A Reanalysis of the 1921–30 Atlantic Hurricane Database*

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ABSTRACT

A reanalysis of the Atlantic basin tropical storm and hurricane database (''best track'') for the period from 1921 to 1930 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. The methodology for the reanalysis process for revising the track and intensity of tropical cyclone data has been detailed in a previous paper on the reanalysis. The 1921–30 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 uncertainty in intensity and track values is estimated for both open-ocean conditions as well as landfalling systems. 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) North Atlantic Hurricane Database (or HURDAT; Jarvinen et al. 1984), also called the ''best track'' since they are the ''best''[1] postseason determinations of tropical cyclone (TC) tracks and intensities for the period from 1921 to 1930. Previous work on the reanalysis that has been officially included into the HURDAT dataset includes the periods from 1851 to 1910 (Landsea et al. 2004a), 1911 to 1920 (Landsea et al. 2008), and 1992's Hurricane Andrew (Landsea et al. 2004b). As the methodology and observational data are nearly identical to those reported for the 1911–20 reanalysis efforts, this paper focuses upon the reanalysis results for the decade of 1921–30. The reader is referred to Landsea et al. (2008) for discussion of the datasets utilized and the methodology employed.

2. New datasets and methodology

The limited observational capabilities of the 1920s were quite similar to that of the previous few decades: measurements from unfortunately placed ships at sea and from coastal weather stations (Landsea et al. 2004a, 2008). The one significant change was with regard to the type of anemometer utilized in U.S.-based observing sites.

The original four-cup anemometer, first developed by Robinson in the 1840s (Kinsman 1969), was still widely used in the United States until the 1920s and in other countries in the region for some time after that. Its

[1] ''Best'' in this case is in contrast to the operational estimates conducted at NHC in support of real-time analyses and predictions. It is quite common for the poststorm best-track positions and intensities to be adjusted slightly from the operational analyses due to additional observations becoming available and/or the ability to put the various measurements into context with subsequent observations.

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TABLE 1. Estimated average positions and intensity errors (uncertainty) in the revised best tracks for the years 1851–1930. Negative bias errors indicate an underestimation of the true intensity. [By the 1920s, nearly all coastal areas in the Atlantic basin were relatively settled and monitored (Landsea et al. 2008).]

Situation	Dates	Position error (n mi)	Intensity error (absolute, kt)	Intensity error (bias, kt)
Open ocean	1851–85	120	25	−15
	1886–1930	100	20	−10
Landfall at sparsely populated area	1851–85	120	25	−15
	1886–1920	100	20	−10
Landfall at settled area	1851–85	60	15	0
	1886–1930	60	12	0

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; Kadel 1926). 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 peak wind measurement of 100 kt in storm 7 during 1926 ("the great Miami hurricane") at the U.S. Weather Bureau station in Miami, Florida. (A standard of 5 min was typically utilized in U.S. Weather Bureau reports of "maximum winds" during this 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. Our current understanding of gustiness in hurricane conditions suggests a boost of 1.06 to convert from a 5-min to a 1-min maximum wind (Powell et al. 1996), giving a best estimate of the maximum 1-min wind of about 82 kt. These older style anemometers were replaced by the more reliably calibrated three-cup anemometers by January 1928 (U.S. Weather Bureau 1927), though these new instruments still suffered from mechanical failures in extreme winds. Anemometers from other countries in the region were gradually upgraded to the new three-cup style generally during the next decade. These corrections to the older style anemometer were thus applied through 1927 for U.S. Weather Bureau stations and for the entire decade elsewhere.

The methodology for reexamining the existing track, intensity, and classification of TCs; for uncovering previously unidentified TCs; and for potentially removing TCs from the database is detailed in Landsea et al. (2008) and is unchanged for what was utilized here for 1921–30. However, new work by Vickery et al. (2009) did allow for a more rigorously defined adjustment of hurricane winds when converting from marine to open-terrain exposure (roughness lengths of 0.03 m). They indicated that a 15% reduction in 1-min winds is appropriate. This is applied on those occasions when a central pressure was available for a TC after landfall, but no direct measurement of the peak winds in the system was obtained. In this case, the central pressure was converted to a maximum marine exposure wind speed (Brown et al. 2006) and then the 15% reduction was applied. Before the availability of the Vickery et al. (2009) paper, a rough reduction of about the same amount was assumed.

One new secondary source for historical hurricanes is Neely (2006) for the country of the Bahamas. This book helped to provide impact information for hurricanes in the Bahamas, as few quantitative observations were typically available from this country during this decade.

3. Track, intensity, and frequency uncertainty estimates

Given that the observational datasets for TCs during 1921–30 were nearly the same as for previous decades and that the methodology for reanalysis had not changed, estimates for errors (uncertainty) and biases are unchanged from the previous decades (Table 1). The estimated average position errors do depend on whether the TC was out over the open ocean or making landfall, the former being substantially uncertain (~100 n mi) and the latter more accurate (~60 n mi). [Before the 1920s, some coastal areas were not sufficiently monitored to allow for a more accurate assessment of position compared with the open ocean cases; Landsea et al. (2008).] It is estimated that the intensity measurements for 1921–30 were in error by an average of 20 kt over the open ocean, with a bias

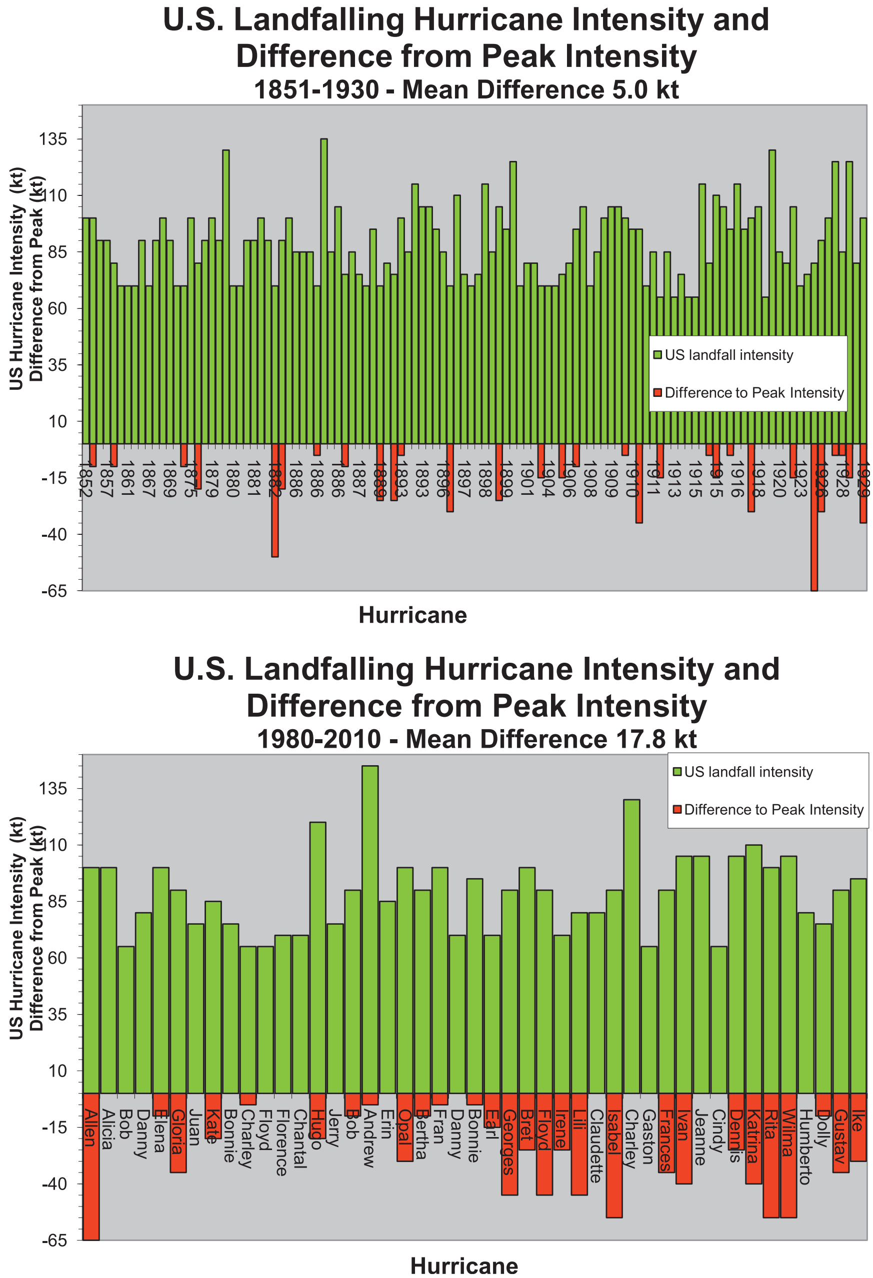


FIG. 1. Comparison of intensity of hurricanes striking the continental United States (green) vs the difference of that wind speed vs the peak lifetime intensity for that hurricane (red). (top) Covering 1851–1930, results include only those hurricanes that struck a settled part of the U.S. coastline (Landsea et al. 2004a, 2008), and (bottom) covering the period 1980–2010 (updated from Blake et al. 2007).

toward underestimating the true intensity (Table 1). For TCs landfalls during the 1920s, uncertainty in the intensity estimates is smaller—~12 kt—and likely has a negligible bias as nearly all coastlines around the western North Atlantic, Gulf of Mexico, and Caribbean Sea were substantially settled and monitored by then. These estimated errors are the same as in the preceding couple of decades. Landsea et al. (2008) has additional information on the position and intensity uncertainty estimates for the reanalysis database relevant for this decade.

Figure 1 provides an explicit quantification of the low bias in intensity for open-ocean TCs in the late nineteenth and early twentieth centuries. Figure 1 shows in green the hurricanes intensities at the time of impact in the continental United States with means of both 89 kt for 1851–1930 and for 1980–2009. The red bars indicate the difference between the U.S. landfall intensity and the peak lifetime intensity of the hurricane, which averages 5.0 kt for 1851–1930 and 17.8 kt for 1980–2009. For the earlier period, 73% (82 of 112) experienced their peak intensity—according to the reanalyzed HURDAT—right at the time of U.S. landfall, whereas only 38% (17 of 45) of the recent U.S. hurricanes experienced their peak at the time of U.S. landfall. An example of a typical case in the 1980–2009 period would be Hurricane Katrina in 2005, which peaked over the open Gulf of Mexico as a 150-kt category 5 event on the Saffir–Simpson hurricane wind scale, but weakened to a high-end category 3 hurricane with 110-kt maximum 1-min winds upon impact with the Louisiana coast a day later. Conversely, a typical example for the 1851 to 1930 era would be storm 3 in 1926 that came ashore in Louisiana with 100-kt maximum 1-min winds, which was also indicated to be the peak intensity for the cyclone. For those more uncommon systems in the earlier period with large (at least 20 kt) differences between the lifetime maximum intensity and the U.S. landfalling intensity, this was primarily due to the hurricane making landfall on another coastline (such as Cuba in storm 10, 1924) at a higher intensity than that at U.S. landfall.

The quite sizable discrepancy in the peak intensity minus U.S. landfall intensity differences—only 5.0 kt for the earlier era and 17.8 kt for the modern hurricanes—requires an explanation. One possibility is that the statistical distributions of hurricanes being sampled from both eras are too dissimilar for a homogeneous comparison. However, evaluating the characteristics of each suggests that the TCs are being drawn from quite similar samples: mean intensities at U.S. impact were 89 kt for 1980–2009 and 89 kt for 1851–1930; percentages of Atlantic coast and Gulf coast landfalls were, respectively, 31% and 69% for 1980–2009 and 37% and 63% for 1851–1930; and the percentages of storms striking in August–October were 78% for 1980–2009 and 80% for 1851–1930.

It appears more likely that the observational deficiencies may be a primary cause of this difference, given that the sample differences do not obviously explain the discrepancy. The inability to adequately monitor the intensities of TCs over the open ocean over 1851–1930 would limit our ability to capture the peak lifetimes of TCs. This reason is also much more likely given that recent TCs on average show a real, substantial weakening before U.S. landfall, especially in the Gulf of Mexico for major hurricanes (Rappaport et al. 2010). This discrepancy—about 13 kt—is quite similar to the more subjectively determined estimates of a 10–15-kt low bias for open Atlantic TC intensity provided in Table 1 and as estimated previously in Landsea et al. (2004a, 2008).

Recent research (e.g., Chang and Guo 2007; Vecchi and Knutson 2008; Landsea et al. 2010) has allowed for more reliable estimates of the number of ''missing'' TCs before the advent of satellite imagery. Vecchi and Knutson (2008) suggest that there was roughly one missed tropical cyclone per year during the 1920s. Landsea et al. (2010) also indicated that there has been a very large increase in the number of short-lived (i.e., less than or equal to about a 2-day duration of tropical storm or greater intensity) TCs in recent years that is likely due to better technology and improved monitoring of these short-lived and typically very weak systems. Villarini et al. (2011) lends support to the hypothesis that the recent increase in short-lived TCs is spurious and not due to climate-related factors. Compared to rates of short-lived TCs in recent years, the results from Landsea et al. (2010) suggest that about four short-lived TCs were missed per year in the 1920s and about one medium- to long-lived TCs (greater than a 2-day duration) was missed every other year. Similarly, Vecchi and Knutson (2011) indicate that about one hurricane per year in the 1920s was either incorrectly classified as a tropical storm or missed completely. These conclusions will be put into the context of the results of the reanalysis, which did lead to a substantial change in the frequency of all TCs and short-lived TCs for the decade of 1921–1930.

4. Results

a. Overall activity

A summary of the yearly changes to HURDAT is provided in Fig. 2 and Table 2. A detailed example of the reanalysis results for the 1928 San Felipe-Lake Okeechobee hurricane is included in the on-line supplemental material. Figure 2 shows the revised and comparison track maps for the individual seasons from 1921 to 1930. It is apparent that most of the track changes introduced for these years are fairly minor (less than a 120-nmi alteration in position at any time during the TC's lifetime) as readily seen in the comparison maps, though occasionally there have been some more dramatic alterations (e.g., storm 5 in 1923, storm 1 in 1927, and storm 1 in 1928). 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, and one existing system in HURDAT was reanalyzed to not be a tropical storm and thus was removed from the database. In total, 14 new TCs had sufficient observational evidence to document their existence and were added into HURDAT: 3 in 1923 and 1924; 2 in 1925 and 1929; 1 in 1921, 1922, 1927, and 1930; and no new systems in 1926 and 1928. Of these 14, 2 of the new TCs were landfalling systems: storm 7 during 1921 in Cuba and storm 1 during 1923 in Louisiana, Mississippi, and Alabama. Additionally, one system during the 1920s in HURDAT was removed because of a lack of gale-force winds (original storm 4 in 1923). In other years in the reanalysis work (e.g., 1891), two separate TCs were found to be actually one continuous system and thus the data were so changed to reflect this, but no such systems were uncovered during the 1920s.

Table 2 lists the original and revised tallies of tropical storms and hurricanes, hurricanes, major hurricanes (categories 3–5 on the Saffir–Simpson hurricane wind scale), 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 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 5.6 yr^{-1} in the original HURDAT to 6.9 yr^{-1} after the reanalysis (Table 2), a 23% increase. This net increase includes new systems that were added into the database as well as one that was originally in HURDAT but was discarded. Both values are substantially below the long-term average of 11.4 yr^{-1} recorded in the satellite era of 1966–2010 (updated from Blake et al. 2007). However, as described earlier, a direct comparison of the total frequency of TCs during the 1920s to the modern climatology is complicated by the occurrence of ''missed'' TCs in the earlier years because of vastly improved monitoring capability, such as satellite imagery and aircraft reconnaissance that is available now. In the original HURDAT, of the 56 TCs, only three were short lived. With the reanalysis, of the 69 TCs for the 1921–30 period, 11 are now indicated to be short-lived TCs. Five of the newly described short-lived TCs were due to a decrease in the original duration recorded and four were brand new TCs not previously recorded. (One of the original short-lived TCs is now reanalyzed to have a longer lifetime.) To more homogeneously compare the 1920s to the more recent era, one must estimate the number of ''missed'' TCs of medium to long durations in the 1921–30 period and remove the likely spurious influence of the short-lived TC trends.[2]

[2] It is important to recognize that the ''missing storm'' estimates of Landsea et al. (2010) are in addition to a ''perfectly reconstructed'' (within the limitations of past observations) hurricane database. A key observational dataset utilized here in the reanalysis and in the Landsea et al. (2010) and Vecchi and Knutson (2008, 2011) sampling studies is the COADS global ship database (Worley et al. 2005). A key assumption of the sampling studies was that all of the TCs observed within COADS were available within HURDAT. With the reanalysis reaching 1930, this is now the case for the hurricane seasons from 1911 to 1930. So, while this reanalysis brings HURDAT closer to a perfectly reconstructed database, the missing storm estimates of Landsea et al. (2010) and Vecchi and Knutson (2008, 2011) should still be included (until such time that additional, new observations can be brought to bear on the reconstructions).

Using the results of Landsea et al. (2010), an average of about one medium to long-lived TC every 2 yr was missed in the 1920s and the modern (1966–2009) climatology of medium to long-lived TCs is 7.7 yr^{-1}. Thus, the best adjusted total of medium to long-lived TCs from 1921 to 1930 is about 6.3 yr^{-1}, which suggests that this decade was quiet relative to the modern era for TC frequency.

Likewise, utilizing the estimate from Vecchi and Knutson (2011) of 1.0 ''missed'' hurricanes per year (either wrongly classified as a tropical storm or completed missed in the HURDAT database), one can directly compare the period 1921–30 with a modern climatology. Adjusting the raw hurricane frequency of 3.9 yr^{-1} (originally 3.6 yr^{-1}) by the estimated 1.0 yr^{-1} missed because of the lack of comprehensive monitoring available early in the twentieth century gives a revised average of 4.9 hurricanes yr^{-1}. This is substantially quieter than the modern climatological value of 6.2 hurricanes yr^{-1} in the satellite era, consistent with the adjusted climate record for all TCs.

In contrast to the substantial increases in TCs and hurricanes, the major hurricane and ACE averages (Table 2) show smaller changes in recorded values. Major hurricanes remained unchanged at 1.7 yr^{-1} (2.4 yr^{-1} recently), and ACE increased slightly from 71.8 to 76.6 yr^{-1} (96.3 yr^{-1} recently). With regard to ACE, three years recorded a substantial increase in activity (ACE higher by at least 10.0—1921, 1923, and 1930), two years saw a decrease in activity (ACE lower—1922 and 1923), and the remaining five years had minor increases in overall intensity, duration, and frequency. To have an ACE with little change or even a modest decrease in some years is likely due to a systematic tendency for the original HURDAT to somewhat overestimate the intensity of hurricanes from 1921 to 1930, especially over the open ocean (e.g., storm 4 in 1927). In general, large changes to intensity (at least a 20-kt alteration at some point in the TC's lifetime) were recorded, either upward or downward, for the majority of individual TCs, typically with more significant changes than those introduced for track. Currently, there exists no method for quantifying the number of missed major hurricanes and ACE for the era of the 1920s. Because of this, any direct comparison of these quantities to the modern era would not be appropriate.

b. Continental U.S. hurricanes

Table 3 summarizes the continental U.S. hurricanes for the period of 1921–30 and the states impacted by these systems. U.S. hurricanes are defined as those hurricanes that are analyzed to cause maximum (1 min) surface (10 m) winds of at least 64 kt for an open exposure along the coast or inland in the continental United States. Hurricanes that make a landfall with the circulation center (eye) of the system crossing the coast as well as those

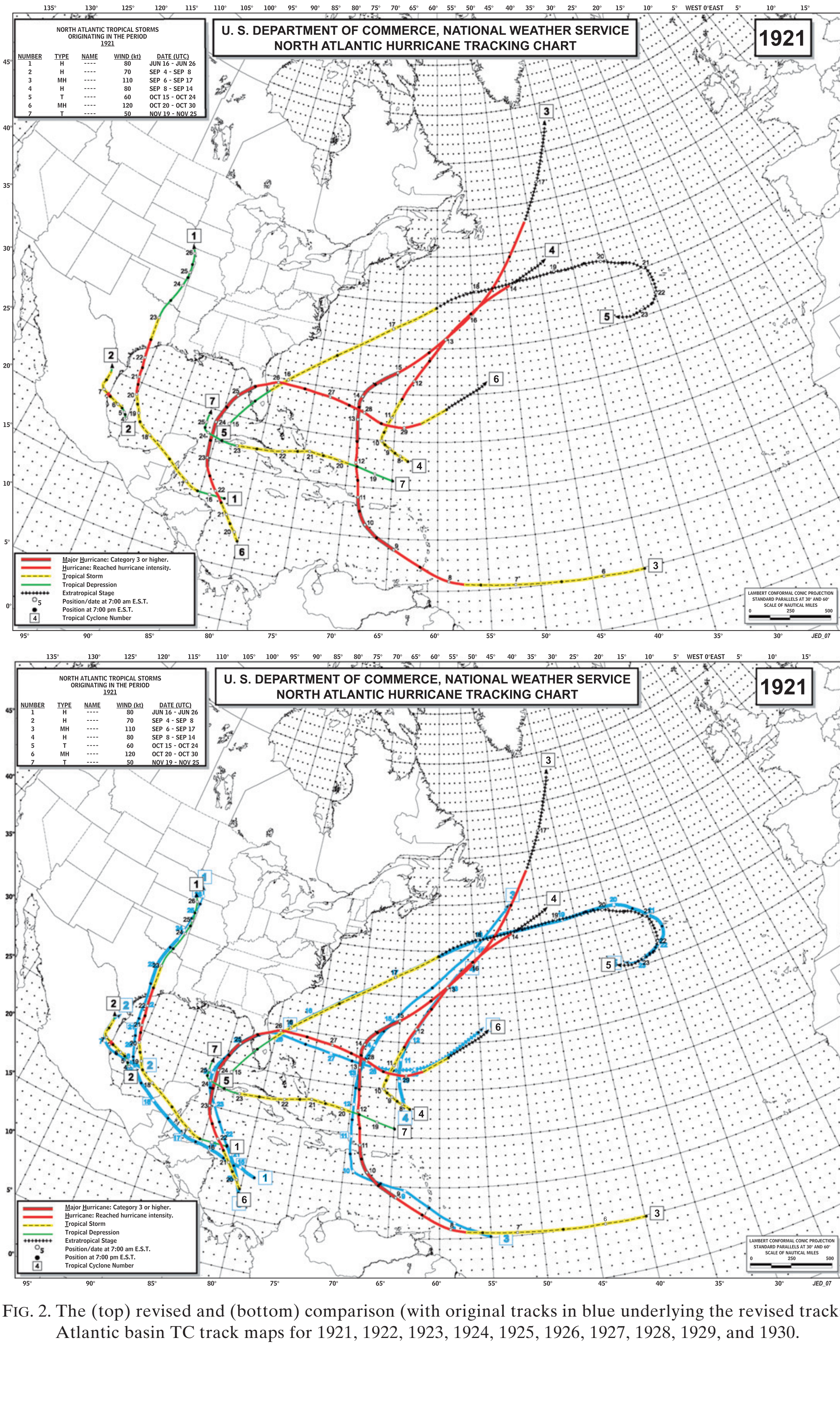
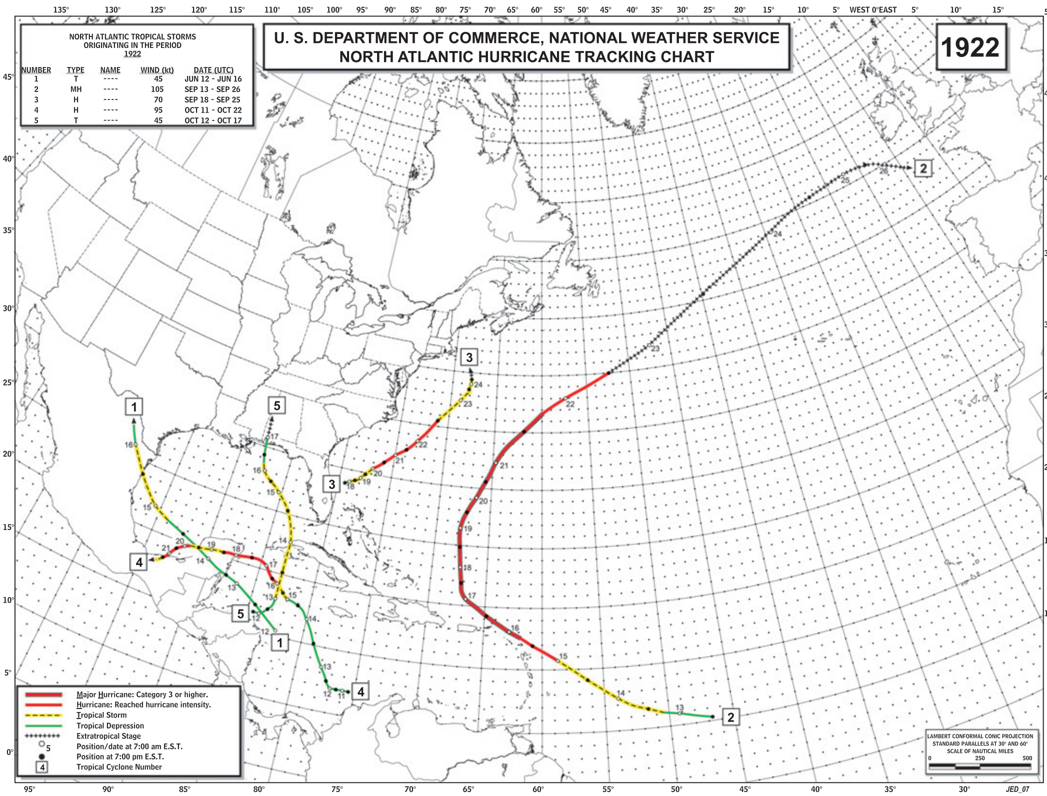
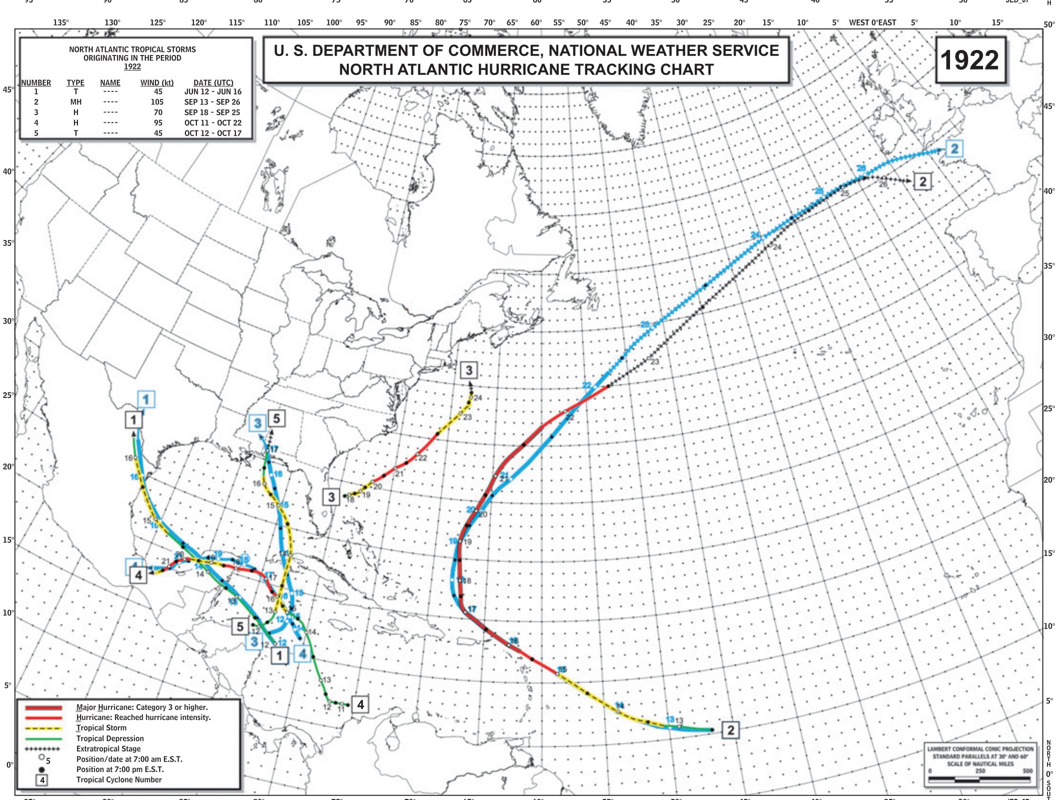


FIG. 2. The (top) revised and (bottom) comparison (with original tracks in blue underlying the revised tracks) Atlantic basin TC track maps for 1921, 1922, 1923, 1924, 1925, 1926, 1927, 1928, 1929, and 1930.





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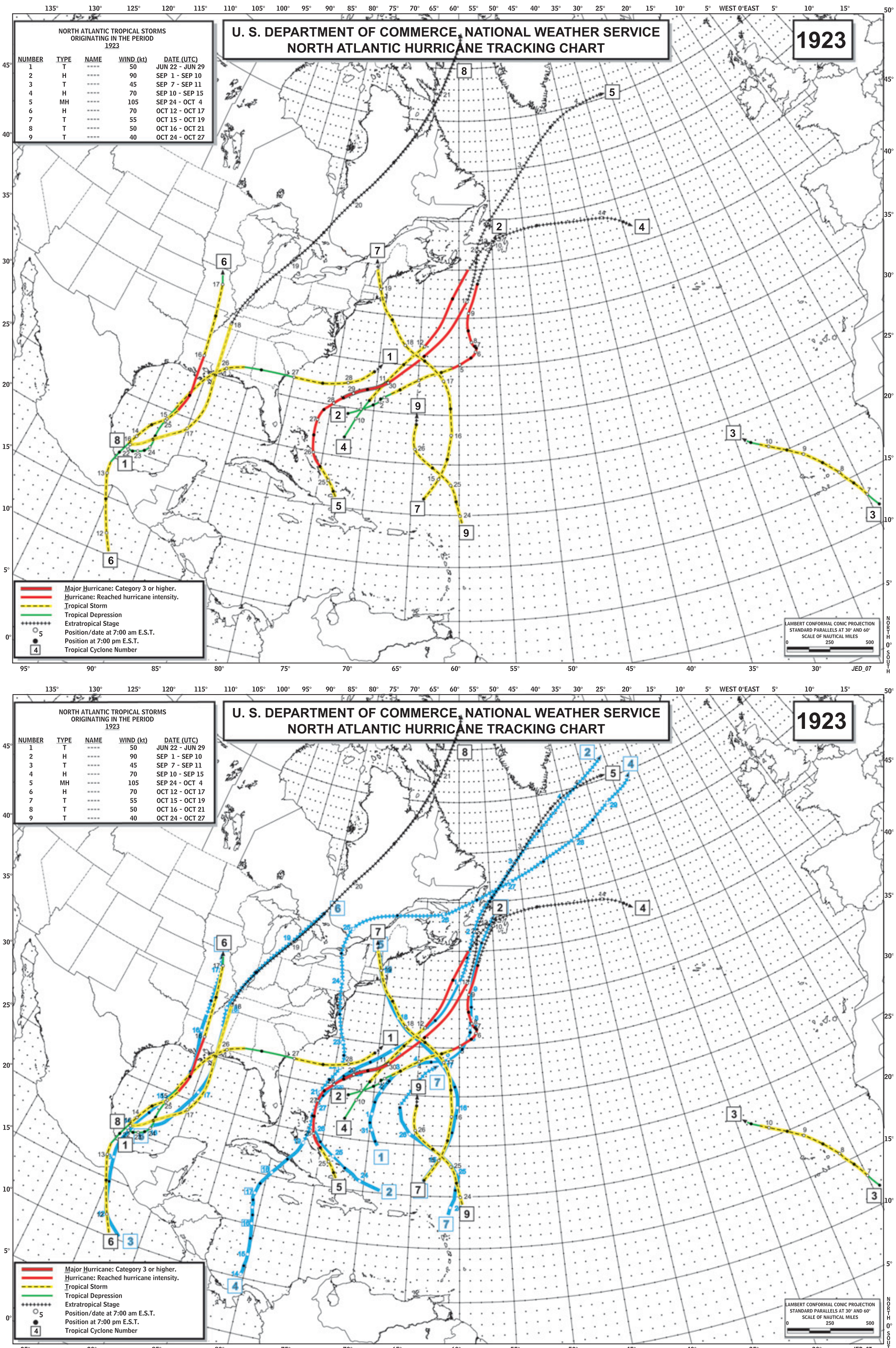

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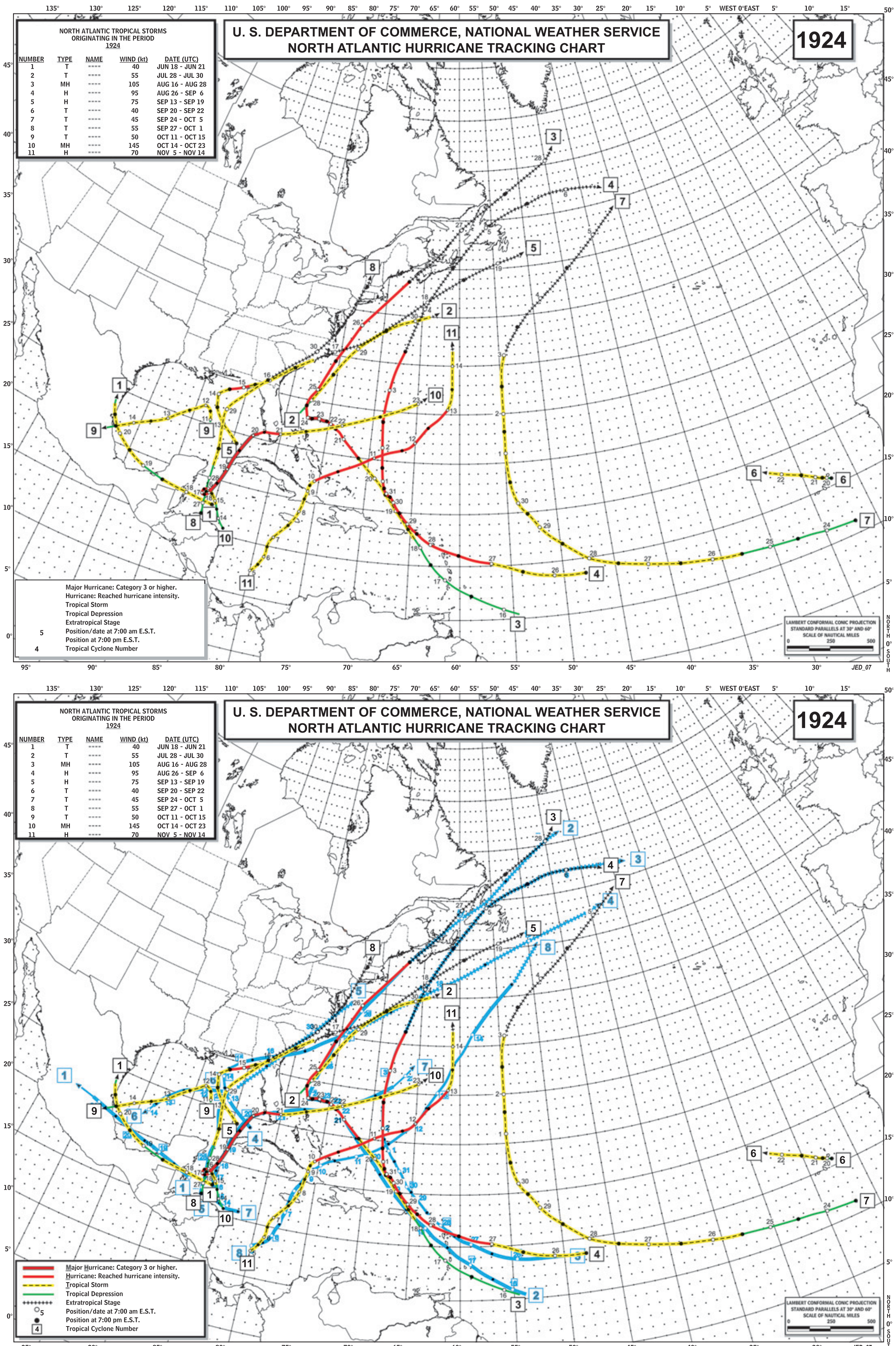

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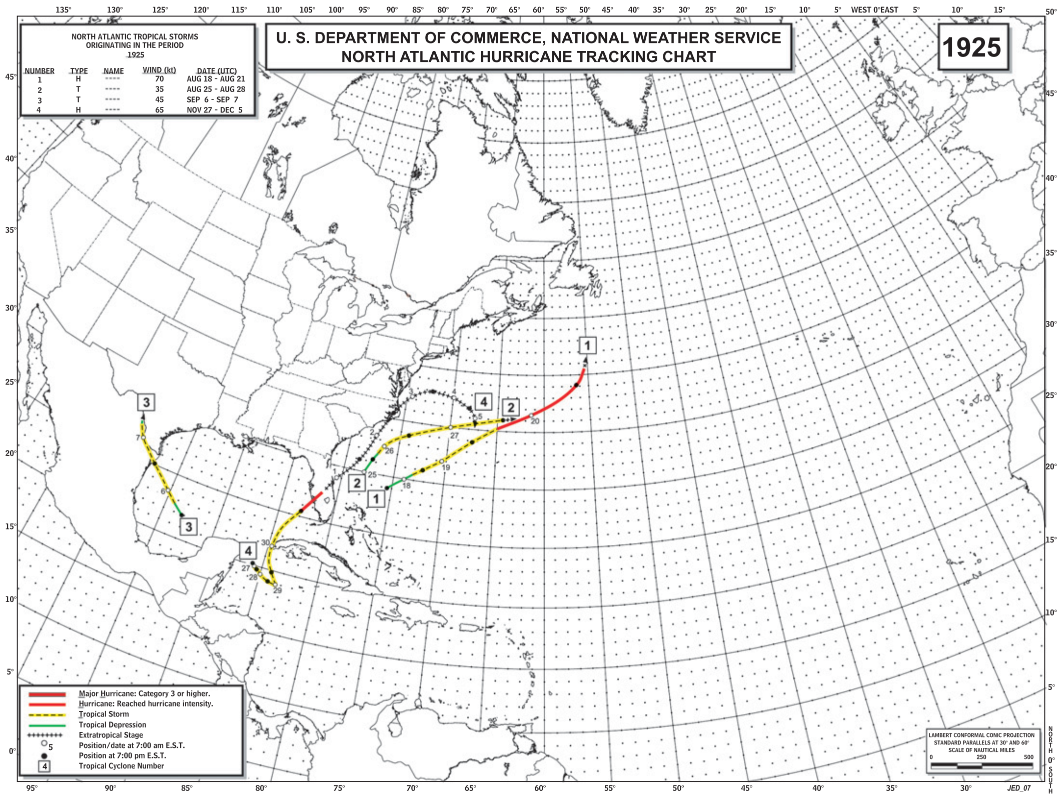

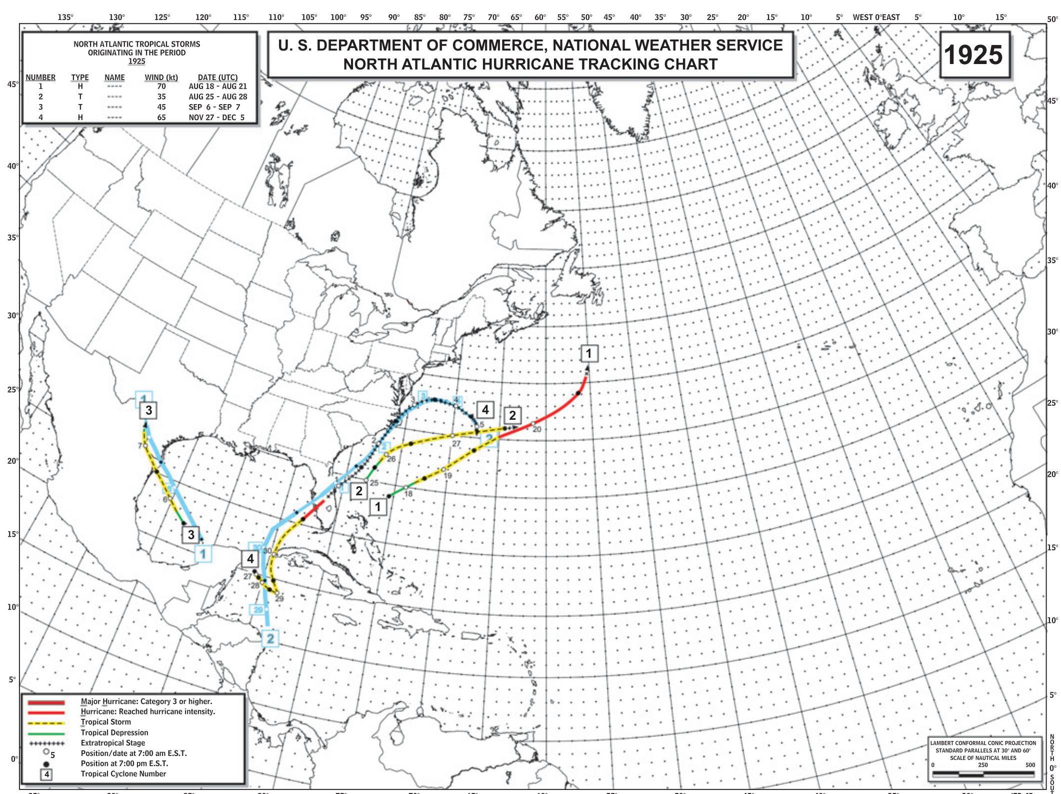

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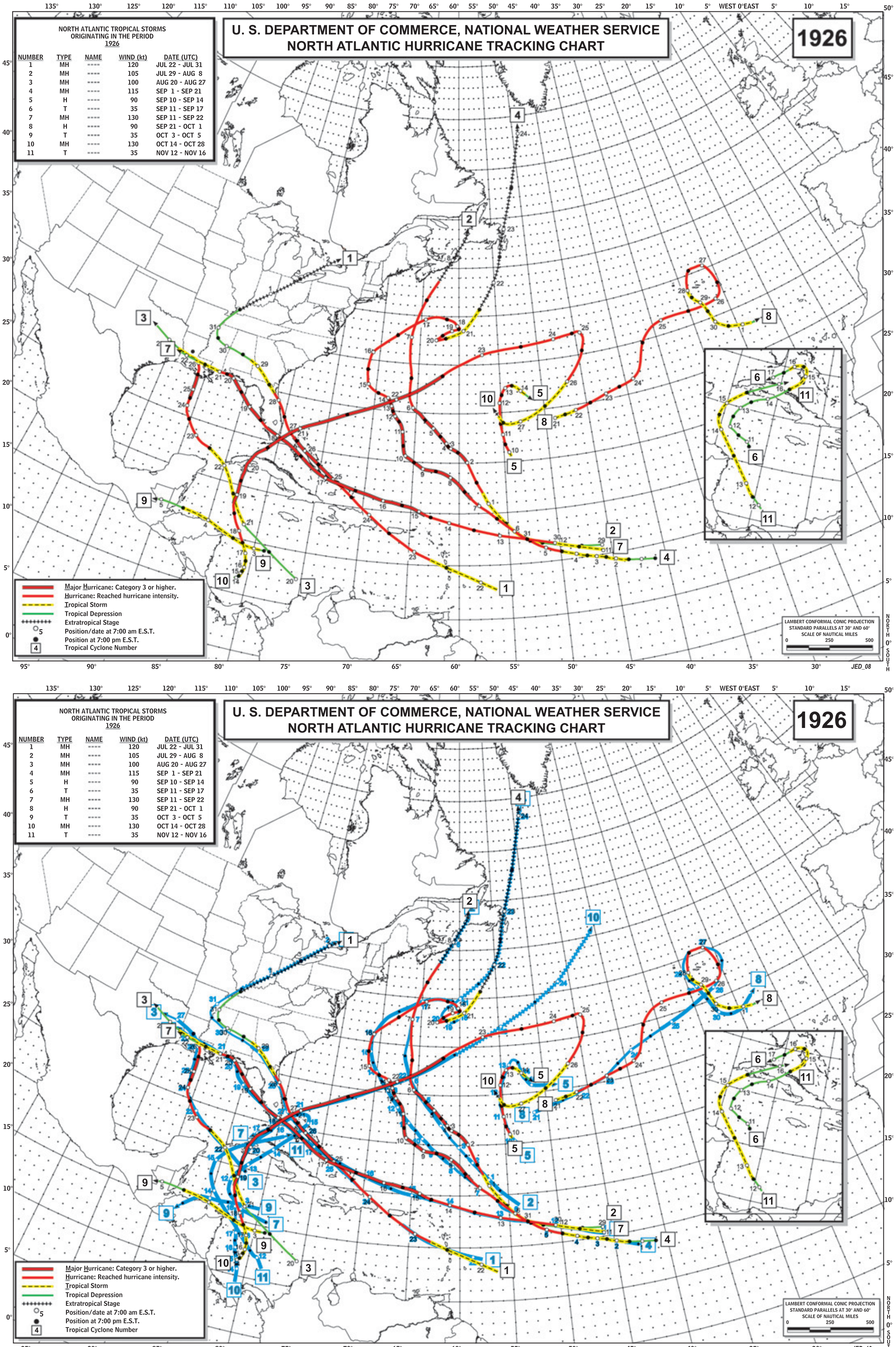

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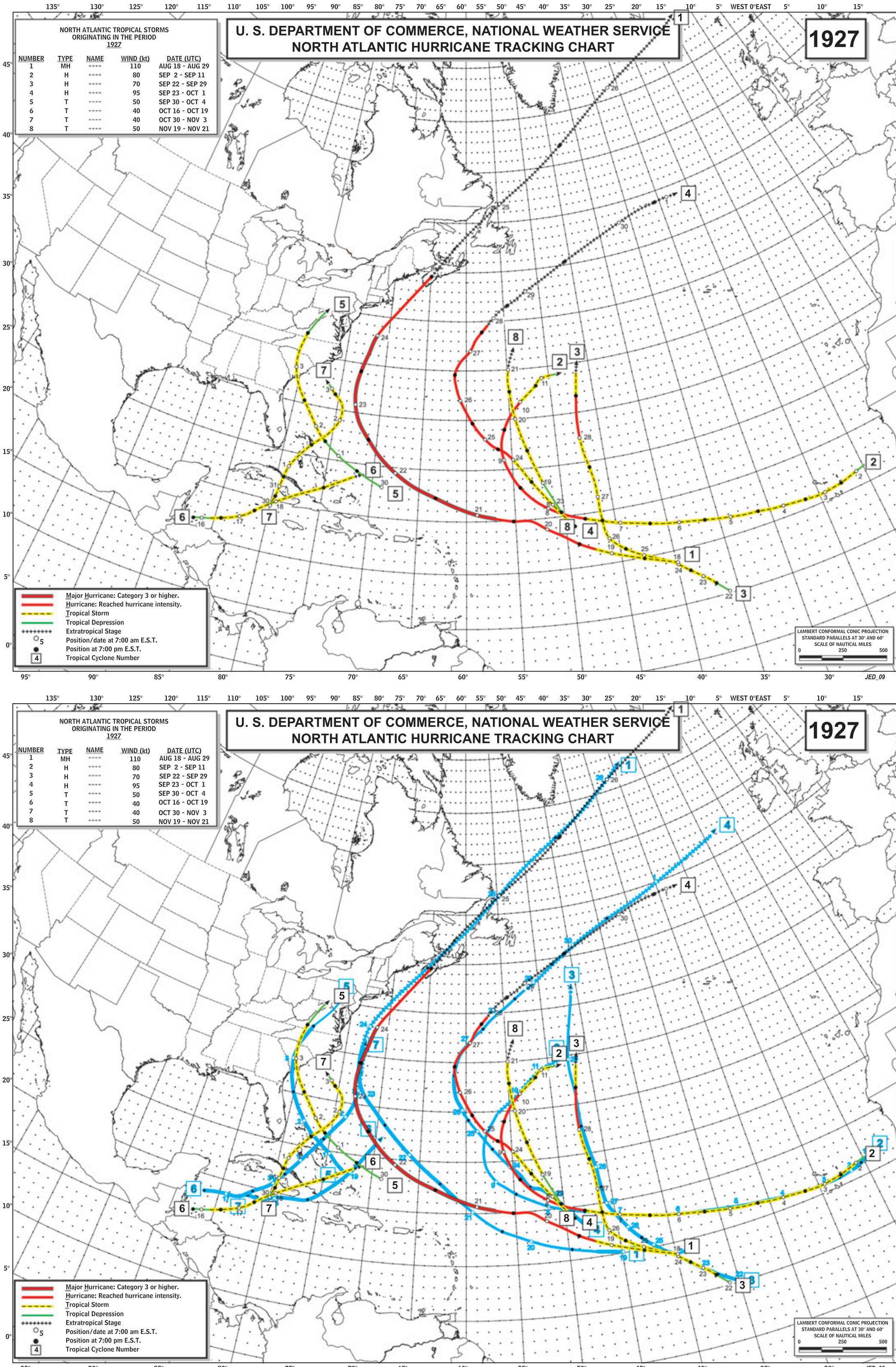

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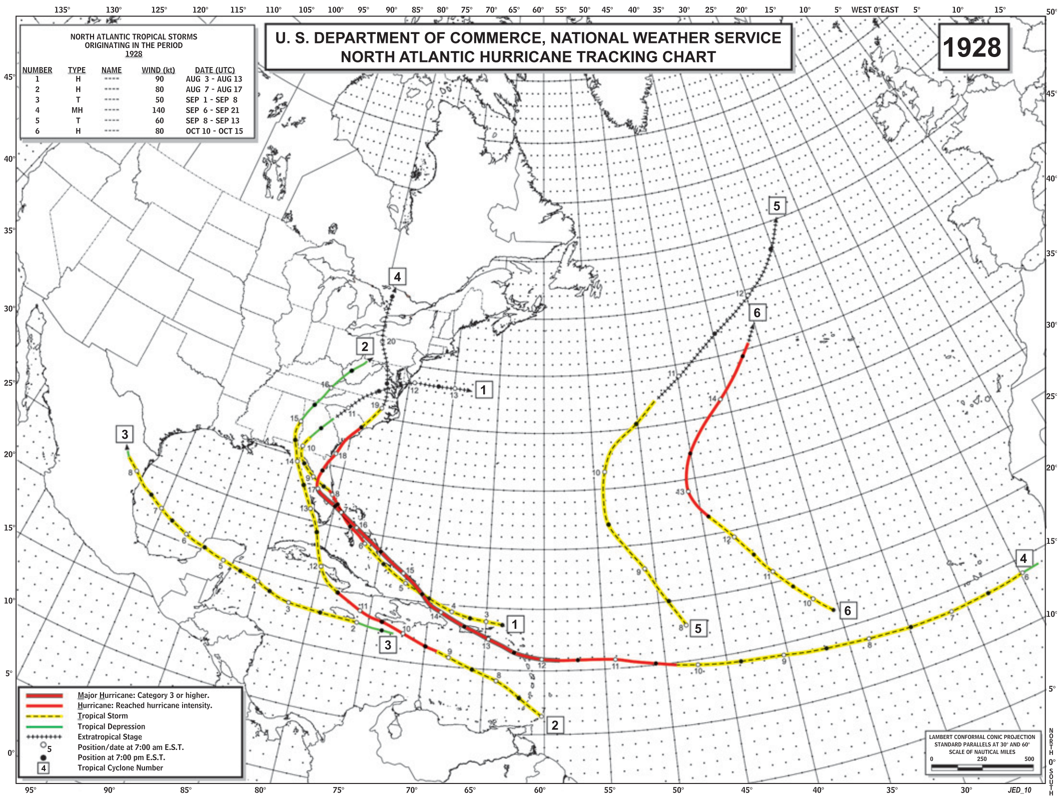

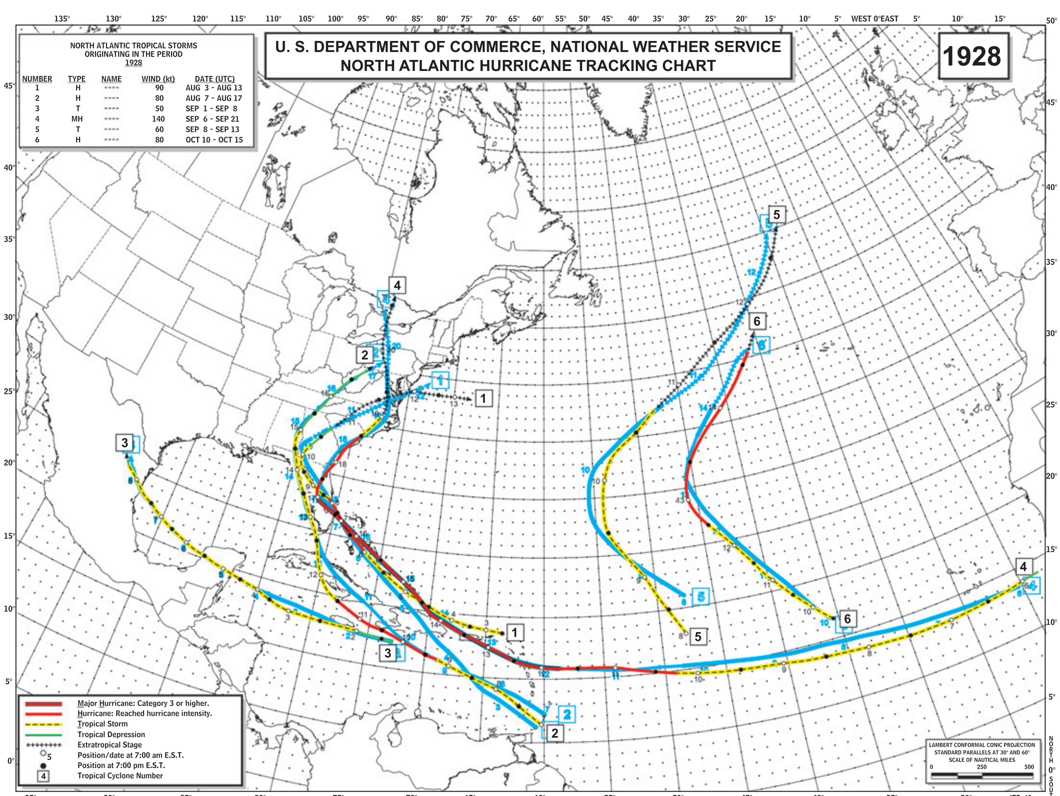

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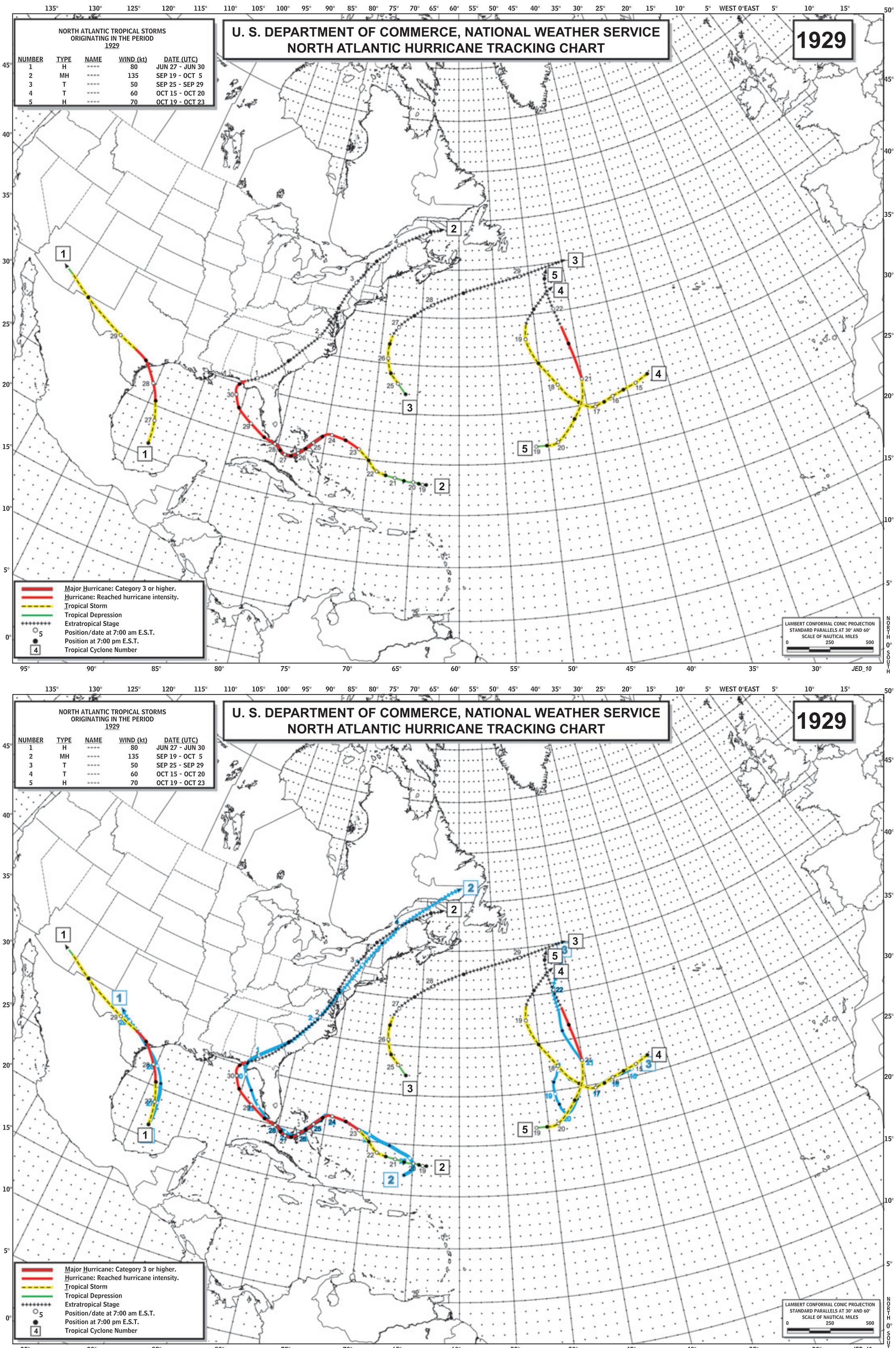

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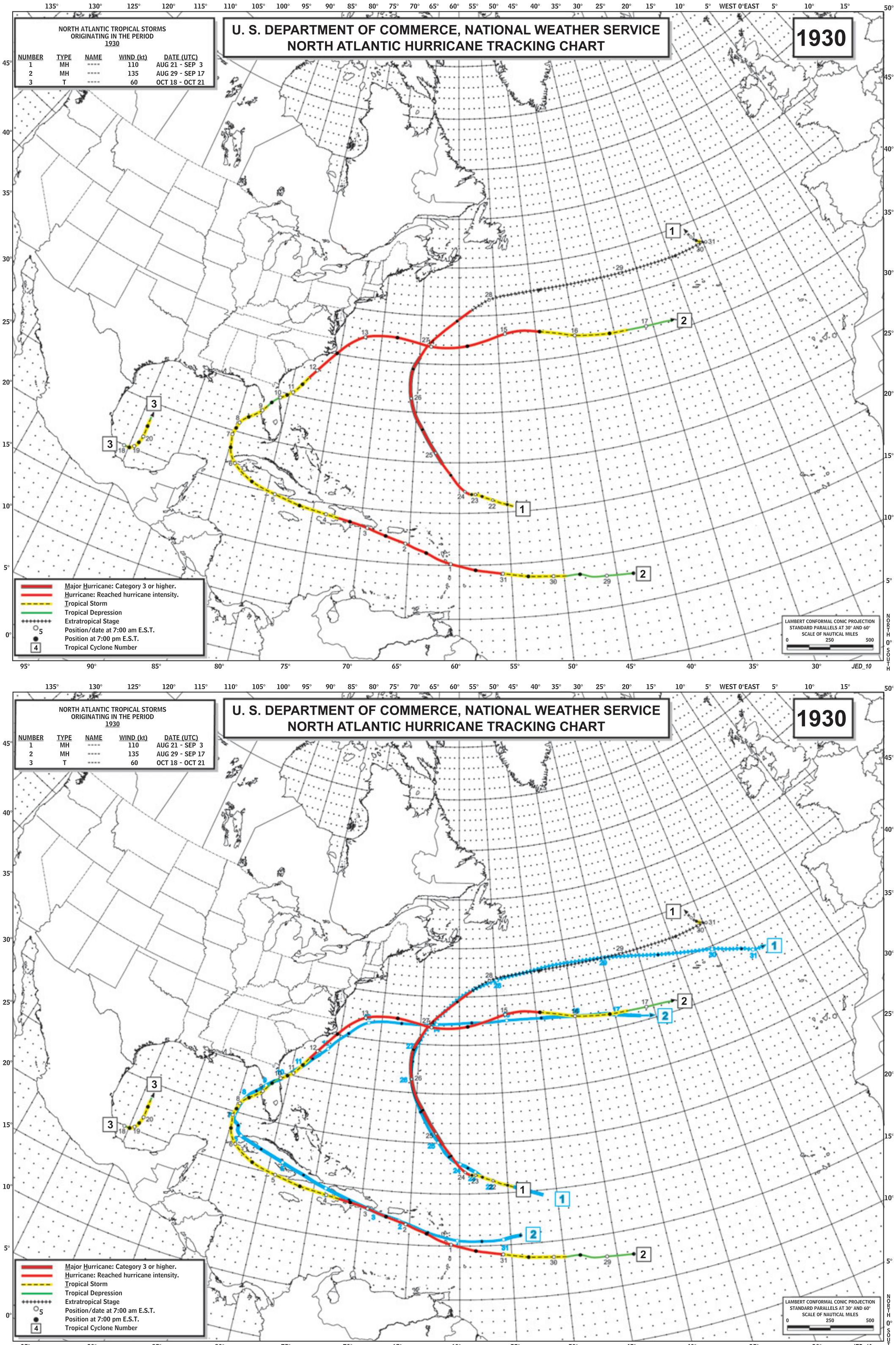

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TABLE 2. Original (revised) tropical storm and hurricane, hurricane, major hurricane, and ACE counts. ACE is expressed in units of 10^4 kt^2.

Year	Tropical storms and hurricanes	Hurricanes	Major hurricanes	ACE
1921	6 (7)	4 (5)	2 (2)	75 (87)
1922	4 (5)	2 (3)	1 (1)	58 (55)
1923	7 (9)	3 (4)	1 (1)	54 (49)
1924	8 (11)	5 (5)	2 (2)	89 (100)
1925	2 (4)	1 (1)	0 (0)	7 (8)
1926	11 (11)	8 (8)	6 (6)	222 (230)
1927	7 (8)	4 (4)	2 (1)	56 (56)
1928	6 (6)	4 (4)	1 (1)	75 (83)
1929	3 (5)	3 (3)	1 (1)	43 (48)
1930	2 (3)	2 (2)	1 (2)	39 (50)
Avg during 1921–1930	5.6 (6.9)	3.6 (3.9)	1.7 (1.7)	71.8 (76.6)
Avg during 1966–2010	11.4	6.2	2.4	96.3

that make a close bypass without landfall 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 radius of maximum wind (RMW). These parameters provide information regarding the sizes 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 original sources, which was then used to determine the maximum wind speeds through the application of one of the Brown et al. (2006) pressure–wind relationships. In the one case 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 both an estimate of the maximum wind and a central pressure at landfall for all U.S. hurricanes.

There were 15 U.S. hurricanes (5 that were major hurricanes) during the 1921–30 period after the reanalysis. No U.S. hurricanes were recorded in 1922, 1925, 1927, or 1930. The total of 15 U.S. hurricanes represents 1 more hurricane than the original HURDAT database contained, with storm 4 in 1925 no longer considered a hurricane at its peak intensity nor at its landfall in southwest Florida and with storm 3 in 1924 (causing category 1 hurricane conditions in North Carolina and Massachusetts) and storm 10 in 1926 (causing category 1 hurricane conditions in south Florida) added in as close bypassing systems. (Originally, these two systems were considered to have caused tropical storm impacts for the United States in HURDAT.) For existing U.S. hurricanes, 12 storms were unchanged in category, 1 was downgraded by a category (storm 1 in 1921, which went from a category 2 in Texas originally to a category 1), and the 1925 southwest Florida hurricane was removed. No major hurricanes were either added or removed from the U.S. hurricane list.

Notable hurricanes that affected the continental United States during 1921–30 (Blake et al. 2007) include storm 10 in 1921 (the ''Tampa Bay hurricane'') in southwest Florida, storm 3 in 1926 in Louisiana, storm 7 in 1926 (the great Miami hurricane) in southeast and northeast Florida and Alabama), storm 4 in 1928 (the ''Lake Okeechobee hurricane'') in southeast and northwest Florida, and storm 2 in 1929 in south Florida.

During the period of 1921–30, the first very destructive hurricane to strike the continental United States was storm 10 during 1921, which hit the southwest coast of Florida just north of Tampa. This hurricane was the last direct strike by a major hurricane in the Tampa–St. Petersburg metropolitan area (Blake et al. 2007). This TC was originally listed as a category 3 with a 952-mb central pressure at landfall and a maximum wind at the last synoptic time before landfall of 90 kt.[3] This central pressure was revised to 958 mb along with a moderately sized RMW of 15 n mi, giving a maximum 1-min wind estimated at

[3] The discrepancy between the original category 3 assessment for U.S. landfall of this hurricane and the 90-kt winds existing originally in HURDAT is a quite common problem in the present dataset. Much of the discrepancy is due to reliance primarily upon the central pressure by Hebert and Taylor (1975) to provide the original Saffir–Simpson hurricane wind scale category at landfall in the United States, while the practice today at the National Hurricane Center and within the reanalysis is to determine the maximum winds at landfall and then let these determine the appropriate category.

TABLE 3. Continental U.S. hurricanes for 1921–30. The first two columns show day and time when the circulation center crossed the U.S. coastline (including barrier islands). Time is estimated to the nearest hour. Columns three and four show the latitude and longitude, respectively, estimated to the nearest 0.1°. Column five shows the estimated maximum (1 min) surface (10 m) winds to occur along the U.S. coast (kt). Column six shows the category on the Saffir–Simpson hurricane wind scale (SSHWS) at landfall based upon estimated maximum 1-min surface winds. Column seven shows the radius of maximum winds, if available, to the nearest 5 n mi. Column eight shows the minimum central pressure (mb) of the hurricane at landfall. Column nine shows the outer closed isobar (OCI), or 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). Column 10 shows the average radius (n mi) of the OCI. Column 11 shows the areas affected: the impacts of the hurricanes upon individual U.S. states using the SSHWS (again through the estimate of the maximum 1-min surface winds at each state). Areas are 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, Delaware; NJ, New Jersey; NY, New York; PA, Pennsylvania; CT, Connecticut; RI, Rhode Island; MA, Massachusetts; NH, New Hampshire; and 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 80.85°W.) Asterisks indicate that the hurricane center did not make a U.S. landfall, but did produce hurricane force winds over land. Position indicated is point of closest approach. Winds stronger than indicated to impact the United States may have existed elsewhere in the hurricane. Central pressure in this case is the hurricane's value at the point of closest approach.

Hurricane No., date	Time (UTC)	Lat	Lon	Max winds	SSHWS category	RMW	Central pressure	OCI	Size	Areas affected	Original assessment
1, 22 Jun 1921	1800	28.6°N	95.9°W	80	1	15	980	1011	225	BTX1, CTX1	BTX2
6, 25 Oct 1921	2000	28.1°N	82.8°W	100	3	20	958	1009	375	BFL3, AFL2, DFL1, CFL1	BFL3, DFL2
0, 1922											
6, 16 Oct 1923	0600	29.2°N	91.0°W	70	1	45	983	1001	250	LA1, MS1	LA1
3, 26 Aug 1924*	0400	35.5°N	74.8°W	65	1	35	963	1009	275	NC1	None
3, 26 Aug 1924*	1900	41.2°N	70.2°W	65	1	40	968	1009	275	MA1	None
5, 15 Sep 1924	1400	29.7°N	85.3°W	75	1	—	980	1011	150	AFL1	AFL1
10, 21 Oct 1924	0100	25.8°N	81.8°W	80	1	20	975	1008	375	BFL1, CFL1	BFL1
0, 1925											
1, 28 Jul 1926	1000	29.0°N	80.8°W	90	2	15	967	1014	300	DFL2, CFL1	DFL2
3, 25 Aug 1926	2300	29.2°N	90.9°W	100	3	20	955	1012	275	LA3	LA3
7, 18 Sep 1926	1200	25.7°N	80.3°W	125	4	20	930	1008	325	CFL4, BFL3	CFL4, BFL3
7, 20 Sep 1926	2200	30.3°N	87.5°W	100	3	15	955	1008	225	AFL3, AL3, MS1	AFL3, AL3
10, 21 Oct 1926*	0300	25.0°N	80.3°W	75	1	20	949	1009	300	BFL1, CFL1	None
0, 1927											
1, 8 Aug 1928	0700	27.3°N	80.2°W	85	2	10	977	1014	150	CFL2	CFL2
4, 17 Sep 1928	0000	26.7°N	80.0°W	125	4	30	929	1009	275	CFL4, BFL3, AFL1, DFL1	CFL4, DFL2
4, 18 Sep 1928	1900	32.5°N	80.3°W	75	1	35	976	1008	350	GA1, SC1	GA1, SC1
1, 28 Jun 1929	2100	28.3°N	96.4°W	80	1	10	982	1007	150	BTX1	BTX1
2, 28 Sep 1929	1300	25.0°N	80.5°W	100	3	30	948	1008	300	BFL3, CFL3	CFL3
2, 1 Oct 1929	0400	30.2°N	85.7°W	70	1	—	975	1011	400	AFL1	AFL2
0, 1930											

landfall of about 100 kt, retaining the system as a category 3 event at landfall.

The next major hurricane to affect the United States was not until 1926. Storm 3 was originally estimated to have a central pressure of 955 mb at landfall in Louisiana and maximum winds of 90 kt at the last synoptic time before landfall. After the reanalysis, the central pressure was unchanged and along with a moderately sized RMW of 20 n mi, the winds at landfall were estimated to be 100 kt, retaining the category 3 hurricane status for this system. Also in 1926, Florida and Alabama were devastated by the great Miami hurricane with about 372 people killed (Pfost 2003). This system was analyzed to have a central pressure of 935 mb at landfall in southeast Florida with winds of 115 kt at the last synoptic time before landfall. At its second landfall in northwest Florida–Alabama, the storm originally had a central pressure recorded of 955 mb and maximum winds of 105 kt at the last synoptic time before landfall. It was originally assessed to be category 4 at landfall in southeast Florida and category 3 at a second landfall in northwest Florida–Alabama. After reanalysis, it was determined that the central pressure at landfall in Miami was slightly deeper at 930 mb and—along with a moderately sized RMW of 20 n mi—had maximum winds of about 125 kt. The second landfall of the hurricane in northwest Florida–Alabama was reassessed

TABLE 4. Major landfalling (noncontinental U.S) hurricanes during 1921–30. The names listed are unofficial ones that the hurricanes are known by at these locations. Max winds are the estimated maximum 1-min surface (10 m) winds (kt) to occur at along the coast at landfall–closest approach. SSHWS is the estimated Saffir–Simpson category at landfall based upon maximum 1-min surface winds. Central pressure is the minimum central pressure (mb) 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 wind is the wind (kt) in HURDAT that was originally provided at landfall–closest approach.

Hurricane No., date	Name	Location	Max wind	SSHWS category	Central pressure	Original wind
3, 11 Sep 1921	—	Dominican Republic	110	3	(951)	80
2, 16 Sep 1922	—	Barbuda, St. Martin, Anguilla, Anegada	100	3	(961)	90
2, 21 Sep 1922	—	Bermuda	100	3	970	130
0, 1923						
10, 19 Oct 1924	Huracan sin Precedentes	Cuba	140	5	910	105
0, 1925						
1, 26 Jul 1926	—	Bahamas	120	4	(938)	120
7, 17 Sep 1926	—	Bahamas	130	4	(926)	130
10, 20 Oct 1926	—	Cuba	130	4	934	105
10, 21 Oct 1926	—	Bahamas	110	3	(948)	100
10, 22 Oct 1926	—	Bermuda	105	3	962	115
0, 1927						
4, 12 Sep 1928	—	Guadeloupe	120	4	940	110
4, 13 Sep 1928	San Felipe	Puerto Rico	140	5	931	140
4, 15 Sep 1928	—	Bahamas	135	4	(920)	135
2, 26 Sep 1929	—	Bahamas	125	4	936	125
2, 3 Sep 1930	—	Dominican Republic	135	4	933	130

to be slightly different than originally estimated: a central pressure of 955 mb and maximum winds of 100 kt. This retains the category 4 and 3 assessments for southeast Florida and northwest Florida–Alabama, respectively. This large (outer closed isobar of 325-n mi radius) and powerful hurricane would cause on the order of $165 billion in total losses today, given society's population and infrastructure in place now (Blake et al. 2007). Such destruction would place it as the most expensive hurricane, after normalization, in U.S. hurricane history since 1900.

Just 2 yr later, southeast Florida suffered another devastating hurricane strike with the impact of storm 4: the Lake Okeechobee hurricane. This system killed on the order of 2500 people (Pfost 2003) and was originally assessed to be a 929-mb central pressure category 4 hurricane at landfall in Palm Beach with maximum winds of 130 kt at the last synoptic time before landfall. After reanalysis, the 929 mb was retained and partly because of a large RMW (30 n mi) for this central pressure and landfall latitude, the maximum winds were assessed to be 125 kt at landfall. This retains the hurricane as a category 4 event at landfall in southeast Florida. If this system were to strike the United States today, it would cause on the order of $35 billion, making it the eighth most expensive hurricane in U.S. history back to 1900 normalized to today's societal vulnerability (Blake et al. 2007).

The last major hurricane to make landfall in the United States was storm 2 in 1929. This system originally made landfall in the Florida Keys as a category 3 hurricane with 948-mb central pressure and maximum winds of 90 kt at the last synoptic time before landfall. After reanalysis, the 948-mb central pressure was retained and—along with a large RMW of about 30 n mi and a slow, 4-kt translational speed—winds of 100 kt were analyzed at landfall. These maximum winds allow for the system to be retained as a category 3 hurricane at landfall.

Overall, there were no additions to the U.S. major hurricanes for the years of 1921–30, nor were there any alterations to the peak category impact at landfall. However, maximum winds in HURDAT were adjusted for all five of these U.S. major hurricanes with one decreased by 5 kt (as was the second landfall of storm 9 during 1926), three increased by 10 kt, and one increased by 15 kt.

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

Outside of the continental United States, major hurricanes impacted several locations during 1921–30 (Table 4). Nine 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. Of the nine, one was newly designated to be a major hurricane after the reanalysis: storm 3 in 1921 that struck the Dominican Republic, the winds from which were increased from 80 to 110 kt at landfall.

The largest impact of any major hurricane was the devastating category 4 hurricane that also struck the Dominican Republic in September 1930 (storm 2 of that year) and killed in the range of 2000–8000 people (Rappaport and Fernández-Partagás 1995). For this hurricane, which had the worst impact and was the most intense in the Dominican Republic's history, a central pressure of 933 mb was observed and the maximum winds at landfall were estimated to be 135 kt.

Cuba was struck by two major hurricanes during this decade: a category 5 hurricane, the ''Huracán sin Precedentes,'' in October 1924 (storm 10 of that year), and a category 4 hurricane in October 1926 (storm 10). The former cyclone caused extraordinary destruction in the western portion of the country (Perez Suarez et al. 2000) with an analyzed central pressure of 910 mb and estimated maximum winds of 140 kt at landfall. The latter hurricane, with an analyzed central pressure of 934 mb and estimated 130-kt maximum winds at landfall, killed about 600 people in Cuba (Perez Suarez et al. 2000). The Huracán sin Precedentes is only one of two category 5 hurricanes documented to have struck Cuba in its long hurricane history (Perez Suarez et al. 2000), the first of which was ''La Tormenta de San Francisco de Borja'' of October 1846 (preceding the current HURDAT database).

The Bahamas were also struck repeatedly by major hurricanes during the decade with one category 3 strike (storm 10 in 1926) and four category 4 strikes (storm 1 in 1926, storm 7 in 1926, storm 4 in 1928, and storm 2 during 1929). Of these, storms 1 (1926) and 2 (1929) had the largest impacts to Bahamian residents with about 300 people killed in the former and extreme destruction caused to Nassau and other islands in the latter (Neely 2006).

Puerto Rico was struck by only one major hurricane during the period 1921–30: storm 4 in 1928, known as ''San Felipe'' locally. This system killed over 300 people (Rappaport and Fernández-Partagás 1995) and is the most intense to ever strike the island with an observed central pressure of 931 mb and observed maximum winds of 140 kt. Originally, San Felipe was the first category 5 hurricane to appear in the HURDAT database anywhere within the Atlantic basin (not just at landfall). However, with the upgrade of the Huracán sin Precedentes (storm 10 during 1924) to a peak 140-kt intensity, this system has supplanted San Felipe as the first category 5 to appear within HURDAT.

To summarize the significant changes to the landfall intensities of these nine major landfalling (noncontinental United States) hurricanes, three had large increases in landfall intensity (storm 3 in 1921, from 80 up to 110 kt; storm 10 in 1924, from 105 up to 140 kt; and storm 10 in 1926, from 105 to 130 kt in Cuba), one had a large decrease in landfall intensity (storm 2 in 1922, from 130 down to 100 kt in Bermuda), and the remainder had small or no alterations in landfall intensity.

5. Summary and future work

Continued progress on the hurricane reanalysis has been made through now the third decade of the twentieth century: 1921–30. While the results provided here are just brief summaries of the thousands of changes introduced into the Atlantic hurricane database, all raw observations, the original and revised HURDAT, annual track maps, metadata regarding changes for individual TCs, and comments from/replies to the Best Track Change Committee can be found online (http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html).

Highlights of accomplishments attained for this stage of the Atlantic hurricane database reanalysis project for 1921–30 include the following:

1) Track alterations were implemented for nearly all TCs in the existing HURDAT, though the majority were for minor changes (i.e., less than 120 n mi in position).
2) Intensity changes were incorporated into nearly all TCs with a much larger proportion with major alterations in their intensity (i.e., greater than or equal to 20 kt) compared with the track, either toward stronger or weaker winds.
3) Fourteen 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 TCs during the era was increased from 5.6 to 6.9 annually because of these net changes, a smaller increase was noted for hurricane frequency and no net changes were noted in the major hurricane numbers. The overall activity, as denoted by accumulated cyclone energy, was increased by about 7%.
5) Fifteen continental U.S. hurricanes were identified, one more than originally listed in HURDAT because of the addition of two new U.S. hurricanes (which originally were considered tropical storm impacts for the United States) and the removal of one during the time period. Of the 14 original U.S. hurricanes, 12 had no changes introduced for the peak category, 1 was downgraded a category, and 1 was removed. No changes were made to the number of major continental U.S. hurricanes (five) for the decade and none of these were adjusted for their top Saffir–Simpson hurricane wind scale category impact.
6) Nine major hurricanes struck other places in the Atlantic basin, one of which was newly classified as a major hurricane. Of the nine, three had large (at least 20 kt) increases in intensity at landfall, while one had a large reduction in landfall winds.

7) Despite the reanalysis changes, there exists significant uncertainty in TC tracks, significant undercounts in TC frequency, and significant underestimation of TC intensity and duration, especially for those systems over the open ocean.

This last point requires some elaboration. In the recent past, there have been some climate change studies utilizing HURDAT that have assumed essentially no missing TCs, no missing portions of TC life cycles, or no underestimating of the intensity of existing TCs beginning in the mid–twentieth century or even back to the beginning of the database in 1851 (e.g., Emanuel 2005; Mann and Emanuel 2006; Holland and Webster 2007). New work (Vecchi and Knutson 2008, 2011; Landsea et al. 2010) has come up with credible, quantitative estimates of how many TCs and hurricanes were likely to have been "missed" even in the reanalyzed historical database. Such work needs to be extended, if possible, to other TC metrics, such as major hurricane frequency and ACE. A measure of the underestimate in the intensity values in HURDAT up to 1930 has been provided in Table 1 with some quantitative analysis in Fig. 1 in support of these estimates. It is incumbent upon HURDAT users to not ignore the likely effects of incomplete sampling on creating spurious trends in various TC metrics.

Considerably more work needs to be accomplished for the Atlantic hurricane database. One essential project is to extend HURDAT back before 1851 to earlier in the nineteenth, eighteenth, and even seventeenth centuries. Such efforts are under way and have begun to yield important results (e.g., Chenoweth 2007; Mock 2008; Wheeler et al. 2009). This may lead to a complete dataset of U.S. landfalling hurricanes for the Atlantic coast from Georgia to New England, as well as for portions of the Caribbean 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 1930, these did not make extensive use of the Comprehensive Ocean–Atmosphere Data Set (COADS) until the decade of the 1910s (Landsea et al. 2004a). Further improvements in HURDAT could be achieved by utilizing this comprehensive ship database for the years of 1851–1910. Finally, an ongoing project is to complete the current reanalysis efforts through the remainder of the twentieth century. Preliminary results from this research (e.g., Hagen 2010) indicate the potential for much increased accuracy and completeness in HURDAT is possible.

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