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"How 'Good' are the Best Tracks? - Estimating Uncertainty in the Atlantic Hurricane Database"

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Abstract:

"Best tracks" are National Hurricane Center (NHC) post-storm analyses of the intensity, central pressure, position, and size of Atlantic and eastern North Pacific basin tropical and subtropical cyclones. This paper estimates the uncertainty (average error) for Atlantic basin best track parameters through a survey of the Hurricane Specialists who maintain and update the Atlantic hurricane database. A comparison is then made with a survey conducted over a decade ago to qualitatively assess changes in the uncertainties. Finally, we discuss the implications of the uncertainty estimates for NHC analysis and forecast products as well as for the prediction goals of the Hurricane Forecast Improvement Program.

1. Introduction:

"Best tracks" are National Hurricane Center (NHC) post-storm analyses of the intensity, central pressure, position, and size of tropical and subtropical cyclones (Jarvinen et al. 1984), and represent the official historical record for each storm. These analyses (apart from those for size) make up the database known as HURDAT, and have been used for a wide variety of applications: verification of official and model predictions of track and intensity (McAdie and Lawrence 2000), development of intensity forecasting techniques (DeMaria 2009), seasonal forecasting (Klotzbach 2007), setting of appropriate building codes for coastal zones (American Society of Civil Engineers 1999), risk assessment for emergency managers (Jarrell et al. 1992), analysis of potential losses for insurance and business interests (Malmquist and Michaels 2000), and climatic change studies (Knutson et al. 2010).

Given the widespread use of HURDAT for meteorological, engineering, and financial decision-making, it is surprising that very little has been published regarding the uncertainties inherent in the database; Torn and Snyder (2012) is a notable exception. This current work estimates the uncertainties through a survey of the best-track authors – the NHC Hurricane Specialists, and compares the survey results to independently derived estimates from Torn and Snyder (2012). A similar survey conducted in 1999 provides some insight into changes in dataset quality during the last decade. Finally, we discuss implications of the uncertainty estimates for NHC analysis/forecast products, as well as for the predictability goals of the Hurricane Forecast Improvement Program (Gall et al. 2012).

2. Best Tracks – Definition, content, and procedures

The NHC develops best tracks for intensity[1], central pressure, position, and size[2] with a precision of 5 kt, 1 mb, 0.1^{o} latitude/longitude (~6 nm), 5 nm, 5 nm, and 5 nm, respectively. Best track intensity and position estimates have been provided for every synoptic time (0000, 0600, 1200, and 1800 UTC) for all tropical storms, hurricanes, and subtropical storms since 1956 (Jarvinen et al. 1984). Prior to 1956, best-track information was analyzed only once or twice a day; interpolation was used to obtain best-track estimates for the remaining synoptic times when the HURDAT database was constructed in the early 1980s (Jarvinen et al. 1984).

Originally, central pressure best-track values were only included into HURDAT if there was a specific observation that could be used explicitly as the best track value. Beginning in 1979, central pressures have been estimated for every synoptic time. Size information has been included in the best track data since 2004. Finally, asynpotic points (primarily to denote times of landfall as well as peak intensities that occurred at times other than the synoptic hours) have been incorporated into the best tracks for the years 1851 to 1935 and 1991 onward. Because the HURDAT format could not accommodate either the size data or asynoptic records, a new format (HURDAT2) has been developed (see Appendix).

A best track is defined as a subjectively-smoothed representation of a tropical cyclone's history over its lifetime, based on a post-storm assessment of all available data. It is important to recognize that the best track is not simply a reissuance of the operational values. Many types of meteorological data arrive with some latency (e.g., microwave imagery, scatterometer data, and Advanced Microwave Sounding Unit [AMSU] - data), and that some data do not become

[1] Maximum 1-min average wind associated with the tropical cyclone at an elevation of 10 m with an unobstructed exposure (Office of the Federal Coordinator for Meteorological Services and Supporting Research 2012).

[2] Cyclone size is described by the maximum extent of winds of 34, 50, and 64 kt in each of four quadrants about the center.

available until well after a storm is over. Furthermore, knowing what happened subsequent to a given point in time can be instrumental in the correct assessment of what was occurring at that point in time. Hurricane Specialists review the entire track with all the available information and put together, from often contradictory data, a history that makes sense with respect to known tropical cyclone dynamics[3].

Because the best tracks are subjectively smoothed, they will not precisely re-create a storm's history, even when that history is known to great accuracy. Aliasing considerations suggest that variations with periods shorter than about 24h (four times the 6-h resolution of the best tracks) cannot be represented by HURDAT. So as the best tracks are constructed, apparent variations, whether in intensity, central pressure, location, or size, with periods shorter that 24 h are typically not captured. This helps ensure that the best tracks values are representative of the 6-h interval surrounding the best-track time. On the other hand, the smoothing (particularly with track) means that there will routinely be small discrepancies between the actual (and well-known) locations of a tropical cyclone and its corresponding best-track value. The smoothing places greater weight to data for which confidence is relatively high (e.g., daylight positions are considered more reliable than nighttime positions). An exception to this smoothing paradigm is made for landfall. Because landfall is defined as the intersection of the tropical cyclone center and the coastline, these points cannot logically be smoothed in time or space; landfall data in the HURDAT2 therefore represent NHC's best estimates of the precise location, intensity, and timing of landfall.

[3] There are some objective methodologies available for weighting various observations to assist in providing best tracks (e.g., the Automated Tropical Cyclone Forecast system – Sampson and Schrader 2000). The current procedure at NHC is for the Hurricane Specialists to use his knowledge and experience to subjectively weight the various observations available and determine the best tracks manually.

At the conclusion of each storm, one of the Hurricane Specialists is assigned to conduct the post-storm analysis on a rotating basis. The Specialist creates a draft best track, which is reviewed at NHC by the other Specialists, the Hurricane Specialists Unit (HSU) Branch Chief, the Science and Operations Officer, the Deputy Director, and the Director. The review process ensures a measure of continuity across the various best track authors.

3. Observations Available for Best Track Assessments:

3a. Intensity

One would expect the quality of the best tracks would vary depending on the amount and reliability of observations that are available for the post-storm assessments. Figure 1 illustrates how the available data can vary from cyclone to cyclone. Hurricane Gordon in 2006 was a cyclone almost exclusively monitored remotely by satellite measurements, with the majority of data provided by the Satellite Analysis Branch (SAB) and Tropical Analysis and Forecast Branch (TAFB) Dvorak analyses (Dvorak 1975, 1984). In addition, observations available in recent years for tropical cyclones well away from land include the Advanced Dvorak Technique (ADT - Olander and Velden 2007), AMSU (Brueske and Velden 2003, Demuth et al. 2006), and scatterometer data from the QuikSCAT and ASCAT satellites (Brennan et al. 2009).

Hurricane Dean had much more aircraft reconnaissance data available for most of its lifetime. Aircraft reconnaissance missions, from both the U. S. Air Force Reserve's 53rd Weather Reconnaissance Squadron C-130s and the NOAA Aircraft Operations Center Orion P-3s, provide flight-level winds that can be adjusted to the surface (Franklin et al. 2003), Stepped

Frequency Microwave Radiometer (SFMR) winds (Uhlhorn et al. 2007), and Global Positioning System (GPS) dropwindsonde winds (Franklin et al. 2003).

Figure 1 gives the appearance of less spread in the observations for Gordon relative to Dean. However, much of the data plotted for Dean will not be representative of the cyclone's intensity (for example, flight-level adjusted winds from the right-rear quadrant of the cyclone). Moreover, close agreement between SAB and TAFB Dvorak estimates does not necessarily indicate smaller uncertainty, because it has been shown that Dvorak intensity analyses are not overly sensitive to the individual performing the analysis (Mayfield et al. 1988, Torn and Snyder 2012).

3b. Central Pressure

Best-track central pressures for cyclones observed primarily by satellite are determined from SAB and TAFB Dvorak analyses, the ADT, and AMSU. In addition, since 2010 the analysis has also used the Knaff-Zehr-Courtney pressure-wind relationship (Knaff and Zehr 2007, Courtney and Knaff 2009) to convert a best track intensity to a corresponding central pressure; the technique also considers the cyclone's size, translational speed, outermost closed isobar, and latitude. Cyclones investigated by aircraft reconnaissance have central pressure measurements that are either observed in situ from GPS dropwindsondes or from adjusting flight-level pressures to the surface using hydrostatic assumptions.

3c. Position

Figure 2 illustrates examples again from Gordon and Dean of the tropical cyclone best track positions and the available fixes. Position estimates for systems like Gordon over the open Atlantic Ocean are limited to SAB and TAFB Dvorak analyses and scatterometer observations.

In contrast, cyclones like Dean that are threatening land have aircraft reconnaissance position fixes once to several times a day, as well as land-based radar fixes primarily from the U.S. WSR-88D Doppler radars as frequently as every 30 minutes. Figure 2 appears to show a larger spread in the center fixes for Gordon, which was a tropical storm at the time, in comparison to Dean, which was a major hurricane for this portion of its lifetime. This suggestion of increased uncertainty for tropical storms versus stronger cyclones will be explored more later in this paper.

3d. Wind Radii

Observations to support wind radii analyses are quite limited. Two satellite-based instruments for estimating wind radii are the ASCAT and the (now defunct) QuikSCAT scatterometers. However, scatterometer passes are infrequent (on the order of one every day or two), they often only sample a portion of the cyclone, and their winds are not well calibrated at the tropical-storm-force wind threshold due to ambiguities introduced by rain contamination (Brennen et al. 2009). Data from the passive WindSat radiometer and OceanSat scatterometer have also been received at NHC in the last couple of years. However, WindSat cannot obtain useful data in rainy conditions and the calibrations for OceanSat are still evolving, making it currently unsuitable for estimating cyclone size. Aircraft reconnaissance observations, such as adjusted flight-level winds, SFMR winds, and GPS dropwindsonde winds, do assist in determining wind radii, but do not provide complete coverage of the surface wind field, given that flight-level and SFMR winds are only available directly along the flight track and GPS dropwindsonde winds are only spot measurements.

3e. Additional considerations

Other data sources, such as ships, moored buoys, and coastal weather stations, are used. But because of their wide spacing and distance from the storm as well as the propensity for them to either actively avoid tropical cyclones (ships) or fail during tropical cyclone events (buoys and stations), these usually do not play a major role in determining tropical cyclone best tracks.

The WSR-88D Doppler radars provide center fixes within about 200 nm of the U.S. coast and wind data from these radars have even a shorter range. Moreover, the radars only measure the wind component directly toward or away from the radar site, and not lower than a few hundred meters above the ground (necessitating a method for adjusting the winds to 10 m). As a consequence, the use of land-based Doppler radar for best track purposes is largely restricted to those few cases near landfall when reconnaissance data are unavailable.

Overall, about 30% of the Atlantic basin best-track times for tropical cyclones have the benefit of aircraft reconnaissance observations (Rappaport et al. 2009). Typically these data are obtained for any tropical cyclone within 500 nm of landfall and west of 52.5ºW in the Atlantic (Office of the Federal Coordinator for Meteorological Services and Supporting Research 2012). Thus even for the Atlantic basin – the only tropical cyclone basin around the world with routine aircraft reconnaissance – the majority of the best-track analyses are substantially dependent on remotely sensed measurements.

4. Methodology for Estimating Best Track Uncertainties:

In early 1999, an unpublished survey was conducted of the six Hurricane Specialists (Lixion Avila, Jack Beven, Miles Lawrence, Max Mayfield, Richard Pasch and Ed Rappaport) and the new NHC Director Jerry Jarrell (who only recently had stopped making best tracks).

Each of them was asked for their subjective estimate of the uncertainty (or average error) in the best tracks that they had developed during the late 1990s for intensity and position. The Hurricane Specialists were asked to provide separate estimates for tropical storms, hurricane and major hurricanes, and also for separate estimates based on data availability (satellite only, satellite and aircraft, and U.S. landfalls).

A very similar survey was conducted in early 2010 of the ten Hurricane Specialists and the HSU Branch Chief (Lixion Avila, Robbie Berg, Jack Beven, Eric Blake, Mike Brennan, Dan Brown, John Cangialosi, Todd Kimberlain, Richard Pasch, Stacy Stewart, and James Franklin). In addition to the intensity and position best track uncertainty (average error) estimates, this survey also included central pressure and 34, 50, and 64 kt wind radii.

Some discussion of the limitations of the survey approach is appropriate here. While the estimates are quantitative, they are subjectively determined by each Hurricane Specialist. In addition, while the average of these estimates is shown here, the sample of participants is small (seven in 1999 and eleven in 2010). The Hurricane Specialists that contributed range from forecasters with decades of hurricane analysis, forecasting and best track experience to those that have only conducted such tasks for a year or two. Thus the results obtained should be considered "ball-park" estimates of uncertainty where virtually none have existed previously. This is especially the case with the changes noted between the 1999 and 2010 surveys, where differences in the experience and expertise of individuals participating may preclude any detailed trend assessment of the results; thus only broad generalizations about the changes over time are included.

5. Results of Best Track Uncertainty Estimates:

The two surveys conducted a decade apart allow for an assessment of the current uncertainty for all of the best track parameters, and provide insight into how the uncertainty for position and intensity has changed over time. Tables 1 and 2 and Figures 3 through 6 provide summaries of the average best track uncertainty estimates as provided by the Hurricane Specialists in 1999 and 2010[4].

5a. Intensity

Intensity best track uncertainty in 2010 (Figure 3, Table 2) shows a moderate dependence upon observations available and a weak dependence upon intensity. Tropical storms have an uncertainty in the peak winds of about 12 kt when sampled primarily by satellite, which drops to about 8 kt for both satellite and aircraft data and U.S. landfalling cyclones. This uncertainty is nearly the same for Category 1 and 2 hurricanes. For major hurricanes, the average uncertainty in intensity is larger - about 14 kt for satellite-only observations, dropping to about 11 kt for satellite and aircraft monitoring and to about 10 kt for U.S. landfalling cyclones. While the values are only moderately sensitive to the intensity, if one puts these results into the context of the uncertainty relative to the absolute value of the intensity, then the relatively uncertainty via satellite-only observations in tropical storms is about 25%, in Category 1 & 2 hurricanes ~15%, and in major hurricanes ~10%. For aircraft/satellite monitoring and for U.S. landfalling cyclones, the relative uncertainty decreases to about 15% for tropical storms, ~10% for Category 1 & 2 hurricanes, and ~8% for major hurricanes. The intensity uncertainty values from NHC Hurricane Specialists in 2010 decreased significantly from those estimated in most parameters

[4] Three Hurricane Specialists – Avila, Beven, and Pasch – participated in both the 1999 and 2010 surveys, allowing for a more homogeneous comparison of the results based just upon their responses. These showed quite similar changes in the estimates of uncertainty compared with the whole sample that is reported here.

about a decade previously. While the uncertainty is about the same for tropical storm intensity back in 1999 (Figure 4, Table 1), the uncertainty was about 2 kt higher for Category 1 & 2 hurricanes and about 4 kt higher for major hurricanes (regardless of observational platform). It is speculated that the increased confidence in the intensity estimates is due to newly available tools during the 2000s of the satellite-based scatterometers, AMSU, and ADT, and aircraft-based SFMR, none of which were routinely used in operations before the 2000s. However, for the bin with the largest decrease in uncertainty – major hurricanes – only the ADT and SFMR would allow for better accuracy at this intensity due to limitations of scatterometers and AMSU at the highest intensities.

5b. Central Pressure

For central pressure best tracks (Figure 4, Table 2), the uncertainty in 2010 increases for stronger cyclones, but only for satellite-based measurements. In this bin, tropical storm central pressures have an uncertainty of about 6 mb, Category 1 & 2 hurricanes about 8 mb, and major hurricanes about 10 mb. To put these central pressure uncertainty values into perspective, one could compare them versus the average pressure-deficit of Atlantic basin tropical cyclones, which would about 20 mb for tropical storms, ~40 mb for Category 1 & 2 hurricanes, and ~70 mb for major hurricanes (Courtney and Knaff 2009). This suggests relative uncertainty of about 30% for tropical storm central pressures, ~20% for Category 1 & 2 hurricanes, and ~15% for major hurricanes monitored primarily by satellite. In contrast, for those systems monitored by both satellite and aircraft as well as U.S. landfalling cyclones, the central pressure best track uncertainty is about 3 mb (~20% for tropical storms, ~10% for hurricanes, and ~5% for major hurricanes). The NHC Hurricane Specialists were not surveyed in 1999 on their estimated uncertainty in the central pressure best tracks.

5c. Position

For position best tracks (Figure 5, Table 2), the uncertainty in 2010 is strongly a function of intensity (more intense cyclones have less position uncertainty) and observational platform (more comprehensive observations decrease the position uncertainty). For tropical storms, satellite-only best tracks have a quite large uncertainty of about 35 nm. This uncertainty decreases to about 22 nm for aircraft and satellite measurements and an even further decreases to about 18 nm for U.S. landfalling tropical storms. To put these position uncertainty values into perspective, one could compare them versus the average size of Atlantic basin tropical cyclones based upon a measure of the surface circulation size, such as the outer closed isobar which has a median of about 150 nm for tropical storms and 200 nm for both Category 1 & 2 hurricanes and major hurricanes (Kimball and Mulekar 2004). This suggests a relative uncertainty in position for cyclones monitored primarily by satellite of about 20% for tropical storms and ~10% for both Category 1 & 2 hurricanes and major hurricanes. Inclusion of aircraft reconnaissance information reduces the uncertainty of position substantially with estimated values of about 22 nm for tropical storms (about 15% relative uncertainty), ~15 nm for Category 1 & 2 hurricanes (~7.5%), and ~11 nm for major hurricanes (~5%). Finally, for cyclones making landfall in the United States, the uncertainty in position decreases even more: about 18 nm for tropical storms (about 10% relative uncertainty), ~12 nm for Category 1 & 2 hurricanes (~5%), and ~8 nm for major hurricanes (~5%). Compared with the estimated uncertainty of the best track positions back in 1999 (Figure 5, Table 1), today's uncertainty in position is judged to be nearly unchanged. This result is somewhat surprising given that there have been improvements in monitoring positions of Atlantic basin tropical cyclones, primarily in satellite-based techniques. For example, the use of microwave imagery became routine during the 2000s (Velden and

Hawkins 2010, Hawkins and Velden 2011), which should allow for better positioning of tropical storms and Category 1 & 2 hurricanes, in the absence of a clear eye in geostationary satellite imagery. Additionally, the QuikSCAT and ASCAT scatterometer data also can be helpful in better determining positions of tropical storms (Brennan et al. 2009).

5d. Wind Radii

The average uncertainty in 2010 of the size best tracks (maximum extent of 34, 50 and 64 kt wind radii) is presented in Table 2 and Figure 6. These are fairly invariant with respect to intensity, but appear to be strongly related to the observational capabilities available. For example, the 34 kt wind radii has an average uncertainty from satellite-only measurements of about 40 nm regardless of intensity, ~30 nm from satellite and aircraft monitored tropical cyclones, and ~25 nm for those systems making landfall. These uncertainties are quite large relative to the average wind radii itself (Kimball and Mulekar 2004): about 45% for tropical storms (with median 34 kt radii of 85 nm), ~30% for Category 1 & 2 hurricanes (median 34 kt radii of 130 nm), and ~30% for major hurricanes (median 34 kt radii of 140 nm) for those systems primarily monitored by satellite. This relative uncertainty drops some to about 35% for tropical storms, ~25% for Category 1 & 2 hurricanes, and ~20% for major hurricanes being observed by both satellite and aircraft. The estimate is further reduced for those cyclones making a U.S. landfall to about 30% relative uncertainty for tropical storms and ~20% for both Category 1 & 2 hurricanes, and ~20% for major hurricanes.

The estimated uncertainty in 2010 for the 50 kt wind radii is about 30 nm from satellite-only monitoring, ~23 nm from satellite and aircraft observations, and about ~18 nm for U.S. landfalling tropical cyclones (Table 2). Climatological median 50 kt wind radii is about 50 nm for tropical storms, ~70 nm for Category 1 & 2 hurricanes, and about 85 nm for major hurricanes (Kimball and Mulekar 2004). This suggests relative uncertainty from satellite-only, satellite and aircraft, and U.S. landfalling of the following: ~55%, 40%, and 35% for tropical storms, ~45%, 35%, and 30% for Category 1 & 2 hurricanes; and ~40%, 30%, and 25% for major hurricanes.

The estimated uncertainty in 2010 for the 64 kt wind radii is about 24 nm from satellite-only monitoring, ~17 nm from satellite and aircraft observations, and about ~13 nm for U.S. landfalling hurricanes (Table 2). Climatological median 64 kt wind radii is about 40 nm for Category 1 & 2 hurricanes and about 50 nm for major hurricanes (Kimball and Mulekar 2004). This suggests relative uncertainty from satellite-only, satellite and aircraft, and U.S. landfalling of the following: ~55%, 40%, and 35% for Category 1 & 2 hurricanes; and ~50%, 35%, and 25% for major hurricanes, respectively.

6. Comparison of Uncertainty Estimates with Earlier Work:

There has only been one previous study that has attempted to quantify the uncertainty in the Atlantic basin best tracks – Torn and Snyder (2012). Their study addressed best track uncertainty for intensity and central pressure as well as operational uncertainty for position.

Torn and Snyder (2012) were able to derive estimates of intensity and central pressure best track uncertainties (binned by intensity) for satellite-only observations by comparing the 2000-2009 SAB and TAFB Dvorak classifications when there existed aircraft reconnaissance within 2 h of the best track time to provide ground truth. They suggested uncertainty values of about 10 kt for tropical storm and about 12 kt for Category 1 & 2 hurricanes and for major hurricanes monitored by satellite-only measurements. Likewise, they analyzed uncertainty values of about 7 mb for tropical storms, 10 mb for Category 1 & 2 hurricanes, and 12 mb for major hurricanes. These values are relatively close to those estimated here in Table 2 based upon a completely different methodology.

For position uncertainty, Torn and Snyder (2012) examined the operational position uncertainty estimates contained in NHC tropical cyclone products. In this case, the operational estimates are described as "position accurate within" x miles, which may be more of an upper bound estimate of the likely error, rather than the average error. Torn and Snyder (2012) analyzed tropical storm uncertainty in position to be about 35 nm, Category 1 and 2 hurricanes to be about 25 nm, and major hurricanes to be about 20 nm, using data from the 2000 to the 2009 hurricane seasons. These are somewhat larger than the uncertainty estimates provided here for best track positions of 30 nm for tropical storms, 20 nm for Category 1 & 2 hurricanes, and 12 nm for major hurricanes (combining the satellite-only and the satellite & aircraft bins in a 30-70 ratio – Rappaport et al. 2009). However, best track values of center locations can differ significantly from NHC operational assessments of these quantities due to additional observations becoming available as well as the opportunity to put subsequent measurements into the context of the life cycle of the tropical cyclone. However, one would expect that in general the best track position uncertainty should be smaller – at times substantially smaller – than the operational estimates. This is because, for example, at night for systems only monitored by infrared geostationary satellites there can be quite large ambiguity in the operational positions. It is not uncommon for the first light visual imagery from geostationary satellites to reveal a position quite far removed from that analyzed overnight. This is known colloquially at NHC as the "sunrise surprise". The best tracks have the ability of hindsight to correct these overnight positions accordingly with this subsequent information and thus would have substantially smaller uncertainty than the operational estimates, which again may be thought of as an upper bound error estimate. Torn and Snyder (2012) did, in contrast to the subjective results obtained here, find a reduction in the position uncertainty during the first decade of the 21st Century. It is possible that the disagreement in the uncertainty changes is due to the semi-quantitative nature of this survey, differing members of the Hurricane Specialists that participated in the survey in 1999 and 2010, or even differing experience levels of the three common Hurricane Specialists between earlier in their career in 1999 and significantly later in their career in 2010.

One can additionally compare the uncertainty results here versus those estimated for best tracks in the pre-satellite and pre-aircraft reconnaissance (Landsea et al. 2012) era. For intensity, the uncertainty today is roughly half of what is was in the late 19th and early 20th Centuries. For position, the uncertainty in recent years has been reduced by about 75% in areas monitored today by satellite primarily and by about 85% for those tropical cyclones with aircraft reconnaissance available today. This is a dramatic increase in accuracy of analysis over a century timescale.

7. Implications of the Results for Analysis and Forecasting:

The results obtained with these surveys of the NHC Hurricane Specialists are relevant to possible changes to both the analyses and forecasts provided by NHC. With the estimates put into a relative context, one can directly compare the various uncertainties obtained. Figure 7 provides these relative uncertainties for each of the six best track quantities stratified by the primary observational platform for all tropical storms and hurricanes collectively. By far, the database with the least uncertainty is position ranging from ~12.5% relative uncertainty for satellite-only monitoring, to 10% for satellite and aircraft measurements, to 7.5% for U.S.

landfalling cyclones. Next are the intensity and central pressure with relative uncertainties ranging from 17.5-20% for satellite-only down to about 10-12.5% for both satellite-aircraft monitoring and at landfall in the United States. However, the best track quantities with the largest uncertainty are the wind radii. For those cyclones making a U.S. landfall, the relative uncertainty is around 25-30% for the 34, 50, and 64 kt wind radii. The uncertainty increases to 27.5-37.5% for cyclones being monitored by satellite and aircraft. The uncertainty is greatest for those tropical cyclones that are only being observed by satellite with 35-52.5% relative uncertainty. Expressing these results into a signal-to-noise context suggests a best 8 to 1 ratio for position to a worst 2 to 1 ratio for 64 kt wind radii from satellite-only monitoring (recall that 70% of Atlantic basin advisories are supported solely by satellite data)

As noted earlier, NHC provides wind radii information both operationally and in best track in quadrants expressed as a single value representing the largest radial extent within that quadrant. This somewhat crude depiction of the surface winds is also used to forecast tropical cyclone size, with 34- and 50-kt size forecasts going out to 72 hr and 64-kt size forecasts going out to 36 h. Such very large uncertainties and very low signal-to-noise ratio in the wind radii is a strong argument for not providing additional specification of the tropical cyclone wind field and for not currently extending the size forecasts out further in time.

These uncertainties also have implications for the forecasting goals of the Hurricane Forecast Improvement Program (HFIP - Gall et al. 2012). The goals for this program include reducing the average track and intensity error by 50% through 120 h by 2019. The overall position uncertainty is about 20 nm for all tropical storms and hurricanes. Figure 8 puts this current uncertainty in position into context with regards to the Days 1 through 5 NHC forecast track errors over the last two decades. It is unlikely that the uncertainty in position will have an effect on the ability to reduce track errors as hoped by HFIP, except perhaps at the Day 1 forecast time which is currently about 50 nm.

Figure 9 compares the current estimated uncertainty in intensity – about 10 kt – with the NHC forecast errors for intensity between Days 1 through 5. It is apparent that the current estimated uncertainty in intensity forecasts is of similar magnitude to the existing average intensity forecast errors at 24 hours. Any sizable reductions in large forecast busts (usually associated with either rapid intensification or rapid weakening) will somewhat lower the average intensity forecast errors. However, unless there are also substantial improvements in our capability to observe the intensity of tropical cyclones, achieving the quantitative HFIP intensity forecast goals could prove very challenging, especially at the shorter forecast leads.

8. Summary and Discussion:

This paper provides estimates of the Atlantic basin best track uncertainties for intensity, central pressure, position, and size for today's tropical cyclones. This is accomplished by taking a survey of the Hurricane Specialists that maintain and update the Atlantic hurricane database. A comparison is then made against a similar survey that was conducted about a decade ago. The main conclusions that arise from this work are the following:

- The best track *intensity uncertainty* increases moderately with intensity and decreases substantially with availability of aircraft monitoring compared with satellite-only observations;
- The best track *central pressure uncertainty* increases moderately with intensity and decreases to much smaller values with the availability of aircraft monitoring;

- The best track *position uncertainty* decreases substantially both with increasing intensity and with the availability of aircraft monitoring;
- The best track *size (wind radii) uncertainty* changes little with intensity, but decreases moderately with the availability of aircraft monitoring;
- The only best track parameter substantially improved with additional monitoring afforded by coastal radars and stations when a cyclone makes a U.S. landfall is the best track size;
- Substantial improvement in the perceived intensity uncertainty was suggested between the 1999 and 2010 surveys. However, little change in the position uncertainty was indicated between the two surveys;
- The best track size (wind radii) have a very poor signal-to-noise ratio, which suggests that any expansion of the current NHC operational analyses of the surface wind and its forecast would be premature at this time;
- The uncertainty inherent in today's best track positions should not be a hindrance to the HFIP track forecast goals by 2019;
- The uncertainty estimated in the current best track intensities may make achieving the HFIP intensity forecast goals by 2019 problematic.

There may be opportunities in the next decade or so to improve our monitoring capabilities and reduce the uncertainties both in operations and in the best track database. For intensity, four potential improvements may be possible. The first is the use of Hurricane Imaging Radiometer instrument (HIRAD – Miller et al. 2011). This aircraft instrument – similar in design to the SFMR – allows for a wide swath of surface winds to be measured, rather than single point values directly below the aircraft. The second is from the use of airborne Doppler radar winds adjusted to approximate surface observations (Powell et al. 2010). This radar capability – currently only existing within the two Orion P-3 aircraft – would have to be transferred to the ten C-130 aircraft that do the vast majority of reconnaissance flights to have a substantial impact on best tracks. The third is from small unmanned aircraft that could directly measure the near surface winds around the radius of maximum winds (Lin 2006). A final opportunity would be from a next-generation satellite-based scatterometer (National Research Council 2007, Brennan et al. 2009) to hopefully replace the now defunct QuikSCAT.

For central pressure uncertainty improvements, this could be obtained by either deployment of small unmanned aircraft into the center of tropical cyclones or the use of tethered blimps (Duvel et al. 2009) to provide these measurements. However, when manned aircraft is available (about 30% of the time in the Atlantic and about 5% of the time in the Northeast Pacific), central pressure values already have quite small uncertainties.

The uncertainty in tropical cyclone position currently is relatively small, but still a difficult operational problem in some circumstances. A next-generation scatterometer could provide some improvements in determining the position of tropical storms and Category 1 & 2 hurricanes. Of concern is the possibility of a degradation of current capabilities in a reduction in the number of low earth orbiting satellites providing microwave image fixes (Velden and Hawkins 2010, Hawkins and Velden 2011). If this degradation were to occur, it could make the position uncertainties that are currently small somewhat worse.

Tropical cyclone size (wind radii) has the largest room for improvement in the current parameters that best tracks are being provided. There are some recently available wind field techniques that have not been widely used in NHC operations that may improve our analyses of tropical cyclone size. The AMSU-based analyses (DeMuth et al. 2006) and the multi-satellite based analyses (Knaff et al. 2011) are undergoing evaluation to determine their skill and utility for improving NHC's wind radii estimates. In the next decade or so, substantially improved wind radii could be obtained from operational implementation of an aircraft-deployed HIRAD, airborne Doppler radar, or a next-generation satellite-based scatterometer. Finally, a geostationary satellite-based AMSU – GeoSTAR (Lambrigsten 2009) – would likely be beneficial in obtaining accurate, high temporal frequency wind radii analyses.

As noted earlier, the substantial uncertainties – especially with regards to intensity and wind radii – may limit the forecast improvements possible in coming years at NHC. New observational capabilities and improved utilization of existing measurements provide optimism for both reduced uncertainties in analyzing crucial tropical cyclone parameters as well as improved predictability.

9. Appendix - The revised Atlantic hurricane database (HURDAT2)

The National Hurricane Center (NHC) conducts a post-storm analysis of each tropical cyclone in its area of responsibility to determine the official assessment of the cyclone's history. This analysis makes use of all available observations, including those that may not have been available in real time. In addition, NHC conducts ongoing reviews of any retrospective tropical cyclone analyses brought to its attention, and on a regular basis updates the historical record to reflect changes introduced via the Best Track Change Committee (Landsea et al. 2004a, 2004b, 2008, 2012, Hagen et al. 2012,). NHC has traditionally disseminated the tropical cyclone historical database in a format known as HURDAT (short for HURricane DATabase – Jarvinen et al. 1984). This report updates the original HURDAT documentation to reflect significant changes to both the format and content for the tropical cyclones and subtropical cyclones of the Atlantic basin (i.e., North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea).

The original HURDAT format substantially limited the type of best track information that could be conveyed. The format of this new version - HURDAT2 (HURricane DATa 2nd generation) - is based upon the "best tracks" available from the b-decks in the Automated Tropical Cyclone Forecast (ATCF – Sampson and Schrader 2000) system database and is described below. Reasons for the revised version include: 1) inclusion of non-synoptic (other than 00, 06, 12, and 18Z) best track times (mainly to indicate landfalls and intensity maxima); 2) inclusion of non-developing tropical depressions; and 3) inclusion of best track wind radii. The original format of HURDAT will be retired once the 2012 hurricane season best tracks become available.

An example of the new HURDAT2 format for Hurricane Irene from 2011 follows in Table A-1. There are two types of lines of data in the new format: the header line and the data lines. The format is comma delimited to maximize its ease in use. The header line has the following format: spaces 1 and 2 – Basin – Atlantic; spaces 3 and 4 – ATCF cyclone number for that year; spaces 5-8, before first comma – Year; spaces 20-29, before second comma – Name, if available, or else "UNNAMED"; spaces 35-37 – Number of best track entries – rows – to follow.

Notes:

1) Cyclone number: In HURDAT2, the order cyclones appear in the file is determined by the date/time of the first tropical or subtropical cyclone record in the best track. This sequence may or may not correspond to the ATCF cyclone number. For example, the 2011 unnamed tropical storm AL20 which formed on 1 September, is sequenced here between AL12 (Katia – formed on 29 Aug) and AL13 (Lee – formed on 2 September). This mismatch between ATCF cyclone

number and the HURDAT2 sequencing can occur if post-storm analysis alters the relative genesis times between two cyclones. In addition, in 2011 it became practice to assign operationally unnamed cyclones ATCF numbers from the end of the list, rather than insert them in sequence and alter the ATCF numbers of cyclones previously assigned.

2) Name: Tropical cyclones were not formally named before 1950 and are thus referred to as "UNNAMED" in the database. Systems that were added into the database after the season (such as AL20 in 2011) also are considered "UNNAMED". Non-developing tropical depressions formally were given names (actually numbers, such as "TEN") that were included into the ATCF b-decks starting in 2003. Non-developing tropical depressions before this year are also referred to as "UNNAMED". Note that the non-developing tropical depressions for 1988 are currently missing from the b-deck files and are therefore not available here either. (These should be included into the new HURDAT2 sometime during 2013.)

The remaining rows of data in the new format are the data lines (Table A-1). These have the following format: spaces 1-4 – Year; spaces 5-6 – Month; spaces 7-8, before 1st comma – Day; spaces 11-12 – Hours in UTC (Universal Time Coordinate); spaces 13-14, before 2nd comma – Minutes; space 17 – Record identifier (see notes below)

L – Landfall (center of system crossing a coastline)

W – Maximum sustained wind speed

P – Minimum in central pressure

I – An intensity peak in terms of both pressure and wind

C – Closest approach to a coast, not followed by a landfall

S – Change of status of the system

G – Genesis

T – Provides additional detail on the track (position) of the cyclone;

spaces 20-21, before 3rd comma – Status of system. Options are:

TD – Tropical cyclone of tropical depression intensity (< 34 knots)

TS – Tropical cyclone of tropical storm intensity (34-63 knots)

HU – Tropical cyclone of hurricane intensity ($\geq$ 64 knots)

EX – Extratropical cyclone (of any intensity)

SD – Subtropical cyclone of subtropical depression intensity (< 34 knots)

SS – Subtropical cyclone of subtropical storm intensity ($\geq$ 34 knots)

LO – A low that is neither a tropical cyclone, a subtropical cyclone, nor an extratropical cyclone (of any intensity)

WV – Tropical Wave (of any intensity)

DB – Disturbance (of any intensity);

spaces 24-27 – Latitude; space 28, before 4th comma – Hemisphere – North or South; spaces 31-35) – Longitude; space 36, before 5th comma – Hemisphere – West or East; spaces 39-41, before 6th comma – Maximum sustained wind (in knots); spaces 44-47, before 6th comma – Minimum Pressure (in millibars); spaces 50-53, before 7th comma – 34 kt wind radii maximum extent in northeastern quadrant (in nautical miles); spaces 56-59, before 8th comma – 34 kt wind radii maximum extent in southeastern quadrant (in nautical miles); spaces 62-65, before 9th comma – 34 kt wind radii maximum extent in southwestern quadrant (in nautical miles); spaces 68-71, before 10th comma – 34 kt wind radii maximum extent in northwestern quadrant (in nautical miles); spaces 74-77, before 11th comma) – 50 kt wind radii maximum extent in northeastern quadrant (in nautical miles); spaces 80-83, before 12th comma) – 50 kt wind radii maximum extent in southeastern quadrant (in nautical miles); spaces 86-89, before 13th comma) – 50 kt wind radii maximum extent in southwestern quadrant (in nautical miles); spaces 92-95, before 14th comma – 50 kt wind radii maximum extent in northwestern quadrant (in nautical miles); spaces 98-101, before 15th comma – 64 kt wind radii maximum extent in northeastern quadrant (in nautical miles); spaces 104-107, before 16th comma – 64 kt wind radii maximum extent in southeastern quadrant (in nautical miles); spaces 110-113, before 17th comma – 64 kt wind radii maximum extent in southwestern quadrant (in nautical miles); spaces 116-119, before 18th comma – 64 kt wind radii maximum extent in northwestern quadrant (in nautical miles).

Notes:

1) Record identifier: This code is used to identify records that correspond to landfalls or to indicate the reason for inclusion of a record not at the standard synoptic times (0000, 0600, 1200, and 1800 UTC). For the years 1851-1935 and 1991 onward, all continental United States landfalls are marked, while international landfalls are only marked from 1991 onward. The landfall identifier (L) is the only identifier that will appear with a standard synoptic time record. The remaining identifiers (see table above) are only used with asynoptic records to indicate the reason for their inclusion. Inclusion of asynoptic data is at the discretion of the Hurricane Specialist who performed the post-storm analysis; standards for inclusion or non-inclusion have varied over time. Identification of asynoptic peaks in intensity (either wind or pressure) may represent either system's lifetime peak or a secondary peak.

2) Time: Nearly all HURDAT2 records correspond to the synoptic times of 0000, 0600, 1200, and 1800. Recording best track data to the nearest minute became available within the b-decks beginning in 1991 and some tropical cyclones since that year have the landfall best track to the nearest minute.

3) Status: Tropical cyclones with an ending tropical depression status (the dissipating stage) were first used in the best track beginning in 1871, primarily for systems weakening over land. Tropical cyclones with beginning tropical depression (the formation stage) were first included in the best track beginning in 1882. Subtropical depression and subtropical storm status were first used beginning in 1968 at the advent of routine satellite imagery for the Atlantic basin. The low status – first used in 1987 - is for cyclones that are not tropical cyclone or subtropical cyclones, nor extratropical cyclones. These typically are assigned at the beginning of a system's lifecycle and/or at the end of a system's lifecycle. The tropical wave status – first used in 1981 - is almost exclusively for cyclones that degenerate into an open trough for a time, but then redevelop later in time into a tropical cyclone (for example, AL10-DENNIS in 1981 between 13 and 15 August). The disturbance status is similar to tropical wave and was first used in 1980. It should be noted that for tropical wave and disturbance status the location given is the approximate position of the lower tropospheric vorticity center, as the surface center no longer exists for these stages.

4) Maximum sustained surface wind: This is defined as the maximum 1-min average wind associated with the tropical cyclone at an elevation of 10 m with an unobstructed exposure. Values are given to the nearest 10 kt for the years 1851 through 1885 and to the nearest 5 kt from 1886 onward. A value is assigned for every cyclone at every best track time. Note that the non-developing tropical depressions of 1967 did not have intensities assigned to them in the b-decks. These are indicated as "-99" currently, but will be revised and assigned an intensity when the Atlantic hurricane database reanalysis project (Hagen et al. 2012) reaches that hurricane season.

5) Central Pressure: These values are given to the nearest millibar. Originally, central pressure best track values were only included if there was a specific observation that could be used explicitly. Missing central pressure values are noted as "-999". Beginning in 1979, central

pressures have been analyzed and included for every best track entry, even if there was not a specific in-situ measurement available.

6) Wind Radii – These values have been best tracked since 2004 and are thus available here from that year forward with a resolution to the nearest 5 nm. Best tracks of the wind radii have not been done before 2004 and are listed as "-999" to denote missing data. Note that occasionally when there is a non-synoptic time best track entry included for either landfall or peak intensity, that the wind radii best tracks were not provided. These instances are also denoted with a "-999" in the database.

General Notes:

The database goes back to 1851, but it is far from being complete and accurate for the entire century and a half. Uncertainty estimates of the best track parameters available for are available for various era in Landsea et al. (2012), Hagen et al. (2012), Torn and Snyder (2012), and within this paper. Moreover, as one goes back further in time in addition to larger uncertainties, biases become more pronounced as well with tropical cyclone frequencies being underreported and the tropical cyclone intensities being underanalyzed. That is, some storms were missed and many intensities are too low in the pre-aircraft reconnaissance era (1944 for the western half of the basin) and in the pre-satellite era (late-1960s for the entire basin). Even in the last decade or two, new technologies affect the best tracks in a non-trivial way because of our generally improving ability to observe the frequency, intensity, and size of tropical cyclones. See Vecchi and Knutson (2008), Landsea et al. (2010), Vecchi and Knutson (2012), Uhlhorn and Nolan (2012) on methods that have been determined to address some of the undersampling issues that arise in monitoring these mesoscale, oceanic phenomenon.

The only aspect of the original HURDAT database that is not contained in the new HURDAT2 is the state-by-state categorization of the Saffir Simpson Hurricane Wind Scale for continental U.S. hurricanes. This information is not a best track quantity and thus will not be included here. However, such U.S. Saffir Simpson Hurricane Wind Scale impact records will continue to be maintained, but within a separate database on the NHC website.

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Figure captions:

Figure 1: Examples of tropical cyclone best track intensities based upon mainly satellite data (top figure) and upon a mixture of satellite and aircraft reconnaissance data (bottom figure). The figures indicate the best track intensities as the green line with blue symbols indicating Dvorak classifications, red symbols indicating aircraft reconnaissance observations, purple symbols indicating NASA QuikSCAT measurements, and gold symbols indicating dropsonde observations.

Figure 2: Best track positions superimposed with available center fixes for Gordon on the 11th and 12th of October 2006 when it was a tropical storm (upper) and for Dean on the 20th and 21st of August 2007 when it was a major hurricane (lower).

Figure 3: 2010 best track intensity uncertainty estimates stratified by intensity (tropical storm, Category 1 and 2 hurricanes, and major hurricanes) and stratified by observational capabilities (satellite-only, satellite and aircraft, and U.S. landfalling cyclones). The solid black lines indicate the ranges of responses. Colored horizontal lines indicate best track uncertainty estimates obtained in 1999.

Figure 4: 2010 best track central pressure uncertainty estimates stratified by intensity (tropical storm, Category 1 and 2 hurricanes, and major hurricanes) and stratified by observational capabilities (satellite-only, satellite and aircraft, and U.S. landfalling cyclones). The solid black lines indicate the ranges of responses.

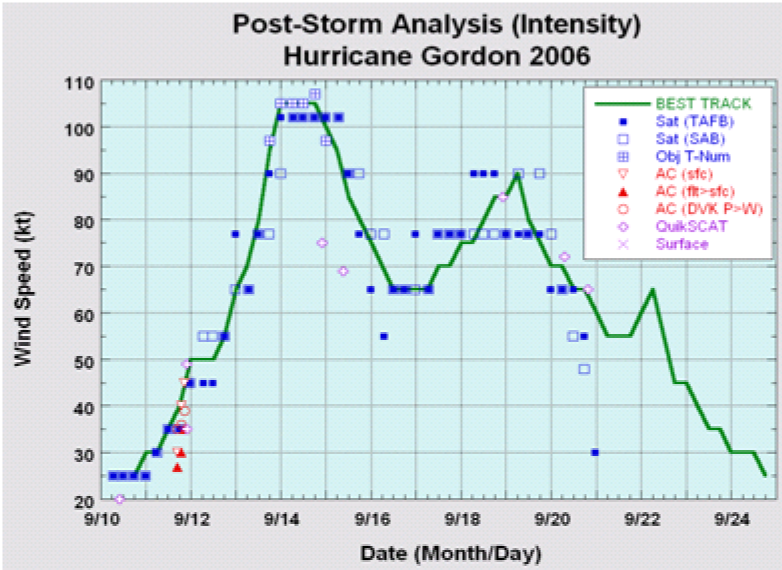
Figure 5: Same as Figure 3, except for best track average uncertainty estimates for position.

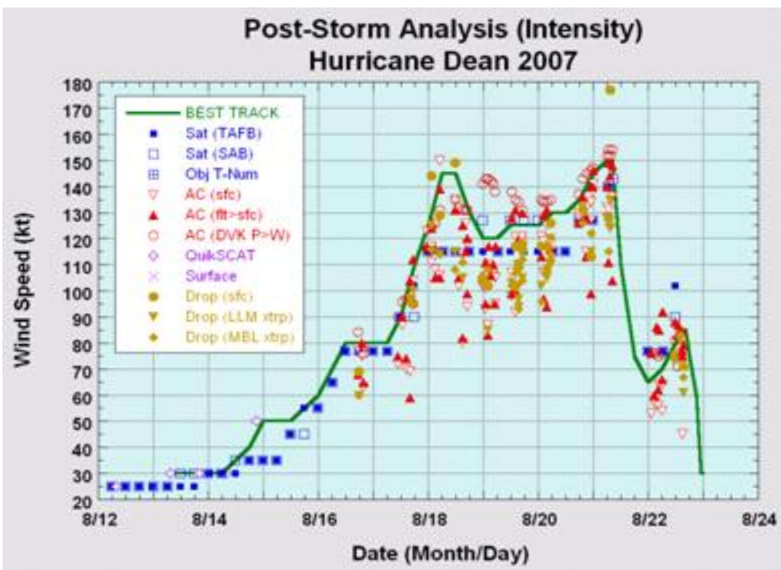
Figure 6: Same as Figure 4, except for best track gale maximum radii uncertainty.

Figure 7: Relative uncertainty in the best tracks for intensity, central pressure, position, 34/50/64 kt wind radii for tropical storms and hurricanes collectively. These are expressed in terms of percent uncertainty relative to average values of the parameters.

Figure 8: Recent trends in NHC Atlantic basin track forecast errors superimposed with the average uncertainties in best track positions currently (solid black).

Figure 9: Same as Figure 8, except for intensity.





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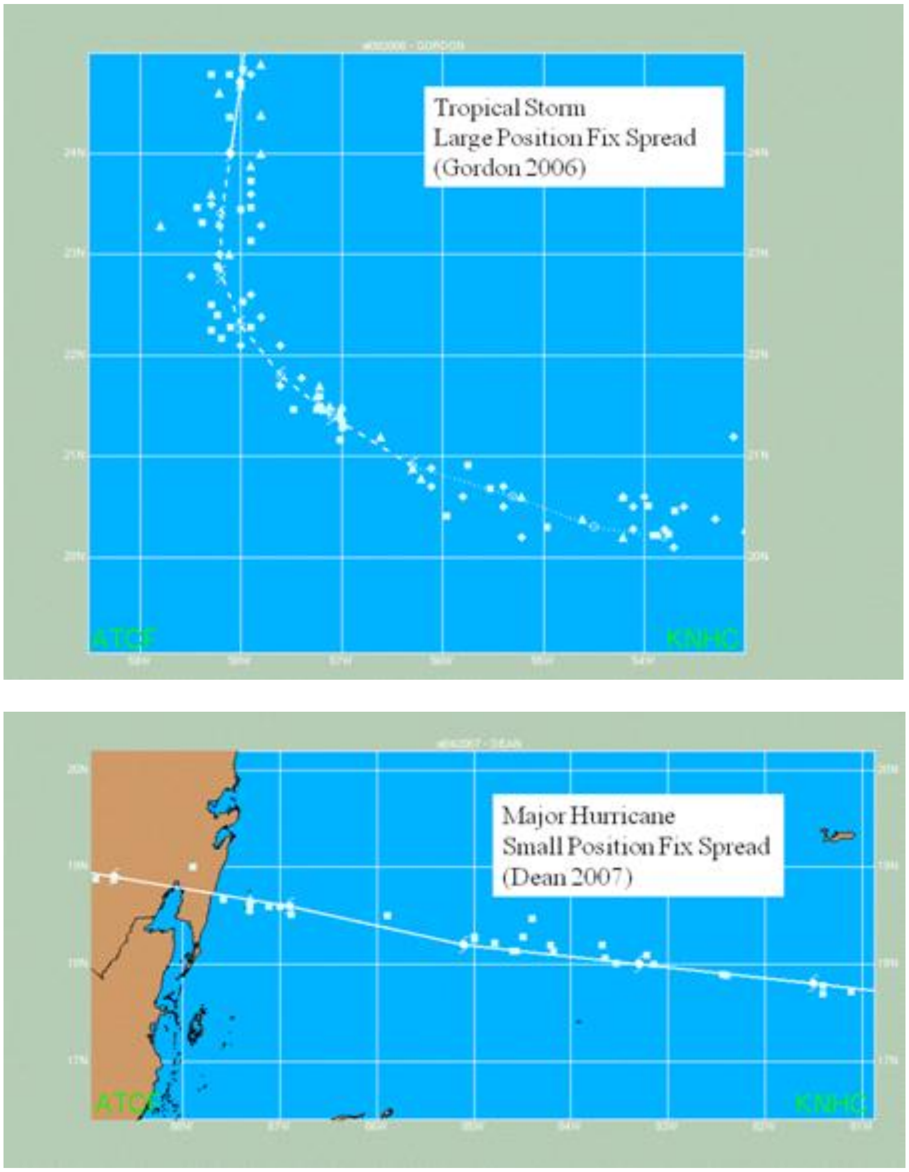

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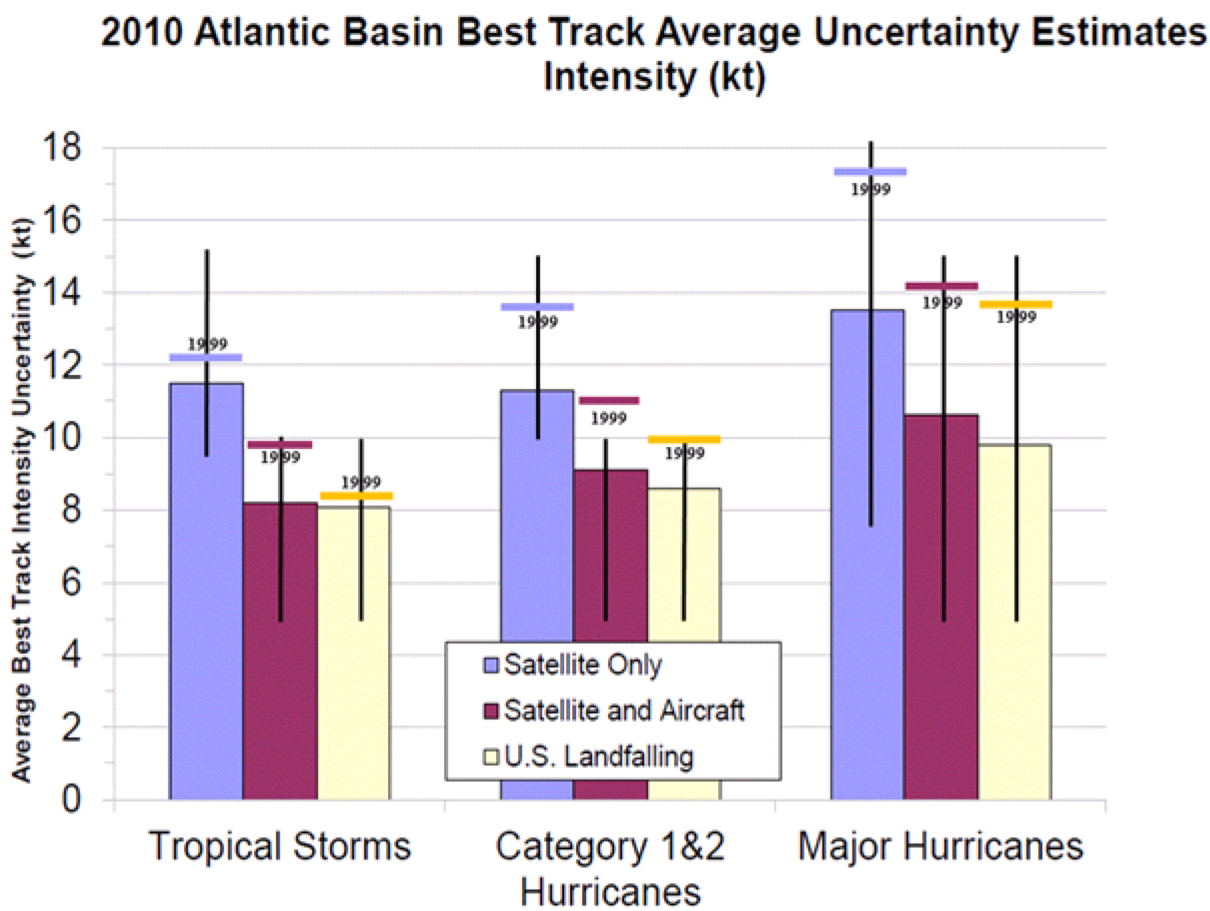

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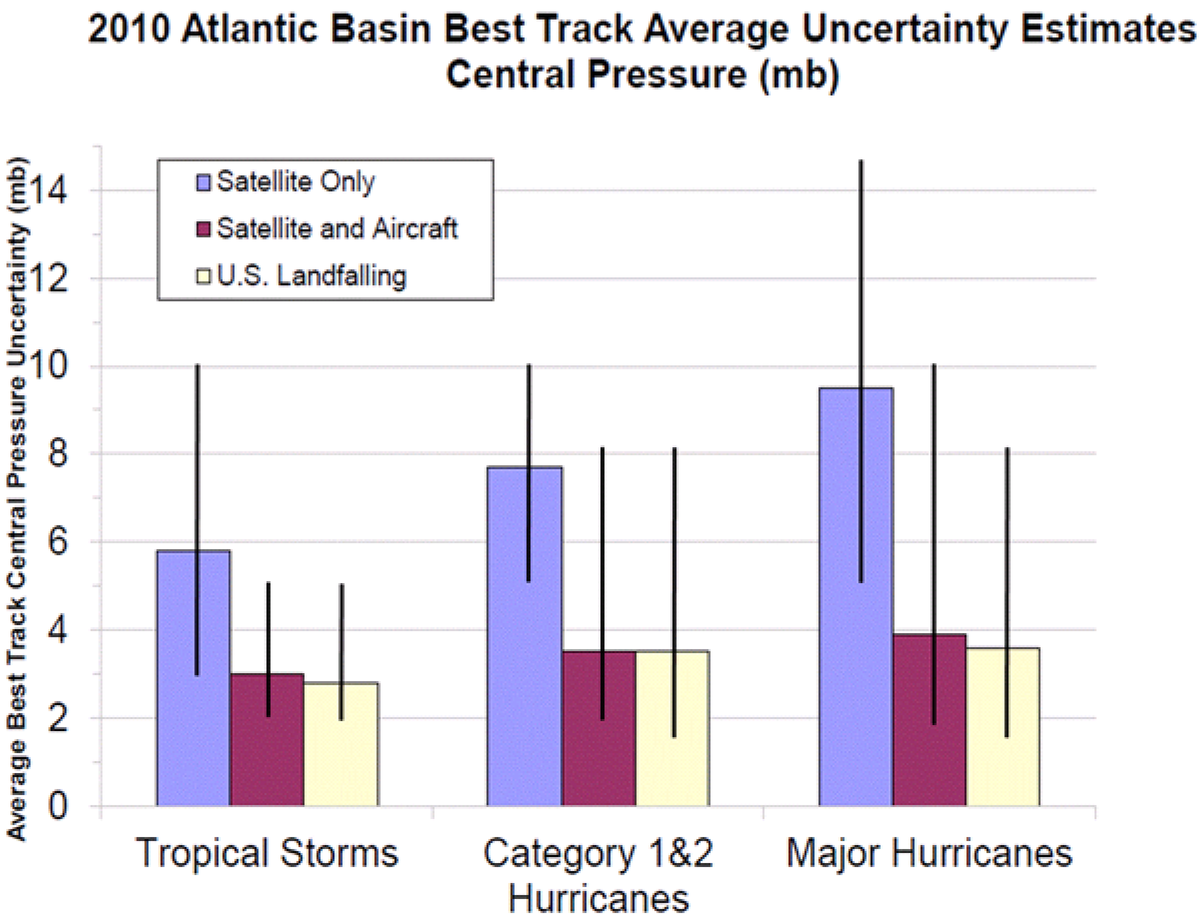


Figure 4: 2010 best track central pressure uncertainty estimates stratified by intensity (tropical storm, Category 1 and 2 hurricanes, and major hurricanes) and stratified by observational capabilities (satellite-only, satellite and aircraft, and U.S. landfalling cyclones). The solid black lines indicate the ranges of responses.

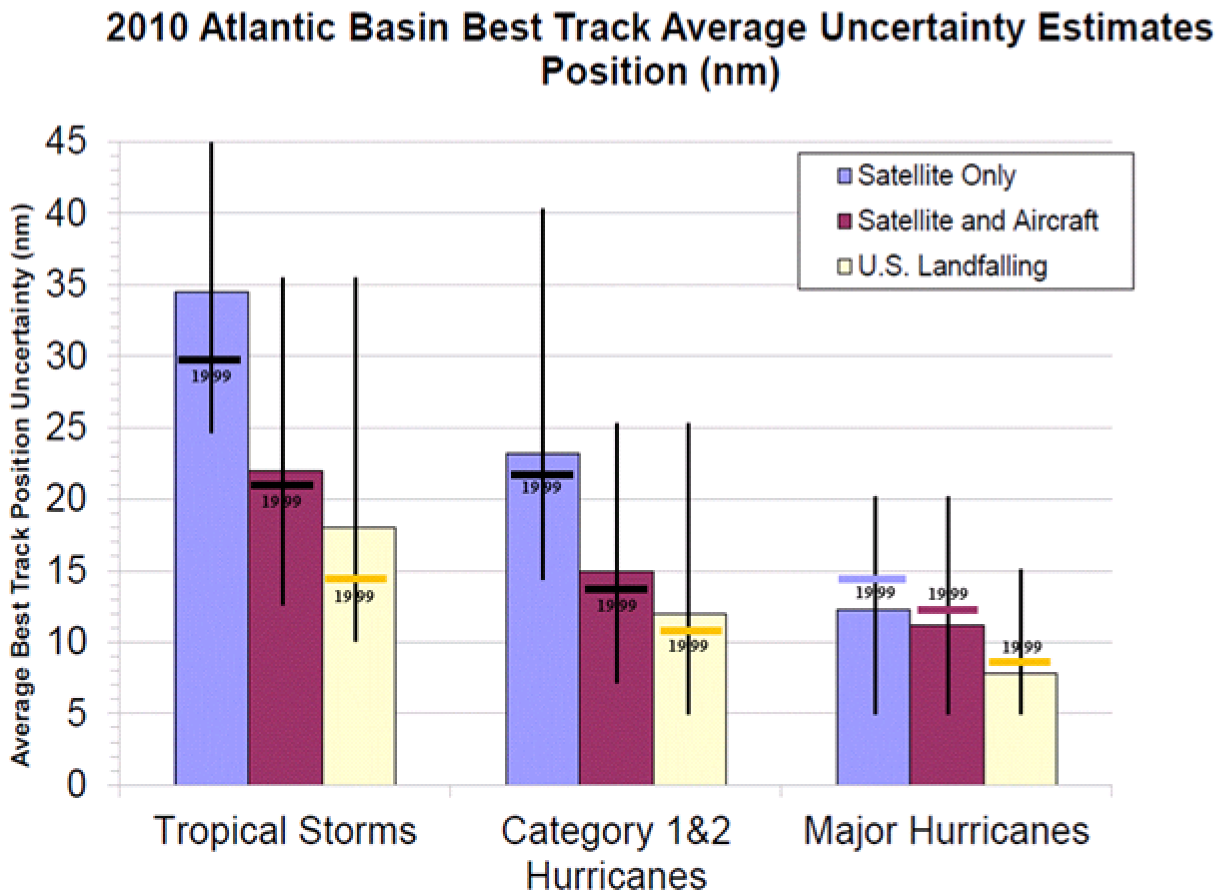


Figure 5: Same as Figure 3, except for best track average uncertainty estimates for position.

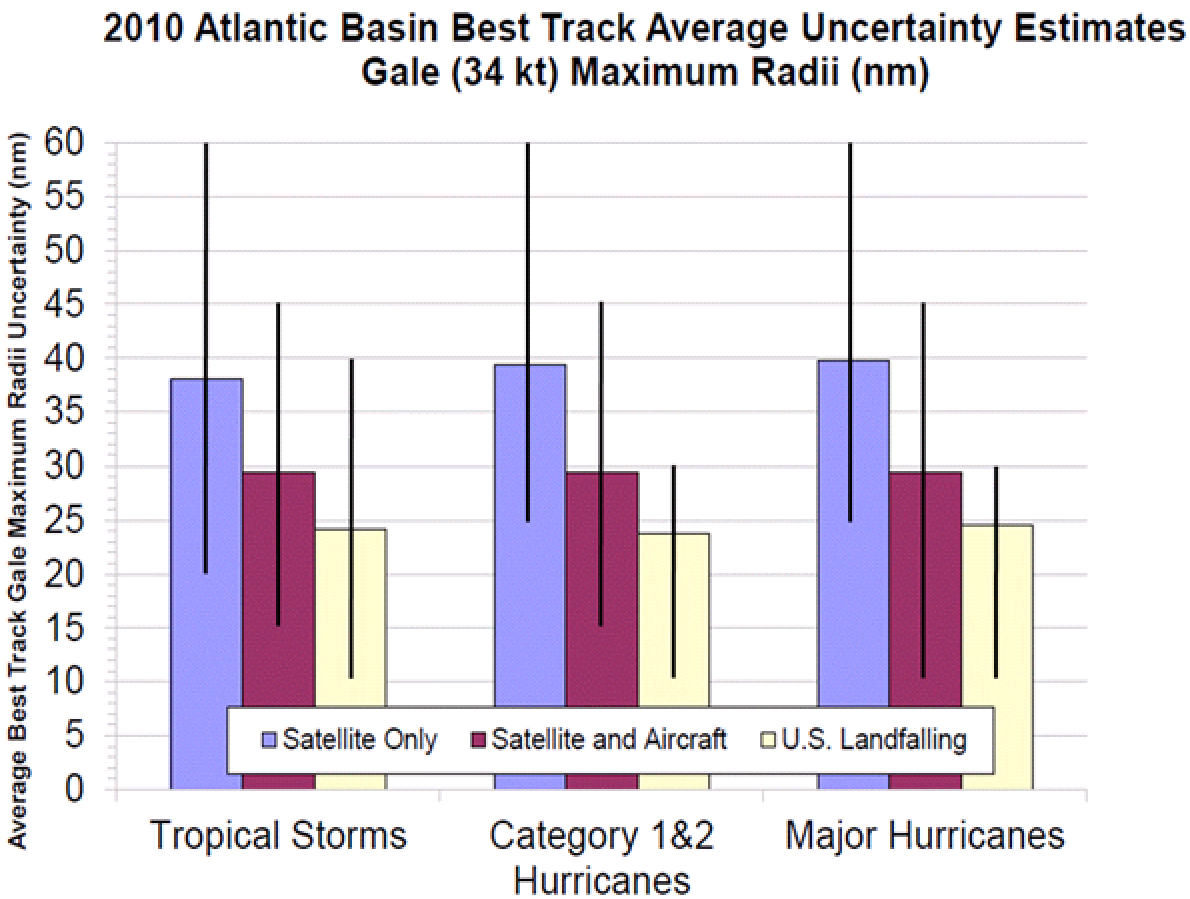
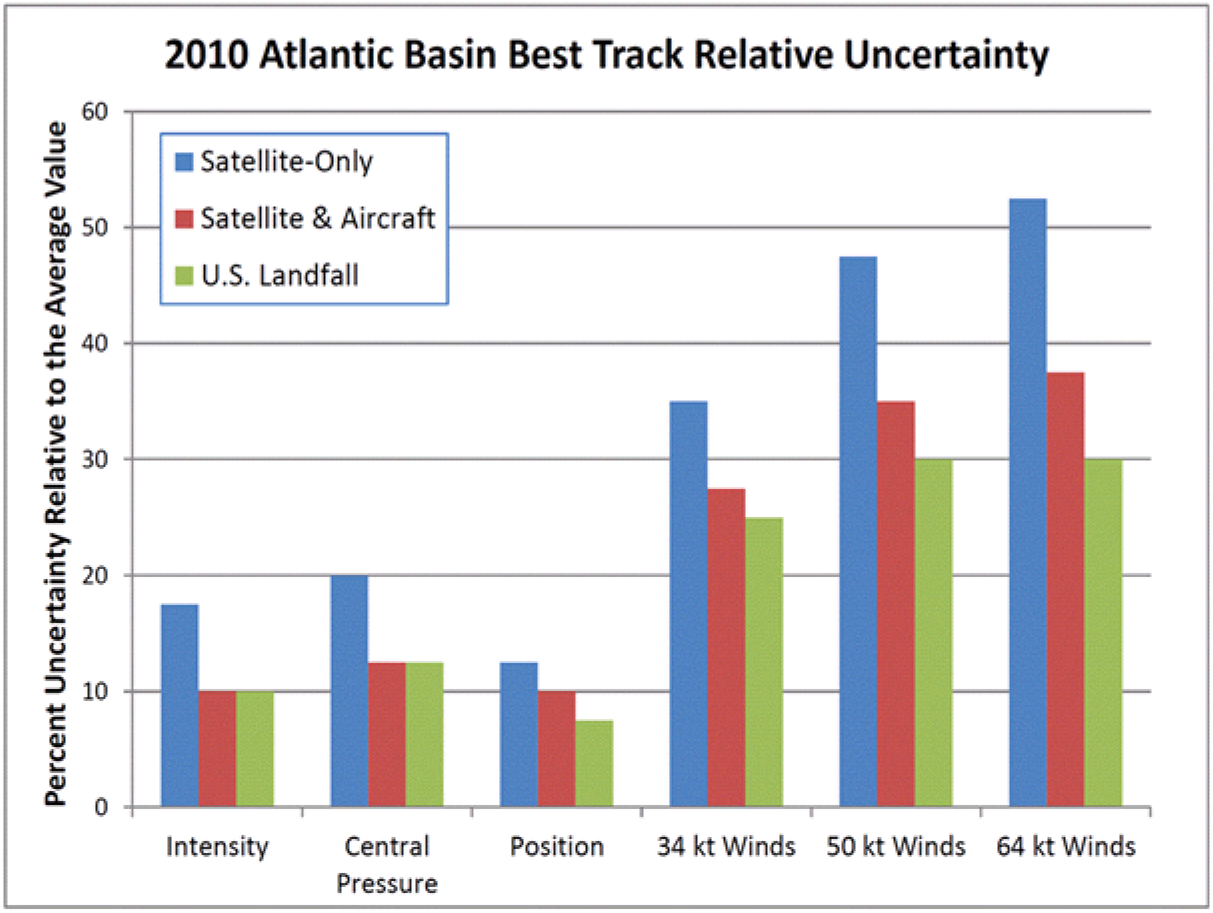


Figure 6: Same as Figure 4, except for best track gale maximum radii uncertainty.



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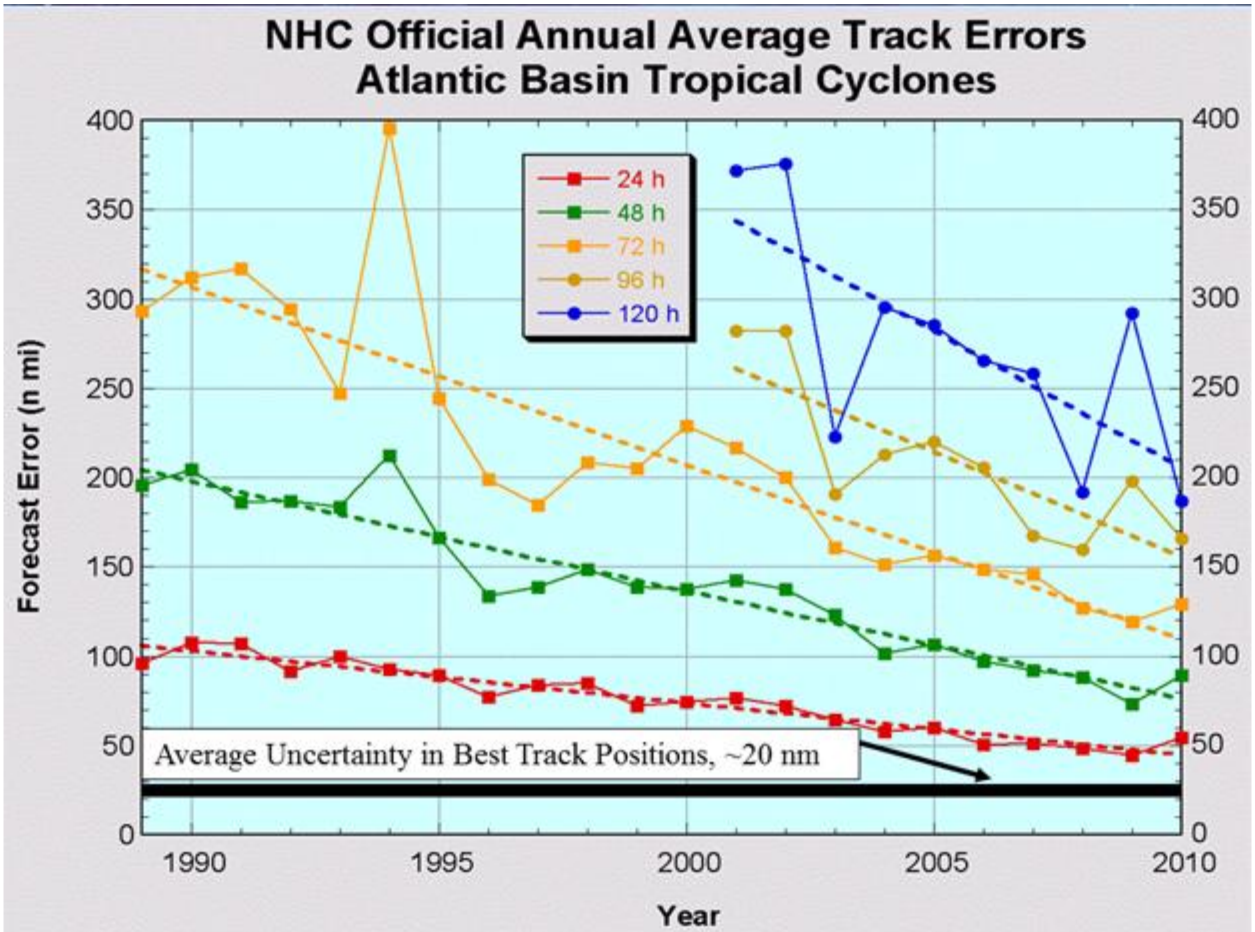

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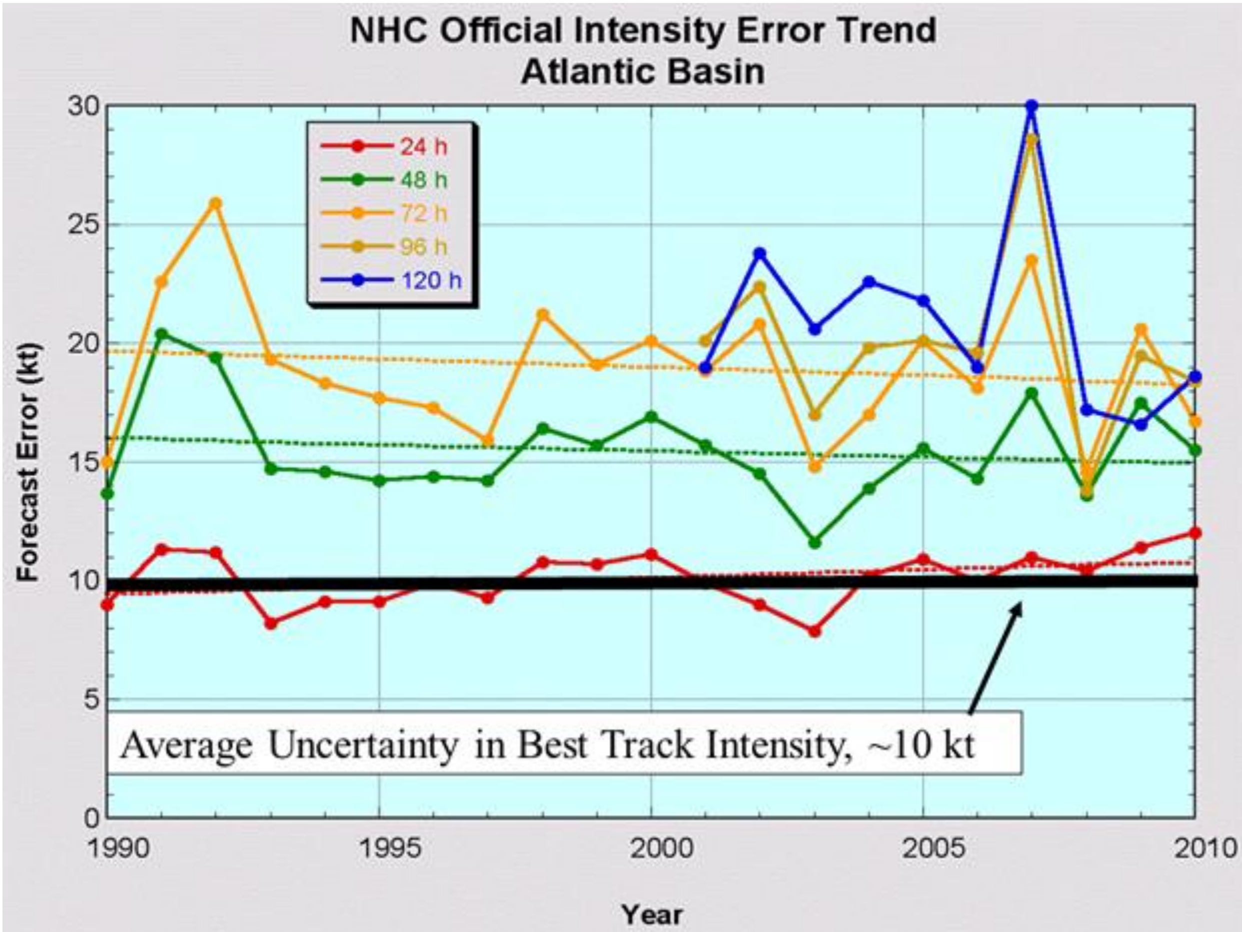

Figure 9: Same as Figure 8, except for intensity.

Table 1: Average best track uncertainty estimates for intensity and position stratified by tropical storms, Category 1 and 2 hurricanes, and major hurricanes, as provided by the NHC Hurricane Specialists in 1999. Ranges of the responses are given within the parentheses.

	Tropical Storms	**Category 1 and 2 Hurricanes**	**Major Hurricanes**
Satellite only			
Intensity (kt)	11.8 (7.5-20)	13.4 (10-22.5)	17.8 (7.5-25)
Position (nm)	28.6 (15-45)	21.2 (12.5-32.5)	14.2 (9-20)
Satellite and Aircraft			
Intensity (kt)	9.6 (5-15)	11.0 (5-17.5)	14.4 (5-20)
Position (nm)	21.8 (12.5-45)	14.1 (9-25)	11.1 (9-15)
U.S. Landfalling			
Intensity (kt)	8.2 (5-10)	9.9 (7.5-12.5)	13.4 (7.5-15)
Position (nm)	14.6 (10-20)	11.9 (9-17.5)	8.1 (5-10)

Table 2: Average best track uncertainty estimates for intensity, central pressure, position, and size stratified by tropical storms, Category 1 and 2 hurricanes, and major hurricanes, as provided by the NHC Hurricane Specialists in 2010. Ranges of the responses are given within the parentheses.

	Tropical Storms	**Category 1&2 Hurricanes**	**Major Hurricanes**
Satellite only			
Intensity (kt)	11.5 (9.5-15)	11.3 (10-15)	13.5 (7.5-18)
Central Pressure (mb)	5.8 (3-10)	7.7 (5-10)	9.5 (5-15)
Position (nm)	34.5 (25-45)	23.2 (15-40)	12.3 (5-20)
Gale (34 kt) Radii (nm)	38 (20-60)	39.4 (25-60)	39.8 (25-60)
Storm (50 kt) Radii (nm)	27.7 (15-50)	30.5 (20-50)	32.3 (20-50)
Hurricane (64 kt) Radii (nm)	N/A	22.5 (7.5-50)	24.4 (7.5-50)
Satellite and Aircraft			
Intensity (kt)	8.2 (5-10)	9.1 (5-10)	10.6 (5-15)
Central Pressure (mb)	3.0 (2-5)	3.5 (2-8)	3.9 (2-10)
Position (nm)	22.0 (12.5-35)	14.9 (7.5-25)	11.2 (5-20)
Gale (34 kt) Radii (nm)	29.5 (15-45)	29.5 (15-45)	29.5 (10-45)
Storm (50 kt) Radii (nm)	21.1 (10-40)	23.4 (15-40)	23.9 (10-40)
Hurricane (64 kt) Radii (nm)	N/A	15.9 (7.5-30)	17.3 (5-30)

U.S. Landfalling			
Intensity (kt)	8.1 (5-10)	8.6 (5-10)	9.8 (5-15)
Central Pressure (mb)	2.8 (2-5)	3.5 (1.5-8)	3.6 (1.5-10)
Position (nm)	18 (10-35)	12 (5-25)	7.8 (5-15)
Gale (34 kt) Radii (nm)	24.1 (10-40)	23.8 (10-30)	24.5 (10-30)
Storm (50 kt) Radii (nm)	16.6 (10-30)	19.3 (10-30)	19.1 (10-30)
Hurricane (64 kt) Radii (nm)	N/A	12.9 (5-25)	13.4 (5-30)

Table A1: The new HURDAT2 data format.

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AL092011,            IRENE,     39,
20110821, 0000,  , TS, 15.0N,  59.0W,  45, 1006,  105,    0,    0,   45,    0,    0,    0,    0,    0,    0,    0,    0,
20110821, 0600,  , TS, 16.0N,  60.6W,  45, 1006,  130,    0,    0,   80,    0,    0,    0,    0,    0,    0,    0,    0,
20110821, 1200,  , TS, 16.8N,  62.2W,  45, 1005,  130,    0,    0,   70,    0,    0,    0,    0,    0,    0,    0,    0,
20110821, 1800,  , TS, 17.5N,  63.7W,  50,  999,  130,   20,    0,   70,   30,    0,    0,    0,    0,    0,    0,    0,
20110822, 0000,  , TS, 17.9N,  65.0W,  60,  993,  130,   30,   30,   90,   30,    0,    0,   30,    0,    0,    0,    0,
20110822, 0600,  , HU, 18.2N,  65.9W,  65,  990,  130,   60,   60,   90,   40,   25,   20,   35,   25,    0,    0,    0,
20110822, 1200,  , HU, 18.9N,  67.0W,  70,  989,  160,   60,   60,   90,   40,   25,   20,   35,   25,    0,    0,    0,
20110822, 1800,  , HU, 19.3N,  68.0W,  75,  988,  160,   60,   40,   90,   40,   30,   20,   35,   25,    0,    0,    0,
20110823, 0000,  , HU, 19.7N,  68.8W,  80,  981,  160,   70,   50,  100,   70,   30,   30,   70,   25,    0,    0,   35,
20110823, 0600,  , HU, 20.1N,  69.7W,  80,  978,  180,  120,   90,  130,   90,   60,   40,   70,   45,   30,   20,   35,
20110823, 1200,  , HU, 20.4N,  70.6W,  80,  978,  180,  120,   90,  130,   90,   60,   40,   70,   40,   30,   20,   35,
20110823, 1800,  , HU, 20.7N,  71.2W,  80,  977,  180,  120,   90,  130,   75,   60,   40,   70,   35,   30,   20,   35,
20110824, 0000,  , HU, 21.0N,  71.9W,  80,  969,  180,  150,   90,  150,   70,   70,   40,   70,   35,   30,   25,   35,
20110824, 0600,  , HU, 21.3N,  72.5W,  95,  965,  180,  150,   90,  150,   70,   70,   40,   70,   35,   30,   25,   35,
20110824, 1200,  , HU, 21.9N,  73.3W, 105,  957,  180,  150,   90,  150,   90,   60,   45,   80,   45,   40,   25,   40,
20110824, 1800,  , HU, 22.7N,  74.3W, 100,  954,  200,  180,  100,  150,  100,   70,   50,   80,   50,   45,   25,   40,
20110825, 0000, L, HU, 23.5N,  75.1W,  95,  952,  220,  180,  100,  150,  100,   90,   50,   80,   60,   60,   25,   50,
20110825, 0600,  , HU, 24.1N,  75.9W,  95,  950,  220,  180,  100,  150,  100,   80,   50,   70,   60,   60,   25,   50,
20110825, 1200,  , HU, 25.4N,  76.6W,  90,  950,  250,  200,  100,  160,  100,  100,   50,   70,   60,   60,   25,   50,
20110825, 1800, L, HU, 26.5N,  77.2W,  90,  950,  250,  200,  125,  160,  110,  100,   50,   75,   70,   60,   25,   50,
20110826, 0000,  , HU, 27.7N,  77.3W,  90,  946,  250,  200,  125,  160,  110,  100,   50,   75,   70,   60,   25,   50,
20110826, 0600,  , HU, 28.8N,  77.3W,  90,  942,  250,  200,  130,  175,  125,  105,   75,   75,   80,   80,   50,   50,
20110826, 1200,  , HU, 30.0N,  77.4W,  85,  947,  250,  200,  130,  175,  125,  105,   75,   75,   80,   80,   50,   50,
20110826, 1800,  , HU, 31.1N,  77.5W,  80,  950,  250,  225,  140,  175,  125,  125,   80,   75,   80,   80,   50,   50,
20110827, 0000,  , HU, 32.1N,  77.1W,  75,  952,  225,  225,  140,  140,  125,  125,   90,   75,   80,   80,   40,   40,
20110827, 0600,  , HU, 33.4N,  76.8W,  75,  952,  225,  225,  140,  140,  125,  125,   90,   75,   80,   80,   40,   40,
20110827, 1200, L, HU, 34.7N,  76.6W,  75,  952,  225,  225,  150,  125,  125,  125,   90,   60,   80,   80,   40,   35,
20110827, 1800,  , HU, 35.5N,  76.3W,  65,  950,  210,  225,  150,  125,  125,  125,   80,   60,   75,   75,   35,   35,
20110828, 0000,  , HU, 36.7N,  75.7W,  65,  951,  210,  225,  150,  125,  150,  150,   80,   60,   75,   75,    0,    0,
20110828, 0600,  , HU, 38.1N,  75.0W,  65,  958,  230,  280,  160,  110,  150,  150,   80,   30,   75,   75,    0,    0,
20110828, 0935, L, TS, 39.4N,  74.4W,  60,  959,  230,  280,  160,  110,  150,  150,   80,   30,    0,    0,    0,    0,
20110828, 1200,  , TS, 40.3N,  74.1W,  55,  963,  230,  280,  130,   50,  150,  150,   80,   30,    0,    0,    0,    0,
20110828, 1300, L, TS, 40.6N,  74.0W,  55,  965,  230,  280,  130,   50,  150,  150,   80,   30,    0,    0,    0,    0,
20110828, 1800,  , TS, 42.5N,  73.1W,  50,  970,  230,  280,  180,   50,  150,  150,   80,   30,    0,    0,    0,    0,
20110829, 0000,  , EX, 44.2N,  72.1W,  45,  979,  230,  315,  250,   50,    0,    0,    0,    0,    0,    0,    0,    0,
20110829, 0600,  , EX, 46.5N,  69.5W,  40,  983,  360,  360,  360,    0,    0,    0,    0,    0,    0,    0,    0,    0,
20110829, 1200,  , EX, 49.1N,  66.7W,  40,  985,  360,  360,  300,    0,    0,    0,    0,    0,    0,    0,    0,    0,
20110829, 1800,  , EX, 51.3N,  63.8W,  40,  987,    0,  360,    0,    0,    0,    0,    0,    0,    0,    0,    0,    0,
20110830, 0000,  , EX, 53.0N,  60.0W,  40,  991,    0,  270,    0,    0,    0,    0,    0,    0,    0,    0,    0,    0,
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