Service Assessment

August/September 2017 Hurricane Harvey

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

Cover Photograph: From August 27–September 4, the National Geodetic Survey (NGS) collected damage assessment imagery in the aftermath of Hurricane Harvey. This image is of the Route I-10 flooding near Lynchburg, TX, just about 20 miles east of downtown Houston, TX. For access to this and other aerial images taken by NGS, please go to https://oceanservice.noaa.gov/news/sep17/hurricane-harvey.html.

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June 2018

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Chief Operating Officer

Preface

Hurricane Harvey, the first major hurricane to make landfall in the United States since Wilma in 2005, produced catastrophic impacts over Southeast Texas and Southwest Louisiana. The center of Hurricane Harvey made landfall near Rockport, TX, as a Category 4 hurricane, producing impacts due to high winds, storm surge, and numerous tornadoes. In a four-day period, many areas received more than 40 inches of rain as the cyclone meandered over eastern Texas and adjacent waters, causing catastrophic flooding. With peak accumulations of over 60 inches of rain, Hurricane Harvey produced the most rain on record for a tropical storm or other weather event in the contiguous United States and caused an estimated 125 billion dollars of damage according to NOAA. At least 68 fatalities in Texas alone were directly attributable to this event, the highest death toll due to a tropical system in that state since 1919.

Because of the highly significant impacts of the event, the National Weather Service assembled a service assessment team to evaluate its performance before and during Hurricane Harvey. NWS's operational leadership will review and consider the findings and recommendations from this assessment. As appropriate, the recommendations will then be integrated into the Annual Operating Plan to improve the quality of operational products and services and enhance the National Weather Service public education and awareness materials related to flooding and other tropical cyclone hazards. The ultimate goal of this report is to help the National Weather Service meet its mission to protect life and property and enhance the national economy.

John D. Murphy
Chief Operating Officer

June 2018

Table of Contents

Table of Figures

Table of Tables

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Executive Summary

Hurricane Harvey is the most significant tropical cyclone rainfall event to impact the United States in terms of peak rainfall and scope since this country started maintaining reliable precipitation records in the 1880s. The hurricane's center made landfall between Port Aransas and Port O'Connor near Rockport, TX, on August 25, 2017, accompanied by 132 mph sustained winds. The storm caused widespread major flooding from east of Austin, TX, eastward through the Houston and Beaumont, TX, metropolitan areas, to Lake Charles, LA. Over the five days Harvey stalled over the area, the storm generated rainfall totals between 35 and 60 inches. The U.S. rainfall maxima records are now held in Jefferson County, TX, where 60.58 inches was reported in Nederland, TX and 60.54 inches near Groves, TX, for the storm.

Hurricane Harvey intensified rapidly in the southwest Gulf of Mexico, strengthening from a tropical depression on August 23 to a Category 4 major hurricane on August 25. Following landfall, the system slowed its northwest progress significantly, changed course, then drifted eastward just off the upper Texas coast until the morning of August 30. East and northeast of the storm's center, heavy rain bands trained repeatedly over Southeast Texas – particularly over the greater Houston and Beaumont/Port Arthur areas – causing major to catastrophic urban flash flooding and river flooding. In addition to the flood damage, extensive tropical wind and storm surge damage also occurred near and east of Hurricane Harvey's landfall point. Portions of the middle Texas coast from Port Aransas to Matagorda sustained the greatest damage from these impacts. Localized structural damage also occurred across southeast Texas due to tornadoes.

NOAA's National Centers for Environmental Information estimated that Hurricane Harvey produced at least 125 billion dollars of damage, the second costliest storm event on record, exceeded only by Hurricane Katrina. Hurricane Katrina caused many more deaths than Hurricane Harvey, 1,833 deaths as compared to 105. Impacts from Hurricane Katrina were mostly from storm surge, while impacts from Hurricane Harvey were mostly from rainfall. Massive flooding due to Hurricane Harvey displaced more than 30,000 people and damaged or destroyed over 200,000 homes and businesses. Hurricane Katrina destroyed 800,000 housing units. Hurricane Harvey also led to extensive impacts to the transportation network across the region, affecting logistics and commerce across the land, air, and sea.

During service assessment interviews, partners overwhelmingly indicated that the National Weather Service performed very well throughout this event. As the event unfolded, the NWS's consistent messaging through multiple communication avenues helped emergency managers, government officials, and media partners maintain good situational awareness. Residents in affected communities were likewise reasonably well prepared and able to take actions that mitigated a potentially much higher loss of life. Hurricane Harvey was one of the broadest tests to date of the NWS's strategic emphasis on coordination and collaboration within a fully integrated field structure. By any measure, the unified performance of National Centers, Weather Forecast Offices, River Forecast Centers, and Regional Operations Centers serves as an encouraging benchmark for the progress the NWS has made toward its goal of fully supporting a Weather-Ready Nation.

Service Assessment Report

1. Introduction

1.1. NWS Mission

The mission of the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) is to protect life and property by providing weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, and to enhance the national economy. NWS disseminates centrally produced data, weather products, and guidance to 122 local Weather Forecast Offices (WFO), 13 River Forecast Centers (RFCs), and 21 Center Weather Service Units (CWSUs). The forecasters at the WFOs and RFCs issue forecasts and hazardous watches, warnings and advisories to the public. They also interface closely with local emergency managers (EMs) and other federal, state and local government partners in the provision of weather, water and climate Impact-based Decision Support Services (IDSS). WFOs and RFCs also collaborate significantly with media partners and other non-government entities in the distribution and explanation of impact weather information. CWSUs are co-located with Federal Aviation Administration (FAA) Air Route Traffic Control Centers (ARTCCs), and provide comprehensive IDSS to air traffic controllers, traffic management units, traffic control centers and control towers in their areas of jurisdiction.

The National Hurricane Center (NHC) issues hurricane, tropical storm, and storm surge warnings for coastal locations. The Weather Prediction Center (WPC) produces a wide range of national weather forecast and analysis products, including Quantitative Precipitation Forecasts (QPF), excessive rainfall products, medium-range and probabilistic rainfall guidance, surface analysis, and a daily weather map. These aforementioned centers, and seven others comprising the National Centers for Environmental Prediction (NCEP), collaborate closely with NWS field offices (i.e., WFOs, RFCs) and with EMs and media partners in the creation, distribution and interpretation of NWS guidance, outlooks, and hazardous watch/warning information.

The NWS Headquarters (NWSH), located in Silver Spring, MD, has six regional headquarters that provide policy and guidance to the WFOs and RFCs. Each of these headquarters also staffs a Regional Operations Center (ROC) that provides tactical field office support and decision support to state and region-level federal partners.

1.2. Purpose of Assessment Report

The NWS may conduct national service assessments for significant hydrometeorological, oceanographic, or geological events when they result in one or more of the following conditions:

- Multiple fatalities
- Numerous injuries requiring hospitalization
- A significant impact on the economy of a large area or population
- Extensive national public interest or media coverage
- An unusual level of attention to NWS operations by the media, EM community, or elected officials

Service assessments evaluate NWS performance and ensure the effectiveness of NWS products and services in meeting the mission. The goal of service assessments is to improve the ability of NWS to protect life and property by identifying and sharing best practices in operations and procedures, recommending service enhancements, and addressing service deficiencies.

This document presents findings and recommendations resulting from the evaluation of NWS performance during Hurricane Harvey, August 25–September 1, 2017. The objectives of this assessment were to identify significant findings and issue recommendations and best practices related to the following key areas:

- NWS forecasts, products, warnings, and services
- Messaging
- Storm intensification
- IDSS and partnerships
- NWS internal systems
- Fully Integrated Field Structure

1.3. Methodology

NWS formed a service assessment team on September 19, 2017. The 12-member team and subject matter experts consisted of employees from WFOs and RFCs, NCEP, NWSH, NWS Central Region Headquarters, U.S. Army Corps of Engineers (USACE), NOAA Office of the Chief Financial Officer, North Carolina Sea Grant, and the NOAA National Severe Storms Laboratory. The team completed the following activities:

- Performed on-site evaluations in Texas and Louisiana from October 8–14
    - Visited and conducted staff interviews at:
        - WFOs Corpus Christi, TX, Houston/Galveston, TX, Lake Charles, LA, and New Orleans/Baton Rouge, LA
        - West Gulf and Lower Mississippi RFCs
        - CWSU Houston
        - Southern Region Headquarters (SRH) and SRH ROC
    - Interviewed local, state and federal EMs, other government officials and the public in the primary impacted areas and jurisdictions
    - Toured damaged areas from near Corpus Christi to Beaumont/Port Arthur, TX
- Conducted remote interviews with staff members of:
    - WFOs Austin/San Antonio and Brownsville, TX
    - NHC and NHC Storm Surge Unit
    - WPC
    - Environmental Modeling Center (EMC)
    - Ocean Prediction Center (OPC)
    - Office of Water Prediction (OWP)
    - Forecast Decision Training Branch
- Evaluated products, messages and other services produced by involved NWS entities
- Compiled a core list of common themes discovered during onsite and remote interviews
- Identified significant findings and recommendations to improve the effectiveness of NWS products, services, communication, and coordination

After a series of internal reviews, the report on the service assessment was approved, signed by the Chief Operating Officer for the National Weather Service, and issued to the American public.

2. Hydrometeorology

2.1. Evolution of Storm

Hurricane Harvey formed from a tropical wave that moved off of the west coast of Africa on August 12. The wave developed into a tropical depression east of Barbados early on August 17 and became Tropical Storm Harvey later that day. The tropical storm moved across the Windward Islands on August 18 but decayed into a tropical wave the next day. The wave moved steadily westward, eventually crossing the Yucatan Peninsula and entering the southwest Gulf of Mexico on August 22. The wave redeveloped into a tropical storm on August 23, steadily increased in strength as it tracked northwestward and underwent rapid intensification to a Category 4 major hurricane on August 25 (**Figure 1**). NHC issued the first Hurricane Watch the morning of August 23 for Texas from Port Mansfield to San Luis Pass 60 hours prior to Hurricane Harvey's landfall.

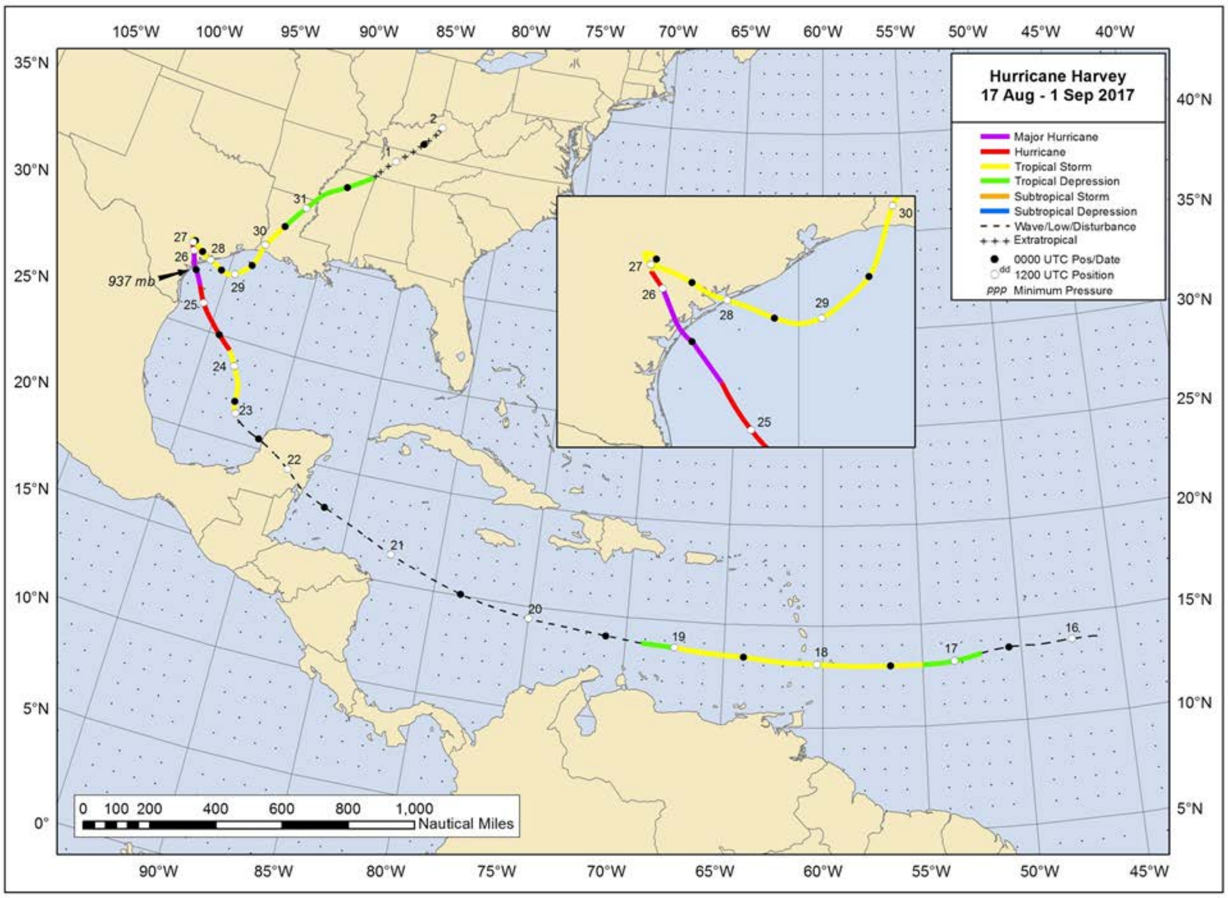

Figure 1: Path of storm as it progressed from a tropical depression to major Hurricane Harvey.
Source: National Hurricane Center Tropical Cyclone Report on Harvey

2.2. Wind and Tornado

On the morning of August 24, data from a Hurricane Hunter aircraft indicated Hurricane Harvey was strengthening quickly and moving over water with anomalously warm Sea Surface Temperatures (SSTs) (**Figure 2**).

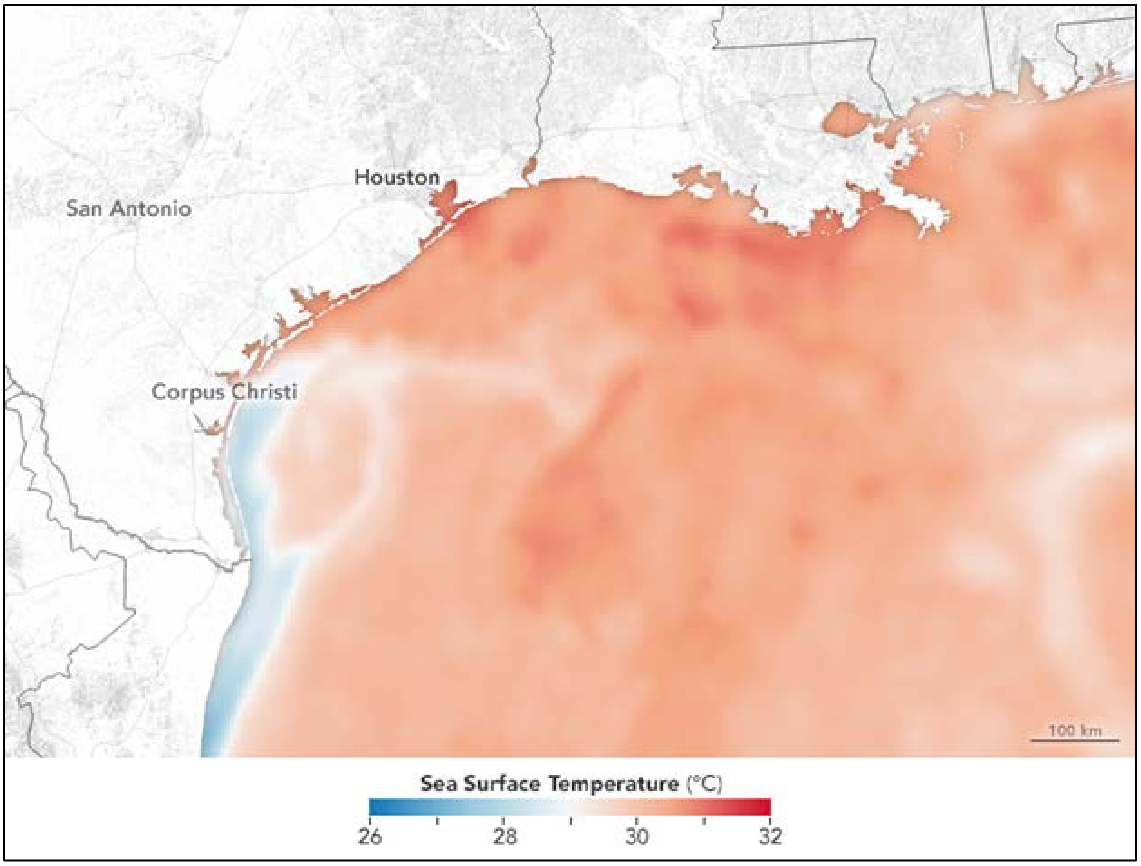

Figure 2: SST observations before Hurricane Harvey's passage. *Source: NASA*

On the morning of August 24, NHC noted Hurricane Harvey's forward speed would slow in a couple of days, due in part to high pressure sliding east from the Intermountain West. As Hurricane Harvey continued to encounter the anomalously warm SSTs over the northwestern Gulf of Mexico with fairly low vertical wind shear, it rapidly strengthened. Hurricane Harvey increased from a Category 2 hurricane on August 25 to a Category 4 major hurricane 12 hours later. The NWS issued an extreme wind warning for a major land falling hurricane with winds of at least 115 mph. The center of Hurricane Harvey made landfall near Port Aransas/Port O'Connor, TX, at 0300 Coordinated Universal Time (UTC) on August 26, with maximum winds estimated around 130 mph and a minimum barometric pressure of 937 millibars (**Figure 3**). This intensity resulted in significant damage to Rockport, TX, which is a coastal town 30 miles northeast of Corpus Christi (**Figure 4**). Port Aransas reported a 132 mph wind gust and Copano Village, TX, reported a wind gust of 125 mph (**Figure 5**). Since many meteorological observation platforms were disabled prior to the arrival of the highest winds, some of the observed wind speeds were likely underestimated, especially near the coast and close to the eyewall.

A total of 52 tornadoes were documented in association with Hurricane Harvey and its remnants, with the great majority of these events occurring across extreme southeast Texas and southwest Louisiana. The WFO Houston county warning area alone experienced 21 of these tornadoes between August 25–27. Nearly all of these tornadoes were rated EF-0 or EF-1 in intensity, resulting in no deaths or serious injuries and mostly minor structural damage.

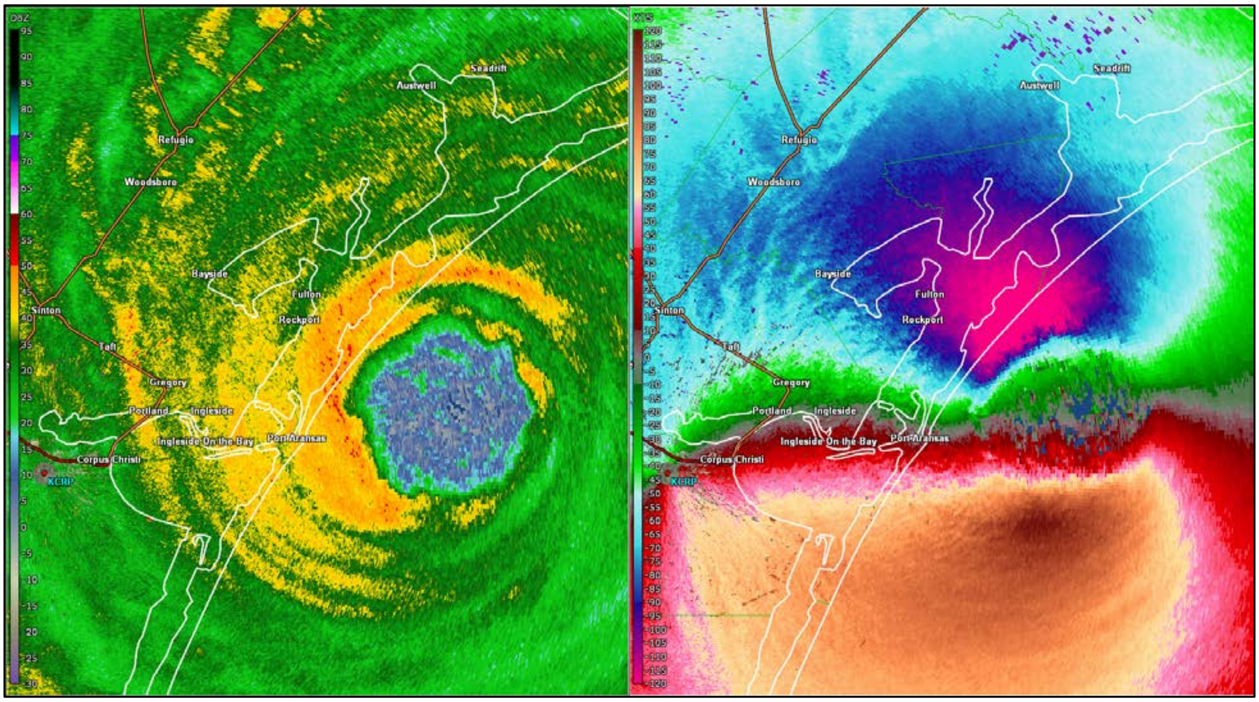

Figure 3: Radar images of Hurricane Harvey prior to center making landfall on San Jose Island, TX: left, 0.5 degree base reflectivity; right, 0.5 degree base velocity. *Source: WFO Corpus Christi, TX*

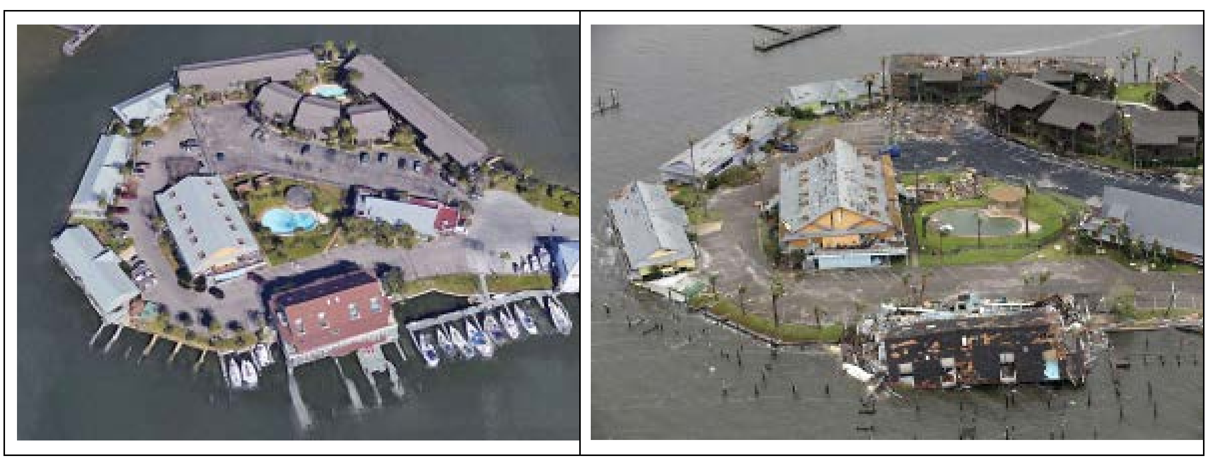

Figure 4: Damage caused by Hurricane Harvey at Key Allegro, Rockport, TX: before (left) and after (right). *Source: CNN article published August 28, 2017*

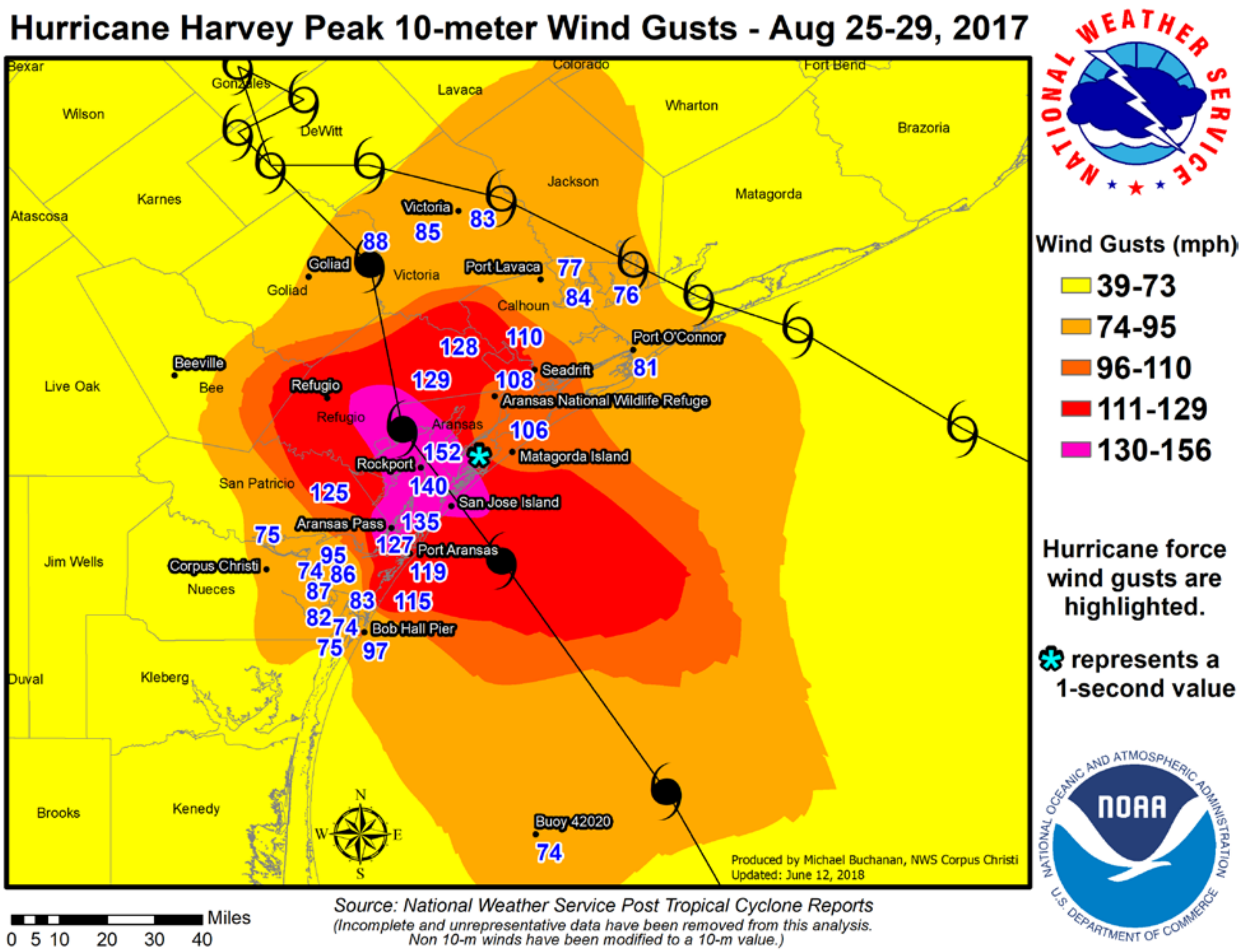

Figure 5: Hurricane Harvey observed peak 10-meter wind gusts. Note: 152-mph gust in Rockport is a 1-second gust, while the NWS standard is a 3-second gust. *Source: WFO Corpus Christi*

2.3. Heavy Rain and Flooding

Rainfall from Hurricane Harvey's outer bands began on the Texas coast between Brownsville and Galveston on Thursday night, August 24. Hurricane Harvey's forward speed slowed to about 5 mph as it approached the coastline and made landfall. The deluge continued well after Harvey's center made landfall and weakened to tropical storm strength early on August 26. Harvey's center then meandered northwest of Victoria, TX. Rainfall amounts over 20 inches were reported in the Corpus Christi area in the first 48 hours after landfall, with historic rainfall amounts falling between Houston and the Louisiana border. These totals were due to the moisture wrapping around the near constant onshore flow of Hurricane Harvey's outer bands. By Sunday morning, August 27, 48-hour rainfall amounts were approaching 25 inches in the Houston area, with most of that rain falling in a 9- to 12-hour time frame late Saturday night and early Sunday morning (**Figure 6**).

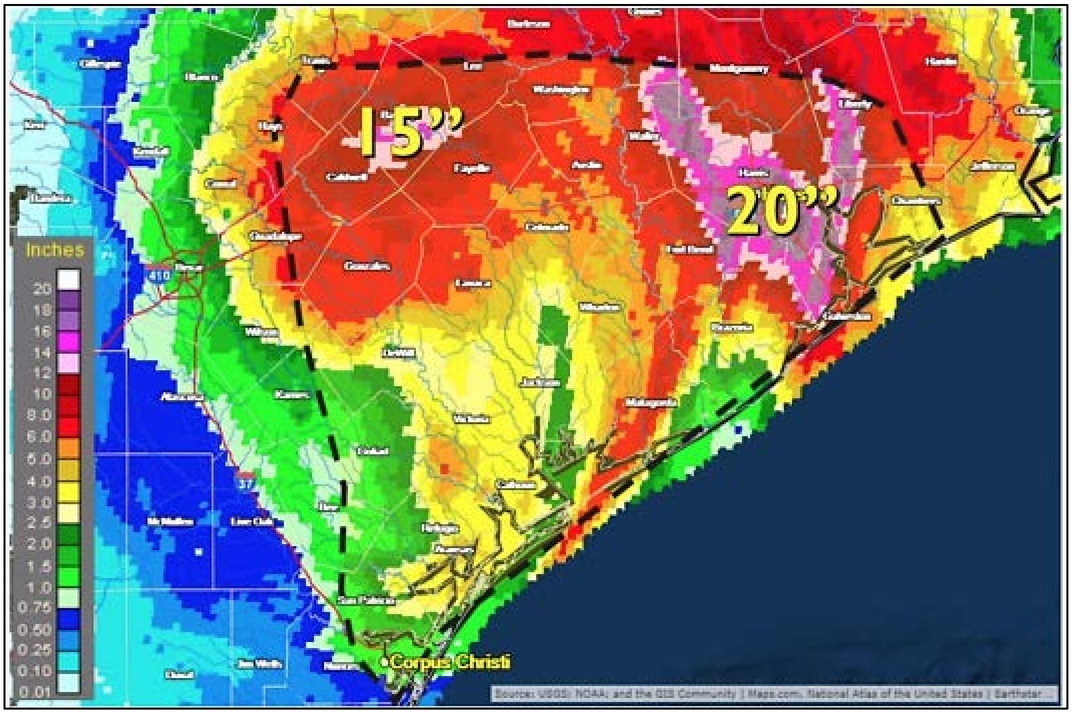

Figure 6: The 24-hour rainfall (radar-estimated) on August 27 showing widespread amounts of 15 inches in Austin, TX, and nearly 20 inches in Houston, TX. *Source: NOAA*

WFO Houston issued its first of 10 flash flood emergency warnings at 9:27 p.m. CDT on August 26 for West Central Harris, Eastern Fort Bend, and Northern Brazoria counties. With saturated soils and rain rates outpacing the drainage capabilities in Houston, significant urban drainage flooding occurred overnight. Water levels in the bayous and streams of metropolitan Houston rose abruptly overnight, inundating structures, washing out roads, requiring high-water rescues, and forcing residents to seek shelter on higher ground (**Figure 7**). Harris County, TX (Houston), Judge Ed Emmett put out the following statement for assistance: "*If you have a boat, we need your help*." Disastrous flooding impacted almost every watershed in Harris County with nearly 57 percent of the Harris County Flood Control District gages measuring record flooding.

Figure 7: Texas Task Force 1 water rescue squad boats move into a flooded community to rescue and evacuate residents impacted by Hurricane Harvey. *Source: Texas Division of Emergency Management*

The center of Tropical Storm Harvey slowly moved east-southeast and back offshore on August 29–30. Heavy rainfall continued across metropolitan Houston spreading across east Texas from Beaumont and Port Arthur, and extending eastward toward Lake Charles, LA. Overall, the heaviest rainfall amounts fell between Houston and Lake Charles with numerous sites recording over 50 inches of rain and two locations in Jefferson County, TX, approximately 10 miles to the southeast of Beaumont, exceeding 60 inches (**Figure 8**).

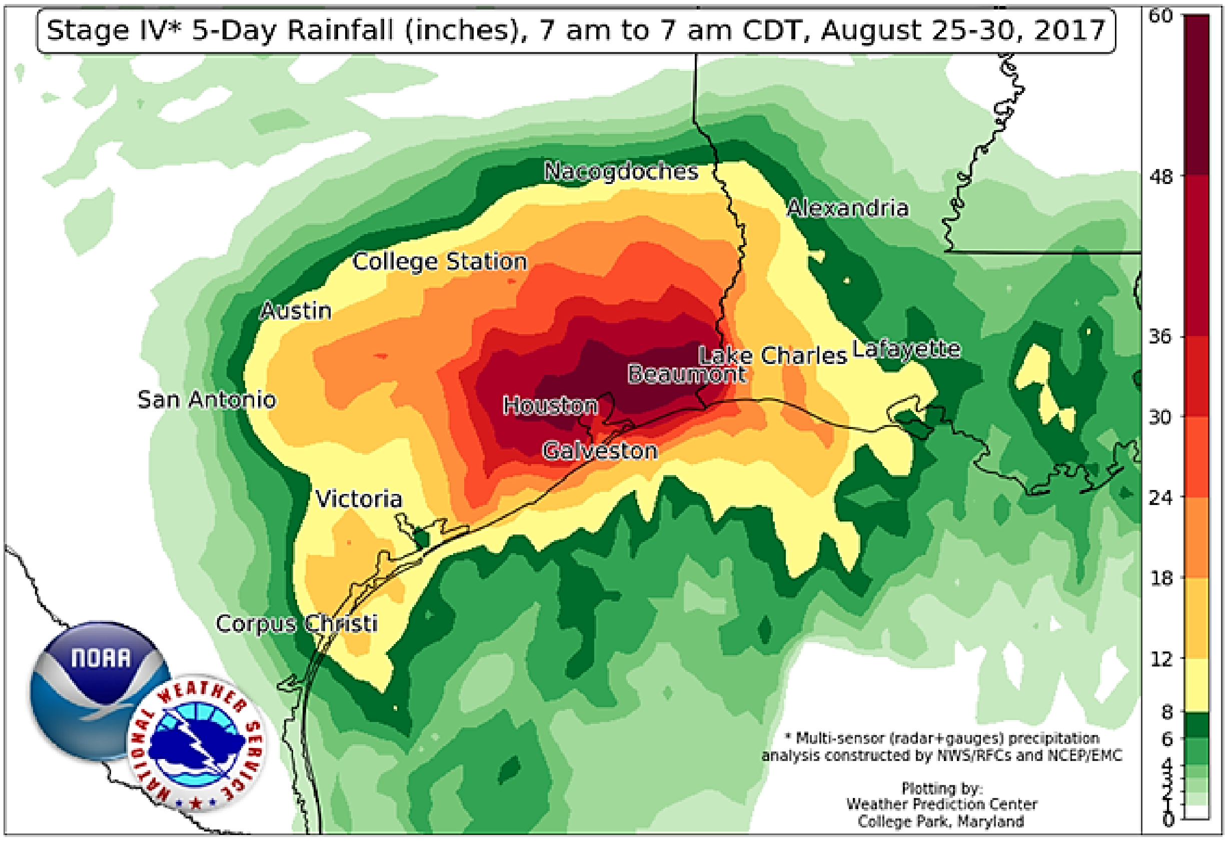

Figure 8: Five-day observed rainfall analysis from 7 a.m., Friday, August 25–30. *Source: NOAA*

The primary impact from Hurricane Harvey was disastrous flooding. Cities from LaGrange, TX, and Victoria, TX, to Lake Charles, LA, experienced widespread flooding that cut off road access to some locations for weeks. Approximately 68 deaths were directly attributed to impacts from Hurricane Harvey, and all but three of these fatalities were due to freshwater flood drowning. Harris County, TX, experienced the highest number of reported fatalities with 36 flooding deaths. According to media reports, over 1 million people were displaced in Texas with 779,000 mandatory and 980,000 voluntary evacuations. In Louisiana, media reported 7,000 mandatory and 133,000 voluntary evacuations. Government and local residents, the "*Cajun Navy*," conducted more than 17,000 water rescues.

Approximately 90 percent (60 out of the 67) of NWS river forecast locations in southeast Texas reached flood stage. Approximately 69 percent (46 out of the 67) reached major flood stage and approximately 46 percent (31 out of the 67) set flood records. The NWS issued more than 300 flood-related warnings. **Table 1** provides a summary of flood warnings by type and WFO.

Table 1: Flood warnings issued between August 20 and September 10 in the area affected by Hurricane Harvey

	Areal Flood Warnings	Flood Warnings	Flash Flood Warnings
WFO Houston	10	105	74[1]
WFO Corpus Christi	5	12	5
WFO Lake Charles[2]	2	24	35[3]
WFO Austin	0	19	5
WFO New Orleans	0	5	6

[1]This total includes 10 flash flood emergency warnings issued by WFO Houston.
[2]Parts of Texas (e.g., Beaumont) are included in the WFO Lake Charles County Warning Area
[3]This total includes 3 flash flood emergency warnings issued by WFO Lake Charles.

Harvey destroyed 300,000 to 500,000 vehicles in Houston according to Fortune Magazine and Cox Automotive. The estimated cost of individually-owned cars damaged in the storm range between $2.7 and $4.9 billion.

According to the Texas Department of Public Safety, 290,063 homes were damaged and 16,930 declared destroyed. The two hardest hit counties were Harris, TX, and Galveston, TX. Flooding in Harris County led to the destruction of 835 homes and damage to 113,136 homes. Flooding in Galveston County resulted in an estimated 1,865 homes destroyed and 22,806 homes damaged. The Federal Emergency Management Agency (FEMA) provided individual and public assistance to 41 counties across Texas (**Figure 9**). In all, NOAA's official estimate of damages was $125 billion dollars.

Baton Rouge and New Orleans were on the eastern edge of the heavy rainfall. Although some streets and underpasses were flooded in New Orleans no structures were significantly damaged or destroyed. Some minor structure and roadway flooding was reported southwest of New Orleans.

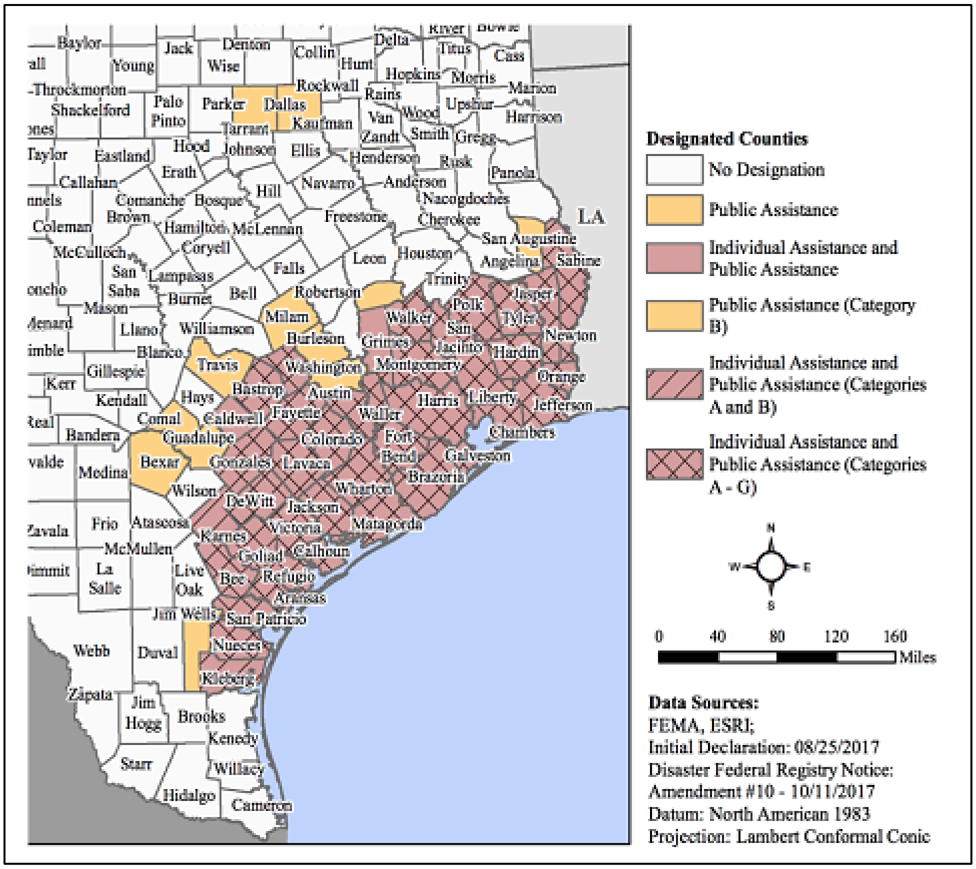

Figure 9: Map of FEMA Texas Disaster Declarations by county.
Source: FEMA Texas Hurricane Harvey (DR-4332)

Gulf Coast oil refineries were significantly impacted by wind and water from Hurricane Harvey. On August 29, 14 refineries were reported to have shut down or were in the process of shutting down. This shutdown affected approximately 17.6 percent of the U.S. refining capacity. The daily loss in output capacity due to the shutdown of Gulf Coast refineries peaked on August 29 at 4 million fewer barrels per day. Refining capacity in million barrels per day is aggregated into three categories: refineries shutdown (see blue in **Figure 10**), refineries in the process of shutting down (orange), and refineries operating at reduced rates (gray). As a result of this event, the oil companies would like to foster a closer working relationship with the NWS, U.S. Coast Guard, and EMs to become more situationally aware of riverine and coastal flooding, which impede access to refineries and their supporting infrastructure. Major flooding as a result of Hurricane Harvey ended around September 10, 2017, when all NWS river forecast points dropped below major flood stage.

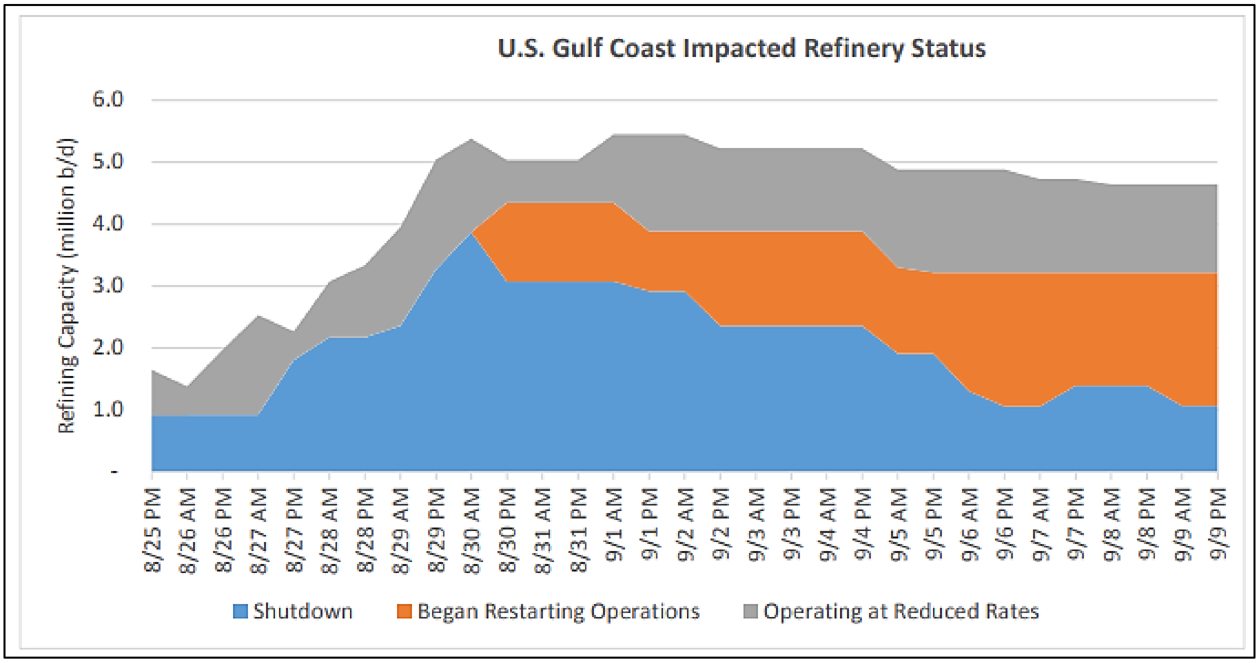

Figure 10: Impacts to Gulf Coast refining capacity as a result of Hurricane Harvey. *Source: U.S. Department of Energy*

2.4. Storm Surge

Storm surge is an abnormal rise of water generated by a storm, over and above the predicted astronomical tides. Storm surge is not to be confused with storm tide, which is defined as the water level rise due to the combination of storm surge and the astronomical tide. Hurricane Harvey caused storm surge of 1 to 2 feet along the lower Texas coast and portions of South Padre Island in Cameron County, TX. There were higher storm surges on the middle and upper Texas coast. The complex geography and bathymetry of the various bays and estuaries along this stretch of the Texas coast led to a wide range of water levels. The highest water level of 10.35 feet above Mean Higher High Water (MHHW) was recorded at Manchester. This was mainly due to excessive runoff from the Buffalo and Brays Bayou into Houston's Shipping Channel. NOAA's National Ocean Service (NOS) tide stations from the Corpus Christi Bay northward to Matagorda Bay, TX, recorded peak storm surge and storm tide levels ranging from approximately 3 to 7 feet (**Figure 11**). The NOS station in Port Lavaca, TX, near Corpus Christi, where the hurricane made landfall, recorded the highest measured storm surge, 6.71 feet, or a storm tide level of 7.06 feet at 5:18 a.m. CDT on August 26. Sixteen storm tide sensors temporarily deployed by the US Geological Survey (USGS) (**Figure 12**) also detected storm tide levels generally between 3 and 6 feet.

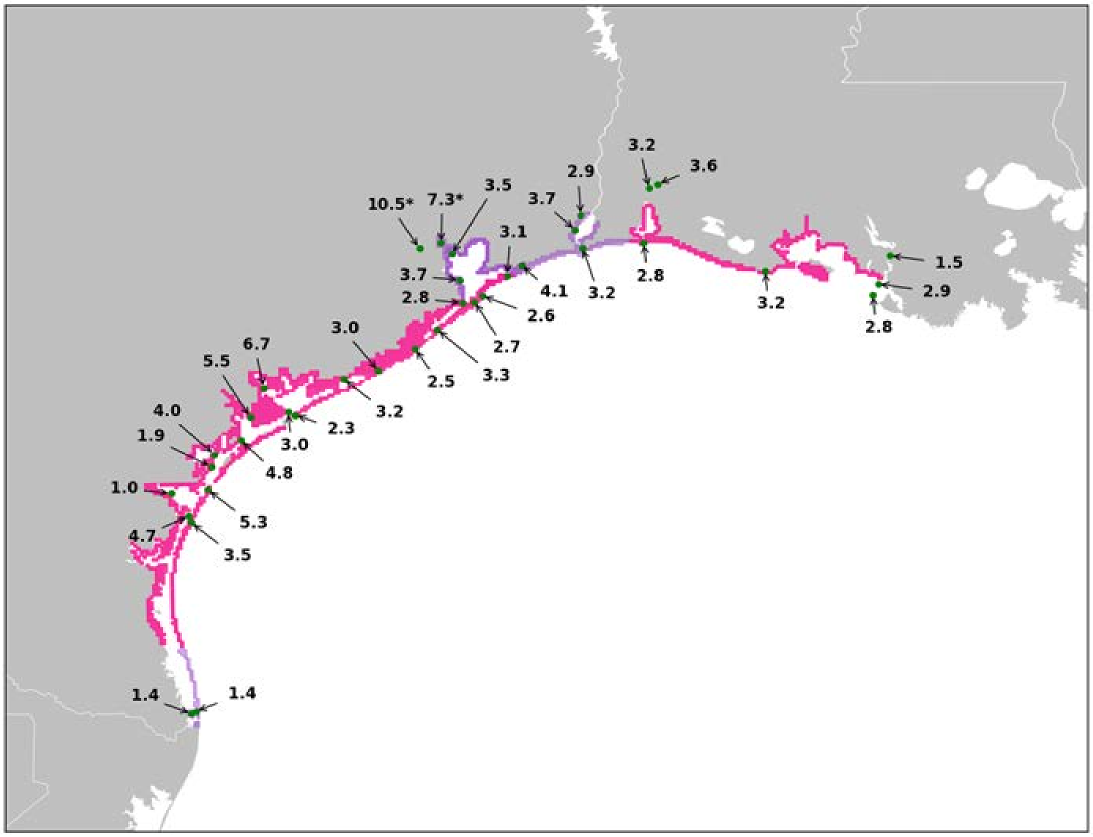

Figure 11: Maximum water levels (feet) measured from tide gauges along the coasts of Texas and Louisiana during Hurricane Harvey and areas covered by storm surge warnings (magenta) and watches (lavender). Water levels are referenced above Mean Higher High Water. *Source: NHC Storm Surge Unit*

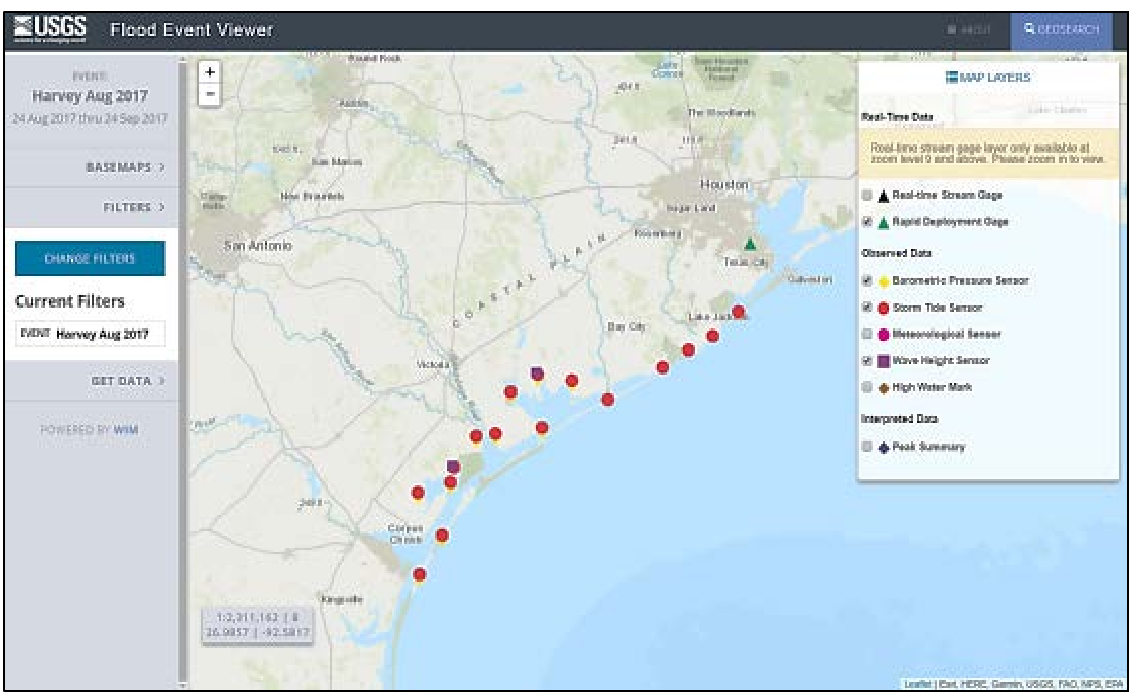

Figure 12: Shown are USGS sensors added to help support Hurricane Harvey operations. *Source: USGS Flood Event Viewer, Hurricane Harvey, August 2017*

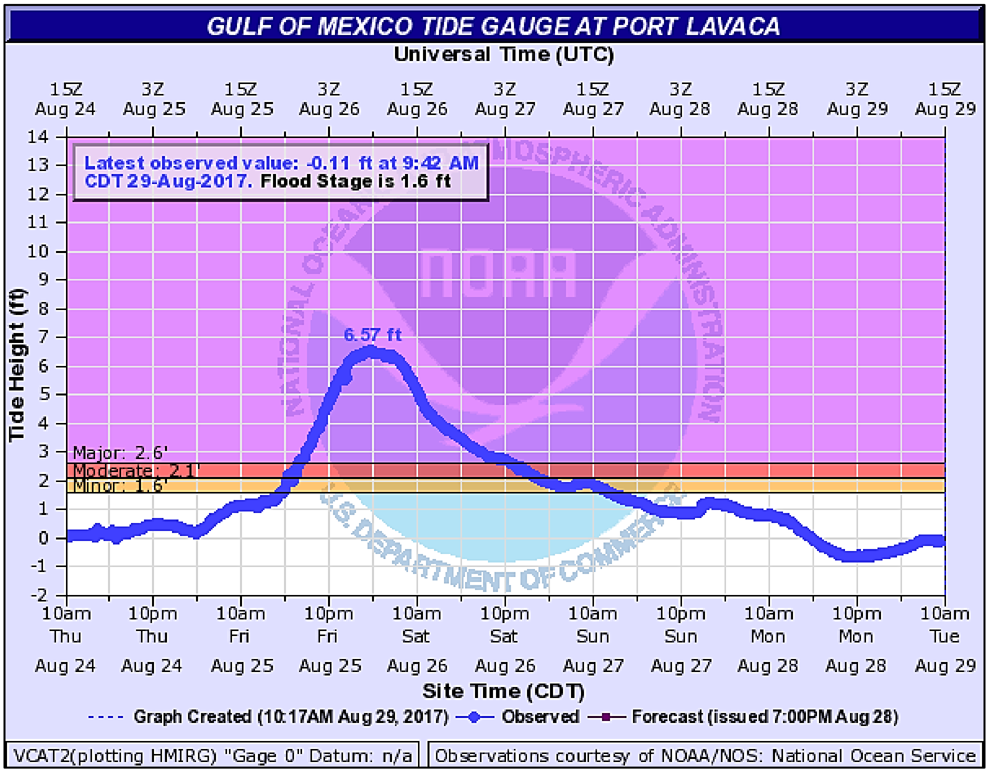

Figure 13: Graph of NOS tide gage at Port Lavaca, TX. *Source: NWS Advanced Hydrologic Prediction Service (AHPS) webpage*

WFO Corpus Christi staff members conducted an extensive multi-day manual survey of high water marks throughout the area. This survey yielded a much more extensive set of water level observations than could be assembled with the limited automatic gage data alone. The highest storm tide level observed by the NWS team within the WFO Corpus Christi area of responsibility was 12.5 feet, in the Aransas National Wildlife Refuge, TX. A 10-foot storm tide level was measured north of Port Lavaca (**Figure 13**) and an 8-foot storm tide level was recorded on the back side of Port Aransas (**Figure 14**). Additional manual storm tide observations of 4 to 7.5 feet were common throughout the area.

Storm surge-induced damage was extensive throughout the middle Texas coast, particularly in areas near and to the immediate northeast of Hurricane Harvey's center landfall location. Numerous beachfront and waterfront homes were inundated by surge, particularly in Calhoun and Aransas counties, where many marinas, docks, piers, and other similar waterfront commercial structures were damaged or destroyed. A large number of boats were damaged or destroyed, usually due to beaching or being slammed against piers or other structures. Many roads immediately along the coast or the various bays and inlets were similarly inundated, leading to roadbed washouts by beach sand. Moderate-to-major beach erosion and damage was observed at several locations, including Copano Bay, the Port Aransas area, and along Mustang Island. The storm surge produced many cuts and breaches along the barrier islands throughout the region, as noted by NOAA overflights (**Figure 15**).

Figure 14: Storm tide high water mark of 3.75 feet above MHHW at Port Aransas High School, Aransas County, TX. *Source: USGS Storm Event Viewer, Hurricane Harvey 2017*

Figure 15: Large 340 meter-long breach at the north end of Matagorda Island produced by storm surge and wave action during Hurricane Harvey. *Source: USGS/NOAA Hurricane Harvey photo comparisons*

Storm surge levels ranged from 2 to 3.7 feet in the WFO Lake Charles area of responsibility with lesser amounts farther east along coastal southeast Louisiana. The WFO Lake Charles area reported only minor inundation of coastal roads and highways. Coastal impacts to Louisiana due to storm surge were mainly across Cameron Parish.

3. Findings, Recommendations, and Best Practices

3.1. Operations and Decision Support Services

3.1.1. Weather Forecast Offices (WFOs)

WFOs responded in an outstanding fashion to the multi-layered impacts and dynamic challenges posed by Hurricane Harvey. This performance was due primarily to operational practices proven effective in previous tropical and high-impact events. For years, local office leaders in this area have emphasized the need for training and readiness with respect to tropical impacts. This long-term planning investment paid major dividends during this historic event. This performance is even more noteworthy given the enormous duress the WFO staffs and their families (particularly those at WFOs Houston and Corpus Christi) endured due to the prolonged flooding and wind impacts posed by Hurricane Harvey.

WFOs Corpus Christi, Austin/San Antonio, Houston, and Lake Charles all instituted 12-hour staffing structures well in advance of landfall. This practice is standard at all offices facing an appreciable tropical threat. Each WFO made a strong effort to assign event coordinators for each shift. This person was responsible for ensuring the decision support, forecast, and observation tasks were executed effectively and that staff fatigue issues were addressed. Staff members and management at the impacted offices indicated this process, with few exceptions, worked very effectively. Much of this success can be attributed to extensive operational training response plans and procedures developed and exercised at these offices. WFO Corpus Christi, for example, used laminated task cards that clearly defined the roles of each staff member on a particular shift. These tools were particularly helpful for forecasters deployed to WFO Corpus Christi from other offices to provide additional support.

Hurricane Harvey clearly illustrated the major shift in service emphasis that was well underway at many coastal WFOs for the past decade or more. Specifically, a large proportion of the value that local government and broadcast partners derive from NWS services comes from personal and group briefings, related textual and graphical briefing resources, certain social media activities, and other interpersonal communications – which augment officially disseminated text-based or grid-derived products. This assessment focused on specific partner response in Texas and Louisiana during Hurricane Harvey – not experiences from other storms in other areas. Thus, care should be taken in extrapolating these perceptions of service value to other coastal regions of the United States.

3.1.1.1. WFO IDSS and Partner Relationships

The service assessment team interviewed a broad cross-section of core local, state, federal, and private sector partners throughout the region affected by Hurricane Harvey. This group included EMs, other government officials, port managers, Coast Guard officials, and the broadcast media. These NWS stakeholders conveyed an overwhelmingly positive feeling about the IDSS delivered by their local WFO partners. Many stakeholders stated that the relatively low death toll from Hurricane Harvey shows that "*someone somewhere got the key information they needed and acted on it*." Multiple EMs and other partners stated they use NWS information (produced by WFOs, RFCs and NCEP Centers) to drive operational decision making and hazard messaging to the community. While some partners stated a near total reliance on NWS information, others mentioned that they relied on various private sector entities as complementary sources of information.

Conference Call Briefings and Emails: Conference call briefings, with and without web conferencing and/or email briefing packages, constituted a very large and critically important component of the WFOs' IDSS.

Every WFO in the region conducted numerous conference call briefings with its partners over a one to two-week period bracketing Harvey's approach, landfall, and departure from the region. Virtually every briefing contained most or all of the following elements: primary NHC track and intensity forecast information, WPC/WFO-collaborated rainfall forecasts, and a full local-scale interpretation of the location, timing, and magnitude of the various impacts expected with Hurricane Harvey. Partners stressed the importance of establishing a daily battle cadence with these calls.

In addition to the briefings led by WFOs (conducted up to several times per day before and following landfall), staff members took part in many other calls being led by local, county, state, or federal EMs or government officials, water community partners, and transportation, energy and media stakeholders. For example, WFO Houston delivered a large number of tailored marine-oriented briefings to the Houston area Port Coordination Team and the Navigation Restoration Team. Each of these teams, in turn, had a diverse cross section of public and private stakeholders associated with the Port of Houston, one of the largest economic engines in Texas and the country. WFOs Corpus Christi and Lake Charles provided similar briefings to their port interests in advance of and following Hurricane Harvey's impacts. Many of these calls were focused on recovery efforts and persisted well after the end of the storm.

The volume and duration of this briefing load was taxing at times. Fortunately, most of the offices were able to distribute the calls among multiple members of the WFO team. While the majority of calls were conducted by WFO management, particularly the Warning Coordination Meteorologists (WCM) and Service Hydrologists (SH), forecasters also led a significant number of calls. For example, the SHs at WFOs Houston, Lake Charles, and Austin/San Antonio conducted or participated in many flood-related calls during the event, and the Marine Focal Point for WFO Houston led a large number of port and marine-related calls.

Best Practice: Many of the WFOs distributed the conference call and briefing load beyond the management team, to include SHs and other members of the WFO. This force-multiplier effect enabled the offices to engage more partners more frequently with a richer set of IDSS content. It also somewhat reduced fatigue on the part of the management teams.

Each of the affected WFO managers and some staff members had well-established relationships—in many cases, "deep relationships"—with elected officials, EMs, media, and other community partners before Hurricane Harvey occurred. These relationships facilitated communication of critical weather information and appropriate partner response as the storm progressed. In particular, WCMs at each of the affected WFOs shared close relationships with many of their EM and media colleagues. These strong relationships facilitated the quick interpersonal transmission of critical IDSS needed for vital community-based decision making. Several government partners cited specific instances where NWS personnel called or texted them at critical junctures. For example, the Rockport City, TX, EM stated that during the eyewall passage of Hurricane Harvey, the Corpus Christi WCM texted him to let him know when he would be able to send out responders to rescue stranded members of the public. The WCM told him how long they had to rescue stranded residents within the calm of Hurricane Harvey's eye before the hazardous conditions resumed.

Much of this relationship building at WFOs Corpus Christi, Houston, and Lake Charles is a product of the frequent EM safety tabletop and full-scale exercises and meetings held with the marine transportation and energy industries. These WFOs have a long tradition of taking part in these preparedness activities, which are essential in light of the unique hazardous material risks in the region. Like many WFOs throughout the NWS, all of the affected offices also host official Integrated Warning Team meetings, comprising of the WFO, media members, and various emergency response stakeholders from the public and private sectors. These meetings are held regularly throughout the year, providing a further opportunity for partners and WFO staff to enhance relationships.

Best Practice: The WFOs well-established relationships with local elected officials, local media, EMs, and other community partners before Hurricane Harvey facilitated communication of critical IDSS before and during the storm.

Off-Site IDSS: Compared with the vast amount of IDSS the WFOs conducted in their offices, the amount of off-site (*e.g.*, at partner venues such as Emergency Operation Centers) IDSS provided during Hurricane Harvey was relatively limited. Off-site IDSS was restricted by staff resources, but primarily due to the efficiency of remote delivery IDSS. WFO Corpus Christi deployed staff members to the Victoria and Corpus Christi EOCs. The Corpus Christi EM stated it was invaluable to have the NWS meteorologist there for four days, adding the EM office could coordinate better with the other EOCs because of this in-house meteorological support. The Victoria EOC personnel stated they derived great value from these forecaster deployments during high-impact events and strongly urged their continuation. Finally, WFO Houston is co-located with the Galveston County EMA and thus an appreciable amount of on-site information was conveyed to that stakeholder.

The Effective Hurricane Messaging (EHM) course, conducted yearly as a collaborative effort by various members of the NWS tropical community, proved to be effective in preparing WFO meteorologists for both on-site and WFO-based IDSS activities. Multiple WFO and SRH personnel have cited a direct link between this course and the improvement of the NWS's tropical weather IDSS effort.

Finding 1: The EHM course has a strong direct benefit to the improved delivery of tropical weather IDSS.

Recommendation 1: The NWS should allocate training resources for additional EHM courses prior to each tropical weather season or seek creative alternatives for offering this training content to local WFO personnel.

NWSChat: NWSChat has been mentioned in previous service assessments dating to the early 2000s and remains a critical tool for direct communication between NWS offices and their core partners. The WFO chatrooms were used extensively during Hurricane Harvey. Numerous EMs used this tool to see what WFO meteorologists were thinking ahead of time and were able to incorporate this knowledge into their operations. Multiple media partners also mentioned that NWSChat is their primary method of communication with the WFO. One media partner discussed how he was able to see where the eye of Hurricane Harvey was live-on air as a result of real-time information on NWSChat from a tablet at the broadcast desk. NWSChat also helps media partners provide better coverage by disseminating real-time storm damage and helping these partners decide when to send news crews to a specific location.

Social Media: Social Media, specifically Facebook and Twitter, was a major asset and a major workload for all the affected WFOs. WFOs Houston/Galveston, Corpus Christi, Lake Charles, and Austin/San Antonio each dedicated at least one staff member 24/7 to social media roles. Each affected WFO distributed a large amount of NWS impact information via Facebook and Twitter, but also spent considerable time responding to specific questions from the public concerning the storm. Social media was also an extremely effective vehicle for identifying exactly what impacts were occurring at specific locations within the affected areas. WFO Houston's social media following doubled during the event and WFO Corpus Christi nearly doubled its number of Twitter followers. WFO Lake Charles increased its Twitter page following by roughly 5,000 people. WFO Houston's social media had millions of readers, with the President of the United States retweeting one of its tweets during Hurricane Harvey (**Figure 16**).

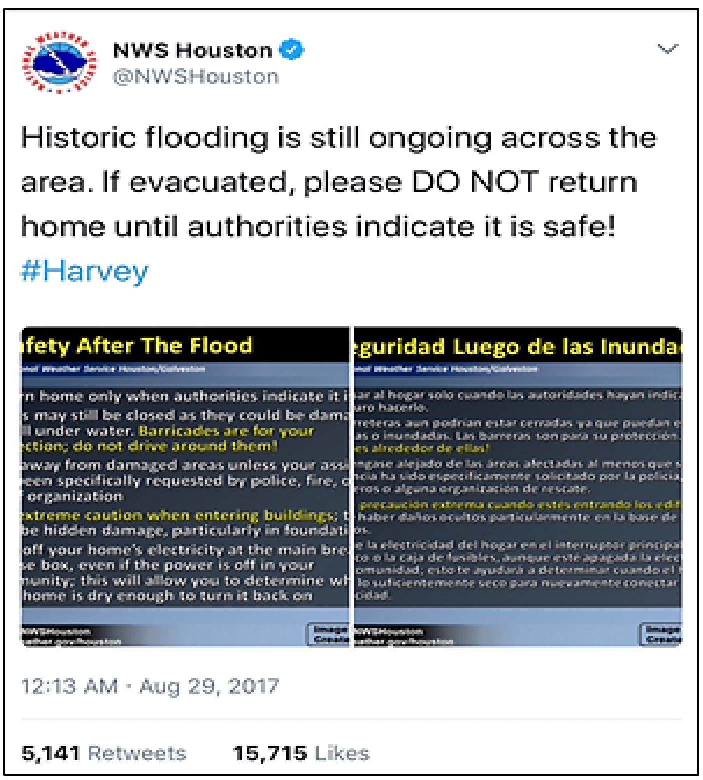

Figure 16: NWS Houston Tweet retweeted by President Trump. *Source: NWS Houston*

Social media was a highly effective vehicle for sharing briefing packages with the public similar to the ones provided to core partners. Much of the core forecast track/wind intensity, storm surge, rainfall and flooding content developed collaboratively between NHC, WPC, and the WFOs/RFCs was repackaged and distributed via WFO social media accounts.

WFO Lake Charles was a formal NWS test site for Facebook Live and this resource was used frequently and effectively during Hurricane Harvey. The WFO conducted 19 Facebook Live sessions, with an average of 19,000 direct views each. In addition, WFO Lake Charles, the Calcasieu Parish Office of Emergency Preparedness, and a local TV station teamed up to do weather briefings that were streamed live on the media member's Facebook Live account. A substantial amount of positive feedback was gathered from local EMs and elected officials on the use of this resource. Other WFOs in the impacted region specifically mentioned that access to Facebook Live would have enhanced their ability to communicate more effectively with the public.

Best Practice: The use of Facebook Live by WFO Lake Charles elicited significant praise for communicating live updates to partners and the general public.

WFOs received numerous specific requests for assistance from residents via their social media feeds. In particular, WFO Houston staff discussed being "shocked" that so many people were asking for high water rescues directly on the WFO Houston Facebook and Twitter feeds. As one staff member mentioned: "*People were begging for help*." **Figure 17** illustrates one example of a public request in response to a WFO Facebook post.

WFO Houston Facebook Post on August 27, 2017: *"This is an extremely dangerous and life-threatening situation. Do not attempt to travel unless you are fleeing an area subject to flooding!"*

Public Citizen's response: *"My family in Baycliff have waist-high water inside their one-story home located right next to the Baycliff Courthouse off of Grand. Do they just sit there and wait it out?"*

Figure 17: WFO Houston/Galveston Facebook post. *Source: WFO Houston/Galveston, TX*

Even though all WFOs effectively used social media during the event, they all agreed that with additional resources, they could have offered even more effective information via these outlets. Some offices do not have a specific, consistent strategy for integrating social media into their communications plan during high-impact events, but they felt such a plan would be valuable in the future. The allocation of staff during these events remains a challenge. WFO managers stated they ideally would like to dedicate even more local resources to the development of graphics and other special content for social media and web pages; however, such allocations must be balanced against the need to resource all other members of a WFO's mission during a high-impact event.

3.1.1.1 WFO Official Products

Two categories of Advanced Weather Interactive Processing System (AWIPS)-issued "official" products required much of the time and attention of local WFO staffs: tropical weather text and web graphic products derived from the National Digital Forecast Database grids and short-fused convective warnings.

Tropical Product Suite: Staff at coastal and adjacent inland WFOs spend considerable amounts of time each year implementing tropical-related AWIPS software, procedural and policy updates, and taking training programs on how to use the software effectively. This major time investment by local Science and Operations Officers (SOO), Information Technology Officers (ITO), and AWIPS and Tropical Focal Points pays off by enabling forecasters to navigate the tropical Graphical Forecast Editor (GFE) processes successfully. Each office has created special reference materials in an attempt to streamline the various GFE actions that must be executed. WFO Corpus Christi created a one-page, GFE cheat sheet that has been replicated at other coastal offices. Despite the presence of resources such as this one, there were inevitable system issues during Hurricane Harvey that required assistance from SRH and members of the national tropical weather training community. This problem has been a common occurrence during tropical systems over the past several years.

At least one forecaster at each affected WFO was dedicated to the tropical product suite during Hurricane Harvey. On occasion at some offices, multiple forecasters were creating and/or editing GFE-related tropical products. Numerous steps and attention to detail are required to execute these tasks, despite the availability of tip sheets and other resource guides. In addition, these products require a significant amount of coordination with adjacent offices and NHC staff. Multiple WFOs affected by Hurricane Harvey specifically cited the workload required to produce the local tropical product suite.

Fact: Executing the NWS local tropical product suite requires a significant staffing investment, both during storms such as Hurricane Harvey and in pre-season training and software preparation activities.

The service assessment team thinks that staff resource investments must be balanced against the service benefits derived from the NWS tropical product suite. Identifying a successful cost-to-benefit ratio for these products was difficult during this assessment. Numerous partners were queried regarding their use of the Hurricane Local Statement (HLS) and other locally-generated text and graphical tropical products. Responses revealed the HLS was not consistently used by this segment of the community during Hurricane Harvey. Rather than accessing storm information from these products, government partners stated they relied almost exclusively on NWS content from email briefings, conference calls, and other IDSS delivery mechanisms. Only a small minority of media respondents in the Texas and southeast Louisiana area said they used the HLS during Hurricane Harvey. The partners interviewed also did not report significant use of other products from the WFO tropical forecast suite. It is unclear whether this lack of use is an issue specific to the western Gulf Coast WFOs, and just during Hurricane Harvey, or a broader issue affecting additional WFOs. It is also possible that the large magnitude of the dominant rain hazard could explain the decrease use of the HLS with Harvey.

Finding 2: The HLS and other GFE-driven local tropical products were not widely used by the media and other core partners during Hurricane Harvey.

Recommendation 2: Local offices, Regional Headquarters, and the NWS Tropical Program should determine whether partners' lack of use of local tropical products was peculiar to Hurricane Harvey or represents a broader condition affecting other coastal areas.

Short-Fused Convective Warnings: Within the primary Hurricane Harvey impact area, WFOs Austin/San Antonio, Corpus Christi, Houston, Lake Charles, New Orleans, and Shreveport issued a combined total of 372 tornado, flash flood, and severe thunderstorm warnings from August 25–30, 2017. In addition, a few coastal offices issued a large number of short-fused marine weather warnings. As evidenced by the large number of warnings, these offices invested a tremendous amount of staff time on radar-based warning decision-making and the issuing short-fused warnings. Timely and specific flash flood warnings (FFW) and flash flood emergencies, particularly in the Greater Houston and Beaumont/Port Arthur areas, were credited by government and media partners with motivating public action and saving numerous lives.

Tornado warnings (TOR) comprised the majority of short-fused convective warnings issued during Hurricane Harvey. Across all of Southern Region (SR), 14 WFOs, extending from Texas to Tennessee and Georgia, issued 311 TORs in conjunction with Hurricane Harvey and its remnants. WFO Houston alone issued 157 TORs, from August 25–28, while WFO Lake Charles issued 61 tornado warnings. Many of these warnings were issued repeatedly for identical locations, coincident in time with FFWs and river flood warnings. **Figure 18** depicts all of the tornado warning polygons associated with Hurricane Harvey from August 25–31, 2017. The cumulative verification statistics for all tornado warnings issued by the six WFOs in the primary Hurricane Harvey affected region are as follows:

- Total tornado warnings: 232
- Probability of Detection: 63 percent, Fiscal Year (FY) 2017 National Average: 59 percent
- False Alarm Ratio: 90 percent, FY17 National Average: 72 percent
- Average Lead Time: 7 minutes, FY17 National Average: 8.7 minutes

The high False Alarm Ratio, short Average Lead Time, and great frequency of spatial repetition resulted in concerns about the effectiveness of the TORs issued during Hurricane Harvey. Responses from EMs and the public reflect a mixed picture however. While some EMs stated that "warning saturation" caused them to tune out the messages (and in some cases, turn off their notifications), other respondents (among both EMs and the public) did perceive a value to the TORs, despite their frequency. They felt the incessant warnings woke people up and motivated them to maintain a higher level of overall weather situational awareness. This increased awareness in turn enabled them to better protect their property or evacuate when the need arose. It is also important to recognize that 23 tornadoes were verified in the Greater Houston Area over a 3-day period during the event, a significant frequency that proves the hazards did exist. WFO Houston detected 88 percent of these tornadoes and issued TORs for them.

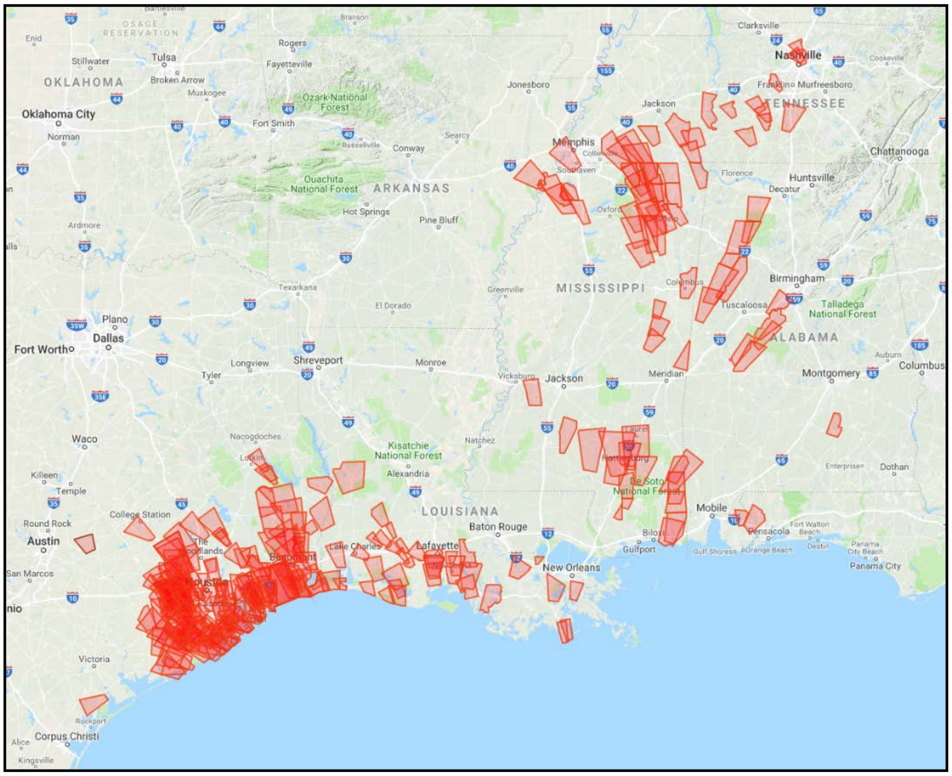

Figure 18: Tornado warning polygons issued by WFOs for August 25–31.
Source: NWS Performance Management website

The persistent banding surrounding the center of Hurricane Harvey produced a very favorable environment for short-duration tropical tornadoes. This situation was well diagnosed by WFO Houston forecasters and certainly by the Storm Prediction Center, which maintained Tornado Watches over Houston for at least 60 continuous hours; however, the sheer number of shallow, fast moving velocity couplets forming within these bands, particularly across southeast Texas, created significant warning challenges. While the coastal WFOs provide adequate training in the detection of individual tropical tornadoes, some forecasters indicated the scale and duration of these events, and the extended radar shifts dedicated to their detection (and to simultaneous flash flood detection), was physically and mentally taxing.

In addition to the large number of TORs, WFOs also issued 134 FFWs during Hurricane Harvey. The vast majority of these FFWs were issued by WFOs Houston and Lake Charles, and many coincided with TORs in effect for the same areas. Again, both positive and negative public response impacts emerged from partner feedback regarding these multiple warnings. A strong perception did exist, however, that the FFWs resulted in lives saved – a conclusion bolstered by the relatively low fatality total for Hurricane Harvey.

3.1.1.2 WFO Administrative Processes

WFO Corpus Christi management noted that most of their staff members evacuated their families because of the hurricane hazards expected in their residential areas. Four employees' families qualified for NOAA evacuation reimbursement due to formal evacuation orders issued by local government authorities. In Texas, these mandatory evacuation zones are tied to storm surge, and are very limited in areal extent. As a result, no other WFO families lived in formal evacuation zones, and thus did not qualify for NOAA reimbursement. During subsequent tropical events in 2017 there was more latitude in providing reimbursements to employees and families.

Finding 3: WFO staff members and their families incurred a financial burden as a result of limitations in NOAA evacuation pay policies. NOAA's evacuation policies were also inconsistent throughout the course of the season, impacting employee morale.

Recommendation 3: NWS CFO should work with NOAA to clarify, clearly communicate, and ensure a consistent application of the evacuation pay policies for employees and dependents before high-impact events.

3.1.2. River Forecast Centers (RFC)

Owing to the overwhelming hydrologic impacts – and decision support needs – arising from Hurricane Harvey's epic rainfall, the WGRFC and the Lower Mississippi River Forecast Center (LMRFC) were critical components of the NWS response from well prior to landfall to many days following its dissipation.

WFOs and government partners in the severely affected regions of southeast Texas stated that the strong support and collaboration provided by WGRFC was critical to their operations during Hurricane Harvey. The long duration of these high-impact operations challenged the WGRFC staff. Management did request assistance (via SRH) early on, and ultimately utilized 3 personnel from other RFCs throughout the event. This did help mitigate staff fatigue and ensured that critical operations were resourced successfully. At the same time, a well-defined onboarding and familiarization process was not in place at WGRFC. As a result, it took varying amounts of time for the deployed personnel to get fully established on the WGRFC network and AWIPS systems, and to become familiar with the RFC's operations.

On August 23rd, WGRFC provided daily Hurricane Harvey briefings which highlighted the outlook for significant river flooding (**Figure 19**). Non-routine river forecasts, generated only during high flows/flooding situations, were issued on 30 consecutive days, beginning August 25 and ending September 24. Prior to August 25, there were no river forecasts for the non-routine forecast locations on the AHPS Hydrograph Web Pages (**Figure 20**). WGRFC did highlight the devastating flooding expected for Texas and Louisiana in their Harvey IDSS Briefings to partners (**Figure 21**) and in the Significant River Flood Outlook product.

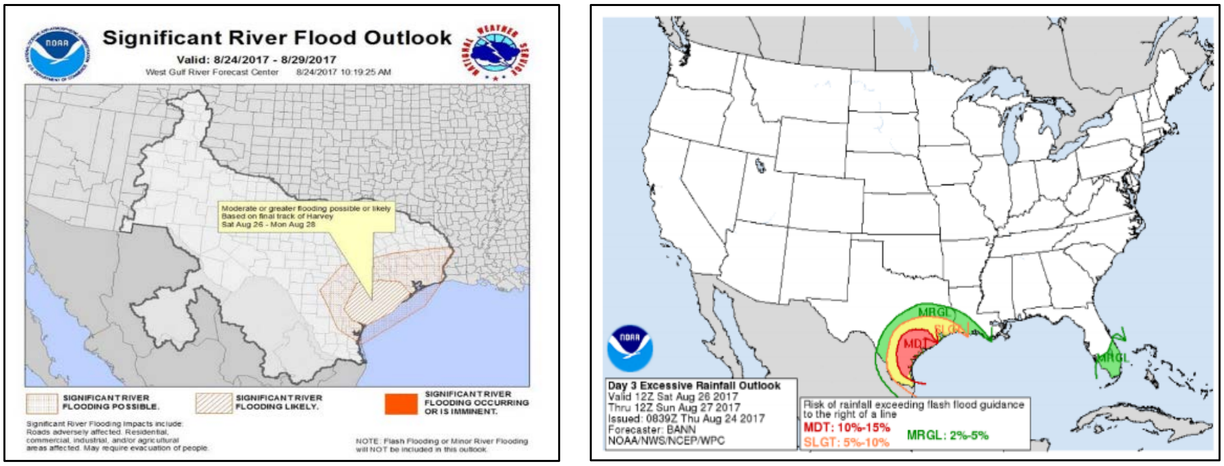

Figure 19: Left, the Significant River Flood Outlook product issued on August 24 by the WGRFC indicating moderate or greater flooding likely. Right, the Excessive Rainfall Outlook issued on the same day with areas showing a moderate risk of exceeding flash flood. *Source, WGRFC*

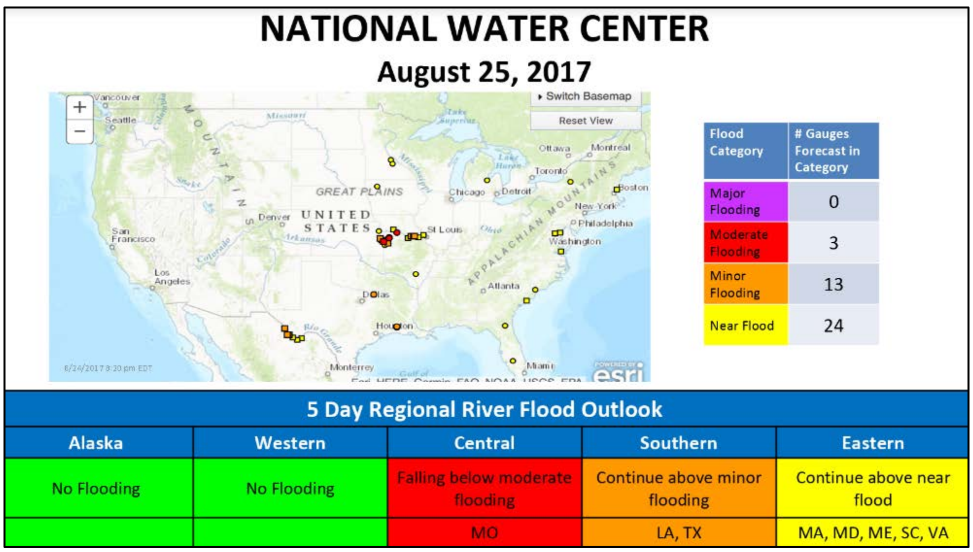

Figure 20: NWC Briefing on August 25. *Source, NWC*

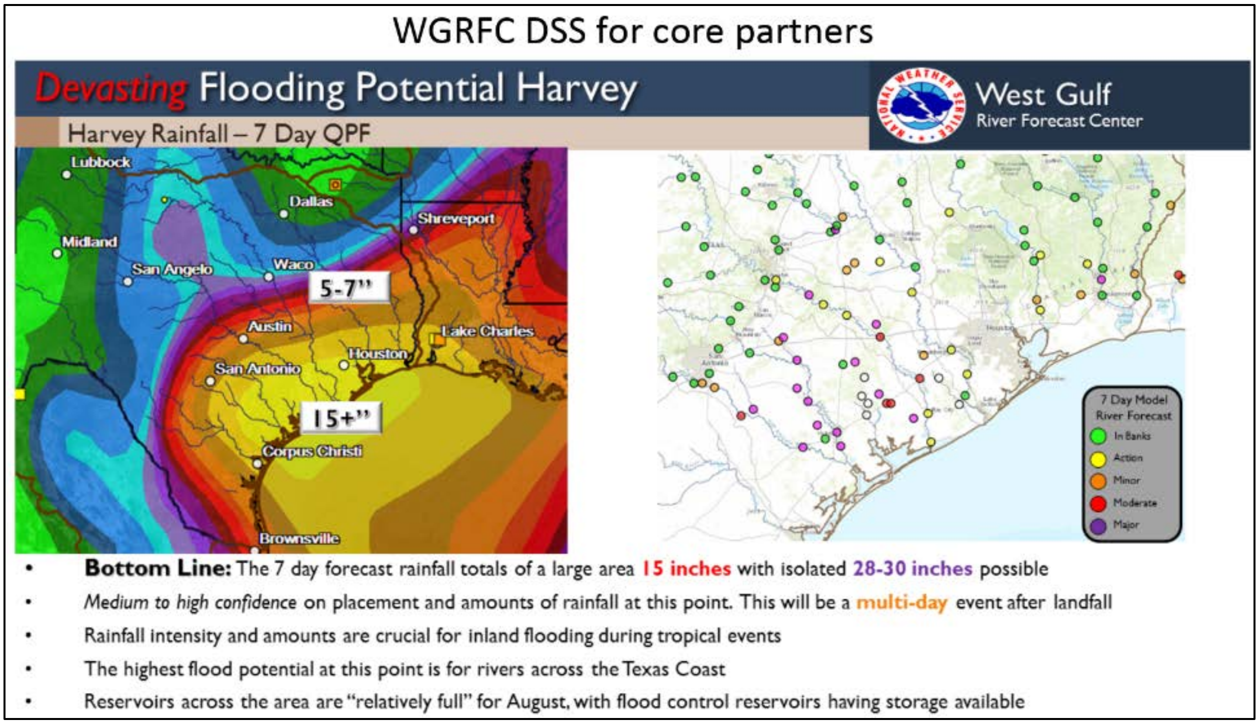

Figure 21: WGRFC DSS for Core Partners on August 25. *Source, WGRFC*

3.1.2.1. RFC Products and Inputs to the Forecast Guidance

WFOs and external partners alike provided significant positive feedback on the quality of RFC forecasts, particularly given the unprecedented magnitude of the flooding. EM and levee improvement district officials from Fort Bend County, Texas (west of Houston) specifically praised the quality of WGRFC's forecast for the Brazos River at Richmond, which crested over 10 feet above flood stage on September 1, 2017. Over 200,000 residents were under an evacuation order, contingent on the WGRFC forecast crest at Richmond. Multiple conference calls were held between county officials, the WFO Houston SH, and personnel from WGRFC, during which extensive forecast and confidence information was conveyed to the partners. The EM for Fayette County, Texas also stated that deterministic and probabilistic stage information produced by WGRFC – and communicated and interpreted by WFO Austin/San Antonio – was extremely useful in her decisions to evacuate flood-threatened residents in LaGrange, Texas.

Probabilistic Quantitative Precipitation Forecasts (**PQPF):** The WGRFC produces an ensemble river forecast product graphic based on 72 hours of WPC's PQPF. During Hurricane Harvey, these hydrographs provided extended guidance beyond the official WGRFC river forecasts (**Figure 22, left**). Although WFOs and the SRH ROC found the PQPF graphic an extremely valuable tool when forecasting the expected major flooding (**Figure 22, right**), there are limitations to the spatial and temporal distribution of the PQPF. The Hydrologic Ensemble Forecast Service (HEFS) is the preferred NWS approach for producing reliable and skillful ensemble streamflow forecasts (see reference to HEFS in these previous service assessments' recommendations: 2008 Midwest Flood #15, 2011 Mississippi Flood #19, and 2011 Missouri/Souris Floods #34). Until RFCs implement HEFS at river locations, the PQPF product will be used to support improved situational awareness and meet critical trusted partner/customer needs to better understand potential flood scenarios. PQPF complements HEFS in that PQPF provides more general uses of how much rainfall is likely and possible.

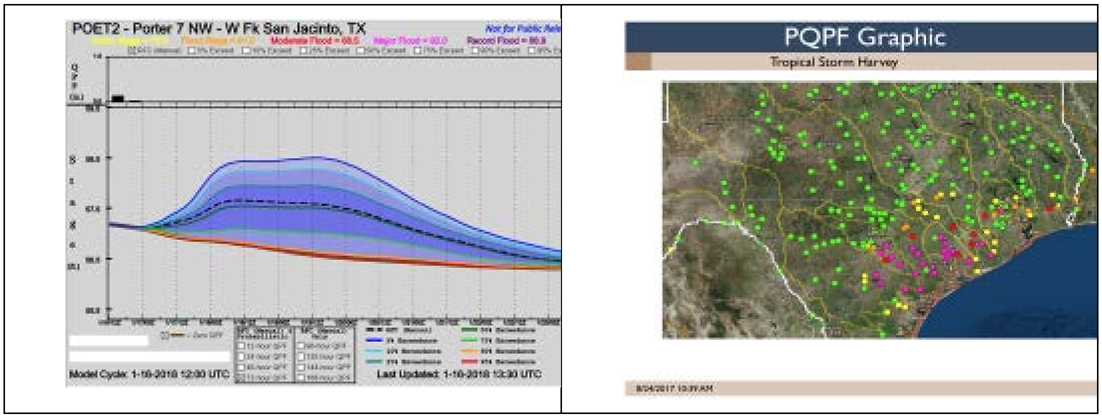

Figure 22: WGRFC IDSS sample hydrograph and graphic based on WPC PQPF.
Source: WGRFC

Finding 4: Although the ensemble forecast hydrographs based on PQPF were found to be useful by WFO Houston and core partners, HEFS is the preferred NWS approach for producing reliable and skillful ensemble streamflow forecasts.

Recommendation 4: The NWS should continue to implement HEFS at additional river forecast locations.

QPF: Both the WGRFC and the LMRFC issued river forecasts with QPF amounts that extended 12 and 24 hours into the future, respectively. During significant regional hydrologic events with higher than normal confidence, each RFC transitions to a longer term QPF forecast window. During Hurricane Harvey, both offices transitioned to a 72-hour QPF window on Friday, August 25. Results of the extended QPF input window were reflected in the next river forecast model runs, with many sites forecast to experience major flooding. EMs and river basin managers understand and concur with 12 and 24 hours of QPF when there is high uncertainty in rainfall; however, extending the QPF beyond 24 hours for Harvey was appropriate.

Use of National Water Model (NWM) by the RFCs and WFOs: The NWM is generated on the Weather and Climate Operational Supercomputing System and provides forecast guidance that augments the official NWS river forecasts provided by the RFCs. RFC and WFO personnel stated that they examined NWM guidance throughout the event. However, they cited the presence of high flows at some points, combined with significant run-to-run variability, as reasons for decreased confidence in the output during the event. Given these concerns, the field offices did not incorporate the NWM products into their hydrologic IDSS to core partners during Hurricane Harvey. Instead, WGRFC, the WFOs, the SRH ROC, and NWS personnel deployed to the Texas State Operations Center (SOC) worked diligently to maintain a consistent message by adhering to the official river forecasts and ensemble information provided by WGRFC (and in Louisiana, from LMRFC).

Despite this common messaging effort, the presence of NWM output in the public sphere was perceived by field personnel to have created some degree of confusion. Academic subject matter experts present in the SOC during Hurricane Harvey distributed NWM guidance to state decision makers, leading to questions of interpretation from the partners. A NWS hydrologist, deployed to the SOC to provide hydrologic IDSS, spent significant time explaining various differences between the official WGRFC forecasts and the NWM output. This activity distracted the hydrologist from other IDSS duties and is perceived to have impacted the partners' overall understanding and confidence in all NWS hydrologic forecasts. In addition, during this high intensity event, key WGRFC staff members were pulled away from their primary missions to handle questions and concerns related to differences between NWM guidance to WGRFC official river forecasts. The Office of Water Prediction did host daily coordination calls involving the National Water Center (NWC), WPC, WGRFC, the SRH ROC, Texas Division of Emergency Management (TDEM), and the USACE to answer questions about the NWM guidance and related products.

Finding 5: The observed run-to-run inconsistencies during Hurricane Harvey created an extra workload for WGRFC and other field entities involved in the provision of IDSS to partners. Some partners expressed uncertainty about official NWS river forecasts, given their discrepancies with the NWM output.

Recommendation 5: RFC forecasts are the official source of river forecast information. All RFCs and OWP should work together to gain a better understanding of NWM strengths and weaknesses and should continue to communicate their model guidance needs while aligning messages for consistency.

3.1.2.2. RFC Communications, IDSS, and Relationships

Dam break: The WGRFC issued a dam break forecast for Louisiana's Vernon Lake. Since the WGRFC did not have an Emergency Action Plan (EAP) with inundation map for these circumstances, they needed to conduct a dam break analysis using DSSWISE to simulate flood waves resulting from this dam incident. This dam break analysis increased WGRFC's confidence in the flood forecast and understanding of the potential downstream impacts. The Decision Support System for Water Infrastructure Security (DSS-WISE) tool is available to federal agencies, dam-safety stakeholders, and state dam-safety offices through the funds and support of FEMA and the University of Mississippi's National Center for Computational Hydroscience and Engineering. This tool includes a two-dimensional numerical flood model with web-based geographic information system (GIS) decision support that can rapidly model dynamic, unsteady flows due to dam break or a flood hydrograph and also has the ability to share EAPs with inundation maps. (See Appendix C, Finding 12 and Recommended Action of The Historic South Carolina Floods of October 1–5, 2015, Service Assessment).

GIS Support: While the WGRFC staff stated that GIS data coming into the office was vital, its sheer volume was overwhelming. This data primarily consisted of satellite and aerial imagery. These large raster files present a considerable challenge to process, review, and manage. Better data assimilation methods are needed to use these resources effectively during a flood event. GIS resources to manage and analyze field reports of flooding and damage to infrastructure would assist IDSS activities, including the creation of maps and graphics for social media and briefings. These resources need to be embedded at the RFCs and WFOs for GIS/IDSS support during events.

Finding 6: WGRFC needed additional GIS resources to keep pace with the data demands imposed by Hurricane Harvey.

Recommendation 6: Additional GIS resources should be available to WFOs and RFCs for high-impact events.

Historical Flood Inundation Maps: Core partners were asked to comment on ways to better understand the impacts from 60 inches of rainfall. Partners noted that local communities have taken an active role in developing post-event Hurricane Harvey historical flood inundation maps to capture the historic Hurricane Harvey flooding and unprecedented rainfall. EMs and river basin managers stated these types of maps based on actual flood events with documented impacts and verified high water marks can be extremely useful in telling the story, understanding the impacts of extreme rainfall, and assisting in community resiliency efforts.

Finding 7: In general, residents did not comprehend the impacts that more than 60 inches of rain would have in their communities. There were no existing products that could effectively communicate the impacts.

Recommendation 7: When the post-event Hurricane Harvey flood inundation maps are made available, the NWS should link to these historic flood maps on the appropriate NWS web pages.

Real-Time Flood Forecast Inundation Maps: Partners commented on model uncertainty with real-time flood forecast inundation maps and issues with these types of products. Some partners complained about the public's perception that upstream reservoir operators were not doing enough to manage or prevent flooding in downstream communities. These perceptions occurred despite the fact that some of the flooding was actually quite localized in origin and unrelated to upstream reservoir operations. Real-time inundation maps can clarify these issues by including the effects from observed and planned reservoir operations as well as local origins.

Basin and emergency managers have day-to-day needs and base operational decisions on events that have happened in the past 24-36 hours. The addition of real-time flood inundation maps to RFC/WFO daily briefings would be extremely valuable to these partners' decisions. Local EMs are concerned with traffic, road safety, and debris removal in their jurisdictions. Those interviewed commented that more detailed road/street networks and active road/street closures should be included on real-time flood inundation maps. They did not use the real-time inundation maps shared by the Texas SOC because the maps failed to show details on the potential of street and road impacts.

At the request of the TDEM Chief, the NWS Director instructed OWP to create and share experimental NWM-based inundation maps with TDEM. OWP developed a process to routinely create these new maps and coordinated with WGRFC and the SRH ROC to simultaneously provide them to the WGRFC, ROC, WPC, and TDEM. These real-time flood inundation maps were an entirely new product using a simplified procedure, known as the Height Above Nearest Drainage technique, to model the extent of flooding. Given OWP was asked to assume a temporary operational posture for the first time, and do so with 24 hours, OWP was not able to provide background information such as a user guide, technical guidelines, and specifications. TDEM stated the inundation maps were valuable, particularly in areas away from mainstem rivers where no other forecast inundation data were available. The NWC-produced inundation maps, when combined with mainstem river inundation information provided by the WGRFC and USACE, informed critical flood mitigation decisions. Partners who used this information indicated that documentation and training are required to better understand and use these maps.

Finding 8: The WGRFC staff had no experience with the NWM flood inundation maps and could not provide guidance or support for these products to core partners.

Recommendation 8: NWS should develop background documentation and training for staff on the use of the NWM-produced inundation maps.

Core partners need to fully understand the limitations of experimental products such as the NWM derived inundation maps prior to their use. Partners would have benefitted from NWS training at a local RFC/WFO workshop or tabletop exercise before being exposed to these products for the first time. The requirement to respond to inquiries regarding the NWM derived maps added an extensive workload to an already taxed WGRFC staff. Some core partners did question the introduction of new and unverified experimental products during an unprecedented flood event on the scale of Hurricane Harvey.

3.1.3. National Hurricane Center Performance

NHC responded in an outstanding fashion to the multi-layered impacts and dynamic challenges posed by Hurricane Harvey. This high performance was due primarily to operational practices proven effective in previous high-impact tropical cyclone events. This long-term planning investment paid major dividends during this historic event.

Hurricane Harvey was one of 17 named storms in the North Atlantic Ocean during the busy 2017 hurricane season and the first of five major hurricanes in continuous succession through September 30, 2017. Hurricane Harvey was the first Category 4 hurricane to make landfall in the United States since Hurricane Charley in 2004.

The 2017 tropical season was the first year that NHC issued operational storm surge watch/warnings. Hurricane Harvey was the first hurricane for which these products were issued. Also during 2017, NHC started issuing watches, warnings, and advisories for potential tropical cyclones that posed a threat of bringing tropical storm or hurricane conditions to land areas within 48 hours. Hurricane Harvey was an excellent example of the value of these products because the storm attained tropical storm strength and impacted the Windward Islands less than 48 hours after NHC issued its first Potential Tropical Cyclone Advisory for the event on August 17.

NHC issued the first of 43 advisories for Potential Tropical Cyclone #9 (Future Hurricane Harvey) at 11 a.m. AST, August 17, 2017, when the system was approximately 300 miles east of Barbados.

Hurricane Harvey later dissipated in the central Caribbean Sea, resulting in a temporary end to advisories on August 19, 2017. The storm’s remnants tracked westward into the Gulf of Mexico and reorganized, resulting in a resumption of advisories at 10 a.m. CDT, Wednesday, August 23, 2017. This advisory included Tropical Storm and Hurricane Watches for most of the Texas Gulf Coast and the northeast Mexican coast. A Storm Surge Watch also was issued from Port Mansfield to High Island, TX.

Best Practice: NHC issues strongly worded tropical weather outlooks the day before Hurricane Harvey formed. In particular, the 18Z (1 PM CDT) outlook specifically mentioned that this system, "could produce storm surge and tropical storm or hurricane force winds along portions of the Texas coast and very heavy rainfall across portions of central and eastern Texas from Friday through the weekend."

3.1.3.1. NHC Track and Intensity Forecasts

NHC track forecasts for Hurricane Harvey were consistent and accurate, pinpointing landfall north of Corpus Christi more than 48 hours in advance. Potential impacts (i.e., storm surge, wind, rainfall) were mentioned in the Tropical Weather Outlook beginning about 72 hours before the arrival of tropical storm-force winds. This achievement was noted not only by the affected WFOs but also by local EMs and other partners. The storm's slowdown over southeast Texas and adjacent waters, which resulted in the epic rainfall event, was also well predicted. Unfortunately, Hurricane Harvey's intensity forecast was far more challenging, as NHC initially did not expect it to rapidly intensify into the strongest storm to hit the United States in more than 10 years.

Signs of intensification were well underway on Thursday, August 24, and by late that day NHC had updated the hurricane and storm surge warnings several times to alert that the storm was likely to stall once it made landfall. By that morning, NHC headlines had included words such as "*life-threatening storm surge and freshwater flooding expected.*"

The actual intensity of Hurricane Harvey increased 30 knots in 24 hours and 65 knots over 48-hours. The wind speed probability products did show a small chance of hurricane-force winds at individual locations along the Texas coast, starting with the first advisory after regeneration. While some WFO IDSS messaging informally included the possibility of intensification, some local partners emphasized the adverse impact the delayed official forecast of higher wind speeds and surge had on their preparations.

Model guidance did not explicitly forecast Harvey to reach hurricane strength before landfall. However, NHC did explicitly mention that possibility. NHC stated the expectation that Harvey would become a hurricane before landfall in Advisory 12, the first advisory issued when Harvey reformed in the Gulf (10 AM CDT 23 August - 60 hours prior to landfall). The 48-hour intensity forecast was for 60 knots and the Tropical Cyclone Discussion stated "Although not explicitly forecast below, we are anticipating Harvey being a hurricane at landfall after the 48-hour forecast point." The issuance of a Hurricane Watch also explicitly stated the possibility of Harvey reaching hurricane strength before landfall. Additionally, NHC wind speed probability product showed a 5-10 percent chance of hurricane force winds occurring at individual locations along the middle Texas coast in Advisory 12 (Public Advisory and Discussion products) (**Figure 23**).

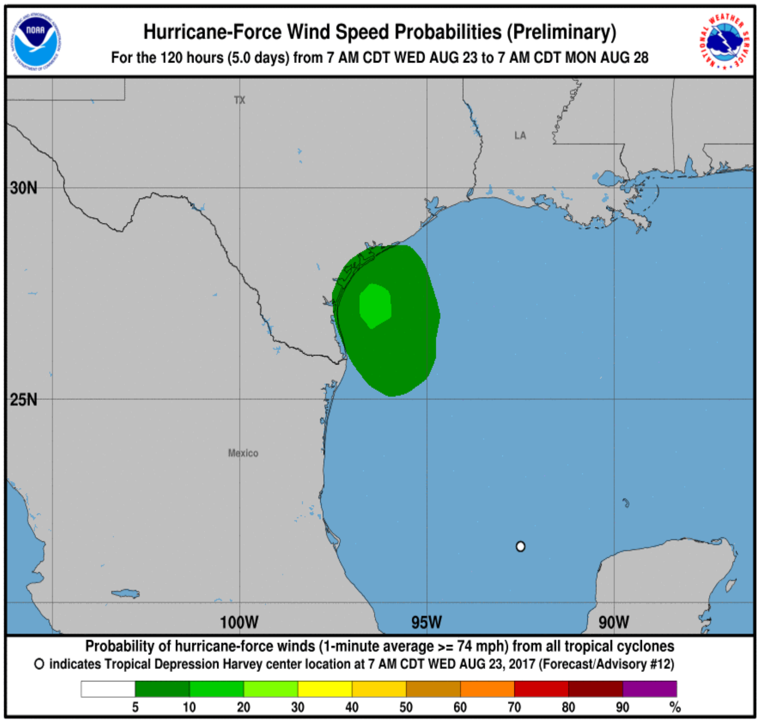

Figure 23: Cumulative probability of sustained hurricane force (64 knot) winds occurring at any individual location during the 120-h period ending at 7 AM CDT Monday, August 28, 2017, from Harvey Advisory 12. *Source: NHC*

In Advisory 14, (10 PM CDT 23 August - 48 h prior to landfall) NHC explicitly forecast Harvey to reach hurricane strength at landfall.

In Advisory 16 (10 AM CDT 24 August - 36 h prior to landfall) NHC forecast Harvey to be a major hurricane at landfall.

In Advisory 18 (issued at 4 PM CDT 24 August - 30 h before landfall) NHC's 24-h intensity forecast was for 110 knots. Public Advisory 18 explicitly stated that Harvey was expected to become a major hurricane before landfall. After this time, NHC intensity forecasts showed Harvey reaching 105 or 110 knots before landfall.

Best Practice: NHC did explicitly mention the possibility and the expectation that Harvey *would* become a hurricane before landfall despite the fact that there was no model guidance explicitly supporting this.

3.1.3.2. NHC Storm Surge Watches and Warnings

Hurricane Harvey provided the first opportunity for the operational use of the NWS storm surge watch/warning products. NHC issued its first Storm Surge Watch product at 10 AM CDT on Wednesday, August 23, covering the area from Port Mansfield to High Island, TX. Predictions included possible storm surge inundations of 4 to 6 feet along the islands and into the bays, with slightly higher inundation in isolated locations. NHC also released a potential storm surge flood map with the initial Storm Surge Watch. The map depicted a reasonable worst-case scenario (i.e., a reasonable upper boundary) of the flooding of normally dry land at particular locations due to storm surge.

Forecast inundation values of 6 to 12 feet Above Ground Level in the region from the north entrance of the Padre Island National Seashore to Sargent were indicated in Advisory 18 (30 h before landfall). These inundation values remained constant until Advisory 22 (4 PM CDT 25 August - 6 h prior to landfall) when the area from Port Aransas to Port O’Connor was specified with a forecast of 9 to 13 feet of inundation. **Figure 24** shows the first Storm Surge Watch issued from Port Mansfield to High Island, highlighted in pink on the right graphic.

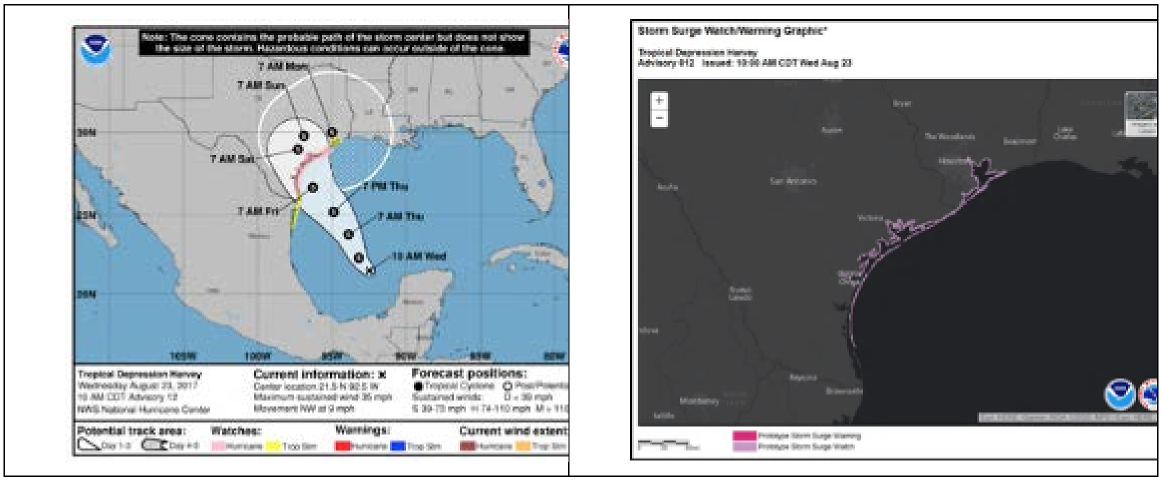

Figure 24: NHC products issued at 10 a.m., Wednesday, August 23. *Source: NHC*

NHC issues a potential storm surge flooding map whenever a storm surge watch or warning or a hurricane watch or warning is in effect for any portion of the Gulf of Mexico or Atlantic Ocean coasts of the continental United States. Product descriptions note that after NHC issues a storm surge watch or warning, there is a 60 to 90 minute delay in the corresponding potential storm surge flood maps.

The storm surge watch/warning text products list forecast water levels above normally dry areas near the coast if the peak surge occurs at high tide. The graphical potential storm surge map is an online map with detailed forecast total-water-level information. The depths shown on the maps represent total water levels (10% chance of being exceeded).

Several WFOs noted inconsistencies between the potential storm surge maps and statements. Some locations exhibited a 2 to 4 foot difference between the map and statement. In addition to site-specific differences, the WFOs often observed that the manual values in the NWS text products were higher than the potential storm surge inundation graphic. This caused confusion among several EMs.

There is a need for continuing collaboration between NHC and WFOs to maximize consistency and enable WFOs to spend more time on IDSS. A successful collaboration example during Harvey was NHC taking the lead to prepare storm surge depth grids within GFE and sharing them within impacted WFOs via Intersite Coordination Grids, at the request for assistance from WFOs. Without this ability, WFOs ingest raw storm surge guidance, named Probabilistic Hurricane Storm Surge, and then manually edit grids within GFE to ensure consistency with nearby offices and NHC. Unfortunately, this process can prove time consuming and difficult, especially for forecasters not familiar with storm surge guidance, vertical datums, and the tropical suite of tools within GFE. Instead, NHC manually created storm surge grids based on their expertise and coordination with WFOs. This step ensured that WFOs initiated their procedures using a grid which was already coordinated thus eliminating the need for WFOs to manually adjust/edit storm surge grids. The process proved successful and WFOs asked NHC to continue producing grids during the entire event. This support helped improve consistency among products issued by NHC and WFOs. In addition, it allowed WFOs to spend more time working with their partners to interpret the tropical products.

3.1.3.3. Coordination and IDSS Activities

There was effective communication and coordination among NCEP Centers and between NCEP and the NWS field offices. For example, NHC and WPC coordinated on the catastrophic flooding messaging. WPC and the NWC collaborated on IDSS to the TDEM. NHC coordinated with SRH on key messages much earlier in the process than it did during past events.

In addition to the standard coordination with WPC and the affected WFOs, NHC began IDSS coordination with SRH and the SR ROC on the morning of August 23. On the following day, NHC also contacted the Chief of the TDEM to give him advanced notice on the transition from tropical storm to major hurricane.

While certainly not a new problem, many NWS partners interviewed in conjunction with Hurricane Harvey noted that the 48-hour window for the products does not provide sufficient lead time to incorporate the products into their evacuation planning. In large population areas with complex transportation systems and other services, many EM decisions typically are made earlier than 48 hours before the onset of tropical storm force winds.

Finding 9: Many NWS partners would like to have probabilistic forecast information, especially rainfall, in advance of the watch and warnings to make evacuation decisions.

Recommendation 9: The NWS should provide forecast information, ideally more probabilistic products containing forecast confidence information (e.g., low, medium, high confidence), to partners at least three days prior to an event to aid with partner evacuation decisions, at the local level.

Prior to landfall, a WFO New Orleans forecaster was deployed to NHC as an IDSS coordinator, providing needed connectivity among impacted WFOs and NHC (consistent with Hurricane Matthew Service Assessment Recommendation #8). One of many roles this coordinator fulfilled was to organize a call with the Texas-area WFOs prior to NHC's forecast upgrade to major hurricane intensity. This call was instrumental in helping local WFOs consider the messaging changes needed when shifting from a Category 1 to Category 3 storm. This coordinator helped facilitate solid collaboration between NHC and local WFOs on storm surge warnings and other watch/warning issues. Unfortunately, this single coordination point of contact occasionally became overwhelmed by the large workload.

Best Practice: A WFO forecaster with substantial tropical and IDSS experience was deployed to NHC to serve as an IDSS coordinator. This position unambiguously benefited both NHC and the WFOs alike.

Finding 10: During complex high-impact events, the NWS inter-office IDSS coordination needs to be 24/7, requiring more than one person.

Recommendation 10: The NHC IDSS coordinator role should be clearly communicated to all parties involved and explicitly resourced to provide around-the-clock coverage during high-impact tropical events. (This reinforces Finding 8 of the October 2016 Hurricane Matthew Service Assessment, See Appendix C.)

3.1.4. Weather Prediction Center

WPC responded in an outstanding fashion in both forecasts and messaging of the unprecedented rainfall of Hurricane Harvey. The WPC began highlighting elevated rainfall totals along the Texas coast on August 19. On August 24, as Harvey was organizing in the Gulf of Mexico, WPC issued the first cumulative QPF forecasts for Hurricane Harvey, with maximum rainfall exceeding 20 inches (**Figure 25, left**). WPC, in collaboration with NHC, RFCs, and WFOs, increased amounts in the rainfall statement through time, culminating in forecasts of 50 inches (**Figure 26**).

The traditional 24-hour and multi-day QPF graphics are highly visible flagship products issued by WPC. Accessed via web pages, social media, and via IDSS briefing slides and email packages, these products were some of the most heavily referenced NWS products during Hurricane Harvey. The overall accuracy and value of the QPFs during Hurricane Harvey were quite good, particularly when placed in a historical context with tropical events of 10 to 20 years ago. This accuracy can be attributed to the increased quality of numerical weather model guidance both in terms of hurricane track and intensity forecasting and global/regional-scale modeling, the ongoing native skill of WPC forecasters, and the increased collaboration with WFOs as part of the integrated field structure.

Although QPF was generally accurate, it wasn’t perfect. Large-scale operational Numerical Weather Prediction models and WPC products had moderately over predicted precipitation totals along and inland of the central Texas coast. This included portions of the greater San Antonio-Austin I-35 urban corridor. This over prediction is likely related to assumptions made about the duration and trajectory of precipitation areas near the center of the land-falling tropical cyclone.

Farther east and northeast, the intense rainfall totals observed along the upper Texas coast, east central Texas, and southwest Louisiana were considerably underrepresented by WPC forecasts and numerical model guidance, particularly during the early phases of the event. This dry bias remained evident in the 120-hour QPF product issued on the morning of August 26 (**Figure 25, right**). In general, the QPF centroid is displaced approximately 110 miles southwest of the center of heaviest rainfall, resulting in a considerable under prediction of precipitation amounts in the corridor between WFOs Houston and Lake Charles.

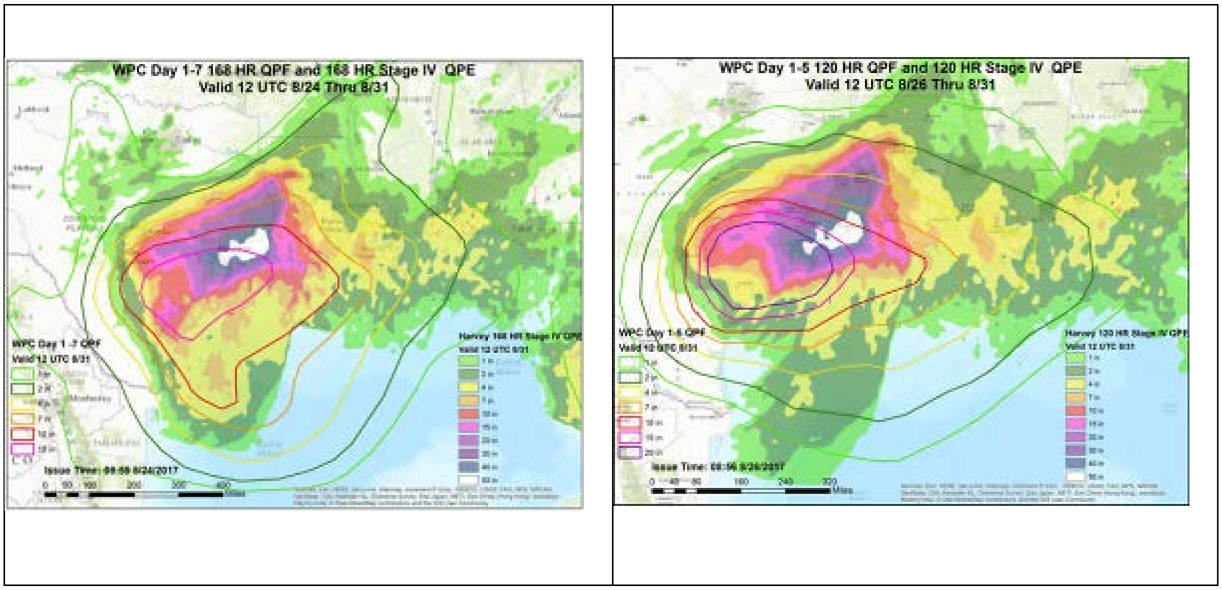

Figure 25: WPC 168-HR and 120-HR QPF contours and QPE color shadings. Source: WPC

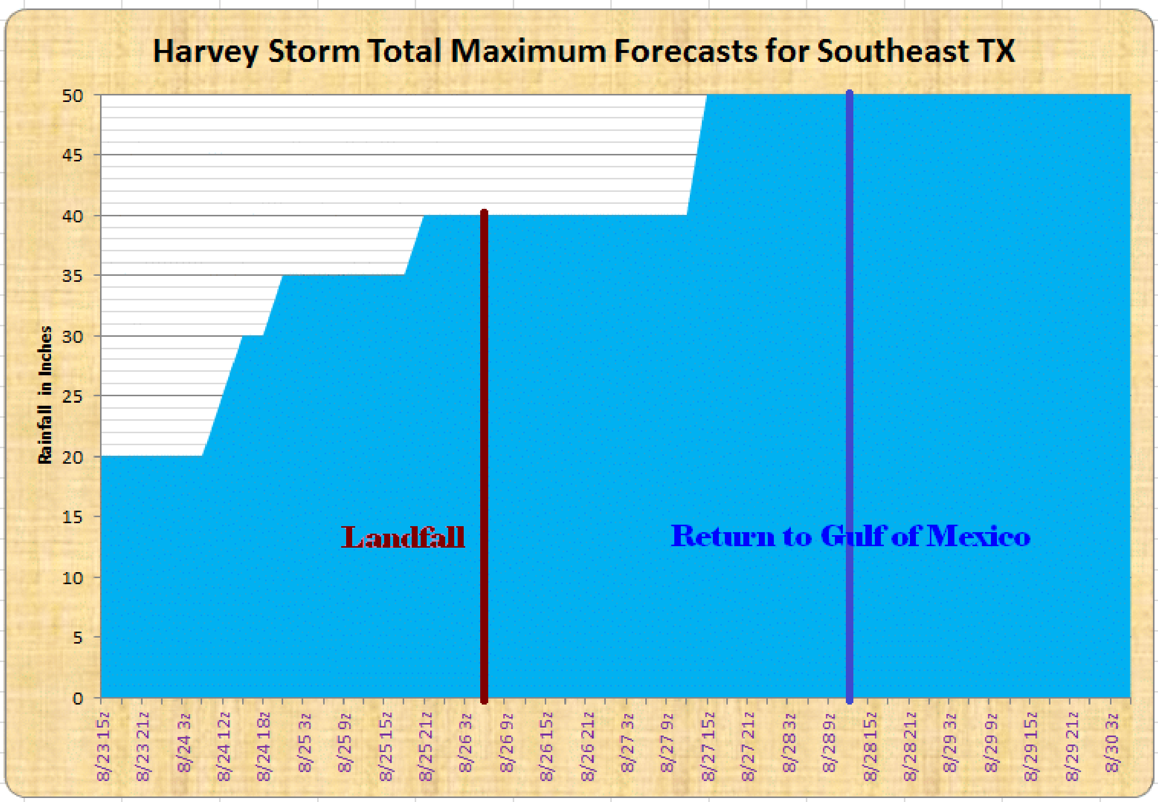

Figure 26: Evolution of Hurricane Harvey storm total maximum rainfall forecast appearing in public advisories. Source: WPC

During Hurricane Harvey, WPC designated daily IDSS shifts, which allowed a forecaster to focus on communication with partners. WPC stated that additional collaboration takes time away from forecasting and affects the timeliness of products. WPC does not have a WCM, unlike other NCEP Centers including AWC, NHC, and the Storm Prediction Center. This service assessment team re-emphasizes the need for WPC to have a WCM as noted in

Recommendation 12b from the October 2016 Hurricane Matthew assessment and Recommendation 7 from the August 2011 Hurricane Irene Service assessment (See Appendix C). The WCM would coordinate messaging during extreme weather events resulting in more effective briefings to NWS partners, similar to the Tweet cited to be extremely helpful by the media: “The breadth and intensity of this rainfall are beyond anything experienced before. Catastrophic flooding is now underway and expected to continue for days.”

During Hurricane Harvey, NHC distributed the tropical cyclone public advisory product. Once the system downgraded to a tropical depression, NHC handed off this product to WPC. WPC then added storm summaries to the product. WPC suggested it would be better to keep the two products separate for consistency since NHC does not include storm summaries in its tropical cyclone public advisory product.

Finding 11: NHC and WPC effectively transitioned the tropical cyclone public advisory product; however, it was a stand-alone product at NHC and became a combined product with storm summaries at WPC.

Recommendation 11: WPC should keep the tropical cyclone public advisory and storm summaries as separate products.

Excessive Rainfall Outlooks: The WPC issued an Excessive Rainfall Outlook which mentioned a Slight Risk in its Day 3 outlook on Tuesday afternoon, August 22. The excessive rain outlooks from August 22 through September 2 depicted elevated flash flood threat levels in association with Hurricane Harvey and its remnant circulation. Each Day 1 graphic showed “High Risk” from August 24 to August 31, when rainfall impacts over Texas and Louisiana were the most significant.

Figure 27 depicts a sequence of Day 1, Day 2, and Day 3 forecast graphics and observed analyses during the peak period of Harvey’s flooding. Similar to the spatial error trends observed with the QPF products, a subtle bias toward higher risk categories exists across the Central Texas coast through much of the event. Despite this trend, the outlooks are qualitatively very good. High risk outlooks are drawn over most of the area’s most heavily affected by devastating flooding. WFOs in the affected areas, particularly WFO Lake Charles, stated that these graphics were quite useful in conveying NWS’s overall confidence in the magnitude of the flash flooding threats. Excessive rain outlook graphics were included in many of the IDSS briefing packages distributed by the WFOs to their local partners.

In an unprecedented move, WPC depicted a High Risk in its Day 3 Excessive Rain Outlook issued Friday afternoon, August 25, valid for the period 12 UTC August 27 to 12 UTC August 28. This High Risk encompassed much of the greater Houston metropolitan area, where catastrophic flooding indeed occurred on August 27.

Best Practice: WFOs incorporated excessive rain outlooks in their IDSS briefings to better convey NWS confidence in flood threats.

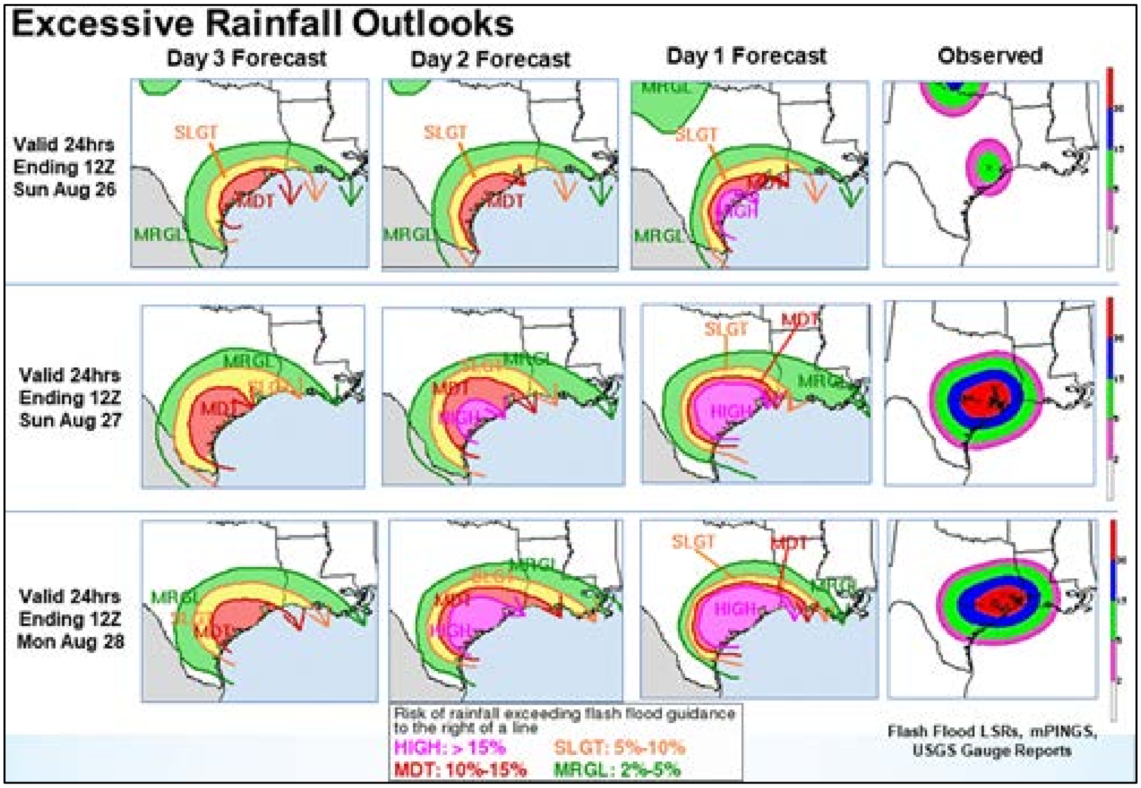

Figure 27: Excessive Rain Outlook Day 1, Day 2, Day 3 forecasts and observed. Source: WPC

Mesoscale Precipitation Discussions: The mesoscale precipitation discussion was a third key precipitation-related product WPC issued during Hurricane Harvey. The mesoscale precipitation discussion is ideally issued 1 to 6 hours prior to the onset of flash flooding, and consists of both a graphic depicting an area of concern and a discussion of pertinent mesoscale meteorological features supporting the heavy rainfall.

WPC issued a total of 45 Hurricane Harvey-related mesoscale precipitation discussions between August 25 and September 1. WPC issued 28 mesoscale precipitation discussions from August 26 to 30 for the Houston area alone. **Figure 28** is a portion of the discussion from Mesoscale Precipitation Discussion #738, issued at 545 PM CDT on Saturday, August 26, a few hours prior to the highest impact flash flooding in the Houston metropolitan area.

> THERE IS A STRONG HIGH RESOLUTION MODEL SIGNAL FOR LOCAL 3.0 TO 5.00+ INCH RAINFALL AMOUNTS THROUGH 0130Z OVER PORTIONS OR THE MIDDLE AND UPPER TX COAST (LED BY THE MOST RECENT HRRR...WHICH SHOWED 6.00+ INCH AMOUNTS IN BANDING BOTH WEST AND EAST OF THE HOUSTON METRO AREA). THE HIGHEST RAINFALL AMOUNTS ARE EXPECTED WHERE THE BANDING PERSISTS...AND WILL PRODUCE SIGNIFICANT FLASH FLOODING INTO THE EVENING HOURS.

Figure 28: Sample mesoscale precipitation discussion. *Source: WPC*

Recent years have seen the proliferation of high-resolution modeling, improvement of global models, and development of bias-corrected QPF sources, quickly advancing meteorology.

Meteorologists are aware of this change, especially those at WPC, who specialize in predicting hazardous rain events. In particular, when the weather system in question is larger in scale, slow-moving, and depicted consistently from one model cycle to the next such, as with Hurricane Harvey, confidence in the precipitation forecast may be much higher than usual. In the case of Hurricane Harvey, it is encouraging that this interplay worked to produce a coordinated message of catastrophic and life-threatening flooding with extensive lead time, including 72-hours of QPF in river forecasts just prior to landfall.

The WPC also had established a strong partnership with SR forecast offices, a result of an increased frequency of large-scale flood events since 2014. In 2017, SR instilled a policy test requiring WFOs to use the WPC QPF as a starting point for forecast collaboration. The frequent practice by SR WFOs and WPC to discuss the QPF and excessive rainfall outlooks during conference calls has bolstered this relationship. WPC and NHC have strengthened their bonds, as have WPC and the WGRFC.

Best Practice: With frequent practice and exchange in working across forecast service domains, WPC, WFOs, and RFCs were ready and able to provide consistent message and service on QPF.

WPC played a leading role in Hurricane Harvey, even more so than for other major events, given the main hazard was prolific rainfall and related flooding. For decades, WPC has honed expertise in rainfall prediction via partnership with RFCs, WFOs, the Hydrometeorological Testbed and academia. WPC's path into the integrated field structure has been a laborious one of building relationships, increasing exposure via numerous forecaster exchange visits and workshops hosted, and operationally proving its value repeatedly by example. However, WPC forecasters continue to struggle with an organizational framework that gives their expertise footing only as trusted advisors, with no real authority over the official forecast, except to make persuasive arguments.

Finding 12: No single office has authority over the official QPF forecast, which can lead to confusion through the NWS field offices and with partners.

Recommendation 12: NWS should explore designating a single authoritative source for QPF.

Environmental Modeling Center: About one week prior to Hurricane Harvey's landfall, global ensemble models indicated uncertainty about whether the initial remnants of Hurricane Harvey would redevelop after crossing the Yucatan Peninsula and make landfall in Mexico or the United States. After an imminent Texas landfall became clear, global and regional guidance signaled the potential for significant rainfall amounts in southeast Texas. EMC provided the model guidance and warning for a catastrophic event a few days before the event, so it was not a surprise for the National Centers and WFOs. The EMC Modeling Evaluation Group conducted a rapid assessment and coordinated effective communication between EMC model developers and model users throughout the NWS and the meteorological community. Through this group, in recent years, lines of communication have been opened between EMC and the National Centers, the NWS regional and local offices, and other partners to alert them of model biases and issues and to provide a forum for model users to report problems they have seen in EMC forecast systems.

Ocean Prediction Center: The OPC serves as the primary storm surge service backup center for NHC. During the 2017 hurricane season, technical configurations had changed which would have prevented backup procedures from working correctly during Hurricane Harvey, despite OPC's testing prior to the season. These technical configuration changes included a lack of monitoring for failed processes on the NCEP Compute Farm ArcGIS virtual machine and regular baseline software updates to the WPC AWIPS system High Performance Computing Network, which conflicted with the pre-established storm surge software configuration. In addition, updates to this AWIPS network shapefiles are still needed since that configuration is diverging from the supported, baseline AWIPS software.

Finding 13: Late delivery of the AWIPS software with the baseline storm surge capabilities for National Centers and limited storm surge program resources prevented the NHC Storm Surge Unit and OPC from effectively synchronizing technical configurations and operational procedures to allow OPC to backup storm surge service.

Recommendation 13: Storm surge training and drills must be resourced, scheduled, and held at least annually between the NHC Storm Surge Unit and OPC forecasters and development staff to ensure they can successfully execute end-to-end service backup.

3.1.5. Southern Region Headquarters and Regional Operations Center

While SRH, to varying degrees, has employed an Incident Command System (ICS) approach to high-impact events since 2011, Hurricane Harvey was the first event where ICS was used comprehensively. All divisions of SRH, including the Administrative Management Division and Systems Operations Division, suspended many of their routine functions and became fully integrated into this ICS structure. Twice daily operations plans were disseminated to all SR field offices, providing key information on SRH and affected office activities. SRH uses a multi-tiered tasking structure in its ROC, in which all staff members can be assigned duties according to their abilities as the scale of potential impacts increases. Due to the amount of remote IDSS deployments and ROC shifts needing coverage, many employees in the SR Operational Services Division (OSD) and Science and Technological Services Division worked operational shifts in the ROC. The incoming field ROC Duty Officer and two previous Duty Officers also provided valuable assistance during the event.

Best Practice: SRH fully used the ICS structure during Hurricane Harvey. This structure helped staff identify and execute key support objectives, ensured that regional resources were properly committed, and facilitated the communication of information to the field offices.

SR has a long history of providing IDSS to Texas state officials during high-impact events. ROC support to TDEM and the SOC in Austin was strong during Hurricane Harvey. The ROC began twice daily, webinar-based briefings to TDEM and other state agencies on Monday, August 21, five days prior to landfall. ROC staff began special briefings to TDEM senior leadership on Tuesday, August 22, and coordinated deployments of NWS personnel to Austin that afternoon. The ROC initially deployed one SRH meteorologist and a hydrologist from WGRFC two days prior to landfall. This two-person IDSS cadre was quickly augmented to four NWS personnel (two meteorologists, and two hydrologists) to provide round-the-clock decision support to TDEM leadership and the rest of the SOC staff through the bulk of the event.

Best Practice: SRH augmented IDSS support staff at TDEM.

Providing IDSS support while deployed requires a deep understanding of the current forecast and the ability to answer questions about the hydrologic forecast model. The WGRFC Senior Hydrologist did not have access to the Community Hydrologic Prediction System (CHPS) forecast system because he was outside of the WGRFC forecast office and not on the AWIPS network. Instead, he relied heavily on phone calls and NWSChat with the WGRFC operations floor, various external resources, and his own knowledge of forecast operations to answer questions about forecast uncertainty.

Finding 14: Deployed hydrologists have limited tools available to answer questions related to forecast uncertainty and sensitivity to forecast precipitation. As IDSS increases in scope and context, the ability to put the forecast modeling into the hands of the DSS advisors will become critical.

Recommendation 14: NWS must provide IDSS-deployed forecasters with the proper tools to answer questions related to the hydrologic forecast uncertainty and what-if conditions.

This IDSS was critically important to the SOC, but represented a large resource commitment. At the same time, FEMA Region VI also requested and received from the ROC on-site IDSS at its Regional Response Coordination Center in Denton, TX. Identifying experienced Texas-specific hydrologic expertise for rapid deployment to Austin is challenging when candidate personnel at WGRFC and the local WFOs are responding to the same impacts. The service assessment team re-enforces IDSS-related Recommendations 8 and 16 of the October 2016 Hurricane Matthew Service Assessment (See Appendix C).

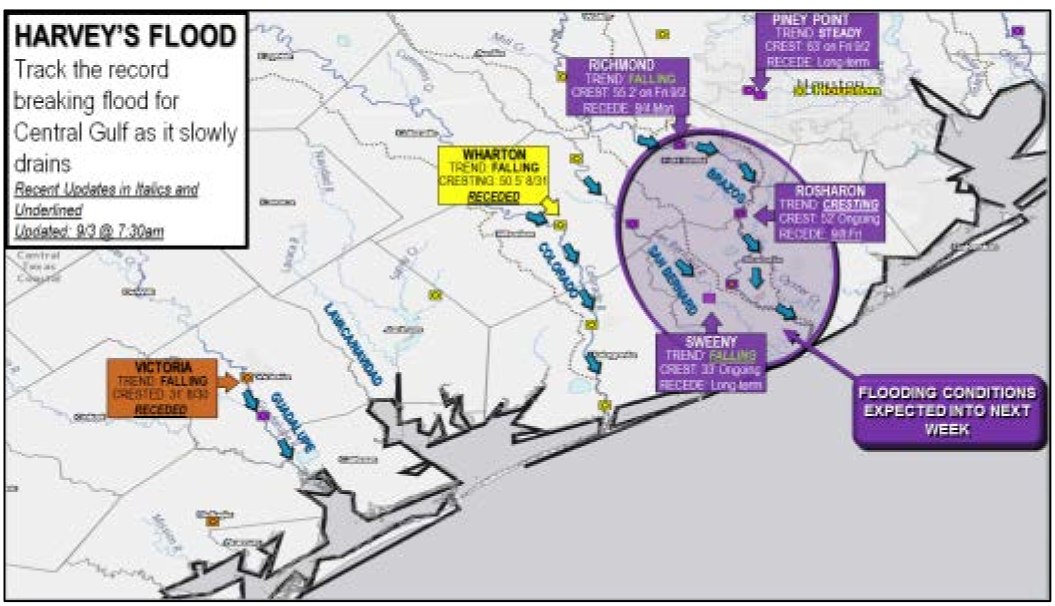

Figure 29: NWS briefing slide on river trends. *Source: NWS SRH*

One of the best ROC practices was developing a set of consistent regional briefing slide templates (**Figure 29**). Both the ROC and the local offices used these templates throughout Hurricane Harvey, saving time and increasing message consistency among IDSS providers.

Best Practice: The ROC developed a set of consistent regional IDSS briefing slide templates to promote a consistent message.

Flood inundation maps were available from a variety of public agencies during Hurricane Harvey, with at times upwards of four different inundation maps available for one particular location. The modeling and mapping methods varied between mapping products and was at times confusing and overwhelming for local stakeholders.

At a Public Assistance Boardroom briefing, FEMA, TDEM, and county EMs stated the Interagency Flood Risk Management (InFRM) flood inundation maps that had been provided to TDEM could also be used for storm damage assessments. The attendees commented that the InFRM maps were most representative of the timing, precision, and accuracy of the flooded neighborhoods. This information is crucial to determining FEMA damage estimates and reimbursement to the community for storm damages and debris removal.

The Chief of Water Resources from USACE Fort Worth District cited four important rules in making these maps, which could be used in near real-time and post disaster recovery.

1. Use WGRFC Forecast Flows and Stages
2. Match at forecast points (stage to stage)
3. Match inundation surfaces among existing maps: FEMA, AHPS, etc.
4. Ignore areas with 0–1 inch of inundation (Initially 25 percent of Houston was shown as inundated before the shallow areas were removed.)

WGRFC worked with the InFRM team to develop real-time flood forecast inundation mapping for Hurricane Harvey. This InFRM effort involved the USACE Fort Worth District, USACE Galveston District, engineering consultants, and a university partner to produce maps carefully coordinated with WGRFC and updated on a daily basis to reflect the current WGRFC crest forecasts. WGRFC also compared the maps to existing inundations maps (FEMA, AHPS), evaluated with local rating curves, and reviewed for consistency with other available data. These checks were critical to provide consistency with existing available information. The RFC provided 11 AHPS flood inundation maps to TDEM, where they were used for planning purposes prior to and during the event for the high-impact areas. TDEM commented on the value of having these mapping data available in GIS format.

The USACE-Fort Worth District has completed a draft report entitled ***Hurricane Harvey Flood Inundation Mapping – After Action Report*** lessons learned, which detailed major findings from the InFRM team.

Finding 15: Flood inundation maps were available from multiple government sources. Users were often confused about the differences between the available maps and did not have any clear guidance on which maps to use.

Recommendation 15: The NWS should work with national IWRSS Partners and local partnerships, such as InFRM, to understand the strengths and weaknesses of different available flood inundation maps and work towards providing best available information with guidance on its use.

3.1.6. Center Weather Service Units

CWSU Houston provided numerous briefings to FAA partners prior to Hurricane Harvey disrupting the National Airspace System. CWSU Houston forecasters provided daily briefing slides to FAA partners within the Houston airspace, but this increased to three briefings per day on August 22. To ensure a consistent message, CWSU forecasters used slides prepared by WFO Houston/Galveston and tailored those slides with additional aviation-related impacts and timing for FAA partners. These actions by the CWSU personnel reduced exposure for loss of life and property. Flight routes and flights started closing on August 22. FAA facilities staff avoided traveling in flooded areas based on river forecasts provided in briefings. Schedules for the facility staff were augmented so they would not travel when tropical storm winds or stronger were forecast. FAA radars were taken off their gears in advance of the arrival of Hurricane Harvey to mitigate damage.

Excessive rains in the Houston area on Saturday night, August 26, flooded the home of one CWSU employee, and road flooding prevented other CWSU staff from working, amplifying understaffing. One CWSU staff member slept in the office for two nights because he could not get home. One employee covered both shifts for several days with CWSU Fort Worth providing backup 2 hours per day from Sunday, August 27, through Wednesday, August 30. There are limited qualified options available to fill an absent CWSU position. The service assessment team reinforces Recommendation 8 of the Historic Nor'easter of January 2016 Service Assessment (See Appendix C).

During the recovery process after a natural disaster, employees from other NWS offices should be deployed by their NWS Region to the impacted office to temporarily relieve staff whose families were directly impacted by the disaster. The service assessment team reinforces Finding 16 of the October 2016 Hurricane Matthew Service Assessment (See Appendix C).

3.1.7. Office of Water Prediction

As was stated earlier, the TDEM Director contacted the NWS Director and requested that OWP assume an operational posture and provide real-time flood forecast inundation mapping information and other NWM-based guidance. This occurred on the morning of Sunday, August 27. Absent personnel to staff the NWC Operations Center, the OWP is focused primarily on research and development and research to operations activities. To respond to this request, the OWP mobilized personnel at the NWC and worked to begin transmitting the requested products. The NWM-based guidance products included "worst case forecast inundation maps," for the next five-day period using the Medium Range GFS-forced NWM and again using the Short Range HRRR-forced NWM. In conjunction with other information provided by the WGRFC and the USACE, these NWM-based guidance products were used by TDEM to position evacuation areas, to stage resources, and to ensure that relief activities were located safely outside of the areas of likely flooding. **Figure 30** provides a sample of these NWM-based Experimental Flood Inundation Maps.

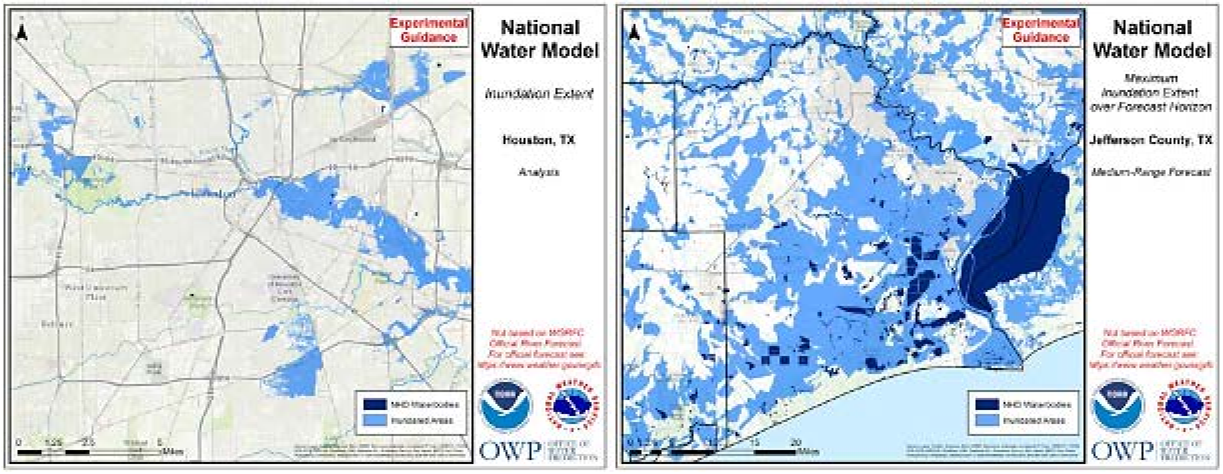

Figure 30: NWM-based experimental flood inundation maps. *Source: OWP Geo-Intelligence*

OWP also provided additional guidance (**Figure 31**) that contributed to an understanding of the flood severity and communication of extreme flooding across the Texas-Louisiana region.

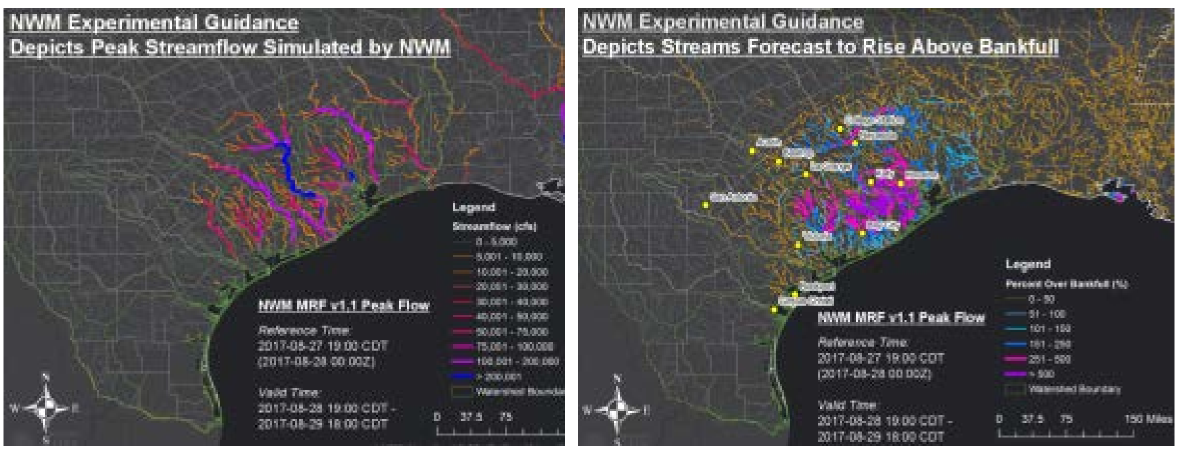

Figure 31: NWM experimental guidance. *Source: OWP Geo-Intelligence Division*

The NWM expanded hydrologic guidance (experimental) to a large number of stream reaches (2.7 million), providing river discharge information at these locations. The model provides analyses and forecasts for a full suite of water budget variables and its channel routing scheme produces discharge/river flows. Although these river flows can be converted to stage using post-processing techniques such as the application of synthetic rating tables, WFOs and core partners consistently commented that forecast river stage should also be provided with the output.

Finding 16: The current version of the NWM provides river discharge information, but users also need river stage information.

Recommendation 16: The OWP should include stage and discharge information in its NWM output.

3.2. Fully Integrated Field Structure

NOAA's performance during Hurricane Harvey demonstrated NWS's ability to adapt, exercise NOAA's capability, and stretch the organization's capacity to leverage a Fully Integrated Field Structure (FIFS). The Operations and Workforce Analysis (OWA) recommended FIFS to make more efficient use of existing resources and increase focus on IDSS before, during, and after extreme weather, water, and short-term climate events.

NOAA and NWS management recognized the increased need for national, regional, and local offices to support each other as Hurricane Harvey developed, evolved, and transformed. With multiple offices spread across different scales, scope, and areas of expertise, NOAA and NWS worked collaboratively to deliver better forecasts, services, and IDSS. This effort culminated in the provision of consistent key messages highlighting main talking points and projected impacts to core partners. The success in IDSS before, during, and after the Hurricane Harvey event was built upon good internal communication, collaboration, and coordination.

Best Practice: Coordination on the forecast and messaging among NCEP, regional headquarters offices, RFCs, and WFOs resulted in consistent messaging.

3.2.1. Core Partners and Deep Relationships

Core partners trust in the NWS, as well as the people behind the forecast and services. They had a solid understanding of the severity and potential impacts due to Hurricane Harvey's rainfall, storm surge, and wind, not only based on the written and verbal messaging from NWS, but also from the increasing tone and inflection of the NWS meteorologists and hydrologists as the storm was ramping up.

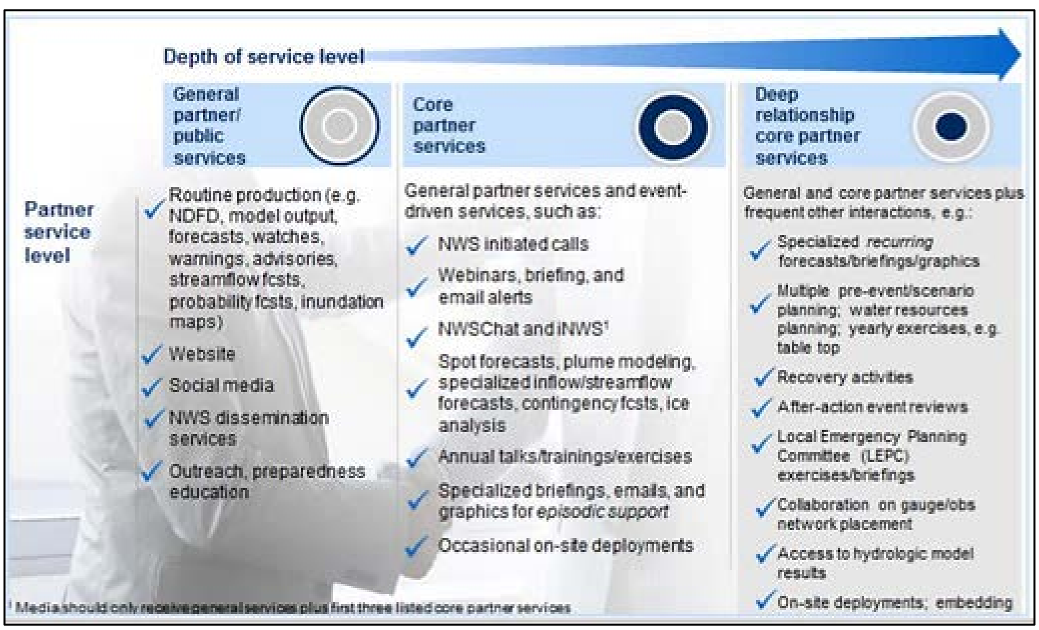

Figure 32: IDSS partnered level of services. *Source: OWA Catalogue*

When there was a need for more information, core partners found the NWS field offices accessible 24x7. When EMs needed higher resolution on the forecast warning, timing, and specificity of impacts, NWS forecasters were able to relay the information, relate to the EM impacts, and provide relevant actionable intelligence. This was accomplished by the NWS forecasters adhering to the IDSS partnered level of services (**Figure 32**).

The core partners commended the NWS for improvements in weather forecasting (extended forecasts, better storm tracking, forecasting impacts to life and property), as well as improvements to the provision of more quantifiable and verifiable information available in real-time as a result of Geostationary Satellite (GOES)-16 satellite observations.

GOES-16 helped users to visualize Hurricane Harvey's intensification, quickly pinpoint its track, and witness the intense bands of rainfall in near real-time (**Figure 33**). Technological innovation can help unlock time and reshape the Collaborative Forecast Process (CFP), described in the next section.

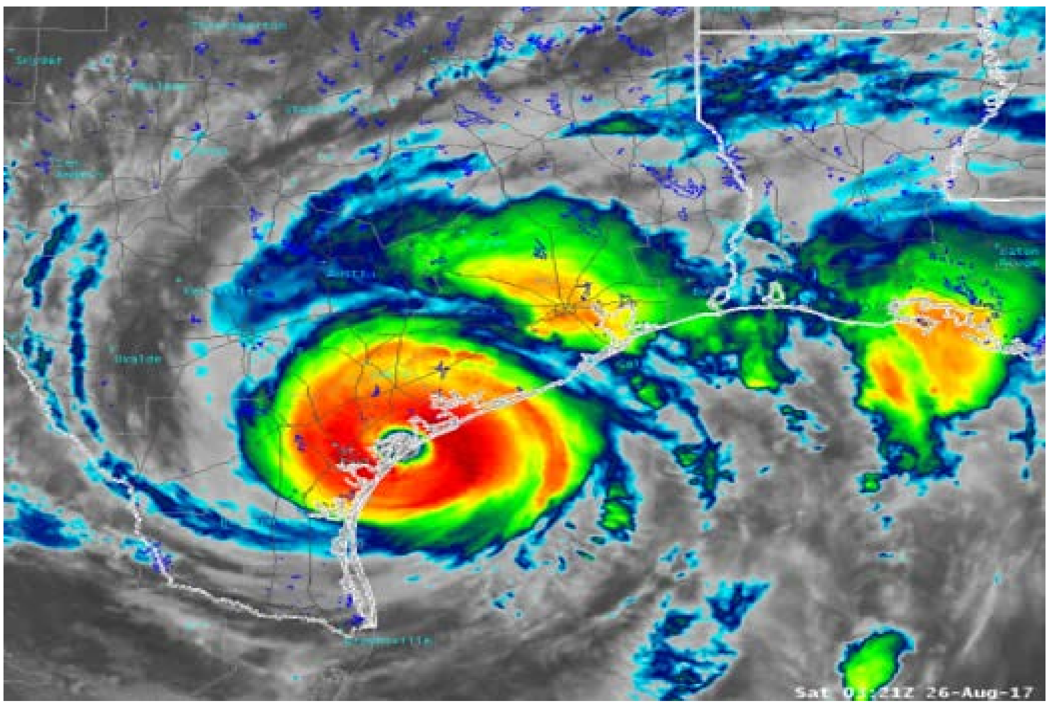

Figure 33: GOES 16 infrared satellite of Hurricane Harvey. *Source: NESDIS and WFO Houston*

3.2.2. Collaborative Forecast Process

The NWS field offices demonstrated their effectiveness as the top of the pyramid in the CFP (**Figure 34**) for IDSS. Together the NWS field offices helped build a Weather-Ready Nation during Hurricane Harvey. This event showed that many of the fundamental components from National Centers were able to effectively support a major event such as Hurricane Harvey.

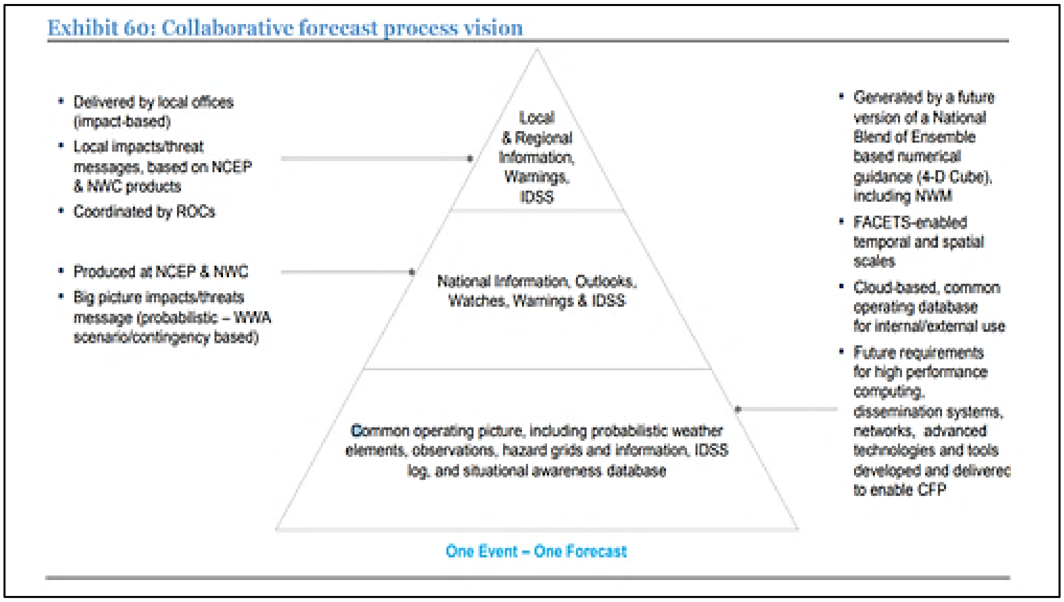

Figure 34: Vision of the Collaborative Forecast Process. *Source: OWA Catalogue, September 2017*

An in-depth analysis into the QPF collaboration process provided more insight into the potential success of OWA's CFP vision from forecast product, impact analysis, to service delivery. As noticed by the service assessment team, initial efforts on QPF collaboration calls to set the verbiage used for messaging (e.g., "catastrophic," "life threatening") were effective and should be considered a best practice for extreme events that cover a large geographical area served by multiple WFOs. WPC coordination calls every 6 hours were unprecedented and WFOs and RFCs indicated they wanted to continue the calls when polled by ROC staff. The NWSH Communications Division appreciated the efforts to coordinate messaging and terminology on early calls in order to present a consistent message across all WFOs and platforms.

In addition, collaboration with NHC was much improved with this event. NHC effectively offered pre-event collaboration when Hurricane Harvey regeneration was still just a possibility. This was the first event during which NHC took part in NWSChats beyond just its Storm Surge Unit. The consistent NHC briefing templates were valuable in providing a consistent look and feel of products between WFOs.

Best Practice: Coordinated terminology between WFOs in extreme events ensured consistent messaging of expected threats in briefings and on social media.

Based on the QPF collaboration for Hurricane Harvey, the assessment team believes that success can be gained with other NWS elements such as the National Blend of Models (**Figure 35**).

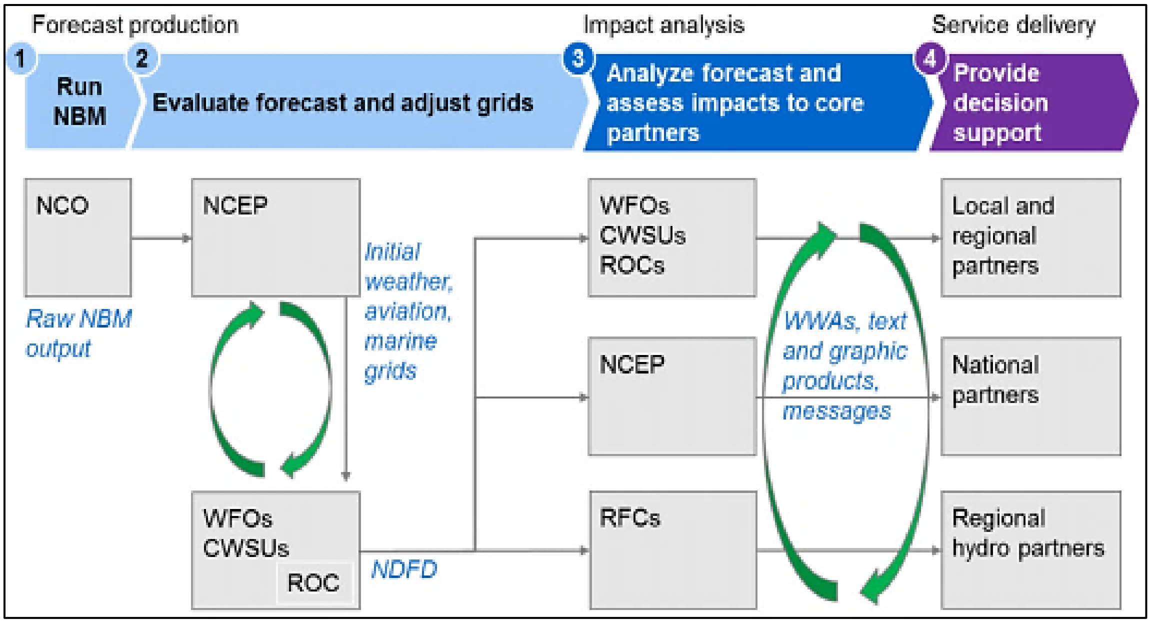

Figure 35: Sample of National Blend of Models in the Collaborative Forecast Process. *Source: OWA Catalogue, September 2017*

3.2.3. Impact-based Decision Support Nexus

The assessment team primarily examined the effectiveness of the collaboration and coordination among the following NWS entities:

- WFOs Austin/San Antonio, Corpus Christi, Houston, Lake Charles, New Orleans
- West Gulf and Lower Mississippi RFCs
- SR ROC
- National Centers for Environmental Prediction: EMC, NHC, and WPC
- NWC and NWC Operations Center
- CWSUs

With few exceptions, there was strong coordination on consistent messaging. Recent emphasis on relationship building within the agency has paid off and was manifested in displays of trust leading to efficient processes and joint decision-making. Several best practices were identified that support a fully integrated field structure across the agency. This structure allowed for a more IDSS user-centric focus.

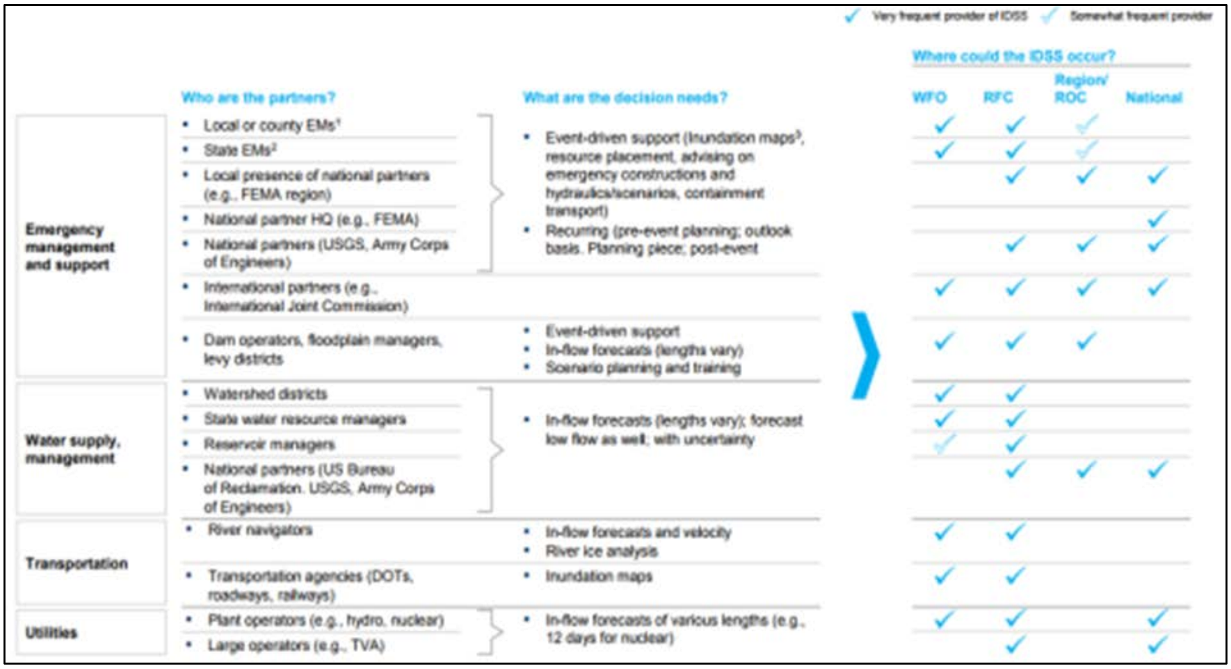

Figure 36: OWA suggested IDSS alignment for the NWS Water Program. *Source: OWA Catalogue, September 2017*

There is a need for consistent collaborative messaging across all service outlets. OWP experimental products simultaneously distributed to TDEM were inconsistent with key messages coming out from SR ROC, RFCs, and WFOs, leading to confusion within SR and among local EMs. Communication during inland flooding events that include clarity on the roles for all NWS organizational units was identified previously in the October 2016 Hurricane Matthew service assessment Recommendations 1 and 12a. The pathway of dissemination and coordination should consider OWA's suggested FIFS IDSS alignment for the NWS Water Program (**Figure 36**).

Finding 17: NWC products and services provided simultaneously to SR ROC, WGRFC, WPC and TDEM caused confusion with official forecasts. Resources were diverted from primary IDSS tasks to address these inconsistencies.

Recommendation 17: NWS should develop a plan for CFP and IDSS for flooding.

WFOs directly impacted by Hurricane Harvey instituted 12-hour staffing structures in advance of landfall, which is a standard practice at all coastal WFOs faced with an appreciable tropical threat, but some of the WGRFC staff exceeded the 12-hour workday. The FIFS concept was heavily embodied at the WFO level for IDSS during Hurricane Harvey, not only by the local WFOs directly affected by the storm's landfall but also by a number of other SR WFOs.

NHC, in particular the storm surge unit, experienced fatigue in issuing 24/7 support for all the storms and advisories given limited staffing (e.g., only one federal employee was in the storm surge unit).

In light of ongoing staffing limitations, and in keeping with the FIFS philosophy, the NWS must refine and enhance strategies for re-allocating tasks and resources between field units when high-impact events overtax the capabilities of individual WFOs or shift teams. Supplemental staffing with knowledgeable skills, background, and experience should be pre-coordinated prior to major events to help the NWS staff and to reduce the potential for burnout. In some cases, this kind of dynamic reallocation may need to occur between offices very quickly and intermittently, perhaps on the time scale of a few hours at a time.

3.3. Systems

The assessment team found WFO technical operations performed successfully throughout the event. There were, however, some hardware and software challenges that impacted the efficiency and effectiveness of WFO performance.

3.3.1. AWIPS Software

3.3.1.1. Graphical Forecast Editor (GFE) Software Challenges

Atlantic Basin offices with tropical cyclone wind watch/warning responsibility began issuing the WFO tropical cyclone local watch/warning product (WFO TCV) during the 2017 tropical season. The WFO TCV text product is a segmented Valid Time Event Code product with each segment a discrete forecast zone that contains land-based tropical cyclone wind and storm surge watches/warnings in effect, meteorological information, threats (i.e., wind, storm surge, flooding rain, tornadoes), and potential impacts. The product is generated from local gridded forecast information and national guidance via the AWIPS GFE and is not intended to be manually edited by the forecaster. This text product is intended for parsing by the weather enterprise and is paired with the WFO HLS to provide a complete, localized tropical forecast.

Fact: The WFO TCV is intended to be an automatically-generated product.

The TCV product requires 120 consecutive hours of *Wind* and *WindGust* grids, 102–114 hours of Wind Speed Probability grids, 72 consecutive QPF grids, and at least one grid of the following: *WindThreat*, *FloodingRainThreat*, or *TornadoThreat*, and for coastal sites one grid of *StormSurgeThreat* and *InundationMax*, and finally 12 plus grids of *InundationTiming*. If any of these grids are missing, it will result in merge conflict that then has to be resolved before a forecaster can continue. In addition, the *Wind* and *WindGust* grids must match the NHC forecast and be collaborated on with neighboring offices.

Harvey's slow movement impacted the *FloodingRainThreat* parameter, which is limited to 72 hours, resulting in an underestimation of the flood threat because the heavy rain window was actually well beyond 72 hours; therefore, manual edits were made to adjust up to "*extreme*" for several locations. Another issue reported related to the rapid intensification of Hurricane Harvey. The TCV product did not have sufficiently high wind speeds requiring forecasters to increase them, by hand editing, from Category 2 up to Category 4.

Finding 18: Several WFOs impacted by Hurricane Harvey reported issues with GFE and the creation of WFO TCV and HLS products, varying from ingest of the pre-TCV and difficulties merging the hazards, to the extra staffing required to check grids and then blend them into coherent product dataset. During forecast package update times, new GFE data related to the WFO TCV, specifically when merging the proposed *StormSurgeThreat*, would erase previous hazard grids. This resulted in wasted staff time recreating these grids from scratch, delaying product issuance.

Recommendation 18: The NWS should ensure that the tropical program has proper and robust software testing and evaluation before national implementation.

3.3.1.2. Flooded Locations and Simulated Hydrographics (FLASH)

WFOs reported that the FLASH project was a valuable tool for issuing flash flood warnings and supporting warning decisions associated with flash floods. As one hydrologist stated, "*This software was super and very valuable in helping us issue flash flood warnings.* [*Flash Flood Monitoring and Prediction] FFMP was helpful as well. We need to get this into the pipeline consistently.*"

Best Practice: WFO Lake Charles stated that having FLASH data in AWIPS was extremely useful because it allowed staff to quickly focus in on areas of greatest threat and upgrade flash flood warnings to flash flood emergencies, more quickly.

3.3.1.3. NCF Support for RFCs

WGRFC experienced a critical system error on the CHPS client, hosted on an AWIPS workstation that was used to produce river forecasts. Fortunately, this issue was isolated to a workstation and was not system-wide so it did not affect the other parts of WGRFC forecast system. WGRFC spent time with NCF to troubleshoot this CHPS problem. This effort should have been transferred to the CHPS operations support staff to more quickly address the issue.

Finding 19: NCF does not have resources to troubleshoot and quickly diagnose CHPS issues.

Recommendation 19: Office of Central Processing should instruct NCF to transfer CHPS issues to CHPS operations support staff.

3.3.2. Communications and Network

WFOs Houston and Corpus Christi held numerous briefings for state and local EMs and other partners leading up to and during the event. Due to the limitations on the number of lines available on the teleconference and webinars, forecasters had to hold duplicative briefings to ensure information was communicated to all essential partners. This limitation doubled the workload at a time when forecasters needed to perform other critical duties. Issues with a limited number of phone lines for WFO/partner briefings was identified as Finding 19 in the October 2016 Hurricane Matthew Service Assessment (See Appendix C). In addition, one EM recommended that the NWS add a video conference capability to traditional audio conference calls.

During the 2017 hurricane season, NHC and WFOs had to rely on communicating via the legacy hurricane hotline. The new hurricane hotline, which is scheduled to be operational in 2018, will allow NHC and the WFOs to share weather graphics information using Digital Video Teleconference Units. Having both voice and video capabilities allows more accurate weather data to reach key decision makers and enables them to make time-critical decisions. During this event, however, NWS had to depend on the legacy hurricane hotline and WFO Corpus Christi experienced issues with the system. WFO Corpus Christi forecasters could hear NHC but they were unable to speak through the hotline, so they had to call in on a separate phone line to communicate. They asked to use the new units but the system was still in beta testing.

Finding 20: WFO Corpus Christi reported that the hurricane hotline capability was not fully functional, inhibiting effective communication.

Recommendation 20: NWS should ensure the hurricane hotline, with the full voice and video capabilities, will be operational for high-impact events in time for the 2018 hurricane season.

WFO Lake Charles and other SR WFOs had significantly slow Internet speeds for several days. In particular, the NWS Enhanced Data Display (EDD) loaded slowly. WFOs experienced significant delays accessing the NWS web services and the desired layers supporting EDD, especially during high-impact events. Latency and reliability issues with NWS web pages was also an issue identified in Finding 20 of the Hurricane Matthew service assessment (See Appendix C).

Finding 21: WFOs reported delays in accessing the EDD, especially during high-impact events.

Recommendation 21: The web services provided by NWS need to be more robust and stable, especially during high-impact events.

CWSU Houston did not have access to AWIPS for nearly three weeks because its router failed. Due to flooding, shipping and communication companies could not get a replacement router delivered and installed at the office. Although this impeded the CWSU's ability to operate and provide decision support to FAA under normal conditions, the CWSU was able to rely on the FAA's Weather and Radar Processor system and web pages to monitor weather conditions.

Finding 22: Necessary backup computer hardware was unavailable at CWSU Houston. The office could not get timely replacements delivered due to local flooding conditions affecting air and highway transportation shipping networks**.**

Recommendation 22: The NWS should build more redundancy into its routers and other key communication devices to avoid a single point of failure**.**

3.3.2.1. Active Directory Login Challenges

Several forecasters dispatched to WFOs impacted by Hurricane Harvey commented it took an unacceptable amount of time to login to an office computer. Once the forecasters were able to login, they couldn't connect to a local drive. This problem occurred because the forecasters were not included in the WFO's directory list.

Finding 23: Dispatched forecasters were not included in the directory list of the affected WFO to which they were assigned.

Recommendation 23: NWS Regional IT staff should add dispatched individuals' active directory accounts from their home WFO to the impacted WFO before the forecasters arrive at the impacted WFOs. This change also includes temporarily removing any home office re-directs or roaming profiles these staff members may have.

3.4. Tropical Program Training

NWS core partners requested more internal NWS staff training and external partner training for new, expanding, and evolving products and services being introduced by NWS. If NWS staff is adequately trained, they can then effectively pass on this knowledge to partners who may want to integrate these new options into their decision making processes.

Best Practice: NHC offers the Effective Hurricane Messaging course, which is a collaborative effort by SR, ER, OCLO, the ROCs, and NHC, as a way to help WFO forecasters become deployable. This course also provides information to the external partners of the different products available and how to interpret them.

Best Practice: NHC offers training on preparedness and product use in various formats, including COMET modules, webinars, and in-person training.

Finding 24: NWS core partners would like to continue to expand their knowledge on the use and interpretation of the different tropical products. Also, WFOs are not fully aware of many of the basic training modules available to understand the fundamentals of the tropical products.

Recommendation 24: A comprehensive coordinated effort should exist between Regional Headquarters, WFOs, and NHC to expand awareness of training opportunities with the goal of understanding and interpreting different tropical products. Training should be prioritized and streamlined to maximize effectiveness of roles and responsibilities in tropical IDSS.

4. Public Engagement and Societal Impacts

The NWS provides life-saving information to the public. Past service assessments demonstrate how that information reaches NWS partners. This section details these findings for Hurricane Harvey, including references to relevant related findings from other service assessment reports.

One prominent issue in the provision of life-saving information includes the reality that certain populations remain underserved by NWS products. Cultural differences and language barriers added an additional layer of vulnerability in Hurricane Harvey-affected areas. As shown in **Figure 37**, a significant diversity of language, ethnicity and race exists in both Texas and Louisiana. Non-English speaking populations need to be considered when creating hazardous weather-related information, as well as relationships with racial and ethnic minority groups. The overwhelming majority of WFO staff and community partners in the Hurricane Harvey-affected region speak English as their first language. In Texas in 2016, 79 percent of the population was white and 12.6 percent was black. Across racial groups, approximately 39 percent of the population identified as ethnically Hispanic/Latino[1]. Approximately 35 percent of residents spoke a language other than English at home. In Louisiana in 2016, 63 percent of the population was white and 32.6 percent was black. About 5 percent of the population was Hispanic or Latino. Approximately 8.5 percent of the population spoke a language other than English at home.

Fact: There is significant racial, ethnic, and language diversity in Texas and Louisiana.

Finding 25: Community partners did not appear to represent the demographic diversity of area populations, potentially limiting audiences served by NWS.

Recommendation 25: WFO staff should continue to initiate new relationships with underserved populations and organizations to ensure a Weather-Ready Nation.

WFO staff members recounted difficulty broadening their networks beyond certain demographic groups. In particular, greater effort needs to be expended to provide consistent service to racial and ethnic minorities, as well as those whose first language is not English. EMs in Texas and Louisiana stated they provided all Hurricane Harvey communications in English, despite the large populations in the area that do not speak English as their first language.

[1]https://www.census.gov/mso/www/training/pdf/race-ethnicity-onepager.pdf U.S. Census Bureau considers race and ethnicity as two separate and distinct concepts.

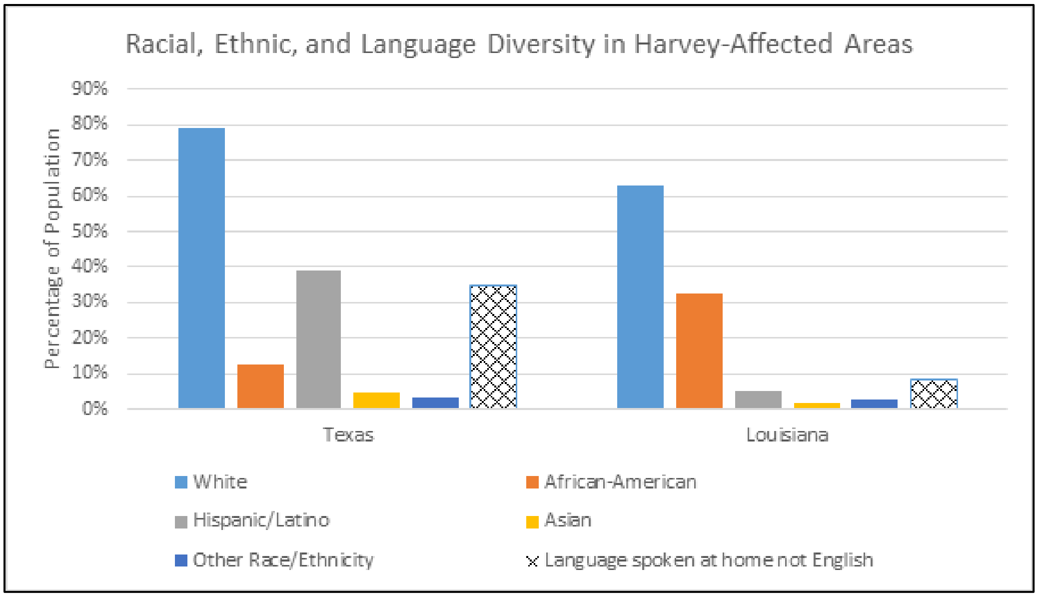

Figure 37: Diversity in Harvey affected states. *Source: U.S. Census Bureau, 2017*

Some best practices for Spanish-speaking populations were observed and critical for communicating information to the public before, during, and after Hurricane Harvey.

Best Practice: NHC provided Spanish-language media support in its media pool during Harvey. This effort was supplemented by staff from WFO Miami, which also provided support for numerous Spanish-language radio interviews during Harvey. WFO San Juan also provided Spanish versions of the tropical cyclone public advisory that were issued on AWIPS and available on the NHC website, and Spanish versions of the tropical cyclone discussion, which were available on the NHC website.

Best Practice: WFO Corpus Christi published its annual Hurricane Guide in Spanish and English. The office also provided printed copies for the past 10 years until funding ran out.

Best Practice: WFO Austin/San Antonio conducted Skype video interviews with CNN in Spanish as well as other interviews in Spanish.

Best Practice: Spanish assistance through the SR Multimedia Assistance in Spanish Team was available during Hurricane Harvey, helping translate flash flood emergencies and messages into Spanish.

In addition to NWS partner interviews, the assessment team conducted 28 structured interviews with the public to provide a basic assessment of the way forecast information was received, understood, and acted upon in preparation for and response to Hurricane Harvey. The sampling procedure targeted members of the public in areas that experienced the worst impacts — inland flooding due to extreme rainfall, river flooding due to poor drainage downstream, high concentrations of tornado warnings, high winds, and storm surge. The number of interviews in affected locations was necessarily small, and the results reported here are therefore not generalizable. Nonetheless, the sample provides insight into a range of experiences across the region.

A concentration of non-native English speakers lived in a mobile home park along a riverbed that experienced extensive inland flooding. One interviewee who lived in the park reported that residents there did not grasp the potential inundation impacts; they thought their homes were protected because they were raised up on blocks at a height sufficient to avoid adverse impacts of prior floods. Flood levels caused by the Hurricane Harvey event exceeded heights experienced in the area. During the mandatory evacuation, park residents left the majority of their belongings in their homes. Many of these people lost all of their belongings as a result. The interviewee believed language was a barrier to understanding the potential inundation impacts. The local population knew how high the river had risen before in feet, but did not realize the difference a few extra feet would make not only in height, but also in horizontal extent from the river and including the embankment where their homes were located.

Fact: The assessment team found some evidence that language was a barrier to effective response.

Almost all interviewees in areas of extreme rainfall reported being aware of the potential flood threat that Hurricane Harvey posed. Many individuals made protective decisions, but not always ahead of time. One Houston interviewee accidentally drove into unforeseen flood waters and required a water rescue. Another interviewee in the Houston area abandoned a car when he/she encountered surprise flood waters – the driver and passenger were out purchasing last-minute supplies when he/she heard how bad the event was going to be for Houston. During a drive from Austin, an individual had encountered heavy rain and localized flooding, when the driver had expected rain to begin the next day.

Fact: The rapid change in the exact position of the heaviest rainfall took some members of the public by surprise, putting them in dangerous driving situations, mainly due to flood waters on the road.

Almost all interviewees reported they had no intention to drive once they heard about the significant flood risk for their area, and most did not drive during the event. Once flooding began, many interviewees noted they continued to receive flood warnings, but at that point they could only shelter in place. Almost all interviewees reported knowing the "*Turn Around, Don't Drown*" slogan, and said that it was well-known in the area, in general, particularly with so many recent flood events. Approximately half of the interviewees heard that flooding in their area was expected to be record-breaking and/or worse than they had ever experienced. Only a minority of interviewees evacuated, but almost all interviewees prepared to stay in shelter by purchasing batteries (anticipating power loss), food, and water.

Fact: *Turn Around, Don't Drown* messaging has achieved widespread understanding in the Houston area.

Finding 26: A majority of those interviewed planned to avoid driving through flood waters, but some were hampered by a lack of understanding of the timing and extent of flooding. The rapid updating of forecasts exposed many people to unanticipated flood threats.

Recommendation 26: Flood forecasts that involve relatively large uncertainties should be delivered in ways that successfully convey the array of potential outcomes, not just the most likely outcome. This includes the communication of uncertainty for multiple forecast attributes such as timing, location, hazard severity, and hazard impacts.

Almost all interviewees reported that local TV was highly influential as a source of weather information during the event, followed by websites/social media, friends and family, local EM, and national TV broadcasts. Many people reported receiving Wireless Emergency Alerts (WEA), but did not rank them as highly influential in their decisions. For those who reported receiving WEAs, none reported turning them off. Some interviewees received numerous tornado warnings through WEA. These individuals noted they appreciated "*the heads up*." Interviewees did not shelter for each warning, but did remain vigilant about the threat. The team found no evidence of a false alarm problem in areas with the most tornado warnings.

Several individuals reported hearing the phrase "*bands of energy*" from local broadcast media, and they claimed this helped them understand the different/ephemeral nature of the hazard embedded in the hurricane's outer bands. A few people specifically noted that it is generally understood that hurricanes are so powerful they can produce tornadoes, and they were not surprised to receive many warnings for them. Interviewees also reported feeling an atmosphere that was conducive to tornadoes. This feeling also motivated them to respond to the threat. The area with the most tornado warnings experienced minor to moderate flooding, but all of those interviewed said they were able to shelter in place.

Fact: Given the extreme and unusual nature of the event, interviewees did not mind receiving a large volume of WEAs.

Interviewees in areas that experienced significant inland river flooding reported they became concerned several days before the event when they heard the threat of inland rainfall between Houston and Austin, but then relaxed their preparatory activities when they saw that they were not going to be in the rainfall bullseye. Most interviewees then took protective action only after they received mandatory evacuation orders enforced by officers going door-to-door. Interviewees reported a lack of understanding regarding how flooding was possible for their location.

Fact: Inland flooding caused by poor drainage was not as well-understood as river flooding in areas.

Appendix A: Acronyms

AHPS	Advanced Hydrologic Prediction System
ARTCCs	Air Route Traffic Control Centers
AWIPS	Advanced Weather Interactive Processing System
CFP	Collaborative Forecast Process
CHPS	Community Hydrologic Prediction System
CWSU	Center Weather Service Unit
DSS-WISE	Decision Support System for Water Infrastructure Security
EDD	Enhanced Data Display
EHM	Effective Hurricane Messaging
EM	Emergency Manager(s)/Emergency Management
EMC	Environmental Modeling Center
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FFW	Flash Flood Warnings
FIFS	Fully Integrated Field Structure
FLASH	Flooded Locations and Simulated Hydrographics
FY	Fiscal Year
GFE	Graphical Forecast Editor
GIS	Geographical Information System
GOES	Geostationary Satellite
HEFS	Hydrologic Ensemble Forecast Service
HLS	Hurricane Local Statement
HQ	Headquarters
ICS	Incident Command System
IDSS	Impact-based Decision Support Services
InFRM	Interagency Flood Risk Management
LMRFC	Lower Mississippi River Forecast Center
MHHW	Mean Higher High Water
NCEP	National Centers for Environmental Prediction
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NWC	National Water Center
NWM	National Water Model
NWS	National Weather Service
NWSH	National Weather Service Headquarters
OCOO	Office of Chief Operating Officer
OPC	Ocean Prediction Center
OSD	Southern Region Operational Services Division
OWA	Operations and Workforce Analysis
OWP	Office of Water Prediction
PQPF	Probabilistic Quantitative Precipitation Forecasts
QPF	Quantitative Precipitation Forecast
RFC	River Forecast Centers

ROC	Regional Operations Center
SH	Service Hydrologists
SOC	State Operations Center
SOO	Science and Operations Officer
SR	Southern Region
SRH	NWS Southern Region Headquarters
SST	Sea Surface Temperatures
TDEM	Texas Division of Emergency Management
TOR	Tornado Warnings
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTC	Coordinated Universal Time (same as Zulu "Z" Time)
WCM	Warning Coordination Meteorologists
WEA	Wireless Emergency Alerts
WFO	Weather Forecast Offices
WGRFC	West Gulf River Forecast Center
WPC	Weather Prediction Center

Appendix B: Findings, Recommendations and Best Practices

Definitions

Best Practice: An activity or procedure that has produced outstanding results during a particular situation that could be used to improve effectiveness and/or efficiency throughout the organization in similar situations. No action is required.

Finding: A statement that describes something important learned from the assessment for which an action may be necessary. Findings are numbered in ascending order and are associated with a specific recommendation or action.

Recommendation: A specific course of action, which should improve NWS operations and services, based on an associated finding. Not all recommendations may be achievable but they are important to document. Recommendations should be clear, specific, and measurable. The team leader and OCOO will compose an action item for each recommendation.

Findings and Recommendations

Finding 1: The EHM course has a strong direct benefit to the improved delivery of tropical weather IDSS.

Recommendation 1: The NWS should allocate training resources for additional EHM courses prior to each tropical weather season or seek creative alternatives for offering this training content to local WFO personnel.

Finding 2: The HLS and other GFE-driven local tropical products were not widely used by the media and other core partners during Hurricane Harvey.

Recommendation 2: Local offices, Regional Headquarters, and the NWS Tropical Program should determine whether partners' lack of use of local tropical products was peculiar to Hurricane Harvey or represents a broader condition affecting other coastal areas.

Finding 3: WFO staff members and their families incurred a financial burden as a result of limitations in NOAA evacuation pay policies. NOAA's evacuation policies were also inconsistent throughout the course of the season, impacting employee morale.

Recommendation 3: NWS CFO should work with NOAA to clarify, clearly communicate, and ensure a consistent application of the evacuation pay policies for employees and dependents before high-impact events.

Finding 4: Although the ensemble forecast hydrographs based on PQPF were found to be useful by WFO Houston and core partners, HEFS is the preferred NWS approach for producing reliable and skillful ensemble streamflow forecasts.

Recommendation 4: The NWS should continue to implement HEFS at additional river forecast locations.

Finding 5: The observed run-to-run inconsistencies during Hurricane Harvey created an extra workload for WGRFC and other field entities involved in the provision of IDSS to partners. Some partners expressed uncertainty about official NWS river forecasts, given their discrepancies with the NWM output.

Recommendation 5: RFC forecasts are the official source of river forecast information. All RFCs and OWP should work together to gain a better understanding of NWM strengths and weaknesses and should continue to communicate their model guidance needs while aligning messages for consistency.

Finding 6: WGRFC needed additional GIS resources to keep pace with the data demands imposed by Hurricane Harvey.

Recommendation 6: Additional GIS resources should be available to WFOs and RFCs for high-impact events.

Finding 7: In general, residents did not comprehend the impacts that more than 60 inches of rain would have in their communities. There were no existing products that could effectively communicate the impacts.

Recommendation 7: When the post-event Hurricane Harvey flood inundation maps are made available, the NWS should link to these historic flood maps on the appropriate NWS web pages.

Finding 8: The WGRFC staff had no experience with the NWM flood inundation maps and could not provide guidance or support for these products to core partners.

Recommendation 8: NWS should develop background documentation and training for staff on the use of the NWM-produced inundation maps.

Finding 9: Many NWS partners would like to have probabilistic forecast information, especially rainfall, in advance of the watch and warnings to make evacuation decisions.

Recommendation 9: The NWS should provide forecast information, ideally more probabilistic products containing forecast confidence information (e.g., low, medium, high confidence), to partners at least three days prior to an event to aid with partner evacuation decisions, at the local level.

Finding 10: During complex high-impact events, the NWS inter-office IDSS coordination needs to be 24/7, requiring more than one person.

Recommendation 10: The NHC IDSS coordinator role should be clearly communicated to all parties involved and explicitly resourced to provide around-the-clock coverage during high-impact tropical events. (This reinforces Finding 8 of the October 2016 Hurricane Matthew Service Assessment, See Appendix C.)

Finding 11: NHC and WPC effectively transitioned the tropical cyclone public advisory product; however, it was a stand-alone product at NHC and became a combined product with storm summaries at WPC.

Recommendation 11: WPC should keep the tropical cyclone public advisory and storm summaries as separate products.

Finding 12: No single office has authority over the official QPF forecast, which can lead to confusion through the NWS field offices and with partners.

Recommendation 12: NWS should explore designating a single authoritative source for QPF.

Finding 13: Late delivery of the AWIPS software with the baseline storm surge capabilities for National Centers and limited storm surge program resources prevented the NHC Storm Surge Unit and OPC from effectively synchronizing technical configurations and operational procedures to allow OPC to backup storm surge service.

Recommendation 13: Storm surge training and drills must be resourced, scheduled, and held at least annually between the NHC Storm Surge Unit and OPC forecasters and development staff to ensure they can successfully execute end-to-end service backup.

Finding 14: Deployed hydrologists have limited tools available to answer questions related to forecast uncertainty and sensitivity to forecast precipitation. As IDSS increases in scope and context, the ability to put the forecast modeling into the hands of the DSS advisors will become critical.

Recommendation 14: NWS must provide IDSS-deployed forecasters with the proper tools to answer questions related to the hydrologic forecast uncertainty and what-if conditions.

Finding 15: Flood inundation maps were available from multiple government sources. Users were often confused about the differences between the available maps and did not have any clear guidance on which maps to use.

Recommendation 15: The NWS should work with national IWRSS Partners and local partnerships, such as InFRM, to understand the strengths and weaknesses of different available flood inundation maps and work towards providing best available information with guidance on its use.

Finding 16: The current version of the NWM provides river discharge information, but users also need river stage information.

Recommendation 16: The OWP should include stage and discharge information in its NWM output.

Finding 17: NWC products and services provided simultaneously to SR ROC, WGRFC, WPC and TDEM caused confusion with official forecasts. Resources were diverted from primary IDSS tasks to address these inconsistencies.

Recommendation 17: NWS should develop a plan for CFP and IDSS for flooding.

Finding 18: Several WFOs impacted by Hurricane Harvey reported issues with GFE and the creation of WFO TCV and HLS products, varying from ingest of the pre-TCV and difficulties merging the hazards, to the extra staffing required to check grids and then blend them into coherent product dataset. During forecast package update times, new GFE data related to the WFO TCV, specifically when merging the proposed *StormSurgeThreat*, would erase previous hazard grids. This resulted in wasted staff time recreating these grids from scratch, delaying product issuance.

Recommendation 18: The NWS should ensure that the tropical program has proper and robust software testing and evaluation before national implementation.

Finding 19: NCF does not have resources to troubleshoot and quickly diagnose CHPS issues.

Recommendation 19: Office of Central Processing should instruct NCF to transfer CHPS issues to CHPS operations support staff.

Finding 20: WFO Corpus Christi reported that the hurricane hotline capability was not fully functional, inhibiting effective communication.

Recommendation 20: NWS should ensure the hurricane hotline, with the full voice and video capabilities, will be operational for high-impact events in time for the 2018 hurricane season.

Finding 21: WFOs reported delays in accessing the EDD, especially during high-impact events.

Recommendation 21: The web services provided by NWS need to be more robust and stable, especially during high-impact events.

Finding 22: Necessary backup computer hardware was unavailable at CWSU Houston. The office could not get timely replacements delivered due to local flooding conditions affecting air and highway transportation shipping networks**.**

Recommendation 22: The NWS should build more redundancy into its routers and other key communication devices to avoid a single point of failure**.**

Finding 23: Dispatched forecasters were not included in the directory list of the affected WFO to which they were assigned.

Recommendation 23: NWS Regional IT staff should add dispatched individuals' active directory accounts from their home WFO to the impacted WFO before the forecasters arrive at the impacted WFOs. This change also includes temporarily removing any home office re-directs or roaming profiles these staff members may have.

Finding 24: NWS core partners would like to continue to expand their knowledge on the use and interpretation of the different tropical products. Also, WFOs are not fully aware of many of the basic training modules available to understand the fundamentals of the tropical products.

Recommendation 24: A comprehensive coordinated effort should exist between Regional Headquarters, WFOs, an NHC to expand awareness of training opportunities with the goal of understanding and interpreting different tropical products. Training should be prioritized and streamlined to maximize effectiveness of roles and responsibilities in Tropical IDSS.

Finding 25: Community partners did not appear to represent the demographic diversity of area populations, potentially limiting audiences served by NWS.

Recommendation 25: WFO staff should continue to initiate new relationships with underserved populations and organizations to ensure a Weather-Ready Nation.

Finding 26: A majority of those interviewed planned to avoid driving through flood waters, but some were hampered by a lack of understanding of the timing and extent of flooding. The rapid updating of forecasts exposed many people to unanticipated flood threats.

Recommendation 26: Flood forecasts that involve relatively large uncertainties should be delivered in ways that successfully convey the array of potential outcomes, not just the most likely outcome. This includes the communication of uncertainty for multiple forecast attributes such as timing, location, hazard severity, and hazard impacts.

Best Practices

Best Practice: Many of the WFOs distributed the conference call and briefing load beyond the management team, to include SHs and other members of the WFO team. This force-multiplier effect enabled the offices to engage more partners more frequently with a richer set of IDSS content. It also somewhat reduced fatigue on the part of the management teams.

Best Practice: The WFOs well-established relationships with local elected officials, local media, EMs, and other community partners before Hurricane Harvey facilitated communication of critical IDSS before and during the storm.

Best Practice: The use of Facebook Live by WFO Lake Charles elicited significant praise for communicating live updates to partners and the general public

Best Practice: NHC issues strongly worded tropical weather outlooks the day before Hurricane Harvey formed. In particular, the 18Z (1 PM CDT) outlook specifically mentioned that this system, "could produce storm surge and tropical storm or hurricane force winds along portions of the Texas coast and very heavy rainfall across portions of central and eastern Texas from Friday through the weekend."

Best Practice: NHC did explicitly mention the possibility and the expectation that Harvey *would* become a hurricane before landfall despite the fact that there was no model guidance explicitly supporting this.

Best Practice: A WFO forecaster with substantial tropical and IDSS experience was deployed to NHC to serve as an IDSS coordinator. This position unambiguously benefited both NHC and the WFOs alike.

Best Practice: WFOs incorporated Excessive Rain Outlooks in their IDSS briefings to better convey NWS confidence in flood threats.

Best Practice: With frequent practice and exchange in working across forecast service domains, WPC, WFOs, and RFCs were ready and able to provide consistent message and service on QPF.

Best Practice: SRH fully used the ICS structure during Hurricane Harvey. This structure helped staff identify and execute key support objectives, ensured that regional resources were properly committed, and facilitated the communication of information to the field offices.

Best Practice: SRH augmented IDSS support staff at TDEM.

Best Practice: The ROC developed a set of consistent regional IDSS briefing slide templates to promote a consistent message.

Best Practice: Coordination on the forecast and messaging among NCEP, regional headquarters offices, RFCs, and WFOs resulted in consistent messaging.

Best Practice: Coordinated terminology between WFOs in extreme events ensured consistent messaging of expected threats in briefings and on social media.

Best Practice: WFO Lake Charles stated that having FLASH data in AWIPS was extremely useful because it allowed staff to quickly focus in on areas of greatest threat and upgrade flash flood warnings to flash flood emergencies, more quickly.

Best Practice: NHC offers the Effective Hurricane Messaging course, which is a collaborative effort by SR, ER, OCLO, the ROCs, and NHC, as a way to help WFO forecasters become deployable. This course also provides information to the external partners of the different products available and how to interpret them.

Best Practice: NHC offers training on preparedness and product use in various formats, including COMET modules, webinars, and in-person training.

Best Practice: NHC provided Spanish-language media support in its media pool during Harvey. This effort was supplemented by staff from WFO Miami, which also provided support for numerous Spanish-language radio interviews during Harvey. WFO San Juan also provided Spanish versions of the Tropical Cyclone Public advisory that were issued on AWIPS and available on the NHC website, and Spanish versions of the Tropical Cyclone Discussion, which were available on the NHC website.

Best Practice: WFO Corpus Christi published its annual Hurricane Guide in Spanish and English. The office also provided printed copies for the past 10 years until funding ran out.

Best Practice: WFO Austin/San Antonio conducted Skype video interviews with CNN in Spanish as well as other interviews in Spanish.

Best Practice: Spanish assistance through the SR Multimedia Assistance in Spanish Team was available during Hurricane Harvey, helping translate flash flood emergencies and messages into Spanish.

Appendix C: Prior Service Assessment Findings and Recommendations to Revisit

Findings and Recommended Actions from Prior Service Assessments: This appendix contains findings from Hurricane Harvey similar to those in prior service assessments. The team would like to re-emphasize these findings and recommended actions which may need additional follow-up.

August 2011 Hurricane Irene Service Assessment

- **Finding 7:** After the HPC briefing on August 25, FEMA removed HPC from the VTCs for the duration of Irene. HPC serves as the backup for NHC and provides the critical rainfall component of the hurricane forecast, the component associated with the majority of fatalities associated with Irene**.**
- **Recommendation 7:** Leveraging the success of NHC briefings, the NWS should support the creation of a Service Coordination Hydrologist (SCH) position at HPC to deliver more effective briefings to key partners.

Historic South Carolina Floods of October 1–5, 2015 Service Assessment

- **Finding 12:** NWS does not provide national Dam Break programmatic software support to RFCs. RFCs have relied on their own expertise and ingenuity to keep the Simplified Dam Break Model software operational.
- **Recommendation 12:** NWS should develop national program and technical support for the Dam Break flood program. Part of this support should involve modernizing the NWS Dam Break Program and associated software. This Part b involves the implementation of required capabilities defined in Part a.

Historic Nor'easter of January 2016 Service Assessment

- **Finding 8:** Emergency employee lodging and food was critical in sustaining operations**.**
- **Recommendation 8:** NWS WFOs Severe Weather and Winter Weather Operations Plans should detail procurement procedures for employee lodging and food as specified within NWSI 1-208, Delegation of Authority for Food/Lodging Expenditures in Advance of or during Major Weather Emergencies or Disasters.

October 2016 Hurricane Matthew Service Assessment

- **Finding 1**: Partners indicated that despite the excellent service and information provided by the NWS they were surprised at the magnitude of flooding they experienced and did not feel that the threat was communicated adequately.
- **Recommendation** 1: The NWS needs to take a comprehensive look at communication related to inland flood threats for both river and flash flooding. This may include confidence-based forecasts, inundation maps, increased educational efforts, pursuing a social science analysis of flood related messaging, and links to WPC's Excessive Rainfall graphics on NHC's web page.

- **Finding 8:** SRH deployed an IDSS coordinator to NHC. This individual attempted to facilitate a consistent message among all NWS entities and partners. The presence of the coordinator was widely lauded by all parts of the NWS. The concept of a deployed IDSS coordinator into a National Center is not in practice at all regional HQ.
- **Recommendation 8:** Regional HQ should consider a model of field support that includes on-site IDSS coordinators at the appropriate National Center(s) during significant events.

- **Finding 12:** While WPC medium-range products highlighted the heavy rain and inland flood threat 96 hours prior to the event, the lack of an integrated, coordinated message at the national level made it difficult to communicate the threat in a holistic manner.
- **Recommendation 12a:** NWS should establish a national plan for communication during inland flooding events that includes clarity on the roles for all internal organizational units.
- **Recommendation 12b:** NWS should explore having a WCM and/or Public Affairs Officer function at the National Center for Weather and Climate Prediction to help with coordination and messaging during events.

- **Finding 16:** Even though significant effort was made to deploy additional personnel to WFOs, the service assessment team found that these deployments fell short of meeting operational needs. Lack of available staffing led to potentially dangerous forecaster fatigue and limitations to WFO IDSS efforts.
- **Recommendation 16:** NWSH and regional HQ should develop a national pool of trained personnel with tropical cyclone experience and IDSS specialists who would be available for deployment to assist WFOs, regardless of NWS region. Special emphasis should be placed on including prior experience in the affected area, IDSS expertise, and multi-lingual language skills.

- **Finding 19:** Several WFOs reported problems with a limited number of phone lines for WFO/partner briefings, restricting partner participation.
- **Recommendation 19:** NWS regions should ensure WFOs understand the protocols and procedures for requesting additional conference phone lines for major event briefings.

- **Finding 20:** Latency and reliability issues with NWS web pages resulted in inconsistency in web services.
- **Recommendation 20:** NWS Internet Dissemination Service, also known as NIDS, should work towards ensuring there is no delay between the issuance of official products and their appearance on official web pages.