On the Classification of Extreme Atlantic Hurricanes Utilizing Mid-Twentieth-Century Monitoring Capabilities*

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ABSTRACT

An investigation is conducted to determine how improvements in observing capabilities and technology may have affected scientists' ability to detect and monitor Saffir–Simpson Hurricane Wind Scale Category 5 hurricanes in the Atlantic Ocean basin during the mid-twentieth century. Previous studies state that there has been an increase in the number of intense hurricanes and attribute this increase to anthropogenic global warming. Other studies claim that the apparent increased hurricane activity is an artifact of better observational capabilities and improved technology for detecting these intense hurricanes. The present study focuses on the 10 most recent Category 5 hurricanes recorded in the Atlantic, from Hurricane Andrew (1992) through Hurricane Felix (2007). These 10 hurricanes are placed into the context of the technology available in the period of 1944–53, the first decade of aircraft reconnaissance. A methodology is created to determine how many of these 10 recent Category 5 hurricanes likely would have been recorded as Category 5 if they had occurred during this period using only the observations that likely would have been available with existing technology and observational networks. Late-1940s and early-1950s best-track intensities are determined for the entire lifetime of these 10 recent Category 5 hurricanes. It is found that likely only 2 of these 10—both Category 5 landfalling hurricanes—would have been recorded as Category 5 hurricanes if they had occurred during the late-1940s period. The results suggest that intensity estimates for extreme tropical cyclones prior to the satellite era are unreliable for trend and variability analysis.

1. Introduction and background

The primary goal of this study is to determine how the most recent Category 5 hurricanes would be analyzed today with the technology and observation network of the period 1944–53. This knowledge, in turn, could help determine the extent to which increases in observational coverage and advances in technology for better detecting Saffir–Simpson Hurricane Wind Scale Category 5 hurricanes have changed from the mid-twentieth century to the present day. Some recent studies (e.g., Emanuel 2005; Webster et al. 2005) relate increases in intense hurricane activity to anthropogenic global warning. Other studies, such as Landsea et al. (2006), suggest that recent technological advances and improved observational capabilities have allowed better detection of intense tropical cyclones (TCs). Klotzbach (2006) indicates that the number of intense hurricanes globally has been steady since approximately 1990 despite simultaneous ocean temperature rises. The observational network today is much more complete than in the first decade of aircraft reconnaissance, as numerous significant technological advances for monitoring TCs were subsequently developed. The improvements in technology and observational capabilities with time are illustrated by McAdie et al. (2009) and are depicted in Fig. 1. The improvements in technology and increases in the number and types of observations almost certainly play a significant role in the detection of intense hurricanes, as, for example, there are no Category 5 hurricanes listed in the Atlantic hurricane

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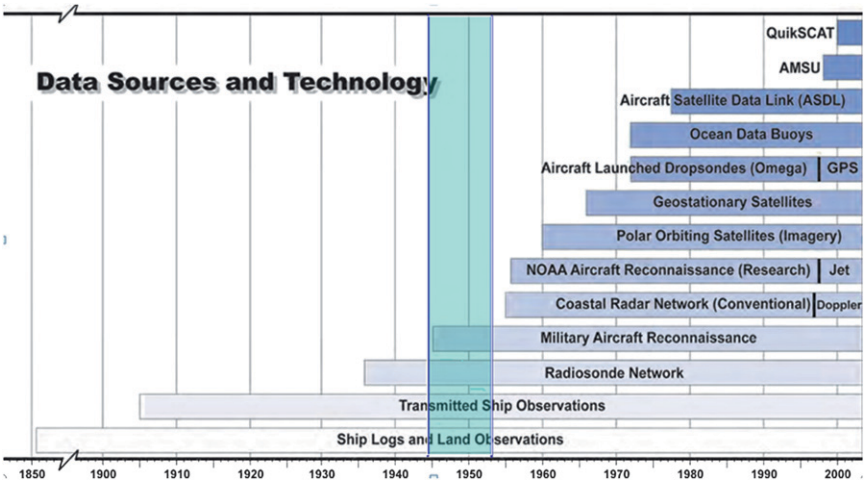

FIG. 1. This graphic adapted from McAdie et al. (2009) shows how TC observational capabilities have evolved as a function of time. The 1944–53 period is highlighted with a blue bar because this is the period against which the recent Category 5 hurricanes are compared.

database (HURDAT) for 1851–1923. From 1924 to 2011, 32 Category 5 hurricanes are recorded to have occurred in the Atlantic Ocean basin.

One might attempt to address the effect of technology by determining how the 10 most recent Category 5 hurricanes in the Atlantic basin (1992–2007) would have likely been analyzed from observations available in the late 1940s and early 1950s. The tracks of the 10 hurricanes are shown in Fig. 2. Most of the 10 Category 5 hurricanes in the Atlantic from 1992 to 2007 were only at Category 5 strength for a short period of time. According to the National Hurricane Center (NHC) best track (Jarvinen et al. 1984), the average Category 5 duration for the 10 most recent Category 5 hurricanes is ~1.4 days. Hurricanes Katrina and Wilma of 2005 were only Category 5 hurricanes for 18 h each, whereas Hurricane Emily was only a Category 5 for 6 h. None of those three storms made landfall as a Category 5. Because of the improved monitoring capabilities coupled with the short duration of Category 5 hurricanes at that intensity, the question to be

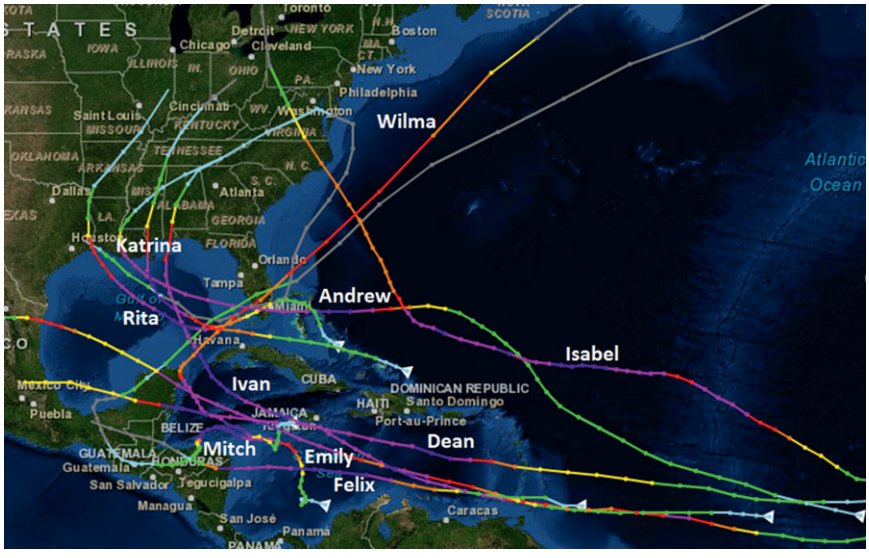

FIG. 2. Track map of the 10 hurricanes that reached Category 5 strength (1992–2007). Colors are defined as follows: light blue—tropical depression, green—tropical storm, yellow—Category 1, orange—Category 2, red—Category 3, pink—Category 4, purple—Category 5, and gray—extratropical.

addressed with this study is, how intense would the 10 most recent Category 5 hurricanes have been analyzed as if these cyclones had been monitored with the technology available in the late 1940s/early 1950s?

Observations of the peak intensity in strong hurricanes were much less common during the late 1940s/early 1950s when compared with recent years because the ability to measure the central pressure and peak winds in major hurricanes was very limited during the late 1940s/early 1950s. A Category 5 designation would be possible if a hurricane made landfall as a Category 5 at or very near a weather station, or if a ship passed through the center while at Category 5 intensity. Aircraft reconnaissance was generally only capable of recording Category 4 conditions at most because of the inability to penetrate intense hurricanes (Hagen et al. 2012).

It was very uncommon for extreme hurricane conditions to be recorded by ships during the first decade of aircraft reconnaissance. From 1944 to 1953, despite numerous ships typically taking observations, there was only one ship that measured a central pressure below 950 mb (hPa). However, from 1911 to 1930, there were 16 such ships. These statistics suggest that ships were 8 times as likely to encounter the center of a major hurricane prior to the beginning of the aircraft reconnaissance era. To assess the typical ship density on a normal day without ongoing tropical cyclones, the ships in the Atlantic Ocean at 1200 UTC 20 September 1950 are compared against the ships at 1200 UTC 20 September 2011 in Fig. 3. There are more than 3 times as many ships in the 2011 plot. Aircraft reconnaissance enabled great improvements in tracking and short-range forecasting beginning in the mid-1940s so that ships would be alerted to steer away from hurricanes. If a Category 5 hurricane made landfall at or near a weather station or near a place with a sufficient coastal population, then it is certainly possible that Category 5 conditions would have been recorded. Figure 4 shows the swaths of Category 5 conditions from the 10 hurricanes from 1992 to 2007 along with the coastal station observing network of the 1944–53 period. This area is approximately 8000 $(\text{n mi})^2$ per system. For comparison, this means that for the average Category 5 hurricane, the surface area that experiences Category 5 winds or pressures is smaller than the area of Puerto Rico, or about 0.1% of the area in the Atlantic basin where tropical cyclones occur.

2. Aircraft reconnaissance

The period 1944–1953 was the first decade of routine military aircraft reconnaissance into Atlantic tropical cyclones (Summer 1944; Porush and Spencer 1945; Sheets 1990). Hagen et al. (2012) explain that the surface and especially the flight-level winds during this decade lack sufficient accuracy and consistency to be given more than a light weight in the reanalysis of the HURDAT intensity. Instead, the reanalysis of intensity relies heavily on aircraft central pressure measurements, when available. Central pressure measurements are converted to maximum wind speeds utilizing the Brown et al. (2006) pressure–wind relationships. Aircraft penetrations (i.e., fly into the eye) were extremely uncommon for major hurricanes from 1944 to 1949 and for Category 4 and 5 hurricanes from 1950 to 1953 because the aircraft were not equipped for the extreme winds and turbulence often experienced in hurricanes of that strength. Instead, circumnavigations would generally be conducted. [For examples of penetration and circumnavigation fixes, see Figs. 2 and 3 of Hagen et al. (2012).] When penetrations were not performed, central pressures could not be obtained, and the intensity of the hurricane is highly uncertain.

During the 6 yr of 1944–49, aircraft reconnaissance provided a total of approximately 200 center fixes—43 of which were by low-level penetration. The other 150-plus center fixes were obtained via circumnavigation and aircraft radar. These penetration fixes were typically provided by both the U.S. Navy PB4Y-2 aircraft and various U.S. Air Force aircraft. Central pressures were reported for the 43 penetration fixes in these 6 yr. On average, this means fewer than one aircraft central pressure per TC $(7\ \text{yr}^{-1})$ was obtained, which is very low when compared with today. For comparison, in 2009, a single season during which Atlantic TC activity was about half of normal, there were 94 aircraft central pressures reported. Because major hurricanes were almost never successfully penetrated from 1944 to 1949, a central pressure deeper than 950 mb was only obtained 1 time.

In 1950, several practices changed [see Hagen et al. (2012) for a description of these changes]. During the period 1950–53, aircraft reconnaissance provided approximately 500 center fixes, and central pressures were reported for about 150 of these. Only two of these (~1%) measured a central pressure deeper than 940 mb. The other 350 fixes that did not obtain a central pressure were obtained by aircraft radar, circumnavigation, 700-mb penetration, or a combination of methods. These statistics indicate that although low-level penetrations and reports of central pressures became more common during the early 1950s, circumnavigations and radar fixes were still the predominant methods for monitoring major hurricanes.

Although aircraft reconnaissance was generally incapable of measuring Category 5 conditions from 1944 to 1953, it is important for this study to know the range of aircraft reconnaissance and where they flew during the first decade of reconnaissance. From all aircraft data

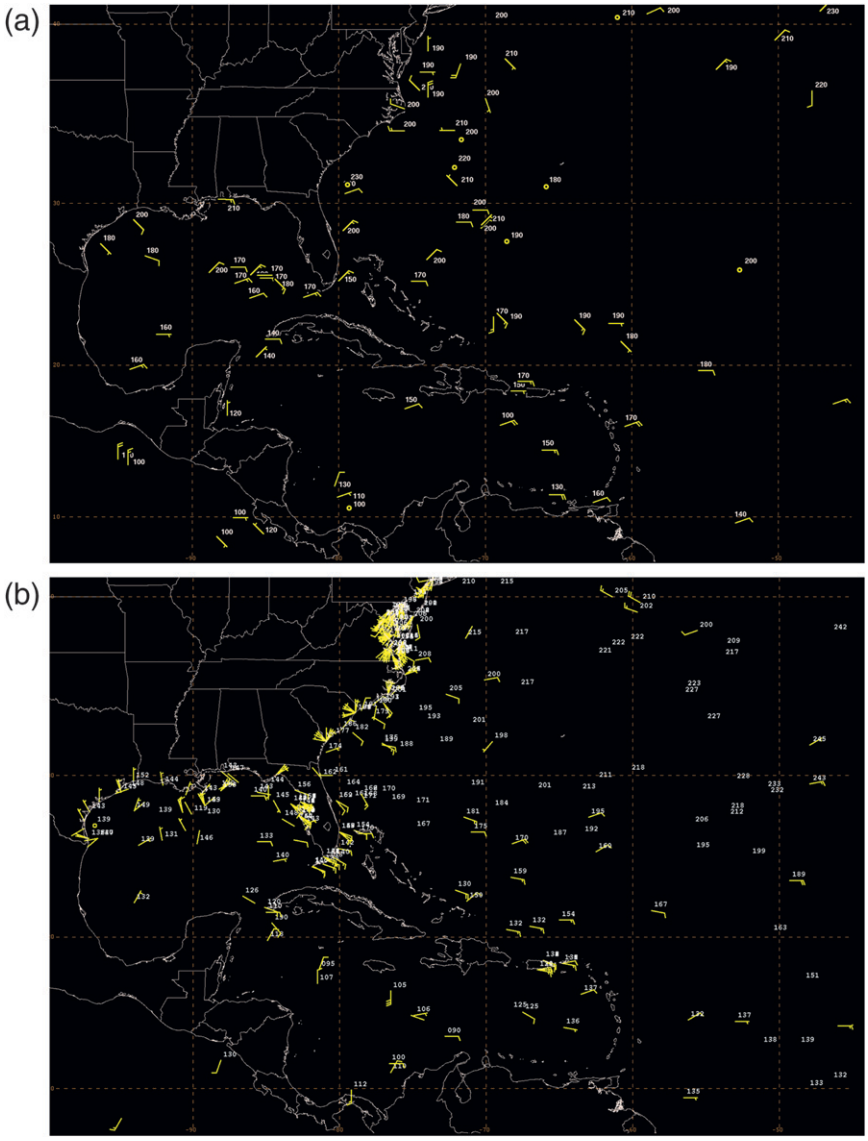

FIG. 3. (top) Ship observations at 1200 UTC 20 Sep 1950, and (bottom) ship and buoy observations at 1200 UTC 20 Sep 2011. Wind barbs—full = 10 kt and half = 5 kt. Pressure is in tenths of millibars (090 = 1009.0 mb).

from the reanalysis of 1944–53 (Hagen et al. 2012), south of 25°N, the eastern edge of the range flown by reconnaissance was 50°W; north of 25°N, the eastern edge was 55°W. The entire Atlantic Ocean west of 55°W and the Gulf of Mexico were well monitored. There were no aircraft flights from 1944 to 1953 that traversed the waters of the southern Caribbean Sea south of 15°N between 70°W and the coast of Central America. However, 1944–53 was a quiet period for hurricanes in the southern Caribbean, as there were only four short-lived tropical storms and no hurricanes that traversed that region. If there were a hurricane in the southern Caribbean during 1944–53, there is no logistic or physical reason why it would not have been flown by aircraft reconnaissance. In fact, aircraft reconnaissance flights were conducted in this region in Hurricane Hazel of 1954 and Hurricane Janet of 1955. For information on how often tropical cyclones were flown by aircraft reconnaissance during 1944–53, see appendix A in the online supplemental material.

3. Methodology

The companion paper—Hagen et al. (2012)—documents the raw observations, methodology, and results of a reanalysis of the 1944–53 hurricane seasons. HURDAT (Jarvinen et al. 1984; McAdie et al. 2009) contains the

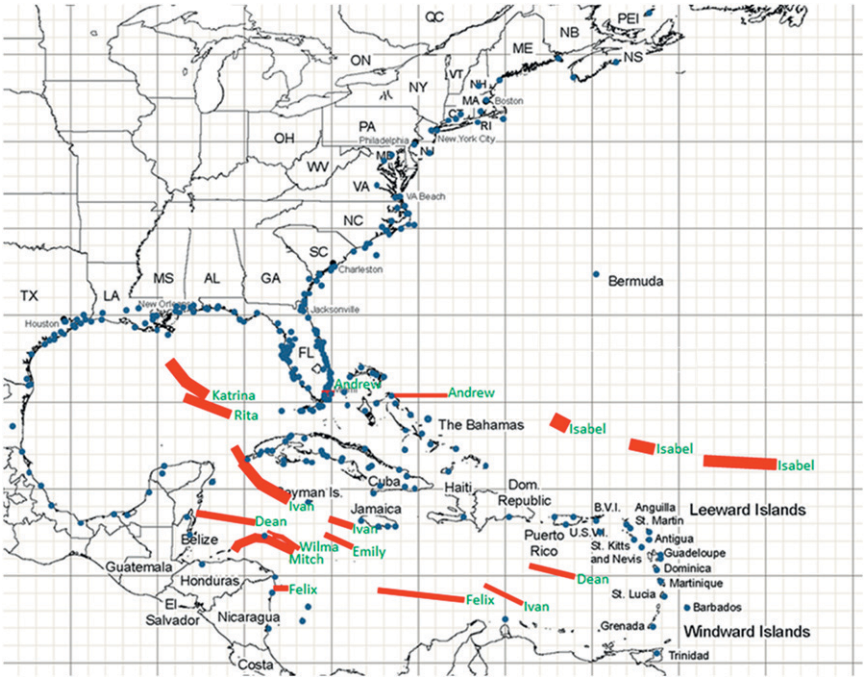

FIG. 4. Swaths of 1992–2007 Category 5 conditions (red) and coastal stations (blue dots) taking observations during the 1944–53 period. The areas in red correspond to the areas inside the RMW when the hurricanes were at Category 5 intensity.

positions and intensities of each recorded Atlantic basin tropical storm, subtropical storm, and hurricane from 1851 to the present. The 10 most recent Category 5 hurricanes—from Andrew in 1992 to Felix in 2007—are similarly "reanalyzed" in the context of observations that would likely have been available in the late 1940s/early 1950s. All observations available to the NHC associated with these recent hurricanes are taken into consideration for the present study. This includes surface-based observations from ships and land stations, aircraft observations including information from dropsondes and stepped-frequency microwave radiometer (SFMR), land-based Doppler radars as well as aircraft radars, and all geostationary, microwave, and scatterometer satellites.[1] During the late 1940s/early 1950s, much of this technology did not yet exist. Therefore, only those observations that likely would have been available during the late 1940s/early 1950s are utilized for determining the intensities (the maximum 1-min 10-m wind associated with the hurricane circulation) that would have been recorded if the hurricane had occurred during that period. To determine which observations would be included for assessing the late 1940s/early 1950s intensities, all satellite observations are obviously excluded because satellites were not yet invented. Most of the 10 most recent Category 5 hurricanes received a Dvorak classification (Dvorak 1984) of 7.0 or higher at some point in their lifetime, indicating Category 5 intensity. The paragraphs that follow discuss how surface data and aircraft data are treated.

Surface data available during the 1992–2007 period includes ships, buoys, Coastal-Marine Automated Network (C-MAN) stations, and other land-based reporting stations. All ships from the 1992–2007 period are included as intensity information that would have been available during 1944–53. As shown in Fig. 2, the amount of ship observations today far surpasses what was typically available in the late 1940s/early 1950s. As explained in section 1 of this manuscript, ships began doing a much better job avoiding the core of major hurricanes starting at the beginning of the aircraft reconnaissance era (as well as in more recent years). Therefore, the consideration of all recent ship observations is a conservative approach given the increase in numbers relative to the late 1940s/early 1950s. However, as ships in that period successfully avoided the cores of major hurricanes, the ship observations are somewhat irrelevant in terms of this study. Buoys and C-MAN stations that went into operation post-1953 are not included.

[1] For details of available observations for these 10 Category 5 hurricanes, refer to the NHC tropical cyclone report archive website as well as the summary articles in *Monthly Weather Review* (Mayfield et al. 1994; Pasch et al. 2001; Lawrence et al. 2005; Franklin et al. 2006; Beven et al. 2008; Brennan et al. 2009).

For land-based coastal stations, there are four rules for which stations are included as intensity information that would have been available during 1944–53. 1) Stations operating with complete observations both during 1992–2007 and 1944–53 are included. 2) Stations in operation during the 1992–2007 period that were not in operation in the late 1940s/early 1950s are not counted. 3) Stations in operation during the late 1940s/early 1950s but had been discontinued during 1992–2007 (e.g., Swan Island) are included as an estimated observation. Although no actual observations are available for the recent hurricanes from these stations, the highest wind/lowest pressure that likely would have been experienced there is estimated based on the NHC best-track intensity, distance from the station, radius of maximum wind (RMW), and radius of 64-kt winds ($1\ \text{kt} \simeq 0.5\ \text{m s}^{-1}$). If the area at or inside the RMW passed over a station in operation during 1944–53 when the hurricane from 1992 to 2007 was at Category 5 intensity, then it is assumed (again conservatively) that Category 5 conditions would have been recorded. 4) Stations in operation during the late 1940s/early 1950s that were also in operation from 1992 to 2007 that had their measuring equipment fail before the height of the storm in 1992–2007 would be included as having experienced Category 5 conditions if the RMW of the hurricane passed over the station while it was a Category 5. Surface measurements that are considered by NHC to have been ''unofficial observations'' are included as information to be utilized for this study.

The methodology for inclusion of aircraft reconnaissance observations is quite different. Aircraft would generally only penetrate the center of tropical storms and weak hurricanes during the late 1940s (see Hagen et al. 2012). It is assumed that no aircraft could penetrate the center of a hurricane with a central pressure of less than 950 mb. This in many cases is a very conservative estimate, as often the reconnaissance crew would avoid penetrations of cyclones with central pressures in the range of 950–970 mb as well. Since aircraft observations underwent some significant changes around 1950, the period 1950–53 is treated as a separate period from 1944 to 1949. The major difference is that for the 1950–53 period, it is assumed that aircraft would not penetrate the center of hurricanes of less than 940 mb, as the reconnaissance crews began flying into the center of somewhat stronger hurricanes in the early 1950s. Aircraft intensity information was only available during daylight hours during the late 1940s and early 1950s, since penetrations of that era required low-level flights where the pilots could physically see the sea surface. Because of these considerations, all aircraft observations at night are excluded. Additionally, all aircraft pressure observations of less than 950 mb (1944–49) and less than 940 mb (1950–53) are excluded.

For aircraft fixes during which the central pressure was less than 950 mb (940 mb), the late 1940s (early 1950s) intensity is determined by utilizing the Brown et al. (2006) pressure–wind relationships for 950 (940) mb, and then adjusting upward slightly by 5 kt to account for the fact that the central pressure would have been an unknown amount deeper than that value. As a hypothetical example, if an aircraft penetrated a hurricane from 1992 to 2007 and found a central pressure of 908 mb, then the pressure would be an unknown value below 950 mb for the late 1940s period. A 950-mb central pressure equals 111 kt according to the Brown et al. (2006) pressure–wind relationship for systems located north of 25°N. If no adjustments for size, speed, environmental pressure or RMW are needed, then 115 kt will be selected as the intensity value after adding 5 kt to account for the fact that the central pressure is an unknown value lower than 950 mb and after rounding to the nearest 5-kt value. Because of these limitations, aircraft reconnaissance was only capable of measuring Category 4 conditions during the late 1940s and early 1950s with one possible exception. For the early 1950s period, aircraft might have been able to confirm Category 5 intensity for intensifying hurricanes south of 25°N for which the central pressure is less than 940 mb only if these TCs are smaller than average, have a high environmental pressure, and a fast-forward motion. In cases such as these for the early 1950s when 10 kt is added to the Brown et al. (2006) southern-intensifying pressure–wind relationship, it is possible to assign a 140-kt intensity (see the Hurricane Felix description in appendix B in the online supplemental material).

After eliminating intensity observations that would not have been available during the late 1940s/early 1950s, the intensities are determined using the remaining observations by applying HURDAT reanalysis methodology, such as the Brown et al. (2006) pressure–wind relationships described above (Hagen et al. 2012; Landsea et al. 2012, 2004b, 2008). After performing these analyses, answers to four questions are addressed: 1) Would the Category 5 hurricane have been recorded at that peak intensity if it had been assessed using the technology available during the late 1940s/early 1950s? 2) What intensity would the storm have been assigned at the time it was a Category 5 and why? 3) What/when was the strongest wind/lowest pressure for the storm that would have been used to determine the intensity using the technology available during the late 1940s/early 1950s, and how was the best-track intensity decided on? 4) How would the total accumulated cyclone energy (ACE) for the hurricane have been different? These questions are answered here for 6 of the 10 Category 5 hurricanes, and the other 4 are discussed in the online supplemental material.

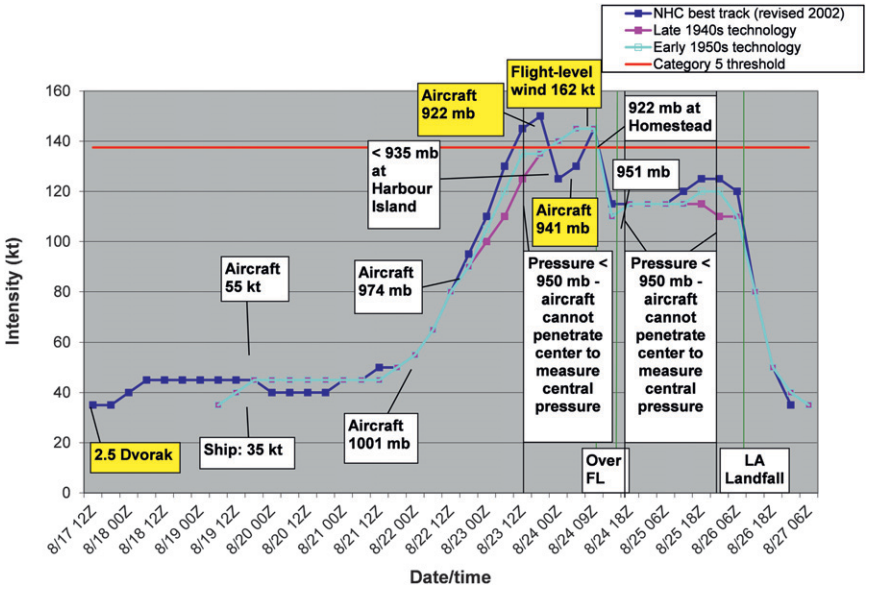

FIG. 5. Best-track comparison graph for Hurricane Andrew (1992): dark blue line is the NHC best-track intensity and light blue line is what the intensity would have likely been with observations available during the early 1950s. The intensity derived from late-1940s technology is shown in pink if it differs from the early-1950s values. Yellow boxes indicate observations that would only be available with recent technology, and white boxes indicate observations that were available during both the late 1940s/early 1950s and today. Vertical green lines indicate landfall/oceanfall times.

4. Results and discussion

Best-track intensity graphs are developed for the entire lifetime of all 10 of the Category 5 hurricanes using the methodology for this study described above. The actual intensities from the NHC best track are compared to the best-track intensity that likely would have been listed if these hurricanes had been assessed using the technology available during the late 1940s/early 1950s. Of the 10 Category 5 hurricanes in this study, 4 of them made landfall as a Category 5 (Andrew—south Florida, Mitch—Swan Island, Dean—Mexico's Yucatán Peninsula, and Felix—Nicaragua), but only Andrew and Mitch passed over a coastal station in operation during the 1944–53 period. The following subsections detail how the questions were answered for 6 of the 10 Category 5 hurricanes. The other 4 are discussed in the online supplemental material.

a. Hurricane Andrew (1992)

Hurricane Andrew (1992) is listed in the revised NHC best track (Rappaport 2010; Landsea et al. 2004a) as a Category 5 at 1200 and 1800 UTC 23 August as well as at the 0900 UTC 24 August landfall south of Miami, Florida. Figure 5 shows the NHC best track for Andrew and the best track likely to be obtained using technology available in the late 1940s/early 1950s. During the first Category 5 period, when Andrew was approaching the Bahamas, intensities of 145 and 150 kt are listed in the NHC best track at 1200 and 1800 UTC 23 August. At 1224 UTC 23 August, aircraft flew to the system but likely would not have been able to penetrate the center in the 1940s or 1950s because the central pressure was less than 940 mb. During the late 1940s (early 1950s), a central pressure of less than 950 (940) mb yielded a wind speed of greater than 111 (121) kt according to the Brown et al. (2006) southern pressure–wind relationship. [Hereafter, the number in parentheses corresponds to the early 1950s value and the number outside the parentheses refers to the late 1940s intensity]. After adding 10 kt due to a small size and high environmental pressure, a wind speed greater than 121 (131) kt is yielded. A 125 (135)-kt intensity is chosen for 1200 UTC 23 August. At 2000 UTC 23 August, Andrew passed directly over the location of a station on Eleuthera Island, Bahamas, when its interpolated intensity was roughly 140 kt, but no observations were recorded there during Andrew. One hour later, a pressure of 935 mb was recorded at Harbor Island (it would have been uncertain whether this was a central pressure value). A central pressure of less than or equal to 935 mb yields a wind speed of at least 126 kt, and after adding 5–10 kt for a small size and high

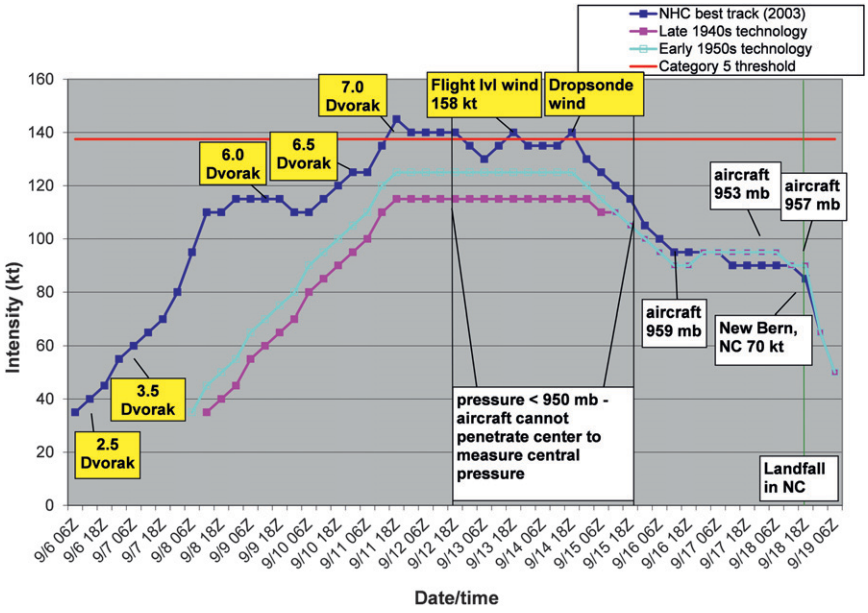

FIG. 6. As in Fig. 5, but for Hurricane Isabel (2003).

environmental pressure, the intensity would have been at least 130–135 kt at the time. A 135-kt intensity is chosen for 1800 UTC 23 August and a 140-kt intensity is chosen for 0000 UTC 24 August for both the late 1940s and early 1950s based on both the Harbour Island observation taken during Andrew and the possibility that Eleuthera would have recorded 140-kt winds or an equivalent pressure.

Andrew made landfall near Homestead, Florida, at 0900 UTC 24 August, where a 922-mb central pressure was recorded by surface observations. A central pressure of 922 mb yields wind speeds of 137 and 130 kt, according to the Brown et al. (2006) south and north of 25°N pressure–wind relationships, respectively. The 922-mb central pressure also yields 139 and 137 kt according to the intensifying subsets of the aforementioned pressure–wind relationships, respectively. A blend of these values gives about 135 kt. Taking into account the small size and high environmental pressure of Andrew, 10 kt is added to the pressure–wind relationship. A 145-kt intensity would have therefore been assigned to Hurricane Andrew for the Florida landfall (for both the late 1940s and early 1950s), meaning that Andrew would have been recorded as a Category 5 hurricane if it occurred during the 1940s–1950s period. The 140-kt intensity chosen for 0000 UTC 24 August would have been brought up to 145 kt by 0600 UTC 24 August. It is likely that the double-peak intensity for Andrew would not have been identified back in the 1940s–1950s. Instead, it is likely that the first Category 5 peak would have been underestimated, though the second peak would have been recorded.

b. *Hurricane Isabel (2003)*

Hurricane Isabel (2003) was a particularly interesting case with a distinct and important difference from the other cases. Isabel likely would have been completely unnoticed for the first 5 days of its lifetime. Aircraft reconnaissance in 2003 did not fly this cyclone during the first day it was a Category 5 hurricane. The first flight into Isabel occurred during the daytime of 12 September. However, given the range of aircraft reconnaissance during 1944–53, which extended to 55°W between 20° and 25°N, it would have been possible for reconnaissance to reach Isabel during the afternoon of 11 September. Isabel is listed in the NHC best track (Beven and Cobb 2010) as a Category 5 from 1800 UTC 11 September to 1800 UTC 12 September and again for 6 h each at 1800 UTC 13 September and at 1800 UTC 14 September. Figure 6 shows the NHC best track for Isabel and the best track likely to be obtained using technology available in the late 1940s/early 1950s. Satellite images indicate that Isabel became a tropical storm on 6 September in the far eastern Atlantic. A 7.0 Dvorak classification on 11 September indicates that Isabel reached Category 5 strength on that day while moving westward near 54°W longitude. Under the assumption that reconnaissance would have intercepted Isabel during the afternoon of 11 September, the best track for Isabel would have begun at 1800 UTC 11 September with a 115 (125)-kt intensity, which compares with 145 kt listed in the NHC best track at that time. This is because the aircraft would not have been able to penetrate the center due to the central

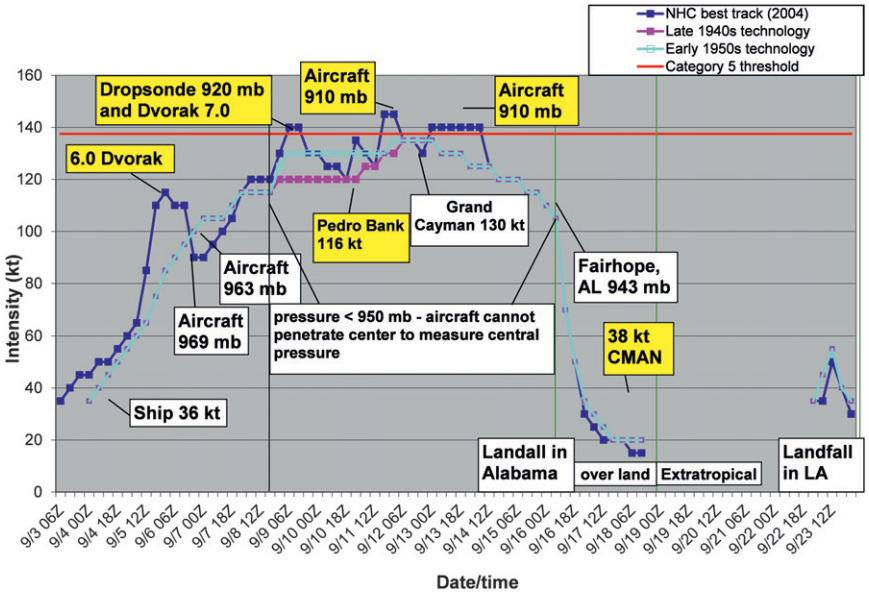

FIG. 7. As in Fig. 5, but for Hurricane Ivan (2004).

pressure being less than 950 (940) mb. A central pressure of less than 950 (940) mb yields a wind speed of greater than 111 (121) kt according to the southern pressure–wind relationship, so 115 (125) kt is chosen for 1800 UTC 11 September. There were no surface observations of Category 5 conditions obtained through the remainder of the times when Isabel was a Category 5, and the central pressure remained below 940 mb for that time. Therefore, Isabel would have been listed with a peak intensity of 115 (125) kt if the hurricane had occurred during the late 1940s (early 1950s). Hurricane Isabel likely would not have been counted as a Category 5 hurricane.

Even though we would not have been able to draw a track for Isabel prior to 1800 UTC 11 September, the intensity is somewhat arbitrarily decreased by 25 kt per day until a 35-kt intensity is indicated on 8 September. Hurricane Isabel has by far the largest ACE disparity between the late 1940s/early 1950s values and the NHC best-track value. The ACE for Isabel would have been 41 (46) instead of 63 if the cyclone had occurred during the late 1940s (early 1950s), but the ACE would have been 29 (32) if counting begins on 12 September when aircraft actually first intercepted the storm.

c. *Hurricane Ivan (2004)*

Hurricane Ivan (2004) fluctuated between a Category 4 and 5 intensity 3 different times during its lifetime according to the NHC best track (Stewart 2010). Ivan was a long-lived hurricane that traveled westward through the Caribbean Sea, passed through the Cayman Islands when its intensity bordered between Categories 4 and 5, moved northwestward into the Gulf of Mexico and then northward, and made a U.S. landfall in Alabama after having weakened to a Category 3 hurricane. Ivan is listed as a Category 5 in the NHC best track from 0600 to 1200 UTC 9 September, from 1800 UTC 11 September to 0000 UTC 12 September, and from 0000 UTC 13 September to 0600 UTC 14 September. Intensities of 140 kt were attained during the first and last of these three periods and 145 kt was attained during the middle period. The best-track comparison graph for Hurricane Ivan is shown in Fig. 7. During the first two of these three Category 5 periods, Ivan was located over the Caribbean Sea and no land stations were in the path of the Category 5 conditions, as shown in Fig. 4. For the first period, a 120 (130)-kt intensity would have been chosen instead of 140 kt from 0600 to 1200 UTC 9 September because aircraft would not have been able to penetrate the center since the central pressure was below 950 (940) mb. During a time when Ivan was a Category 4, Pedro Bank, Jamaica, recorded a peak 1-min wind of 116 kt during the morning of 11 September, although the Pedro Bank observation is not counted for this study because there was no station there in the 1940s/1950s. During the second Category 5 period, Ivan was located about 35 n mi from Negril Point, Jamaica, with an RMW of about 10 n mi and an intensity of 140 kt. Negril Point was a station during the late 1940s/early 1950s, but it was too far away to have recorded Category 5 conditions in Ivan. At 1500 UTC 12 September, when Ivan was a Category 4 according to the NHC best track, Grand Cayman recorded a peak 1-min wind of 130 kt and that station was also present during the 1940s/1950s

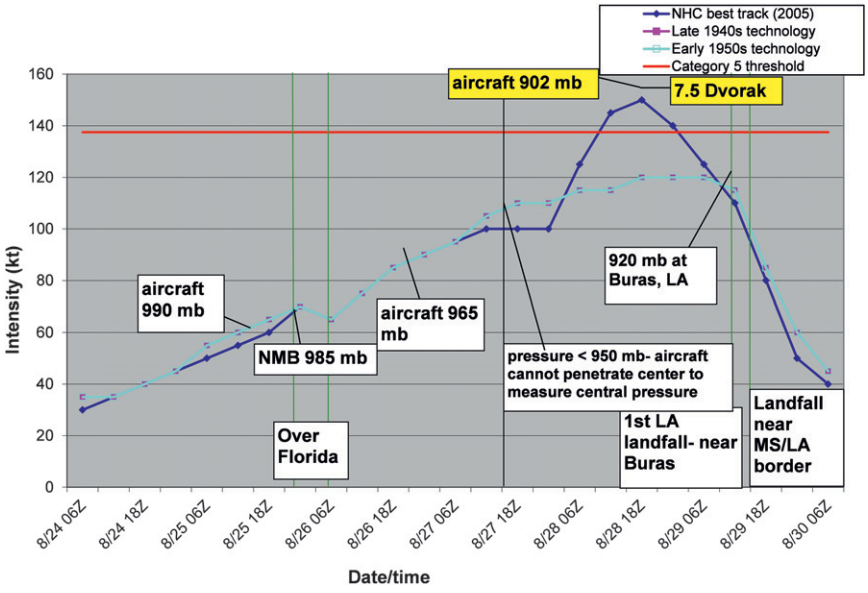

FIG. 8. As in Fig. 5, but for Hurricane Katrina (2005).

and is thus counted. Grand Cayman was located on the right side of the storm and within three-tenths of a degree latitude/longitude of the center. A 135-kt intensity is chosen using the reanalysis methodology to generally select an intensity slightly above the highest available reliable wind observation because of the likelihood that one would not sample the most intense portion of the cyclone. During the third Category 5 period of Hurricane Ivan, the center passed about 15 n mi southwest of the station at Cabo de San Antonio, Cuba. This station is in operation today and was also in operation during the 1940s/1950s. The RMW of Ivan was about 15 n mi at the time. Although the right RMW is approximated to have grazed Cabo de San Antonio, the highest wind recorded there was only 96 kt, and the anemometer did not fail. Thus from this observation, one would not deduce Category 5 or even Category 4 conditions at this time for Ivan.

After the Grand Cayman observation of 130 kt at 1500 UTC 12 September, there is no additional information regarding the peak intensity of the hurricane and there are no more surface observations of the peak conditions until landfall near the Alabama–Florida border. At landfall near the Alabama–Florida border, a 105-kt intensity is chosen based on a 943 mb central pressure observation. The peak intensity for Hurricane Ivan would have been about 135 kt—a high end Category 4—if the cyclone had occurred during the late 1940s and early 1950s based on the 130-kt wind recorded at Grand Cayman.

d. Hurricane Katrina (2005)

Hurricane Katrina (2005) is listed as a Category 5 in the NHC best track (Knabb et al. 2005) from 1200 UTC 28 August to 0000 UTC 29 August with intensities of 145, 150, and 140 kt while located in the central Gulf of Mexico. Figure 8 shows the NHC best track for Katrina and the best track likely to be obtained using technology available in the late 1940s/early 1950s. On 28 August, aircraft would not have been able to penetrate the center because the central pressure was less than 940 mb, which yields greater than 123 and 120 kt for intensifying systems south and north of 25°N, respectively, but the hurricane was large with a low environmental pressure. At 1116 UTC 29 August, a 920-mb central pressure was measured at Buras, Louisiana. A central pressure of 920 mb equals 132 kt according to the pressure–wind relationship for north of 25°N. A 120-kt peak lifetime intensity would have been chosen for Katrina for both the late 1940s and early 1950s (after subtracting 10 kt for the large size and low environmental pressure of Katrina) from 1800 UTC 28 August through the first Louisiana landfall, which occurred at 1100 29 August. The intensity is analyzed to have reached 115 kt at 0600 UTC 28 August and 120 kt at 1800 28 August. During the 18 h when Katrina was a Category 5 (1200 UTC 28 August–0000 UTC 29 August), intensities of about 115, 120, and 120 kt would likely have been assigned instead of 145, 150, and 140 kt. The rapid intensification and subsequent rapid weakening that occurred in the Gulf of Mexico would not have been captured with the observational platforms of the late 1940s/early 1950s, and Katrina very likely would not have been listed as a Category 5. It would have been assumed that Katrina slowly intensified until reaching its peak intensity at landfall in Louisiana. The 920-mb central pressure of Katrina at

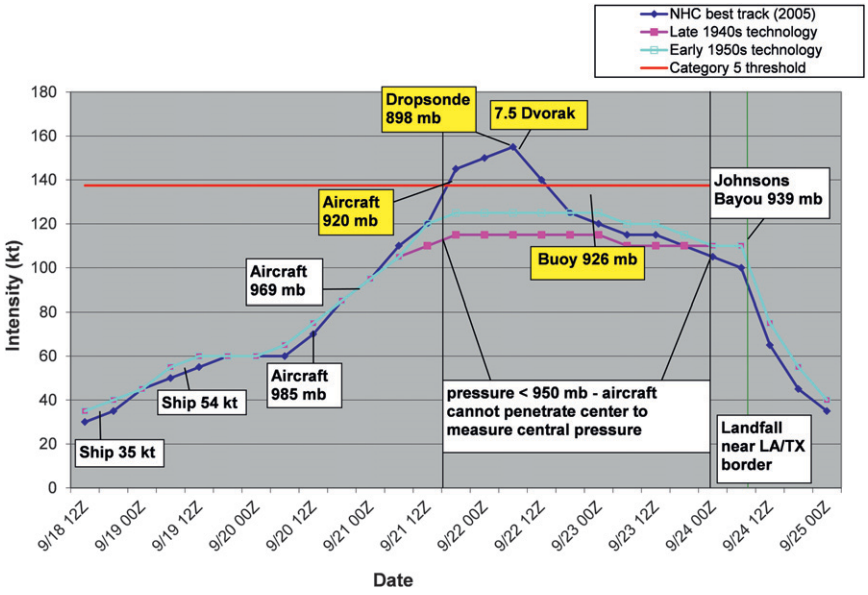

FIG. 9. As in Fig. 5, but for Hurricane Rita (2005).

landfall was so low, a 120-kt Category 4 landfall intensity would have been analyzed instead of the actual 110-kt Category 3 intensity even after subtracting 10 kt from the Brown et al. (2006) pressure–wind relationship because of the large size of the cyclone and the low environmental pressure.

e. Hurricane Rita (2005)

Hurricane Rita was a Category 5 in the central Gulf of Mexico for the 24 h from 1800 UTC 21 September through 1200 UTC 22 September, according to the NHC best track (Knabb et al. 2006), and it attained a peak intensity of 155 kt at 0600 UTC 22 September. Figure 9 shows the NHC best track for Rita and the best track likely to be obtained using technology available in the late 1940s/early 1950s. At 1517 UTC 21 September, aircraft would not have been able to penetrate the hurricane because the central pressure was less than 950 (940) mb. That yields greater than 113 kt and greater than 110 kt for the late 1940s (greater than 123 and greater than 120 kt for the early 1950s) according to the intensifying subsets of the Brown et al. (2006) south and north of 25°N pressure–wind relationships, respectively. Winds of greater than 112 kt (greater than 122 kt) are chosen from this blend, and no additional adjustment is necessary for Rita during this time. A 115-kt intensity is therefore chosen for the late 1940s, and a 125-kt intensity is chosen for the early 1950s. Late on 22 September, at 2250 UTC, a buoy in the Gulf of Mexico recorded a 926-mb pressure, but this buoy was not there in the 1940s/early 1950s and is not included. Hurricane Rita made a U.S. landfall near the Louisiana–Texas border with a 100-kt intensity and a 937-mb central pressure according to the NHC best track. A 939-mb pressure was recorded at Johnsons Bayou, but this station was not in operation during the 1940s/1950s. However, the station at Port Arthur was in operation. Based on a 949-mb pressure recorded there with simultaneous 82-kt winds, a landfall central pressure of approximately 939 mb would have been estimated using reanalysis methodology (slightly higher than the 937-mb landfall central pressure in the NHC best track). A 939-mb central pressure equals 116 kt according to the Brown et al. (2006) north of 25°N pressure–wind relationship. A 110-kt landfall intensity would have likely been selected for the landfall intensity (100 kt in NHC best track) due to a lower-than-normal environmental pressure. Hurricane Rita would have been listed with a peak intensity of 115 (125) kt in the late 1940s (early 1950s) in the Gulf of Mexico with a 110-kt landfall intensity for both periods. According to the analysis, the ACE for Rita would have been 22 (24) if Rita had occurred during the late 1940s (early 1950s), and this is slightly less than the ACE of 25 that was actually produced by Rita according to the NHC best track.

f. Hurricane Wilma (2005)

Hurricane Wilma (2005) is listed as a Category 5 in the western Caribbean from 0600 to 1800 UTC 19 October according to the NHC best track (Pasch et al. 2006), with a peak intensity of 160 kt listed at 1200 UTC 19 October. Figure 10 shows the NHC best track for Wilma and the best track likely to be obtained using technology available in the late 1940s/early 1950s. At 2309 UTC 18 October, aircraft recorded a central pressure of 954 mb.

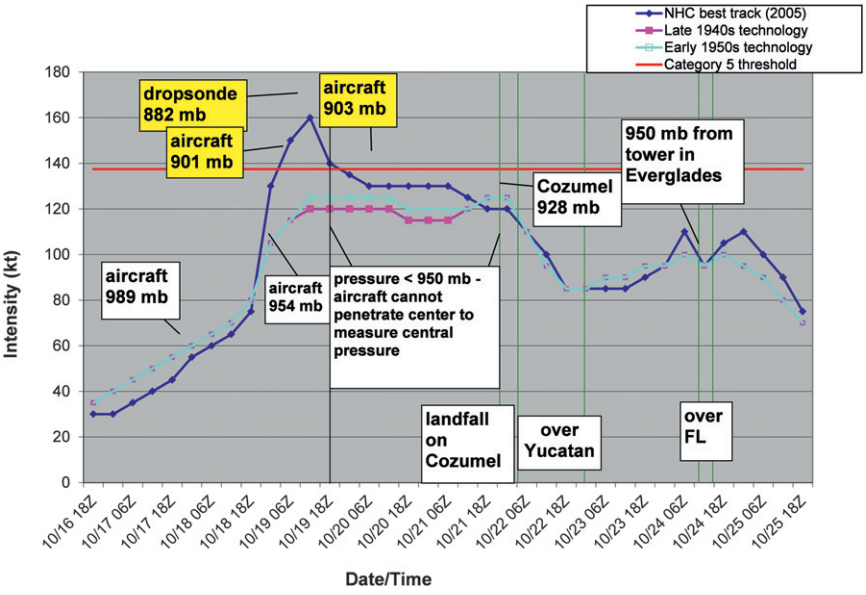

FIG. 10. As in Fig. 5, but for Hurricane Wilma (2005).

The next aircraft flight occurred at night, and no intensity information was available during the late 1940s/early 1950s at night. That is the night when Wilma underwent its extreme rapid intensification. The first fix during daylight occurred at 1806 UTC 19 October. Aircraft in the late 1940s and early 1950s would not have been able to penetrate the center since the central pressure was below 940 mb. A 120 (125)-kt intensity is chosen for 1200 UTC 19 October (160 kt according to NHC best track). Wilma passed ~20 mi north-northeast of Swan Island as a 140-kt Category 5 according to the NHC best track. The RMW was about 5 n mi at the time. Because of Wilma's tiny size at the time, it is unlikely that Swan Island would have recorded Category 5 conditions since the station was located well outside the RMW on the typically weaker (left) side of the cyclone. A couple of days later, after Wilma had weakened to a Category 4, a 928-mb pressure was recorded at Cozumel, Mexico, at 2100 UTC 21 October. It would have been known that this observation occurred inside the RMW, with light (but not calm) winds. Assuming a central pressure of about 927 mb, this value equals 133 kt according to the Brown et al. (2006) southern pressure–wind relationship. Subtracting 10 kt for a very slow speed and a large storm yields 123 kt, which rounds to 125 kt, and 125 kt is chosen as the peak late 1940s intensity from 1800 UTC 21 October through landfall near Puerto Morelos, Mexico, at 0300 UTC 22 October. The peak early 1950s intensity is also 125 kt—first from 1200 UTC 19 October to 1200 UTC 20 October and again from 1800 UTC 21 October to the landfall at 0300 UTC 22 October. Therefore, Wilma likely would not have been known to have attained a Category 5 intensity with the technology available during the late 1940s/early 1950s.

Hurricane Wilma rapidly intensified from 75 to 160 kt in a period of 18 h. This rapid intensification was observed via satellite intensity estimates and aircraft observations, including a dropsonde that indicated a central pressure of 882 mb—the lowest pressure ever recorded in the Atlantic Basin. Like Katrina, if Wilma had occurred during the 1940s/1950s, the extreme rapid intensification very likely would not have been captured.

g. Overall results, discussion, and error analysis

The results in Table 1 show that Category 5 conditions likely would have been observed for only 2 (3) of these 10 Category 5 hurricanes if these storms occurred during the late 1940s (early 1950s). On average, there were much fewer observations of the peak intensity of TCs during the late 1940s/early 1950s, especially because there were no satellites and because aircraft would not generally fly into the eye of strong hurricanes. During the lifetimes of 2 of the 10 hurricanes—Andrew and Mitch—there were land stations that measured (or could have measured) Category 5 winds or pressures indicative of a Category 5. All of the observations that actually incurred Category 5 conditions during the other eight hurricanes were from observational technologies or practices that did not exist during the late 1940s (satellites, aircraft penetrations of major hurricanes, dropsondes, and SFMR surface wind measurements). However, if Hurricane Felix (2007) had occurred during the early 1950s, it likely would have been considered a Category 5 according to today's analysis techniques.

TABLE 1. Summary of results for Category (Cat) 5 hurricanes. Best-track peak is the peak intensity of the hurricane listed in the official NHC best-track database, and early 1950s and late 1940s peak is the value (kt) that the peak intensity would have likely been analyzed as if the hurricane had occurred during the early 1950s and late 1940s, respectively. Boldface indicates the storms that remain at Category 5 when the older measurement technology is used.

Recent Category 5 hurricane	Duration as Category 5 (days)	Best-track peak (kt)	Early 1950s peak (kt)	Late 1940s peak (kt)	Best-track ACE (10^{-4} kt^2)	Early 1950s ACE (10^{-4} kt^2)	Late 1940s ACE (10^{-4} kt^2)
Andrew—1992	0.62	150	**145—Cat 5**	**145—Cat 5**	28	26	25
Mitch—1998	1.75	155	**140—Cat 5**	**140—Cat 5**	36	35	34
Isabel—2003	1.75	145	125—Cat 4	115—Cat 4	63	46	41
Ivan—2004	2.50	145	135—Cat 4	135—Cat 4	70	66	63
Emily—2005	0.25	140	135—Cat 4	125—Cat 4	33	31	31
Katrina—2005	0.75	150	120—Cat 4	120—Cat 4	20	19	19
Rita—2005	1.00	155	125—Cat 4	115—Cat 4	25	24	22
Wilma—2005	0.75	160	125—Cat 4	125—Cat 4	39	35	34
Dean—2007	1.00	150	135—Cat 4	130—Cat 4	35	36	34
Felix—2007	1.00	150	**140—Cat 5**	130—Cat 4	18	16	15
Avg	1.37	150	133—Cat 4	128—Cat 4	37	33	32

The analyses indicate that all of the hurricanes in the study that did not reach Category 5 strength would have been classified as a Category 4. The reader is reminded that the methodology employed is somewhat conservative. For example, many times during the late 1940s the aircraft often did not penetrate the center of hurricanes with central pressures in the 950s or even the 960s. If this criteria of, say, a 960-mb threshold were utilized, many of these cyclones would have been listed with a peak intensity of only Category 3 strength.

One hypothesis in Hagen et al. (2012) is that TCs that were actually 120 kt and higher during the 1944–53 period were likely underestimated in intensity since the most intense part of the storm was not sampled for these hurricanes. That hypothesis can be tested utilizing statistics from this study. For all times during which the Category 5 hurricanes from 1992 to 2007 utilized here were at or above a 120-kt intensity, the NHC best-track intensity (kt) is subtracted from what the best-track intensity would have been listed as if these hurricanes had been analyzed using technology available during the late 1940s and early 1950s. The intensity averaged over all 6-hourly cases would have been approximately 12.5 kt lower for the 10 most recent Category 5 hurricanes utilizing technology of the late 1940s and about 8.0 kt lower for the early 1950s period, as shown in Table 10 in Hagen et al. (2012). Table 1 from the present study indicates that the peak intensity of each of the individual 10 Category 5 hurricanes would have been underestimated by 22 kt (17 kt) if these hurricanes had been monitored by technology available in the late 1940s (early 1950s).

There is some uncertainty as to the number of Category 5 hurricanes (out of the 10 discussed here) that would have been known to be Category 5 utilizing technology available during the late 1940s/early 1950s. The intensity is determined by first removing observations of recent technology from the analysis and then applying reanalysis methodology to assign the intensity. Therefore, for determining the uncertainty of the selected intensity values, a range of ±5 kt from the values chosen is appropriate, as an intensity 5 kt lower or higher could have been chosen for many of the 6-hourly values. If this 5-kt flexibility range is used for the intensity values chosen for this study, then the number of storms that would have been considered Category 5 hurricanes (out of 10) is in the range of 1–3 for the late 1940s and 1–6 for the early 1950s. Wilma, Katrina, Rita, and Isabel are the storms that would have been least likely to have been recorded as a Category 5 during the late 1940s/early 1950s period, since their peak analyzed intensity would have been only in the 115–125-kt range. Emily also would have been highly unlikely to have been recorded as a Category 5 because it was only a Category 5 for 6 h over the central Caribbean Sea. Andrew would have been most likely to have been recorded as a Category 5. The next most likely are Mitch and Felix, and the fourth and fifth most likely are Ivan and Dean due to those storms' close passage to land stations and the amount of time as a Category 5.

5. Category 4 hurricanes

All 10 of the Category 5 hurricanes discussed in the previous sections of this paper would likely have been recorded at least as a Category 4 for their peak intensity utilizing technology available during the late 1940s/early 1950s. This is because all of these cyclones attained their

peak intensities in the western half of basin, where aircraft reconnaissance is available. During recent years, there have been a number of Category 4 hurricanes that might have only been classified as weak hurricanes or even tropical storms if they had taken place at the same location during the late 1940s and early 1950s. For example, during the period 2003–10, 3 Category 4 hurricanes that would have been most likely listed with a peak intensity substantially less than Category 4 if monitored by technology available in the 1940s/1950s are Karl (2004), Omar (2008), and Julia (2010). Karl (Beven 2004) and Julia (Beven and Landsea 2010) remained in the eastern Atlantic, well out of the range of aircraft reconnaissance. Karl recurved prior to reaching the range of aircraft reconnaissance of the late 1940s/early 1950s and did not pass near any land. Therefore, the existence of the tropical cyclone is unlikely to have been observed via aircraft reconnaissance or land stations. Although ships avoided Karl's inner core (45 kt was the highest wind recorded from a ship in Karl's periphery), ships may not have been able to avoid Karl completely as easily in the 1940s/1950s because there would have been no aircraft reconnaissance observations for forecasters to warn ships to avoid the hurricane. Julia may not even have been recorded as a hurricane, as no tropical-storm-force winds were recorded by ships in the data-sparse eastern Atlantic. Hurricane Omar (Beven and Landsea 2009) was only a Category 4 for 6 h (at night), and this classification was due to an SFMR measurement. With late 1940s/early 1950s technology, Omar would likely have been listed with a peak intensity of either a Category 1 or 2 hurricane. The strongest winds to occur on land were Category 1 conditions. The hurricane was never a major hurricane during the daytime, so aircraft reconnaissance would have measured a low-end Category 2 or a high-end Category 1, depending on the time of flights during the day.

Such extreme TCs occurring in the eastern Atlantic and/or reaching extreme intensity levels for only a brief period would have been problematic to properly observe in the late 1940s and early 1950s. A strong low bias in their intensities would have led to a substantial undercount of Category 4 and 5 hurricanes and in the total ACE. The results of Hagen et al. (2012) showed that major hurricanes were generally not penetrated by aircraft reconnaissance from 1944 to 1949 and Category 4 and 5 hurricanes were generally not penetrated from 1950 to 1953. The results of the present study indicate that if a hurricane in the western half of the basin was a Category 4 or 5 hurricane for an entire day, then it likely would have been sampled (but not penetrated) by aircraft reconnaissance once, and the sampling would have been good enough to suggest a Category 4 intensity according to the somewhat conservative methodologies used in this study.

6. Summary and conclusions

The main point of this paper is to show how the intensity of extreme tropical cyclones would be analyzed differently using the technology of the 1940s/1950s as compared with today. Whenever the 10 most recent Category 5 hurricanes were at or above a 120-kt intensity, the analyzed intensity during the 1944–53 period would have been about 10 kt lower on average due to the inability to observe Category 5 conditions from platforms other than with surface observations. As a consequence, there are likely to have been several Category 4 and 5 hurricanes misclassified as being weaker prior to the satellite era. The results show that if the 10 most recent Category 5 hurricanes occurred during the late-1940s period, only 2 of them would be considered Category 5 hurricanes (and 3 of 10 for the early-1950s period). Three recent Category 4 hurricanes were identified that would likely not have been counted as major hurricanes if they had occurred during the late 1940s/early 1950s. This research suggests that the counts of Category 4 and 5 hurricanes (at least through 1953 and likely beyond that year) are not nearly as reliable as they are today. Future studies that discuss frequency trends of Atlantic basin Category 4 and 5 hurricanes must take into account the undercount biases that existed prior to the geostationary satellite era due to the inability to observe these extreme conditions.

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REFERENCES

Beven, J. L., II, 2004: Tropical cyclone report: Hurricane Karl, 16–24 September 2004. National Hurricane Center Rep., 9 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL122004_Karl.pdf.]

——, and C. W. Landsea, 2009: Tropical cyclone report: Hurricane Omar (AL152008), 13–18 October 2008. National Hurricane Center Rep., 15 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL152008_Omar.pdf.]

——, and H. Cobb, cited 2010: Tropical cyclone report: Hurricane Isabel, 6–19 September 2003. [Available online at http://www.nhc.noaa.gov/2003isabel.shtml?.]

——, and C. W. Landsea, 2010: Tropical cyclone report: Hurricane Julia (AL122010), 12–20 September 2010. National Hurricane Center Rep., 17 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL122010_Julia.pdf.]

——, and Coauthors, 2008: Atlantic hurricane season of 2005. *Mon. Wea. Rev.,* **136,** 1109–1173.

Brennan, M. J., R. D. Knabb, M. Mainelli, and T. B. Kimberlain, 2009: Atlantic hurricane season of 2007. *Mon. Wea. Rev.,* **137,** 4061–4088.

Brown, D. P., J. L. Franklin, and C. W. Landsea, 2006: A fresh look at tropical cyclone pressure-wind relationships using recent

reconnaissance-based "best track" data (1998-2005). Preprints, *27th Conf. on Hurricanes and Tropical Meteorology,* Monterey, CA, Amer. Meteor. Soc., 3B.5. [Available online at http://ams.confex.com/ams/27Hurricanes/techprogram/paper_107190.htm.]

Dvorak, V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, 45 pp.

Emanuel, K. A., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature,* **436,** 686–688.

Franklin, J. L., R. J. Pasch, L. A. Avila, J. L. Beven II, M. B. Lawrence, S. R. Stewart, and E. S. Blake, 2006: Atlantic hurricane season 2004. *Mon. Wea. Rev.,* **134,** 981–1025.

Hagen, A. B., D. Strahan-Sakoskie, and C. Luckett, 2012: A reanalysis of the 1944–53 Atlantic hurricane seasons—The first decade of aircraft reconnaissance. *J. Climate,* **25,** 4441–4460.

Jarvinen, B. R., C. J. Neumann, and M. A. S. Davis, 1984: A tropical cyclone data tape for the North Atlantic basin, 1886–1983: Contents, limitations, and uses. NOAA Tech. Memo. NWS NHC 22, 21 pp.

Klotzbach, P. J., 2006: Trends in global tropical cyclone activity over the past twenty years (1986–2005). *Geophys. Res. Lett.,* **33,** L10805, doi:10.1029/2006GL025881.

Knabb, R. D., J. R. Rhome, and D. P. Brown, 2005: Tropical cyclone report: Hurricane Katrina. National Hurricane Center Rep., 43 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL122005_Katrina.pdf.]

——, D. P. Brown, and J. R. Rhome, 2006: Tropical cyclone report: Hurricane Rita, 18–26 September 2005. National Hurricane Center Rep., 33 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL182005_Rita.pdf.]

Landsea, C. W., and Coauthors, 2004a: A reanalysis of Hurricane Andrew's intensity. *Bull. Amer. Meteor. Soc.,* **85,** 1699–1712.

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

——, B. A. Harper, K. Hoarau, and J. A. Knaff, 2006: Can we detect trends in extreme tropical cyclones? *Science,* **313,** 452–454.

——, and Coauthors, 2008: A reanalysis of the 1911–20 Atlantic hurricane database. *J. Climate,* **21,** 2138–2168.

——, S. Feuer, A. B. Hagen, D. A. Glenn, J. Sims, R. Perez, M. Chenoweth, and N. Anderson, 2012: A reanalysis of the 1921–30 Atlantic hurricane database. *J. Climate,* **25,** 865–885.

Lawrence, M. B., L. A. Avila, J. L. Beven II, J. L. Franklin, R. J. Pasch, and S. R. Stewart, 2005: Atlantic hurricane season of 2003. *Mon. Wea. Rev.,* **133,** 1744–1773.

Mayfield, M., L. Avila, and E. N. Rappaport, 1994: Atlantic hurricane season of 1992. *Mon. Wea. Rev.,* **122,** 517–538.

McAdie, C. J., C. W. Landsea, C. J. Neumann, J. E. David, E. Blake, and G. R. Hamner, 2009: *Tropical Cyclones of the North Atlantic Ocean, 1851-2006*. Historical Climatology Series 6-2, National Climatic Data Center and the National Hurricane Center, 238 pp.

Pasch, R. J., L. A. Avila, and J. L. Guiney, 2001: Atlantic hurricane season 1998. *Mon. Wea. Rev.,* **129,** 3085–3123.

——, E. S. Blake, H. D. Cobb III, and D. P. Roberts, 2006: Tropical cyclone report: Hurricane Wilma, 15–25 October 2005. National Hurricane Center Rep., 27 pp. [Available online at http://www.nhc.noaa.gov/pdf/TCR-AL252005_Wilma.pdf.]

Porush, I. I., and O. C. Spencer, 1945: Report on hurricane reconnaissance operations during 1944. Headquarters, Army Air Forces Weather Wing, 10 pp.

Rappaport, E., cited 2010: Preliminary report: Hurricane Andrew, 16–28 August, 1992. [Available online at http://www.nhc.noaa.gov/1992andrew.html.]

Sheets, R. C., 1990: The National Hurricane Center – Past, present, and future. *Wea. Forecasting,* **5,** 185–232.

Stewart, S. R., cited 2010: Tropical cyclone report: Hurricane Ivan, 2–24 September 2004. [Available online at http://www.nhc.noaa.gov/2004ivan.shtml?.]

Summer, H. C., 1944: North Atlantic Hurricanes and tropical disturbances of 1944. *Mon. Wea. Rev.,* **72,** 237–240.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang, 2005: Changes in tropical cyclone number, duration, intensity in a warming environment. *Science,* **309,** 1844–1846.