chen and Omstedt, 2005). As the Baltic Sea is connected to the adjacent North Sea only through the narrow and shallow Danish straits, SL oscillations on timescales shorter than 1 month are characterized by oscillations of a quasi-closed system. Pronounced seiches have been observed but all in all, they are energetically insignificant, i.e. are not detectable as a peak in the spectrum (Neumann, 1941; Wubber and Krauss, 1979). Combined with storm surges, seiches can lead to extreme compound events (Weisse et al., 2021). In addition, the amplitude of the diurnal and semi-diurnal tides is small within the Baltic Sea in clear contrast to the North Sea (Maagard and Krauss, 1966).

On timescales longer than 1 month, the mean SL in the Baltic Sea approximately follows the SL in Kattegat, outside the Baltic Sea, but with larger variance at the northernmost and easternmost bays (Samuelsson and Stigebrandt, 1996).

It is expected that SLR in the southern Baltic Sea approximately follows the projected GMSLR (or slightly less) due to the melting of ice sheets and glaciers and the expansion of the warming water (Hieronymus and Kalén, 2020; Meier et al., 2022a; Pellikka et al., 2020; Weisse et al., 2021). However, in the northern sub-basins of the Baltic Sea, GIA (Sect. 3.3) is the dominant driver (Ekman, 1996). Land uplift with a maximum of about 10 mm per year close to the Swedish city Luleå, and slight subsidence along the southern Baltic Sea coasts were found (Vestøl et al., 2019) (Fig. 7). Over 1995–2020, rates of VLM were estimated to range between 0 mm yr^{-1} in the southern Baltic Sea to 10 mm yr^{-1} in the northern Baltic Sea in the Gulf of Bothnia (Oelsmann et al., 2024, Fig. 19b).

Due to the seasonality of the wind fields over the Baltic Sea region, SL in winter is generally highest, especially in mild winters with a high North Atlantic Oscillation index. During periods of strong westerly winds, the Baltic Sea temporarily fills with additional water from the North Sea, also leading to higher storm surges. Storm surges are a threat to low-lying Baltic Sea coastlines (Dieterich et al., 2019; Meier et al., 2004; Wolski et al., 2014).

6.5.2 Past sea level changes

During the 20th century, the global mean SL and thus also the geocentric mean SL in the Baltic Sea rose by about 1–2 mm yr^{-1} (Madsen et al., 2019; Meier et al., 2022b; Oppenheimer et al., 2019; Stramska and Chudziak, 2013; Weisse et al., 2021, Sect. 3.1). In Stockholm, for example, geocentric SL rose by about 20 cm between 1886 and 2009 (Hammarklint, 2009). Over 1950–2014, rates of reconstructed RSLR over the Baltic Sea were estimated at -1.1 ± 0.4 mm yr^{-1} when GIA effects are included and 1.8 ± 0.4 mm yr^{-1} after removal of GIA effects (Table 3, Dangendorf et al., 2019, Fig. 19a). Over the last 2–3 decades, global mean SL rose at rates of 3–4 mm yr^{-1} (Oppenheimer et al., 2019; Weisse et al., 2021; Sect. 2.2; Fig. 6). However, such rates are spatially non-uniform and include impacts of multidecadal variations in wind fields (Passaro et al., 2021). Although the Baltic Sea is warming faster than other coastal seas worldwide (Belkin, 2009), the impact of local thermal expansion is smaller than wind effects (Gräwe et al., 2019). The current acceleration of SLR in the Baltic Sea is small and could only be detected through spatial averaging of ob-

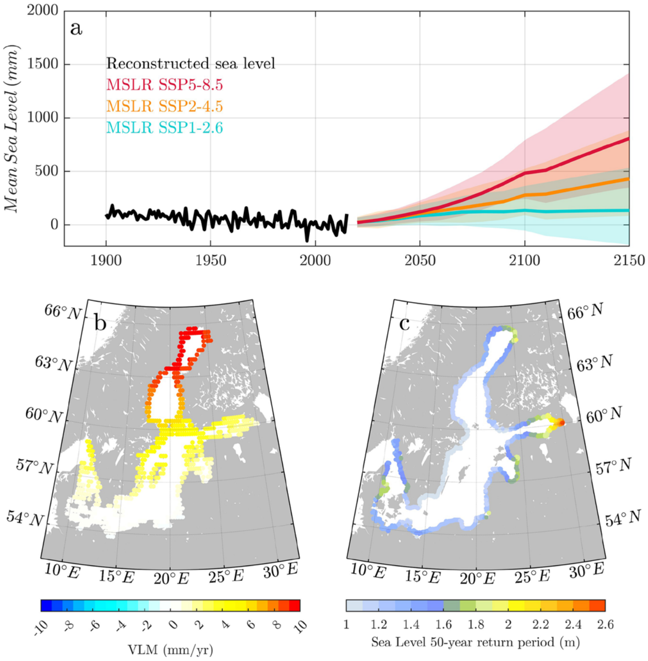

Figure 19. **(a)** Yearly reconstructed basin-average (Fig. 14) mean relative SL over 1900–2014 from Dangendorf et al. (2019) with the effect of GIA and GRD from contemporary mass loss of land-based ice, together with basin-average projected multi-model ensemble mean relative SL until 2100 and relative to 1995–2014 under SSP1-2.6, SSP2-4.5, and SSP5-8.5. Shading indicates the 17th–83rd percentile uncertainties under SSP2-4.5 and SSP5-8.5 obtained from AR6 IPCC. Projections were obtained from AR6 IPCC accounting for VLM (including GIA) effects. **(b)** Linear trends of VLM over 1995–2020 (Oelsmann et al., 2024). **(c)** The 50-year return levels of coastal extreme SLs from the GTSM dataset (Yan et al., 2020).

servations (Hünicke and Zorita, 2016). However, the amplitude of the seasonal cycle significantly increased during the 20th century (Hünicke and Zorita, 2008). The land uplift in the northern Baltic Sea as a result of GIA is still faster than geocentric SLR, so the SL there is currently falling relative to the land (Groh et al., 2017; Hill et al., 2010; Hünicke et al., 2015; Richter et al., 2012; Vestøl et al., 2019; Weisse et al., 2021).

For the 20th century, ESLs in the Baltic Sea probably did not rise more than global mean SL (Donner et al., 2012; Madsen et al., 2019; Meier et al., 2022b; Ribeiro et al., 2014; Wolski et al., 2014). In terms of extreme still levels, the 50-year return levels of the recent past range from 1 m along a large part of the eastern coast of Sweden to 2.6 m in the Gulf of Finland (Fig. 19c).

ESLs in the Baltic Sea are caused by pronounced atmospheric cyclones that sometimes interact with seiches on daily timescales and with volume changes on weekly timescales. As long-term changes in wind fields (frequency, intensity, and position of cyclones) on timescales longer than 100 years have not been detected and changes in other drivers such as tides or non-linear interactions are small, ESLs therefore have not significantly changed relative to the mean SL. This conclusion is supported by a paleoclimate model study for the adjacent North Sea that shows no difference between the impact of warmer and colder climate periods on ESLs (Lang and Mikolajewicz, 2019). Studies that nevertheless report an increase in ESLs such as Ribeiro et al. (2014) might be affected by the influence of the pronounced multidecadal variability of the wind fields (Marcos et al., 2015b; Marcos and Woodworth, 2017; Wahl and Chambers, 2016).

6.5.3 21st century projections

As the Baltic Sea is almost completely landlocked and has a complex, highly variable coastline and topography with many individual sub-basins, internal sills, and underwater channels, global climate models such as in CMIP6 cannot sufficiently resolve the physics and processes of the Baltic Sea in general and water level oscillations in particular. Therefore, projections of ESLs for this basin require high-resolution regional climate models, which are driven by global models, for example, using the statistical and dynamical downscaling approaches (Gröger et al., 2021). An overview about the most recent projections is given by Weisse et al. (2021) and Meier et al. (2022a).

Under medium- and high-emission scenarios, global mean and, thus, Baltic Sea SL will continue to rise during the 21st century (Bamber et al., 2019; Oppenheimer et al., 2019, Table 3). For the Baltic Sea, the contemporary GRD-induced SLR (Gregory et al., 2019) from the melting Antarctic ice sheet will be more pronounced than that from the melting Greenland ice sheet (Grinsted et al., 2015; Hieronymus and Kalén, 2020). Pellikka et al. (2018, 2020) regionalized nine GMSLR projections based on different methods (process-based, semi-empirical) and different emission scenarios (RCP2.6, 4.5, 6.0, 8.5) and found that the SL in the Baltic Sea will rise by about 90 % of the global mean rate.

Future changes in ESLs in the Baltic Sea depend on future changes in mean SL and large-scale atmospheric circulation in combination with changing wind patterns. Model projections do not agree on changes in atmospheric circulation, and therefore their relevance for future ESLs remains unclear (Christensen et al., 2022; Meier et al., 2022a; Räisänen, 2017). For the Baltic Sea, changes in mean SL are expected to have a greater impact on future extreme values than changes in atmospheric circulation (Gräwe and Burchard, 2012). SL fluctuations are dampened by the sea ice cover during winter when the ocean surface is shielded from the wind stress. Therefore, it can be concluded with a relatively high degree of confidence that future sea ice loss caused by warming will result in higher ESLs in the northern Baltic Sea in those regions that have previously been ice covered and that will be free of ice in future (Meier et al., 2022b). This would lead to an increase in significant wave height, coastal erosion, and resuspension of sediment (Girjatowicz, 2004;

Leppäranta, 2013; Orviku et al., 2011). Available projections of ESLs on the European coasts have so far considered all influencing factors by linear superposition, i.e. geocentric mean SLR and land uplift, tides (negligible in the Baltic Sea), storm surges, and waves (e.g. Vousdoukas et al., 2016, 2017). The results of some studies, such as Vousdoukas et al. (2016, 2017), suggested that ESLs will rise more than mean SL due to small changes in the large-scale atmospheric circulation, such as a northward shift of Northern Hemisphere storm tracks and westerly winds and an increase in the North Atlantic and Arctic oscillations (e.g. IPCC, 2013). Similar results were recently reported by Dieterich and Radtke (2024). However, these changes in the large-scale atmospheric circulation over the Baltic Sea region are not consistently depicted in the CMIP5 and CMIP6 global climate models, meaning that these ESL projections have only little confidence.

For further details, the reader is referred to the Baltic Earth Assessment Reports (e.g. Meier et al., 2023; Christensen et al., 2022; Meier et al., 2022b, a; Rutgersson et al., 2022; Weisse et al., 2021).

Box 2: A selection of historical storms causing coastal flooding in Europe and their consequences

Many severe marine flooding events have affected European coastlines throughout history (Ferrarin et al., 2022; Haigh et al., 2015, 2017; Paprotny et al., 2018). For example, large numbers of people (perhaps as many as 10 000 to 100 000 people per event) may have been killed around the coastline of the North Sea during events in 1099, 1206, 1287, 1421, 1446, 1507, and 1717 (Gönnert et al., 2001). The "Big Flood" of 31 January–1 February 1953 killed 1836 in the Netherlands, 28 in Belgium, 307 in England, and 19 in Scotland, and damage costs were over EUR 2 billion in today's prices (Gerritsen, 2005; McRobie et al., 2005). This event, together with the 16–17 February 1962 flood in Germany, were the driving force for major improvements in sea defences (e.g. the Delta Programme in the Netherlands) and led to the establishment of storm surge forecasting and warning services (Gerritsen, 2005; Gilbert and Horner, 1986). On 3 January 2018, Storm Eleanor crossed the North Sea and caused large storm surges along the coasts of the Netherlands. Based on the water level forecasts, five barriers of the Delta Works were closed. In particular, the automated closure of the Maeslantkering, one of the largest mobile storm surge barriers worldwide, was tested during Eleanor by adjusting the water level critical threshold, leading to the second closure of the storm surge barrier since its completion in 1997. On the other side of the North Sea, the Thames Barrier was also raised to protect London from flooding.

During the winter of 2013/14, the UK, France, and Spain experienced an unusual sequence of storms and some of the most significant coastal floods in the last 60 years (Garrote et al., 2018; Spencer et al., 2015; Toimil et al., 2017).

Venice and the northern Adriatic Sea have long suffered the impact of rising SL, experiencing several coastal floods, with the most intense events occurring in 1966, 1979, 2018, and 2019 (Lionello et al., 2021b). It is worth noting that four of the eight largest flooding events in Venice since 1872 happened in 2018 and 2019 (Lionello et al., 2021b), suggesting a possible change in frequency. Below, a focus is given on the Venice case, and on two storms: Xynthia and Gloria.

Venice: November 1966, November 2019 (Mediterranean Sea)

Since the mid-20th century, the frequency of floods of the historical centre of Venice has been progressively increasing (Lionello et al., 2021a). Two extreme water levels, namely the floods of 4 November in 1966 (De Zolt et al., 2006) and 12 November 2019 (Ferrarin et al., 2021), have dramatically exposed the issue of the security of the local monumental heritage and economic activity. The November 2019 extreme water level was analysed in detail by Giesen et al. (2021), and the Copernicus Marine Service could forecast the anomaly 3 d in advance. This has motivated the construction of the MoSE defence system, which was first operated to prevent the flooding of the city in 2020 (Lionello et al., 2021a). MoSE temporarily closes the inlets of the Venice Lagoon, preventing the ESLs from reaching the city centre. MoSE relies on an accurate SL forecast (see Umgiesser et al., 2021, for a review), which failed in the case of 12 November 2019 (Ferrarin et al., 2021) and is based on the concept that the frequency and duration of closures are limited. This principle might become unrealistic in the second part of the 21st century, where long closures will have negative impact on the lagoon ecosystems and the ship traffic.

The highest floods are produced by the southeasterly wind blowing above the shallow northern Adriatic Sea and associated with the passage of a mid-latitude cyclones above northern Italy (Lionello et al., 2021b). On 12 November 2019, an unprecedented substantial contribution of a small mesoscale cyclone was among the multiple causes of the extreme event (Ferrarin et al., 2021). The increased frequency of floods is produced by the increase in the relative mean SL (Lionello et al., 2021a) at a rate of 2.5 mm yr^{-1} in the past 150 years, resulting from approximately equal contributions of vertical land movements and mean SLR (Zanchettin et al., 2021).

The likely range of North Adriatic relative level projections at the end of the 21st century goes from 32 cm (lower limit of the RCP2.6 low emission scenario) to 110 cm (upper limit of the RCP8.5 high emission scenario), and it might reach 1.8 m in a high-end scenario (Zanchettin et al., 2021). However, divergence among scenarios occurs after 2050, the time at which all values are in the range 20–40 cm (Zanchettin et al., 2021). It is estimated that preventing the flood of the city centre would require the closure of the inlets for 2–3 weeks, 2 months, and 6 months per year in correspondence with RSLR of 30, 50, and 75 cm, respectively (see Lionello et al., 2021a, and references therein).

Storm Xynthia (northeastern Atlantic)

The Storm Xynthia hit the Atlantic coast of France, especially Vendée and Charente-Maritime, during the night of 27–28 February in 2010 (Fig. 20). Xynthia caused 41 flood-related deaths (Vinet et al., 2012), 79 injured, and 500 000 affected people. Dikes were overtopped and damages were estimated to a total of EUR 2.5 billion with 4800 houses flooded, 120 km of coast eroded, failure and damages to flood defences occurred along a coastline of 200 km, and 50 000 ha of land areas flooded (e.g. Kolen et al., 2013).

Although the storm characteristics (atmospheric pressure, winds) were less exceptional than previous storms such as Storm Martin in December 1999 or Storm Klaus in 2009, it resulted in exceptional coastal floods as the peak of the storm surge (reaching 1.53 m at La Rochelle) was reached during spring high tides (+3.0 m with a coefficient of 102 at La Rochelle)

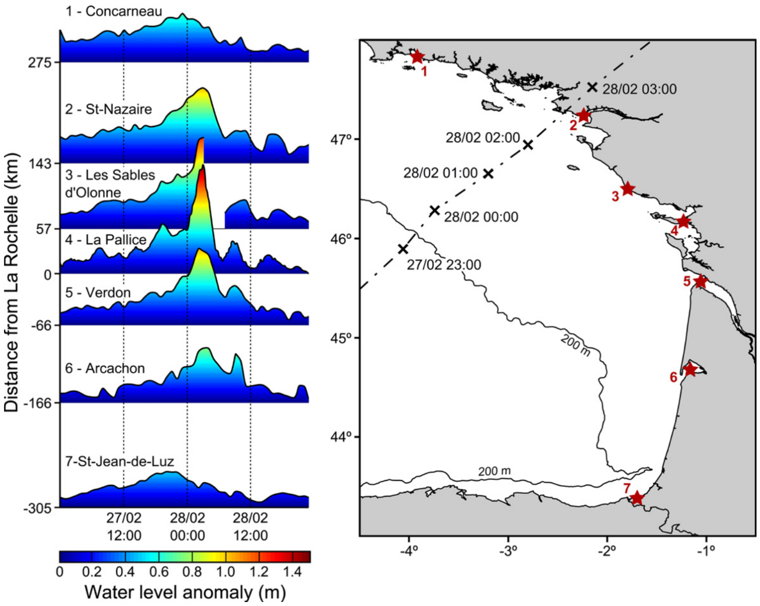

Figure 20. Storm surge during Xynthia along the French coast of the Bay of Biscay, showing a maximum at La Pallice station (station 4). Extracted from Bertin et al. (2012).

and with high waves (7.5 m of maximum significant wave height). Tide gauges recorded water levels reaching +4.51 m NGF (official levelling in France) at La Rochelle (8.01 m with respect to hydrological zero). Such water levels are well above the centennial level for Vendée and Charente-Maritime, estimated at +4.0 m NGF (Simon, 2008), and are estimated to correspond to a 200–250-year return period.

Xynthia was a tipping point for adaptation to coastal floods and associated risk management for France due to its high impact. Following Xynthia, different measures were implemented. A national coastal flood early warning system was developed by national agencies (SHOM and Météo-France), and the prevention fund for major natural hazards, known as the Barnier Fund, was extended to marine flooding. As such, since April 2010, owners of houses that were severely damaged or are threatened due to their location in areas with a high risk of coastal flooding have been allowed to sell their property to the French state. A total of 1176 properties were sold to the French state for a total of EUR 330 million. Dikes were repaired for an amount of EUR 300 million, and more than 300 local priority coastal risk prevention plans were defined.

Storm Gloria (Mediterranean Sea)

Storm Gloria was formed by a low-pressure system of Atlantic origin that intensified over the western Mediterranean starting on 19 January 2020 and lasting until 26 January 2020. It affected the eastern coasts of Spain and the Balearic Islands, with intense and sustained winds that led to record-breaking wind waves (Fig. 21) and heavy precipitation (Amores et al., 2020; de Alfonso et al., 2021; Pérez-Gómez et al., 2021; Toomey et al., 2022a). It caused severe damage along the coasts of the Spanish mainland and the east of the Balearic Islands, including a total of 13 fatalities, flooding and strong erosion, with economic losses of several million euros and damage to power supply networks.

In situ wave observations from deep-water buoys provided measurements of significant wave height over 8 m, exceeding all historical records and corresponding to return periods of several centuries when only previous measurements are accounted for (de Alfonso et al., 2021). Likewise, in situ SL observations from tide gauges along the eastern Spanish coasts measured storm surges over 50 cm (Amores et al., 2020; Pérez-Gómez et al., 2021). In particular, in the southern Gulf of Valencia, a hydrodynamic-wave-coupled model simulation quantified the effect of wave setup as large as 40 % of the total storm surge observed, which was close to 70 cm (Fig. 21) due to sustained strong winds (Amores et al., 2020).

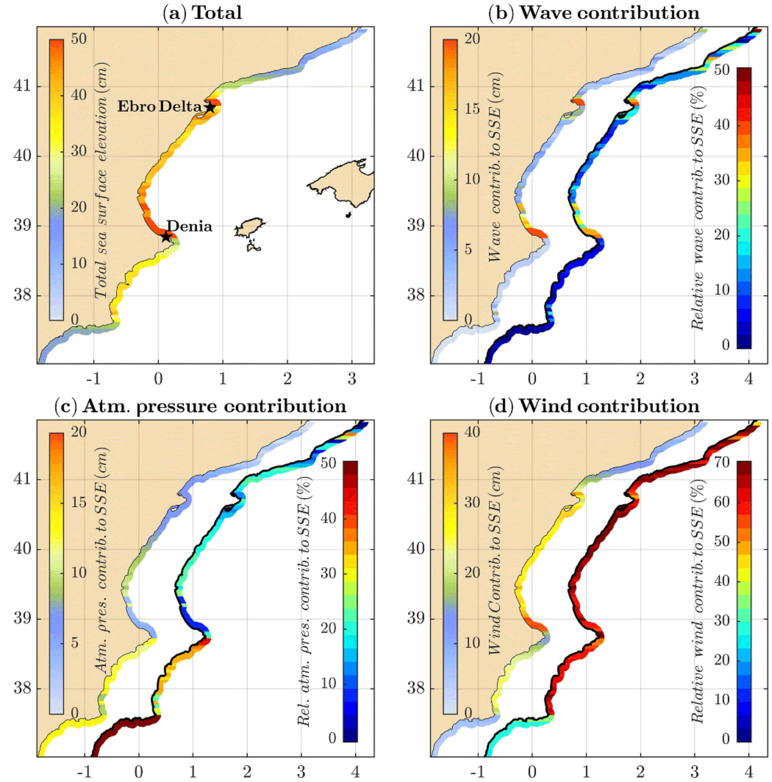

Figure 21. Storm Gloria **(a)** total sea surface elevation (SSE) along a coastal strip affected by the storm in the western Mediterranean Sea and contributions to SSE: **(b)** wave setup, **(c)** atmospheric pressure, and **(d)** wind setup contributions to the storm surge. In panels **(b)**–**(d)**, the absolute (relative) contributions are indicated by the profile on the left (right). Values for contributions to SSE in absolute terms are given in centimetres. Values for contributions to SSE in relative terms are given as percentages. Note that the colour scales for the wind contribution have higher limits. From Fig. 6 in Amores et al. (2020).

7 Conclusions

This paper provides an assessment of regional to local historic and future SL changes in Europe, both for the long-term trends and for extremes. It complements existing global and European assessments by providing additional geographical and contextual details, as scoped with stakeholders during dedicated regional workshops and the Sea Level Rise Conference 2022 (see Jiménez et al., 2024, in this report). European regional seas present contrasting environments, from the microtidal and enclosed Mediterranean and Black seas, to the open ocean in the northeastern Atlantic with large tides and exposition to extra-tropical storms, to the uplifting northern Baltic Sea and European Arctic. The main drivers of RSLR and of ESLs thus vary along European coastlines. Key processes and drivers or specificities of each European regional sea with regard to SL changes are reviewed.

In terms of SLR, geocentric SL trends since 1993 have been on average slightly above the global mean rate, with only a few areas showing no change or a slight decrease. VLM, notably due to GIA and human activities, can lead to substantial regional to local deviations between geocentric and relative SL changes, especially over the uplifting northern Baltic and hotspots of coastal subsidence.

Projected mean RSLR is the largest in the northeastern Atlantic, North Sea, and Mediterranean and Black seas and lowest in the European Arctic and Baltic Sea. The Baltic Sea exhibits strong spatial gradients of projected RSLR, with SLR close to the global mean in the southern basin, and relative SL fall in the northern Baltic due to GIA.

ESLs will occur more frequently along most European coasts during the 21st century. Amplification factors of the frequency at which ESLs will occur during the 21st century broadly show a meridional gradient, mostly related to the spatial amplitudes of tides and of storm-induced SL variability. The largest amplification factors are projected for southern Europe, especially in the microtidal Mediterranean Sea. The lowest (but positive) amplification factors are projected for northern Europe, in macro-tidal regions exposed to storms and induced large surges such as the southeastern North Sea. ESLs are projected to occur less frequently in the northern Baltic Sea due to a relative mean SL fall.

Several knowledge gaps are identified. An important one concerns ESLs, including the contribution from wind waves, dynamic changes in tides, surges, and wave setup and runup; non-linear interactions between these drivers of ESLs; and marine and fluvial or pluvial extreme compound events. Regionally downscaled projections or more local information of relative mean and ESL changes are needed with characterized uncertainties. A major uncertainty for SLR remains attached to ice sheets instabilities and overall contributions, and more robust projections beyond 2100 are needed. Finally, the interpretation of regional SLR variations for local perceptions and decision-making is also an area needing improvement.

Appendix A: List of acronyms

ABUMIP	Antarctic Buttressing Model Intercomparison Project
AR5	Fifth Assessment Report of the IPCC
AR6	Sixth Assessment Report of the IPCC
CMIP6	Coupled Model Intercomparison Project Phase 6
C3S	Copernicus Climate Change Service
EMODnet	European Marine Observation and Data Network
ESL	Extreme sea level
EuroGOOS	European Global Ocean Observing System
GESLA	Global Extreme Sea Level Analysis
GHG	Greenhouse gases
GIA	Glacial isostatic adjustment
GLOSS	Global Sea Level Observing System
GMSLR	Global mean sea level rise
GNSS	Global Navigation Satellite Systems
GRD	Gravity, rotation, deformation
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
ISMIP6	Ice Sheet Model Intercomparison Project for CMIP6
LARMIP	Linear Antarctic Response to Basal Melting Model Intercomparison Project
MICI	Marine ice cliff instability
MISI	Marine ice sheet instability
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (USA)
PSMSL	Permanent Service for Mean Sea Level
RCP	Representative Concentration Pathways
RSLR	Relative sea level rise
SL	Sea level
SLR	Sea level rise
SONEL	Système d’Observation du Niveau des Eaux Littorales (France)
SROCC	IPCC Special Report on the Ocean and the Cryosphere in a Changing Climate
SSP	Shared Socioeconomic Pathways
VLM	Vertical land motion
WCRP	World Climate Research Programme

Data availability. Data used in this paper are available from IPCC AR6 (projection data available from https://doi.org/10.5281/zenodo.5914709, Garner et al., 2021), GESLA (https://doi.org/10.7289/V5V40S7W, Caldwell et al., 2001; Woodworth et al., 2016), PSMSL (http://www.psmsl.org/data/obtaining/, PSMSL, 2024; Holgate et al., 2013), Copernicus Marine Service (https://doi.org/10.48670/MOI-00215, EU Copernicus Marine Service, 2019a; https://doi.org/10.48670/MOI-00237, EU Copernicus Marine Service, 2019b; https://doi.org/10.48670/MOI-00264, EU Copernicus Marine Service, 2019c), and the Copernicus Climate Data Store (https://doi.org/10.24381/cds.8c59054f, Yan et al., 2020). Data from Dangendorf et al. (2019) are available from the corresponding author on request. Data from Jevrejeva et al. (2023) are available from their Supplementary Files. Statistics on present-day uplift, geoid, gravity, and Stokes coefficient rates derived from Caron et al. (2018) are available at https://vesl.jpl.nasa.gov/solid-earth/gia (Jet Propulsion Laboratory, 2024). The authors acknowledge the use of the Utide software (https://www.mathworks.com/matlabcentral/fileexchange/46523-utide-unified-tidal-analysis-and-prediction-functions, Codiga, 2024).

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Sea Level Rise in Europe: Impacts and consequences

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Abstract. Sea level rise has major impacts in Europe which vary from place to place and in time, depending on the source of the impacts. Flooding, erosion, and saltwater intrusion lead via different pathways to cause various consequences in coastal regions across Europe. Flooding, via overflow, overtopping, and breaching, damages assets, the environment, and people. Coastal erosion leads also to damage, and saltwater intrusion affects ecosystems and surface waters and salinizes coastal aquifers, diminishing freshwater availability and causing salt damage to crops and health issues in people. This paper provides an overview of the various impacts and consequences of sea level rise in Europe.

1 Introduction

Sea level rise (SLR) is a major threat for coastal zones, inducing hazards such as coastal flooding (mild and chronic at high tides or intense and episodic during storms), permanent submersion of coastal zones, coastal erosion, salt intrusion in surface- and groundwater (with adverse impacts on drinkable water and agriculture), problems with water management, and coastal ecosystem degradation or loss (affecting coastal wetlands and contributing to coastal zone protection, biodiversity conservation, and carbon storage). As sea level is bound to rise over the next few centuries (Melet et al., 2024), it is with great certainty that coastal zones and communities will be increasingly threatened by sea level changes at various timescales, ranging from episodic extreme events to interannual–centennial changes and trends linked to climate change and modes of variability (Hallegatte et al., 2013; Oppenheimer et al., 2019; Cooley et al., 2022; Glavovic et al., 2022; Bednar-Friedl et al., 2022). Locally, these threats can be reinforced by subsidence caused by human activities like

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groundwater pumping or groundwater fluid extraction for energy purposes (Carbognin and Tosi, 2002).

Impacts of SLR result from the combination of sea level changes, exposure, and vulnerability (Cardona et al., 2012). Sea level changes with a focus on Europe are discussed in Melet et al. (2024). This paper aims to describe the different impacts of sea level rise in Europe, following the physical evidence expressed by Melet et al. (2024), and is intended for local and governmental stakeholders planning on raising awareness and considering adaptation measures in their region. We attempt to provide an aggregation of the consequences in a heterogeneous landscape of information.

The increased hazards posed by SLR in response to climate change have been identified as the main driver of future rise in coastal flood risks, with the relative importance of trends in exposure, related to coastward migration, urbanization, and rising asset values, diminishing over time (Vousdoukas et al., 2018a). However, population and economic activities are expected to change in Europe and worldwide as well, possibly also increasing the exposure. Coastal zones are increasingly more densely populated than the hinterland (Small and Nicholls, 2003) and exhibit higher rates of population growth and urbanization, which are concentrating economic assets and critical infrastructure. Coastal migration is driven by the combinations of specific economic, geographic, and historical conditions and includes the concentration of densely settled agricultural areas in well-watered fertile deltas and coastal plains (Hugo, 2011; McGranahan et al., 2007). It plays particularly on longer timescales but is hard to quantify. The exposure of people and assets to SLR hazards is therefore widespread and increasing and can thereby extend to a change in the vulnerability to SLR (e.g., urbanization changes the imperviousness of flood-prone areas; Andreadis et al., 2022). Figure 1 shows that the coastal zones in Europe (EU) are highly urbanized; more than 30 million people live in the 100-year event flood coastal plain and 50 million in the contiguous and hydrologically connected zone of land along the coast and below 10 m elevation (sometimes referred to as the low-elevation coastal zone (LECZ); Neumann et al., 2015). Whether the number of people exposed changes over time depends on assumptions on future developments of fertility, mortality, and migration.

A land use planning strategy in coastal lowlands can reduce exposure of the EU population to SLR (see Bisaro et al., 2024). A good example is, for instance, by developing coastal setback zones, which are buffer spaces defined by a specific distance from the shoreline's highest water mark where new developments in potentially exposed coastal regions are restricted. This can reduce the exposure of new urban development by at least 50 % in most EU countries by 2100 (Wolff et al., 2023).

Due to the large economic value of coastal zones, economic losses due to coastal flood risks are huge (Abadie et al., 2020; Hallegatte et al., 2013). Presently, the expected annual damage from coastal flooding for Europe alone is around EUR 1.25 billion but could increase by 2–3 orders of magnitude if coastal adaptation is only maintained to its current level (Vousdoukas et al., 2018a). The impacts of floods (both marine and riverine/pluvial) on people, the built environment, and the economy is one of the four key climate-change-induced risks identified for Europe (Bednar-Friedl et al., 2022). Deltas are particularly vulnerable to SLR because of, among other factors, the large population pressure. In Europe, the main deltas are those of the Rhine–Meuse–Scheldt (NL), Rhône (FR), Po (IT), and Ebro (SP) rivers. Rotterdam and London are amongst the world's most exposed cities in terms of the population living in the 100-year event flood plain if there were no flood protection (Hallegatte et al., 2013). In addition to human fatalities, economic losses due to coastal flood risks are considerable. European cities for which the annual average losses due to coastal flooding by 2050 will increase particularly, assuming present-day defense standards or flood probability, tend to be concentrated along the Mediterranean coast (Hallegatte et al., 2013). These cities (e.g., Venice) were built close to the shore since the historical sea level variability has been low (e.g., small tidal range and interannual variability); as a consequence, changes in the mean sea level are felt earlier than in regions where the sea level variability is higher.

Therefore, SLR creates risks for people, ecosystems, land uses, the built environment, and human activities (Cooley et al., 2022). In this paper, a summary of the sixth cycle of the Intergovernmental Panel on Climate Change (IPCC) report is provided (Sect. 2). Then, various impacts of SLR are discussed from a European perspective, using the source, pathway, and receptor (SPR) framework introduced in Sect. 3. SLR impacts are discussed for coastal flooding (Sect. 4), coastal erosion (Sect. 5), and saltwater intrusion (Sect. 6).

2 Summary of previous assessments relevant to Europe

An updated assessment of the impact and risks for natural and human systems by SLR is provided by the recent Sixth Assessment Report of the Intergovernmental Panel on Climate change (IPCC AR6), whose Working Group II (WG2; Pörtner et al., 2022) assessed the impacts, adaptation, and vulnerabilities related to climate change. SLR is considered in many chapters, particularly in Chap. 3 ("Ocean and coastal ecosystems and their services") (Cooley et al., 2022; see cross-chapter Box 3 for an overall summary) and Chap. 6 ("Cities, settlements and key infrastructure") (Dodman et al., 2022), with more focused material presented in the cross-chapter in Paper 2 ("Cities and settlements by the sea") (Glavovic et al., 2022). Material directly addressing European regional issues is included in Chap. 13 ("Europe") (Bednar-Friedl et al., 2022) and in the cross-chapter Paper 4 ("Mediterranean region") (Ali et al., 2022). The material on SLR covered by AR6 WG2 (Dodman et al., 2022) and

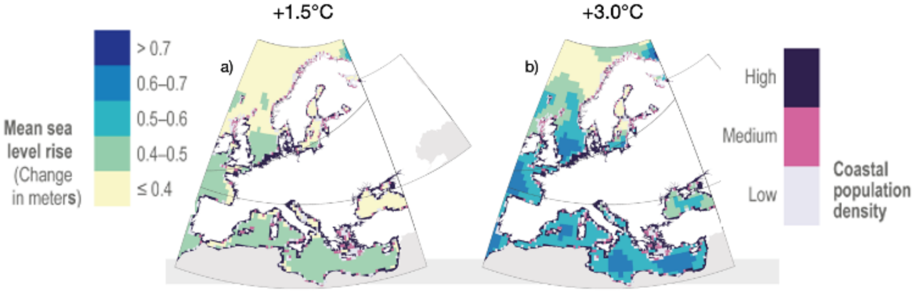

Figure 1. Mean sea level rise (SLR; in m) and coastal population density in Europe for global warming levels of +1.5 and +3 °C. SLR data consider the long-term period (2081–2100) and SSP1-2.6 for **(a)** and SSP3-7.0 for **(b)**. Adapted from Fig. 13.4 in Chap. 13 of AR6 WG2 (Bednar-Friedl et al., 2022).

the AR6 Synthesis Report (Core Writing Team et al., 2023) builds on and updates the work presented by Oppenheimer et al. (2019) and the AR6 reports.

There is extensive evidence that at global scale, relative SLR is already impacting ecosystems, human livelihoods, infrastructure, food security, and the climate mitigation potential at the coast (Pörtner et al., 2022). Observed impacts include chronic flooding at high tides, more frequent episodic flooding during storms, wetland and underground water salinization and ecosystem transitions, increased erosion, and coastal flood damages. SLR poses risks for cities, settlements, and populations in low-elevation coastal zones, cultural heritage along coasts, and threatens the very existence of some island nations. The large exposure caused by the disproportional concentration of population and economic activities in coastal areas leads to high risks which are very likely to increase further with future SLR. In addition, risks in the agriculture sector and nature conservation are induced by the salinization of groundwater, estuaries, wetlands, and soils. The IPCC AR6 WG2 shows that these risks will generally increase with SLR. Along many European coastlines, extreme water levels, coastal floods, and sandy coastline recession are projected to increase during the 21st century, mainly because of the increase in relative SLR.

According to the IPCC AR6 WG2, it is with great certainty that an acceleration in the SLR will increase risks to people and infrastructure from the inundation and extreme floods along European low-lying coasts and estuaries. Related damages will increase at least 10-fold even before the end of the 21st century, assuming the present levels of adaptation and mitigation measures. Annual expected damage (which today is EUR 1.3 billion) is foreseen to increase disproportionately with global warming. It is estimated to be in the range of EUR 13–39 billion by 2050 at global warming levels between 2 and 2.5 °C and EUR 93–960 billion by 2100 between a 2.5 and 4.4 °C temperature increase. Assuming the present distribution of population and protection levels, the increase in the number of people at risk depends on the emission scenario; with respect to the present, an extra 10 million people will be at risk of experiencing a 100-year flood event under a very high-emission scenario (RCP8.5) by 2100, whereas just below 10 million people will be at risk under a low-emission scenario (RCP2.6) by 2150. Along low-lying coasts and estuaries, flood risks might further increase because of compounding storm surges, waves, rainfall, and river runoff events, but to date, this has been poorly quantified (see also Sect. 4). Port operations may be negatively affected by SLR in northern and western Europe. In Mediterranean ports, the negative effects are to be expected by a combined change in wave regimes and sea level.

In the IPCC AR6 WG2, it is shown that soft cliffs and beaches in Europe are most affected by coastal erosion. Observations suggest that 27 %–40 % of Europe's sandy coast are already eroding today, although there is no convincing evidence that past erosion of sandy shorelines can be attributed to climate change or SLR. At the same time, there is a great deal of certainty that SLR will increase the sandy shoreline retreat in the future, but the actual rates are very uncertain. On a centennial timescale, coastal erosion and flooding will become an existential threat for some coastal communities and UNESCO World Heritage sites, especially in the Mediterranean region (Reimann et al., 2018; Sabour et al., 2020), where the problem of propagation of waves in ports is also foreseen in future. Moreover, seawater intrusion in coastal aquifers and surface waters is projected to increase by the combination of overexploitation and SLR, with pronounced impacts on agricultural productivity.

The IPCC AR6 WG2 shows that warming is the main climate hazard for European coastal ecosystems. However, rapid SLR (potentially aggravated by human-induced subsidence) is also expected to have negative impacts by reducing the surface area of intertidal flats (e.g., the Wadden Sea) that cannot always be compensated by sediment accumulation. By 2100 under intermediate scenarios, coastal erosion will cause the loss of 4.2 %–5.1 % of the present values of ecosystem services and reduce their contribution to shoreline protection across Europe. The vulnerability of Europe's coastal subtidal seagrass meadows and intertidal salt marshes to SLR is particularly high in the microtidal areas of the Baltic and Mediterranean coasts, with a potential loss of 75 % of Posi-

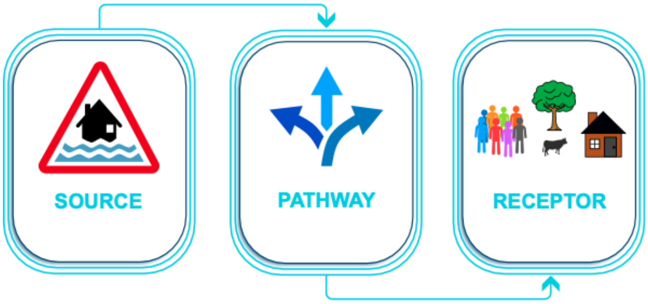

Figure 2. Source, pathway, and receptor (SPR) conceptual model (after Sayers et al., 2002).

donia oceanic seagrass habitats in the Mediterranean Sea. In addition, non-sea-level-related coastal squeeze is also a threat which may cause ecosystem loss.

3 The source, pathway, and receptor framework

To describe the main impacts of SLR across Europe, we use the concept of the source–pathway–receptor (SPR), proposed by Sayers et al. (2002), as an alternative approach to the traditional exposure vulnerability approach (Nicholls et al., 2007). The "source" describes the origin of the event that causes flooding. The "pathway" is the route that a hazard takes to reach the "receptors" and includes processes and characteristics of the coastline influencing or mediating the hazard. The receptor is the exposed element (e.g., people, property, and environment) that may be harmed by the event and the corresponding social, economic and environmental effects on the receptors. The concept is illustrated in Fig. 2. The SPR concept will be applied to coastal flooding (Sect. 4), erosion (Sect. 5), and saltwater intrusion (Sect. 6). The SPR concept has been used in many coastal contexts, for example, by Thorne et al. (2007), Donovan et al. (2013), Villatoro et al. (2014), and Haigh et al. (2022).

4 Coastal flooding and compounding flood events

The first pronounced impact of SLR that we consider is coastal flooding. A schematic overview of the SPR concept for coastal flooding is provided in Fig. 3. Coastal floods are amongst the most impactful hazards – both in Europe and globally – with wide-ranging social, economic, and environmental consequences. Many severe flooding events have affected European coastlines throughout history (Haigh et al., 2015, 2017; Paprotny et al., 2018; Ferrarin et al., 2022). An increase in the coastal flooding frequency is one of the most certain and costly consequences of SLR (Nicholls and Cazenave, 2010). Flood defense standards in many European countries are among the highest in the world (Sect. 4.2). However, significant populations and assets are in coastal flood plains and are threatened when defense infrastructure fails or is exposed to flooding exceeding the protection standard. Furthermore, the impacts of coastal flooding are likely to increase as flood defense infrastructure is aging, as the coastal population continues to grow, and as urbanization and development in low-elevation coastal zones continue (Stevens et al., 2016; McMichael et al., 2020). In addition, further decline in the extent of natural habitats (i.e., salt marshes, mudflats, shingle beaches, and sand dunes), which act as a natural buffer against flooding, has the potential to increase coastal flood risks (Campbell and Keddy, 2022).

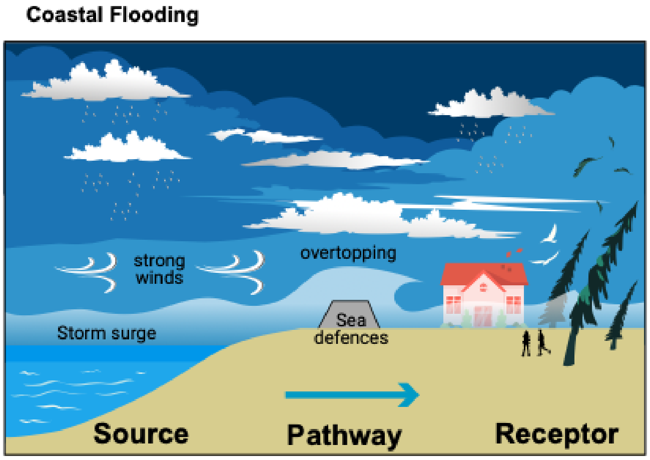

Figure 3. The SPR concept visualized for flooding. Note that overtopping can also be replaced by overflow or breaching.

Multiple drivers, some related to climate change and others not, influence coastal flood risk and its future change. These different drivers can be considered using the SPR conceptual model, as explained in Sect. 3. The source of coastal floods (describing the origin of the event) is formed by extreme coastal water levels (including the contributions from tides, storm surge and wave runup superimposed on the relative mean sea level). The influence of climate change on the source component of coastal flooding is discussed in Sect. 4.1 and in Melet et al. (2024, Sects. 4.3 and 5.3). In estuaries, the compounding influence of rainfall and fluvial input can be important, leading to compound flooding, which is described as a special case in Sect. 4.2. The pathway represents how seawater makes its way onto normally dry land to cause flooding. Climate change, especially SLR, can significantly affect this pathway, in addition to modifying the source profile. This influence of SLR on pathways is discussed in Sect. 4.3. Receptors are discussed in Sect. 4.4. Initiatives to develop flood-related climate services in Europe are discussed in Sect. 4.5.

4.1 Source of flooding

Coastal floods are governed by anomalously high water levels exceeding a site-specific threshold. Extreme coastal water levels (ECWLs) arise as combinations of different drivers, namely (1) astronomical tides; (2) storm surges and associated seiches; (3) waves, including setup, infragravity waves, and swash (e.g., Dodet et al., 2019); and (4) relative mean sea level (including SLR and land subsidence) (see also Melet et al., 2024). These four components exhibit considerable intra- and interannual variability (e.g., driven by tidal cycles) (Haigh et al., 2011) or climate variability, such as the North Atlantic Oscillation (Hurrell, 1995; Mentaschi et al., 2017; Boucharel et al., 2023), or changes in wave climate (Morim et al., 2019; Melet et al., 2020) or ocean processes at basin scales (Menna et al., 2022; Meli et al., 2023). In addition, there are non-linear interactions between the four components (Horsburgh and Wilson, 2007; Idier et al., 2019; Arns et al., 2020). Long-term changes in any or all of the four components can modify the variability in the frequency and magnitude of ECWLs and thus affect coastal flooding.

ECWLs, and hence the frequency of coastal flooding events, are impacted by climate change in three main ways (Pugh and Woodworth, 2014), as also argued in Melet et al. (2024): (1) SLR affects the ECWLs directly by raising the baseline mean water level and leading to lower storm surge and/or wave elevations necessary to cause flooding; (2) rising mean sea levels alter water depths and therefore modify the propagation and dissipation of the tide and storm surge components or alter wave processes in shallow water (e.g., Arns et al., 2017; Chaigneau et al., 2023); and (3) climate variations in the tracks, speed, strength, and frequency of weather systems may alter the intensity and/or duration and frequency of storm surges and waves (and variations in rainfall and river discharge in estuaries).

As discussed in Melet et al. (2024, Sects. 4.3, 5.3), direct changes in the mean sea levels appear to have been the main driver of observed changes in ECWLs in the past (Menéndez and Woodworth, 2010; Marcos et al., 2015; Ferrarin et al., 2022) and are projected to dominate changes in extremes along the European coastline in the future, increasing the likelihood of coastal flooding (Vousdoukas et al., 2016, 2017). However, changes in storm surges (Calafat and Marcos, 2020; Calafat et al., 2022; Muis et al., 2020) and wave height (Benetazzo et al., 2022; Vousdoukas et al., 2018b; Aarnes et al., 2017) have and may also play a substantial role in the changes in ECWLs in some European regions in the future. Coastal flooding could also be influenced by changes in tides, especially in regions with a shallow water depth. Regionally coherent changes (positive and negative) in the tidal range have been observed in historic sea level records around both European and global coastlines and are projected to occur in the future with changes in water depth driven by SLR and factors such as ice sheet extent and ocean warming (Pickering et al., 2012; Ferrarin et al., 2015; Idier et al., 2017; Haigh et al., 2020). Changes in tidal range are likely to be smaller than ±15 % of mean SLR along most coastlines.

The relative contribution of SLR to changes in coastal flooding depends on different factors. Areas with small tidal (∼ 2 m) amplitude will be primarily affected by mean sea level changes. For example, in the Mediterranean Sea, extreme sea levels that are now occurring once in a century are expected to occur at a higher frequency in future, depending on climate scenarios, but in some places they are expected to occur even more frequently than annually. This intensification is stronger than the overwash and flooding in the south of Portugal, where current return periods of 1 in 100 years can reduce to lower than 1 in 20 years by 2055 and 1 in 10 years by 2100 (Ferreira et al., 2021). Venice is an exception for the Mediterranean Sea, as the existing protection measures are higher than for most of the south European coastlines and could potentially protect the monumental city during the next few decades (Lionello et al., 2021; Mel et al., 2021).

4.2 Compound flooding

Many coastal settlements along the European coastline are in estuaries and lagoons (e.g., London, Rotterdam, Hamburg, Venice, and Lisbon). In these coastal regions, floods can arise not only from climate-driven changes in oceanographic sources (e.g., tides, storm surges, and waves) but also via river discharge (fluvial) and direct surface runoff (pluvial). These mainly arise from heavy precipitation but are also incurred via snowmelt. Many cities and towns located along coastline can also experience flooding during heavy rainfall because of insufficient drainage during high tides (Van Den Hurk et al., 2015). In the past, flood risk assessments typically considered the oceanographic, fluvial, and pluvial drivers of flooding separately. However, in coastal regions, floods are often caused by more than just one factor, which can be physically correlated (e.g., with storms). Furthermore, the adverse consequences of a flood can be greatly exacerbated when the oceanographic, fluvial, and/or pluvial drivers occur concurrently or in close succession (i.e., a few hours to days apart), depending on local characteristics which influence lag times between variables. This can result in disproportionately extreme events, referred to as "compound flood events", which do not necessarily have the same driver but coincide in time. Zscheischler et al. (2018) define compound events as "a combination of multiple drivers and/or hazards that contributes to societal or environmental risk". Flood drivers are typically causally related through associated weather patterns (the modulator; Zscheischler et al., 2020), and therefore, it is assumed that stronger dependence between drivers increases the impact of compound floods (Wahl et al., 2015).

In recent years there has been a large increase in the number of studies that have started to investigate compound flood events in Europe. Many studies have been undertaken for specific localized regions in Europe, such as the Rhine delta, the Netherlands (Kew et al., 2013; Khanal et al., 2018); Brest, France (Mazas and Hamm, 2017); Santander, Spain (Rueda et al., 2016); Ravenna, Italy (Bevacqua et al., 2017); Venice, Italy (Ferrarin et al., 2022); and the River Trent, the Yare basin, the River Ancholme, and the rivers Taff and Ouse in

East Sussex in the UK (Granger, 2001; Mantz and Wakeling, 1979; Thompson and Law, 1983; Samuels and Burt, 2002; and White, 2007, respectively). Larger-scale assessments of compound flood events have been undertaken more recently for the UK (Svensson and Jones, 2002, 2004; Hendry et al., 2019) and for Europe (Petroliagkis et al., 2016; Paprotny et al., 2018; Camus et al., 2021, 2022; Bevacqua et al., 2019, 2020b). On a quasi-global scale, which obviously includes Europe, Ward et al. (2018) and Couasnon et al. (2020) assessed the dependence between coastal and river flooding, using observational datasets and reanalysis, respectively.

Most of these studies quantified the statistical dependence between flooding sources as an indirect measure of the flooding hazard called compound flooding potential. The analysis of the interdependencies has been primarily limited to storm surge and precipitation (compound surge–rain events; Wahl et al., 2015; Wu et al., 2018) or to surge and river discharge (compound surge–discharge events; Ward et al., 2018; Couasnon et al., 2020; Hendry et al., 2019). In those studies, precipitation is considered a fluvial proxy, which can be assumed as an equivalent driver to discharge in small to medium-sized river catchments (Bevacqua et al., 2020a). Waves can be included as part of the total sea level by adding it linearly to the storm surge and/or astronomical tide components (Bevacqua et al., 2019). Statistical studies have notably shown that (a) the joint exceedance probability of compound surge–discharge events is on average a factor of 2–4 higher when the dependence is considered (Van Den Hurk et al., 2015; Ward et al., 2018; Santos et al., 2021); (b) ignoring the dependence between precipitation and surge can overestimate the flooding return period considerably (Bevacqua et al., 2019; Fig. 4a); and (c) the river discharge of the 50-year compound flood is up to 70 % larger, subject to the occurrence of extreme water levels (Ganguli and Merz, 2019a). Simulations of the non-linear interactions of these flood drivers at local scale using coupled modeling approaches demonstrate a rise in the extreme sea levels at some locations along the estuaries (e.g., in the Netherlands (Van Den Hurk et al., 2015) and in northwestern Spain (Bermúdez et al., 2021)). Recently, a global analysis of simulated river flood levels using a global coupled river–coast flood model framework showed that surge exacerbates 1-in-10-year flood levels at 64 % of the river mouths analyzed, with a mean increase of 11 cm (Eilander et al., 2020). Furthermore, 55 % of the world coastlines face compound storm surge and wave extremes which increase the potential coastal flooding (Marcos et al., 2019).

Although different sampling methods to identify compound events and dependence measures to quantify compound flooding potential have been used, several hotspots have been identified along the European coastlines. High joint occurrences of extreme river discharge and storm surge events are found on the coasts of Portugal, the Strait of Gibraltar, the west-facing coasts of north and central Europe (Heinrich et al., 2023b), and along the southwest coast of the UK (Hendry et al., 2019). Also, the northern and eastern Mediterranean coasts and the coast of Tunisia appear as compound flooding hotspots (Couasnon et al., 2020; Camus et al., 2021; Eilander et al., 2020). Regarding precipitation and surge, higher dependency is concentrated along the Atlantic coast and in the Mediterranean Sea (particularly in the regions of the Gulf of Valencia in Spain, northwest Algeria, the Gulf of Lion in France, the Adriatic coast of the Balkan Peninsula, the Aegean coast, southern Türkiye, and the Mediterranean–Levantine region) (Bevacqua et al., 2019; Camus et al., 2021; Fig. 4a).

Historical trends in compound flooding resulting from high coastal water levels and peak river discharge have been assessed over northwestern Europe (near the North and the Baltic seas) over 1901–2014 using 37 stream gauges (Ganguli and Merz, 2019b). Increasing trends were identified in the region from 47 to 60° N, while decreasing trends were identified along higher-latitude coasts ($> 60°$ N).

In most regional-, continental-, or global-dependence-based analyses, compound events are identified using a two-sided conditional sampling to bivariate drivers (Wahl et al., 2015; Ward et al., 2018; Couasnon et al., 2020; Camus et al., 2021), which implies that events are either conditioned to one driver or the other. Another approach is to select pairs of high values when both variables exceed individual high percentiles (e.g., 95th percentile; as in Bevacqua et al., 2019). However, extreme water levels might be driven by events not being extreme themselves. Impact-focused approaches, modeling the relationship between extreme water levels and underlying drivers, allow the selection of large-impact events whose drivers are not necessarily extreme (Bevacqua et al., 2017; Bermúdez et al., 2019; Santos et al., 2021). Most of these studies rely on modeled data products which generally capture compound flooding but contain biases, false positive, or missed extremes (Paprotny et al., 2020).

Climate change can affect flooding dynamics through SLR, changes in each of the flood drivers, and in the interaction processes between them. However, regarding compound flooding, climate change also impacts precipitation (as average temperatures increase, more evaporation occurs, which, in turn, increases overall precipitation) and therefore river flow. SLR has been shown to increase the future compound flood hazard (Moftakhari et al., 2017; Ganguli et al., 2020; Heinrich et al., 2023a). However, uncertainties due to internal climate variability and climate model differences dominate the large uncertainty in the concurrence of flood extremes in addition to changes in the drivers (e.g., storm surges or river discharge) themselves (Bevacqua et al., 2021). Large-scale sea level/rainfall-driven compound flooding potential is projected to increase globally by more than 25 % by 2100 under the RCP8.5 scenario compared to present times (Bevacqua et al., 2020b). The probability of compound flooding due to the co-occurrence of high sea level and precipitation is projected to robustly increase (40 %–80 %) by the end of the 21st century, particularly in northern Europe, e.g.,

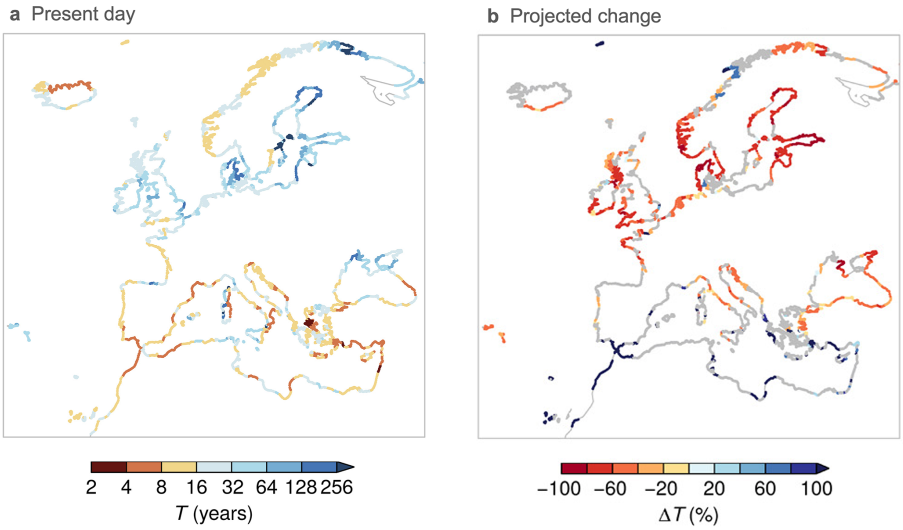

Figure 4. **(a)** Present-day (1980–2014) probability of potential compound flooding (CF). Return periods of CF (co-occurring sea level and precipitation extremes, i.e., larger than the individual 1-year return levels) based on ERA-Interim data. **(b)** Future probability of potential CF multi-model mean of projected change (%) of CF return periods between future (2070–2099) and present (1970–2004) climate (Bevacqua et al., 2019).

along the west coast of Great Britain, northern France, the east and south coast of the North Sea, but also along the coastlines of the eastern half of the Black Sea (Bevacqua et al., 2019; Fig. 4b). These results contrast with a predominant decrease in the compound flood hazard projected for northwestern Europe in the middle of the 21st century (Ganguli et al., 2020), which may be caused by the fact that the two studies considered different flooding drivers and multi-model ensembles.

In terms of pathways for the impact of compound flooding, elevated sea levels can block or slow down river drainage into the sea, leading to increased upstream water levels which can overflow river channels onto adjacent floodplains, thereby increasing inundation extent. Besides, floodwater can also erode riverbanks and cause breaking of the embankments, leading to further flooding. Hydrodynamic modeling is required to provide a detailed spatial mapping of water levels in estuaries or coastal river deltas. However, high-resolution hydrodynamical modeling, which includes the non-linear interaction between hydraulic processes, topography, and human interventions, is only feasible at a local scale.

In terms of receptors, historical information on past damaging floods reveals that compound events have occurred in many locations in Europe. According to the HANZE database (Paprotny et al., 2018), out of 1564 floods that occurred in 37 European countries between 1870 and 2016, 23 (i.e., 1.5 %) were identified to be compound floods recorded in six different countries (the Adriatic Sea, Italian regions of Veneto and Friuli–Venezia Giulia, the Mediterranean and the western coast of France, Ireland, UK, Belgium, and Poland). Specific examples of compound events include flooding in December 2000 in Brittany, France – 600 people were affected by a coastal flood that occurred due to the combination of heavy precipitation over several river catchments and a storm surge generated by an extra-tropical storm (Paprotny et al., 2018) – and a flood in December 1999 in Lymington, UK – the town was flooded due to tidal locking of the high runoff down the Lymington River by a large surge produced by the same storm system, with this flooding overwhelming recently upgraded defenses (Ruocco et al., 2011; Hendry et al., 2019).

4.3 Pathway for coastal flooding

Seawater tends to inundate normally dry land via three main pathways: (1) by still water simply overflowing where the water level exceeds the elevation of a natural (e.g., barrier beaches) or artificial (e.g., sea wall) barrier; (2) by waves overtopping a natural or artificial barrier; and (3) by breaching and lowering of a natural or artificial barrier, often as a consequence of prolonged overwashing or erosion at the frontal face of the barrier or by groundwater seepage (Fig. 3). Climate change, and other factors, can influence these pathways, altering local flood risk profiles. For example, SLR in regions with hard structures like barriers or dikes typically lead to a decline in the extent of natural habitats, such as salt marshes, mudflats, and sand dunes, which can act as a natural buffer to flooding (Hall et al., 2019). Decline in these natural features (and the deterioration of the flood protection infrastructure) can impact flood pathways and can increase flood hazard. In contrast, building new or maintaining and improving existing flood defenses or the application of artificial nourishment and stabilization of beaches can alter flood pathways and reduce flood risk along coasts and stabilize beaches and dunes (Haigh et al., 2022) or provide more space for water through managed re-alignment. With higher SLR, coastal flooding will progressively change due to changes in the pathway from overtopping to overflow, high-tide flooding, and ultimately permanent flooding (Ali et al., 2022).

It is increasingly recognized that natural systems that provide important buffering against floods are in decline across parts of Europe. For example, Campbell and Keddy (2022) identified a 136 (confidence interval 39–236) km^2 loss of the salt marsh extent from 2000 to 2019 across Europe. Other green adaptation options include the restoration of seagrass meadows (which reduce wave height and sediment erosion) and the creation of buffer zones (Wolff et al., 2023). With mean SLR accelerating over the coming century, and thereby increasing pressure on the narrow coastal zone, there is likely to be a continued decline in the extent of natural systems (often called coastal squeeze) that contributes to natural buffers reducing coastal flood risk, which will lead to defense capital and maintenance costs increasing dramatically (Haigh et al., 2022). This is corroborated by projections of shoreline retreat along most of the global shorelines induced by SLR (Vousdoukas et al., 2020; Sect. 5) and a consequent reduction in ecosystem services (Paprotny et al., 2021). There is also concern that raising existing coastal defenses, or building new ones, will come at the cost of further biodiversity losses (Bednar-Friedl et al., 2022).

Obviously, current flood risk around the coastline of Europe would be considerably higher without the decades of investment into extensive flood risk management infrastructure. Data on flood defenses over time are not well documented, but massive investments in defenses have occurred over the 20th century and early 21st century in Europe. For example, extensive flood defense infrastructure has been built in the Netherlands as part of the Delta Works, and standards of protection along stretches of the Dutch coastline now reach 1-in-10 000-year levels (Eijgenraam et al., 2014). Governing policy directives incorporate future SLR into the periodic risk assessments and defense strategy updates (Kothuis and Kok, 2017). Nearly a quarter of England's coast is now defended (Sayers et al., 2015). Around 20 movable storm surge barriers have been built around the coast of Europe since 1958, offering flood protection to millions of people and trillions of Euros of infrastructure (Mooyaart and Jonkman, 2017). This includes 6 surge barriers in Netherlands (e.g., Eastern Scheldt and Maeslant barriers; Fig. 5), 13 in the UK (e.g., Thames and Hull barriers), and 1 in Italy (the Mose barrier system for protecting the historical city of Venice and the lagoon settlements operating since October 2020), while a new surge barrier is being constructed in Belgium (Nieuwpoort). However, storm surge barriers can be used to mitigate the flood impact only in semi-enclosed coastal environments (such as bays, estuaries, and lagoons) but not along coasts facing the open sea. Extensive beach nourishment has also taken place in many European countries to counteract coastal erosion and flooding. For example, the Dutch coast is one of the most heavily nourished coasts globally (Brand et al., 2022); since 1990, more than 300 nourishment programs have taken place (including the notable Sand Engine project; Roest et al., 2021), adding an average of 12 million m^3 annually to the 432 km of Dutch coastline.

However, as sea levels continue to rise, it will become increasingly costly to maintain existing flood defenses and surge barriers and to carry out coastal nourishments. In the UK, Sayers et al. (2015) showed that length of coastal defenses "highly vulnerable" to failure would almost double (triple) under 0.5 m (2.5 m) mean SLR, with the number of properties affected rising by around 160 % (490 %). Furthermore, many of the existing storm surge barriers will need to be strongly upgraded or replaced over the coming century as the sea level rises. For example, plans are underway to replace the Thames Barrier in around 2070, with options including a new barrier built farther downstream of the current one (Environment Agency, 2021). The Eastern Scheldt Barrier (Fig. 5) was designed for only 40 cm SLR, implying that a revision is needed to avoid it to be closed too often with higher sea level (Haasnoot et al., 2020), with the consequence being that the availability of maintenance windows decreases too much.

4.4 Receptors of flooding

Regarding coastal flooding, the receptor is the entity (e.g., people, property, and environment) that may be harmed by the flooding and the corresponding social, economic, and environmental consequences. The consequences associated with coastal flood events can be broadly grouped into social (e.g., loss of life, number of people evacuated, damage to residential property, or loss of cultural heritage), economic (e.g., overall monetary cost; disruptions to ports, transport, energy, public services, and water systems; and agricultural production losses) and environmental (e.g., coastal erosion and degradation or losses of coastal habitats) impacts (Haigh et al., 2017). Importantly these consequences can be long-lasting (e.g., injury or long-term physical and mental health effects; Jackson and Devadason, 2019) and can also extend outside of the coastline area directly impacted by flooding (e.g., disruption to transport or supply chains; Dawson et al., 2016). As SLR and increases in storminess enhance flood risk and its consequences, the number of receptors in flood-prone areas will grow accordingly. Changes in land use and increasing asset values in floodplains can also increase the consequences of coastal flooding (Haigh et al., 2022). In contrast, improvements in flood forecasting, early warning, emergency response, and planning can greatly reduce the consequences of flooding (Sect. 4.5). Careful spatial planning and building codes can be effective at reducing risk. Evidence from Haigh et al. (2017) suggests that the number and consequences of coastal floods have declined since 1915 in the UK, reflecting better defenses and improvements

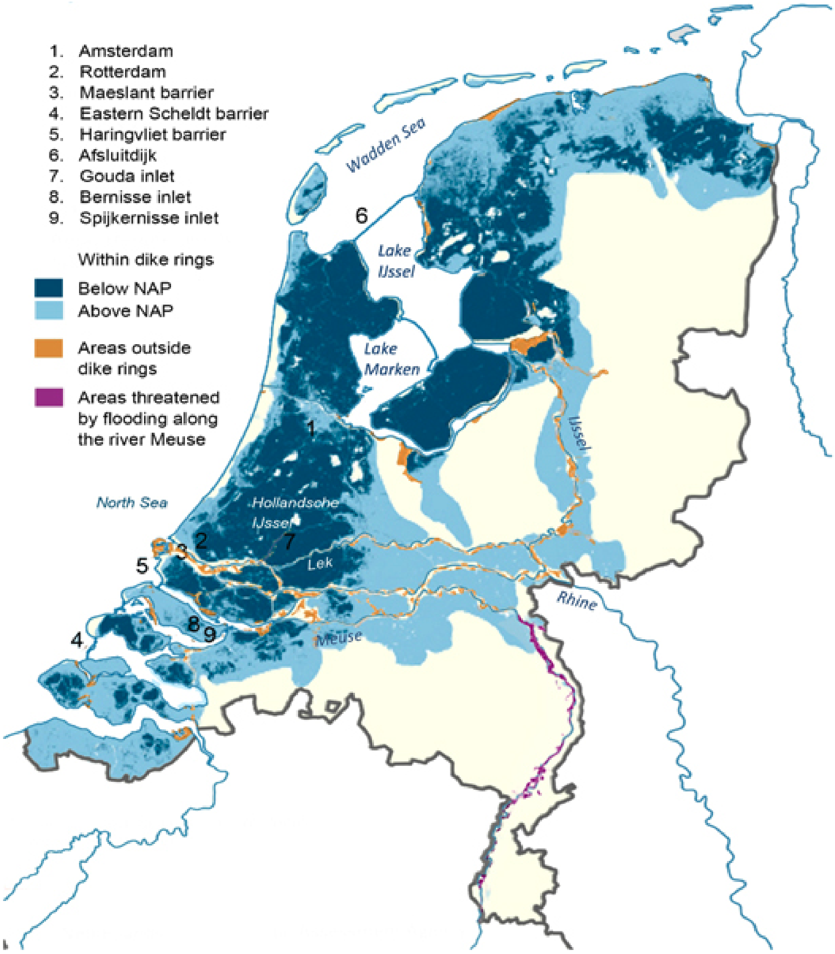

Figure 5. Map of the Netherlands showing flood-prone zones (blue shading) and features of the water management system. NAP is the Amsterdam Ordnance Datum which is the reference plane for sea level height in the Netherlands. Extracted from Haasnoot et al. (2020).

in flood forecasting, warning, emergency response, and planning (Haigh et al., 2022). As a concrete example, more than 2000 lives were lost around the coastlines of the North Sea during the flood of 1953; however, similar conditions occurring in December 2013 hardly had any societal impact, which can be attributed to these improvements and infrastructure investments (Wadey et al., 2015).

Paprotny et al. (2019) estimated present and future flood extents under different assumptions for coastal protection, which is a known source of uncertainty (Hinkel et al., 2021). Without considering any protection, the flooded area from the 100-year event is showing a discernible increase only towards the end of the century (6 %–10 % in average for Europe, depending on the emissions scenario; Fig. 6), and the effects of SLR are mainly demonstrated as higher flood depths. But after including coastal protection in the simulations, the flooded area is projected to increase by 10 %–15 % in 2050, depending on the emissions scenario, and by 12 %–20 % by the end of the century; for the size of the area of flooding in kilometers squared, see Table 4 in Paprotny et al. (2019) for more details. For more rare events, like a 1000-year event, SLR will drive a 48 %–67 % increase in the flood extent by the year 2100 (Paprotny et al., 2019). The country level flood extents depend on different factors, such as the exposure to extreme weather conditions, the protection standards in place, as well as the country's size and the percentage of low-lying coastal areas. For the baseline, the UK and Norway have the largest flood extent area, exceeding 4500 km^2 for the 100-year event for each country. This is a result of their long coastlines exposed to intense weather conditions. Denmark and Germany follow with values around 3000 km^2, and for these cases, the main driver is the flat and low-lying configuration of the coastal zones. Other countries with flood extents slightly below 2000 km^2 are Greece and Italy, both characterized by long coastlines.

It is noteworthy that also low-flood-level events (i.e., nuisance flooding; Moftakhari et al., 2018) may have high impacts from the disruption of everyday routine activities and property damages, especially in lowland settlements. SLR is expected to increase not only the frequency of ECWLs but

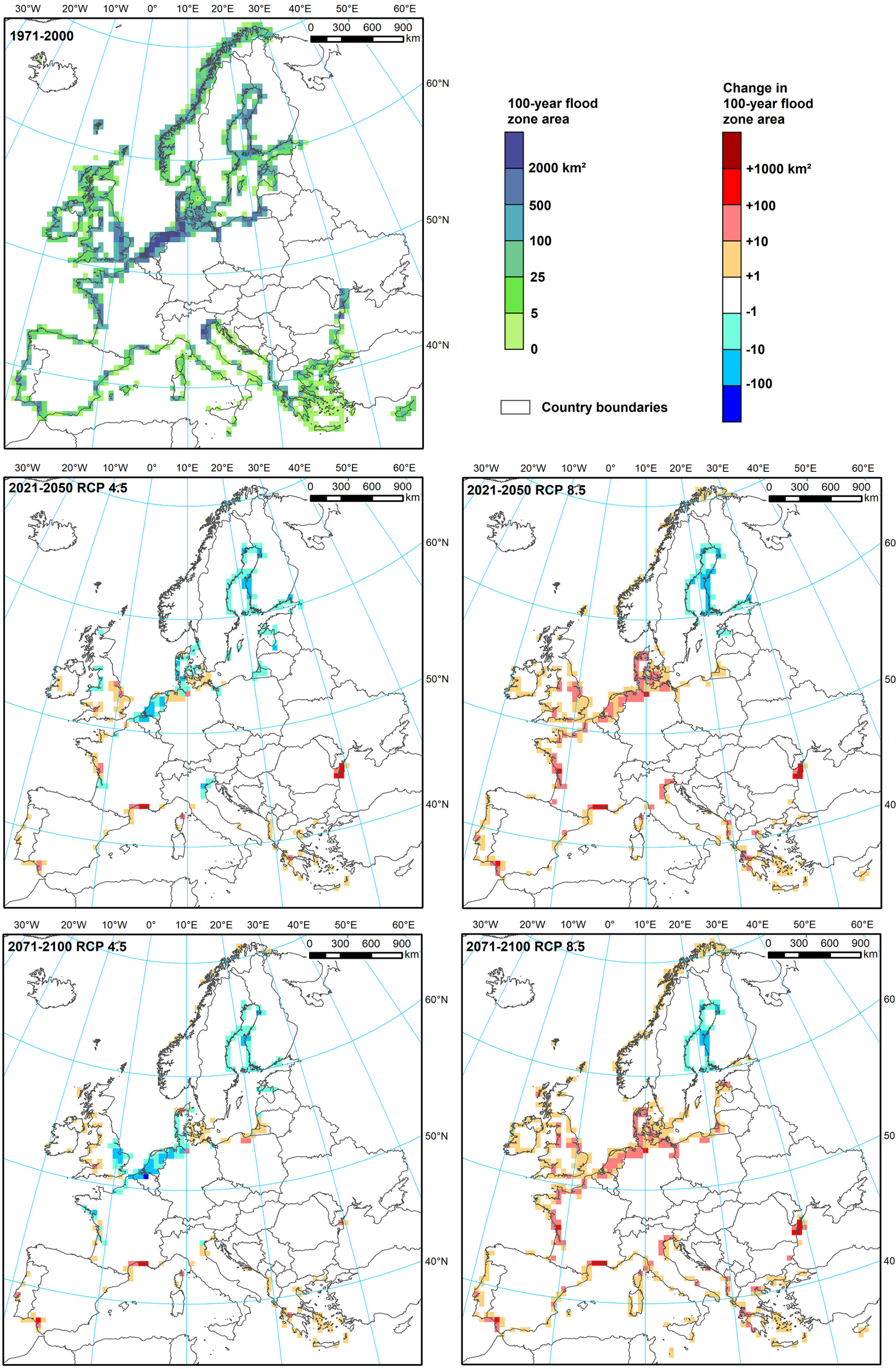

Figure 6. Indication of the current area vulnerable for flooding with a return period of once in 100 years and for two different time slices under two different climate scenarios. Data are from Paprotny et al. (2018).

also the frequency of low-level floods, when the astronomic tide will become a major driver of flood events (Ferrarin et al., 2022). Towards the end of the century, SLR will also result in permanent flooding of certain areas. For example, in the Balearic Islands, and by the year 2100, 7.8–27.7 km^2 and up to 10.9–36.5 km^2 will be permanently lost to SLR under RCP4.5 and RCP8.5 emission scenarios, respectively (Luque et al., 2021).

Pan-European assessments of future coastal flood risk show general trends and allow for regional comparisons but also come with large uncertainty due to data scarcity and non-stationary conditions (Hinkel et al., 2021; Vousdoukas et al., 2018b) and cannot replace local studies (Paprotny et al., 2019). For example, flood assessment results are very sensitive to the coastal protection standards assumed which are largely unknown along most of the European coastline (Scussolini et al., 2016). Another crucial factor is the digital elevation data. Since several countries lack high-resolution lidar data, many assessments are based on less accurate global datasets, which come with vertical biases exceeding the extent of anticipated SLR (Bove et al., 2020; Kulp and Strauss, 2018; Yamazaki et al., 2017). Despite these limitations, all known flood risk assessments highlight an increase in the flooded area during the century, which also accelerates as SLR gathers pace.

4.5 Initiatives to develop flood-related climate services in Europe

The EU Adaptation Strategy emphasizes the significance of climate services in adapting to climate change. As defined by the Global Framework for Climate Services (Hewitt et al., 2012) of the World Meteorological Organization (WMO), "Climate services provide climate information to help individuals and organizations make climate smart decisions". According to the European Commission's Roadmap for Climate Services (European Commission, 2015) definition, climate services cover

> the transformation of climate-related data – together with other relevant information – into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counseling on best practices development and evaluation of solutions and any other services in relation to climate that may be used for the society at large. (Galluccio et al., 2024)

Information on past and future sea level change close to the coastline is being made available but still suffers from various limitations (e.g., resolution, incomplete physics in models, and scarcity of observations). In parallel, core European services have been put in place. Yet, authoritative, consistent, and decision-oriented climate services to support policies and decision-making with SLR are still in their early development worldwide.

The European Union's Earth observation program (Copernicus) monitors our planet and its environment for the ultimate benefit of society. This includes the monitoring of sea level changes and the provision of ancillary fields needed to assess coastal SLR risks, as well as the transformation of the wealth of satellite, in situ, and integrated numerical model information into added-value datasets and information usable by scientists, managers, decision-makers, and the wider public to guide adaptation and to support related policies and directives (Melet et al., 2021).

New initiatives in the framework of dedicated European research projects in the Horizon Europe program are also underway, for instance, the Coastal Climate Core Services (CoCliCo) project. CoCliCo aims to deliver an open web platform that will provide up-to-date information on present and future SLR and its impacts to support decision-making on coastal flood risk management and adaptation. The platform will grant access to the latest and consistent hindcasts and projections of sea level, process-based coastal flood maps and shoreline change estimates, flood exposure, and vulnerability information, as well as adaptation strategies and options. Users of the platform will be able to visualize, download, and analyze high-quality geospatial information layers encompassing multiple decision-oriented coastal risk scenarios. For shorter timescales, early-warning systems (EWSs) are integrated systems allowing a real-time monitoring of potential natural hazards, issuing natural hazard warnings with a few days of lead time. Informing the relevant stakeholders (e.g., civil protection agencies, regional and local authorities, and environmental agencies) is part of an integrated risk management procedure to mitigate risks. EWSs can play a critical role in classical disaster risk management cycles, supporting the preparedness and response phases, including the deployment of emergency measures for rapid response after a disaster, as well as longer-term damage assessment after the occurrence of an event. EWSs are an efficient adaptation measure by providing more than a 10-fold return on investment (Global Commission on Adaptation, 2019). The H2020 European Copernicus Coastal Flood Awareness System (ECFAS) project aims at contributing to the evolution of the Copernicus Emergency Management Service (CEMS) by demonstrating the technical and operational feasibility of a European coastal flood awareness system. Such a system will complement the existing early-warning system of the CEMS for river/pluvial floods, CEMS–EFAS (European Flood Awareness System), by adding a pan-European marine coastal flood awareness system and by tackling coastal resilience to climate risk (marine storminess and exposure). ECFAS provides an integrated risk cycle monitoring and management service from water level forecasts at the coast with a 5 d lead time (Irazoqui Apecechea et al., 2023) and rapid mapping of coastal floods and impacts on population and assets (Le Gal et al., 2022) to Risk and Recovery Mapping (RRM) for adding coast-targeted products in the aftermath of a marine flood event (e.g., shoreline displacement and maps of flooding and damages). At a national scale, the Norwegian mapping authority developed a web tool for inundation mapping, showing extreme still water levels and the projected sea level, including statistics on the areas, roads, and buildings affected now and in the future (Breili et al., 2020; https://www.kartverket.no/en/at-sea/se-havniva/se-havniva-i-kart, last access: 14 July 2024). The web tool includes statistics on the areas, roads, and buildings affected now and in the future. The German Sea Level Monitor (https://meeresspiegel-monitor.de/index.php.en, last access: 14 July 2024) provides observed and projected changes at tide gauges along the German North Sea and Baltic Sea coast.

5 Coastal erosion

5.1 Definition and drivers of coastal erosion

Coastal erosion is the permanent loss of land to the sea. The coastal zone hosts a wide variety of systems, like estuaries, lagoons, barrier islands, sandy and gravel beaches, dunes, cliffs, rocky shores, and built areas. The morphological changes in each of the above environments can take place at different timescales and are driven by a wide range of natural and anthropogenic factors (Mentaschi et al., 2018). Sandy beaches are the most common beach typology (Davenport and Davenport, 2006), occupying 31 % of the ice-free global coastline (Luijendijk et al., 2018). They are also particularly prone to erosion (EUROSION, 2004), especially given the fact that human development has deprived coastal systems from their natural capacity to accommodate, or recover from, erosion (Small and Nicholls, 2003). In addition, human interventions and dams tend to prevent terrestrial sediments from reaching the coastline, which favors coastal erosion (Milliman, 1997). As a result of the above, Europe's beaches have been eroding (EUROSION, 2004; Masselink et al., 2022), a trend which is projected to accelerate with climate change and SLR (Vousdoukas et al., 2020).

One of the consequences of erosion is shoreline change, which is the combined result of numerous factors, such as wind and wave climates, terrestrial sediment supply, geological control, and human interventions, among others. There is a clear cause-and-effect relationship between increasing sea levels and shoreline retreat (Bruun, 1962), which justifies the eroding trend reported by large-scale (Hinkel et al., 2013; Vousdoukas et al., 2020), regional (Toimil et al., 2017; Alvarez-Cuesta et al., 2021), or local-scale studies (Alvarez-Cuesta et al., 2021; Toimil et al., 2021; de Santiago et al., 2021; Luque et al., 2021; Romagnoli et al., 2022). Negative sediment budgets can be another factor driving a robust erosion trend, especially at sandy beaches (López-Olmedilla et al., 2022). The former can be the result of several potential natural or anthropogenic factors. In addition, several of the observed changes can relate to quasi-periodical climatic patterns affecting the wave regime (e.g., Barnard et al., 2015).

Apart from major drivers like the ones mentioned above, beach erosion and accretion often depend on a delicate balance of contrasting forces with very similar amplitudes and are therefore very difficult to predict. This applies to all scales; i.e., each wave can transport sand both towards and away from the coast (Vousdoukas et al., 2014), while storms drive erosion that can be followed by complete or partial recovery (e.g., Kroon et al., 2008; Lee et al., 1999). Moreover, the impact of extreme storm events is very much controlled by the initial beach morphological state and thus by meso- to macroscale processes (e.g., Qi et al., 2010; Vousdoukas et al., 2012). In this section, the source, pathway, and receptor are discussed for coastal erosion in Sect. 5.2. Monitoring methods, including field surveys, video monitoring, and Earth observation, are discussed in Sect. 5.3. Historical shoreline changes in Europe are summarized in Sect. 5.4, while projected shoreline changes are summarized in Sect. 5.5. Finally, interactions between coastal erosion and coastal flooding are addressed in Sect. 5.6.

5.2 SPR for coastal erosion

5.2.1 Source for erosion

Coastal erosion shares the same sources as coastal flooding; e.g., all of the components that drive ECWLs (tides, storm surges, waves, and SLR) can drive coastal erosion (Fig. 7). In addition, given that coastal erosion is strongly related to the sediment budget, sediment sources and sinks are very important. As a result, human development and dams play an important role as they tend to prevent terrestrial sediments from reaching the coastline, thus favoring coastal erosion (Anthony et al., 2019; Milliman, 1997; Meli and Romagnoli, 2022). Other natural factors which can deplete sediment from the subaerial beach are the occurrence of submerged canyons or rocky scarps in the nearshore that can act as natural barriers to onshore sediment transport (Bosserelle et al., 2021; Vousdoukas et al., 2009).

5.2.2 Pathway for erosion

Sandy beach erosion takes place when the sediment budget of a given area becomes negative. Understanding coastal change is a very challenging task since erosion or accretion is a result of multiple factors like (i) processes that take place in various temporal and spatial scales (Kroon et al., 2008; Larson and Kraus, 1994); (ii) the presence of various features which emerge through complex self-organization processes often linking different scales and processes (Murray et al., 2009; Werner, 1999); (iii) the intrinsic uncertainty in predicting the intensity and frequency of extreme events, as well as the related beach morphological response (Coco et al., 2014; Vousdoukas et al., 2012); and (iv) the high complexity of long-term processes like sediment transport and vertical

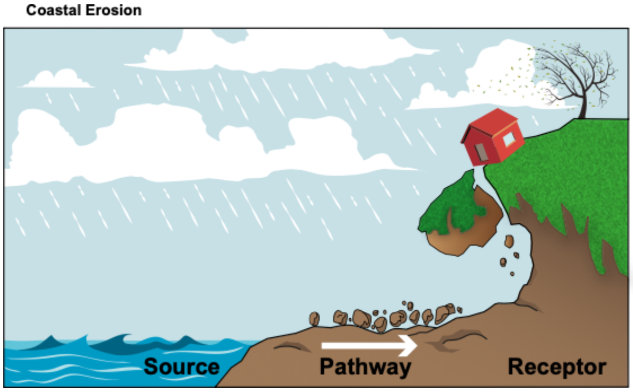

Figure 7. Source, pathway, and receptor framework for coastal erosion.

land motion, which are also interconnected with, among others, geological and meteorological phenomena (Gallop et al., 2011; Vousdoukas et al., 2007), as well as human interventions which are increasing in number and extent (Luijendijk et al., 2018; Mentaschi et al., 2018). In principle, coastal erosion can be the result of any process that alters the sediment transport patterns. This can be hydrodynamic (changes in wave intensity or direction, sea level, etc.) (Sierra and Casas-Prat, 2014), related to the presence of obstacles like hard structures (Loureiro et al., 2012; Noble, 1978), or factors that affect the erodibility of the coast (Feagin et al., 2019).

5.2.3 Receptor and consequences for erosion

Coastal erosion is the process by which the land is worn away and is permanently submerged in water and can take many forms, such as the loss of sand dunes, cliffs, or beaches and can have several consequences. Among them are the destruction of buildings, roads, and other infrastructure located near the coast.

Moreover, coastal erosion can have significant impacts on the environment, economy, and human health and safety as it can lead to habitat loss for coastal species, reduce the recreational value of beaches, and increase the risk of flooding and storm damage for coastal communities.

5.3 Monitoring methods for coastal erosion

Coastal monitoring is crucial to gaining a better understanding of the likely impacts of climate change at the coast. While the long-term implications of SLR have received considerable attention, Nicholls et al. (2007) point out that more attention needs to be given to finer temporal and spatial scales, including the localized impacts of potential changes in wave climate and storminess regimes. However, monitoring the coast at higher temporal (daily to decadal) and spatial (three-dimensional) resolutions presents many challenges. Conventional survey techniques for ongoing beach surveys are both costly and labor-intensive, and meaningful trends typically require several years of data to emerge (Short and Trembanis, 2004). Currently, only half a dozen multi-decadal, high-resolution coastal monitoring programs are in operation worldwide, with few examples in Europe, including Truc Vert (France) since 2005, the Emilia–Romagna coast (Italy) since 1983, and Noordwijk (the Netherlands) since 1964.

The various monitoring methods for coastal erosion are described briefly in Table 1, highlighting the evolution from traditional to present-day monitoring techniques.

5.4 Historical shoreline change

A comprehensive European study of coastal erosion collected and analyzed aerial photographs and local surveys up to 2002 to estimate coastal erosion at the scale of Europe (EUROSION, 2004). About 20 % of the European Union's coastline suffered serious erosion impacts, with the area lost or seriously impacted estimated at $15\,\mathrm{km}^2\,\mathrm{yr}^{-1}$. More recent studies at the continental to global scale confirmed that large stretches of the European coast are suffering from erosion. Using freely available optical satellite images captured since 1984, in conjunction with machine learning and image analysis methods, the shoreline changes have been mapped at a global scale (Luijendijk et al., 2018; Mentaschi et al., 2018). The application of an automated shoreline detection method to the sandy shorelines resulted in a global dataset of shoreline change rates for the 33-year period between 1984–2016 (Luijendijk et al., 2018). Analysis on satellite-derived sandy beach detection reveals that about 35 % of the European coastline is sandy, which agrees largely with the 40 % EUROSION estimate (EUROSION, 2004). Analysis of the satellite-derived shoreline data indicates that 22 % of the European sandy beaches are eroding at rates exceeding $0.5\,\mathrm{m\,yr}^{-1}$, while 26 % are accreting and 52 % are stable. This means that in Europe a total of more than 8200 km of sandy beaches have significantly retreated over the last decades. Areas that experience severe erosion (and accretion) are found at various locations across Europe (see Fig. 8). About 4 % of the European sandy beaches experience erosion rates classified as severe ($> 3\,\mathrm{m\,yr}^{-1}$). Erosion rates exceed $5\,\mathrm{m\,yr}^{-1}$ along 2 % of the sandy shoreline. The statistics of Europe are rather similar to the global statistics stating that 24 % (28 %) of the world's beaches are eroding (accreting) (Luijendijk et al., 2018). It is important to highlight that several of the accreting or stabilizing trends found in Europe are due to human interventions, either through beach hardening or nourishment projects (Lansu et al., 2024).

5.5 Future shoreline change

Mediterranean beaches are more susceptible to the negative effects of SLR because they are narrower as a consequence of the lower tidal range and milder wave climate. This is highlighted by both large-scale (Vousdoukas et al., 2020) and regional-scale projections (Monioudi et al., 2017). For

Table 1. Summary of the methods for monitoring coastal erosion.

Type of method	Brief description of the method
Field surveys	GPS surveys have proven to be a successful method for beach topographical profiling on sandy coasts (Harley et al., 2011; Hansen and Barnard, 2010). Marine drones such as autonomous surface vehicles (ASVs) are usefully applied for monitoring the nearshore in shallow water and for testing the effects of mitigation strategies against erosion (Stanghellini et al., 2022). Both techniques are commonly used for monitoring morphological changes in the short term and involve repeating measurements at regular intervals to understand the physical aspects of coastal environments, including daily, monthly, and annual variations in specific parameters (Komar, 1998; Short, 1999). Spatial scales of such surveys are typically from hundreds of meters to several kilometers.
Video monitoring	Coastal video monitoring systems (e.g., Holman and Stanley, 2007; Stringari and Power, 2022) are ideal for long-term deployments (i.e., years) acquiring data continuously and covering a few kilometers of coastline. Images are processed to generate the system's "basic products", namely time-averaged, variance, snapshot, and time stack images, which are all projected in geographic coordinates using standard photogrammetric techniques. Then, a set of post-processing tools allows extracting quantitative information on various coastal processes at various temporal and spatial scales, such as beach face/shoreline morphology, inner bar configuration, rip-/longshore current systems, and wave runup. Moreover, they have been proved to be useful coastal management tools, supporting sustainable and safe recreational beach use (Jiménez et al., 2007).
Drones	For the past 10 years, drones or small unpiloted aerial vehicles (e.g., Vousdoukas et al., 2011) have been used more frequently for coastal monitoring (Chapapría et al., 2022). These unpiloted aerial vehicles are equipped with cameras and other sensors that allow researchers to collect high-resolution images and data over kilometers of the coastline. This technology offers several advantages over traditional methods of monitoring. Drones can cover a larger area than ground-based surveys and provide more detailed images than satellite imagery. Additionally, drones can be deployed quickly and easily, making them ideal for collecting data in remote or hard-to-reach areas. Such unpiloted vehicles can be also terrestrial (Didier et al., 2015) or floating (Stanghellini et al., 2022), collecting information in an autonomous manner.
Terrestrial 3D laser scanning	Terrestrial 3D laser scanning (TLS) or terrestrial lidar has increasingly become the method of choice for beach surveying (e.g., Pietro et al., 2008). Portable scanners allow the completion of beach surveys in excess of hundreds of meters, with sub-centimeter spatial resolution, during the course of a few hours. These advances provide a reliable means of addressing geomorphic relationships, as well as along- and cross-shore changes on the beach, while the accuracy and spatial resolution is practically impossible with traditional GPS surveys. The technique has been very recently introduced in coastal research and has several unexploited possibilities.
Earth observation from space	In recent years, a new source of geospatial data for studies from the regional to planetary scale is provided by Earth observation satellites generating an ever increasing flow of raster image data. An exponential increase in the availability of free geospatial data has recently emerged with the Copernicus Earth observation and monitoring program of the European Union that delivers satellite imagery complemented by in situ observations (Malenovský et al., 2012). The positional accuracy of satellite-derived shorelines (SDSs) based on single images has been evaluated to range between 1.6 and 10 m (e.g., Liu et al., 2017). The increasing availability, resolution, and spatial coverage of satellite imagery in recent years now provide a powerful alternative to derive reliable global-scale shoreline data.

example, a recent study in the Balearic Islands projects at least 20 % of the islands' beaches losing more than 50 % of their surface by the end of the century, even if greenhouse gas emissions are mitigated (Luque et al., 2021). But even projections along the Atlantic coast report shoreline retreat, e.g., in the range of 10–45 m under the middle-of-the-road (RCP4.5) scenario and 14–66 m under the very high-emission (RCP8.5) scenario by the year 2100 for 150 km of Basque coast (de Santiago et al., 2021). A recent pan-European study projects a mean SLR-driven median shoreline retreat of 97 m (54 m) under RCP8.5 (respectively, under RCP4.5) by the year 2100. This retreat translates to 2500 km^2 (1400 km^2) of SLR-driven coastal land loss (Athanasiou et al., 2020; Fig. 9). Given the complexity of coastal morphodynamics, projections of shoreline changes come with high uncertainties. The future variability in wave forcing is more prominent until 2060 with regard to uncertainties, whereas after that year the uncertainties in predicting sea

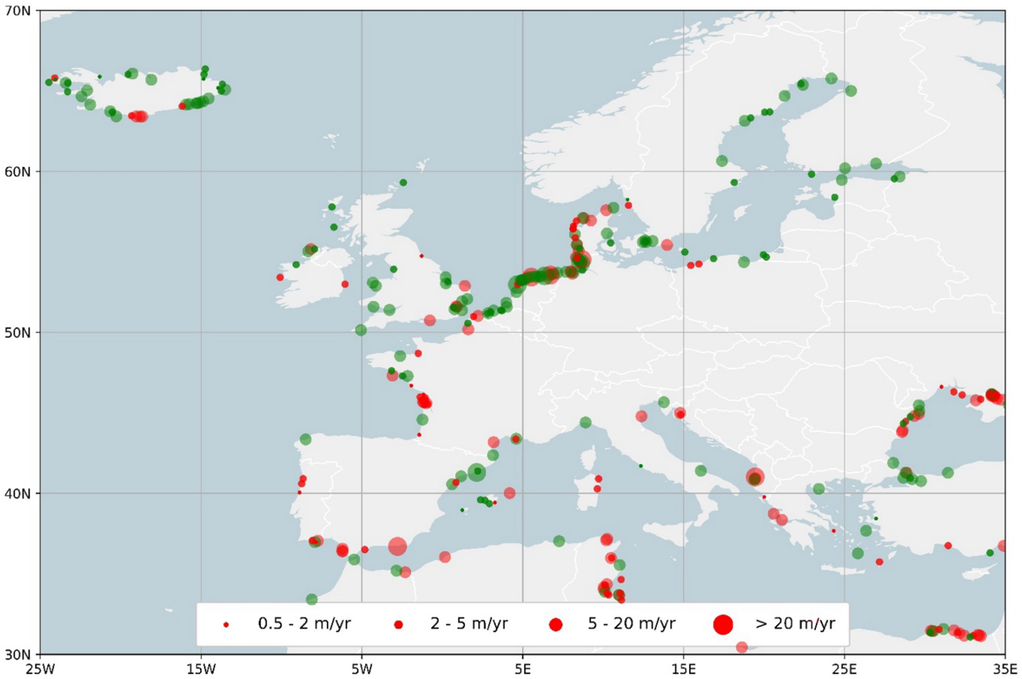

Figure 8. Hotspots of long-term shoreline changes in the European beaches since 1984; the red (green) circles indicate erosion (accretion) for the four relevant shoreline dynamic classifications (see the legend; data are based on Luijendijk et al., 2018).

level rise become dominant (D'Anna et al., 2021, 2022). Of similar amplitude is also the uncertainty associated with the choice of geophysical datasets in continental-scale assessments (Athanasiou et al., 2020), reaching 45 % (26 %) of the variance in coastal land loss projections for Europe by 2050 (2100). Among the major sources of uncertainty is the geological control that can be expressed through the coastal slope (Thiéblemont et al., 2019) or through the presence of hard impermeable structures that can limit shoreline retreat to values that are substantially lower than the projected ones (e.g., Lansu et al., 2024). Even if certain future erosion risk assessments take such effects into account, by considering the spatial distribution of hard surfaces near the coast (e.g., Paprotny et al., 2021; Vousdoukas et al., 2022), this information is only available for the present, and future trends of coastal squeeze are difficult to predict (Silva et al., 2020).

5.6 Coastal erosion and flooding interactions

Coastal erosion and flooding are extremely interrelated impacts that influence each other (Sallenger, 2000; Pollard et al., 2019; Leaman et al., 2021). Erosion is a physical phenomenon through which sand is removed from the shoreface and deposited elsewhere, usually offshore. Erosion and deposition processes can change the shoreface, which affects coastal flooding caused by high water levels. In turn, these high water levels can cause further erosion or deposition. This feedback manifests itself on different timescales. In the short term, coastal morphology plays a significant role in wave energy dissipation, the total water levels reaching the coast, dune breaching, and subsequent flooding. SLR is expected to increase the frequency of episodic erosion and flooding, which in turn could be altered by changes in storminess. At longer timescales, SLR is expected to drive permanent erosion and inundation (Nicholls and Cazenave, 2010; Cazenave and Le Cozannet, 2014). This effect could be compensated or enhanced in areas with intense alongshore gradients in longshore sediment transport or chronic fluvial sediment supply. Higher water levels cause wave-driven erosion to occur higher up in the profile, resulting in net erosion and deposition on the nearshore bottom (Bruun, 1962). Additionally, deeper water reduces wave refraction and allows waves to get closer to the shore before breaking (Arns et al., 2017; Chaigneau et al., 2023), leading to increased flooding. A coastline subject to sustained erosion over time may lead to the loss of natural flood defenses (Toimil et al., 2023a, b).

The need for the joint modeling of flooding and erosion has long been recognized in the literature (Bilskie et al., 2014; Passeri et al., 2015a; Lentz et al., 2016). However, most studies to date continue to analyze these two impacts separately because of the complex relationship between driving processes and morphological response (Pollard et al., 2019; Toimil et al., 2020, 2023a). Amongst the studies that couple flooding and erosion, most of them have typically focused on historical events without considering climate change (McCall et al., 2010; Gharagozlou et al., 2020; Van Ormondt et al., 2020). These studies have primarily been conducted at the storm scale and have used

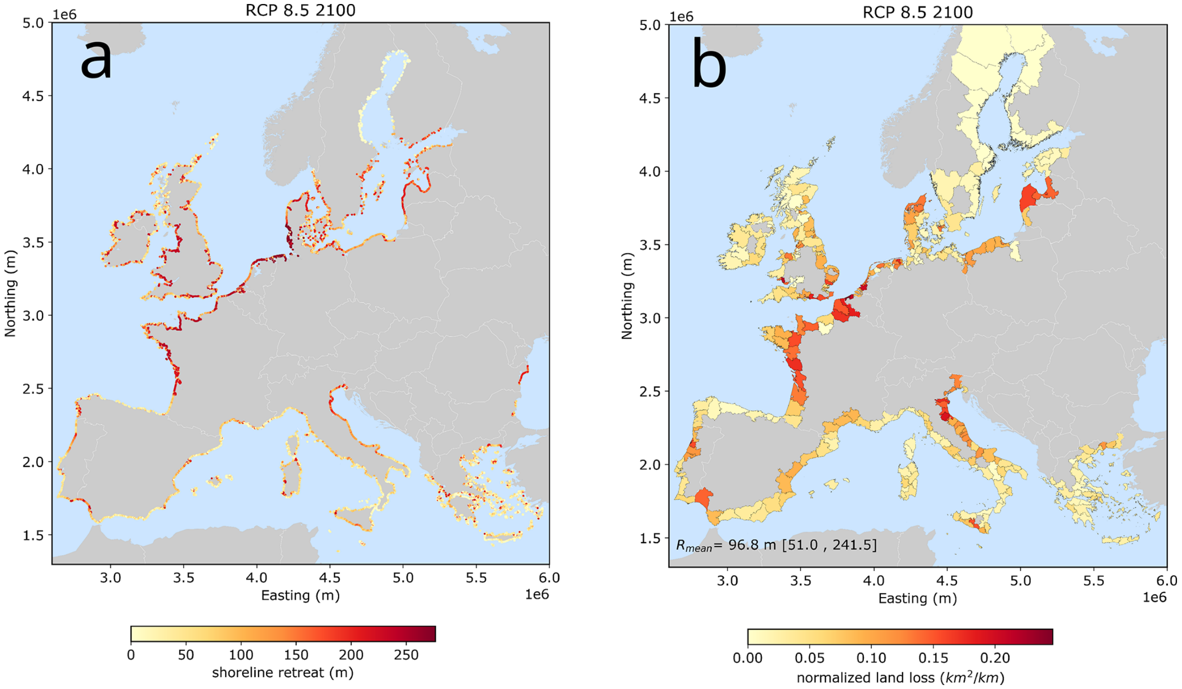

Figure 9. Projections of shoreline retreat (in m) **(a)** and land loss (in km^2) per kilometer of coastline **(b)** for Europe in the year 2100 under a very high-emission scenario (RCP8.5) (from Athanasiou et al., 2020).

pre- and post-storm topo-bathymetry data to simulate erosion and breaching using a hydro-morphodynamic model. Following the same modeling approach but in the context of climate change, some studies have incorporated the effect of SLR on hydrodynamic forcing conditions (Passeri et al., 2018; Grases et al., 2020). Sanuy and Jiménez (2021) presented a more recent application in the Tordera Delta (Spain) where the baseline topo-bathymetry was modified to consider medium-term erosion.

Studies that consider long-term shoreline changes in flooding follow more diverse approaches. Stripling et al. (2017) delivered flood maps considering long-term changes in seawall toe levels along the west coast of Calabria (Italy) and in an idealized coastal stretch around Holderness (UK). As for climate change studies, Dawson et al. (2009) developed a methodology to account for shoreline changes in coastal flood projections along the East Anglian coast (UK). Dawson et al. (2009) linked coastal flooding due to storms and SLR with long-term erosion by adjusting the likelihood of flood defense structure failure based on shoreline changes. Other studies have examined the effect of shoreline changes on coastal flooding considering an empiric (Grilli et al., 2017) and surveyed profile translation due to SLR (Barnard et al., 2019) and also due to SLR and changes in the sediment budget (Passeri et al., 2015b, 2016). Also using real profiles, Toimil et al. (2023a) proposed a suite of numerical and statistical models to analyze the influence of storm morphodynamics, SLR, erosion, and longshore sediment transport on total water levels and coastal flooding along a 40 km coastal stretch in the Spanish Mediterranean.

Current studies highlight the need to consider the interconnections between hydrodynamics and morphodynamics to better understand the functioning of the coastal system. Changes in topographic representations can alter the path and pattern of maximum water levels (Bilskie et al., 2014). Toimil et al. (2023a) found that total water levels are mainly affected by storm erosion and profile geometry and that long-term erosion is the main shoreline change contributor to the flooded area.

To date, existing research in the EU focuses on the eastern Mediterranean and North Sea basins. In the eastern Mediterranean, studies encompass a wider range of coastal typologies than in the North Sea, including cliffs, deltas, and beaches with varying levels of anthropization. Most studies model the interaction of medium- and long-term coastal changes with episodic flooding, but few additionally consider storm erosion as a flood enhancer (Toimil et al., 2023a, b). This can be particularly important for extreme weather events of high return periods, regardless of the type of coastline. The largest gap lies in studies that combine the interaction of hydro-morphological processes under climate change scenarios, as such studies are very limited in both basins. However, knowledge on the potential effects of these interconnections and the enhancing role of SLR is key information for decision-makers to make informed decisions about the future management of coastal communities.

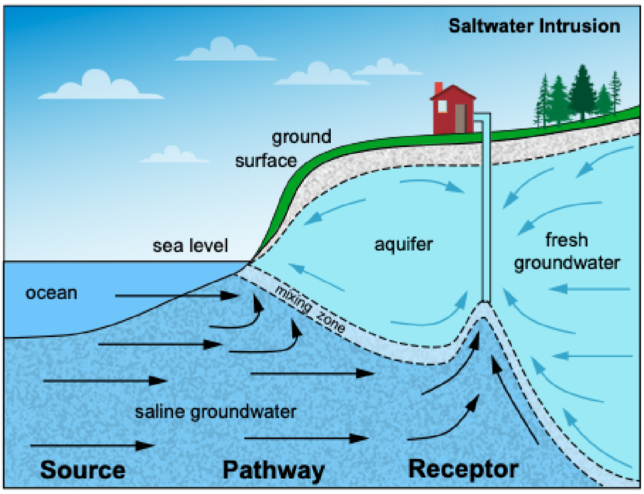

Figure 10. A visualization of the source, pathway, and receptor framing for saltwater impacts.

6 Saltwater intrusion

6.1 Processes and monitoring of saltwater intrusion

Saltwater intrusion (SWI) represents the increased extent of the mixing zone between inland freshwater and saltwater (source), therefore increasing the salt content both in surface waters and in groundwaters (pathway). SWI can hinder the use of water for agriculture due to salt damage to crops (e.g., Maas and Hoffman, 1977), for ecology in freshwater wetlands (Herbert et al., 2015), and can threaten coastal communities that rely on freshwater supplies for their livelihood (receptor) (e.g., drinking water that is too salty can lead to cardiovascular diseases; He and MacGregor, 2011; see Fig. 10).

Rivers and aquifers (good permeable water-bearing porous media) contaminated by high salinity decrease freshwater storage and water quality, reduce soil fertility (e.g., Qadir et al., 2014; Russ et al., 2020), impact on vegetation and freshwater species (Wicke et al., 2011), and affect human health. Moreover, in deltaic regions, SWI can also negatively impact ecosystem services and aquaculture activities such as clam or shrimp farming (e.g., Dierberg and Kiattisimkul, 1996; Hou et al., 2022) (Fig. 11). SWI is a slow but increasingly present hazard affecting European coasts, especially in deltas, islands, and estuaries. In these low-elevation coastal zones, climatic changes (including sea level rise) combine with the changes induced by human activities such as reducing river flows causing salt wedge shifts (Maselli and Trincardi, 2013). Figure 11b shows several processes causing problems induced by SWI such as extracting groundwater, creating controlled low-lying areas (polders), and reducing in urbanized area freshwater depletion into the groundwater systems (sealing). As a result of climate change (and associated SLR) and human-induced activities, impacts of SWI are likely to increase (e.g., Befus et al., 2020; Oude Essink et al., 2010; Zamrsky et al., 2024). In this section, we discuss the main impacts of SWI, again using the source (Sect. 6.2), pathway (Sect. 6.3), and receptor/consequence (Sect. 6.4) framework.

The scarcity of data often poses a challenge for the sustainable management of groundwater resources worldwide. Mapping and monitoring the spatial extent of near-coastal fresh groundwater resources usually requires detailed information for large coastal regions, which is often not available, whereas in situ measurements are time- and labor-consuming. To address this challenge, remotely sensed data can be a cost-effective way to gather both surface and groundwater information, covering a large area in a short period. For instance, airborne electromagnetic geophysical methods are particularly useful for detecting groundwater salinity affecting the conductivity of the groundwater. Such methods have been executed in Denmark (Duque et al., 2022), Germany (Siemon et al., 2015), and the Netherlands (Delsman et al., 2018).

6.2 Source of saltwater intrusion

Surface SWI threatens water resourcing and freshwater availability, especially in low-lying coastal areas such as deltas and estuaries (van Engelen et al., 2022), which are characterized by natural complex interactions between fresh and saline waters (Horner-Devine et al., 2015; Valle-Levinson, 2010). The inland intrusion of saline waters along the river courses is controlled by the forces acting at both the river and the sea domains, namely the advective dispersion associated with the river flow, the steady shear dispersion associated with the estuarine exchange flow, and the tidal pumping (Lerczak et al., 2006). The balance among these forces is regulated mostly by the combined action of river discharge and sea level oscillations (Bellafiore et al., 2021). Surface heat fluxes (evaporation) and the salt content in corresponding seawater also play a role in determining the extent of surface SWI. Therefore, while more evident in drought conditions (e.g., the extended 2022 drought in the Po Valley – Italy; Bonaldo et al., 2023), the processes regulating SWI and the concurring effects cannot be attributed just to one single driver. Moreover, these natural drivers can act both on short timescales, as tidal fluctuations, storm surges, and hurricanes, and at the long timescales, as climatic ,fluctuations, subsidence. and, among others, SLR. In general, the variation in surface SWI does not only affect the extension of the affected area but also can lead to the predominance of some hydrodynamic processes, for example, shifting the system from a diffusive- to an advective-dominated river dynamics (e.g., the Po river). Also, a modification of the environmental conditions in transitional areas can vary the extent of eury-, poly-, meso-, and oligohaline areas (Rodrigues et al., 2019). The concurring processes affecting surface SWI are linked to progressive river discharge decrease, increased surface heat fluxes (evaporation), and increase in the salt content and in the relative sea level. In Europe, several estuarine and deltaic

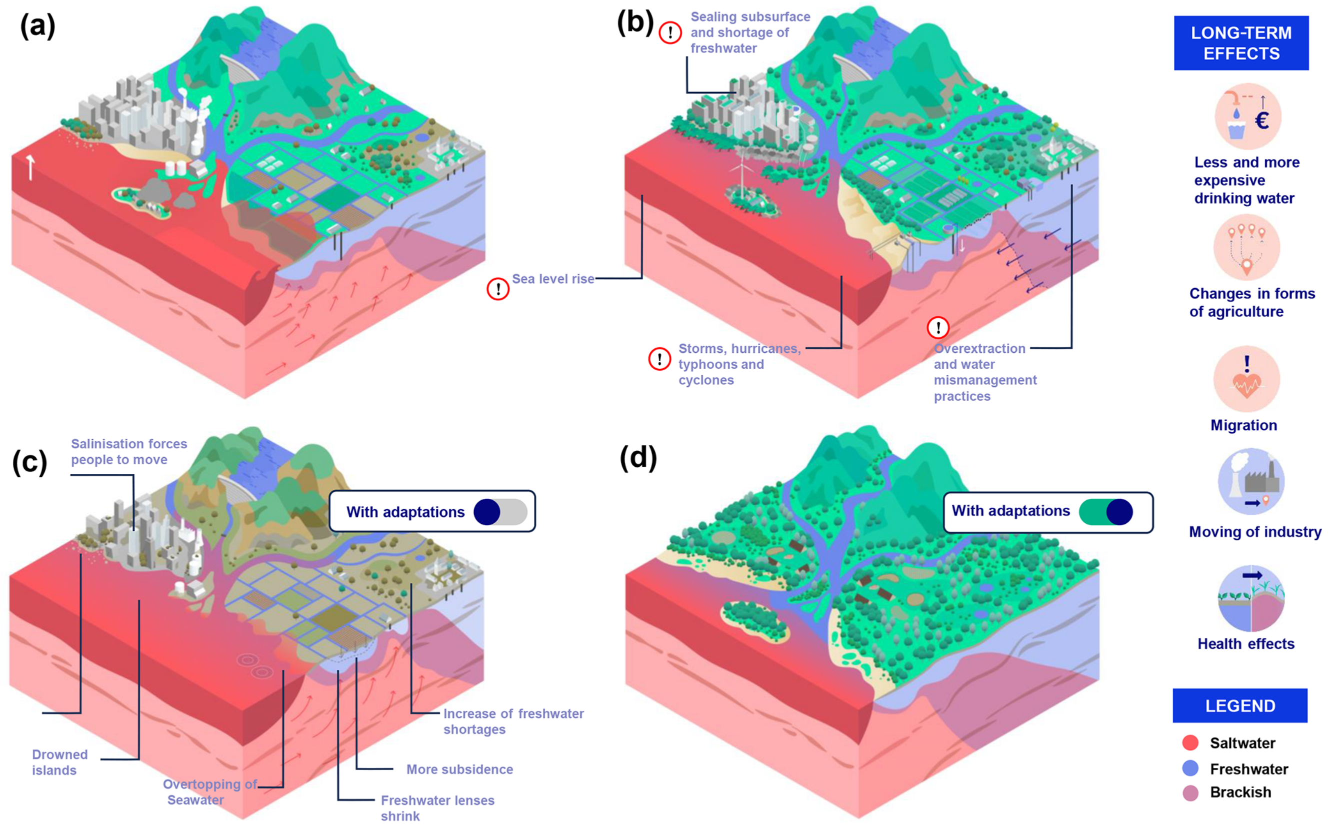

Figure 11. Salinization of (ground)water resources and land for different stages of progressive development. Saltwater is represented in red/pink, brackish water in purple, and freshwater in blue. **(a)** Situation in the distant past, before human settlements. **(b)** Current situation, with effects due to climate change and human activities. **(c)** Situation in the future without adaptation. **(d)** Situation in the future with adaptation. Source: Deltares (2023).

systems are suffering from the progressive increase in surface SWI. Not surprisingly, this process occurs both in micro- and macro-tidal environments (e.g., the Po river and Elbe Estuary, respectively), with different sea salinity values (ranging from less haline ones in the Atlantic or North Sea to the more haline ones in the Mediterranean) and higher or lower surface heat fluxes. These environmental conditions trigger the predominance of one of the several saltwater drivers. As an example, the Tagus Estuary is exposed to a tidal excursion of up to 3.8 m, which is also amplified by resonance. Therefore, even in normal conditions, saltier seawater intrudes, affecting 43 % of the estuary area (intertidal zone). The combination of tides and the periodic exposure to droughts, with several low discharge events, seem to massively affect the system (Rodrigues et al., 2019).

The European coast already includes several cases of increased saltwater intrusion in the groundwater system (Fig. 12). Studies on the quantification of effects of changed drivers show their relative effect. In the Minho and Lima estuaries, in the northern coast of Portugal, the future SLR scenarios identify a progressive increase in saltwater extension, and the effect of the most extreme SLR scenarios is leading to a transgression of the saltier front of several kilometers (Pereira et al., 2022). In this case, SLR is identified as the dominant driver for increased saltwater intrusion when compared to future river discharge reduction. On the other hand, the quantification of the relative effect of SLR and reduced river discharge in future climate change scenarios leads to opposite conclusions in a microtidal Mediterranean system, such as the Po river delta. River discharge reduction affects SWI more than SLR (Bellafiore et al., 2021). SLR and climate-change-induced salinization are also predicted to worsen in several coastal locations in the North Sea (e.g., the Netherlands – Bonte and Zwolsman, 2010; Belgium – Bertels and Willems, 2022). In all deltaic and estuarine systems, the evaluation of changes in drivers should be carried out, considering possible additional long-term modifications of the morphologic environment, for example, due to subsidence.

Added to these natural factors and often acting in combination with them, several anthropogenic activities can exacerbate SWI by lowering the surface freshwater supply. Examples are changes in land use and land drainage, ir-

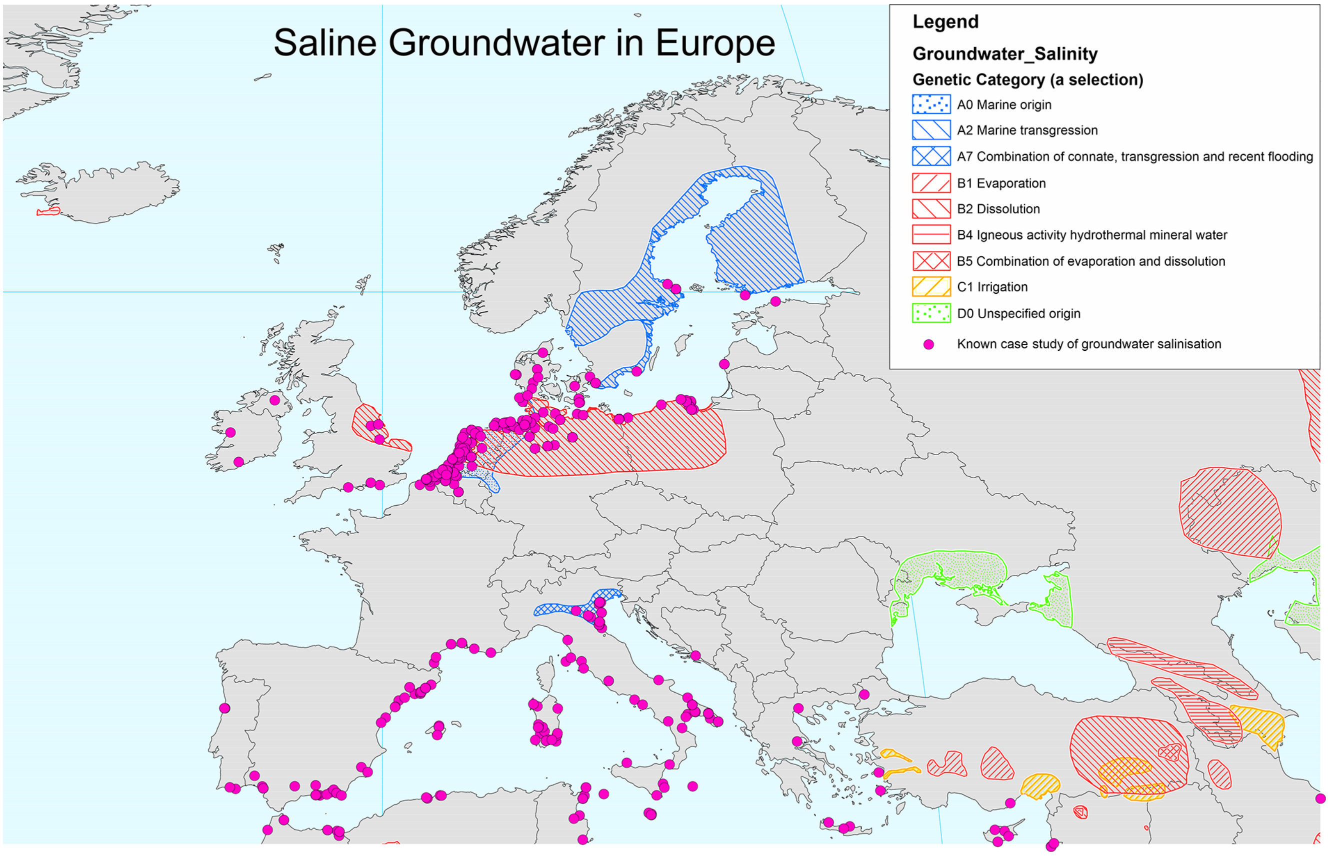

Figure 12. Case studies (not exhaustive) for which the groundwater salinization is occurring in the coastal zone around Europe (updated and after Post et al., 2018, and Van Weert et al., 2009), where it may cause multi-faceted impacts combined with sea level rise changes.

rigation, hydropower production, and over-exploitation of coastal aquifers.

6.3 Pathway for saltwater intrusion

For SWI, the pathway reflects how seawater reaches coastal freshwater resources and causes their salinization. In estuaries and deltas, river branches are the preferential way to transport seawater upstream – through salt wedge intrusion along the riverbed and by lateral inflow of the river into the aquifers. Land salinization and aquifer contamination can also result from coastal inundation with saline waters through floods induced by storm surges (Cantelon et al., 2022). The coastal morphology and geological characteristics are therefore strongly influencing the saltwater pathway and determining complex hydrogeological interactions between groundwater, surface water, and marine water. As explained in Sect. 6.2, climate change may enhance SWI drivers by raising the mean relative sea level, as well as by reducing the net freshwater supply in rivers and aquifers. However, as for coastal flooding, SLR will also shorten the pathway of saltwater to reach land and freshwater resources by squeezing the coastline, thereby facilitating coastal inundation and intrusion of marine waters. In addition, several anthropogenic activities exacerbate SWI by altering the river mouth and coastal morphology, such as diversions of waterbodies, river channel deepening, salt marsh reduction, and human-induced subsidence (White and Kaplan, 2017) (Fig. 11).

Several prevention and adaption measures have been undertaken in the last few decades to limit coastal inundation and ingression of saline waters along the river channels and the aquifers in Europe. Anthropogenic interventions can affect SWIimpacted areas by increasing the downstream flow of freshwater (e.g., river diversion, optimization of freshwater withdrawals, and deliveries) or by preventing the upstream transport of saline water. All of the flood barriers and measures limiting land inundation described in Sect. 4 have the co-benefit of limiting the salinization of soil and intrusion of saltwater into surface and groundwater systems. The most adopted engineered strategy to prevent salt wedges from intruding in estuaries and deltas is the installation of (often submerged) mechanical barriers (gates, dams, dikes, and levees) near the river mouth that physically block the upstream flow of saline water (White and Kaplan, 2017; InCom WG, 2021). However, salt barriers are regularly damaged and breached during floods and are not effective during extreme droughts when the saline layer occupies the largest portion of the water column.

Regarding groundwater, subsurface barrier walls (such as sheet piles, clay trenches, and injection of chemicals) are considered one of the most effective methods for inhibiting SWI (Armanuos et al., 2020). Various coastal managed aquifer recharge (MAR) schemes can be implemented to mitigate groundwater salinization in the coastal zone (Dillon et al., 2019; Oude Essink, 2001) (see e.g., Fig. 13). Sprenger et al. (2017) identify successful coastal MAR systems for the Netherlands (Amsterdam and The Hague areas), Spain (Barcelona (Llobregat) delta), Italy (Po delta), Belgium (De Panne), and Portugal (the Algarve). These include increasing artificial recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer, injecting or infiltrating (purified) freshwater near the shoreline to create freshwater injection barriers, and enabling land reclamation to create a foreland where a freshwater body can develop or delay the inflow of saline groundwater. This is, for instance, a consequence of the sand suppletion (the Sand Engine in South Holland, the Netherlands), where the foreland better protects the low-lying hinterland against flooding (Huizer et al., 2016).

6.4 Receptor and consequences of saltwater intrusion

The progressive salinization of water resources has severe and long-lasting consequences for several social (e.g., reduction in the drinking water reservoirs), economic (e.g., water systems, agricultural production, and land losses), and environmental (e.g., degradation or losses of freshwater habitats and changes in biodiversity) issues. According to Cooper et al. (1964), groundwater SWI is a natural occurrence in coastal groundwater systems. However, human activities such as excessive freshwater pumping from coastal aquifers (Custodio, 2002; Custodio and Bruggeman, 1987; Mastrocicco and Colombani, 2021; Schmork and Mercado, 1969) often disrupt this natural process and even cause land subsidence (Minderhoud et al., 2017). The interaction between groundwater and surface water can also be significant, with saline groundwater sometimes exfiltrating towards surface water systems (de Louw et al., 2011; Delsman, 2015) and negatively impacting agricultural use and nature (Stofberg et al., 2015).

In densely populated and industrialized coastal regions around the world (Neumann et al., 2015), including areas in Europe, groundwater often serves as the primary source of freshwater. Several studies have examined the future availability of groundwater worldwide under climate change and related SLR (Green et al., 2011; Taylor et al., 2013) and human activities (e.g., Wada et al., 2010, 2014). Projected SLR is expected to exacerbate water stress in these densely populated areas, potentially leading to the overexploitation and salinization of groundwater resources due to upconing (the upward flow of) saline water. This situation is further compounded by the growing demand for freshwater in the future. Groundwater extraction in deltas leads to the accelerated salinization of coastal freshwater aquifers and land subsidence if groundwater infiltration is limited by low permeable layers (Herrera-García et al., 2021).

The influence of SLR on coastal groundwater systems has been studied since the 1990s (Navoy, 1991; Oude Essink, 1996; Sherif and Singh, 1999). More recent contributions concern (global) conceptual analyses based on analytical comparisons of freshwater–saltwater interfaces (Chang et al., 2011; Chesnaux, 2015; Chesnaux et al., 2021; Ferguson and Gleeson, 2012; Mazi et al., 2014; Werner and Simmons, 2009), 2D cross-sectional model studies (Ketabchi and Jahangir, 2021; Michael et al., 2013; Zamrsky et al., 2024), and 3D model studies (Befus et al., 2020; Loáiciga, 2009; Mabrouk et al., 2018; Masterson and Garabedian, 2007; Oude Essink et al., 2010; Rasmussen et al., 2013; Vandenbohede et al., 2008; Delsman et al., 2023), whereas the effects of SLR on coastal groundwater systems have been reviewed in Ketabchi et al. (2016).

7 Conclusions

In this chapter, the main impacts of SLR, namely coastal flooding, erosion, and saltwater intrusion, have been reviewed using the concept of the source, pathway, and receptor. Regarding coastal flooding, SLR, along with changes in storm surge and wave height and, in some places, increases in tidal range, has driven an increase in the frequency with which extreme coastal water levels are exceeding high thresholds (source). This, in turn, along with an ongoing decline in the extent of natural habitats that act as a buffer against flooding (pathways) and rapid population growth and urban encroachment in flood-prone areas (receptors), has driven an increase in coastal flooding and its impact (consequences) around the coast of Europe. However, current flood risk around the coastline of Europe would be considerably higher without the decades of investment into extensive flood risk management infrastructure and advances in flood forecasting and emergency response. At the same time, losses in major events that exceed defense design standards are growing and are expected to increase massively in the future with higher rates of SLR, unless further adaptation is taken. Furthermore, events with low flood levels (i.e., nuisance flooding) are likely to increase, causing widespread disruption of everyday routine activities and property damages, especially in low-lying areas.

Coastal erosion shares the same source as flooding, i.e., extreme waves and storm surge, even though in many areas additional long-term anthropogenic, geological, and climatic factors are also important, as they affect sediment budgets (Pathways). A total of more than 8200 km of Europe's sandy beaches has significantly retreated over the last

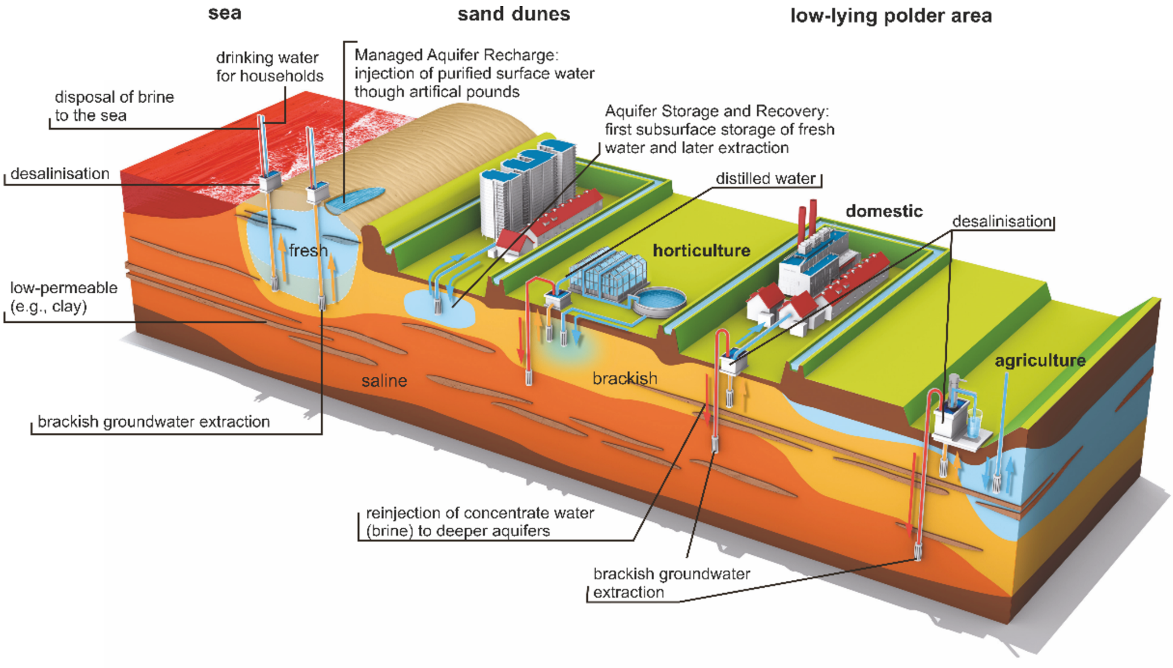

Figure 13. Concept proposed for managing water resources in coastal areas, ensuring a reliable supply of freshwater for domestic, industrial, and agricultural purposes. To store excess freshwater, large-scale coastal managed aquifer recharge (MAR) and aquifer storage and recovery (ASR) methods can be used (see the text). Additionally, brackish groundwater can be intercepted to prevent the salinization of aquifers and low-lying areas, while also providing a source of freshwater after desalination (after https://www.coastar.nl/, last access: 14 July 2024).

decades, as found at various locations across the continent (receptors). Climate change and rising seas are expected to accelerate the current trend, and retreating shorelines combined with built areas backshore will result in coastal squeeze and threaten sandy beaches. The above will not only have social, economic, and ecological consequences but is also expected to also exacerbate coastal flooding.

In many regions in Europe, saltwater intrusion into surface and groundwater systems is emerging as a problem. Sea level rise is an important driver (source). SLR facilitates coastal inundation and the intrusion of marine waters into freshwater resources (pathway). But other (human) processes also play an important role, such as groundwater extractions and low-lying areas attracting saltwater and reduced fresh river flows. These processes diminish freshwater availability, leading to health risks caused by drinking water that is too salty and less freshwater for economic purposes (e.g., salt damage to crops) and nature (stresses on existing biodiversity). A wide variety of adaptation measurements has been developed over the last few decades, reducing the impact of saltwater intrusion. At the same time, projected SLR is expected to increase the impact of saltwater intrusion in the densely populated coastal areas of Europe, particularly in combination with the growing demand for freshwater in the future. The first signals of the compounding effects of flooding, erosion, and saltwater intrusion are emerging. The adaptation measures also reduced exposure at some places, but an overview on these is lacking. This is also true for the possible negative impact of SLR on coastal ecosystems and estuaries (e.g., degradation of marshes, wetlands, and saltwater intrusions). This impact maybe through SLR itself or indirectly through measures implemented to protect the land from flooding or other adverse effects, but there is too little scientific literature available to assess this.

In summary, we can conclude that the impacts of SLR are emerging at many places across Europe, and it might be expected that these impacts on freshwater availability will increase over time, thereby providing an incentive for further mitigation measures, whereas, at the same time, smart adaptation measures are needed to reduce the impacts themselves.

Data availability. No data sets were used in this article.

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Sea Level Rise in Europe: Adaptation measures and decision-making principles

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Abstract. Sea level rise (SLR) will increasingly impact European countries in the coming decades, posing challenges for coastal decision-making and the design and implementation of adaptation measures to address coastal risks. The impact of SLR extends to its physical damages, encompassing socio-economic and environmental repercussions. European countries are engaged in the development and implementation of adaptation measures to bolster coastal resilience. While significant strides in SLR adaptation have been made in recent years, this paper aims to provide a catalogue of adaptation measures in European basins to guide their design and implementation and to present approaches suitable for supporting coastal adaptation decision-making and addressing uncertainty. The assessment of SLR adaptation measures in Europe is based on the cataloging of 17 measures following International Panel on Climate Change (IPCC) classification of *accommodate, protect, advance* and *retreat* responses to SLR, supplemented with sub-key types of measures, including socio-economic, physical and technological as well as nature- and ecosystem-based. Surveying the relevant literature on European sea basins, the paper shows that adaptation strategies on Europe's coasts constitute a mix of hard and soft measures, planning measures, policy developments and stakeholder and community engagements. Across all the basins, a common theme is the shift towards a combination of traditional engineering solutions with soft measures, including nature-based solutions, integrating local communities into decision-making processes and emphasising the importance of continuous monitoring and flexible management strategies. In addition, the context, decisions and experiences with coastal adaptation vary considerably across places and regions in terms of the time horizons considered, the scale of investments involved and the risk acceptance preferences of decision-makers and their constituencies. In this sense, the paper provides an overview of the common features of coastal adaptation decisions and the key aspects that need to be considered in coastal adaptation decision-making, i.e. considering multiple criteria and interests, implementing low-regret and flexible options, keeping future options open and factoring SLR into decisions that need to be made today.

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1 Introduction

Global coastal systems are witnessing an increase in sea level rise (SLR), ocean acidification and rising ocean temperature, severely exposing people in low-lying areas to natural hazards and leading to significant environmental and socio-economic damages (Merkens et al., 2016). European coasts are subjected to an increase in sea levels and an increase in SLR adverse impacts, in particular coastal flooding, saltwater intrusion, coastal erosion and negative impacts on ecosystems and estuaries, affecting the ability of coasts to adapt to the changing climate (as demonstrated in van de Wal et al., 2024).

A major concern for many countries is *how* to reduce exposure to SLR and enhance coastal resilience. For several centuries decision-makers have implemented traditional engineering solutions, herein referred to as grey options, as they dominated thinking and practice in coastal protection against SLR (Sancho, 2023; Kraus, 1996; van Koningsveld et al., 2008). A recent body of scientific evidence is proving that context-adjusted nature- and ecosystem-based solutions (i.e. green and blue options) as well as hybrid solutions can similarly reduce the risk of coastal flooding and erosion induced by SLR (Kuwae and Crooks, 2021).

Despite the growing attention placed on coastal adaptation, there is limited reporting of adaptation measures in the peer-reviewed literature and in policy documents, as they often present broad objectives rather than detail concrete measures. While systematic reviews have been done of global civil and environmental infrastructures of coastal adaptation to SLR (Nazarnia et al., 2020), of the role of protected areas in community adaptation in coastal areas (Ferro-Azcona et al., 2019), of studies performing socio-economic assessments of climate change adaptation in coastal areas (Riera-Spiegelhalder et al., 2023), of the limits of participation and co-production in climate adaptation within European coastal communities (Sartorius et al., 2024) and of public preferences regarding coastal adaptation measures (Mallette et al., 2021), European regional studies on adaptation solutions encompassing multiple types of measures – civil infrastructures, nature-based solutions or social, economic and institutional ones – are lacking. Besides, compliance with coastal laws by states and private actors is still overlooked in the scientific literature, despite being a critical aspect for addressing the impacts of sea level rise.

To facilitate climate action against SLR, the International Panel on Climate Change (IPCC) identifies four types of responses to SLR that guide countries in designing effective adaptation strategies: (i) *accommodate*, (ii) *protect*, (iii) *advance* and (iv) *retreat* (Oppenheimer et al., 2019). These represent four different approaches for adapting to natural hazards by reducing risks, exposure and vulnerability in low-lying coastal areas. Similarly, the European Environment Agency (EEA) developed the Key Type of Measures for Adaptation to Climate Change framework to report climate adaptation actions in EEA member countries. It has two categories of measures (*key types* and *sub-key types*), including socio-economic, physical and technological as well as nature- and ecosystem-based ones (Leitner et al., 2020). The advantage of using frameworks is that they help to standardise existing efforts in climate adaptation and capitalise on individual action for collective action while guiding the development of new efforts.

The contribution of this paper is twofold. First, in an effort to facilitate the diversification of local and national adaptation strategies portfolios for decision-makers, it collects and discusses 17 coastal adaptation measures implemented in European basins and provides a categorisation following the frameworks of the IPCC and EEA. Second, it presents approaches suitable for supporting coastal adaptation decision-making and addressing uncertainty. In doing so, it aims to fill the research gap within the coastal adaptation strategies landscape, to provide new analysis of and reflections on the existing adaptation measures in European basins, and to support decision-making.

As for the structure, Sect. 2 and its subsections present state-of-the-art SLR adaptation measures in Europe and aim to provide guidance for the design and implementation of adaptation policies in European basins. The section is further complemented by a series of in-depth analyses showcasing the implementation of adaptation measures in Venice, Italy, in Aveiro, Portugal, and in the Wadden Sea. Section 3 and its subsections first briefly review decision science terminology and then present key aspects that need to be considered in coastal adaptation decision-making, together with some example tools that can be used for addressing them.

2 Assessment of adaptation measures in Europe

A systematic scientific literature review was carried out, consisting of 247 scientific peer-reviewed articles, reports, policy documents and other grey literature to identify a list of adaptation measures, provide their description and find examples of best practices. The literature was collected through an iterative mixed-method approach (Fig. 1). First, 127 articles were identified using Web of Science Core Collection, searching the keywords “coastal adaptation” OR “coastal governance” AND “sea level rise” (topic) AND 2017–2023 (year published) AND Europe (topic). The review considered papers written between 2017 and 2023 to find the most up-to-date literature and provide emerging contexts and measures regarding SLR. Second, grey literature was included: 43 strategies, management and adaptation plans from different countries, regions and cities as well as 32 other sectoral reports and documents, comprising Maritime Spatial Planning country information. Third, 45 additional scientific studies were identified through references in peer-reviewed papers and included in the literature review.

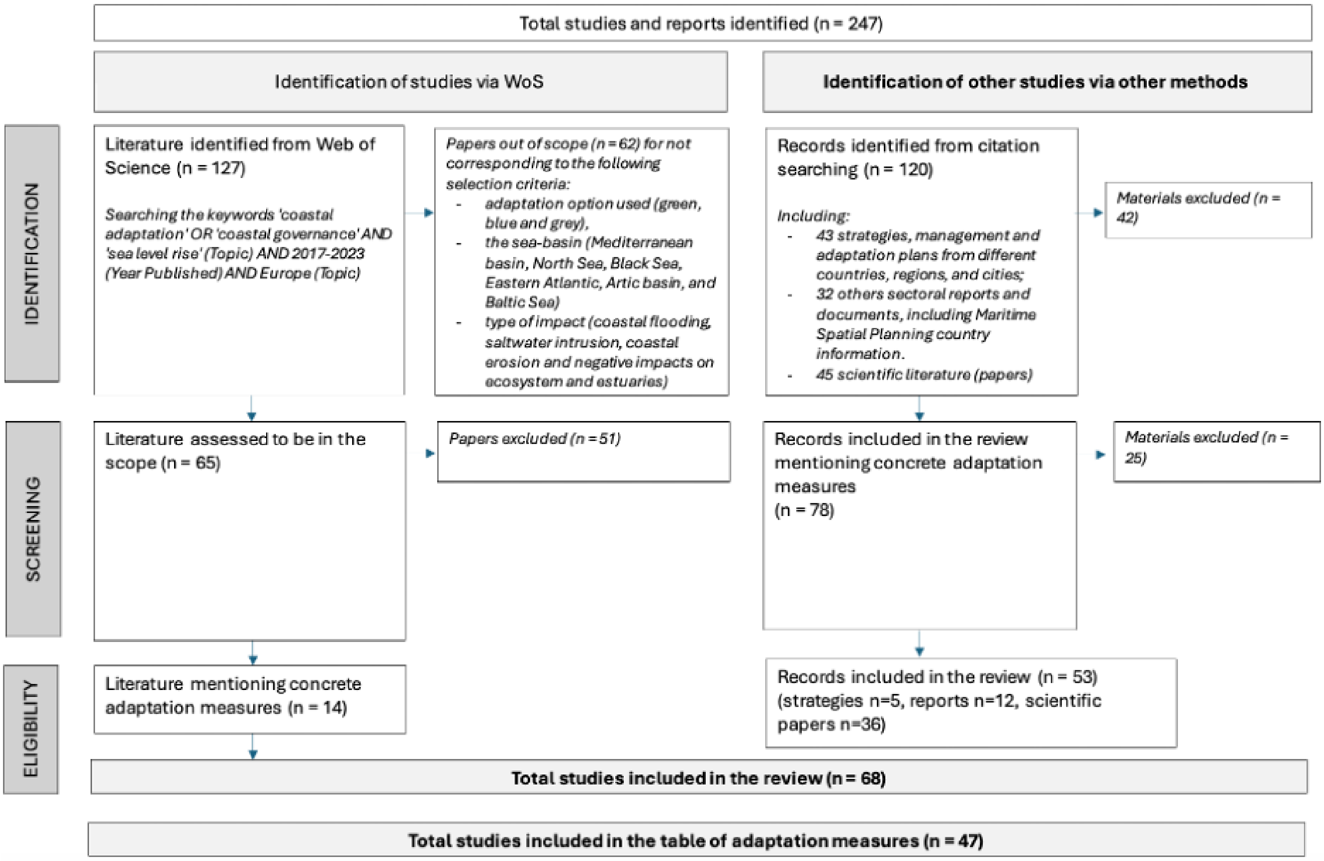

Figure 1. Methodological systematic review process.

A selection of the literature was carried based on the following criteria: the type of adaptation option (green, blue and grey), the sea basin (Mediterranean basin, North Sea, Black Sea, eastern Atlantic, Arctic basin and Baltic Sea) and type of impact (coastal flooding, saltwater intrusion, coastal erosion and negative impacts on ecosystems and estuaries). For a targeted collection of the literature, we have limited the search words. However, further research could be broadened to incorporate additional keywords such as “coastal strategy”, “coastal defence”, “adaptation to coastal flooding”, “adaptation to coastal erosion”, “adaptation to saltwater intrusion” and “adaptation of coastal ecosystems”.

The main outcome of the literature review, which is represented in Table 1, is the collection and categorisation of 17 adaptation measures to SLR focusing on European sea basins and targeting four climate impacts: *coastal flooding, saltwater intrusion, coastal erosion and impacts on ecosystems and estuaries* (see van de Wal et al., 2024). Table 1 lists the identified measures and provides information on the type of response, the sub-key type of measure (sub-KTM), the sea basin, the impact and the literature.

The top-level categorisation of adaptation measures is along the four main types of responses to SLR identified by the IPCC. First, accommodate measures involve preparing for and responding to coastal hazards. They include a range of responses, such as using early-warning systems, building flood-proof structures, managing groundwater and implementing insurance and policy instruments. Second, protect measures aim to reduce risks and impacts of coastal hazards through hard defence and soft defence measures. Additionally, nature- or ecosystem-based adaptation measures are also considered protect measures. Third, advance measures include strategies such as raising and advancing coastal land, e.g. by creating new raised ports, raising urban embankments and creating vegetated areas to promote natural land growth. Lastly, retreat measures include different adaptation measures, ranging from relocating human activities and infrastructure away from high-risk coastal areas to less vulnerable ones to restoring ecosystems by leaving coastal areas alone.

Adaptation measures are further categorised along the sub-KTM dimension developed by the EEA (Leitner et al., 2021). This categorisation is based on five main Key Types of Measures (KTM) and 11 sub-KTM, i.e. Governance and Institutional (policy instruments; management and planning; coordination cooperation and network) (see Bisaro et al., 2024), Economic and Finance (financing and incentive instruments; insurance and risk-sharing instruments), Physical and Technological (grey options; technological options), Nature Based Solutions and Ecosystem-based Approaches (green options; blue options) and Knowledge and Behavioural change (information and awareness raising; capacity building, empowering and lifestyle practices).

It should be noted that it can be difficult to draw clear distinctions when categorising measures, as the adaptation measures identified in the table can often be implemented at different levels of governance and at different spatial scales (see Bisaro et al., 2024). Moreover, some measures may in practice include activities across multiple sub-KTM and even combine multiple types of responses. For example, urban land raising (advance measure) may be appropriately combined with improved building codes (accommodate measure) in order to effectively reduce coastal risks, as in Hamburg's Hafen City (Bisaro et al., 2020). To ease the categorisation, the measures were classified based on the primary response and sub-KTM addressed.

The literature review shows that accommodate measures are the most widely discussed, followed by protect measures, advance measures and finally retreat measures. The most common sub-KTM is management and planning, followed by grey, green and blue options, insurance and risk-sharing instruments and technological options. The sea basins most covered in the literature are, respectively, the eastern Atlantic, the Mediterranean Sea, the North Sea and the Baltic Sea. Lastly, most measures focus on avoiding coastal flooding and erosion, while studies on ecosystems, estuaries and saltwater intrusion are very scarce. Based on the categorisation described above, the following section looks at each measure individually.

2.1 Types of responses to sea level rise

2.1.1 Accommodate

Accommodate measures include a range of biophysical, architectural and institutional responses. They do not directly prevent coastal impacts but rather mitigate coastal risks by reducing the vulnerability of coastal residents, ecosystems, human activities and the built environment, thus enhancing coastal communities' resilience. Accommodate is usually implemented in response to coastal hazards, coastal flooding, salinisation and other sea-borne hazards rather than directly to address SLR. The main advantage of accommodate measures is that they are generally both low-cost and highly cost-efficient in all contexts. This high cost–benefit ratio means that implementing them is much cheaper than not intervening (Oppenheimer et al., 2019). Accommodate measures can have additional advantages by producing and disseminating useful information, raising awareness of coastal risks among residents and promoting safer behaviour (Bongarts Lebbe et al., 2021).

Flood-proofing and raising buildings is an adaptation measure that involves the use of building techniques with specific designs and materials that are primarily aimed at flood risk reduction. Dry and wet-proof techniques have shown their effectiveness in reducing impacts of short periods of flooding (Ventimiglia et al., 2020). For long periods of high water, an appropriate measure is to raise buildings by elevating their height or constructing new ones at higher elevations (pile-dwelling construction or building on stilts). These can mitigate the risk of flooding and coastal inundation. Floating or amphibious buildings also offer the opportunity to float when flooding occurs for several months (Dal Cin et al., 2021). In the Netherlands, the latter technique has been tried with houses capable of adapting to different water levels (Oppenheimer et al., 2019). In Spain, the National Adaptation Plan focuses on the importance of using flood-proofed materials and building designs for critical infrastructure in coastal cities (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016).

Increasing resilience of critical infrastructure involves solutions mainly composed of grey measures. Critical infrastructure is an asset that is essential for the maintenance of vital societal functions, mainly in the transport and energy sectors, e.g. ports, airports, highways or nuclear power plants. Critical infrastructure is often located near the coast, e.g. Schiphol Airport at 4 m below sea level in the Netherlands or Nice Côte d'Azur Airport in France at 3 m above sea level (Cavalié et al., 2023). The risks not only relate to the possible asset damages, but also concern the potential blockages and the disruption of economic activities that may result from infrastructure failure, as it could substantially increase the severity of the impact (Koks et al., 2023). This measure does not consist of precise preventive actions but instead involves methods to mitigate the risk of upholding the functionality of the infrastructure. An example of how port authorities are dealing with climate change risks is provided by the government-led Ports of Spain, which manages 28 ports in the country. The Port Authority has adopted several measures to adapt to flooding and storm surges, including advanced early-warning systems, a new Spanish Ports Strategic Plan and the implementation of a Port Climate Change Observatory (see the box on "Climate change impacts and adaptation: status and challenges for the Spanish Ports system" in Bisaro et al., 2024). This critical infrastructure perspective is rarely addressed in the scientific literature and is more studied in the US than in Europe (Koks et al., 2023).

The sub-KTM management and planning include among others adaptation of groundwater management. Groundwater is an overexploited resource that is being used globally at an alarming and unsustainable rate, affecting its capacity to act as a natural buffer against coastal flooding (Ward et al., 2020). In turn, the conservation of groundwater reservoirs, the limit of water use and the optimisation of water reuse can avoid salinisation and increase the adaptive capacity of coastal areas. This calls for human activities conducive to the preservation and sustainable management of groundwater resources, in particular through improved land man-

Table 1. Adaptation measures to sea level rise.

Response		Adaptation measure	Sub-KTM	Sea basin	Impact	References
Accommodate	1	Flood-proofing and raising buildings	Grey options	North Sea, Mediterranean Sea	Coastal flooding, coastal erosion	Dal Cin et al. (2021), Ventimiglia et al. (2020), Oppenheimer et al. (2019), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016)
	2	Adaptation measures to increase resilience of critical infrastructure	Grey options	Mediterranean Sea	Coastal flooding	Cavalié et al. (2023), Koks et al. (2023)
	3	Adaptation of ground-water management	Management and planning	North Sea	Coastal flooding, salt-water intrusion	2023 Delta Programme (2023), Ward et al. (2020), Oppenheimer et al. (2019)
	4	Sustainable fisheries and aquaculture management	Management and planning	Baltic Sea	Impacts on ecosystems and estuaries	Payne et al. (2021), Oppenheimer et al. (2019)
	5	Climate risk insurance schemes	Insurance and risk-sharing instruments	Mediterranean Sea	Coastal flooding	Bednar-Friedl et al. (2022), Oppenheimer et al. (2019), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016)
	6	Consideration of climate change in credit risk and project finance assessments	Insurance and risk-sharing instruments	Mediterranean Sea	Coastal flooding	2023 Delta Programme (2023), MITECO (2020), Oppenheimer et al. (2019), Netherlands Sovereign Green Bond (2023)
	7	Integration of climate change adaptation in coastal zone management plans	Policy instruments	Eastern Atlantic	Coastal flooding, coastal erosion	Bednar-Friedl et al. (2022), McEvoy et al. (2021), OECD (2019), Ministerio de Agricultural y Pesca, Alimentación y Medio Ambiente (2016)
	8	Early-warning systems and flood preparedness	Technological options	Eastern Atlantic, Mediterranean Sea	Coastal flooding	European MSP Platform (2022), Oppenheimer et al. (2019), Republic of Estonia (2017), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016)
	9	Develop a risk culture within the population	Information and awareness raising	Baltic Sea, eastern Atlantic, Mediterranean Sea	Coastal flooding	Zeng et al. (2020), Stelljes et al. (2018)

Table 1. Continued.

Response		Adaptation measure	Sub-KTM	Sea basin	Impact	References
Protect	10	Hard defence for coastal management (dams, dikes, levees, etc.)	Grey options	Eastern Atlantic, North Sea	Coastal flooding, coastal erosion	2023 Delta Programme (2023), Del-Rosal-Salido et al. (2021), Egberts and Riesto (2021), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016), van Koningsveld et al. (2008), Hinkel et al. (2014), Lincke and Hinkel (2018), Tiggeloven et al. (2020), Vousdoukas et al. (2020), Hinkel and Nicholls (2020)
	11	Restoration and management of coastal ecosystems	Green and blue options	Eastern Atlantic	Impacts on ecosystems and estuaries, coastal flooding, coastal erosion	Moraes et al. (2022), Presidência do Conselho de Ministros (2019), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016), Buisson et al. (2012), Barbier et al. (2011)
	12	Beach and shoreface nourishment	Green and grey options	Eastern Atlantic, North Sea, Mediterranean Sea,	Coastal flooding, coastal erosion, impacts on ecosystems and estuaries	Tiede et al. (2023), 2023 Delta Programme (2023), Saengsupavanich et al. (2023), Sancho (2023), Mendes et al. (2021), de Schipper et al. (2021), Staudt et al. (2021), Pinto et al. (2020), Buisson et al. (2012)
	13	Other soft defence measures for coastal management (reloading littoral strips, cliff reshaping, polymer grids)	Green, blue and grey options	Eastern Atlantic	Coastal erosion	Oppenheimer et al. (2019), Presidência do Conselho de Ministros (2019), Buisson et al. (2012)
Advance	14	Raising and advancing coastal land	Green options	North Sea, eastern Atlantic	Coastal flooding, coastal erosion, impacts on ecosystems and estuaries	Van Den Hoven et al. (2022), Moraes et al. (2022), Laporte-Fauret et al. (2021), Bisaro (2019), Schuerch et al. (2018), Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (2016)
Retreat	15	Planned relocation	Management and planning	Eastern Atlantic, Mediterranean Sea	Coastal flooding, coastal erosion, impacts on ecosystem and estuaries	Sayers et al. (2022), Government of Portugal (2021), OECD (2019), Thorsen et al. (2021), Schuerch et al. (2018), Van Den Hoven et al. (2022)
	16	Restricting new developments in flood-prone areas	Management and planning	North Sea	All	2023 Delta Programme (2023), Oppenheimer et al. (2019)
	17	Managed realignment	Green and blue option	Mediterranean Sea Baltic Sea	Coastal flooding	Schuerch et al. (2018), Van Den Hoven et al. (2022), Thorsen et al. (2021), Bisaro et al. (2024)

agement practices in upper basins or in urban areas through rainwater harvesting and the use of pervious pavements (Oppenheimer et al., 2019). For instance, the Freshwater Delta Programme in the Netherlands aims to prevent water shortage in the present and near future (2050) and includes comprehensive measures to maintain a healthy groundwater system, using spatial planning and other context-specific strategies (2023 Delta Programme, 2023). The multiple benefits of sustainable groundwater management make it both an accommodate measure and a protect measure. For a more extensive discussion of prevention and adaptation measures to limit groundwater salinisation, see van de Wal et al. (2024).

The sub-KTM management and planning also include sustainable fisheries and aquaculture management. In recent years, the literature and political action in Europe have focused more on overexploitation of living marine resources than on climate change impacts, which is a severe issue, particularly in southern Baltic states (Payne et al., 2021). In studies that focus on climate-related drivers of fisheries and aquaculture, ocean warming and acidification are considered more influential than SLR (Oppenheimer et al., 2019). However, future projections of SLR and their implications for fisheries and aquaculture are an understudied area.

Climate risk insurance schemes can play an important role in enhancing coastal resilience and reducing vulnerability. These mechanisms can provide financial security to coastal communities and businesses to mitigate the financial impacts of loss events such as coastal flooding and storm events (see Bisaro et al., 2024). They have mainly been used in the context of agriculture and urban areas (Oppenheimer et al., 2019). The European insurance industry has developed flood-specific products, notably through risk-based flood insurance schemes that can induce risk-averse behaviour, and it is also investing in the field of risk analysis (Bednar-Friedl et al., 2022). Spain has developed specific insurance and reinsurance schemes like the "extraordinary risk insurance" for risks specifically deriving from SLR in coastal areas, including extraordinary floods and atypical cyclonic storms (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016). More recently, governments have been funding post-disaster mechanisms, making flood insurance compulsory or taking on the role of reinsurer in public–private partnerships. Well-designed insurance schemes may also include measures such as reduced prices of the insurance if homeowners implement preventive adaptation measures, e.g. not keeping high-value items on the ground floor, which increase the overall effectiveness of insurance (Bednar-Friedl et al., 2022). However, when poorly designed, insurance schemes can also perpetuate the risk and incentivise maladaptation. An example is the provision of insurance pay-outs to rebuild assets in a location that is increasingly experiencing flood risk without proportionally increasing premiums. Moreover, increasing climate risks could put a strain on public budgets, leading to the withdrawal of support for publicly funding insurance and potentially reducing the availability or affordability of insurance products for poor households and some households in high-risk areas. Similarly, increasing risks may lead to decreased offerings of private insurances due to either insolvency or them exiting markets (Bednar-Friedl et al., 2022).

Addressing climate change in credit risk and project finance assessments is an accommodate measure as it orients investors towards projects that enhance adaptation. Consideration of climate change in credit and finance assessments can thus mobilise financing of specific projects against SLR through the public and private sectors, international climate funds and other innovative financing solutions. In 2019, the Netherlands issued the first certified Sovereign Green Bond by a European country (Netherlands Sovereign Green Bond, 2023). A large proportion of the bond proceeds was used to fund the Delta Programme, a sophisticated flood risk management system that enhances resilience to SLR and improves freshwater supply, among other benefits. The Delta Programme also has a specific Delta Fund, which is a separate item of the central government budget and includes EUR 21 billion available for the period 2023–2036 (2023 Delta Programme, 2023). An example of a tool for financing adaptation projects is to raise funds from the sale of newly generated lands coming from the implementation of advance measures (Oppenheimer et al., 2019). Another example is provided by the PIMA Adapta Plan for the Promotion of the Environment for the Adaptation to Climate Change in Spain, an operational tool that finances adaptation projects using emission rights, among others (MITECO, 2020).

The literature emphasises the key role of integrating SLR information into coastal adaptation strategies and plans. An illustrative case is Spain. Since 2004, Spain has prioritised climate change adaptation measures that protect its vulnerable coastline. The first National Plan for Adaptation to Climate Change (PNACC), approved in 2006, identified coastal impact assessment as a priority. The second (2009–2014) and third (2014–2020) PNACCs identified coastal zones and the development of a strategy for the adaptation of the coasts to climate change as a priority line of action, which was de facto adopted in 2016 (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016). The current PNACC (2021–2030) foresees the development of risk analysis tools and the definition of adaptation initiatives on the coasts and at sea, the facilitation of coastal and marine adaptation through regulatory frameworks, the integration of coastal risks into plans and programmes as well as the fostering of institutional coordination and social participation for adaptation on the coasts and at sea.

SLR entered into innovative governance instruments that have been developed to overcome administrative barriers in coastal governance, e.g. the 2023–2027 Toulon Bay Contract which involves 40 local stakeholders in a decentralised, participatory and bottom–up approach to adapt to flooding and erosion risks (Métropole Toulon Provence Méditerranée, 2023). Further information on coastal governance instruments is provided in the section "Equity and Social Vulnerability" in Bisaro et al. (2024).

The literature also stresses the importance of studying multiple time horizons and different scenarios of SLR. The effectiveness of some adaptation strategies has been compromised by the use of only a few scenarios and the use of a single time horizon as opposed to multiple ones (OECD, 2019). For example, in Venice's adaptation pathways, only shared socio-economic pathways SSP1–2.6 and SSP5–8.5 were considered without using intermediate scenarios. As such, once critical relative sea level thresholds are reached, the remaining upper limit will represent a low-likelihood but high-impact storyline (Bednar-Friedl et al., 2022). Similarly, if planning only accounts for the short term, they may no longer be adequate once the adaptation measures are finally completed, especially given that major permeant interventions may take a long time to implement (Bednar-Friedl et al., 2022).

The implementation responses to SLR have been facilitated by the advancement of predictive tools and cartographic techniques designed to forecast the extent and repercussions of such rise and the subsequent floodings (Mcleod et al., 2010). Technological options include early-warning systems and flood preparedness, and they support all types of responses to varying degrees. They are conventionally considered an accommodate measure because they allow people to remain in the hazard-prone area but help improve preparedness and response by providing advance warning in the face of imminent danger. However, early-warning systems are also used in other types of responses, such as in protection (in the case of mobile protection defences like the Thames Barrier and the MOSE barrier in Venice; see Box 1) and retreat (in the case of extreme events evacuating people) responses. They have short implementation times and low impacts on the environment, but their implementation and effectiveness largely depend on good forecasting, predictable hazardous events and definition of adequate early-warning indicators (Oppenheimer et al., 2019). Thus, they are less well suited to accommodating slow onset change. Spain's adaptation plan has examples of early-warning systems and also evacuation protocols, which are carried out in coordination with societal organisations as well as local communities affected by the dangers (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016). Estonia offers another interesting case of actions aimed at improving knowledge of SLR and flood preparedness. Its strategy incorporates an accommodate measure to develop sea level forecasting systems for areas prone to coastal flooding (Republic of Estonia, 2017). As a result, Estonia has implemented a Maritime Spatial Plan for 2022, which includes a study of the expected SLR along the −3 m contour from the coast, specifically in the Pärnu Bay area (European MSP Platform, 2022).

Developing a risk culture within the population subcategorised as information and awareness raising relies on an understanding of how people perceive risk and act in particular ways (Zeng et al., 2020). This can be an effective adaptation measure as some of the basic requirements for successful collaboration in communities to manage and cope with extreme events are "culture of risk memory", "trust in scientific information and community" as well as trust in coastal authorities (Stelljes et al., 2018). This measure could equally be considered part of a long-term retreat measure because developing a risk culture prepares the population for potential future relocation.

2.1.2 Protect

Protect measures aim to reduce the risks and impacts of coastal hazards. These measures typically entail the construction and upgrade of hard and soft defences (OECD, 2019) but can also refer to restoration and management of coastal ecosystems.

Hard defence for coastal management includes the implementation and upgrade of physical structures such as dams, dikes, levees, groynes, breakwaters, artificial reefs, sea walls, jetties, storm surge gates, flood barriers and other types of defences. These are classified as grey measures that aim to prevent coastal erosion and flooding.

Hard defences have been very widely applied for centuries to prevent coastal erosion and flooding. The North Sea coastline of Belgium, the Netherlands and Germany is protected by dike systems complemented by other measures such as sand nourishment, dunes and surge barriers. Hard defences have also been implemented to counter relative SLR caused by land subsidence, such as areas with young sediments like the Italian Po Delta, the Netherlands and northern Germany (van Koningsveld et al., 2008).

Some advantages of hard defences are that they have long life spans, and their costs are reasonably well known and can be estimated. Generally, hard defences are highly effective at protection but generally leave a low risk of failure unless defences are built so wide that they cannot breach (De Bruijn et al., 2013). There are also economic motivations linked to the cost–benefit ratio of investments. Generally, hard protect measures are economically beneficial in urban areas as they have high cost–benefit ratios, and this has also been widely found to be true for 21st century SLR (Hinkel et al., 2014; Lincke and Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas, et al., 2020). For rural and less densely populated areas, hard protection is generally not economically beneficial, which suggests that alternative measures, in particular ecosystem-based measures or retreat, are often better solutions (Hinkel and Nicholls, 2020).

Negative consequences of coastal protection infrastructure include the need for ongoing maintenance and alterations in natural coastal dynamics, due to e.g. loss of plants and mosses, and hard defence measures can also negatively impact cultural heritage by changing the existing landscape (Egberts and Riesto, 2021). Some examples of this can be seen in the national adaptation plans of Spain (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016) and the Netherlands (2023 Delta Programme, 2023). An example of hard defence in the context of cultural heritage and landscape protection is the renowned MOSE system in Venice that after several decades of discussion and development entered into operation on 3 October 2020 (see Box 1 below).

Box 1: The MOSE system for protecting Venice and its lagoon

On 4 November 1966, due to an extreme and unexpected meteorological event, the water level reached 194 cm above the historical mean sea level and remained above 110 cm for 22 h. On 16 April 1973, the Italian Parliament promulgated the first Special Law for Venice, declaring the protection of Venice and its lagoon to be of primary national interest. Figure 2 demonstrates how the frequency of floods in the city increased from 30 to 95 events per decade, 1970–1079 and 2010–2019 (Fig. 2).

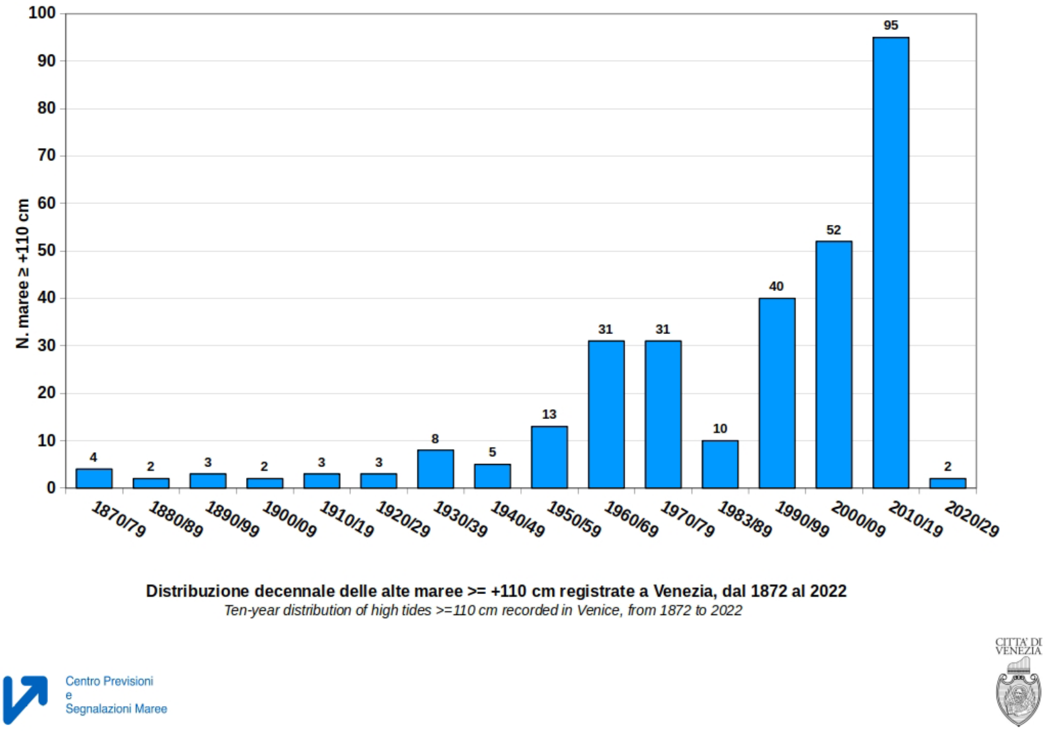

Figure 2. Number of city flooding events in Venice per decade. The distribution indicates the number of events with a sea level higher than 110 cm. The original source of this figure is the Municipality of Venice – Centro Previsioni e Segnalazioni maree.

After a long period of discussions, prototype testing and design revisions, the construction of the MOSE barriers began in 2003 and became operational for the first time on 3 October 2020, effectively protecting the centre of Venice and all the lagoon settlements. The MOSE barriers are an essential part of a much wider safeguarding approach that includes littoral island defence, adaptation measures in the urban settlements, ecological and morphological restoration of the lagoon (the largest in the Mediterranean Sea, ca. 550 km^2), de-pollution and defence measures in the lagoon basin (2068 km^2).

The “Venice SLR defence approach” is a mixture of protect and accommodate interventions which represent a continuation of what the Serenissima Republic of Venice did in its millenary history. The narrow littoral islands of Pellestrina and Lido, which separate the Venice Lagoon from the Adriatic Sea, were made of sandbanks when the lagoon was formed around 6000 years ago. However, already 7 centuries ago, the need to protect the coastal settlements from sea storms led the Republic of Venice to develop a complex defence system made of wooden poles (“palade”) that were regularly renovated. In the 18th century, this defence was replaced by massive stone sea walls (“murazzi”) placed on the shore. Since 2000, the ancient sea walls have been repaired and reinforced by a new shore in the form of gyrons built in front of them, with sand taken from the Adriatic Sea. This is the largest confined sand nourishment that occurs in Europe (Figs. 3 and 4).

The MOSE steel barriers placed at the lagoon’s inlets can provide a complete closure of the lagoon from the sea, for a total length of 1.56 km divided into four arrays. They can guarantee a difference of 2 m between the lagoon and the sea level offshore, maintaining the level of the lagoon at the safe level of 100 cm above sea level during storm events of up to 300 cm (the maximum event ever measured is 204 cm). Each of the 78 floodgates is 20 m wide and varies its length according to the depth of the four inlets.

They normally lie inside big concrete caissons placed on the seabed, connected by two hinges on one end and filled with water. To close the barrier, the air is pumped into the gates by compressors, allowing them to float at the desired angle for

Figure 3. The Venice Lagoon and its three inlets. The original source of this figure is the Consorzio Venezia Nuova – Concessionaire of the Ministry of Infrastructure of Italy).

Figure 4. The new shore realised in front of the old murazzi on the island of Pellestrina. The original source of this figure is the Consorzio Venezia Nuova – Concessionaire of the Ministry of Infrastructure of Italy.

closure. Each gate floats independently of the others to avoid the risk of stress concentration that a single, longer barrier might experience (Fig. 5).

After some tests (Fig. 6), the MOSE barriers became operational for the first time on 3 October 2020 and in the first three winters operated 50 times, effectively protecting Venice from floodings, including severe ones (Fig. 7).

The closure of the lagoon should be kept to a minimum, for both ecological and economic reasons. The protection strategy foresees the raising of the city's pedestrian walkways to a minimum level of 110 cm above sea level. In fact, throughout its history, Venice has constantly raised the level of its buildings to cope with the relative SLR (eustacy and subsidence). In the last century, cultural heritage and landscape protection together with a faster SLR made these adaptation measures harder to

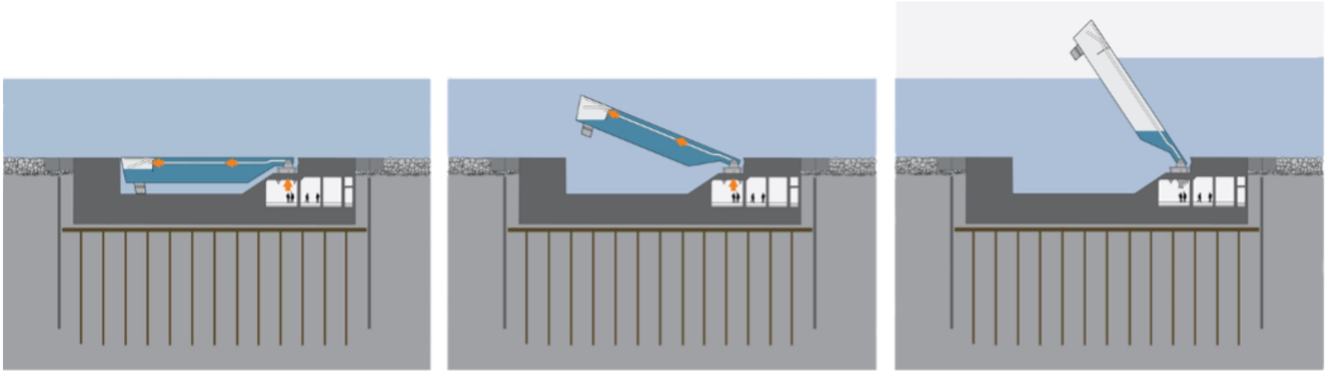

Figure 5. MOSE barrier functioning scheme. The original source of this figure is the Consorzio Venezia Nuova – Concessionaire of the Ministry of Infrastructure of Italy.

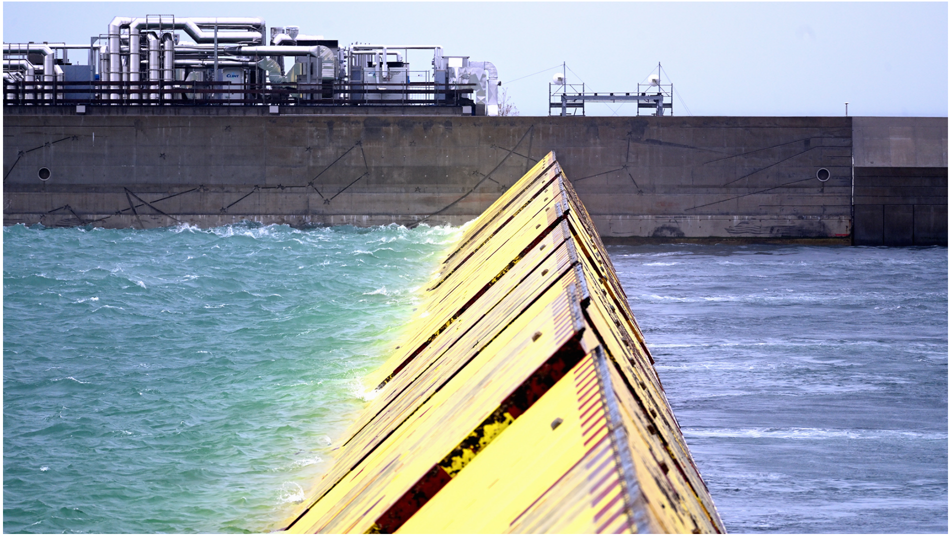

Figure 6. MOSE barriers on the Lido during a storm on 15 November 2020. In the picture the sea is on the left and the lagoon is on the right.

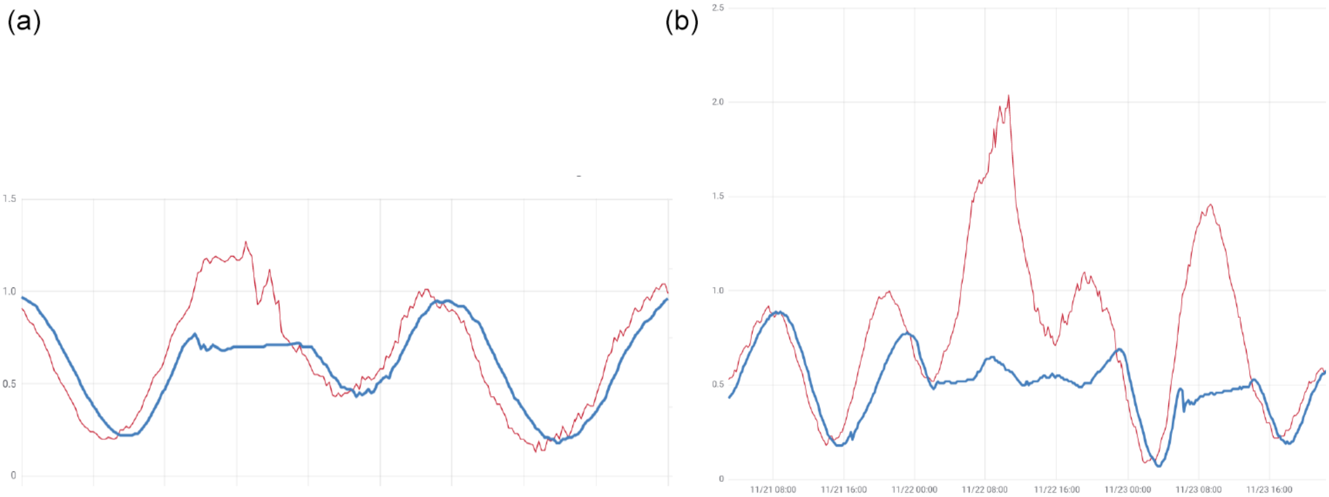

Figure 7. Sea level in the Adriatic (red) and inside the lagoon (blue) during the events of 3 October 2020 **(a)** and 22 November 2022 **(b)**.

implement. However, since the early 2000s Venice has continued to raise the level of the public pavements. Piazza San Marco represents a special case because of the presence of relevant artefacts placed at a much lower altimetric level.

In this case, an "impermeabilisation" strategy has been chosen, which consists in raising the level of the entire island of San Marco to 110 cm and in revising all the rainwater drains by installing suitable valves. These complex works are underway and will take several years to complete; in the meantime, in order to protect the most important monument, St. Mark's Basilica, from further saltwater intrusion, a glass barrier has been erected in front of the basilica facing the piazza (Fig. 8).

Figure 8. The glass barriers in front of St. Mark's Basilica provide effective protection, also from minor "acqua alta" events.

Once the main problem has been given a solution, other issues will continue to challenge science and policy.

As the rise in sea level continues, the frequency of barrier closures will increase: managing a regulated lagoon requires specific observational and modelling tools to be kept up to date. Further de-pollution and morphological interventions against salt marsh erosion are also needed.

It is well known that the paradigm of mobile barriers works up to a 50–60 cm SLR; above this threshold, these gates will be permanently closed and a different protection scheme should be provided. What this new system will be has not been discussed yet. In the coming decades, however, Venice will continue to be a multi-disciplinary and transdisciplinary laboratory for testing SLR adaptation measures for the whole world.

Soft defences for coastal management include different types of green, blue and grey options. One major difference between hard and soft protect measures is their respective impacts on natural sedimentary dynamics and equipment reversibility (Buisson et al., 2012). Two main examples of soft defences are dominating the discourse and are being extensively used in practice. First, the restoration and management of coastal ecosystems are common green and blue options used as an alternative to traditional approaches. Coastal vegetated ecosystems and biogenic reefs can self-adapt to SLR through different mechanisms (Moraes et al., 2022). These types of measures help to reduce erosion and flooding, in addition to providing a habitat for numerous species and other environmental benefits for local ecosystems (Barbier et al., 2011). Examples can be found in Spain (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016), Portugal (Presidência do Conselho de Ministros, 2019) and France (Buisson et al., 2012). This latter study shows how France successfully restored marshes and other vegetated ecosystems, protecting against wave energy and limited erosion and sediment accumulation. In the UK, the creation, restoration and enhancement of estuarine, coastal and marine habitats are funded through the Environmental Land Management (ELM) scheme. One initiative in this scheme is Restoring Meadows, Marshes, and Reefs, which aims to restore at least 15 % of three priority habitats by 2043, providing support to farms to restore habitats along the coasts and support upstream improvements (Department for Environment, Food and Rural Affairs, 2023).

Second, beach and shoreface nourishment is the artificial supply of sand and occasionally gravel or small pebbles to increase coastal sediments. This expands the sand volume or width of the beach, allowing it to counter coastal erosion and sometimes to advance seawards (de Schipper et al., 2021). Providing beach space is beneficial for tourism and recreational activities (Mendes et al., 2021). The objective of this nourishment is to compensate for the littoral imbalance caused by natural erosion and anthropogenic impacts (Buisson et al., 2012). In the literature, the difference between beach nourishment and shoreface nourishment is mainly related to the location of sand placement, which may be, respectively, on the subaerial beach (above-water beach) or the subtidal beach (submerged near-shore beach profile) in the form of an underwater mound (Mendes et al., 2021). The materials are dredged from offshore and inland sources, including nearby navigation channels. For example, the Lisbon Port Authority regularly maintains the outer Tagus estuary navigation channel by dredging sand that can be used for beach nourishment (Sancho, 2023).

Beach nourishment has been applied more extensively in Europe since the 1990s. In particular, in the eastern Atlantic Ocean the increase in the number of beach nourishments has been accompanied by a reduction in the number of hard coastal structures, contributing to improvements in coastal sediment management (Pinto et al., 2020). In Portugal, an extensive beach nourishment programme was carried out in the framework of a coastal management master plan between 2007 and 2019 (Mendes et al., 2021; Pinto et al., 2020). The programme placed 4.5×10^6 m^3 of sand along a 3.8 km northern shoreline (Sancho, 2023). In Spain, the Adaptation Plan envisions the regeneration of beaches and artificial dune systems to reduce erosion and revitalise coastal ecosystems. As part of the Adaptation Plan, in the sandy area of Liencres, several interventions have been made to restore one of the largest dune systems of the Cantabrian Sea (Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2016). In the Netherlands, Tiede et al. (2023) studied the changes in shoreline and coastal developments using satellite data of a sand nourishment initiative. The study compares images from the natural evolution period (1984–1990) and the recent nourished period (1996–2022), where approximately half of the sandy transects were nourished regularly in combination with small groynes to support the project (see van de Wal et al., 2024). In brief, the study showed an increase in the share of stable or accreting transects from 67 % to 89 %, while the share of eroding segments fell by 20 % (Tiede et al., 2023). Similarly, the Wadden Delta Programme includes different operations of sand nourishment on the North Sea side of the Wadden Islands, protecting them against flooding and also preserving ecosystem functions (2023 Delta Programme, 2023).

Nourishment is a flexible and fast coastal management option that is adaptable to changing conditions, remaining relatively cheap even if nourishments have to be repeated. However, the recent literature questions the sustainability of sand nourishments (Saengsupavanich et al., 2023; Staudt et al., 2021). Criticisms stress the environmental impacts in both sediment extraction and at nourishment sites, in particular in relation to the destruction of habitats, disruption of bird and other animal nesting, coverage and subsequent suffocation of benthic organisms, the increase in water turbidity and shifts in median grain size and grain-size distribution depending on the chosen material. In addition, large uncertainties in the long-term ecological and geomorphological impacts of nourishment remain (Staudt et al., 2021).

Other examples of soft defence measures include the use of geotextile structures as sand containers, the creation of artificial reefs to reduce wave energy and prevent beach erosion, as well as plant debris cover, windbreaks and plantations (Buisson et al., 2012). For instance, hydraulic pilings made of wooden rods vertically planted in the sediment at regular intervals limit sedimentary transport and favour beach stability in pilot studies in France (Buisson et al., 2012). Another example of a soft measure is cliff strengthening and stabilisation, which includes green and grey options that focus on reducing erosion and enhancing natural protection along coastal cliffs. This includes a range of techniques such as reloading littoral strips to compensate for sediment imbalances caused by marine erosion, cliff reshaping, drainage systems and the use of anchoring elements like bolts, tie rods, polymer grids, pinned nets and rip-rap strips (Buisson et al., 2012). This category of measure is employed in several countries, such as Croatia (Omiš) (Oppenheimer et al., 2019), Italy (Marche) (Addressing coastal erosion in Marche region, Italy) and Portugal (Presidência do Conselho de Ministros, 2019).

2.1.3 Advance

Raising and advancing coastal land (2024) has a long history of use to protect communities from natural hazards. Only recently has advance become a response to SLR on its own (Pörtner et al., 2019). Advance measures for coastal management include all those solutions that create or advance new land by expanding into the sea or ocean. Advance measures may be green or grey and mainly address coastal flooding, coastal erosion and biodiversity loss. Grey land reclamation emerges as an adaptation measure, particularly in high-value urban areas in Europe and globally (Bisaro et al., 2020). Raising and advancing coastal land (2024) is being pursued in major coastal cities, where new ports, harbour areas and safer urban embankments have been created in raised areas (Bisaro, 2019). At the global level, the most common land uses in reclaimed spaces are port extensions, exemplified by the two major ports in the Netherlands, Rotterdam and Amsterdam, which reclaimed 1106 and 337 ha, respectively, between 2000 and 2020 (Sengupta et al., 2023). Advance measures can also be ecosystem-based by including measures based on conservation and restoration of sediment systems, coral barriers or coastal vegetation by applying several techniques, such as excavation of foredune notches, dune thatching, dune grass planting, dune fencing or hybrid combinations of a dike core in a dune (Oppenheimer et al., 2019). For instance, in south-western France the excavation of foredune notches re-established an ecomorphological dynamic promoting landward sand transport and foredune landward translation, without threatening biodiversity.

2.1.4 Retreat

Retreat includes measures focused on reducing the level of exposure to coastal hazards by relocating human activities, infrastructure or even cities from highly exposed to less exposed areas. Retreat necessitates rethinking the entire coastal system as well as accepting that particular assets will need to be removed entirely (Bongarts Lebbe et al., 2021). The advantage of these types of measures is their effectiveness in both low- and high-risk coastal areas. However, they are solely applicable in regions with low population density (Oppenheimer et al., 2019). Retreat incorporates a wide range of measures mostly categorised as management and planning. Retreat measures have been implemented in various European sea basins, e.g. in the eastern Atlantic Ocean, the Baltic Sea and the Mediterranean Sea.

Planned relocation applies to individuals and critical assets, including the removal of existing hard infrastructure (OECD, 2019). This measure involves the governance and institutional planning behind the relocation of activities from high-risk areas, land acquisition and the expropriation of operations. Deciding to relocate a community has complex trade-offs: on the one hand there is an opportunity to reduce potential damages and meet the different needs and conditions of the community and, on the other hand, there are the high costs and direct impacts on people’s lives, which require extensive engagement with the community and clear incentives (Sayers et al., 2022; OECD, 2019). For instance, approximately 30 % of England’s coastline is likely to be under increasing pressure by the 2050s, affecting more than 120 000 properties, and a large but still unknown proportion of these properties will need to be relocated (Sayers et al., 2022). Another example is provided by Portugal, which has reported to the European Commission several measures that the country is implementing to manage the risk of SLR, including the progressive removal of constructions that are located in flood-critical territories along the coastline through spatial planning instruments (Government of Portugal, 2021).

Restricting new developments in flood-prone areas and defining setback zones is an approach to support planned relocation. An example is the Dutch Freshwater Delta Programme that spatially restricted development based on fluctuation levels (2023 Delta Programme, 2023). These flood-prone areas can be replaced with marshes or activities like aquaculture or salt-tolerant cultivation areas (Oppenheimer et al., 2019). The governance of flood-prone areas is also addressed in the Protocol on Integrated Coastal Zone Management (ICZM) of the Barcelona Convention (UNEP, 1995) – the main regional legally binding Multilateral Environmental Agreement in the Mediterranean, which entered into force in the European Union in 2011 after ratification. Article 8 of the protocol identifies a setback zone of a minimum of 100 m in width from the shoreline as a measure to protect coastal settlements and infrastructure from adverse impacts and is the first international legal instrument to require the use of coastal setback zones. Notably, the protocol links setback zones with adjacent areas such as wetlands and natural forests, which allows for the restoration of biodiversity and can serve as nature-based solutions (NbS) to adapt to the effects of climate change (Adriadapt, 2022).

An emerging option is managed realignment, a coastal adaptation strategy that entails the landward relocation of coastal defences to allow previously protected areas to restore tidal exchange and coastal habitats. A successful example of managed realignment in European basins, and the first large-scale example in Denmark, is the restored Gyldensteen Coastal Lagoon in the western Baltic Sea, where the ecological status improved and species richness increased after 5 years (Thorsen et al., 2021). Managed realignment as an adaptation strategy for the Ravenna coastline in 2100 can be found in Box 2 in Bisaro et al. (2024).

2.2 Limits and trade-offs of adaptation measures

The adaptation measures discussed in the preceding section are generally subject to trade-offs that should be considered when planning coastal adaptation. While accommodate measures offer benefits such as cost-effectiveness and immediate relief, the financial cost of implementing these measures can be a challenge for some communities. Protect measures provide important risk reduction benefits. However, they can severely disrupt natural coastal processes and harm marine life. Even soft protection or advance measures can have similar, localised ecological effects (for example, altering sediment transport patterns may unintentionally lead to erosion in neighbouring regions). While sea walls provide coastal protection, they can also exacerbate erosion by affecting the entire ecosystem and thus diminishing the ability of the system to respond naturally to different conditions (Rijn, 2011). These measures may also impact cultural heritage sites and alter coastal areas in addition to requiring high maintenance costs. Lastly, retreat measures potentially displace entire communities and can involve the loss of assets and business activities (e.g. tourism-related activities). They therefore generally require complex governance and coordination among multiple stakeholders and are limited to regions with low population density. To accurately analyse existing trade-offs, understanding the effectiveness and feasibility of these measures is important. Currently, there is a critical literature gap in this regard. Information is lacking on the effectiveness of measures in reducing risk and the economic, technological, institutional, socio-cultural, geophysical and ecological feasibility of implementing them. Existing analyses of effectiveness and feasibility are typically undertaken for particular types of responses at the global level rather than for individual measures. There is thus a scientific need to evaluate the effectiveness and feasibility of individual measures and in context-specific cases. This represents a research gap that, if addressed, could advance knowledge and significantly contribute to the field of coastal adaptation.

Finally, while the identified measures can help communities and governments to adapt to the challenges posed by SLR, addressing SLR in coastal areas requires careful consideration of the trade-offs associated with accommodate, protect, advance and retreat measures. In an effort to minimise the trade-offs and to provide a multi-faceted, integrated and sustainable solution to rising sea levels, novel approaches combine more than one adaptation measure and develop hybrid solutions (see Box 2).

Box 2: The role of hybrid solutions – a combination of green and grey options

Hybrid approaches combine the construction of specific grey options or built infrastructure with the simultaneous installation of restored or newly created natural infrastructure. For example, removable sea walls or flexible flood gates can be installed simultaneously with salt marsh and oyster reef restoration. Combining green or blue and grey protect measures is expected to be more effective and less costly under particular circumstances (Browder et al., 2019). For example, a hybrid approach can be implemented whereby natural infrastructure provides protection benefits for small to medium events, while built infrastructure is included in the measure for additional protection against larger events. Advantages of the hybrid approach include that it can be used in areas where there is little space to implement natural measures alone, it capitalises on the best characteristics of built and natural measures, it allows for innovation in designing coastal protection systems, and it can provide a greater level of confidence than natural approaches alone (Sutton-Grier et al., 2015).

Case study – coastal lagoon of Aveiro, Portugal

The coastal lagoon of Aveiro, Portugal, has long been studied for its peculiar configuration, high biodiversity and ecological value and its severe exposure to natural hazards (Lopes et al., 2017; Mendes et al., 2021; Pinto et al., 2020; Ribeiro et al., 2021; Stronkhorst et al., 2018). Situated along the Atlantic coast, Aveiro is extremely vulnerable to coastal erosion and SLR and thus requires integrated and sustainable management of coastal resources. Accordingly, over the last decade, Aveiro has applied a hybrid approach to coastal management by combining adaptation measures that mix traditional hydraulic engineering with green options (Stronkhorst et al., 2018), also known as “building with nature” (Chen et al., 2022).

One of the distinguishing aspects used in Ria de Aveiro is the combination of hard defences, beach nourishment and restoration of wetlands. Over the years, Aveiro has built approximately 10 sea walls and 20 groynes and combined these hard defences with beach nourishment along the coast to reinforce and enlarge beaches, providing natural barriers against tides and storms (Stronkhorst et al., 2018). Along with the latter two measures, Aveiro has restored previously abandoned salt pans. The latter plays a fundamental role in the mitigation of flooding and the protection of coastal communities as it increases the capacity to absorb excessive water during high tides and storm surges, thereby creating a natural protection against flooding. Overall, the hybrid approach has helped to increase the resilience to climate change in the coastal area of Aveiro, protect local communities, enhance recreational use and finally preserve coastal ecosystems.

Box 3: Sea level rise and World Heritage Sites: the case of the Wadden Sea

SLR and associated coastal hazards have been identified as a major threat to both natural and cultural coastal world heritage (Marzeion and Levermann, 2014; Sesana et al., 2020). Recent studies indicate that accelerating SLR is expected to exacerbate the pressure on World Heritage Sites (WHSs) through, among others, more frequent flooding or increasing erosion, with the number of threatened sites increasing sharply towards the end of the century in all scenarios (Reimann et al., 2018; Vousdoukas et al., 2022). For cultural heritage, potential impacts may range from direct damage to archaeological structures, buildings and monuments to changes in landscapes and visitor behaviour (Phillips, 2015). For natural WHSs, coastal erosion, permanent submergence and salt intrusion are examples of SLR-related processes that may alter the character and nature of a site, thus affecting its Outstanding Universal Value.

Adaptation of WHSs to SLR is particularly complex due to the potentially adverse implications of adaptive measures for heritage significance (Phillips, 2015) but also because different sites, due to their nature, have very different adaptation needs and no "one-fits-all solution" exists. Nevertheless, in some cases, natural areas may accommodate some of these disruptions and maintain ecological equilibrium by migrating landwards (Vousdoukas et al., 2022), if not constrained by coastal development, or even seawards where conditions allow. However, little information exists in the literature regarding potential adaptation options for heritage managers and policy-makers (Reimann et al., 2018). Although some adaptation options such as managed retreat, ecosystem-based adaptation and relocation have been proposed in the context of WHS adaptation to SLR (e.g. Vousdoukas et al., 2022), which mainly due to their non-intrusive nature appear to offer promising alternatives in some cases, a better understanding regarding their effectiveness and their suitability for specific sites is required for their implementation. Further adaptation barriers include the lack of institutional frameworks and policies specific to WHSs as well as financial and socio-cultural barriers (Fatorić and Biesbroek, 2020).

One example of adaptation of WHSs comes from the Wadden Sea, which has been a UNESCO World Heritage Site since 2009. The Wadden Sea is located in the North Sea between the coastlines of Denmark, Germany and the Netherlands and is the largest unbroken system of intertidal sand and mud flats in the world and one of the last remaining large-scale, intertidal ecosystems where natural processes continue to function largely undisturbed. The site includes the Dutch Wadden Sea Conservation Area, the German Wadden Sea National Parks of Lower Saxony and Schleswig-Holstein and a large part of the Danish Wadden Sea maritime conservation area (UNESCO, 2023). It is a large coastal wetland environment with tidal channels, sandy shoals, sea-grass meadows, mussel beds, sandbars, mudflats, salt marshes, estuaries, beaches and dunes (Schuerch et al., 2014; UNESCO, 2023), the development of which is driven by diverse morpho- and hydro-dynamics (Benninghoff and Winter, 2019). SLR projections for the Dutch Wadden Sea show a significant rise for all the scenarios and, in particular, a rise of 0.76 ± 0.36 cm under representative concentration pathway (RCP) 8.5 (Vermeersen et al., 2018).

Accelerated SLR can have important implications for the Wadden Sea, affecting sediment balance and potentially leading to permanent submergence in parts, despite its intertidal flats being effective sediment sinks and appearing to be quite resilient against even high rates of SLR (Hofstede et al., 2018). In fact, data from the last 2 decades indicate an expansion of intertidal areas but a reduction and deepening of subtidal areas and channels in some parts (Benninghoff and Winter, 2019). However, observed changes in tidal asymmetry in the German Wadden Sea suggest that sediment accretion trends may be coming to an end (Hagen et al., 2022). Furthermore, future projections indicate a transition from a tidal-flat-dominated system to a lagoon-like system, despite increased accumulation of sediment in the back-barrier basin, as this accumulation appears to be far too weak to compensate for the rise in mean sea level (Becherer et al., 2018). Such changes can potentially have dramatic implications for the unique ecosystem of the Wadden Sea (Becherer et al., 2018). Moreover, beyond a critical rate of SLR, major changes in ecotope distribution are projected to occur (Timmerman et al., 2021), and adaptation strategies such as inland migration of the shoreline can result in larger impacts, including the formation of a deep tidal basin with large subtidal habitats and a shifted intertidal zone (Timmerman et al., 2021). Besides SLR, potential changes in storm activity and characteristics can further affect the development of the site, particularly its wetlands, partially exacerbating or even counteracting the effects of SLR (Schuerch et al., 2013).

Although the future of the Wadden Sea under SLR appears to be a topic of concern and the need for adaptation is widely recognised (e.g. Heron et al., 2020), little has been done in terms of developing adaptation plans for the region. This is, in part, due to complexities related to the nature of the site, existing coastal protect measures and the involvement of three countries in its management. An example of such a plan is the integrated climate change adaptation strategy established by the German state of Schleswig-Holstein with the aim of maintaining the present functions and structures as well as the integrity and dynamic nature of the Wadden Sea ecosystem over the long term for its section of the Wadden Sea site (Hofstede and Stock, 2018). Developing such plans for the entire basin presents many challenges but is imperative for preserving the Wadden Sea and maintaining its World Heritage status.

3 Approaches for decision-making

This section presents approaches suitable for supporting coastal adaptation decision-making. A large number of approaches (methods, tools) are available in the literature and are being applied in practice to support coastal adaptation decisions (i.e. to find a suitable alternative given some criteria), and it is impossible to provide a comprehensive overview. Hence, we limit ourselves here to presenting key aspects that need to be considered in coastal adaptation decision-making, together with some example tools that can be used for addressing them. Towards this end, we first clarify the decision science terminology (Sect. 3.1) and review the common characteristics of coastal adaptation decisions (Sect. 3.2). Then, the section continues to present the key aspects that need to be considered in coastal adaptation decision-making, which are (i) considering multiple criteria and interests (Sect. 3.3), (ii) implementing low-regret and flexible options (Sect. 3.4), (iii) keeping future options open (Sect. 3.5), (iv) factoring SLR into decisions that need to be made today (Sect. 3.6) and (v) revisiting decisions iteratively together with monitoring (Sect. 3.7).

3.1 Decision science terminology

A decision involves a pre-defined set of options (also called alternatives or actions) to choose from, wherein each alternative can consist of a combination of measures. For example, common coastal adaptation measures include upgrading dikes, restoring coastal wetlands and installing building-level flood shields. An adaptation option may then consist in increasing the dike height by 1 m, restoring salt marshes in front of the dike and implementing flood shields to protect against floods with a water depth of 2 m. Typically, coastal decisions are not one-shot decisions but consist of sequences of decisions over time. Hence, the decision consists in choosing an adaptation pathway, which is a sequence of options applied over time (also called "policy" or "strategy" in some branches of decision science). Note that this general notion of adaptation pathways is independent of the method "adaptation pathway analysis" (Haasnoot et al., 2013), which is one tool that can be applied to produce adaptation pathways.

Approaches (methods, tools) to decision-making involve both participatory and analytical methods, which fulfil complementary roles in supporting adaptation decisions. Participatory methods (also called transdisciplinary, co-production or co-creation methods) target the social processes of learning and cooperating among stakeholders and possibly researchers (Anderson and McLachlan, 2016; Cornwall, 2008; Watson, 2014). Analytical methods, in turn, support the identification of suitable options or adaptation pathways in those situations in which it is not obvious what to do. They do so by helping to identify options that perform best or well with regards to the preferences of the stakeholders. Towards this end, each option is characterised by one or several criteria, which measure any relevant social, ecological or economic value associated with choosing and implementing the alternative (Kleindorfer et al., 1993). Criteria commonly used in the coastal adaptation domain include cost of options, avoided damages, longevity of options, robustness of options, flexibility of options as well as social acceptance.

3.2 Common characteristics of coastal adaptation decisions

Coastal adaptation decision-making is challenging due to the following characteristics.

- *Diversity of fundamentally different measures.* Section 2 highlighted that there are four fundamentally different ways to respond to SLR (protect, accommodate, advance and retreat), with each way having advantages and disadvantages. In addition, each of these categories entails many measures, which again come with their own advantages and disadvantages.

- *Multiple objectives and trade-offs.* Whatever approach to coastal adaptation is taken, the choice and planning of adaptation pathways generally need to consider multiple objectives. Adaptation policy is not only about SLR and flood risk but also needs to consider many other policy objectives, such as socio-economic development, human safety, biodiversity and water quality as well as the numerous human activities that coastal systems support, including shipping, agriculture, aquaculture, tourism and fishing. Therefore, there is generally no single "best" solution that satisfies all objectives. Instead, coastal adaptation decisions are characterised by trade-offs. For example, restoring wetlands for coastal protection and biodiversity reduces the space available for industrial or urban land use.

- *Diverse interests and social conflict.* Coastal decisions are generally characterised not only by multiple objectives, but also by diverse and often conflicting interests of stakeholders involved in and affected by the decisions, which gives rise to social conflicts (Oppenheimer et al., 2019). For example, homeowners or tourism operators may prefer not to have dikes in front of their homes if these jeopardise the view of the beach. As a consequence, stakeholders generally disagree on how to rank objectives or which criteria to apply for measuring progress towards objectives (see Bisaro et al., 2024, for governance arrangements, e.g. Marine Spatial Planning to address diverse interests in coastal adaptation).

- *Long-time horizons.* Many coastal decisions involve adaptation measures with long lead times and lifetimes (Haasnoot et al., 2020). For example, coastal protection infrastructure such as dikes, sea walls and breakwaters usually involves decision horizons of 30 to 100 years and more (Burcharth et al., 2014), and major protection infrastructure such as storm surge barriers generally takes decades to plan and implement and hence may be built for even longer lifetimes (Gilbert and Horner, 1986). Similarly, land use planning, coastal risk zoning and coastal realignment decisions (Hino et al., 2017) may have effects that last several decades, extending to over a century.

- *Large and deep uncertainties.* The long-time horizons involved in some coastal adaptation decisions are specifically challenging due to the large and deep uncertainties involved in long-term projections (i.e. 50 years and more) of SLR. Deep uncertainty means that SLR experts cannot attach a single unambiguous probability distribution to future SLR, because they cannot agree on an unambiguous method for deriving probabilities or because their subjective probability judgements differ (Kwakkel et al., 2010; Lempert and Schlesinger, 2001; Weaver et al., 2013). Projections of long-term SLR and other climate change variables are generally deep, because these depend on emission scenarios. However, also within a given emission scenario, uncertainty is large. For example, according to the latest IPCC report, there is a 65 % chance that sea levels will rise by 0.6 to 1.0 m until 2100 in all emission scenarios considered, with increases of up to 1.6 m or more also being possible (Fox-Kemper et al., 2021).

3.3 Considering multiple criteria and interests

Given the multi-objective and social conflict nature of the coastal decisions described above, participatory methods and multi-criteria decision analysis (MCA) methods can support most coastal decisions. MCA methods are standard methods for addressing multi-objective problems. These methods help stakeholders to structure the process of decision-making into a series of steps, to identify their preferences and to choose an option that is consistent with those preferences (Cinelli et al., 2020; Greco et al., 2016). For example, the MCA method called analytical hierarchy process guides stakeholders through pairwise comparisons of criteria in order to transform their preferences into weights for aggregating criteria into a single score for each option (Saaty, 1980). MCA methods have been applied widely in a coastal context (Townend et al., 2021; Le Cozannet et al., 2013; Hinkel et al., 2023). These methods are also an integral part of many decision-making tools, such as dynamic adaptation policy pathway (DAPP) analysis (Haasnoot et al., 2013), to which we will return later below.

MCA methods can, to some extent, also contribute to addressing social conflicts, e.g. by supporting the analytic search for compromises between stakeholders' divergent preferences (Munda, 2008), but the suite of available participatory methods entails much more, also beyond those methods that have a more analytical focus. Examples of such approaches include climate risk narratives (Jack et al., 2020), anticipatory learning (Tschakert and Dietrich, 2010), living laboratories (Bergvall-Kåreborn and Ståhlbröst, 2009) and citizens' juries, planning cells and consensus conferences (Escobar and Elstub, 2017). Generally, the normative literature on adaptation suggests that any analytical method for supporting adaptation should be embedded in a participatory process that includes all stakeholders in order to build trust, enhance legitimacy, reduce social conflicts and advance fairness and justice (Michels and De Graaf, 2010; Callahan, 2007; Irvin and Stansbury, 2004).

It is important to note that participation is not automatically a key to success. A growing empirical literature that describes how adaptation processes play out in practice shows that participatory processes often fail to deliver, either because they are poorly designed and implemented, conflicts cannot be overcome, or interests of powerful actors dominate outcomes (Harman et al., 2013; Oppenheimer et al., 2019). This resonates with a larger empirical literature in the field of public participation, which has found that many participatory processes are tokenisms, in which the have-nots are informed or heard but the power-holders retain the right to decide (Hoppe, 2011; White, 1996; Arnstein, 1969).

Two conclusions can be drawn from this discrepancy between the normative and descriptive literature. First, more empirical work is needed for understanding under which conditions participatory adaptation processes deliver. Second, it needs to be acknowledged that participation cannot solve all problems, in particular not those related to power asymmetries rooted deeply in social structure.

3.4 Implementation of low-regret measures

One immediate and generally recognised priority in coastal adaptation is the implementation of no- or low-regret measures. What this means in practice depends on the context, but generally this includes generic accommodate measures such as awareness raising, emergency planning and early-warning systems (Lumbroso et al., 2017). The strength of these measures is that they have high cost–benefit ratios over short time horizons, which means that implementing them today produces almost immediate net benefits (Oppenheimer et al., 2019). Early-warning systems have one of the highest cost–benefit ratios and should be a universal response (Rogers and Tsirkunov, 2010). However, these measures alone are only effective for current conditions, and small rises in sea level therefore need to be combined and/or replaced with other approaches if SLR is substantial.

Other low-regret measures can be found when addressing the local drivers of relative SLR and coastal hazards. These may include (1) the preservation of coastal wetlands to reduce both surge and wave impacts as well as the maintenance of sufficient accommodation space for these to migrate inland with SLR; (2) the maintenance of natural sediment supply by reducing dam building in rivers, which in turn reduces the risk of wetland loss and erosion; and (3) the reduction of anthropogenic drivers of subsidence and building land elevation with natural processes (Nicholls et al., 2021b).

Retreat is generally not a low-regret measure for densely populated and heavily used coastal areas, but it may be for rural areas if sufficient space is available to convert dry land into coastal wetlands that contributes to coastal protection. In the aftermath of disaster, retreat may also become low-regret for more densely populated zones when reconstructing livelihoods in situ becomes as costly as relocating. After Superstorm Sandy, for example, a number of flooded formerly developed areas around New York were purchased and not rebuilt, although this was a reactive rather than proactive response (Braamskamp and Penning-Rowsell, 2018). In Europe, one example of retreat happening after a disaster was Cyclone Xynthia, which hit the French Atlantic coast in February 2010, killing 47 people and causing total damages of about EUR 1.5 billion, which led to the decision to relocate some houses and neighbourhoods (Rouhaud and Vanderlinden, 2022). It must, however, be noted that part of this decision was later taken back due to strong civil opposition, which illustrates the difficult and socially contested nature of coastal retreat in general (Hino et al., 2017).

3.5 Keeping future options open

Given the large uncertainty about by how much sea levels will rise in the coming decades, an important policy priority is to keep future options open (Hinkel et al., 2019; Hallegatte, 2009). One way to do this is to postpone long-term decisions that do not need to be made today. Many decisions about retreating from the shoreline, in particular for urban areas, fall into this category (Oppenheimer et al., 2019). While SLR may rise by several metres, posing existential threats to coastal zones, there is also a substantial chance that SLR may stay below 30 cm by 2100 (50th percentile of SPP1–1.9) if Paris Agreement goals are reached. Protecting coasts from the latter amount of SLR is economically efficient and relatively cheap for about 90 % of the global population, as coastal population tends to be concentrated in coastal urban areas making up about 10 % of the global coastline (Lincke and Hinkel, 2018; Tiggeloven et al., 2020; Vousdoukas et al., 2020). Hence, a practical strategy for urban areas is to wait and observe how SLR observations and projections develop over the next decades, providing a robust basis for retreat versus protect decisions (Hinkel et al., 2019).

Another way of keeping future options open is by implementing flexible options that can be upgraded or changed over time once more is known about future SLR. This is generally an argument in favour of implementing soft and sediment-based measures such as NbS instead of hard measures, because the former can either self-adjust to relative SLR (in the case of coastal wetlands; see Box 2) or can easily be adjusted (in the case of sediment nourishment). However, flexibility can also be built into hard infrastructure. For example, in Germany, new coastal dikes are built with a wider crest than is necessary today, which allows further raising at low costs if SLR turns out to be higher than originally anticipated (MELUR-SH, 2012).

Postponing the decision and building flexibility in the current options raises questions of timing: by how much a decision should be postponed or how much flexibility should be built in. These questions can be addressed from an economic point of view by a class of methods termed real-option analysis (ROA), which is covered in the next subsection.

3.6 Factoring SLR into decisions that need to be made today

Some long-term decisions cannot be postponed and need to be made today. This may include decisions related to critical infrastructure, urban renewal, inadequate coastal protection, land use planning and land reclamation. As these and similar decisions have time horizons of decades to over a century (Azevedo de Almeida and Mostafavi, 2016; Haasnoot et al., 2020), factoring SLR into such decisions is beneficial. A range of analytical methods for supporting these kinds of decisions exists.

One classical set of methods for decision-making under deep uncertainty (i.e. without probabilities) is *robust decision-making* (van der Pol et al., 2023), which refers to a range of methods that identify adaptation measures that are effective in a wide range of scenarios (Heal and Millner, 2014; Lempert and Schlesinger, 2001; Wilby and Dessai, 2010). This includes so-called exploratory modelling, which uses models to create a large ensemble of plausible future scenarios and then searches visualisation techniques to identify robust options (Lempert and Schlesinger, 2000). Robust decision-making (RDM) also includes methods that follow similar ideas, such as robust optimisation (Ben-Tal et al., 2009), information gap theory (Ben-Haim, 2006) and classical approaches such as minimax and minimax regret (Savage, 1951). The latter approaches (i.e. minimax or minimax regret) are simple and low burden to apply and constitute a useful addition to e.g. standard cost–benefit analysis carried out for different sea level rise scenarios (van der Pol et al., 2021). The more complex approaches such as exploratory modelling and robust optimisation are generally applied in the context of an expensive coastal infrastructure project, such as upgrading the port of Los Angeles? (Sriver et al., 2018).

Another set of analytical methods for long-term decision-making under SLR is found in the so-called *adaptive decision-making* methods. These methods are suitable if adaptation decisions are not made as single-shot decisions today but as sequences of decisions at several moments in time, a situation frequently found in the coastal adaptation context. These methods aim at finding adaptation measures that are robust against a wide range of futures in that they are flexible to allow adjustments over time once more about SLR is known (New et al., 2022; Marchau et al., 2019).

Broadly, two categories of analytical adaptive decision-making (ADM) approaches exist (Völz and Hinkel, 2023). A first category of these methods starts with a user-defined set of adaptation options and then an analysis of how these options can be sequenced over time in different scenarios (e.g. SLR) in order to achieve the desired objectives (Walker et al., 2001). A widely used tool for such adaptive planning is adaptation pathway analysis (Haasnoot et al., 2013, 2012), which graphically explores how available adaptation measures can be sequenced over time, in order to reach adaptation goals. This analysis also considers the lead times of adaptation measures (i.e. the time needed for planning and implementing adaptation measures), because rapid SLR may lead to insufficient time being left to plan and implement measures with long lead times, such as surge barriers, as these usually take decades to plan and implement (Haasnoot et al., 2020). A prominent example where this approach has been applied is the Thames Barrier in the UK, which protects the city of London. Within the Thames Estuary 2100 project, adaptation pathway analysis has been applied, next to other approaches, in order to find out whether there is sufficient time to upgrade or replace the Thames Barrier under a rapid acceleration of SLR (Ranger et al., 2013).

The second category consists of *economic ADM approaches*, which identify optimal adaptation decision rules by taking into account information about what will be learned in the future about the development of key climate variables. These methods are often found under the labels of real-option analysis (Wreford et al., 2020) and optimal control studies (Hermans et al., 2020). Importantly, these methods consider future learning about relevant variables (e.g. mean and extreme sea levels) in the economic valuation of adaptation measures in order to find optimal trade-offs between investing today, including the cost of flexible design, and postponing investment decisions until additional information is available (Dixit and Pindyck, 1994). Hence, these methods can provide justifications for whether implementing flexible adaptation measures today are worth the extra costs. This is specifically relevant for public decisions that involve expensive and long-lasting infrastructure, as found on coasts, because the public sector needs to justify public money being spent wisely. While ROA applications of adaptation to coastal and river floods are growing (Dawson et al., 2018; Kim et al., 2019; Hino and Hall, 2017; Linquiti and Vonortas, 2012; Woodward et al., 2011, 2014; Ryu et al., 2018), to date they are poorly connected to state-of-the-art SLR science. The first steps towards closing this gap were taken by Völz and Hinkel (2023), who developed SLR learning scenarios based on the SLR scenarios of the IPCC's Sixth Assessment Report (AR6).

A critical and difficult decision that needs to be made in the application of all of the above-mentioned decision analysis methods is how much SLR should be considered in a particular decision. Importantly, sea level science can only give a partial answer to this question, because the other part of the answer depends on the uncertainty preferences of the stakeholders involved in and affected by the decisions. When stakeholders are uncertainty-tolerant and the value at risk is relatively low, then the "standard" IPCC scenarios, which provide a so-called *likely* range of possible future SLR, are a good basis for decision-making (Oppenheimer et al., 2019). If stakeholders are less tolerant of uncertainties, which is often the case in urban contexts, then higher SLR scenarios should also be considered. This is because the IPCC's *likely* range is the 66 % central interval of future SLR, which means there is a 17 % chance of SLR exceeding the likely range, which may be too large a chance for uncertainty-averse stakeholders (Hinkel et al., 2015; Nicholls et al., 2021a). In this case, more unlikely SLR scenarios should be considered, with the exact choice depending on the stakeholders in the specific case. The IPCC AR6, for example, states that, in the case of unlikely but rapid melting of the ice sheets, a 2 m rise in sea level by 2100 cannot be excluded in an unabated emission scenario (SPP5–8.5) (Fox-Kemper et al., 2021).

3.7 Revisiting decisions iteratively and monitoring

No matter which decision analytical method is applied, a final and critical priority is to set up an iterative policy- and decision-making process (Fig. 9) that regularly revisits decisions and that includes a monitoring framework, through which SLR and other relevant variables are monitored and appropriate action can be triggered if a relevant threshold is crossed (Walker et al., 2001, 2013). The idea is to implement no- or low-regret options and flexible measures today and then monitor SLR, ESL and other decision-relevant variables in order to be able to identify when decisions and new policies are required. Importantly, a monitoring system is essential for identifying the need for action in sufficiently early time to allow planning and implementation before negative impacts occur (Hermans et al., 2017). One well-known framework that entails this idea (and combines it with the adaptation pathway analysis covered in the last subsection) is DAPP (Haasnoot et al., 2013). This method has been widely applied in various contexts and has, for example, been integrated into the national guidance for coastal hazard and climate change decision-making in New Zealand (Lawrence et al., 2018).

4 Summary: key developments per basin

Adaptation to SLR in Europe has been approached through various types of measures to accommodate, protect, advance and retreat. Below, we summarise the main developments organised by the different sea basins.

In the Baltic Sea basin, for accommodate measures, progress has been made, with several Baltic nations incorporating SLR projections into their spatial planning and land

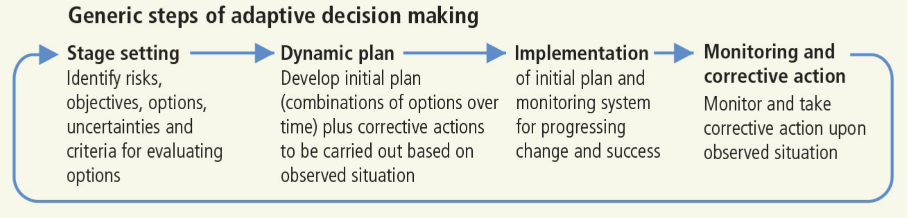

Figure 9. The adaptive decision-making cycle. Source: extracted from the original figure available at SPM.5d (IPCC, 2019).

use regulations. Notably, Estonia has implemented a Maritime Spatial Plan for 2022 that integrates SLR information. In terms of protect measures, upgrading coastal defences, e.g. with sea walls, embankments and dikes, has been implemented, while nature-based solution initiatives to restore and create wetlands and coastal marshes that can act as buffer zones and reduce wave energy are also underway. For instance, the Danish Baltic coast provides the first large-scale example of successful managed realignment with the restored Gyldensteen Coastal Lagoon, which has to date enhanced ecological status and species richness in the project area (Thorsen et al., 2021). The Baltic Sea basin has also seen progress in marine environment conservation, which can potentially enhance living marine resources and related fishing activities. Key to furthering coastal adaptation in the basin is ensuring that solutions are also linked to financing mechanisms that can mobilise co-finance, e.g. from the private sector, to supplement national public funding.

In the North Sea basin, SLR information has been integrated into coastal planning at the national and sub-national levels in most countries, while North Sea basin countries are implementing different mixes of hard and soft protect measures. In the Netherlands, the Delta Programme includes a comprehensive mix of measures to maintain a healthy groundwater system, using spatial planning and other context-specific strategies while providing more space for water and enhancing urban and ecological values. Sand nourishment is also growing in importance as a coastal protect measure in the Netherlands, alongside dike upgrading and reinforcement. In Germany, there is an emphasis on integrated coastal zone management and dike upgrading and widening that incorporates flexibility for future SLR. In the UK, a mix of protection, beach nourishment and managed retreat is being considered for different sections of the coastline. These countries each reflect different approaches to addressing uncertainty that should be iterated and revisited as more information on SLR becomes available in the future.

In the Mediterranean Sea basin, key developments include the mainstreaming of SLR information into planning through the development of national adaptation plans, e.g. in Spain and Italy. Furthermore, insurance is emerging as an accommodate measure to address SLR-related risks, e.g. in Spain and France. Soft protect measures, such as sand nourishment and nature-based solutions more broadly, are important in the Mediterranean Sea basin, with coastal reforestation and the restoration of dunes and marshes implemented in various regions to act as natural barriers. Other examples are cliff strengthening and stabilisation measures that include green and grey options focusing on reducing erosion and enhancing natural protection along coastal cliffs, e.g. in Croatia and Italy. Several major urban areas in the basin have initiated large-scale adaptation measures. For example, the Venice MOSE project is a system of mobile barriers constructed to protect Venice from high tides and flooding, while the city of Barcelona has introduced green infrastructure projects that focus on permeability and water retention to combat both SLR and increased rainfall. Such differentiated measures appropriate to the specific biophysical and socio-economic context at issue should be further supported through participatory co-development approaches for coastal decision-making (Bisaro et al., 2024).

In the Black Sea basin, there is an increased emphasis on developing monitoring and early-warning systems to help manage SLR and the associated flood risks. Furthermore, efforts have focused on upgrading and modernising existing coastal infrastructure to enhance resilience to rising sea levels. For example, in Romania, a major initiative combining sand nourishment and cliff stabilisation with marine measures including artificial reef building is being implemented to reduce coastal erosion risks exacerbated by SLR and to enhance resilience in the tourism sector. Furthermore, implementation of such nature-based solutions that also benefit local economies is promising and should be explored for scaling up coastal adaptation in the basin.

In the Atlantic Ocean basin, countries are implementing a range of adaptation measures, with an emerging focus on nature-based solutions and improved spatial planning to reduce risks to coastal development across the entire basin. Soft protect measures, such as cliff strengthening and sand nourishment, are being implemented in Portugal, while restoration measures, protecting against wave energy and therefore limiting erosion and sediment accumulation, are being implemented in Spain, Portugal and France. Advance strategies are also being implemented through nature-based solution approaches, as in Spain, where the national adaptation plan envisions the regeneration of beaches and artificial dune systems to reduce erosion and revitalise coastal ecosystems, e.g. in the restoration of one of the largest dune systems of the Cantabrian Sea. Furthermore, in France, coastal land in the south-west of the country has been advanced with the creation of a vegetated area with the specific intention of supporting natural accretion of land and surrounding low areas. Finally, retreat measures are also being implemented, such as in Portugal, where the progressive removal of constructions located in flood-critical territories along the coastline is being implemented through spatial planning instruments to manage the risk of SLR.

Common themes and general trends are further highlighted in the conclusion.

5 Conclusions

This paper has conducted a review of the literature on coastal adaptation. The main outcome of this process, which is summarised in Table 1, was the collection and categorisation of 17 adaptation measures to SLR, focusing on European sea basins and targeting four climate impacts, namely coastal flooding, saltwater intrusion, coastal erosion and impacts on ecosystems and estuaries. The table combines two categorisations regarding the responses to SLR: first, a top-level categorisation of adaptation measures according to the four main types of response identified by the IPCC and a further elaboration taking into account the sub-Key Type of Measure (sub-KTM) to SLR developed by the EEA. By reviewing the relevant literature on European sea basins, the paper has shown that adaptation strategies on Europe's coasts include a mix of hard and soft measures, planning measures, policy developments and stakeholder and community engagement. A common theme across all the basins is the shift towards a combination of traditional engineering solutions with soft measures, such as nature-based solutions.

The measures discussed in this paper are generally subject to trade-offs that should be considered when planning for coastal adaptation. In order to accurately analyse existing trade-offs, it is important to understand the effectiveness and feasibility of these measures. The paper identified a critical gap in the literature in this regard. In particular, there is a scientific need to assess the effectiveness and feasibility of individual measures and in context-specific cases. Such a research gap, if addressed, could advance knowledge and contribute to the field of coastal adaptation. Hence, these findings suggest that the literature review can be expanded to include more studies and that more research is needed to learn about the trade-offs of implementing each of these measures.

In terms of decision-making approaches, the paper has shown that coastal adaptation is a complex undertaking, mainly because of five key common characteristics, namely the diversity of fundamentally different measures, the multiple objects and trade-offs, the multiple interests and social conflicts, the long time horizon, and the large and deep uncertainties involved in such decisions. To support decision-making processes, analytical tools are available, ranging from relatively straightforward tools such as adaptation pathway analysis and multi-criteria analysis to technically complex methods such as robust decision-making and real-option analysis.

Integrating local communities into decision-making processes and emphasising the importance of continuous monitoring and flexible management strategies are notable trends. Ensuring that these trends lead to appropriate mixes of coastal adaptation measures being found depends on the continued support and involvement of public and private sector stakeholders in effective multi-level governance. To this end, it should be noted that there is a large discrepancy between the normative and descriptive literature in the participatory approaches for supporting decisions, and more empirical work is therefore needed to understand the conditions under which participatory adaptation processes are delivered.

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Sea Level Rise in Europe: Governance context and challenges

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Abstract. Sea level rise (SLR) will affect Europe's coasts over the coming decades and beyond, giving rise to ongoing challenges in governing coastal and marine areas. Progress is being made in adapting to and addressing these challenges at both national and sub-national levels across all major European sea basins. This paper assesses progress in coastal adaptation governance in Europe by, first, characterising the socio-economic and political contexts in European sea basins and then by reviewing coastal-adaptation-relevant policy frameworks in place at regional and national levels within each of these sea basins. The regional frameworks reviewed are derived from regional sea conventions and are assessed for their legal status and their inclusion of SLR information. The national coastal policy frameworks reviewed include national adaptation plans focusing on coastal areas and marine spatial planning instruments for all European member states, as well as public financing arrangements for coastal adaptation, focusing on flood risk reduction measures. Key national policies for coastal adaptation are assessed for which coastal hazards they address, the extent to which they incorporate sea level rise information and their inclusion of SLR-specific adaptation measures. Finally, the paper presents governance challenges that arise due to the complexity of adaptation to SLR, i.e. time horizon and uncertainty, cross-scale and cross-domain coordination, and equity and social vulnerability, and discusses examples illustrating how each of these challenges is being addressed in different European sea basins. The paper finds that for all basins, regional policy frameworks generally do not include specific provisions for SLR or coastal adaptation, while at the national level, significant progress on SLR governance is being made. For all basins except for the Black Sea, all countries have reported observed and future SLR hazards and have adopted adaptation strategies. The inclusion of adaptation measures specific to SLR is less advanced, as most sea basins have at least one country that does not include specific SLR adaptation measures in either their adaptation strategies or their marine spatial plans. Regarding SLR governance challenges, key examples of how these are being addressed include approaches for incorporating flexibility into coastal planning, e.g. dynamic adaptation pathways in the Netherlands or dike crest widening in Germany, as well as co-development of nature-based adaptation solutions in Italy. Examples of addressing equity and social vulnerability challenges include the emerging issue of climate ligation illustrated through several court cases on liability for SLR-related damage.

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1 Introduction

Sea level rise (SLR) will affect Europe's coasts over the coming decades and beyond, giving rise to ongoing challenges for governing coastal and marine areas. Sea level rise will increase the frequency and intensity of coastal flood hazards; alter shoreline dynamics, potentially increasing coastal erosion; and increase saltwater intrusion, altering risk profiles in European coastal and marine areas (cf. van de Wal et al., 2024, for a comprehensive review). These impacts must be integrated into coastal governance approaches in order to ensure resilience, equity and sustainability over the long term.

Coastal governance can be defined as a comprehensive framework comprising institutional, structural and legal arrangements – primarily policies, regulations and economic activities, as well as social and cultural institutions established through processes of assessment, consultation and decision-making in a multiscale structure ranging from the local to the global level (Stephenson et al., 2019). Coastal governance thus involves heterogeneous subjects, such as coastal management, land-use planning, environmental law and policies, and environmental science, that interact within coastal governance structures. As an arena where the effects of many land-based and sea activities intersect, coastal governance is thus complex and can be characterised by not only conflict but also policy integration (Van Assche et al., 2020). The latter requires in-depth knowledge of coordination mechanisms, governance planning and related challenges. In this context, the challenges of managing Europe's sea basins in a healthy, productive, safe and resilient manner (Ocean governance) have emerged and are exacerbated by the cumulative nature of the impacts of activities carried out in coastal areas and of sea level rise. Thus, coastal governance challenges under SLR involve increasing complexity due to the long time horizons and uncertainty involved in planning for SLR, cross-scale and cross-domain coordination needed to deal with the scale of the challenge, and ensuring equity and addressing social vulnerability in adaptation to SLR. This paper set outs to assess progress in Europe in addressing these challenge by both reviewing the regional and national policy contexts in which coastal governance takes place and examining specific examples of approaches.

In order to do so, the paper focuses on six European sea basins: the north-east Atlantic Ocean, Mediterranean Sea, Black Sea, Baltic Sea, North Sea and Arctic Ocean. For each basin, the paper reviews (i) key intersections between geopolitics and socio-economics of the basin and SLR; (ii) coastal governance policies in force to clarify the enabling and constraining conditions of the institutional frameworks relevant to the European Union; and (iii) financial arrangements for coastal adaptation, decision-making under uncertainty, and cross-cutting and cross-domain coordination. Further, the paper then (iv) analyses approaches to governance challenges related to SLR in a fair, equal and democratic way in Europe. Finally, the concluding section discusses how governance challenges caused by SLR are being addressed within each of the basins. Throughout the paper, specific examples of approaches to addressing these governance challenges have been highlighted in text boxes in the relevant sections.

2 Geopolitical and socio-economic context of SLR governance

2.1 Geopolitical context in European sea basins

SLR may exacerbate geopolitical conflicts and act as a risk multiplier (Stephenson et al., 2019). It has relevant socio-economic, environmental and cultural consequences for European daily lives (European Environment Agency, 2024a), threatening livelihoods and industry, food and water security, health, infrastructure, critical services, and cultural heritage. Low-lying areas and coastal zones are particularly vulnerable (Horton et al., 2018), which poses substantial challenges to many European countries where millions of people live in coastal settlements (European Environment Agency, 2024b).

European sea basins have become geopolitical hotspots in recent years, and against this background, addressing SLR-related challenges will require a high degree of cooperation and joint action across sea basin boundaries, with specific and tailored strategies. In this respect the EU has been employing great efforts to foster positive cooperation and promote further connectivity in these regions, which can be challenging, especially in contexts where there is a mix of EU member states and associated countries, as in the case of the Mediterranean and Black seas (see "Key multilateral policy frameworks governing coastal adaptation" under the "Coastal governance" section).

SLR and the challenges it poses comprise a geopolitical issue for all European sea basins. Some of the sea basins have already experienced clear geopolitical issues related to sea level rise, and these have been reported in the literature. The following paragraphs elaborate on these specific examples that have already been tracked, and although some of the sea basins do not yet have specific examples, the geopolitical challenges that have emerged in one sea basin can easily be verified in the others in the future.

The Mediterranean Sea basin is a non-homogeneous area that has witnessed the emergence of state fragility, conflicts and security threats in countries that will be unevenly affected by the impacts of SLR. In northern Africa, for instance, saltwater intrusion is contaminating land and freshwater resources, destroying crops and livelihoods alike. Southern Europe and low-lying coastal regions, including many densely populated cities, are hotspots for risks such as erosion and saltwater intrusion aggravated by SLR (European Environment Agency, 2024a). Despite these effects of SLR in southern Europe, the European shore has better tools and levels of resilience against such impacts than other bordering countries of the Mediterranean Sea basin, which demonstrates that overcoming geopolitical and socioeconomic challenges will require a high level of cooperation and joint action across borders (de Marignan, 2023). Hence, priorities in this sea basin include promoting conflict prevention and peacebuilding, counter-piracy, maritime security, counterterrorism, and the management of migration flows. This signals that strengthening partnerships with all neighbouring countries is a strategic imperative for the EU (European Commission, 2021b).

SLR also poses challenges for infrastructural security in the sea basins, as it can affect vessel navigation, critical waterways, transportation routes and berthing with ports. Damage to lighthouses and erosion of coastal roads are also risks. In addition to coastal facilities, low-lying military installations, especially in naval bases in the Black Sea, are also particularly susceptible to SLR (Mihailov et al., 2023). In this sea basin, therefore, the key issues are long-term stability, conflict management and the consolidation of a stable energy supply.

Critical maritime infrastructure is a salient issue for the Baltic Sea countries due to their role in energy security, underwater security and military planning (Swistek and Paul, 2023). Two elements are central to the SLR in the Baltic Sea basin: while the relative increase in SLR may be counteracted by land uplift in the northern areas, the ice cover situation will further decrease with a lowering of the maximum sea ice extent. Besides, SLR could also affect oil and gas operations, competition for energy resources, and potentially strategic positions on global trade routes (Thangaraj and Chowdhury, 2022). Hence, the strategic interests in this sea basin are energy security, trade and business, transnational crime, and targeted influence on societies in terms of information and cyberspace.

As a major transport hub in Europe, the North Sea basin hosts a strong transport and logistics industry (CPMR North Sea Commission, 2020). It is an attractive setting for offshore wind farms, with renewable-energy potential expected to increase as new technologies emerge and Europe's electricity networks are modernised (Mjahed, 2023). Sea-based energy supplies and maritime energy infrastructure are becoming increasingly relevant within European infrastructural decoupling from land-based supplies, and offshore wind farms and undersea power cables are likely to cover a relevant part of the electricity demand of Europe in the maritime region (Just Climate, 2022). Over the next decades, therefore, the North Sea is likely to play a key role in Europe's energy transition for net-zero emissions and in achieving the EU's climate targets, which require further policies and investment in green energy sources, technologies and grid infrastructure (CPMR North Sea Commission, 2020).

The Atlantic Ocean basin is the largest in terms of gross value added (GVA) and plays an important role in the blue economy of the EU (EU Blue Economy Observatory, 2024). Its countries play a vital role in maintaining international stability and security to balance the power distribution within the region (Adhitama, 2019), with regard to key issues such as maritime surveillance, the exercise of sovereignty at sea and the sustainable exploitation of natural resources (see Sect. 2.2). Further, international cooperation on aspects of communication systems such as submarine cables or cooperation between islands and Atlantic spaces is also important geopolitically and for security in the basin (Instituto de Defesa Nacional, 2022).

In the Arctic Ocean, as permafrost melts and coastlines erode, there is likely to be competition over land claims for oil and gas reserves, natural minerals, hydrocarbon, and rare earth elements useful for modern technology, also making the region a site of increasing global competition for profitable trade routes (Gross, 2020). The EU's engagement in the Arctic Ocean is crucial for European security, given the interest in resources and transport routes (European Commission, 2021b).

This overview signals that the European Union faces the challenge of aligning long-term climate goals with short-term supply chain security and managing energy independence with geopolitical risks and uncertainties.

2.2 Economic context in European sea basins

The EU economy significantly relies on service sectors, which accounted for more than 70 % of the value added to the economy in 2020, while importing about two-thirds of its energy, especially natural gas and crude oil. In 2020, the total weight of goods transported through EU ports by short sea shipping was 1.7×10^9 t (Eurostat, 2022). The European Climate Risk Assessment observes that SLR will increase the frequency and severity of coastal flooding in Europe, with potentially devastating impacts on Europe's population, infrastructure and economic activities (European Environment Agency, 2024a, c). In this sense, SLR may have relevant economic consequences for GDP at regional and sectoral levels in Europe. Predictions demonstrate that damage caused by SLR could amount to EUR 871.8 billion for the continent by the end of the century, a GDP loss of 1.26 % for the whole of the European Union (Cortés Arbués et al., 2024).

EU policy relevant to coastal and marine areas is guided by the European Commission's Sustainable Blue Economy Partnership, which stipulates that activities such as fisheries, coastal tourism and maritime transport reduce their environmental and climate impacts, tackle biodiversity loss and create alternatives to fossil fuels. Investment in new technologies is also a priority, with special attention given to wave and tidal energies, development of innovative fishing gear, and restoration of marine ecosystems, each of which may also create green jobs and business (Eurostat, 2022). The *EU Blue Economy Report 2023* shows that most of the sectors have increased their economic development since 2020.

For instance, from 2010 to 2020, GDP has increased +25 % for living resources, +25 % in port activities, +1762 % in offshore wind energy, and +22 % in ship building and repair. Notably, employment in the offshore wind energy sector surged by 20 times over the last decade (European Commission, 2023b).

Table 1 describes, for each sea basin, the currently significant economic sectors in coastal and marine areas as well as emerging sectors relevant to the EU sustainable blue economy approach.

3 Coastal governance

The governance of SLR involves a broad range of institutions, actors and stakeholders. In addition to the affected countries and their governmental agencies, commercial entities – mainly of manufacturing, transport, fisheries and tourism; fossil fuel users and producers; and international, non-governmental and also scientific organisations make up the key actors in play (Douglas and Kaspari, 2019). Regarding the norms, policy frameworks relevant to SLR governance at European sea basin spheres are in place at two levels: the regional level through multilateral agreements between states and the national level. The latter remains the key level for the management of coastal and marine areas because national policy-makers maintain decision-making authority for the planning as well as design, implementation and financing of measures in coastal and marine areas in Europe. A further key dimension of governance is the financing of coastal adaptation and approaches to public finance of coastal adaptation, which are also reviewed below.

3.1 Key multilateral policy frameworks governing coastal adaptation

The policy and governance frameworks currently in place to tackle the impacts of climate change on coastal areas include diverse and cross-cutting instruments. At the international level, these mainly include the UN 2030 Agenda for Sustainable Development, the United Nations Convention on the Law of the Sea (UNCLOS), other regional sea conventions (RSCs) and the integrated coastal zone management (ICZM) process. At the European level, while the European Green Deal generally targets the protection of oceans and coasts, it does not include specific instruments or measures concerning SLR. However, other policies have previously addressed issues related to SLR, as in the case of specific directives such as the Maritime Spatial Planning Directive (European Commission, 2014b), the Floods Directive (European Commission, 2007) and the Marine Strategy Framework Directive (European Commission, 2008), which are relevant policies for climate resilience in coastal zones.

Furthermore, aiming to make the adaptation process more systemic, the 2021 EU Strategy on Adaptation to Climate Change recognises the importance of addressing climate impacts and resilience in all sectors and areas, including coastal zones.

The 2030 Agenda for Sustainable Development is a global action programme aimed at guiding the action of individual states and the international community in the different areas of sustainable development. The 2030 Agenda for Sustainable Development and its sustainable development goals (SDGs) have become an international reference framework for sustainable development, understood in its three dimensions of economic growth, social inclusion and environmental protection. The “fight against climate change” is goal number 13 of the agenda and is composed of five targets, among which are those that call for “strengthening resilience and adaptation to climate-related risks and natural disasters in all countries” (13.1) and for “integrating climate change measures into national policies, strategies and planning” (13.2). Besides, for the first time, the conservation and sustainable use of the oceans were addressed in an overarching global policy agenda. SDG 14 – Life Below Water – brings ocean governance to the forefront of the dialogue on sustainable development, enabling a structure that can benefit ecosystems as well as people and their livelihoods (Vierros, 2017).

UNCLOS is the international agreement which sets forth the legal framework for all activities on the oceans and seas. UNCLOS defines the rights and responsibilities of states with respect to their use of the oceans and establishes principles of protection of the marine environment, including the ecosystem-based approach, the precautionary principle and sustainable development. UNCLOS provisions approach the limits of maritime zones and the rights of passage and navigation through them, establishing principles on how states should determine the breadth of the maritime zones.

Regarding climate change and SLR, this legal framework is mainly relevant due to legal implications of SLR on baselines from which the outer limits and boundaries of maritime zones are determined (e.g. some parts of the world may witness a substantial shift in the configuration of the coasts, which can consequently affect base points and baselines). UNCLOS is one of the most widely ratified treaties under the international law framework and is currently a legally binding instrument for 168 signatories, including the EU. Under this treaty, the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) was adopted in 2023. This international legally binding treaty aims at ensuring the responsible use of the marine environment, maintaining the integrity of ocean ecosystems and conserving marine biological diversity. While countries’ exclusive economic zones are legally separate entities from the BBNJ, they have an ecological and biological connection. Thus, governance in this context would benefit from an ecosystem approach that considers species that cross political boundaries. This approach would be positive for fishery resources; migratory species; and coastal communities for which ecosystems have economic, social and cultural im-

Table 1. Key economic sectors and developments in coastal and marine areas in European sea basins (see all the references in the table footnotes).

Sea basin	Current economic sectors	Emerging sectors
Mediterranean Sea[a]	*Coastal and maritime tourism.* This is the world's leading tourism area with 35 % of all international tourist arrivals. It accounts for 13 % of Mediterranean countries' exports. In 2018, 2.3 million businesses employed 12.3 million individuals in tourism-related sectors. *Fishing and aquaculture.* This sector accounts for a workforce and employment of 1 million people. The total revenue from marine capture fisheries for the Mediterranean area was estimated at USD 2.7 billion, while the total employment on board fishing vessels was 166 000 in 2020. USD 12 billion is the estimated combined output of fisheries and aquaculture, and 112 % is the increase in aquaculture production in the EU Mediterranean countries expected in 2030 in comparison to 2010.	*Desalination.* This is a blue economy emerging sector with more than 2300 operational desalination plants in the EU producing about 9.2×10^6 m^3 d^{-1} of desalinated water. *Floating offshore wind.* This is a viable option for deep waters, possibly opening new markets, as the highest resource potential for ocean energy. *Offshore green energy development.* Italy, Spain and Albania have signed a memorandum of understanding for the development of five green hydrogen projects in the Mediterranean Basin (three in Italy, one in Albania and one in Morocco). In Spain, Naturgy and Energas have announced a plan for a green hydrogen project off the coast of Asturias.
Black Sea[b]	*Fishing.* The total revenue from marine capture fisheries was estimated at USD 241 million in 2020, with a total employment on board fishing vessels of 28 000. *Aquaculture.* Production has grown from over 500 000 t of farmed seafood in 2017 to over 700 000 t in 2019, helping to boost food security and providing jobs and incomes.	*Ocean energy.* The potential for wave energy and floating offshore wind may open new markets in this basin, fostering EU competitiveness.
Baltic Sea[c]	*Shipping and port activities.* These account for 15 % of the world's cargo traffic in 2017. *Fishing.* In 2018, the fleets numbered 290 vessels and employed 4265 full-time-equivalent workers. The revenue generated amounted to EUR 215 million, 74 % of which came from Poland, Sweden, Finland and Denmark.	*Offshore wind energy.* Currently only 2.8 GW of total capacity is installed, and the Baltic's eight border countries are committed to increasing that to 19.6 GW by 2030. Offshore energy is projected to multiply 5-fold by 2030 and 30-fold by 2050 on an EU-wide level. *Wave energy.* This is a renewable source with localised exploitable potential. *Offshore green hydrogen.* Its development has an important source through the wind energy of the sea.
North Sea[d]	*Shipping and port activities.* This is one of the world's busiest shipping grounds with over 7600 ships passing through hotspot areas of this sea basin. *Oil and gas.* This is western Europe's most important oil and gas production area that yields high-quality crude oil with a low sulfur content. *Fishing.* This is one of the world's most important fishing grounds, with around 6600 active fishing vessels.	*Wave energy, wind energy and floating solar photovoltaic energy.* Regarding the potential of floating photovoltaics, the Dutch government aims to develop pilot projects in the North Sea in the period 2021–2026 to monitor the efficiency and environmental impact of such installations. *Offshore wind energy.* Germany, France, Belgium and the Netherlands intend to jointly build 150 GW of offshore wind energy by 2050. The states also plan to collaborate on joint offshore wind projects, energy islands and offshore grid infrastructure, as well as strengthening renewable hydrogen production.
North-east Atlantic Ocean[e]	*Coastal and maritime tourism.* This area offers high-quality tourism, and in 2019, Lisbon was the most visited port of call for cruise ships along the Atlantic coast of Europe, with 310 port calls. *Shipping and ports.* Shipping activities have increased by 34 % since 2019, including in 73 % of marine protected areas, and western Scotland experienced the largest increase in vessel density. *EU blue economy.* This is the largest sea basin in terms of GVA (36 % of the EU blue economy GVA). In 2017, the blue economy in the Atlantic Ocean employed 1.20 million people.	*Ocean energy.* At the European level, the Atlantic coast has notably the highest resource potential for wave and tidal energies, which are expected to be further developed up to 2030 with new EU resources and projects such as EnergyMare and the improvement of technologies. Deep-sea mining, environmental monitoring, desalination and offshore wind are also relevant sectors for the future.

Table 1. Continued.

Sea basin	Current economic sectors	Emerging sectors
Arctic Ocean[f]	*Oil and natural gas.* Important resources of minerals, notably hydrocarbons, and two of the world's major producing areas for oil and natural gas lie in the Arctic, namely north-western Siberia and the North Slope of Alaska. *Fishing, shipping and manufacturing.* These are strong industries in these sectors at the macroeconomic level. In 2016, the Arctic provided about USD 281 billion per year in terms of food, mineral extraction, oil production, tourism, hunting, existence values and climate regulation.	*Fibre cables and data centres.* Strategically located for global connectivity, the melting Arctic ice creates new opportunities for the tech industry. Technologies can benefit from the cold climate and abundant hydropower, and some of the largest data centres are scheduled to be built in the region. *Raw materials underground.* A warmer climate will enable mining in previous inaccessible zones. The region is rich in raw materials that are relevant to green technologies, e.g. used in batteries for electric cars and wind turbines.

[a] Plan Bleu (2022), FAO (2020), European Commission (2021c), Interreg Sudoe (ECCLIPSE: Assessment of Climate change in Ports of Southwest Europe), ISPI (2023). [b] FAO (2020, 2022), Kakachia et al. (2022). [c] Just Climate (2022), Krūmiòš and Kïaviòš (2022), Swistek and Paul (2023). [d] Chirosca et al. (2022), CPMR North Sea Commission (2020), Mjahed (2023). [e] UNCTAD (2022), O'Garra (2017), European Commission (2014–2020). [f] Mancebo Silva (2022), Gross (2020), European Commission (2021d).

portance. Marine areas beyond national jurisdiction present particular challenges, since they need integrated approaches but there is no organisation or institution in charge of the overall management responsibility. Besides, except for UNCLOS, current international regulation and institutional arrangements are all sectoral in nature (Vierros, 2017).

The regional sea conventions (RSCs) are cooperation structures set up to bring together states and neighbouring countries that share marine waters to protect the marine environment of a specific region. Some of these instruments are part of the United Nations Environment Programme (UNEP) Regional Seas Programme,[1] and they provide inter-governmental frameworks to address the ecological degradation of the oceans and seas at a regional level. While in an initial phase they focused on sea pollution, they are currently embracing the ecosystem approach to managing marine resources. There are also different protocols annexed to these treaties, including those on integrated coastal zone management (ICZM) through which one can address disaster reduction and climate change adaptation issues.

The European Commission has adopted initiatives such as the EU Maritime Security Strategy (EUMSS), which since 2014 has aimed to protect the EU's economic and infrastructure interests at sea; safeguard the marine environment; uphold international law – in particular the United Nations Convention on the Law of the Sea; and ensure training against growing cyber and hybrid threats. In 2023, the European Commission enacted an update of the EU Maritime Security Strategy and its action plan. The document approaches SLR as a climate-related challenge with a long-term and rolling-basis time frame for actions that are mainly related to developing awareness and preparedness for the phenomenon. In this sense, the management of risks and threats involves increasing "knowledge on the effects of climate change, SLR, storm surges, and environmental degradation on maritime security and addressing related risks and threats" (European Commission, 2023a). Besides, the Marine Strategy Framework Directive (MSFD) is the EU's main tool to protect and conserve the health of coasts and seas, aiming to achieve a good environmental status of the EU's marine waters and sustainably protect the resource base upon which marine-related economic and social activities depend. Adopted in 2008, the MSFD made the ecosystem-based approach legally binding for managing the EU's marine environment and maintaining resilient ecosystems while securing a sustainable use of marine resources.

The European regional sea conventions are the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR); the HELCOM Convention on the Protection of the Marine Environment of the Baltic Sea (Helsinki Convention); the Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention or BAR-

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[1] UNEP's Regional Seas Programme has three types of regional sea conventions, namely (a) UNEP-administered – established and directly administered by UNEP, who provides secretariat functions, managing of finances and technical assistance – comprising five regional sea conventions and two action plans (Wider Caribbean, East Asian seas, East Africa region, Mediterranean, Northwest Pacific, West and Central Africa; the Regional Office for Europe administers the Tehran Convention (Caspian Sea)); (b) non-UNEP administered – established under the auspices of UNEP, but another regional body provides the secretariat and administrative functions (Black Sea region, North-East Pacific region, Red Sea and Gulf of Aden region, ROPME Sea Area, South Asian Seas, South-East Pacific Region, Pacific Region); and (c) independent – not established by UNEP but cooperates with the Regional Seas Programme and attends regular meetings (Arctic Region, Antarctic Region, Baltic Sea, North-East Atlantic region). Details on the UNEP Regional Seas Programme are available at https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme/regional-seas-programme (last access: 15 January 2024).

CON), including, for example, the UN Environment Programme Mediterranean Action Plan (UNEP/MAP); and the Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention, under the Black Sea Commission, BSC). These policy mechanisms support regional sea protection and play an important role in achieving consistent marine assessments. Although the RSCs are not part of the EU system, the European Commission is a contracting party to three of them (HELCOM, OSPAR and UNEP/MAP). In HELCOM and OSPAR, most contracting parties are also members of the EU, whereas this is not the case for BARCON and the Bucharest Convention (Black Sea Commission, 1992). Besides the policies, the regional organisations for Europe's seas that have been establishing a regional cooperation are the Baltic Marine Environment Protection Commission (HELCOM), OSPAR, BARCON, the BSC and the Arctic Council (European Environment Agency, 2022; Ocean Governance, 2024).

There are also other important initiatives at the level of sea basins as well. Regarding the Mediterranean Sea basin, in 2014 the European Council adopted the EU Strategy for the Adriatic and Ionian Region (EUSAIR), which is a macro-regional strategic instrument aimed at supporting the integration of the western Balkans, providing political and financial support to enhance economic development, security, and sustainable tourism. This multilevel governance structure adopts a flexible, non-regulatory cooperation framework and helps to promote political and economic stability, thus fostering a solid foundation for European integration (European Commission, 2014a). Its 2020 Action Plan, however, does not mention SLR (European Commission, 2020a).

In 2017, the European Council adopted the Initiative for the sustainable development of the Blue Economy in the Western Mediterranean (WestMED Initiative; WESTMED Blue Economy Initiative, 2023). As a sea basin strategy (Kos and Štoka, 2021),[2] the WestMED Initiative focuses on generating growth, creating jobs and providing a better living environment for the population while preserving the services performed by the Mediterranean ecosystem (WestMED Initiative). Its framework for action mentions SLR only once, as part of the "sustainable fisheries and coastal community development" objective. The text highlights the critical role of knowledge for informing decision-making processes and investments that should fully consider climate change effects such as rising sea levels and coastal erosion (European Commission, 2017). These policies demonstrate that strengthening a Mediterranean partnership is a strategic imperative for the EU (European Commission, 2021b). In this path, the 2021 European Neighbourhood Policy (European Commission, 2021b) aims to enhance cooperation with Southern Neighbourhood countries[3] and promote conflict prevention and peacebuilding, counter-piracy, maritime security, and counterterrorism. The policy approaches environmental issues through a strategic priority of actively supporting measures to conserve, protect and restore the biodiversity of the Mediterranean (European Commission, 2021b). In the Black Sea basin, the Black Sea Synergy is a key EU initiative. In force since 2007, it has established sectors of cooperation such as (i) blue growth and economy; (ii) fisheries; (iii) environmental protection and climate change; (iv) cross-border cooperation; (v) civil society engagement, democracy and human rights; and (vi) energy and transport (European Commission, 2019b). The broader framework of the Black Sea Synergy also involves the Common Maritime Agenda (CMA) for the Black Sea, which is a bottom-up and EU sea basin strategy to enhance regional cooperation for achieving a sustainable blue economy. Besides engaging with bordering countries from inside and outside the EU, the CMA also involves a scientific pillar, the Strategic Research and Innovation Agenda (SRIA) for the Black Sea, which provides inputs for science-based decision-making (European Commission, 2019a).

As far as the Baltic Sea basin is concerned, the European Union Strategy for the Baltic Sea Region (EUSBSR) is the first internal EU strategy for a European macro-region. Based on an integrated long-term approach, this initiative has, since 2009, been pursuing the three pillars of saving the sea, connecting the region and increasing prosperity in the sea basin. Its sub-objectives include the promotion of clean and safe shipping; reliable energy markets; and climate change adaptation, risk prevention and management.

Regarding the North Sea basin, there is currently no formal strategy in force. However, the North Sea Region 2030 Strategy – a non-European Commission-steered strategy and voluntary initiative[4] – focuses on four priority areas: a productive and sustainable sea and a region that is climate-neutral, connected and smart.[5] The strategy sets goals in environmental, economic, infrastructure and socio-economic targets and builds on the strong industrial and research clusters already present in the North Sea basin countries (CPMR North Sea Commission, 2020). Environmental and climate

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[2] EU sea basin strategies are established between member states and non-EU countries; the regional level is less involved – they target only sea basin neighbouring countries and have a higher policy coordination potential (European Commission, states and regions).

[3] Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestine, Syria and Tunisia.

[4] "Non-EC-steered strategies" do not involve the European Commission; they are established between regional authorities and members of the CPMR (Conference of Peripheral Maritime Regions) and involve only the regional level, and thus there is lower policy coordination potential (only regions) (Kos and Štoka, 2021). For details, see https://blueair.adrioninterreg.eu/wp-content/uploads/2021/11/Technology-Park-Ljubljana.pdf (last access: 15 January 2024).

[5] A "smart" region refers to fostering economic diversification to ensure viable jobs and also developing innovative industries based on sustainable energy and tourism, a circular economy, and digitalisation.

objectives for 2030 include the creation of a healthy marine environment with the enhancement of blue economy sectors and sustainable aquaculture and fisheries, the production of more renewable energy, the increasing restoration of degraded ecosystems, and the fostering of climate adaptation measures (cf. Galluccio et al., 2024) to become climate-resilient (CPMR North Sea Commission, 2020). In terms of marine infrastructure, the region seeks to develop clean shipping and accessible transnational transport affordable for all social groups. For the socio-economic sphere, the region is focusing on smart specialisation strategies by fostering new industries based on marine resources, sustainable energy and tourism, a circular economy, and digitalisation which can increase employment rates with a more skilled workforce and seeks to include migrants in this process.

As for the Atlantic Ocean basin, the Atlantic Maritime Strategy (European Commission, 2011) is an EU sea basin policy adopted in 2011 that identifies challenges and opportunities under five thematic headings, namely implementing an ecosystem approach, reducing Europe's carbon footprint, sustainably exploiting the natural resources of the Atlantic seabed, responding to threats and emergencies, and promoting socially inclusive growth (European Commission, 2011). The strategy was updated in 2020 with an action plan (European Commission, 2020b) which does not mention SLR but focuses on four key thematic pillars: (i) Atlantic ports as gateways and hubs for the blue economy; (ii) promotion of blue skills of the future and ocean literacy; (iii) research, development and innovation and the exploitation of marine renewable energy; and (iv) healthy and resilient coasts. Promoting the role of ports in the sustainable development of sectors such as coastal tourism, aquaculture and shipbuilding is of key political and socio-economic interest to the transition to a carbon-free economy. Finally, the Atlantic Maritime Strategy also focuses on climate risk management and adaptation measures (see Galluccio et al., 2024) to protect coastal habitats and biodiversity and make Atlantic coastal areas more resilient. Subsequently, the circular economy, zero pollution and energy efficiency could contribute to the development of more sustainable practices, benefiting local economies and employment rates (European Commission, 2020b).

As for the Arctic Ocean, the EU's updated Arctic policy of 2021 focuses on three main issues, namely (i) maintaining peaceful cooperation in the region and developing strategic foresight on emerging security challenges; (ii) addressing climate-change-related challenges and making the Arctic more resilient with concerted action on black carbon and permafrost thaw; and (iii) supporting the sustainable development of the region with a focus on vulnerable groups such as Indigenous peoples, women and future generations. Another EU priority in the Arctic is to promote a precautionary and science-based approach to Arctic fisheries. Indeed, the EU is a party to the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, which entered into force in 2021 (European Commission, 2021b) and which has financed several scientific initiatives in the region. Finally, the EU intends to further strengthen Arctic marine governance and to further develop relations with partners in the region to ensure clean and sustainably managed seas (European Commission, 2021b).

The overview of international, regional and sea basin policies shows that integrating various management approaches undertaken by sectors into a comprehensive and cohesive plan is a challenge that remains in coastal governance.

Table 2 summarises the existing global, European and regional conventions and treaties that are directly or indirectly related to SLR and climate change management. Note that "soft law" refers to non-binding norms, principles, standards or guidelines that are used in international law and international relations.

Table 2. Key coastal policy frameworks: main objectives and relevance for SLR.

	Type of instrument		Objective		
Instrument	International or regional jurisdiction? Which sea basin?	Legally binding or soft law?	Main objectives	Specific measures on coastal adaptation?	Specific information on SLR
UN Convention on the Law of the Sea (UNCLOS – 1982)[a]	International, all	Legally binding	Define the rights and responsibilities of states in their use of the seas and oceans	No	Legal implications for baselines from which the outer limits and boundaries of maritime zones are determined
Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction – BBNJ Agreement (High Seas Treaty)[b]	International, all	Legally binding	Conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction	No	No
UN 2030 Agenda for Sustainable Development[c]	International, all	Soft law	A global plan that sets out to achieve prosperity that is respectful of the planet and its inhabitants (based on five dimensions: people, planet, prosperity, peace and partnership)	No	No
Helsinki Convention (HELCOM – 1992)[d]	Regional, Baltic Sea	Legally binding	Protect from all sources of pollution, preserve biological diversity and promote the sustainable use of marine resources	No	No
Barcelona Convention (1995)[e]	Regional, Mediterranean Sea	Legally binding	Ensure sustainable management of marine and coastal natural resources, prevention of and reduction in pollution	Partially (Integrated Coastal Zone Management Protocol – ICZM Protocol)	No
Bucharest Convention (1992)[f]	Regional, Black Sea	Legally binding	Cooperation to protect the coastal and marine environment in the Black Sea; prevent, reduce and control the pollution	No	No
EU Strategy for the Baltic Sea Region (2009)[g]	Regional, Baltic Sea	Soft law	Improve sea basin governance, ensure a good environmental and ecological status of the marine and coastal areas	No	No
EU Strategy for the Adriatic and Ionian Region (EUSAIR – 2014)[h]	Regional, Mediterranean Sea	Soft law	Improve sea basin governance, ensure a good environmental and ecological status of the marine and coastal areas	No	No

Table 2. Continued.

Instrument	Type of instrument: International or regional jurisdiction? Which sea basin?	Type of instrument: Legally binding or soft law?	Objective: Main objectives	Objective: Specific measures on coastal adaptation?	Objective: Specific information on SLR
Initiative for the sustainable development of the Blue Economy in the Western Mediterranean (WestMED Initiative, 2017)[i]	Regional, Mediterranean Sea	Soft law	Help public institutions, academia, local communities, and small- and medium-sized enterprises to develop maritime projects to strengthen the blue economy	General mention of adaptation to climate change in coastal cities	SLR is a major threat to coastal ecosystems and economies
European Neighbourhood Policy – 2021 Renewed partnership with the Southern Neighbourhood – A new agenda for the Mediterranean[j]	Regional, Mediterranean Sea	Soft law	Foster stability, security and prosperity in the EU's south and east neighbouring regions; set out a renewed agenda for the relaunching and strengthening of the strategic partnership between the EU and its Southern Neighbourhood partners	Yes	No
Black Sea Synergy initiative (2007)[k]	Regional, Black Sea	Soft law	Strengthen cooperation on good governance, environment, maritime policy and fisheries	No	No
The Common Maritime Agenda for the Black Sea[l]	Regional, Black Sea	Soft law	Support regional cooperation for a more sustainable blue economy in the Black Sea (developed in the broader framework of the Black Sea Strategy)	Yes	SLR is considered a major climate change effect, putting coastal and marine ecosystems at risk
The European Union Strategy for the Baltic Sea Region (EUSBSR)[m]	Regional, Baltic Sea	Soft law	The first macro-regional strategy in Europe aimed at saving the sea, connecting the region and increasing prosperity	No	SLR would affect at least 16 million people that live on the coast
North Sea Region 2030 Strategy[n]	Regional, North Sea	Soft law	Define four priority areas for cooperation: productive and sustainable, climate-neutral, connected, and smart North Sea region	Yes	Developing new methods to adapt to SLR sea temperatures and extreme weather events; the regions that will be affected by SLR, heavy rain showers, and long hot and dry summers should anticipate these events

Table 2. Continued.

Instrument	Type of instrument		Objective		
	International or regional jurisdiction? Which sea basin?	Legally binding or soft law?	Main objectives	Specific measures on coastal adaptation?	Specific information on SLR
Atlantic Maritime Strategy (2014)[o]	Regional, north-east Atlantic Ocean	Soft law	Unlock the potential of the blue economy while preserving marine ecosystems and addressing climate change, protect and enhance the marine and coastal environment, create a socially inclusive and sustainable model of regional development	No	No
The EU's Arctic policy (updated in 2021)[p]	Regional, Arctic Ocean	Soft law	Help preserve the Arctic as a region of peaceful cooperation to slow the effects of climate change and to support the sustainable development of Arctic regions	Yes	Arctic changes cause SLR; disturb weather systems; and lead to coastal erosion, biodiversity loss and the destruction of ecosystems
Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (2018)[q]	Regional, Arctic Ocean	Legally binding	Ban unregulated fishing activities in the central Arctic Ocean and set up a joint scientific programme to improve parties' understanding of the ecosystems and potential fisheries	No	No
Trilateral Wadden Sea Cooperation (1978)[r]	Regional, North Sea	Soft law	Protect and conserve this sea as an ecological entity through common policies and management, monitor and assess the quality of the sea ecosystem in collaboration with national and regional authorities	Despite SLR being recognised as a major challenge, no specific adaptation measures are addressed	No
Marine Strategy Framework Directive (MSFD – 2008/56/EC)[s]	Regional, all	Legally binding	Require each coastal maritime strategy (MS) to prevent and restore damaged ecosystems to good environmental status (GES)	No	No
Marine Spatial Planning Directive (2014/89/EU)[t]	Regional, all	Legally binding	Make maritime spatial planning mandatory for all coastal MSs, promote the sustainable growth of maritime economies and areas	No	No

Table 2. Continued.

	Type of instrument		Objective		
Instrument	International or regional jurisdiction? Which sea basin?	Legally binding or soft law?	Main objectives	Specific measures on coastal adaptation?	Specific information on SLR
Bologna Charter (2012)[u]	Regional, Mediterranean Sea	Soft law	Promote a common framework for strategic actions aimed at the protection and sustainable development of Mediterranean coastal areas	Yes – a joint action plan (BC-JAP) proposing a strategy for assisting adaptation	BC-JAP includes the design of structural works for coastal protection and adaptation to climate change, fostering adaptive management solutions for the resilience of coastal systems and the efficient use of funding frameworks from the European to national and regional scales
EU Strategy on Adaptation to Climate Change (2021)[v]	Regional, all	Soft law	Reinforce the adaptive capacity of the EU and minimise vulnerability to the impacts of climate change, step up adaptation planning and climate risk assessments	Yes (importance of closing the gap on climate impacts in coastal areas) – promotion of blue–green nature-based solutions for coastal adaptation	SLR is an increasing worry for coastal areas, which produce 40 % of the EU GDP and are home to about 40 % of its population.

[a] UN Convention on the Law of the Sea (UNCLOS): https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf (last access: 15 January 2024). [b] Agreement under UNCLOS on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (i.e. the High Seas Treaty or BBNJ Agreement): https://www.un.org/bbnj/sites/www.un.org.bbnj/files/draft_agreement_advanced_unedited_for_posting_v1.pdf (last access: 15 January 2024) and https://undocs.org/Home/Mobile?FinalSymbol=a%2Fconf.232%2F2023%2F4&Language=E&DeviceType=Desktop&LangRequested=False (last access: 15 January 2024). The agreement is open for signature by all states and regional economic integration organisations from 20 September 2023 to 20 September 2025 and will enter into force 120 d after the date of deposit of the 60th instrument of ratification, approval, and acceptance or accession. [c] UN 2030 Agenda for Sustainable Development: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf (last access: 15 January 2024). [d] Helsinki Convention (HELCOM): https://helcom.fi/wp-content/uploads/2019/06/Helsinki-Convention_July-2014.pdf (last access: 15 January 2024). [e] Barcelona Convention: https://wedocs.unep.org/bitstream/handle/20.500.11822/31970/bcp2019_web_eng.pdf (last access: 15 January 2024). [f] Bucharest Convention: https://cil.nus.edu.sg/wp-content/uploads/2019/02/1992-Bucharest-Convention-for-the-Protection-of-the-Black-Sea-Against-Pollution-1.pdf (last access: 15 January 2024). [g] EU Strategy for the Baltic Sea Region: https://ec.europa.eu/regional_policy/sources/policy/cooperation/macro-regional-strategies/baltic/council_concl_30102009.pdf (last access: 15 January 2024). [h] EU Strategy for the Adriatic and Ionian Region (EUSAIR): https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733584/EPRS_BRI(2022)733584_EN.pdf (last access: 15 January 2024) and https://www.adriatic-ionian.eu/wp-content/uploads/2018/02/com_357_en.pdf (last access: 15 January 2024). [i] Initiative for the sustainable development of the Blue Economy in the Western Mediterranean (WestMED Initiative: https://maritime-spatial-planning.ec.europa.eu/practices/westmed-initiative-towards-initiative-sustainable-development-blue-economy-western (last access: 15 January 2024). [j] European Neighbourhood Policy – 2021 Renewed partnership with the Southern Neighbourhood – A new agenda for the Mediterranean: https://www.eeas.europa.eu/sites/default/files/joint_communication_renewed_partnership_southern_neighbourhood.pdf (last access: 15 January 2024). [k] Black Sea Synergy initiative: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52007DC0160&from=SV (last access: 15 January 2024). [l] The Common Maritime Agenda for the Black Sea: https://black-sea-maritime-agenda.ec.europa.eu/about/our-mission (last access: 15 January 2024). [m] The European Union Strategy for the Baltic Sea Region (EUSBSR): https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/733703/EPRS_BRI(2022)733703_EN.pdf (last access: 15 January 2024). [n] North Sea Region 2030 Strategy: https://cpmr-northsea.org/policy-work/north-sea-region-2030-strategy/ (last access: 15 January 2024). [o] Atlantic Maritime Strategy: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0782 (last access: 15 January 2024) [p] The EU's Arctic policy (updated in 2021): https://www.eeas.europa.eu/eeas/joint-communication-stronger-eu-engagement-peaceful-sustainable-and-prosperous-arctic_en (last access: 15 January 2024). [q] Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean: https://oceans-and-fisheries.ec.europa.eu/news/arctic-agreement-prevent-unregulated-fishing-enters-force-2021-06-25_en (last access: 15 January 2024) and https://www.mofa.go.jp/files/000449233.pdf (last access: 15 January 2024). [r] Trilateral Wadden Sea Cooperation: https://www.waddensea-worldheritage.org/trilateral-wadden-sea-cooperation (last access: 15 January 2024). [s] Marine Strategy Framework Directive (MSFD – 2008/56/EC): https://eur-lex.europa.eu/eli/dir/2008/56/oj (last access: 15 January 2024). [t] Marine Spatial Planning Directive (2014/89/EU): https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0089 (last access: 15 January 2024). [u] Bologna Charter: https://bur.regione.emilia-romagna.it/bur/area-bollettini/bollettini-pubblicati/2013/luglio-periodico-parte-seconda-1a-quindicina.2013-07-03.6371477984/approvazione-dello-schema-della-carta-delle-regioni-europee-per-la-promozione-di-un-quadro-comune-di-azioni-strategiche-dirette-alla-protezione-e-sviluppo-sostenibile-delle-aree-costiere-del-mediterraneo-denominata-carta-di-bologna-2012/bologna-charter-2012 (last access: 15 January 2024) and https://maritime-spatial-planning.ec.europa.eu/practices/bologna-charter-2012 (last access: 15 January 2024). [v] EU Strategy on Adaptation to Climate Change: https://climate-adapt.eea.europa.eu/en/eu-adaptation-policy/strategy (last access: 15 January 2024).

Box 1: Emerging challenges of sea level rise for international law

The International Law Commission of the United Nations General Assembly A/CN.4/761 (UNGA, 2023) signals some relevant upcoming challenges related to sea level rise, such as the legal stability regarding baselines and maritime zone delimitation; effects of the situation whereby an agreed land boundary terminus ends up being located out at sea; and the consequences of when overlapping areas of the exclusive economic zones of opposite coastal states, delimited by bilateral agreements, no longer overlap. The exercise of sovereign rights and jurisdictions of coastal states is also of note, since historic waters, titles and rights and the permanent sovereignty over natural resources can be impacted by SLR with possible loss or gain of benefits by third states. Within statehood issues, sea level rise stresses concern about the practice on the requirements for the configuration of a State as a subject of international law and for the continuance of its existence, as is the case of the status of submerged islands, for instance. Regarding the protection of individuals, impacts of sea level rise point to issues of nationality, international security, forced migration and human rights violations. In this sense, the regulation of displacement and statelessness, as well as international cooperation on humanitarian assistance, encompasses concerns which will require further elaboration under international law.

Furthermore, SLR has the potential to significantly impact the spatial extent of national claims to maritime jurisdiction and change to the low-water line along the coast. This physical shift poses fundamental legal questions of how to deal with the jurisdictions of territories losing their lands and the pushback of the limits of the maritime zones and of how to react if the current baseline moves inland as a consequence of sea level rise, if water previously under national jurisdiction could become part of the high seas, and finally if the changes to the baselines should impact maritime boundaries between states with opposite or adjacent coasts.

Aiming to anticipate the challenges ahead, the current legal international regime must address gaps in the frameworks in force. This implies the need to elaborate on innovative and practical solutions to address SLR impacts, notably on forced human displacement and on the very existence of the land territory of some states ("Stressing Rising Seas Already Creating Instability, Conflict, Secretary-General Says Security Council Has Critical Role in Addressing Devastating Challenges", United Nations, 2023). No single agreed solution to address these issues has been achieved so far. However, tools such as the further development of customary international law; protocols for the United Nations Framework Convention on Climate Change (UNFCCC); amendments of the provisions of UNCLOS; interpretations of the new High Seas Treaty, namely the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) adopted in 2023; and advisory proceedings on climate change may guide international legal responses to rising sea levels in the future.

3.2 Key national policy frameworks governing coastal adaptation

Climate adaptation has become a policy theme for national governments in the last few decades[6]. In Europe, already in 2013, the EU Strategy on Adaptation to Climate Change had moved adaptation up the policy agenda for member states. Although non-binding, the strategy prompted member states to develop their own adaptation policies, and to date, all member states have approved a national adaptation strategy, a national adaptation plan or both. The United Kingdom provides a good example of climate adaptation policy with the Climate Change Act 2008. The act does not contain a specific long-term goal for adapting to climate change but requires an assessment of the risks of climate change on a 5-year cycle. Through the National Adaptation Programme, the act obliges the government to set out objectives for adaptation and a programme to meet them, publishing policy programmes to address the risks identified in the latest climate change risk assessment. In addition, the Climate Change Committee – an independent advisory body – monitors progress on adaptation targets every 2 years (Climate Change Committee, 2020).

However, while there are concrete policy outputs at the national level for climate adaptation in general in all European members states, assessing the state of coastal adaptation in particular in the 22 maritime member states[7] remains challenging. The approaches that countries take to coastal adaptation policy differ between them according to the institutional arrangements and specific geographical and social circumstances. For example, coastal adaptation may be embedded in general climate adaptation policies or strategies as well as in sectoral or location-specific (i.e. sub-national) policies, strategies and plans.

In order to assess progress at the national level on coastal adaptation, we therefore focused on two reporting mechanisms for climate adaptation and planning in marine areas that make available comparable information on coastal adaptation governance across different countries at the national level. These mechanisms are, first, the EU governance monitoring framework, which makes available country progress on climate adaptation policies through the Climate-ADAPT platform, and second, the European Maritime Spatial Planning Platform, which reports on the country progress of member states in implementing the Maritime Spatial Planning Directive (European Commission, 2014b), which explicitly calls for planning to consider the impacts from climate change and to design interventions that are "resilient" to its effects.

Table 3 shows the results of this analysis reporting on the observations and future projections of SLR hazards in each country, the status of its coastal adaptation policy, and the status and context of its MSP policies with respect to SLR. Generally, the information reported by the countries shows that sea level rise already affects and is expected to impact almost all EU coastal countries. Indeed, many member states identified sea level rise and coastal erosion as a major hazard currently and in the future, with only Bulgaria and Cyprus not reporting future hazards associated with SLR. Despite this, not all coastal adaptation plans or MSPs include measures to adapt to sea level rise. Indeed, only 5 countries include specific measures to adapt to SLR in their coastal adaptation policies. Slightly more, 10 out of 22 countries, include SLR adaptation measures in their MSPs, indicating the significance of MSPs as a coastal adaptation policy instrument; however this number remains relatively low (less than half of countries) in terms of overall inclusion of SLR adaptation measures. Out of 22 countries, 9 do not yet include SLR adaptation measures at all in coastal adaptation policies and MSPs. Table 3 thus shows an observed lag between recognising the risk of SLR and taking adaptation action at the national level. These results are consistent with recent analysis of OECD countries' coastal adaptation policies, which found that states often first adopt an information provision strategy regarding coastal risks, while policies that allocate funds for protection and SLR risk reduction are slower to emerge (OECD, 2019).

Beyond the overview presented in Table 3, more granular content analysis of the national coastal adaptation and MSP policies in EU member states provides the following further insights into progress in coastal adaptation policy frameworks at the national level.

First, although many member states have initiated coastal adaptation actions, most measures address the consolidation of knowledge and reducing uncertainty, as well as measures for improving governance and institutional capacity; a good example is provided by the National Climate Change Adaptation Plan of Spain, which highlights the necessity of improving the regulatory framework to facilitate adaptation on coasts and at sea (see Galluccio et al., 2024). There are however some examples of member states that are already implementing concrete SLR adaptation measures. For example, Belgium issued a royal decree establishing marine spatial planning for the period 2020 to 2026 in the Belgian sea areas. The decree stipulates that an entire island is dedicated to testing innovative solutions for coastal defence, such as

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[6] The following mechanisms were used to collect data for the analysis conducted in Sect. 3.2: (a) the Governance of the Energy Union and Climate Action monitoring framework (Regulation (EU) 2018/1999 and its implementing regulation), which requires member states to report information every 2 years about the observed and future climate change impacts and the status of climate adaptation policies (the first round of reporting was carried out in 2021, and the information is available via Climate-ADAPT country profiles), and (b) the framework of the Maritime Spatial Planning Directive (Directive 2014/89/EU), which explicitly calls for planning to consider the impacts from climate change and to design interventions that are "resilient" to its effects (the European Commission constantly monitors the implementation of the MSP Directive in member states).

[7] We consider the 27 EU member states, with the exclusion of Austria, the Czech Republic, Hungary, Luxembourg and Slovakia.

Table 3. Assessment of national policies for coastal adaptation and maritime spatial planning policies in Europe. Note: n/a – not applicable.

Country	Sea basin	Reported chronic hazards		Coastal adaptation policy			Maritime spatial planning	
		Observed	Future	Strategy adopted?	List of measures?	Measure addressing SLR?	Enforced?	Addresses SLR?
Belgium	North Sea and Arctic	SLR, coastal erosion	SLR	Yes	Yes	No	Yes	Yes
Bulgaria	Black Sea	Coastal erosion	–	Yes	Yes	No	No	n/a
Croatia	Mediterranean Sea	SLR	SLR	Yes	No	No	No	n/a
Cyprus	Mediterranean Sea	Coastal erosion	–	Yes	No	No	No	n/a
Denmark	North Sea and Arctic and Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	No	No	Yes	No
Estonia	Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	Yes	Yes	Yes
Finland	Baltic Sea	SLR	SLR	Yes	Yes	No	Yes	No
France	Atlantic coast and Mediterranean Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	No	Yes	Yes
Germany	North Sea and Arctic and Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	Yes	Yes	No
Greece	Mediterranean Sea	Coastal erosion	SLR, coastal erosion	Yes	No	No	No	n/a
Ireland	Atlantic coast	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	Yes	Yes	Yes
Italy	Mediterranean Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	No	No	n/a
Latvia	Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	No	Yes	Yes
Lithuania	Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	No	Yes	Yes
Malta	Mediterranean Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	No	No	Yes	Yes

Table 3. Continued.

Country	Sea basin	Reported chronic hazards		Coastal adaptation policy			Maritime spatial planning	
		Observed	Future	Strategy adopted?	List of measures?	Measure addressing SLR?	Enforced?	Addresses SLR?
The Netherlands	North Sea and Arctic	SLR, coastal erosion	SLR	Yes	Yes	Yes	Yes	Yes
Poland	Baltic Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	No	No	Yes	Yes
Portugal	Atlantic Coast	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	Yes	Yes	No
Romania	Black Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	No	No	Yes	Yes
Slovenia	Mediterranean Sea	SLR	SLR	Yes	No	No	Yes	No
Spain	Atlantic Coast and Mediterranean Sea	SLR, coastal erosion	SLR, coastal erosion	Yes	Yes	Yes	Yes	Yes
Sweden	Baltic Sea	Coastal erosion	SLR, coastal erosion	Yes	No	No	Yes	No

Sources: table developed by the authors based on Climate-ADAPT and the European MSP Platform. This table is a summary of adaptation and maritime spatial planning policies in Europe with a focus on SLR-related issues. Its sources are Climate-ADAPT (https://climate-adapt.eea.europa.eu/#t-countries, last access: 15 January 2024) and the European MSP Platform (https://maritime-spatial-planning.ec.europa.eu/msp-practice/countries, last access: 15 January 2024). The European MSP Platform is available at https://maritime-spatial-planning.ec.europa.eu/msp-practice/countries (last access: 15 January 2024). As for the specific countries, see Belgium (Belgian National Climate Change Adaptation Strategy: https://www.cnc-nkc.be/sites/default/files/report/file/be_nas_2010_0.pdf, last access: 15 January 2024; Belgian National Adaptation Plan 2017–2020: https://www.cnc-nkc.be/sites/default/files/report/file/nap_en.pdf, last access: 15 January 2024), Croatia (Climate Change Adaptation Strategy for the period to 2040 with a view to 2070: https://prilagodba-klimi.hr/, last access: 15 January 2024), Denmark (How to manage cloudburst and rain water – Action plan for a climate-proof Denmark: https://en.klimatilpasning.dk/media/590075/action_plan.pdf, last access: 15 January 2024), Estonia (Climate Change Adaptation Development Plan until 2030: https://envir.ee/media/912/download, last access: 15 January 2024), Finland (Finland's National Strategy for Adaptation to Climate Change: http://urn.fi/URN:ISBN:952-453-231-X, last access: 15 January 2024; Finland's National Climate Change Adaptation Plan 2030: https://mmm.fi/paatokset/paatos?decisionId=0900908f807fc600, last access: 15 January 2024), France (Stratégie nationale d'adaptation au changement climatique: https://www.ecologie.gouv.fr/sites/default/files/ONERC_Rapport_2006_Strategie_Nationale_WEB.pdf, last access: 15 January 2024; 2e Plan national d'adaptation au changement climatique (PNACC-2): https://www.ecologie.gouv.fr/sites/default/files/2018.12.20_PNACC2.pdf, last access: 15 January 2024), Germany (Deutsche Anpassungsstrategie an den Klimawandel: https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaanpassung/das_gesamt_bf.pdf, last access: 15 January 2024), Greece (National Strategy for Adaptation to Climate Change: https://ypen.gov.gr/wp-content/uploads/legacy/Files/Klimatiki%20Allagi/Prosarmogi/20160406_ESPKA_teliko.pdf, last access: 15 January 2024), Ireland (National Adaptation Framework: https://www.gov.ie/en/publication/fbe331-national-adaptation-framework/, last access: 15 January 2024), Italy (National Adaptation Strategy to climate change: https://www.mase.gov.it/sites/default/files/archivio/allegati/clima/documento_SNAC.pdf, last access: 15 January 2024; Piano Nazionale di Adattamento ai Cambiamenti Climatici: https://www.mase.gov.it/sites/default/files/PNACC_DOCUMENTO_DI_PIANO.pdf, last access: 15 January 2024), Latvia (Latvian National Plan for Adaptation to Climate Change until 2030: https://www.varam.gov.lv/en/media/32915/download?attachment, last access: 15 January 2024), Lithuania (National Climate Change Management Agenda: https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/219a2632a6b311ecaf79c2120caf5094?jfwid=-56ckr0gcc, last access: 15 January 2024; National Energy and Climate Plan: https://energy.ec.europa.eu/system/files/2022-08/lt_final_necp_main_en.pdf, last access: 15 January 2024), the Netherlands (Adapting with ambition – National climate adaptation strategy 2016 (NAS): https://www.atachcommunity.com/fileadmin/uploads/atach/Documents/Country_documents/Netherlands_Strategy_VA_2016.pdf, last access: 15 January 2024; Nationaal Uitvoeringsprogramma Klimaatadaptatie: https://open.overheid.nl/documenten/dpc-2f1a2258b86c19919999b03a927ca9e3ba0498af/pdf, last access: 15 January 2024; Nationaal Uitvoeringsprogramma Klimaatadaptatie, 2023), Poland (Polish National Strategy for Adaptation to Climate Change by 2020 with the perspective by 2030: https://bip.mos.gov.pl/fileadmin/user_upload/bip/strategie_plany_programy/Strategiczny_plan_adaptacji_2020.pdf, last access: 15 January 2024), Portugal (National Adaptation to Climate Change Strategy (ENAAC 2020): https://files.dre.pt/1s/2015/07/14700/0511405168.pdf, last access: 15 January 2024; Action Plan for Adaptation to Climate Change (P-3AC): https://dre.pt/application/conteudo/123666112, last access: 15 January 2024), Romania (National Climate Change and Low Carbon Green Growth Strategy: http://www.mmediu.ro/categorie/cadrul-national/408, last access: 15 January 2024), Spain (National Climate Change Adaptation Plan 2021–2030: https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/pnacc-2021-2030-en_tcm30-530300.pdf, last access: 15 January 2024; Climate Change Adaptation: Work Programme 2021–2025: https://www.miteco.gob.es/es/cambio-climatico/temas/impactos-vulnerabilidad-y-adaptacion/pt1-pnacc_tcm30-535273.pdf, last access: 15 January 2024) and Sweden (Nationell strategi för klimatanpassning: https://www.regeringen.se/contentassets/8c1f4fe980ec4fcb8448251acde6bd08/171816300_webb.pdf, last access: 15 January 2024).

Table 4. Coastal adaptation decision-making and fiscal arrangements in multilevel governance systems in Europe.

	Set strategic goal	Set coastal flood safety rules	Design measure	Fiscal control	
				Set public investment budget	Set tax base and rates
The Netherlands	National	National (regulate)	National	National	National
United Kingdom	National–regional–local	National (incentivise)	Local	National–local	National–local
Germany (Schleswig-Holstein)	Regional (state dikes)	Regional (regulate)	Regional	National–regional	Regional
Spain	National	National	National–local	National	National
Italy	Regional	Regional	Regional	Regional	National Regional
	Hybrid national–regional bodies (basin authorities)	Hybrid national–regional bodies (basin authorities)	Hybrid national–regional bodies (basin authorities)	National	National

seawalls, to contain future rising sea levels (Belgian Government, 2020).

Second, concerning the coastal adaptation governance modes in place for coastal adaptation, member states differ substantially in governance modes according to their different institutional architectures. Coastal adaptation requires coordination, both vertically between central governments and sub-national bodies such as regions or municipalities and horizontally between adjacent regions and central authorities with specific sectoral competencies, and this plays out differently according to the institutional arrangements in member states. Vertical coordination modes occur in several member states. In Belgium, for example, the federal government delegates the three regions to draw up specific local adaptation plans. Denmark also adopts a form of vertical coordination but with a direct relationship between the state and municipalities. The 2012 Danish national adaptation plan does not include direct action to address sea level rise, but it stipulates that municipalities develop a local adaptation plan that requires coastal municipalities to manage SLR risks. The central government provides support in terms of information such as the web portal http://klimatilpasning.dk (last access: 15 January 2024) and the yearly State of the Environment report (CMCC, 2021; https://miljotilstand.dk, last access: 27 June 2024) by the Danish Environmental Protection Agency, which includes a chapter on climate change and SLR. Italy provides another example of vertical coordination between the central state and regions for coastal adaptation. The Italian constitution recognises the legally binding competencies of Italian regions regarding spatial and territorial management. However, the Italian National Adaptation Strategy (Ministero dell'Ambiente e della tutela del territorio e del mare, 2015) does not prescribe specific actions for the regions, and thus there remains some lack of clarity regarding adaptation competencies between different levels of government. The National Climate Change Adaptation Plan (Ministero dell'Ambiente e della tutela del territorio e del mare, 2023) aims to set out these responsibilities; however it is not yet approved. Despite these barriers, the constitutional legal structure has provided a sufficient basis for fruitful cooperation between the central state and the regions in coastal erosion management (see Box 2). Further, a set of regional coastal adaptation plans have been developed both as part of this collaboration and under the ICZM Protocol adopted by the Barcelona Convention (CMCC, 2021).

For horizontal coordination modes, the Netherlands provides an example of horizontal coordination. The Dutch climate adaptation action is based on two pillars, the 2016 National Adaptation Strategy (The Netherlands, 2016) and the Delta Programme (Alphen, 2015). Important for horizontal coordination, the Delta Programme, which focuses on flood risk management and adapting the Netherlands to SLR over the long term, has mainstreamed adaptation to SLR into all its decision-making process and measures. For instance, in 2019, the Dutch government launched the Sea Level Rise Knowledge Programme as part of the Delta Programme, which is an extensive research and development agenda on SLR seeking to both improve forecasting capacity and identify adaptation solutions, thus involving coordination across multiple sectors of society. France addresses coastal adaptation through two parallel systems: one provides a coastal risk management framework with coastal adaptation measures, while the other deals specifically with adaptation to climate change – with policies that include coastal issues as well. The coastal governance structure includes different administrative authorities with responsibilities and competencies for coastal adaptation measures to address SLR. While the national adaptation plan does not include specific SLR adaptation measures, the national strategy includes some recommendations for adaptation in coastal areas, such as to carefully study and plan strategic retreat, taking into account the foreseeable consequences of SLR. The country also has specific regional and local documents dealing with climate adaptation and SLR, such as "plans de prévention des risques littoraux" and strategic sea basin documents.

Finally, Sweden provides an example of hybrid horizontal and vertical coordination modes. Collaboration among the county administrative boards (CABs) of Skåne and Halland, the Swedish Geotechnical Institute (SGI), and the Geological Survey of Sweden (SGU) involves four public bodies working together with the different coastal municipalities in the counties of Skåne and Halland to address the problems of coastal erosion and rising sea levels in these areas.

Governance structures play a key role in coping with the short- and long-term effects of climate change and guaranteeing populations' safety. However, in a changing climate scenario, fragmented institutional power and a lack of communication across different levels of the management framework hinder the adoption of cross-cutting and coordinated preventive measures, ultimately reducing the adaptive capacity of societies. Moreover, to scale up defences in a planned manner and to mobilise resources towards climate-resilient territories, institutions and governmental infrastructures should align with the most up-to-date scientific knowledge on climate change. In turn, calibrating governance instruments could significantly influence a country's ability to manage climate challenges, which reveals that political–institutional structures may interfere in the level of vulnerability of society (see Sect. 3.1).

In summary, national governments are crucial in supporting coastal adaptation to SLR, notably by ensuring the relevant actors have the correct incentives and tools to adapt, as well as by removing potential distortions. Governments should take a proactive approach to improve the coordination, efficiency and effectiveness of actions implemented at lower levels of governance. Key areas for improving coastal adaptation involve enhancing access to information and guidance, ensuring that regulations and economic instruments are coherent, considering climate risks in funding decisions, and monitoring the effectiveness of policy interventions (OECD, 2019).

Box 2: Vertical collaboration scheme without legally binding policies for coastal adaptation – the case of Italy

In Italy, the management of coastal areas is a shared competence between all levels of government (national, regional and local) and different sectors of the public administration, resulting in fragmentation and poor coordination in coastal management (Buono et al., 2015). Further, coastal erosion is a salient issue with a recent study of Italian coasts' exposure to sea level rise finding that expected damage from erosion without adaptation was EUR 219 million per year, with beach loss of ca. 500 000 $m^2\,yr^{-1}$. With relevant adaptation costs estimated as EUR 37.9 million per year, EUR 7.9 million of which is for nourishment interventions, resulting in a reduction in expected damage to less than EUR 7 million per year, for each million euros invested in adaptation, about EUR 5 million could be saved through avoided damage (MATTM-Regioni, 2018).

In this context, the Ministry of Environment and Energy Security has initiated coordinated management of coastal erosion risk, through the national board on coastal erosion (MATTM-Regioni, 2018), involving the Italian coastal regions. One output of the board is the Italian guidelines for coastal protection from erosion and climate change impacts (MATTM-Regioni, 2018). The document offers an overview of all possible options for managing coastal erosion and provides recommendations for technicians and experts tasked to design interventions to combat erosion. The guidelines consider previous similar initiatives at the European, national and local level that represent good practices from the last few decades, in line with EU Directive 2007/60/EC on the assessment and management of flooding and submersion risks.

3.3 Coastal adaptation financing arrangements

A major component of coastal adaptation governance is the financing of measures to address SLR. Coastal adaptation presents major coastal adaptation financing needs in Europe. Current estimates of investments needed globally to raise current coastal protection up to standards of the most flood-risk-intolerant countries are up to USD 4 trillion (Nicholls et al., 2019). Moreover, investment needs will increase with socio-economic development and sea level rise (SLR) and could lead to up to USD 70 billion in annual protection costs globally by 2100, a significant share of which will be in Europe (Hinkel et al., 2014). Further, investments needed to adapt to other sea-level-rise-related risks, such as salinity intrusion and coastal erosion, will increase these investment needs further (Bisaro et al., 2020).

Meeting these needs is largely a public funding challenge, as governments often have statutory requirements to provide coastal protection and are otherwise either explicit or implicit insurers of last resort (Bisaro et al., 2020). Meeting coastal adaptation funding needs is challenging because many coastal adaptation measures generally have high upfront investment costs with benefits from avoided damage materialising over the medium to long term. Various fiscal instruments are available to fund such measures, including taxation; public debt instruments, e.g. "green bonds" (Keenan, 2019); and cost-sharing arrangements with the private sector, e.g. public–private partnerships (Bisaro and Hinkel, 2018).

Funding challenges necessarily involve multiple levels of government because coastal adaptation measures often span multiple scales and jurisdictions beyond the immediate physical location where flooding or other SLR impacts may occur (Woodruff et al., 2020). This can give rise to distributional conflicts across different levels of government, e.g. over who pays for a given measure (Storbjörk and Hedrén, 2011), and between jurisdictions, e.g. over who receives funding for measures (Osberghaus et al., 2010), that can hinder public investments. Barriers to coastal adaptation financing also arise at the local level, where social acceptance of new taxes or levies to fund protection or beach nourishment measures may be low (Mullin et al., 2019), where low risk awareness may hinder support for local government finance instruments (Merrill et al., 2018), and where there may be a lack of capacity and misaligned performance incentives for local officials (Moser et al., 2019).

One potentially major source of funding for adaptation to SLR in Europe is the European Investment Bank (EIB) through their Blue Sustainable Ocean Strategy (Blue SOS), which aims to improve the health of oceans and coastal environments and increase sustainable economic activity. Through the strategy, the EIB committed to doubling lending to sustainable ocean projects to EUR 2.5 billion over the period 2019–2023. Further, the EIB aims to mobilise at least EUR 5 billion of investments that contribute to improving the health of oceans. In particular, the Blue SOS targets sustainable coastal development and protection and makes finance available through long-term loans and other instruments for governments and the private sector. Further, the facility provides technical assistance to support project promoters in preparing and implementing their sustainable ocean projects.

An example of EIB-funded coastal protection projects is the "Protection against coastal erosion – Phase II" project financed by the Cohesion Fund under the Large Infrastructure Operational Programme (LIOP) 2014–2020. The project has a significant positive environmental impact and contributes to the protection of the Romanian Black Sea coast from coastal erosion and floods exacerbated by climate change (Coastal Erosion Protection, 2023), enhancing compliance with EU environmental law, in particular the Water Framework Directive, the Floods Directive and the Marine Strategy Framework Directive. The project aims to generate substantial economic benefits, the most important of which are (i) environmental benefits from improved protection of marine habitats and species within Natura 2000 sites (wetlands) and of freshwater lakes against sea intrusion, (ii) benefits from improved recreational value of beaches, and (iii) avoided costs of damage to properties and infrastructure. In addition to the advisory support, favourable conditions of the EIB loan (i.e. longer maturity and below market interest rate) have a significant impact on the operation (Coastal Erosion Protection, 2023).

Countries take different public finance approaches to coastal adaptation. These approaches can be characterised in multilevel governance regimes along different public planning and fiscal dimensions and by their distribution between national (centralised) and local (decentralised levels; Hooghe et al., 2016). Key dimensions of characterising public finance approaches to coastal adaptation have been developed in Bisaro et al. (2020) and include the following dimensions:

- *Setting strategic goals.* Which levels of government (co-)determine the medium- to long-term goal for coastal risk management? Authority for such goal setting may be implicit or explicitly defined, e.g. through establishment of a statutory body for goal setting. Typical goals are to protect, accommodate, retreat and avoid.

- *Setting coastal flood safety rules.* Which levels of government (co-)determine rules for coastal flood safety? Typical types of rules are flood safety norms, funding rules and planning regulations.

- *Designing coastal adaptation measures.* Which levels of government (co-)determine the design of individual measures? Project design may be carried out by national-level implementing agencies; by designated local authorities; or by entities comprising several levels of government, often in consultation with citizens/stakeholders at the coast.

- *Enacting fiscal control.* Which levels of government (co-)determine the total budget for coastal adaptation and dedicated tax revenues, i.e. tax base and rates? General revenue taxes and dedicated coastal flood risk reduction levies may be set by national, regional or local governments depending on tax legislation.

Table 4 shows several examples of coastal public finance arrangements within Europe. Even within this sub-set of examples, there are a range of approaches to financing coastal adaptation from centralised approaches, e.g. the Netherlands and Spain (López-Dóriga et al., 2020), to more decentralised approaches, e.g. the UK. Further, there are hybrid approaches, such as in Germany, where along some parts of the coast a centralised approach is taken at the federal state level, e.g. in Schleswig-Holstein at the Baltic Sea, while for other parts of the coast, financing and decision-making are devolved to the local level.

Italy represents another interesting case of a hybrid approach, which is somewhere between a centralised and federal system of government. The central state has devolved the competence of territorial management including coastal areas to the regions and the competence of flood risk management to the river basin authorities. These competencies are shared and sometimes overlapping, which can in some cases lead to fragmentation (see Table 4).

Beyond public finance arrangements for coastal protection and risk management in general, some countries have dedicated funds for addressing the increasing risks and associated costs of adaptation due to SLR. In France, the national government provided EUR 500 million to fund flood prevention measures, particularly in coastal areas, through the national flood plan ("plan submersions rapides"). The United Kingdom has established a GBP 2.6 billion 6-year capital investment programme (2015–2021) to reduce flood and coastal risk, which the second National Adaptation Programme estimated would provide over GBP 30 billion in overall economic benefits (e.g. reduced damage) and would benefit 300 000 households by 2021 (Department for Environment, Food & Rural Affairs, 2018). In Germany, a special instrument (Sonderrahmenplan) to accelerate implementation of coastal protection due to climate change risks was established in 2009, which provides EUR 25 million for all coastal federal states annually until 2025 (EUR 550 million total) (OECD, 2019). Further, in addition to public funding, innovative financing instruments for mobilising private finance, e.g. green bonds, are also emerging as a potentially important source of finance for coastal adaptation in Europe and are broadly supported by the EU (European Union, 2020). For instance, coastal protection activities are potentially aligned with the EU sustainability taxonomy (Alessi et al., 2019).

Managed retreat as an adaptation strategy is also receiving increasing attention. To date, in Europe, public financing for retreat or relocation measures, e.g. though buyouts or compensation of private property owners, has however been implemented only in a fragmented way through small-scale pilot projects, e.g. in the UK (Atoba et al., 2021) or Germany (de la Vega-Leinert et al., 2018). While public finance for such strategies can be rationalised on the basis of reducing overall costs of coastal protection to the public purse, it is important to consider the distributional implications of housing availability and affordability, employment opportunities, and facilitating collective relocation processes when implementing managed-retreat strategies (Braamskamp and Penning-Rowsell, 2018). Buyouts and managed-retreat programmes should be carefully designed to avoid creating or exacerbating existing socio-spatial inequalities, particularly by ensuring that retreat does not disproportionately affect already disadvantaged areas, in terms of both areas that are retreated from and areas that will receive immigration from retreat initiatives. Additionally, providing practical and psychological support during the relocation process is essential in alleviating feelings of loss and in addressing cultural and psychological impacts (Dannenbarg et al., 2019) (see Sect. 3.3).

Finally, several observations can be made regarding the outlook for coastal adaptation finance under future sea level rise. SLR is likely to increase the costs of maintaining current protection levels and coastal adaptation costs more broadly. This has several implications for coastal adaptation public finance arrangements. First, centralised public finance arrangements that exhibit little overlap between coastal adaptation beneficiaries and funders are likely to come under increasing pressure from SLR. For example, centralised funding arrangements in Germany entail a significant re-distribution of federal funds to coastal federal states for building and maintaining state dikes. As SLR increases the significance of this re-distribution in the national economy, these arrangements may be reconsidered. Relatedly, hazard-based flood safety standards as currently used in Schleswig-Holstein, which maintains state dikes that protect up to a 1-in-200-year flood hazard event, may also be reconsidered in favour of risk-based safety standards due to rising protection costs under SLR. Risk-based standards weigh the costs of protection against the value of protected assets and thus are more economically efficient. Second, under SLR, decentralised arrangements may lead coastal communities to be overwhelmed by the increasing financial burden from SLR due to budget and capacity constraints (Moser et al., 2019) and by resistance from local vested interests to raising new funds (Beatley, 2012). Finally, across all decentralised arrangements, coastal adaptation measures other than protection (such as retreat) are likely to become more important, as the costs of protecting the coast will outweigh the benefits, particularly in rural areas (Lincke and Hinkel, 2018).

4 Complexity and challenges

Despite the similarity in coastal issues in areas facing SLR, complexity in adaptation approaches derives from the great variety of the coastal settings considered, such as in physical (processes), socio-economic (development and activities) and administrative terms (governance), and from intrinsic uncertainties in sea level rise estimates.

A major source of uncertainty for long-term policies, in fact, is the assessment of SLR at the regional to local scale. Indeed, regional and local differences in changes in mean and extreme sea levels can be observed along the European coasts due to different processes (cf. Melet et al., 2024). Thus, despite IPCC being the most reported source of climate information in SLR planning in Europe (McEvoy et al., 2021) and recognising that global SLR information does contribute to advances in local agenda setting and awareness raising (Blankespoor et al., 2023), global projections are not suitable for all basins/sub-basins. The reconstruction of coastal vertical movements and of the local sea level variability at the sub-basin scale (see, for instance, Meli et al., 2023; Oelsmann et al., 2024) is crucial for supporting local/regional hazard assessment and related mitigation/adaptation policies. Addressing these challenges relies on the development of adaptive planning approaches, integrated with monitoring activities able to capture signals that may suggest updating or changing the plans and that allow the verification of their effectiveness (see Sect. 3.1). Cross-domain and cross-sectoral coordination is essential and should be based on the involvement of stakeholders and local communities in planning local adaptation, also through participatory processes (see Sect. 3.2). Furthermore, distributive and procedural justice challenges as well as vulnerability issues are also essential to address when designing and implementing the adaptation policy framework (see Sect. 3.3).

4.1 Time horizon and uncertainty

The rate, timing and amount of sea level rise over longer time horizons (roughly, beyond 2050) create deep uncertainty for decision-makers in coastal areas (van den Hurk et al., 2022). Traditional planning time frames and tools (e.g. economic assessments to compare alternative actions) and conventional political systems are typically not well suited to addressing long-term and uncertain risks when balancing clear, near-term policy objectives. Public support also tends to prioritise current needs while undervaluing long-term risks. For example, developing coastlines is an attractive proposition in many parts of Europe, where demand for housing in coastal areas is high. However, further development of vulnerable coastlines creates a lock-in to protect assets against increasing risks from sea level rise in the future. This challenge is illustrated in the case of nuclear reactors planned on the French coast.

Box 3: Case 1 nuclear reactors – lock-in and balancing near-term benefits and long-term risks

Long time horizons and uncertainties in the timing of sea level rise on local coastlines are especially relevant to long-lived infrastructure, such as new-generation nuclear plants. France is planning to add new nuclear reactors in two coastal plants: Penly, in Normandy, and Gravelines, close to the Belgian border. The expected lifetime of these nuclear reactors is at least 60 years, not including construction and dismantling. Hence, these plants will still be in place in 2100 and beyond, when scenarios well above 1 m of sea level rise cannot be excluded if a collapse of marine ice sheets in Antarctica is initiated. While the decision to implement these two reactors was announced by the national government in February 2022, the following year, the national chamber of accounts raised the issue that flood risks induced by sea level rise will be different in the two locations: in Penly, the nuclear reactors are located 11 m above sea level on the toe of a chalk cliff, whereas in Gravelines the plant is located in a polder area, largely below sea levels at high tide. In Gravelines, flood damage may not directly affect the plant itself but could compromise access through road damage, posing challenges to safe operation. There is currently no evidence that high-end scenarios involving ice sheet collapse are considered in territorial adaptation plans in the area of Gravelines, nor are there signals that the plans in Gravelines may be cancelled or amended due to consideration of high-end sea level rise. If the decision is confirmed, it will result in a long-term legacy that could lock in investments for coastal protections in the Gravelines area for several generations. However, a positive decision would also create immediate and near-term economic benefits for the territory via the construction and operation of the new reactors and support France's current energy and climate policy objectives.

Strategies for addressing uncertainty over long time horizons, such as dynamic adaptive policy pathways, link near-term actions with keeping long-term options open, to avoid maladaptation or lock-in under future climate or socio-economic conditions. The Dutch Delta Programme (Alphen, 2015) and the Thames Estuary 2100 Plan (Ranger et al., 2013) are two well-documented cases of adaptation pathways in practice. A challenge in implementing adaptive planning methods is establishing and operationalising a mechanism to monitor for locally relevant signals that indicate when it is time to consider a new action (Haasnoot et al., 2018). Existing governance and institutional structures are typically designed for "predict-and-act" planning and are less suited to adaptive planning, which requires trusted knowledge holders, a monitoring programme, a relatively stable political environment that respects established processes, and often the integration of different agencies (e.g. coastal authorities, spatial planning, environmental protection) (Hermans et al., 2017). The Dutch Delta Programme and the Thames Estuary have both implemented long-term, comprehensive monitoring programmes in their adaptive planning strategies.

Box 4: Dutch Delta – monitoring for signals in adaptive planning

The Dutch Delta Programme takes an adaptive approach that makes use of scenarios, adaptive strategies and a 6-year review period. The programme also relies on a signal group of independent, multidisciplinary experts who advise the Delta Commissioner annually on external scientific and societal trends and knowledge relevant to the programme. This *anticipatory* monitoring should signal when a change to the (adaptive) strategy may be needed. A separate *retrospective* monitoring group monitors the implementation and effectiveness of the plan.

In line with knowledge at the time, in 2014 the Delta Commissioner proposed adaptation to prepare for SLR of 0.3–1.0 m in 2100 (relative to 1990). In 2017, the signal group advised exploring the accelerated SLR scenarios and the implications for the Dutch Delta. This triggered a 2017 study on the topic, followed by an inventory of strategies to deal with accelerated SLR, in 2019. These strategies are currently elaborated upon in a dedicated programme, the SLR Knowledge Programme.

Accounting for potential long-term risks while making near-term decisions and keeping future options open are critical to avoiding lock-in and maladaptation. This can be achieved in different adaptation strategies. For example, protective measures, such as seawalls, can be built with a larger foundation than needed for the current protection height to allow the walls to be raised easily under higher amounts of sea level rise. By contrast, preventative actions, like restricting development of coastal zones, land buyouts and short-term land-use arrangements, can avoid lock-in (see Galluccio et al., 2024).

Most countries in Europe use 2100 as the long-term horizon for sea level rise planning (McEvoy et al., 2021). However, to plan and implement adaptation strategies often takes decades (Haasnoot et al., 2020). The MOSE barrier – Venice, Italy – timeline illustrates that it took over 50 years from an initiating event to a fully operational system, in 2020 (IPCC, 2022; see Fig. 1). Recent studies suggest that under high-emission scenarios, closures of the barrier for more than 2 months per year are virtually certain by the 2080s and closures of 6 months per year are likely by the end of the century (Lionello et al., 2021).

The long lead times required by especially large-scale adaptation may require taking decisions before there are clear signals. Accelerated sea level rise could further reduce the window to act (Haasnoot et al., 2020). In cases where retreat is a plausible future adaptation strategy, decision-makers often face the need to take preparatory action or decide whether to continue investment in the area long before public opinion may recognise the need for retreat. However, early action can allow more equitable and managed retreat in the long run (Haasnoot et al., 2021).

At the European level, preparedness and disparities in adaptation planning for SLR vary significantly across countries. Despite having significant populations living in low-lying coastal areas, many EU countries either are not planning for SLR (e.g. Bosnia and Herzegovina, Latvia, Malta, Montenegro, Romania, Slovenia, Ukraine) or are considering relatively low projections (i.e. less than 0.65 m by 2100, including countries like France, Italy and Spain). At the national level of planning, most countries are using SLR amounts that occur in all projections, independent of climate change and emission scenarios (between 0.15 and 0.35 m by 2050), including Albania, Croatia, Cyprus, Denmark, France, the Netherlands, Norway, Portugal, Spain and Ukraine. There are relatively few countries that consider high-end scenarios and time horizons beyond 2100 (McEvoy et al., 2021).

4.2 Cross-scale and cross-domain coordination

Both vertical (national to regional–local) and horizontal (intersectoral, cross-regional and interdisciplinary) coordination mechanisms are the base for integrating adaptation into sectoral policies and for shared management of responsibilities at multiple administrative levels. As indicated in Sect. 3.2, at the European level some member states have established national coordination bodies dealing with intersectoral policy coherence or regulatory mainstreaming of adaptation into sectoral policies. These coordination processes play an essential role in supporting local governments to develop and implement local adaptation strategies and action plans. Nonetheless, extensive effort is still required by local authorities to initiate, support and foster knowledge transfer and exchange of information within the area through consultations including academic institutions and stakeholders. Co-development processes are essential in these contexts. An example of a local adaptation plan developed in collaboration with the research community is the case of the municipality of Ravenna (see Box 5). To be effective, such plans require a strong commitment to co-creation processes with the wider community of stakeholders at the coast.

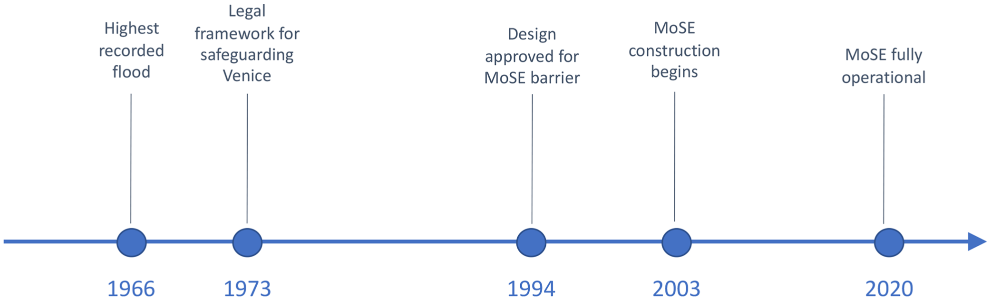

Figure 1. The timeline of milestones in the lead, design, construction and operationalisation of the MOSE barrier, in Venice, illustrates the significant time needed to implement large-scale adaptation to sea level rise.

Box 5: Ravenna municipality visions for 2100

In line with the EU initiatives “Covenant of Mayors” and “Mayors Adapt”, aimed at promoting environmental policies for the mitigation of climate change impacts towards sustainable and resilient territories, a local adaptation plan has been developed by the municipality of Ravenna in the recent action plan PAESC (Comune di Ravenna, 2020). An effort was made to integrate different competencies and points of view (urbanistic, naturalistic, etc.) and to consider the different challenges involved in the coastal sector, such as natural areas and ecosystems and agricultural and touristic activities.

The timeline of the strategic scenario for the proposed adaptation strategies and for the realisation of a first “transition stage” is fixed to 2050. The adaptation strategies aim at enhancing the resilience potential of the territory and, besides the protection of coastal settlements, include the re-naturalisation and reinforcement of the dune and paleo-dune systems, the improvement of the hydraulic network in the internal area, and the creation of a “buffer” zone for flooding and salinisation processes. This mid-term scenario should allow for the identification of the main challenges and specific barriers to face and overcome in the longer term.

The SebD (scenarios’ evaluation by design) method has been applied to evaluate the suitability of future adaptation strategies through the reconstruction of landscape transformation scenarios in 2100 by considering the high-end IPCC RCP8.5 scenario for SLR. In the plan, possible adaptation options are proposed for two particularly critical, low-lying coastal areas of the Ravenna territory, the ones most potentially exposed to marine ingression and local sea level rise. The two areas have high naturalistic environmental value (both include natural reserve areas) and are located in the southern and in the northern coastal sectors of the municipality of Ravenna. The effects of two different possible approaches have been tested, one more rigid–conservative using pre-existing structures and the other more dynamic and evolving. This enabled the evaluation of more suitable medium- to long-term adaptation strategies and related impacts. In the first case, the present setting and location of the territory are intended to be maintained in the future configuration, with a general stiffening of the present coastal defence structures (see, for instance, Fig. 2). In the second approach, the geomorphological characteristics of the natural systems should guide adaptive planning for future coastal land-use and ecosystem management. In this case, managed retreat of the coastline (apart from coastal settlements), a shift of transitional habitats and a partial transformation in land use (to wetland, marsh and forest areas) are foreseen (Fig. 3). This plan should support coastal adaptation decisions and the future selection of the most suitable adaptive strategies and related territorial transformative processes. Decisions and changes in planning will also be based on integrated, multidisciplinary monitoring activities in the territory, to be scheduled in the next stage of the PAESC with the involvement of academic institutions (University of Bologna).

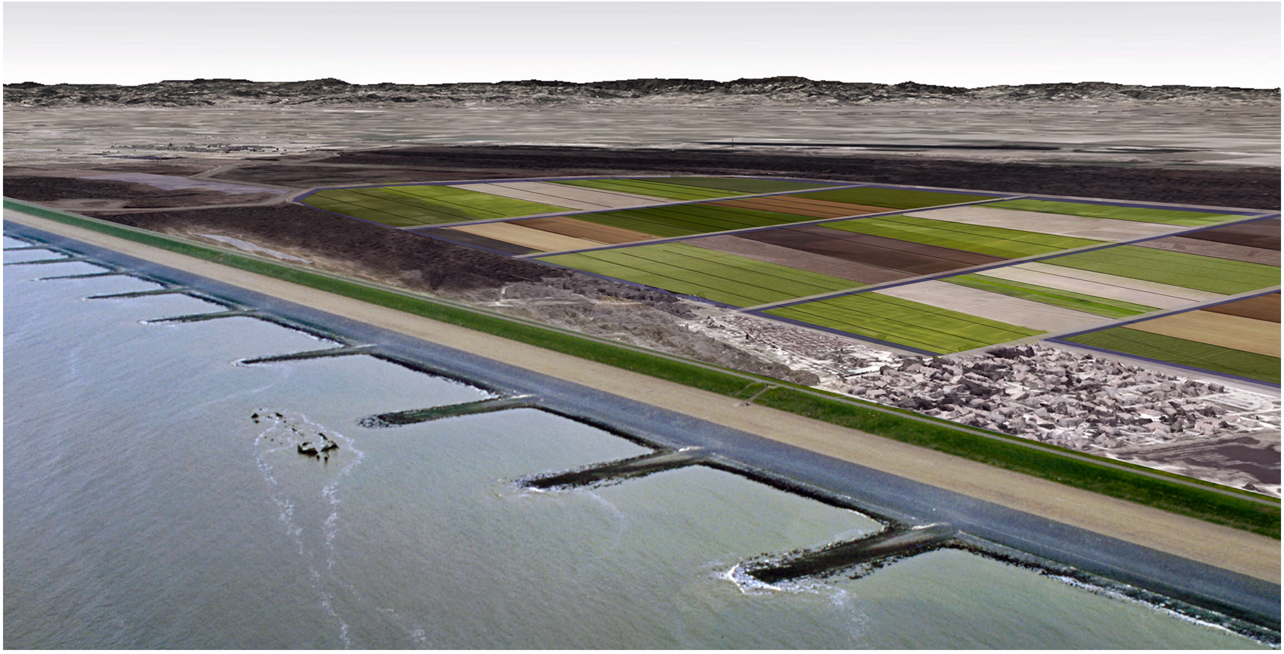

Figure 2. Computer-generated image of a possible configuration in 2100 (considering the IPCC RCP8.5 projections for SLR) in the southern coastal area of the municipality of Ravenna (Lido di Classe–Lido di Dante), according to a rigid–conservative approach, with maintenance of the coastal defence structures and the coastline position and prevalent agricultural land use in internal areas. The original source of this figure is Lobosco and Mencarini (2023).

Figure 3. Computer-generated image of possible configuration in 2100 (considering the IPCC RCP8.5 projections for SLR) in the southern coastal area of the municipality of Ravenna (Lido di Classe–Lido di Dante), according to a dynamic and evolutive approach, considering managed realignment of the coastline, the construction of a new dune line and the partial environmental transformation of the territory. The original source of this figure is Lobosco and Mencarini (2023).

Cross-cutting challenges also arise with respect to the involvement of stakeholders and local communities in the processes of planning local adaptation. Challenges include a lack of communication from local authorities to communities leading to a lack of knowledge and understanding and related negative perceptions of adaptation plans (Buono et al., 2015). Participatory methods (see also Galluccio et al., 2024) based on the involvement of stakeholders (citizens, local communities, public administration and companies, private companies, working activities, coastal users, local associations, and NGOs) can enhance communication and facilitate collaboration and consensus building. Communication, consultation and outreach are thus fundamental steps in the process of developing and implementing local coastal adaptation. The case of Texel, the Netherlands (Box 8), provides an example of the need for effective communication and co-development processes involving both coastal management experts and local communities.

Another aspect of cross-level and cross-domain challenges in coastal adaptation governance is the governance of critical infrastructure, such as ports, which plays a key role in the economic activity beyond the coast. Ports play a crucial role in a nation's economy by serving as vital gateways for international trade, facilitating the movement of goods and fostering economic growth (international shipping transports more than 80 % of global trade all over the world, according to the International Maritime Organization (IMO)). Due to their location on coasts, ports are particularly vulnerable to climate change, including rising sea levels combined with changes in the wave and wind regime or the frequency and intensity of storms. These changes may turn into an increased average time of operation disruption, potential damage to infrastructures and higher maintenance costs, impacting trade flows and the overall economy. An increase in the size of ships over the last few years may be aggravating these effects as greater draughts and construction of new and more exposed infrastructures are required.

Potential impacts of rising sea levels on port operations include the frequent interruption of low-lying coastal road and rail due to storm surges and flooding of terminal areas, more frequent flooding and potential damage of infrastructure in low-lying areas, erosion of infrastructure support, and changes in harbour facilities to accommodate higher tides and surges (UNCTAD, 2022). Further, changes in the tide and higher water level fluctuations are expected to cause periods of extremely low water levels on key inland waterways such as the Rhine in Europe or the Yangtze in China, with a negative effect on vessel loading and navigation planning.

It is therefore essential to enhance port resilience and minimise the adverse effects of climate change on ports' economic contributions. Individual risk analysis and adaptation measures must be considered for each port, depending on its oceanographic, meteorological and environmental conditions; coastal topography; relevant activities; and proximity to urban areas and other natural ecosystems. On the other hand, port governance systems are complex and vary around the world, from ports publicly owned and operated by government entities, allowing for direct control and coordination of port activities, to landlord models, where the government or port authority owns the land and infrastructure but contracts out operations to private companies, to fully privatised ports, where private companies own and manage all aspects of port operations. There are therefore scientific, technical, socio-economic and governance challenges, some of them shared with other economic sectors and others specific to the port activity, meaning adaptation strategies may differ significantly from one country to another. The effort made by Spain is a good example of such complexity and related cross-domain impacts of SLR.

Box 6: The Slufter on Texel, the North Sea – balancing stakeholder values with scientific information in seeking effective solutions for Texel's coastal problems

To maintain the coast, to protect land from flooding by the sea, and to build infrastructure that provides a desirable living environment now and in the future, Dutch coastal management has traditionally involved collaboration between different social actors and decision-makers (Avoyan and Meijerink, 2021; Lodder and Slinger, 2022). Indeed, decision-making along the coast has faced challenges in embracing local knowledge and moving towards innovative or potentially equitable solutions (Slinger et al., 2022). Given that inputs of professional experts are necessary in designing coastal solutions to fit the social, ecological and technical requirements of the local environment along the Dutch coast, the question of how to balance stakeholder perspectives with scientific information when seeking effective solutions becomes salient.

In two case studies on Texel, the westernmost island in the Wadden Sea, ongoing coastal management practice did not use locally crafted solutions – although local and regional authorities frequently organise participatory processes and multiple scientific research projects have been running and are ongoing on the island (de Vos et al., 2010). Both studies revealed the deep competence of local people, the knowledge that can be harvested to broaden and enrich the design space for coastal solutions, and a willingness on the part of the stakeholders to become involved in crafting such local solutions.

The first study was an innovative co-design process on Texel, in which local stakeholders and coastal experts were tasked with seeking an effective solution for the beach erosion problem on south-west Texel. The co-design collaborative process was configured according to theoretically founded principles for participatory design processes (D'Hont, 2020) and consisted of three main workshops between 2016–2017, involving local stakeholders and disciplinary experts (including engineers, geomorphologists, ecologists, coastal managers and governance specialists), to check the feasibility of envisioned solutions (cf. Cunningham et al., 2014; Klaassen et al., 2021; Slinger et al., 2014; Slinger and Kothuis, 2022).

While participants in the co-design process initially proposed innovations in the bio-geophysical system (e.g. nourishment programmes, dredging, relocation of the beach pavilion), later iterations increasingly considered potential adaptations in actor networks and institutions (e.g. remuneration schemes, coalition building). Overall, the co-design process facilitated an appreciation of the social–ecological system complexity inherent to flood defence on the island of Texel and revealed the potential to generate new types of solutions by bringing local knowledge to the foreground in the process.

These findings are consistent with a second case study, in which the role of system understanding in supporting integrated management of a small estuary was explored: the Slufter on Texel. The area includes a sand dike which forms a component of the primary flood defence of Texel, protecting the hinterland from flooding from the North Sea. The results of this study (D'Hont et al., 2014; D'Hont and Slinger, 2022) underline the close-knit and well-informed nature of the island community of Texel. For example, citizens know how to access and alert relevant authorities, and local citizens are well-organised and are vocal in stakeholder groups, such as village committees (D'Hont, 2020).

Overall, the need to create environments in which technical experts can engage local knowledge in developing better solutions through co-design was identified. Such environments support the search for environmentally just decisions in a coastal context, enhancing the distribution of benefits while employing inclusive decision-making practices.

Box 7: Ports' climate change impacts and adaptation – status and challenges for the Spanish port system

In Europe, the vast majority of port managing bodies in 2022 are publicly owned (ESPO, 2022). As an example, in Spain the Ministry of Transport, Mobility and Urban Agenda defines the port policy and development strategy of the state-owned port system. This is composed of 46 general-interest ports administered by 28 port authorities (PAs), organically dependent on this ministry through the state public agency Ports of the State.

In October 2022, a new strategic plant for Spanish ports was approved, including the development of a climate change adaptation plan for the ports, aiming to ensure the operability of physical elements and critical assets and to anticipate and react efficiently to downtime, disruption or operational delays. The plan identifies two goals, aligned with the second Spanish National Climate Change Adaptation (2021–2030): (i) the Spanish port system adaptation plans defined by 2025, with implementation completed by 2030, and (ii) a port climate change observatory including the monitoring of impacts implemented in 2025.

This ambitious plan requires the coordinated effort of Ports of the State and the 28 port authorities, both to implement the new measures and to continue those already initiated. As an example of an accommodation adaptation measure, Ports of the State has successfully implemented an advanced early warning system of essential climate variables in the last few decades. This system is composed of one of the most complete observational networks in the country, measuring sea level, waves, currents and other oceano-meteorological variables, with 30 years of data in some cases and more than 70 operational models forecasting sea level, waves, circulation and wind at regional, coastal and harbour scales. All these data are integrated in the Portus visualisation tool and Cuadro de Mando Ambiental (CMA, not to be confused with CMA for Common Maritime Agenda, used elsewhere in this paper) environmental management dashboard, which integrates additional tools and downstream services to support harbour decision-makers and operators. This activity will be continued and even enhanced, with possible densification of the observational network as required for the climate change observatory at each port. In addition, high-resolution models will be a key element for the development of climate projections at the scale required by the ports in the framework of the climate change adaptation strategy. This system will contribute to risk analysis and feed the climate component of the future port climate change observatory, which will link the oceano-meteorological data with the record of impacts in the ports.

The future roadmap builds on experiences of ports in Spain. In 2016 Ports of the State published, in collaboration with the Spanish State Meteorological Agency and other institutions, a vulnerability assessment of Spanish ports to climate change (Gomis Bosch and Álvarez Fanjul, 2016), analysing past trends and future projections of oceano-meteorological variables. Campos et al. (2019) proposed a downscaling modelling methodology for addressing local effects at the port scale, which was applied to the Port of Gijón, in the north of Spain. Several lessons have also been learnt from the Interreg Sudoe project ECCLIPSE (Assessment of Climate change in Ports of Southwest Europe, https://ecclipse.eu/, last access: 22 November 2023), led by the Valenciaport Foundation with the participation of Ports of the State and based on the World Association for Waterborne Transport Infrastructure (PIANC) methodology for port climate change adaptation (PIANC, 2020), applied to the ports of Valencia (Spain), Aveiro (Portugal) and Bordeaux (France). In 2022, the Balearic Islands Port Authority developed a first climate change adaptation plan for the ports of the Balearic Islands, with scientists and coastal engineers of the Universitat Politècnica de Catalunya (UPC; Sierra et al., 2022).

In the new roadmap to achieve the Spanish ports' strategic goals, Ports of the State will include the provision of relevant climate information, ensuring the use of common data and models, a link with the scientific community through the establishment of a group of experts and participation in research projects, and the development of a common methodology and best practices for implementation of high-resolution risk analysis and adaptation plans at the port level. The final adaptation measures, including consideration of economic, social and environmental impacts, will be approved and adopted by each individual Port Authority, relying on the risk analysis and the vulnerability assessment of an inventory of physical assets and port activities. A port community including public and private bodies will be established at each port for recording climate change impacts at the required spatial resolution, with a user-friendly application that should facilitate reporting to individual port actors. The record of damage to assets or impacts on operations can be sensitive information as it may negatively affect the interests of the affected party (ranging from economic to reputational interests). This element of the port climate change observatory will have to reconcile the principles of transparency and confidentiality of information, providing aggregated analysis that can inform decision-making while limiting the publication of individualised data, establishing restricted access based on the type of data or keeping information management within the scope of the port authority.

4.3 Equity and social vulnerability

The EU adaptation strategy introduced the concept of "just resilience" to acknowledge that the impacts of climate change are not evenly distributed across society and that benefits from climate adaptation need to be fairly distributed (European Commission, 2021b). This change builds on the rationale of "leaving no one behind" in climate mitigation and adaptation agendas. Achieving equal adaptation requires dealing with diverse levels and forms of social vulnerability throughout the adaptation process, ensuring both effective protection of communities and individuals from the adverse effects of climate impacts and the avoidance of disproportionate consequences of adaptation measures (Brisley et al., 2012; Reckien et al., 2018; Sayers et al., 2017).

Justice has been emerging as a key criterion for designing and implementing climate adaptation policies that recognise and address existing social vulnerabilities (Sayers, 2017). Environmental justice is widely acknowledged to encompass two main dimensions: distributive[8] and procedural justice (cf. Schlosberg, 2007).

i. *Distributive justice* focuses on the equitable allocation of burdens, disadvantages and benefits arising from climate impacts and adaptation efforts among individuals, places and generations.

ii. *Procedural justice* relates to the fairness of political procedures and decision-making processes related to adaptation, encompassing aspects such as representativeness, inclusion, openness, transparency and capacity to influence.

Further concepts have also been introduced in adaptation policies, namely recognition and restorative justices. While *recognition justice* focuses on recognising social differences, *restorative justice* highlights the need to identify and respond to the damage that has already occurred or to cases where mitigation actions are no longer possible or effective (Forsyth et al., 2021). Recently, the concept of *just resilience* in all its dimensions has been addressed by the European Environment Agency (EEA) in the report "Towards 'just resilience': leaving no one behind when adapting to climate change" (European Environment Agency, 2022).

Given the ever-increasing importance of justice issues for policy and decision-making, this section focuses on the challenges posed by ensuring distributive and procedural justice approaches when addressing sea level rise impacts, defining adaptation measures and designing decision-making processes. These aspects are discussed in-depth below, and Table 5 presents a summary of how adaptation responses and measures interact with vulnerability factors and (re)produce unequitable outcomes. Despite the relevance of justice issues, there is a significant gap for both research and concrete examples at the European level. For this reason, the section is somewhat lacking in regional differentiation and examples. Nonetheless the concepts addressed remain valid for all European sea basins.

Adaptation measures may also have positive justice impacts. In this regard, a recent literature review in Europe (see Riera-Spiegelhalder et al., 2023; Moraes et al., 2022) has shown support for nature-based solution (NbS) approaches as a cost-effective means for coastal adaptation, highlighting their multiple co-benefits, such as biodiversity enhancement, aesthetic values, carbon sequestration, water quality improvement and economic opportunities for livelihood diversification. Although NbS projects aim to deliver positive environmental and socio-economic outcomes, there is still limited understanding of how vulnerable and marginalised communities can benefit from them (Boyland et al., 2022). In this sense, NbS approaches are likely to be more effective when used in conjunction with other measures as part of a comprehensive climate change adaptation strategy (Riera-Spiegelhalder et al., 2023). Stakeholder participation in identifying co-benefits of NbS implementation is key to determining whether and how NbS projects can protect the coast and address the needs of coastal communities (Moraes et al., 2022; Davies et al., 2021). The case of Roggenplaat in the Netherlands (Kaufmann et al., 2021) shows that uncertainty related to the dynamic and unpredictable effects of NbS projects can cause new challenges to coast-dependent economic activities (e.g. oyster farming) and distributional trade-offs, where collective interests are put above individual economic livelihoods.

In addition, coastal contracts are a good example of a governance model that promotes participatory coastal planning and management (see Ernoul et al., 2021). Initially developed for rivers in the early 1980s, voluntary environmental contracts have been widely used for wetland management in Italy and France. These contracts consist in agreements negotiated between stakeholders through inclusive decision-making processes and multi-actor cooperation, involving both public and private entities. They aim to integrate expertise, perceptions and common concerns; facilitate coordination between institutions at different levels; and align policies and funding for joint actions. The experience of coastal contracts in the Gulf of Oristano (Sardinia, Italy) has shown that they can serve as a model for multilevel cooperation that stimulates economic growth and environmental sustainability, raises community awareness, and ensures that decisions are evidence-based and aligned with ecosystem and community needs (Puddu and Etzi, 2024).

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[8] Distributive justice refers to the equitable distribution of income and wealth among the members of a given society. It is therefore concerned with the preferred framework for political processes and structures to fairly distribute benefits and burdens among the individual members of a community.

Table 5. Interaction of adaptation responses and vulnerability factors in (re)producing inequitable outcomes.

Type of adaptation response	Response description and examples	Justice implication	Vulnerability factors	References
Protect/ advance	Building hard (e.g. seawalls) and soft (e.g. beach nourishment and dune rehabilitation) protective structures to hold or advance the shoreline	– Coastal protection prioritises high-density areas, leading to property devaluation and limited land-use options in low-density and underprivileged areas (distributive justice). – Powerful stakeholders with economic interests at risk dominate decision-making, favouring options aligning with their interests (procedural justice).	– Income – Source of livelihood – Absence of access to services and infrastructures	McGinlay et al. (2021), Hinkel et al. (2018)
Accommodate	Implementing technological, architectural and urban planning solutions, such as elevating buildings and infrastructures, adapting drainage systems, and strengthening monitoring and early warning solutions and insurance schemes to promote safer behaviour	– Affordability challenges regarding insurance and proofing measures arise for low-income households, rented households and non-homeowners (distributive justice). – Elderly individuals and those with lower education levels face challenges in accessing information on coastal risks (procedural justice).	– Income – Home property – Age – Education – Digital literacy	Hudson et al. (2019), Tesselaar et al. (2020)
Retreat	Relocation of infrastructures and exposed houses, neighbourhoods or entire cities	– Relocation disproportionately affects low-income and rural communities, resulting in loss of social ties, negative mental-health impacts and housing challenges (distributive justice). – Lack of psychological and social support exacerbates the sense of loss in managed retreat/relocation (distributive justice). – Decision-making often disregards local priorities, place-specific cultures and livelihoods, leading to vertically imposed decisions (procedural justice).	– Physical isolation – Physical and mental health – Source of livelihood – Income	Kind et al. (2020), Ciullo et al. (2020), Siders et al. (2021), de la Vega-Leinert et al. (2018), Dannenbarg et al. (2019), Sayers et al. (2022)

4.3.1 Distributive aspects of coastal SLR impacts

Faced with sea level rise, communities and infrastructures located in coastal areas are expected to face increasing damage and losses due to increased erosion, flooding and storms (IPCC, 2022). The gradual rise in sea levels and associated impacts from the intensification of extreme weather events will manifest in the form of property devaluation and damage to material assets such as buildings, transport and energy infrastructures (Lager et al., 2023). Further, natural and infrastructural assets related to tourism, fishery, agriculture and cultural heritage will also be affected as well as there being intangible aspects with respect to, for example, place-based knowledge, memories, values and traditions (Breil et al., 2021).

Communities reliant on coastal resources and infrastructure for their livelihoods, such as coastal tourism-based or agriculture-based communities, may bear the brunt of the consequences of SLR, experiencing not only economic losses due to environmental change (e.g. reduction and changes in use of available land, disruption of coastal ecosystem functioning, soil and aquifer salinisation) but also adverse effects on mental well-being due to environmental stress and anxiety related to, for example, loss of income (Foudi et al., 2017; IPCC, 2022).

The distribution and severity of these impacts will be influenced not only by the level of hazard exposure but also by personal and social factors of vulnerability. The housing market often drives lower-income groups towards areas more susceptible to flooding, as these regions offer more affordable housing options (European Environment Agency, 2022). In the United Kingdom, coastal communities are frequently characterised by higher levels of deprivation, consisting of low-income groups and elderly populations who may experience declining income, property values and health because of increased risk (Buser, 2020).

4.3.2 Distributive aspects of adaptation measures

Regarding distributive aspects of SLR adaptation, areas with lower populations and asset density are often deemed unsuitable for costly private and public investments in protective infrastructure such as coastal defences, consequently increasing property devaluation and insurance pricing while decreasing land-use options in already-fragile areas (Landry et al., 2003; Hinkel et al., 2018; Sayers et al., 2022).

In this context, coastal defences are often perceived as socially inequitable, as they tend to prioritise the interests of coastal residents living in high-value areas over spatially distant groups regardless of their socio-economic differences (Cooper and Mckenna, 2008). There are notable disparities in the groups affected by SLR, and the loss of homes or decline in property values will vary among second-home owners and long-term residents. Impacts of declining property values also extend to the loss of social and family ties, negative effects on mental health, and challenges in accessing suitable alternative housing options (Hardy et al., 2017).

Despite adaptation options increasingly shifting from hazard protection to increasing coastal resilience (van den Hurk et al., 2022), this shift often leans towards a risk-based approach, favouring managed retreat and accommodate options that tend to more negatively affect low-income or marginalised groups (Dannenbarg et al., 2019). Without adequate compensation or support programmes, low-income households may face challenges in affording quality flood insurance or implementing flood-proofing measures (Hudson et al., 2019). The tension between increasing risks and insurance systems regarding financial recovery and vulnerable areas is further elaborated in Box 8, “Addressing distributive justice in insurance schemes”. Moreover, adaptation measures and associated support tend to be available primarily to homeowners and not to those residing in rented or social housing, who often include the most vulnerable groups in many EU countries (cf. Tesselaar et al., 2020). Notably, only Belgium, France, Romania and Spain have implemented public-sector initiatives that cover flood risk through an equitable solidarity-based system (European Environment Agency, 2022). In addition, some areas at higher risk of flooding are inhabited by populations either unable or unwilling to move to safer locations (European Environment Agency, 2020; Filčák, 2012).

Among the factors leading to the unequitable distribution of *adaptation benefits*, scholars raise substantial criticism regarding the narrow use of cost–benefit analysis (CBA), e.g. focusing on the metric of money, as a decision-making tool for adaptation planning. Indeed, CBA is often legally prescribed to determine coastal adaptation options, and when applied narrowly, it can often result in favouring engineered solutions and prioritising areas with high population and asset density while disadvantaging poorer and rural areas with lower exposed values, which are often the key focus of managed-retreat programmes (Ciullo et al., 2020; Kind et al., 2020; Siders et al., 2021). Further, CBA, when narrowly applied, may fail to acknowledge interests and values that are challenging to monetise, neglecting ecological, socio-cultural and psychological impacts, such as mental stress from relocation or loss of social ties, place identity or cultural heritage (Maldonado, 2014; Tubridy et al., 2022). Moreover, managed retreat, nature-based solutions and ecosystem-based adaptation solutions may not fare well in CBA, particularly when high discount rates are applied, due to the initial high costs associated with them despite their potential long-term benefits (Bongarts Lebbe et al., 2021).

4.3.3 Procedural aspects of adaptation

Assessing and selecting adaptation measures can involve substantial conflict as adaptation can intensify inequalities and concentrate wealth in certain groups or hurt vulnerable members of society (Sovacool et al., 2015).

Failure to adequately acknowledge and involve vulnerable groups and diverse knowledge systems and interests poses a risk of excluding or not prioritising options that could benefit the less powerful segments of society. Often options benefitting less powerful segments of society do not reach the agenda, whilst more powerful groups might dominate the discussion and decision-making and prioritise options that align with their interests and minimise their expenses and losses (Breil et al., 2021). In this regard, some vulnerable groups have been using the courts to address violations of their rights and seek compensation for SLR-related damage in climate litigation cases. This topic is further detailed in Box 9, “Sea level rise as an emerging legal issue before the courts – catching the eye for climate litigation”.

Therefore, if a “participatory parity” in decision-making is to be achieved, marginalised groups should be meaningfully engaged in these processes. This involves including and supporting the most disadvantaged individuals in understanding the issues at hand and contributing their knowledge to assessing and identifying solutions, enabling all groups to have a voice and influence on the assessment, design and implementation of measures while considering and addressing diverse capacities and power dynamics (Lager et al., 2023). This can be addressed through decision-making approaches that rely on joint fact-finding and co-creation processes to accommodate societal preferences, raise awareness and facilitate greater learning, and gain support (Bongarts Lebbe et al., 2021). Such approaches can enable greater consideration in decision-making of often-neglected social factors such as local priorities, place-specific cultures and livelihoods. Such inclusive decision-making aims to balance more technocratic approaches that can perpetuate procedural injustice and may lead to conflicts (Rocle et al., 2020; Tubridy et al., 2022).

Another challenge is for inclusive coastal management and adaptation to ensure that community involvement is initiated at the outset of coastal decision-making processes. Often co-production processes are limited to agenda setting and evaluation (Mees et al., 2018), while community consultations may solicit input only on pre-selected options, informed by coastal management professionals and experts’ decisions about problem definition or solution finding (Blunkell, 2016; Few et al., 2007). Limiting stakeholder involvement, for example by inviting stakeholders only to select from predefined solutions rather than to contribute to scenario building, can risk reinforcing or recreating existing inequalities within new institutional frameworks (Schuerch et al., 2022).

Experiences on the German Baltic Sea coast show that managed retreat can be successfully negotiated to bring benefits to all major parties when conducted with inclusive participation. Stakeholders are prepared to trade some losses for individual and collective gains. In contrast, when such projects are implemented in a top-down manner without involving the affected parties, local opposition can arise (de la Vega-Leinert et al., 2018).

Box 8: Addressing distributive justice in insurance scheme

With increasing risks, the burden on public budgets and insurers to absorb impacts will rise drastically over the medium and long term (Ocean & Climate Platform, 2022). According to the "Commission Staff Working Document" of the European Commission, the existing insurance systems risks being inadequate in facilitating financial recovery and, at the same time, may inadvertently encourage the continuation of high-risk developments in vulnerable areas (European Commission Directorate-General for Climate Action, 2018). However, the expertise of the insurance industry in risk assessment and quantification can play a pivotal role in advancing the principles of "build back better" or even "build forward better". Insurers can contribute to strengthening risk information through assessment, communication and price signalling (European Commission, 2021a). Moreover, insurance systems covering risks separately tend to be less cost-effective compared to single insurance products that address multiple risks, which is crucial given that many cities face compound risks (Ocean & Climate Platform, 2022). However, not all risks are fully insurable by private providers or compensated by national funds, as is the case of the Fund for the Prevention of Major Natural Hazards in France that does not count erosion as eligible.

When private insurers can only partially cover or cannot cover relevant risks, governments can consider public–private partnerships, as illustrated by the Danish Storm Council (Paleari, 2019). Insurance and compensation systems that rely on collective solidarity, such as those based on shared responsibility in France and the Netherlands or universal flood coverage in the United Kingdom, offer extensive coverage and distribute risks more evenly (European Commission Directorate-General for Climate Action, 2018). Finally, governments can also act by providing tax incentives or subsidies. In this regard, the provision of subsidies and technical support to redevelopment can be planned through community-driven approaches to assessing vulnerability and needs (e.g. community profiling at the village or neighbourhood level) to identify vulnerable subjects and sites for redevelopment and have oversight of redevelopment in a bottom-up process (Breil et al., 2018).

Box 9: Sea level rise as an emerging legal issue before the courts – catching the eye for climate litigation

Climate change litigation is an emerging field that raises legal or factual issues relating to climate change before adjudicatory bodies (Sabin Center for Climate Change Law and Columbia Law School, 2023). These cases have spiked in recent years, and currently there are about 300 climate cases in around half of European countries, making European courtrooms increasingly relevant to addressing climate change (United Nations Environment Programme, 2020).[9] SLR has figured indirectly in European litigation so far, but disruptive scientific predictions for the future and the ever-growing robustness of attribution science[10] (IPCC, 2022; Ekwurzel et al., 2017) make litigation targeting SLR, both its causes and its consequences, likely to increase. To date, European climate litigation approaches to sea level rise include the violation of human rights, the breaching of (mainly) mitigation obligations by granting new licences for fossil fuel activities and liability of damage to investments in flood-prone areas.

Human rights to life, health, territory, and culture are highly threatened by sea level rise. A prominent vulnerable group in climate litigation comprises children, youth and future generations, since they will bear the burden of sea-level-rise-related harms far more and for longer than adults and have limited participation in political decisions. In the case *Sacchi et al. vs. Argentina et al.* (Sacchi et al. v. Argentina et al., 2019), 16 children discussed whether the respondent countries violated children's rights under international law by insufficiently cutting greenhouse gas emissions and failing to protect them from carbon pollution by the world's major emitters. The case has a strong transnational feature since it involves European Union members – France, Germany and Sweden – as well as a sea basin perspective, encompassing the Mediterranean-bordering countries of Tunisia and Türkiye. Sea level rise is only indirectly claimed as one of the climate-related events that violate human rights. However, the United Nations Committee on the Rights of the Child acknowledged extraterritorial responsibilities for transboundary harms. In this sense, not only the state where the event occurred or where the emissions were generated but also a state whose jurisdiction controlled the emissions if there is a causal link between the events can be held accountable for the damage. This understanding can lead to transnational liability for countries or companies with headquarters in Europe, even when their activities are carried out abroad.

In cases challenging environmental licences that grant permits for new fossil fuel projects, sea level rise is usually indirectly approached as a consequence of climate change potentiated by fossil fuel activities. The *Greenpeace vs. North Sea Transition Authority* case discussed approval for an oil and gas field in the North Sea, and the *Greenpeace Ltd vs. (1) Secretary of State for Business, Energy and Industrial Strategy and (2) the Oil and Gas Authority* and *Uplift vs. (1) SSBEIS and (2) the OGA (North Sea oil and gas licensing)* cases challenged the North Sea Transition Authority for granting the 33rd Offshore Licensing Round for oil and gas. Some cases combine both human rights and fossil fuel permit arguments. The *Greenpeace Nordic and Others vs. Norway* challenged the licence to develop deep-sea oil and gas extraction in the Barents Sea. Pending before the European Court of Human Rights (ECtHR) and discussing whether Norway has violated fundamental rights, this is a potential "impact case", since it may impact the effectiveness of the European convention system and national legal systems as well. Despite the transversal role of sea level rise, this case raises the issue of ECtHR possibly requiring countries to reconsider their oil and gas policies and strengthen their due diligence obligations to avoid climate harm (Setzer and Higham, 2022). Sea level rise appears as an associated climate impact in other cases around Europe[11] – most of them combining human rights claims as well. Although many lawsuits are filed against governments, one may observe that they can have indirect effects on financial institutions as they may result in stronger regulation for mitigation and adaptation and changes in licensing for specific sectors, which affects portfolio investments and involves financial costs to comply (Sarra and DeMarco, 2021).

Moreover, sea level rise may appear as *climate damage* in transnational lawsuits against the private sector. As an example, in *Asmania et al. vs. Holcim* (2022), inhabitants of an Indonesian island sued the Swiss company Holcim, requesting compensation for climate-change-related damage, such as flooding, reduction in carbon dioxide emissions and financial contributions to adaptation measures. The plaintiffs argue that sea level rise is destroying their livelihoods and the defendant bears a significant amount of responsibility due to its tremendously high emissions. This is a groundbreaking claim which engages the private sector on a transnational-level dispute. It may also highlight the insufficiency of monetary compensation in scenarios involving non-economic losses such as culture, traditional knowledge and displacement. The possibility of going beyond the remedies for ex post harms and asking for injunctive relief is also a relevant argument arising from this case.

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[9] Regarding the European Union, the countries with the largest number of cases are Germany, France and Spain. Outside the EU but still in Europe, the United Kingdom is also of note.

[10] Regarding attribution science, the causal chain for slow-onset events such as sea level rise is scientifically clear in a condition sine qua non formula and in terms of contributory causation. Climate science can trace back sea level rise with Carbon Majors emissions and already shows that 26 %–32 % of sea level rise is attributable to historical emissions, while 11 %–14 % is related to recent emissions.

[11] *Milieudefensie et al. vs. Royal Dutch Shell plc*, *Armando Ferrão Carvalho and Others vs. The European Parliament and the Council of the European Union*, *Notre Affaire à Tous and Others vs. France*, and the remarkable *Urgenda Foundation vs. State of the Netherlands*.

Finally, sea level rise also appears as an emerging concern for the private sector due to the liability of damage to investments in flood-prone areas. The insurance industry is facing an increasing risk associated with sea level rise and climate litigation, both as an investor with shareholder obligations and as an underwriter to claims against its policyholders. Insurers will have to deal with the uncertainty and reach of liability exposure for climate-change-related claims, which can pose a threat to the industry itself. Besides, climate litigation cases have been increasingly targeting Carbon Majors (Heede, 2014) for their contribution to the crisis, which affects liability insurers, who have a duty to defend the policyholders challenged in these lawsuits. Since 2018, lawsuits have been strengthening the argument that Carbon Majors created a public nuisance and, as such, should be responsible for paying for the damage associated with climate change and for the costs of adaptation to, inter alia, rising sea levels (British Institute of International and Comparative Law, 2021).

In the governmental sphere, many industrialised countries have advocated insurance mechanisms as a principle and effective means to deal with climate-related damage (Vanhala and Hestbaek, 2016). This, in turn, raises questions for companies on embedding the management of climate-related risks as part of core business risk management to reduce litigation. The further development of such cases in European litigation is yet to be seen.

Table 6 synthesises formal aspects of the aforementioned cases.

Table 6. Climate litigation cases.

Case and status	Parties	Principal law	Year	Jurisdiction	Sea basin
Sacchi et al. vs. Argentina et al., decided	Individuals and government	United Nations Framework Convention on Climate Change, Paris Agreement, United Nations Convention on the Rights of the Child	2019	United Nations Committee on the Rights of the Child	Mediterranean Sea
Greenpeace vs. North Sea Transition Authority, pending	NGOs and government	Regulation 16 of the Offshore Petroleum and Pipelines (Assessment of Environmental Effects)	2022	England and Wales High Court of Justice	North Sea
Greenpeace Ltd vs. (1) Secretary of State for Business, Energy and Industrial Strategy and (2) the Oil and Gas Authority and *Uplift vs. (1) SSBEIS and (2) the OGA (North Sea oil and gas licensing)*, pending	NGOs and government	Petroleum Act 1998, Environmental Assessment of Plans and Programmes Regulations 2004	2022	England and Wales High Court of Justice	North Sea
Greenpeace Nordic and Others vs. Norway, pending	NGOs, individuals, and government	European Convention on Human Rights	2021	European Court of Human Rights	Arctic Ocean
Greenpeace Nordic Ass'n vs. Ministry of Petroleum and Energy (People vs. Arctic Oil), decided	NGOs and government	Norwegian constitution, European Convention on Human Rights	2016	Supreme Court of Norway	Arctic Ocean
Asmania et al. vs. Holcim, pending	Individuals and private company	–	2022	The Justice of the Peace of the Canton of Zug, Switzerland	–

5 Summary: key developments per basin

Regarding *policy frameworks* relevant to coastal adaptation (Sect. 3.1), the Mediterranean Sea basin has three regional instruments in force, only one of which is legally binding. Two of these instruments have statements on coastal adaptation, and only one – a soft-law charter – includes specific information on SLR. The Black Sea, east Atlantic Ocean and Baltic Sea basins each have two different regional instruments, one soft law and the other legally binding. However, for all three basins, none of the regional instruments address specific measures for coastal adaptation or sea level rise. The North Sea basin has one specific soft-law instrument that, while recognising SLR as a major challenge, does not, however, contain provisions or guidelines on coastal adaptation measures. No specific treaty was mapped concerning the Arctic Ocean. Further, there are international legally binding instruments that apply to all countries in Europe; however these also do not provide specific measures on coastal adaptation. Of the three EU policy instruments that apply to all European sea basins, only the soft-law EU Strategy on Adaptation to Climate Change acknowledges the risks of SLR and provides measures for coastal adaptation. The two legally binding directives on marine strategy and marine spatial planning do not make specific provisions for SLR or coastal adaptation measures.

Regarding the *state of coastal adaptation at national level* (Sect. 3.2), almost all countries in the Mediterranean Sea basin have reported SLR as an already-observed or future expected hazard with the exceptions of Cyprus, whose national policies do not mention SLR at all. All countries have adopted adaptation policy strategies, but only France and Spain provide a list of adaptation measures, the latter specifically to address SLR. Only four countries have enforced maritime spatial planning, and three of these instruments address SLR. Further, countries are taking different approaches to funding coastal adaptation measures, with Spain having a centralised national funding approach, whereas in Italy funding for measures is distributed across multiple levels of government. In terms of addressing cross-domain governance challenges, progress of the Ports of the State in Spain in advancing climate change monitoring systems and adaptation measures illustrates the potential positive spillovers of coastal adaptation to sectors and economic activities beyond the coast.

All North Sea basin countries have reported SLR as both an observed and a future chronic hazard. Adaptation policy strategies have been adopted by the four countries, but only half of them have a list of measures, and Germany is the only one that provides specific measures to address SLR. All countries include maritime spatial planning, but only Belgium and the Netherlands address SLR in theirs. Further, countries' approaches to funding coastal adaptation also differs substantially within the basin. The Netherlands' funding is highly centralised and concentrated at the national level, whereas the UK has decentralised both coastal adaptation and decisions to local authorities. Germany has a hybrid approach of centralised funding for some portions of the coast, with decentralised funding responsibilities at other locations. The North Sea basin also shows several examples of incorporating flexibility into governance processes and adaptation measures to address the challenges of uncertainty in long-term SLR. In the Netherlands, dynamic adaptation pathways explicitly incorporate flexibility into the approach of the Delta Programme, while in Germany, dike reinforcement includes additional widening of dike crests in order to reduce future costs of increasing dike heights should high-end SLR materialise. Finally, progress is being made on co-development processes that engage local communities on equal footing with experts and coastal managers, as illustrated in the case of Texel in the Netherlands.

Of EU Black Sea basin countries, only Romania reported SLR as both an observed and a future chronic hazard. Both Romania and Bulgaria have adopted adaptation policy strategies; however only Bulgaria lists adaptation measures, and neither country specifically addresses SLR. Neither country has maritime spatial planning in force.

All Baltic Sea basin countries have reported SLR as an observed and future chronic hazard, except for Sweden which reported it only as a future one. All have adopted adaptation policy strategies; five of them list measures, but only Estonia and Germany specifically address SLR. Maritime spatial planning has been enforced by all, but Estonia, Latvia and Lithuania are the only ones addressing SLR in their MSP documents.

SLR is an observed and future chronic hazard in all Atlantic Ocean basin countries. All countries have adopted adaptation policy strategies with a list of measures, and only France does not include measures specifically addressing SLR. Maritime spatial planning is also enforced by all countries, and only Portugal does not specifically address SLR in their MSP document. In terms of addressing the challenges of uncertainty in SLR and risks associated with lock-in of coastal planning decisions with long time horizons, in France, there is little evidence that high-end scenarios are being considered in the siting and design of new nuclear power plants at the coast.

In the Arctic Ocean basin, Norway is considering mid-range SLR scenario information in its planning approaches.

6 Conclusion

SLR may exacerbate geopolitical conflicts and acts as a potential risk multiplier with relevant socio-economic, environmental and cultural consequences for Europe. Addressing the challenges of SLR will therefore require a high degree of cooperation and joint action across sea basin boundaries and the engagement of multiple stakeholders. Such coordination and engagement will enable the European Union to address the challenges of reconciling long-term climate goals with short-term supply chain security and managing energy independence in the context of geopolitical risks.

Relevant policy frameworks for SLR governance exist at regional and national levels. The latter remains the key level for coastal and marine management, as national policymakers retain the decision-making authority for planning and implementing measures in coastal and marine areas. Each sea basin has policy instruments aimed at safeguarding strategic interests related to the sea, in cooperation with different actors. Approaches to coastal adaptation policies vary among countries at the national level according to institutional arrangements and geographical and social circumstances. Although SLR is already affecting and is expected to affect almost all EU coastal countries and has been identified as a major hazard by almost all EU member states, only a few countries include specific measures to adapt to SLR in their coastal adaptation policies. This indicates that there is still a gap between the recognition of SLR risks and the adaptation measures to address them through policies at the national level. Further, as cumulative SLR impacts that often have a cross-boundary character are unlikely to be effectively managed in a fragmented way, the analysis points to the need for a more holistic and integrated approach to coastal governance in European sea basins.

In terms of public financing arrangements for coastal adaptation, a wide variety of approaches are observed across countries, particularly in addressing flood risk reduction. Highly centralised arrangements in which tax revenue is collected and distributed by the central government, which also determines flood safety levels, are observed, for instance, in the Netherlands. In contrast, decentralised models, where greater financing responsibility is borne by municipal or local governments, are observed in the UK and for parts of the German Baltic Sea coast. Further, there is an emerging emphasis, supported at the EU level, on innovative instruments for scaling up private finance for coastal adaptation (European Commission, 2019b).

Analyses of time horizons and uncertainty show that the rate, timing and amount of regional and local sea level rise over longer time horizons (roughly beyond 2050) are highly uncertain. This points to the governance challenge of implementing adaptive planning approaches that support decision-makers to act in the short term while avoiding lock-in and maladaptation in the longer term. This is particularly the case for planning and implementing adaptation strategies that include large-scale interventions, which often take decades, may require taking decisions before uncertainty is reduced or risk responding too late. In contrast, traditional planning time frames and tools, as well as conventional policy systems and decision-making, are often not well suited to addressing long-term and uncertain risks when balancing clear, short-term needs. The evidence on how countries in Europe take uncertainty and time horizons into account when planning for SLR offers a mixed picture. At the national level, many countries use 2050 and 2100 as planning horizons for SLR. Very few countries consider horizons beyond 2100, despite long-term commitments to SLR and the long life span of many interventions. Most countries report planning for ranges of SLR that occur in almost all emissions scenarios, suggesting that relatively few countries are addressing uncertain high-end or accelerated SLR.

Another key SLR governance challenge relates to the need for coordination approaches (national to regional–local, intersectoral and interdisciplinary) to integrate adaptation to SLR into sectoral policies and to share responsibilities across different levels of governance. In order to develop and implement local adaptation strategies and action plans, local authorities are encouraged to promote knowledge transfer through broad consultations involving coastal management experts and stakeholders, local coastal user communities, and local associations. To this end, participatory methods can improve communication and facilitate consultation and outreach. While there are emerging examples of such co-development processes for coastal adaptation across Europe, greater investment in such processes, including in awareness raising for coastal communities, will be key in ensuring that participation can be scaled up to meet SLR governance challenges across Europe. Further, it should be noted that this is already broadly supported at the EU level through initiatives such as EU science diplomacy, which could be leveraged to ensure the sharing of experiences and knowledge of coastal adaptation across disciplines and European regions (European Union Science Diplomacy Alliance, 2024).

Finally, it should be emphasised that participatory governance approaches also play a critical role in recognising and addressing social vulnerabilities and inequalities emerging from or exacerbated by SLR impacts and adaptation responses. Vulnerable communities, such as low-income and marginalised groups, often bear a disproportionate burden of climate impacts, yet they can be overlooked in decision-making processes, perpetuating existing socio-economic inequalities. Integrating social justice and vulnerability considerations into coastal management and adaptation strategies is therefore imperative to ensure equitable coastal adaptation. Achieving distributive justice and legitimacy in adaptation efforts requires decision-making processes that involve diverse stakeholders to develop viable pathways that address the needs of vulnerable groups. However, translating these principles into practice faces challenges around Europe due to dominant practices in adaptation planning and decision-making, in particular the reliance on cost–benefit analysis and non-inclusive sustained engagement processes. Considering other methods and governance approaches to vulnerability assessment and adaptation appraisal, such as multi-criteria analysis and coastal contracts, can facilitate European sea basins, countries and coastal communities in better addressing the justice and vulnerability challenges posed by SLR.

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