On the Classification of Extreme Atlantic Hurricanes Utilizing Mid-20th Century Monitoring Capabilities

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Abstract

An investigation is conducted to determine how improvements in observing capabilities and technology may have affected our ability to detect and monitor Saffir-Simpson Hurricane Wind Scale Category 5 hurricanes in the Atlantic basin during the mid-20th 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 ten recent Category 5 hurricanes recorded in the Atlantic from Hurricane Andrew (1992) through Hurricane Felix (2007). These ten hurricanes are placed into the context of the technology available in the period of 1944-1953, the first decade of aircraft reconnaissance. A methodology was created to determine how many of these ten recent Category 5s likely would have been recorded as Category 5s 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 ten recent Category 5s. It is found that likely only two of these ten – 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 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-20th century to 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 ~1990 despite simultaneous ocean temperature rises. The first routine aircraft reconnaissance missions into hurricanes in the Atlantic began in 1944 (Summer 1944; Sheets 1990). However, the observational network today is much more complete than that available in the first decade of aircraft reconnaissance (1944-1953), 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 Figure 1.

One might attempt to address the effect of technology by determining how the most recent Category 5 hurricanes in the Atlantic basin (1992-present) would have likely been analyzed from observations available in the late 1940s and early 1950s. Most of the ten Category 5 hurricanes in the Atlantic from 1992 to the present were only at Category 5 strength for a short period of time. For example, Hurricanes Katrina and Wilma of 2005 were only Category 5 hurricanes for 18 hours each, and Hurricane Emily (2005) was only a Category 5 for a mere six hours. 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 addressed with this study is: How intense would the ten most recent Category 5 hurricanes have been analyzed as if these cyclones had occurred during the late 1940s-early 50s?

2. Methodology

A companion paper – Hagen et al. (2011) – documents the raw observations, methodology, and results of a reanalysis of the 1944-53 hurricane seasons. The hurricane database (HURDAT) (Jarvinen et al. 1984; McAdie et al. 2009) contains the positions and intensities of each recorded Atlantic Basin tropical storm, subtropical storm, and hurricane from 1851-present. The ten 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 National Hurricane Center (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.[2] During the late 1940s-early 50s, much of this technology did not yet exist. Therefore, only those observations that likely would have been available during the late 1940s-early 50s are utilized for determining the intensities (the maximum

[2] For details of available observations for these ten 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. 2004; Franklin et al. 2006; Beven et al. 2008; Brennan et al. 2009).

1-min 10m wind associated with the hurricane circulation) that would have been recorded if the hurricane had occurred during that time period. This methodology excludes all satellite observations, but includes all surface-based observations including all buoy and C-MAN stations even if they went into operation post-1953 (a conservative methodology). Also, surface observations that are considered by NHC to have been "unofficial observations" are included as information to be utilized for this study. Since aircraft would only generally penetrate the center of tropical storms and weak hurricanes during the late 1940s (see Hagen et al. 2011), 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 will be 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 minor changes around 1950, the time period 1950-53 is treated as a separate period from 1944-49. The only difference is that for the 1950-53 period, it is assumed that aircraft would not penetrate the center for hurricanes less than 940 mb, as the reconnaissance crews began flying into the center of somewhat stronger hurricanes in the early 1950s. Also, 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. Due to 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 (~5 kt) to account for the fact that the central pressure is actually an unknown amount deeper than that value. Aircraft surface wind visual estimates of the ten recent Category 5 hurricanes are included (excluding SFMR data – which began aboard the Air Force C-130s in 2007), but only for penetrations for which the central pressure is 950 (940) mb or higher. Moreover, flight-level winds from the reconnaissance aircraft during the late 1940s to early 1950s were often unreliable (especially in high wind conditions) and were not utilized much in the reanalysis of the era (Hagen et al. 2011). Thus they are not considered for this study. After eliminating intensity observations that would not have been available during the late 1940s-early 50s, the intensities are determined (using the remaining observations) by applying HURDAT reanalysis methodology (Hagen et al. 2011; Landsea et al. 2004b, 2008, 2011). 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 occurred during the late 1940s-early 50s? (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 during the late 1940s-early 50s, and how was the Best Track intensity decided upon? (4) How would the total Accumulated Cyclone Energy (ACE) for the hurricane have been different? These questions were answered for all ten Category 5 hurricanes and are summarized in the results section.

According to the NHC Best Track, the average Category 5 duration for the ten recent Category 5 hurricanes is ~1.4 days. Observations of the peak intensity in strong hurricanes were much less common (as will be shown) during the late 1940s-early 50s

compared with more recently, and the ability to measure the central pressure of major hurricanes was limited during the late 1940s-early 1950s unless the storm made landfall near or at a weather station or in a populated coastal location. The only way that a Category 5 hurricane over the open ocean would have been counted as a Category 5 in this study is if a ship (or buoy) recorded Category 5 strength winds or a corresponding pressure value, which rarely happens. However, if a Category 5 hurricane makes 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. During the late 1940s and early 1950s, aircraft reconnaissance was only capable of measuring Category 4 conditions with one possible exception. For the early 1950s period, aircraft might have been able to confirm Category 5 intensity for intensifying hurricanes south of 25N 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. southern-intensifying pressure-wind relationship, it is possible to assign a 140 kt intensity (see Hurricane Felix description in the results section). Of the ten Category 5 hurricanes in this study, four of them made landfall as a Category 5 (Andrew- south Florida, Mitch- Swan Island, Dean- Mexico's Yucatan Peninsula, and Felix- Nicaragua), but this does not necessarily mean these would have been recorded as a Category 5 hurricane if they had occurred during the late 1940s-early 1950s.

3. 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. (2011) explains that the surface and especially the flight-level winds during this decade lacked sufficient accuracy and consistency to be given more than a light weight in the reanalysis of the HURDAT intensity. Instead, the reanalysis of intensity relied 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 were extremely uncommon for major hurricanes from 1944-49 and for Category 4 and 5 hurricanes from 1950-53 because the aircraft were not equipped for the extreme turbulence often experienced in hurricanes of that strength. Instead, circumnavigations would generally be conducted. When penetrations were not performed, central pressures could not be obtained, and the intensity of the hurricane is highly uncertain.

During the six years of 1944-1949, aircraft reconnaissance provided a total of approximately 200 center fixes – 43 of which were by low-level penetration. The other 150+ center fixes were obtained via circumnavigation and aircraft radar. [For examples of penetration and circumnavigation fixes see Figures 2 and 3 of Hagen et al. (2011).] These penetration fixes were typically provided by both the Navy PB4Y-2 aircraft and various Air Force aircraft. Central pressures were reported for the 43 penetration fixes. On average, this means less than one aircraft central pressure per TC (seven per year) was obtained (a very low number 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. Due to the fact that major hurricanes were almost never

successfully penetrated from 1944-1949, a central pressure deeper than 950 mb was only obtained one time.

In 1950, several practices changed (see Hagen et al. 2011 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 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 quite common.

4. Results and discussion

Best Track intensity graphs are developed for the entire lifetime of all ten 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 occurred during the late 1940s-early 50s. The following subsections detail how the questions were answered for the individual ten Category 5 hurricanes.

a. Hurricane Andrew (1992)

Hurricane Andrew (1992), the most damaging hurricane in the history of the United States at the time (not adjusted for population and wealth increases) (Pielke et al. 2008), is listed in the revised NHC Best Track (Landsea et al. 2004a; Rappaport 1993) as a

Category 5 on August 23 at 12 and 18Z as well as August 24 at the 09Z landfall south of Miami, FL. Figure 2 shows the NHC Best Track for Andrew and the best track likely to be obtained using technology available in the late 1940s/early 1950s. For the first period, intensities of 145 and 150 kt are listed in the NHC Best Track at 12 and 18Z on the 23rd. On August 23 at 1224Z, 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 yields a wind speed of greater than 111 (121) kt according to the Brown et al. (2006) southern pressure-wind relationship. 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 the 23rd at 12Z. On August 23 at 21Z, a pressure of 935 mb was recorded at Harbor Island, Bahamas (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 environmental pressure, the intensity would have been at least 130-135 kt at the time. A 135 kt intensity is therefore chosen for the 23rd at 18Z for both the late 1940s and early 1950s.

Andrew made landfall near Homestead, FL on the 24th at 09Z 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, respectively, according to the Brown et al. southern and north of 25N pressure-wind relationships. 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 – 136 kt – is chosen. 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-50s time period. The 135 kt intensity chosen at 18Z on the 23rd would have been brought up to 140 kt by 00Z on the 24th and 145 kt by 06Z on the 24th. It is likely that the double peak intensity for Andrew would not have been identified back in the 1940s-50s. Instead, it is likely that the first Category 5 peak would have been underestimated, though the second would have been recorded.

b. Hurricane Mitch (1998)

Hurricane Mitch (1998) passed directly over Swan Island as a Category 5 hurricane. During the 1940s-50s, there was a full weather station on the island, but it was abandoned during the 1980s. If Mitch occurred during the late 1940s-early 1950s, it would have been possible that the Category 5 conditions experienced there would have been recorded directly by an anemometer or indirectly by the barometer. Therefore, it is assumed that the Category 5 conditions would have been observed. Mitch is listed in the NHC Best Track (Guiney and Lawrence 1999) as a Category 5 from October 26 12Z through October 28 00Z. Figure 3 shows the NHC Best Track for Mitch and the best track likely to be obtained using technology available in the late 1940s/early 1950s. On October 27 around 00Z, Mitch passed over Swan Island, where a central pressure of about 910 mb could have been recorded. A central pressure of 910 mb equals 147 kt according to the Brown et al. southern pressure-wind relationship. A 140 kt intensity is chosen because 5 kt is subtracted for a slow speed. Therefore, if Mitch occurred in the late 40s-early 50s, a

peak intensity of 140 kt would be listed (as shown in Figure 3) instead of the 155 kt peak intensity in the NHC Best Track.

c. Hurricane Isabel (2003)

Hurricane Isabel (2003) was a particularly interesting case with a distinct and important difference from the other nine cases- it was out of range of aircraft reconnaissance during part of the time when it was a Category 5 hurricane. Isabel is listed in the NHC Best Track (Beven and Cobb 2003) as a Category 5 from September 11 18Z – September 12 18Z and again for six hours each at 18Z on the 13th and 18Z on the 14th. Figure 4 shows the NHC Best Track for Isabel and the best track likely to be obtained using technology available in the late 1940s/early 1950s. Isabel originated from an African easterly wave, and satellite images showed it became a tropical storm on September 6 in the far eastern Atlantic. A 7.0 Dvorak classification on September 11 indicated that Isabel had reached Category 5 strength on that day while moving westward near 45˚ W longitude. The first day when Isabel became a Category 5 hurricane, it is quite possible that it would not have even been detected yet because it traversed an area outside of the shipping lanes. When aircraft reconnaissance first reached Isabel on the 12th of September, the aircraft would not have been able to penetrate the center because the central pressure was less than 940 mb. In the late 1940s (early 1950s) 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. 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, so Isabel would have been

listed with a peak intensity of 115 (125) kt if the hurricane had occurred during the late 40s (early 50s). Hurricane Isabel therefore likely would not have been counted as a Category 5 hurricane.

When Isabel would have been first discovered in the late 1940s (early 50s) (September 12th around 18Z), the analyzed 115 (125) kt intensity at that time was kept constant back for 24 hours due to the possibility that aircraft reconnaissance during the late 40s-early 50s could have monitored Isabel on the 11th when the cyclone reached 50W. Before the 11th of September, the intensity is somewhat arbitrarily decreased by 25 kt per day until a 35 kt intensity is indicated on the 8th of 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 September 12 when aircraft actually first intercepted the storm.

d. Hurricane Ivan (2004)

Hurricane Ivan (2004) fluctuated between Category 4 and 5 intensity three different times during its lifetime according to the NHC Best Track (Stewart 2004). Ivan was a long-lived hurricane that traveled westward through the Caribbean Sea, passed through the Cayman Islands when it was at borderline Category 4/5 intensity, 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 06-12Z on September 9, from 18Z on the 11th – 00Z on the 12th, and

from 00Z on the 13th – 06Z on the 14th. 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 Figure 5. For the first of those three periods, a 120 (130) kt intensity would have been chosen during the late 1940s (early 1950s) instead of 140 kt on September 9 from 06 – 12Z because aircraft would not have been able to penetrate the center since the central pressure was below 940 mb. For the second Category 5 period for Ivan, Pedro Bank, Jamaica recorded a peak 1-min wind of 116 kt during the morning of the 11th, and at 15Z on the 12th, Grand Cayman recorded a peak 1-min wind of 130 kt. 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. After the Cayman Islands observation of 130 kt at 15Z on the 12th, 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 when a 105 kt intensity is chosen based on a 943 mb central pressure observation. Therefore, 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.

e. Hurricane Emily (2005)

Hurricane Emily (2005) is listed in the NHC Best Track (Franklin and Brown 2006) as having only reached Category 5 strength for six hours (at July 17 00Z). Figure 6 shows

the NHC Best Track for Emily and the best track likely to be obtained using technology available in the late 1940s/early 1950s. The observations available that would have been used to determine the peak intensity of Emily are as follows: From July 16 at 1328Z (1718Z) until at least July 17 at 1715Z (July 16 2341Z), the central pressure was less than 950 (940) mb and the aircraft would not have been able to penetrate the center during the late 1940s (early 1950s). A central pressure of less than 950 (940) mb yields a wind speed of greater than 113 (123) kt from the intensifying subset of the Brown et al. southern pressure-wind relationship. Adding several knots to the pressure-wind relationship for a small size and a fast speed rounds to greater than 120 (130) kt. A peak intensity of 125 kt would have been chosen from July 16 12Z to July 17 18Z for the late 1940s, and a 135 kt peak intensity would have been chosen from July 16 18Z to July 17 00Z for the early 1950s. Therefore, Hurricane Emily likely would not have been listed as a Category 5 hurricane if it had occurred during the late 1940s or early 1950s.

f. Hurricane Katrina (2005)

Hurricane Katrina (2005) is listed as a Category 5 in the NHC Best Track (Knabb et al. 2005) from August 28 12Z – August 29 00Z with intensities of 145, 150, and 140 kt while located in the central Gulf of Mexico. Figure 7 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 August 28th, aircraft would not have been able to penetrate the center because the central pressure was less than 940 mb. On August 29 at 0948Z, a National Ocean Service (NOS) tide gauge recorded a pressure of 922 mb, and then a 920 mb central pressure was measured at Buras, LA on August 29 at 1116Z. A central

pressure of 920 mb equals 132 kt according to the pressure-wind relationship for north of 25N. 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 August 28 18Z through the first Louisiana landfall, which occurred at August 29 11Z. The intensity is analyzed to have reached 115 kt by August 28 at 06Z and 120 kt by August 28 at 18Z. During the 18 hour time when Katrina was a Category 5 (August 28 12Z – August 29 00Z), 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 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 Louisiana landfall. The central pressure of Katrina at landfall (920 mb) 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.

g. Hurricane Rita (2005)

Hurricane Rita was a Category 5 for the 24 hours from 18Z on September 21 through 12Z on September 22, according to the NHC Best Track (Knabb et al. 2006), and it attained a peak intensity of 155 kt at 06Z on September 22. Figure 8 shows the NHC Best Track for Rita and the best track likely to be obtained using technology available in the late

1940s/early 1950s. On September 21 at 1517Z, aircraft would not have been able to penetrate the hurricane because the central pressure was less than 940 mb. Late on the 22nd, at 2250Z, a buoy in the Gulf of Mexico recorded a 926 mb pressure which would have been the peak intensity observation for the entire lifetime of Rita. If the assumption is made that the 926 mb observation is a central pressure value, the pressure-wind relationship yields 133, 127, 136, and 133 kt for south of 25N, north of 25N, south of 25N and intensifying, and north of 25N and intensifying subsets, respectively. A 133 kt intensity is chosen from this blend. Subtracting by 5 kt for a slow speed/large size yields 128 kt, which rounds to 130 kt. Since it would not have been certain whether the 926 mb observation was a central pressure, a peak lifetime intensity of 135 kt would have been chosen from 9/22 18Z to 9/23 00Z for the late 1940s and from 9/22 12Z to 9/23 00Z for the early 1950s. Hurricane Rita therefore would not have been considered a Category 5 if only late 1940s and early 1950s technology was available for observing the cyclone. According to the analysis, the ACE for Rita would have the 26 if it had occurred during the early 1950s, which is more than the 25 in the NHC Best Track. This is because an intensity 10-15 kt higher than in the NHC Best Track would have been analyzed from 22 September until landfall on the 24th due to the 926 mb buoy measurement and a 939 mb pressure measured at Johnsons Bayou, LA. Also, the intensity in the 1950s would have been higher than the intensity in the late 1940s on the 21st due to the slightly better aircraft capabilities of the early 1950s which explains the higher ACE for the early 1950s.

h. Hurricane Wilma (2005)

Hurricane Wilma (2005) is listed as a Category 5 on October 19 from 06-18Z according to the NHC Best Track (Pasch et al. 2005), with a peak intensity of 160 kt listed at 12Z on the 19th. Figure 9 shows the NHC Best Track for Wilma and the best track likely to be obtained using technology available in the late 1940s/early 1950s. On October 18th at 2309Z, aircraft recorded a central pressure of 954 mb. The next aircraft flight occurred at night, and no intensity information was available during the late 1940s-early 1950s at night. The first fix during daylight on the 19th occurred at 1806Z. Aircraft in the late 1940s-early 1950s would not have been able to penetrate the center since the central pressure was below 940 mb. A late 1940s (early 1950s) intensity of 120 (125) kt is chosen for 12Z on 19 October (160 kt according to NHC Best Track). A couple of days later, a 928 mb pressure was recorded at Cozumel, Mexico on October 21 at 21Z. 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. 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 October 21 18Z through landfall near Puerto Morelos, Mexico on October 22 at 03Z. The peak early 1950s intensity is also 125 kt-first from 12Z on the 19th to 12Z on the 20th and again from 18Z on the 21st to the landfall at 03Z on the 22nd. Therefore, Wilma likely would not have been known to have attained Category 5 intensity if it had occurred during the late 1940s-early 1950s. Hurricane Wilma rapidly intensified from 75 to 160 kt in a period of 18 hours. This rapid intensification was observed via satellite intensity estimates and aircraft observations including a dropsonde which 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-50s, the extreme rapid intensification would not have been captured.

i. Hurricane Dean (2007)

Hurricane Dean (2007) is listed as a Category 5 hurricane in the NHC Best Track (Franklin 2008) on August 18 from 06-12Z and again on August 21 from 00Z to the 0830Z landfall in Mexico. The Best Track comparison graph for Hurricane Dean is shown in Figure 10. On August 17 at 2332Z, aircraft recorded a 946 mb central pressure, and on the 18th at 1323Z, aircraft would not have been able to penetrate the center in the early 1950s because the pressure was less than 940 mb. A pressure of less than 940 mb yields greater than 123 kt according to the intensifying subset of the southern pressure-wind relationship. After adding 5 kt for a fast speed/small size, a wind speed of greater than 128 kt is obtained. A 135 kt intensity is chosen for the peak early 1950s intensity from August 18 at 06Z through August 19 at 00Z. A peak late 1940s intensity of 130 kt would have been chosen on August 18 from 00-18Z. The central pressure of Dean stayed below 940 mb through the 1st landfall, which occurred at 0830Z on the 21st. No surface observations near Category 5 intensity on land were recorded during this landfall even though Dean made landfall as a Category 5 according to the NHC Best Track. Since there were no surface observations of Category 5 conditions during the 2nd Category 5 period either, Dean would have likely been listed with a peak intensity of only Category 4 for both the late 1940s and early 1950s. The ACE of Dean would have been slightly higher than in the NHC Best Track if it had occurred during the early 1950s. This is mainly due to interpolations between intensity observations during the first few days of

Dean's life. Also contributing to the higher early 1950s ACE is the methodology to decrease the intensity by 25 kt per day backwards from August 16 at 18Z, when a 90 kt intensity was assigned based on a 974 mb aircraft central pressure (recall this methodology was also used in Isabel).

j. Hurricane Felix (2007)

Figure 11 shows that Hurricane Felix (2007) is listed as a Category 5 in the NHC Best Track (Beven 2008) from September 3 00Z-12Z and again on September 4 at 12Z (the point right at landfall). On September 2 at 2307Z, the aircraft in the late 1940s (early 1950s) likely would have been unable to penetrate the center since the central pressure was below 950 (940) mb, and this continued through at least September 3 at 1227Z (in the early 1950s, a 942 mb central pressure would have been measured at 1227Z). For the intensity on September 3 at 00Z, a central pressure of less than 950 (940) mb yields a wind speed of greater than 113 (123) kt according to the intensifying subset of the Brown et al. southern pressure-wind relationship. At that time, the cyclone's forward motion was a fast 17 kt and its radius of outer closed isobar (ROCI) was a small 125 nmi so 10 kt is added to the pressure-wind relationship. This yields an intensity of greater than 125 (135) kt after rounding to the nearest 5 kt value. Therefore, 130 kt is chosen for the late 1940s and 140 kt is chosen for the early 1950s on September 3 from 00-06ZZ. Therefore, Felix likely would have been listed as a Category 5 hurricane if it had occurred during the early 1950s period, but likely not during the late 1940s period. Felix made landfall in Nicaragua as a Category 5 on September 4 at 12Z. There was a coastal station about 17 nm from the center, but the station's barometer and anemometer stopped

working before the peak of the storm. As with Dean, Category 5 conditions were not measured from surface observations on land for Felix. A late 1940s-early 1950s intensity of 120 kt is chosen for the landfall based on the data that would have been available with the reanalysis methodology.

k. Overall results

The results in Table 1 show that Category 5 conditions likely would have been observed for only two (three) of these ten Category 5 hurricanes if these storms occurred during the late 1940s (early 50s). On average, there were much fewer observations of the peak intensity of TCs during the late 1940s-early 50s, especially because there were no satellites and because aircraft would not generally fly into the eye of strong hurricanes. During the lifetimes of two of the ten hurricanes, 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). The two hurricanes that likely would have been classified as Category 5s if they occurred during the late 1940s are Andrew (1992) and Mitch (1998). Additionally, Felix (2007) likely would have been considered a Category 5 in the early 1950s.

Although Table 1 shows that only two (three) of the ten cyclones would have been listed as Category 5 hurricanes if they had occurred during the late 1940s (early 1950s), the analyses performed indicate that the other eight (seven) hurricanes would

have been classified with a Category 4 peak strength. The reader is reminded that the methodology employed is quite 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, it is likely that some of these cyclones would have been listed with a peak intensity of only Category 3 strength.

One hypotheses in Hagen et al. (2011) is that TCs that were actually 120 kt and higher (during the 1944-1953 period) were likely underestimated in intensity since the most intense part of the storm was not sampled for these intense hurricanes. The hypothesis in that study was tested utilizing statistics from this study. For all times during which the Category 5 hurricanes from 1992-2007 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 occurred during the late 1940s and early 1950s. The intensity averaged over all 6-hourly cases would have been approximately 12 kt lower if the ten most recent Category 5 hurricanes had occurred during the late 1940s period and about 8 kt lower if they had occurred during the early 1950s period than the intensities listed in the NHC Best Track, as shown in Table 9 in Hagen et al. (2011). However, Table 1 from the present study indicates that the peak intensity of each of the individual ten Category 5 hurricanes would have been underestimated by 20 kt (16 kt) if these hurricanes had occurred in the late 1940s (early 1950s).

l. Discussion and error analysis

There is some uncertainty as to the number of Category 5 hurricanes (out of the ten discussed here) that would have been known to be Category 5s if they had occurred during the late 1940s-early 1950s. The analyzed intensity values are based on observations that likely would have been available during the late 1940s-early 1950s from methodology documented in Landsea et al. (2008) and Hagen et al. (2011). 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 plus/minus 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 ten) is in the range of one to four for the late 1940s and one to seven for the early 1950s. Wilma, Katrina, 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. Andrew would have been most likely to have been recorded as a Category 5.

Hurricane Andrew would have been observed to be a Category 5 hurricane only under the assumption that the meteorological instrumentation that measured the Category 5 conditions would have been present in the same location in the late 1940s, which is reasonable, as Homestead has had barometer readings during the 1940s and earlier. Both Hurricane Andrew and Hurricane Mitch would have been observed to be a Category 5 only if the instrumentation was not blown away or destroyed before the Category 5 conditions were recorded. Therefore, it is possible that all ten of these Category 5s would

not have been categorized as Category 5s during the late 1940s/early 1950s period. On the other hand, before satellites, ships may have been slightly more prone to run into hurricanes than more recently (though none would purposely steer into the eye of a major hurricane simply to observe the central pressure). This is countered to a large degree by the decision to incorporate any buoy observations in the recent Category 5s to be included as measurements obtained in the late 1940s/early 1950s. All of these factors add uncertainty to this study, though overall, the assumptions utilized here tend to be conservative and that, if anything, the study may somewhat overestimate the ability to measure extreme intensity in the late 1940s/early 1950s.

The observation network that existed during the late 1940s and early 1950s was generally much more sparse than it is today (with the notable exception of Swan Island as discussed above). Therefore, it is very likely that most of the peak intensity observations during these storms would have been missed. With the observational capabilities, density, and practices of the late 1940s and early 1950s, very few peak intensity observations in Category 4 and 5 hurricanes would have been observed.

5. Category 4 hurricanes

All ten of the Category 5 hurricanes discussed in the previous sections of this paper would have been recorded at least as a Category 4 for their peak intensity if they had occurred 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 may have only been classified as weak hurricanes or even tropical storms if they had

taken place during the late 1940s and early 1950s. For example, during the period 2003-2010, three Category 4 hurricanes that would have been most likely to be listed with a peak intensity substantially less than Category 4 if they had occurred in the 1940s-50s 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 could have been listed as a Category 2 because a buoy measured a 958 mb pressure one day before it became extratropical. Julia may not have even been recorded as a hurricane, as no surface observations or even tropical storm force winds were recorded. Hurricane Omar (Beven and Landsea 2009) was only a Category 4 for six hours (at night) and this classification was due to an SFMR measurement. During the late 1940s-early 1950s, 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 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 of time would have been problematic to properly observe in the late 1940s and early 1950s. A strong low bias in their intensities would lead to a substantial undercount of Category 4 and 5 hurricanes and in the total ACE.

6. Summary and conclusions

The main point of this paper is to show how the intensity of extreme tropical cyclones would be analyzed differently in the 1940s-50s compared with today. Whenever the ten

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 ten most recent Category 5 hurricanes occurred during the late 1940s period, only two of them would be considered Category 5 hurricanes (and three of ten 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 period. 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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List of Tables.

Table 1. Summary of results. Best Track Peak is the peak intensity of the hurricane listed in the official NHC Best Track database, and Early 1950s and 1940s Peak is the value (kt) that the peak intensity would have likely been analyzed as if the hurricane would have occurred during the early 1950s or late 1940s, respectively.

Category 5 Hurricanes – Results

Recent Category 5 Hurricane	Duration as Cat 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	2.5	145	135- Cat 4	135- Cat 4	70	66	64
Emily- 2005	0.25	140	135- Cat 4	125- Cat 4	33	31	30
Katrina- 2005	0.75	150	120- Cat 4	120- Cat 4	20	19	19
Rita- 2005	1	155	135- Cat 4	135- Cat 4	25	26	25
Wilma- 2005	0.75	160	125- Cat 4	125- Cat 4	39	35	34
Dean- 2007	1	150	135- Cat 4	130- Cat 4	35	36	34
Felix- 2007	1	150	**140- Cat 5**	130- Cat 4	18	16	15
Average	**1.37**	**150**	**134- Cat 4**	**130- Cat 4**	**37**	**34**	**32**

Table 1. Summary of results. Best Track Peak is the peak intensity of the hurricane listed in the official NHC Best Track database, and Early 1950s and 1940s Peak is the value (kt) that the peak intensity would have likely been analyzed as if the hurricane would have occurred during the early 1950s or late 1940s, respectively.

List of Figures.

Figure 7. Same as Figure 2, but for Hurricane Katrina (2005).

Figure 8. Same as Figure 2, but for Hurricane Rita (2005).

Figure 9. Same as Figure 2, but for Hurricane Wilma (2005).

Figure 10. Same as Figure 2, but for Hurricane Dean (2007).

Figure 11. Same as Figure 2, but for Hurricane Felix (2007).

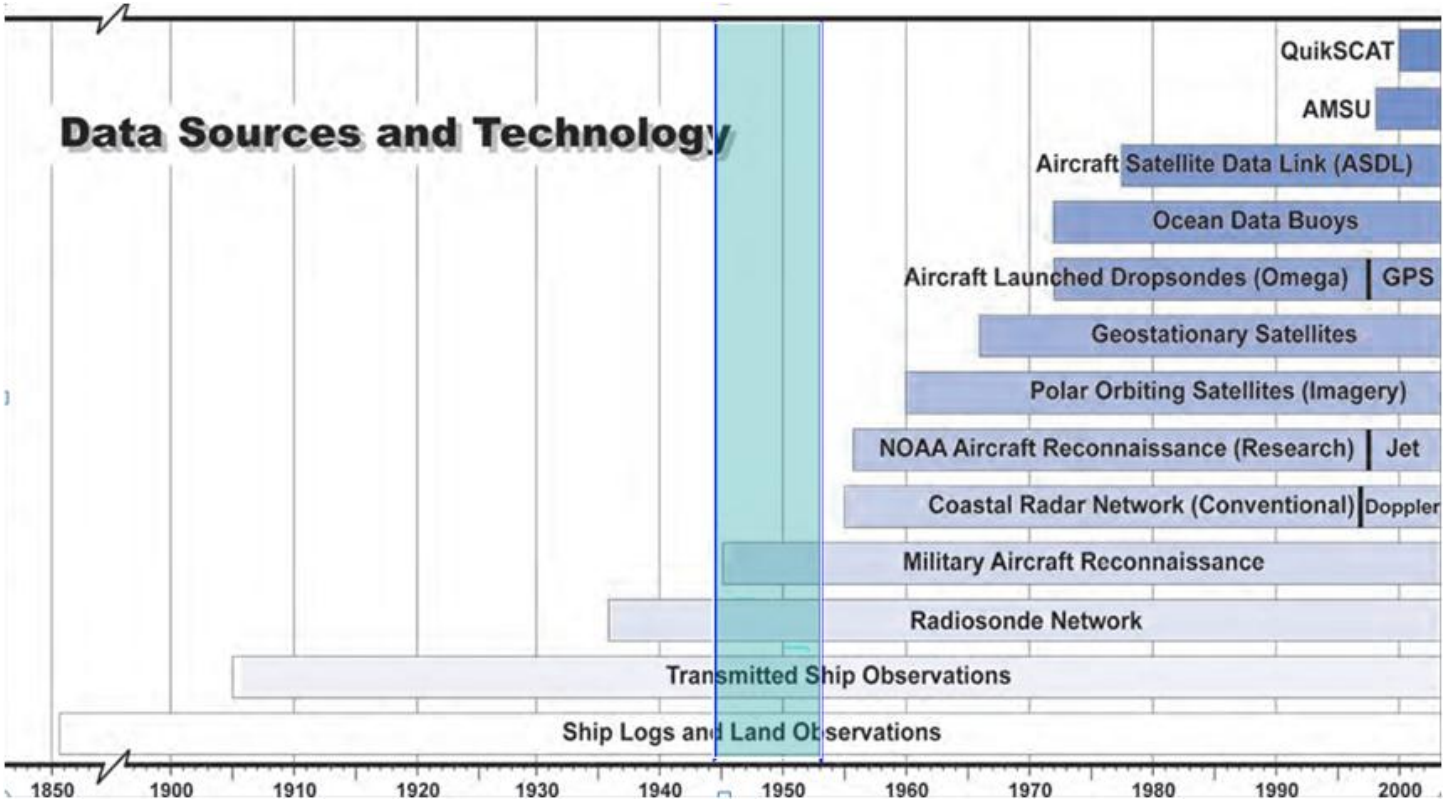

Figure 1. This graphic adapted from McAdie et al. (2009) shows how tropical cyclone observational capabilities have evolved as a function of time. The 1944-1953 period is highlighted with a blue bar because this is the time period against which the recent Category 5 hurricanes are compared.

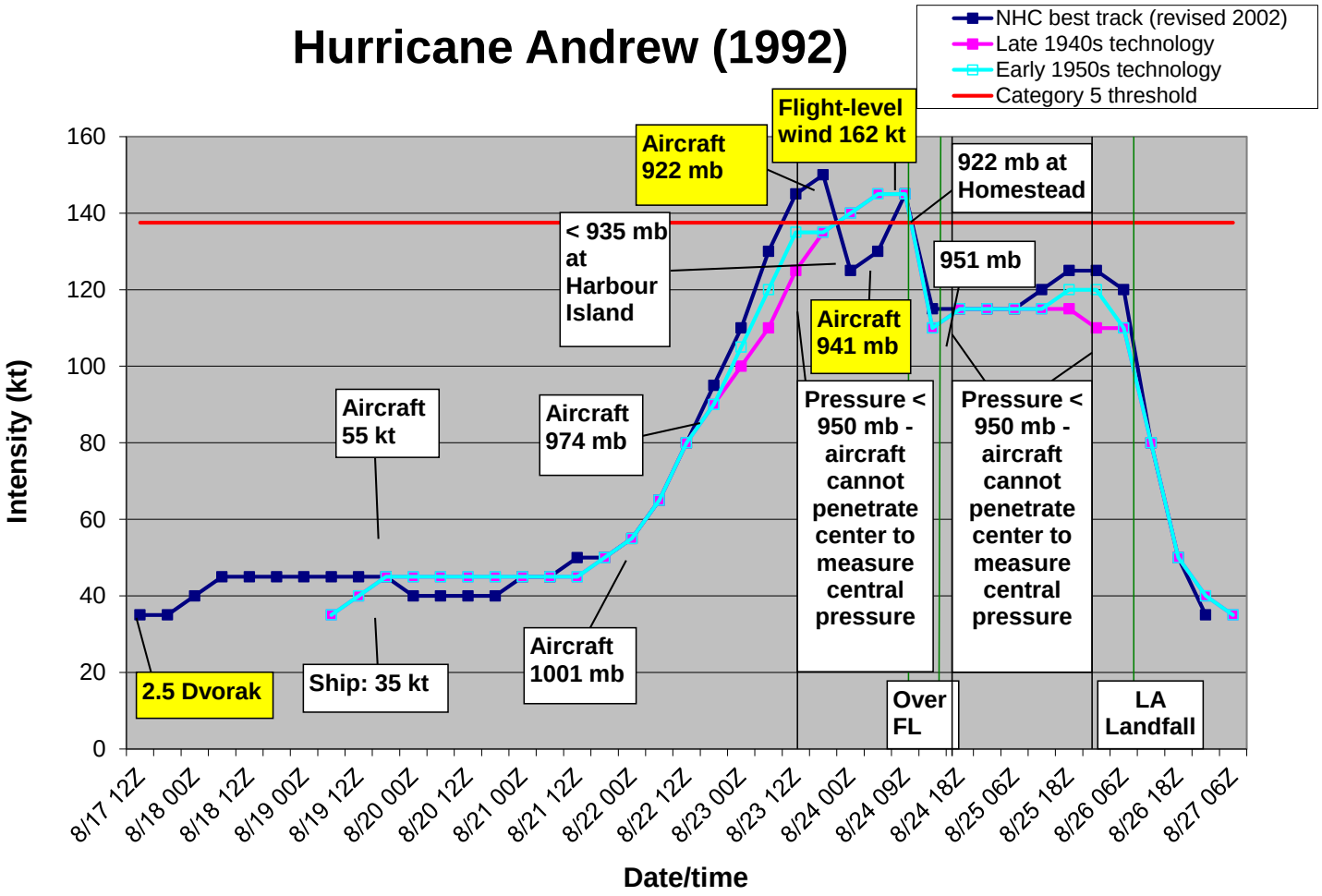

Figure 2. Best Track comparison graph for Hurricane Andrew (1992). Dark blue line is the NHC Best Track intensity and pink (light blue) line is what the intensity would have likely been with observations available during the late 1940s (early 50s). Yellow boxes indicate observations that would only be available with recent technology and white boxes indicate observations that were available during both the late 1940s-early 50s and today. Vertical green lines indicate landfall/oceanfall times.

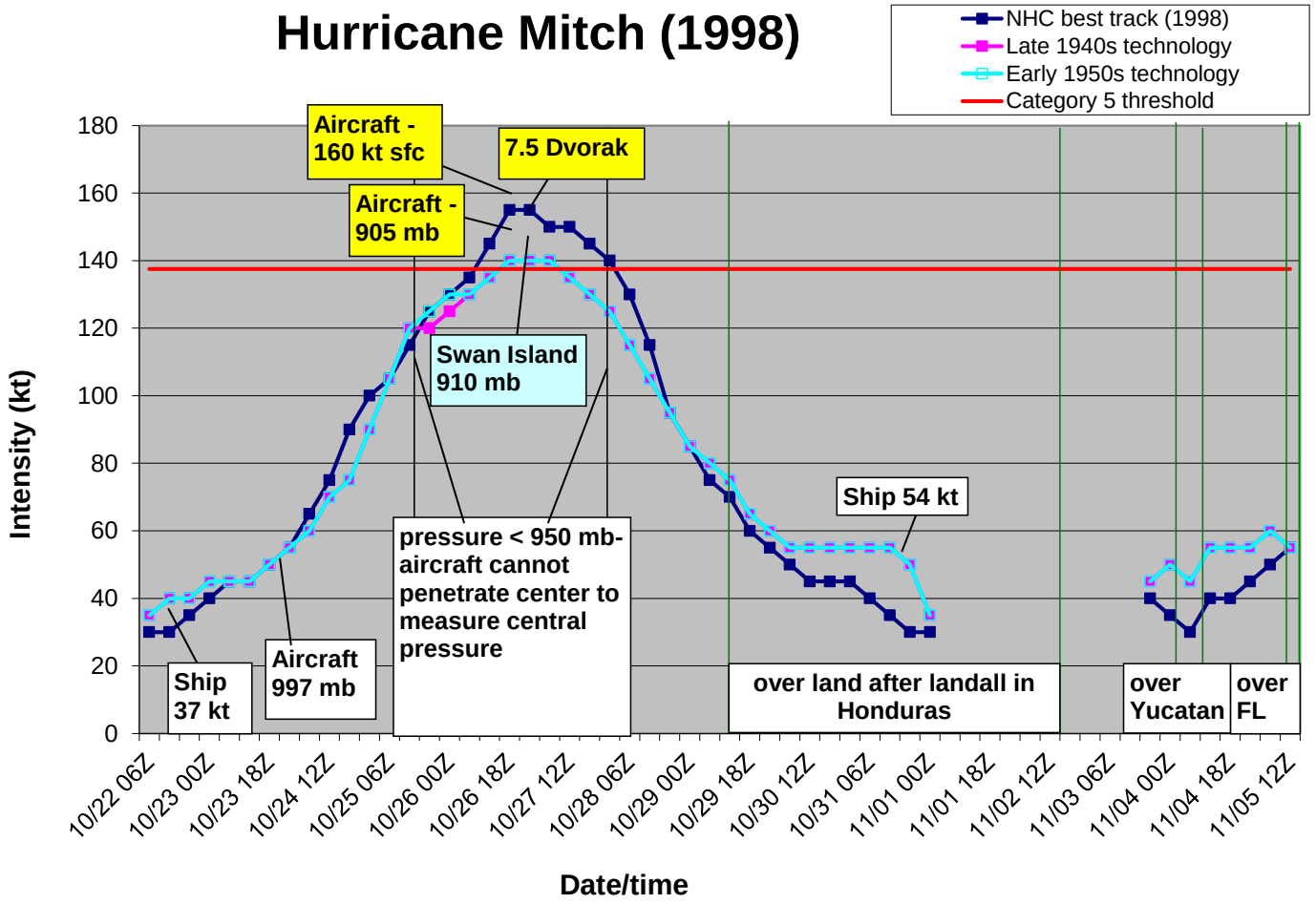

Figure 3. Same as Figure 2, but for Hurricane Mitch (1998). Light blue box indicates observation likely available in 1940s-50s, but not available today.

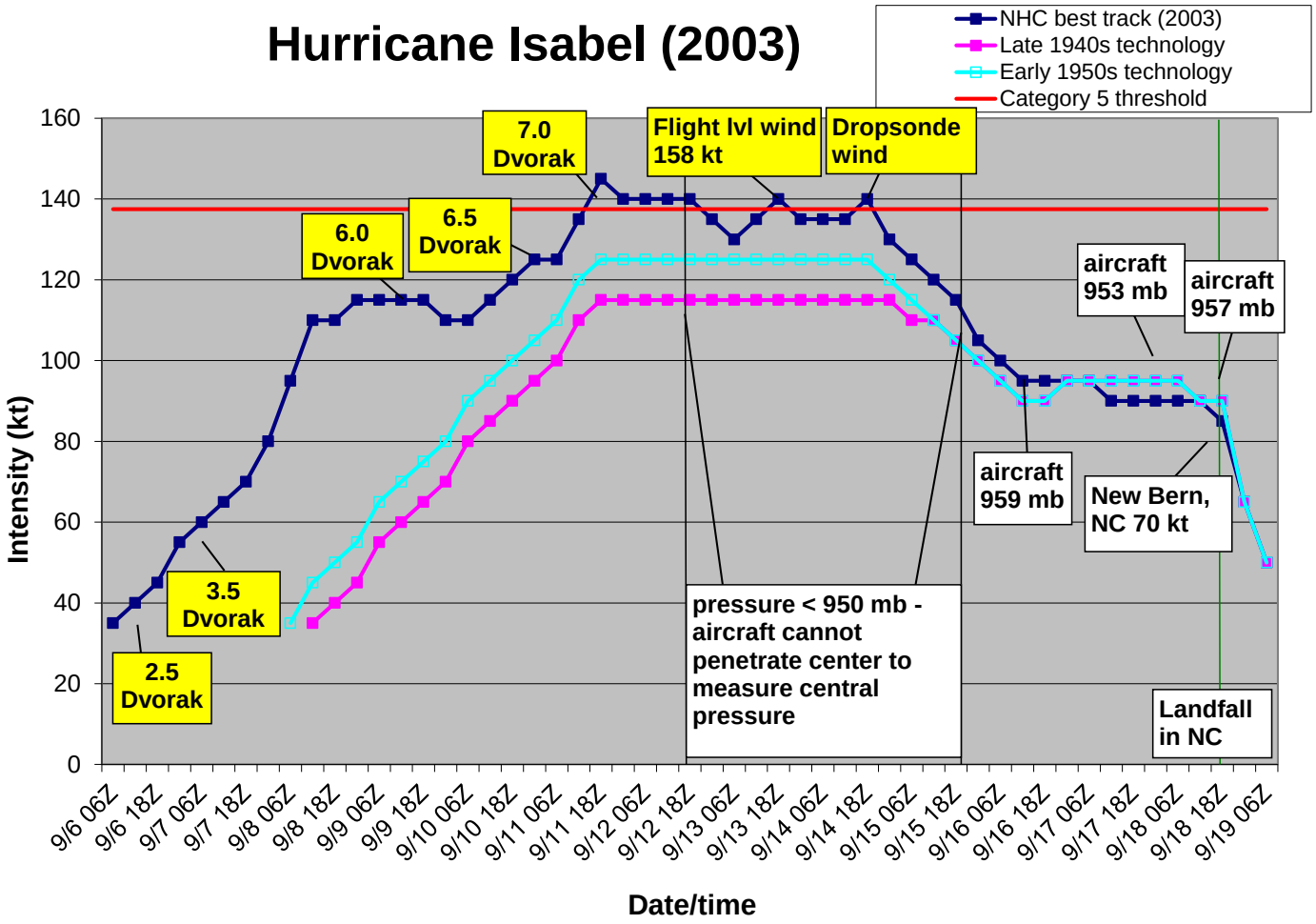

Figure 4. Same as Figure 2, but for Hurricane Isabel (2003).

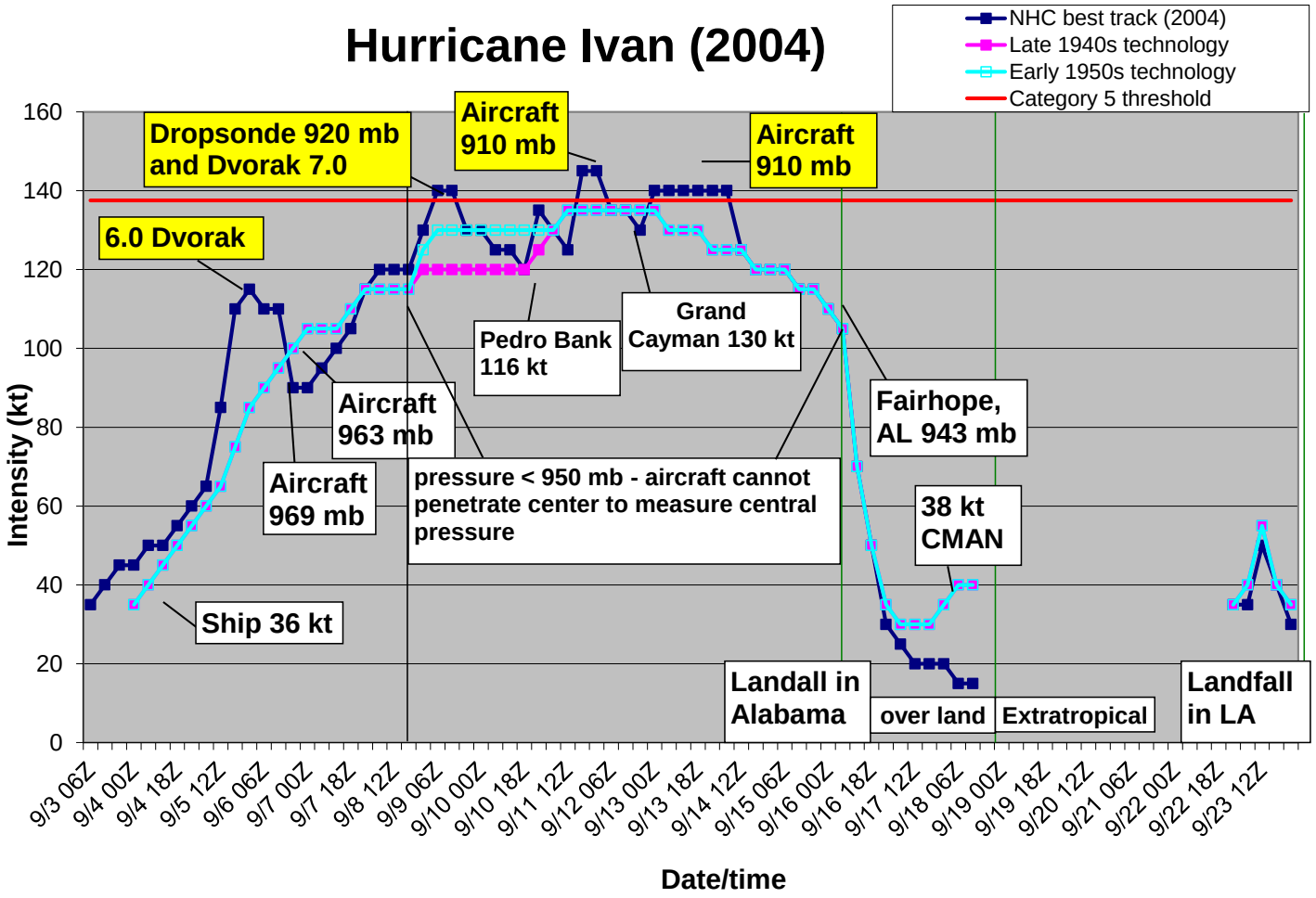

Figure 5. Same as Figure 2, but for Hurricane Ivan (2004).

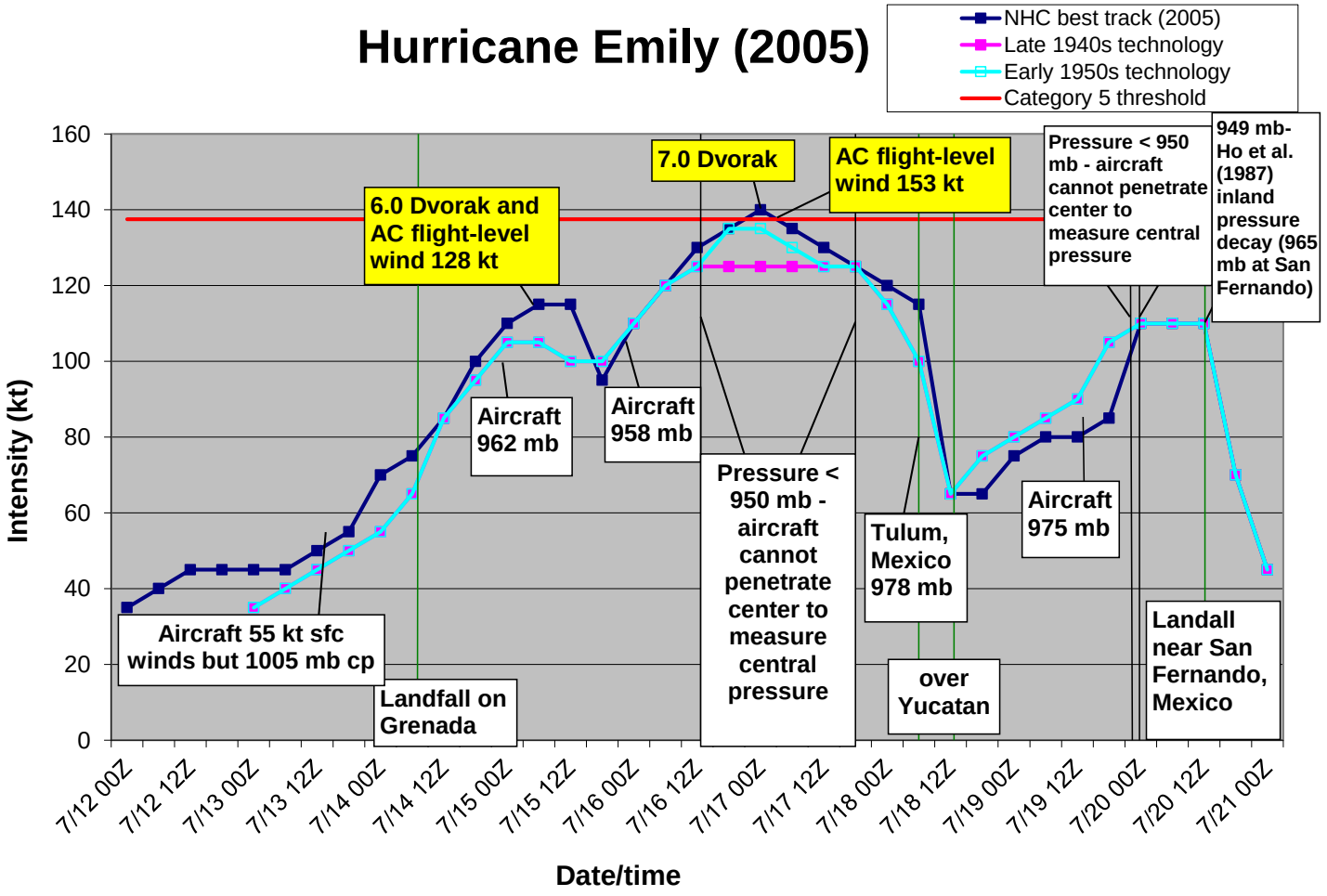

Figure 6. Same as Figure 2, but for Hurricane Emily (2005).

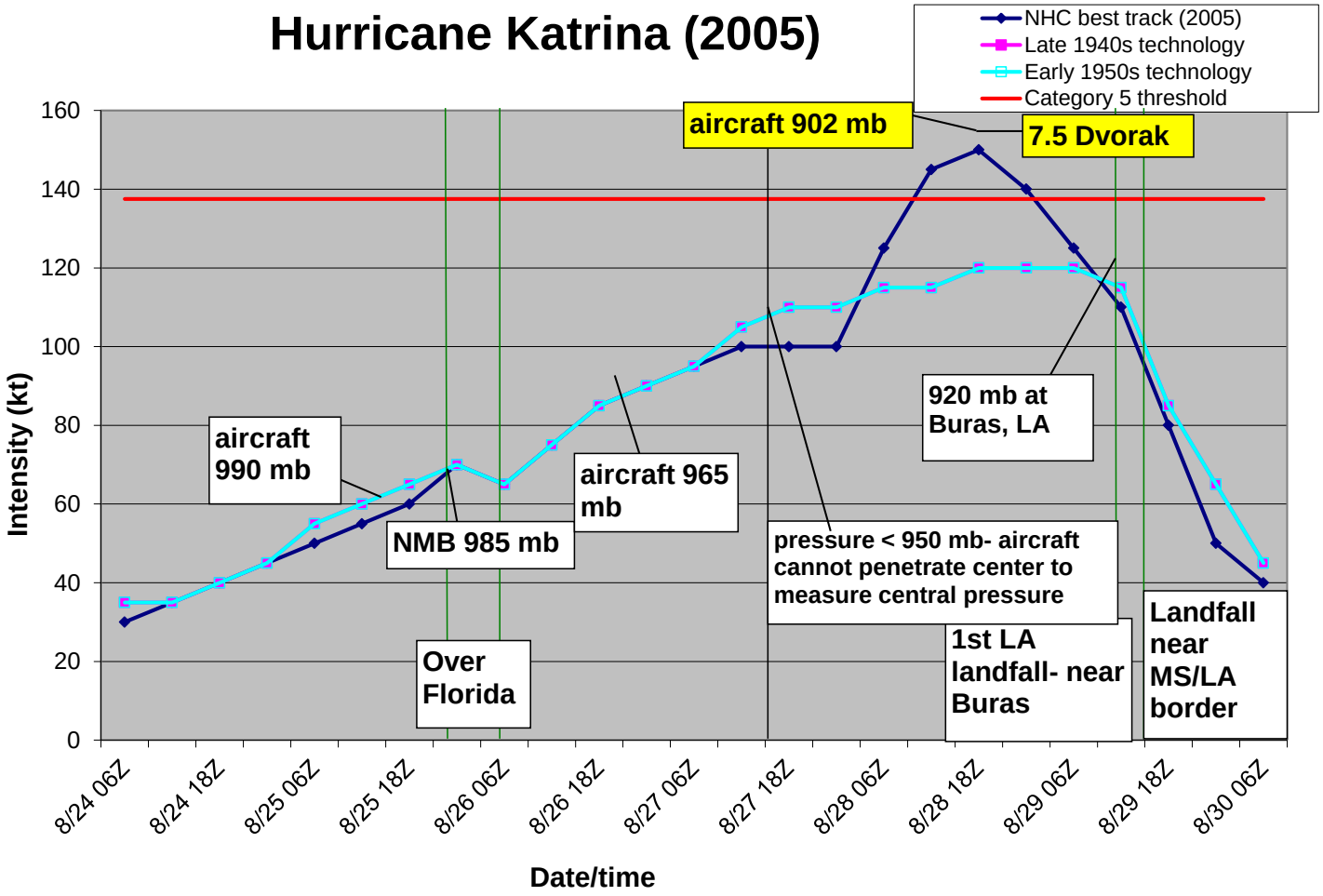

Figure 7. Same as Figure 2, but for Hurricane Katrina (2005).

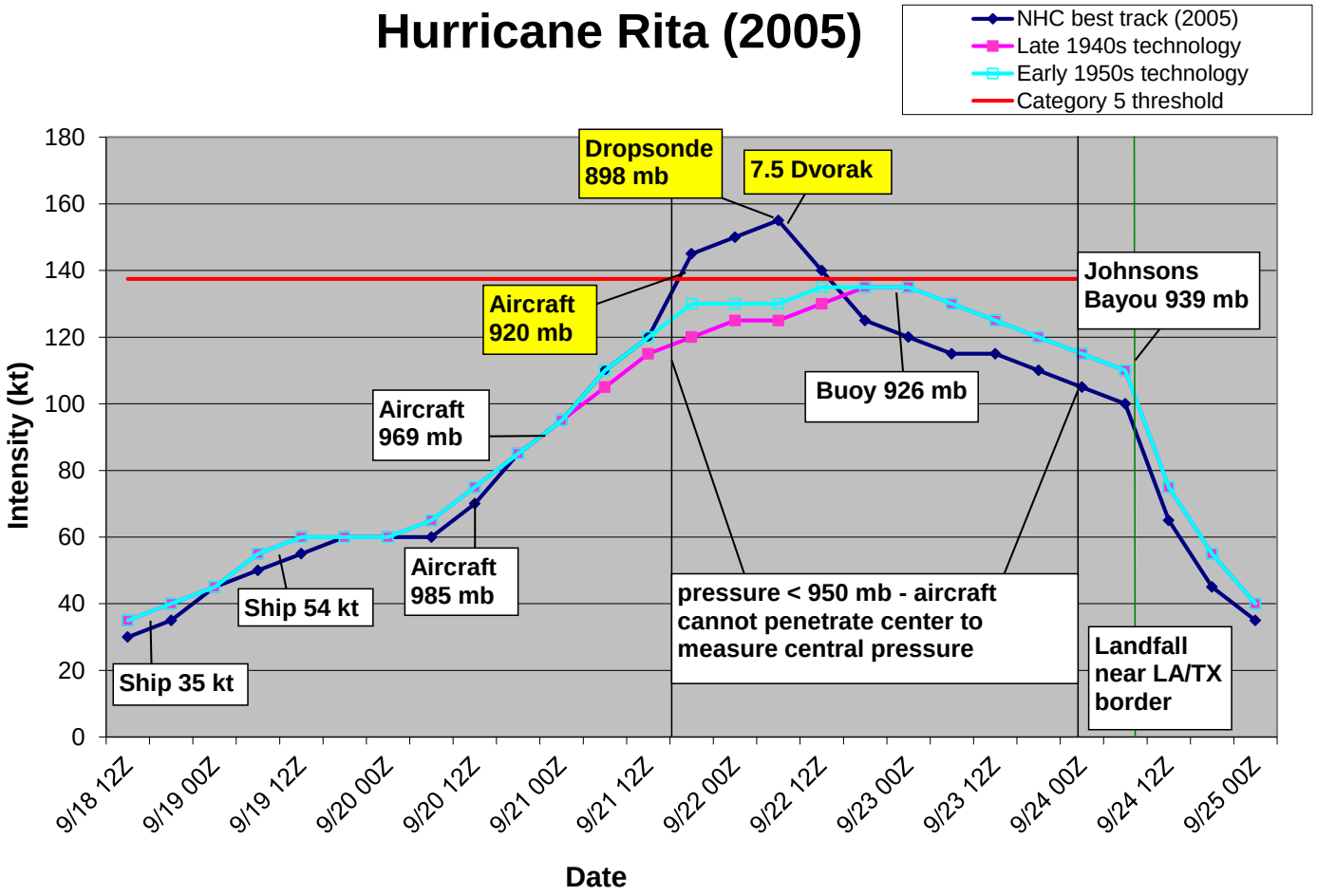

Figure 8. Same as Figure 2, but for Hurricane Rita (2005).

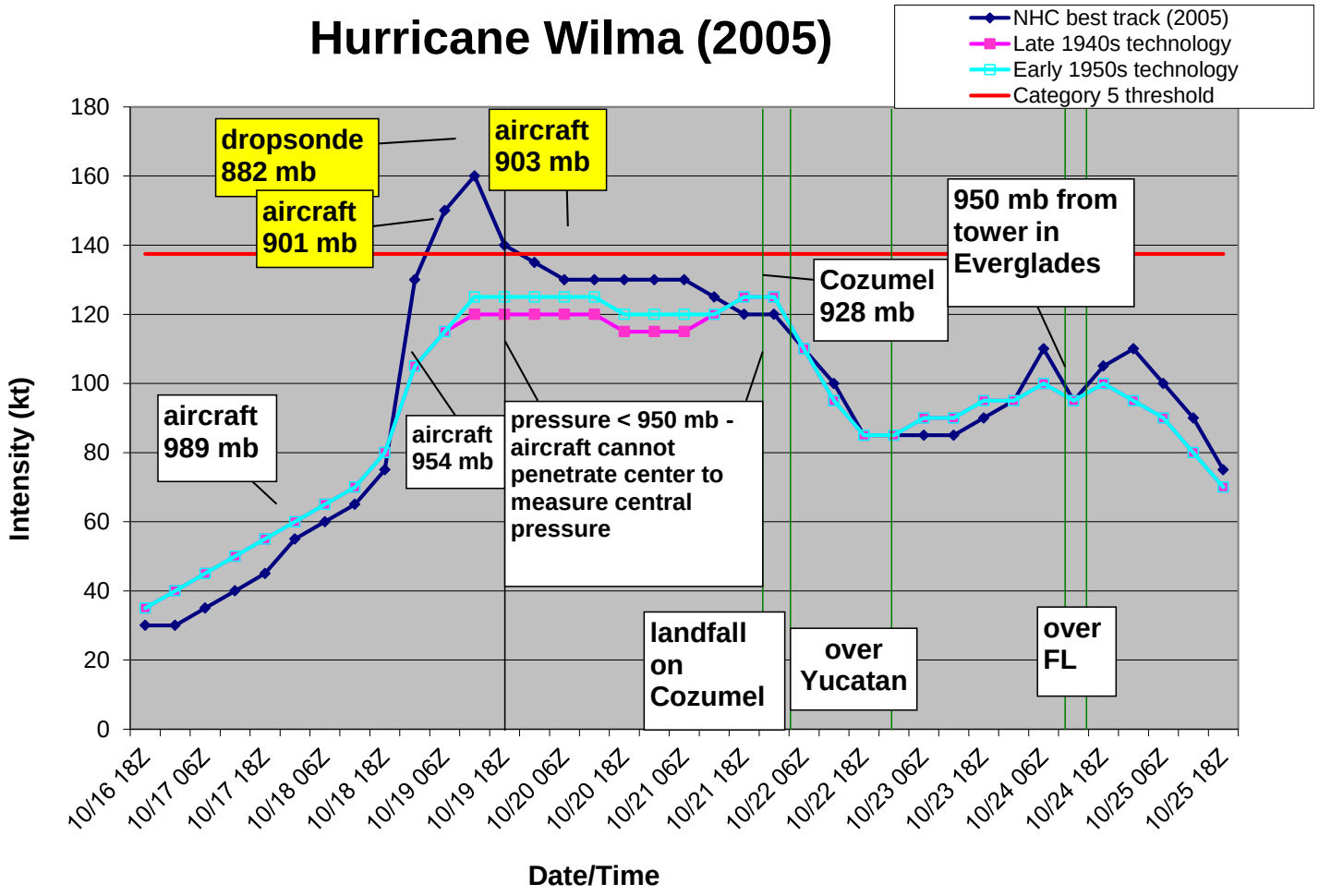

Figure 9. Same as Figure 2, but for Hurricane Wilma (2005).

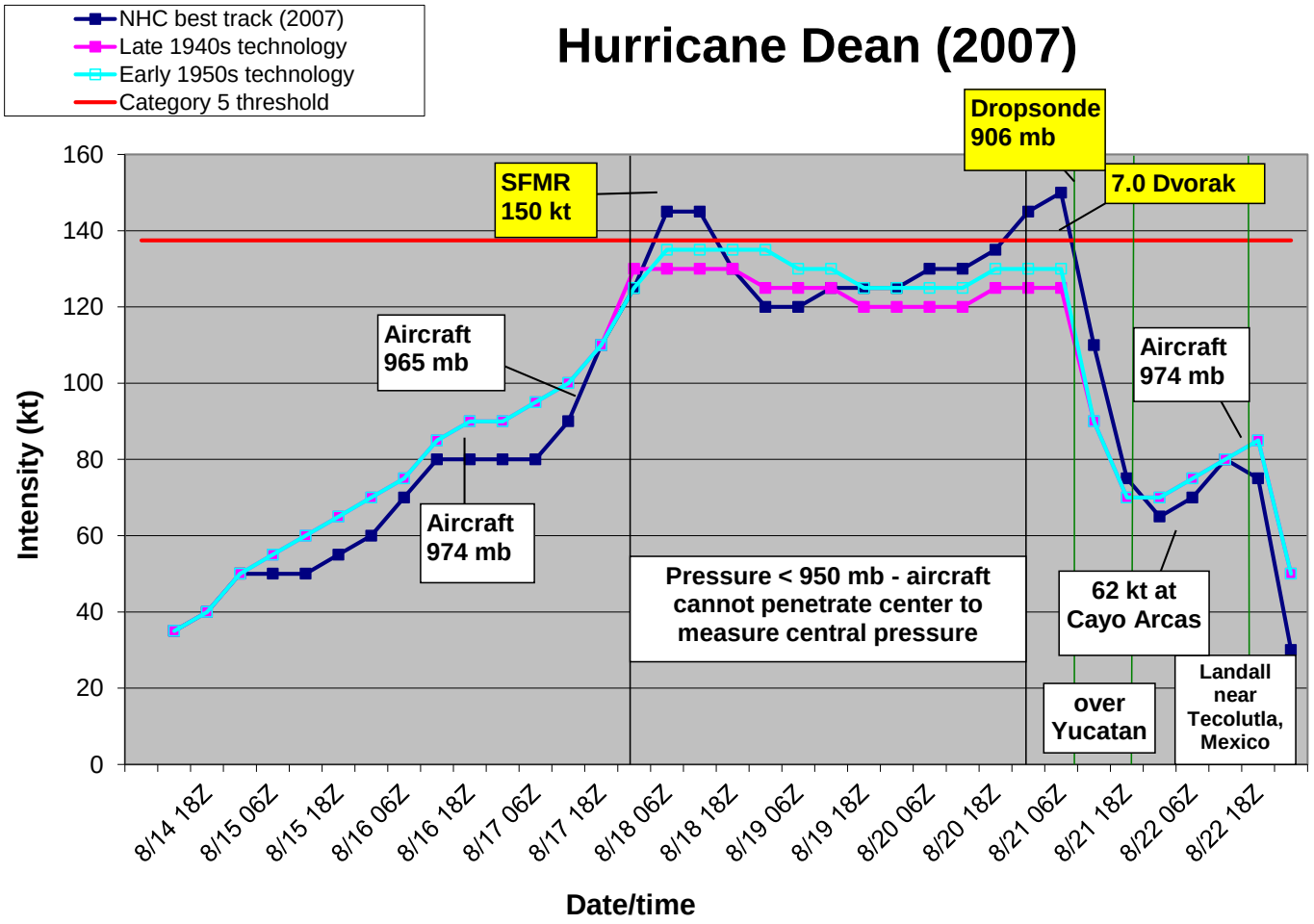

Figure 10. Same as Figure 2, but for Hurricane Dean (2007).

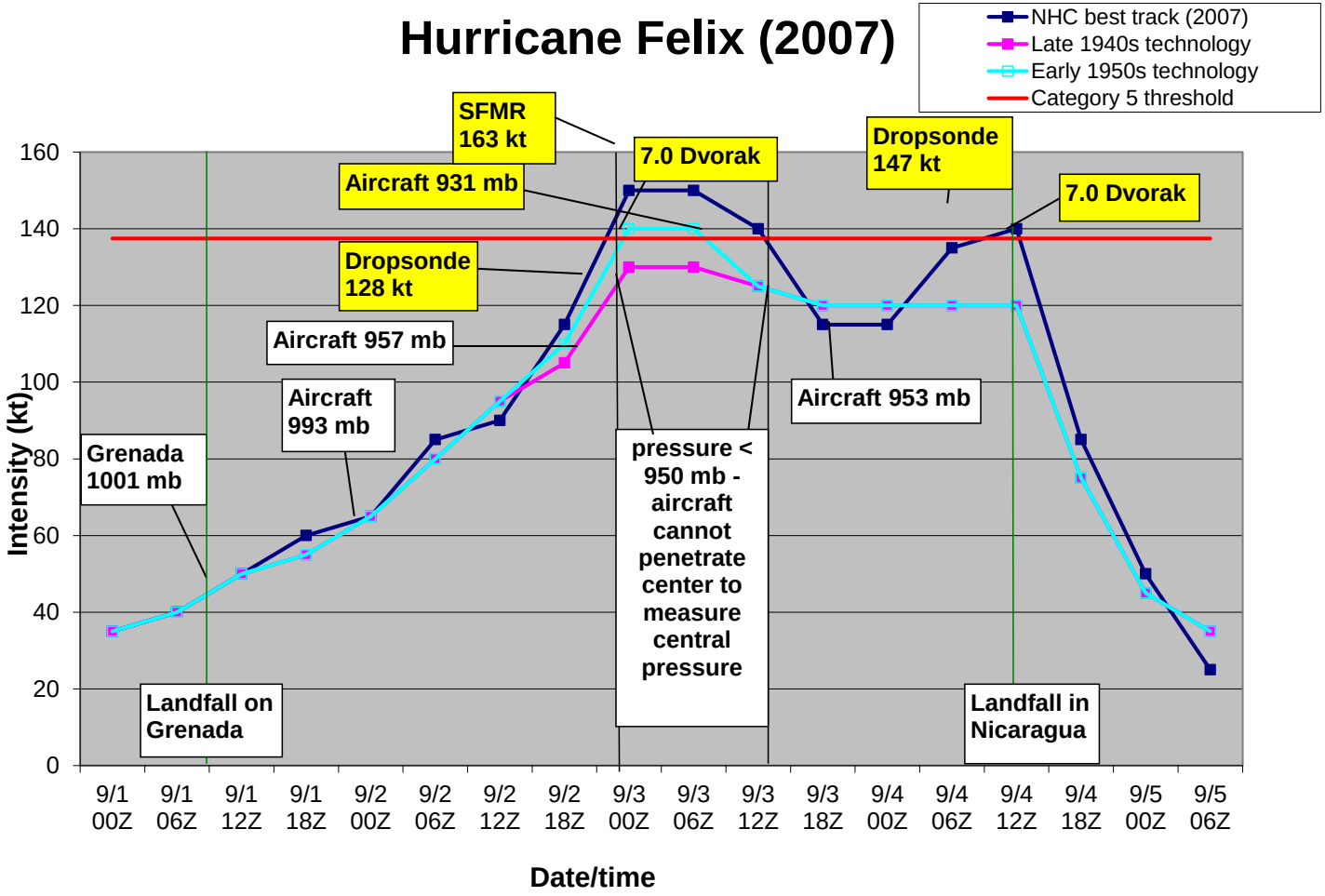

Figure 11. Same as Figure 2, but for Hurricane Felix (2007).