A New Compilation of North Atlantic Tropical Cyclones, 1851–98*

MICHAEL CHENOWETH

Elkridge, Maryland

(Manuscript received 9 December 2013, in final form 31 July 2014)

ABSTRACT

A comprehensive new compilation of North Atlantic tropical cyclone activity for the years 1851–98 is presented and compared with the second-generation North Atlantic hurricane database (HURDAT2) for the same years. This new analysis is based on the retrieval of 9072 newspaper marine shipping news reports, 1260 original logbook records, 271 Maury abstract logs, 147 U.S. marine meteorological journals, and 34 Met Office (UKMO) logbooks. Records from throughout North America and the Caribbean region were used along with other primary and secondary references holding unique land and marine data. For the first time, North Atlantic daily weather maps for 1864/65, 1873, and 1881–98 were used in historical tropical cyclone research. Results for the years 1851–98 include the omission of 62 of the 361 HURDAT2 storms, and the further reduction resulting from the merging of storms to a total of 288 unique HURDAT2 tropical cyclones. The new compilation gave a total of 497 tropical cyclones in the 48-yr record, or an average of 10.4 storms per year compared to 6.0 per year in HURDAT2 less the author's omissions. Of this total, 209 storms are completely new. A total of 90 hurricanes made landfall in the United States during this time. Seven new U.S. landfalling hurricanes are present in the new dataset but not in HURDAT2. Eight U.S. landfalling hurricanes in HURDAT2 are now considered to have only tropical storm impact or were actually extratropical at landfall. Across the North Atlantic, the number of category-4 hurricanes based on the Saffir–Simpson hurricane wind scale, compared with HURDAT2, increased from 11 to 25, 6 of which made U.S. landfall at category-4 level.

1. Introduction

The second-generation North Atlantic (NATL) hurricane database (HURDAT2) is the longest and most complete record of tropical cyclone (TC) activity in any of the world's oceans (Landsea et al. 2004; Landsea and Franklin 2013). Despite this status, the ability to detect and attribute changes in a variety of tropical cyclone parameters with radiative forcing changes, aerosols, and internal climate variability (Knutson et al. 2010; Villarini et al. 2011) is highly uncertain. TC frequency in the NATL has a multidecadal variability that coexists with observational deficiencies prior to the satellite era. Trend analysis is highly subject to the endpoints used (Vecchi and Knutson 2008). Other parameters such as the location of tropical cyclogenesis, duration, and intensity are also subject to high uncertainty about their past behavior. This limits their usefulness in assessing model-based projections of changes in TC behavior due to the high signal-to-noise ratio in HURDAT2-derived parameters. One approach to reducing uncertainties is to improve the TC historical record (Knutson et al. 2010).

HURDAT2 originated in the 1960s as a project to support the Apollo Space Program. Subsequent updates, which include the recent conversion from the original HURDAT dataset (Landsea et al. 2004) to the HURDAT2 dataset (Landsea and Franklin 2013), corrected numerous random and systematic errors. The most extensive research to locate new data on historical TCs throughout the NATL basin was initiated by Fernandez-Paratagas and Diaz (1995a). Their search used three newspapers [*New York Times*, *Gaceta de la Habana*, and *The Times* (London)] along with the *Monthly Weather Review* as the main sources of data along with a number of secondary sources. New information on 106 previously unknown TCs from 1851 to 1910 was uncovered (Fernandez-Paratagas and Diaz 1995a,b, 1996a,b, 1997; hereafter FP&D 1995a,b, 1996a,b, 1997, respectively).

* Supplemental information related to this paper is available at the Journals Online website: http://dx.doi.org/10.1175/JCLI-D-13-00771.s1.

Corresponding author address: Michael Chenoweth, 6816 Ducketts Lane, Elkridge, MD 21075.
E-mail: mike.chenoweth@verizon.net

DOI: 10.1175/JCLI-D-13-00771.1

The data sources used included those available to Fernandez-Partagas in Miami but are insufficient to locate many storms. First, none of the newspapers was the most authoritative or complete source available in each of the three cities. Contemporary data aggregators combed through a much larger set of newspapers to provide more ship weather reports. In London, *Lloyd's List* was the best source for international coverage from U.K. ports and U.K. colonies and also provided items culled from other European countries and their colonial newspapers. In Havana, *Diario de la Marina* was the official Cuban newspaper that was focused on marine shipping. In New York City, various newspapers including the *New York Shipping List,* the *New York Maritime Register* (both aggregators), and the *New York Herald* and other dailies were consistently better than the *New York Times* in comprehensive reporting of weather encountered by ships at sea. The *New York Times* ceased regular detailed reporting of ship weather in their shipping news section after the 1877 hurricane season.

Second, three cities is insufficient to truly sample all of the ships that plied the NATL in the late nineteenth century. Even if every ship sailing to New York and London was captured in the newspaper accounts this leaves out ships that did not sail to both ports. Chenoweth and Divine (2008) showed that HURDAT failed to capture 28% of all TCs passing through the Lesser Antilles because of incomplete coverage in 1851–98. TCs encountered by ships outbound from New York or London toward the South Atlantic and beyond would go unreported in newspapers unless they are reported by an inbound ship or non-Atlantic-region newspapers are used.

Third, newspapers themselves have limitations that can only be captured in other sources. As national government weather centers began to be established in the late 1800s, there was a gradual shift of ship weather reports from marine shipping news sections to professional journals (particularly meteorological and hydrographical journals) and government gazettes and statistical yearbooks. Even the best data aggregators were reporting fewer ship weather reports by the late 1880s in both the United Kingdom and the United States. Also, newspaper accounts are poor second choices to the original logbook of the ship itself.

This work is part of a larger multicentury reconstruction of NATL TC history. The driving impulse of this research has been to locate original records to start the analysis anew. Existing datasets and chronologies contain secondary and derivative sources that must be viewed with caution because of the frequent propagation of errors from unreliable sources. Some of these issues were addressed in Chenoweth (2006). When original records are not available, secondary accounts were used if reliable source citations were provided.

By using an extensive collection of new resources, and not relying on any previous reconstruction until its sources and assumptions were checked with the newly acquired data, it was possible to significantly increase knowledge of nineteenth-century NATL TC activity. In doing so, it reduces both the high false positive rate of historical TCs in the secondary literature and the high false negative rate by the discovery of previously unidentified storms.

This paper employs a similar methodology to HURDAT2 but is not incorporated into HURDAT2 with the exception of about 15 storms. Differences in storm totals and U.S. landfalling hurricanes between the two datasets will be examined. [Supplemental material provides a copy of the new database along with metadata.]

2. Data sources

a. Data repositories and sources

The location of data repositories and the primary and secondary sources used in this study are included in the online supplement. The core source data for the compilation consists of 9072 newspaper ship news weather reports along with 1712 logbooks and logbook abstracts. [The total number of logbooks and newspaper reports used for each storm (excluding those on the daily map series from 1881 to 1898) are included in Table S1 of the supplemental material to provide a rough guide to the number of observations. Land-based weather journals are not included in Table S1. Other secondary sources, such as accounts in professional journals, are likewise not included.] For those storms common to both HURDAT2 and the new dataset ($N = 293$; see Table S1), there are about 4.9 times more newspaper items recovered for the new dataset ($N = 7623$) than by FP&D (1995a,b, 1996a,b) ($N = 1558$).

b. Daily weather map series

In this section, the focus is on the use of nineteenth-century daily NATL weather maps and their role in producing the new compilation. Their importance is noteworthy for never having been used in any previous reanalysis work.

Historical daily weather maps, such as those for the United States from 1871 onward (available online at http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html) were useful in tracking storms in waters near the U.S. coast and after making landfall. Daily maps for October 1877 through June 1884 (excluding September–October 1880) covering the entire Northern Hemisphere were published in the *Bulletin of International Meteorological Observations* (*BIMO*) along with tabulated data used to populate the maps. This resource was also useful in determining the large-scale synoptic weather situation needed to assess candidate TCs. However, low ship numbers in 1877–80 limited its usefulness. The *BIMO* maps do not include map symbols for ship weather reports whereas Toynbee (1878) published NATL daily weather maps for August 1873 that provided both data tables and plotted weather reports.

The new compilation ends after 1898 because daily weather maps are available for the entire Northern Hemisphere beginning in 1899 (Jenne 1975) and used by FP&D in their reanalysis work for 1899–1910 (e.g., FP&D 1997). (These once-daily maps are available at http://www.lib.noaa.gov/collections/imgdocmaps/synoptic_weather_maps_northern_hemisphere.html.)

Recently, a previously unused source of NATL daily weather maps was rediscovered at the Met Office (UKMO) National Meteorological Archive (MOA). This map series, entitled *Tägliche Synoptische Wetterkarten* (*TSW*; i.e., daily synoptic weather charts), was published by the Danish Meteorological Institute and the German Marine Observatory (Dänisches Meteorologischen Institut und Deutsche Seewarte 1884–1931) and covers December 1880–February 1912 (excluding September 1882 through August 1883, which was published by the Met Office as part of the International Polar Year). The maps were produced on a regular basis with gaps in publication in 1900, 1916–20, and 1923–30. The final set for December 1911–February 1912 was published in 1931.

Unlike the maps in the *BIMO*, the *TSW* covered only the NATL and provided more robust ship numbers than in *BIMO* and better resolution. This allowed for reading the plotted weather reports, which were not also provided in tabular form as in the *BIMO*. These German and Danish merchant marine data are not included in deck 192/215 in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Worley et al. 2005; Woodruff et al. 2011). The deck 192 observations were deliberately omitted from the master database in ICOADS because both it and Marine Data Bank (MDB) deck 215 were derived from the same original German punched cards and more observations were present in deck 215. Most of the original records have recently been digitized by Deutsche Seewetteramt in Hamburg (W. Gloeden 2013, personal communication). The bulk of the additional data not included in ICOADS is from the Atlantic region, according to the ICOADS web page (http://icoads.noaa.gov/mdb_tdf11.html). Data discrepancies between the two records may be reconciled once these new digital records can be incorporated into ICOADS. The names and types of each ship, about 200 in number, were included in each issue of the *TSW*. (A sample of *TSW* maps is included in the supplemental material.)

Mitchell (1924) made use of a portion of the *TSW*, as well as U.S. Hydrographic Office (currently known as the Naval Oceanographic Office) daily weather charts, in his compilation of NATL TCs for the years 1887–1923. However, he missed storms that remained in the eastern Atlantic or misinterpreted the information. For example, a tropical storm properly identified in November 1888 is then confused with a separate extratropical storm that formed off the southeast coast of the United States. This incorrect track is included as HURDAT2 storm 9 of 1888. (A map for 23 November 1888 is in the supplemental material depicting both lows.)

The discovery of the *TSW* led to follow-on investigation of a French document with daily weather maps for June–December 1864 first reported by David Roth (2012, personal communication). Further research led to the discovery that this was the *Atlas des Mouvements Généraux de l'Atmosphère* (*AMGA*), published in Paris (Observatoire Impérial de Paris 1868). This is the earliest set of NATL daily weather maps ever published and it was found that additional maps were published in 1869 that covered all of 1865. Hundreds of French merchant and naval vessels were used to construct the maps and were previously unavailable in any format. Contact was made with officials in Météo France who provided access to online versions of the daily map series for each day from June 1864 through December 1865. This data source was incorporated into the new compilation and a sample included in the online supplement.

The main focus of the original search for TCs was for the months of May through December because of the high time investment to find relatively rare out-of-season storms in newspaper accounts. The *TSW* (and *BIMO*) did allow for all months to be examined for the 1881–98 hurricane seasons. Therefore, when making comparisons of the new compilation with HURDAT2, storms originating in the months of January through April are removed to ensure a valid comparison for all years since 1851.

3. Methodology

a. Detection and storm-track production

Weather data were gathered, collated, and analyzed to produce new storm tracks for the years 1851–98. As in FP&D (1995a,b, 1996a,b, 1997) the land and sea weather reports were hand-plotted on maps to estimate TC positions and produce a subjectively smoothed storm track. Wind direction observations were used to determine the approximate location of low pressure centers from an assumption of symmetric surface wind flow with an inflow angle of 20° (Jelesnianski 1993) and this approach is implicit in FP&D (1995a,b, 1996a,b, 1997) and stated in Landsea et al. (2008). The raw observations were used to estimate storm center positions, or ‘‘center fix’’ as used in Landsea et al. (2004). The estimated center of low pressure was first determined before any attempt at classifying the TC or estimating its maximum wind speed. The estimated position errors are considered to be comparable to estimates made by Landsea et al. (2004): 60 nmi along the coast and 120 nmi in the open ocean (1 nmi ≈ 1852 m).

b. Criteria for accepting new storms

The National Hurricane Center (NHC) defines a tropical cyclone as ‘‘a warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface circulation about a well-defined center’’ (http://www.nhc.noaa.gov/aboutgloss.shtml). Landsea et al. (2008) used the following criteria for adding new storms (of tropical storm or greater intensity) in the prereconnaissance, presatellite era: 1) nonfrontal (not an extratropical cyclone); 2) closed surface wind circulation; and 3) at least two separate observations of tropical storm force winds (at least 34 kt; 1 kt ≈ 0.51 m s^{-1}) or the equivalent in sea level pressure (~1005 hPa or lower). The two separate observations could come from the same observing site or two different sites. The rule minimizes possible errors from instrumentation or typographical errors. Additionally, with datasets like ICOADS (Woodruff et al. 2011) ship identification is sometimes incomplete or absent. Likewise, daily map series contain weather reports from unidentified ships. The NHC Best Track Change Committee (BTCC) makes the decision to include new storms into HURDAT2.

These same criteria were used in the new compilation. Omissions of storms that happen to be included in HURDAT2 are a result of new data sources and analysis.

Multiple independent reports did not guarantee inclusion into the new compilation. Over 11 000 newspaper ship weather accounts alone were considered. A large number of marginal cases were rejected resulting from the lack of a critical piece of information, or the absence of sufficient detail in any of the sources to admit its inclusion. A total of 102 candidates in 1851–98 were determined to be extratropical storms and were not included as a result of the methodology and source criticism applied. Likewise, an additional 211 candidates were excluded because of the lack of sufficient evidence (in most cases likely extratropical), 47 were considered to be tropical waves, 14 were classified as tropical depressions (never achieving storm status in their lifetimes), and another six were classified as tropical lows. About 43% of all of the candidate storm systems collated from ship reports and other sources (369 of 866) did not make the final cut to be considered TCs.

In a few instances there is only a single source providing observations confirming the presence of a tropical cyclone. If the source provides unambiguous meteorological observations describing a sequence of events (two or more discrete observations) over a period of time this meets the HURDAT2 criteria for two or more separate observations.

Readers interested in viewing data submitted by the author to the BTCC in the past can read them either online at the HURDAT2 web page (www.aoml.noaa.gov/) or can view two examples included in the supplemental material (HURDAT2 storm 2 of 1857 and storm 8 of 1859). Readers are also referred to Chenoweth and Mock (2013) for another example of the methodology for a new storm presently under consideration for inclusion by the BTCC. Finally, Chenoweth (2009) documents a Florida hurricane that occurred in June 1816 while record cold prevailed in New England.

c. Criteria for rejecting or omitting storms

The rejection or removal of a storm from HURDAT2 by the BTCC is done when ‘‘sufficient observations’’ provide reasonable certainty that no tropical storm force winds were present throughout any point of the life cycle of ‘‘a non-frontal, closed-circulation’’ structure.

The new compilation rejected any candidate systems (whether or not presently included in HURDAT2) when the observations indicated that throughout the life cycle of the system there was no evidence of tropical storm or stronger winds, a system’s energy was generated from the contrast of warm and cold air, or the evidence for a closed surface circulation was not present.

Source criticism included a careful parsing of the precise wording of the accounts for ambiguities that could lead to multiple interpretations, and the absence of critical evidence. Ships often reported encountering hurricane-force winds in extratropical storms or considered themselves to be in a hurricane when experiencing subhurricane-force winds. Reports of hurricane winds from only a single point of the compass are highly suspect in most cases. The collation of large numbers of reports allowed for relative weightings of the reliability of any individual source with respect to others. Marginal cases always received additional scrutiny.

d. *Reasons for omitting HURDAT2 storm*

When failed candidate systems happened to be included in HURDAT2, the reason for the inclusion of the system in HURDAT2 was examined. This was done by examining the data from FP&D (1995a,b, 1996a,b), Fernandez-Partagas's interpretation of it, and the comments of the BTCC for accepting the storm. Information from other contributors for pre-1899 storms was also considered when present.

Fernandez-Partagas took a skeptical view to a number of systems he studied but he employed an extremely conservative approach and never recommended removing any storms. The BTCC committee did reject eight of his original storms and merged a set of two others in the years 1851–98. Since the initial round of reanalysis, two other storms were rejected by the BTCC, one of which was originally suggested by this author.

The new compilation reveals abundant evidence that sufficient observations exist for rejecting a large number of storms included by previous compilers. (Table S2 of the supplemental material lists the storms rejected and the general reason for excluding each.) A common reason for exclusion was the utter absence of tropical storm–force winds. Also, the confusion of extratropical lows and associated troughs of low pressure and embedded cold fronts resulted in bad assumptions by the U.S. Signal Corps (predecessor to the National Weather Service) that heavy rains and stormy weather were part of a TC. Without the Bjerknes polar front model or other theoretical concepts at hand, contemporary meteorologists did not interpret their data in ways presently available. This led to the observation of an apparent trend of preferred landfalling TCs on Florida's Gulf coast relative to Florida's Atlantic coast prior to 1900 (Doehring et al. 1994) that can now be seen to be false.

Another reason for exclusion of storms is due to the lack of sufficient precisely dated and precisely located observations to accurately maintain continuity on individual observation platforms. (The supplemental material dissects HURDAT2 storm 1 of 1862 and reveals the incorrect assumptions and misinterpretations of the source data that provided the basis for this storm in HURDAT2 and that led to its omission from the new compilation.)

e. *Categorization of storms*

The determination of tropical versus extratropical status rests on examining evidence in the surface fields for a synoptic-scale closed low pressure that is nonfrontal in nature, with little or no temperature contrast across the center, and over tropical or subtropical waters, with specific classification of the system depending upon the estimated sustained maximum 1-min winds. Transition of tropical cyclones to extratropical (posttropical) stages is better estimated with daily weather maps. When synoptic maps are unavailable, there is a necessary amount of arbitrariness in the choice of timing of the transition. This can be partly compensated by considering the season of the year, the location of the storm, the seasonally dependent SSTs likely to be present, and any evidence available in the observations indicating asymmetries in the wind field, expansion of gale force winds at higher latitudes, and the sequence of events described in individual accounts. (See the supplemental material for detailed case studies that involve storms that were extratropical at some points in their life cycle.)

Once a system was classified as having been a tropical (or likely subtropical) cyclone then a specific category was determined. As with HURDAT2, peak winds were determined from central pressure observations, in situ anemometer measurements (essentially nonexistent prior to 1871) adjusted for instrumentation bias, Beaufort wind force, wind-induced damage to property on the coast, and storm tide. Unlike HURDAT2, in some instances, a modified Fujita scale estimate of wind-induced damage on land was used to approximate peak winds on land in the same manner as in Boose et al. (2001, 2004). Representative maximum wind-induced damage provided an estimated wind speed maximum. Collocated wind force estimates were used with the wind-induced damage reports for categorization into tropical depression, tropical storm, hurricane, and major hurricane categories (Chenoweth 2007). Peak wind-induced damage reports to manmade structures and vegetation were used to estimate peak wind speed of a TC and consideration was given to the location of the reports (coastal, inland, and topography).

The methodology of Boose et al. (2001, 2004) has a slight positive bias in its reconstructed versus actual damage in their damage-based empirical wind model. Likewise, Chenoweth (2007) considered that structural damage indicating major hurricane intensity in the Lesser Antilles in the nineteenth century should include all wind speeds >90 kt, compared to the modern threshold of >95 kt. Therefore, there is a possible high bias in the estimated maximum wind speeds relative to HURDAT2 in cases where pressure data at or near the storm center is not available in at least the Lesser Antilles region and possibly elsewhere in the North Atlantic basin. However, assigned classifications of major hurricanes still use the >95-kt threshold in the database.

At sea, reports rely mainly on Beaufort scale wind force terms and damage that can be assigned primarily to wind such as the shearing of ships' masts, which typically only occurs with hurricane-force winds. As in Landsea et al. (2004), major hurricane status for ships in the open ocean was generally not assigned unless pressure data were available. The uncertainty in wind speed estimates are considered to be about 15 kt in coastal areas and 25 kt in the open ocean in agreement with Landsea et al. (2004).

Unlike HURDAT2, tropical depression stages are routinely included in the years 1851–98 in the new compilation. At sea, tropical depressions and tropical lows of <25 kt were not classified as such or included in the new compilation. Inland, there was no use of any inland decay model when no inland wind force or wind damage data were available. With only a few exceptions, there was normally abundant information to track dissipation of U.S. landfalling TCs. Outside of the United States, such information was rare. In such instances, dissipation rates are subjectively estimated and topographical differences in decay rates are taken into account.

Wind speeds were assigned in 5-kt increments. In HURDAT2, 10-kt increments are used from 1851 to 1885. These differences need to be kept in mind when comparing estimates of peak wind speed for U.S. landfalling hurricanes from this analysis and the HURDAT2 record. The use of 5-kt increments allowed for direct incorporation of wind–pressure relationship wind speed values and for realistic extrapolation of wind speeds between observation points. This should not distract from the real uncertainty in any wind speed value in this era because of the lack of anemometers capable of recording high wind values at this time (Fergusson and Covert 1924).

f. Wind–pressure relationships

Maximum sustained wind speeds can be estimated from peripheral or central pressure data in the center of a TC or the hurricane eyewall (Landsea et al. 2004). Regional variations applied were those from Landsea et al. (2004) and updated in the Gulf of Mexico region by Brown et al. (2006). The radius of maximum wind (RMW) could sometimes be reliably estimated in the Lesser Antilles (Chenoweth 2007) and in other scattered instances where the translational speed of the TC could accurately be determined. The usual absence of simultaneous accurate environmental pressure data limited the ability to estimate RMW by measuring the distance from the storm center to the nearest peak wind-induced damage report.

This uncertainty exists in the *AMGA* and *TSW* daily weather map series. *AMGA* maps are for 0800 local ship time but because of the difficulty in obtaining adherence even to the local time, the actual plotted data ranged from approximately 0600 through 1000 local time (Observatoire Impérial de Paris 1868). These maps are not truly synchronous and this uncertainty was considered when using the data in producing storm tracks. Similar uncertainty exists in the *TSW* map series (1881–98) because there is no commentary included in the atlases to provide metadata. The *TSW* maps depict plotted land and marine weather reports for "0800" but land data from North America are taken from U.S. Signal Corps station data from their original reports made at 0735 Washington, D.C., mean time (1243 UTC). This was the stated time used in the August 1873 maps (Toynbee 1878) and an allowance of 1 h from the stated time was allowed. When the ship time was more than 1 h from 1243 UTC this was notated on the map.

Provided no decisive new instrumental or storm surge data were found, the wind speed and RMW values in HURDAT2 were used. There are differences in location and time and intensity of landfall in many instances although usually the differences are relatively small. A few storms have already been provided to the BTCC and are a part of the HURDAT2 record (HURDAT2 storm 2 of 1857, and storms 5 and 8 of 1859). The author also contributed to previous reanalysis of portions of the tracks of other HURDAT2 TCs including storm 2 of 1861, storm 6 of 1862, storm 7 of 1866, storm 6 of 1887, storm 7 of 1887, storm 15 of 1887, storm 7 of 1891, storm 8 of 1891, storm 6 of 1901, storm 3 of 1904, and one not making a land impact, storm 3 of 1909. Other systems were provided classed only as tropical depressions or otherwise are not included in HURDAT2, and none of these storms is in the new compilation.

g. Single-point tropical cyclones

HURDAT2 has a number of "single-point" TCs that were included into the dataset from the work of FP&D (1995a). Landsea et al. (2004) state: "This was typically due to one encounter of a tropical cyclone by a ship or the landfall of the system along the coast with no prior recorded contact with a ship or other coastal location." No such storms were allowed into the new compilation. Instead, new data were found to confirm bad data status or extend the tracks of those that were found to be real TCs.

h. Counting subtropical storms and tropical depressions

The distinction between a subtropical storm and a tropical storm is difficult to determine from only surface-based data (Guishard et al. 2009). It is assumed that subtropical storms would be considered tropical storms if detected in the past, although 10 of the 497

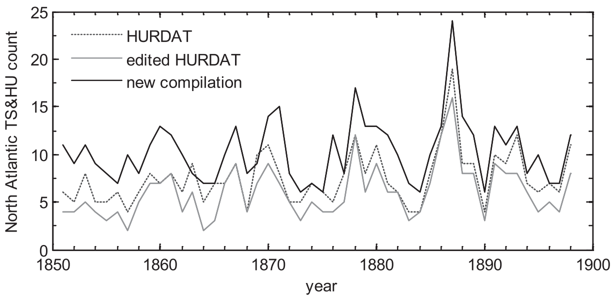

FIG. 1. The number of detected tropical cyclones in the North Atlantic originating in the months May through December from 1851 to 1898 showing the number in HURDAT2 as of October 2013 (dotted line); HURDAT2 (less the author's omission) numbers without identified false positives following the new compilation for 1851–98 (gray line); and the new compilation for 1851–98 (black line). The original HURDAT2 total of 361 storms was determined to actually include only 288 distinct storms. The new compilation also found an additional 209 new tropical cyclones not previously included in HURDAT2.

storms in 1851–98 are notated as subtropical storms in their entire life cycle to alert the users to evidence from the available surface data (closed low, temperature, and the observed distribution of gale-force winds around the low, in particular). Evidence for organized convection, which is associated with current TC classification including subtropical storms, is not easily discerned from a network of surface station data. In both Landsea et al. (2008) and the new compilation this criterion is not included in making new storm additions in the presatellite era. Finally, tropical depressions that never further developed were found but are not used in the results presented here.

i. Uncertainty in tropical cyclone counts

Landsea et al. (2004) estimated the number of "missed" TCs to be about 0–6 storms per year from 1851–85 and 0–4 storms per year from 1886–1910 under the assumption of decreasing ship numbers, coastline population, and available observations back in time. The new compilation has more observations and a comparison of the numbers in Fig. 1 indicates that from 1851 to 1885 anywhere from 1 to 8 storms were missed in the "edited" HURDAT2 counts and from 1886 to 1898, 0–8 storms were missed. On average, there are 4 more storms in the new compilation from 1851 to 1885 and 3 more storms from 1886 to 1898 than in HURADT2. Vecchi and Knutson (2008) estimated about 0–6 (about 0–4) missed storms during 1878–87 (1888–98) in their ship-track adjusted methodology. Their estimates, within its own stated methodological assumptions, broadly fall in range with the new compilation's difference from the edited HURDAT2.

The uncertainty in the new compilation is estimated between −1 and +2 storms annually when historical daily weather maps are not available, thereby accounting for possible merging or splitting of storms, or false positives. In years with NATL daily weather map the estimate is 0–2 storms. These differences from HURDAT2 and Vecchi and Knutson (2008) arise from the vastly improved sample size of the new compilation, the actual increase in ship platforms back in time (see http://homepages.ihug.co.nz/~j_lowe/C16ComparisonBVLL.htm), and slower moving ships on average, and therefore the increased likelihood of encounters with tropical cyclones.

j. New TC database

A database with the new storm positions and intensity for 1851–98 is included in the supplementary material. This database can be considered in its content to be equivalent to the best tracks in the original HURDAT but does not include storm size as in HURDAT2 (Landsea and Franklin 2013). These data are formatted with the same data fields as in the original HURDAT format now no longer used operationally. This includes position (to the nearest 0.1° latitude and longitude) estimates every 6 h from 0000 UTC (0000, 0600, 1200, and 1800 UTC), along with intensity (maximum sustained 1-min surface winds at 10 m) and central or peripheral pressure if available. The HURDAT2 storm number is provided in the first field and the new storm number is provided in the second field. The first field is blank when a new storm not present in HURDAT2 was found. The gaps in the HURDAT2 storm number sequence are a result of some HURDAT2 storms being rejected. In some instances, where storms have been merged or split, more than one HURDAT2 storm number may appear in one new storm listing. Although the present database only contains main synoptic hour data, it can include any selected time.

A metadata file of all newspaper accounts used for 1851–98 is also included in the supplemental material. This metadata file provides the name of the newspaper, the date of its publication, the location of the weather reported, and the date(s) covered in the weather report. The actual storm accounts are not included in this database. Narrative accounts of a few of the individual storms have been published (Chenoweth and Mock 2013) or provided to the NHC BTCC in the past (although new data have accumulated in most instances for these submissions since their first provision to the BTCC). (Examples of past submissions are included in http://www.aoml.noaa.gov/hrd/hurdat/metadata_jun2013.html.)

In comparison, HURDAT2 presently includes full write-ups of each storm written by a variety of contributors and screened by the NHC BTCC for quality control and critical review. In addition to the HURDAT2 database itself, there is a metadata file documenting changes within HURDAT2 to each TC from reanalysis, a center fix file of raw observations, a compilation of U.S. landfalling TCs, and also a record of comments and replies by the contributors and the committee. This more complete set of data provides greater visibility to their much smaller total of raw data input used in HURDAT2 and additional ''value-added'' files relative to the new compilation presented here.

4. Results

a. Tropical cyclone numbers

The new compilation revealed that 62 of 361 TCs present in HURDAT2 as of August 2013 were not actually TCs. (Table S2 in the supplemental material presents the list of storms that were excluded and the reasons for their exclusion.) There are 22 storms that are misidentified as separate storms when they are actually the same storm (HURDAT2 storms 2 and 3 of 1852; 4 and 5 of 1856; 4 and 5 of 1862; 2 and 3 of 1863; 7 and 8 of 1869; 3 and 4, and 7 and 8 of 1870; 1 and 2 of 1871; 6 and 7 of 1880; 7 and 8 of 1891; and 7 and 8 of 1898). Once these 22 separate storms are combined into 11 storms, this reduces the total to 288 or an average of 6.0 storms per year in HURDAT2 less the author's omissions. The new compilation produced a total of 497 TCs, an average of 10.4 storms per year. (Table S3 in the supplemental material lists each storm in the new compilation along with date, location, intensity, and other data.) Figure 1 depicts the differences in storm numbers from 1851 to 1898 among HURDAT2, HURDAT2 less the author's omissions, and the new compilation.

b. Impact of *TSW* daily map series on initial analysis

An initial analysis was completed in February 2013. In April 2013, the *TSW* map series was used for the first time in modern TC reanalysis.

The rediscovery of this important source allowed for a test of the initial analysis work that had no such maps prior to 1899. The maps allowed for ambiguous cases to be fully resolved resulting in both the inclusion of new (13) and rejection of existing (4) storms. Only one new storm and one new rejected storm occurred prior to 1884, when the *BIMO* data were available for the first version. In the 15 years (1884–98) that had daily maps for the second round of reanalysis, an average of 0.8 new storms and 0.2 new rejected storms were found, a net increase of 0.6 storms per year.

The use of data in the *AMGA* (Observatoire Impérial de Paris 1868, 1869) allowed for adjustments to the original analysis as occurred with the *TSW* series. Two new storms were added and one was removed, a net increase of 0.5 storms per year, which is similar to the net increase observed using the *TSW* map series.

With 20 years of independent map data available to check the initial analysis, there are a total of 15 new storms and 5 rejected storms. This is three false negatives for every false positive. This is close to the same ratio for the derived differences with HURDAT2, which in comparison with the new compilation had 209 false negatives versus 62 false positives, a 3.4:1 ratio. Using the discovery rate of 1864/65 and 1881–98, this gives an estimate for the remaining 28 years that a net increase of 14 TCs remain to be found. This would bring the total for 1851–98 to 511 TCs, an average of 10.6 TCs per year.

Figure 2 depicts the 1873 North Atlantic tropical cyclone tracks from HURDAT2 and compared with the new tracks from the new compilation. This year is chosen as it has features that are typical of most other years: 1) two storms from HURDAT2 (storms 1 and 4) that are omitted; 2) it benefits from daily weather maps for the month of August (Toynbee 1878), which allowed for modifications of the track, intensity, and extratropical transition of storm 2 in HURDAT2; and 3) it includes new storms not in HURDAT2.

HURDAT2 identifies 11 NATL hurricanes reaching category 4 on the Saffir–Simpson hurricane scale. The new compilation identifies 25 category-4 hurricanes and no hurricane of category-5 intensity.

c. U.S. landfalling tropical cyclones

A more detailed look at landfalling TC statistics and trends will be presented in another paper. [Table S2 (column H) in the supplemental material identifies the 27 U.S. landfalling tropical storms presently in HURDAT2 that do not appear in this new compilation and Table S4 shows U.S. landfalling hurricanes included in the new compilation compared with that in HURDAT2 as of October 2013.] HURDAT2 lists 93 U.S. landfalling hurricanes but the new compilation identifies six of these to only have been tropical storms at landfall (or impact on shore) and two others as extratropical, which reduces the total to 85 U.S. landfalling hurricanes.

The new compilation has a total of 91 hurricanes making landfall or producing hurricane force winds along the U.S. coast without the center crossing land. Seven of the hurricanes are newly discovered. Two storms (HURDAT2 storms 8 of 1861 and 6 of 1888) are now analyzed to have been extratropical at U.S. landfall impact in HURDAT2. Seven other HURDAT2 U.S. landfalling hurricanes were analyzed to only be tropical storm intensity at landfall or maximum landfall impact [HURDAT2 storm 8 of 1861 (new tropical storm

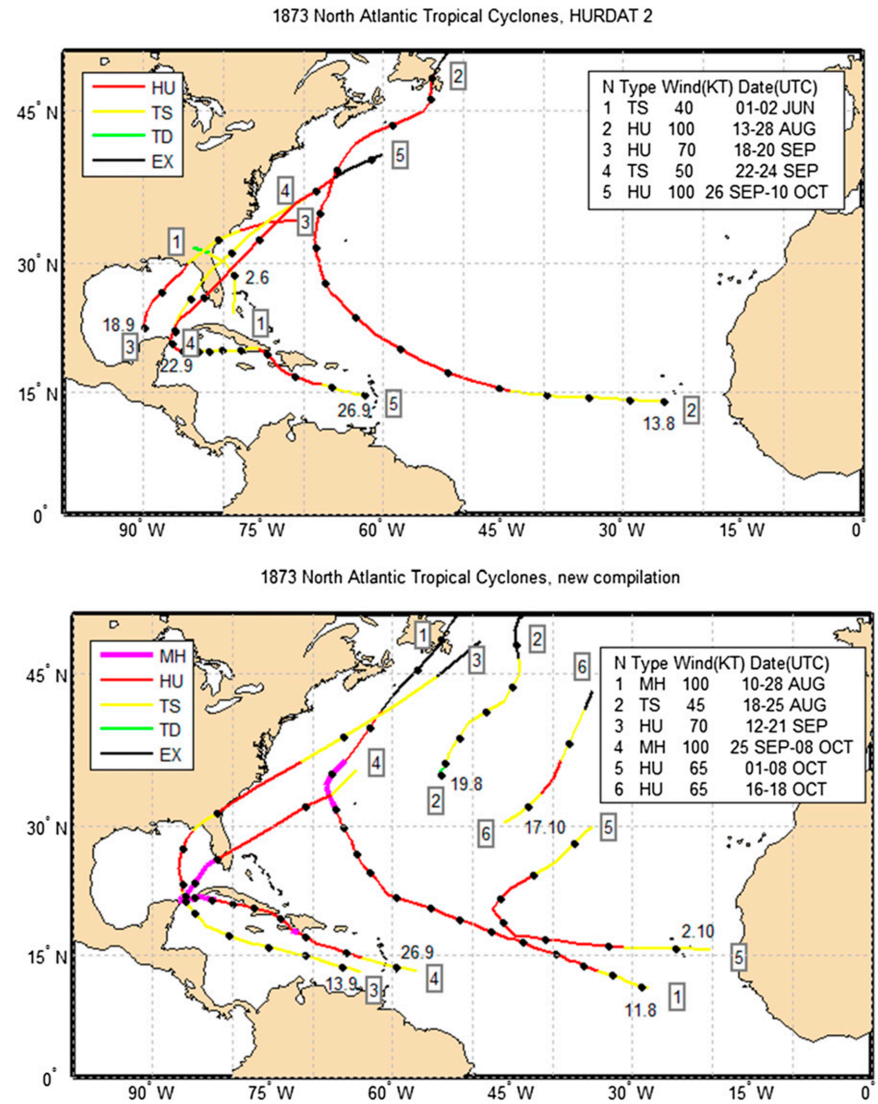

FIG. 2. North Atlantic tropical cyclone tracks for the 1873 hurricane season based on data from (top) HURDAT2 and (bottom) the new compilation. The dates of each storm are expressed in UTC. Black dots indicate the 0000 UTC estimated center of each storm. The date of the first plotted 0000 UTC report is indicated along with the season's storm number near the start of each track. Storm positions north of 50°N are not presented in these maps. Classification of storm intensity includes green for tropical depression, yellow for tropical storm, red for hurricane, purple for major hurricanes (Saffir–Simpson hurricane wind scale category 3 or higher), and black for extratropical stage. The new compilation rejected two HURDAT2 storms but added three new storms in the eastern half of the Atlantic.

landfall in Louisiana not in HURDAT2 and extratropical by the time it reached North Carolina, where HURDAT2 lists it being a hurricane); storm 9 of 1880; storms 2 and 4 of 1886; storm 1 of 1888; storm 6 of 1889; and storm 2 of 1896]. The downgrading of two U.S. landfalling hurricanes in 1886 drops the number of U.S. hurricane landfalls from 7 to 5. This gives 1985, 2004, and 2005 as the years with the most (6) U.S. landfalling hurricanes in a single season.

The seven new hurricanes were located all along the U.S. coast from south Texas to southeast Massachusetts and all before 1875. Three of the hurricanes are entirely new [July 1854 (south Texas), October 1857 (southeast Florida), and May 1863 (northwest Florida)] while the others are presently included in HURDAT2 as either tropical storms or offshore hurricanes whose impact only reached tropical storm intensity on land [storm 4 of 1863, storm 2 of 1867, and storms 1 and 2 of 1871 (one storm with two separate hurricane landfalls in the new compilation; HURDAT2 presently lists each as separate tropical storms at landfall); storm 7 of 1871; and storm 4 of 1874]. The 1874 south Texas storm was a category-3 major hurricane. The remaining storms were evaluated to be category-1 or category-2 hurricanes in their impacts. HURDAT2 also benefited from this analysis work in the inclusion of a previously unknown Florida landfalling hurricane in October 1859 (storm 8 in HURDAT2) provided by the author.

Eight landfalling U.S. hurricanes were upgraded to category 3 or 4 based on new information. These storms in HURDAT2 are storm 4 of 1854, storm 6 of 1860, storm 4 of 1865, storm 7 of 1865, storm 7 of 1867, storm 9 of 1870, storm 4 of 1880, and storm 4 of 1887. Since five of these involve small increments in wind speed from 90 to 100 kt (1854, 1860, 1865, 1867, and 1880) there is the potential for differences in categorization arising from methodological differences. However, new pressure data are available for the 1867 and 1880 storms to further support their recategorization. There are now six U.S. landfalling hurricanes at category-4 level from 1851 to 1898: HURDAT2 storms 1 of 1856, 3 of 1875, 2 of 1880, 5 of 1886, 10 of 1893, and 7 of 1898.

One HURDAT2 major hurricane (storm 3 of 1888) was reduced to a 95-kt category-2 storm. No source for the claim of a 14-foot (~4.3 m) storm tide at Miami was available in the popular reference book cited by the NHC BTCC. For this reason, along with the absence of other evidence supporting a storm so intense in the area, this storm was not considered a major hurricane anywhere in its course. Barometric pressure data were available in Louisiana for the landfall location to classify the storm as a 95-kt TC.

5. Discussion and conclusions

A new compilation of North Atlantic tropical cyclones (NATL TCs) for the years 1851–98 was described providing the data sources and methodology used for identifying, categorizing, and constructing new storm tracks. Differences with the 1851–98 portion of the HURDAT2 database were examined. A total of 497 TCs were identified from 1851 to 1898, an average of 10.4 storms per year. This compares with 6.0 storms per year after the noninclusion and merging of storms from HURDAT2 data. For the first time, daily North Atlantic weather maps for the years 1864/65, 1873, and 1881–98 were used in TC research. The unique data used to produce these maps constitute an additional major new source of information for NATL TC history. It also disproves the popular notion that data availability in the late nineteenth century is poorer than in the early twentieth century. Instead, data sources and repositories were forgotten, ignored, or overlooked for many years and many reasons.

There are also new updates to the history of U.S. landfalling TCs, with 27 landfalling tropical storms in HURDAT2 indicated as being nontropical or nonexistent events. Seven new U.S. landfalling hurricanes are present in the new dataset that are not in HURDAT2. Two U.S. landfalling hurricanes in HURDAT2 are excluded as a result of their being extratropical at time of impact and six other hurricane impacts are reduced to tropical storm impact.

Future refinements to these results are possible. Inland decay models (Kaplan and DeMaria 1995) could be systematically employed to make small adjustments in postlandfall storm intensity. Likewise, storm surge models (Jelesnianski et al. 1992) could be used with the new track positions and observed storm surge data to further refine landfall intensity values. Hurricane impacts in particular states could benefit from application of the Accurate Environmental Forecasting, Inc. (AEF) RealTrack hurricane model (Dickinson et al. 2004). As with all such TC datasets, the largest uncertainties exist in the estimated maximum wind speed. For storm position and dating, and the discovery of previously unknown TCs, the new compilation presented here represents a major step forward in more accurately characterizing the TC record of the North Atlantic.

Unread still are Danish daily weather maps for the NATL listed in a catalog published by Bibliothek der Deutschen Seewarte (1890). These maps were also a joint effort between the Danish Meteorological Institute and Deutsche Seewarte and depict the weather at 0800 local time for ships at sea (Deutsche Seewarte 1879). The maps were published from 1876 to 1880 and run from September 1873 to November 1876. The series is entitled "Cartes synoptiques journalieres embrassant l'Europe et le nord de l'Atlantique" and authored by Nils Hoffmeyer. Contact with the Danish Meteorological Institute confirmed that the maps had been moved to the Danish State Archives. In future, the maps will be consulted to further improve the new compilation.

A companion paper will examine trends in tropical cyclone parameters to include storm numbers, cyclogenesis, duration, and accumulated cyclone energy. This will be done by appending the new compilation to the HURDAT2 record for 1899–2013 and performing the statistical analysis on the period of record 1851–2013.

Acknowledgments. The author acknowledges the generous assistance of Philippe Dandin, Jean-Pierre Javelle, Sylvie Jourdain, and Nadine Cenac of Météo France in answering questions and providing data associated with the French daily weather map series; Jens H. Christensen of the Danish Meteorological Institute for confirming the existence and location of the Danish daily weather map series; and the staff of the Met Office National Meteorological Archive for assistance in working with the German daily weather map series and providing other resources used in this study. Mary Lou Cumberpatch of the NOAA Central Library also kindly assisted in locating resources used in this study. Chris Landsea, National Hurricane Center, Miami, provided important and useful suggestions to an earlier version of this paper. Cary Mock, University of South Carolina–Columbia, generously provided data. Dmitry Divine, Norwegian Polar Institute, Tromsø, Norway, produced the figures.

REFERENCES

Bibliothek der Deutschen Seewarte, 1890: *Katalog der Bibliothek der Deutschen Seewarte zu Hamburg.* Hamburg, 619 pp.

Boose, E. R., K. E. Chamberlin, and D. R. Foster, 2001: Landscape and regional impacts of hurricanes in New England. *Ecol. Monogr.,* **71,** 27–48, doi:10.1890/0012-9615(2001)071[0027:LARIOH]2.0.CO;2.

——, M. I. Serrano, and D. R. Foster, 2004: Landscape and regional impacts of hurricanes in Puerto Rico. *Ecol. Monogr.,* **74,** 335–352, doi:10.1890/02-4057.

Brown, D. P., J. L. Franklin, and C. Landsea, 2006: A fresh look at tropical cyclone pressure–wind relationships using recent reconnaissance-based ''best track'' data (1998–2005). *27th Conf. on Hurricanes and Tropical Meteorology,* Monterey, CA, Amer. Meteor. Soc., 3B.5. [Available online at https://ams.confex.com/ams/27Hurricanes/techprogram/paper_107190.htm.]

Chenoweth, M., 2006: A re-assessment of historical Atlantic basin tropical cyclone activity, 1700–1855. *Climatic Change,* **76,** 169–240, doi:10.1007/s10584-005-9005-2.

——, 2007: Objective classification of historical tropical cyclone intensity. *J. Geophys. Res.,* **112,** D05101, doi:10.1029/2006JD007211.

——, 2009: Daily synoptic weather map analysis of the New England cold wave and snowstorms of 5 to 11 June 1816. *Historical Climate Variability and Impacts in North America,* L. A. Dupigny-Giroux and C. J. Mock, Eds., Springer, 107–121.

——, and D. Divine, 2008: A document-based 318-yr tropical cyclone record for the Lesser Antilles, 1690–2007. *Geochem. Geophys. Geosyst.,* **9,** Q08013, doi:10.1029/2008GC002066.

——, and C. J. Mock, 2013: Hurricane Amanda: Rediscovery of a forgotten U.S. Civil War Florida hurricane. *Bull. Amer. Meteor. Soc.,* **94,** 1735–1742, doi:10.1175/BAMS-D-12-00171.1.

Dänisches Meteorologischen Institut und Deutsche Seewarte, 1884–1931: *Tägliche Synoptische Wetterkarten für den Nordsatlantischen Ozean und die anliegenden Theile der Kontinente.* Copenhagen and Hamburg.

Deutsche Seewarte, 1879: Ueber das fortschreiten barometerischer Depressionen auf dem Nord-Atlanticschen Ocean. *Wochenschr. Astron. Meteor. Geogr.,* **22,** 156–158.

Dickinson, M., G. D. Rowe, R. Richardson, I. Ginis, and L. Rothstein, 2004: Use of numerical weather prediction technology for simulation of historic tropical cyclones. *26th Conf. on Hurricanes and Tropical Meteorology,* Miami, FL, Amer. Meteor. Soc., 16C.4. [Available online at https://ams.confex.com/ams/pdfpapers/75936.pdf.]

Doehring, F., I. W. Duedall, and J. M. Williams, 1994: Florida hurricanes and tropical storms 1871–1993: An historical survey. Florida Sea Grant Program Tech. Paper TP-71, Institute of Technology, Melbourne, FL, 118 pp.

Fergusson, S. P., and R. N. Covert, 1924: New standards of anemometry. *Mon. Wea. Rev.,* **52,** 216–218, doi:10.1175/1520-0493(1924)52<216:NSOA>2.0.CO;2.

Fernandez-Partagas, J., and H. F. Diaz, 1995a: A reconstruction of historical tropical cyclone frequency in the Atlantic from documentary and other historical sources. Part I: 1851–1870. NOAA, Climate Diagnostics Center. [Available online at http://www.aoml.noaa.gov/hrd/Landsea/Partagas/part1.htm.]

——, and ——, 1995b: A reconstruction of historical tropical cyclone frequency in the Atlantic from documentary and other historical sources. Part II: 1871–1880. NOAA, Climate Diagnostics Center. [Available online at http://www.aoml.noaa.gov/hrd/Landsea/Partagas/part2.htm.]

——, and ——, 1996a: A reconstruction of historical tropical cyclone frequency in the Atlantic from documentary and other historical sources. Part III: 1881–1890. NOAA, Climate Diagnostics Center. [Available online at http://www.aoml.noaa.gov/hrd/Landsea/Partagas/part3.htm.]

——, and ——, 1996b: A reconstruction of historical tropical cyclone frequency in the Atlantic from documentary and other historical sources. Part IV: 1891–1900. NOAA, Climate Diagnostics Center. [Available online at http://www.aoml.noaa.gov/hrd/Landsea/Partagas/part4.htm.]

——, and ——, 1997: A reconstruction of historical tropical cyclone frequency in the Atlantic from documentary and other historical sources. Part V: 1901–1908. NOAA, Climate Diagnostics Center. [Available online at http://www.aoml.noaa.gov/hrd/Landsea/Partagas/part5.htm.]

Guishard, M. P., J. L. Evans, and R. E. Hart, 2009: Atlantic subtropical storms. Part II: Climatology. *J. Climate,* **22,** 3574–3594, doi:10.1175/2008JCLI2346.1.

Jelesnianski, C. P., 1993: The habitation layer. Guide to global tropical cycle forecasting, WMO Tech. Doc. WMO/TC-560, Rep. TCP-31. [Available online at http://www.cawcr.gov.au/publications/BMRC_archive/tcguide/ch4/gg_ch4.htm.]

——, J. Chen, and W. A. Shaffer, 1992: SLOSH: Sea, lake and overland surges from hurricanes. NOAA Tech. Rep. NWS 48, U.S. Dept. of Commerce, 71 pp.

Jenne, R. L., 1975: Data sets for meteorological research. NCAR Tech. Note IA-111, 194 pp.

Kaplan, J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. *J. Appl. Meteor.,* **34,** 2499–2512, doi:10.1175/1520-0450(1995)034<2499:ASEMFP>2.0.CO;2.

Knutson, T. R., and Coauthors, 2010: Tropical cyclones and climate change. *Nat. Geosci.,* **3,** 157–163, doi:10.1038/ngeo779.

Landsea, C., and J. Franklin, 2013: Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Wea. Rev.,* **141,** 3576–3592, doi:10.1175/MWR-D-12-00254.1.

——, and Coauthors, 2004: The Atlantic Hurricane Database Re-Analysis Project: Documentation for 1851–1910 alterations and additions to the HURDAT database. *Hurricanes and Typhoons: Past, Present, and Future,* R. Murnane and K. Liu, Eds., Columbia University Press, 177–221.

——, and Coauthors, 2008: A reanalysis of the 1911–20 Atlantic hurricane database. *J. Climate,* **21,** 2138–2168, doi:10.1175/2007JCLI1119.1.

Mitchell, C. L., 1924: West Indian hurricanes and other tropical cyclones of the North Atlantic Ocean. Weather Bureau Rep. 840, U.S. Government Printing Office, 47 pp.

Observatoire Impérial de Paris, 1868: Atlas des mouvements généraux de l'atmosphère. Redige par l'Observatoire sur les documents fournis par les observatories et les marines de la France et de l'Etranger: Annee 1864, Juin-Decembre. Charles Chauvin, 20 pp. and 214 charts.

——, 1869: Atlas des mouvements généraux de l'atmosphère. Redige par l'Observatoire sur les documents fournis par les observatories et les marines de la France et de l'Etranger: Annee 1865. Charles Chauvin. [Published in four quarterly editions.]

Toynbee, H., 1878: A discussion of the meteorology of the North Atlantic during August 1873. London Meteorological Office, Official 32, 32 charts.

Vecchi, G. A., and T. R. Knutson, 2008: On estimates of historical North Atlantic tropical cyclone activity. *J. Climate,* **21,** 3580–3600, doi:10.1175/2008JCLI2178.1.

Villarini, G., G. A. Vecchi, T. R. Knutson, M. Zhao, and J. A. Smith, 2011: North Atlantic tropical storm frequency response to anthropogenic forcing projections and sources of uncertainty. *J. Climate,* **24,** 3224–3238, doi:10.1175/2011JCLI3853.1.

Woodruff, S. D., and Coauthors, 2011: ICOADS release 2.5: Extensions and enhancements to the surface marine meteorological archive. *Int. J. Climatol.,* **31,** 951–967, doi:10.1002/joc.2103.

Worley, S. J., S. D. Woodruff, R. W. Reynolds, S. J. Lubker, and N. Lott, 2005: ICOADS release 2.1 data and products. *Int. J. Climatol.,* **25,** 823–842, doi:10.1002/joc.1166.