ANNUAL WEATHER SUMMARY

Atlantic Hurricane Season of 2010*

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ABSTRACT

The 2010 Atlantic hurricane season was marked by above-average tropical cyclone activity with the formation of 19 tropical storms. A total of 12 of the storms became hurricanes and 5 became major hurricanes (category 3 or higher on the Saffir–Simpson hurricane wind scale). In addition, there were two tropical depressions that did not reach storm strength. These totals were well above the long-term averages of 11 named storms, 6 hurricanes, and 2 major hurricanes. The areas most affected by the 2010 storms were eastern Mexico, Central America, and the island nations of the western Caribbean Sea, where multiple strikes occurred. In addition, two hurricanes struck eastern Canada. Despite the high level of activity, no hurricanes made landfall in the United States in 2010. The death toll from the 2010 Atlantic tropical cyclones was 189.

A verification of National Hurricane Center official forecasts during 2010 is also presented. The 2010 mean track errors were slightly larger than the previous 5-yr average at 12 and 24 h and much smaller at the other forecast times, even though the 2010 track forecasts were more difficult than normal. The 2010 mean intensity forecast errors were larger than the previous 5-yr average at 12–48 h, smaller at the longer forecast times, and had a high bias at all forecast times. As with the track forecasts, the 2010 intensity forecasts were more difficult than normal at all forecast times.

1. Introduction

Tropical cyclone activity during the 2010 Atlantic season (Fig. 1, Table 1) was well above average with the formation of 19 tropical storms—tying the 1995 season for the third-highest total on record (Lawrence et al. 1998). In total, 12 storms became hurricanes—the second-highest total on record behind the 15 observed in 2005 (Beven et al. 2008). Five of the hurricanes became major hurricanes [maximum 1-min winds equal to or greater than 96 kt ($1 \text{ kt} = 0.5144 \text{ m s}^{-1}$), corresponding to category 3 or greater on the Saffir–Simpson hurricane wind scale¹].

¹ As of the 2010 hurricane season, the Saffir–Simpson hurricane scale has been revised and renamed the Saffir–Simpson hurricane wind scale in order to emphasize that the scale only addresses hurricane-related wind impacts. The scale no longer includes central pressure, and it does not address the other hurricane-related impacts of storm surge, rainfall-induced flooding, and tornadoes.

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(Saffir 1973; Simpson 1974; Schott et al. 2010)]. These numbers are well above the long-term (1966–2009) averages of about 11, 6, and 2 named storms, hurricanes, and major hurricanes, 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 2010 was about 190% of the long-term (1951–2000) median value of $87.5 \times 10^4 \text{ kt}^2$. In addition, there were two tropical depressions that did not reach storm strength. The 2010 activity was concentrated during the climatological peak of the season, with five cyclones each forming in August and October and eight forming in September. The latter tied the record for the most Atlantic cyclones forming in a month with August 2002 (Pasch et al. 2004), September 2004 (Franklin et al. 2006), and August 2007 (Brennan et al. 2009).

The above-average activity was likely the result of two factors. First, the sea surface temperatures (SSTs) across the tropical Atlantic Ocean and Caribbean Sea were the warmest on record (Blunden et al. 2011). Based on a merged climatological SST dataset, the SSTs in the Atlantic between the Lesser Antilles and Africa for the entire hurricane season were 0.86°C above the climatological

FIG. 1. Tracks of Atlantic tropical storms and hurricanes during 2010.

normal for 1981–2010. This value is 0.2°C higher than the previous record observed in 2005. Second, the emergence of La Niña during the summer was associated with a large area of lower-than-average vertical wind shear over most of the tropical Atlantic Ocean and Caribbean (Fig. 2).

Despite the abundance of hurricanes, none made landfall in the United States. This was the first time on record that a season with nine or more hurricanes did not feature a U.S. hurricane landfall. Activity during 2010 was focused primarily in the deep tropics, with two clusters noted. The first cluster of cyclones formed in the western Caribbean and moved generally northwestward or westward toward Central America and Mexico. These tracks were likely due to persistent ridging across the U.S. southern plains and the northwestern coast of the Gulf of Mexico (Fig. 3). The other cluster was centered over the central tropical Atlantic. These storms tended to recurve to the east of the United States, likely due to persistent baroclinic troughs over the western Atlantic and the eastern United States (Fig. 3).

The 2010 cyclones heavily impacted land areas around the western Caribbean and southwestern Gulf of Mexico. Alex, which struck Mexico, was the strongest June hurricane since Alma in 1966 (Sugg 1967). Karl became the strongest hurricane on record in the Bay of Campeche and struck the coast of Mexico near Veracruz as a category 3 hurricane. Matthew and Nicole caused flooding and deaths over Central America and Jamaica, with Cuba being affected again a few weeks later by Paula. Hermine, which had an unusual origin as an eastern North Pacific cyclone, affected northeastern Mexico and Texas. Richard made landfall in Belize in October at category 2 strength. Elsewhere, Earl skirted the northern Leeward Islands and the East Coast of the United States before making landfall as a hurricane in Nova Scotia, Canada. The strongest hurricane of the season was Igor, a category 4 hurricane that later struck Newfoundland as a category 1 hurricane and caused some of the worst effects on that island in generations. The season concluded with Tomas—the latest hurricane during a season to strike the

TABLE 1. 2010 Atlantic hurricane season statistics.

Storm name	Class*	Dates**	Max 1-min wind (kt)	Min pressure (mb)	Deaths	U.S. damage [\$ million (U.S. dollars)]
Alex	H	25 Jun–2 Jul	95	946	23	<25
Two	TD	8–9 Jul	30	1005		
Bonnie	TS	22–24 Jul	40	1005		
Colin	TS	2–8 Aug	50	1005		
Five	TD	10–11 Aug	30	1008		
Danielle	MH	21–30 Aug	115	942	1	
Earl	MH	25 Aug–4 Sep	125	927	5	18
Fiona	TS	30 Aug–3 Sep	55	998		
Gaston	TS	1–2 Sep	35	1005		
Hermine	TS	5–9 Sep	60	989	6	240
Igor	MH	8–21 Sep	135	924	3	
Julia	MH	12–20 Sep	120	948		
Karl	MH	14–18 Sep	110	956	14	
Lisa	H	20–26 Sep	75	982		
Matthew	TS	23–26 Sep	50	998	78	
Nicole	TS	28–29 Sep	40	995	13	
Otto	H	6–10 Oct	75	976		
Paula	H	11–15 Oct	90	981	1	
Richard	H	20–25 Oct	85	977	1	
Shary	H	28–30 Oct	65	989		
Tomas	H	29 Oct–7 Nov	85	982	44	

* Tropical depression (TD) maximum sustained winds 38 mph or less; tropical storm (TS), winds 39–73 mph; hurricane (H), winds 74–110 mph; and major hurricane (MH), winds 111 mph or higher.

** Dates based on UTC time and include tropical depression stage.

Windward Islands in centuries, and which later affected Haiti, Cuba, and the southeastern Bahamas as a rare November hurricane. The 2010 cyclones were directly responsible for 188 deaths: 65 in Nicaragua, 44 in Mexico, 35 in Haiti, 13 in Jamaica, 11 in the United States, 8 in St. Lucia, 4 in Honduras, 2 each in Canada and Guatemala, and 1 each in Puerto Rico, the U.S. Virgin Islands, El Salvador, Belize, and Curacao.

2. Individual cyclone summaries

The individual cyclone summaries below are based on poststorm 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. In-depth descriptions of data sources have been provided previously (e.g., [Franklin and Brown 2008](#); [Rappaport et al. 2009](#)). There were two significant changes in data sources between the 2009 and 2010 seasons. The first was the failure of the QuikSCAT scatterometer in December 2009. The second was the presence of research aircraft data from the National Science Foundation (NSF), the National Center for Atmospheric Research, and the National Aeronautics and Space Administration (NASA) special field experiments during 2010: the Pre-Depression Investigation of Cloud

Systems in the Tropics (PREDICT) and the Genesis and Rapid Intensification Processes (GRIP; [Montgomery et al. 2012](#)). These data augmented the National Oceanic and Atmospheric Administration's (NOAA's) Intensity Forecasting Experiment (IFEX) field program.

FIG. 2. (top) Atlantic 200–850-hPa vertical shear vectors and (bottom) anomalies during August–October 2010. The magnitudes are expressed in m s^{-1} with a contour interval of 2 m s^{-1} .

FIG. 3. Atlantic hurricane tracks from August to September 2010 superimposed on 500-hPa height anomalies (m).

Poststorm 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 (since 2003) the 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 the 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” (Office of the Federal Coordinator for Meteorology 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.² The dates given in Table 1 only include the tropical and subtropical stages.

Damage in the United States during 2010 was less than \$300 million (U.S. dollars). Damage in other countries in the Atlantic basin was significantly greater, and is included (in U.S. dollars) in the storm summaries when available. Descriptions of the type and scope of damage are taken from a variety of sources, including federal, local, and international government officials, media reports, and local National Weather Service (NWS) Weather Forecast Offices (WFOs). 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 for selected cyclones are also provided in the online supplemental material to this paper (Tables S1–S6). All dates and times are based on coordinated universal time (UTC).

a. Hurricane Alex

1) SYNOPTIC HISTORY

Alex’s genesis does not appear to be directly associated with an African tropical wave, but rather with a perturbation within the intertropical convergence zone (ITCZ) that was first identified on 17 June at very low latitudes over the central Atlantic Ocean. Over the next few days this feature moved west-northwestward over the deep tropical Atlantic and intermittently enhanced deep convection in the ITCZ. By 20 June, the system had crossed the Windward Islands and produced a large area of disturbed weather affecting much of the southeastern Caribbean Sea. The disturbance subsequently moved west-northwestward across the Caribbean with fluctuating levels of organization. By 1800 UTC 24 June, a surface low had formed over the northwestern Caribbean about 90 n mi (1 n mi = 1.852 km) northeast of Cabo Gracias a Dios on the border of Nicaragua and Honduras, but it lacked sufficient organized deep convection to be classified as a tropical cyclone. The low drifted northwestward to west-northwestward for about a day while deep convection increased and became more organized near and around the center. It is estimated that the system became a tropical depression by 1800 UTC 25 June about 80 n mi north-northeast of Puerto Lempira, Honduras (Fig. 1).

The cyclone moved west-northwestward to westward with an increase in forward speed and strengthened into a tropical storm around 0600 UTC 26 June. Alex’s center passed about 30–60 n mi to the north of the Bay Islands of Honduras and approached the coast of Belize late on 26 June. Maximum sustained winds reached 55 kt shortly before the center made landfall near Belize City around 0000 UTC 27 June.

Alex crossed Belize and the southern Yucatan Peninsula of Mexico on 27 June, although satellite images indicate that the system remained well organized while over land. The cyclone weakened to a minimal tropical storm just before moving back over water, then it reintensified over the southwestern Gulf of Mexico starting early on 28 June. Weakening of a deep-layer subtropical ridge that extended from the Bahamas across the Gulf of Mexico later that day caused Alex to slow down and turn toward the north-northwest. The ridge built to the north

² 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.

of the storm on 29 June, and Alex turned toward the west-northwest at an increased forward speed. In an environment conducive for additional strengthening (SSTs of 29°C or warmer and weak northerly vertical shear) Alex became a hurricane around 0000 UTC 30 June. The hurricane slowed its forward speed and jogged toward the north-northwest on 30 June, possibly due to a temporary weakening of a midtropospheric ridge near the northwest Gulf of Mexico coast. Alex then turned toward the west and west-southwest on 1 July, as the ridge again rebuilt. Steadily intensifying right up until landfall, Alex became a category 2 hurricane by 0000 UTC 1 July and reached an estimated peak intensity of 95 kt as it made its final landfall near Soto la Marina, in a sparsely populated region of the state of Tamaulipas in northeastern Mexico around 0200 UTC 1 July.

Alex continued moving west-southwestward while rapidly weakening over land and became a tropical storm by 1200 UTC 1 July. After the center crossed the extreme southern part of the Mexican state of Nuevo León, Alex weakened to a tropical depression in the state of San Luis Potosí by 0000 UTC 2 July. The cyclone dissipated over the high terrain of central Mexico a few hours later.

2) METEOROLOGICAL STATISTICS

The estimated maximum intensity of 95 kt is based on a Stepped Frequency Microwave Radiometer (SFMR)-estimated surface wind of 87 kt just east of the center about an hour prior to landfall and the assumption that stronger winds occurred north of the center of this west-southwestward-moving hurricane. Furthermore, Doppler radar velocity data from Brownsville, Texas, radar indicated that the maximum winds increased during the last hour before landfall.

Selected surface observations from land stations and data buoys are given in Table S1 in the online supplemental material. The highest official wind observation was at Port Isabel, Texas, where sustained winds of 44 kt with a gust to 54 kt were measured. No official meteorological observations were received near the landfall location in Mexico.

Alex produced phenomenally heavy rain over extreme northeastern Mexico, where storm total precipitation estimates exceeded 500 mm over a fairly large area. A maximum of 803.2 mm occurred at Estanzuela in Nuevo Leon state, while Monterey in Nuevo Leon reported 411 mm. Rainfall totals of 125–250 mm or more were observed over the eastern portions of south Texas.

Storm surge heights were generally below 1.5 m along the lower Texas coast, but significantly greater storm surges likely occurred near the landfall location in Mexico.

Nine tornadoes were reported in Texas: two in Cameron County, one in Willacy County, two in Refugio County,

one in Nueces County, one in Kleberg County, and two in Aransas County. All were rated as EF0 intensity and caused only minor damage.

3) CASUALTY AND DAMAGE STATISTICS

Although media accounts of fatalities are conflicting, the storm is believed to have directly caused 21 deaths in the state of Nuevo León. The torrential rains resulted in severe flooding over northeastern Mexico. The city of Monterrey was particularly hard hit with significant damage to its infrastructure. Four bridges were destroyed and, according to the Associated Press, “major streets turned [in]to rampaging rivers that gashed ravines through the pavement down to sewage lines and buried vehicles window deep in rocks and sand.” A rough damage estimate in Mexico, based on media reports, is \$1.5 billion (U.S. dollars).

In Texas, there was about \$10 million (U.S. dollars) worth of damage to agriculture in Hidalgo County and 9000 customers lost power in extreme southern Texas. Alex caused two deaths in Guatemala. Reports from the Belize National Emergency Management Organization suggest Alex’s impacts there were minimal.

b. Tropical Storm Bonnie

A tropical wave moved westward from the coast of Africa on 10 July and crossed the tropical Atlantic Ocean accompanied by little convection. The wave approached the northern Leeward Islands on 18 July, with convection increasing as it interacted with an upper-level low north of Hispaniola. Although vertical wind shear slowed development, a weak surface low pressure system formed along the north end of the wave axis early on 22 July. The surface low moved west-northwestward to the north of the upper-level low, with the shear weakening and backing from southwesterly to southerly. This allowed the formation of a tropical depression at 0600 UTC that day just south of Acklins Island in the central Bahamas (Fig. 1).

The cyclone moved northwestward into an upper-level col region between the upper-low and a broad trough to the north. This further decreased the shear and allowed the depression to strengthen into a tropical storm near 0000 UTC 23 July over the central Bahamas. Bonnie reached its peak intensity of 40 kt, 6 h later near southern Andros Island. Later on 23 July, increasing southeasterly vertical shear caused Bonnie to weaken, and it made landfall along the southeastern coast of Florida near Elliot Key at around 1430 UTC with maximum winds of 35 kt. The storm weakened to a tropical depression a few hours later over the Everglades.

Continuing shear, dry midlevel air, and a lack of persistent central convection led to additional weakening

over the eastern Gulf of Mexico. Bonnie degenerated into a nonconvective remnant low pressure system early on 25 July about 60 n mi southeast of the mouth of the Mississippi River. The low made landfall about 4 h later near the southeastern tip of Louisiana and dissipated over east-central Louisiana after 1800 UTC that same day.

Bonnie's peak intensity of 40 kt at 0600 UTC 23 July is based on a 10-min-average wind report of 37 kt from Mangrove Cay, Bahamas (WMO 78085), at 0400 UTC 23 July. The strongest wind speed reported during Bonnie's trek across south Florida was a 10-min wind of 41 kt with a gust to 49 kt at Fowey Rocks (elevation 44 m above sea level). Storm total rainfall in Florida was generally around 50 mm, with a maximum of 82.6 mm at Bal Harbour. Bonnie caused minor impacts in the Bahamas and south Florida.

c. Tropical Storm Colin

Colin's formation resulted from the interaction of a surface trough and a tropical wave over the eastern Atlantic Ocean. The trough, located several hundred nautical miles southwest of the Cape Verde Islands, was generated by a slow-moving tropical wave that departed the west coast of Africa on 28 July. After the nearly stationary trough separated from the wave, the wave continued westward across the tropical Atlantic. A couple of days later, a second tropical wave, which was larger and moving faster than the trough, entered the eastern Atlantic. This second wave and the trough combined on 31 July to form a broad low pressure area about 750 n mi west-southwest of the Cape Verde Islands early on 1 August. The associated deep convection increased in organization that day; however, the system lacked a well-defined circulation. On 2 August, data from the Advanced Scatterometer (ASCAT) instrument showed a better-defined circulation, indicating the formation of a tropical depression at 1200 UTC (Fig. 1).

The depression moved west-northwestward at 15–20 kt to the south of a strong subtropical ridge over the central Atlantic, and it became a tropical storm at 0600 UTC 3 August while centered about 840 n mi east of the Lesser Antilles. The forward speed increased to 25–30 kt by 1200 UTC 3 August, and as a result, the system was unable to maintain a closed surface circulation, degenerating into a trough of low pressure by 1800 UTC that day. The trough, which continued to produce tropical storm-force winds, moved rapidly west-northwestward for about another 24 h before decelerating.

As the trough approached a weakness in the subtropical ridge over the western Atlantic it continued to decelerate. A well-defined low-level circulation reformed by 1200 UTC 5 August and the system regained tropical storm status. Maximum sustained winds reached 50 kt

late that day. Thereafter, strong westerly vertical shear caused Colin to weaken as it turned northward on 6 August and northeastward the next day. By 0000 UTC 8 August, Colin weakened to a tropical depression while located about 170 n mi south-southwest of Bermuda. During the next several hours the circulation became elongated, and Colin again degenerated into a trough about 100 n mi southwest of Bermuda. The remnant trough produced showers and wind gusts to near-tropical storm force on Bermuda as it passed west of the island later that day. The trough dissipated early on 9 August about 150 n mi northwest of Bermuda.

d. Hurricane Danielle

The origin of Danielle was complex. A strong tropical wave with associated 4-mb (1 mb = 1 hPa) pressure falls over 24 h crossed the west coast of Africa on 18 August. A day later, a nearly stationary disturbance formed within an active ITCZ (associated with the West African monsoon) a few hundred nautical miles south-southwest of the Cape Verde Islands. As the wave passed the ITCZ disturbance on 20 August, a large and elongated low-level circulation with poorly organized convection developed over the tropical Atlantic Ocean east of 30°W. The next day, the convection increased in both coverage and organization, and a smaller-scale circulation formed along the southwestern end of the larger gyre. This circulation is estimated to have become a tropical depression around 1800 UTC 21 August about 450 n mi west-southwest of the Cape Verde Islands (Fig. 1).

Embedded within strong low-level westerly flow, the depression moved slowly westward and became a tropical storm about 12 h after genesis, although subsequent development was slowed by moderate northeasterly vertical shear. The proximity of the cyclone to another disturbance at the eastern end of the eastern Atlantic gyre briefly caused Danielle to turn west-northwestward to northwestward on 22 August. On 23 August, the storm began moving more quickly on a generally westward course in response to a building low- to midlevel ridge over the east-central Atlantic. The shear decreased around this time, and Danielle rapidly strengthened into a hurricane around 1800 UTC that day while centered about 960 n mi west of the southernmost Cape Verde Islands.

Wind shear associated with a shortwave trough moving southwestward in the subtropical Atlantic between 45° and 50°W stopped development on 24 August and caused Danielle to weaken. The trough also weakened the ridge, which resulted in the cyclone turn toward the west-northwest. Late on 25 August the hurricane turned northwestward, and its forward speed decreased in response to a new weakness developing in the subtropical

FIG. 4. *Aqua* MODIS visible image of Hurricane Danielle near maximum intensity at 1740 UTC 27 Aug 2010. [Image courtesy of the Naval Research Laboratory, Monterey, CA (www.nrlmry.navy.mil/TC.html).]

ridge over the central Atlantic. Decreasing shear allowed strengthening on 26 August, and Danielle reached an estimated peak intensity of 115 kt at 1800 UTC 27 August while located about 440 n mi south-southeast of Bermuda (Fig. 4). The cyclone slowed further on 27–28 August as it reached the western periphery of the subtropical ridge. Gradual weakening then began as the hurricane began a slowly evolving eyewall replacement cycle (ERC).

Danielle continued to slowly weaken in response to increasing southwesterly shear ahead of a deep mid- to upper-level trough moving offshore of the east coast of the United States. This same feature caused the cyclone to recurve into the westerlies on 29–30 August, bringing it over progressively cooler waters. Danielle weakened to a tropical storm around 1800 UTC 30 August about

1085 n mi west-northwest of the Azores and became posttropical³ 6 h later when its deep convection dissipated. The low accelerated northeastward on 31 August over the north-central Atlantic and became extratropical around 1800 UTC that day. On 1–2 September, the extratropical gale center turned northward with a decreasing forward speed over the far North Atlantic. It dissipated several hundred nautical miles east-southeast of the southern tip of Greenland on 3 September.

³ The term “post-tropical” was introduced into NHC operations in 2010 to refer to a cyclone that no longer possesses sufficient tropical characteristics to be considered a tropical cyclone. Former tropical cyclones that have become extratropical, as well as remnant lows, are two classes of post-tropical cyclones.

The most noteworthy surface observation during Danielle was from the ship *Geysir* (call sign WCZ552), which reported a peak wind of 64 kt (averaging period unknown) and a minimum pressure of 974.1 mb at 1300 UTC 30 August while located about 20 n mi east-southeast of the center. While the hurricane did not directly affect land, swells generated by Danielle impacted the East Coast of the United States and caused one fatality: a 47-yr-old man who drowned in rough surf conditions at Seagull Park in Satellite Beach, Florida. Lifeguards in Florida also rescued 68 people in Brevard County and several dozen in Volusia County from rough surf or rip currents.

e. Hurricane Earl

1) SYNOPTIC HISTORY

Earl originated from a strong tropical wave that departed the west coast of Africa on 23 August. A closed surface circulation developed along the wave axis by 0000 UTC 24 August and the associated thunderstorm activity became organized as the low moved south of the Cape Verde Islands later that day. By 0600 UTC 25 August, the low acquired sufficient convective organization to be considered a tropical depression when centered about 200 n mi west-southwest of the Cape Verde Islands (Fig. 1). The convective curved banding continued to expand and become better organized, and the system strengthened to a tropical storm 6 h later.

Strong subtropical ridging over the eastern Atlantic steered Earl westward to west-northwestward at a forward speed of 15–20 kt for the next few days. Meanwhile, the storm gradually strengthened over SSTs of 28°–29°C and in an environment of light to moderate vertical wind shear. Earl became a hurricane by 1200 UTC 29 August when centered about 220 n mi east of the northern Leeward Islands. Around that time, the cyclone neared a weakness in the subtropical ridge caused by Hurricane Danielle to its north, and Earl slowed and gradually turned northwestward.

Rapid intensification occurred between 0600 UTC 29 August and 1800 UTC 30 August, with the maximum sustained winds increasing from 55 to 115 kt. Earl was centered just northeast of the northern Leeward Islands when it became a major hurricane near 1200 UTC 30 August. Shortly thereafter, Earl began an ERC that was well observed with both the San Juan Doppler radar and aircraft flight-level wind data (Fig. 5). This halted intensification, and the maximum sustained winds remained near 115 kt for the next 24 h. Southwesterly shear increased late on 31 August, which resulted in Earl weakening to a category 3 hurricane by 0000 UTC 1 September. Later that day, the eye became more distinct with increased and more symmetric deep convection,

presumably due to a decrease in shear. Earl reintensified to category 4 strength by 1800 UTC 1 September and reached its peak intensity of 125 kt 12 h later, when it was centered about 380 n mi southeast of Wilmington, North Carolina.

Earl then rapidly weakened as it turned northward, likely due to the combination of the weakening phase of another ERC, an increase in south-southwesterly shear, cooler waters, and a drier environmental air mass. By late on 3 September, Earl was a category 1 hurricane as the center passed offshore of the mid-Atlantic and northeastern U.S. coastline. Air Force reconnaissance data indicate that Earl weakened to a tropical storm by 0000 UTC 4 September, while centered about 130 n mi south-southeast of the eastern tip of Long Island, New York.

Microwave imagery suggested that an increase in organization occurred after the plane departed the cyclone, and Earl restrengthened to a hurricane as it accelerated to a forward speed of about 30 kt by 1200 UTC 4 September. Earl made landfall as a hurricane about 3 h later near Liverpool, Nova Scotia, Canada, and as a strong tropical storm on Prince Edward Island around 1900 UTC 4 September. It became extratropical by 0000 UTC 5 September in the Gulf of St. Lawrence as it interacted with an upper-level low; this interaction also caused the system to slow down and turn toward the north. Meanwhile, the cyclone steadily weakened and is estimated to have merged with another low by 0600 UTC 6 September over the Labrador Sea.

2) METEOROLOGICAL STATISTICS

Aircraft observations in Earl include flight-level, SFMR, and dropwindsonde observations, as well as 48 center fixes from 12 operational missions by the 53rd Weather Reconnaissance Squadron (53WRS) of the U.S. Air Force Reserve Command. In addition, the NOAA Aircraft Operations Center (AOC) WP-3D aircraft flew 11 missions as part of the triagency PREDICT-IFEX-GRIP field project and released a total of 381 dropwindsondes. The NOAA G-IV jet flew seven synoptic surveillance missions around Earl. In addition, the NASA Global Hawk unmanned aircraft made its first ever Atlantic hurricane mission when it overflew Earl on 2 September at an altitude of approximately 20 km.

The analyzed peak intensity of 125 kt at 0600 UTC 2 September is based on an aircraft-measured 700-mb flight-level wind of 140 kt at 0710 UTC 2 September, and a 3-h average objective satellite intensity estimate of T6.4 or 125 kt from the (University of Wisconsin–Madison) UW-CIMSS advanced Dvorak technique (ADT; Olander and Velden 2007) at 0600 UTC 2 September. The estimated minimum pressure of 927 mb at 0600 UTC 2 September is based on a dropwindsonde report of

FIG. 5. (a) WSR-88D San Juan reflectivity image of Hurricane Earl at 0557 UTC 31 Aug. The white line shows the NE-SW flight path of a 53WRS aircraft through the storm near that time. (b) Flight-level winds (kt) along the flight leg shown in (a).

929 mb with a 25-kt surface wind at 0708 UTC 2 September. The most significant surface observation occurred when the center of Earl passed directly over NOAA buoy 41046. The buoy reported a minimum pressure of 942.6 mb around 0700 UTC 1 September, and a 1-min mean wind of 71 kt with a gust to 87 kt just prior to the minimum pressure (Table S2 in the online supplemental material).

The landfall intensity in Nova Scotia is based mainly on surface observations. Maximum 10-min mean winds

of 56 kt were reported at McNabs Island and Beaver Island, and 55 kt at Osbourne Head. Applying a 1.11 adjustment (Harper et al. 2009) to these values yields a maximum 1-min surface wind of 61–62 kt. Although aircraft data only supported an intensity of about 60 kt 12 h earlier, the increase in organization observed in microwave imagery after that time suggested strengthening before landfall. Based on the adjusted observations from McNabs Island and Beaver Island, the increased organization, and the assumption that higher winds

occurred elsewhere, Earl is estimated to have been a hurricane with 65-kt winds in Nova Scotia.

Elsewhere along the track of Earl, sustained tropical storm-force winds with gusts to near hurricane force were reported in the Leeward Islands, the Virgin Islands, and the Outer Banks of North Carolina. Tropical storm conditions were also reported over Puerto Rico, and along other portions of the U.S. East Coast from Virginia to Maine.

Earl produced a widespread area of 75–125 mm of rainfall across the northern Leeward Islands, with Antigua receiving nearly 200 mm. Rainfall totals in the 75–125-mm range were also common over far eastern North Carolina, southeastern Massachusetts, and eastern Maine. In Canada, rainfall totals of up to 75 mm occurred in New Brunswick.

The highest storm surge value reported was 1.30 m at Hatteras Village, North Carolina. Earl produced a surge of up to 1 m across a large portion of the U.S. coast from North Carolina to Maine. Storm tide values of near 5.8 m were reported in Maine, but these were dominated by tidal effects. In Canada, Bedford Basin at the head of Halifax Harbor reported a surge of 1.2 m.

3) CASUALTY AND DAMAGE STATISTICS

Five deaths resulted from Earl. Along the coast of New Jersey, two men (aged 20 and 23) drowned in rough surf. A 7-year-old girl was swept out to sea in large waves at Acadia National Park in Maine; a 54-year-old man drowned while trying to swim ashore in Blind Bay, Nova Scotia; and a 14-year-old girl died as a result of the high surf in northeastern Florida.

The hurricane produced high waves over a large portion of the western Atlantic for several days. Media reports indicate Earl caused flooding from surge and high waves in low-lying areas and damaged homes and buildings in portions of the northern Leeward Islands. Antigua and Barbuda suffered the most damage, totaling about \$12.5 million (U.S. dollars). In North Carolina, numerous homes along the coast were flooded by storm surge, with Hyde and Dare counties reporting monetary damage estimates over \$2 million and \$0.5 million (U.S. dollars), respectively. Downed trees and power lines were reported in eastern Massachusetts, and similar damage was reported in Nova Scotia and western Newfoundland, Canada. The total damage estimate associated with Earl is around \$45 million, of which about \$18 million (U.S. dollars) occurred in the United States.

f. Tropical Storm Fiona

Fiona developed from a convectively active tropical wave with a well-defined cyclonic circulation that moved off the west coast of Africa on 25–26 August. A broad

area of low pressure was analyzed along the wave axis on 27 August. The low moved westward for the next couple of days, and most of the convection dissipated for a 24-h period beginning on 29 August. Deep convection redeveloped and the low acquired a well-defined center of circulation early on 30 August. It is estimated that a tropical depression formed at 1200 UTC that day about 900 n mi east of the Lesser Antilles (Fig. 1). The depression became a tropical storm 6 h later.

Located on the southwestern periphery of a midlevel ridge over the central Atlantic, Fiona moved west-northwestward at 20–25 kt for the next 24 h and began to steadily strengthen after 1200 UTC 31 August as it moved closer to the northern Leeward Islands. The cyclone turned toward the northwest on 1 September, and the center passed about 55 n mi northeast of the island of Barbuda at 1200 UTC. Fiona strengthened to an estimated peak intensity of 55 kt by 1800 UTC that day, but increased northeasterly vertical shear associated with the outflow from Hurricane Earl led to Fiona subsequently weakening. The cyclone moved toward the northwest for another 24 h, then it turned toward the north-northwest and then toward the north on 2–3 September between the midlevel ridge and Earl. Deep convection dissipated late on 3 September, and Fiona became a posttropical cyclone with 35-kt winds at 0000 UTC 4 September while centered about 95 n mi south of Bermuda. The winds dropped below gale force 6 h later, and Fiona moved northeastward as a remnant low, dissipating later that day.

g. Tropical Storm Gaston

A strong tropical wave moved across the African coast on 28 August. A convective burst produced a midlevel circulation near the wave axis on 30 August, and the convection consolidated near this feature later that day. On 31 August, a broad surface low was evident, with curved banding features forming by that evening, and a tropical depression formed by 0600 UTC 1 September, located about 800 n mi west-southwest of the Cape Verde Islands (Fig. 1). The depression strengthened to a tropical storm 6 h later. However, the associated convection diminished late on 1 September, and Gaston degenerated to a remnant low on 2 September. Sporadic convective bursts continued for the next several days as the low moved westward across the tropical Atlantic, through the Leeward Islands, and into the Caribbean Sea. Dropsonde data from an NSF research mission on 5 September indicated that very dry air was present south of the low and appeared to be wrapped into it. This is likely why Gaston weakened after genesis and had difficulty maintaining persistent convection. The system weakened to a trough on 8 September just southeast of the Dominican Republic.

The estimated peak intensity of 35 kt is based on a blend of subjective [Dvorak \(1984\)](#) intensity estimates and ASCAT data, with the ASCAT data indicating that the Dvorak estimates were generally too high. The ASCAT data suggest a peak intensity of 30–35 kt and it is possible that Gaston never attained tropical storm strength.

h. Tropical Storm Hermine

Eastern North Pacific Tropical Depression Eleven-E made landfall on the coast of Mexico early on 4 September. It then degenerated into a remnant low as it moved northward across the high terrain of the Mexican states of Oaxaca and Chiapas. The midlevel circulation, accompanied by the weak surface low, continued northward into the southern Bay of Campeche later that day. Organized convection redeveloped and it is estimated that a tropical depression formed at 1800 UTC 5 September ([Fig. 1](#)). The depression became a tropical storm about 12 h later, around the time when nearby NOAA buoy 42055 reported tropical storm-force winds.

The strengthening cyclone moved on a heading between north and north-northwest at an average speed of 12 kt over the western Gulf of Mexico on 6 September. Maximum sustained winds reached 60 kt as the center of Hermine made landfall on the coast of northeastern Mexico about 25 n mi south of Brownsville, Texas, at 0200 UTC 7 September. Hermine remained a tropical storm for about 16 h after landfall while moving northward over Texas. The cyclone weakened to a tropical depression over central Texas by 0000 UTC 8 September, and then continued northward and northeastward over Oklahoma. It degenerated to a remnant low on 10 September and dissipated later that day over southeastern Kansas.

Hermine brought tropical storm conditions to portions of northeastern Mexico, as well as portions of southern and central Texas. Harlingen, Texas, reported the strongest observed winds—a 2-min mean wind of 51 kt and a gust to 63 kt at 0559 UTC 7 September (anemometer elevation 10 m). Storm surges of 0.5–1.0 m occurred along the southern Texas coast. Widespread heavy rains occurred over portions of Texas and Oklahoma, with Georgetown Lake, Texas, reporting a storm total of 415.8 mm. Nine tornadoes occurred in Texas, with the most notable being an EF-1 near Seagoville and an EF-2 near Dallas.

Five deaths occurred in Texas and one in Oklahoma. One person drowned when caught in strong rip currents. Two others died while swimming in a flooded river, while the other three persons were washed off the road while driving around barricades. Hermine produced an

estimated \$240 million (U.S. dollars) in damage in the United States.

i. Hurricane Igor

1) SYNOPTIC HISTORY

Igor's origin can be traced to a tropical wave and accompanying broad area of low pressure that moved off the African coast late on 6 September. The system moved slowly westward for a couple of days while deep convection consolidated near the center of the low. By 0600 UTC 8 September, the surface circulation was sufficiently well defined and the deep convection was sufficiently organized to designate the formation of a tropical depression centered about 80 n mi southeast of the southernmost Cape Verde Islands ([Fig. 1](#)). The cyclone strengthened into a tropical storm within 6 h.

After becoming a tropical storm, the cyclone lost some organization when it interacted with a trailing disturbance that rotated around the northern portion of the broad circulation. Deep convection diminished and became sheared to the west of the center, and the storm weakened to a tropical depression by 1200 UTC 9 September. Embedded within the circulation of the monsoon trough over the tropical eastern Atlantic, Igor moved slowly westward or west-northwestward for a couple of days. Around 1200 UTC 10 September, vertical shear began to relax and Igor regained tropical storm strength. By that time the steering flow became dominated by a building midtropospheric ridge over the eastern Atlantic, and Igor moved westward at a forward speed that increased to as much as 22 kt. Possibly due to the moderate northerly shear and a relatively stable atmospheric environment, Igor's strengthening was rather unsteady over the next 36 h, but the cyclone eventually reached hurricane strength by 0000 UTC 12 September. Shortly thereafter, however, the central convective cloud pattern became symmetric, the upper-level outflow increased markedly, and the maximum sustained winds rapidly increased to an estimated 130 kt by 0000 UTC 13 September. Igor's forward speed decreased during that day while the hurricane remained on a nearly due westward heading.

After exhibiting some hints of a concentric eyewall structure, Igor's maximum winds decreased to 115 kt by 0600 UTC 14 September. However, the hurricane soon restrengthened to an estimated peak intensity of 135 kt around 0000 UTC 15 September ([Fig. 6](#)). Igor was now moving west-northwestward in response to a weakness in the subtropical ridge created by a broad deep-layer trough near the northeastern United States. The start of an ERC a few hours later caused the hurricane to weaken again to near 115 kt. Igor's final strengthening episode

FIG. 6. *Aqua* MODIS visible image of Hurricane Igor approaching maximum intensity at 1724 UTC 14 Sep 2010. [Image courtesy of the Naval Research Laboratory, Monterey, CA (www.nrlmry.navy.mil/TC.html).]

occurred late on 15 September while the new outer eyewall contracted slightly at the end of the ERC, and the maximum winds increased to an estimated 125 kt by 0600 UTC 16 September. The hurricane wobbled between a northwestward and west-northwestward heading as its eye passed a little over 300 n mi northeast of the northernmost Leeward Islands early on 17 September.

Over the next couple of days, Igor gradually turned toward the north between the western periphery of the subtropical ridge and a persistent deep-layer trough near the northeastern United States. Meanwhile, the cyclone steadily weakened, at least partly due to southwesterly shear that became fairly strong by late on 18 September as well as the intrusion of drier air into the core. Although it was weakening, Igor expanded in size and tropical storm-force winds extended some 300 n mi

from the center over the northern semicircle. By the time the center passed about 35 n mi west-northwest of Bermuda around 0230 UTC 20 September, the maximum sustained winds had decreased to 65 kt.

The hurricane turned north-northeastward, then northeastward, and accelerated to a forward speed of near 40 kt ahead of a trough near the Canadian Maritimes. The cyclone's size continued to increase, with the area of tropical storm-force winds becoming roughly 750 n mi wide. Igor's intensity increased to 75 kt, possibly due to baroclinic forcing, as it made landfall near Cape Race, Newfoundland, around 1500 UTC 21 September. The center of the hurricane then straddled the east coast of the Avalon Peninsula of Newfoundland from 1500 to 1700 UTC 21 September. Almost immediately after departing Newfoundland, Igor became

a vigorous extratropical cyclone. The cyclone turned northward and north-northwestward, with its center moving over the North Atlantic between Labrador and Greenland on 22 September, and Igor was absorbed by another large extratropical cyclone by early on 23 September.

2) METEOROLOGICAL STATISTICS

The peak intensity of Igor was estimated to be 135 kt based on a blend of objective (advanced Dvorak technique) and subjective Dvorak technique estimates. The 53WRS flew six missions into Igor, measuring peak 700-mb flight-level and surface winds of 130 and 98 kt, respectively, and a minimum central pressure of 940 mb. These measurements occurred near 1600 UTC 16 September on the first aircraft mission into the hurricane, about 40 h after the time of Igor's estimated maximum intensity. NOAA data buoy 41044, located over the tropical Atlantic, measured a minimum pressure of 940.3 mb at 0050 UTC 17 September while the center of Igor passed about 15 n mi to its north (Table S3 in the online supplemental material).

A maximum 10-min wind of 59 kt was measured at the official reporting site in Bermuda (TXKF) with higher winds reported from sites on the island with wind sensors well above the standard 10-m anemometer elevation. Applying a gust factor of 1.11 to the TXKF sustained wind observation yields an estimated peak 1-min wind of 65 kt (Harper et al. 2009). A rainfall total of 81.0 mm was measured in Bermuda, and a storm surge of 0.5 m was measured by a NOAA tide gauge at St. George on the north coast of the island.

The highest 10-min wind report from an official observing site in Newfoundland was 66 kt at Bonavista, which, after applying the 1.11 gust factor, gives an estimated peak 1-min wind of 73 kt. Wind gusts of 84 and 88 kt were measured at Bonavista and Sagona Island, respectively. Rainfall totals generally ranged from 100 to 200 mm over eastern Newfoundland with a maximum total of 238.0 mm at St. Lawrence, a total unprecedented for that site. Storm surges of 0.6–1.0 m were measured around eastern Newfoundland with a maximum surge of 1.1 m observed in St. John's Harbour.

3) CASUALTY AND DAMAGE STATISTICS

A woman was swept out to sea and presumed drowned by a large wave in Arecibo, Puerto Rico. In St. Croix, a boy drowned while swimming with his father in high surf.

Igor produced minimal damage in Bermuda, with downed trees and signs reported across the island. The main causeway connecting St. David's and St. George's Islands sustained minor damage and was closed to one lane of traffic for several days. The *Royal Gazette*

indicated that there was no loss of life, and damage was estimated at less than \$500,000 (U.S. dollars) immediately after the storm. Approximately 28 000 residents in Bermuda lost power during the storm.

In Newfoundland, the impacts from Igor were decidedly more severe, and the Canadian Hurricane Centre described Igor as "Newfoundland's most damaging hurricane in 75 years" (Fogarty 2011). High winds toppled many trees, especially in urban areas, and caused some structural damage over the eastern peninsulas. Extensive damage occurred due to the heavy rains and associated flooding that washed out roads and several bridges, leaving eastern Newfoundland essentially isolated from the rest of the island. On the Bonavista and Burin Peninsulas, road washouts cut off several communities from the main road system connecting those areas to the island. One death was attributed to Igor in Newfoundland—a man who was swept out to sea when his driveway washed out. Damage in Newfoundland is estimated at almost \$200 million (U.S. dollars).

j. Hurricane Julia

The system that spawned Julia was a vigorous tropical wave that emerged from the coast of West Africa on 11 September and produced a 50-kt easterly wind at 925 mb in Dakar, Senegal. Development began almost immediately upon reaching the Atlantic, and a tropical depression formed at 0600 UTC 12 September about 250 n mi southeast of the southernmost Cape Verde Islands (Fig. 1). Twelve hours later the cyclone became a tropical storm. Julia moved west-northwestward past the Cape Verde Islands during 12–14 September along the southwestern periphery of a deep-layer ridge. Slow intensification occurred until early on 14 September, when a ragged, banded eye became apparent in satellite imagery. Rapid intensification ensued, with Julia becoming a hurricane around 1200 UTC that day and reaching an estimated peak intensity of 120 kt 24 h later (Fig. 7).

On 15 September, Julia turned toward the northwest and accelerated around a mid- to upper-level low to its southwest. This feature caused moderate vertical shear over Julia, which weakened the cyclone below major hurricane intensity after 0600 UTC 16 September. The hurricane then turned back toward the west-northwest as it was steered primarily by a deep-layer ridge to its north and east. On 17 September, Julia moved within 780 n mi to the east of the much larger Hurricane Igor. This allowed upper-level outflow from Igor to impinge upon Julia and cause additional weakening, with the cyclone dropping below hurricane intensity late that day. Julia recurved between Igor and the deep-layer ridge during

FIG. 7. Defense Meteorological Satellite Program (DMSP) visible image of Hurricane Julia near maximum intensity at 0851 UTC 15 Sep 2010. [Image courtesy of the Naval Research Laboratory, Monterey, CA (www.nrlmry.navy.mil/sat_products.html).]

17–20 September as it progressively turned toward the northwest, north, northeast, and finally to the east.

A short-lived reintensification occurred on 18 September. After that, strong shear completely removed the convection from the cyclone. It is estimated that Julia degenerated to a post-tropical low by 1800 UTC 20 September, which slowly decayed below gale force a day later. The remnant low turned back toward the west on 23–24 September and dissipated into an open trough after 1800 UTC 24 September.

Julia is the strongest hurricane in the Atlantic hurricane database to be recorded east of 40°W. However, it is highly unlikely that either its category 4 status or its 1.25-day duration as a major hurricane would have been observed in this location before the advent of routine

satellite imagery and Dvorak intensity estimates in the 1970s.

Tropical storm conditions may have occurred in portions of the southern Cape Verde Islands. However, there were no reports of casualties or damages from Julia.

k. Hurricane Karl

1) SYNOPTIC HISTORY

Karl originated from a broad low pressure system that formed when a tropical wave interacted with an elongated trough of low pressure that extended northeastward across northern South America and into the southwestern North Atlantic Ocean. The tropical wave exited the African coast on 1 September and moved

steadily westward for the next week or so. The wave merged with the South American trough on 8 September, with the resulting low forming just east of the Windward Islands. Over the next few days, the low moved westward to west-northwestward across the Windward Islands into the Caribbean Sea while producing intermittent small bands of deep convection well removed from the surface center. Even though convection remained disorganized during this period, the overall surface wind field and vertical structure slowly became better defined. After a temporary decrease in organization early on 13 September seen in NASA and NOAA research flight data, development resumed later that day, and it is estimated that a tropical depression formed at 1200 UTC 14 September over the northwestern Caribbean about 325 n mi east of Chetumal, Mexico (Fig. 1). Convective organization continued to improve and the system strengthened into a tropical storm 6 h later.

Karl moved westward, and the maximum sustained winds increased to 55 kt before the center made landfall on the eastern coast of the Yucatan Peninsula of Mexico near Rio Huach at approximately 1245 UTC 15 September. Under the influence of a broad subtropical high pressure system located over the Gulf of Mexico and the southeastern United States, Karl moved west-northwestward across the Yucatan Peninsula and into the Bay of Campeche by 0600 UTC 16 September. While Karl weakened over land, conventional and microwave satellite imagery (not shown) indicated that the convective organization and vertical structure actually improved, with the appearance of an eyelike feature and an increase in convective banding.

Rapid intensification began over the warm waters of the Bay of Campeche, and Karl became a hurricane by 1800 UTC 16 September. The western extent of the subtropical ridge to the north of Karl strengthened and built southward, which caused the hurricane to make a turn toward the west-southwest early on 17 September. Karl reached major hurricane status shortly after 0600 UTC 17 September and its peak intensity of 110 kt just 6 h later, when the hurricane was located 45 n mi northeast of Veracruz, Mexico (Fig. 8). Increasing northeasterly vertical shear and the possible entrainment of dry air into the western portion of the cyclone then caused a slight weakening; however, Karl was still a major hurricane at landfall along the Mexican coast about 10 n mi northwest of Veracruz at 1645 UTC 17 September. Karl continued west-southwestward and weakened rapidly as its small circulation interacted with the mountains of coastal Mexico. The cyclone became a tropical storm at 0000 UTC 18 September and a depression 6 h later. Interaction with the rugged terrain of central Mexico led to Karl dissipating shortly thereafter about 75 n mi west-southwest of Veracruz.

Karl's maximum intensity of 110 kt makes it the strongest hurricane (and the only major hurricane) on record in the Bay of Campeche (i.e., south of 21°N latitude), surpassing Hurricane Item in 1950, which had maximum sustained winds of 95 kt (Norton 1951).

2) METEOROLOGICAL STATISTICS

The 53WRS completed 5 aerial reconnaissance missions and provided 23 center fixes. On 16 September, a NOAA AOC WP-3 aircraft conducted a research flight into Karl between the scheduled 53WRS reconnaissance missions. Several missions were conducted into the pre-Karl disturbance by NASA and NOAA aircraft as part of the PREDICT program. NASA also conducted a Global Hawk mission over Karl while the cyclone was over the Bay of Campeche.

The oil platform *Ocean Nugget* (19.46°N, 92.07°W), located over the Bay of Campeche about 20 n mi east-southeast of Karl's center, reported a sustained wind of 52 kt at 1330 UTC 16 September (Table S4 in the online supplemental material). Two NOAA automated stations located in Veracruz harbor also reported 10-min tropical storm-force winds. At the Veracruz, Mexico airport (MMVR), a 10-min wind of 40 kt with a gust to 50 kt occurred at 1700 UTC 17 September.

Karl rapidly intensified between 0600 UTC 16 September and 1200 UTC 17 September with an intensity increase of 65 kt in 30 h—roughly double the standard 30-kt/24-h threshold rate for rapid intensification (Kaplan and DeMaria 2003). During this exceptional strengthening process, reconnaissance data indicate that Karl's eye contracted from an average diameter of 20 n mi down to 8 n mi. Mexican radar data indicated erosion of the western eyewall just prior to landfall. It is hypothesized that this was due to dry subsiding air entraining into the cyclone's circulation from the Sierra Madre Oriental mountain range, as the available data showed little evidence of an ERC.

Rainfall from Karl across the Yucatan Peninsula averaged 75–125 mm. Over mainland Mexico, there was a large area of 250–380-mm rainfall amounts covering most of the northwestern half of the state of Veracruz, with a maximum of 452.9 mm at Mislanta. The heavy rainfall extended well inland, and runoff from the Sierra Madre Oriental caused severe floods and mud slides throughout much of the state of Veracruz, and also in the states of Tabasco, Chiapas, Oaxaca, Puebla, Tlaxcala, Nuevo León, and Tamaulipas.

3) CASUALTY AND DAMAGE STATISTICS

Karl caused only slight damage on the Yucatan Peninsula. However, the hurricane pummeled east-central Mexico with damaging winds and heavy rains. About

FIG. 8. DMSP visible image of Hurricane Karl near maximum intensity at 1224 UTC 17 Sep 2010. [Image courtesy of the Naval Research Laboratory, Monterey, CA (www.nrlmry.navy.mil/TC.html).]

3500 people sought refuge in shelters set up at schools throughout the state of Veracruz where the greatest impacts from Karl were felt. Reliable estimates are that more than 40 000 people were left homeless. More than 20 000 homes were flooded and more than 50 000 people lost electricity or water utilities. Helicopter crews from the Mexican Navy rescued about 40 families trapped on a hill surrounded by floodwaters in the town of San Pancho, north of the city of Veracruz. South of Veracruz in Cotaxtla, homes were flooded up to their roofs and at least seven people were washed away in a nearby flood-swollen river. Recovery crews removed approximately 18 000 tons of debris throughout the state of Veracruz during poststorm cleanup operations.

Media reports indicate that a total of 14 people were killed, with most of the deaths occurring in the state of

Veracruz. A 61-year-old woman and a 2-year-old girl were killed and two other people were injured when a mud slide buried a house in the town of Nexticapan. The insurance risk modeling company AIR Worldwide estimated total damage costs in Mexico at \$206 million (U.S. dollars).

1. Hurricane Lisa

Lisa developed from a tropical wave that exited the west coast of Africa on 16 September. A couple of days later, a broad area of low pressure developed along the wave axis southwest of the Cape Verde Islands. On 19–20 September, the circulation became better defined and thunderstorm activity associated with the low slowly gained organization. At 1800 UTC 20 September, when the system was located about 400 n mi west of the Cape

Verde Islands it acquired enough organization to be considered a tropical depression (Fig. 1), and it became a tropical storm 6 h later. The steering flow associated with an unusually weak subtropical ridge over the eastern Atlantic and a large midlatitude trough over the northeastern Atlantic caused Lisa to move slowly northward after genesis. On 21 September, Lisa turned southeastward and then eastward the next day in weak westerly flow to the south of the deep-layer trough.

Thunderstorm activity became limited on 22 September, possibly due to the entrainment of drier air. This caused Lisa to weaken to a tropical depression by 1800 UTC that day. The weakening was short lived, however, and the depression regained tropical storm status 18 h later. After that, Lisa turned northeastward and the maximum winds rapidly increased from 35 to 65 kt in about 21 h on 24 September, with a small eye becoming evident in infrared and microwave satellite imagery. Lisa reached a peak intensity of 75 kt at 0000 UTC 25 September about 240 n mi northwest of the Cape Verde Islands. Shortly thereafter, the hurricane turned to the north over progressively cooler water and into an area of strong westerly upper-level winds. This caused the hurricane to weaken very rapidly, and Lisa degenerated to a remnant low by 1800 UTC 26 September. The low moved northwestward and northward, eventually dissipating by 0600 UTC 29 September about 515 n mi south-southwest of the Azores Islands.

m. Tropical Storm Matthew

Matthew had its origins in the southern part of the tropical wave that spawned Hurricane Julia. This system moved westward across the Atlantic and produced squally weather in the Windward Islands on 20 September. A surface low formed along the wave axis over the Caribbean Sea early on 22 September, and the low developed into a tropical depression by 1200 UTC 23 September about 490 n mi east of Cabo Gracias a Dios (Fig. 1). Aircraft data indicated that the depression reached tropical storm strength 6 h later.

For most of its lifetime, a subtropical ridge to the north steered Matthew westward or west-northwestward at 15–20 kt. The storm gradually strengthened to a peak intensity of 50 kt just before landfall at 1900 UTC 24 September in extreme northern Nicaragua about 20 n mi south of Cabo Gracias a Dios. Little change in strength occurred for the next 6 h as the storm moved west-northwestward across northern Honduras. Matthew began to gradually weaken after that, and that trend continued as the center moved into the Gulf of Honduras shortly after 0600 UTC 25 September. Matthew made a final landfall around 1500 UTC 25 September about 10 n mi north-northeast of Monkey River Town, Belize. The cyclone weakened

to a tropical depression around 1800 UTC as it moved inland across Belize and into northern Guatemala, and the surface circulation dissipated over southeastern Mexico on 26 September. Even after the surface low dissipated, heavy rainfall continued over portions of central and eastern Mexico for the next couple of days.

Puerto Lempira, Honduras, reported 10-min mean winds of 40 kt at 2300 UTC 24 September. The main impact from Matthew was heavy rainfall across Nicaragua, Honduras, Belize, Guatemala, El Salvador, and portions of eastern and central Mexico. Rainfall data from the National Meteorological Service of Honduras indicate that 100–200 mm of rain occurred during 24–26 September in that country, with the largest amounts along the northwestern coast and along the southern border with El Salvador and Nicaragua. Peak rainfall amounts from Honduras and Guatemala were in the 127–178-mm range. Rainfall totals of 125–245 mm were observed across portions of several Mexican states, including Veracruz, Chiapas, and Oaxaca, with Acayucan, Veracruz, reporting 424.9 mm.

Matthew was the deadliest cyclone of the 2010 Atlantic season, with media reports indicating a total of 78 fatalities: 65 in Nicaragua, 8 in Mexico, 4 in Honduras, and 1 in El Salvador. In addition, heavy rainfall associated with the remnants of Matthew was partly responsible for a landslide in Santa Maria Tlahuitoltepec in the Mexican state of Oaxaca on 28 September that killed 4 with 12 others missing. The flooding from Matthew and its remnants caused damage to property and crops in Nicaragua, Honduras, and Guatemala. However, no monetary damage estimates were available.

n. Tropical Storm Nicole

A large area of low pressure was present over the northwestern Caribbean Sea, the Gulf of Mexico, and the eastern Pacific Ocean on 26 September as the remnants of Tropical Storm Matthew moved westward into Central America. The low drifted east-northeastward on 27 September, with the circulation elongated from east to west and most of the convection located well east of the center. Early the next day, a center of circulation became better defined, with reports of near-gale-force winds well southeast of the center. When the associated convection became better organized, the low became a tropical storm near 1200 UTC 28 September, centered about 65 n mi south of the Isle of Youth, Cuba (Fig. 1). Nicole reached a peak intensity of 40 kt shortly thereafter. The cyclone moved generally northeastward due to southwesterly deep-layer flow ahead of an approaching midlatitude trough. Surface observations indicate that the circulation center, which was never particularly well

defined, became untrackable as it crossed Cuba on 29 September, marking Nicole's dissipation as a tropical cyclone. A broad area of low pressure remained, however, which accelerated northeastward and began to take on frontal characteristics. Extratropical transition was complete by 0600 UTC 30 September in the northwestern Bahamas, with the low eventually becoming absorbed by a new low forming over eastern North Carolina.

Nicole was an unusual tropical cyclone for the Atlantic basin, with a structure more resembling that of a monsoon depression of the Indian or western Pacific Oceans. The radius of maximum winds was 130–200 n mi from the center. However, deep convection was located within about 90–120 n mi of the center, which was close enough to warrant a tropical or subtropical intensity estimate. In addition, Advanced Microwave Sounding Unit data suggested that Nicole was warm core in the mid- to upper levels, with the warm core strengthening with time, more typical of a tropical cyclone.

Nicole brought extremely heavy rain to portions of Jamaica, Cuba, and southern Florida. The maximum reported amount 950.5 mm at Belleisle, Jamaica. Other totals included 321.1 mm at North Key Largo, Florida, and 234.2 mm at Cabo Cruz, Cuba. Thirteen people died in Jamaica, primarily because of severe flooding. More than 300 000 households were without power on that island during the storm and the National Work Agency of Jamaica estimated that repairs to the country's infrastructure would cost approximately \$235 million (U.S. dollars). Minor flooding damage was reported in Florida.

o. Hurricane Otto

Otto developed from a tropical wave that interacted with an upper-level trough over the central Atlantic Ocean. The wave moved over the northern Leeward Islands early on 4 October in the form of a broad and highly elongated trough of low pressure. The surface trough gradually sharpened, and a subtropical depression formed when a well-defined circulation developed under the upper-level trough by 0600 UTC 6 October about 230 n mi north-northwest of San Juan, Puerto Rico. The depression strengthened to a subtropical storm 6 h later (Fig. 1). Otto reached an intensity of 55 kt as a subtropical storm on 7 October, then weakened slightly. Later that day, the system transformed into a tropical cyclone and intensified again. Otto became a hurricane by 1200 UTC 8 October and reached its maximum intensity of 75 kt about 12 h later. During that time, Otto accelerated toward the northeast as it became embedded in deep-layer southwesterly flow. Increasing vertical shear caused the cyclone to weaken on 9 October, and Otto fell below hurricane strength by that evening. The

storm became extratropical the next day while located about 900 n mi east-northeast of Bermuda.

The extratropical cyclone persisted for about four days while weakening gradually, initially racing northeastward but then slowing its forward speed and turning southeastward near the Azores on 12 and 13 October. The system lost its frontal characteristics by 0600 UTC 14 October and degenerated to a low-level cloud swirl by that time. The weak remnant low slowed further and eventually dissipated about 250 n mi west of Morocco around 0000 UTC 18 October.

The core of Otto did not impact land areas. However, heavy rainfall associated with Otto and its precursor disturbance occurred during 4–8 October over the eastern Caribbean Sea, with rainfall totals exceeding 380 mm measured across the northeastern Caribbean islands. The heavy rains caused significant damage to portions of the northeastern Caribbean islands, including Puerto Rico, the U.S. Virgin Islands, and the British Virgin Islands, as mudslides overturned cars, toppled power lines, flooded homes, and washed out roads.

p. Hurricane Paula

Paula had a complex origin involving a frontal boundary trailing from former Tropical Storm Nicole, a cyclonic gyre over the northwestern Caribbean Sea, and possibly two weak tropical waves, one of which helped spawn Hurricane Otto. These features combined to produce a persistent area of disturbed weather over the western Caribbean during 5–9 October, and a broad low pressure area formed on 10 October. This low developed into a tropical depression by 0000 UTC 11 October while centered about 100 n mi southeast of Cabo Gracias a Dios (Fig. 1). The depression then strengthened to a tropical storm 6 h later.

The center of Paula moved northwestward across Cabo Gracias a Dios near 1200 UTC 11 October and then reemerged over the northwestern Caribbean while being steered around the southwestern periphery of the subtropical ridge. The cyclone rapidly intensified over 29°C waters and reached hurricane intensity around 0000 UTC 12 October while centered about 85 n mi north-northwest of Puerto Lempira. Paula continued to strengthen during the day, reaching its estimated peak intensity of 90 kt around 1800 UTC, and it then moved toward the north-northwest and north as it came under the influence of a midlatitude trough over the Gulf of Mexico. Paula was a small cyclone, with hurricane-force winds extending no more than 20 n mi from the center and tropical storm-force winds no more than 60 n mi from the center. Indeed, the eye of Paula moved within 50 n mi of NOAA buoy 42056, and yet the highest wind reported by the buoy was 29 kt with a gust to 31 kt.

Paula gradually weakened on 13 October while it headed northward toward the Yucatan Channel and an area of stronger vertical wind shear over the Gulf of Mexico. The hurricane stayed far enough offshore to prevent tropical storm-force winds and heavy rainfall from reaching the Yucatan coast of Mexico, and Paula turned north-northeastward ahead of the midlatitude trough early on 14 October. Increasing southwesterly shear caused Paula to weaken to a tropical storm around 1200 UTC while heading northeastward toward the north coast of Cuba. The storm made landfall around 1500 UTC 14 October between Santa Lucía and Puerto Esperanza in the province of Pinar del Río, with maximum sustained winds near 55 kt. Weakening continued as Paula moved eastward across Cuba. The cyclone became a depression by 0600 UTC 15 October and then a remnant low 6 h later as it moved back offshore over the Atlantic Ocean near Sagua la Grande in the province of Villa Clara. The low dissipated completely a few hours later.

The highest measured wind from a land station was 44 kt with a gust to 59 kt at La Palma, Cuba. The Royal Caribbean cruise ship *Radiance of the Seas* (call sign C6SE7) reported winds of 44 kt and a pressure of 1013 mb at 1300 UTC 12 October.

Reports from Honduras indicate that 150–200 mm of rain fell in some regions. In Cuba, the maximum storm total rainfall was 185.9 mm at Bahía Honda, Pinar del Río, with general amounts of 75–125 mm reported elsewhere in Pinar del Río, La Habana, Ciudad La Habana, and Matanzas. Paula caused one fatality: a drowning in high surf at Cancun, Mexico. Minor damage to property was reported in Cuba and Honduras.

q. Hurricane Richard

1) SYNOPTIC HISTORY

On 15 October, an area of disturbed weather was noticed within a persistent and broad trough over the southwestern Caribbean Sea, west of the coast of Colombia. On 17–18 October, the interaction of the disturbance with a tropical wave moving into the region resulted in the development of a midlevel cyclonic circulation offshore of the northeastern coast of Nicaragua. A weak surface low subsequently formed early on 19 October about 135 n mi north of Cabo Gracias a Dios. The low moved northwestward to north-northwestward around the periphery of a low- to midlevel ridge located to its east. The circulation became slightly better defined early the next day, and it is estimated that a tropical depression formed about 170 n mi north of Cabo Gracias a Dios around 0600 UTC 20 October (Fig. 1).

A shortwave trough passing through the southeastern United States caused the depression turned northward and

then northeastward at a decreased forward speed on 19–20 October. The trough produced moderate southwesterly vertical shear and advected mid- to upper-level dry air into the cyclone, which prevented development during this time. The shortwave moved into the western Atlantic on 20–21 October, and a low- to midlevel ridge building behind it over the Gulf of Mexico caused the depression to turn eastward and then southeastward. As this took place, decreasing shear allowed the depression to strengthen into a tropical storm around 1200 UTC 21 October, while located about 180 n mi northeast of Cabo Gracias a Dios. During the next couple of days, the ridge north of the cyclone shifted eastward, which caused Richard to complete three-quarters of an anticyclonic loop by turning southward, southwestward, and then westward.

The ridge strengthened further, and Richard accelerated on a course just north of due west on 23–24 October, while a moistening environment allowed the storm to strengthen. Satellite imagery showed a banding eye early on 24 October, and Richard became a hurricane around 0600 UTC that day about 180 n mi east-southeast of Belize City. Steady intensification continued until the hurricane made landfall with an estimated intensity of 85 kt around 0040 UTC 25 October near Gales Point, Belize, about 20 n mi south of Belize City. After crossing Belize, Richard weakened to a tropical storm over the mountainous terrain of northern Guatemala. Further weakening occurred as the cyclone turned west-northwestward to northwestward around the western periphery of the low- to midlevel ridge to its east late on 25 October and early on 26 October. Richard became a tropical depression about 115 n mi south of Campeche, Mexico, at 1800 UTC 25 October and degenerated into a remnant low 6 h later about 20 n mi southeast of Ciudad del Carmen, Mexico. In a strong westerly shear environment, the low dissipated in the eastern Bay of Campeche late on 26 October.

2) METEOROLOGICAL STATISTICS

The maximum aircraft flight-level (700 mb) wind measured in Richard was 86 kt in the northeast quadrant of the circulation at 2030 UTC 24 October, and a minimum pressure of 981 mb was observed 2 min earlier. The maximum SFMR wind estimate was 77 kt around 2000 UTC. Radar data from Belize indicated an increase in organization after that time. Thus, the estimated landfall winds and pressure of 85 kt and 977 mb are based on extrapolation of the aircraft-observed deepening rate. Satellite imagery indicated that Richard remained well organized for several hours after moving inland.

Selected surface observations from land stations and buoys are given in Table S5 in the online supplemental

material. While no observations are available from the coastal landfall area, several unofficial wind observations of tropical storm-force winds were received from a sparsely populated area of west-central Belize to the south of the track of Richard's center.

3) CASUALTY AND DAMAGE STATISTICS

Media reports indicate that one death was directly attributed to Richard: a man died when the boat on which he and two others were sailing capsized in the region where the hurricane made landfall. An indirect death occurred when a man was mauled to death by a jaguar that escaped when its cage was struck and opened by a fallen tree.

Media reports indicate that Richard caused widespread power outages, downed trees, ripped off roofs, and caused minor structural damage in Belize. One report indicates that there was \$32 million (U.S. dollars) in damage to the citrus industry, with about 80% of the grapefruit and nearly 25% of the orange crop lost. The hurricane passed near the Bay Islands of Honduras, but had minimal impact there. Total damage estimates associated with Richard are reported to be in excess of \$80 million (U.S. dollars).

r. Hurricane Shary

A broad area of low pressure formed along the southern portion of a nearly stationary frontal system over the central Atlantic about 700 n mi east-northeast of Puerto Rico on 27 October. The disturbance interacted with an upper-level low associated with the midoceanic trough, resulting in an asymmetric cloud pattern more commonly observed in subtropical systems. By 28 October, the disturbance moved toward the west-northwest away from the upper low, and a low-level center of circulation became better defined closer to the convection, suggesting that the system had acquired tropical characteristics. It is estimated that a tropical depression formed at 1800 UTC that day about 450 n mi south-southeast of Bermuda (Fig. 1), and that the depression became a tropical storm 6 h later.

The cyclone slowed down significantly and turned northward and then northeastward as the steering flow weakened ahead of a strong cold front. Reconnaissance aircraft data indicated that Shary was just below hurricane strength by 1800 UTC 29 October. Subsequently, a short-lived decrease in vertical shear allowed the storm to intensify into a hurricane 6 h later when an eye feature became apparent in microwave data. By then, Shary was embedded within southwesterly flow ahead of an approaching cold front and moving rapidly toward the northeast. The cloud pattern deteriorated rapidly after 1200 UTC 30 October as the cyclone interacted with the front, and Shary became extratropical by 1800 UTC that

day. The circulation of Shary dissipated within the frontal zone shortly thereafter.

s. Hurricane Tomas

1) SYNOPTIC HISTORY

Tomas formed from a vigorous tropical wave that moved off the coast of Africa on 24 October. The wave produced considerable deep convection as it moved at low latitudes across the eastern Atlantic. The associated disturbed weather showed signs of organization by 26 October, and increasing organization the following day prompted the initial Dvorak satellite intensity estimates while it was centered about 1000 n mi east-southeast of Trinidad. Development continued in an increasingly conducive upper-level wind environment, and it is estimated that a tropical depression formed around 0600 UTC 29 October a little over 400 n mi southeast of Barbados. Under very well-defined upper-tropospheric outflow, the west-northwestward-moving cyclone intensified into a tropical storm within 6 h. A northward motion at a decreasing forward speed brought center near the southern coast of Barbados around 0900 UTC 30 October. Tomas then turned west-northwest and became a hurricane a couple of hours after departing Barbados. Maximum sustained winds reached 85 kt as the eye of the hurricane moved over the northern coast of St. Vincent around 2000 UTC 30 October, while the intense northern eyewall passed over St. Lucia.

After moving through the Windward Islands, Tomas encountered an atmospheric environment that became increasingly unfavorable as west-southwesterly vertical shear steadily increased. The low-level center became exposed well to the west of the main convective mass, and Tomas weakened to a tropical storm by 0000 UTC 1 November. Although the vertical shear relaxed considerably the next day, the system developed an elongated and tilted circulation and was affected by some midlevel dry air. Tomas weakened to a tropical depression by 0000 UTC 3 November as it turned northward over the central Caribbean. Later that day, the low-level circulation and deep convection became better organized and Tomas regained tropical storm strength. However, subsequent intensification was slow until early on 5 November, when deep convection became more concentrated near the center and the inner core apparently became better defined. Tomas turned northward to northeastward ahead of an unusually deep mid-tropospheric trough and reintensified into a hurricane around 0600 UTC 5 November.

Later on 5 November, the hurricane center moved between Jamaica and the southwest peninsula of Haiti and then through the Windward Passage. A modest

increase in shear over Tomas caused the cyclone to weaken once again to a tropical storm while it approached Caicos Island early on 6 November. After passing Caicos Island, Tomas intensified into a hurricane for a third and final time. This status was short lived, however, as vertical shear increased rapidly on 7 November and very dry air invaded the circulation. Tomas weakened back to a tropical storm by 1200 UTC that day and became extratropical by 0000 UTC 8 November. As an extratropical low, Tomas turned sharply eastward and then accelerated and rotated around a broad cyclonic gyre over the western Atlantic on 9–10 November. The system slowly weakened and was absorbed by another extratropical low a couple hundred nautical miles south of Newfoundland early on 11 November.

2) METEOROLOGICAL STATISTICS

The estimated maximum intensity of Tomas, 85 kt, is based on a 10-min wind observation of 77 kt from Hewanorra Airport in St. Lucia at 1926 UTC 30 October (Table S6 in the online supplemental material) along with application of the gust factor of 1.11 to convert from a 10-min average to a maximum 1-min average (Harper et al. 2009). In addition, there was an SFMR surface wind estimate of 85 kt at 0537 UTC 31 October from the 53WRS. Tomas produced phenomenal amounts of rainfall in St. Lucia, with totals ranging from 530 to 640 mm and a maximum total of 668.0 mm from Desraches over about a 23-h period.

It should be noted that on 3–4 November, one center within the broad circulation of the cyclone apparently dissipated while a new one formed farther to the north and northwest. Consequently, the northwestward track of Tomas around this time represents a smoothed motion of the overall cyclonic circulation.

3) CASUALTY AND DAMAGE STATISTICS

Tomas was responsible for 44 deaths: 35 in Haiti, 8 in St. Lucia, and 1 in Curacao.

The hurricane battered St. Lucia, producing severe and widespread damage. High winds toppled trees and power lines. The heavy rains generated mud slides and landslides that flooded or swept away numerous houses, some commercial buildings, bridges, and vehicles. Flood waters rendered roads impassable, and the associated landslides tore away large portions of St. Lucia's main highway. The agricultural sector of the country sustained extensive damage as most of the banana and plantain crops or trees were destroyed. The total damage is estimated to be around \$336.15 million (U.S. dollars).

Damage in Barbados and St. Vincent was less severe. Tomas downed trees and power lines, ripped off roofs,

and knocked out power on these islands. Approximately 1200 homes were damaged in Barbados, and island-wide damage was estimated to be near \$8.5 million (U.S. dollars). Damage estimates were \$3.3 million (U.S. dollars) in St. Vincent and the Grenadines.

Heavy rains associated with Tomas triggered floods and landslides in Haiti as it passed near that country. The core of the heaviest winds and rains remained offshore, however, which likely prevented a significantly larger death toll. The rains due to Tomas caused mud slides in some areas and flooding that destroyed homes and blocked roads. There are no monetary damage estimates for Haiti.

3. Nondeveloping depressions

a. Tropical Depression Two

This cyclone formed from a tropical wave that emerged from the coast of Africa on 24 June and reached the Yucatan Peninsula on 6 July. Surface observations showed that a low pressure area formed in association with the system over the southwestern Gulf of Mexico on 7 July, and the low developed into a tropical depression near 0000 UTC 8 July about 250 n mi southeast of Brownsville, Texas. A midlevel ridge over the southern United States steered the depression quickly northwestward for 12 h to a position about 45 n mi east of Brownsville. At that point, the depression abruptly turned westward with a decrease in forward speed, and it subsequently made landfall near 1400 UTC 8 July over the southern end of South Padre Island just northeast of Port Isabel, Texas. The center continued westward across extreme south Texas into northeastern Mexico by 0000 UTC 9 July, and the system degenerated to a remnant low shortly thereafter. The low gradually turned northwestward during the ensuing 24 h and dissipated over northern Mexico early on 10 July.

The depression produced 25–75 mm of rain across extreme south Texas. This, and additional rainfall produced by the cyclone over northern Mexico, added to the major flooding along the Rio Grande River begun by Hurricane Alex. A storm surge of 0.3–0.6 m occurred along the coast of extreme south Texas.

b. Tropical Depression Five

A low pressure area associated with a decaying frontal trough moved from the western Atlantic across the Florida peninsula on 8–9 August. The circulation of the low gradually became better defined, and by 1800 UTC 10 August the low became a tropical depression about 105 n mi west of Naples, Florida. The convection diminished soon thereafter, likely due to vertical wind shear

TABLE 2. Homogenous comparison of official and CLIPER5 track forecast errors in the Atlantic basin for the 2010 season for all tropical and subtropical cyclones. Averages for the previous 5-yr period are shown for comparison.

	Forecast period (h)						
	12	24	36	48	72	96	120
2010 mean OFCL error (n mi)	34.2	54.2	71.6	89.1	129.4	166.0	186.7
2010 mean CLIPER5 error (n mi)	53.0	107.5	165.9	229.8	332.2	400.1	469.7
2010 mean OFCL skill relative to CLIPER5 (%)	35.5	49.6	56.8	61.2	61.0	58.5	60.3
2010 mean OFCL bias vector (°/n mi)	052/4	027/7	019/8	034/10	120/8	116/23	098/32
2010 No. of cases	365	327	292	259	198	149	115
2005–09 mean OFCL error (n mi)	31.8	53.4	75.4	96.8	143.8	195.6	252.1
2005–09 mean CLIPER5 error (n mi)	46.9	97.3	155.4	211.6	304.8	387.9	467.8
2005–09 mean OFCL skill relative to CLIPER5 (%)	32.2	45.1	51.5	54.3	52.8	49.6	46.1
2005–09 mean OFCL bias vector (°/n mi)	307/5	307/11	311/18	314/24	308/22	347/13	034/31
2005–09 number of cases	1459	1300	1145	1013	802	618	479
2010 OFCL error relative to 2005–09 mean (%)	7.5	1.5	−5.0	−8.0	−10.0	−15.1	−25.9
2010 CLIPER5 error relative to 2005–09 mean (%)	13.0	10.5	6.8	8.6	9.0	3.1	0.4

and midlevel dry air associated with a nearby upper-level low. By 0600 UTC 11 August, the depression degenerated into a broad remnant low about 125 n mi west of Naples. The low became a little better organized as it approached the coast of southeastern Louisiana on 12 August. While the system produced a broad area of 20–25-kt winds, the convection never gained enough organization to be reclassified as a tropical depression. Later that day, the low moved slowly northward across the Chandeleur Islands off the coast of southeastern Louisiana and then turned northeastward and made landfall along the coast of Mississippi around 0600 UTC 12 August. The low then made an anticyclonic loop across portions of Mississippi, Alabama, western Georgia, and the Florida Panhandle before reentering the northern Gulf of Mexico on 16 August. The next day the low turned northwestward and again crossed the Mississippi coast, eventually dissipating over southwestern Mississippi by 0600 UTC 18 August.

Locally heavy rains accompanied the remnants of the depression across the Gulf Coast states, with some totals larger than 250 mm reported. Widespread street flooding occurred in New Orleans and Jefferson Parish, with a few buildings flooded in Jefferson Parish. Street flooding in Mobile, Alabama, also caused some property damage.

4. Forecast verifications and warnings

For all operationally designated tropical (or subtropical) cyclones in its area of responsibility, the NHC issues an official forecast of each 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). At the conclusion

of the season, forecasts are evaluated and verified by comparing the projected positions and intensities to the corresponding poststorm analyzed 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 cyclone at both the forecast's initial time and at the projection's valid time. All other stages of development (e.g., tropical wave, low, extratropical) are excluded. For verification purposes, forecasts from special advisories⁴ do not supersede the original forecast issued for that synoptic time. Additional information on verification of the NHC official forecasts, as well as for objective guidance models, is provided by [Cangialosi and Franklin \(2011\)](#).

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 2010 season, along with results averaged for the previous 5-yr period (2005–09).

⁴ Special advisories are issued whenever an unexpected significant change has occurred or when U.S. watches or warnings are issued between regularly scheduled advisories.

TABLE 3. Homogenous comparison of official and Decay-SHIFOR5 intensity forecast errors in the Atlantic basin for the 2010 season for all tropical and subtropical cyclones. Averages for the previous 5-yr period are shown for comparison.

	Forecast period (h)						
	12	24	36	48	72	96	120
2010 mean OFCL error (kt)	7.6	12.0	13.9	15.5	16.7	18.4	18.6
2010 mean Decay-SHIFOR5 error (kt)	8.9	13.4	16.9	19.9	23.2	25.4	26.3
2010 mean OFCL skill relative to Decay-SHIFOR5 (%)	14.6	10.4	17.8	22.1	28.0	27.6	29.3
2010 OFCL bias (kt)	0.2	1.4	2.4	3.2	3.8	2.9	3.1
2010 No. of cases	365	327	292	259	198	149	115
2005–09 mean OFCL error (kt)	7.0	10.7	13.1	15.2	18.6	18.7	20.1
2005–09 mean Decay-SHIFOR5 error (kt)	8.6	12.5	15.8	18.2	21.0	22.7	21.7
2005–09 mean OFCL skill relative to Decay-SHIFOR5 (%)	18.6	14.4	17.1	16.5	11.4	17.6	7.4
2005–09 OFCL bias (kt)	0.1	0.5	0.0	−0.5	−0.8	−2.1	−2.0
2005–09 No. of cases	1459	1300	1145	1013	802	618	479
2010 OFCL error relative to 2005–09 mean (%)	7.9	12.1	6.1	2.0	−10.2	−1.6	−7.5
2010 Decay-SHIFOR5 error relative to 2005–09 mean (%)	3.5	7.2	7.0	9.3	10.5	11.9	21.2

During the 2010 season the NHC issued 365 verified forecasts with mean track errors ranging from 34 n mi at 12 h to 187 n mi at 120 h. The 120-h mean forecast error was the lowest since the NHC began making 120 h forecasts in 2001. The 2010 mean track errors were slightly larger than the previous 5-yr average at 12–24 h and much smaller than that average at the other forecast times. Track forecast skill over CLIPER5 ranged from 36% at 12 h to near 60% at 48 h and beyond, and the skill was higher than the average for the preceding 5 years. It should be noted that the 2010 CLIPER5 track errors were larger than the previous 5-yr average, indicating that the 2010 forecasts were more difficult than normal.

Two cyclones had track forecast errors notably above the seasonal average. Danielle recurved more sharply into the westerlies than forecast, resulting in large 96- and 120-h forecast errors. Lisa's unclimatological eastward motion in the eastern Atlantic was very poorly forecast, with many forecasts at right angles (or worse) to the actual track. This storm had the largest mean track errors of all the 2010 cyclones from 48 to 120 h.

Intensity forecast error is defined as the absolute value of the difference between the forecast and best track intensity at the forecast verifying time. Intensity forecast skill is assessed by using version 5 of the Decay-Statistical Hurricane Intensity Forecast model (Decay-SHIFOR5, or 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 to 72 h.

Table 3 presents the results of the NHC official intensity forecast verification for the 2010 season, along with results averaged for the preceding 5-yr period. The 2010 mean intensity forecast errors ranged from 8 kt at 12 h to near 18 kt at 96–120 h. Compared to the previous 5 years, the mean errors were larger at 12–48 h and smaller at the longer forecast times. The 2010 forecast skill was less than the previous 5-yr average at 12–24 h and greater at the other forecast times. The 2010 DSHIFOR5 mean errors were larger than those of the previous 5 years at all times, again indicating that the 2010 forecasts were more difficult than normal. The 2010 official mean errors showed a high bias at all forecast times. This seems to have resulted from forecasts that kept weakening storms too intense (e.g., Danielle, Igor, Julia, and Tomas) and weak systems that strengthened less than forecast (e.g., Colin and Gaston). It should be noted that despite the seasonal high bias, the NHC experienced its typical problems in underforecasting rapid intensification during Earl, Igor, Julia, Karl, and the early strengthening of Tomas.

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.⁵ A watch means that the conditions are possible within that area within the next 48 h. Table 4 shows the watch and warning lead times for cyclones

⁵ The NHC has 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.

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 2010. 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)
Alex*	Lower Texas coast	H	59	47
TD Two	Lower Texas coast	TS	None issued	14
Bonnie	Southern Florida and Florida Keys	TS	None issued	24
Bonnie	Northern Gulf coast	TS	Dissipated prior to approaching watch area	Dissipated prior to approaching warning area
TD Five	Northern Gulf coast	TS	None issued	Dissipated prior to approaching warning area
Earl	U.S. Virgin Islands and Puerto Rico	TS	45	27
Earl	Mid-Atlantic states	H	57	37
Earl	New England	H	55	37
Hermine*	Lower Texas coast	TS	None issued	17
Nicole	Southern Florida and Florida Keys	TS	None issued	Dissipated prior to approaching warning area
Paula	Florida Keys	TS	TS conditions remained south of watch area	None issued

* The cyclone made landfall in Mexico, with the lead times based on the landfall time there.

that affected or had the potential to affect the United States and its territories in 2010. 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.

Some of the 2010 warnings were meteorologically problematic. A tropical storm warning was issued for the U.S. Gulf Coast during Bonnie and for south Florida during Nicole, which degenerated below tropical cyclone status before reaching the warning area. Tropical storm warnings were also issued for portions of the U.S. Gulf Coast for Tropical Depressions Two and Five in anticipation that these systems would strengthen prior to landfall. These warnings failed to verify as the cyclones did not strengthen.

For the past four years, the NHC has been making probabilistic forecasts of tropical cyclone genesis as a part of the Tropical Weather Outlook (TWO) product issued every 6 h, and these were made public for the first time in 2010. These forecasts are expressed as subjectively derived percentage chances of development during the ensuing 48 h, which in turn are grouped into low (less than

30% chance), medium (30%–50% chance), and high (greater than 50% chance) categories. Verification statistics for 2010 (not shown) indicate these forecasts have reliability at the high and low ranges, but are less skillful in the medium category. Several difficult genesis forecasts occurred during 2010 with the precursor disturbances for Danielle, Fiona, Igor, Julia, Karl, and Tomas due to uncertainty as to how quickly these systems would form in environments that appeared favorable.

There was a special forecast circumstance involving Colin. When the tropical cyclone degenerated on 3 August, it was thought that environmental conditions would later become favorable for redevelopment. The last issued official forecast correctly indicated that Colin could regenerate, but this occurred about 78 h earlier than was forecast. The probability of redevelopment in the TWOs issued between the times Colin was a tropical cyclone remained in the low category until about 12 h before reformation, when it was raised to medium.

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the 2010 season. Ethan Gibney of the I.M. Systems Group at the NOS Coastal Services Center produced the track chart. Internationally, much of the local impact information 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. Jay Titlow of Weatherflow contributed several observations from Hurricane Earl. Mr. Henry Plett, a private weather observer in Belize, provided some of the data for Hurricane Richard.

REFERENCES

- Aberson, S. D., 1998: Five-day tropical cyclone track forecasts in the North Atlantic basin. *Wea. Forecasting*, **13**, 1005–1015, doi:[10.1175/1520-0434\(1998\)013<1005:FDTCTF>2.0.CO;2](https://doi.org/10.1175/1520-0434(1998)013<1005:FDTCTF>2.0.CO;2).
- Bell, G. D., and Coauthors, 2000: Climate assessment for 1999. *Bull. Amer. Meteor. Soc.*, **81**, S1–S50, doi:[10.1175/1520-0477\(2000\)81\[s1:CAF\]2.0.CO;2](https://doi.org/10.1175/1520-0477(2000)81[s1:CAF]2.0.CO;2).
- Beven, J. L., and Coauthors, 2008: Atlantic hurricane season of 2005. *Mon. Wea. Rev.*, **136**, 1109–1173, doi:[10.1175/2007MWR2074.1](https://doi.org/10.1175/2007MWR2074.1).
- Blunden, J., D. S. Arndt, and M. O. Baringer, 2011: State of the Climate in 2010. *Bull. Amer. Meteor. Soc.*, **92**, S1–S236, doi:[10.1175/1520-0477-92.6.S1](https://doi.org/10.1175/1520-0477-92.6.S1).
- Brennan, M. J., R. D. Knabb, M. Mainelli, and T. B. Kimberlain, 2009: Atlantic hurricane season of 2007. *Mon. Wea. Rev.*, **137**, 4061–4088, doi:[10.1175/2009MWR2995.1](https://doi.org/10.1175/2009MWR2995.1).
- Cangialosi, J. P., and J. L. Franklin, 2011: 2010 National Hurricane Center forecast verification report. NOAA/NWS/NCEP/National Hurricane Center, 77 pp. [Available online at www.nhc.noaa.gov/verification/pdfs/Verification_2010.pdf.]
- DeMaria, M., J. A. Knaff, and J. Kaplan, 2006: On the decay of tropical cyclone winds crossing narrow landmasses. *J. Appl. Meteor. Climatol.*, **45**, 491–499, doi:[10.1175/JAM2351.1](https://doi.org/10.1175/JAM2351.1).
- Dvorak, V. E., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, National Oceanic and Atmospheric Administration, Washington, DC, 47 pp.
- Fogarty, C. T., 2011: Hurricane Igor 2010: Newfoundland's most damaging hurricane in 75 years. *Can. Meteor. Oceanogr. Soc. Bull.*, **38** (6), 209–217.
- Franklin, J. L., and D. P. Brown, 2008: Atlantic hurricane season of 2006. *Mon. Wea. Rev.*, **136**, 1174–1200, doi:[10.1175/2007MWR2377.1](https://doi.org/10.1175/2007MWR2377.1).
- , R. J. Pasch, L. A. Avila, J. L. Beven, M. B. Lawrence, S. R. Stewart, and E. S. Blake, 2006: Atlantic hurricane season of 2004. *Mon. Wea. Rev.*, **134**, 981–1025, doi:[10.1175/MWR3096.1](https://doi.org/10.1175/MWR3096.1).
- Harper, B. A., J. D. Kepert, and J. D. Ginger, 2009: Guidelines for converting between various wind averaging periods in tropical cyclone conditions. WMO Tech. Doc. WMO/TD-1555, World Meteorological Organization, 52 pp. [Available online at www.wmo.int/pages/prog/www/tcp/documents/WMO_TD_1555_en.pdf.]
- Jarvinen, B. R., and C. J. Neumann, 1979: Statistical forecasts of tropical cyclone intensity for the North Atlantic basin. NOAA Tech. Memo. NWS NHC-10, 22 pp.
- Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting*, **18**, 1093–1108, doi:[10.1175/1520-0434\(2003\)018<1093:LCORIT>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<1093:LCORIT>2.0.CO;2).
- Knaff, J. A., M. DeMaria, B. Sampson, and J. M. Gross, 2003: Statistical, 5-day tropical cyclone intensity forecasts derived from climatology and persistence. *Wea. Forecasting*, **18**, 80–92, doi:[10.1175/1520-0434\(2003\)018<0080:SDTCIF>2.0.CO;2](https://doi.org/10.1175/1520-0434(2003)018<0080:SDTCIF>2.0.CO;2).
- Lawrence, M. B., B. M. Mayfield, L. A. Avila, R. J. Pasch, and E. N. Rappaport, 1998: Atlantic hurricane season of 1995. *Mon. Wea. Rev.*, **126**, 1124–1151, doi:[10.1175/1520-0493\(1998\)126<1124:AHSO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<1124:AHSO>2.0.CO;2).
- Montgomery, M. T., and Coauthors, 2012: The Pre-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) Experiment: Scientific basis, new analysis tools, and some first results. *Bull. Amer. Meteor. Soc.*, **93**, 153–172, doi:[10.1175/BAMS-D-11-00046.1](https://doi.org/10.1175/BAMS-D-11-00046.1).
- Neumann, C. B., 1972: An alternate to the HURRAN (hurricane analog) tropical cyclone forecast system. NOAA Tech. Memo. NWS SR-62, 24 pp.
- Norton, G., 1951: Hurricanes of the 1950 season. *Mon. Wea. Rev.*, **79**, 8–15, doi:[10.1175/1520-0493-79.1.8](https://doi.org/10.1175/1520-0493-79.1.8).
- Office of the Federal Coordinator for Meteorology, 2010: National Hurricane Operations Plan (FCM-P12-2010). NOAA/OFCM, 175 pp. [Available online at <http://www.ofcm.gov/nhop/10/nhop10.htm>.]
- Olander, T. L., and C. S. Velden, 2007: The advanced Dvorak technique: Continued development of an objective scheme to estimated tropical cyclone intensity using geostationary infrared satellite imagery. *Wea. Forecasting*, **22**, 287–298, doi:[10.1175/WAF975.1](https://doi.org/10.1175/WAF975.1).
- Pasch, R. J., M. B. Lawrence, L. A. Avila, J. L. Beven, J. L. Franklin, and S. R. Stewart, 2004: Atlantic hurricane season of 2002. *Mon. Wea. Rev.*, **132**, 1829–1859, doi:[10.1175/1520-0493\(2004\)132<1829:AHSO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2004)132<1829:AHSO>2.0.CO;2).
- Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24**, 395–419, doi:[10.1175/2008WAF2222128.1](https://doi.org/10.1175/2008WAF2222128.1).
- Saffir, H. S., 1973: Hurricane wind and storm surge. *Mil. Eng.*, **423**, 4–5.
- Schott, T., and Coauthors, 2010: The Saffir-Simpson Hurricane Wind Scale. National Weather Service, 4 pp. [Available online at <http://www.nhc.noaa.gov/pdf/sshs.pdf>.]
- Simpson, R. H., 1974: The hurricane disaster—Potential scale. *Weatherwise*, **27**, 169–186, doi:[10.1080/00431672.1974.9931702](https://doi.org/10.1080/00431672.1974.9931702).
- Sugg, A. L., 1967: The hurricane season of 1966. *Mon. Wea. Rev.*, **95**, 131–142, doi:[10.1175/1520-0493\(1967\)095<0131:THSO>2.3.CO;2](https://doi.org/10.1175/1520-0493(1967)095<0131:THSO>2.3.CO;2).
- Texas Tech University, 2006: A recommendation for an enhanced Fujita scale (EF-scale). Texas Tech University, 111 pp. [Available online at <http://www.depts.ttu.edu/nwi/Pubs/FScale/EFScale.pdf>.]