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Atlantic Hurricane Season of 2011

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ABSTRACT

The 2011 Atlantic season was marked by above average tropical cyclone activity with the formation of nineteen tropical storms. Seven of the storms became hurricanes and four became major hurricanes (category 3 or higher on the Saffir-Simpson Hurricane Wind Scale). The numbers of tropical storms and hurricanes were above the long-term averages of 12 named storms, 6 hurricanes, and 3 major hurricanes. Despite the high level of activity, Irene was the only hurricane to hit land in 2011, striking both the Bahamas and the United States. Other storms, however, affected the United States, eastern Canada, Central America, eastern Mexico and the northeastern Caribbean Sea islands. The death toll from the 2011 Atlantic tropical cyclones is 81.

National Hurricane Center mean official track forecast errors in 2011 were smaller than the previous 5-yr means at all forecast times except 120 h. In addition, the official track forecast errors set records for accuracy at the 24-, 36-, 48-, and 72-h forecast times. The mean intensity forecast errors in 2011 ranged from about 6 kt at 12 h to about 17 kt at 72 and 120 h. These errors were below the 5-yr means at all forecast times.

1. Introduction

Tropical cyclone activity during the 2011 Atlantic season (Fig. 1, Table 1) was well above average with the formation of nineteen tropical storms – tying the 1995 and 2010 seasons for the third highest total on record behind 2005 and 1933. Seven storms became hurricanes, and four of the hurricanes became major hurricanes [maximum 1-min winds of greater than 95 kt (1 kt = 0.5144 ms^{-1}), corresponding to category 3 or higher on the Saffir-Simpson Hurricane Wind Scale SSHWS, (Saffir 1973, Simpson 1974, National Weather Service 2010)]. In addition, there was one tropical depression that did not reach storm strength. The numbers of tropical storms, hurricanes and major hurricanes were above the long-term (1981–2010) averages of about 12, 6, and 3, respectively. In terms of accumulated cyclone energy [(ACE; Bell et al. 2000); the sum of the squares of the maximum wind speed at 6-h intervals for tropical (or subtropical) storms and hurricanes], activity in 2011 was about 137% of the long-term (1981–2010) median value of 92.4 $\times 10^4$ kt^2, the 11th busiest year since 1981.

The above-average activity observed in 2011 was primarily the result of two factors: Above-normal sea-surface temperatures (SSTs) and below-normal vertical wind shear prevailed across most of the tropical Atlantic Ocean and Caribbean Sea for the peak months of August to October (Fig. 2). Low vertical wind shear over the tropical Atlantic generally coincides with the presence of a La Nina event in the Pacific Ocean (Gray 1984), and this was the case during 2011.

Although some of the tropical cyclones originated from frontal systems in the subtropics and moved generally northeastward over the Atlantic, most of them formed in the deep tropics, with four major hurricanes developing from tropical waves. One group of tropical cyclones formed in the western Caribbean Sea and moved generally toward Central America and Mexico, steered by the flow around a ridge located across the U. S. southern plains and the northwestern coast of the Gulf of Mexico. The other group of tropical storms formed over the central tropical Atlantic and recurved over the western part of the basin; This resulted from a tendency for a middle-latitude trough to become established along the U.S east coast (Fig. 3), and this flow pattern steered most of the storms away from the eastern seaboard. Still, one hurricane, Irene struck the United States and the Bahamas. A total of 81 deaths can be attributed to tropical cyclone activity from the 2011 hurricane season.

2. Individual storm summaries

The individual cyclone summaries in this paper are based on post-storm meteorological analyses by the National Hurricane Center (NHC) using *in situ* and remotely sensed data from geostationary and polar-orbiting satellites, aircraft reconnaissance, weather radars, ships, buoys, and conventional land-based surface and upper-air observations. The National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES) and Meteosat-9 serve as the primary platforms. GOES-East and Meteosat-9 provide the visible and infrared imagery that serve as input for position and intensity estimates based on the Dvorak classification technique (Dvorak 1984; Velden et al. 2006). Subjective Dvorak intensity estimates used by NHC are performed by NHC's Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB) in Camp Springs, Maryland. The Advanced Dvorak Technique (ADT; Olander and Velden 2007) is an objective method that also provides additional satellite intensity estimates of tropical cyclones using geostationary imagery. In-depth descriptions of all data sources have been provided in previous seasonal summaries (e.g., Franklin and Brown 2008), and by Rappaport et al. (2009). There were no significant changes in data sources during the 2011 season.

Post-storm analyses result in the creation of a "best track" database for each cyclone, consisting of 6-hourly representative estimates of the cyclone's center location, maximum sustained (1-min average) surface (10-m) wind, minimum sea-level pressure, and maximum extent of 34-, 50-, and 64-kt winds in each of the four ordinal (northeast, southeast, southwest, and northwest) quadrants of the cyclone. A system is designated as a tropical cyclone in the best track at a particular time if NHC determines that it satisfies the following definition: "A warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center, (OFCM 2010). The tracks and statistics for the season's tropical storms and hurricanes, including their depression, extratropical, and remnant low stages (if applicable), are shown in Fig. 1 and Table 1, respectively[1]. The dates given in Table 1 only include the tropical and subtropical stages.

Damage in the United States due to this season's cyclones was about $16 billion, mostly attributable to Irene and Lee. Damage in other countries (in U. S. dollars) in the NHC area of responsibility is included in the storm summaries when available. Descriptions of the type and scope of damage are taken from a variety of sources, including U. S. Federal, local, and international government officials, media reports, and local National Weather Service (NWS) Weather Forecast Office (WFOs) in the affected areas. Tornado counts are based on reports provided by the WFOs and/or the NWS Storm Prediction Center. The strength of the tornadoes is rated using the Enhanced Fujita (EF) Scale (Texas Tech University 2006). Tables of observations are provided for selected cyclones (Irene and Lee) on a separate appendix. All dates and times are based on Coordinated Universal Time (UTC).

a. Tropical Storm Arlene, 28 June-1 July

Arlene formed from a tropical wave that emerged from the coast of Africa on 13 June. The wave moved westward with little distinction until it reached the western Caribbean Sea on 25 June, when the associated shower activity increased as the wave interacted with an upper-level trough. Little change in organization occurred the next day when the wave crossed Central

[1] Tabulations of the 6-hourly best track positions and intensities can be found in the NHC Tropical Cyclone Reports, available at http://www.nhc.noaa.gov/pastall.shtml. These reports contain storm information omitted here due to limitations of space, including additional surface observations and a forecast and warning critique.

America and the Yucatan Peninsula of Mexico. The wave moved into the Bay of Campeche on 27 June, when a broad area of low pressure formed. The wind circulation became better defined on 28 June, accompanied by a slight increase in the convective organization. An aircraft investigated the system and found tropical-storm-force winds to the north of the center of the low, suggesting the formation of a tropical storm near 1800 UTC 28 June about 260 n mi east-southeast of Tampico, Mexico. Steady development occurred while Arlene moved generally westward, and the cyclone's maximum sustained winds reached 55 kt before the center of the storm made landfall near Cabo Rojo, Mexico around 1300 UTC 30 June. Arlene dissipated over the mountains of Central Mexico early on 1 July.

The U.S Air Force Reserve 53rd Weather Reconnaissance Squadron made three flights into Arlene. The maximum observed flight-level winds at 1500 ft were 64 kt at 2027 UTC 29 June. An automated station at Isla Lobos, Mexico (just east of Cabo Rojo) reported sustained winds of 36 kt and a peak gust of 48 kt at 1115 UTC 30 June. Arlene brought heavy rain to eastern Mexico. Data from the National Meteorological Service of Mexico show widespread daily rainfall totals in excess of 150 mm in for 29-30 June and 30 June – 1 July. Tamesi, in the state of Tamaulipas, reported 348 mm of rain in 24 h from 30 June –1 July. Locally heavy rains also occurred over extreme southern Texas.

Media reports indicate that 18 people died directly due to Arlene in Mexico. Most of the deaths appear to have been due to freshwater floods and mudslides in the eastern part of that country. One indirect death occurred due to electrocution caused by a downed power line.

b. Tropical Storm Bret, 17-22 July

Bret's origin was non-tropical. Early on 16 July, a shortwave trough that moved off the coast of the southeastern United States induced the formation of a broad low pressure system along a weak stationary front. The low moved slowly south-southeastward to a position about 120 n mi east of Cape Canaveral, Florida, while convection gradually became organized near the low-level center. Data from a reconnaissance flight indicated that a tropical depression formed around 1800 UTC 17 July about 60 n mi north of Grand Bahama Island.

The depression moved slowly southeastward and steadily intensified, becoming a tropical storm 6 h later. Bret approached Grand Bahama Island early on 18 July before lifting out to the northeast. As vertical wind shear steadily decreased, convection gradually increased near the storm's center, and an eye feature became apparent in visible and microwave satellite imagery. A reconnaissance plane sampling the cyclone's inner core found a reliable Stepped-Frequency Microwave Radiometer (SFMR) surface wind of 59 kt at about the same time that the eye developed, and it is estimated that Bret reached its peak intensity of 60 kt at 1800 UTC 18 July. As Bret moved northeastward, the vertical shear increased and sea surface temperatures decreased, resulting in weakening of the cyclone. Bret lost all of its deep convection and became a remnant low pressure system that dissipated by 1200 UTC 23 July about 425 n mi south-southwest of Cape Race, Newfoundland.

c. Tropical Storm Cindy, 20-22 July

Cindy's incipient disturbance was first identified in satellite imagery late on 17 July, when an area of relatively concentrated cloudiness and showers developed about 300 n mi west-southwest of Bermuda. The disturbance formed along a decaying surface front as a weak mid- to upper-level trough moved over the western Atlantic. The next day a broad low pressure area formed northwest of Bermuda from the disturbance as it moved east-northeastward. Shower and thunderstorm activity became better organized, and early on 20 July the low pressure area developed a well-defined center. This resulted in the formation of a tropical depression about 265 n mi east of Bermuda at 0600 UTC 20 July.

The depression moved east-northeastward at 20 to 25 kt and became a tropical storm 6 h later. Cindy reached a peak intensity of 60 kt at 1800 UTC 21 July when a ragged eye-like feature appeared in satellite images. Cindy turned northeastward in mid-latitude southwesterly flow over the central Atlantic, and it remained on this general heading until dissipating in the North Atlantic.

d. Tropical Storm Don, 27-30 July

Don originated from a tropical wave that moved off the west coast of Africa on 16 July and then across the Lesser Antilles and the eastern Caribbean Sea on 23 July, producing wind gusts of up to 35 kt in Puerto Rico and the U. S. Virgin Islands. The wave continued westward and early on 26 July the thunderstorm activity became more concentrated south of Cuba around a broad surface low associated with the wave. A tropical depression formed around 0600 UTC 27 July about 50 n mi northeast of Cancun, Mexico. It strengthened to a tropical storm 12 h later.

After reaching tropical storm status, Don moved across the Gulf of Mexico and it encountered an environment characterized by light to moderate northerly vertical shear and relatively dry air, which likely prevented significant intensification. Don reached its peak intensity of 45 kt around 0000 UTC 29 July while centered about 345 n mi east-southeast of Corpus Christi, Texas, and the cyclone maintained this intensity for about 18 h. After that time, the storm began to weaken as deep convection rapidly decreased near the center, likely due to increasing vertical wind shear and entrainment of dry air from drought-stricken areas in northeastern Mexico and southern Texas.

Don weakened to a tropical depression and crossed the Texas coast around 0230 UTC 30 July along the Padre Island National Seashore just to the northeast of Baffin Bay. After landfall, Don degenerated to a remnant low by 0600 UTC 30 July when centered near Alice, Texas and then quickly dissipated.

The estimated peak intensity of Don is based on SFMR wind maxima of 43 kt and 46 kt at 0007 UTC and 1712 UTC 29 July, and an 850-mb flight-level wind maximum of 56 kt at 1713 UTC that day. The highest sustained wind measured on land at an official observing site was 30 kt at Laredo, Texas, and the highest gust was 36 kt at Waldron Field, Texas. The highest rainfall total was 65 mm at Bay City, Texas, well northeast of where the center made landfall.

Don produced storm tide values of .3 to .76 m above mean lower low water along the Texas coast. The highest observed storm tide value was .78 m at the Bob Hall Pier in Corpus Christi. The highest reported storm surge was .58 m at the Bob Hall Pier.

e. Tropical Storm Emily, 2-7 August

Emily formed from a tropical wave that emerged from the west coast of Africa on 25 July. The system continued westward and as it passed through the Lesser Antilles, a large area of winds near tropical storm force was already present. Air Force reconnaissance data indicate that a tropical storm formed around 0000 UTC 2 August about 30 n mi northwest of Martinique.

Emily continued moving west-northwestward and passed about 150 n mi south of Puerto Rico on 2 and 3 August. There was some increase in westerly shear by 3 August, and Emily did not strengthen as its low-level center became partially exposed to the west of the main convective mass. A vigorous burst of thunderstorms developed east of the center early the next day while Emily was passing to the south of Hispaniola, and aircraft data indicated that a low-level center reformed closer to the convection. Later on 4 August, however, the low-level center accelerated west-northwestward and Emily's surface circulation degenerated into an open wave as it approached the southwestern tip of Haiti around 1800 UTC.

The mid-level remnants of Emily moved west-northwestward through the southern and central Bahamas on 5 August. Surface pressures began falling as this feature reached the western Bahamas early on 6 August, and surface observations indicated that a new low pressure center formed just north-northwest of Andros Island. Aircraft data revealed that the system regenerated into a tropical depression around 1800 UTC that day as it was approaching the eastern end of Grand Bahama Island and then strengthened into a tropical storm 6 h later.

Emily's second period as a tropical storm was brief. Northerly to northeasterly vertical wind shear caused Emily to degenerate into a remnant low by 1200 UTC 7 August while centered about 230 n mi northeast of Grand Bahama Island, and then dissipated into an open trough around 0000 UTC 8 August. The remnants of Emily accelerated east-northeastward across the central Atlantic on 8 August, producing a large area of gale-force winds. Although the system briefly became better organized, the strong westerly wind shear prevented regeneration from occurring a second time.

Heavy rains associated with Emily occurred over portions of the Lesser Antilles, where Martinique recorded a total of 150 mm. The largest rainfall totals in Puerto Rico were generally over the eastern part of the island, with Caguas reporting the largest amount of 209 mm. An unofficial rainfall total of 528 mm was reported in Neiba in the Dominican Republic. Although no sustained tropical-storm-force winds were reported from this region, wind gusts in some of the passing bands were of tropical storm strength (e.g., a gust to 45 kt was observed at Buck Island in the British Virgin Islands.)

Heavy rains also caused several rivers to overflow their banks in Puerto Rico and Hispaniola. Three hundred homes were reportedly damaged in Haiti, but damage elsewhere on the island was light. Floods caused several large landslides in Martinique, but damage was minor.

f. *Tropical Storm Franklin, 12-13 August*

An area of low pressure formed along a frontal system around 1200 UTC 12 August over the western Atlantic. The low lost its frontal characteristics as convection increased, and the system became a tropical depression at 1800 UTC about 200 n mi north of Bermuda.

The depression was compact, with its cloud field extending no more than 150 n mi across. Embedded in deep-layer southwesterly flow, the depression moved northeastward at about 20 kt and strengthened to a tropical storm 12 h after genesis. Franklin reached its peak intensity of 40 kt 6 h later, just before it developed frontal characteristics and became an extratropical cyclone. The extratropical low degenerated into a trough of low pressure by 0600 UTC 16 August about 500 n mi west-southwest of the Azores.

g. *Tropical Storm Gert, 13-16 August*

A cold front moved southward over the central Atlantic on 7 and 8 August and lost much of its temperature gradient by 9 August. The resulting frontal trough remained nearly stationary to the northeast of the northern Leeward Islands during the next several days, and an upper-level shortwave trough induced the development of a well-defined low pressure system around 0600

UTC 13 August. Persistent deep convection developed near the low later that day, and a tropical depression formed around 1800 UTC about 370 n mi southeast of Bermuda. The depression strengthened and became a tropical storm 12 h later.

Gert moved slowly west-northwestward through early 14 August, but a deep-layer trough near the east coast of the United States caused Gert to abruptly turn toward the northwest and north later that day. The storm strengthened little during that time due to northwesterly shear and entrainment of drier air from the west. The environment became a little more conducive for strengthening on 15 August, and Gert reached an estimated peak intensity of 55 kt around 1200 UTC as it was moving northward about 90 n mi to the east of Bermuda. Gert began to weaken soon after reaching its peak intensity due to an increase in northeasterly shear and decreasing sea-surface temperatures. The cyclone turned northeastward and lost its tropical characteristics around 1200 UTC that day while centered about 435 n mi northeast of Bermuda, but it continued to produce gale-force winds for another 12 h. The remnant low accelerated northeastward at nearly 30 kt ahead of a cold front, dissipating after 1800 UTC 17 August about 400 n mi east of Cape Race, Newfoundland.

h. Tropical Storm Harvey, 19-22 August

The precursor to Harvey was a tropical wave that departed the coast of Africa on 10 August. This system initially showed signs of organization, with abundant convection and an accompanying surface low. Convection diminished on 12 August, however, perhaps due to dry air entrainment and easterly shear. The low dissipated by the next day. As the system moved over warmer waters in the western tropical Atlantic, the wave regained some of its convective vigor on 14 August. Surface data indicated that the system lacked a closed surface circulation as it traversed the eastern and central Caribbean Sea. The convection increased in both coverage and organization on 18 August when the system was in the western Caribbean Sea, and a tropical depression formed by 0000 UTC 19 August about 70 n mi northeast of Cabo Gracias a Dios on the border of Nicaragua and Honduras.

In an environment of moderate easterly wind shear and over very warm waters, the tropical cyclone gradually strengthened, becoming a tropical storm by 1200 UTC 19 August. Meanwhile, a mid-level ridge over the Gulf of Mexico steered Harvey toward the west-northwest just to the north of mainland Honduras and the Bay Islands. In the last several hours before landfall, convection became deeper near the center, and radar images from Belize along with aircraft data indicated that an eye was trying to form. Although that feature did not materialize, reconnaissance and satellite data suggested Harvey reached a peak intensity of 55 kt at landfall near Dangriga, Belize around 1730 UTC 20 August. The storm weakened to a tropical depression over northwestern Guatemala and moved over the Bay of Campeche just before 1800 UTC 21 August. Harvey turned toward the west shortly after that, and a flare-up of convection near and west of the center caused the system to intensify slightly. Surface data from Mexico indicated that Harvey became a tropical storm again with 35-kt winds by 0000 UTC 22 August, and the storm made landfall around 0200 UTC that day near Punta Roca Partida, Mexico. Harvey quickly weakened and dissipated over the high terrain of Mexico shortly after 1200 UTC 22 August, when the system was located about 85 n mi southwest of Veracruz, Mexico.

According to the Associated Press, high winds and heavy rain were noted in Dangriga, Belize during the storm, but there were no reports of damage or casualties there. In Mexico, three people were killed in San Lucas Zoquiapam, Oaxaca due to a mudslide hitting their home.

Although no specific rainfall totals are available, Harvey caused significant floods, and 334 homes were reported damaged in the city of Veracruz.

i. Hurricane Irene, 21-28 August

1. Synoptic History

Irene originated from a vigorous tropical wave that exited the west coast of Africa on 15 August, accompanied by a large area of cloudiness and thunderstorms. The convection diminished when the wave moved just south of the Cape Verde Islands the next day, but the wave maintained a well-defined mid-level circulation. Showers and thunderstorms gradually regenerated while the wave continued westward across the tropical Atlantic, and the cloud pattern became better organized by the time the system was halfway between the west coast of Africa and the Lesser Antilles on 17 August. A reconnaissance aircraft investigated the system for several hours on 20 August, finding surface winds of 40-45 kt but no well-defined closed low-level circulation. Just before the conclusion of the mission, the aircraft meteorologist was able to close off a circulation near the southern edge of the convection about 120 n mi miles east of Martinique, marking the formation of a tropical storm shortly before 0000 UTC 21 August.

After genesis, Irene moved toward the west-northwest across the extreme northeastern Caribbean Sea, gaining organization and strength on 21 August. As the center of the cyclone moved over St. Croix around 2300 UTC that day, an interval of light winds associated with the center was observed and, in fact, an Air Force Reserve Hurricane Hunter aircraft was able to depart from there for its mission during that period of calm.

Irene continued west-northwestward and the center passed over the eastern shore of Puerto Rico at 0535 UTC 22 August. The cyclone became a hurricane while moving over the island a short time later, but the hurricane-force winds did not affect the island and occurred only over water north of the center. The hurricane moved very close to the north coast of Hispaniola on 23 August, and despite a favorable atmospheric environment of low shear, the interaction of Irene's circulation with the high terrain of Hispaniola likely delayed additional intensification. As it moved away from Hispaniola early on 24 August, however, Irene began to strengthen. It became a category 3 hurricane with a peak intensity of 105 kt and a central pressure of 957 mb at 1200 UTC 24 August when it was centered between Mayaguana and Great Inagua in the southeastern Bahamas. The eye was then about 18 n mi in diameter based on hurricane hunter reports. The hurricane continued moving west-northwestward, and the eye crossed Acklins and Crooked Islands near 1500 UTC 24 August. These islands likely experienced category 3 hurricane conditions. Irene weakened a little bit when its core moved over Long Island, Bahamas around 0000 UTC 25 August.

A mid-tropospheric trough developed over the eastern United States on 24 August, and the subtropical ridge that had been steering Irene west-northwestward across the southeastern Bahamas shifted eastward. Embedded within the associated flow pattern, Irene turned toward the north-northwest and north as it moved across the central and northwestern Bahamas. The eye passed between Exuma and Cat Island around 0600 UTC 25 August, crossed Eleuthera a few hours later, and then reached the Abaco Islands in the northwestern Bahamas around 1800 UTC 25 August. By then, Irene had weakened further and these islands probably experienced category 2 hurricane conditions. Although Irene's winds decreased during this period and the eye became less discernible in satellite images, its circulation expanded and the central pressure continued to fall, dropping to 942 mb by 0600 UTC 26 August.

The hurricane continued northward and passed well offshore of the east coast of Florida and Georgia while weakening. Irene made landfall near Cape Lookout, North Carolina at 1200 UTC 27 August with an intensity of 75 kt, producing category 1 hurricane-force winds within a swath primarily to the east of the center over the North Carolina sounds and the Outer Banks. Irene then moved north-northeastward, with its center passing just offshore of the Delmarva Peninsula, and then made another landfall very near Atlantic City, New Jersey, at Brigantine Island at 0935 UTC 28 August. Although Irene's intensity at the New Jersey landfall was 60 kt, winds of that strength were confined to the waters east of the center. Irene continued moving north-northeastward and the center moved over Coney Island, Brooklyn, New York around 1300 UTC 28 August, and then over Manhattan, New York City about 1 h later. Once again, the storm's strongest winds at the time of landfall (55 kt) continued to occur primarily well to the east of the center. Irene moved north-northeastward over the northeastern United States and became extratropical when its center was near the New Hampshire/Vermont border around 0000 UTC 29 August. The cyclone was absorbed by a frontal system at 0600 UTC 30 August over northeastern Canada.

2. Meteorological Statistics

Irene was well sampled by reconnaissance aircraft. There were 19 missions performed by the 53rd Weather Reconnaissance Squadron of the U. S. Air Force Reserve Command and 16 by NOAA Aircraft Operations Center WP-3D aircraft. There were also seven missions involving the NOAA G-IV high-altitude jet to sample the environment surrounding Irene.

Eleuthera reported a minimum pressure of 952.4 mb at 0900 UTC 25 August as the eye moved near that island, and Marsh Harbor in the Abacos measured a minimum pressure of 950.4 mb at 1700 UTC 25 August. These pressures are very similar to those reported by a reconnaissance aircraft near those times. An automatic weather station at West End in Grand Bahama reported sustained winds of 79 kt at 0100 UTC 26 August.

The analyzed maximum wind speed of 105 kt at 1200 UTC 24 August is based on a 700-mb flight-level peak wind of 116 kt at 1430 UTC that day, measured by a hurricane hunter aircraft in the northeastern eyewall. After the time of this peak wind observation, the closed eyewall feature evolved into a more fractured structure, and the strong flight-level winds were no longer penetrating down to the surface sufficiently to support the maintenance of a 105-kt intensity. In contrast, the central pressure continued to drop for another 15 h to 942 mb at 0600 UTC 26 August as measured by a dropsonde but by then Irene's estimated intensity had decreased to 90 kt.

Shortly before the center of Irene moved over New York City, flight-level winds measured by the reconnaissance aircraft would typically have supported hurricane intensity at the surface. SFMR and dropsonde wind data, however, showed that the standard flight level to surface wind adjustment continued to be inappropriate; the observed surface wind values at that time supported only a 55-kt intensity. The latest observation to definitively support an analysis of hurricane intensity was an SFMR report of 66 kt well to the east of the center near 0103 UTC 28 August.

Irene produced copious amounts of rain in Puerto Rico, with a maximum observed of 560 mm in Gurabo Abajo, which caused major flooding in the northeastern portion of the island. In addition, Irene produced a large swath of 125 to 250 mm of rain along the east coast of the mainland United States and nearby inland areas from North Carolina northward. The maximum rainfall amount observed was near 400 mm in Bayboro, North Carolina, as indicated in Fig. 4.

Irene was a large hurricane, and generated high waves and storm surge over a large portion of the western Atlantic basin for several days. The highest storm surge reported by a tide gauge was 2.1 m at 0354 UTC 28 August at Oregon Inlet Marina, North Carolina. Post storm surveys suggest that a storm surge of 2.4 to 3.3 m occurred within portions of Pamlico Sound. Storm surge heights between 1.2 and 1.8 m were measured along the coast from New Jersey northward. Figure 5 shows selected peak wind and storm surge measurements in Irene. Additional storm surge information can be found from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) at http://tidesandcurrents.noaa.gov.

Irene spawned several tornadoes along its path over the eastern United States. The strongest was an EF2 tornado that touched down in Columbia, North Carolina, destroying a few manufactured homes. There were also two EF1 tornadoes in North Carolina, one EF1 tornado in Pennsylvania, two EF0 tornadoes in New York, and two tornadoes of unknown intensity in Virginia.

3. Casualty and Damage Statistics

Reports indicate that Irene was responsible for 49 direct deaths: 5 in the Dominican Republic, 3 in Haiti, and 41 in the United States. Surprisingly, there were no reported deaths in the Bahamas where Irene was the strongest. For the United States, 6 deaths were attributed to storm surge/waves or rip currents, 15 to wind, including falling trees, and 21 to rainfall-induced floods.

According to media reports and a summary provided by the Meteorological Service of the Dominican Republic, Irene caused flooding from surge and high waves in low-lying areas and damaged homes in portions of the north coast of the Dominican Republic. Damage from flooding caused by rains was extensive across Puerto Rico and was severe near the area of Gurabo Abajo.

In the mainland United States, Irene caused widespread damage to homes and felled trees from North Carolina northward, and produced extensive power outages. In North Carolina, the flow from the sound to the ocean damaged Highway 12, cutting it in several places. The most severe surge damage occurred between Oregon Inlet and Cape Hatteras, but significant storm surge damage also occurred along southern Chesapeake Bay. In the Hampton Roads area, and along coastal sections of the Delmarva Peninsula from Ocean City, Maryland southward, storm surge flooding was comparable to that from Hurricane Isabel of 2003. In New Jersey and eastern Pennsylvania, Irene produced torrential rains that resulted in major flooding and several record breaking crests on rivers. A storm surge of 3-5 ft along the New Jersey shore caused moderate to severe tidal flooding with extensive beach erosion.

Since the cyclone's strongest winds were over water to the east of the path of the center, New York City escaped severe damage. Nonetheless, a storm surge of 3-6 ft caused hundreds of millions of dollars in property damage in New York City and on Long Island. Tropical-storm-force winds along with heavy rains resulted in power outages that lasted to around one week for up to 3 million residents, mainly across Connecticut and Long Island.

Irene's main impact, however, was from rainfall. Catastrophic floods occurred in New Jersey, New York and New England, especially in central and southern Vermont where widespread rainfall amounts of 100 to 175 mm occurred. These rains caused devastating flash floods across many mountain valleys with some record breaking flood stages occurred on larger rivers. This flood event will likely rank second to the November 1927 flood, with nearly 2400 roads, 800 homes and businesses, 300 bridges, and a half dozen railroad tracks destroyed or damaged from the flooding in southern Vermont. Three towns in the Catskill Mountains in New York were uninhabitable after the floods.

In the United States, the Insurance Services Office, Inc., reported that the hurricane caused an estimated $4.3 billion in losses. Doubling this figure in an attempt to account for uninsured losses results in an estimated total of $8.6 billion. Based on National Flood Insurance Program data, it is estimated that Irene caused $7.2 billion in losses from inland flooding and storm surge. Using these figures, the total damage estimate is $15.8 billion. A detailed summary of the damage can be found in post-storm reports of local National Weather Service offices in affected areas.

j. Tropical Storm Jose, 27-28 August

Jose originated from a mesoscale convective system that developed north of an upper-level low on 25 August about 700 n mi east-southeast of Bermuda. A surface low formed the next day and the associated convection gradually increased in organization. The low became a tropical depression at 0600 UTC 27 August while located about 305 n mi south-southeast of Bermuda. Despite strong northeasterly vertical wind shear caused by the outflow from Hurricane Irene, the depression strengthened into a tropical storm by 1200 UTC 27 August. Jose reached a peak intensity of 40 kt early on 28 August, and maintained this intensity as it passed about 55 n mi west of Bermuda around 1800 UTC 28 August. After passing Bermuda, Jose accelerated toward the north and north-northeast and degenerated into a remnant low near 0000 UTC 29 August. The low was absorbed by a cold front later that day south of Nova Scotia.

k. Hurricane Katia, 29 August-10 September

A vigorous tropical wave accompanied by a broad low pressure system moved off the west coast of Africa on 27 August. The disturbance continued on a westward track while deep convection gradually increased in organization. By 0600 UTC 29 August, the low acquired sufficient convective organization to be designated a tropical depression when it was located about 375 n mi southwest of the southwesternmost Cape Verde Islands.

The depression gradually strengthened despite being under the influence of easterly vertical wind shear, and became a tropical storm around 0000 UTC 30 August. Katia reached hurricane intensity by 0000 UTC 1 September when it was located about 1175 n mi east of the Leeward Islands and changed little in intensity for almost 72 h thereafter.

The vertical wind shear decreased and Katia began a period of rapid intensification. Katia reached its peak intensity of 120 kt at 0000 UTC 6 September about 470 n mi south of Bermuda. Earlier, around 1235 UTC 4 September, the hurricane's eye passed over or very near NOAA buoy 41044, which recorded a wind gust of 94 kt. Although rapid weakening began almost immediately after Katia had reached its peak intensity, the wind field expanded. The hurricane accelerated east-northeastward and moved over sea-surface temperatures of near 22^{o} C. Katia then lost tropical characteristics, becoming a large and powerful extratropical low pressure system by 1200 UTC 10 September when it was located about 250 n mi south-southeast of Cape Race, Newfoundland. The cyclone turned northeastward and skirted the northern coast of Scotland around 1200 UTC 12 September and produced hurricane-force wind gusts across most of the British Isles. The cyclone continued northeastward for the next 24 h, and the circulation was absorbed within a larger extratropical low pressure system over the North Sea by 0000 UTC 13 September.

l. *Unnamed Tropical Storm, 1-2 September*

A short-lived unnamed tropical storm originated from a low-level trough located to the south of Tropical Storm Jose. A large area of disorganized showers and thunderstorms was present on 28 August along the surface trough a few hundred miles to the southwest of Bermuda. Convection increased markedly on 31 August and became organized enough to designate the formation of a tropical depression near 0000 UTC 1 September, about 290 n mi north of Bermuda.

The depression moved slowly and erratically and became a tropical storm 12 h after genesis. Only small changes in intensity occurred for the next 24 h, as the storm accelerated northeastward and entered a more baroclinic low-level environment. Extratropical transition occurred around 0000 UTC 3 September about 300 n mi south-southeast of Halifax, Nova Scotia, and the low degenerated into a trough 24 h later well south of Newfoundland.

m. *Tropical Storm Lee, 2-5 September*

1. Synoptic History

Lee developed from a tropical wave that moved off the west coast of Africa on 18 August accompanied by a broad low pressure area. The low, however, moved northwestward and encountered hostile environmental conditions that prevented development. Meanwhile, the southern portion of the wave continued westward across the Caribbean Sea during the next week or so and moved into the southeastern Gulf of Mexico on 31 August, where shower and thunderstorm activity increased in organization. A broad area of low pressure formed from this system over the central Gulf of Mexico on 1 September, and data from a NOAA Hurricane Hunter aircraft mission indicated that a tropical depression formed around 0000 UTC 2

September about 190 n mi southwest of the mouth of the Mississippi River. The depression moved slowly northward and strengthened into a tropical storm 12 h later.

Despite about 20-kt of westerly vertical wind shear (850-200 mb layer), due in part from an upper-level low to the northwest of the cyclone, the convective organization of the system continued to improve during the daylight hours of 2 September, and surface as well as reconnaissance aircraft data indicate that Lee gradually strengthened. Early the next day, the separation between Lee and the upper-level low decreased and the two systems became co-located around 0600 UTC 3 September. During this time, the overall satellite appearance of Lee began to take on the appearance of a subtropical cyclone. Although the cyclone maintained a weak warm core, the expanding radius of maximum winds, and the fact that Lee continued to deepen despite having relatively weak convection near the center, suggest that Lee was best classified as a subtropical cyclone by 1200 UTC 3 September. During this transformation, Lee turned northwestward and reached a maximum intensity of 50 kt at 1200 UTC 3 September while centered about 60 n mi southwest of Morgan City, Louisiana. After that time, Lee slowed down and meandered just off the south-central coast of Louisiana during the next 12-18 h. Dry mid-level air began wrapping around the southern and eastern portions of the circulation, causing the convection near the center to gradually decrease. Early on 4 September, Lee turned east-northeastward and accelerated, making landfall around 1030 UTC along the coast of Louisiana, about 10 n mi south-southeast of Intracoastal City. Although the central pressure of Lee had continued to slowly fall, reaching 986 mb at the time the center crossed the coast, a weakening gradient caused the maximum winds to decrease to 40 kt by landfall. These winds were occurring over water well to the south and east of the center.

After landfall, Lee moved north-northeastward and then became nearly stationary over south-central Louisiana late on 4 September. During this time, the cyclone weakened slightly but maintained subtropical storm strength, as 35-kt winds continued over the northern Gulf of Mexico. Early on 5 September, Lee merged with a strong cold front that was moving southward over the south-central United States and Lee became extratropical by 0600 UTC. Soon thereafter, the cyclone began to accelerate east-northeastward. The system's strongest winds increased again, this time near the frontal boundary over the Gulf waters, even as the low center moved across southern Mississippi and southern Alabama on 5 September. By 0000 UTC 6 September, winds associated with the low dropped below gale force and the extratropical low moved into northwestern Georgia. After that, the low continued to weaken as it turned northward. It dissipated by 0000 UTC 7 September over extreme northwestern Georgia.

2. Meteorological Statistics

The estimated 50-kt peak intensity of Lee is based on a maximum 850-mb flight-level wind of 60 kt that was measured over southeastern Louisiana about 110 n mi east-northeast of the center shortly before 1200 UTC 3 September. The peak intensity is also supported by data from the oil rig *West Sirius* (call sign 3EMK6), which recorded 46 kt within the primary band of shower and thunderstorm activity about 140 n mi east-southeast of the center several hours earlier than the aforementioned aircraft observation.

Numerous oil platforms over the northern Gulf of Mexico reported tropical-storm-force winds in association with Lee. The highest wind observations were 51 kt at *Mississippi Canyon311a* (KMDJ) and 52 kt at *Mississippi Canyon 802* (42362) platforms. The anemometers on these oil rigs are, however, quite elevated, at 90 m and 122 m, respectively. Using the standard wind adjustment factor from those heights yields a 10-m surface wind estimate of about 42 kt for both observations (Franklin et al 2003). The highest wind gust recorded from an oil platform was 63 kt at the *Louisiana Offshore Oil Port* (LOPL1- elevation 58 m).

Sustained tropical-storm-force winds were reported at some land-based observing stations near the coasts of Alabama, Mississippi, Louisiana, and extreme eastern Texas during the time Lee was classified as a tropical or subtropical cyclone. The highest 1-min sustained wind report from a land station was 43 kt with a gust to 47 kt at a University of Alabama mesonet site on Dauphin Island, Alabama at 1944 UTC 3 September. A 2-min sustained wind of 40 kt with a gust to 50 kt was observed at the Lakefront Airport in New Orleans at 1128 UTC 4 September. Winds of 34 kt with a gust to 41 kt were also reported in Galveston, Texas, early on 4 September.

After Lee became extratropical, surface observations indicate that the cyclone strengthened. The strongest winds associated with the low occurred primarily over the northern Gulf of Mexico, but some land-based observing stations recorded stronger winds when Lee was an extratropical cyclone than during its (sub)tropical storm stages. The highest sustained winds observed over land on 5 September were 42 kt at New Orleans Lakefront Airport at 1455 UTC and 44 kt from a University of South Alabama mesonet site at Dauphin Island at 1316 UTC. Sustained winds of 28 to 36 kt with gusts to 51 kt were reported at observing sites in the Florida Panhandle.

Strong onshore winds from Lee along the northern Gulf Coast produced elevated water levels from Louisiana eastward into the Florida Panhandle for several days. The highest storm tides reported during the event were 1.2 to 1.8 m along the coasts of Mississippi and southeast Louisiana. The highest storm surge reported was 1.4 m at Amerada Pass, Louisiana. Storm tides of .9 to 1.5m were reported in Alabama, and values of 2.6 to .9 m were observed in portions of the Florida Panhandle. The highest storm surge in Florida or Alabama was 1.3 m at a National Ocean Service tide gauge at the Coast Guard Sector-Mobile station, near the north end of Mobile Bay. Storm tides of 1.2 to 1.8 m were also observed at tide gauges along the coasts of Lake Pontchartrain and Lake Maurepas in Louisiana. The highest recorded storm surge in this area was 1.2 m at the New Canal Station in the West Lakeview section of New Orleans.

Lee produced heavy rainfall along the northern Gulf Coast and along its path across the southeastern United States (Fig. 6). Rainfall amounts of 250-375 mm were reported over a large area along the northern Gulf Coast from southeastern Louisiana eastward across southern Mississippi and southern Alabama. The highest storm total rainfall in this area was 395 mm at Holden, Louisiana, with 320 mm observed at both New Orleans Lakefront Airport and near Mobile, Alabama. A large rain swath of 180-250 mm with isolated maximum amounts to 355 mm also occurred north of the cyclone's center path across south-central Mississippi, northern Alabama, extreme northwestern Georgia, and eastern Tennessee.

Moisture from Lee and its remnants spread northeastward along a frontal boundary that became stationary across the Mid-Atlantic States and southern New York. This produced a second area of extremely heavy rainfall from eastern Virginia northward across Maryland, eastern Pennsylvania, New Jersey, southern New York, and portions of southern New England from 5 -10 September.

The rain over the Mid-Atlantic States fell across areas that had already experienced a wet summer, including significant rains from Hurricane Irene less than two weeks before. This led to major flooding along the Susquehanna River, which in some areas broke high-water records that were set nearly 40 years earlier in the aftermath of Hurricane Agnes (1972). In Wilkes-Barre, Pennsylvania, the river crested at 12.9 m, which broke the previous record of 12.4 m set in June 1972. Along the Swatara Creek in Hershey, Pennsylvania, the previous record flood mark set after Agnes was exceeded by 3.0 m during this event.

Lee and its remnants produced 46 tornadoes, mainly across the southeastern United States. Tornadoes on 3 and 4 September occurred primarily along the northern Gulf Coast from southern Louisiana eastward to the Florida Panhandle. These tornadoes were generally short-lived and rated either EF0 or EF1. On 5 September, several tornadoes and damaging thunderstorm wind gusts were reported across Georgia, North and South Carolina, and portions of north Florida. Tornado touchdowns were reported in Douglas, Cobb, and Cherokee counties in Georgia. They were also reported over central North Carolina on 6 September and in northeastern Virginia and southern Maryland on 7 September.

1. Casualty and Damage Statistics

Lee was responsible for three direct deaths during its time as a (sub)tropical cyclone: two from rough surf and one from inland flooding. Media reports indicate that flooding largely related to the remnants of Lee was responsible for at least 12 additional deaths in the eastern United States; seven in Pennsylvania, four in Virginia, one in Maryland, and one in Georgia. Nearly all of these deaths occurred when individuals tried to cross flooded roadways in vehicles or were swept away in flood waters.

Most of the damage caused by Lee was the result of storm surge or freshwater flooding. Storm surge flooding from Lake Pontchartrain inundated more than 150 houses in Jefferson and St. Tammany Parishes in Louisiana. Minor storm surge flooding was also reported outside the hurricane protection levees in St. Bernard and Orleans Parishes. Freshwater flooding was reported in low-lying areas of southeastern Louisiana and southern and central Mississippi. Several roads were inundated by floodwaters in Hancock, Jackson, and Harrison Counties in Mississippi, while in Neshoba County in the central portion of the state, 35 roads were damaged with five of those completely washed out.

The rain from Lee's remnants exacerbated the flood situation in the mid-Atlantic states and caused some of the most severe flooding in this region's history. The worst flooding occurred along the Susquehanna River and its tributaries in western New York and Pennsylvania. In western New York, water levels topped levees along the river, which inundated several cities including Waverly, Owego, Vestal, Endicott, Johnson City, and downtown Binghamton. In some of these areas, water levels broke previous record heights that were set in 2006. Numerous roads were closed in the area and 20,000 people were ordered to evacuate Binghamton. In Pennsylvania, the forecast of flooding led to the evacuation of about 100,000 people, including 10,000 people and the Governor's residence in the downtown Harrisburg area. The most significant flooding occurred in towns along the Susquehanna River, including Tunkhannock, Pittston, Edwardsville, Nanticoke, Wilkes-Barre, and Harrisburg. In Dauphin and Lebanon Counties in the greater Harrisburg area, nearly 5,000 homes were damaged or destroyed. Numerous roads and 18 bridges were also damaged in Pennsylvania.

Wind damage associated with Lee was more isolated and generally consisted of downed trees and power lines, and mostly minor damage to structures near the Gulf Coast. A few areas of moderate damage, likely in association with tornadoes, occurred over isolated parts of the southeastern United States. Areas that reported significant residential structural damage include: the western end of Dauphin Island, near Gulfport, Mississippi, and Pensacola, Florida. The long-lived EF1 tornado in Cherokee County, Georgia, damaged about 400 homes in the Brookshire and Towne Lake Hills South subdivisions near Woodstock, Georgia.

According to the Property Claim Services of the Insurance Services Office, Inc., Lee produced an estimated $315 million in insured losses in the United States. Media reports indicate the flooding from the remnants of Lee produced more than one billion dollars in damage in the Mid-Atlantic and Northeast United States.

n. Tropical Storm Maria, 6-16 September

A tropical depression formed by 1800 UTC 6 September about 700 n mi west-southwest of the southern Cape Verde Islands from a tropical wave that had moved across the west coast of Africa a few days earlier. The cyclone moved quickly west-northwestward at 15 to 20 kt and reached tropical storm intensity 6 h later when centered about 790 n mi west-southwest of the southern Cape Verde Islands.

Southwesterly vertical wind shear displaced the deep convection from the center. By early on 9 September, Maria slowed to around 15 kt and deep convection began to redevelop closer to the low-level circulation. Data from an Air Force Reserve Hurricane Hunter aircraft mission into Maria later that day indicated, however, that the low-level circulation lost definition, even as the system was producing maximum sustained winds of around 45 kt mainly to the northeast of the center. Maria dissipated as a tropical cyclone around 1200 UTC 9 September.

The remnants of Maria, accompanied by a strong mid-level circulation, turned northwestward and approached the Lesser Antilles by late on 9 September. A new surface center developed around 1200 UTC 10 September about 40 n mi east-southeast of Antigua, and Maria again became a tropical storm at that time. Maria experienced strong westerly vertical wind shear as the center passed to the north of the Virgin Islands and Puerto Rico the next day.

Maria then turned northwestward and northward, and the vertical wind shear relaxed somewhat during the next day or so. The cyclone then slowly strengthened and reached hurricane intensity around 1800 UTC 15 September about 135 n mi northwest of Bermuda. On 16 September, Maria became embedded in the mid-latitude flow and accelerated northeastward, reaching an estimated peak intensity of 70 kt at 0000 UTC that day, before weakening due to cooler waters and increasing vertical wind shear. Maria was a tropical storm with 60-kt winds when the center made landfall around 1830 UTC 16 September near Cape St. Mary's on the Avalon Peninsula of Newfoundland, Canada. These strongest winds remained offshore, though sustained tropical-storm-force winds were observed at Cape Race, Bonavista, and Sagona Island, with wind gusts above 50 kt observed at all of those locations as well as at St. Lawrence. The cyclone's circulation was absorbed by a frontal system shortly thereafter.

As Maria and its remnants passed near and north of the Leeward Islands and the Virgin Islands on 9-11 September, the strongest observed sustained wind was 45 kt at La Desirade, located just to the east of Guadeloupe. Tropical-storm-force wind gusts were observed on Antigua, Guadeloupe, Marie-Galante, Barbuda, St. Maarten/St. Martin, St. Croix, and St. Thomas. In several of these locations, the strongest winds occurred before Maria regenerated into a tropical cyclone. Widespread rainfall totals of 125 to 280 mm were observed in Puerto Rico, with a maximum of 300 mm at Aibonito. Rainfall totals in the Leeward Islands were generally 25 to 50 mm.

Maria produced storm surge values of 0.2 m in Barbuda, St. Croix, St. John, Vieques, Mona Island, and Puerto Rico. The highest observed storm tide was 0.6 m above Mean Lower

Low Water at Arecibo on the northern coast of Puerto Rico. As Maria passed west of Bermuda on 15 September, sustained winds of 34 kt were reported at L.F. Wade International airport, along with a peak wind gust of 43 kt.

The estimated landfall intensity of 60 kt is based on subjective Dvorak intensity estimates and a 10-min average wind of 52 kt from Environment Canada buoy 44138 at 1520 UTC, which suggests a peak 1-min wind of 57 kt when applying an adjustment factor of 1.11 (Harper et al. 2009). Rainfall amounts in the Burin Peninsula and the south coast of Newfoundland were around 60 mm, with a total of 63 mm observed at St. Lawrence.

o. Hurricane Nate, 7-11 September

1. Synoptic History

Nate originated from the frontal trough that was responsible for the extratropical transition of Tropical Storm Lee. The front moved through the western half of the Gulf of Mexico on 5 September and became stationary from the south-central Gulf of Mexico to the Bay of Campeche later that day. An area of low pressure formed along the southern end of the front around 1800 UTC 6 September about 160 n mi northwest of Ciudad del Carmen, Mexico. The circulation of the low separated from the front on 7 September while convection increased but remained disorganized. Scatterometer data indicated that the low had gale-force winds by this time, but these winds were at least partially associated with a strong low-level pressure gradient behind the weakening cold front. A curved convective band formed over the western semicircle of the circulation later that day, marking the formation of a tropical storm around 1800 UTC 7 September about 140 n mi north of Villahermosa, Mexico.

Embedded within a weak steering flow, Nate drifted southeastward and gradually strengthened. Data from a reconnaissance aircraft and a nearby oil rig indicated that Nate reached hurricane strength around 1800 UTC that day when it was located about 70 n mi north-northwest of Ciudad del Carmen. The broad wind field and slow forward motion of the cyclone over the shallow waters of the Bay of Campeche caused significant upwelling of the oceanic mixed layer, which resulted in a large area of significantly cooler waters under Nate. The combination of dry air and a lower oceanic heat content caused the intensity and coverage of deep convection in the cyclone to decrease considerably early on 9 September, resulting in weakening.

As Nate moved westward away from the upwelled waters on 10 September, convection around the circulation became reinvigorated. A brief re-intensification of the cyclone began around 1200 UTC that day, despite the still relatively dry air in the near-storm environment. The mid-level ridge over Mexico strengthened around this time, and Nate responded by moving more quickly toward the west. Some weakening occurred and the low- and mid-level centers became detached; the mid-level center moved inland north of Veracruz while the low-level center of the weakening tropical storm crossed the coast of northeastern Mexico near Barra de Tecolutla at 1600 UTC 11 September. Rapid weakening occurred after landfall, and Nate dissipated by 0600 the next day.

2. Meteorological Statistics

U.S. Air Force Reserve Hurricane Hunter aircraft flew a total of six missions in Nate and obtained 16 fixes. The maximum observed flight-level wind (850 mb) in Nate was 82 kt southeast of the center at 1815 UTC on 8 September. Data received in post-analysis from Eco-1, a Petróleos Mexicanos (PEMEX) oil rig located in the southeast quadrant of the cyclone indicated a 1-minute sustained wind of 72 kt at an elevation of 30 m. This occurred several hours after the time of the peak winds measured by the aircraft, also to the southeast of the center. An adjustment of the oil rig observation to the standard 10 m height, using the mean hurricane dropwindsonde profile, yields a peak sustained surface wind estimate of 67 kt. These data and the earlier reconnaissance measurements support the estimate of Nate's peak intensity of hurricane strength.

3. Casualty and Damage Statistics

There were four direct deaths associated with Nate. Ten workers were forced to abandon their lifeboat on 8 September after evacuating the *Trinity II* oil rig and only seven survived. Lightning killed a nine-year-old child in the state of Veracruz. No serious damage was reported in association with Nate's landfall in eastern Mexico. Press reports indicate that about 800 homes were damaged in Veracruz.

p. Hurricane Ophelia, 20 September-3 October

A surface low developed from the interaction of a tropical wave and the Intertropical Convergence Zone (ITCZ) about 750 n mi west-southwest of the Cape Verde Islands. The low became a tropical depression around 1800 UTC 20 September about 1300 n mi east of the Lesser Antilles. ASCAT surface wind data prior to 0000 UTC 21 September suggest that the system had strengthened to a 40-kt tropical storm by that time.

Ophelia intensified slowly in an environment of moderate southwesterly shear during the next 24 to 36 h as it moved westward over the tropical Atlantic. Very valuable data from ship *Donaugracht* (PBSY) and NOAA buoy 41041, along with scatterometer data, indicate that

Ophelia reached its first peak intensity of 55 kt around 0600 UTC 22 September about 850 n mi east of the Lesser Antilles. Southwesterly shear increased later on 22 September, causing the cyclone to weaken over the next couple of days as it approached the northern Leeward Islands and Ophelia degenerated into a remnant low pressure system about 1200 UTC 25 September. Conventional satellite and microwave data indicate that the remnant circulation dissipated by 0000 UTC 26 September.

Although the low-level center of the tropical cyclone had dissipated, the associated deep convection lingered along with a well-defined mid-level circulation. An elongated surface circulation redeveloped within the convection around 0000 UTC 27 September, and the circulation developed sufficient definition by 1200 UTC that day for the system to be considered a tropical depression when it was 170 n mi east of the northern Leeward Islands. Ophelia moved slowly northwestward over the next day or so, becoming a tropical storm again around 0600 UTC 28 September about 130 n mi east of the northern Leeward Islands.

Ophelia strengthened steadily as it turned northward and became a hurricane around 1800 UTC 29 September. It then reached major hurricane status when it was centered almost midway between the northern Leeward Islands and Bermuda. As Ophelia approached Bermuda, the eye became more distinct and deep convection gained symmetry. The eye of the hurricane passed directly over NOAA buoy 41049 at 0830 UTC 1 October. The buoy reported a maximum 1-min wind of 84 kt with a gust to 101 kt in the northern eyewall and a minimum pressure of 952.8 mb. It is estimated that Ophelia reached its peak intensity of 120 kt around 0000 UTC 2 October, when it was located about 120 n mi east-northeast of Bermuda. The wind field associated with the major hurricane was compact, however, such that winds on Bermuda did not even reach tropical storm force. Ophelia accelerated north-northeastward after reaching its peak intensity and weakened rapidly when it encountered strong southwesterly shear and much cooler waters. Ophelia lost its tropical characteristics just before it made landfall over southern Newfoundland around 1000 UTC 3 October. The extratropical low turned east-northeastward and weakened over the North Atlantic.

q. Hurricane Phillipe, 24 September - 8 October

An area of low pressure with deep organized convection formed around 0000 UTC 23 September as a tropical wave crossed the west coast of Africa. The overall organization increased and a tropical depression formed at 0600 UTC 24 September about 225 n mi south of the southernmost Cape Verde Islands. The depression strengthened to a tropical storm 6 h later.

During the next few days, Philippe wobbled westward with slight fluctuations in intensity and became a 65-kt hurricane at 0000 UTC 4 October about 475 n mi northeast of the Leeward Islands. The cyclone weakened to a tropical storm by 1200 UTC that day and made a slow but sharp turn toward the northwest and north over the western Atlantic on 5 October.

The cyclone reintensified again and became a hurricane about 400 n mi south-southeast of Bermuda at 0600 UTC 6 October, reaching its maximum intensity of 80 kt around 1800 UTC. Philippe began to weaken on 7 October and became an extratropical cyclone 12 h later when it merged with a cold front.

r. Hurricane Rina, 23-28 October

A relatively low-latitude tropical wave left the west coast of Africa on 9 October and moved westward, accompanied by weak thunderstorm activity. The wave moved through the Windward Islands four days later, with thunderstorms increasing at that time aided by a diffluent upper-level wind field. On 19 October, the wave showed some signs of additional organization, but easterly shear was too strong for tropical cyclone development. A cold front entering the northwestern Caribbean Sea might have contributed some low-level vorticity to the system, but the wave appears to have been the main focus for genesis. Convection intensified near the wave axis on 21 October, which resulted in the formation of a nearly stationary broad surface low in the western Caribbean. The next day, surface observations indicated falling pressures in the area and a better-defined low-level circulation. Thunderstorms increased markedly near and to the west of the center, and a tropical depression formed by 0600 UTC 23 October about 55 n mi north of Providencia Island, east of Nicaragua.

A broad mid-level trough over the southeastern United States caused a weakness in a ridge near Florida and, as a result, the depression moved northward. The system became a tropical storm and then rapidly intensified over the deep warm waters of the western Caribbean, becoming a hurricane by 1800 UTC 24 October and a major hurricane 24 h later. During that time, mid- to upper-level ridging rebuilt over the Gulf of Mexico, and the hurricane slowed down, gradually turning toward the west. Rina reached a peak intensity of 100 kt and a minimum pressure of 966 mb around 0000 UTC 26 October, when the tropical cyclone was 220 n mi east-southeast of Chetumal, Mexico. This was based based on a NOAA SFMR measurement of 103 kt at 2240 UTC 25 October, with another SFMR reading of 98 kt also taken by the Air Force Reserve several hours later.

The conducive upper-level winds did not last very long, however, and Rina dropped below major hurricane strength 12 h later. Increasing southeasterly and southerly shear caused Rina to weaken further for the next couple of days. The cyclone moved generally toward the west-northwest and northwest on 26 and 27 October, becoming a tropical storm near 1200 UTC

27 October about 75 n mi south-southeast of Tulum, Mexico. Rina turned northward and strong southerly shear caused additional weakening. The tropical storm made landfall near Paamul, Mexico, about 10 n mi southwest of Playa del Carmen, with an intensity of 50 kt near 0200 UTC 28 October. The center of Rina remained over land for about 9 h before emerging into the Yucatan Channel. Strong southerly shear caused all convection near the center to dissipate, and Rina degenerated into a remnant low in the Yucatan Channel by 1800 UTC 28 October. The remnant low moved toward the east-northeast and east within the low-level flow ahead of a cold front, and dissipated early the next day just southeast of the western tip of Cuba.

s. Tropical Storm Sean, 8-11 Nov

The origin of Sean from an extratropical low was unusual but not unprecedented. On 3 November, a low pressure system formed along a frontal zone over the central United States and moved off the U.S. east coast the next day. Earlier, this frontal system produced heavy snow in Colorado. The extratropical low became nearly stationary between Bermuda and the Bahamas during 6-7 November, after it separated from an eastward-moving mid-latitude frontal trough. Cloudiness and showers gradually increased around the low while a surface circulation became better defined by 1800 UTC 6 November, with a large field of tropical-storm-force winds to the east of the center. Over the next 36 h, both the distribution of the wind field and convection became more symmetric, and it is estimated that a subtropical storm formed at 0600 UTC 8 November about 385 n mi southwest of Bermuda. At this time, the surface center was co-located with an upper-level low which developed in the same area; hence, the subtropical classification.

Sean moved erratically and quickly transitioned into a tropical storm by 1800 UTC that day when the cyclone separated from the upper-level low, the convection became concentrated near the center, and the system developed upper-level outflow. Sean gradually intensified within an environment of light to moderate vertical wind shear. A weak middle-level ridge of high pressure to the northeast of the cyclone forced Sean to move slowly west-northwestward and then northward for the next 24-36 h. During that time, Sean intensified a little more when a ring of convection developed around an eye-like feature, and the cyclone reached its peak intensity of 55 kt with a 982 mb minimum pressure at 1200 UTC 10 November. By then, Sean had turned toward the north-northeast ahead of an approaching trough and accelerated. An increase in shear induced by the approaching trough, along with cooler waters, resulted in Sean's weakening early on 11 November.

The center of Sean passed about 75 n mi to the west-northwest of Bermuda at 1200 UTC 11 November while the circulation was becoming elongated ahead of the frontal system. By 0000 UTC 12 November, Sean lost its tropical characteristics, and it dissipated 24 h later when it merged with a cold front in the northeastern Atlantic.

The Marine Operations Center in Bermuda reported sustained surface winds of 37 kt and a wind gust to 54 kt near 0900 UTC 11 November as the center of Sean passed close to the island. Although visible satellite imagery showed an eye-like feature during most of the day on 9 November, which is typical of cyclones of hurricane intensity, the surrounding convection was not strong enough to classify the system as a hurricane using the Dvorak technique. A lower intensity estimate was also supported by data from a concurrent reconnaissance aircraft flight, which reported maximum surface winds of only 52 kt.

3. Non-Developing Depressions

a. Tropical Depression Ten, 25-27 August

A well-defined tropical wave crossed the west coast of Africa on 22 August and continued westward across the tropical Atlantic. By 0000 UTC 25 August the deep convection became organized into curved bands, indicating the formation of a tropical depression about 350 n mi west-southwest of the southernmost Cape Verde Islands

The tropical cyclone was best organized right around the time of genesis and was closest to becoming a tropical storm at that time. Thereafter, moderate to strong northeasterly shear prevented the system from strengthening as it moved west-northwestward. By 0000 UTC 27 August, practically all of the associated thunderstorms vanished and the low-level circulation opened up into a northeast-southwest-oriented trough. The system dissipated over the far eastern tropical Atlantic.

4. Forecast Verifications and Warnings

For all operationally designated tropical or subtropical cyclones in the Atlantic and eastern North Pacific basins, the NHC issues an official forecast of the cyclone's center location and maximum 1-min surface wind speed. Forecasts are issued every 6 h, and contain projections valid 12, 24, 36, 48, 72, 96, and 120 h after the forecast's nominal initial time (0000, 0600, 1200, or 1800 UTC)[2]. At the conclusion of the season, forecasts are evaluated by comparing the projected positions and intensities to the corresponding post-storm derived "best track" positions and intensities for each cyclone. A forecast is included in the verification only if the system is classified in the final best track as a tropical (or subtropical[3]) cyclone at both the forecast's initial time and at the projection's valid time. All other stages of development (e.g., tropical wave,

[2] The nominal initial time represents the beginning of the forecast process. The actual advisory package is not released until 3 h after the nominal initial time, i.e., at 0300, 0900, 1500, and 2100 UTC.

[3] For the remainder of this section, the term "tropical cyclone" shall be understood to also include subtropical cyclones.

[remnant] low, extratropical) are excluded[4]. For verification purposes, forecasts associated with special advisories do not supersede the original forecast issued for that synoptic time; rather, the original forecast is retained[5]. All verifications in this report include the depression stage.

Track forecast error is defined as the great-circle distance between a cyclone's forecast position and the best track position at the forecast verification time, while track forecast skill represents a normalization of forecast error against some standard or baseline, and is positive when the forecast error is smaller than the error from the baseline. To assess the degree of skill in a set of track forecasts, the track forecast error can be compared with the error from CLIPER5, a climatology and persistence model that contains no information about the current state of the atmosphere (Neumann 1972; Aberson 1998). If CLIPER5 errors are unusually low during a given season, for example, it indicates that the year's storms were inherently easier to forecast than normal, or otherwise unusually well-behaved.

Table 2 presents the results of the NHC official track forecast verification for the 2011 season, along with results averaged for the previous 5-yr period, 2006-2010. In 2011, the NHC issued 383 Atlantic basin tropical cyclone forecasts[6], a number well above the average over the previous five years (274). Mean track errors ranged from 28 n mi at 12 h to 245 n mi at 120 h. It is seen that mean official track forecast errors in 2011 were smaller than the previous 5-yr mean at all forecast times except 120 h. In addition, the official track forecast errors set a record for accuracy at the 24-, 36-, 48-, and 72-h forecast times. Over the past 15 years or so, 24–72-h track forecast errors have been reduced by about 50%, although it appears that track forecast skill

[4] Possible classifications in the best track are: Tropical Depression, Tropical Storm, Hurricane, Subtropical Depression, Subtropical Storm, Extratropical, Disturbance, Wave, and Low.

[5] Special advisories are issued whenever an unexpected significant change has occurred or when watches or warnings are to be issued between regularly scheduled advisories. The treatment of special advisories in forecast databases changed in 2005 to the current practice of retaining and verifying the original advisory forecast.

[6] This count does not include forecasts issued for systems later classified to have been something other than a tropical cyclone at the forecast time.

has leveled off during the past few years. Track forecast error reductions of about 40% have occurred over the past 10 years for the 96-120 h forecast periods. Vector biases were consistently north-northwestward in 2011 (i.e., the official forecast tended to fall to the north-northwest of the verifying position). An examination of the track errors shows that the biases were primarily along-track and fast, but there was a cross-track bias as well. Track forecast skill in 2011 ranged from 33% at 12 h to 62% at 48 h.

Forecast intensity error is defined as the absolute value of the difference between the forecast and best track intensity at the forecast verifying time. Skill in a set of intensity forecasts is assessed using Decay-SHIFOR5 (DSHIFOR5) as the baseline. The DSHIFOR5 forecast is obtained by initially running SHIFOR5, the climatology and persistence model for intensity that is analogous to the CLIPER5 model for track (Jarvinen and Neumann 1979, Knaff et al. 2003). The output from SHIFOR5 is then adjusted for land interaction by applying the decay rate of DeMaria et al (2006). The application of the decay component requires a forecast track, which here is given by CLIPER5. The use of DSHIFOR5 as the intensity skill benchmark was introduced in 2006. On average, DSHIFOR5 errors are about 5-15% lower than SHIFOR5 in the Atlantic basin from 12-72 h, and about the same as SHIFOR5 at 96 and 120 h.

Table 3 compares official forecasts to the DSHIFOR5 model that serves as a benchmark of intensity forecast skill. Mean forecast errors in 2011 ranged from about 6 kt at 12 h to about 17 kt at 72 and 120 h. These errors were below the 5-yr means at all forecast times. Official forecasts had little bias in 2011. DSHIFOR5 errors were also below their 5-yr means at all forecast times, indicating the season's storms were easier than normal to forecast. There has been virtually no net change in error over the past 15-20 years, although forecasts during the current decade, on average, have been more skillful than those from the previous one.

A hurricane (or tropical storm) warning is a notice that 1-min sustained winds of hurricane (or tropical storm) force are expected within a specified coastal area within the next 36 h[7]. A watch means that the conditions were possible within that area within the next 48 h. Table 4 shows the watch and warning lead times for cyclones that affected or had the potential to affect the United States in 2011. The issuance of watches and/or warnings for territories outside of the United States is the responsibility of their respective governments, and those statistics are not presented here. Because observations are generally inadequate to determine when hurricane or tropical storm conditions first reach the coastline, lead time is defined here as the time between the issuance of the watch or warning and the time of landfall or the closest point of approach of the cyclone center to the coastline. This definition will usually result in an overestimation of lead times for preparedness actions, particularly for hurricanes, since tropical storm conditions can arrive several hours prior to the onset of hurricane conditions.

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[7] NHC extended its watch and warning lead times by 12 h starting in the 2010 season, such that a hurricane or tropical storm warning signifies that 1-min sustained tropical storm force winds are expected to begin within the next 36 h. A watch now means those conditions are possible within the next 48 h.

contained in the individual storm summaries was provided by the meteorological services of the affected countries. In the United States, much of the local impact information is compiled by the local NWS Weather Forecast Offices. The NWS National Data Buoy Center and the National Ocean Service provided summaries for their data.

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Table Captions

Table 1. 2011 Atlantic hurricane season statistics.

Table 2. Homogenous comparison of official and CLIPER5 track forecast errors in the Atlantic basin for the 2011 season for all tropical and subtropical cyclones. Averages for the previous 5-yr period are shown for comparison.

Table 3. Homogenous comparison of official and Decay-SHIFOR5 intensity forecast errors in the Atlantic basin for the 2011 season for all tropical and sub-tropical cyclones. Averages for the previous 5-yr period are shown for comparison.

Table 4. Watch and warning lead times (defined as the time between the issuance of the watch or warning and the time of landfall or closest approach of the center to the coastline) for tropical cyclones affecting the United States in 2011. If multiple watch or warning types (TS or H) were issued, the type corresponding to the most severe conditions experienced over land is given.

Figure Captions

Figure 1. Tracks of Atlantic tropical storms and hurricane during 2011.

Figure 2. Atlantic Sea Surface Temperature Anomalies (top) in degress Celsius during August through October 2011 and Atlantic 200-850 hPa vertical shear vectors anomalies in ms^{-1} (bottom) during August through October 2011.

Figure 3. Atlantic and eastern North Pacific named storm tracks from August through September 2011 superimposed on 500 hPa height anomalies (m).

Figure 4. Rainfall totals associated with Hurricane Irene. This map was produced by the NOAA Hydrometeorological Prediction Center.

Figure 5. Selected sustained wind coastal observations in knots associated with Hurricane Irene (top) and selected storm surge values in feet associated with Hurricane Irene (bottom). Maps were produced by the NHC storm surge unit.

Figure 6. Rainfall totals associated with Tropical Storm Lee. This map was produced by the NOAA Hydrometeorological Prediction Center.

Table 1. 2011 Atlantic hurricane season statistics.

Storm Name	**Class**[a]	**Dates**[b]	**Max. 1-min Wind (kt)**	**Min. Pressure (mb)**	**Deaths**	**U. S. Damage ($million)**
Arlene	TS	28 Jun – 1 Jul	55	993	22	
Bret	TS	17 – 22 Jul	60	995		
Cindy	TS	20 – 22 Jul	60	994		
Don	TS	27 – 30 Jul	45	997		
Emily	TS	2 – 7 Aug	45	1003		
Franklin	TS	12 – 13 Aug	40	1004		
Gert	TS	13 – 16 Aug	55	1000		
Harvey	TS	19 – 22 Aug	55	994	3	
Irene	MH	21 – 28 Aug	105	942	49	7000
Ten	TD	25 – 26 Aug	30	1006		
Jose	TS	27 – 28 Aug	40	1006		
Katia	MH	29 Aug – 10 Sep	120	942		
Unnamed	TS	1-2 Sep	40	1002		
Lee	TS	2 – 5 Sep	50	986	3	510
Maria	H	6 – 16 Sep	70	983		
Nate	H	7 – 11 Sep	65	994	4	
Ophelia	MH	20 Sep – 3 Oct	120	940		
Philippe	H	24 Sep – 8 Oct	80	976		
Rina	MH	23 - 28 Oct	100	966		
Sean	TS	8-11 Nov	55	982		

[a] TD - tropical depression maximum sustained winds 38 mph or less; TS - tropical storm, winds 39-73 mph; H - hurricane, winds 74-110 mph; MH - major hurricane, winds 111 mph or higher.

[b] Dates based on UTC time and include tropical depression stage

Table2. Homogenous comparison of official and CLIPER5 track forecast errors in the Atlantic basin for the 2011 season for all tropical cyclones. Averages for the previous 5-yr period are shown for comparison.

	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
2011 mean OFCL error (n mi)	28.2	43.4	57.1	70.8	109.7	166.6	244.7
2011 mean CLIPER5 error (n mi)	42.3	82.5	133.6	185.8	278.9	360.0	411.7
2011 mean OFCL skill relative to CLIPER5 (%)	33.3	47.4	57.2	61.9	60.7	53.7	40.5
2011 mean OFCL bias vector (°/n mi)	332/3	347/8	347/11	350/17	336/28	335/38	332/57
2011 number of cases	339	297	260	226	176	140	113
2006-2010 mean OFCL error (n mi)	30.8	50.2	69.4	89.2	133.2	174.2	214.8
2006-2010 mean CLIPER5 error (n mi)	47.5	97.7	155.3	216.9	323.3	402.2	476.1
2006-2010 mean OFCL skill relative to CLIPER5 (%)	35.1	48.6	55.3	58.9	58.8	56.7	54.9
2006-2010 mean OFCL bias vector (°/n mi)	322/3	315/6	312/9	319/11	300/6	098/4	104/2
2006-2010 number of cases	1231	1089	954	839	662	503	387
2011 OFCL error relative to 2006-2010 mean (%)	-8.4	-13.5	-17.7	-20.6	-17.6	-4.4	13.9
2011 CLIPER5 error relative to 2005-2010 mean (%)	-10.9	-15.6	-14.0.	-14.3	-14.0	-10.5	-13.5

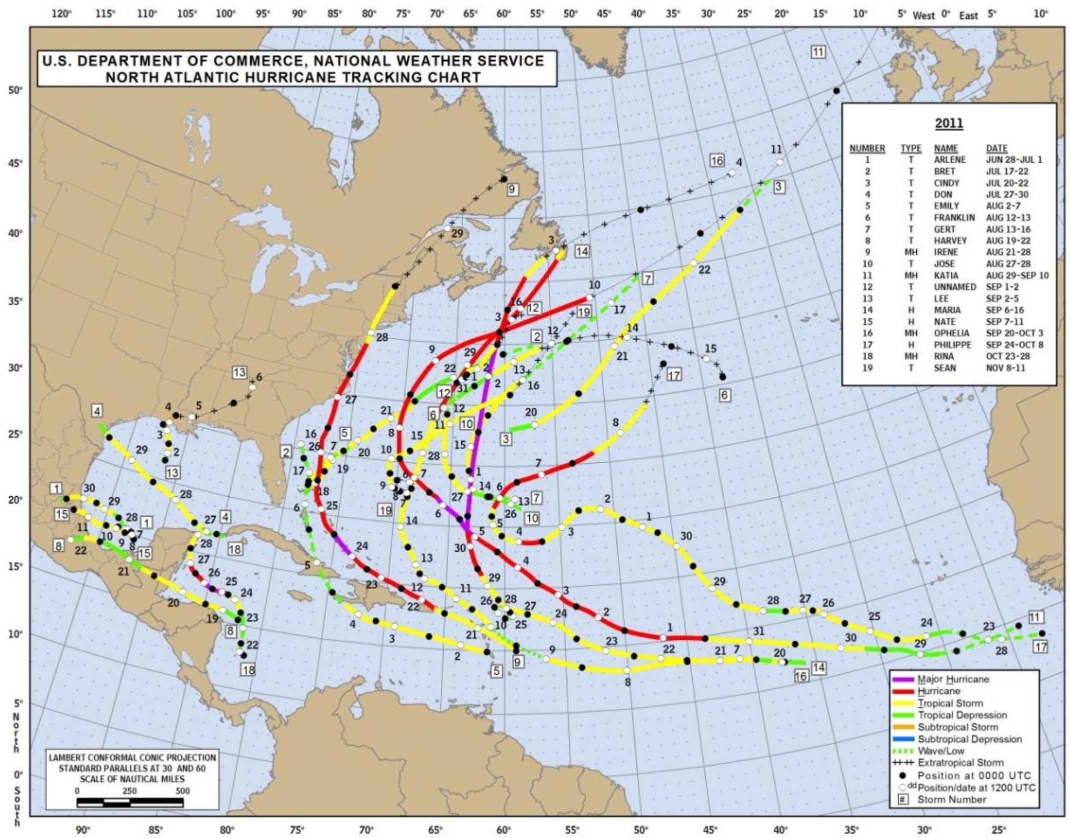
Table 3. Homogenous comparison of official and Decay-SHIFOR5 intensity forecast errors in the Atlantic basin for the 2011 season for all tropical cyclones. Averages for the previous 5-yr period are shown for comparison.

	Forecast Period (h)						
	12	**24**	**36**	**48**	**72**	**96**	**120**
2011 mean OFCL error (kt)	6.3	9.7	12.0	14.4	16.6	16.2	16.5
2011 mean Decay-SHIFOR5 error (kt)	6.9	10.4	12.2	13.5	16.7	17.3	13.9
2011 mean OFCL skill relative to Decay-SHIFOR5 (%)	8.7	6.7	1.6	-6.7	0.6	-8.0	-18.7
2011 OFCL bias (kt)	-0.5	0.3	0.4	0.7	0.2	0.2	-1.0
2011 number of cases	339	297	260	226	176	140	113
2006-10 mean OFCL error (kt)	7.3	11.0	13.2	15.1	17.2	17.9	18.7
2006-10 mean Decay-SHIFOR5 error (kt)	8.5	12.3	15.5	17.9	20.2	21.9	21.7
2006-10 mean OFCL skill relative to Decay-SHIFOR5 (%)	14.1	10.6	14.8	15.6	14.9	18.3	13.8
2006-10 OFCL bias (kt)	0.2	1.1	1.5	2.1	2.7	2.4	2.2
2006-10 number of cases	1231	1089	954	839	662	503	387
2011 OFCL error relative to 2006-10 mean (%)	13.7	11.8	9.1	4.6	3.5	9.5	11.8
2011 Decay-SHIFOR5 error relative to 2006-10 mean (%)	18.8	15.4	20.6	24.6	17.3	21.0	35.9

Table 4. Watch and warning lead times (defined as the time between the issuance of the watch or warning and the time of landfall or closest approach of the center to the coastline) for tropical cyclones affecting the United States in 2011. If multiple watch or warning types (TS or H) were issued, the type corresponding to the most severe conditions experienced over land is given.

Storm	Landfall or Point of Closest Approach	Watch and/or Warning Type	Watch Lead Time (h)	Warning Lead Time (h)
Don	Lower Texas coast	TS	48	36
Irene	Surf City to North Carolina/Virginia border	H	51	39
Lee	Pascagoula, MS to Sabine Pass, TX	TS		58

Fig. 1. Tracks of Atlantic tropical storms and hurricanes during 2011.



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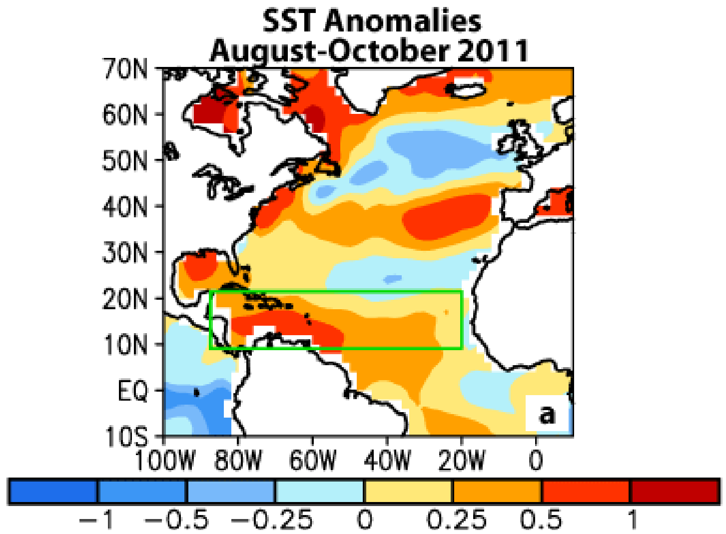

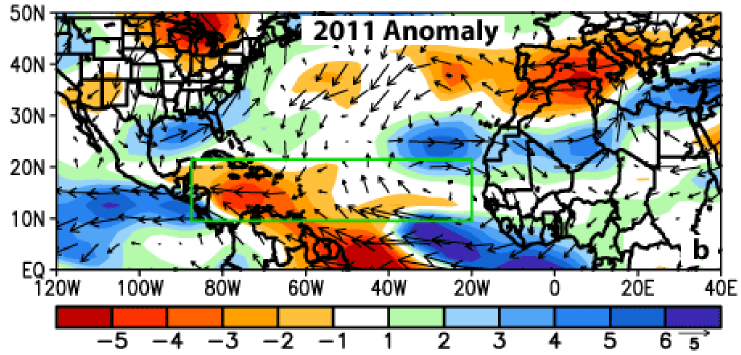

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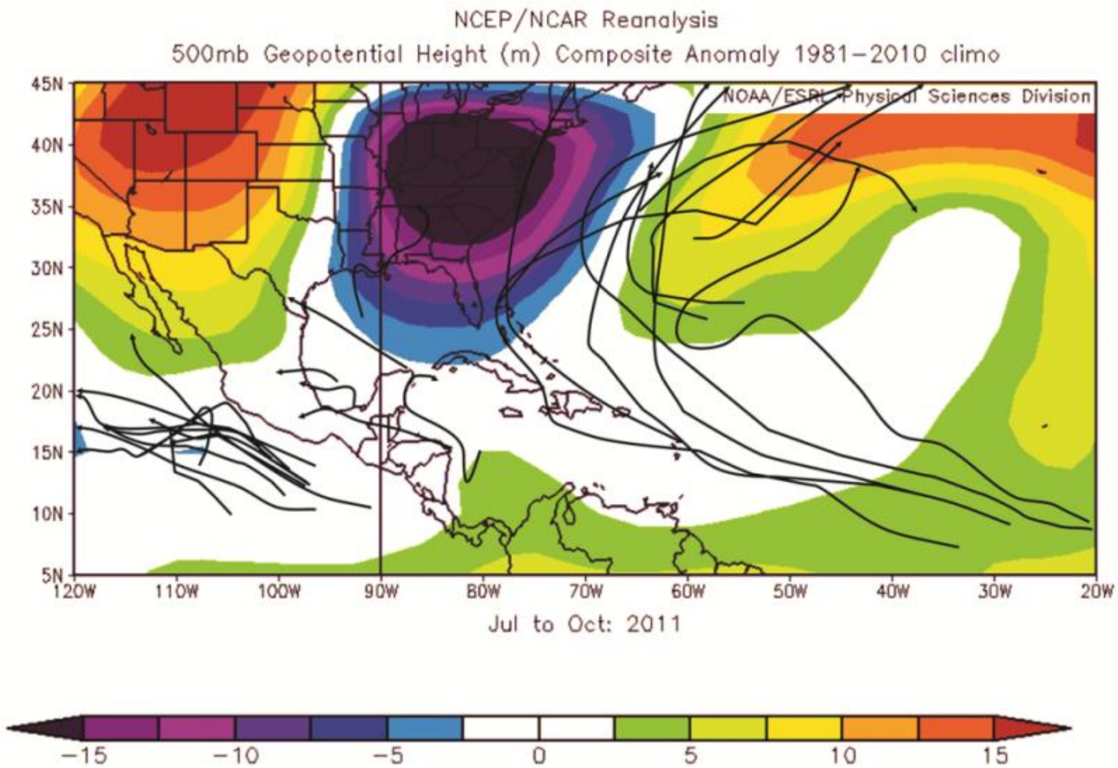
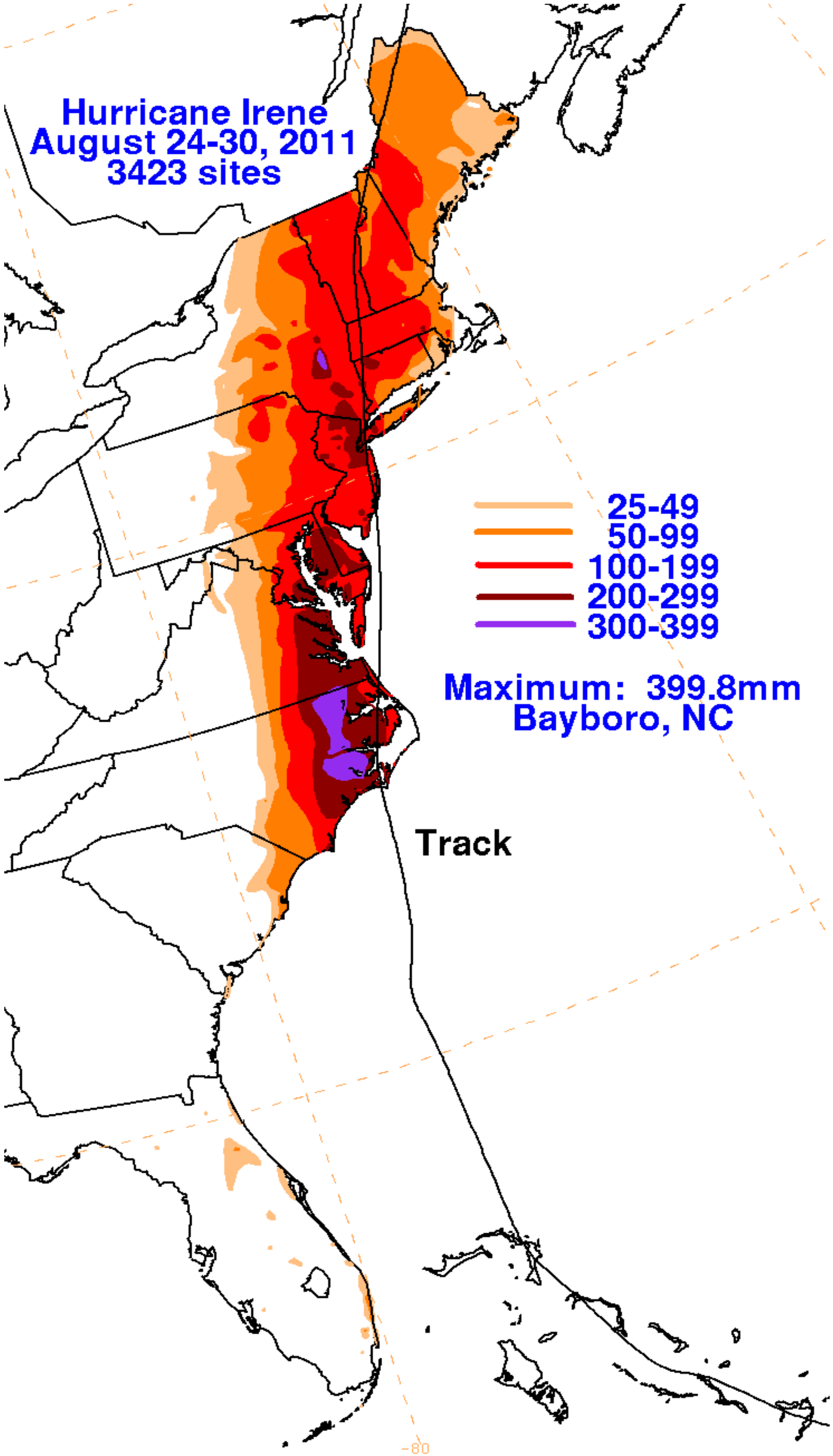


Fig. 4. Rainfall totals associated with Hurricane Irene. This map was produced by the NOAA Hydrometeorological Prediction Center.



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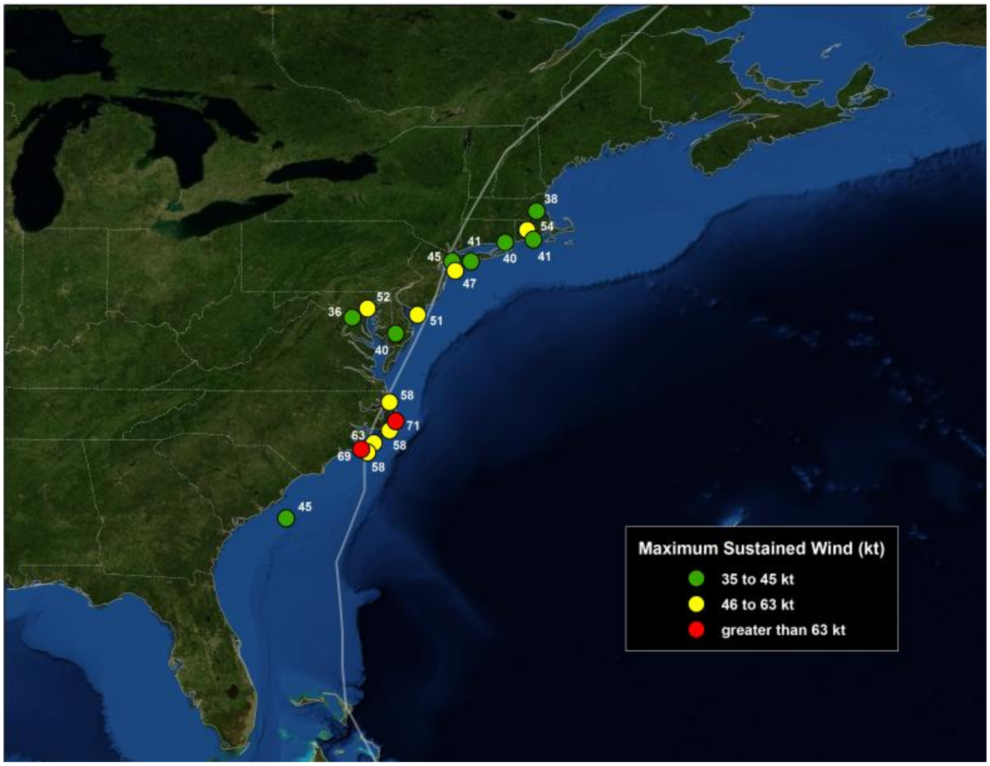

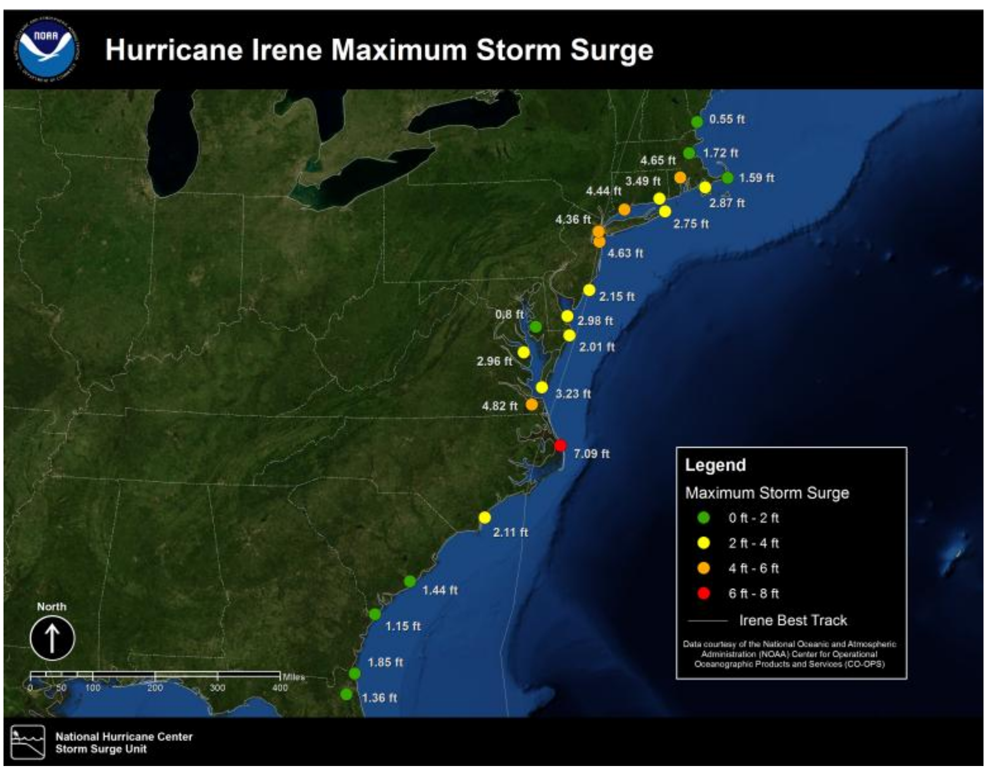

Fig. 6. Rainfall totals associated with Tropical Storm Lee. This map was produced by the NOAA Hydrometeorological Prediction Center.