A Reanalysis of the 1911–20 Atlantic Hurricane Database

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ABSTRACT

A reanalysis of the Atlantic basin tropical storm and hurricane database ("best track") for the period of 1911–20 has been completed. This reassessment of the main archive for tropical cyclones of the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico was necessary to correct systematic biases and random errors in the data as well as to search for previously unrecognized systems. A methodology for the reanalysis process for revising the track and intensity of tropical cyclone data is provided in detail. The dataset now includes several new tropical cyclones, excludes one system previously considered a tropical storm, makes generally large alterations in the intensity estimates of most tropical cyclones (both toward stronger and weaker intensities), and typically adjusts existing tracks with minor corrections. Average errors in intensity and track values are estimated for both open ocean conditions as well as for landfalling systems. Finally, highlights are given for changes to the more significant hurricanes to impact the United States, Central America, and the Caribbean for this decade.

1. Introduction

This paper details efforts to reanalyze the National Hurricane Center's (NHC's) North Atlantic hurricane database [HURDAT; also called the "best track" since they are the "best" postseason determination of tropical cyclone (TC) tracks and intensities] for the period of 1911–20. The original database of 6-hourly TC (including tropical storms and hurricanes, but not nondeveloping tropical depressions) positions and intensities was assembled in the 1960s in support of the Apollo space program to help provide statistical TC track forecasting guidance (Jarvinen et al. 1984). Since its inception, this database (available online at http://www.nhc.noaa.gov/pastall.shtml) has been utilized for a wide variety of additional projects: setting of appropriate building codes for coastal zones (ASCE 2000), risk assessment for emergency managers (Jarrell et al. 1992), analysis of potential losses for insurance and business interests (Malmquist and Michaels 2000), intensity forecasting techniques (DeMaria and Kaplan 1999), verification of official and model predictions of track and intensity (McAdie and Lawrence 2000), seasonal forecasting (Gray 1984), and climatic change studies (Landsea et al. 1999). Unfortunately, HURDAT was not designed with all of these uses in mind when it was first put together and not all of them may be appropriate, given its original motivation and limitations.

There are many reasons why a reanalysis of the HURDAT dataset was both needed and timely. HURDAT contained many systematic biases and ran-

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dom errors that needed correction (Neumann 1994). For example, in the early part of the twentieth century, a TC's intensity and position were only estimated once per day, which was later interpolated to 6-h intervals for HURDAT. Such a linear interpolation scheme is problematic for systems that make landfall because of the tendency for TCs to retain their intensity until the time that the center crosses the coast followed by a period of exponential decay (Kaplan and DeMaria 1995). Cases where the TC's winds were artificially weakened before landfall in HURDAT occurred in a majority of landfalling hurricanes in the first half of the twentieth century. Other systematic errors included unrealistic translational velocities at the beginning and/or end of the TC track because of the digitization process in the 1960s and a lack of realistic wind speed decay when a TC traversed substantial peninsulas and islands (such as the Yucatan of Mexico and Hispaniola).

Additionally, as our understanding of TCs developed over the years, analysis techniques at NHC have changed and led to biases in the historical database that have not been addressed. For example, Landsea (1993) documented an artificial change to the central pressure–maximum wind relationship, where the HURDAT winds in the 1940s to the 1960s were systematically stronger than those in the 1970s and 1980s for the same central pressure. Another methodological concern is that the winds in HURDAT just before a hurricane landfall in the United States often do not match the assigned Saffir–Simpson hurricane scale. C. J. Neumann and J. Hope developed the first digital HURDAT records with 6-hourly position and maximum wind estimates in the late 1960s (Jarvinen et al. 1984), before the Saffir–Simpson scale was devised (Saffir 1973; Simpson 1974). The U.S. Saffir–Simpson scale categorizations for the twentieth century were first assigned by Hebert and Taylor (1975), based primarily upon central pressure observations or estimates at landfall. It was not until the late 1980s that the use of the Saffir–Simpson scale categorization was based upon the winds exclusively, which is the current standard at NHC (OFCM 2005). Thus, reanalysis efforts in Landsea et al. (2004a,b) and in the work presented here have utilized the estimated maximum sustained winds for assignment of Saffir–Simpson category to be consistent with today's analysis techniques. Finally, new understanding of the wind structure in hurricanes from GPS-based dropwindsondes launched in the eyewalls of hurricanes since 1997 have provided a systematic way to adjust aircraft flight-level winds to the surface (Dunion et al. 2003; Franklin et al. 2003). This new methodology has already been applied to 1992 Hurricane Andrew (Landsea et al. 2004b) and resulted in numerous revisions to that TC's wind speed records. Such standardization will be crucial for reanalysis efforts during the post-1943 reconnaissance era, as aircraft data have provided a substantial portion of HURDAT wind speed estimates during the last several decades.

The first phase of the reanalysis efforts for the period of 1851 through 1910 was reported in Landsea et al. (2004a). That earlier work covered the era that was first fully investigated by Fernández-Partagás and Diaz (1996) and resulted in the introduction of 240 TCs during a period of 35 yr (1851–85) in HURDAT, detailed 22 new TCs from 1886 to 1910, and made alterations to about 200 other tropical storms and hurricanes in that latter time period. The current paper moves forward sequentially in time to the second decade of the twentieth century.

Data sources will be described in the next section followed by a discussion of the methodologies used to estimate TC track and intensity, their likely errors, and criteria utilized to either add new TCs or to remove systems from HURDAT. The results section goes through the overall changes implemented for the 1911 through 1920 timeframe and highlights changes in some of the more noteworthy hurricanes that have impacted the United States and other countries in the North Atlantic basin. The summary and future work section revisits the larger points within the paper and mentions the directions to be taken to move forward with the project. Finally, the appendix describes in full the reanalysis of a single TC that occurred during this period—the 1919 Key West hurricane.

2. Data sources

The Atlantic HURDAT contains 6-hourly intensity [maximum sustained 1-min winds at the surface (10 m) and, when available, central pressures] and position (to the nearest 0.1° latitude and longitude) estimates of all known tropical storms and hurricanes from 1851 to today (Jarvinen et al. 1984; Landsea et al. 2004a). Tropical storms and hurricanes that remained out over the Atlantic Ocean waters during the second half of the nineteenth century and first half of the twentieth century had relatively few chances to be observed and thus included into HURDAT. This is because, unlike today, the wide array of observing systems, such as geostationary/polar-orbiting satellites, aircraft reconnaissance, radars, and moored/drifting buoys, were not available. Landsea (2007) provides an example of the typical distribution of marine observations available in the early twentieth century versus those that are taken today. Detection of tropical storms and hurricanes up until the mid-1940s was limited to those tropical storms and hurricanes that affected ships and those that impacted land. Until the utilization of two-way radio in the first decade of the twentieth century, the only way to obtain ship reports of hurricanes at sea was after the ships made their way back to port. Observations from these late ship reports were not of use to the fledgling weather services in the United States and Cuba operationally, though some of them were available for post-analyses of that season's TC activity. The year 1909 marked the first time that a ship reported a hurricane by radio in the Atlantic basin (Neumann et al. 1999). Despite the substantial increase in shipping traffic during the first few decades of the twentieth century, more widespread utilization of onboard barometers and the use of radio to both send and receive reports about these storms led to modest decreases in ship-based observations of TCs because of better knowledge of where the systems were occurring and where they would likely track. It is estimated that more than three tropical cyclones a year were likely missed in the pre-geostationary satellite era between 1900 and 1965 (Landsea 2007).

The bulk of the data utilized for the reanalysis efforts for the period of 1911–20 are ship observations from the *Historical Weather Map* (*HWM*) series, the Comprehensive Ocean–Atmosphere Data Set (COADS; Woodruff et al. 1987), *Monthly Weather Review* (*MWR*), and miscellaneous ship reports obtained from the National Climatic Data Center. The *HWM* series, a reconstruction of daily surface Northern Hemispheric synoptic maps begun by the U.S. Navy and U.S. Weather Bureau in the 1920s, was conducted for the years 1899 through 1969. While COADS is one of the most comprehensive observational ship databases available and often contains most ship observations found in *HWM*, there are some data in *HWM* not available in COADS. *Monthly Weather Review* regularly published an "Ocean Gales and Storms" section that had significant [gale force winds ($\geq$34 kt, or 17.5 m s^{-1})] ship observations, which also were occasionally not found in COADS. Overall, for TCs over the open ocean, COADS provided the majority of relevant ship observations for the reanalyses. It is to be noted that COADS was not generally utilized in the reanalysis efforts for the period of 1851–1910 conducted by Fernández-Partagás and Diaz (1996) and quality controlled/digitized by Landsea et al. (2004a).

Once a TC impacted land in the early twentieth century, then both station-based meteorological observations and more anecdotal reports become readily available. Station data are available from *HWM*, the U.S. Weather Bureau Original Monthly Records (OMR; available online through the National Climate Data Center's Climate Database Modernization Program: http://www.ncdc.noaa.gov/oa/climate/cdmp/cdmp.html), *MWR*, the Cuban meteorological journal *Reseña,* and original sources from the Mexican Weather Service. The *MWR*, in particular for the era of the 1910s, was quite detailed in providing many raw observations as well as providing descriptions of the impacts of the landfalling systems both in the United States and elsewhere in the Atlantic basin. *MWR* also routinely provided a graphic called Tracks of the Centers of Cyclones that was the first depiction of TC (and extratropical storm) positions twice a day in the United States, northern Mexico, southern Canada, the Gulf of Mexico, and the northwest Atlantic Ocean. Although this was a useful product, it was still often necessary to consult the original observations of the U.S. Weather Bureau found in the OMR reports to best estimate exact landfall position and intensity.

Other miscellaneous data sources that helped provide information on the track and intensity of existing TCs and helped identify previously overlooked systems included the following for the period of 1911–20: Barnes (1998a,b); Boose et al. (2001, 2004); Cline (1926); Connor (1956); Dunn and Miller (1960); Ellis (1988); Hall (1913); Ho et al. (1987); Hudgins (2000); Jarrell et al. (1992); Jarvinen et al. (1985); Kasper et al. (1998); Mitchell (1932); Neumann et al. (1999); O. Perez (1971, personal communication); Perez Suarez et al. (2000); Rappaport and Fernández-Partagás (1995); Roth (1997a,b); Roth and Cobb (2001); Schwerdt et al. (1979); Tannehill (1938); Tucker (1982); Wiggert and Jarvinen (1986); and various newspaper accounts.

All available oceanic and coastal observations were then analyzed once daily (more frequently if the TC was over heavily trafficked shipping lanes or over land with more data being available) and the resulting estimated TC positions and intensities compared with the *HWM*, *MWR*, and original HURDAT tracks. Changes to the original HURDAT were made only if observations supported making substantial alterations to the track (generally at least 0.3° latitude–longitude) and intensity (generally at least 10 kt, 1 kt = 0.5144 m s^{-1}). The appendix (see Fig. A1) provides an example of the synoptic analysis conducted for one day during storm 2, 1919 (the Key West hurricane). Possible alterations considered for each storm were for genesis, duration of the system, intensity, and decay and/or transformation into an extratropical cyclone. (Subtropical storms, which are included into HURDAT beginning in 1968, are not a category explicitly used in the reanalysis during the 1910s due to lack of information about thermodynamical structure in the vertical and convective organization. Some TCs of the 1910s, however, do appear because of their large size to have some subtropical

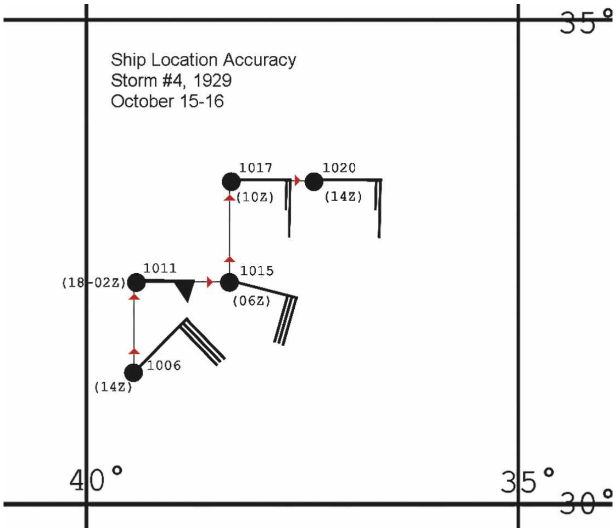

FIG. 1. Ship location accuracy example from COADS database. The red line with arrows misleadingly suggests a zigzagged ship track according to COADS. Times of observations are given in parentheses. Sea level pressure (mb) and wind barbs are provided. The resolution of ship observations in COADS during early in the twentieth century is typically given in 1.0° to 0.5° latitude–longitude increments, which contribute toward uncertainty in the location of TCs.

cyclone characteristics and a few of these might have been subtropical storms. Such systems are noted as such in their metadata write-up.) All official revisions to HURDAT have been examined, commented upon, and approved by the NHC Best Track Change Committee.

3. Track estimation and errors

TC positions were determined in this study primarily by wind direction observations from ships and coastal stations and secondarily by sea level pressure measurements and reports of damages from winds, storm tides, and freshwater flooding. With these observations and the knowledge that the surface flow in a TC is relatively symmetric [i.e., circular flow with an inflow angle of 10°–20°; Houston et al. (1999)], a relatively reliable estimate of the center of the storm can be obtained from a few peripheral wind direction measurements (see Fig. 2 from Landsea et al. 2004a). While geographical positions of TCs in HURDAT were estimated to the nearest 0.1° latitude–longitude (~6 n mi, 1 n mi = 1.852 km), the average errors were typically much larger in the early twentieth century than this precision might imply. Holland (1981) demonstrated that even with the presence of numerous ships and buoys in the vicinity of a strong TC that was also being monitored by aircraft reconnaissance, there were substantial errors in estimating its exact center position from the ship and buoy data alone. Another complicating issue in utilizing ship observations from COADS is that most ships of the era provided position estimates to a resolution of 0.5° to 1.0° latitude–longitude because of the imprecision in navigation at the time (Fig. 1). Based upon these considerations, storms documented over the open ocean during the period of 1911–20 were estimated to have position errors that averaged 100 n mi, with ranges of 150–240 n mi errors being quite possible in data-sparse regions of the Caribbean Sea and central North Atlantic Ocean (Table 1). This position error estimate is the same as the preceding 25 yr despite increased shipping traffic, because of the increasing ability of ships at sea to steer clear of an encounter with a TC.

At landfall, knowledge of the location of the TC was generally more accurate, as long as the storm came ashore in a relatively populated region (Table 1). By the early part of the twentieth century most coastal locations along the Gulf of Mexico, Caribbean Sea, and western North Atlantic were settled and thus impacts of TCs facilitated more accurate estimates of landfall positions. The main exception to this was along the Mexican coastline, where—because of the ongoing conflict later named the Mexican Revolution—there was substantially decreased meteorological monitoring from

TABLE 1. Estimated average position and intensity errors and frequency undercounts in the revised best track for the years 1851–1920. Negative bias errors indicate an underestimation of the true intensity. By 1920, only a few coastal areas in the Atlantic basin remained sparsely populated (i.e., less than two people per square mile), though some coastal regions (such as in Mexico due to the ongoing Mexican Revolution) were not well monitored. The tropical storm and hurricane undercount refer to annual numbers of systems that likely were not observed based upon density of ship traffic across the Atlantic basin.

Situation	Dates	Position error (n mi)	Intensity error (absolute) (kt)	Intensity error (bias) (kt)	Tropical storm and hurricane undercount
Open ocean	1851–85	120	25	−15	4–6
	1886–1920	100	20	−10	3–4
Landfall at sparsely populated area	1851–85	120	25	−15	1–2
	1886–1920	100	20	−10	0–1
Landfall at settled area	1851–85	60	15	0	0
	1886–1920	60	12	0	0

1910 until 1920. Average errors for position at and after landfall from 1911 to 1920 were on the order of 60 n mi (110 km) with somewhat smaller values occurring over densely populated and meteorologically monitored locations like Puerto Rico and the U.S. mainland coast between Georgia and Maine.

4. Intensity estimation and errors

In comparison with TC position and track, analysis of TC intensity is much less straightforward when analyzing cyclones from the first half of the twentieth century. Intensity, described as the maximum sustained 1-min surface (10 m) winds, is recorded at a resolution of 10 kt from 1851 to 1885 and 5 kt for the period of 1886 to date. The reanalysis of peak winds for the Atlantic basin TCs that occurred from 1911 to 1920 was based upon (in decreasing order of weighting) central pressure observations, in situ wind observations from anemometers, Beaufort wind estimates, peripheral pressure measurements, wind-caused damages along the coast, and storm tide. These various observations are similar to what were available for the first reanalyses conducted for the years of 1851–1910, though the measurements from instruments become relatively more common during 1911–20.

Sea level central pressure (eye) measurements can provide relatively reliable estimates of the maximum wind speeds in a TC in the absence of in situ observations of the peak wind strength. If central pressure is not available, it can be estimated from peripheral (eyewall or rainband) pressure measurements if accurate values of the radius of maximum wind (RMW) and environmental (or surrounding) sea level pressure can also be obtained. Typically, this was possible at landfall when the RMW was estimated by measuring the mean distance from the hurricane's track to the location of the peak storm surge and/or peak wind-caused damages. Central pressure can then be estimated from an empirical formula found in Schloemer (1954) and Ho (1989).

Once a central pressure has been estimated, maximum wind speeds can be obtained from a pressure–wind relationship. The current standard pressure–wind relationship for use in the Atlantic basin by NHC (OFCM 2005) is that developed by Dvorak (1984) [modified from earlier work by Kraft (1961)]. The earlier reanalysis work (Landsea et al. 2004a) developed new pressure–pressure relationships that were latitude dependent. The resultant pressure–wind relationships for the four regions of the Gulf of Mexico, southern latitudes (south of 25°N), subtropical latitudes (25°–35°N), and northern latitudes (35°–45°N) gave similar results to Dvorak (1984) for weaker TCs with relatively high pressures (>980 mb) but differed significantly for stronger hurricanes. For example, for a central pressure of 960 mb, both the Gulf of Mexico and southern latitude relationships would suggest a maximum wind of 100 kt, while the subtropical latitude relationship gives 94 kt and the northern latitudes only 90 kt. Compared to Dvorak (1984), the Gulf of Mexico and southern latitude relationships are most similar, while the subtropical and northern latitude relationships indicate significantly weaker winds than Dvorak. These latitudinally based pressure–wind relationships from Landsea et al. (2004a) were utilized exclusively in the reanalysis for 1851–1910 and were the primary tool for 1911–20.

A new set of pressure–wind relationships based upon data since 1998 were developed by Brown et al. (2006). While similar to Landsea et al. (2004a) for the southern and subtropical latitudes, Brown et al.'s association for the Gulf of Mexico suggest weaker winds for given pressures in the hurricane intensity range. They found no significant difference in the pressure–wind relationship between those TCs in the Gulf of Mexico versus those over the Atlantic within the same latitude belt, which was in contrast to Landsea et al. Moreover, Brown et al. were also able to stratify by those TCs that are deepening and those that are filling. They did not have enough cases north of 35°N to evaluate the northern latitudes relationship. The Brown et al. revised relationships were utilized for Gulf of Mexico hurricanes for the period 1911–20.

The use of pressure–wind relationships to estimate winds in TCs has a few associated caveats. First, for a given central pressure, a smaller-sized TC (measured either by RMW or radius of hurricane winds) will produce stronger winds than a large TC (Knaff and Zehr 2007). Vickery et al. (2000), building from earlier work by Ho et al. (1987), developed a statistical relationship between RMW and central pressure, environmental pressure, and latitude from hurricanes that made landfall in the continental United States. Tropical storms and hurricanes with observed/estimated RMWs that were smaller (larger) by 25%–50% from the these climatological RMW values for their given central pressure, environmental pressure, and latitude had wind speeds increased (decreased) in the reanalysis work by about 5 kt above that suggested by the latitudinally based pressure–wind relationships. TCs with RMW dramatically (more than 50%) different from climatology had winds adjusted by about 10 kt, accordingly. It is acknowledged that this is a somewhat arbitrary adjustment process, though there is not a straightforward alternative available.

Another caveat concerns the translational speed of the TC. In general, the translational speed is an additive factor on the right side of the storm and a negative factor on the left for Northern Hemisphere TCs (Callaghan and Smith 1998; Knaff and Zehr 2007). At low to medium translational speeds (less than around 20 kt), the variation in storm winds on opposite sides of the storm track is approximately twice the translational velocity, although there is substantial uncertainty and nonuniformity regarding this impact on TC winds. At faster translational speeds, this factor is somewhat less than 2 (Boose et al. 2001). Storms that move at least 50% faster than the regionally dependent climatological translational speeds (Neumann 1993; Vickery et al. 2000) have been chosen in the reanalysis to have higher (5 kt) maximum wind speeds than slower storms with the same central pressure at that location. Similarly, storms with significantly slower than usual rates of translational velocity (>50%) are given slightly reduced winds (5 kt) for a given central pressure.

One final adjustment to maximum winds provided by central pressure is based upon the environmental pressure. TCs embedded in higher (lower) than climatological environmental pressures will have stronger (weaker) pressure gradients and thus increased (decreased) winds if all other factors are equal (Knaff and Zehr 2007). While the climatological pressures vary by month and location, in general, when environmental pressures are higher than about 1016 mb, 5-kt additional wind would be indicated over that suggested by the pressure–wind relationship, while pressures lower than about 1010 mb would suggest lowering the winds by about 5 kt.

For many early twentieth-century storms, the central pressure could not be estimated from peripheral pressure measurements with the Schloemer equation because values for the RMW were unknown. However, one can get a wind from the peripheral pressure based upon the latitudinally based pressure–wind relationships. This wind would represent a minimum estimate of what the strongest winds were at the time, given that the central pressure would be lower, perhaps by a few mb, perhaps by substantially more. In most of these cases, the best-track winds chosen for the reanalysis were 5–10 kt higher than that suggested by the pressure–wind relationship itself.

For land-based observations of wind speed, the period of the 1910s was just before a time of transition regarding the type of anemometer generally being utilized. The original four-cup anemometer, first developed by Robinson in the 1840s (Kinsman 1969), was still widely used in the United States and other countries until the 1920s. Its primary limitations were in calibrating the instrument and its mechanical failure in hurricane-force wind conditions. Even as late as the 1890s, the highest wind that could be reliably calibrated with this instrument was only about 30 kt (from a whirling machine, similar in structure to a record player), due to a lack of reliable comparisons with a known quantity of faster motion. By the early 1920s, wind tunnels allowed for calibration against much stronger winds. These showed that the winds from the early cup anemometers had a strong overestimation bias, which was most pronounced at hurricane-force wind speeds (Fergusson and Covert 1924). For example, when these instruments indicated winds of minimal hurricane force of 64 kt, the true wind was only 50 kt. Moreover, most of these early four-cup anemometers were disabled or destroyed by the TC before sampling the highest winds. One of the strongest observed winds in an Atlantic hurricane by this type of anemometer was a 5-min sustained wind measurement of 100 kt in storm 11, 1916 at Mobile, Alabama (Kadel 1926). (A standard of 5 min was typically utilized in U.S. Weather Bureau reports of "maximum winds" in the era, due to instrumental uncertainties in obtaining shorter time period winds.) With the availability of reliable calibrations beginning in the 1920s, the true velocity of this observation was determined to be only about 77 kt. Current understanding of gustiness in hurricane conditions suggests a boost of 1.06 to convert from a 5- to a 1-min maximum sustained wind (Powell et al. 1996), giving a best estimate of the maximum 1-min sustained wind of about 82 kt. These older style anemometers were replaced by the more reliably calibrated three-cup anemometers during the mid- and late 1920s (Fergusson and Covert 1924), though these new instruments still suffered from mechanical failure in extreme winds. These corrections were thus applied for the 1910s and had been previously incorporated into the 1851–1910 time period reanalysis efforts (Landsea et al. 2004a).

However, the bulk of wind speed observations in Atlantic basin TCs during 1911–20 were those subjective determinations of oceanic winds using the Beaufort scale. This scale was refined and promoted as a wind force scale for sailing ships by Admiral Francis Beaufort and required in all British Royal Navy log entries by 1838 (Kinsman 1969). Subsequently, the scale evolved into one associated with specific wind speed ranges as specified by interpretations of the sea state, rather than the wind's impact on a ship's sails as sailing ships were replaced by those with engines later in the nineteenth century. Due to limitations at the top end of the Beaufort scale, the COADS, *HWM*, and other ship data sources of the time generally list reports of "hurricane"-force winds as 70-kt winds. The listed wind speeds were boosted to 90 kt only when ship reports included terms such as "severe," "violent," "terrific," or "great hurricane." Hurricanes at sea were not reanalyzed with a best-track intensity value of a major hurricane (Saffir–Simpson scale category 3, 4, or 5; 96 kt or greater maximum surface wind speeds) unless corresponding central/peripheral pressure data were able to confirm such an intensity. Caution was warranted in the direct use of these Beaufort scale wind estimates for tropical storm and hurricane intensity assignments due to a lack of consistency and standardization in the scale during the early twentieth century (Cardone et al. 1990). However, in many cases, these Beaufort scale measurements by mariners were the primary tools available for estimating the intensity of TCs in this era.

In the absence of instrumental observations of winds and pressure, one can utilize wind-caused destruction and storm surge measurements to make estimates of intensity of TCs at landfall. Indeed, the work of Boose et al. (2001, 2004), which utilized wind-caused destruction in New England and Puerto Rico to assess hurricane impacts, favorably matched instrument-based assessments in Ho et al. (1987) and Ho (1989) and in the reanalysis work reported in Landsea et al. (2004a) for the period of 1851–1910. Such damage assessments can narrow down the uncertainty of intensity estimates for landfalling hurricanes in settled areas within about one category on the Saffir–Simpson scale. However, wind-caused destruction alone is too complex to reliably estimate an exact maximum wind speed. In addition to maximum winds encountered, hurricane wind damage is also dependent on the duration of destructive winds, the wind steadiness (change of wind direction), the exposure, and the building materials, workmanship, and building codes employed in the construction of the structures (Cochran 2000; Dunion et al. 2003). Thus wind-caused damage from hurricanes is only given a small weight in determining intensity at landfall.

Storm surge measurements can also assist in the determination of TC intensity at landfall, such as that listed in the Saffir–Simpson hurricane scale (Simpson 1974). However, such categorizations are only a rough estimate and are extremely variable because of several factors other than intensity: RMW, coastline shape, local offshore bathymetry/inland topography, astronomical tides, wave setup, and inflow angle (i.e., Jelesnianski et al. 1992). However, one can utilize several reliable storm surge measurements along with an accurate track of the landfalling hurricane in sensitivity tests using the Sea, Lake, and Overland Surges from Hurricanes (SLOSH; Jelesnianski et al. 1992) model to obtain a central pressure and RMW that produces the best fit of the simulated storm surge values to the observations. This has been done for several landfalling hurricanes, such as the 1915 Galveston hurricane (storm 2; Wiggert and Jarvinen 1986) and the 1898 Brunswick hurricane (storm 7; Sandrik and Jarvinen 1999). With these derived central pressure and RMW values, the maximum winds can then be straightforwardly estimated, but an isolated maximum storm surge value without the assistance of SLOSH modeling runs is of limited use in estimating landfall intensity.

Once the landfall intensity of a U.S. continental hurricane strike is determined, the spatial variations (what U.S. states or portions of states) are analyzed and compared with the existing classification in HURDAT. In addition to the previously mentioned factors that are utilized for determining maximum wind, a simple parametric wind model (Schwerdt et al. 1979) is employed to assist in the delineation of states impacted. This model, given inputs of TC position, translational speed and direction, maximum wind, RMW, and location of interest, provides the approximate winds (marine exposure) for that location. A series of runs with the model can provide estimated peak sustained winds experienced at that location, which allows for an objective determination of Saffir–Simpson scale categorization for places not directly impacted by the right front quadrant RMW where the peak wind typically resides. For example, the Key West major hurricane of 1919 (storm 2, 1919, see the appendix) was originally assessed to be a category 4 for both southwest Florida (BFL4) at landfall in the Florida Keys and again when it reached south coastal Texas (ATX4). After the reanalysis of meteorological data and applications of Schwerdt et al.'s model, it was determined that the conditions at the Keys landfall were unchanged (category 4 for southwest Florida). However, the peripheral impacts were increased to include a category 2 impact for southeast Florida (BFL2). Additionally, the peak impact in Texas was downgraded to category 3 for south coastal Texas (ATX3), but central coastal Texas was also added as category 3 (BTX3).

After landfall, existing HURDAT TC intensity estimates are problematic as mentioned earlier because of errors introduced by interpolation and the often unrealistic, complete lack of weakening when the systems were over peninsulas and large islands. Analyses of intensity in the decaying phase over land are primarily based upon observations of pressures and winds as well as models of pressure and wind decay for TCs described below. An observation of central pressure after landfall can be easily converted to an equivalent maximum wind with the appropriate pressure–wind relationship. However, these algorithms were derived assuming overwater conditions. The use of the associations for TCs overland must consider the increased roughness length of most land surfaces and the dampening of the maximum sustained wind speeds that result. In general, maximum sustained wind speeds over open terrain exposures (roughness lengths of 0.03 m) are about 5%–10% slower than overwater wind speeds (Powell and Houston 1996), though for rougher terrain the wind speed decrease is substantially greater. Ho et al. (1987) developed several relationships for the decay of TC central pressure after landfall, which were stratified by geographic location and value of the pressure deficit (environmental pressure minus central pressure) at landfall. This pressure decay model can be utilized to estimate central pressure for a weakening system after landfall or to analyze the pressure at landfall given a central pressure reading well inland.

Because of the mesoscale nature of TCs, even for systems that made landfall in a relatively data-rich region like the United States, only rarely are there enough direct winds observations to reasonably insure that an actual measurement of maximum winds were made. The Kaplan and DeMaria (1995, 2001) inland wind decay model provided guidance for determining wind speeds after landfall of a TC. This model utilizes the maximum wind at landfall and provides decayed maximum wind speed values out to about two days after landfall. The decay of winds by the model over higher terrain areas, such as Hispaniola and much of Mexico, is inadequate (e.g., Bender et al. 1985). For these cases, a faster rate of decay than that given from the model (on the order of 30% accelerated rate of decay) was utilized in the reanalysis. The results from the Kaplan and DeMaria inland wind decay model were compared with available observations and only utilized when actual pressure and wind data were too sparse to adequately estimate the maximum wind from direct observations.

Original and reanalyzed best-track intensity estimates for the 1910s were based mainly upon observations by ships at sea, which more often than not, would not sample the most intense part of the storm (typically only 30–60 n mi in diameter). Holland (1981) demonstrated that even in a relatively data-rich region of ship and buoy observations within the circulation of a TC, the actual intensity was likely to be substantially underestimated. Figures 3 and 4 from Landsea et al. (2004a) provided a graphic demonstration of this for major Hurricane Erin of 2001 that made a close bypass of Bermuda. Aircraft winds extrapolated to the ocean surface indicated maximum surface winds of about 100 kt in Erin at 1930 UTC 9 September 2001. However, despite transiting within 85 n mi of Bermuda, the highest observed surface winds from ships and coastal stations were only around 40 kt. Such an underestimation of TC intensities was likely common in the presatellite and preaircraft reconnaissance era. It is estimated that the intensity measurements for 1911–20 were in error an average of 20 kt over the open ocean, with a bias toward underestimating the true intensity (Table 1). These values are the same as the period of 1886–1910 but smaller than 1851–85. For TCs landfalls during the 1910s, intensity estimates were improved and show a negligible bias as most coastlines around the western North Atlantic, Gulf of Mexico, and Caribbean Sea were substantially settled by that time (Table 1). Again, these values are the same as the period of 1886–1910 but smaller than 1851–85. A notable exception to this for landfalling TCs is for Mexico, due to the lack of meteorological monitoring during the Mexican Revolution of 1910–20.

5. Criteria for adding new or removing existing tropical cyclones

Based upon examination of the *Historical Weather Maps*, monthly synoptic assessments contained in *Monthly Weather Review*, the COADS ship database, and other sources, potentially new TCs were considered for inclusion into the Atlantic hurricane database. The current definition of "tropical cyclone" utilized at the National Hurricane Center today is the following (OFCM 2005): "[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." Given that only TCs of tropical storm intensity or greater are included into HURDAT, the definition of tropical storm is also relevant: "[a] tropical cyclone in which the maximum sustained surface wind speed (using the U.S. 1-minute average) ranges from 34 kt (39 mph or 63 km/hr) to 63 kt (73 mph or 118 km/hr)."

Systems were thus considered for inclusion into HURDAT during the era of the 1910s based upon the following criteria:

1) nonfrontal (not an extratropical cyclone);
2) closed surface wind circulation; and
3) at least two separate observations of sustained tropical storm force winds (at least 34 kt) or the equivalent in sea level pressure (roughly 1005 mb or lower). The two separate observations could come from the same ship/station or two different platforms.

Systems that could not unambiguously meet all of these criteria were not included into HURDAT but were described in the metadata file as a possibility.

On occasion, there were systems listed in HURDAT that appeared to not be TCs based upon today's definitions. However, only if it could be reasonably certain through sufficient observations that no tropical storm force winds were present at any point throughout the time that the system maintained a nonfrontal, closed circulation structure, would a listed TC be considered for removal.

As with other changes in HURDAT, additions of new TCs and removal of existing TCs were officially decided by the NHC Best Track Change Committee.

6. Results

a. Overall activity

A summary of the yearly changes to HURDAT is provided in Fig. 2 and Table 2. Figure 2 shows the revised and original track maps for the individual seasons from 1911 to 1920. It is apparent that most of the track changes introduced for these years are fairly minor (less than a 120 n mi alteration in position at anytime during the TC's lifetime) as easily seen in the case of the five original TCs in 1915, though examples can be seen of more dramatic alterations on occasion (e.g., old storm 4/new storm 6 in 1911, old storm 6/new storm 7 in 1912, storm 3 in 1913). Despite making relatively minor changes overall, nearly every existing TC was adjusted for at least some portion of its track.

In addition to track alterations of existing systems, new TCs were discovered and added into HURDAT for the first time and one existing system in HURDAT was reanalyzed to not be a tropical storm and thus removed from the database. In total, 13 new TCs had sufficient observational evidence to document their existence and were added into HURDAT: two in 1911, 1913, 1916, and 1919; one in 1912, 1915, 1917, 1918, and 1920; and no new systems in 1914. Of these 13, 4 of the new TCs were landfalling systems: new storm 6, 1913 in Cuba (as a hurricane); new storm 1, 1916 in Florida; new storm 5, 1916 in Mexico (possibly a hurricane); and new storm 4, 1919 in Georgia. Additionally, one system during the 1910s in HURDAT was removed because of a lack of gale force winds (old storm 8 in 1916). In other years in the reanalysis work (e.g., 1891), two separate TCs were found to be actually one continuous system and thus so changed to reflect this. There also has been a TC removed from HURDAT because the system was shown to be an extratropical cyclone throughout its lifetime (e.g., old storm 5, 1855). However, for the period of 1911 through 1920, no such TCs were identified.

Table 2 lists the original and revised tallies of tropical storms and hurricanes, hurricanes, major hurricanes, and accumulated cyclone energy [ACE; an index for overall TC activity that takes into account the total frequency, intensity, and duration of TCs; Bell et al. (2000)]. ACE is calculated by summing the squares of the estimated 6-hourly maximum wind speed in knots to be found in HURDAT for all periods while the system is either a tropical storm or hurricane.

The average number of tropical storms and hurricanes increased from 4.9 per year in the original HURDAT to 6.1 after the reanalysis (Table 2). This net increase includes new systems that we added into the database as well as the one that was originally in HURDAT but was discarded. Both values are substantially below the long-term average of 11.1 per year recorded in the satellite era of 1966–2006 (Blake et al. 2007). The tropical storms and hurricanes that stayed out at sea for their duration and did not encounter ships will at this point remain undocumented for the time period of the 1910s. It is estimated that the number of undetected tropical storms and hurricanes for the 1911–20 era is on the order of 3–4 per year (Table 1). While this is an improvement over the number missed in the first three and a half decades in HURDAT (4–6 per year during 1851–85), it is the same estimate as the previous 25 yr. This is the case despite the increased shipping traffic from 1911 to 1920, because of the better ability of mariners to avoid TC encounters with the more widespread employment of onboard barometers. (The use of two-way radios likely also contributed toward fewer encounters of ships with TCs, but presumably there had to be at least one encounter with the TC by a ship for other ships to avoid a known storm.) By no means should the TC record for the Atlantic basin as a whole be considered complete for either the frequency or intensity of tropical storms and hurricanes for the years 1851–1920. [These estimates of "missed" tropical storms and hurricanes are narrowed from that originally shown in Landsea et al. (2004a), based upon the new work presented in Landsea (2007).]

In contrast, the hurricane, major hurricane, and ACE averages (Table 2) show smaller changes in recorded values. Hurricane frequency had a small increase from 3.5 to 3.8 per year (6.2 per year in the modern era), major hurricanes remained unchanged at 1.3 per year (2.3 per year recently), and ACE dropped slightly from 61.1 to 58.7 per year (91.0 per year recently). The decrease in ACE is likely due to a systematic tendency for the original HURDAT to somewhat overestimate the intensity of hurricanes from 1911 to 1920, especially over the open ocean (e.g., storm 3, 1913; old storm 9/new storm 10, 1916). With regards to ACE, one year

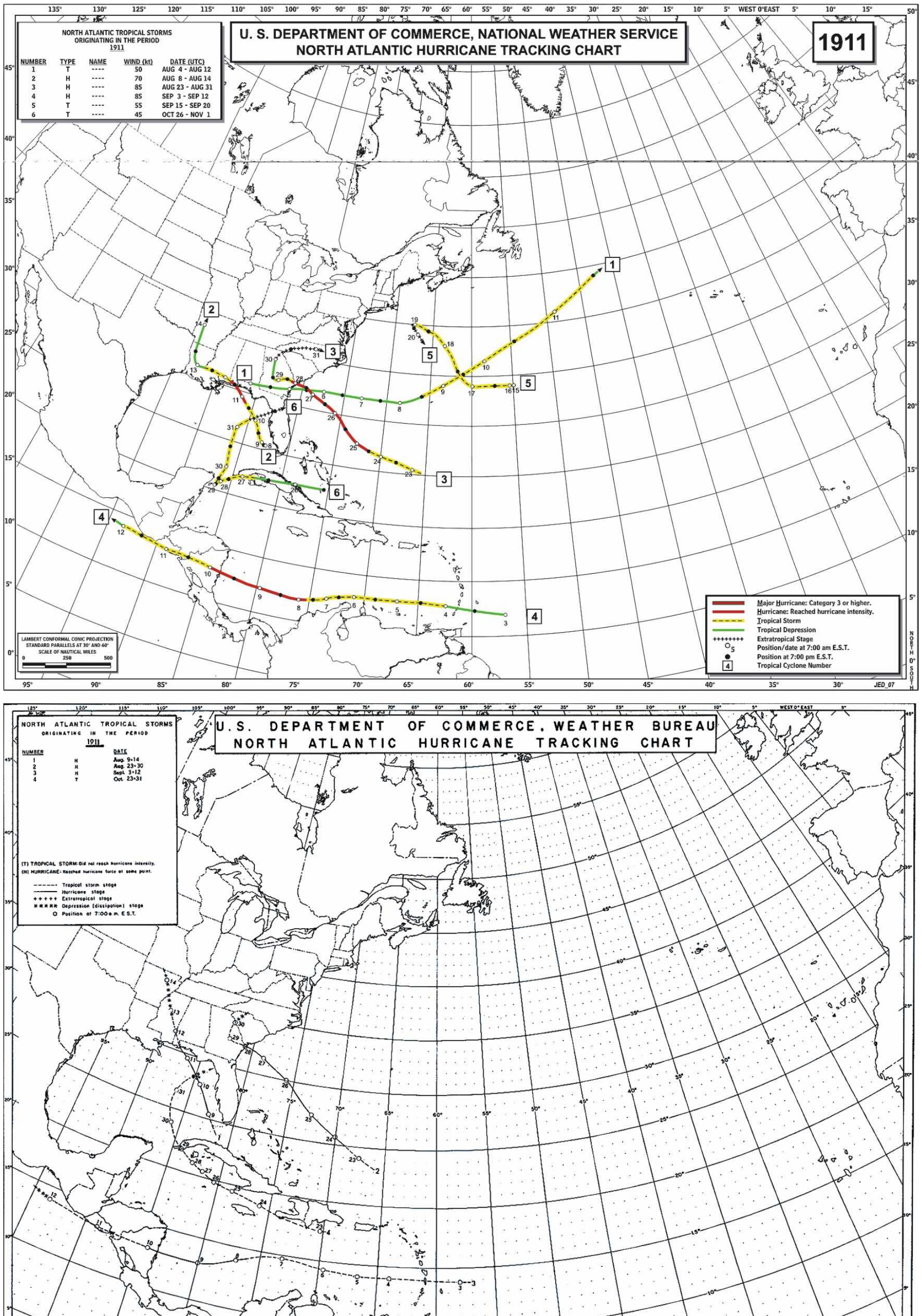

FIG. 2. The (top) revised and (bottom) original Atlantic basin TC track map for 1911, 1912, 1913, 1914, 1915, 1916, 1917, 1918, 1919, and 1920.

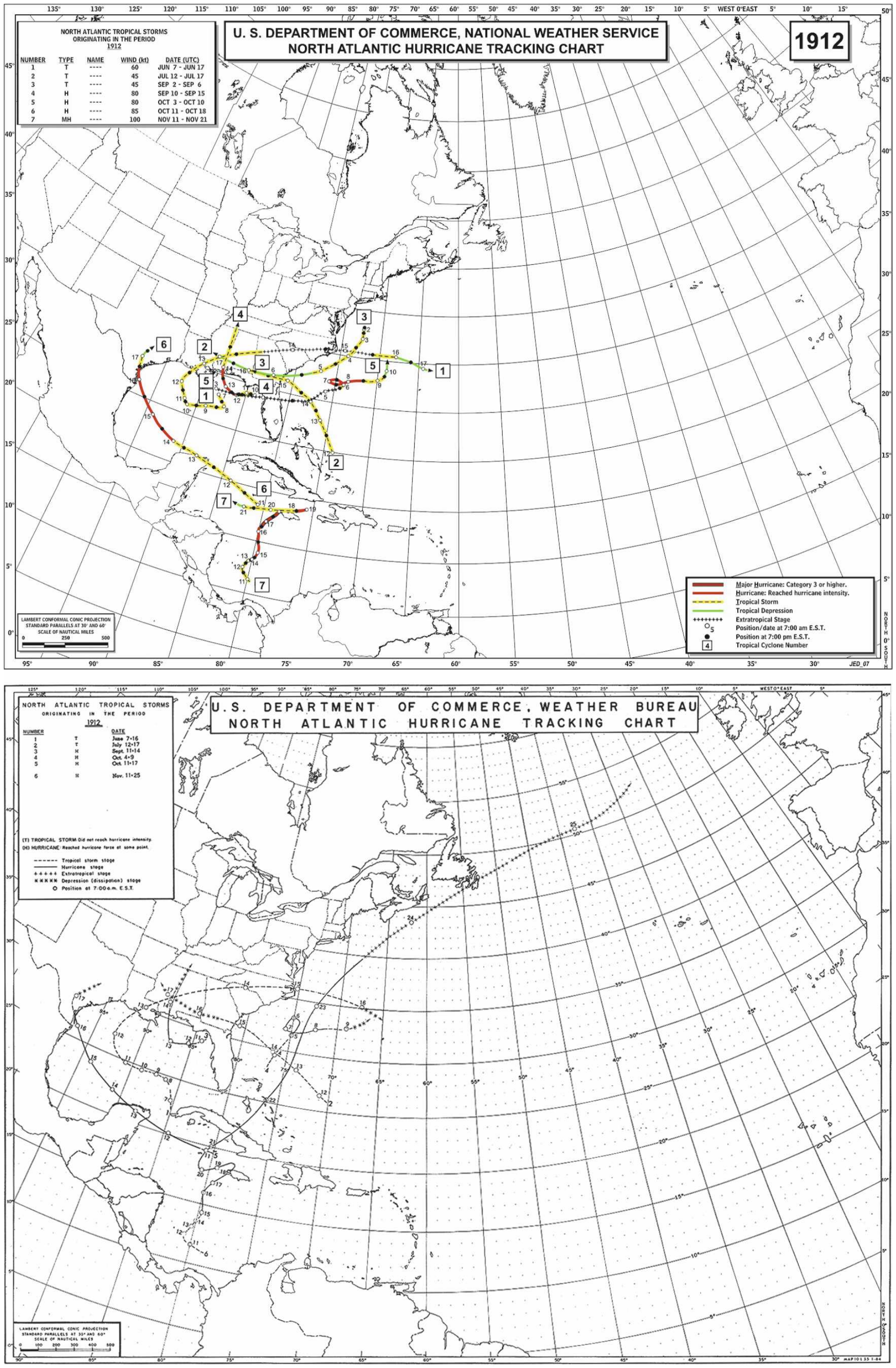

FIG. 2. (*Continued*)

recorded a substantial increase in activity (ACE higher by at least 10.0–1918), two years saw a substantial decrease in activity (ACE lower by at least 10.0, 1912 and 1916), and the remaining seven years had minor alterations in overall intensity, duration, and frequency. Despite a moderate increase in the number of tropical storms and hurricanes because of the use of more data than were available to meteorologists of the era, the

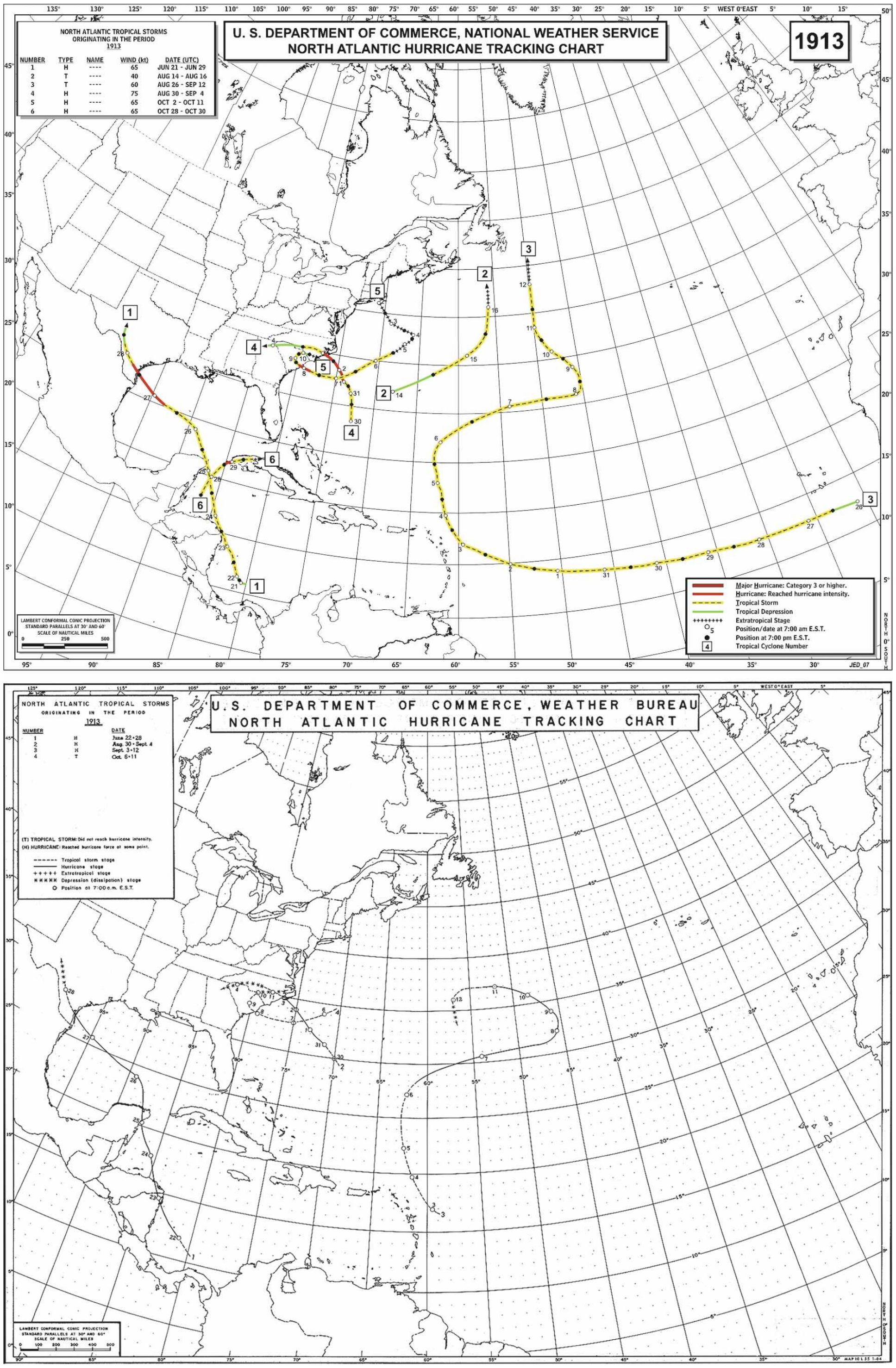

FIG. 2. (*Continued*)

overall activity is slightly reduced by a modest amount because of the correction of an overestimation in intensity in the original HURDAT. In general, large changes to intensity (at least a 20-kt alteration at some point in the TC's lifetime) were recorded, both upward and downward, for the majority of individual TCs, typically with more significant changes than those introduced for track.

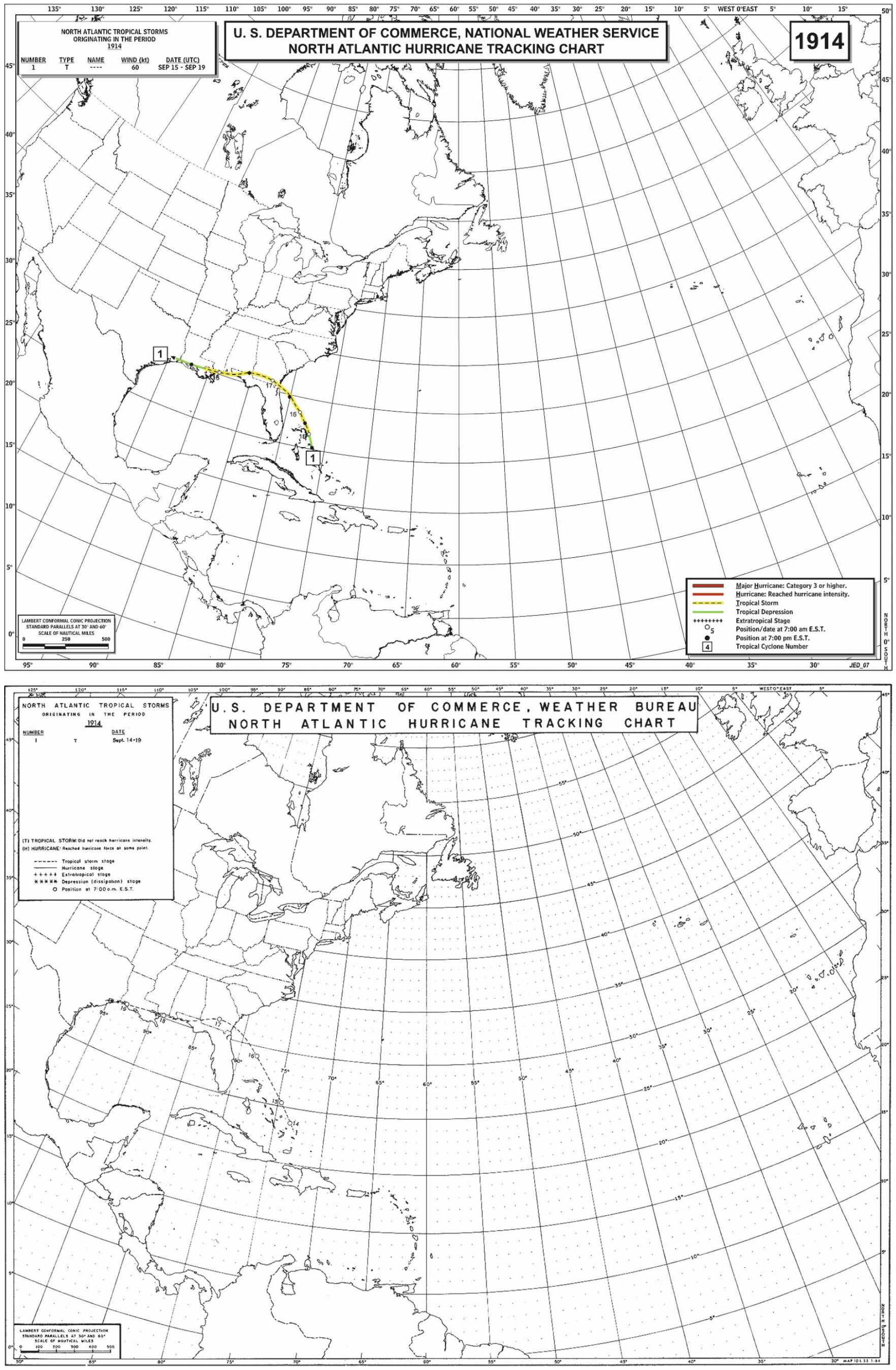

FIG. 2. (*Continued*)

b. Continental U.S. hurricanes

Table 3 summarizes the continental U.S. hurricanes for the period of 1911–20 and the states impacted by these systems. U.S. hurricanes are defined as those hurricanes that are analyzed to cause maximum sustained (1 min) surface (10 m) winds of at least 64 kt for an open exposure on the coast or inland in the continental United States. Hurricanes that make a direct landfall

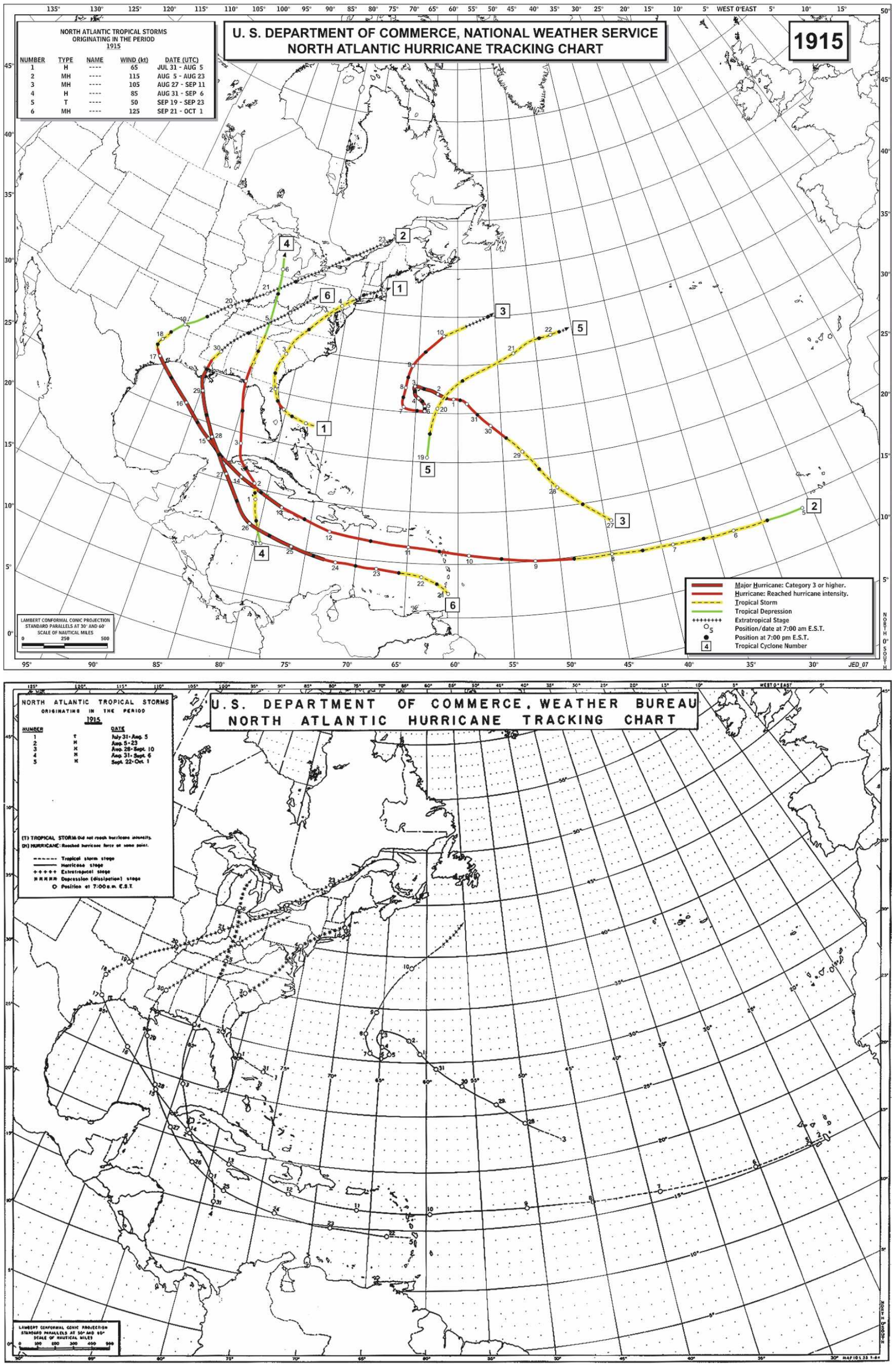

FIG. 2. (*Continued*)

with the circulation center (eye) of the system crossing the coast as well as those that make a close bypass are considered. In addition to the parameters also common to HURDAT (e.g., latitude, longitude, maximum winds, and central pressure), the U.S. hurricane compilation also includes the outer closed isobar, the mean size of the outer closed isobar, and, when available, the RMW. These parameters provide information regard-

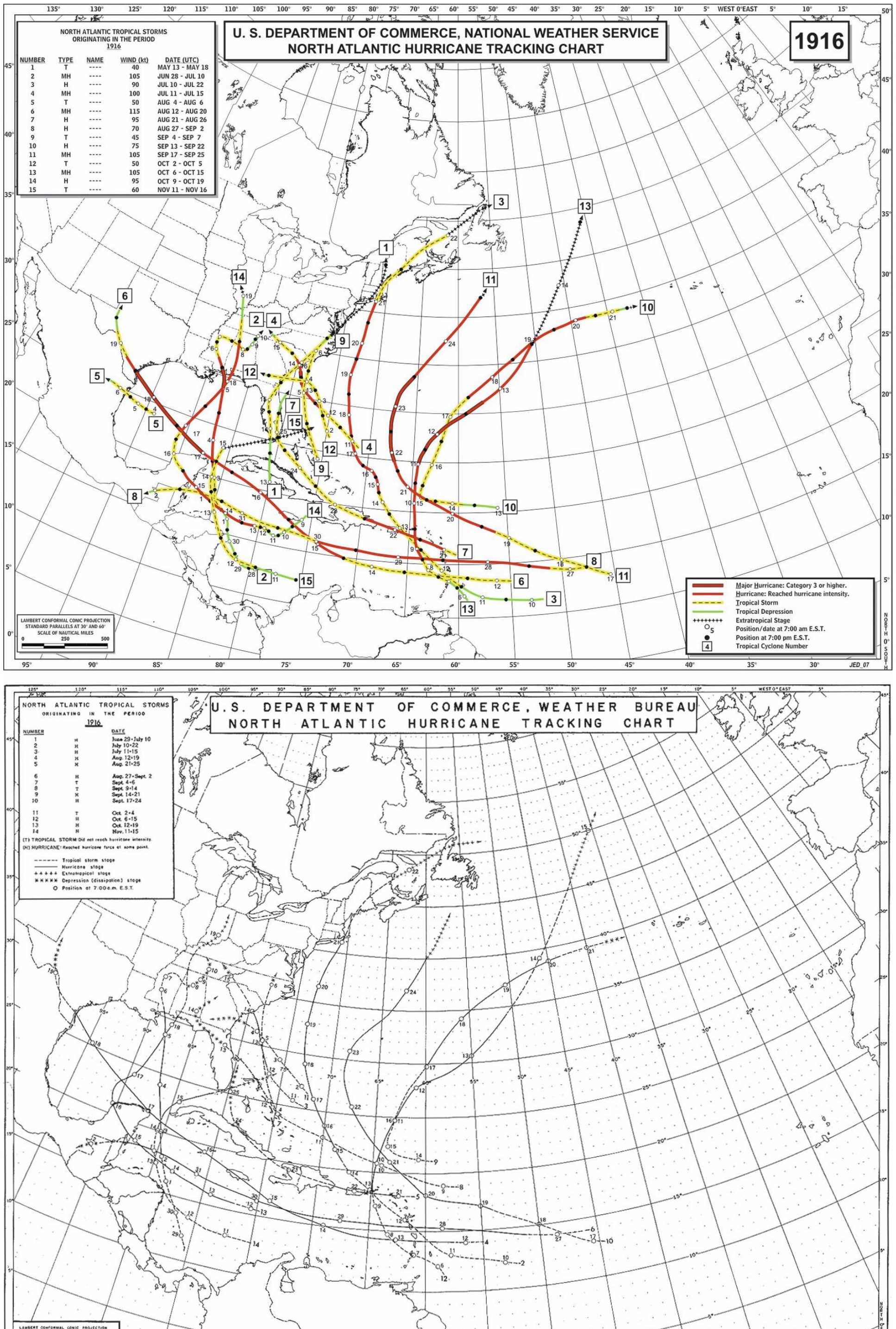

FIG. 2. (*Continued*)

ing the size of the hurricanes, which can vary considerably from system to system. For these TCs, winds listed in HURDAT in the last 6-hourly period before landfall are now consistent with the assigned Saffir–Simpson hurricane-scale category, which was not the case in the original HURDAT database before the reanalysis efforts. For most U.S. hurricanes of this era, a central pressure observation or estimate was obtained from

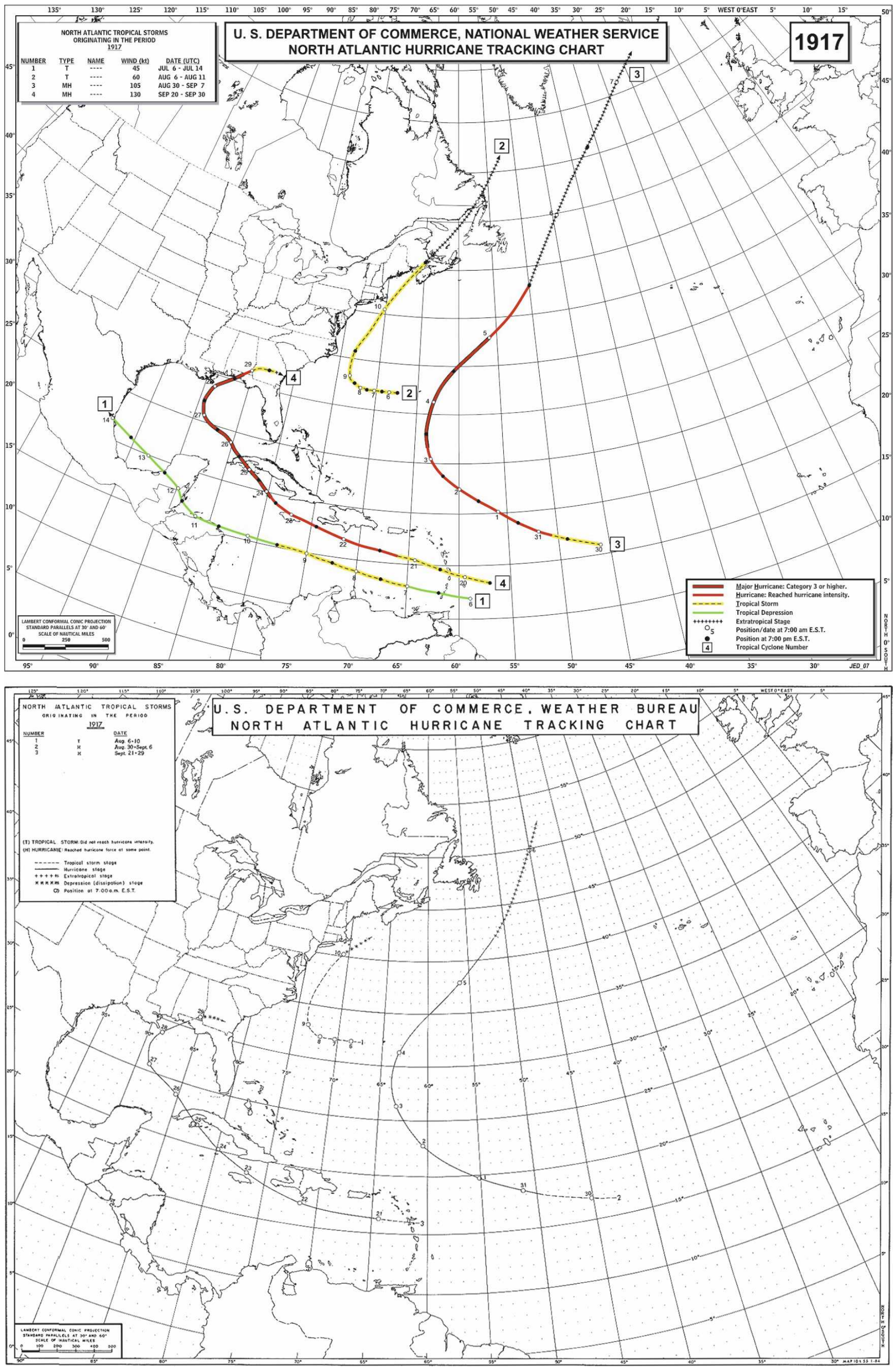

Fig. 2. (*Continued*)

original sources, Ho et al. (1987) or other references, which was then used to determine maximum wind speeds through the application of one of the new pressure–wind relationships. In the cases where there was no central pressure value directly available, the estimated winds at landfall were then used via the pressure–wind relationship to back out a reasonable central pressure. In either case, the objective was to provide

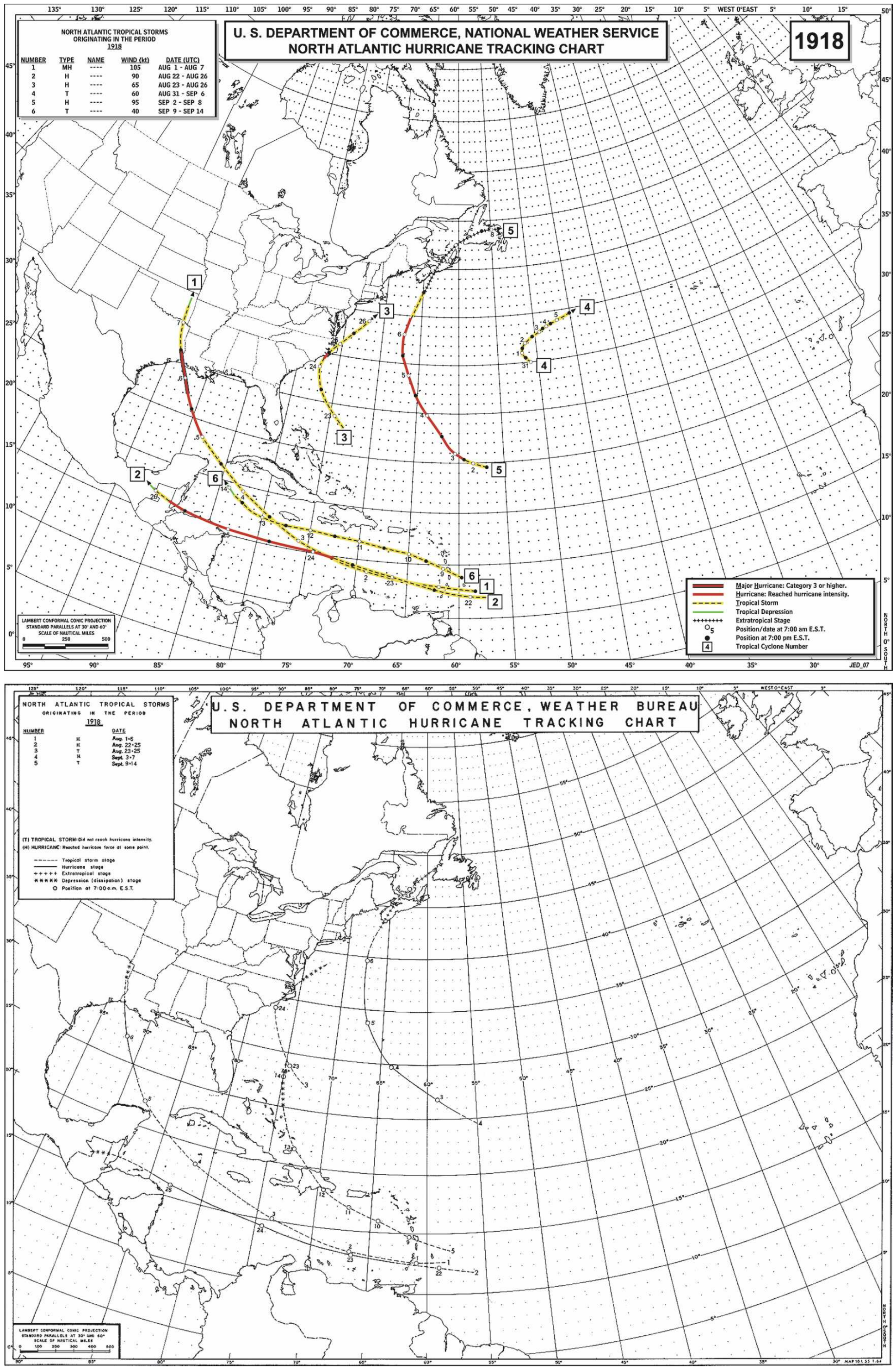

FIG. 2. (*Continued*)

both an estimate of the maximum wind and a central pressure at landfall for all U.S. hurricanes.

There were 20 U.S. hurricanes (7 that were major hurricanes) during the 1911–20 period after the reanalysis. This represents the same number as that contained in the original HURDAT database, with three new U.S. hurricanes added (storm 5, 1913 as a category 1 in South Carolina; storm 1, 1915 as a category 1 in

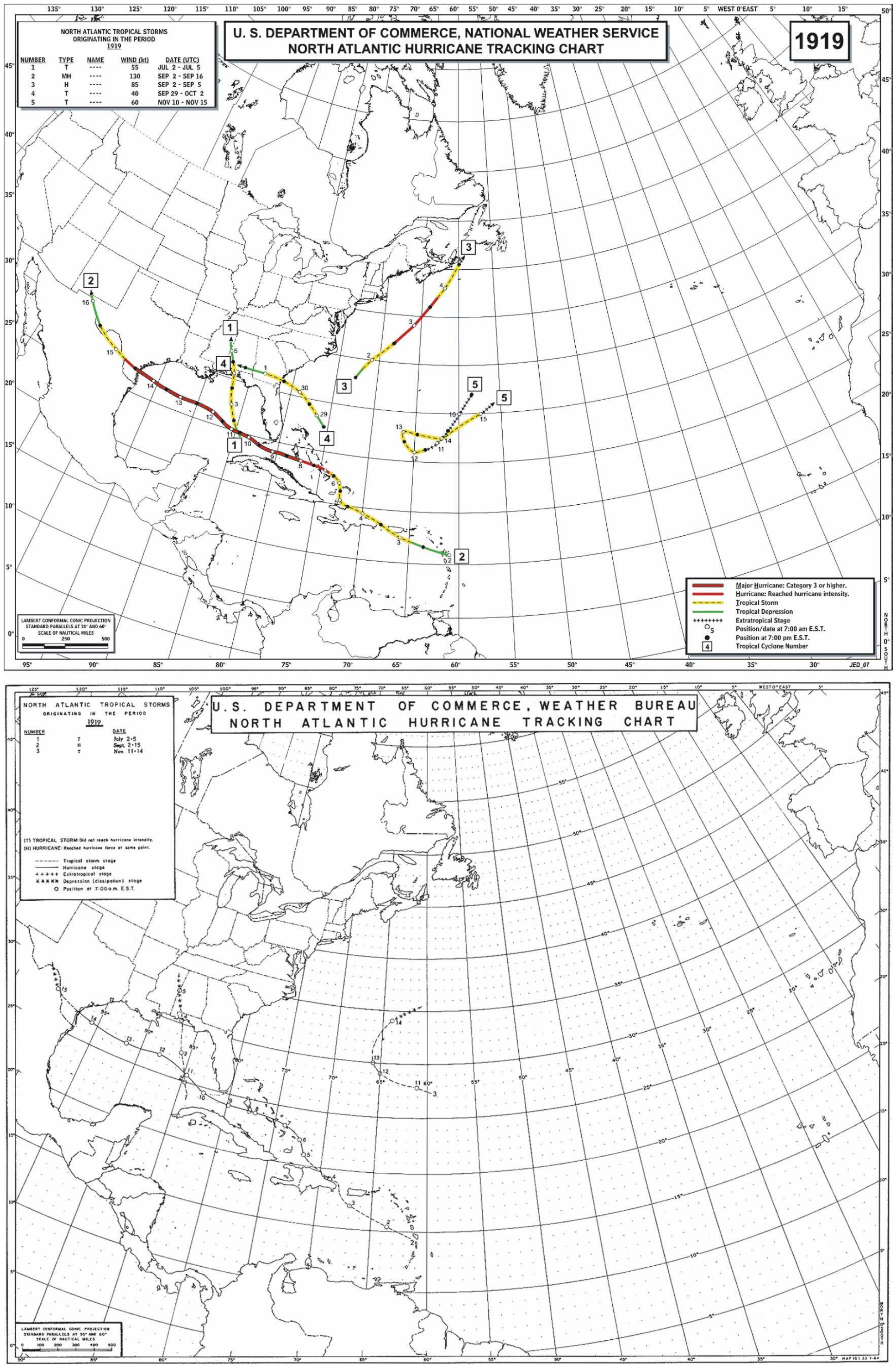

FIG. 2. (*Continued*)

northeast Florida; and storm 3, 1918 as category 1 in North Carolina) and three U.S. hurricanes removed. Two of the three removed former U.S. hurricanes were analyzed instead to only be of tropical storm intensity at landfall (old storm 2/new storm 3, 1916 in Massachusetts and storm 3, 1920 in North Carolina) and the other one was analyzed instead to be an extratropical cyclone by landfall (old storm 14/new storm 15, 1916 in south-

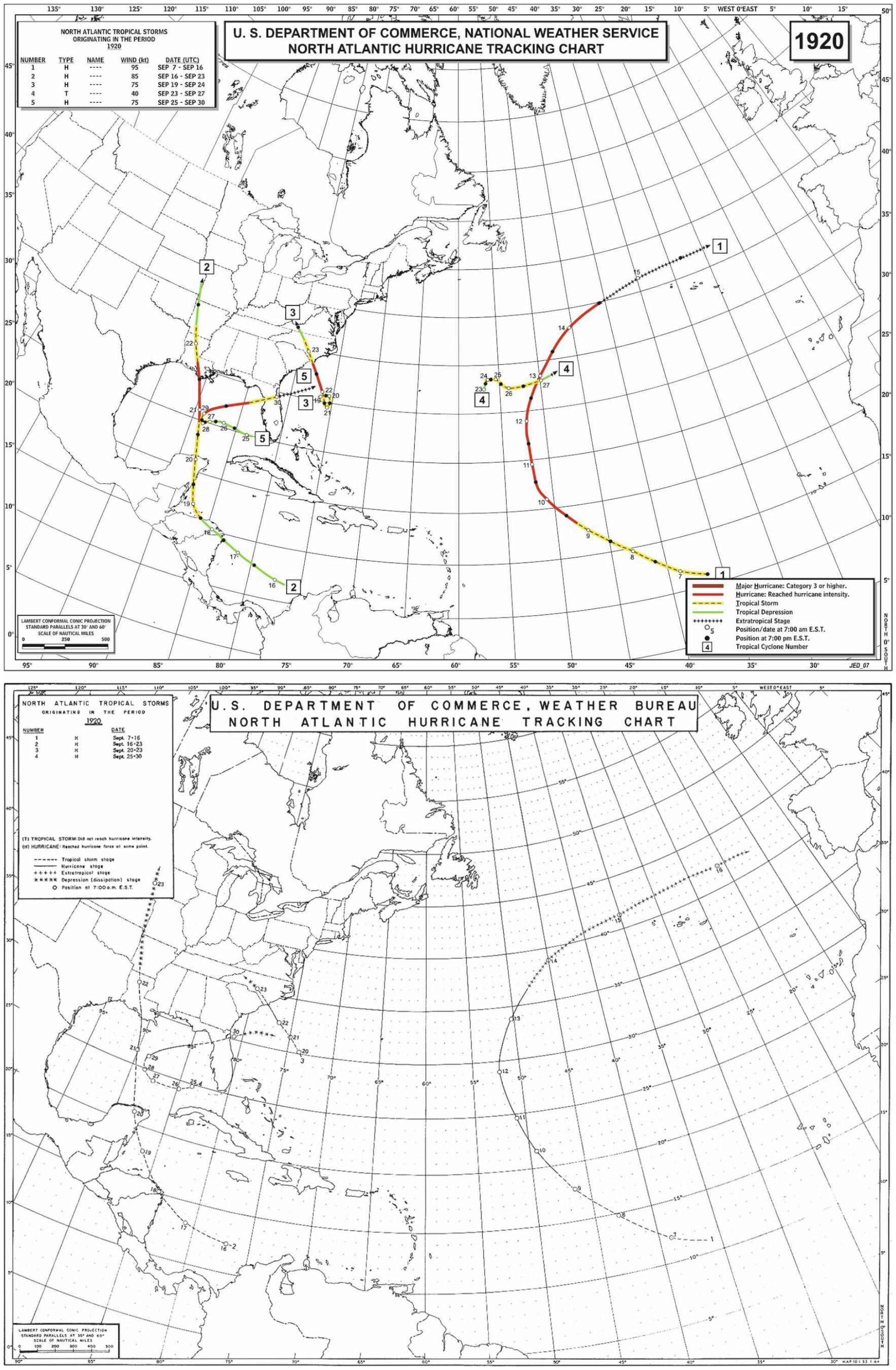

FIG. 2. (*Continued*)

west Florida). No major hurricanes were either added or removed from the U.S. hurricane list.

Notable hurricanes that affected the continental United States for 1911 through 1920 (Blake et al. 2007) after reanalysis include storm 2, 1915 category 4 in north Texas; old storm 5/new storm 6, 1915 category 3 in Louisiana; old storm 4/new storm 6, 1916 category 4 in south Texas; and storm 2, 1919

Table 2. Original/revised tropical storm and hurricane, hurricane, major hurricane and ACE counts. ACE is expressed in units of 10^4 kt^2.

Year	Tropical storms and hurricanes	Hurricanes	Major hurricanes	ACE
1911	4/6	3/3	0/0	36/35
1912	6/7	4/4	1/1	74/56
1913	4/6	3/4	0/0	43/36
1914	1/1	0/0	0/0	3/3
1915	5/6	4/5	3/3	118/127
1916	14/15	11/10	6/5	177/144
1917	3/4	2/2	2/2	52/61
1918	5/6	3/4	0/1	29/40
1919	3/5	1/2	1/1	48/55
1920	4/5	4/4	0/0	31/30
Average 1911–20	4.9/6.1	3.5/3.8	1.3/1.3	61.1/58.7
Average 1966–2006	11.1	6.2	2.3	91.0

Table 3. Continental U.S. hurricanes: 1911–20. Date and time are the day and time when the circulation center crosses the U.S. coastline (including barrier islands). Time is estimated to the nearest 1 h. Lat/Lon is location estimated to the nearest 0.1° latitude and longitude. Max winds are the estimated maximum sustained (1 min) surface (10 m) winds to occur along the U.S. coast. Saffir–Simpson is the estimated Saffir–Simpson hurricane scale at landfall based upon maximum sustained surface winds. RMW is the radius of maximum winds (primarily for the right front quadrant of the hurricane), if available. Central pressure is the minimum central pressure of the hurricane at landfall. Central pressure values in parentheses indicate that the value is a simple estimation (based upon a pressure–wind relationship), not directly measured or calculated. OCI is the sea level pressure at the outer limits of the hurricane circulation as determined by analysis of the outer closed isobar (in increments of 1 mb). Size is the quadrant-averaged radius of the OCI (in increments of 25 n mi). States affected is the impact of the hurricane upon individual U.S. states by Saffir–Simpson scale (again through the estimate of the maximum sustained surface winds at each state).* Original assessment is the Saffir–Simpson categorization by states originally provided in HURDAT.

Storm No.–Date (mm/dd/yyyy)	Time (UTC)	Lat (°N)	Lon (°W)	Max winds (kt)	Saffir–Simpson	RMW (n mi)	Central pressure (mb)	OCI (mb)	Size (n mi)	States affected	Original assessment
2–8/11/1911	2200	30.3	87.5	70	1	—	(985)	1013	250	AFL1, AL1	AFL, AL1
3–8/28/1911	0900	32.2	80.7	85	2	27	972	1014	225	SC2, GA1	SC2, GA2
4–9/14/1912	0800	30.3	88.4	65	1	50	(988)	1007	150	AL1, AFL1	AL1
6–10/16/1912	1800	27.1	97.4	85	2	—	(973)	1012	250	ATX2	ATX1
1–6/28/1913	0100	27.1	97.4	65	1	—	(988)	1009	200	ATX1	ATX1
4–9/3/1913	0800	34.7	76.6	75	1	38	976	1016	200	NC1	NC1
5–10/8/1913	1400	33.1	79.4	65	1	—	(989)	1012	150	SC1	TS
1914–None											
1–8/1/1915	1800	28.7	80.8	65	1	15	990	1015	175	DFL1	TS
2–8/17/1915	0700	29.2	95.1	115	4	25	940	1009	325	CTX4, BTX1, LA1	CTX4
4–9/4/1915	1100	30.0	85.4	80	1	25	982	1012	225	AFL1	AFL1
6–9/29/1915	1800	29.1	90.3	110	3	20	944	1009	300	LA3, MS2	LA4
2–7/5/1916	2100	30.4	88.4	105	3	26	950	1008	250	MS3, AL2, AFL2	MS3, AL3
4–7/14/1916	0800	32.9	79.5	95	2	20	960	1013	175	SC2	SC1
6–8/18/1916	2200	27.0	97.4	115	4	25	932	1012	250	ATX4	ATX3
14–10/18/1916	1400	30.4	87.4	95	2	19	970	1010	325	AL2, AFL2	AL2, AFL2
4–9/29/1917	0200	30.4	86.6	100	3	40	949	1011	250	AFL3, LA2, AL1	AFL3
1–8/6/1918	1800	29.8	93.2	110	3	12	(955)	1012	150	LA3, CTX1	LA3
3–8/24/1918	2100	34.8	76.8	65	1	30	(988)	1917	225	NC1	TS
2–9/10/1919	0700	24.6	82.9	130	4	15	927	1009	275	BFL4, CFL2	BFL4
2–9/14/1919	2100	27.2	97.3	100	3	35	950	1006	250	ATX3, BTX3	ATX4
2–9/22/1920	0100	29.1	90.8	85	2	28	975	1009	250	LA2	LA2

* ATX, south Texas; BTX, central Texas, CTX, north Texas; LA, Louisiana; MS, Mississippi; AL, Alabama; AFL, northwest Florida; BFL, southwest Florida; CFL, southeast Florida; DFL, northeast Florida; GA, Georgia; SC, South Carolina; NC, North Carolina; VA, Virginia; MD, Maryland; DE, Delware; NJ, New Jersey; NY, New York; PA, Pennsylvania; CT, Connecticut; RI, Rhode Island; MA, Massachusetts; NH, New Hampshire; ME, Maine. In Texas, south is roughly from the Mexico border to Corpus Christi; central is from north of Corpus Christi to Matagorda Bay; and north is from Matagorda Bay to the Louisiana border. In Florida, the north–south dividing line is from Cape Canaveral (28.45°N) to Tarpon Springs (28.17°N). The dividing line between west–east Florida goes from 82.69°W at the north Florida border with Georgia, to Lake Okeechobee and due south along longitude 80.85°W.

category 4 in south Florida and category 3 in south Texas.

During the period of 1911–20, the first very destructive hurricane to strike the continental United States was storm 2, 1915, which hit the north Texas coast near Galveston, killed about 275 people, and would cause on the order of $71 billion in total damages if the same system made landfall today (Blake et al. 2007). This TC was originally listed as a category 4 for the north Texas coast with a 945-mb central pressure at landfall. The revised central pressure of a deeper 940 mb along with a large RMW of 25 n mi suggests winds of about 115 kt, which supports a category 4 status. Also in 1915, old storm 5/new storm 6 struck Louisiana south of New Orleans, killed about 275 people, and was originally listed as a 931-mb category 4 hurricane at landfall. The reanalysis raised the central pressure upward to 944 mb, which along with a large RMW of 26 n mi suggests winds of about 110 kt necessitating a reduction to a category 3 at landfall. In the following year of 1916, old storm 4/new storm 6 made landfall in along the south Texas coast as a category 3 hurricane with a central pressure of 948 mb in HURDAT originally. The reanalysis of this system gave a deeper central pressure of 932 mb and a large RMW of 25 n mi, suggesting winds at landfall of 115 kt, upgrading this hurricane to a category 4 in south Texas. In 1919, storm 2 hit the Florida Keys and south Texas as a category 4 hurricane in both locations originally, killing 287 people, and causing about $14 billion in damages if the same system were to hit today. The Florida Keys landfall retained the 927-mb central pressure in HURDAT and along with the moderately sized 15 n mi RMW gave winds of 130 kt, keeping the system as a category 4 at that location. However, in south Texas, the hurricane is reanalyzed to have had a central pressure of 950 mb, a large 35 n mi RMW, and a low environmental pressure of 1006 mb, giving winds of about 100 kt, and it was downgraded to a category 3 for this second U.S. landfall.

Summarizing, there were only three sizable alterations for U.S. major hurricanes in the reanalysis (Table 3): old storm 5/new storm 6, 1915 was revised downward from a category 4 to a category 3 in Louisiana; old storm 4/new storm 6, 1916 was increased from a category 3 to a category 4 in southern Texas; and storm 2, 1919 was decreased from a category 4 to a category 3 in southern Texas (though category 4 was retained for the Florida Keys).

c. *Major hurricanes outside of the continental United States*

Outside of the continental United States, major hurricanes impacted only a few locations from 1911 to 1920. Three separate major hurricanes made landfall either in the Lesser Antilles, Greater Antilles, or Bermuda. Of note was that all of Central America, including all of the east coast of Mexico, was spared from any direct strikes by major hurricanes during this time period. However, the 1910s also corresponded with the Mexican Revolution, so monitoring of the weather and particularly of hurricanes in Mexico was incomplete during this time and it is possible that a major hurricane may have been misclassified as a minor hurricane along Mexico's Gulf Coast.

Two of the more noteworthy major hurricane impacts for 1911–20 were the following (Rappaport and Fernández-Partagás 1995; Pielke et al. 2003; Blake et al. 2007): old storm 6/new storm 7, 1912 in Jamaica that killed 200 people and old storm 3/new storm 4, 1917 in Cuba (known as "Nueva Gerona"). Both of these had substantial changes to their intensity, though only the track of the 1912 hurricane had major alterations. The 1912 hurricane in Jamaica was originally assessed to be a 130 kt at landfall but was downgraded to a 100-kt category 3 based upon a 965-mb central pressure at landfall and small RMW. (Most damage from this slow moving hurricane was rainfall-produced flash flooding, which has a weak relationship to intensity of the system.) The 1917 Nueva Gerona hurricane in Cuba was revised upward from 100 kt up to a 120-kt category 4 hurricane with a 928-mb central pressure at landfall. Overall of the three major hurricane strikes listed in Table 4, one (the 1917 Nueva Gerona in Cuba) had a substantial increase in listed intensity and one (the 1912 Jamaican hurricane) had a sizable reduction in intensity at landfall.

7. Summary and future work

Historical TC reconstructions are inevitably subject to revisions whenever new archived information is uncovered or when new analysis techniques are devised. Thus, while a couple thousand alterations and additions to HURDAT have been completed for the years 1911–20, this does not ensure that there may not be further changes once new information or revised physical understanding is made available. Such an archive of historical data, especially one based upon quasi-objective interpretations of limited observations of a mesoscale feature like a TCs intensity, should always be one that can be revised when more data or better interpretations of existing information becomes available. A key to the analyses conducted here is that all of the raw meteorological observations, in addition to the smoothed best-track revisions, are made available for the first time (all raw observations, revised HURDAT, annual track maps, metadata regarding changes for individual tropi-

Table 4. Major landfalling (noncontinental United States) hurricanes: 1911–20. The names listed are unofficial ones that the hurricanes are known by at these locations. Max winds are the estimated maximum sustained (1 min) surface (10 m) winds to occur at along the coast at landfall/closest approach. Saffir–Simpson is the estimated Saffir–Simpson hurricane scale at landfall based upon maximum sustained surface winds. Central pressure is the minimum central pressure of the hurricane at landfall/closest approach. Central pressure values in parentheses indicate that the value is a simple estimation (based upon a pressure–wind relationship), not directly measured or calculated. Original winds are the winds in HURDAT that were originally provided at landfall/closest approach.

Storm No.–Date	Name	Location	Max winds (kt)	Saffir–Simpson	Central pressure (mb)	Original winds (kt)
1911–None						
7–11/18/1912	——	Jamaica	100	3	965	130
1913–None						
1914–None						
2–8/13/1915	——	Cayman Islands	100	3	(960)	100
2–8/14/1915	——	Cuba	105	3	(955)	105
1916–None						
4–9/25/1917	Neuva Gerona	Cuba	130	4	928	100
1918–None						
1919–None						
1920–None						

cal cyclones, and comments from/replies to the National Hurricane Center's Best Track Change Committee can be found online at http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html). This allows users to inspect the changes made to TCs of interest, see the observations that the changes are based upon, and come to differing conclusions if warranted.

Highlights of accomplishments attained for this stage of the Atlantic hurricane database reanalysis project for 1911–20 are as follows:

1) Track alterations were implemented for most TCs in the existing HURDAT, though the majority was for minor changes.
2) Intensity changes were incorporated into nearly all TCs with a much larger proportion with major alterations in their intensity, either toward stronger or weaker winds.
3) Thirteen new TCs were discovered and added into HURDAT, while one system was removed from the database because it was not of tropical storm intensity.
4) While the frequency of tropical storms during the era was increased from 4.9 to 6.1 annually because of these net changes, the overall effect of track and intensity alterations was to produce slightly less activity during the era than existed originally because of a small overestimation bias in the intensity of some existing TCs.
5) Twenty continental U.S. hurricanes were identified, the same as that originally listed in HURDAT. This same tally was due to the addition of three new U.S. hurricanes and the removal of three hurricanes during the time period. No changes were made to the number of major continental U.S. hurricanes, though two category 4 U.S. hurricanes were reclassified as a category 3 strike and one category 3 was upgraded to a category 4.
6) Only three major hurricanes struck other countries in the Atlantic basin, with the Cayman Islands, Cuba, and Jamaica being impacted. Of these, one had a substantial increase in intensity and one was sizably reduced in intensity at landfall.
7) Despite the reanalysis changes, there exists significant uncertainty in TC tracks, significant undercounts in TC frequency, and significant underestimation of TC intensity, especially for those systems over the open ocean.

However, much more work still needs to be accomplished for the Atlantic hurricane database. One essential project is a Fernández-Partagás and Diaz (1996) style reanalysis for the years before 1851. This may lead to a complete dataset of U.S. landfalling hurricanes for the Atlantic coast from Georgia to New England back to at least 1800, given the relatively high density of population extending that far into the past. While the reanalysis efforts thus far have extended HURDAT back to 1851 and revised it through 1920, these did not make extensive use of COADS until the decade of the 1910s (Landsea et al. 2004a). Further improvements in HURDAT could be achieved by utilizing this massive ship database for the years of 1851–1910. An ongoing project is to complete the current reanalysis efforts through the remainder of the twentieth century. Beginning in 1944, the Atlantic TC database incorporates aircraft reconnaissance data. Already, methodologies have been established on how to objectively reanalyze TCs with highly detailed aircraft reconnaissance observations (Dunion et al. 2003; Landsea et al. 2004b). Additionally, new techniques for utilizing pressure–wind relationships in the context of global reanalysis datasets are also emerging (e.g., Knaff and Zehr 2007). Work to complete the Atlantic hurricane basin database reanalysis is crucial because of current important questions that are being raised about anthropogenic climate change on TC activity (WMO 2007).

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APPENDIX

Reanalysis of a Tropical Cyclone

All Atlantic basin tropical storms and hurricanes in the new best-track database are accompanied by a "metadata file." This file consists of a day-by-day listing of peak meteorological observations and previous estimates of the storm's position and intensity. The metadata also contains a descriptive paragraph about the particular methodology employed for making changes in the genesis, track, intensity, and decay of that TC, including what sources were crucial for revising the best track, whether or not a wind–pressure relationship was utilized, if wind decay models were used for inland wind estimates, and any other pertinent information. All of the tropical storms and hurricanes for the period of 1911–20 are considered "UNNAMED." However, many of these storms have been recognized by various informal names. These are included in the metadata file when at all possible. The following is an example of a single metadata entry for storm 2, 1919 the Key West hurricane. Table A1 provides significant (near hurricane force and greater) reports collected for this system and made available in the raw database. Figure A1 provides a single, daily analysis of the synoptic observations available at 1200 UTC 10 September 1919.

a. Storm #2, 1919 (The Key West Hurricane)

Major changes to the track and intensity are shown in Neumann et al. (1999). Evidence for these alterations comes from the *Historical Weather Map* series, the COADS ship database, *Monthly Weather Review*, the Original Monthly Records from the National Climatic Data Center, Connor (1956), Dunn and Miller (1960), Schwerdt et al. (1979), Jarvinen et al. (1985), Ho et al. (1987), Jarrell et al. (1992), and Perez Suarez et al. (2000).

1 SEPTEMBER

HWM and COADS observations possibly indicate a wave approaching the Lesser Antilles without any indication of a closed low (though data are sparse east of the islands). No gale force winds (or equivalent in pressure) were observed.

2 SEPTEMBER

HWM indicates a closed low of at most 1010 mb at 13.5°N, 64°W. HURDAT lists this system as a tropical storm at 15.4°N, 63.5°W at 1200 UTC. The "Summary of the Hurricanes of 1919, 1920, and 1921" (Day 1921) does not begin the system until either late on the 2nd or early on the 3rd. Available observations suggest that the cyclone was substantially east-northeast of HURDAT's position. No gale force winds (or equivalent in pressure) were observed. "The minor disturbance . . . was first noted on the evening of September 2 . . . a little west of the island of Antigua" (*MWR*).

3 SEPTEMBER

HWM indicates a closed low of at most 1010 mb at 16°N, 66°W. HURDAT lists this system as a tropical storm at 17°N, 67°W at 1200 UTC. Day (1921) shows a center near 18°N, 65°W. Available observations suggest a center east-northeast of HURDAT's estimate. No gale force winds (or equivalent in pressure) were observed. "This . . . minor disturbance moved west-northwestward at about a normal rate, passing near the southern portion of the island of Porto [*sic*] Rico" (*MWR*).

Table A1. Significant (near–hurricane force and greater) reports collected in the database for storm 2, 1919 (the Key West hurricane). Note that the complete database includes all reports of gales force (34 kt) or stronger and 1005-mb pressures or lower. Sources shown here are *MWR* and OMR. Notes include the ship name, minimum pressure, and maximum winds, if known.

Day	Observation time (UTC)	Pressure (mb)	Wind (kt)	Direction	Location	Lat (°N)	Lon (°W)	Source	Ship/comments
1919 STORM 2 Sep									
9 Sep	0300	960			Ship	24.0	79.0	*MWR*	Corydon
9 Sep	2000	938	70	N	Ship	24.6	82.9	*MWR*	Winona
10 Sep		937			Rebecca Shoals	24.5	82.5	*MWR*	
10 Sep		932			Dry Tortugas	24.6	82.9	*MWR*	Eye
10 Sep		927			Ship	24.6	82.9	*MWR*	Fred W. Weller–Eye
10 Sep	0000	933			Ship	24.6	82.9	*MWR*	Winona
10 Sep	0000	984	61	NE	Key West	24.5	81.8	*MWR*	Max-W (no further obs)
10 Sep	0048		59	NE	Sand Key	24.5	81.9	*MWR*	Max-W (no further obs)
10 Sep	0100	982		NE	Key West	24.5	81.8	*MWR*	
10 Sep	0200	981		NE	Key West	24.5	81.8	*MWR*	
10 Sep	0300	980		NE	Key West	24.5	81.8	*MWR*	
10 Sep	0400	930			Ship	24.6	82.9	*MWR*	Winona–Eye
10 Sep	0400	976		NE	Key West	24.5	81.8	*MWR*	Min-P
10 Sep	0410	960		SE	Sand Key	24.5	81.9	*MWR*	Min-P
10 Sep	0500	935		NW	Ship	24.6	82.9	*MWR*	Winona
10 Sep	0500	979		E	Key West	24.5	81.8	*MWR*	
10 Sep	0600	981		E	Key West	24.5	81.8	*MWR*	
10 Sep	0700	983		E	Key West	24.5	81.8	*MWR*	
10 Sep	0800	933		NW	Ship	24.6	82.9	*MWR*	Winona
10 Sep	0800	984		E	Key West	24.5	81.8	*MWR*	
10 Sep	1200	931		SE	Ship	24.6	82.9	*MWR*	Winona
10 Sep	1400	933		SE	Ship	24.6	82.9	*MWR*	Winona
10 Sep	1800	941		NW	Ship	24.6	82.9	*MWR*	Winona
11 Sep	0100	941			Ship	24.6	82.9	*MWR*	Winona
11 Sep	0700	945		SE	Ship	24.6	82.9	*MWR*	Winona
11 Sep	1400	947		SE	Ship	24.6	82.9	*MWR*	Winona
11 Sep	1900	962		SE	Ship	24.6	82.9	*MWR*	Winona
12 Sep	0300	963		SE	Ship	24.6	82.9	*MWR*	Winona
12 Sep	1300	944			Ship	26.2	87.8	*MWR*	Lake Deval–Eye?
12 Sep	2000	948			Ship	27.0	89.0	*MWR*	Lake Grandon
12 Sep	2100	942			Ship	27.0	88.5	*MWR*	Tegulcigalpa–Eye?
13 Sep	0400	931			Ship	26.5	90.5	*MWR*	Berwyn–Eye
14 Sep	1300	950			Ship	27.0	95.0	*MWR*	F.R. Kellogg–Eye
14 Sep	1600	982	59	N	Corpus Christi	27.8	97.5	OMR	
14 Sep	1700		61		Corpus Christi	27.8	97.5	OMR	Max-W (no further obs)
14 Sep	2000	970			Corpus Christi	27.8	97.5	*MWR*	Min-P
15 Sep	0000	985		E	Corpus Christi	27.8	97.5	OMR	

4 September

HWM indicates a closed low of at most 1010 mb at 20°N, 70°W. HURDAT lists this system as a tropical storm at 19.2°N, 69°W at 1200 UTC. Day (1921) shows a center at 19°N, 69.5°W. Available observations suggest a center between all three estimates. No gale force winds (or equivalent in pressure) were observed.

5 September

HWM indicates a closed low of at most 1010 mb at 21°N, 73°W. HURDAT lists this system as a category 1 hurricane at 21°N, 71.8°W at 1200 UTC. Day (1921) shows a center near 20.5°N, 72°W. Available observations suggest a center west of the *MWR* summary estimate. No gale force winds (or equivalent in pressure) were observed. "By the evening of the 4th it had reached the north coast of the island of Santo Domingo with a barometer reading of about 29.80 inches. On the morning of the 5th the center of the disturbance was approximately 100 miles southwest of Turks Island with about the same barometric pressure" (*MWR*).

6 September

HWM indicates a closed low of at most 1010 mb at 21.5°N, 72.5°W. HURDAT lists this system as a category 1 hurricane at 22.2°N, 72.4°W at 1200 UTC. Day

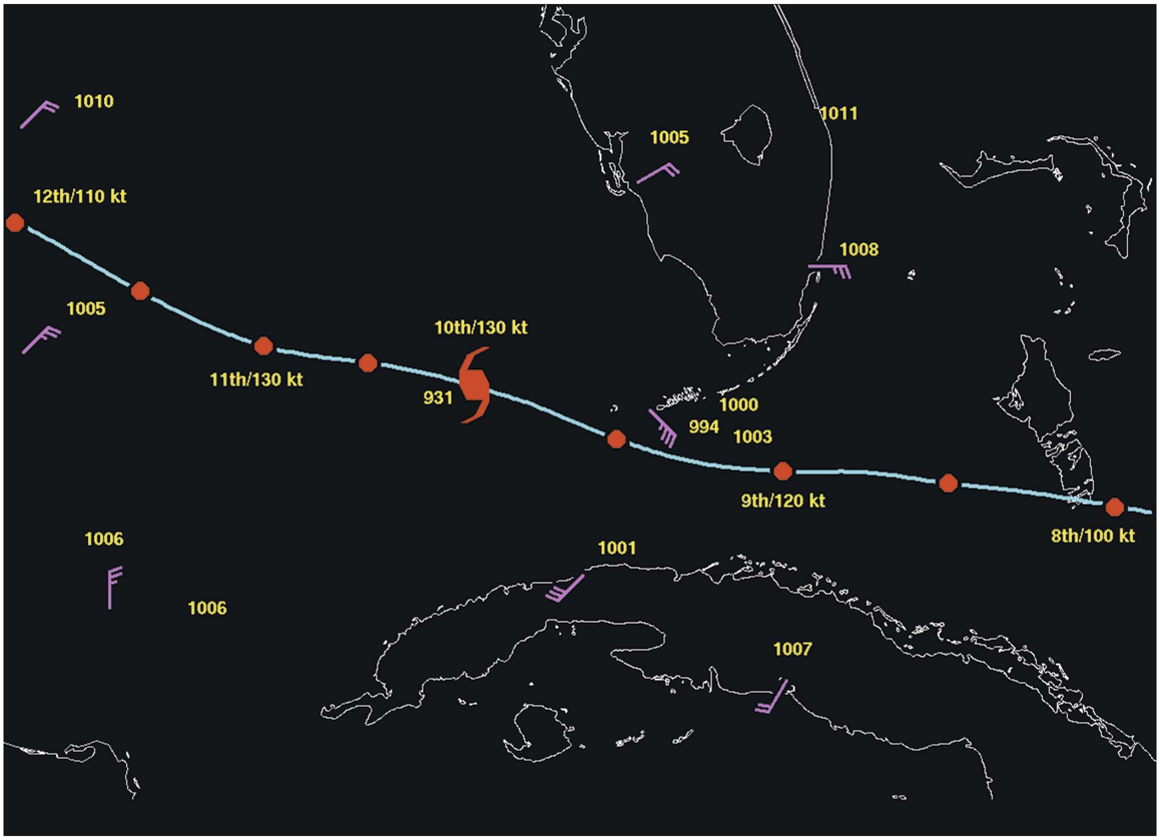

FIG. A1. Synoptic analysis for storm 2, 1919 (the Key West hurricane) at 1200 UTC 10 Sep 1919. Observations of wind (full barb is 10 kt) and sea level pressure from ship and weather stations are provided. The track of the hurricane is given in blue with revised positions and maximum winds every 6 h.

(1921) shows a center near 21.5°N, 72.5°W. Available observations suggest a center west of the HURDAT estimate. No gale force winds (or equivalent in pressure) were observed. "By the evening of the 5th the winds at Turks Island had changed from east to west, and were southerly over Santo Domingo and Haiti, still light in character, apparent evidence that the disturbance had recurved to the northeastward during the day, and that it was moving in that direction in very moderate form" (*MWR*).

7 September

HWM indicates a closed low of at most 1010 mb at 22°N, 73.5°W. HURDAT lists this system as a category 2 hurricane at 23.4°N, 74.1°W at 1200 UTC. Day (1921) shows a center near 23°N, 73.5°W. The *MWR* Tracks of Lows shows a center near 23°N, 74.5°W with 1003 mb (a.m.). Available observations suggest a center just southwest of HURDAT's estimate. Ship highlight: 35 kt SE and 1009 mb at 26°N, 74.4°W at 2300 UTC (COA-DS). "On the evening of the 6th pressure and wind conditions over Santo Domingo and the Bahamas indicated the possible presence of a disturbance over the eastern Bahamas. Conditions were slightly more pronounced on the morning of the 7th . . . there were slight indications of a disturbance over the central Bahamas" (*MWR*).

8 September

HWM indicates a closed low of at most 1005 mb at 21.5°N, 76°W. HURDAT lists this system as a category 3 major hurricane at 23.9°N, 77°W at 1200 UTC. Day (1921) shows a center near 23.5°N, 76°W. The *MWR* Tracks of Lows shows a center near 23.5°N, 77°W with 998 mb (a.m.). Available observations suggest a position just southwest of HURDAT's estimate. Ship highlight: 35 kt NNE and 1006 mb at 25.5°N, 80.5°W at 2100 UTC (COA). Station highlight: 51 kt NE and 998 mb at Nassau at 0100 UTC (*MWR*) "A belated report on September 8 that a severe storm could be located south of and near the Andros Islands" (*MWR*).

9 September

HWM indicates a closed low of at most 1000 mb at 23.5°N, 81.5°W. HURDAT lists this system as a category 3 hurricane at 24°N, 79.8°W at 1200 UTC. Day (1921) shows a center near 24°N, 79.5°W. The *MWR* Tracks of Lows shows a center near 24°N, 79.5°W. Available observations suggest that the center was between the *HWM* and HURDAT estimates. Ship highlights: 70 kt N and 938 mb at 24.6°N, 82.9°W at 2100 UTC (*MWR*). Station highlights: 50 kt NE and 986 mb at Key West at 2300 UTC (*MWR*); 57 kt NE at Sand Key at 1748 UTC (*MWR*).

> Considerable local damage was done in Miami and vicinity, although nothing very serious resulted. Tides were unusually high and many small boats suffered. The greatest loss was probably in the fruit crop . . . Press reports indicated that considerable damage was also done along the northwest coast of Cuba . . . The greatest [shipping loss was] the Spanish steamship Valbanera, off Rebecca Shoals Light, about 40 miles west of Key West. The vessel arrived off Morro Castle, Habana, on September 9, but owing to the hurricane, was unable to enter the harbor, and nothing further was heard from her until a diver discovered her beneath the waters off Rebecca Shoals. The Valbanera was from Spanish ports for New Orleans, via Habana, and her 400 passengers and crew of 88 must have perished (*MWR*).

"El Huracan del Valvanera—Category 1 in Cuba—September 9 and 10" (Perez Suarez et al. 2000).

10 September

HWM indicates a closed low of at most 995 mb at 24°N, 82°W. HURDAT lists this system as a category 4 hurricane at 24.6°N, 82.7°W at 1200 UTC. Day (1921) shows a center near 24.5°N, 83°W. The *MWR* Tracks of Lows shows a center near 24.5°N, 83°W. Available observations suggest that the center is west-northwest of HURDAT's estimate. Ship highlights: 927 mb (eye?) at 24.6°N, 82.9°W (*MWR*); 930 mb (eye?) at 24.6°N, 82.9°W at 0500 UTC (*MWR*). Station highlights: 937 mb at Rebecca Shoals Light; 932 mb (eye) at Dry Tortugas; 82 kt NE at 0148 UTC and 960 mb at 0510 UTC at Sand Key.

> The storm center passed about 30 or 40 miles south of Key West about midnight of September 9. At this time the barometer at Key West read 28.83 inches with an east wind of an estimated velocity of 105 miles an hour, which increased slightly during the next hour. At Sand Key, the lowest barometer at about the same time was 28.35 inches, a difference of 0.48 inch within a distance of 8 miles . . . The following report on the storm at Key West and vicinity was prepared by Mr. H. B. Boyer, official in charge of the Weather Bureau office at that place: "The storm that passed over Key West on September 9 and 10 was, without question, the most violent experienced since records at this station began. While the minimum barometric reading, 28.81 inches, was not as low as that recorded in 1909 (28.52) and in 1910 (28.47), the violence of the wind was undoubtedly greater. It is to be regretted that owing to the vibrations of the tower supporting the wind instruments the anemometer cups were shaken loose and blown away at 7:30 pm on the 9th in gusts ranging between 75 and 80 miles an hour, and thereafter until 3:35 p.m. of the 10th the wind-velocity record was lost. The wind-vane was blown away at 12:45 a.m. of the 10th during the winds of greatest intensity . . . In the terrific gusts that prevailed during the height of the storm stanch brick structures had walls blown out and large vessels, firmly secured, were torn from their fastenings or moorings and blown on the bank . . . the great loss, estimated at $2,000,000 . . . Owing to the very slow progressive movement of the storm in this vicinity, winds of gale force and over lasted continuously from about 7 a.m. of the 9th to about 9:30 p.m. of the 10th . . . From the forenoon of the 9th squalls of wind and rain progressively increased in force and frequency, culminating in terrific gusts of great violence between midnight of the 9th and 2 a.m. of the 10th . . . Probably not a structure on the island escaped being damaged more or less . . . three lives were lost by drowning" . . . The report of the storm experiences at Sand Key, Fla., was prepared by Mr. Eugene M. Barto, observer, and is as follows: "The record showed that the anemometer cups blew away at 9:35 p.m. with a wind velocity of 84 miles an hour. The wind vane was probably blown away shortly after midnight. This was also the time of the lowest barograph record, which was 28.35 . . . The highest [wind] recorded was 94 miles an hour from the northeast at 8:39 p.m." . . . The center of the storm passed directly over Dry Tortugas, 65 miles west of Key West, with a reported barometer reading of 27.51 inches, while at Rebecca Shoals Light, about 40 miles west of Key West, the lowest reading was 27.66 inches . . . The steamship Winona went ashore at 10 a.m., September 10, on a reef on the northeast portion of the Tortugas group, near Pulaski Shoals . . . the barometer [fell at midnight on the 9th] to 27.45 inches . . . A later report from the tank steamer, Fred W. Weller, showed a barometer reading of 27.36 inches in the vicinity of Dry Tortugas on September 9 . . . These [close readings] within a very limited area, make it safe to assume that they were substantially correct (*MWR*).

"September 10, 1919, 929 mb Central Pressure, 24.6N, 82.9W Landfall Point, 15 n mi Radius of Maximum Wind" (Ho et al. 1987); "1008 mb environmental pressure, 115 kt maximum 1 min surface wind" (Schwerdt et al. 1979); "Tropical Cyclones in Florida, September 9-10, Key West, Major, Marine casualties 300 plus" (Dunn and Miller 1960). "Saffir-Simpson Category 4 for FL Keys/S TX with 927 mb central pressure" (presumably for FL landfall) (Jarrell et al. 1992).

11 SEPTEMBER

HWM indicates a closed low of at most 995 mb at 25.5°N, 87°W. HURDAT lists this system as a category 4 hurricane at 25.6°N, 84.7°W at 1200 UTC. Day (1921) shows a center near 25.5°N, 86°W. The *MWR* Tracks of Lows shows a center near 26°N, 85.5°W. Available observations suggest that the center is southwest of the HURDAT estimate. Ship highlights: 45 kt SSE and 998 mb at 26.6°N, 85.8°W at 2300 UTC (COA). "[One the 11th], the tide reached a crest of 5.55 feet above low-water mark, 2 feet higher than ever before recorded in the annals of the United States Engineers. The tide did some little damage along that section of the coast, but none of consequence" (*MWR*).

12 SEPTEMBER

HWM indicates a closed low of at most 995 mb at 27N, 89W. HURDAT lists this system as a category 4 hurricane at 26.7N, 88W at 12 UTC. Day (1921) shows a center near 26.5N, 88W. The *MWR* Tracks of Lows shows a center near 26.5N, 88W. Available observations suggest that the center is just south of the *MWR* Summary and Tracks estimates. Ship highlights: 944 mb (eye?) at 26.2N, 87.8W at 14 UTC (*MWR*); 948 mb at 27N, 89W at 22 UTC (*MWR*); 942 mb (eye?) at 27N, 88.5W at 23 UTC (*MWR*).

> After the morning of the 10th, at which time the storm center was apparently very near Dry Tortugas, Fla., its path could only be approximated. It happened, however, that a report received by mail from the steamship Lake Deval nearly two weeks after the storm located the center with a fair degree of definiteness on the morning of the 12th [about 150 miles south-southeast of the mouth of the Mississippi River] (*MWR*).

13 SEPTEMBER

HWM indicates a closed low of at most 995 mb at 27°N, 92.5°W. HURDAT lists this system as a category 4 hurricane at 26.5°N, 91.6°W at 1200 UTC. Day (1921) shows a center near 26°N, 91°W. The *MWR* Tracks of Lows shows a center near 26.5°N, 91°W. Available observations suggest that the center is west of the HURDAT estimate. Station highlights: 36 kt SE and 1002 mb at Burrwood at 1200 UTC (*MWR*). Ship highlights: 931 mb (eye) at 26.5°N, 90.5°W at 0500 UTC (*MWR*). "The tide was 6 feet above normal on Lake Borgne and on Grand Isle, and 5 to 6 feet above normal on Lake Ponchartrain, on the afternoon of the 13th . . . By a little after sunset the tide [at Port Aransas] had reached 5 feet above mean sea level" (*MWR*).

14 SEPTEMBER

HWM indicates a closed low of at most 995 mb at 27.5°N, 96.5°W. HURDAT lists this system as a category 2 hurricane offshore Texas at 27°N, 95.7°W at 1200 UTC. Day (1921) shows a center near 27°N, 95.5°W. The *MWR* Tracks of Lows shows a center near 27°N, 96°W. Available observations suggest that HURDAT's estimate is most accurate. Station highlights: 61 kt at 1800 UTC and 970 mb at 2100 UTC at Corpus Christi (OMR). Ship highlights: 950 mb (eye?) at 27°N, 95°W at 1400 UTC (*MWR*).

> On the morning of September 14 the storm center was not far from the coast of Texas, between Corpus Christi and Brownsville, and during the day in passed inland, with marked although with steadily diminishing intensity . . . The tide . . . reached its highest point of 8.8 feet [at Galveston] at 7 a.m. of the 14th. Two men lost their lives in the storm in this immediate vicinity [Galveston] . . . both men were apparently overtaken by the rising tide and drowned . . . From reports received the height of the tide accompanying the storm ranged in this district from about 4 feet at Orange, Tex., to approximately 13 feet at Port O'Connor, Tex. With this tide and the high wind accompanying it, some damage resulted at many points, especially along the water front. At Seabrook, Tex., there were a few buildings, mostly light structures, destroyed . . . At points to the south of Galveston, however, there was more damage done . . . At Matagorda, Palacios, and Port Lavaca, Tex., there was considerable damage to wharves, fish houses, and small boats. Similar damage resulted at Port O'Connor, Tex . . . Stretching along the beach [of Corpus Christi] for 23 blocks homes were crushed and hurled away or wrecked by the tidal wave, which reached a depth of 15 feet in some places. Over much of the beach section not an indication of former homes now remains, except here and there a bathtub or part of a brick chimney . . . In the downtown [Corpus Christi] district utter demolition of some of the city's most important industrial and public plants marked an area extending for six blocks along the water front and more than a block in width, while beyond that block, extending back toward the bluff section, every commercial establishment's first floor was wrecked, and in some cases the entire building rendered useless, over a corresponding area two blocks wide. The tremendous property damage is be-

coming daily more apparent and prominent business men and other trained observers predicted to-night [Sep. 18] that $20, 000, 000 would be a conservative estimate of the monetary loss in Corpus Christi. 284 bodies, almost entirely those of Corpus Christi victims, have been found . . . Details of conditions at Port Aransas and other parts of the islands between Corpus Christi Bay and the Gulf were ascertained . . . The docks and buildings in Port Aransas have been wiped out with the exception of a school building . . . The large oil tanks there also were destroyed. The five who lost their lives [at Port Aransas] were drowned while attempting to leave the island in a lifeboat . . . The Gulf storm caused a 6-foot tide here [Anahuac, Mexico], but Anahuac is situated on a 25-foot bank of Trinity Bay, hence no damage was done. The wind reached a velocity of perhaps 30 miles . . . The storm was only the second September storm of this character of any consequence that reached the south Texas coast during the last 45 years, the other having occurred in 1910. The storm of 1919 was by far the more violent of the two, and was probably the greatest of all Gulf storms . . . The full force of the storm was experienced between Aransas Bay and the mouth of the Rio Grande, where the high tides resulted in a toll of 183 dead and 174 missing (*MWR*).

"Sep. 14, Estimated Lowest Pressure 27.36 [for Dry Tortugas on the 10th], Tide Info–Corpus Christi 16′, Galveston 8.8′, Aransas Pass 11.5′, Brownsville 3.6′, Port Isabel 8′, Sabine 8′, Anahuac 10′, La Porte 8.5′, Carancahua 13′ Ingleside 12′, Velasco 10′, Port O'Connor 13′" (Connor 1956). "Sep. 14, Landfall point of 27.2N, 97.3W, 950 mb Central Pressure, 35 n mi Radius of Maximum Wind" (Ho et al. 1987). "1007 mb environmental pressure" (Schwerdt et al. 1979). "Tropical Cyclones in Texas, Sep. 14, Corpus Christi, Extreme, 300-600 killed, damage $20, 270, 000" (Dunn and Miller 1960). "Saffir-Simpson Category 4 in FL Keys/S TX with 927 mb central pressure" (presumably for FL not TX) (Jarrell et al. 1992). "Landfall around 18 UTC on the 14th, 950 mb central pressure, 35 n mi radius of maximum wind, 1010 mb ambient pressure, assumed that central pressure filled from 931 mb to 950 mb the six hours before landfall, after landfall analyzed 977 mb around 00 UTC on the 15th" (Jarvinen et al. 1985).

15 SEPTEMBER

HWM indicates a closed low of at most 990 mb at 28°N, 100.5°W. The *MWR* Tracks of Lows shows a center near 28°N, 100.5°W. HURDAT lists this system as a tropical depression at 28.2°N, 100.2°W at 1200 UTC. Available observations suggest a center west of the HURDAT estimate. Station highlights: 49 kt E at 1400 UTC and 993 mb at 1140 UTC at Del Rio (OMR).

16 SEPTEMBER

HWM does not analyze a closed low, though a weak center is near 31.5°N, 106°W. No gale force winds (or equivalent in pressure) were observed.

b. Summary

Genesis for this tropical cyclone was delayed by 12 h consistent with the poorly organized circulation exhibited by numerous observations on the 2nd at 1200 UTC. Minor changes to the track were made on most days in accordance with available observations. The exception was the 2nd where a major shift to the east-northeast was introduced. Decay of the tropical cyclone was delayed a day to account for a more intense system still in existence on the 15th as well as a weak vortex apparent from observations on the 16th. Intensity from the 2nd to the 6th reduced significantly based upon available observations, which also agrees with the *Monthly Weather Review* analyses of a weak tropical cyclone during these dates. Hurricane intensity is analyzed to have been attained on the 7th (two days later than originally shown in HURDAT). A 998-mb peripheral pressure with 51-kt winds from Nassau at 0100 UTC on the 8th suggests winds of at least 51 kt from the southern pressure–wind relationship, 95 kt retained in HURDAT, as it appears that Nassau was on the outskirts of a large hurricane. Winds are also retained from 0000 to 1200 UTC on the 8th as the cyclone became a major hurricane. A 938-mb peripheral pressure (not eye) at 2100 UTC on the 9th suggests winds of at least 120 kt from the southern pressure–wind relationship, 125 kt chosen for HURDAT (up from 110 kt originally). Three eye pressure measurements were observed near Dry Tortugas, Florida, early on the 10th: 927, 930, and 932 mb; 927 mb was selected by Jarrell et al. (1992) and is retained here for HURDAT, which suggests 129 kt from the southern pressure–wind relationship. Ho's (1987) estimate of an RMW of 15 n mi is quite close to the 14 n mi for climatology for this central pressure and latitude (Vickery et al. 2000). Thus 130 kt is chosen for HURDAT at 0600 UTC on the 10th, up from 115 kt originally. This retains the category 4 assessment for the Florida Keys. Because of the revised definitions of the boundary between southwest and southeast Florida (BFL and CFL, accordingly) and through an application of the simplified wind model in Schwerdt et al. (1979), category 2 conditions are estimated to have occurred in the Upper Keys and thus southeast Florida (CFL2). As is typical, anemometers at Key West and Sand Key were rendered inoperable before the passage of peak winds and these only recorded at most category 1 conditions.

Three low pressure readings were observed from ships on the 12th: 944 mb at 1400 UTC, 948 mb at 2100 UTC, and 942 mb at 2200 UTC. It is likely that the 944- and 942-mb values were central pressure readings and these are included as such into HURDAT; 944 and 942 mb suggest winds of 118 and 116 kt, respectively, from the Gulf of Mexico pressure–wind relationship. The new Brown et al. (2006) north of 25°N pressure–wind relationship gives winds of 111 and 113 kt, respectively; 110 kt is chosen for HURDAT late on the 12th and early on the 13th based upon these observations. However, an eye reading of 931 mb was measured by ship on 0400 UTC of the next day on the 13th. This value suggests winds of 128 kt from the Gulf of Mexico pressure–wind relationship. The new Brown et al. (2006) pressure–wind relationship for north of 25°N suggests winds of 123 kt; 125 kt is chosen for HURDAT, up from 115 kt originally at 0600 UTC on the 13th.

The hurricane weakened significantly before landfall in Texas. A likely central pressure reading of 950 mb on 1500 UTC on the 14th suggests winds of 110 kt from the Gulf of Mexico pressure–wind relationship. Both Ho et al. (1987) and Jarvinen et al. (1995) accepted this value as a likely landfall pressure along with an RMW of about 35 n mi. It is to be noted that the 950-mb central pressure and 35 n mi RMW values provide a good match in SLOSH model runs against observed storm surge measurements (Jarvinen et al. 1985). Climatological RMW for this latitude of landfall and central pressure is substantially smaller, 18 n mi (Vickery et al. 2000). This would suggest that the maximum sustained winds were about 100 kt both at 1500 UTC at the ship report and at about 2100 UTC at landfall in Texas. The new Brown et al. (2006) pressure–wind relationship for north of 25°N filling cyclones also analyzes about 101 kt; 100 kt at landfall represents a reduction in the analyzed Saffir–Simpson category assigned to south Texas from a 4 down to a 3 (ATX3). However, the wind speed in HURDAT at 1800 UTC on the 14th right before landfall is adjusted upward sharply from 75 to 100 kt in the reanalysis. Application of the Schwerdt et al. (1979) idealized hurricane wind profile suggests that central Texas (BTX) should also be considered a category 3 impact (BTX3), which is reasonable given the landfall position was very close to the boundary between south and central Texas coast. Peak observed winds after landfall (within plus/minus 2 h of synoptic times) were 34 kt at San Antonio at 0000 UTC on the 15th, 44 kt at San Antonio at 0600 UTC, and 49 kt at Del Rio at 1200 UTC. [These convert to 29, 37, and 41 kt, respectively, after accounting for the high bias of the anemometer used and adjusting to a peak 1-min wind from these peak 5-min values (Fergusson and Covert 1924; Powell et al. 1996).] However, with the landfall between Corpus Christi and Brownsville and with the anemometer at Corpus Christi becoming inoperable after 1700 UTC, higher winds were quite likely present at 0000 and 0600 UTC on the 15th. A run of the Kaplan and DeMaria (1995) inland wind decay model suggests winds of 71, 49, and 35 kt, for the same synoptic periods. Given the low bias of the Kaplan and DeMaria model for the 1200 UTC time, winds after landfall are chosen to be somewhat higher than the model: 75, 55, and 40 kt, respectively.

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