A Reanalysis of the 1944-1953 Atlantic Hurricane Seasons – The First Decade of Aircraft Reconnaissance

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Abstract

The main historical archive of all tropical storms, subtropical storms and hurricanes in the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico from 1851-present is known as HURDAT, which is the fundamental database for meteorological, engineering, and financial studies of these cyclones. Previous work has demonstrated that a reanalysis of HURDAT is necessary because it contains many random errors and systematic biases. The Atlantic Hurricane Reanalysis Project is an ongoing effort to correct the errors in HURDAT, and to provide as accurate of a HURDAT database as is possible with utilization of all available data. For this study, HURDAT is reanalyzed for the period 1944-1953, the first decade of the "aircraft reconnaissance era." The track and intensity of each existing tropical cyclone in HURDAT is reassessed, and previously unrecognized tropical cyclones are discovered, analyzed, and recommended to the HURDAT Best Track Change Committee for inclusion into HURDAT (existing tropical cyclones may be removed from the database as well if analyses indicate evidence that no tropical storm existed). Changes to the number of tropical storms, hurricanes, major hurricanes, accumulated cyclone energy, and U.S. landfalling hurricanes are recommended for most years of the decade. Estimates of uncertainty in the reanalyzed database for the decade are also provided.

1. Introduction

This paper explains the reanalysis of the Atlantic hurricane database (HURDAT) for the period 1944-1953, which is the first decade of aircraft reconnaissance. The main objective of the Atlantic Hurricane Reanalysis Project (AHRP) is to improve the accuracy and completeness of HURDAT (or, at the very least, to understand and quantify the existing biases). New data sources have become available recently containing observations from past decades, and it is essential that all available observations from these sources are utilized for the reanalysis. Landfall parameters for U.S. landfalling hurricanes are provided because many of the intensities have not been specified at landfall and are not accurate.

The Atlantic hurricane database contains many errors and systematic biases (Landsea et al. 2004a, 2008). When the original database was constructed, the position and intensity of tropical cyclones (TCs) were estimated only twice daily (at 00Z and 12Z) during the 1944-1953 period. The 06Z and 18Z positions and intensities were interpolated (Jarvinen et al. 1984; Landsea et al. 2008). This interpolation often created intensity inaccuracies for landfalling hurricanes. As in Landsea et al. (2008), which describes the reanalysis of the 1911-1920 Atlantic hurricane seasons, it was found here that for numerous TCs during the first decade of aircraft reconnaissance that the translational velocities at the beginning and/or the end of TC tracks often showed unrealistic accelerations or decelerations because of the digitization of hand drawn track maps back in the 1960s during the compilation of the original HURDAT database. Some of the systematic biases appeared in the original HURDAT database because the understanding of TCs was not as advanced as it is today. For example, knowledge of pressure-wind relationships and knowledge of how wind speed changes with height in TCs were both limited. Another systematic bias is that the Saffir-Simpson Hurricane Wind Scale (SSHWS) (Simpson 1974; Schott et al. 2010) categories for U.S. hurricane landfalls, first assigned by Hebert and Taylor (1975), do not match up with the maximum wind speed at landfall (Landsea et al. 2008). This is because those original designations were based on central pressure, whereas today, the SSHWS category is determined by maximum wind speed. For the reanalysis, detailed landfall parameters are analyzed and added to HURDAT including consistency between the maximum wind and the Saffir-Simpson category at U.S. landfall.

In addition to reanalyzing each TC listed in the HURDAT database from 1944-1953, a thorough search was conducted for TCs that existed but were not originally listed in HURDAT. When a potential TC not existing in HURDAT is identified, analyses of all available data from all sources are conducted. If these indicate that the system in question is likely a TC that was previously missed and therefore undocumented in HURDAT, it is then recommended for inclusion into the database.

Position and intensity uncertainty estimates for the reanalysis are provided. It is shown that uncertainty varied tremendously from case to case since there are huge variations in the amount of observations available. Because of this, uncertainties for this reanalysis are quantified for each general observational type available (e.g., low-level aircraft penetration, aircraft circumnavigation, no aircraft flights, etc.).

The HURDAT database contains the recommended positions and intensities of all recorded Atlantic Basin tropical storms, subtropical storms and hurricanes from 1851-present. Previous to this study, the AHRP has been completed and approved by the

HURDAT Best Track Change Committee (BTCC) for the years 1851-1930, as well as 1992's Hurricane Andrew, and these changes have already been made available to the community (Landsea et al. 2004a, b, 2008, 2011). Preliminary research has already been conducted for the years 1931-1943, and the BTCC is currently reviewing these years. The current study discusses recommended changes for the years 1944-1953. Although this study only focuses on the reanalysis of HURDAT from 1944-1953, it is important to understand how observational practices have evolved over time. Since 1851, the observational network has become more dense, and new tools and technology have been created for better monitoring of TCs. Prior to the aircraft reconnaissance era, TCs that stayed far away from any land areas would only be noticed and recorded if a ship encountered the storm at sea. Thus 1944 marked the advent of a new era in substantially improved monitoring of Atlantic basin TCs.

2. Methodology

a. Data sources

Many sources of data are utilized for the reanalysis. Some of the data sources utilized for the reanalysis of 1944-1953 that were also utilized for the reanalysis of the 1911-1930 period include the Historical Weather Maps series (HWM) (Reichelderfer 1944-1953); the Comprehensive Ocean-Atmosphere Dataset (COADS) (Woodruff 1987); articles, tables, charts, and maps from Monthly Weather Review (MWR); Original Monthly Records (OMR) of U.S. coastal stations from the National Climatic Data Center (NCDC); monthly climatological data summaries from NCDC; meteorological observations from

Caribbean islands and Mexico maintained by their respective governments or weather services; newspaper articles, reports and personal accounts in publications such as Barnes (1998, 2001) and Tucker (1995); as well as other sources such as Connor (1956), Dunn and Miller (1960), Harris (1963), Schwerdt et al. (1979), Jarrell et al. (1992), and Perez et al. (2000). For more information regarding those data sources, see Landsea et al. (2004a, 2008).

New data sources utilized for AHRP beginning in the 1940s and 1950s include National Hurricane Center (NHC) microfilm of synoptic weather maps (microfilm), the U.S. Navy hurricane logbooks, also referred to as Annual Tropical Storm reports (ATS) (e.g. U. S. Navy 1950, 1951; Raftery 1953; Minter 1954), and the U.S. Air Weather Service (AWS) reports (e.g. USAWS 1948, 1949, 1951). The microfilm synoptic maps, which are kept back to the early 1940s, were constructed operationally by the U.S. Weather Bureau forecasters. These analyzed maps were utilized as part of the foundation for hurricane forecasting. The microfilm synoptic maps from every six hours are available in most cases except for TCs in the eastern half of the Atlantic. South of about 25N latitude, the eastern edge of the microfilm map was about 55W longitude. This may be because microfilm maps did not extend beyond the range of aircraft reconnaissance. For U.S. landfalling hurricanes, hourly microfilm maps are usually available. Microfilm is the major source of aircraft reconnaissance information utilized from 1944-49 and is one of the most important sources of aircraft information from 1950-53 as well. Communications and messages between the hurricane forecasters in the Weather Bureau office and the flight crew on the reconnaissance aircraft in the TC are often displayed in the corners of the microfilm maps. In addition to the abundance of aircraft information available on the maps, these maps often contained additional ship observations that were not in COADS. The utilization of the microfilm maps along with HWM and COADS is necessary for the reanalysis process and has led to numerous changes made to HURDAT. The U.S. Air Weather Service reports and the U.S. Navy hurricane logbooks are vital as well, but these are not available for the first few years of aircraft reconnaissance. ATS reports are available every year from 1950 onward and thus were utilized for the reanalysis of the 1950-53 seasons. AWS reports utilized in the reanalysis of the 1944-1953 hurricane seasons include reports with information on the 1947, 1948, and 1950 hurricane seasons. The AWS report on 1950 was extremely detailed.

b. Pressure-wind relationships

Typically, as the central pressure of a TC decreases, the maximum wind increases. There was little knowledge of and there were no publications on relating central pressure to maximum wind speed prior to Kraft (1961). Several subsequent updated pressure-wind relationships have been published up to Brown et al. (2006). The Brown et al. (2006) relationships are used for the reanalysis of HURDAT for all TCs south of 35N latitude, and the Landsea et al. (2004a) pressure-wind relationships are utilized for TCs north of 35N. Reanalysis methodology described in Landsea et al. (2008) allows for analyzed intensities to deviate by as much as 10 kt from the Brown et al. pressure-wind relationship for cases when storm size, RMW, speed, and/or environmental pressure deviate significantly from average values of these parameters.[2]

[2] Recently, new pressure-wind relationships (Knaff and Zehr 2007; Courtney and Knaff 2009) have been introduced which explicitly include these environmental effects. However, the relationships require an explicit tropical storm force wind radii analysis, which is problematic until recent years. Moreover, introduction of these new techniques would cause a heterogeneous jump in the intensities

The pressure-wind relationships are used to translate available central pressure observations in the reanalysis to maximum wind speed values. Central pressures are important for the intensity reanalysis because central pressures were measured much more often than the maximum wind speed in a TC and because central pressures were most often more accurate than wind speed observations and estimates during the decade. Central pressure measurements for TCs over the open ocean prior to the aircraft reconnaissance era were extremely uncommon. After the initiation of aircraft reconnaissance, central pressure observations were more routinely available for tropical storms and Category 1 and 2 hurricanes.

c. Aircraft reconnaissance

The first year during which routine planned military aircraft reconnaissance missions were conducted into Atlantic hurricanes and tropical storms was 1944 (Sheets 1990; Summer 1944; Porush and Spencer 1945). Different types of aircraft were utilized for reconnaissance missions during the first decade of aircraft reconnaissance. The Army Air Force (AAF) operated four B-25 aircraft in 1944-45 (Porush and Spencer 1945). The Air Force (formerly the AAF) operated B-29 aircraft from 1946 to beyond 1953, and the B-17 was also utilized for reconnaissance during 1947 (Sheets 1990; USAWS 1948, 1949, 1951). The Navy used a version of the B-24 called the PB4Y-1 Liberator in 1944-45 (Porush and Spencer 1945; David Reade, personal communication, 2010). In 1946, the Navy switched to the PB4Y-2 Privateer aircraft for low-level hurricane

in HURDAT as Landsea et al. (2004a) for north of 35°N and Brown et al. (2006) for south of 35°N have been utilized for 80 years of reanalysis (1851-1930) thus far. It is an option for future researchers to re-reanalyze HURDAT with these newest techniques.

reconnaissance. The PB4Y-2 was the aircraft that was utilized the most by the Navy for Atlantic hurricane reconnaissance from 1946-1953, and in 1953, the Navy added the P2V aircraft to compliment the PB4Y-2 (Charlie Neumann, personal communication, 2010). The Navy also operated a PB-1W aircraft (the Navy version of the B-17) equipped with Airborne Early-Warning (AEW) radar starting in 1947 as an extra aircraft utilized only for U.S. hurricane landfall threats (USAWS 1951; Reade, personal communication, 2010). The PB-1W flew primarily at night to obtain position fixes.

Important instrumentation on most of the reconnaissance aircraft during the first decade of aircraft reconnaissance included a height altimeter, pressure altimeter, and drift meter. The surface pressure at the location of the aircraft is considered accurate to within 2 to 3 mb on average when the plane is flying at 1,500 ft or lower. The drift meter aids in determining the flight level wind speed. Different aircraft contained different types of radars, but many suffered greatly from precipitation attenuation. The two types of aircraft radars that had the least attenuation were the AEW radar and the AN/APS-20 (Airborne Search and Detection) radar that was installed on the P2V aircraft beginning in 1953 (Reade, personal communication, 2010).

Aircraft reconnaissance navigation was accomplished by a method called dead reckoning (DR). Using the DR method, the navigator would note the time and position of the last island or coast seen before flying to intercept the TC. Every 30 minutes, the navigator calculated the new position of the aircraft based on the speed and direction the aircraft was traveling during the previous 30 minutes. Once the periphery of the TC was reached, the new position would be calculated every 15 minutes. Most flights during the 1940s and many flights during the early 1950s used the TC azimuthal winds as a tail wind to gradually circle closer to the center of the TC before deciding whether to perform penetration or to simply circumnavigate the storm. Because of the frequent heading changes in high wind conditions, navigators often fell behind in their position calculations (Neumann, personal communication, 2010). The navigational position error was dependent on the distance from the TC to any coast/island and on the amount of time spent by the aircraft in high wind conditions. Aircraft center fix position accuracy could also be aided by intercepting loran (radio) signals. The aircraft must have been in a location where radio signals could be intercepted and was available roughly one-quarter of the flights to improve upon the DR position fix. Although DR was used on all reconnaissance flights, whenever loran was available, positions are considered more accurate than when loran is not available.

Significant errors in positioning, which were rather common, contributed directly toward substantial flight-level wind calculation errors. In concordance with drift meter measurements for measuring flight-level wind, the navigator calculated the flight-level winds every 15 minutes along with the position based on the speed that the aircraft should have been traveling and the extra distance covered as a result of the tail wind on the aircraft as it slowly circled toward the center of the TC (Neumann, personal communication, 2010). However, the considerable uncertainty in the location of the plane precluded accurate total distance measurements and thus also the flight-level winds. For this reason, flight-level wind measurements contained significant errors that increased with increased winds (Hugh Willoughby, personal communication, 2010). The Navy, which was very influential in hurricane forecasting and best-track preparation from 1946-1964, placed considerable reliance on the maximum wind reports from the aircraft.

These highly uncertain guesses were often placed into the official best tracks and are the values found in the original HURDAT database (Neumann, personal communication, 2010). Flight-level winds are not considered to be a reliable aid for reanalyzing the HURDAT intensity until the installation of the inertial navigation systems on the P-3s in the mid-1970s (Sheets 1990) and on the Air Force planes around 1990.

In addition to the flight-level wind estimates, surface winds were analyzed by the aerologist through viewing the sea-state during low-level flights (below cloud base) during the day. Surface wind speed estimates did not suffer from the same type of inaccuracies as the flight-level winds because navigational error did not factor into surface wind estimates. However, the surface winds were subjective estimates whereas the flight-level winds were measured semi-objectively. There was no standardized way to determine wind speed from the sea-state until the publication of a photo catalog in 1952 linking wind speed to sea-state (Neumann 1952). A photo from this publication corresponding to reported 70 kt surface winds is shown in Figure 1. A large limitation to this catalog, however, was the lack of calibration of these visual conditions with actual measured wind speeds, especially for winds above a Category 1 hurricane. Winds below minimal hurricane force from this catalog likely are better constrained by observed winds, due to its basis on the Beaufort Scale (Kinsman 1969). The Beaufort Scale, created by Sir Frances Beaufort in 1806, was used by ships to estimate wind speed (Kinsman 1969). In official military coding messages, aircraft reconnaissance would report surface wind speed at the location of the aircraft if the sea-state was visible and was not obscured by clouds. The highest number that could be reported in the military coding was 12 (64 kt +). If a higher surface wind speed was observed, the aerologist on the flight would use plain text to deliver his wind speed estimate to the Joint Hurricane Warning Center in Miami, FL, but this information was sometimes not communicated, inaccurate, or not available. The average uncertainty in surface wind speed estimates for wind speeds lower than about a Category 2 hurricane is believed to be about 15 kt, and the error was likely higher in high wind speed conditions. There was also likely a high bias of several knots, which will be discussed later. Due to the numerous factors that can increase the inaccuracies in estimated surface winds, it is assumed that the errors in the estimated surface winds and the errors in the flight-level winds are of a similar magnitude on average. Both types of aircraft winds were not very reliable data and are only weighted lightly for making changes to the original HURDAT intensity.

The types of flight patterns utilized by aircraft for hurricane reconnaissance can be separated into two types – low-level penetrations and circumnavigations. When aircraft are able to penetrate the eye or center at low-levels, a central pressure can be reported. An example of a low-level penetration from 1948 Storm 5 by a Navy reconnaissance aircraft in the north-central Gulf of Mexico is shown in Figure 2. When a central pressure is available, this value is converted to a wind speed using the Brown et al. (2006) pressure-wind relationships. An eye diameter was often reported by the aircraft, which can be converted to an RMW using the Kimball and Mulekar (2004) relationships. The eye diameter along with the environmental pressure, size, and speed of the storm are used to make adjustments of plus/minus 0-10 kt to the Brown et al. pressure-wind relationship, if necessary, to determine maximum wind speed. For the reanalysis of 1944-1953, determining the intensity using the pressure-wind relationship plus the adjustment factor is likely more reliable than using the more uncertain surface wind speed estimates and flight-level wind speed measurements.

On nearly all flights for major (Category 3, 4, and 5 on the SSHWS) hurricanes and many flights for minor (Category 1 and 2 on the SSHWS) hurricanes, the cyclone was not penetrated for one of two reasons. The first is that the decision would sometimes be made not to penetrate past about the 70 kt isotach because it was believed to be too dangerous to attempt to penetrate further. For example, for the Hurricane Dog reconnaissance flight on September 4, 1950, the decision had been made to circumnavigate the cyclone because previous flights had advised against penetration due to the extreme intensity of the storm (U.S. Navy 1950). The second reason is that even when they attempted to penetrate the center, they often would be forced to abort the penetration before the RMW or eye was reached due to severe turbulence causing the aircraft to become uncontrollable. When penetration was not performed, the circumnavigation flight technique was usually conducted. A classic example of the circumnavigation flight technique from a flight in 1948 Storm 3 on the afternoon of August 29, 1948 is shown in Figure 3. Although 25 aircraft center fixes were obtained for 1948 Storm 3 (Figure 4), none were obtained by penetration. Thus, no central pressures were obtained for the entire lifetime of the storm. Circumnavigation was a common flight pattern used for major hurricanes. During circumnavigation, a center position was estimated, but there is little that can be used for the intensity reanalysis as there were no central pressures reported during circumnavigation. For this reason, very few central pressures indicative of major hurricane intensity were reported during 1944-53.

Thus, aircraft central pressures were only reported during daylight hours due to the need to visually see the ocean surface and primarily in tropical storms and minor hurricanes. Beginning in 1950, penetrations were generally attempted more often and for somewhat stronger hurricanes compared with the late 1940s (roughly a Saffir-Simpson category stronger on average). Nevertheless, it was still a common occurrence in the 1950s for a plane to attempt a penetration and have to abort before the RMW or even the inner core was reached due to extreme turbulence causing the plane to become uncontrollable.

There were additional changes that came about in 1950 as well. Although the B-29 was utilized by the Air Force beginning in 1946 for Atlantic hurricane reconnaissance, 700-mb penetrations began being performed much more often beginning in 1950 for many TCs east of about 70W longitude (USAWS 1951; U.S. Navy 1950). The 700 mb height in the eye would often be reported beginning around 1950. Extrapolation of surface pressure from 700 mb was not performed since temperature data outside the aircraft was not available. Extrapolations of 700 mb heights to obtain surface pressures without temperature data is considered to have errors too large to be counted as central pressure values in HURDAT. Also, 1950 was the first year that dropsondes were used regularly in the Atlantic for TC monitoring. Information regarding the surface pressure encountered by the dropsonde just before splash landing was received by the plane crew. However, there was no wind information or position information for the dropsondes, so these surface pressures cannot be assumed as central pressures as many of them would splash under the eyewall (Willoughby, personal communication, 2010). Nevertheless, the combination of reported 700 mb heights and dropsonde pressures complimented accurate central pressures from low-level penetrations to provide more intensity information than was available during the 1940s.

Figure 5 shows how many aircraft central pressures were reported during 1950-53 and 1944-1949. About 38 aircraft central pressures per year were reported in 1950-53 compared with about 7 aircraft central pressures per year from 1944-1949. For comparison, in 2009, a year during which Atlantic TC activity was about half of normal, there were 94 aircraft central pressures reported. During the 1950-53 period, there were a total of 23 central pressures with a value below 970 mb, whereas from 1944-49, a central pressure below 970 mb was recorded on only six occasions. The lowest aircraft central pressure obtained during the first ten years of Atlantic aircraft reconnaissance was 929 mb in Hurricane Carol of 1953.

Performing penetrations and obtaining central pressures were not the highest priorities during the first decade of aircraft reconnaissance, especially from 1944-1949. The most important priority was locating the position of the center (and thus determining a direction and speed of movement). Secondary priorities included estimating or measuring the maximum wind speed of the cyclone, estimating the size of the storm, reporting eye diameter (when possible), central pressure or lowest pressure encountered, cloud type, and perhaps writing a short description of how well the center is organized (USAWS, 1948, 1949, 1951). It was generally known by meteorologists during the first decade of aircraft reconnaissance that as the maximum winds in a hurricane increase, the central pressure should decrease, but specific knowledge of pressure-wind relationships did not exist until Kraft (1961). It was common for a central pressure to be reported with a maximum wind estimate which was 20 to sometimes more than 40 kt above what the central pressure would suggest according to the Brown et al. (2006) pressure-wind relationship. There has been no systematic change to the way aircraft central pressures have been observed and reported from the 1940s to today, but there have been many significant changes to the way the maximum wind speed has been measured, estimated, and reported by aircraft reconnaissance (Sheets 1990; Franklin et al. 2003).

In cases for which the center could not be penetrated after attempting, the aerologists commonly reported intensities of 100 to more than 120 kt, even if the maximum visual surface wind and maximum flight-level winds encountered were significantly lower than that reported value. A quote from the U. S. Navy Annual Tropical Cyclone report for Hurricane Dog of 1950 provides an example of a maximum intensity guess that was made on September 6, 1950:

"*As in previous flights into this storm, no penetration was planned because of the severity of the turbulence…it was considered desirable and adequate to circumnavigate at approximately the 70 kt wind circle. Features of this flight include the observation of the extremely large swells ahead of the hurricane, and the extent of hurricane winds over a very large area. It is believed that highest winds near the center were probably in excess of 150 kt*" (U. S. Navy 1950).

These practices often led to many high biases in reporting maximum winds, which had been documented for the 1940s to 1960s in HURDAT previously (Landsea 1993). During many penetration cases, the maximum flight-level wind encountered would often be reported as the storm intensity, leading to additional high biases in the original HURDAT since the maximum flight-level (400 – 1000 ft) wind encountered during penetration cases is usually substantially higher than the maximum surface winds in a TC (Franklin et al. 2003).

d. Reanalysis steps

There are several systematic steps that are included in the process of reanalyzing the HURDAT database for each year. This process is described in detail in Landsea et al. (2004a, 2008) and is briefly summarized here. The first step is to obtain all available raw observations and compile them into a single database. Both the HWM and microfilm synoptic weather maps are scanned and printed out in order to plot all observations from all sources onto a single synoptic map corresponding to a specific time. Observations are plotted onto the synoptic maps one to four times daily for each storm, depending on the amount of data available on a particular day. After the synoptic observations are plotted and the observation database is completed, a metadata file is composed for every TC. The daily metadata paragraphs include descriptions of synoptic analyses and contain key observational data. Next, the reanalyzed positions and intensities for each storm for every six hours are carefully chosen. Changes are made to HURDAT only when available observations provide enough evidence that the previous HURDAT position or intensity is in substantial error (roughly at least 0.2° latitude and/or longitude for position and at least 10 kt for intensity). After the HURDAT tracks and intensities have been reanalyzed, a paragraph summarizing the reasoning for significant changes is added to the end of the metadata for each TC.

After the existing TCs during a year are reanalyzed, a thorough search is conducted for potential missing TCs (referred to as *suspects*) using synoptic maps as well as all other available sources. There were only a few suspects for which there were aircraft reconnaissance flights, so most of the data and methodology for adding new storms in

HURDAT is explained in Landsea et al. (2004a, 2008).

In addition to surface data from ships and land stations, the reanalysis of the 1944-1953 hurricane seasons utilizes aircraft data and land-based radar data for the track analysis. Landsea et al. (2004a, 2008) describe the methodology for determining the reanalyzed track in the absence of aircraft reconnaissance and radar data. However, for the period of 1944-1953, aircraft data was available on more than half of the days of all recorded TCs. For recorded TCs west of 55W from 1947 onward, aircraft flights were performed on more than three-fourths of the days. An aircraft center fix is a position estimate of a TC from an aircraft flight. When determining the track, all aircraft center fixes for the entire lifetime of the TC are obtained. The center fixes are then interpolated to 6-hourly positions, placing more weight on the more reliable center fixes. The center fixes from 1948 Storm #3 are shown in Figure 4. Next, all ship data is analyzed to determine whether the positions suggested by the aircraft center fixes are accurate as aircraft navigation, especially far from land, could contain sizeable errors. Occasionally, reliable ship data near the center revealed evidence that the aircraft fix position was significantly in error. However, for many TCs, there were multiple aircraft center fixes each day with sparse ship coverage, and the reanalyses for these cases relied primarily on aircraft information. Beginning in 1950, the operational hurricane forecast center of the U.S. Weather Bureau and the Navy conducted post-season analyses and drew a best track for all storms. Interestingly, the original HURDAT positions often do not match this best track. Indeed, data available in this reanalysis have shown positions from both sources to be inaccurate on several occasions.

3. Reanalysis results and discussion

All changes to HURDAT shown here are preliminary and have not yet been approved by the HURDAT Best Track Change Committee. The results shown here are the changes that we are recommending to the committee. Users of HURDAT should either wait until the committee has approved the reanalysis of 1944-1953 or utilize these results with caution.

a. Overall activity

Recommended changes to the number of tropical storms and hurricanes, hurricanes, major hurricanes, and accumulated cyclone energy (ACE) for each year (1944-1953) are shown in Table 1. Twenty-one additional tropical cyclones were identified and are proposed to be added into HURDAT during these ten years with one proposed removal, bringing the total number of TCs for the period from 103 to 123 (an increase of 2.0 per year). Eighteen of the 21 additional TCs were tropical storms, and three were hurricanes. These three new hurricanes, along with one previous tropical storm that is reanalyzed to be a hurricane and two previous hurricanes that are reanalyzed to instead be tropical storms, tentatively increases the total number of hurricanes for the ten year period from 64 to 66 (an increase of 0.2 per year). The number of major hurricanes tentatively decreased from 36 to 27 (a decrease of 0.9 per year). Ten hurricanes previously listed in HURDAT as major hurricanes are preliminarily revised downward in intensity to minor hurricane status, and one minor hurricane is preliminarily increased to major hurricane status. Seven of those ten major hurricanes are reanalyzed downward due to evidence of overestimation of winds by aircraft reconnaissance. Those seven cases are a small sample of the numerous hurricanes with various original intensities that were revised downward. This is the overwhelming reason why the reanalyzed ACE is lower than the original ACE despite the addition of many new storms during the decade. The average seasonal ACE declined from 107 to 98 units. The revised-comparison track map and details of highlighted revisions for 1944 are shown in Figure 6 and Table 2. Track maps and details of revisions for the reanalysis years of 1945 to 1953 are available in the on-line appendix in Figures A1-A9 and Tables A1-A9.

During the first decade of aircraft reconnaissance, of the 21 new TCs introduced into HURDAT, roughly half of these occurred in the western half of the basin (or within the range of aircraft reconnaissance), and the other half occurred mainly in the eastern half of the basin. The greatest reasons for missed cyclones in the western half of the basin are due to changes in analysis techniques and designation practices. A secondary reason is that more data has recently become available for detecting these cyclones. For cyclones in the eastern half of the basin or in locations where aircraft reconnaissance was not available, the primary reason for missed cyclones was a lack of real-time (or operationally available) ship data for detecting these cyclones. The COADS ship database remains the most useful data source for locating evidence of missing TCs in the eastern half of the basin during the reanalysis of the first decade of aircraft reconnaissance.

b. U.S. tropical storms and hurricanes

Table 3 lists all hurricanes and tropical storms that impacted the coastline of the continental United States as well as those that made a direct landfall. There were a total of 23 hurricanes that impacted the coastline of the continental U.S. from 1944-53. For comparison, a recent ten-year period that was also particularly active, 1996-2005, had 24 U.S. hurricanes. Eight major hurricanes impacted the U.S. during the 1944-53 period, and there were nine during the 1996-2005 period. In addition to the 23 U.S. hurricanes, 24 tropical storms impacted the U.S. (1944-53), which means the total number of tropical cyclones impacting the U.S. during the period was 47. Of the 24 tropical storms, 3 were systems newly introduced into HURDAT.

Table 4 shows that there are 17 U.S. landfalling hurricanes (1944-53) with proposed changes to the SSHWS category that impacted one or more states/regions. Changes are made to the maximum U.S. landfall category for eight of these hurricanes, with two downgrades by one category and six upgrades by one category. One system that was originally listed as a major hurricane – the 1944 Great Atlantic Hurricane – was downgraded from a peak Category 3 to a Category 2 impact, making the system a minor hurricane at landfall. A system that was originally listed as a minor hurricane – 1949 Storm #11, which made landfall near Freeport, TX – is upgraded from a peak Category 2 to a Category 3 impact, making the system a major hurricane at landfall. The five most intense U.S. landfalling hurricanes during this ten-year period in terms of wind speed all made landfall in the southern Florida counties of Palm Beach, Broward, Miami-Dade, Monroe, and Collier. The analyzed landfall intensity of all five of these hurricanes was (1945 Homestead – 115 kt, 1947 Fort Lauderdale – 115 kt, 1948 Everglades City – 115 kt, 1949 Palm Beach – 115 kt, and Hurricane King of 1950, which made landfall at Miami – 110 kt) in the range from 110-115 kt (a high end Category 3 to a low end Category 4). The Palm Beach hurricane of 1949 is tentatively upgraded from a Category

3 to a Category 4 at landfall. However, the wind speed in HURDAT is lowered from 130 to 115 kt. This is a typical example of the inconsistencies between HURDAT and the SSHWS Category for U. S. landfall. The 1945 Homestead hurricane is another example of an increase in Saffir-Simpson category from 3 to 4 but a decrease in wind speed from 120 to 115 kt.

c. Hurricane impacts outside of the continental U.S.

Table 5 lists all hurricane landfalls and impacts (1944-53) for land areas outside of the continental U.S. Many of these hurricanes made direct landfalls; however, several others passed close enough to islands or countries for hurricane force winds to be experienced on land without the center crossing the coast. Those hurricanes are included in this list as well and contain the maximum wind likely experienced on land as calculated by the Schwerdt et al. (1979) model in the absence of information that contrarily indicates a higher or lower intensity. There were no landfalling Category 5 hurricanes analyzed, but countries that experienced one or more major hurricane impacts during the decade include Cuba (3 major hurricanes), The Bahamas (3), Jamaica (2), Mexico (2), and Antigua and Barbuda (1). Bermuda experienced a Category 2 impact four times during the ten-year period.

Two of the hurricanes with the largest impacts for countries outside of the U.S. were the Cuba hurricane of October 1944 and Hurricane Charlie of 1951, which affected Jamaica and Mexico. The former developed in the southern Caribbean on 12 October, affected the Cayman Islands from the 14^{th}-16^{th} with Category 2 conditions and then made landfall in western Cuba on 18 October, 1944 as a Category 4 hurricane. The intensity was increased from 105 to 120 kt for the Cuban landfall based on two pieces of data. A 937 mb central pressure was measured on land near the time of landfall, and as the cyclone was exiting the north coast of Cuba, a 122 kt (25 sec averaged) wind was recorded at Havana. This hurricane killed 300 people in Cuba (Perez et al. 2000). Hurricane Charlie of 1951 was a classic straight-mover through the Caribbean that originated from an easterly wave in August. It made landfall in Jamaica near Kingston with an analyzed intensity of 110 kt (an increase from 95 kt originally). This hurricane killed 152 in Jamaica, injured 2,000, left 25,000 homeless, and caused $65,000,000 of damage on that island (Norton 1952). The hurricane then made landfall in the Yucatan Peninsula of Mexico as a 115 kt hurricane, where 70% of crops were destroyed. After emerging into the Bay of Campeche, Charlie's final landfall occurred at Tampico, Mexico, also as a major hurricane. This last landfall caused at least 100 deaths and $1,160,000 in damage. In total, hurricane Charlie caused at least 250 deaths and $75,000,000 in damage (Tannehill 1956).

d. Aircraft central pressures

Figure 5 shows the frequency of reported available aircraft central pressures. One central pressure observation represents one aircraft penetration for which a central pressure was reported. All aircraft observations of less than 960 mb for the entire decade regardless of whether they are a central pressure are listed in Table 6. A threshold of 960 mb is chosen for this table because this value is about the general cutoff for major hurricane intensity according to the Brown et al. (2006) pressure-wind relationships. These pressure-wind relationships also indicate that a value near 945 mb is the borderline between Category 3 and 4 intensity. A 920 mb central pressure is a general approximation for the borderline of Category 4 and 5 intensity. There were very few pressure readings indicative of major hurricanes compared to the number of major hurricanes that existed previously in the original HURDAT database during this decade. From 1944-1953, there were five hurricanes for which a Category 4 intensity was confirmed by an aircraft pressure measurement. This number compares with 16 Category 4 or greater hurricanes listed in HURDAT originally and 14 shown in the reanalyzed HURDAT for this ten year period. There was one hurricane for which a Category 5 intensity was assigned in the reanalysis based on an aircraft central pressure measurement of 929 mb reported along with a tiny RMW of 3 nmi (1953 Hurricane Carol). This number compares with three Category 5 hurricanes listed in HURDAT originally and one shown in the reanalyzed HURDAT for the ten year period. For two of the TCs previously listed as Category 5 hurricanes (1950 Hurricane Dog and 1951 Hurricane Easy), aircraft pressure information available at least once per day indicated maximum wind speeds substantially below the Category 5 threshold at the time HURDAT originally listed Category 5 intensity. Category 5 wind speeds were likely placed into the original HURDAT database due to maximum wind speed guesses by the onboard aerologist for those two hurricanes. For 1947 Storm 4, Category 5 wind speeds were placed into the original HURDAT database due to a 140 kt surface observation in the Bahamas, but multiple sources indicated it was an estimated – not a measured – wind. This wind speed is found in the reanalysis to be too high based on other information that indicates a likely central pressure in the range of 944-951 mb on that day. Whenever there was not a central pressure measurement to justify an intensity change, no change would be made to the HURDAT intensity, but several of the major hurricanes were downgraded due to central pressure information that indicated a weaker intensity. However, it is highly likely that the true number of extremely intense hurricanes is underrepresented in the revised HURDAT file due to the infrequent sampling of the highest winds and/or central pressure in these extreme hurricanes.

The original HURDAT database contains central pressure values in 92 of the 6-hourly time slots during the ten years of 1944-53. The reanalyzed HURDAT contains central pressure values in 301 of the 6-hourly time slots. Aircraft central pressures are responsible for 23 of the 92 central pressures that were listed in the original HURDAT. Aircraft reconnaissance is found to have been partially or solely responsible for 201 of the 301 central pressures in the revised HURDAT (aircraft is solely responsible for only 193 of those 201 as sometimes a ship and a plane would be inside the eye simultaneously). Other types of central pressures are measured when the center of a TC passes over a ship or a land station, but some of the central pressures in the revised HURDAT are calculated from peripheral observations using the aforementioned methodology.

e. Error estimates for reanalyzed HURDAT based on aircraft reconnaissance

An assessment of the accuracy and bias of the winds in HURDAT is conducted utilizing the 193 aircraft central pressure measurements. These observations with the derived wind speed values in both the original and the revised HURDAT database are compared with the Brown et al. (2006) pressure-wind relationship to calculate the root mean squared error (RMSE) and biases for various central pressure bins. The Brown et al. curve utilized for this statistical analysis is an average of the south of 25°N and the 25-

35°N relationships. As was previously stated, the original wind speeds in the Best Track were often taken directly from the aircraft reconnaissance wind speed estimates, which are not reliable observations. This method is not a fully representative data sample because for TCs that were major hurricanes in reality, central pressures were observed much less frequently. For TCs that were tropical storms and Category 1 hurricanes in reality, central pressures were observed much more frequently.

The results of the method are shown in Table 7 and Figure 7. For times when aircraft reconnaissance reported a central pressure value, the intensities in the original HURDAT database contain an RMSE of 19.9 kt with a bias of +13.3 kt compared to the wind speed suggested by the Brown et al. pressure-wind relationships (the data is present for 193 of the 6-hourly HURDAT points during the ten-year period). The 19.9 kt RMSE for the original HURDAT is much higher than the 9.3 kt RMSE found by Brown et al. (2006) for more recent data and reflects a lack of knowledge of pressure-wind relationships and a lack of standardized reliable wind observations in the original HURDAT. The positive bias decreases with increasing intensity as shown in Table 7. It is interesting to note from Figure 7 that there are several cases for which the original HURDAT winds were much weaker than what the central pressure value would suggest. Some of these cases are due to issues with the intensity interpolation of the original HURDAT. For other cases, winds as strong as what these pressures suggest were simply not observed, especially when only one penetration was performed. The values obtained for the original HURDAT are much larger than those obtained for the revised HURDAT (5.7 kt for RMSE and +2.7 kt for average bias). One would expect negligible biases in the revised HURDAT intensities with the Brown et al. (2006) pressure-wind relationships, as the former is based in large part of the output from the latter. There are a few possible reasons for why the average bias in the revised HURDAT is not exactly zero (as it was hoped that the biases in HURDAT could be eliminated with the reanalysis). One reason could be that the Brown et al. curve utilized for this comparison is not an exact match for the average applicable Brown et al. curve. Another reason is that the size, speed, RMW, and environmental pressure were not taken into account on a case-by-case basis for this comparison. If more than half of the storms were smaller than climatology or fast-moving, it would lead to an apparent average high bias. A third reason is because the central pressures that are compared with the maximum wind speeds can be off in time by as much as three hours. For TCs undergoing rapid intensity changes, the analyzed wind speed could differ significantly from the pressure value in the same time slot. Although the average bias in the reanalyzed HURDAT is not zero according to this analysis, the value of +2.7 kt is significantly improved over the value of +13.3 kt indicated by the original HURDAT maximum winds for cases when central pressures listed in the revised HURDAT are due to aircraft reconnaissance pressure information only.

f. Subjectively derived reanalysis uncertainty estimates

Estimates of the average position and intensity uncertainties for HURDAT for the first decade of aircraft reconnaissance are shown in Tables 8 and 9 along with estimates for the period 1851-1930 provided in Landsea et al. (2008, 2011). The last two rows in Tables 8 and 9 are subjective estimates from an average of the NHC Hurricane Specialists for recent time periods. For position, open ocean cases without aircraft showed only slight improvements from the early decades of the HURDAT era. This decrease in uncertainty is solely due to an increase in ship traffic from the 1800s to the mid-20th century. The position improvement is much more significant in recent years because of the widespread monitoring of the whole basin provided by geostationary satellites. Average position uncertainty on days with reconnaissance fixes is estimated to be about 35 nmi during the first decade of aircraft reconnaissance, and this improved greatly with the inertial navigation system a few decades later. Average position uncertainty for settled areas of the coastline for U.S. landfalling hurricanes showed significant improvement from the 19th century. This is largely due to the numerous (sometimes hourly) aircraft center fixes that were usually provided during the last day or so leading up to a U.S. landfall. Also, the coastal radar network was beginning to be developed during the late 1940s, and by 1950, there were at least four land-based radars in operation along the coastal areas between Texas and Virginia. These radars were located at Boca Chica (NAS), FL; Freeport, TX; Norfolk, VA; and Gainesville, FL (Gentry 1951).

The intensity uncertainties in HURDAT are stratified similarly to those for track except the aircraft reconnaissance group is divided into two groups- one for which central pressures were measured, and the other for when they were not measured (Table 9). There was a significant difference in the average uncertainty between the two groups. During the first decade of aircraft reconnaissance, intensity estimates are more reliable when aircraft central pressures are available. However, for open ocean cases without aircraft reconnaissance, intensity uncertainty likely did not incur any improvements over the 1886-1930 period. Although ships were more numerous, there was not an increase in the number of ships that observed the highest winds and/or central pressures in TCs. The HURDAT intensity biases are shown in Table 10. Intensities are substantially underestimated in HURDAT for open ocean cases when aircraft reconnaissance was not present. For cases when aircraft central pressures were measured there is little, if any, bias in the HURDAT intensities provided. However, for the cases when the aircraft estimated the maximum winds but did not provide a central pressure, there may be positive biases for Category 1 and 2 hurricanes over-estimated on the order of +5 kt on average in the reanalyzed HURDAT. This bias for those cases remains because the HURDAT intensity can only be reduced if there is enough observational evidence to lower the intensity. TCs that were actually 120 kt and higher are likely underestimated in intensity since the most intense part of the storm was not sampled. To test this hypothesis, statistics from a companion Category 5 study (Hagen and Landsea 2011) are utilized. For all times that extreme hurricanes from 1992-2007 were at or above a 120 kt intensity, the actual NHC best track intensity is subtracted from the intensity value which likely would have been analyzed for these systems given the reconnaissance technology available in the late 1940s and early 1950s. This mean difference is 10 kt, which is thus indicated in Table 10.

4. Summary and conclusions

The first decade of aircraft reconnaissance was an active period for Atlantic hurricanes, especially with respect to impacts in the U.S. and Caribbean. The number of TCs was significantly increased as a result of the reanalysis as 21 TCs were added during the decade. However, the number of major hurricanes and ACE were decreased as a result of the reanalysis due in large part to overestimation of winds from aircraft reconnaissance in the original HURDAT. Hundreds of track and intensity changes to HURDAT are recommended to the BTCC. Although one or more major track alterations are only recommended for 37% of the existing TCs of the decade, one or more major intensity changes are recommended for 49% of existing TCs.

HURDAT position and intensity estimates from 1944-1953 are substantially more accurate than the estimates for the period 1851-1930 due largely to aircraft reconnaissance. The most significant bias that existed during the first decade of aircraft reconnaissance was the tendency for aircraft to overestimate the wind speeds in many TCs. For flights during which a central pressure was measured, this bias is eliminated. Ship traffic was more dense in many areas of the basin during the 1940s and 1950s compared with the second half of the 19th century. This assisted in having a more complete record of TC frequency, but not necessarily TC intensity as ships did their best to avoid sampling the most intense portion of TCs. Although there likely have been some storms that were missed (even after this reanalysis), the intensity accuracy in HURDAT is perhaps a more alarming issue than the number of TCs that remain unaccounted for. Several missed TCs were found in this reanalysis, but the average intensity uncertainty was likely improved only slightly due to the low number of aircraft central pressures observed, the limitations of the Brown et al. (2006) pressure-wind relationship, and the lack of reliable flight-level and surface wind observations from aircraft.

In conclusion, the primary goal of this paper is to provide documentation of the Atlantic Hurricane Reanalysis Project for the first decade of aircraft reconnaissance (1944-1953). Aircraft reconnaissance equipment, techniques, procedures, and limitations have been described. A results summary as well as detailed uncertainty estimates for the reanalyzed positions and intensities have been provided. An important point of this paper is to demonstrate the limitations of the HURDAT database, especially with regards to TC intensity analysis accuracy. This research suggests that for many cases, the intensities listed in HURDAT (at least through 1953, and likely beyond that year) are not nearly as reliable as intensity estimates today.

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List of Tables.

Table 1. Original/revised tropical storm and hurricane, hurricane, major hurricane, and ACE counts for 1944-1953 along with the 1944-1953 averages. ACE = $10^{-4}\Sigma\ v^{2}_{max}$ where v_{max} is the maximum wind value (kt). The maximum winds are summed for all 6-hourly periods for the entire year.

Table 2. 1944 revisions. Major track (position) changes are defined by changes that are greater than or equal to 2° latitude/longitude and major intensity changes of 20 kt or more from the values shown in HURDAT originally.

Table 3. Tropical cyclones that affected the United States from 1944-1953. Many TCs made multiple U.S. landfalls which are listed here. Direct landfalls are included as well as close approaches of hurricanes and tropical storms that caused at least tropical storm conditions on land. * indicates a close approach (not a direct landfall) with the center of the system staying offshore or making landfall in Mexico, and the wind speed value listed is the analyzed maximum wind experienced on land in the U.S. (therefore the original HURDAT intensity value is left blank for those cases). The original HURDAT intensity column is left blank elsewhere for new storms and new analyzed landfalls. & indicates a brand new tropical cyclone to HURDAT. For all hurricane impacts, maximum wind, central pressure, OCI, and ROCI are required. For all tropical storm impacts, maximum wind is the only value required to be provided. RMW is provided for hurricane impacts only if the value is known.

Table 4. Original vs. revised hurricane impacts for U.S. states by Saffir-Simpson category. 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, NJ- New Jersey, NY- New York, CT- Connecticut, RI- Rhode Island, MA- Massachusetts, ME- Maine. Changes to maximum U.S. landfall category are indicated in underline and bold.

Table 5. Hurricane impacts outside of the continental U.S. (1944-1953). "Wind at coast" is the peak estimated (1 min) surface (10 m) winds to occur at the coast at landfall/closest approach. "Revised max wind" is the maximum wind in the revised HURDAT at the point just prior to landfall or point of closest approach. "Original max wind" is the maximum wind in HURDAT that was originally provided at the point just prior to landfall or point of closest approach. Non-landfalls are denoted by a * symbol. New hurricanes to HURDAT are indicated by &.

Table 6. All available aircraft pressure observations of less than 960 mb for first ten years of aircraft reconnaissance. "Maybe" in three of the above cases indicates the surface pressure was measured by dropsonde.

Table 7. Wind speed root mean squared error and biases of the original vs. revised HURDAT measured against the Brown et al. pressure-wind relationships for times when

central pressures are listed in the revised HURDAT that are there only because of aircraft pressure observations. The RMSE of all the observations in the Brown et al. (2006) study is 9.3 kt. The data used to construct Table 1 and Figure 6 is identical.

Table 8. Average position uncertainty estimates in the reanalyzed HURDAT for different time periods stratified by using different observation methods. (References: Landsea et al. 2008, 2011).

Table 9. Average intensity uncertainty estimates in the reanalyzed HURDAT for different time periods stratified using different observation methods. (References: Landsea et al. 2008, 2011).

Table 10. Average intensity bias estimates in the reanalyzed HURDAT for different time periods stratified using different observation methods and by *actual* storm intensity only for when aircraft reconnaissance flights did not report central pressure values. (References: Landsea et al. 2008, 2011).

Preliminary Original vs. Revised HURDAT Comparison

Year	Tropical storms and hurricanes	Hurricanes	Major hurricanes	ACE
1944	11/14	7/8	3/3	96/105
1945	11/11	5/5	3/1	67/63
1946	6/8	3/4	1/0	22/24
1947	9/10	5/5	2/3	112/91
1948	9/10	6/6	4/4	106/93
1949	13/16	7/7	3/3	98/99
1950	13/16	11/11	8/6	243/210
1951	10/12	8/8	5/3	137/126
1952	7/11	6/5	3/2	87/70
1953	14/15	6/7	4/2	104/97
avg 1944-53	10.3/12.3	6.4/6.6	3.6/2.7	107/98

Table 1. Original/revised tropical storm and hurricane, hurricane, major hurricane, and ACE counts for 1944-1953 along with the 1944-1953 averages. ACE = $10^{-4}\Sigma\ v^2_{max}$ where v_{max} is the maximum wind value (kt). The maximum winds are summed for all 6-hourly periods for the entire year.

Revisions for the 1944 hurricane season

Storm #	Previous Storm #	Date	Orig. Peak Intensity (kt)	Revised Peak Intensity (kt)	Major/Minor Track Change	Major/Minor Intensity Change	Genesis/Decay Change
1	1	7/13 - 7/20	80	65	minor	minor	ET 12 hr later
2	2	7/24 - 7/28	55	55	major	minor	None
3	3	7/30 - 8/4	80	65	minor	minor	Genesis 18 hr earlier, Decay 12 hr earlier
4	4	8/16 - 8/24	105	105	major	major	Genesis 6 hr earlier, Decay 6 hr later
5	5	8/18 - 8/23	50	50	minor	none	Genesis 30 hr earlier
6	6	9/9 - 9/11	45	50	major	minor	added ET 1st 36 hr; Decay 12 hr later
7	7	9/9 - 9/16	120	120	minor	major	None
8	8	9/19 - 9/22	70	70	minor	major	None
9	9	9/21 - 9/28	85	85	major	minor	ET 24 hr earlier
10	-----	9/30 - 10/3	-----	45	-----	-----	New storm
11	10	9/30 - 10/3	40	40	major	none	Genesis 24 hr earlier
12	-----	10/11-10/17	-----	70	-----	-----	New hurricane
13	11	10/12-10/24	105	120	minor	major	Genesis 6 hr earlier, ET 12 hr earlier, Decay 24 hr later
14	-----	11/1 - 11/3	-----	60	-----	-----	New storm

Table 2. 1944 revisions. Major track (position) changes are defined by changes that are greater than or equal to 2° latitude/longitude and major intensity changes of 20 kt or more from the values shown in HURDAT originally. “ET” is extratropical storm transition.

U.S. Tropical Cyclones (1944-1953)

Date- Storm #	Landfall time	Lat (˚N)	Lon (˚W)	Location	Landfall int. (kt)	Orig. int. (kt)	CP (mb)	OCI (mb)	ROCI (nmi)	RMW (nmi)
8/1/1944- Storm 3	2300Z	33.9	78.1	Oak Island, NC	65	80	990	1014	175	10
8/22/1944- Storm 5	1700Z	26.0	97.1	Port Isabel, TX	40*	-----	-----	-----	-----	-----
9/10/1944- Storm 6	1600Z	29.1	90.4	W of Grand Isle, LA	50	40	1001	-----	-----	-----
9/10/1944- Storm 6	2300Z	30.3	88.3	Dauphin Island, AL	50	35	1001	-----	-----	-----
9/14/1944- Storm 7	1300Z	35.2	75.0	Cape Hatteras, NC	90*	-----	942	1010	325	15
9/15/1944- Storm 7	0300Z	40.9	72.3	Southampton, NY	95	75	953	1008	325	30
9/15/1944- Storm 7	0345Z	41.3	71.5	Matunuck, RI	95	75	955	1008	325	30
10/18/1944- Storm 13	2000Z	24.6	82.9	Dry Tortugas, FL	105	105	949	1010	350	30
10/19/1944- Storm 13	0700Z	27.2	82.5	Venice, FL	90	90	962	1011	375	35
6/24/1945 - Storm 1	0800Z	28.6	82.7	Brooksville, FL	70	80	985	1011	200	-----
6/26/1945 - Storm 1	0100Z	34.7	76.6	Cape Lookout, NC	60*	-----	-----	-----	-----	-----
8/27/1945- Storm 5	1600Z	28.3	96.6	Port O'Connor, TX	95	120	963	1010	150	20
9/5/1945 - Storm 7	0000Z	26.5	82.1	Fort Myers, FL	40	35	-----	-----	-----	-----
9/15/1945- Storm 9	1930Z	25.3	80.3	Ocean Reef, FL	115	120	949	1011	125	10
9/15/1945- Storm 9	2000Z	25.4	80.4	Florida City, FL	115	120	949	1011	125	10
9/17/1945- Storm 9	1100Z	32.1	80.8	Hilton Head, SC	75	45	991	1013	275	-----
7/6/1946 - Storm 2	0800Z	33.9	78.2	Oak Island, NC	40	40	-----	-----	-----	-----
10/8/1946- Storm 6	0200Z	27.5	82.6	Bradenton, FL	75	65	980	1009	325	35
11/1/1946- Storm 7	2100Z	26.6	80.1	Palm Beach, FL	40	40	1002	-----	-----	-----
11/3/1946- Storm 8	0500Z	35.0	76.1	Ocracoke Is., NC	35&	-----	-----	-----	-----	-----
8/2/1947- Storm 1	0000Z	26.0	97.1	Port Isabel, TX	35*	-----	-----	-----	-----	-----
8/22/1947- Storm 3	1400Z	29.1	90.3	W of Grand Isle, LA	40	-----	-----	-----	-----	-----
8/24/1947- Storm 3	2200Z	29.1	94.9	Galveston, TX	70	70	984	1010	75	-----
9/17/1947- Storm 4	1630Z	26.2	80.1	Fort Lauderdale, FL	115	135	945	1010	275	20
9/19/1947- Storm 4	1400Z	29.6	89.5	SE of New Orleans, LA	95	80	964	1010	250	25
9/8/1947- Storm 5	1400Z	30.3	88.2	Dauphin Island, AL	45	35	-----	-----	-----	-----
9/23/1947- Storm 6	2200Z	28.9	82.7	Crystal River, FL	55	50	-----	-----	-----	-----
10/7/1947- Storm 7	0400Z	30.8	81.5	St. Marys, GA	50	40	-----	-----	-----	-----
10/11/1947- Storm 9	1900Z	24.5	82.8	Dry Tortugas, FL	75*	-----	983	1010	275	-----
10/12/1947- Storm 9	0200Z	25.4	81.2	NW of Cape Sable, FL	80	70	978	1009	250	-----

10/15/1947- Storm 9	1100Z	31.8	80.9	Savannah, GA	90	75	966	1009	300	-----
7/9/1948- Storm 2	0700Z	30.3	87.3	Pensacola, FL	35	35	-----	-----	-----	-----
9/4/1948- Storm 5	0800Z	29.2	90.4	W of Grand Isle, LA	65	65	986	1009	225	-----
9/21/1948- Storm 8	1700Z	24.6	81.6	Sugarloaf Key, FL	110	105	950	1008	250	10
9/22/1948- Storm 8	0500Z	25.8	81.3	Everglades City, FL	115	100	940	1007	300	-----
10/5/1948- Storm 9	1800Z	24.7	81.2	Marathon, FL	90	110	963	1009	225	15
10/5/1948- Storm 9	2100Z	25.1	80.9	Flamingo, FL	90	110	963	1009	225	-----
8/24/1949- Storm 1	1200Z	34.3	76.1	Cape Lookout, NC	70*	-----	977	1016	175	-----
8/26/1949- Storm 2	2300Z	26.6	80.0	Palm Beach, FL	115	130	954	1011	225	25
9/4/1949- Storm 5	1200Z	29.3	90.6	Houma, LA	50	40	-----	-----	-----	-----
9/13/1949- Storm 7	0800Z	34.3	77.8	Wrightsville Beach, NC	35&	-----	-----	-----	-----	-----
10/4/1949- Storm 11	0500Z	28.8	95.6	SW of Freeport, TX	100	115	960	1009	200	15
8/31/1950- Baker	0300Z	30.2	88.0	Fort Morgan, AL	75	75	979	1003	250	20
8/31/1950- Baker	0400Z	30.7	87.9	E of Mobile, AL	75	75	979	1003	250	20
9/11/1950- Dog	0600Z	35.2	75.5	Cape Hatteras, NC	35*	-----	-----	-----	-----	-----
9/5/1950- Easy	1700Z	29.1	82.8	Cedar Key, FL	105	105	958	1009	325	15
9/6/1950- Easy	0400Z	28.5	82.7	Brooksville, FL	90	85	965	1008	300	-----
10/18/1950- King	0500Z	25.7	80.2	Miami, FL	110	95	955	1005	200	5
10/21/1950- Love	1000Z	29.5	83.4	Cross City, FL	60	60	-----	-----	-----	-----
5/17/1951- Able	2100Z	25.8	80.2	Miami, FL	40*	-----	-----	-----	-----	-----
10/2/1951- How	1000Z	26.7	82.3	Fort Myers, FL	55	55	-----	-----	-----	-----
10/5/1951- How	0800Z	36.0	76.0	Cape Henry, VA	45*	-----	-----	-----	-----	-----
2/3/1952- Storm 1	0400Z	25.4	81.1	Cape Sable, FL	55	45	-----	-----	-----	-----
8/31/1952- Able	0300Z	32.3	80.6	Beaufort, SC	85	90	980	1011	175	-----
8/28/1952- Storm 3	0200Z	33.7	78.7	N. Myrtle Beach, SC	50&	-----	-----	-----	-----	-----
6/6/1953- Alice	1700Z	30.3	85.9	Panama City, FL	40	35	-----	-----	-----	-----
8/14/1953- Barbara	0200Z	34.9	76.3	Ocracoke Is., NC	80	90	975	1015	150	-----
8/14/1953- Barbara	0500Z	35.4	76.1	Nebraska, NC	75	70	978	1015	150	-----
8/14/1953- Barbara	0900Z	36.1	75.7	Kitty Hawk, NC	75	70	978	1015	150	-----
9/1/1953- Storm 3	0800Z	31.6	81.1	N of Brunswick, GA	35	30	-----	-----	-----	-----
9/7/1953- Carol	1200Z	41.2	70.2	Nantucket, MA	50*	-----	-----	-----	-----	-----
9/7/1953- Carol	1800Z	44.9	67.0	Eastport, ME	45*	-----	-----	-----	-----	-----
9/20/1953- Storm 7	1700Z	29.0	82.8	Crystal River, FL	35	40	-----	-----	-----	-----
9/26/1953- Florence	1600Z	30.3	86.2	Panama City, FL	80	80	975	1009	225	-----

10/4/1953- Storm 10	0000Z	25.3	80.3	Ocean Reef, FL	35*	-----	-----	-----	-----	-----
10/9/1953- Hazel	1500Z	26.6	82.3	Captiva, FL	65	60	987	1011	300	-----
10/9/1953- Hazel	1600Z	26.7	82.1	Ft. Myers, FL	65	60	987	1011	300	-----

Table 3. Tropical cyclones that affected the United States from 1944-1953. Many TCs made multiple U.S. landfalls which are listed here. Direct landfalls are included as well as close approaches of hurricanes and tropical storms that caused at least tropical storm conditions on land. * indicates a close approach (not a direct landfall) with the center of the system staying offshore or making landfall in Mexico, and the wind speed value listed is the analyzed maximum wind experienced on land in the U.S. (therefore the original HURDAT intensity value is left blank for those cases). The original HURDAT intensity column is left blank elsewhere for new storms and new analyzed landfalls. & indicates a new tropical cyclone to HURDAT. For all hurricane impacts, maximum wind, central pressure, OCI, and ROCI are required. For all tropical storm impacts, maximum wind is the only value required to be provided. RMW is provided for hurricane impacts only if the value is known.

Changes to U.S. Hurricanes (1944-1953)

Year/Storm	Original	Revised	Cat/state changes
1944 Storm 3	NC1	NC1	None
1944 Storm 7	*NC3* VA3 NY3 CT3 RI3 MA2	*NC2* VA2 NJ1 NY2 CT1 RI2 MA1	*NC -1*; VA -1; add NJ; NY -1; CT -2; RI -1; MA -1
1944 Storm 13	BFL3 DFL2	BFL3 DFL1 AFL1	NE FL -1; add NW FL
1945 Storm 1	AFL1	AFL1	None
1945 Storm 5	BTX2	ATX2 BTX2 CTX1	Add S TX (+2); add N TX
1945 Storm 9	**CFL3**	**CFL4** BFL3 DFL1 SC1	**SE FL +1**; add SW FL (+3), NE FL, SC
1946 Storm 6	BFL1	BFL1 AFL1	Add NW FL
1947 Storm 3	CTX1	CTX1	None
1947 Storm 4	CFL4 LA3 MS3 BFL2	CFL4 LA2 MS2 BFL2	LA -1; MS -1
1947 Storm 9	GA2 SC2 CFL1	GA2 SC2 BFL1 CFL1	Add SW FL
1948 Storm 5	LA1	LA1	None
1948 Storm 8	**BFL3** CFL2	**BFL4** CFL2	**SW FL +1**
1948 Storm 9	CFL2	BFL2 CFL2	Add SW FL
1949 Storm 1	NC1	NC1	None
1949 Storm 2	**CFL3**	**CFL4** BFL1 AFL1 DFL1 GA1	**SE FL +1**; add SW FL, NW FL, NE FL, GA
1949 Storm 11	**CTX2**	**CTX3** BTX1	**N TX +1**; add C TX
1950 Baker	AL1	AL1 AFL1	Add NW FL
1950 Easy	AFL3	AFL3 BFL1	Add SW FL
1950 King	CFL3	CFL3 DFL1	Add NE FL
1952 Able	**SC1**	**SC2**	**SC +1**
1953 Barbara	NC1	NC1	None
1953 Carol	*ME1*	*TS*	*Remove ME*
1953 Florence	AFL1	AFL1	None
1953 Hazel	**TS**	**BFL1**	**SW FL +1**

Table 4. Original vs. revised hurricane impacts for U.S. states by Saffir-Simpson category. 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, NJ- New Jersey, NY- New York, CT- Connecticut, RI- Rhode Island, MA- Massachusetts, ME- Maine. Increases (decreases) to maximum U.S. landfall category are indicated in bold (italics).

Hurricane Impacts Outside of the Continental U.S. (1944-1953)

Date/Storm #	Landfall time	Location	Lat (˚N)	Lon (˚W)	Category	Wind at coast	Revised max wind (kt)	Original max wind (kt)
8/20/1944- Storm 4	1600Z	Jamaica	18.2	76.3	3	105	105	105
8/22/1944- Storm 4	1100Z	Mexico	20.0	87.5	1	80	80	80
9/20/1944- Storm 8	1000Z	Mexico	21.1	86.8	1	70	70	70
9/21/1944- Storm 8	2000Z	Mexico	18.4	93.4	1	70	70	70
10/16/1944 Storm 13	0600Z	Cayman Is.	19.3	81.4	2	85*	90	80
10/18/1944- Storm 13	0000Z	Cuba	21.4	82.9	4	115	115	105
10/18/1944- Storm 13	0800Z	Cuba	22.5	82.9	4	120	120	105
9/14/1945- Storm 9	0600Z	Turks & Caicos	21.3	71.7	2	85	85	105
9/15/1945- Storm 9	0800Z	Bahamas	23.7	77.7	3	110	110	110
10/4/1945- Storm 10	1300Z	Belize	16.2	88.8	1	75	75	60
10/12/1945- Storm 11	1200Z	Cuba	21.6	79.3	1	80	80	85
9/13/1946- Storm 4	0000Z	Bahamas	25.9	77.3	1	65	65	65
10/4/1946- Storm 5	1800Z	Azores	38.5	28.5	1	70&	70	-----
8/15/1947- Storm 2	1100Z	Mexico	21.9	97.6	3	100	100	95
9/17/1947- Storm 4	0600Z	Bahamas	26.5	78.7	3	110	110	140
10/20/1947- Storm 10	1500Z	Bermuda	32.3	64.8	2	90*	105	105
9/13/1948- Storm 6	1800Z	Bermuda	32.3	64.9	2	95*	110	110
9/19/1948- Storm 8	1200Z	Cayman Is.	19.3	81.4	2	85*	90	75
9/20/1948- Storm 8	2200Z	Cuba	22.3	82.1	3	110	110	95
9/21/1948- Storm 8	0100Z	Cuba	22.7	82.1	3	110	110	100
10/5/1948- Storm 9	0700Z	Cuba	22.4	83.2	3	110	110	105
10/6/1948- Storm 9	0800Z	Bahamas	26.8	75.6	2	85*	85	85
10/7/1948- Storm 9	2200Z	Bermuda	32.3	64.8	2	90	90	90
8/26/1949- Storm 2	1000Z	Bahamas	25.0	77.3	3	100	100	100
9/21/1949- Storm 10	1200Z	St. Croix	17.7	64.9	1	65*	65	65
9/21/1949- Storm 10	2100Z	Puerto Rico	18.0	67.2	1	65*	70	70
8/21/1950- Able	1600Z	Canada	44.5	63.7	1	65	65	35
8/22/1950- Baker	0400Z	Antigua	17.0	61.7	2	85*	90	90
9/1/1950- Dog	0600Z	Antigua	17.2	61.8	4	125*	125	90

9/3/1950- Easy	0100Z	Cuba	21.5	82.7	1	70	70	70
9/3/1950- Easy	0700Z	Cuba	22.7	82.4	1	80	80	70
10/11/1950- Item	0400Z	Mexico	18.8	95.9	1	80	80	65
10/16/1950-King	2200Z	Cuba	20.9	78.3	1	80	80	95
5/18/1951- Able	0900Z	Bahamas	26.9	78.0	1	75	75	70
8/18/1951- Charlie	0300Z	Jamaica	17.9	76.9	3	110	110	95
8/20/1951- Charlie	0300Z	Mexico	20.4	87.3	4	115	115	115
8/22/1951- Charlie	1900Z	Mexico	22.2	97.8	3	100	100	110
9/2/1951- Dog	1200Z	Martinique	14.4	60.9	1	80*	80	100
9/2/1951- Dog	1200Z	St. Lucia	14.1	60.9	1	65*	80	100
10/24/1952- Fox	1600Z	Cuba	21.7	81.0	4	125	125	130
10/24/1952- Fox	1800Z	Cuba	22.0	80.9	4	125	125	130
10/26/1952- Fox	0800Z	Bahamas	24.7	76.3	1	75	75	100
9/7/1953- Carol	2000Z	Canada	44.2	66.4	1	75	75	65
9/7/1953- Carol	2200Z	Canada	45.3	65.8	1	70	70	65
9/18/1953- Edna	0200Z	Bermuda	32.3	64.8	2	90*	100	100

Table 5. Hurricane impacts outside of the continental U.S. (1944-1953). "Wind at coast" is the peak estimated (1 min) surface (10 m) winds to occur at the coast at landfall/closest approach. "Revised max wind" is the maximum wind in the revised HURDAT at the time of landfall or point of closest approach. "Original max wind" is the maximum wind in HURDAT that was originally provided at the point just prior to landfall or point of closest approach. Non-landfalls are denoted by a * symbol. New hurricanes to HURDAT are indicated by &.

Lowest Aircraft Pressure Observations (1944-1953)

Lowest Aircraft Pressure (mb)	Central pressure?	Storm	Revised intensity (kt) at time of observation	HURDAT original intensity (kt)
929	yes	1953 Hurricane Carol	140	130
937	yes	1951 Hurricane Easy	125	140
938	yes	1947 Storm 4	125	125
940	yes	1952 Hurricane Fox	120	125
942	yes	1953 Hurricane Carol	115	125
942	yes	1952 Hurricane Fox	110	95
943	maybe	1950 Hurricane Dog	125	145
944	yes	1953 Hurricane Carol	120	75
944	maybe	1950 Hurricane Dog	120	160
945	yes	1953 Hurricane Carol	110	105
951	yes	1948 Storm 8	105	80
951	yes	1947 Storm 4	110	135
952	yes	1947 Storm 4	115	115
953	yes	1950 Hurricane Able	105	120
953	yes	1950 Hurricane Dog	110	75
953	maybe	1950 Hurricane Dog	110	75
956	no	1947 Storm 4	110	140
957	yes	1951 Hurricane Easy	95	120
958	yes	1950 Hurricane Able	100	120
958	yes	1952 Hurricane Charlie	100	100

Table 6. All available aircraft pressure observations of less than 960 mb for first ten years of aircraft reconnaissance. "Maybe" in three of the above cases indicates a surface pressure was measured by dropsonde. "No" indicates a peripheral pressure.

Wind Speed Errors based on Aircraft Data (Revised vs. Original HURDAT) and on Brown et al. (2006)

Aircraft central pressure (mb)	RMSE (kt) Revised	RMSE (kt) Original	Average bias (kt) Revised	Original
All (N = 193)	5.7	19.9	+2.7	+13.3
990-1009 mb (N = 90)	6.8	21.1	+3.8	+15.9
970-989 mb (N = 73)	4.4	18.8	+1.9	+13.6
929-969 mb (N = 30)	5.0	18.4	+1.2	+4.6

Table 7. Wind speed root mean squared error and biases of the original vs. revised HURDAT measured against the Brown et al. pressure-wind relationships for times when central pressures are listed in the revised HURDAT that are there only because of aircraft pressure observations. The RMSE of all the observations in the Brown et al. (2006) study is 9.3 kt. The data used to construct Table 7 and Figure 7 is identical.

HURDAT Position Uncertainty Estimates

Year	US Landfalling (settled)	Open ocean with aircraft reconnaissance	Open ocean without aircraft reconnaissance
1851-1885	60 nmi	N/A	120 nmi
1886-1930	60 nmi	N/A	100 nmi
1944-1953	20 nmi	35 nmi	80 nmi
Late 1990s	12 nmi	15 nmi	25 nmi
Late 2000s	12 nmi	15 nmi	25 nmi

Table 8. Average position uncertainty estimates in the reanalyzed HURDAT for different time periods stratified by using different observation methods. (References: Landsea et al. 2008, 2011).

HURDAT Intensity Uncertainty Estimates

Year	US Landfalling (settled)	Open ocean with aircraft central pressure	Open ocean without aircraft central pressure	Open ocean (no aircraft)
1851-1885	15 kt	N/A	N/A	25 kt
1886-1930	12 kt	N/A	N/A	20 kt
1944-1953	11 kt	13 kt	17 kt	20 kt
Late 1990s	10 kt	12 kt	N/A	15 kt
Late 2000s	9 kt	10 kt	N/A	12 kt

Table 9. Average intensity uncertainty estimates in the reanalyzed HURDAT for different time periods stratified using different observation methods. (References: Landsea et al. 2008, 2011).

HURDAT Intensity Error Biases

Year	US Landfalling	Open ocean with aircraft central pressure	Open ocean with aircraft- no central pressure (30-60 kt)	Open ocean with aircraft- no central pressure (65-95 kt)	Open ocean with aircraft no central pressure (100-115 kt)	Open ocean with aircraft no central pressure (120+ kt)	Open ocean with no aircraft
1851-1885	0 kt	N/A	N/A	N/A	N/A	N/A	-15 kt
1886-1930	0 kt	N/A	N/A	N/A	N/A	N/A	-10 kt
1944-1953	0 kt	0 kt	+3 kt	+5 kt	0 kt	-10 kt	-10 kt
Late 1990s - 2000s	0 kt	0 kt	N/A	N/A	N/A	N/A	0 kt

Table 10. Average intensity bias estimates in the reanalyzed HURDAT database for different time periods stratified using different observation methods and by *actual* storm intensity only for when aircraft reconnaissance flights did not report central pressure values. (References: Landsea et al. 2008, 2011).

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observation at 27.5N, 74.2W). Other numbers pertain to clouds, temperature, and humidity. The estimated center fix position is indicated by the tropical cyclone symbol. (Figure adapted from USAWS 1949).

Figure 4. Aircraft center fixes (Teal dots) for 1948 Storm 3. The original HURDAT track (with black hurricane symbols) is also shown.

Figure 5. Total number of aircraft central pressures reported during the 6 years from 1944-49 vs. the 4 years from 1950-53.

Figure 6. 1944 revised-comparison track map. Faded light blue lines correspond to the original HURDAT tracks.

Figure 7. Comparison plot of original HURDAT winds vs. revised HURDAT winds with central pressures listed in the revised HURDAT that came from aircraft data only.

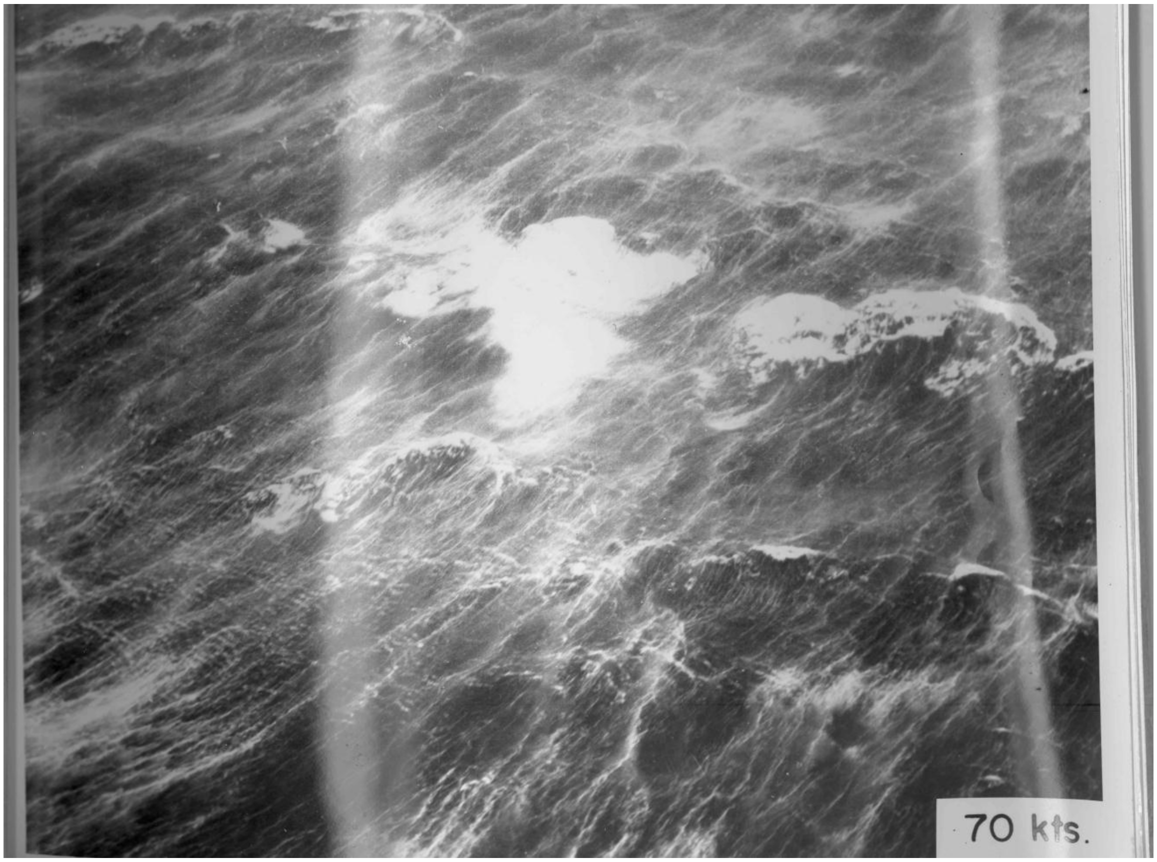

Figure 1. Photo of the sea-surface in 70-kt winds (Neumann 1952).

Hurricane Flight Track – Penetration

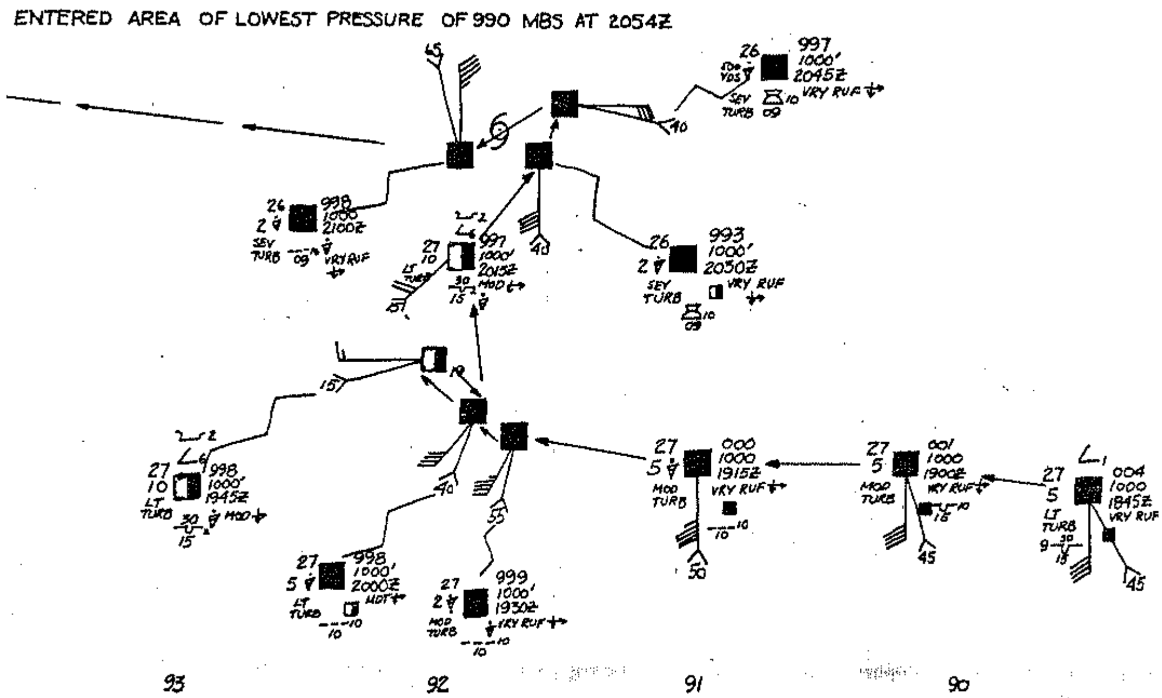

Figure 2. Low–level penetration performed by Navy reconnaissance aircraft at an altitude of 1,000 feet into 1948 Storm 5 in the north-central Gulf of Mexico on 3 September, 1948 at 2054Z (USAWS 1949). Observations are plotted along flight track of the aircraft and contain information on flight-level and surface winds, surface pressure, flight-altitude, and time and position of the observation. The observation taken just after a central pressure of 990 mb was measured (located just southwest of the center) indicates NNW flight-level winds of 65 kt at 1,000 ft altitude with an extrapolated surface pressure of 998 mb. This observation occurred at 2100Z (6 min after the center fix at 2054Z).

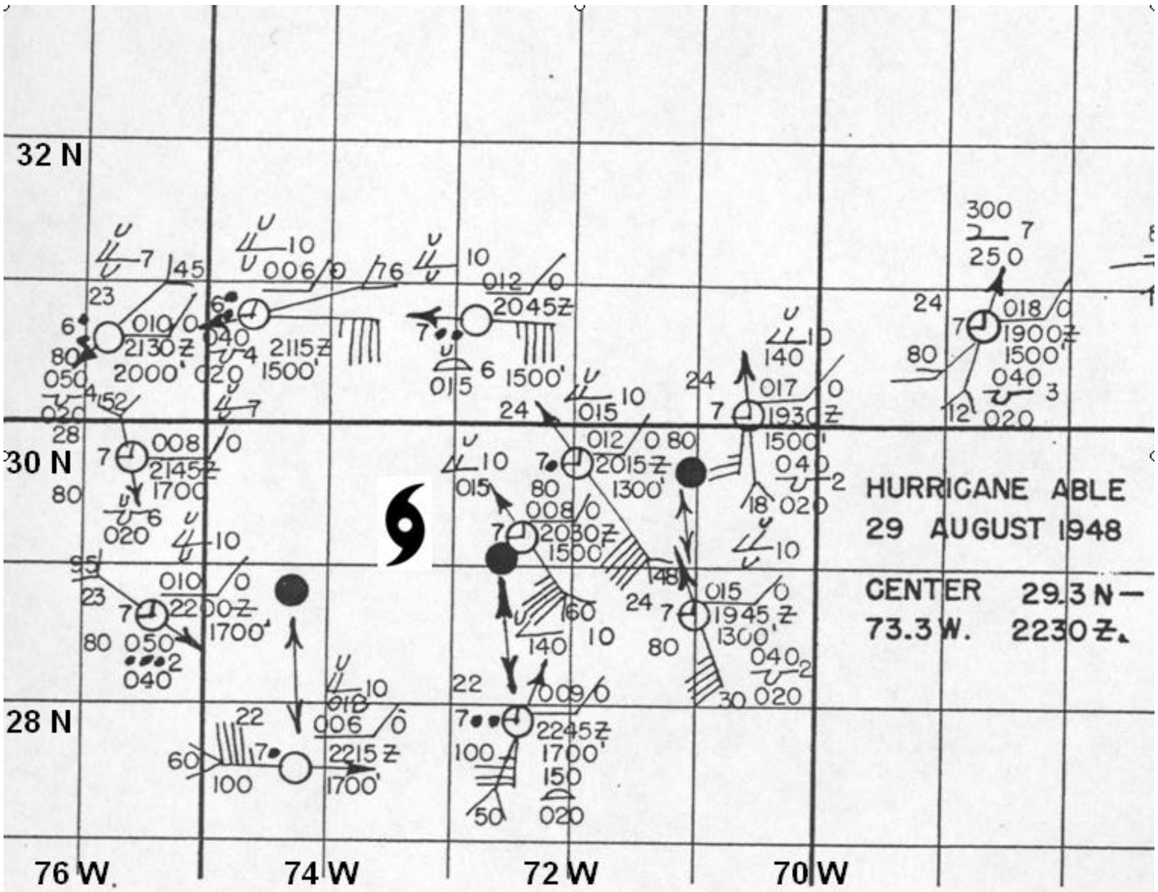

Figure 3. The August 29, 1948 afternoon flight track from 1948 Storm #3. The figure shows observations recorded every 15 minutes of an aircraft circling around the periphery of the hurricane, never penetrating closer to the center than the 1006 mb isobar. Flight-level wind speeds (kt) are indicated by the number shown in the tail of the wind barb. For example, focusing on the observation at 27.5N, 74.2W, the flight-level wind is 60 kt from the west at a flight-level of 1,700 ft at 2215Z. Surface wind (obtained from visual surface estimates) is indicated by the wind barbs where 1 barb is equal to 2 forces of wind on the Beaufort Scale (four and a half barbs is equal to 40 kt). Pressure at the location of the aircraft extrapolated down to the surface is shown above and to the right of the circle (in whole millibars with the first digit removed- 1006 mb in the example observation at 27.5N, 74.2W). Other numbers pertain to clouds, temperature, and humidity. The estimated center fix position is indicated by the tropical cyclone symbol. (Figure adapted from USAWS 1949).

1948 Storm 3

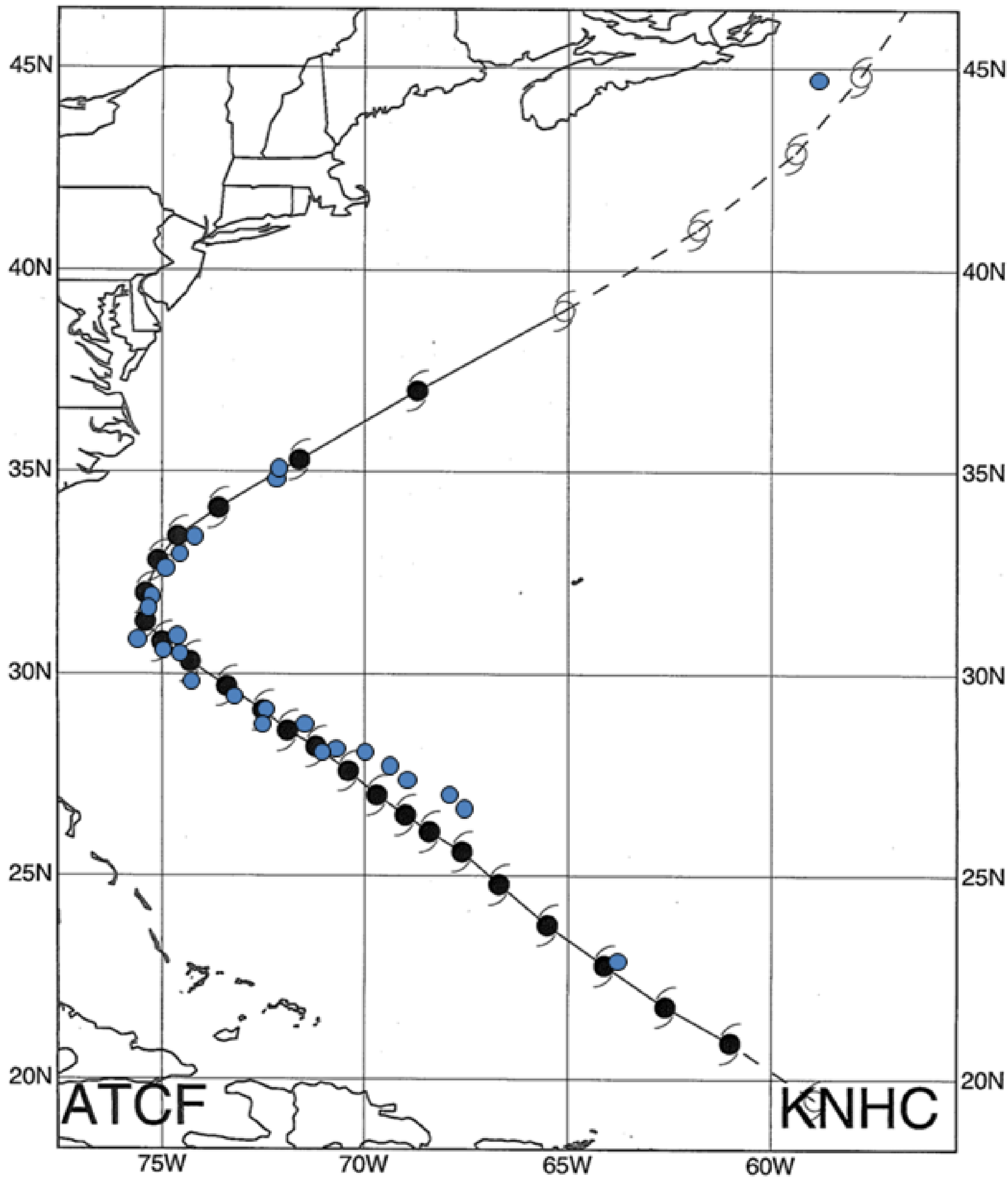

Figure 4. Aircraft center fixes (teal dots) for 1948 Storm 3. The original HURDAT track (with black hurricane symbols) is also shown.

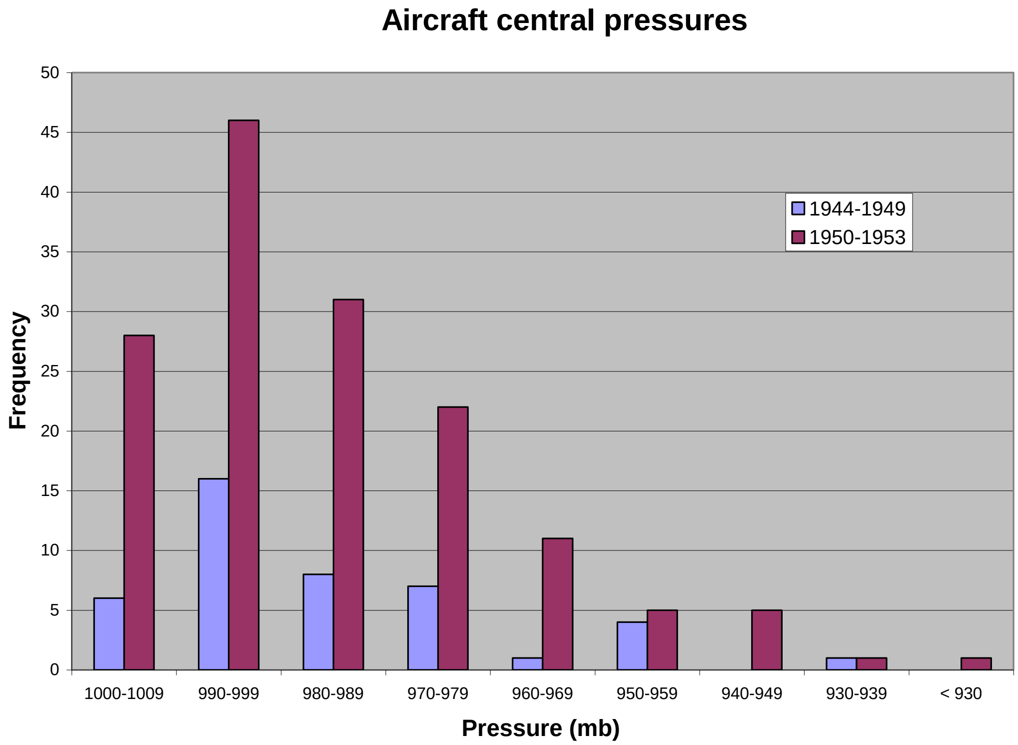

Figure 5. Total number of aircraft central pressures reported during the six years from 1944-49 vs. the four years from 1950-53.

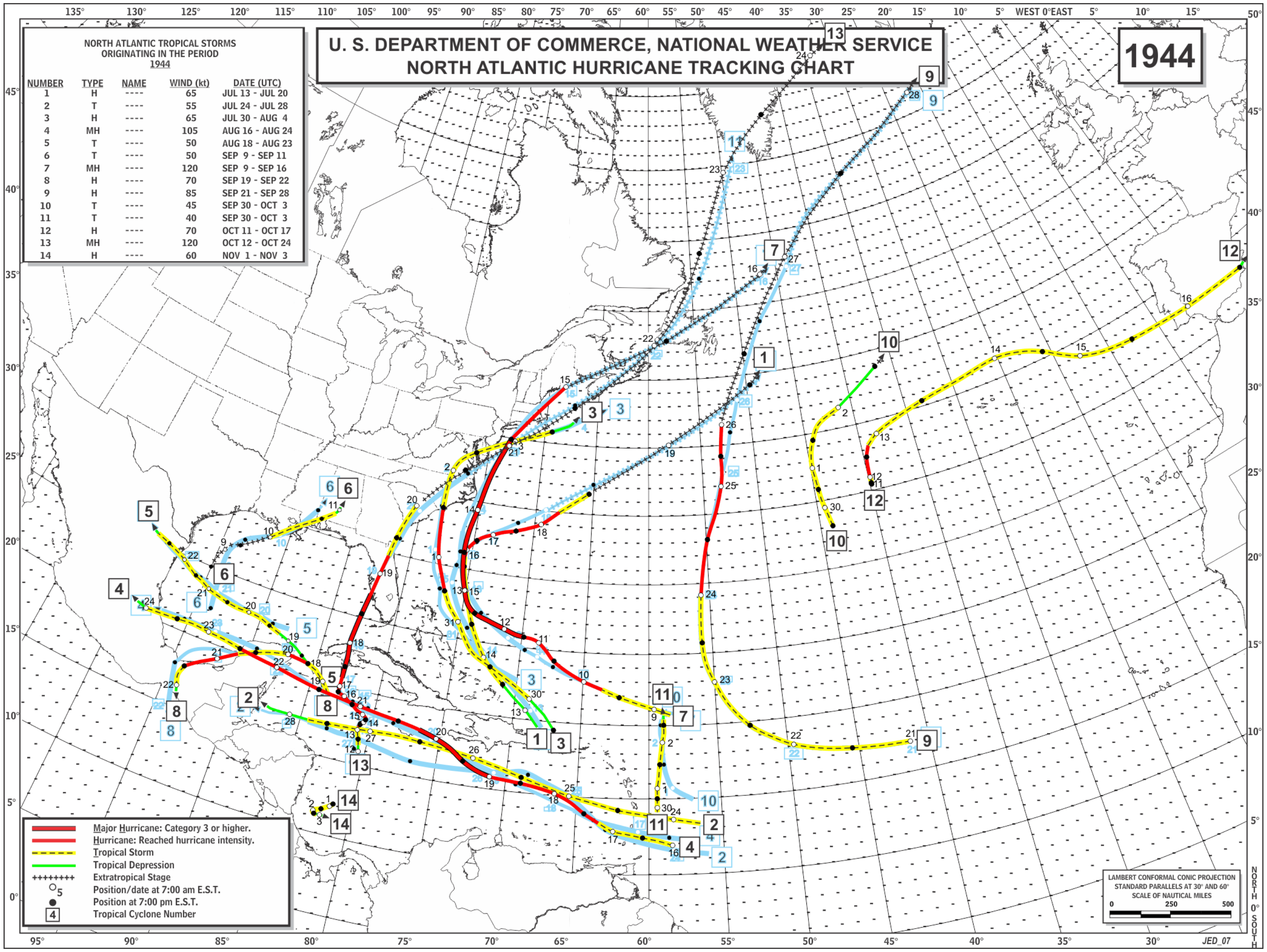

Figure 6. 1944 revised-comparison track map. Faded light blue lines correspond to the original HURDAT tracks.

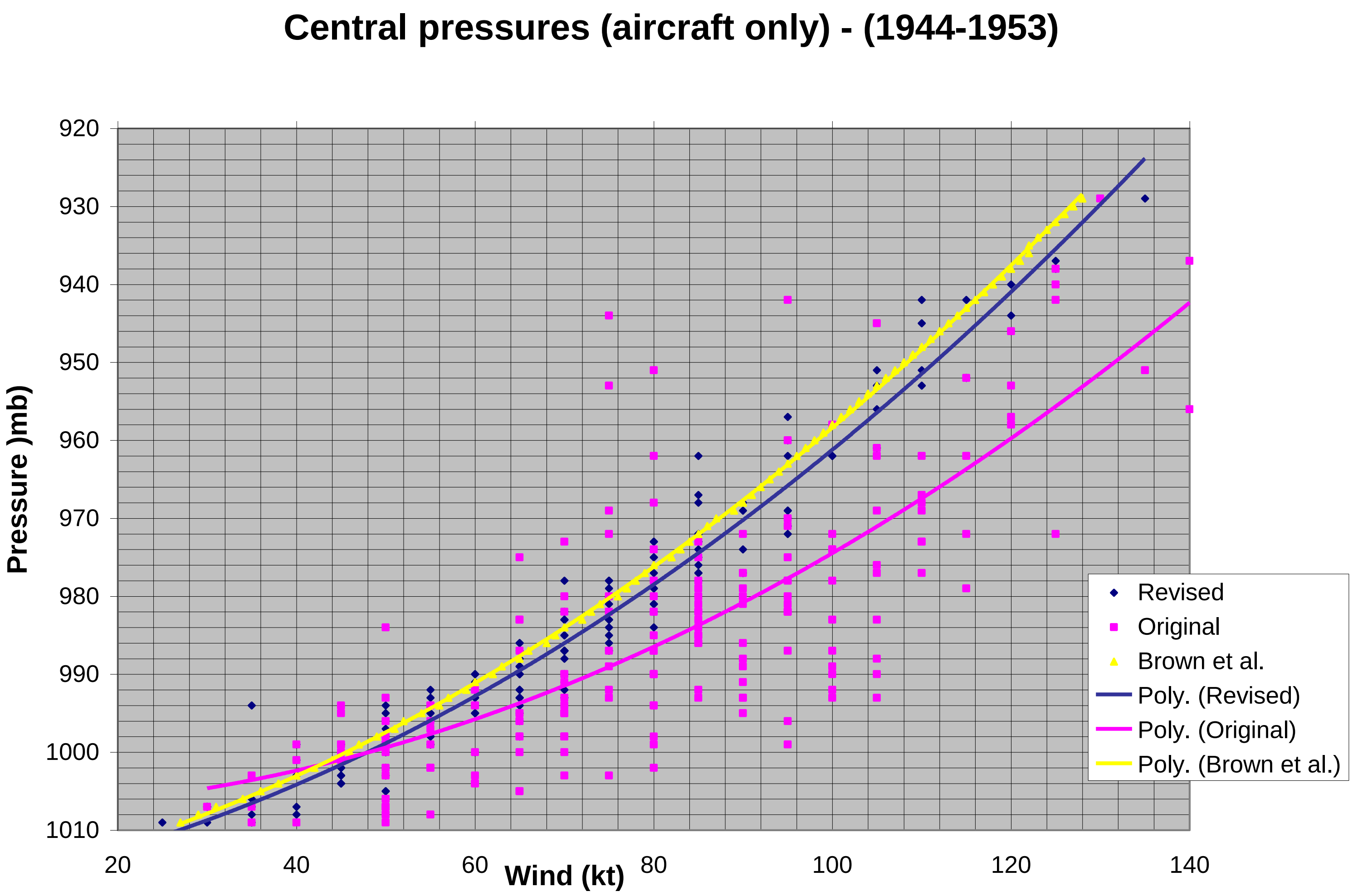

Figure 7. Comparison plot of original HURDAT winds vs. revised HURDAT winds with central pressures listed in the revised HURDAT that came from aircraft data only.