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ORIGINAL PAPER

Global drought monitoring with drought severity index (DSI) using Google Earth Engine

Ramla Khan[1,2] · Hammad Gilani[1]

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Abstract
Unlike most disasters, drought does not appear abruptly. It slowly builds over time due to the changes in different environmental and climatological factors. It is one of the deadly disasters that has plagued almost every region of the globe since early civilization. Droughts are scientifically being studied with the help of either simple or composite indices. At 500-m spatial resolution, this study presents global scale drought severity index (DSI), a composite index using Moderate Resolution Imaging Spectroradiometer (MODIS), 8-day temporal resolution evapotranspiration (ET), potential evapotranspiration (PET), and normalized difference vegetation index (NDVI). This index is mainly used to identify meteorological droughts and also has proven reliable for studying agriculture droughts. In this study, Google Earth Engine (GEE), a cloud-based geospatial data computational platform, is used for drought mapping and monitoring from 2001 to 2019. For annual DSI spatial maps, the statistical median is computed ranging from − 1 to + 1, which means drought struck or dry regions have values closer to negative, and wet zones have values near to positive. For the validity of DSI results, the findings are compared with available records of droughts struck in previous years. This study declares that continent-wise, Australia, Africa, and Asia have the most extreme and frequent drought events while South America and North America come a close second. Europe is the least affected by this particular weather event when compared to other continents.

1 Introduction

According to a special report, "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)", released by the Intergovernmental Panel on Climate Change (IPCC) for climate change and natural disasters, weather extremes and climate events may not appear harmful individually but their accumulative effect can be seen in the form of deadly droughts with time (IPCC 2012). During a dry season, the water demand of society and the available amount falls short (Elhag and Zhang 2018). In humid areas like the Amazon forest, a mere 10% decrease in precipitation will not cause any lasting damage, but the same situation in a semi-arid area like northeast Brazil will be a definite cause for concern (Food and Agriculture Organization of the United Nations 2019). Droughts can affect regions that are not directly hit by it; for example, if a mountainous area receives less rainfall and snow than usual and it causes dryness, then the areas which rely on groundwater and streams that comes from those mountains will also be subjected to impacts of the dry season (IDMC 2020). Drought is one of the costliest disasters humankind faces all over the world (Wang et al. 2019). It impacts socio-economic sectors like tourism, energy, water supply, agriculture, energy, infrastructure, and the country's economy (Meza et al., 2019). For instance, in the year 2008, concerns regarding the development of a La Niña event raised alarms about drought and consequently about a massive shortage of energy production in the electric power plants in Chile (Peterson et al. 2009).

In 2018, a global survey was conducted for indicators and their relevance to drought assessment by collaborating with the United Nations (UN) university and Global Drought Observatory (GDO). The research was an expensive and detailed study, focusing on the agriculture and water sector, but the summary was that a vast majority of researchers voted in favor of indicator-based assessment of drought (Meza et al. 2019). These indicators are numerically computed and introduced by experts working on climate change

✉ Ramla Khan
ramla.khan@open.ac.uk

[1] Department of Space Science, Institute of Space Technology, Islamabad 44000, Pakistan

[2] Environment Earth and Ecosystem Sciences (EEES) School, The Open University, Milton Keynes MK7 6AA, UK

issues. There are three approaches used for drought monitoring through indices: with only one index, a combination of indices, and hybrid/composite indicators. The single or simple index requires only one climatic/hydro-meteorological variable for its computation while a combination of multiple single indices to formulate a single composite index (WMO and GWP 2016).

Drought severity index (DSI) is a composite index that assimilates variables of vegetation and evapotranspiration (Wang et al. 2019). DSI is categorized mainly for measuring meteorological droughts (Zargar et al. 2011) and can also be used for observing agriculture drought (Elhag and Zhang 2018). It was first introduced by Mu et al. (2013) using the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite normalized difference vegetation index (NDVI) and evapotranspiration products for the computation. However, in this study, instead of taking the mean of the yearly maps, the statistical median was opted because it gave clearer and more accurate results. Also, the results are discussed in much more detail for almost every country throughout the globe.

Google Earth Engine (GEE) is a cloud-based platform and runs on Python API and Java scripting (Gorelick et al. 2017). It is a powerful tool for dealing with big geo-datasets. It is also faster than traditional software and can reduce the processing time in half. GEE also has many datasets available in its repository that researchers with limited coding backgrounds can readily and easily use.

2 Materials and methods

2.1 Datasets

This study used freely available datasets from the repository of GEE; MODIS satellite terra sensor evapotranspiration (ET), and potential evapotranspiration (PET) 8-Day Global 500 m (Mu et al. 2007) and MODIS Terra NDVI 8-Day Global 500 m (Didan et al. 2015). In GEE, ET and PET dataset are available from January 2001 to the present, while the NDVI availability date is from February 2000 to the present. So in this study, DSI mapping and monitoring is done from 2001 to 2019. MODIS derives the product for evapotranspiration through Penman–Monteith equation-based algorithm. The input data for the algorithm is the summation of nightly and daytime daily evapotranspiration and vegetation data with a temporal resolution of 8 days (Running et al. 2019).

Evapotranspiration studies the ecosystem, which in extension analyzes the carbon, water, and energy cycle. The ratio of ET to PET determines the available water in a terrestrial environment and helps study dry seasons in a region (Mu et al. 2012). The agriculture sector is the one most affected by droughts at the beginning of dry season, and almost 18% of the global population is employed in this sector (Meza, et al. 2019).

2.2 Methodology

In this study, MODIS terra data is used for analysis and computation. The parameters used in this index are evapotranspiration (ET), potential evapotranspiration (PET), and normalized difference vegetation index (NDVI).

Before computing DSI, the preprocessing performed on datasets is cloud percent reduction, shadows removal, filtering timeline of our study, rescaling values to monthly data, and masking vegetation data.

The methodology for computation is as follows: first, the ratio between evapotranspiration and potential evapotranspiration is computed. In the second step, the ratio is standardized. Thirdly, the precomputed product of NDVI from MODIS is standardized. Fourthly, the sum of both standardized values is calculated. In the final step, the sum from the previous step is standardized, and that value is named drought severity index or DSI.

The equations of the study are:

$$Tran = ET / PET \tag{1}$$

In the above equation, Tran denotes the symbol for the ratio between the input variables. ET means evapotranspiration, and PET symbolizes potential evapotranspiration.

$$Z1 = \frac{Tran_i - Tran_{mean}}{Tran_{SD}} \tag{2}$$

In Eq. 2, Z1 represents the standardizing ratio for the transpiration ratio calculated in Eq. 1. $Tran_i$ means transpiration ratio of the specified 8-day period, $Tran_{mean}$ symbolizes transpiration mean/average, and $Tran_{SD}$ indicates the value of the standard deviation for the transpiration ratio.

$$Z2 = \frac{NDVI_i - NDVI_{mean}}{NDVI_{SD}} \tag{3}$$

In Eq. 3, Z2 represents a symbol of the standardizing ratio for the NDVI values. $NDVI_i$ indicates NDVI value of the specified 8-day period, $Tran_{mean}$ symbolizes NDVI mean/average, and $Tran_{SD}$ indicates the value of the standard deviation for the NDVI value of a specified period.

$$Z = Z1 + Z2 \tag{4}$$

Z represents the sum of standardized values from Eqs. 2 and 3.

$$DSI = \frac{Z_i - Z_{mean}}{Z_{SD}} \tag{5}$$

In Eq. 5, DSI denotes the drought severity index, and Z values standardize ratio from Eq. 4. Z_i is the value of the specified period, Z_{mean} symbolize mean/average, and Z_{SD} indicates the value of the standard deviation for the Z value of a specified period.

3 Results

For spatial maps, the statistical median is computed for the final product for the yearly result. The reason for not taking mean instead of the median is that the results are shown more clearly. A visual aid, for this reason, is shown in Fig. 1 with 2001 as an example. Four areas are circled in the Fig. 1 that shows the extreme droughts visible only with statistical median.

The range chosen is from -1 to $+1$, which means droughts will have values close to -1, and wet zones will have values near $+1$. The results discussed will mainly include extreme cases.

The maps are read in close detail on the GEE map by zooming in and slightly reducing the opacity to observe the boundaries of countries. The maps shown in Fig. 2 are at 100% opacity and zoomed out to cover the whole globe. The results are discussed in detail below.

3.1 North America

3.1.1 2001

More than half of Mexico is going through an extremely dry season. In the USA, Texas, Oklahoma, and California show dark red patches of extreme drought; North Carolina, South Carolina, Georgia, San Francisco, and Florida have mild and severe droughts in certain areas. The Dominican Republic has extreme and mild dry situations in certain areas.

3.1.2 2002

Arizona, California, Texas near the Mexico border, and southern Nevada in the USA are facing extreme dry seasons. Kansas and Colorado are facing mild to severe drought. Mexico has an extreme drought in certain parts, and severe and mild in others. Quebec and Ontario in Canada are displaying red patches of extreme and severe dry situations.

3.1.3 2003

In the USA, Texas is facing extreme drought; California and New Mexico have mixed severe and extreme dry situations. Mexico is going through an extreme and severe dry period near the USA border.

3.1.4 2004

Cuba is facing extreme dryness while Arizona and the neighboring areas are going through mild and severe dry periods.

3.1.5 2005

The only notable dry patch in the whole continent is in the middle of Mexico that ranges from mild to severe.

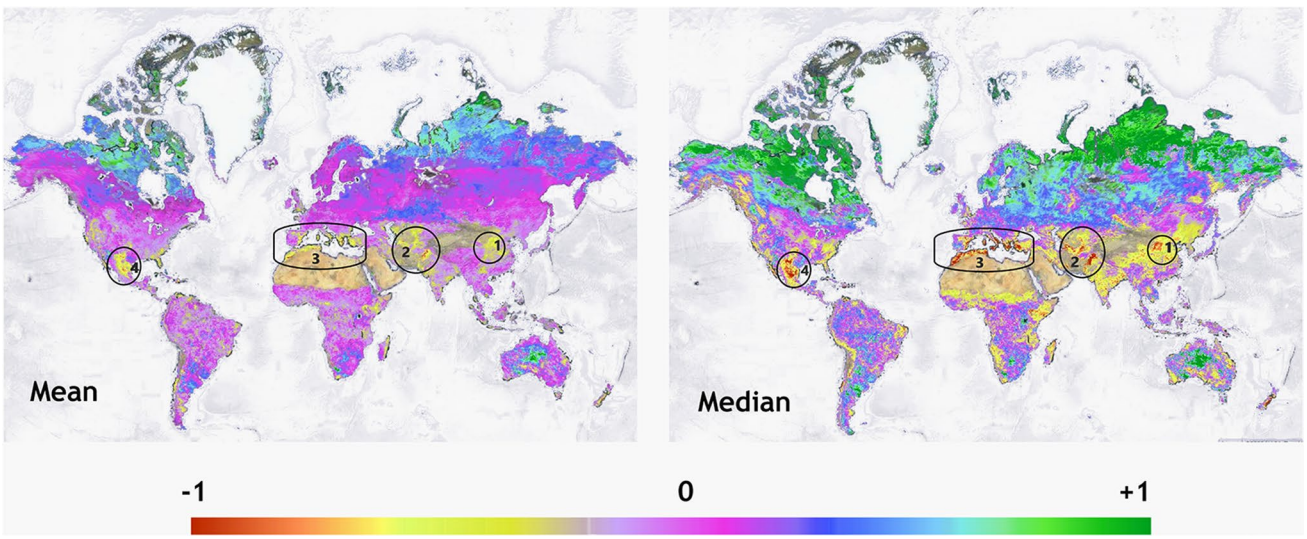

Fig. 1 Right side map shows the mean value of twelve months, and the left side map is the statistical median for 2001

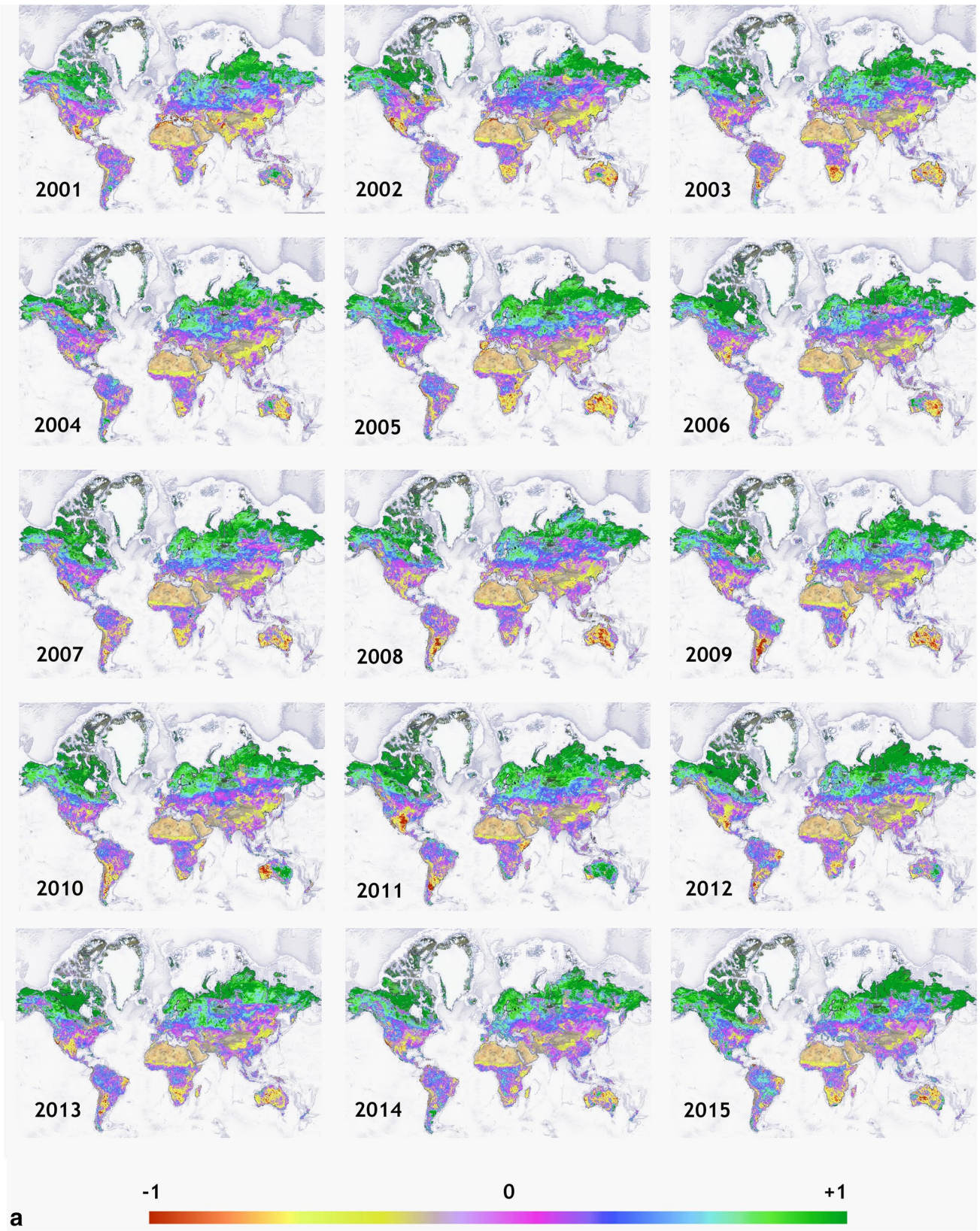

Fig. 2 **a** Spatial maps of DSI from 2001 to 2015. **b** Spatial maps of DSI from 2016 to 2019

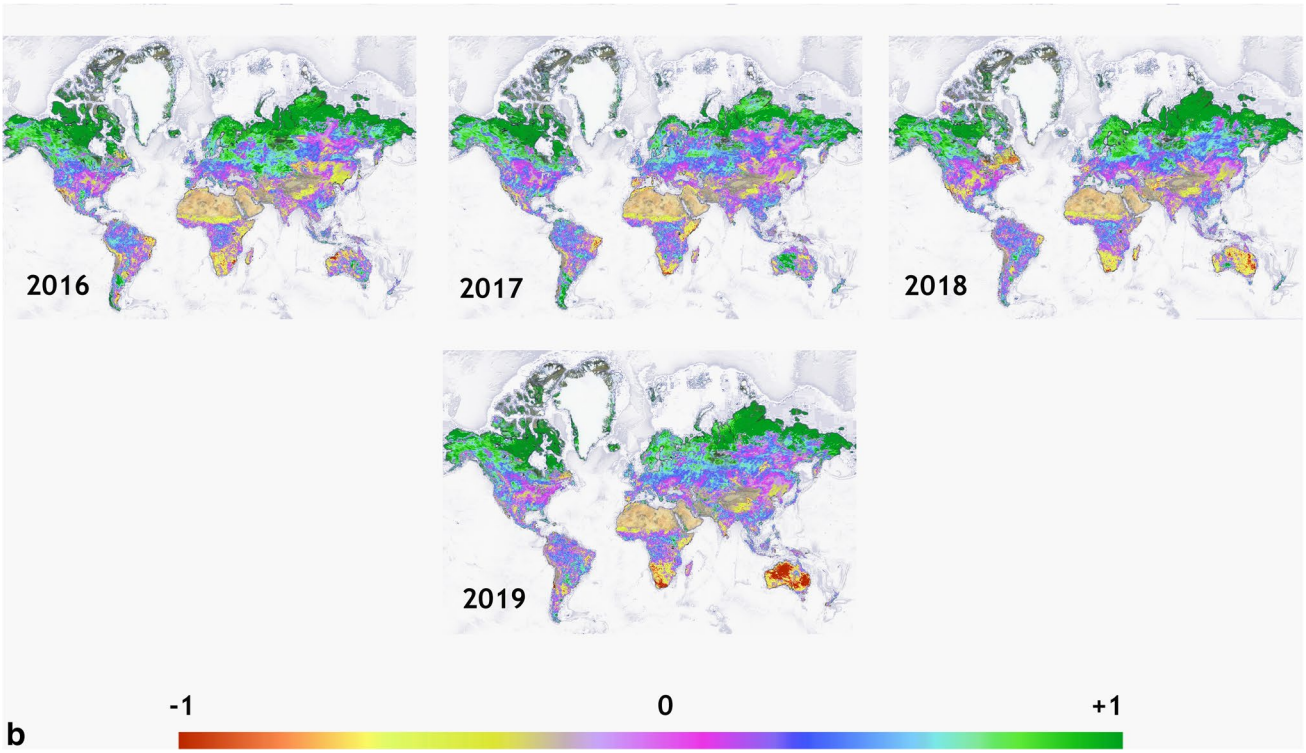

Fig. 2 (continued)

3.1.6 2006

Mild to extreme dry situation found in Mexico towards the north and in Texas and Oklahoma in the USA. Mild dryness can also be seen towards California and Arizona in the USA.

3.1.7 2007

Arizona and California in the USA and Baja California in Mexico are showing cases of severe to extreme droughts.

3.1.8 2008

Mild to a greater extent and severe in small areas a drought season could be noticed in the whole Mexico and Texas, Arizona, California, and Nevada in the USA.

3.1.9 2009

Texas has severe to extreme drought. The states of Nevada, California, Arizona, and New Mexico in the USA are going through cases of mild to severe droughts. Mexico has also spots of severe and mild dryness near the USA border.

3.1.10 2010

Mild to slightly severe dryness in a very small area is noticed towards the east of the USA.

3.1.11 2011

This year shows the worst case of the extreme dry season that spans over Texas, the majority of New Mexico and Oklahoma, and some parts of Arizona and Kansas. Mexico also seems to be suffering from an extreme drought that has reached almost every part of the country.

3.1.12 2012

In the USA, Texas and New Mexico are displaying evidence of mild to severe and slightly extreme dry season. Mexico has a large patch of extreme drought.

3.1.13 2013

The state of California in the USA is extremely dry this year. Colorado, Texas, and New Mexico in the USA are

ranging in dryness from mild to extreme. The country of Mexico has also mild to the severe dry season.

3.1.14 2014

In the USA, the states of Texas, California, and a small part of Nevada towards the south are in extreme drought. Mexico has recovered slightly from the last 3 years' worst drought but there are still signs of mild and severe dryness in parts of the country, especially the ones near the USA border.

3.1.15 2015

California state in the USA and the Gulf of California in Mexico are the only regions with mild and extreme dryness cases. The rest of the continent is exceptionally in a better state this year.

3.1.16 2016

The same situation is noticed this year as 2015, with the only exception of drought reducing to the south of the state of California and a mild dry period in Arizona State.

3.1.17 2017

The states of Wyoming, Idaho, and California are the only regions in the continent this year to show small signs of mild and severe dryness.

3.1.18 2018

The provinces of Quebec, Ontario, and Newfoundland and Labrador in Canada are extremely dry, and in the USA, the regions of Texas, California, and Arizona are displaying severe and extreme dryness this year.

3.1.19 2019

Newfoundland and Labrador are severely dry, while in the USA, the dryness this year is in the form of very small patches of extreme cases that are found in the states of Florida, Montana, California, and Wyoming.

3.2 South America

3.2.1 2001

Extreme dry situation is observed towards northeast Brazil, northern parts of Venezuela, a very small portion of the state of Rio de Janeiro in Brazil, towards Los Angeles and Concepcion in Chile, and San Juan and Perito Moreno in Argentina.

3.2.2 2002

A very small region in Paraguay and Bolivia, a vast area of Santa Rosa in Argentina, and almost half of the state of Mato Grosso Do Sul and parts of state of Sao Paolo in Brazil are going through mild and severe dryness.

3.2.3 2003

Argentina is particularly dry during this year. Brazil is facing severe and mild dryness throughout the country near the South Atlantic Ocean.

3.2.4 2004

Peru and Bolivia, a small area of Argentina, and the state of Rio Grande Do Sul in Brazil are facing mild and severe dryness.

3.2.5 2005

Peru shows extreme cases of drought while northeast Brazil and Argentina are mildly dry. Amazonia faced dry season as well.

3.2.6 2006

Argentina is the only country displaying mild to extreme dryness. Mild dryness is seen towards Peru and northeast Brazil.

3.2.7 2007

Mild and severe dry situation dominates parts of Brazil, Paraguay, and Peru. Chile is only mildly dry and in a small portion. Argentina is displaying severe to extreme dryness in the middle.

3.2.8 2008

Argentina and Uruguay are exhibiting extreme conditions of dryness that span over a large extent of the respective countries. Bolivia and Peru are displaying mild to severe droughts. Brazil in the southeast and Chile are only mildly dry.

3.2.9 2009

A large portion of Argentina is going through extreme dryness. Paraguay, Bolivia, and the state of Rio Grande Do Sul of Brazil are showing mild dry seasons. The otherwise warm and dry northeast Brazil is exceptionally wet this year.

3.2.10 2010

Extreme droughts are noticed in a vast area of Argentina, Paraguay, and Bolivia. Uruguay, Peru, and South Brazil have mild cases of dryness.

3.2.11 2011

Smack in the middle of Argentina is a massive dark patch of extreme drought, and towards the east of the country, the drought ranges from mild to severe. Santa Cruz de la Sierra of Bolivia also has evidence of extreme drought.

3.2.12 2012

Northeast Brazil and the west of Argentina have huge evidence of extreme dry season this year.

3.2.13 2013

Northeast Brazil has extreme drought this year too. The drought in Argentina has not reduced its intensity but it has shifted to the north, where it is even spread to Paraguay and the middle of the country. Chile is also exhibiting mild dryness.

3.2.14 2014

An almost no notable portion of northeast Brazil, north Peru, and south of Chile has severe and mild dry seasons.

3.2.15 2015

Northeast Brazil has a severe and extreme drought. South of Chile and north of Venezuela near the Caribbean Sea are also extremely dry. Argentina is mildly dry in certain parts.

3.2.16 2016

Northeast Brazil and south of Argentina are mild to extremely dry while Bolivia and Peru are mild to severely dry.

3.2.17 2017

The only case of drought this year is seen towards northeast Brazil, and it is mild to extreme.

3.2.18 2018

Drought of northeast Brazil has reduced from extreme to slightly severe, and a mild case of dryness has also emerged in a small area of Argentina.

3.2.19 2019

Chile has an extreme case of dryness, and Argentina has mild and severe small dry patches in the middle of the country. In the heart of the continent, Pantanal is also suffering from the dry season.

3.3 Africa

3.3.1 2001

The only vegetative parts lie near the river banks in Tunisia and Algeria, and they are in extreme dry situations. Morocco as a whole is going through a dry season. Somalia and the parts of Ethiopia that share a border with Somalia and Madagascar are in extreme and mild dry season periods in one part or the other.

3.3.2 2002

Severe and extreme situations are observed in Namibia, northern parts of South Africa, a small area in Zambia towards the south, and Botswana. Western Kenya, Tunisia, Algeria, and north eastern Uganda are facing extreme drought.

3.3.3 2003

Botswana and Namibia, are gone through extreme dry periods. South Africa is facing mild and extreme droughts throughout the country. A small part of Algeria and Morocco are facing severe dryness.

3.3.4 2004

Botswana and South Africa are having extreme dry seasons while Namibia is only mildly dry.

3.3.5 2005

Ranging from extreme to severe droughts are noticed in Zambia, South Africa, Tanzania, Botswana, Morocco, Namibia, and Angola. Algeria, Mozambique, and Kenya show mild dry seasons.

3.3.6 2006

Algeria has a small severe dry patch while Kenya, Ethiopia, Madagascar, and Tanzania have mild dryness.

3.3.7 2007

Morocco is extremely dry while Zimbabwe, South Africa, Botswana, Namibia, and southern Angora are ranging in dryness from mild to severe and extreme.

3.3.8 2008

Algeria and Morocco are severe to extremely dry. Somalia, Ethiopia, Zimbabwe, Mozambique, and Botswana are exhibiting mild to severe dryness. South Africa and Namibia are mildly dry and only in certain parts.

3.3.9 2009

A small part of South Africa that lies to the south of the country and all of Kenya are displaying extreme droughts. Somalia and Ethiopia are showing mild and slightly severe dryness.

3.3.10 2010

Somalia and two separate regions in South Africa, one to the north and the other to the south, display clear signs of extreme dryness. South of Madagascar also has some signs of severe drought.

3.3.11 2011

Somalia, Ethiopia, and Kenya are enduring extreme droughts this year. A tiny region in Sudan shows severe dryness while the rest of the country is mildly dry. South Africa and Namibia are exceptionally wet this year.

3.3.12 2012

Zimbabwe, south of Mozambique, and Botswana exhibit signs of dryness that range from mild to extreme. There is a small straight line of severe drought passing through Ethiopia. West of Angola and southeast of Kenya are also mildly dry.

3.3.13 2013

Botswana, northeast Namibia, the center of Zimbabwe and South Africa, and southwest Angola are mild to extremely dry.

3.3.14 2014

There are no severe or extreme droughts this year. The whole continent is mostly in no drought situation or mildly dry.

3.3.15 2015

Ethiopia, Kenya, Tanzania, Zimbabwe, and Mozambique are mildly dry, while the majority of South Africa, south of Angola, north of Namibia, and regions of Botswana near the South African border are facing extreme dry seasons.

3.3.16 2016

The most extreme drought noticed on the map lies to the south of Mozambique in the form of large and dark patches of red. Areas near the shared border of South Africa and Botswana are experiencing mild to extreme dryness. Namibia has a moderately severe case of drought that covers most of the country's north side. Tunisia, Morocco, Algeria, and the rest of South Africa are mildly dry.

3.3.17 2017

Extreme cases of dryness are noticed to the east of the continent in Somalia, Kenya, and Tanzania; to the north in Morocco, Algeria, and Tunisia; and towards the south in the South Africa region. Madagascar and Ethiopia are mildly dry.

3.3.18 2018

Southern regions of both Madagascar and South Africa are extremely dry. Namibia, Botswana, and Guinea are mildly dry.

3.3.19 2019

South Africa has the worst case of extreme dryness that extends to more than half of the country. The vast area of Namibia is severely and extremely dry while small regions of Mozambique and Angola are mild to severely dry. Somalia, Kenya, Zambia, and Morocco are mildly dry.

3.4 Europe

3.4.1 2001

Extreme droughts are observed in Greece, northeast and southeast parts of Spain, more than half Italy, southern parts in Albania, a very small part in Romania and Bulgaria near the black sea, and western Turkey. Madrid in Spain is going through a mixture of the mild and severe dry season.

3.4.2 2002

The only red patch this year in Europe is found in Italy towards the south and in Zaragoza in Spain.

3.4.3 2003

France, Italy, and the UK are facing severe and extremely dry seasons in certain parts.

3.4.4 2004

No extreme or severe situation was noticed in Europe this year.

3.4.5 2005

Portugal and Spain are facing extreme and severe drought situations throughout the whole region. The rest of the continent shows no anomalies.

3.4.6 2006

Spain shows mild to severe dry periods throughout the country while France has mild dryness towards the areas near the bank of the Balearic Sea.

3.4.7 2007

Spain towards Barcelona, France in Monaco and neighboring areas, Italy in the middle, and Albania suffer from mild to extreme dryness. Greece and west Turkey are going through mild to severe dryness situations.

3.4.8 2008

Mildly dry situation dominates this year for many European countries. These countries are Italy, Portugal, Spain, Greece, Croatia, west Turkey, and France.

3.4.9 2009

Spain, Portugal, and France are mild to extremely dry while Italy, UK, and Ukraine are mild to moderately severe dry.

3.4.10 2010

The dryness noticed this year is somewhere between mild and severe in the UK, France, and Austria.

3.4.11 2011

Italy is slightly severe dry while the rest of the countries show no signs of harmful droughts.

3.4.12 2012

A mild dryness is noticed towards Romania, France, Spain, and the south of Ukraine.

3.4.13 2013

The UK and small regions in France and Germany are mildly dry.

3.4.14 2014

Towards southeast Spain, there is an extreme drought noticeable.

3.4.15 2015

Only mild dryness is noticed in Spain.

3.4.16 2016

Spain has a slightly severe to an extreme case of dryness towards its southeast.

3.4.17 2017

Portugal and especially Spain are severe to extremely dry, while Sardinia in Italy is mild to extremely dry.

3.4.18 2018

A small patch of land in Portugal is extremely dry. France has mild to severe cases of dryness in the middle. European Russia has evidence of mild dryness in a small area.

3.4.19 2019

Spain towards the southwest and Portugal towards the southeast are mild to severely dry. A small region in France, Germany, and Austria is suffering from a mild case of dryness.

3.5 Asia

3.5.1 2001

More than half of Pakistan, almost all vegetation in Turkmenistan, vast areas of Afghanistan and Uzbekistan, parts of Kazakhstan near the Caspian Sea, and Shanxi, Ningxia, Henan, and Inner Mongolia in China are going through extreme dry situations. The rest of China, almost the whole of India, Jordan, Syria, and Lebanon are displaying a combination of mild and severe dry situations.

3.5.2 2002

Pakistan in the majority, parts of Azerbaijan, and Rajasthan of India face extreme drought. China is going through a mild dry season.

3.5.3 2003

China is mildly dry. Pakistan in the middle and India towards the south are facing extreme drought.

3.5.4 2004

Pakistan is facing extreme drought while China, Thailand, and India are mildly dry.

3.5.5 2005

India and China are going through dry periods that range from mild to severe in certain parts. Thailand and Vietnam show extreme to severe drought conditions, while Cambodia is mildly dry.

3.5.6 2006

Mild drought in the majority of China, Turkmenistan, and India, while severe in very small areas of the same countries, are the dominant droughts this year in Asia. Uzbekistan and Pakistan have mild droughts.

3.5.7 2007

Mild to severe droughts are found towards east Turkey, Cyprus, Turkmenistan, Uzbekistan, and India. Syria and China are mildly dry.

3.5.8 2008

A large number of countries are showing severe and extreme droughts this year. The Republic of Cyprus, Turkey towards the southeast, Turkmenistan, Afghanistan, and Iraq have dryness ranging from severe to extreme. Uzbekistan, Syria, Tajikistan, Iran, Yemen, and Saudi Arabia have drought situations ranging from mild to extreme. Severe and mild droughts are also seen in China and Indonesia.

3.5.9 2009

Iraq, Iran, and Yemen are severe to extremely dry. China, Pakistan, Turkmenistan, and India are having dry seasons in the range of mild to slightly severe.

3.5.10 2010

Patches of extreme and severe droughts are seen in Syria, Iran, Iraq, Turkey, Lebanon, Israel, Turkmenistan, and the southeastern corner of Russia. Those with mild dryness are China, India, Myanmar, Thailand, Uzbekistan, and Cambodia.

3.5.11 2011

A minimal area in the southeast corner of Pakistan, vast regions of Uzbekistan, and Turkmenistan are extremely dry while China, Tajikistan, Iran, and Iraq have mild dry seasons.

3.5.12 2012

China has evidence of severe dryness in more than one province. India and Turkmenistan have specific areas that are dry in the range of somewhere between mild and severe. In Pakistan, extreme cases of dryness are seen in Potohar and Sindh.

3.5.13 2013

Mild to severe dryness is seen towards Qinghai, Tibet, and Henan provinces of China, and also towards Syria and neighboring countries, and towards the south of India. Aktau Aktay of Kazakhstan and west of Turkmenistan are extremely dry.

3.5.14 2014

Southern corner of India, vast areas of Turkmenistan and Azerbaijan, and a small area towards the west of Afghanistan are in extreme and severe drought situations.

3.5.15 2015

Only mild dryness is noticed this year and is found in China, Pakistan, Iran, Iraq, and Syria.

3.5.16 2016

Small regions in Afghanistan, Uzbekistan, Iran, Syria, and neighboring countries, and Thailand have patches of extreme dryness. The areas near the shared border of Mongolia and Russia on both sides are severely dry. Turkmenistan, Pakistan, and India have evidence of mild dryness in certain areas.

3.5.17 2017

Syria, Iraq, and the south of India have evidence of mild to severe dryness. China is mildly dry.

3.5.18 2018

Afghanistan, Uzbekistan, Turkmenistan, Iran, and Pakistan show extreme patches of dryness.

3.5.19 2019

Extreme dryness is found in China, India, Azerbaijan, and Cambodia. Turkmenistan, Pakistan, Iran, and Yemen are exceptionally wet this year.

3.6 Australia

3.6.1 2001

Southeastern parts of New Zealand are in the claws of extreme drought. Australia has a combination of mild and severe drought throughout South Australia, West Australia, and Queensland.

3.6.2 2002

Except for a small portion in the middle of Australia, the whole country is in the clutches of the severe and extreme dry season.

3.6.3 2003

Severe and extreme dry situation is noticed towards the south of New Zealand and the whole of Australia.

3.6.4 2004

Mild and extreme dryness is noticed towards Queensland and New South Wales. South Australia and Northern Territory are going through a severe and mild drought.

3.6.5 2005

Northern Territory and Western Australia have extreme dryness, Queensland and New South Wales display severe to extreme dryness, and South Australia shows mild to severe dry patches.

3.6.6 2006

Extreme and severe drought spans over the whole area of Queensland and New South Wales, while the Northern Territory and South Australia are having almost the same intensity of drought but limited to certain zones.

3.6.7 2007

Towards the north, the drought is mild, but going towards the south makes the drought mild to extreme. Even the otherwise cold region of Tasmania is going through a severe dry phase. New Zealand is also displaying severe and mild dryness in certain areas.

3.6.8 2008

Queensland displays less severe drought than the rest of Australia, where extreme and severe droughts dominate the map.

3.6.9 2009

Mild to severe dryness is spanning over almost the whole country of Australia except for Tasmania.

3.6.10 2010

This year, extreme drought is confined only towards Western Australia. New Zealand is mildly dry in certain areas. It is also a good point to notice that the majority of Australia is extremely wet this year.

3.6.11 2011

Mild to slightly extreme dryness is noted only in the southwest corner of Western Australia. The rest of the continent is exceptionally wet.

3.6.12 2012

Dryness noticed this year is relatively in a small area and is mostly mild and extreme in very small patches.

3.6.13 2013

New South Wales and far west of Western Australia are the only areas with mild dryness. The rest of the territories of mainland Australia have severe to extreme droughts.

3.6.14 2014

Mild to extreme droughts are noticed all over mainland Australia with moderate patches of wet areas in between too. All in all, the situation is dire but not as intense as some years.

3.6.15 2015

Once again, droughts ranging from mild to extreme are common this year in mainland Australia. Cheviot and neighboring areas in New Zealand near the back of River Tasman have a bright red patch of extreme dryness.

3.6.16 2016

Extreme dryness patch noticed this year is relatively small and is found in the northwest part of Western Australia. The rest of the mainland has mild dryness and no droughts at all.

3.6.17 2017

No notable dryness is noticed this year.

3.6.18 2018

South Australia and Western Australia have mild to severe dry seasons while the rest of the territories of mainland Australia are exhibiting mild to extreme dry periods.

3.6.19 2019

Worst case of dryness is noticed this year that ranges from severe to extreme and is covering almost the whole of mainland Australia.

4 Discussion

Two countries in North America are noticed in "Sect. 3" with regards to constant droughts: Mexico and the USA. Mexico has a warm and dry climate towards the north and annual rainfall of fewer than 100 mm, while towards the south of the country, the climate is wet tropical, and the annual rainfall exceeds beyond 3000 mm (Méndez and Magaña 2010). The USA has been the focus of droughts and other natural disasters for a long time (Kogan 1997), and it has been observed through many research studies that perhaps greenhouse gasses and anthropogenic activities contribute a lot towards the recurring droughts in states like California (Folger and Cody 2015). Research has proven that droughts towards the southeast of the USA mostly occur due to the dwindling soil moisture and extreme heat (Xu et al. 2018).

In 2003, a constant wave of dry season was noticed towards northeastern Mexico and the western side of the USA (Levinson and Waple 2004). In 2005, the droughts were limited to the center of the USA, while towards the southwest and northeast, severe precipitation was recorded (Shein 2006). Mexico had a warmer season in 2006, and the interior of the USA went through an intense dry season. This year was one of the two warmest ones for the USA and Canada. Also, the same year observed El Nino phenomena in the central USA and the Caribbean towards the end (Arguez 2007). Noticeable drought was detected in the USA in 2008 due to the dry period from October to June towards southern Texas and extremely low precipitation from December to June in south-central Texas. Mexico suffered several causalities due to the severe droughts and then the wildfires that followed soon after (Peterson et al. 2009). Texas and Hawaii suggested agriculture loss due to drought in 2009. California and the state of Alberta also suffered from an intense dry season in 2009. Mexico suffered from two droughts in 2009; the first one appeared in March and April, causing loss to the economy and livestock, while the second intense drought hit the country after June due to the appearance of El Nino (Arndt et al. 2010). Droughts first originated in the southwest in 2011 and spread to Central Plains and then southeast in the USA. Palmer hydrological index noted a record of low-level precipitation in the history of 117 years in major parts of the USA. Extreme to severe drought in 2011 in Mexico was one of the worst cases of the dry season that covered 85% of the area of the country in June and caused huge loss to the economy and livelihood of the residents (Arndt and Blunden 2012). More than half of Mexico was declared under drought in May of 2013 (Jessica Blunden and Arndt 2014). California was under threat of intense drought during the whole year of 2015 (Jessica Blunden and Arndt 2016). Droughts developed towards northeast and southeast in the USA in 2016, while the previous droughts towards the West and Great Plains lessened in intensity due to the high precipitation (Jessica Blunden and Arndt 2017). Drought took a heavy toll on USA in 2017 with one quarter of the country going through the dry season by the end of the year. Drought is noticed towards the south of Mexico due to high temperatures than usual and less precipitation in 2017 (Jessica Blunden et al. 2018). Oregon and a large portion of the southwest faced severe and extreme droughts for the whole year of 2018. Southern Mexico's severe dry season resulted in water shortage and a negative impact on pastures in 2018 (Jessica Blunden and Arndt 2019).

From our results, we have observed that droughts in Mexico are mostly observed of extreme nature and are more than often occurring towards the north of the country. It is also observed that droughts in Mexico and southern states of the USA occur in most cases at the same time and of the same intensity. Our study points out that in the current century the

areas most affected by extreme and severe droughts in the USA are the states of Texas, California, Nevada, and Arizona. Other states such as Florida, New Mexico, and Kansas also suffer from frequent droughts that range from mild to severe in intensity.

The results of our study point towards recurring and extremely dry seasons towards Brazil and Argentina. Our studies also regard some of mild to severe droughts towards Peru, Chile, and Venezuela.

Western Amazonia suffered the driest season in the history of 40 years in 2005 (Shein 2006). Modulation due to Madden–Julian oscillation was observed in the warmer than usual year 2006 throughout the continent (Arguez 2007). The grassland and steppe's of Argentina, Uruguay, Paraguay, and southern Brazil faced intense droughts in 2008 due to the 60 to 80% less than normal precipitation (Peterson et al. 2009). Argentina, Uruguay, Paraguay, and southern Brazil again suffered from droughts in 2010 and experienced shortage of water in the hydropower stations and also the supply of water to the summer crops was impacted (Arndt et al. 2010). Amazon faced a major drought in 2010 that started during the El Nino and increased in intensity during the La Nina (J. Blunden et al. 2011). Northeast Brazil experienced an intense dry season despite the record of above average precipitation in other parts of the country in 2012 (J. Blunden et al. 2013). The drought from previous year extended to 2013 and caused huge losses to agriculture in northeast Brazil (Jessica Blunden and Arndt 2014). Colombia and Venezuela suffered from dry season for almost the whole year in 2015. Northeast and southeastern Brazil still suffered from intense droughts that started in previous years (Jessica Blunden and Arndt 2016). Brazil and Bolivia faced droughts in 2016 due to drier than usual weather that lasted most of the year. Amazon also went through a dry season due to El Nino (Jessica Blunden and Arndt 2017). The drought continuing from previous years took a turn for the worst in 2017 in west-central Brazil and made it the worst case of drought in the last 57 years. Chile and Argentina suffered from wildfires due to the drought that erupted at the beginning of 2017 (Jessica Blunden et al. 2018). 2018 brought severe to extreme dry season in northeastern Brazil and Paraguay. The La Nina was weak in 2018, resulting in one of the worst droughts in 50 years in Argentina (Jessica Blunden and Arndt 2019).

Argentina is the largest crop yielding country of South America, making it essential agriculture-wise (Kogan 1997). The impacts of droughts on the agriculture sector are of particular interest because it heavily depends on the water, which is a basic need for survival for all living beings, and also a hit to agriculture has caused massive famines in the past (Meza, et al. 2019). Northeast Brazil has 95% farmland dependent on rain and adds that a high percentage of its inhabitants live in poverty, so naturally, the impacts of droughts on this region are severe (Cunha et al. 2018). The increased dry seasons in Brazil have made policymakers, scientists, and the government worried over its impacts on the socio-economic, food, and the fast-shifting of some of the lands towards desertification (Marengo et al. 2017).

The results of our study indicate that in the continent Africa the worst cases of droughts are noticed towards Eastern Africa, Southern Africa, and the northern parts. In the center of Africa, the situation is not that dire and there are almost no signs of extreme to severe dry seasons. Towards its southern parts, the island of Madagascar also suffers from time to time due to severe dryness. In Eastern Africa, the countries suffering more frequently and the most are Ethiopia and Somalia. Kenya also goes through extreme dry seasons but not as much as the other two countries. South Africa suffers from extreme droughts but other countries of south like Namibia, Botswana, Zimbabwe, Mozambique, and Angola also go through severe and extreme dryness frequently. Towards the north, Morocco, Algeria, and Tunisia went through extreme droughts at the beginning of the century and then through severe and mild dry seasons for the rest of the vast majority of the century.

African countries are prone to droughts and have already pushed many countries towards desertification and its impact on agriculture has raised food insecurity in the inhabitants (Eckstein et al. 2020). Meza et al. (2019) concluded in their research that the ten countries most vulnerable to droughts are Zimbabwe, Namibia, Botswana, Morocco, Kosovo, East Timor, Mauritania, Lesotho, Kazakhstan, and Algeria. Seven out of ten of the aforementioned countries belong to the African continent. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), there is a high probability of reduced annual rainfall towards Northern Sahara Africa and Mediterranean Africa. There is also a high chance of reduced rainfall in the winter season towards South Africa and a slight increase in annual mean of precipitation towards Eastern Africa (Knox et al. 2012). Studies indicate that anthropogenic activities in the Indian Ocean caused the warming of the ocean which reduced the precipitation rate by 15% in the crop growing seasons towards the eastern and southern Africa, and as a result, the crop yield is severely impacted all across sub-Saharan Africa (Conway et al., 2011).

Ethiopia has faced some intense mega droughts and suffered the consequences. The drought in Ethiopia in 2009 alone affected six million people and the country had to rely on foreign aid to deal with the aftermaths (Bayissa et al. 2018). Similarly, in 2015–2016, an El Nino event triggered an extreme drought towards eastern Africa that affected ten million inhabitants of Ethiopia, and once again the issue of food insecurity was risen (Delbiso et al. 2017). Evidence is available that suggests the cause of the 2015 drought in South Africa was due to sea surface temperature change which leads to high atmospheric temperature and less

rainfall (Eckstein et al. 2020). In 2003, droughts prevailed towards the southern Africa and certain regions of Greater Horn (Levinson and Waple 2004). Persistent dry season was noticed in the year 2005 over majority of Greater Horn throughout the year 2005 while in the same year, towards the southern Africa the precipitation was below normal during the beginning but gradually returned to normal (Shein 2006). Eastern Africa faced a worst case of drought in a decade during 2011. The dryness was caused by below average rainfall that resulted mostly from La Nina. Somalia, Kenya, and Ethiopia were majorly impacted by this drought (Arndt and Blunden 2012). The drought in 2014 in South Africa was deemed a worst case of dry season in 80 years span. From May to October in 2014, the island of Madagascar also suffered from severe drought season (Jessica Blunden and Arndt 2014). Ethiopia faced worst case of drought in a decade in 2015 due to El Nino. In 2015, Somalia, Malawi, Zimbabwe, and Kenya also suffered severe dry seasons (Jessica Blunden and Arndt 2016). Central and certain northeastern parts experienced dry season in Africa in 2016 due to below average precipitation (Jessica Blunden and Arndt 2017). Crops across the South Africa were severely impacted due to severe drought in 2018 (Jessica Blunden and Arndt 2019).

For Europe, the results in this study conclude that extreme and severe dry seasons are not that common when compared to the rest of the continents. The countries that show signs of extreme dryness for more than once in the recent century were Spain, Portugal, France, and Italy. Other countries were either very small to notice on the map or were suffering from mild dry seasons and not condemning its inhabitants to food insecurity. The other notable point in the study was the coincidence of droughts occurring more than once at the same time in Portugal and Spain. France also joined sometimes in the dryness when these two countries were suffering but not that often. Italy showed signs of extreme dryness that were noteworthy on more than one occasion and that spread to a larger portion of the country.

2005 was above normal in the eastern Europe and below normal towards the western parts with respect to precipitation. UK was exceptionally warm while Iberian Peninsula suffered a severe drought (Shein 2006). Europe was warmer than usual in the year 2007 with records of heat waves in the summer and autumn as well (Arguez 2007). Iberia, Spain, and Portugal suffered from intense droughts in 2008 (Peterson et al. 2009). In the summer of 2011, drought was observed towards the eastern parts of England. In the same year, dry season in the spring in western and central England became cause for wildfires. Austria, Bulgaria, and Romania suffered from forest fires due to drought in the autumn season (Arndt and Blunden 2012). Slovenia faced extreme drought in 2013 (Jessica Blunden and Arndt 2014). In 2015, from the southwestern Iberia towards the eastern Europe, cases of droughts were noted after the long-lasting heat waves and rainfall deficiency. Several wildfires also erupted across the Europe due to constant drought and heat (Jessica Blunden and Arndt 2016). Iberian Peninsula and France went through drought seasons due to 20% below average precipitation (Jessica Blunden and Arndt 2017). A record breaking high temperature was noticed across Italy and Turkey that resulted in heatwaves and severe drought season in 2017. Spain and Portugal also faced severe to extreme droughts in 2017 with the year declared as second driest for Spain and third driest for Portugal since 1965. Portugal suffered heavy losses due to the wildfires emerging due to dry season (Jessica Blunden et al. 2018). Central and Northern Europe saw record high air temperature that resulted in droughts across the region (Jessica Blunden and Arndt 2019).

Climate model studies have predicted that there would be a significant decline in the precipitation level in the Mediterranean region, and the countries will get affected in the agriculture sector due to the dryness (Vicente-Serrano 2007). However, droughts towards this region have shown no lasting impact on the gross primary production of the vegetation (Vicca et al. 2016). Extreme events in this continent have impacted biodiversity in the form of endangering of species, heat waves, migration of animals, and a rise in the carbon dioxide level (Thuiller et al. 2005).

The results of our study in the case of Asia are suggesting the vulnerability of certain countries to frequent and extreme droughts, namely, Pakistan, Kazakhstan, India, China, and Azerbaijan. Other countries like Afghanistan, Syria, Turkmenistan, Iran, and Iraq also showcase extreme droughts at one point or another on more than one occasion. The dry season in India, Turkmenistan, and China are extreme, but they seldom cover the vast majority of the country. On the other hand, Pakistan, Azerbaijan, and Kazakhstan showcase where more than half of the country's agriculture is under the thrall of extreme dry season. Countries in the neighboring of Syria, like Israel, Lebanon, Jordan, etc., also showed signs of severe droughts at one point or another.

In 2003, the precipitation returned to near normal that helped to reduce the long-running droughts of previous years in southwest Asia, and the same year was slightly warmer for Russia (Levinson and Waple 2004). In 2005, certain parts of the continent noted record snowfall and precipitation while other parts suffered due to the delayed monsoon and above normal temperature (Shein 2006). January to March in 2008 was a season of severe drought towards northern China, and the main reason was 30 to 80% less precipitation than usual. 2008 was also severe to extreme droughts in parts of India and Iran (Peterson et al. 2009). Crops across China were severely damaged due to the arrival of the intensely dry season in 2009. In the same year, Pakistan and India went through one of the worst droughts recorded in history (Arndt et al. 2010). Russia faced heatwaves and drought-related

catastrophes in 2010 (J. Blunden et al. 2011). Sri Lanka went through one of its worst cases of the dry season in 2012 that hugely impacted the economy (J. Blunden et al. 2013). China and Pakistan faced dry season of severe intensity in certain parts in 2013 (Jessica Blunden and Arndt 2014). Twenty-eight provinces of Iran went through severe drought conditions in 2016 (Jessica Blunden and Arndt 2017). Iran and Japan suffered from severe to extreme droughts in 2017 (Jessica Blunden et al. 2018).

Agriculture and livestock are the main sources of income for more than half the population of people living in rural areas of South Asia and the recent climate change is hitting that sector hard (Knox et al. 2012). Similarly, in South-East Asia, another agriculture-dependent region, droughts are a frequent occurrence and mostly hit during the seasons when the El Nino phenomenon is active (ESCAP 2019). The region of Kazakhstan has only one-tenth of its land used for crop sowing while the remaining is rangeland used for livestock grazing and the repeated dry seasons do not bode well for either sector (Kogan 1997). Droughts in India also impact agriculture and often hit the arid and semi-arid parts of the country (Muthumanickam et al. 2011). North China is an important region for the wheat sown in winter for China and droughts regularly occur in this part which is a cause of concern for both the government and the public (Zhang et al., 2016). Pakistan is prone to droughts and despite being blessed with the heavy monsoon in summer and western disturbances in the winter, almost every province of the country has suffered through a dry season at one point or another (PMD 2018).

In this study, it was noticed that mainland Australia goes through extreme dry seasons that span over almost the whole area more frequently. The only years where there were no signs of severe droughts for the study period were 2001, 2011, 2012, and 2017. In 2016, there was only a small area that was affected by extreme dryness while the rest of mainland Australia was going through good season precipitation wise. The other notable point in the study was that Tasmania was the only region of Australia that seldom saw a dry season that span over a vast area of the Island. New Zealand was sometimes observed going through mild and severe dryness but the affected area was mostly limited to one or other corners of the country.

2003 observed the warmest June in New Zealand and caused damages across the Australia due to constant heat and droughts (Levinson and Waple 2004). Despite the fact that the temperature rebounded in the second half of 2005 in Australia, this year was noticeably warmer that resulted in severe dry season in the first half (Shein 2006). Australia suffered from intense droughts and storms in the year 2006 (Arguez 2007). A prolong dry season in the southeast of Australia caused shortage of water in the Murray-Darling basin in 2008 (Peterson et al. 2009). A large number of area in the New Zealand suffered from soil moisture deficiency and consequent drought in 2010 (J. Blunden et al. 2011). 2013 was worst year both intensity wise and area covered with respect to dry season in New Zealand (Jessica Blunden and Arndt 2014). The drought in 2014 in Australia led to many bushfires (Jessica Blunden and Arndt 2015). The extreme and long drought of 2018 in Australia contributed to a larger extent towards the eruption of fires in 2018/2019 and damaged most of the crops (Jessica Blunden and Arndt 2019). 2019 brought record high intensity of droughts in Australia that lead to heavy bushfires across the country (Jessica Blunden et al. 2020).

Climate model studies have predicted that there will be a 40% rise in the dry seasons towards Eastern Australia, and the overall pattern of precipitation will also change, and so will the temperature rise (Quiggin 2010). Studies have shown that almost every extreme drought has occurred in the last 100 years due to the El Nino phenomenon and will continue so in the future (Braganza et al. 2003). A study published in 2005 pointed out that due to frequent droughts, in the last 50 years, the country's agriculture has reduced contribution from 20 to only 5% towards the gross domestic product (GDP), and the employment rate has also decreased (Horridge et al. 2005). The droughts destroy fruits and vegetable yield in the country, leading to a shortage of supply for the general public, and once the demand rises, almost every product spike considerably (Quiggin 2010). According to the Australian crop report ABARES, the yield of crops will fall in major areas where the agriculture sector usually flourishes (ABARES 2019).

5 Conclusion

Droughts are seen with recurring frequency throughout the globe, with certain parts experiencing more extreme dry seasons than others. Continent-wise, Australia, Africa, and Asia have the most extreme and frequent drought events while South America and North America come a close second. Europe is the least affected by this particular weather event when compared to other continents. This study declares countries vulnerable to extreme droughts are: Central America and southern Mexico in North America; Argentina, northeast Brazil, and southeast Brazil in South America; Italy, Spain, and Portugal in Europe; Ethiopia, Kenya, Morocco, Tasmania, Zimbabwe, Mozambique, Namibia, and South Africa in the African Continent; Pakistan, India, China, Azerbaijan, Iraq, Syria, Iran, and Kazakhstan in Asia; and the whole mainland Australia. The research performed in this article can be used to achieve the sustainable development goal that demands climate action and mitigation.

Author contribution Supervision, project administration, writing—review and editing, and validation were performed by Dr. Hammad Gilani. Data curation, formal analysis, investigation, methodology, software, visualization, and writing—original draft were the duty of Ramla Khan. The main idea of the research was the combined effort of both authors.

Data availability All the datasets are available in the repository of Google Earth Engine (GEE). The details and specifications of each dataset have already been mentioned in "Section 2.1."

The links to each, along with their titles, are mentioned below:

MOD16A2.006: Terra Net Evapotranspiration 8-Day Global 500 m: https://lpdaac.usgs.gov/products/mod16a2v006/

MODIS Terra Vegetation Indices 16-Day Global 500 m: https://lpdaac.usgs.gov/products/mod13a1v006/

KBDI: Keetch-Byram Drought Index: https://developers.google.com/earth-engine/datasets/catalog/UTOKYO_WTLAB_KBDI_v1

TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces, University of Idaho: https://developers.google.com/earth-engine/datasets/catalog/IDAHO_EPSCOR_TERRACLIMATE

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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