NATIONAL HURRICANE CENTER TROPICAL CYCLONE REPORT

HURRICANE GRACE

(AL072021)

13–21 August 2021

Brad J. Reinhart, Amanda Reinhart, and Robbie Berg
National Hurricane Center
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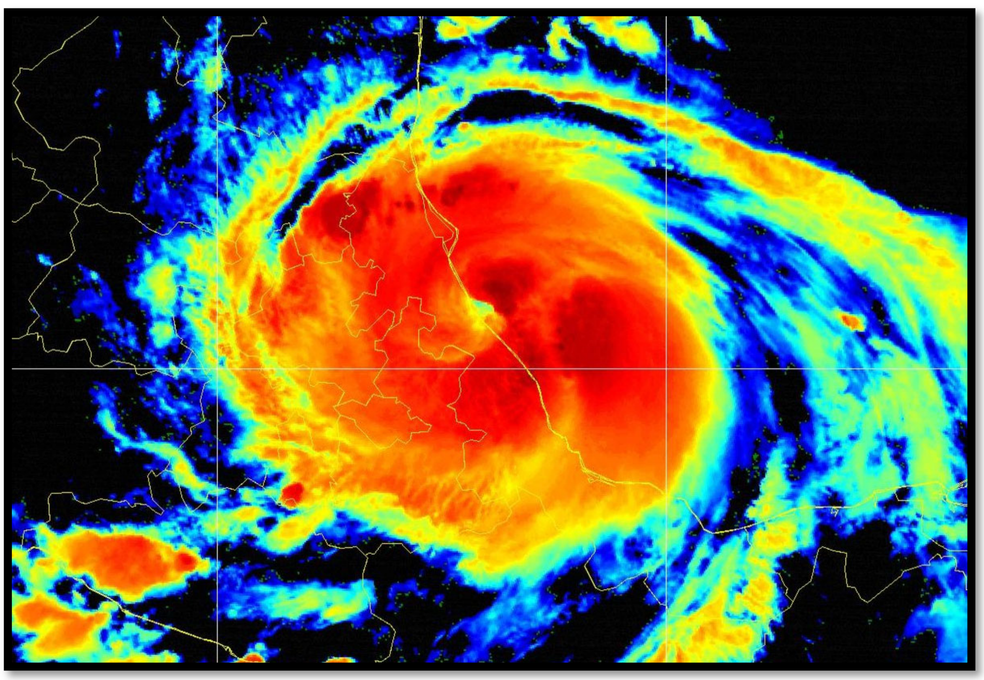

GOES-16 INFRARED SATELLITE IMAGE OF CATEGORY 3 HURRICANE GRACE MAKING LANDFALL ALONG THE COAST OF MEXICO NEAR TECOLUTLA AT 0530 UTC 21 AUGUST 2021. IMAGE COURTESY NOAA/NESDIS/STAR.

Grace struck the mainland coast of Mexico as a category 3 hurricane (on the Saffir-Simpson Hurricane Wind Scale), making it the strongest hurricane on record to make landfall in the state of Veracruz. Grace also hit the Yucatan Peninsula of Mexico as a category 1 hurricane and made landfall as a tropical storm in the Dominican Republic and Jamaica. The tropical cyclone was responsible for 16 direct fatalities in Mexico and Haiti and resulted in over $513 million (USD) in damage.

Hurricane Grace

13–21 AUGUST 2021

Table of Contents

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SYNOPTIC HISTORY

Grace originated from a tropical wave that moved off of the west coast of Africa on 9 August. The wave was associated with a broad area of convection as it passed south of the Cabo Verde Islands on 10 August. A mid-level cyclonic circulation emerged in visible satellite imagery later that day, but scatterometer surface wind data indicated the circulation did not extend down to the surface. The wave continued westward at about 20 kt across the tropical eastern Atlantic on 11–12 August, producing some deep convection that was concentrated ahead of the wave axis due to 15–20 kt of easterly deep-layer wind shear. An elongated surface trough of low pressure developed on 12 August about 1200 n mi east of the Lesser Antilles, and a small area of deep convection continued near the northern portion of the trough axis. Scatterometer data from that day revealed winds of 25–30 kt with the disturbance, but the system still lacked a well-defined, closed surface circulation. The disturbance continued moving quickly westward, and the low-level circulation became better defined in scatterometer and microwave data early on 13 August. By 0600 UTC that day, the system possessed sufficient convective organization to mark the formation of a tropical depression when it was centered about 880 n mi east of the Leeward Islands. The "best track" chart of the tropical cyclone's path is given in Fig. 1, with the wind and pressure histories shown in Figs. 2 and 3, respectively. The best track positions and intensities are listed in Table 1[1].

The depression raced westward to the south of a broad subtropical ridge extending across the western and central Atlantic Ocean. A burst of deep convection developed near the center of the depression early on 14 August, and the cyclone strengthened into Tropical Storm Grace by 1200 UTC that day, while centered about 270 n mi east-southeast of the Leeward Islands. However, Grace's satellite appearance became disheveled later that day, and the poorly organized cyclone weakened to a tropical depression by 0000 UTC 15 August, shortly before reaching the Leeward Islands. Despite its elongated satellite appearance, ship observations early that day suggest the system maintained a closed surface circulation as it moved over the northeastern Caribbean Sea and passed south of Puerto Rico. Grace remained a depression through early 16 August as it struggled with bouts of dry air entrainment and the decoupling of its low- and mid-level centers due to its fast forward motion. However, the depression exhibited increased signs of convective organization as it approached Hispaniola later that morning. Aircraft data showed that Grace regained tropical storm intensity by 1200 UTC 16 August, when it was located about 40 n mi east of Isla Beata, Dominican Republic. Radar data indicate Grace

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[1] A digital record of the complete best track, including wind radii, can be found on line at ftp://ftp.nhc.noaa.gov/atcf. Data for the current year's storms are located in the *btk* directory, while previous years' data are located in the *archive* directory.

made landfall on the southern tip of the Dominican Republic's Pedernales province just south of Oviedo around 1630 UTC that day.

The center of Grace passed just offshore of Haiti's Tiburon Peninsula early on 17 August and moved westward toward Jamaica. The cyclone remained far enough offshore to strengthen as it moved over 29.5°C sea-surface temperatures (SSTs) within a low (~10 kt) deep-layer shear environment. Grace made landfall as a 50-kt tropical storm around 1400 UTC 17 August on the northeastern coast of Jamaica near Black Hill (Fig. 4). After maintaining its intensity while quickly passing over Jamaica, Grace strengthened as it moved over the high oceanic heat content of the northwestern Caribbean Sea. Grace became a hurricane by 1200 UTC 18 August, when it was located just 15 n mi west-southwest of Grand Cayman. This resulted in a direct hit[2] on the island. Later that day, aircraft data indicated the hurricane's intensity briefly plateaued as it moved westward at about 15 kt toward the Yucatan Peninsula of Mexico. However, microwave data early on 19 August (Fig. 5) showed signs of resumed intensification, as the hurricane developed a tighter inner core and a more pronounced mid-level eye as it neared the coast. Grace made landfall as a 75-kt, category 1 hurricane along the east coast of the Yucatan Peninsula just south of Tulum, Mexico around 0945 UTC 19 August (Fig. 6).

Grace weakened to a tropical storm as it moved across the Yucatan Peninsula on 19 August. The cyclone emerged over the southwestern Gulf of Mexico late that day, and it continued moving westward on 20–21 August around the southern extent of a deep-layer ridge over the northern Gulf of Mexico. The cyclone underwent a period of rapid intensification on 20 August, within a low to moderate deep-layer shear environment over 30°C SSTs in the Bay of Campeche. Grace regained hurricane intensity less than 18 h after moving offshore, and aircraft data indicate that Grace strengthened into a major hurricane (Category 3 on the Saffir-Simpson Hurricane Wind Scale) by 0000 UTC 21 August, when it was located about 90 n mi east of Tuxpan, Mexico. A warm, 30 n-mi-wide eye emerged in infrared satellite imagery shortly thereafter, and the hurricane's structure continued to improve in satellite and radar data as the center neared the coast of mainland Mexico (Figs. 7 and 8). Grace made landfall as a 105-kt major hurricane (cover image) along the coast of the Mexican state of Veracruz just north of Tecolutla around 0530 UTC 21 August.

After landfall, the tropical cyclone moved west-southwestward toward the complex topography of central Mexico. Grace rapidly weakened to a tropical storm by 1200 UTC 21 August about 60 n mi southwest of Tuxpan, and the surface circulation dissipated by 1800 UTC that day. However, the mid-level remnants of Grace crossed central Mexico and reached the southwestern coast of Mexico early on 22 August. These remnants contributed to the formation of Tropical Storm Marty[3] in the eastern North Pacific basin by 0000 UTC 23 August.

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[2] Glossary of NHC Terms: https://www.nhc.noaa.gov/aboutgloss.shtml

[3] Brown, Dan. "Tropical Cyclone Report: Tropical Storm Marty." National Oceanic and Atmospheric Administration / National Weather Service / National Hurricane Center, 30 Sep 2021, www.nhc.noaa.gov/data/tcr/EP132021_Marty.pdf

METEOROLOGICAL STATISTICS

Observations in Grace (Figs. 2 and 3) include subjective satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB), objective Advanced Dvorak Technique (ADT) estimates and Satellite Consensus (SATCON) estimates from the Cooperative Institute for Meteorological Satellite Studies/University of Wisconsin-Madison. Observations also include flight-level, stepped frequency microwave radiometer (SFMR), and dropwindsonde observations from 19 aircraft missions into Grace. This includes 11 flights of the U.S. Air Force Reserve Command's 53rd Weather Reconnaissance Squadron's WC-130 aircraft and 8 flights of the NOAA WP-3D Orion aircraft. These missions provided a total of 42 center fixes for Grace from 14–21 August. There were also 3 synoptic surveillance flights of the NOAA G-IV aircraft that provided information on Grace's environment on 14–15 and 18–19 August.

Data and imagery from NOAA polar-orbiting satellites including the Advanced Microwave Sounding Unit (AMSU), the NASA Global Precipitation Mission (GPM), the European Space Agency's Advanced Scatterometer (ASCAT), and Defense Meteorological Satellite Program (DMSP) satellites, among others, were also useful in constructing the best track of Grace. Weather radar data from Guadeloupe, Puerto Rico, Cuba, Mexico, and Belize were also utilized for the best track analysis.

Ship reports of tropical-storm-force winds associated with Grace are given in Table 2, and selected surface observations from land stations and data buoys are given in Table 3.

Winds and Pressure

Grace's 105-kt peak intensity from 0000 UTC 21 August through its landfall near Tecolutla at 0530 UTC that day is based on flight-level winds and SFMR-derived surface winds from the Air Force Reserve Hurricane Hunters. The aircraft measured SFMR surface winds of 105 kt shortly after 0200 UTC, with a peak 700-mb flight-level wind of 115 kt in the northeastern eyewall that reduces to a surface intensity of 103.5 kt using the standard 90% adjustment factor. A 2344 UTC 20 August center dropsonde measured a 968 mb surface pressure with 11-kt surface winds, and a dropsonde at 0333 UTC 21 August reported a 970 mb surface pressure with 28-kt surface winds. Both of these observations support a minimum central pressure of 967 mb shortly before landfall in mainland Mexico.

Grace's landfall intensity of 35 kt in the southwestern portion of the Dominican Republic around 1630 UTC 16 August is based on flight-level winds and SFMR data from the Air Force Reserve Hurricane Hunters. The aircraft recorded a peak 925-mb flight-level wind of 45 kt at 1641 UTC that day, which reduces to a 34-kt surface intensity using the standard 75% adjustment factor. The aircraft also reported reliable SFMR surface winds of 35–40 kt over deeper waters offshore the Dominican Republic as the center neared the coast. The landfall intensity is consistent with T2.5/35 kt Dvorak estimates from TAFB at 1200 and 1800 UTC that day. The landfall pressure of 1007 mb is based on the extrapolated minimum pressure from the aircraft and the Knaff-Zehr-Courtney (KZC) pressure estimate.

Grace's landfall intensity of 50 kt on the northeastern coast of Jamaica around 1400 UTC 17 August is supported by aircraft reconnaissance data and scatterometer winds. The Air Force Reserve Hurricane Hunters recorded a peak 850-mb flight-level wind of 62 kt around the estimated time of landfall, which reduces to a surface intensity of 50 kt. The aircraft also reported believable SFMR winds of 45–49 kt offshore Jamaica shortly after landfall, which was consistent with a 1433 UTC scatterometer pass that showed offshore winds slightly greater than 45 kt. The landfall pressure of 1004 mb is based on a blend of dropsonde data and KZC pressure estimates. A 1251 UTC dropsonde measured a 1007 mb surface pressure with 20-kt surface winds roughly one hour before landfall.

Grace's landfall intensity of 75 kt on the Yucatan Peninsula near Tulum around 0945 UTC 19 August is based on a T4.5/77 kt Dvorak estimate from SAB at 0600 UTC and a T4.4/74.6 kt ADT estimate around the time of landfall. The landfall pressure of 978 mb is based on an in-situ measurement by Josh Morgerman (iCyclone) taken in Tulum as the eye of Grace passed over the location.

Leeward Islands and Greater Antilles

Grace weakened to a tropical depression by the time it reached the Leeward Islands. The airport on La Désirade Island of Guadeloupe recorded a sustained wind of 24 kt at 2300 UTC 14 August with a gust to 33 kt as Grace quickly passed over the island. Elsewhere, a 30-kt gust was reported in the town of Bethesda on Antigua. Numerous observations from the U.S. Virgin Islands and Puerto Rico indicate that Grace produced sustained winds of 20–30 kt as it passed south of these islands. A few WeatherFlow sites in Puerto Rico and the U.S. Virgin Islands reported tropical-storm-force wind gusts, including 36 kt at Isla Culebrita Light and Two Brothers.

Tropical-storm-force wind gusts were reported over southern portions of the Dominican Republic and Haiti as the center of Grace passed over the southern tip of Hispaniola. La Romana International Airport (MDLR) reported a gust of 35 kt at 0900 UTC 16 August, and a gust to 37 kt was measured at 2100 UTC that day at María Montez International Airport (MDBH) in Barahona. In Haiti, a 35-kt gust was reported at Toussaint Louverture International Airport (MTPP) in Port-au-Prince at 2052 UTC 16 August.

Grace produced sustained tropical-storm-force winds on Jamaica as the center of the storm passed over the island on 17 August. Norman Manley International Airport (MKJP) in Kingston recorded tropical-storm-force winds for several hours, with a maximum sustained wind of 41 kt at 2000 UTC and a peak gust of 47 kt at 1800 UTC. A gust of 41 kt was measured at Sangster International Airport (MKJS) in Montego Bay at 2100 UTC, and a 44-kt gust was reported at 2100 UTC in the Mona neighborhood near Kingston.

Grace became a hurricane as it passed very close to Grand Cayman on 18 August. A couple of observing sites on the island reported near hurricane-force conditions before failing. Owen Roberts International Airport (MWCR) reported a sustained wind of 59 kt and a gust of 82 kt at 1050 UTC, shortly before the automated weather station was damaged by strong winds. A minimum pressure of 993 mb was recorded at the airport at 1200 UTC. Elsewhere, a Citizen Weather Observer Program station with an elevation of 14 m on the north side of Grand Cayman near Rum Point measured a sustained wind of 63 kt and a gust of 83 kt at 1031 UTC, shortly before the station went offline.

Although the center of Grace passed well south of Cuba, the storm may have briefly produced tropical-storm-force conditions on Isla de la Juventud. The La Fe weather station near the center of the island measured a sustained wind of 32 kt with a gust of 44 kt at 1745 UTC 18 August. Farther east, a gust of 35 kt was reported at the Vilo Acuña Airport on Cayo Largo del Sur at 1705 UTC. Several weather stations in the Pinar del Río province reported tropical-storm-force wind gusts, including 44 kt at Cabo San Antonio and 43 kt in Pinar del Río. Elsewhere, a few locations in eastern Cuba briefly gusted to tropical storm force on 17 August as Grace passed over Jamaica. A gust to 39 kt was measured at the Antonio Maceo Airport (MUCU) in Santiago de Cuba at 1750 UTC that day.

Mexico

Grace brought hurricane conditions to a portion of the Yucatan Peninsula of Mexico on 19 August near where the center made landfall. Hurricane-force wind gusts were reported to the north of the landfall location along coastal portions of the state of Quintana Roo early that day. A WeatherFlow station in Playa del Carmen measured a sustained 10-m wind of 58 kt at 0909 UTC with a gust to 74 kt. Another WeatherFlow site in Tulum reported a sustained wind of 52 kt at 0928 UTC with a gust to 79 kt. Farther north, a WeatherFlow station in Cancun recorded a sustained wind of 55 kt at 1006 UTC with a gust to 69 kt. A minimum pressure of 978.0 mb was measured at 1013 UTC by Josh Morgerman (iCyclone) in Tulum. Grace weakened to a tropical storm as it quickly crossed the Yucatan Peninsula. A sustained wind of 41 kt with a gust to 56 kt was reported at the Mérida International Airport (MMMD) at 1946 UTC 19 August, shortly before the center of Grace emerged over the southwestern Gulf of Mexico.

Grace made its second landfall in Mexico as a major hurricane on 21 August along a sparsely populated stretch of the coast of Veracruz state. As a result, surface observations were very limited in the region, and measurements near the landfall location were unavailable. An automated weather station in Tuxpan reported a sustained wind of 40 kt with a gust to 65 kt at 0600 UTC. Farther south, a personal weather station just southeast of Xalapa reported a sustained wind of 35 kt at 1030 UTC with a gust to 57 kt. The lowest reported pressure of 981.4 mb was measured by Josh Morgerman (iCyclone) in La Guadalupe along the southern edge of Grace's eye. He also recorded a pressure of 985.7 mb slightly farther south in La Vigueta.

Storm Surge[4]

Grace is estimated to have raised water levels along the coast of the Yucatan Peninsula of Mexico by as much as 3 to 5 ft above normal tide levels near and to the north of the landfall

[4] Several terms are used to describe water levels due to a storm. **Storm surge** is defined as the abnormal rise of water generated by a storm, over and above the predicted astronomical tide, and is expressed in terms of height above normal tide levels. Because storm surge represents the deviation from normal water levels, it is not referenced to a vertical datum. **Storm tide** is defined as the water level due to the combination of storm surge and the astronomical tide, and is expressed in terms of height above a vertical datum, i.e. the North American Vertical Datum of 1988 (NAVD88) or Mean Lower Low Water (MLLW). **Inundation** is the total water level that occurs on normally dry ground as a result of the storm tide, and is expressed in terms of height above ground level. At the coast, normally dry land is roughly defined as areas higher than the normal high tide line, or Mean Higher High Water (MHHW).

location of Tulum. A Mexico meteorological service tide gauge in Puerto Morelos, about 50 n mi north of Tulum, measured a peak water level about 3 ft above normal tide levels, suggesting that higher water levels occurred between there and Tulum. Another tide gauge farther north on Isla Mujeres measured a peak of about 1.5 ft above normal tide levels. Tide gauge data were not available along the Gulf coast of Mexico where Grace made its second landfall, but it is estimated that water levels rose by as much as 6 to 9 ft above normal tide levels in the area near and to the north of the second landfall near Tecolutla.

Grace produced negligible water level rises in Puerto Rico and the U.S. Virgin Islands when it passed to the south as a tropical depression. The highest storm surge measured by a National Ocean Service (NOS) tide gauge was 0.64 ft above normal tide levels at Mayaguez, Puerto Rico, resulting in a peak water level of 0.6 ft above Mean Higher High Water (MHHW).

Rainfall and Flooding

Greater Antilles

Grace produced 1–3 inches of rainfall across portions of Puerto Rico and the U.S. Virgin Islands, but no significant flooding impacts were reported. Southwestern portions of the Dominican Republic (Fig. 9) received 5–9 inches (127–229 mm) of rainfall, which triggered flash flooding and landslides. In Haiti, 12.95 inches (329 mm) of rain was measured in Savane Zombie and 7.26 inches (184.4 mm) was reported in Fonds-des-Negres. The heavy rainfall and resulting flooding compounded the suffering of tens of thousands of residents who were left homeless following a devastating 7.2-magnitude earthquake that struck southern Haiti on 14 August. Flash flooding in Les Cayes necessitated over a dozen water rescues, and significant flooding was also reported in coastal towns including Cayes-Jacmel and Bainet. In Jamaica, Grace produced 5–10 inches (127–254 mm) of rainfall over portions of the island, with a maximum of 14.07 inches (357.5 mm) measured in Bois Content. This excessive rainfall resulted in flash flooding, river flooding, and landslides, particularly across the eastern parishes of Jamaica (Fig. 10). Water rescues were conducted at the Bog Walk Gorge after some motorists became stranded by Rio Cobre flooding near the Flat Bridge. On Grand Cayman, 7.60 inches (193.0 mm) of rain fell at the Owen Roberts International Airport in Georgetown, and some localized flooding was reported on the island. No significant flooding impacts were reported in Cuba.

Maximum reported rainfall totals by location:

<u>Jamaica</u>: 14.07 inches (357.5 mm) in Bois Content
<u>Haiti</u>: 12.95 inches (329 mm) in Savane Zombie
<u>Dominican Republic</u>: 9.45 inches (240.1 mm) in Polo
<u>Cayman Islands</u>: 7.60 inches (193 mm) in George Town
<u>Cuba</u>: 3.90 inches (99 mm) at Acueducto Minas de Matahambre
<u>Puerto Rico/U.S. Virgin Islands</u>: 3.44 inches (87.4 mm) in Vieques

Mexico

Grace produced a swath of 2–5 inches (51–127 mm) of rainfall across portions of the Mexican states of Quintana Roo, Yucatan, and Campeche on 18–19 August as it moved across the Yucatan Peninsula (Fig. 11). The highest rainfall totals were reported near the southern border of Quintana Roo and Yucatan, with a maximum of 7.20 inches (183.0 mm) in Peto. There were some reports of minor to moderate urban flooding in areas including Playa del Carmen, but no significant flood impacts from Grace were noted in the Yucatan Peninsula. Grace's second landfall in mainland Mexico resulted in 4–8 inches (102–203 mm) of rainfall over large portions of the Mexican states of Veracruz, Hidalgo, Puebla, and San Luis Potosi on 20–21 August with locally higher amounts (Fig. 12). A storm total maximum of 15.69 inches (398.5 mm) of rainfall was reported in Atlapexco, with 11.99 inches (304.5 mm) of rain measured in Xicotetepec de Juárez and 10.24 inches (260.0 mm) in Paso de Piedras. This torrential rainfall triggered landslides and produced significant flash and river flooding, primarily in the states of Veracruz and Puebla. Flooding was also reported farther north in Ciudad Madero.

CASUALTY AND DAMAGE STATISTICS

Grace was responsible for 12 direct deaths[5] in Mexico and at least 4 in Haiti. The 7.2-magnitude earthquake that struck Haiti just days earlier killed over 2,000 people and injured many more, which makes it very difficult to distinguish between victims of the earthquake and Grace. Thus, the complete death toll in Haiti remains uncertain as of the time of this report.

In Mexico, there were eight direct fatalities reported in the state of Veracruz. Six family members (a mother and five children) were killed in the Brisas del Río Sedeño neighborhood of Xalapa by a landslide that buried their home. Another young girl died in a landslide in a nearby neighborhood in Xalapa, and an adult was killed by a roof collapse in Poza Rica. There were four direct fatalities in the state of Puebla. Two people died after their home was buried by a landslide in Huauchinango. Elsewhere, a man was killed in Olintla after being struck by a roof tile that was lofted into the air by strong winds, and another man died in Tlaola when a tree fell on top of him. One indirect fatality was reported in Olintla after a woman suffered a heart attack during the storm.

In Haiti, Grace resulted in four fatalities in the Sud-Est Department, according to a report from the Caribbean Disaster Emergency Management Agency (CDEMA). The details of those fatalities are unknown as of the time of this report.

Grace produced over $513 million (USD) in damage in Mexico and portions of the Greater Antilles, according to the Global Catastrophe Recap produced by Aon.

[5] Deaths occurring as a direct result of the forces of the tropical cyclone are referred to as "direct" deaths. These would include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered "indirect" deaths.

Greater Antilles

Flash floods and landslides damaged hundreds of homes and cut off several communities in southern portions of the Dominican Republic. In Haiti, Grace's winds, heavy rainfall, and flooding worsened the ongoing humanitarian crisis that followed the earthquake by destroying makeshift shelters and interrupting rescue and recovery efforts. In Les Cayes, a shelter for displaced residents was destroyed by Grace's wind and heavy rain, and the storm forced officials to relocate patients that were being treated outside the heavily damaged local hospital. About 500 homes were flooded in Marigot, and landslides blocked some roads in the earthquake-ravaged Tiburon Peninsula.

In Jamaica (Fig. 10), Grace's strong winds over saturated ground brought down trees and power lines, which resulted in power outages that affected around 100,000 customers across the country. A tree fell on a house in Port Maria, but no injuries were reported. Some other homes and buildings suffered roof damage, including the Annotto Bay Fire Station. Over 600 hectares of banana and plantain crops were damaged in the northeastern parishes. Much of the damage in Jamaica was the result of flash flooding and landslides. A bridge collapsed in Troy near the Trelawny/Manchester Parish border, and some vehicles in and around Kingston were disabled by floodwaters. Overall, almost 200 roads across the country were affected by flooding, downed trees and power lines, or other debris from landslides (Fig. 13).

Grace downed numerous trees and power lines on Grand Cayman (Fig. 14), which led to widespread power outages that affected over 27,000 customers across the island. Some large trees were snapped or uprooted at the Queen Elizabeth II Botanic Park. Numerous homes and buildings were damaged, with at least one complete roof failure reported and some balconies destroyed on condominium complexes. Battering waves and storm surge caused beach erosion and grounded several boats that became unmoored. The Cayman Islands National Weather Service reported that storm surge rose to the threshold of the door of the General Aviation Terminal at Owen Roberts International Airport. No major impacts were reported on Little Cayman or Cayman Brac.

Mexico

Strong winds associated with Grace's first landfall in Quintana Roo (Fig. 15) downed trees and power lines in municipalities including Benito Juárez, Cozumel, Solidaridad, and Tulum. Almost 700,000 customers lost power as Grace crossed the Yucatan Peninsula. Some homes and structures received roof damage, and about 20 schools in Quintana Roo suffered minor damage. A downed road sign obstructed a lane of the highway between Playa del Carmen and Tulum. Josh Morgerman (iCyclone) reported roof and sign damage between Tulum and Playa del Carmen, as well as some downed trees and branches that blocked portions of the highway. He also noted some evidence of minor storm surge inundation that had occurred on the coastal streets of Playa del Carmen.

More significant damage occurred in mainland Mexico (Fig. 16) where Grace made landfall as a major hurricane. Some of the hardest-hit locations included the coastal towns of Tecolutla, La Guadalupe, and Costa Esmeralda, where numerous homes and buildings were damaged or destroyed. In total, 110,000 homes were damaged across the states of Veracruz, Puebla, and Hidalgo. Downed trees and power lines led to power outages that affected about

330,000 people in the state of Veracruz and 316,000 people in the state of Puebla. Veracruz state experienced significant damage from flooding, including deadly landslides and building collapses. In the capital of Xalapa, water rescues were performed as flash flooding inundated homes and businesses and disabled vehicles. Flooding along the Actopan River forced the closure of a highway. Around 3,000 schools were damaged in Veracruz state, and approximately 200,000 combined hectares of corn, beans, citrus, and banana crops were damaged. Grace caused 34 landslides in Puebla state, several of which blocked roads with debris and cut off some communities. More than 3,000 producers in the municipality of Xicotepec reported damage to crops including corn, coffee, citrus, peppers, and tomatoes. Grace also destroyed many greenhouses in the municipality of Huauchinango, which significantly impacted the local poinsettia production.

FORECAST AND WARNING CRITIQUE

Genesis

The genesis of Grace was not well forecast. Table 2 provides the number of hours in advance of formation associated with the first NHC Tropical Weather Outlook (TWO) forecast in each likelihood category. The tropical wave from which Grace developed was introduced into the 5-day and 2-day TWO with a low (<40%) chance of formation 60 h prior to genesis. The 5-day formation chances were raised to medium (40–60%) and high (>60%) categories in the TWO 42 h and 12 h, respectively, before formation. For the 2-day outlook, the disturbance was given a medium and high chance of formation only 12 and 6 h before genesis occurred, respectively. The disturbance was sheared and elongated as it raced across the eastern Atlantic, and two vorticity centers emerged along the wave axis. It was unclear which vorticity center would become the dominant feature, and there were inconsistent signals in the global models as to whether genesis would occur at all given the wave's fast forward motion. These factors likely contributed to the shorter-than-typical genesis lead time. Although genesis occurred earlier than expected, Grace was generally a poorly organized tropical cyclone during the first few days of its lifetime.

Track

A verification of NHC official track forecasts for Grace is given in Table 5a. Official forecast track (OFCL) errors were greater than the mean official errors for the previous 5-yr period at all forecast times. The climatology and persistence (OCD5) errors were lower than their respective means from 12 to 72 h, which suggests Grace's track in the short term should have been easier to forecast than an average Atlantic tropical cyclone. A homogeneous comparison of the official track errors with selected guidance models is given in Table 5b. Due to the homogeneity requirement, the UKMET model (EGRI) and the Florida State Superensemble (FSSE) were not included in the verification. For the 12–72-h forecast periods, the official NHC forecasts were more skillful than the individual global and regional models. The consensus aids were the best performing track guidance for Grace, particularly the GFS/ECMWF simple consensus (GFEX) and the variable consensus TVDG, which applies double weighting to the GFS, ECMWF, and UKMET global models.

An examination of early NHC track forecasts for Grace (Fig. 17a) reveals a very large right-of-track bias. During this time period, Grace was a fairly disorganized tropical cyclone, with a fast forward motion that prevented the low- and mid-level centers from remaining vertically aligned. Grace remained a weaker system as it moved across the northeastern Caribbean Sea, and it was steered quickly westward to west-northwestward by lower-level ridging instead of slowing down and turning northwestward as much of the global guidance suggested. As Grace's organization improved and the cyclone strengthened, later NHC track forecasts (Fig. 17b) were more tightly clustered and correctly indicated two landfalls in Mexico.

Intensity

A verification of NHC official intensity forecasts for Grace is given in Table 6a. Official forecast intensity (OFCL) errors were greater than the mean official errors for the previous 5-yr period at all forecast periods. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 6b. The consensus aids generally had lower errors than the official NHC forecasts at most forecast periods, with the best performing models including the HFIP corrected consensus approach (HCCA) and the variable consensus aids IVCN and IVDR. The Naval Research Laboratory's COAMPS-TC model (CTCI) also performed well and had lower errors than OFCL from 24–120 h.

Grace's early intensity forecasts were challenging due to the cyclone's fast forward motion and its potential for significant land interaction as it moved across the northern Caribbean Sea. Initially, NHC forecasts called for modest strengthening within a weak deep-layer shear environment over 27–28°C SSTs as the system crossed the Leeward Islands and northeastern Caribbean Sea. However, the decoupling of Grace's low- and mid-level centers due to its forward speed prevented the cyclone from strengthening during this period. Then, erroneous track forecasts (Fig. 17a) indicated that Grace would move over the higher terrain of Hispaniola and Cuba, which was expected to weaken the system. Instead, Grace followed a more westward track that limited its land interaction and brought the center over the deep, warm waters of the northwestern Caribbean Sea. This allowed Grace to strengthen and strike the Yucatan Peninsula as a hurricane.

Grace's rapid intensification over the southwestern Gulf of Mexico was not well anticipated by NHC forecasters or most of the intensity guidance. While official NHC forecasts (Fig. 18a) did consistently call for Grace to strengthen into a hurricane once it emerged over the warm Gulf waters, the magnitude of Grace's intensification was greatly underestimated. The Hurricane Weather Research and Forecasting model (HWFI, Fig. 18b) showed more strengthening than official forecasts or the consensus aids, but none of the guidance explicitly showed Grace becoming a major hurricane before landfall.

Wind Watches and Warnings

Coastal wind watches and warnings associated with Grace are given in Table 7.

IMPACT-BASED DECISION SUPPORT SERVICES (IDSS) AND PUBLIC COMMUNICATION

The NHC was already in communication with emergency managers regarding Tropical Storm Fred on 10 August, when the tropical disturbance that would later become Grace was first introduced into the Tropical Weather Outlook. The NHC continued to brief FEMA HQ, FEMA Regions 2 and 4, along with the State of Florida through 16 August when it became clear that Grace was no longer a threat to the United States. These decision support briefings were coordinated through the FEMA Hurricane Liaison Team, embedded at the NHC. The Tropical Analysis and Forecast Branch of NHC provided a total of four live briefings from 15–17 August to Districts 7 and 8 of the U.S. Coast Guard in support of their life-saving mission.

NHC conducted several Facebook Live broadcasts for Grace. Key messages for Grace were included in NHC forecast discussions and on the NHC website in graphical format from 13–21 August. These key messages were also disseminated through official NHC social media accounts.

ACKNOWLEDGEMENTS

Data in Table 3 were compiled from reports issued by the NWS Weather Forecast Office in San Juan, Puerto Rico, National Data Buoy Center, and NOS Center for Operational Oceanographic Products and Services. Data from international meteorological services for Antigua and Barbuda, Guadeloupe, Dominican Republic, Haiti, Cuba, Jamaica, Cayman Islands, Mexico, and Belize were also incorporated into Table 3. John Cangialosi created the Grace "best track" map (Fig. 1). Tiffany O'Connor, Matthew Green, and Chris Landsea contributed to the IDSS summary. Josh Morgerman (iCyclone) provided data he collected during both of Grace's landfalls in Mexico.

Table 1. Best track for Hurricane Grace, 13–21 August 2021.

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
13 / 0600	15.0	46.7	1010	30	tropical depression
13 / 1200	15.2	48.7	1010	30	"
13 / 1800	15.3	50.8	1010	30	"
14 / 0000	15.4	52.8	1010	30	"
14 / 0600	15.7	54.8	1010	30	"
14 / 1200	16.1	57.2	1009	35	tropical storm
14 / 1800	16.2	59.5	1009	35	"
15 / 0000	16.5	61.7	1010	30	tropical depression
15 / 0600	16.7	63.7	1010	30	"
15 / 1200	16.9	65.4	1010	30	"
15 / 1800	17.0	66.7	1011	30	"
16 / 0000	17.1	68.1	1011	30	"
16 / 0600	17.2	69.6	1010	30	"
16 / 1200	17.5	70.8	1007	35	tropical storm
16 / 1630	17.7	71.4	1007	35	"
16 / 1800	17.8	71.7	1007	35	"
17 / 0000	17.9	73.2	1006	35	"
17 / 0600	18.0	74.8	1006	40	"
17 / 1200	18.2	76.1	1005	45	"
17 / 1400	18.2	76.6	1004	50	"
17 / 1800	18.3	77.4	1003	50	"
18 / 0000	18.3	78.6	1000	50	"
18 / 0600	18.7	80.1	998	55	"
18 / 1200	19.2	81.5	993	65	hurricane
18 / 1800	19.6	83.0	990	70	"

Date/Time (UTC)	Latitude (°N)	Longitude (°W)	Pressure (mb)	Wind Speed (kt)	Stage
19 / 0000	19.7	84.8	988	70	"
19 / 0600	19.9	86.4	985	70	"
19 / 0945	20.1	87.5	978	75	"
19 / 1200	20.2	88.1	994	60	tropical storm
19 / 1800	20.5	89.5	998	45	"
20 / 0000	20.8	91.1	994	55	"
20 / 0600	20.7	92.6	991	60	"
20 / 1200	20.6	93.8	982	75	hurricane
20 / 1800	20.6	94.7	975	85	"
21 / 0000	20.7	95.8	967	105	"
21 / 0530	20.6	97.1	967	105	"
21 / 0600	20.6	97.2	969	100	"
21 / 1200	20.2	98.0	988	60	tropical storm
21 / 1800					dissipated
21 / 0000	20.7	95.8	967	105	minimum pressure and maximum wind
16 / 1630	17.7	71.4	1007	35	landfall just south of Oviedo, Dominican Republic
17 / 1400	18.2	76.6	1004	50	landfall near Black Hill, Jamaica
19 / 0945	20.1	87.5	978	75	landfall near Tulum, Mexico
21 / 0530	20.6	97.1	967	105	landfall near Tecolutla, Mexico

Table 2. Number of hours in advance of Grace's formation associated with the first NHC Tropical Weather Outlook forecast in the indicated likelihood category. Note that the timings for the "Low" category do not include forecasts of a 0% chance of genesis.

	Hours Before Genesis	
	48-Hour Outlook	**120-Hour Outlook**
Low (<40%)	60	60
Medium (40%-60%)	12	42
High (>60%)	6	12

Table 3. Selected ship reports with winds of at least 34 kt for Hurricane Grace, 13–21 August 2021.

Date/Time (UTC)	Ship call sign	Latitude (°N)	Longitude (°W)	Wind direction/ speed (kt)	Pressure (mb)
16 / 0900	MAOR6	15.2	66.6	120 / 37	1010.2
16 / 1600	C6EJ5	21.5	74.4	070 / 37	1020.0
16 / 1900	C6EJ5	20.5	74.0	070 / 37	1017.0
17 / 1600	C6EJ5	14.8	71.9	100 / 40	1019.0
19 / 1400	C6XS8	19.5	84.9	130 / 38	1012.9
19 / 1800	C6WW4	17.6	84.9	110 / 40	1013.2
19 / 1800	A8MH2	22.8	85.8	110 / 42	1016.0

Table 4. Selected surface observations for Hurricane Grace, 13–21 August 2021.

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Guadeloupe									
International Civil Aviation Organization (ICAO) Sites									
La Désirade AP (TFFA) (16.34N 61.01W)	14/1600	1011.1	14/2300	24 (1 min)	33				0.63
Antigua and Barbuda									
National Ocean Service (NOS) Sites									
Barbuda (BARA9) (17.59N 61.82W)	14/2124	1011.8							
Other Sites									
Bethesda, Antigua	14/2200	1010.6	14/2202		30 (10 m)				1.35
U.S. Virgin Islands									
ICAO Sites									
St. Croix – Henry E Rohlsen AP (TISX) (17.70N 64.81W)	15/0853	1011.5	15/0648	21	31				0.95
St. Thomas – Cyril E King AP (TIST) (18.34N 64.97W)									2.86
NOS Sites									
Charlotte Amalie (CHAV3) (18.33N 64.92W)	15/0836	1011.9	15/0530	20 (8 m)	26	0.34		0.4	
Lime Tree Bay (LTBV3) (17.69N 64.75W)	15/0818	1012.3	15/1018	19 (10 m)	28	0.32		0.4	
WeatherFlow Sites									
Two Brothers (XBRO) (18.34N 64.82W)			15/0440	28 (11 m)	36				
Buck Island (XBUK) (18.28N 64.89W)			15/1055	27 (12 m)	34				
Community Collaborative Rain, Hail, & Snow Network (CoCoRaHS) Sites									
Charlotte Amalie West 4.2 WNW (VI-ST-5) (18.36N 65.02W)									3.14
Puerto Rico									
ICAO Sites									

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
San Juan – Luis Muñoz Marín Intl. AP (TJSJ) (18.45N 66.00W)	15/0856	1012.9	15/1456	18	27				0.68
NOS Sites									
Magueyes Island (MGIP4) (17.97N 67.05W)	15/1912	1011.7	16/0442	22 (7.5 m)	30	0.53		0.6	
Esperanza (ESPP4) (18.09N 65.47W)	15/0818	1011.9	15/2242	22 (10.5 m)	26	0.31		0.4	
Mayaguez (MGZP4) (18.22N 67.16W)	15/1924	1011.2	16/0518	19 (11.5 m)	23	0.64		0.6	
WeatherFlow Sites									
Isla Culebrita Light (XCUL) (18.31N 65.23W)			15/1300	29 (11 m)	36				
Las Mareas (XMRS) (17.93N 66.16W)			15/1403	28 (10 m)	35				
El Cocal Yabucoa (XECY) (18.02N 65.86W)			15/1331	24 (39 m)	34				
Remote Automated Weather Stations (RAWS) Sites									
Vieques (VIEP4) (18.43N 65.84W)									3.44
Cabo Rojo (CRRP4) (18.09N 67.15W)									2.66
Other Sites									
San Lorenzo (SNLP4) (18.15N 65.97W)									2.18
Quebrada Arenas (SLMP4) (18.11N 65.96W)									2.16
Dominican Republic									
ICAO Sites									
Barahona – María Montez Intl. AP (MDBH) (18.20N 71.10W)	16/0900	1010.2	16/2300	25	37				7.35
La Romana Intl. AP (MDLR) (18.42N 68.95W)	15/2100	1010.5	16/1600	16	35				1.54
Other Sites									
Polo									9.45
Enriquillo									8.13
Bonao									6.41
Cabral									5.83
Bani									5.74
Mirador Sur – Santo Domingo									4.78

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
El Millón – Santo Domingo									4.44
Anamuya									4.38
Azua									4.20
Jardin Botanico									4.19
Neyba									4.00
Haiti									
ICAO Sites									
Port-au-Prince – Toussaint Louverture Intl. AP (MTPP) (18.58N 72.29W)			16/2052	22	35				
Other Sites									
Savane Zombie									12.95
Fonds-des-Negres									7.26
Petit Trou Des Nippes									3.57
Cayes									3.03
Jamaica									
ICAO Sites									
Kingston – Norman Manley Intl. AP (MKJP) (17.93N 76.78W)	17/2030	1007.2	17/2000	41	47				9.78
Montego Bay – Sangster Intl. AP (MKJS) (18.50N 77.91W)			17/2100	30	41				
Other Sites									
Mona			17/2100		44				6.96
Bois Content									14.07
Crofts Hill									12.12
Constant Spring FP									11.26
Mamee Ridge									9.02
Marshalls Pen									8.86
Bowden Pen									8.83
Norris Ramble									8.82

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Comfort Castle									8.65
Sherwood Forest									8.39
Nine Miles									7.92
Knockpatrick									7.78
Moore Town									7.56
Gibralter									7.53
Tulloch Estates									7.37
Bybrook									7.17
Palmer's Hut									7.17
Wakefield									7.17
Albany									7.11
Morant Bay									6.95
Quickstep									6.75
Serge Island									6.55
Old England									6.49
Potsdam									6.49
Ingleside									6.45
Providence									6.25
Mount Horeb									6.02
Cuba									
ICAO Sites									
Cayo Largo Del Sur – Vilo Acuña AP (MUCL) (21.62N 81.55W)			18/1705	21	35				
Santiago de Cuba – Antonio Maceo AP (MUCU) (19.97N 75.84W)			17/1850	20	39				
Holguín – Frank Pais AP (MUHG) (20.79N 76.32W)			17/1901	19	34				
Other Sites									
La Fe (78321) (21.73N 82.77W)			18/1745	32	44				
Cabo San Antonio (78310) (21.87N 84.95W)			19/0226		44				
Pinar del Río (78315) (22.42N 83.68W)			18/1722		43				

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
San Juan y Martinez (78314) (22.28N 83.83W)			18/2214		38				
La Palma (78316) (22.77N 83.55W)			18/1834		34				
Acueducto Minas de Matahambre									3.90
Embalse Los Palacios									2.60
Cayman Islands									
ICAO Sites									
Grand Cayman – Owen Roberts Intl. AP (MWCR) (19.29N 81.36W)	18/1200	993 I	18/1050	59 I	82 I				7.60
Other Sites									
North Side (FW5906) (19.37N 81.27W)	18/1031	1000.7 I	18/1031	63 I (14 m)	83 I				
Mexico									
Quintana Roo									
Playa del Carmen (XPDC) (20.58N 87.12W)	19/0852	996.4	19/0909	58 (11 m, 1 min)	74				
Cancún (XCCN) (21.06N 86.78W)	19/0857	1006.1	19/1006	55 (11 m, 1 min)	69				
Tulum (XTUL) (20.32N 87.36W)			19/0928	52 (10 m, 1 min)	79				
Puerto Morelos (XPRM) (20.83N 86.89W)	19/1001	999.8	19/1002	51 (10 m, 1 min)	66				
Cozumel (XCOZ) (20.53N 86.94W)	19/0843	998.4	19/0914	44 (11 m, 1 min)	59				
Cancún Intl. AP (MMUN) (21.03N 86.87W)	19/0843	1006.5 I	19/1041	37	52				
Cancún (21.03N 86.85W)	19/0900	1005.4	19/0800		46				
Kantunilkin (21.10N 87.49W)			19/1010		35				
Tulum (iCyclone) (20.21N 87.46W)	19/1013	978.0							
Akumal (iCyclone) (20.40N 87.32W)	19/0928	991.4							
Cozumel (20.48N 86.91W)	19/0830	999.4							5.20
Playa del Carmen (iCyclone) (20.62N 87.09W)	19/0854	999.7							

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
Yucatán									
Mérida Intl. AP (MMMD) (20.95N 89.65W)	19/2047	1001.4 [I]	19/1946	41	56				
Peto									7.20
Oxkutzcab									6.77
Becanchén									3.94
Ticul									3.46
Campeche									
Campeche Intl. AP (MMCP) (19.85N 90.55W)	20/2344	1006.6 [I]	20/1933	25	35				
Hecelchakán									4.33
Bolonchen									3.74
Veracruz									
Tuxpan (20.96N 97.42W)	21/0500	1001.2	21/0600	40	65				
Xalapa (19.51N 96.84W)			21/1030	35	57				
La Guadalupe (iCyclone) (20.38N 96.92W)	21/0455 21/0509 21/0512	981.4							
La Vigueta (iCyclone) (20.32N 96.86W)	21/0500	985.7							
Paso de Piedras									10.24
El Raudal									9.98
Milcahual									9.27
Puebla									
Xicotepec de Juárez									11.99
Sontalalco									10.68
La Soledad									9.46
Hidalgo									
Tulancingo			21/1000		35				
Atlapexco									15.69
San Felipe Orizatlán									12.05
Zacualtipán									11.70
Offshore									
NOAA Buoys									

Location	Minimum Sea Level Pressure		Maximum Surface Wind Speed			Storm surge (ft)[c]	Storm tide (ft)[d]	Estimated Inundation (ft)[e]	Total rain (in)
	Date/ time (UTC)	Press. (mb)	Date/ time (UTC)[a]	Sustained (kt)[b]	Gust (kt)				
42056 – Yucatan Basin (19.82N 84.95W)			19/0108	47 (4 m, 1 min)	54				
42055 – Campeche (22.12N 93.94W)	20/1200	1004.3	20/1801	41 (4 m, 1 min)	49				

[a] Date/time is for sustained wind when both sustained and gust are listed.
[b] Except as noted, sustained wind averaging periods for C-MAN and land-based reports are 2 min; buoy averaging periods are 8 min.
[c] Storm surge is water height above normal astronomical tide level.
[d] For most locations, storm tide is water height above the North American Vertical Datum of 1988 (NAVD88). Storm tide is water height above Mean Lower Low Water (MLLW) for NOS stations in Puerto Rico, the U.S. Virgin Islands, and Barbados.
[e] Estimated inundation is the maximum height of water above ground. For some USGS storm tide pressure sensors, inundation is estimated by subtracting the elevation of the sensor from the recorded storm tide. For other USGS storm tide sensors and USGS high-water marks, inundation is estimated by subtracting the elevation of the land derived from a Digital Elevation Model (DEM) from the recorded and measured storm tide. For NOS tide gauges, the height of the water above Mean Higher High Water (MHHW) is used as a proxy for inundation.

Table 5a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Hurricane Grace. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	27.9	42.4	62.7	80.4	97.9	120.3	212.5	365.3
OCD5	37.9	71.2	117.7	169.1	235.0	304.8	451.8	643.5
Forecasts	31	29	27	25	23	21	17	13
OFCL (2016-20)	23.9	36.3	49.1	63.9	83.7	94.1	128.1	169.7
OCD5 (2016-20)	45.1	97.2	157.2	216.7	257.6	325.4	414.4	490.0

Table 5b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Hurricane Grace. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 5a due to the homogeneity requirement.

Model ID	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	23.8	35.0	54.0	65.0	72.7	89.4	149.9	172.5
OCD5	33.5	62.4	106.6	161.3	245.3	324.6	506.2	750.0
GFSI	24.1	38.1	55.6	72.8	93.2	118.9	190.8	**171.8**
HMNI	**22.0**	39.4	61.0	74.4	80.8	91.8	**140.7**	**131.3**
HWFI	30.9	54.7	82.6	100.0	120.8	151.6	181.9	**152.2**
EMXI	24.4	35.9	56.5	65.1	75.1	100.6	**144.5**	**109.7**
CMCI	23.9	36.9	57.1	75.3	102.5	135.4	227.7	282.8
NVGI	30.9	45.4	65.2	81.5	101.1	128.9	167.8	**111.1**
CTCI	29.0	46.4	62.2	76.7	99.9	125.8	168.8	264.6
AEMI	**23.4**	35.3	**53.9**	**64.9**	80.7	109.3	164.0	**106.5**
HCCA	24.1	37.8	55.0	67.1	76.9	95.3	153.1	173.1
TVCX	24.0	35.9	**50.5**	**61.5**	**70.1**	**87.3**	**137.3**	**110.2**
GFEX	**22.8**	**31.7**	**49.1**	**58.0**	74.1	**89.0**	**140.0**	**84.3**
TVCA	24.8	37.2	**51.2**	**63.2**	73.3	90.4	**141.0**	**121.7**
TVDG	**23.6**	36.1	**50.9**	**61.3**	74.6	**86.7**	**134.0**	**95.7**
TABD	26.0	44.7	68.9	98.8	138.0	195.3	310.6	213.8
TABM	25.4	41.4	60.1	78.0	94.5	124.3	200.3	272.4
TABS	42.9	88.1	125.0	151.8	165.1	163.2	172.1	229.3
Forecasts	24	23	21	18	15	13	7	2

Table 6a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Hurricane Grace. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	6.9	9.8	12.2	15.4	15.0	14.3	20.3	25.0
OCD5	8.5	13.1	16.2	17.4	19.5	18.4	18.2	18.5
Forecasts	31	29	27	25	23	21	17	13
OFCL (2016-20)	5.4	8.0	9.6	10.9	11.5	12.1	13.3	14.5
OCD5 (2016-20)	7.0	11.0	14.3	16.8	18.5	19.7	21.7	23.0

Table 6b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Hurricane Grace. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 6a due to the homogeneity requirement.

Model ID	Forecast Period (h)							
	12	24	36	48	60	72	96	120
OFCL	6.2	9.1	12.1	16.7	15.3	12.7	17.5	25.0
OCD5	8.2	13.1	16.2	18.7	20.1	17.4	21.2	**17.5**
GFSI	7.8	10.4	**11.7**	**15.3**	18.7	18.0	26.7	44.0
HMNI	**6.0**	**7.6**	**10.7**	**15.8**	15.5	15.3	20.8	33.5
HWFI	6.2	9.5	13.2	**16.1**	**14.0**	16.0	29.3	**13.0**
EMXI	9.3	12.8	13.2	**14.8**	22.7	29.3	44.5	57.5
CMCI	9.9	13.1	13.2	**16.1**	17.3	17.7	23.0	31.5
NVGI	7.8	12.4	14.8	**13.5**	**14.0**	14.3	24.5	44.5
CTCI	6.8	**9.0**	**9.3**	**12.5**	**14.5**	**12.6**	**16.8**	**23.0**
AEMI	9.0	13.1	14.0	**14.9**	16.0	18.1	26.3	35.0
HCCA	**5.3**	**7.4**	**10.8**	**13.8**	**14.5**	12.8	**12.5**	27.0
DSHP	7.6	11.2	15.5	20.0	21.3	22.0	17.8	26.0
LGEM	8.2	12.1	16.9	19.4	19.5	16.9	**15.3**	29.0
ICON	**5.9**	**8.7**	12.1	**16.5**	16.8	16.0	**10.3**	**18.0**
IVCN	**5.9**	**8.5**	**11.1**	**15.4**	**15.1**	13.9	**10.5**	**19.0**
IVDR	**5.7**	**8.2**	**10.1**	**14.3**	**14.1**	13.0	**10.7**	**20.0**
Forecasts	24	23	21	18	15	13	6	2

Table 7. Watch and warning summary for Hurricane Grace, 13–21 August 2021.

Date/Time (UTC)	Action	Location
13 / 1500	Tropical Storm Watch issued	Antigua, Barbuda, St. Kitts and Nevis, and Montserrat
13 / 1500	Tropical Storm Watch issued	Saba and Sint Eustatius
13 / 2100	Tropical Storm Watch issued	U.S. Virgin Islands and Puerto Rico, including Vieques and Culebra
13 / 2100	Tropical Storm Watch issued	Anguilla and British Virgin Islands
13 / 2100	Tropical Storm Watch issued	St. Martin and St. Barthelemy
13 / 2100	Tropical Storm Watch issued	Sint Maarten
14 / 0000	Tropical Storm Watch changed to Tropical Storm Warning	St. Martin and St. Barthelemy
14 / 0000	Tropical Storm Watch changed to Tropical Storm Warning	Sint Maarten
14 / 0000	Tropical Storm Watch changed to Tropical Storm Warning	Antigua, Barbuda, St. Kitts and Nevis, and Montserrat
14 / 0000	Tropical Storm Watch changed to Tropical Storm Warning	Saba and Sint Eustatius
14 / 0000	Tropical Storm Watch changed to Tropical Storm Warning	Anguilla
14 / 0900	Tropical Storm Watch changed to Tropical Storm Warning	U.S. Virgin Islands and Puerto Rico, including Vieques and Culebra
14 / 1200	Tropical Storm Watch changed to Tropical Storm Warning	British Virgin Islands
14 / 1500	Tropical Storm Watch issued	Dominican Republic from Cabo Frances Viejo to Cabo Caucedo
15 / 0000	Tropical Storm Watch issued	Samana westward to Haiti/DR Border
15 / 0000	Tropical Storm Watch issued	Haiti/DR Border eastward to Cabo Caucedo
15 / 0000	Tropical Storm Warning issued	Cabo Caucedo northward to Samana
15 / 0300	Tropical Storm Watch issued	Entire coast of Haiti
15 / 0300	Tropical Storm Warning discontinued	Anguilla and British Virgin Islands
15 / 0300	Tropical Storm Warning discontinued	Antigua, Barbuda, St. Kitts and Nevis, and Montserrat

15 / 0900	Tropical Storm Warning modified to	Dominican Republic from Samana to S Bdr Haiti/DR
15 / 1200	Tropical Storm Warning discontinued	St. Martin and St. Barthelemy
15 / 1200	Tropical Storm Warning discontinued	Sint Maarten
15 / 1200	Tropical Storm Warning discontinued	Saba and Sint Eustatius
15 / 2100	Tropical Storm Warning changed to Tropical Storm Watch	Dominican Republic from S Bdr Haiti/DR to Samana
15 / 2100	Tropical Storm Warning discontinued	U.S. Virgin Islands and Puerto Rico, including Vieques and Culebra
16 / 1200	Tropical Storm Watch issued	Jamaica
16 / 1500	Tropical Storm Watch issued	Southern coast of Cuban provinces of Ciego de Avila, Sancti Spiritus, Cienfuegos, and Matanzas
16 / 1500	Tropical Storm Watch issued	Isla de la Juventud
16 / 1500	Tropical Storm Warning issued	Southern coast of Cuban provinces of Santiago de Cuba, Granma, Las Tunas, and Camaguey
16 / 1500	Tropical Storm Warning issued	Cayman Islands
16 / 1800	Tropical Storm Watch discontinued	Dominican Republic
17 / 0300	Tropical Storm Watch issued	Southern coast of Cuban province of Pinar del Rio
17 / 0900	Hurricane Watch issued	Cabo Catoche to Punta Allen
17 / 1200	Tropical Storm Watch changed to Tropical Storm Warning	Jamaica
17 / 1800	Tropical Storm Watch discontinued	Haiti
17 / 2100	Tropical Storm Warning issued	Cancun to Cabo Catoche
17 / 2100	Tropical Storm Warning issued	Punta Herrero to Puerto Costa Maya
17 / 2100	Hurricane Watch discontinued	Cabo Catoche to Cancun
17 / 2100	Hurricane Watch issued	Cayman Islands
17 / 2100	Hurricane Warning issued	Cancun to Punta Herrero
18 / 0300	Tropical Storm Watch issued	Dzilam to Campeche
18 / 0300	Tropical Storm Warning modified to	Southern coast of Cuban provinces of Granma, Las Tunas, and Camaguey

18 / 0300	Tropical Storm Warning modified to	Cancun to Dzilam
18 / 0900	Tropical Storm Watch discontinued	Southern coast of Cuban provinces of Ciego de Avila, Sancti Spiritus, Cienfuegos, and Matanzas
18 / 0900	Tropical Storm Warning discontinued	Southern coast of Cuban provinces of Granma, Las Tunas, and Camaguey
18 / 0900	Tropical Storm Warning discontinued	Jamaica
18 / 0900	Tropical Storm Warning modified to	Cancun to Campeche
18 / 1500	Hurricane Watch discontinued	Cayman Islands
19 / 0000	Tropical Storm Warning discontinued	Cayman Islands
19 / 0300	Tropical Storm Watch issued	Cabo Rojo to Puerto de Altamira
19 / 0300	Hurricane Watch issued	Puerto Veracruz to Cabo Rojo
19 / 1500	Hurricane Watch changed to Hurricane Warning	Puerto Veracruz to Cabo Rojo
19 / 1500	Tropical Storm Watch discontinued	Cuba
19 / 1500	Tropical Storm Warning modified to	Tulum to Campeche
19 / 1500	Tropical Storm Warning discontinued	Punta Herrero to Puerto Costa Maya
19 / 1500	Tropical Storm Warning issued	Cabo Rojo to Barra del Tordo
19 / 1500	Hurricane Warning discontinued	Cancun to Punta Herrero
20 / 0300	Tropical Storm Warning modified to	Progreso to Campeche
20 / 0900	Tropical Storm Warning discontinued	Progreso to Campeche
21 / 1500	Tropical Storm Warning modified to	Puerto Veracruz to Barra del Tordo
21 / 1500	Hurricane Warning discontinued	All
21 / 2100	Tropical Storm Warning discontinued	All

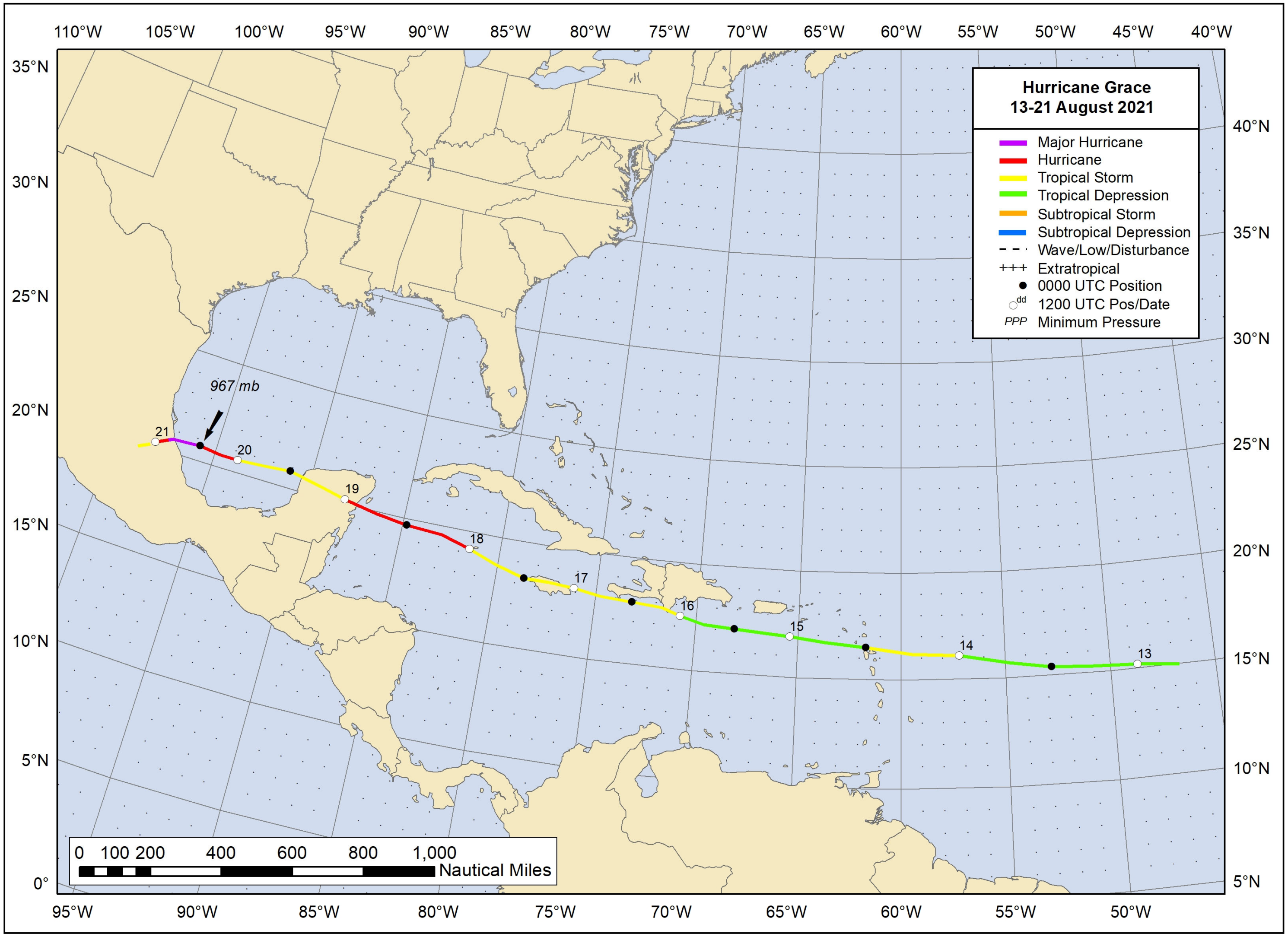

Figure 1. Best track positions for Hurricane Grace, 13–21 August 2021.

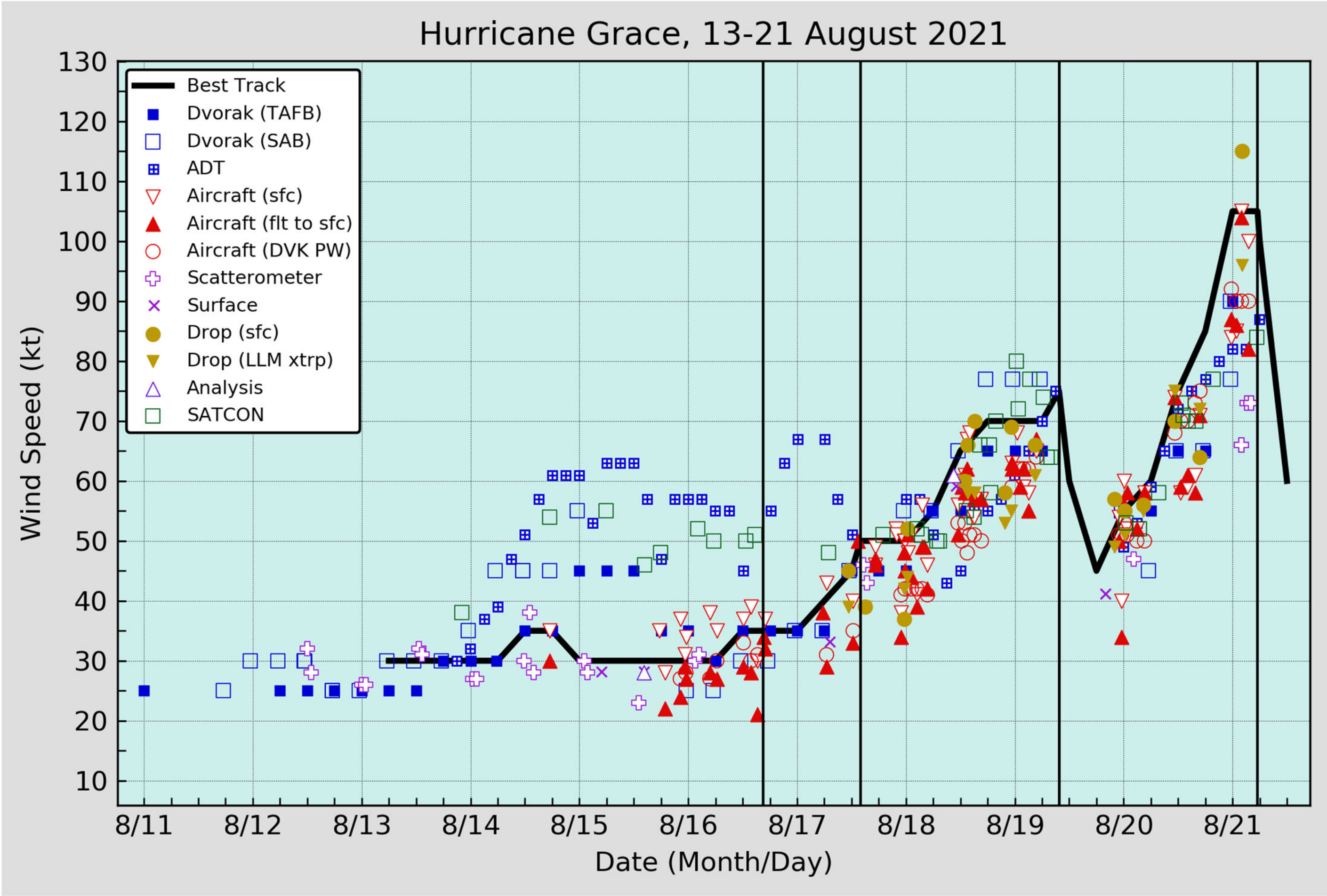

Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Grace, 13–21 August 2021. Aircraft observations have been adjusted for elevation using 90%, 80%, and 75% adjustment factors for observations from 700 mb, 850 mb, and 925 mb, respectively. Dropwindsonde observations include actual 10 m winds (sfc), as well as surface estimates derived from the mean wind over the lowest 150 m of the wind sounding (LLM). Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. Dashed vertical lines correspond to 0000 UTC, and solid vertical lines correspond to landfalls.

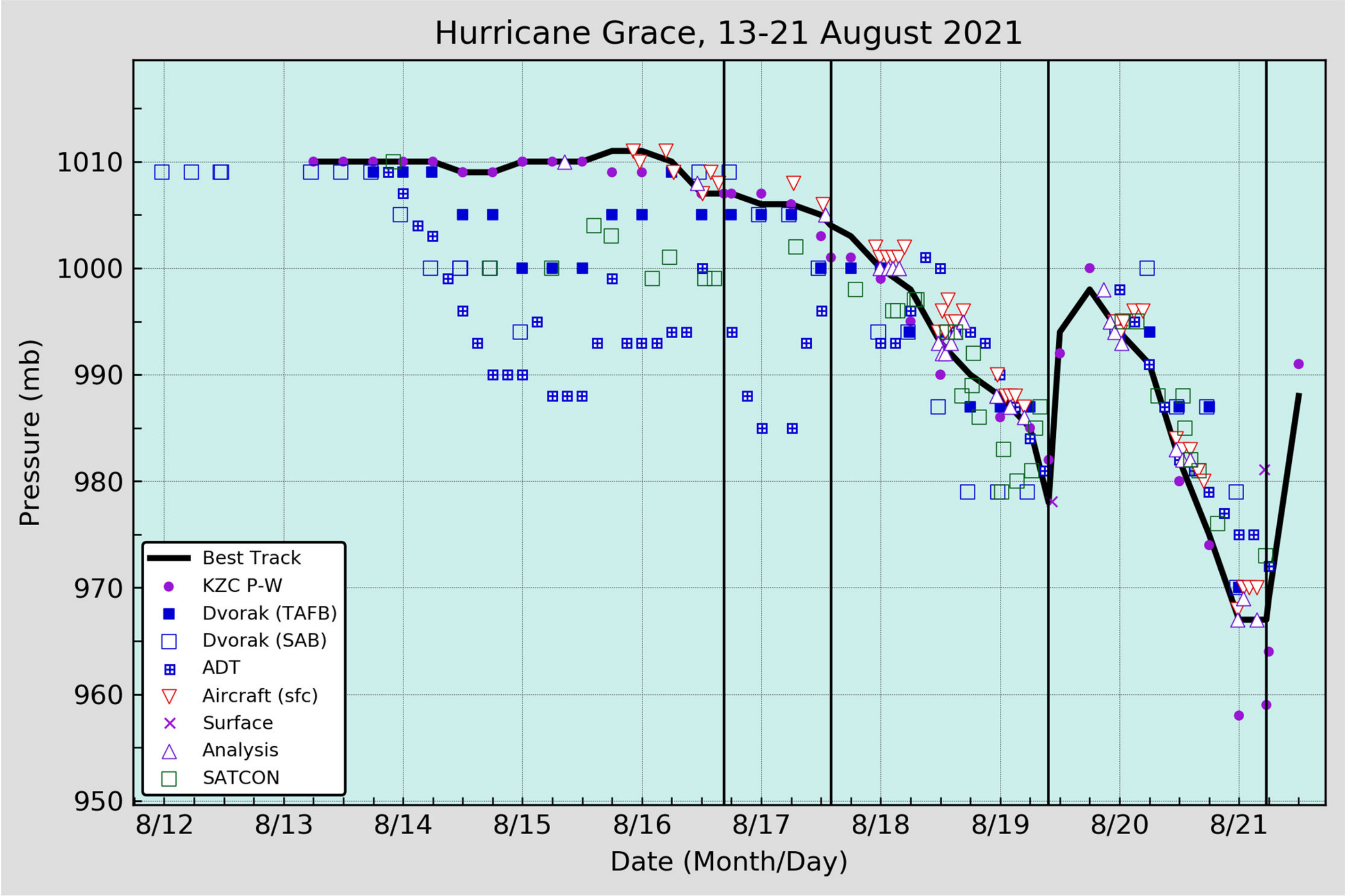

Figure 3. Selected pressure observations and best track minimum central pressure curve for Hurricane Grace, 13–21 August 2021. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. KZC P-W refers to pressure estimates derived using the Knaff-Zehr-Courtney pressure-wind relationship. Dashed vertical lines correspond to 0000 UTC, and solid vertical lines correspond to landfalls.

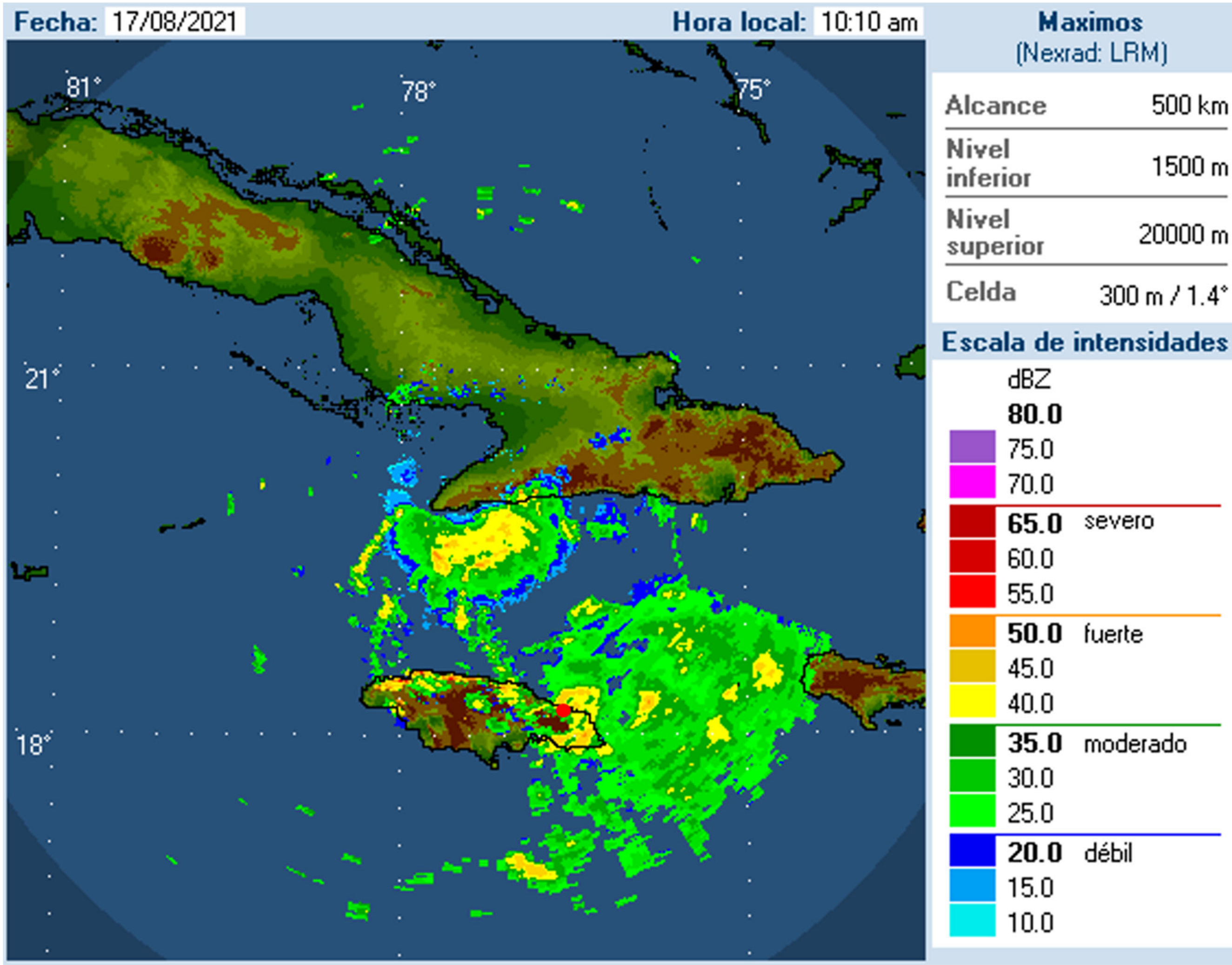

Figure 4. Pilón, Cuba radar image of Tropical Storm Grace at 1410 UTC 17 August, shortly after Grace's landfall along the northeastern coast of Jamaica. The red marker indicates the estimated center position. Image courtesy Cuban Meteorological Institute via Brian McNoldy, Univ. of Miami, Rosenstiel School.

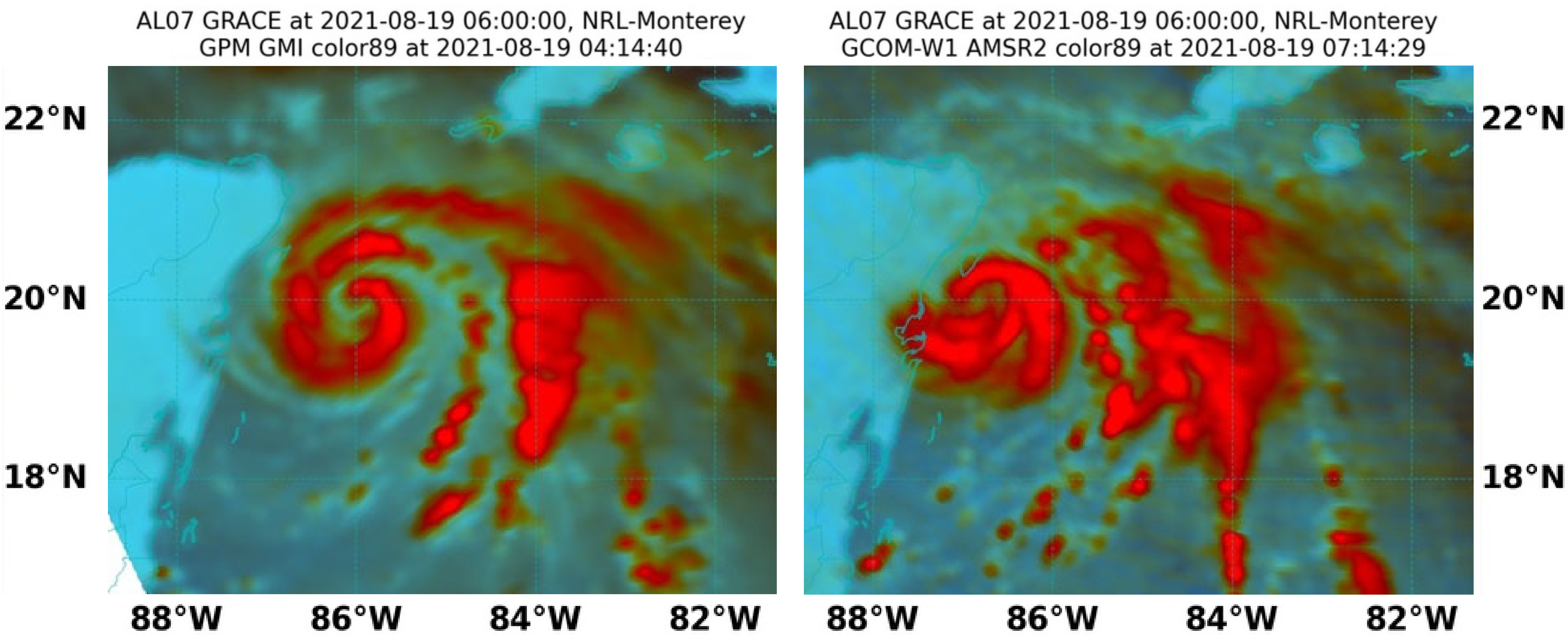

Figure 5. Passive 89-GHz color composite microwave images of Hurricane Grace at 0414 UTC 19 August (left) and 0714 UTC 19 August (right), shortly before it made landfall on the Yucatan Peninsula of Mexico. Images courtesy NRL Monterey.

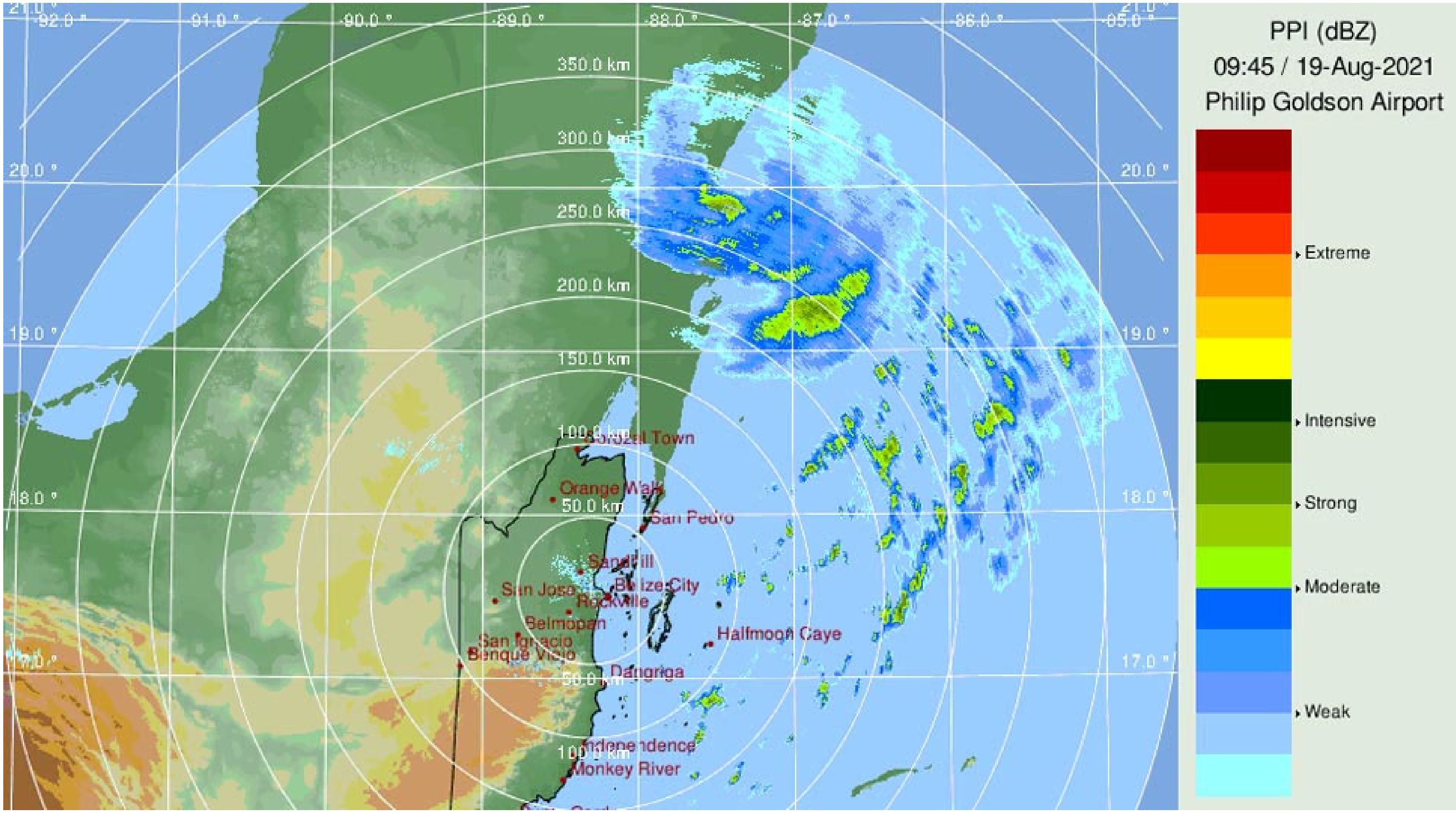

Figure 6. Belize radar image at 0945 UTC 19 August, around the time of Hurricane Grace's landfall on the Yucatan Peninsula of Mexico. Image courtesy of the National Meteorological Service of Belize.

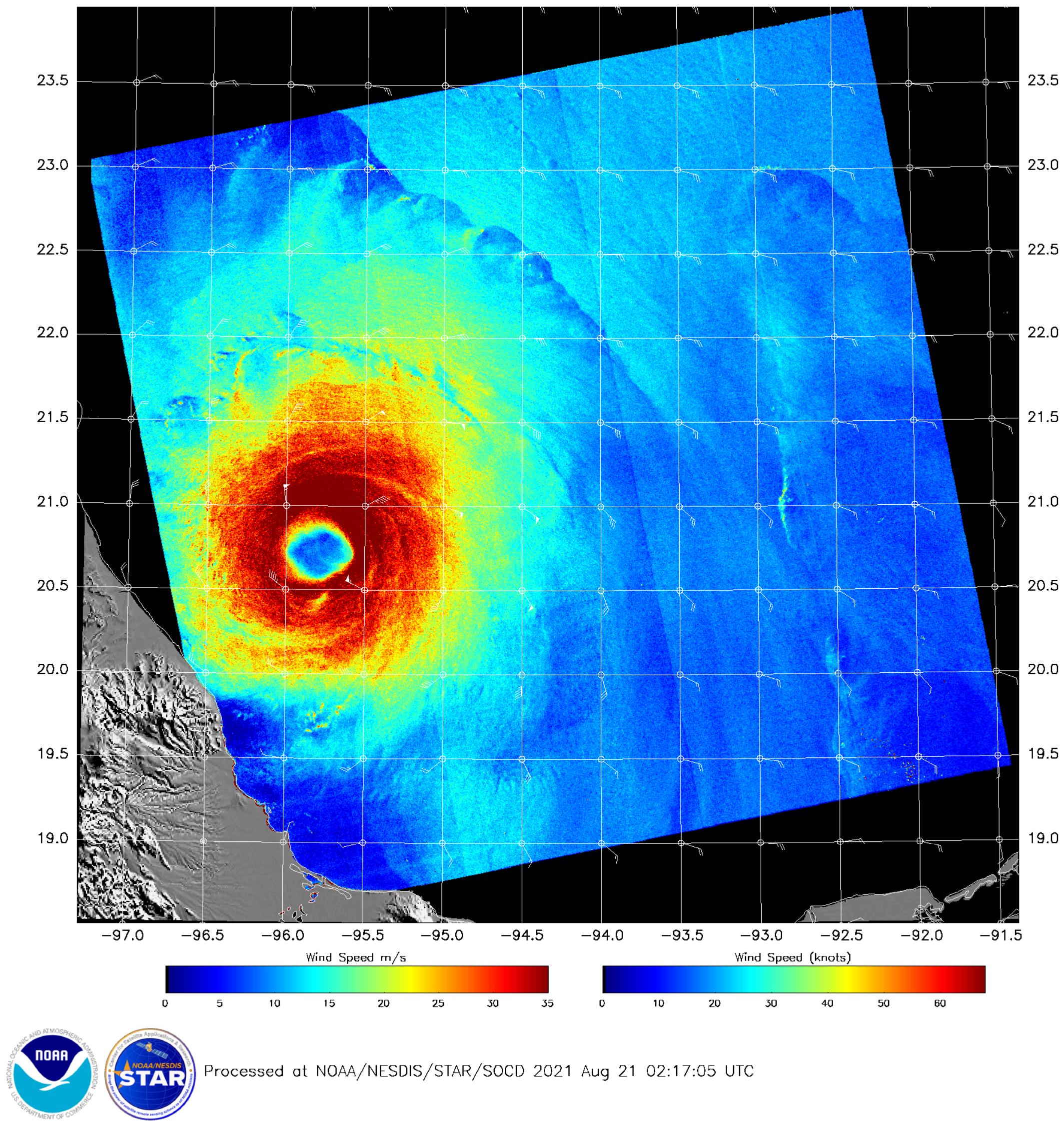

Figure 7. Preliminary Synthetic Aperture Radar (SAR) imagery of Hurricane Grace at 0022 UTC 21 August over the southwestern Gulf of Mexico. Image courtesy NOAA/NESDIS/STAR.

Figure 8. Altamira, Mexico radar image of Hurricane Grace at 0442 UTC 21 August, shortly before its landfall along the coast of mainland Mexico near Tecolutla. Image courtesy of the National Meteorological Service of Mexico.

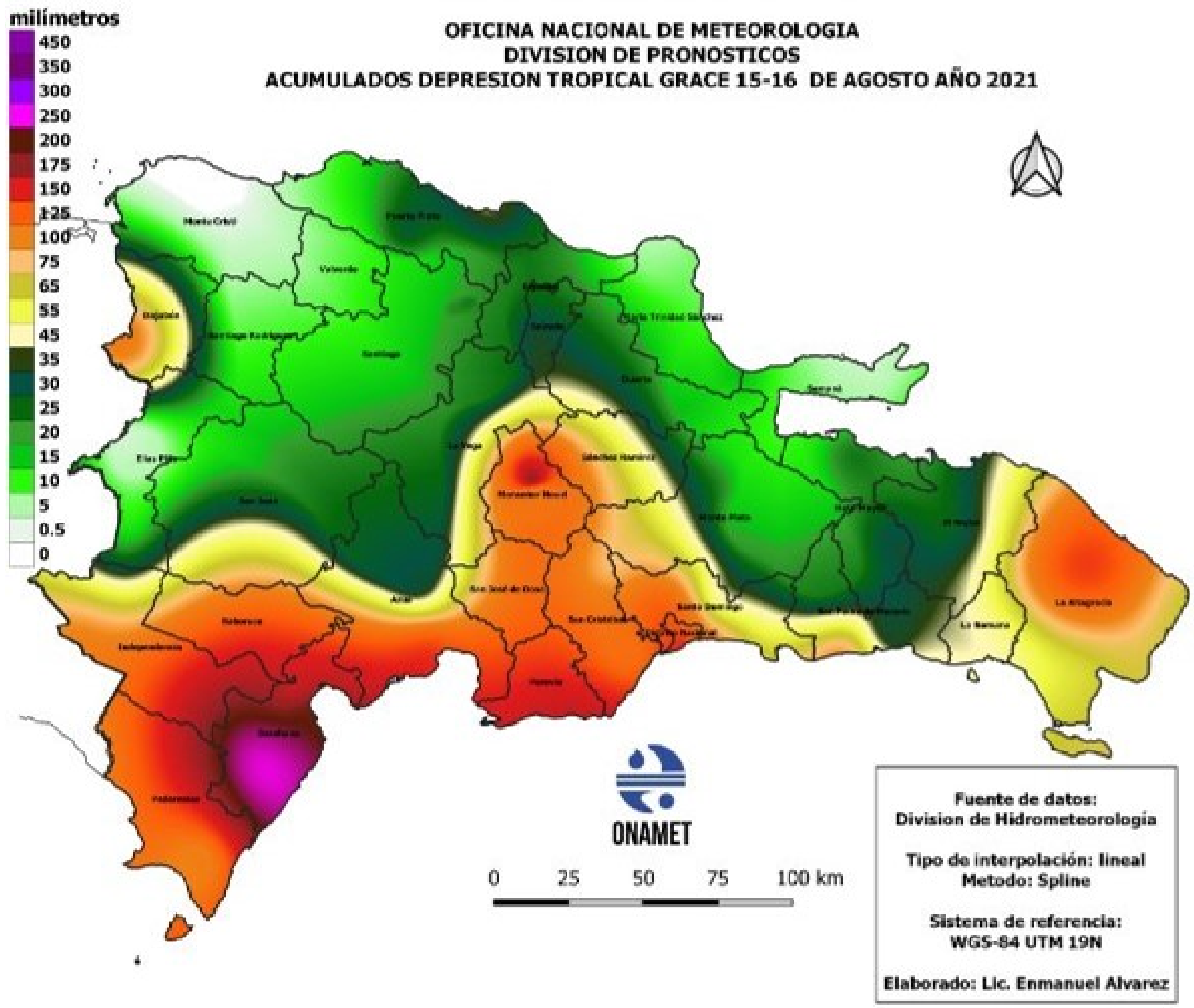

Figure 9. Rainfall accumulations (mm) from Grace in the Dominican Republic. Image courtesy of the National Meteorological Service of the Dominican Republic (ONAMET).

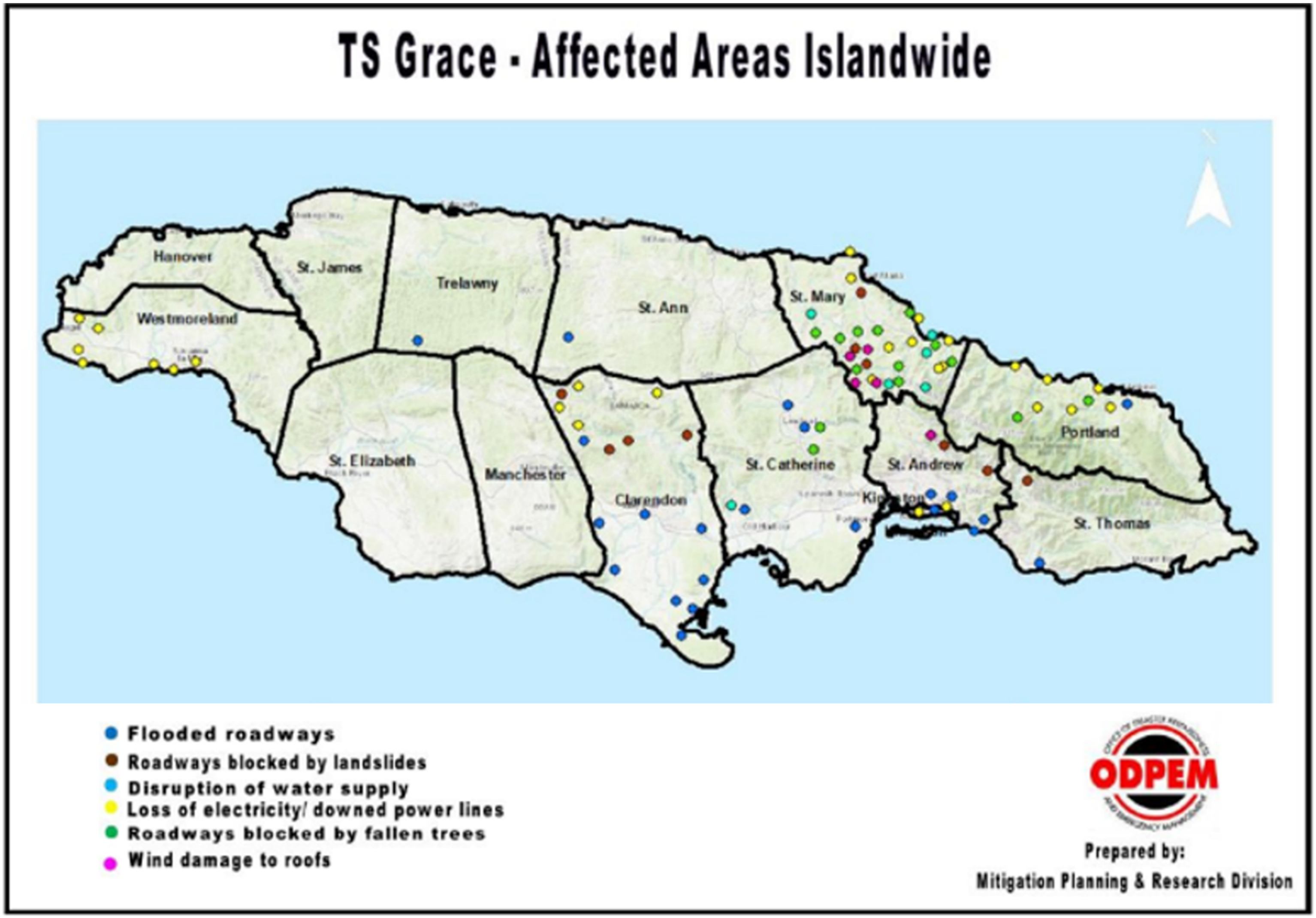

Figure 10. Map of flooding and damage reports across Jamaica from Grace. Image courtesy of Jamaica's Office of Disaster Preparedness and Emergency Management (ODPEM) via the Caribbean Disaster Emergency Management Agency.

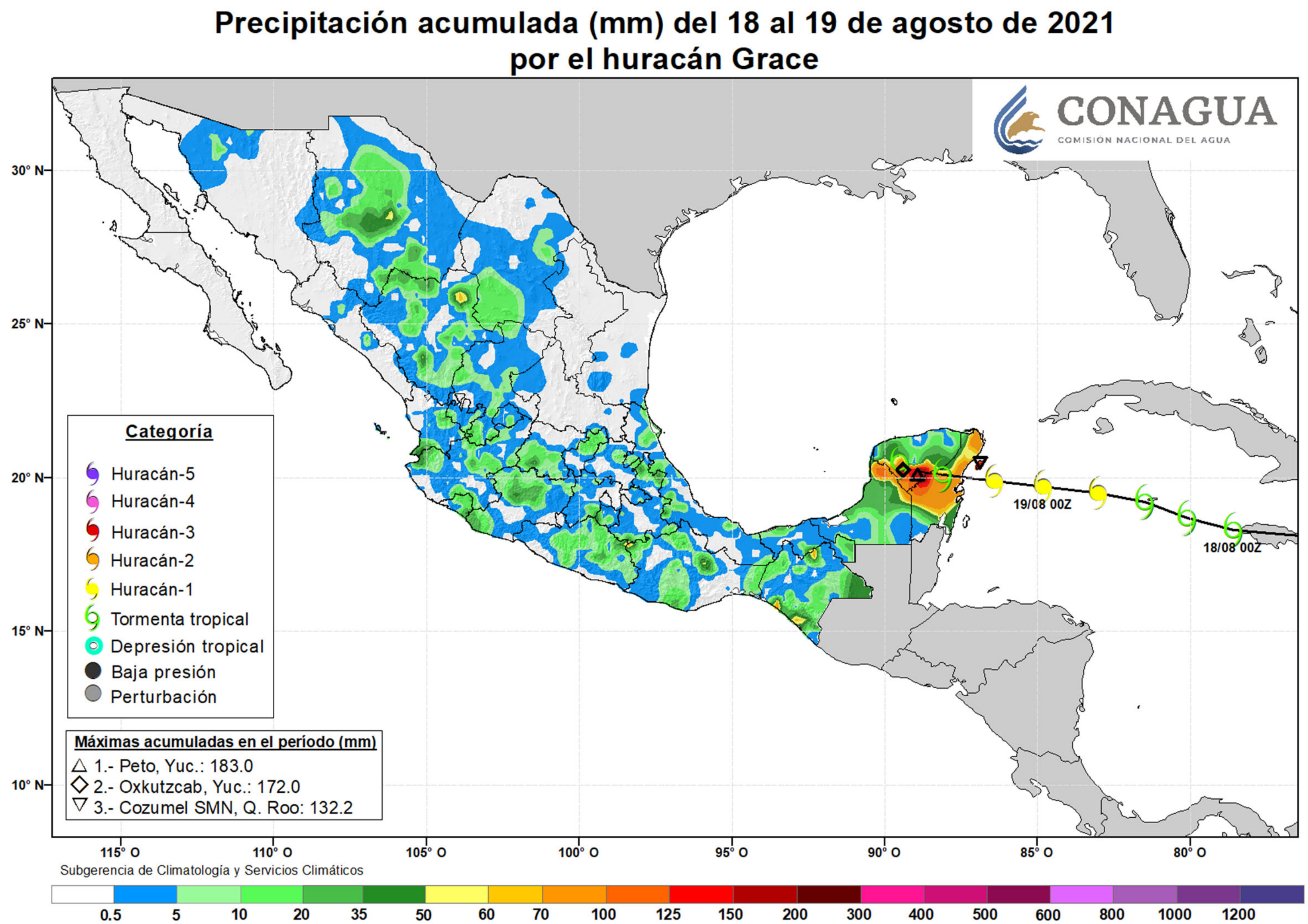

Figure 11. Rainfall accumulations (mm) from 18–19 August 2021 during Hurricane Grace's first landfall in Mexico. Track and intensity are based on the operational NHC assessment. Image courtesy of CONAGUA and the National Meteorological Service of Mexico.

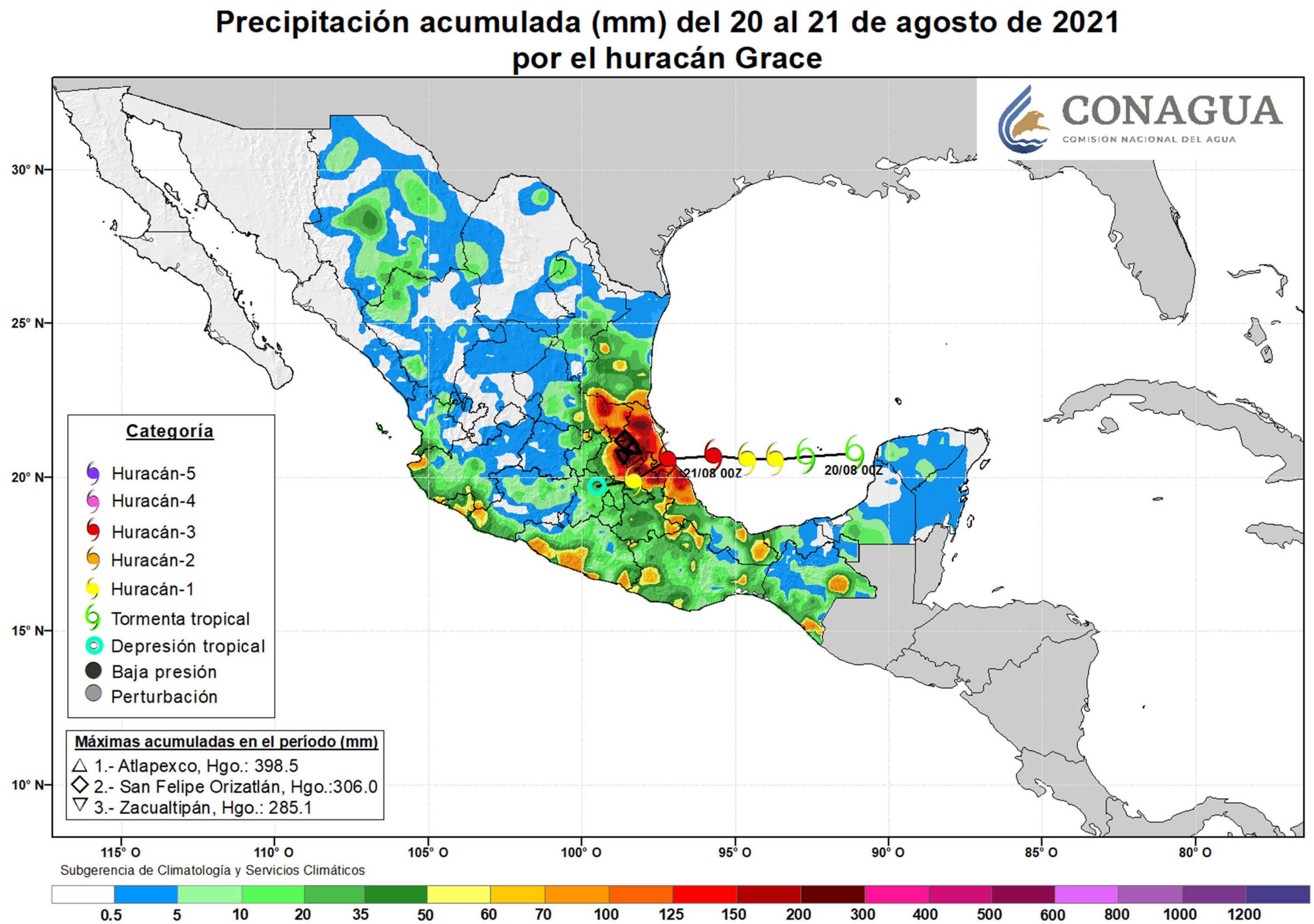

Figure 12. Rainfall accumulations (mm) from 20–21 August 2021 during Hurricane Grace's second landfall in Mexico. Track and intensity are based on the operational NHC assessment. Image courtesy of CONAGUA and the National Meteorological Service of Mexico.

Figure 13. Damage on Jamaica caused by Grace. Left: Landslide debris blocking a road in Westmoreland Parish. Right: Troy Bridge collapse at the border of Manchester and Trelawny Parishes. Photo credit: *Jamaica Observer*.

Figure 14. Damage and flooding on Grand Cayman caused by Grace. Top row photo credit: Taneos Ramsay, *Cayman Compass*. Bottom row photo credit: Cayman Islands police helicopter X-Ray One via *Cayman Compass*.

Figure 15. Hurricane Grace impacts in the Mexican state of Quintana Roo. Left: Damaged power lines and debris along a highway in Tulum. Photo credit: Marco Ugarte/*Associated Press*. Right: A downed highway sign blocking a highway in Tulum. Photo credit: Paola Chiomante/*Reuters*.

Figure 16. Hurricane Grace impacts in the Mexican state of Veracruz. Top left: Damaged home along the coast in Tecolutla. Photo credit: Felix Marquez/*Associated Press*. Top right: Destroyed building in Costa Esmeralda. Photo credit: Yahir Ceballos/*Reuters*. Bottom left: Six people perished in this landslide that buried a home in Xalapa. Photo credit: *Reuters*. Bottom right: Severe flash flooding in Xalapa. Photo credit: *Infobae*.

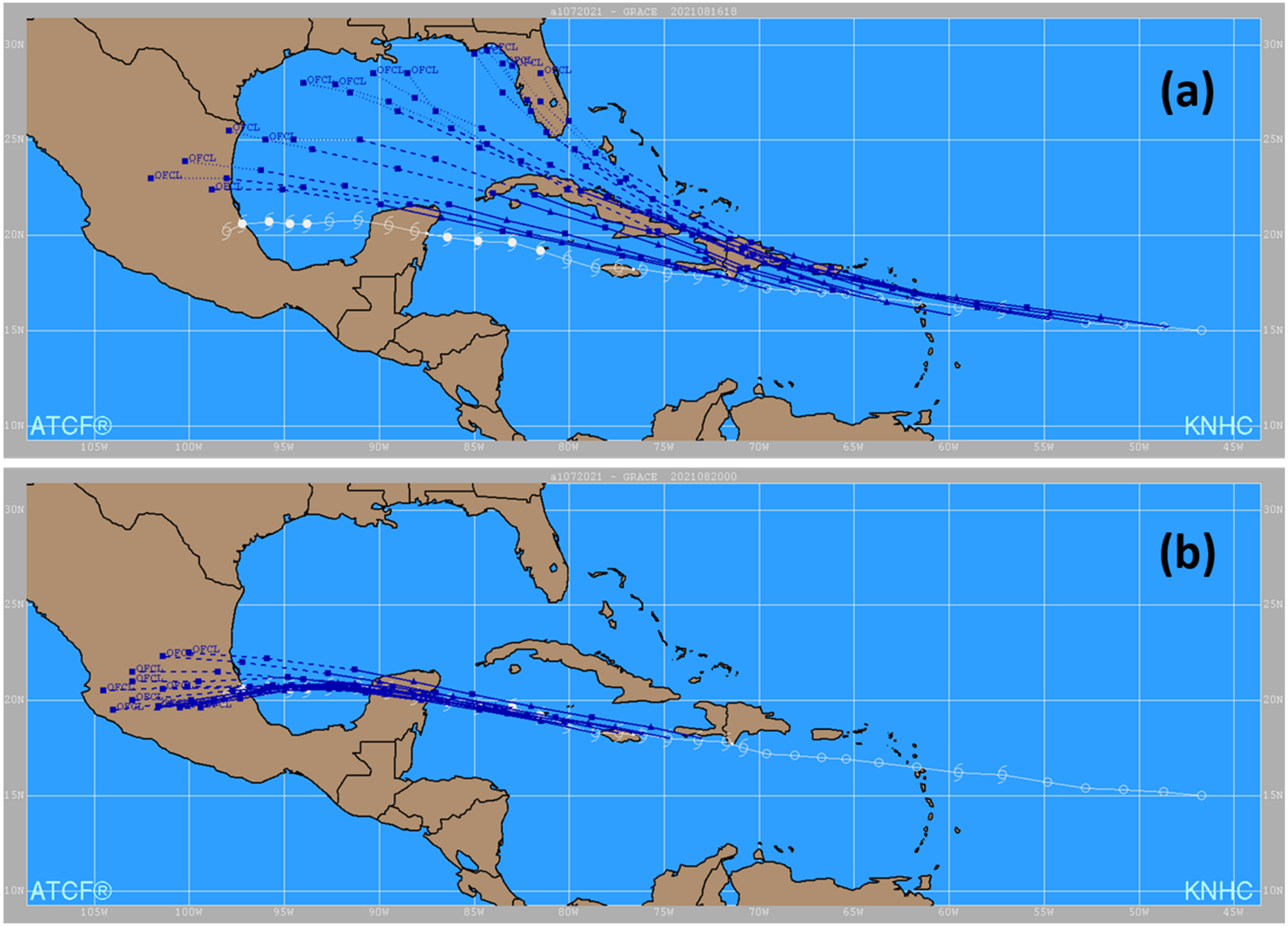

Figure 17. NHC five-day official track forecasts (blue lines) for Grace from (a) 1800 UTC 13 August to 1800 UTC 16 August and (b) 0000 UTC 17 August to 0000 UTC 20 August. The best track of Grace is indicated by the solid white line and cyclone symbols in both images.

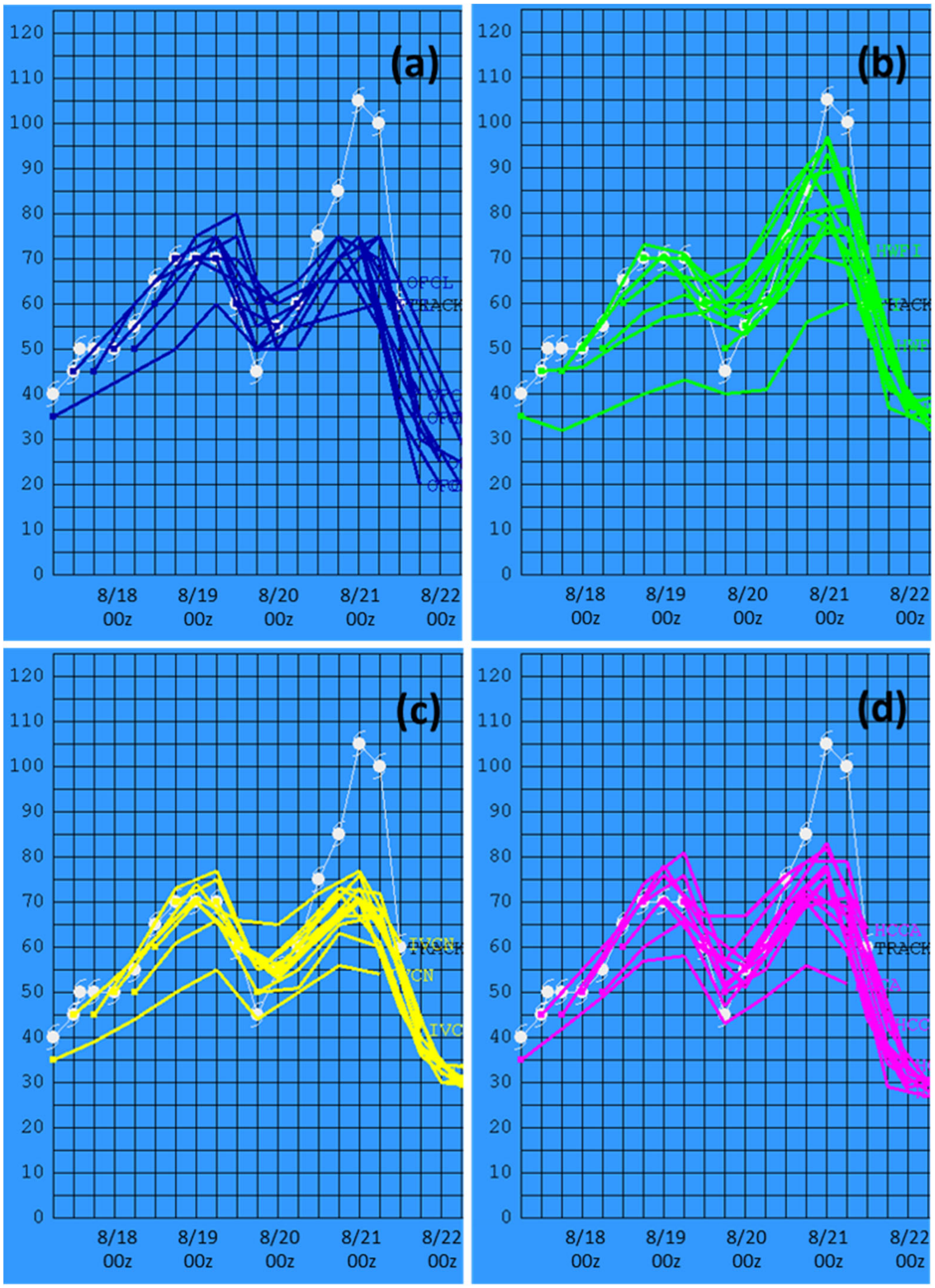

Figure 18. (a) NHC official [OFCL, blue], (b) Hurricane Weather Research and Forecasting model [HWFI, green], (c) Intensity variable consensus [IVCN, yellow], and (d) HFIP corrected consensus approach [HCCA, pink] intensity forecasts (kt) for Grace from 0600 UTC 17 August to 0600 UTC 20 August. The best track intensity of Grace is indicated by the solid white line and cyclone symbols at 6-h intervals.