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Quantifying the Possible Existence of Undocumented Atlantic Warm Core Cyclones in NOAA/CIRES 20th Century Reanalysis Data

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THE FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS AND SCIENCES

QUANTIFYING THE POSSIBLE EXISTENCE OF UNDOCUMENTED ATLANTIC WARM-
CORE CYCLONES IN NOAA/CIRES 20TH CENTURY REANALYSIS DATA

By
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This thesis is dedicated to my delightful fiancée, Erica Staehling, for her contributions to this project as both as a scientist and a life partner. Thank you for everything. *Awkward and upward.*

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ABSTRACT

The lack of satellite imagery prior to 1966 and limited aircraft reconnaissance has led to an indefinite number of tropical cyclones (TCs) in the Atlantic Basin remaining undetected by traditional surface observational networks. As a result, these cyclones were not identified by operational forecasting centers like the National Hurricane Center and are not a part of the consensus Atlantic TC climatology. While previous research suggests that this historical undersampling exists, there is considerable disagreement as to its true magnitude. However, it is widely accepted that these “missing storms” have led to difficulties in interpreting long-term trends in TC activity, adding uncertainty to the dialogues over the nature, role, and existence of the Atlantic Multi-decadal Oscillation and the possible influence of climate change on TC activity, among many others.

This research seeks to add information to Atlantic Basin TC climatology by developing a scheme to identify previously unknown potential cyclones in the pre-satellite era. The technique utilizes advances in global reanalysis methods to identify candidate events within certain probabilistic bounds in order to improve existing TC Best-Track reanalysis efforts. Briefly, a series of thermodynamic proxies of TC passage in the NOAA/CIRES 20th Century Reanalysis dataset is first constructed. Signatures in these metrics that are of similar amplitude and morphology to known TCs but do not correspond to known Best-Track cyclones are identified within the reanalysis solution for the test hurricane seasons of 1951 through 1958. Synoptic verification of these candidate events using historical surface observation datasets sorts the events into three broad confidence bins.

The most common outcome of the observational verification process is that the candidate event does not represent a credible possible addition to BT climatology. However, a small but significant number of the candidate events were found to present highly compelling cases for further examination by ongoing TC climatology revision efforts and may eventually warrant addition to the Best-Track database. Several of these candidate events, representing a broad range of possible uses of the technique, are presented in detailed case studies. Additionally, application of the reanalysis-based methodology to the Eastern Pacific Basin demonstrates promise for use in other TC basins around the world. In general, results suggest that future work extending the technique developed in this research may potentially lead to a more complete

climatological record of global TC incidence and an improved understanding of long-term trends in activity.

CHAPTER ONE

INTRODUCTION

The tremendous strides in observational technology over roughly the latter half of the 20th and first decade of the 21st Centuries have revolutionized the forecasting and understanding of tropical cyclones (TCs). After decades of relying solely on often incomplete and time-lagged surface-based observations, an impressive array of new tools has become available in the past 65 years. Major advances, including the advent of aircraft reconnaissance in 1944, near real-time geostationary satellite imagery in 1966, and remotely sensed microwave data and surface windfield estimates in the past decade [Landsea 2007] have resulted in improved theories regarding the structure and fundamental physical processes of TCs. These platforms have also enabled superior operational coverage of the Atlantic Basin. Along with improvements in numerical weather prediction and data assimilation schemes, advances in observing system technologies have played a major role in reducing track forecasting error over the last several decades [Rappaport *et al.*, 2009].

However, these technologies have also led to large discontinuities in the climatological record, since the percentage of TCs that were observed and subsequently recorded have increased dramatically with time. This non-homogeneity of the dataset makes reaching conclusions regarding long-term trends in activity difficult. As this research endeavors to improve the quality of such records in the pre-satellite era, a review of Atlantic Basin TC climatology is presented first, with a subsequent discussion of previous and ongoing efforts to revise and expand the climatological record.

1.1 TC Climatology

For reasons that remain unclear, the total number of TCs that develop annually in all basins worldwide generally ranges between 80 and 90 [Frank and Young, 2007]. Of this baseline, the Atlantic Basin typically accounts for approximately 10 to 15% of global TC activity in any given year. In the satellite era (1966-2009), there have been on average 11.3 tropical

storms (sustained winds of 17 to 32 m s⁻¹), 6.2 hurricanes (33 to 49 m s⁻¹), and 2.3 major hurricanes (≥ 50 m s⁻¹) in the North Atlantic Basin annually; however, the Atlantic also has the highest interannual variability in activity of any active basin worldwide, making long-range prediction of seasonal activity notoriously difficult. Figures 1.1 and 1.2 show the favored developmental regions for TCs, which stretch from the Gold Coast of West Africa to eastern North America, including the Caribbean Sea and the Gulf of Mexico, as well as a significant portion of the subtropical Western Atlantic. Temporally, cyclogenesis is most common in late August and September with a secondary peak in mid-October, as shown in Figure 1.3. Cyclogenesis frequency varies most strongly with the annual cycle of low-latitude sea surface temperature [Emanuel 2005], but is also highly influenced by longwave ridge and trough locations and upper-level wind shear among other factors [Gray 1979; Frank and Ritchie, 2001].

Figure 1.4 shows the annual counts of tropical storms, minor hurricanes, and major hurricanes in the Atlantic Basin since 1886, along with 10-year moving averages for each of these categories. The data for this plot is drawn from the National Hurricane Center’s North Atlantic “Best-Track” hurricane database (BT), first compiled by *Jarvinen et al.* [1984] and subsequently amended to include Atlantic Basin TCs as they occur and to reflect the intensity correction recommended in *Landsea* [1993]. Since the advent of detailed recordkeeping, the moving averages of all three bins have seen dramatic increases in the number of observed TCs, with an approximate nominal doubling during the 20th Century. Many studies have also noted an interdecadal pattern of several generally active decades followed by several inactive decades. This quasi-periodicity is hypothesized to be linked to a coupled ocean-atmosphere oscillation, termed the Atlantic Multi-decadal Oscillation (AMO) by *Schlesinger and Ramankutty* [1994], that involves persistent areas of warm and cool sea surface temperature anomalies (see Figure 1.5) caused by flux changes in the Atlantic’s meridional overturning circulation [Kerr 2000]. The AMO has been shown to exert a strong influence on decadal variations in Atlantic TC activity [Goldenberg et al., 2001], and could influence interannual variability by exciting a favorable dynamical environment through the Atlantic Meridional Mode [Vimont and Kossin, 2007]. Another theory holds that the AMO is a statistical artifact that is not robust after detrending sea surface temperature data. This theory instead links trends in TC count to anthropogenic warming in Atlantic sea surface temperatures over the period [Mann and Emanuel, 2006].

Unfortunately, the observation biases caused by technological advances in how TCs are detected in the Atlantic BT dataset make assessment of long-term trends in Atlantic Basin TC activity structurally challenging. Because of this uncertainty, the assumptions made regarding the appropriate pre-satellite era “correction” to BT annual aggregate activity vary dramatically between studies and directly lead to different conclusions. For example, *Holland and Webster* [2007] assume “essentially zero” correction by the mid-20th Century, while *Mann et al.* [2007] find that no correction is merited after 1944, concluding that positive trends in TC activity are linked proximately to anthropogenically-forced warming SSTs. At the other end of the spectrum, *Landsea* [2004] estimates a corrective factor of two to four TCs per year and subsequently finds in *Landsea* [2007] that there is no distinguishable trend in activity after this corrective factor is applied.

Several statistical studies have attempted to empirically estimate the proper scaling of this corrective factor. *Chang and Guo* [2007] show that the percentage of open ocean cyclones in the pre-satellite era (1904-1965) is 12.8% of the TC count, a value that increases to 21.2% between 1966 and 2005 (See Table 1.1). By assuming a constant proportion of open ocean TCs in the pre-satellite and satellite-era, this study estimates that an average of 1.2 TCs per year were not detected during the years 1900-1965. *Vecchi and Knutson* [2008] demonstrate a variable adjustment to annual TC count is necessary prior to 1965 to correct for the relative scarcity of ship reports in the open ocean. This adjustment, as well as those from *Chang and Guo* [2007], *Landsea* [2007] and *Mann et al.* [2007], is shown in Figure 1.6. Finally, *Landsea et al.* [2010] demonstrate that there is little to no long-term trend in the annual count of medium- and long-lived TCs since 1878, therefore implying that *Holland and Webster’s* [2007] findings are primarily an artifact of low observation density in the pre-satellite era, a particular issue for short-lived TCs in the open ocean.

While each of these treatments of BT are informative, the statistical approach to correcting pre-satellite TC climatology is limited by both study design and the inherently unpredictable nature of the cyclogenesis process itself. An alternative method that reduces these drawbacks is to directly re-examine the observational record itself in order to recover new information, which was not attempted by these statistical studies. Research efforts of this type are detailed in the next section.

1.2 Efforts to Revise and Expand TC Climatology

With the “true” number of historical TCs an open question, expanding and improving the quality and reliability of the BT database has naturally been a focus of research for the past several decades. After the initial compilation of BT by *Jarvinen et al.* [1984] and subsequent updates by *Neumann et al.* [1993], *Fernandez-Partagas and Diaz* [1996, hereafter FPD96] was the first study to attempt both a systematic re-evaluation of existing BT track data for 19th Century cyclones and an expansion of the time domain of Atlantic climatology back to 1851. To do so, they gathered records from pre-existing lists of storms, historical documents, scientific publications including *Monthly Weather Review*, newspaper accounts, and marine logs, comparing these observations to existing climatology when applicable. As a result, 105 additional TCs were “discovered” in the 1851 through 1890 Atlantic hurricane seasons, as shown in Table 1.2. This represented an increase of over 50% in the number of known TCs for these decades.

The success of FPD96 led directly to the establishment of the Atlantic Hurricane Database Reanalysis Project, hereby denoted the HURDAT project. This effort, first described in detail in *Landsea et al.* [2004, hereafter L04] for the years 1851-1910, and subsequently updated for the 1911-20 seasons in *Landsea et al.* [2008, hereafter L08], essentially is a continuation and expansion of the FPD96 technique. In general, the HURDAT project employs a careful methodology to both systematically revise the track and intensity of existing BT cyclones and add “new” or remove “existing” TCs to/from the historical record when strongly supported by newly discovered observations or when prior observations are reconsidered in the context of new science. In order to be considered for inclusion, candidate events must satisfy the National Hurricane Center’s criteria for adding a new TC to BT [*OFCM* 2005], by presenting a closed surface circulation, two wind or pressure observations supporting tropical storm intensity, and a non-frontal thermodynamic structure. Major improvements in L08 over earlier reanalyses include analyzing an even broader set of available data, encompassing the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) [*Woodruff et al.*, 1987; *Worley et al.*, 2005] for the first time, and implementing strict quality-control processes on all observation sources.

The HURDAT project has made extensive revisions and additions to existing Atlantic Basin TC climatological records. L04 resulted in the introduction of 22 TCs (0.88 TC/year) and the adjustment of the tracks and intensities of approximately another 200 systems in BT for the 1886 through 1910 hurricane seasons. With the inclusion of ICOADS data, L08 identified more new storms per year in the 1911 through 1920 seasons than 1886-1910, finding 13 “new” TCs (1.3 TCs/year). The old and revised seasonal tracking maps for the 1911 hurricane season, in which two new TCs were found, are shown in Figure 1.7. It should be noted that this review process is ongoing, and while the most recent peer-reviewed publication of HURDAT project results is found in L08, studies of several additional decades of Atlantic TC activity have been performed [*Hagen* 2010]. As of February 2011, the HURDAT reanalysis project has completed recommended revisions to BT through the 1953 hurricane season [*Hagen*, personal communication 2010].

While the HURDAT revision process has been phenomenally successful, it has several drawbacks, including being time- and energy-intensive to perform. Additionally, even a relatively dense region of ship reports in the open ocean will not necessarily yield a representative estimate of actual cyclone intensity [*Holland* 1981], with errors compounding dramatically in low-observation regimes. In a revision process completely dependent on manual analysis of surface observations, this may result in small, weak, or poorly observed TCs not being sufficiently apparent in existing datasets to be “tagged” for further study. The current research project is an attempt to objectively identify potential candidates for addition to BT; as such, several datasets fundamental to the development of a new prioritization and classification technique for candidate TC events are described in the next section.

1.3 Datasets

1.3.1 The Twentieth Century Reanalysis

In general terms, a reanalysis is defined as a hindcasting numerical weather prediction scheme that assimilates historical weather observations and returns the most likely atmospheric state for a given time with respect to the governing equations and physics of that model [*Thorne and Vose*, 2010]. In the decade and a half since the NCEP/NCAR 40-Year Reanalysis, the first

global and long-term reanalysis [Kalnay *et al.*, 1996], was released, there have been a number of extensions and modifications to the original technique. Currently, there are five other high-quality global reanalyses publically available, namely the NCEP-DOE AMIP-II Reanalysis [Kanamitsu *et al.*, 2002], the European Center for Medium Range Weather Forecasting’s ERA-40 [Uppala *et al.*, 2005], the Japan Meteorological Agency’s JRA-25 [Onogi *et al.*, 2007], NASA’s MERRA [Bosilovich *et al.*, 2006], and NCEP’s Climate Forecast System Reanalysis [Saha *et al.*, 2006]. While extremely useful to the meteorological and climatological communities, each of these datasets share a common drawback for the purposes of this study. Since they all depend on assimilating upper-level rawinsonde observations to solve for the vertical structure of the atmosphere, none of the reanalyses produce fields for the years prior to 1948 when such observations are rare [Bronnimann *et al.*, 2005]. This limits the usefulness of traditional reanalysis products as tools for revising pre-satellite era tropical climatology.

The NOAA/CIRES 20th Century Reanalysis (20CR) is the first product to make global reanalysis data available for the years before the advent of systematic upper-level monitoring. This is accomplished using a technique first described in Whitaker *et al.* [2004], in which an ensemble Kalman filter [Burgers *et al.*, 1998] is applied to assimilated sea level pressure (SLP), sea surface temperature (SST), and sea ice observations. In practice, the 20CR’s ensemble Kalman filter solves the problem of combining a given distribution of observations with a prior background distribution and integrating forward in time [Compo *et al.*, 2011]. Therefore, the 20CR is best understood not as a scheme that reconciles and contours observations, but rather as a global circulation model nudged each six hours with a large number of surface observations.

A unique feature of the 20CR is the model’s ability to recover information about the upper troposphere exclusively from surface observations by utilizing the statistically stable relationships (co-variances) that exist between state variables at adjacent atmospheric levels [Whitaker *et al.*, 2003]. In practical terms, these equations capture the relatively limited degrees of freedom that characterize a tropospheric column above a surface observation; for instance, a SLP observation of 1035 hPa cannot physically be associated with an anomalously warm tropospheric profile. During assimilation, a small random term is applied to the surface data to account for observation error, and 56 ensemble members are run assimilating slightly varying surface observations and the corresponding estimated vertical profiles [Compo *et al.*, 2011]. The mean of these ensemble members is a best estimate of the vertical structure of the atmosphere,

and the variance between the members provides the uncertainty of that estimate. In Figure 1.8, *Compo et al.* [2006] demonstrates the technique in a pre-20CR test case for which modern-era observations are pored to the low spatial density of SLP records typical of the early 20th Century. Using the filtered ensemble method, the skill of the anomaly correlation exceeds 0.9 relative to the NCEP/NCAR reanalysis in the middle and lower troposphere and around 0.85 near the tropopause. This shows that even when upper-level observations are not assimilated and surface observations are sparse, the ensemble Kalman filter still produces a very reasonable estimate of the upper-atmospheric state.

Two versions of the 20th Century Reanalysis were subsequently produced using this general technique. The first was 20th Century Reanalysis version 1 (20CRv1) spanning the years 1908-1958 [*Compo et al.*, 2008], which acted as an operational test of the method. Version 2 (20CRv2), encompassing the years 1871 through 2008 [*Compo et al.*, 2011], was subsequently released in early 2010. Each version of the 20CR has a spatial resolution of two degrees longitude and latitude globally and seventeen tropospheric vertical levels. Gridded output fields and uncertainties are produced at 0000, 0600, 1200, and 1800 UTC each day from the 56-member filtered ensemble.

The SLP observations assimilated into the 20CR are taken from the International Surface Pressure Databank version 2 [*Yin et al.*, 2008], which concatenates land and marine observations. In the 20CRv2, estimated minimum central pressure “observations” for TCs from *Knapp et al.* [2010] are also assimilated into the reanalysis model, which is a departure from the methodology of the earlier 20CRv1 in which they are not. For cases where there is no BT SLP estimate available, a central pressure “observation” is estimated from IBTrACS maximum sustained windspeed using a gradient wind balance relationship [*Compo et al.*, 2011]. Using the 20CRv2 ensemble mean as an initial condition, 24-hour forecasts of observed SLP (using the reanalysis model with no further observations assimilated after hour zero) demonstrate significant skill against persistence in the northern hemisphere at all pressure levels from 1871 onward (Figure 1.9) and have root mean squared errors that are slightly higher but comparable to the ERA-40 and NCEP/NCAR reanalyses for the latter half of the 20th Century (Figure 1.10). Geopotential height fields in 20CRv2 also are in good agreement with the small number of *in situ* upper-level observations taken prior to 1948, as shown in Figure 1.11.

1.3.2 The International Best Track Archive for Climate Stewardship

While the current research project is primarily concerned with the climatological record of TCs in the Atlantic Basin, a component of the work requires TC track data from the Eastern Pacific and a portion of the Central Pacific Basins. Therefore, an archive is desired that encompasses a broader geographic region than the Atlantic BT database, while upholding similar standards of quality control, active maintenance, and data sourcing. The International Best Track Archive for Climate Stewardship, or IBTrACS [Knapp *et al.*, 2010] meets these criteria and is the source for all TC position and intensity data used in this project. IBTrACS itself is not a reanalysis, but simply collates all available regional TC climatology sets into one master database, noting serious discrepancies in intensity and position where necessary. A summary of the data sources aggregated by IBTrACS is shown in Table 1.4. For the Atlantic Basin, BT (as modified by FPD96, L04, and L08) is the only extant climatological record; so it is incorporated directly into IBTrACS with no modification.

1.4 Objectives

Despite the enormous impact of Atlantic Basin TCs, relatively little attention has been paid to the construction, maintenance, and quality of TC climatology databases until the past two decades. At the same time, the short timeline of trustworthy historical data and rapid evolution of observational technologies has resulted in a number of theories regarding the existence, magnitude, and causation of long-term trends in seasonal TC activity. While efforts like the HURDAT reanalysis project subject the widest possible set of available surface data to rigorous expert analysis and dramatically improve the quality of Atlantic BT, by nature such efforts are limited by the information contained in the observations themselves. In short, increasing the speed, thoroughness, and portability to other basins of reanalysis techniques would be of great value to our understanding of long-term trends in TC activity and help make assessment of TC-related risks more accurate.

The general thesis of this research project is that recent advances in global reanalysis techniques extending reliable and high-resolution gridded data back to 1871 may offer a new pathway to objectively identify and assess candidate TCs more quickly than current methods.

Chapter 2 of this work describes the methodology of deriving a mean tropospheric signature of Atlantic Basin TC passage in the NOAA/CIRES 20th Century Reanalysis [*Compo et al.*, 2011] and briefly compares the results with other reanalysis datasets. To determine whether seeking these signatures in the pre-satellite era can enhance ongoing BT reanalysis efforts, the search for and subsequent verification in observational data of candidate events are presented in Chapter 3. Selected case studies representing an array of possible analytical outcomes of verifying candidate events are described in detail in Chapter 4, and the methodology is tested on the Eastern Pacific Basin in Chapter 5. The final chapter concludes with a short summary and some ideas for future challenges and applications of this technique.

Figure 1.1: Points of TC genesis during 1-10 September for the years 1851-2009 for the Atlantic and 1949-2009 for the Eastern Pacific. This figure depicts named storms only, not subtropical storms or unnamed storms. Courtesy: NHC (<http://www.nhc.noaa.gov/pastprofile.shtml>).

Figure 1.2: Same as in Figure 1.1, except for 11-20 September. Courtesy: NHC (<http://www.nhc.noaa.gov/pastprofile.shtml>).

Figure 1.3: Number of all TCs and hurricanes active per 100 years during the Atlantic hurricane season, by intensity. This figure clearly shows the climatological peak of activity around 10 September. Courtesy: Joseph Spain.

Figure 1.4: Seasonal activity in the North Atlantic Basin for the years 1886 through 2008, for TCs of tropical storm, hurricane, and major hurricane intensity. Dashed lines are individual year totals, and the solid lines indicate 10-year trailing moving averages for each bin. Data for Atlantic Multidecadal Oscillation cold and warm cycles and satellite coverage is also plotted to contextualize the climatology.

Figure 1.5: Monthly values of the Atlantic Multidecadal Oscillation index for January 1856 through December 2009. Note the quasi-periodic changes from cool to warm regimes. The black line is a 12-month moving average of the monthly AMO index. Courtesy: NOAA ESRL (<http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data>).

(b) “Missing storm” adjustments to HURDAT Tropical and Subtropical Storm Counts (1878-2006)

Figure 1.6: Proposed “missing storm” adjustments to BT climatology from 1880 to present for several recent studies [Vecchi and Knutson, 2008], revealing a wide range of possible corrective factors for the pre-satellite era.

Figure 1.7: The revised (upper) and original (lower) Atlantic Basin TC track map for the 1911 hurricane season [Landsea et al., 2004]. Two new TCs have been added during the HURDAT revision process, and the track and intensity data of several others has been substantially altered.

Figure 1.8: Variation of Northern Hemisphere 20CRv2 predictive skill for December 2001 using different assimilation systems and the same surface pressure observations simulating an 1895 network [Compo *et al.*, 2011]. At left, colored curves show the monthly averaged 6-hourly RMS differences over the Northern Hemisphere (20° – 90° N) between geopotential height analyses from full NCEP–NCAR reanalysis and assimilation experiments using only surface pressure observations at 1895 densities. Thin solid black curves show RMS errors of modern NWP forecasts at days 1 through 5. The thick solid black curve shows climatological standard deviation. At right, colored curves show the monthly average of 6-hourly anomaly pattern correlations over the Northern Hemisphere of 20CRv2 geopotential height anomalies from full NCEP–NCAR reanalyses and assimilation experiments.

Figure 1.9: Time series of the 20CRv2 24-hour RMS forecast skill verified using all pressure observations (blue) and the expected skill from 24-hour persistence (black) from 1870 to 2008 calculated over the extratropical Northern Hemisphere [*Compo et al.*, 2011]. The square root is calculated on the annually averaged squared differences between the observation and the forecast. The expected persistence skill is determined from the climatological variance of the 24-hour pressure tendency from NCEP–NCAR reanalyses at the locations of the observations.

Figure 1.10: Local anomaly correlation between six-hourly anomalies of 300 hPa geopotential height from ERA-40 and 20CRv2 over the period 1958-1978 [Compo *et al.*, 2011]. Anomalies are computed separately for each dataset with respect to the mean annual cycle. The area north of the thick black line is where ERA-40 and NCEP-NCAR reanalyses correlate highly (≥ 0.975).

Figure 1.11: Comparison of 500 hPa geopotential height anomalies at Lindenberg, Germany from upper-air observations in the Comprehensive Upper Air Historical Network and 20CRv2 analyzed anomalies interpolated to the time and location of the observations [Compo *et al.*, 2011]. Anomalies are with respect to the mean annual cycle of the period shown. Blue dots show anomalies from 1950 to present, and red dots show anomalies from data spanning 1905 to 1938.

Table 1.1: TC count data by decade for the revised Atlantic BT dataset, based on proximity to the United States and other landmasses [*Chang and Guo, 2007*]. Note the dramatic increase in the proportion of overall seasonal activity attributed to open ocean TCs in the satellite era.

Table 1. Decadal Averaged TC Counts Based on HURDAT Data Set^a

Class ^b	04–13	20–29	30–39	46–55	56–65	66–75	76–85	86–95	96–05
All	71	58	98	104	87	103	94	99	148
US	36	25	40	41	30	25	30	25	50
CC (CC/US)	18 (0.50)	15 (0.60)	43 (1.08)	30 (0.73)	21 (0.70)	20 (0.80)	14 (0.47)	26 (1.04)	35 (0.70)
NS (NS/US)	10 (<u>0.28</u>)	10 (<u>0.40</u>)	8(<u>0.20</u>)	16 (<u>0.39</u>)	22 (0.73)	36 (1.44)	34 (1.13)	22 (0.88)	33 (0.66)
OO (OO/US)	7 (<u>0.19</u>)	8 (<u>0.32</u>)	7 (<u>0.18</u>)	17 (0.41)	14 (0.47)	22 (0.88)	16 (0.53)	26 (1.04)	30 (0.60)

^aUnderlined numbers are those that are less than half of the 4-decade average from 1966–2005, during which the ratios are: CC/US – 0.73; NS/US – 0.96; OO/US – 0.72.

^bClass US: Hits continental US. Class CC: Hits any continent (other than US) and any island in the Caribbeans. Class NS: Near shore – hits other islands or within 300 km of land or islands. Class OO: Open ocean.

Table 1.2: A comparison of the Best-Track TC count in the Atlantic Basin prior and subsequent to the publication of *Fernandez-Partagas and Diaz* [1996].

Number of known storms

Period	Before this study*	New storms this study	Current (updated) totals
1851–60	33	31	64
1861–70	25	51	76
1871–80	65	11	76
1881–90	70	12	82
Totals (1851–90)	193	105	298

* This column represents the storm totals found in Neumann et al. (1993), starting in 1871, and the totals from all the available lists, as referenced in the text, for the previous 20 yr.

CHAPTER TWO

REANALYSIS CLIMATOLOGY

To determine whether the 20th Century Reanalysis datasets are a useful tool for aiding studies of TC climatology, it must first be demonstrated that the reanalysis is capable of realistically resolving TCs. To do so with confidence, it is necessary to construct a detailed climatology for the North Atlantic Basin within the domain of the 20CR and to then assess the mean response of the reanalyzed historical atmosphere to known cyclones. In this chapter, a careful study of layer thickness climatology is performed and described in detail, with an eye towards recruiting the metrics that are most sensitive to historical TC passage based on the essentials of thermodynamic storm structure. The efficacy of this metric is then tested with regard to existing BT data. Finally, the results from the 20CR dataset are compared against those obtained using a similar technique in a different reanalysis dataset.

2.1 Long-term Climatology in the 20CR

To understand how instances of TC passage differ from the mean atmospheric state in the 20CR, a set of climatological norms within the modelspace is first calculated. The first parameter that must be defined is the geographical scope over which the climatology will be computed. For the purposes of this study, this region is defined as the North Atlantic Ocean from 100° to 20°W and 0° to 60°N, within which essentially all the cyclogenesis in the Basin takes place. The process of constructing a full climatology is repeated for three variants of the 20CR: the first dataset is the full first version of the reanalysis [*Compo et al.*, 2008], the 20CRv1, which spans 1908 to 1958. The next is the second version of the reanalysis [*Compo et al.*, 2011], the 20CRv2, with the first two decades trimmed due to low observational density, resulting in a domain of 1891 to 2008. The final variant is a subset of 20CRv2 for the years 1908 to 1958 (20CR0858v2). Vital statistics for each of the reanalysis datasets are found in Table 2.1. Comparing results from the 20CRv1 and 20CR0858v2 allows a clean comparison of these TC data assimilation

techniques detailed in Section 1.3.1, while comparing results from the 20CRv2 and 20CRv20858 will reveal whether significant changes in aggregate response to TC passage have occurred in the model between the pre-satellite and satellite eras.

Additionally, for each of the 20CRv1, 20CRv2, and the 20CR0858v2 datasets, two separate climatologies were calculated. In the first, all the datapoints in the reanalysis are used to prepare the climatology with no filtering of any kind. In the second variety, all 20CR datapoints within five degrees of an IBTrACS TC for three days before and after TC passage are not included in calculating the climatology. This step is an attempt to remove as much of the influence of TCs on the local normals as possible, consistent with the atmospheric temporal footprint found by *Hart et al.* [2007]. Theoretically, TCs should account for a fair percentage of the observed variability in the climatology of the deep tropics, because while the individual events are rare, they produce anomalies on the order of many sigma against a generally low-variability background state [Swanson 2008]. This removal was accomplished by preparing a mask for reanalysis gridpoints in geographic or temporal proximity to a known BT cyclone. This mask was applied to the second version of climatology for all three datasets, resulting in a total of six sets of annual norms for various iterations of the 20CR data.

The study parameters thus defined, a gridded climatology is prepared for each of the six versions of the reanalysis. Since warm-core cyclones can be expected to influence geopotential height even in a coarse reanalysis [Schenkel and Hart, 2011], norms for nine layer thicknesses that are thermodynamically relevant for TCs (300-950 hPa, 250-950 hPa, 200-950 hPa, 300-900 hPa, 250-900 hPa, 200-900 hPa, 300-850 hPa, 250-850 hPa, 200-850 hPa) are calculated. The lower and upper bounds of these layers loosely correspond to the top of the boundary layer and the approximate tropopause, respectively. At each gridpoint within the northern Atlantic Basin study area, the mean and variance of geopotential thickness for these layers is calculated for each of the 1460 six-hourly output times in the annual cycle, where $t=1$ is 0000 UTC on 1 January and $t=1460$ is 1800 UTC on 31 December, with the process repeated for each full and TC-masked version of the 20CR. (When applicable, leap days are also trimmed from the datasets.) As an example, the mean 300-850 hPa geopotential thickness at 20° N, 60° W for 1200 UTC on 1 June in the full 20CRv1 reflects the average 300-850 hPa thickness at 20° N, 60° W of all 51 records for 1 June at 1200 UTC between 1908 and 1958. Assuming that a TC existed at this location at 1200 UTC on 1 June 1908 and no other 1 June 1200 UTCs, the TC-masked 20CRv1 850 hPa

height mean would be the 50-year average of level heights at this location and time for 1909 through 1958.

These processes yield the model's assessment of normal heights (and standard deviations of height) for a particular location and synoptic time. A similar process uses these averages to calculate the mean and variance in each of the six datasets. These results are discussed in the next section.

2.2 TC Climatology in the 20CR

2.2.1 Calculating TC Climatology

Before tabulating the statistical signatures of TC passage in the 20CR, a brief comparative look at the data obtained from the calculated layer means and variances in the six versions of the reanalysis is warranted. As a general sanity check on the quality of the derived climatology, a study of the annual cycles of regionally averaged sigma is prepared for each of the datasets. Briefly, these studies were prepared by taking the mean variances of layer thicknesses at the gridpoints within three broad zonal boxes: the tropics (0° to 20° N), the subtropics (20° to 40° N), and the mid-latitudes (40° to 60° N). This process was repeated for all 1,460 timesteps in the annual cycle. If the climatological study is realistic, a positive relationship would be expected between latitude and the mean variance of layer thicknesses due to the dominance of the seasonally stable Hadley cell in the Tropics [*Dima and Wallace, 2003*]. An annual cycle of increased variance in the winter months and lower variance in the summer months would also be expected.

Figure 2.1 shows results for the TC-masked 20CRv2 dataset, revealing that these features of tropical circulation are well-captured by the reanalysis. Similar results are obtained for the other five 20CR-derived climatological databases, demonstrating that the reanalysis gets seasonal variability that is intuitively correct zonally. To estimate the maximum magnitude of the effect of removing TC footprints from the reanalysis climatology (to the extent possible) using the masking technique described in the previous chapter, Figure 2.2 plots the difference between the mean 300-850 hPa layer thickness in the TC-masked and unmasked versions of the 20CR0858v2, normalized by the standard deviation of the unmasked version, for the most

climatologically active day in the Atlantic hurricane season (see Figure 1.3). This figure shows that reductions in the normalized average layer thickness are greatest along the climatologically-favored path of peak season intense TCs to the north of the Greater Antilles, with lesser reductions elsewhere in the basin in favored development and propagation areas (see Figure 2.3). Since this is precisely the effect that would be predicted assuming the successful removal of events causing strong warm (positive) thickness anomalies, it follows that the identification of TC signatures in the 20CR is aided by removing the known signatures when defining climatological baselines. Therefore, the TC-masked versions of the 20CRv1, 20CRv2, and 20CR0858v2 will be used almost exclusively in the remainder of this study for all purposes.

These three databases of layer thickness climatology are used to identify the temporal and spatial thermodynamic signature of TC passage using a modified version of the *Hart et al.* [2007] methodology. For thirty days before and after IBTrACS-indicated passage, the normalized thickness anomaly ΔZ in each layer was calculated every six hours using the following:

$$\Delta Z(t,L) = [M(t,L) - \mu(t,L)] / \sigma(t,L), \quad (1)$$

where L is the nearest reanalysis gridpoint to the IBTrACS TC location at passage time, t is the appropriate six-hour timestep in the annual cycle, M is the thickness in the 20CR, and μ and σ are the mean and variance of layer thickness from the climatology of the reanalysis, respectively. This normalization process was shown to reliably identify and rank statistically significant synoptic-scale events by *Hart and Grumm* [2001]. The procedure is repeated in the 20CRv1, 20CRv2 and 20CR0858v2 datasets for each six-hourly TC position in IBTrACS, excluding tropical depressions, subtropical cyclones (as records for these were not consistently kept over the full 1891-2008 study period), and extratropical cyclones. The process yields a set of 9,195 sixty-day TC passage response sequences for the 20CRv1 and 20CR0858v2 and 23,570 sequences for the 20CRv2 dataset.

The nine layer thicknesses for which means and variances were calculated in the re-analyses represent a matrix of three lower tropospheric levels likely to be above surface level given the 20CR's resolution in an Atlantic Basin TC (950, 900, and 850 hPa) and three upper tropospheric levels likely to be near the highest cyclonic levels in a TC (300, 250, and 200 hPa). Of the nine layers, the 300-850 hPa layer thickness yielded the highest average normalized response at TC passage in the 20CRv2, as shown in Table 2.2. Therefore, the thickness of the

300 to 850 hPa layer is found to be a useful proxy for the passage of TCs (consistent with *Hart* [2003]) and will serve as the experimental metric for the remainder of this study.

2.2.2 TC Passage Signatures in 20CR

The mean normalized 300-850 hPa thickness anomalies at TC passage, binned by the maximum sustained BT wind, are shown in Table 2.3. Positive values of the normalized thickness anomaly represent a thicker 300-850 hPa layer than the climatological value from reanalysis. As layer thickness represents an integration of virtual temperature with height, deep warm-core cyclones can be expected to yield positive thickness anomalies relative to climatology even in a low-resolution model. Therefore, the results in Table 2.3 agree well with what would be predicted from TC dynamics and the specifications of each reanalysis model, e.g., whether or not BT observations are assimilated. Of particular note are 1), the normalized thickness response increases with intensity in all versions of the reanalysis and 2) response is approximately doubled in 20CRv2 and 20CR0858v2 compared to 20CRv1. This is likely due not only to the inclusion of BT “observations” in v2, but also that version 1 of the reanalysis must resolve TCs with no assistance from BT, and thus may not place the circulation center (or maximum thickness anomaly) near the BT position. This is a possible source of underestimating the 300-850 hPa thickness anomaly responses to TC passage in the 20CRv1.

While these persistent anomalies, consistently observed even in version 1, increase confidence that the 20CR is capable of diagnosing TCs in low-observation regimes without the help of a bogussing scheme, it is also essential to show that the results in Table 2.3 are not due to the different time domains of 20CRv1 and 20CRv2. In Figure 2.4, average normalized 300-850 hPa layer thickness anomalies at TC passage are presented by dataset for both unaltered climatology and the TC-masked climatology. The key finding is that there is a generally stable amplitude of normalized response between 20CRv2 and 20CR0858v2, with the average anomaly for all named cyclones just under $+3\sigma$ for the modified climatology in both cases. Therefore, Figure 2.4 and Table 2.1 show that 20CR is as equally capable of analyzing TCs during the pre-satellite as satellite eras. This would be expected since satellite data is not assimilated into the reanalysis and ship observation density has only increased modestly in the past three to five decades in the eastern Atlantic [*Vecchi and Knutson*, 2008], it does show the 20CR removes the observation bias caused by the beginning of the satellite era. Finally, removing TC footprints

from climatology before calculating the mean layer response yields an approximately 15% increase in the normalized passage anomalies in all three datasets. Therefore, this process therefore significantly aids efforts to identify candidate events of true significance and re-affirms the choice of using the TC-masked climatology in this research.

Figures 2.5, 2.6, and 2.7 show the average normalized 300-850 hPa thickness anomaly for a 60-day time series centered on TC passage in the 20CRv1, 20CRv2, and 20CR0858v2 reanalysis datasets, respectively. As in Table 2.3, these results are categorized into three intensity bins for tropical storms, minor hurricanes of Saffir-Simpson categories 1 and 2 intensity, and major hurricanes of Saffir-Simpson categories 3, 4, and 5 intensity [Saffir 1973, Simpson 1974]. There are several important similarities between these figures, as well as some key differences that reinforce earlier points. Between prior to five days before TC passage in the 20CRv1, 20CRv2, and 20CR0858v2 datasets, there is little to no anomalous response in the thickness anomalies. The mean response values, fairly constant at less than 0.3σ for all intensities, perhaps indicate that active hurricane seasons are generally characterized by deeper environmental thicknesses than climatology, or interannual or interdecadal changes in mean. Another possible explanation for this consistently positive bias is that it represents the cumulative contributions of occasional passages of TCs in the weeks before the arrival of the TC being studied at the proscribed point. In both version 1 and version 2, the positive thickness anomalies first become apparent 3-4 days prior to TC passage, increase rapidly until the time of passage, and decay quickly thereafter, albeit with a slightly longer rightward tail as the anomalies subside again to less than $+0.3\sigma$ by 3-5 days after passage. This is consistent with the e-folding timescale of atmospheric response found by *Schenkel and Hart* [2011].

While the resting state of normalized 300-850 hPa thickness anomalies beyond five days from passage is similar across all intensity categories, the peak response again scales well with intensity in both versions of 20CR. Figure 2.4 shows that mean thickness anomaly at TC passage is approximately $+1.1$, $+1.7$, and $+2.7\sigma$ in 20CRv1 and approximately $+1.8$, $+3.9$, and $+5.7\sigma$ in 20CRv2 for tropical storms, minor hurricanes, and major hurricanes, with similar values as 20CRv2 in the 20CR0858v2 test. For reference, $+1.29$, $+1.65$, and $+2.33\sigma$ represent the 90th, 95th, and 99th percentile, respectively, in a Gaussian distribution. One significant result is that even though assimilating estimated SLP observations from IBTrACS results in a roughly doubled peak response in 20CRv2 compared to 20CRv1, even in version 1 the normalized

thickness anomaly response at passage is significantly different from zero at a 95% confidence level for both minor and major hurricane intensities. Therefore, even when the model was fed only with historical observations from ships and land for the 1908-1958 period, 20CRv1 analyzes TC structure with some degree of statistical significance and depicts a warm-core low in the vicinity of the BT position without the “help” of directly assimilating an estimated minimum central pressure. This result is encouraging because it is therefore plausible that the model could independently diagnose a TC supported by historical surface observations even when no record of a storm exists in BT.

Further examining the resolution and structure of BT cyclones in the 20CRv1, Figure 2.8 shows the 2-D spatial structure of 300-850 hPa normalized layer thickness anomalies for six TC intensity bins ranging from weak tropical storms to Category 4 and 5 hurricanes on the Saffir-Simpson scale. Anomalies are plotted within a $10^\circ \times 10^\circ$ box centered on the TC location as determined by the 1908-1958 records in BT. This figure reveals that the layer thickness TC proxy does in fact mimic the generally compact and symmetric warm-core signature of real-world TCs in the reanalysis with reasonable fidelity. In general, the reanalysis model is able to capture the TC’s synoptic-scale footprint but not mesoscale or finer structure. Response amplitude also continues to increase smoothly with intensity, with the exception of similar presentations of the strong tropical storm and Category 1 composite anomalies. As a final note, a minor north/south asymmetry is noted for the stronger tropical storm categories and above, with greater average anomalies at equal distances north of the BT center than to the south. This may reflect a systematic placement of TCs north of their BT position estimates in the 20CRv1, or possibly is driven by the model’s own dynamics. Another possible explanation is that the coarse resolution of the 20CR leads to modeled TCs being larger than reality, which could lead to increased beta drift and a northward track bias in the absence of surface observations to correct for this tendency.

Previous figures have examined with the mean normalized response to TC passage in the various versions of the 20CR, but in order to state with confidence that the reanalysis consistently resolves TCs well, a sense of the distribution of these anomalies about the mean is necessary. Figures 2.9, 2.10, and 2.11 plot the proportion of normalized thickness anomalies relative to the total number observed within 5-kt increments of intensity, at TC passage. The mean response for each 5-kt intensity bin is also plotted. Cooler colors represent less common

normalized thickness anomalies and warmer colors represent the most common states for a given intensity. These are typically clustered about the mean (black line). For example, in Figure 2.9, the furthest left column of colored grid cells represents the spread of all model-derived thickness anomalies for TCs with a BT intensity of 35 kts. The cell bounded by 0.5 and 1.0σ on the y-axis and 35 and 40 kts on the x-axis is red, meaning that approximately 17% of all 35-kt intensity TCs in BT recorded passage thickness anomalies between 0.5 and 1.0σ in the 20CRv1.

Figures 2.9, 2.10, and 2.11 are rich in information and are consistent with earlier conclusions. First, even when intensity is broken into 5-kt increments, the response amplitude continues to demonstrate a fairly linear increase with intensity in all three datasets. Again, the slope of the line is less steep in the 20CRv1 and steeper in the 20CRv2 and 20CR0858v2, due to the assimilation of BT-derived pressure observations in the latter two datasets. As such, the clustering of the anomaly distribution about the mean response is “tighter” in version 1 and generally more diffuse in the version 2 sets. Figures 2.10 and 2.11 also reveal that the version 2 anomaly distributions are positively skewed, with a long “tail” of anomalies extending upward from the mean to approximately 10σ for major hurricanes. The distribution of anomalies in 20CRv1 is generally more symmetric about the mean. However, in all three plots, with the exception of very weak tropical storms, there are few TC events that register negative anomalies. Instead, the majorities of TCs in each dataset register over the 1.5σ threshold that generally represents a statistically significant (i.e., 95% t-test) signal in the reanalysis model. For a visualization of the percentage of TC six-hourly positions exceeding 1.5σ by intensity, see Figure 2.12.

2.3 TC Passage Signatures in Other Reanalyses

An additional check on the efficacy of the TC passage response data can be obtained by repeating the study methodology on another reanalysis dataset and comparing the results with the various versions of the 20CR. The baseline NCEP/NCAR Reanalysis [Kalnay *et al.*, 1996; hereafter referred to as NCEP/NCAR] was selected for this purpose for several reasons. First, the NCEP/NCAR, like the 20CR, is freely available. Second, of the reanalysis datasets discussed in Section 1.3.1, it has the longest time range (except the 20CRv2), spanning the years 1948 to

present, which includes nearly two decades of the pre-satellite era. This allows a more direct and meaningful comparison between the 20CR results and the normalized response in the NCEP reanalysis than the other options.

NCEP/NCAR produces a best estimate of historical atmospheric state using an ensemble Kalman filter that assimilates both historical surface observations and upper-level radiosonde data. It has a spatial resolution of $2.5^\circ \times 2.5^\circ$ globally, with seventeen vertical levels, including ten in the troposphere (1000, 925, 850, 700, 600, 500, 400, 300, 250, and 200 hPa). Gridded output is produced four times a day, at 0000, 0600, 1200, and 1800 UTC. Both the spatial and the vertical resolution of the NCEP/NCAR reanalysis output are coarser than the 20CR. Unlike version 2 of the 20CR but similar to 20CRv1, NCEP/NCAR does not assimilate SLP data from BT. Therefore, like 20CRv1, the NCEP/NCAR reanalysis is not “informed” of the presence of TCs other than through the model’s ability to resolve them from observations or generate them through forward integration in time.

A 1948-2008 subset of NCEP/NCAR dataset was analyzed using a streamlined version of the methodology described in Section 2.2.1. This process included constructing a new version of the TC mask from BT and calculating TC-masked layer thickness means and variances for the North Atlantic Basin. As in the 20CR, the 300-850 hPa layer thickness is used as the experimental metric in the NCEP/NCAR reanalysis study. With this climatology in hand, the mean normalized layer thickness response to TC passage is calculated using the same techniques that were employed on the 20CRv1, 20CRv2, and 20CR0858v2, but adapted to the lower spatial resolution of the NCEP/NCAR. This results in a set of 12,387 sixty-day TC passage sequences, one for each six-hourly TC position in BT between 1948 and 2008.

Figure 2.13 shows the average normalized 300-850 hPa thickness anomaly for a 60-day time series centered on TC passage in NCEP/NCAR and is the analog for Figures 2.5-2.7. As in the earlier figures, there is a generally positive thickness anomaly background state outside of five days of TC passage of less than $+0.25\sigma$. It is clear that the maximum normalized response at TC passage is significantly smaller for all intensity classifications than in either 20CRv1 or 20CRv2, with the aggregate response about 30% smaller than version 1 and 70% lower than version 2. There is also noticeably less difference in peak response between minor and major hurricanes in the NCEP/NCAR dataset. In Figure 2.14, the distribution of the TC passage response by intensity is shown, as in Figures 2.9-2.11. This plot shows that the variance about

the mean in the NCEP/NCAR is much smaller and more normally distributed than either version of the 20CR. However, the slope at which mean response increases with intensity is much less steep than in Figures 2.9-2.11. From Figure 2.12, it is clear that the proportion of TC passages exceeding the key statistical threshold of 1.5σ in NCEP/NCAR lags far behind 20CRv2, but also trails 20CRv1 at almost all intensities. This is very interesting, considering that the 20CRv1 assimilates only surface observations between 1908-1958. Though it utilizes radiosonde data and the denser observational network of the latter half of the 20th Century, the NCEP/NCAR reanalysis' different physics package, poorer spatial resolution, or less advanced interpolation scheme means that it cannot independently diagnose TCs as robustly as the 20CR.

To summarize, comparing the aggregate response of 300-850 hPa layer thicknesses to TC passage in the NCEP and 20CR reanalyses reveals the importance of model resolution and assimilation techniques on analyzing and simulating TCs within the climatological record. Yet, this comparison and the totality of results in Chapter 2 also demonstrate a consistent ability of reanalysis datasets to resolve warm-core cyclones, even when they are not force fed into the model. The emergence of a stable and significant proxy for TC passage over thousands of data points offers insight into how a real-world TC that is not recorded in BT might manifest itself in the 20CR. Based on these results and the model's disparate data assimilation techniques, a first expectation is that non-Best Track TCs nonetheless will often be resolved with a normalized thickness response amplitude similar to that of known TCs in version 1. This theory will be tested in Chapter 3.

Annual Cycle of 300-850hPa Thickness Mean Sigma in North Atlantic Basin

Figure 2.1: The annual climatological cycle of 300-850 hPa layer thickness variance for the North Atlantic Basin in the 20CRv2 for the years 1891-2008. Tropics, Subtropics, and Mid-Latitudes represent the mean variance averages over 100° W – 20° W for $0 - 20^{\circ}$ N, $20 - 40^{\circ}$ N, and $40 - 60^{\circ}$ N, respectively.

Normalized Impact of TC Removal on Mean 300-850 hPa Thickness for Peak Season 20CRE0858v2

Figure 2.2: Normalized change in mean 300-850 hPa layer thickness caused by removing TC footprints from climatology as described in Section 2.1. This plot shows the impact of TC removal on the means for 0000 UTC on 10 September, very close to the climatological peak of hurricane season.

Figure 2.3: Climatologically prevalent TC tracks during September from Atlantic BT for the years 1886-2009. Courtesy: NHC (<http://www.nhc.noaa.gov/pastprofile.shtml>).

Figure 2.4: A comparison of mean normalized response in 300-850 hPa thickness fields at the time of TC passage for 20CR version 1, version 2, and the 1908-1958 subset of version 2. Mean response for both TC-masked and raw climatologies are plotted.

Figure 2.5: Normalized 300-850 hPa thickness anomalies for sixty days centered on TC passage in version 1 of the 20CR for the 1908 to 1958 Atlantic Basin hurricane seasons. Results are categorized by the maximum sustained wind at TC passage as tropical storms (17 to 32 m s^{-1}), minor hurricanes (33 to 49 m s^{-1}), and major hurricanes ($\geq 50 \text{ m s}^{-1}$), along with the number of six-hourly TC position points in BT belonging to each bin.

Figure 2.6: Same as in Figure 2.5 but for version 2 of the 20CR, spanning the years 1891-2008.

Figure 2.7: Same as in Figure 2.6, but for a 1908 to 1958 trimmed subset of version 2.

Figure 2.8: Mean normalized 300-850 hPa layer thickness anomalies in a 10° by 10° box centered on the TC position from BT. The six individual plots represent the average responses in six intensity bins.

Figure 2.9: Distribution of 300-850 hPa thickness anomalies at TC passage relative to a 5-kt maximum sustained wind intensity bin for the 20CRv1. The colormap represents the proportion of individual six-hourly positions for a given 5-kt intensity range that fall within a given one-half σ range. The black line is the mean normalized anomaly at passage within the bin. Intensities over 135 kts are included in the far right bin.

Figure 2.10: Same as Figure 2.9, except for 20CRv2.

Figure 2.11: Same as Figure 2.10, except for 20CR0858v2.

Figure 2.12: Proportion of TCs within 5 kt intensity bins for which the maximum normalized 300-850 hPa thickness anomaly at TC passage exceeds 1.5σ . Curves for all four reanalysis datasets considered in Chapter 2 are plotted.

Figure 2.13: Same as in Figure 2.5, for the 1948 to 2008 span of the NCAR/NCEP Reanalysis.

Figure 2.14: Same as Figure 2.9, except for the NCAR/NCEP Reanalysis.

Table 2.1: Specifications of reanalysis datasets used in this research.

Reanalysis Dataset	Years Covered	Spatial Resolution	Vertical Resolution	Assimilates Estimated SLP?
20CRv1	1908-1958	2°x2°	24 levels	No
20CRv2	1871-2008	2°x2°	24 levels	Yes
20CR0858v2	1908-1958	2°x2°	24 levels	Yes
NCAR/NCEP	1948-present	2.5°x2.5°	17 levels	No

Table 2.2: Mean normalized response for various layer thicknesses in the 20CRv2.

Layer (lower level, in columns; upper level, in rows)	950 hPa	900 hPa	850 hPa
200 hPa	1.92	1.96	2.02
250 hPa	2.22	2.28	2.36
300 hPa	2.64	2.73	2.84

Table 2.3: Mean normalized 300-850 hPa thickness anomaly at TC passage by intensity and reanalysis dataset.

Reanalysis Dataset	Tropical Storms	Minor Hurricanes	Major Hurricanes	All Intensities
20CRv1	1.11	1.61	2.68	1.49
20CRv2	1.89	3.80	5.52	2.93
20CR0858v2	1.67	3.97	6.10	2.96

CHAPTER THREE

CANDIDATE EVENTS

As demonstrated in Chapter 2, TCs in the Atlantic Basin have a stable passage signature in the 20CR relative to 300-850 hPa thickness layer climatology. This signature is consistently present in both version 1 and version 2 of the 20CR reanalysis, and is apparent in both the satellite and pre-satellite eras. Having quantified a signal, it logically follows that searching for cases similar to known TC passages that do not correspond to a Best Track cyclone position is one way to objectively detect candidate events that may represent a real-world TC. This chapter describes in detail the techniques developed to identify individual candidate events (CEs) within the 20CR, as well an extensive assessment of the performance of this method using historical records of surface observations.

3.1 Identification of Candidate Events in the 20CR

As discussed previously, there has been minimal research concerning the structure and resolution of TCs in reanalysis data. Those studies that do exist are primarily concerned with the representation of TCs in reanalysis datasets during the satellite era [*Manning and Hart, 2007; Schenkel and Hart, 2011*]. However, neither of these studies utilizes either version of the 20CR. *Emanuel [2010]* attempts to recover information about cumulative historical seasonal TC activity prior to the satellite era from the 20CRv1. His study, based on a model downscaling technique first applied to the NCEP/NCEP Reanalysis in *Emanuel [2006]*, backs out seasonal activity using the modeled response of randomly generated TC vortices to environmental parameters provided by the 20CRv1 for 1908-1958. *Emanuel [2006]* concludes that there is no clear trend in Northern Hemisphere TC activity over these decades, and also finds that downscaled event frequency is highly correlated with seasonally averaged genesis potential index [*Emanuel and Nolan, 2004*]. Still, *Emanuel [2010]* does not parse individual TCs in the 20CR. Rather, he uses the gridded reanalysis data as boundary conditions for a separate TC genesis model.

A review of the existing body of literature has shown that there are no previous attempts to catalogue undocumented TC-like events in the 20CR or reanalysis datasets in general. Therefore, great care must be exercised in the experimental design of the candidate event search. *Walsh et al.* [2007] demonstrate that the TC detection rate in models is highly dependent on grid resolution and the selected synoptic criteria. For the purposes of this study, these features will be identified in version 2 of the 20CR, using the local 300-850 hPa mean and variance climatology derived for the TC-masked variant of 20CRv2. Version 2 is selected over version 1 because 20CRv2 assimilates an expanded library of SLP observations compared to version 1, making it more likely to have the observations necessary to resolve missing TCs. There also have been a handful of upgrades to the model physics that improve fidelity to the real atmosphere over version 1 [*Compo et al.*, 2011]. Additionally, because 20CRv2 better resolves known TCs, it is more capable of correctly discerning the impact of those TCs on the synoptic environment and seasonal climate, which may reduce the number of spurious TCs generated by the model. As an initial test of the study methodology, the search for candidate events is conducted for the 1951 through 1958 Atlantic Basin hurricane seasons. These years were selected because they had not yet been subjected to the HURDAT revision process at the time of this study, making the results less redundant and more useful to operational reanalysis.

The first attempt to locate a set of CEs for further consideration applied an algorithm to the 1951-1958 20CRv2 reanalysis grids that returned all points that met certain criteria designed to filter the raw data to the events most likely to represent TCs. These criteria include:

- time of year (June 1—November 30);
- location (over water);
- latitude (south of 30° N);
- analyzed SLP (less than 1014 hPa);
- proximity to BT cyclone (none within 10°);
- normalized 300-850 hPa thickness (over 1.65σ , or approximately a 95% confidence level that the anomaly is statistically distinct from the mean thickness).

Despite modifying the criteria several times to be more restrictive, this method yielded an unmanageably long set of over 100,000 individual gridpoints during the 8-year time span. These points include large areas of warm thickness anomalies in the tropical North Atlantic due to interannual variability, broad low- and mid-level ridging, and other causes unrelated to TCs and

their precursor disturbances. To further refine these results into a useful form, a manual search algorithm was applied to winnow the list to more credible candidates. As above, the criteria applied to locate candidate events (CEs) were designed to identify cases in 20CRv2 six-hourly output for which the given event 1) was located over the Atlantic between 0°-60°N latitude, 2) did not correspond to an IBTrACS TC, and 3) had a significant normalized 300-850 hPa warm thickness anomaly. To remove larger-scale warm thickness anomalies caused by interannual variability (e.g., ENSO) and low- and mid-level ridging inconsistent with cyclonic signatures, three-panel synoptic maps were created. These maps, examples of which are shown in Figures 3.1, 3.2, and 3.3, plot the 300-850 hPa thickness anomaly, SLP and 850 hPa relative vorticity, and 850 hPa streamlines, respectively. If an IBTrACS TC exists at the synoptic time, its location and identifying number are also plotted on the figures. These three-panel figures were generated at 12 hour time steps during the TC seasons (1 June to 30 November) of the years 1951 through 1958.

The resulting 2,912 plots are then individually scrutinized for evidence of TCs, which will be referred to as candidate events (CEs). In general, to be defined as a CE, an area of interest needs to show persistence by maintaining significant thickness anomalies over 1.65σ for two consecutive twelve-hourly periods. Additionally, the anomalies need to be corroborated in low-level fields by demonstrating a compact and symmetric presentation that is broadly consistent with a warm-core cyclone relative to the coarse reanalysis grid. Increased consideration is also given to events that were analyzed by the reanalysis as having a closed SLP isobar of 1010 hPa or lower, positive 850 hPa relative vorticity exceeding $2.0 \times 10^{-5} \text{ s}^{-1}$, or a closed circulation in the analyzed 850 hPa streamlines. By first identifying a potential CE in the layer thickness fields and then verifying it to first-order in other metrics that respond strongly to TC passage, non-tropical causes of warm anomalies are filtered from the resulting set of CEs. In general, the technique is a hybrid of objective and subjective methods that utilizes the discretion of the synoptician to narrow the search and determine which events are possible missing TCs.

Applying this search method to the 1951 through 1958 Atlantic Basin hurricane seasons in the 20CRv2 yields a preliminary list of 68 CEs meriting closer evaluation outside of the reanalysis. These CEs represent 54 potential TCs that are unknown to the climatological record, as well as 14 cases where the reanalysis indicates that the track of an existing Best-Track TC may need to be extended. In each of the eight seasons assessed, there are at least seven 20CR

candidate cases where a “missing TC” or track extension is possible, with a maximum of 15 events during the 1955 hurricane season. This consistency, as well as the fact that the movement of many CEs generally falls along and resembles common TC tracks, suggests that a non-trivial number of the cases represent actual cyclones that can be verified by inspection of ground-truth observational data.

3.2 Verification of Candidate Events

In order to demonstrate that the selection technique is useful, it must be shown that the 20CR can identify events that further analysis indeed shows may merit inclusion in BT. Therefore, a procedure is needed to assess and classify the candidates as objectively as possible using non-reanalysis data sources, so that the success rate of the 20CR can be quantified. This section describes the data sources, visualization techniques, and classification schemes that are used to determine how likely a CE meets the standards of evidence for addition to BT or significant modification of an existing BT entry.

3.2.1 Historical Surface Observation Datasets

The first step toward verifying the set of candidates found in the 20CRv2 for the 1951 through 1958 hurricane seasons is to develop an alternative dataset in which to test the reanalysis’ predictions. Therefore, the 68 CEs identified in section 3.1 are assessed using historical databases of ship-based and land-based observation records. For the purposes of this project, because the majority of CEs do not make landfall and are located over the open ocean for the vast majority of their life cycle, maritime records are the most important. A comprehensive set of historical ship observations are provided by the International Comprehensive Ocean-Atmosphere Data Set, Release 2.5 [Woodruff *et al.*, 2010, hereafter ICOADS]. The ICOADS is the most extensive collection of surface marine meteorological observations available, merging a number of smaller datasets together while exercising basic quality controls. This database incorporates approximately 261 million reports since 1662, an improvement over the 238 million records in the earlier Release 2.4. As Figure 3.4 shows, there

are approximately 1 million observations globally per year during 1951, which increases to around 1.5 million per year by the end of the test period in 1958.

Historical observations for land-based surface stations are provided by the National Climatic Data Center's Integrated Surface Database Version 2 [Lott 2004], which similar to ICOADS is a central depository for earlier datasets. Observations were extracted from the ISD for the American East Coast and Gulf Coast, the Mexican Gulf and Caribbean coasts, as well as observations from Central America, the Lesser Antilles, the Greater Antilles, and the Cape Verde Islands. Surface temperature, surface pressure, wind speed, and wind direction data are taken from ICOADS and the ISD.

3.2.2 Individual Candidate Event Study Maps

The large amount of information in the historical surface databases means that an efficient means of parsing observations and quickly evaluating the CEs is necessary. To this end, a series of CE-centered, mesoscale maps are made for each CE. Each six hours (0000, 0600, 1200, and 1800 UTC) over the lifetime of each CE, a plot was made of normalized 300-850 hPa thickness anomalies and SLP derived from the 20CR fields (contoured). These reanalysis fields were then overlain with all available ship- and land-based wind speed, wind direction, SLP, and (when available) surface temperature observations from ICOADS and the ISD. These charts typically span a spatial area of approximately 16 degrees of latitude by 16 degrees of longitude that is centered on the CE, although the side length can vary between 8 and 20 degrees square based on the size of the thickness anomaly and the density of surface observations. An example of the individual CE study map is given in Figure 3.5.

These synoptic maps are then individually analyzed for evidence of a closed circulation and wind or pressure observations supporting TC status. Each map is analyzed in accordance with the criteria for adding new TCs to the Atlantic hurricane database outlined in L08, with the synoptician specifically looking for wind reports exceeding 34 kts and SLP observations of 1005 hPa or lower. While closing off a circulation center by recording winds from all four cardinal directions may not be possible given the density of observations available, the presence of a wind vector from the opposite direction as the apparent propagation vector of the CE is also an important sign of the presence of a closed circulation. As the six-hourly maps were scrutinized

for each of the 68 CEs, careful notes were taken regarding location, estimated minimum central pressure, and key wind speed and direction observations.

3.2.3 Phase Space Analysis

In several cases, especially late-season cyclones located in the subtropical North Atlantic, ship-based observations unambiguously supported the existence of tropical storm force winds and a closed circulation in association with the CE, but it was unclear whether the low retained the warm-core and nonfrontal thermodynamic structure necessary to be classified as a TC. To further add to the menu of possibilities, subtropical cyclones were not formally defined until the late 1960s [*Hebert and Poteat, 1975*], so even very strong hybrid lows prior to this time are not included in BT prior to the HURDAT revision process. While the presence of the 300-850 hPa thickness anomalies themselves broadly indicates anomalous warming in the lower troposphere, the coarse resolution of the 20CR and ambiguities originating in interpolation require additional methods to assess the three-dimensional thermodynamic structure of these events.

One simple method that is used to check for the presence of obvious frontal boundaries is plotting surface temperature on the individual CE study maps. A tight and persistent longitudinal temperature gradient can indicate the existence of a fully or partially baroclinic cyclone, rather than a primarily barotropic low. A more sophisticated tool that performs an analogous task in all three axes is the cyclone phase space diagram [*Hart 2003*]. Plots of cyclone phase space (B: lower-tropospheric storm-motion-relative thermal asymmetry and $-V_T^U$ and $-V_T^L$: thermal wind in the upper and lower troposphere, respectively) were made for the life of the CE using the 20CRv2 to further assess its thermodynamic and dynamic structure. Figures 3.6 and 3.7 track the evolution of a single CE with time, measuring thermal asymmetry versus lower level thermal wind, and upper-level thermal wind versus lower-level thermal wind, respectively. While these plots allow the best possible assessment of the depth and strength of the warm-core associated with the CE in the 20CRv2 and greatly aid classification efforts, they are derived from the reanalysis output, not from independent observations. Therefore, the assessment of thermodynamic structure is only as good as the quality of the 20CRv2 itself.

3.2.4 Binning Scheme

After carefully assessing the individual CE study maps (and cyclone phase space plots, when applicable) for all 68 cases in the 1951 through 1958 Atlantic hurricane season, the CEs are subsequently classified into one of three broad confidence categories depending on the level of observational support for BT inclusion:

- **Type 1** events are those for which the available surface observations are sufficient to demonstrate conclusively that there is no real-world TC associated with the reanalysis thickness anomaly. A common example is an easterly wave with moderate thickness anomalies that ship observations reveal may have modest turning in the surface windfield, but no evidence suggesting there are no associated westerly or tropical storm force winds with the wave.
- **Type 2** events are those for which there are too few surface observations in the vicinity to make a meaningful judgment of whether a TC did or did not exist at the suggested location. This category includes cases for which there is observational support for a closed circulation but the thermodynamic structure of the cyclone is ambiguous. Type 2 events are most common in very low observation environments.
- **Type 3** events reflect those for which surface observations generally support the existence of a warm core, closed circulation, and tropical storm force winds at some point in the CE window, meaning the event is potentially a “missing” TC in accordance with the L08 classification criteria. In general, these occur in more densely observed environments, although on occasion one or two extremely compelling observations can singlehandedly result in Type 3 binning.

One caveat to this scheme is that CEs during the course of their existence in the 20CR can pass from one bin to another due to changes in organization of the feature itself or variations in environmental observation density. In general, a CE is scored as the “highest” bin it achieves in its lifetime. Thus, Type 2 classification supersedes Type 1, and Type 3 classification supersedes both Type 1 and Type 2. It should be stressed that this methodology is only designed to act as a probabilistic filter for CEs, and that any event identified would still require the more rigorous HURDAT reanalysis process, only after which would potential revisions to BT be considered. The results of applying this verification and classification technique to the actual CEs are given in the next section.

3.3 Results of Observational Verification of Candidate Events

3.3.1 General Characteristics of Verified Candidate Events

Applying the observational verification process detailed in Section 3.2 to the set of 68 CEs representing potential missing TCs and track extensions for the Atlantic Basin between June 1951 and November 1958 yields 34 Type 1, 20 Type 2, and 14 Type 3 classifications, or 50%, 29%, and 21% of the total, respectively. Proportional breakdowns by classification for the 277 total CE-days in the study period are very similar. The average normalized maximum 300-850 hPa thickness anomalies, calculated for each CE every six hours, are 1.92σ , 2.17σ , and 2.33σ for Type 1, Type 2, and Type 3 cases, respectively, as shown in Figure 3.8. This figure also plots the 95% confidence interval for each classification type. Notably, the confidence ranges for Type 1 and Type 3 CEs do not overlap. The confidence interval for Type 2 events overlaps and is broader than both other categories, which is an expected outcome given that the Type 2 bin contains both CEs that were “real-world” Type 1’s and “real-world” Type 3’s. This shows that subjective assessment of “confidence” in the CE’s chances of representing an actual TC from the observations agrees with the objectively-derived thickness anomaly metric from the 20CRv2.

The most important results of this assessment are summarized in Figure 3.9 and Figure 3.10, which show the six-hourly tracks of all 54 potential “missing TC” events and the 12 Type 3 CEs in the 20CRv2, respectively. Table 3.1, which contains a brief description of each of the 14 CEs classified as Type 3 events, shows there is strong observational evidence to suggest the existence of a real world TC associated with the reanalysis thickness anomalies. For each of these events, the table includes the portion of the basin where the CE is generally located, the mean normalized 300-850 hPa thickness anomaly observed in the 20CR over the event’s lifetime, and a brief description of some of the critical ship observations that led to the case’s classification as a Type 3 event. Table 3.1 indicates that many of the 14 events (including 12 potential missing TC cases and 2 potential track extensions to existing BT cyclones) are associated with observations that highly suggest the existence of a TC in accordance with the L08 criteria, including verified tropical storm force winds, low surface pressures, and clearly closed surface circulations. Additionally, Figure 3.10 demonstrates that the 12 Type 3 CEs

originate in climatologically favored regions for TC genesis and follow tracks that are common and realistic given seasonal steering currents. Qualitative descriptions from the reanalysis model along with quantitative verification data from ICOADS and the ISD for each of the 14 Type 3 events, along with the other 54 Type 1 and Type 2 CEs are provided as a supplement to this text in Appendix A. A detailed narrative description of a selection of representative case studies from Table 3.1 and elsewhere can be found in Chapter 4.

Since the data summarized in Table 3.1 and given in full in Appendix A is of immediate value to ongoing efforts to evaluate and improve the TC climatology of the Atlantic Basin, these results were shared freely with the HURDAT project team at the Atlantic Oceanographic and Meteorological Laboratory in Miami, FL. This close collaboration has yielded an independent check on the quality of this study's results, since some of the case studies have subsequently been subjected to the HURDAT's extremely rigorous verification process. With HURDAT revision process completed through the 1953 hurricane season, two of the Type 3 CEs listed in Table 3.1 have been recommended to the National Hurricane Center's Best Track Change Committee for inclusion in the TC climatology [*Hagen*, personal communication 2010]. These events are highlighted in bold in Table 3.1. While only three Type 3 events have been subjected to the scrutiny of the HURDAT project thus far, it is encouraging that two of the three have met the high standard for recommended addition to BT. These early successes lend credibility to the reanalysis methodology presented here.

3.3.2 Temporal Distribution of Verified Events

A macro-scale check on the efficacy of the verified CE data is to test how closely the cumulative distribution of cases conforms to the intraseasonal long-term TC incidence climatology first shown in Figure 1.3. Table 3.2, which breaks down the number of CEs for 1951-1958 by month and classification type, shows that just under half (32) of the 68 total CEs occur during the climatological peak months of the Atlantic TC season, August and September. However, the Type 3 events that have a better chance of being missing real world TCs are more likely during the latter half of the season, with October actually having the most Type 3 CEs (5).

This late-season skewness is plotted in Figure 3.11. Between 1 June and 30 November, this figure shows the total number of CEs occurring on a particular day, as well as the 20-day centered moving averages of both total CEs and exclusively Type 3 CEs. While the small sample

size ($N=68$) makes a perfectly Gaussian distribution unrealistic, the smoothed distribution of all CEs does generally resemble Figure 1.3, albeit with a somewhat late bias and a peak value averaging 3.0 CEs per day around 1 October. The displacement of the moving average of the Type 3 CEs is even more pronounced, with a maximum moving average value of about 1.0 Type 3 events per day around 10 October. It is likely that some of this effect is explained by the non-classification of subtropical cyclones during the 1950s. Since hybrid lows are most common in the fall as mid-latitude westerly incursions cause an increasingly baroclinic atmospheric environment over still-warm SSTs in the subtropical Atlantic, the number of CEs in late September and October may thus be somewhat artificially inflated. Other possible explanations include variations in ship tracks over the year, changes in favored genesis methods during the season, and simple chance due to the small number of years investigated. Further studies of additional pre-satellite era TC seasons are necessary to resolve this issue.

Finally, Figure 3.12 shows the distribution of the CEs within the three classification bins for each Atlantic hurricane season between 1951 and 1958. Results are unremarkable, with all seasons showing between 7 and 10 CEs with the exception of an outlier, 1955 (15 CEs). There may be a slight trend towards a higher proportion of Type 3 events by the end of the series. This could be due to increased observational density during the late 1950s compared to the early part of the decade (see Figure 3.4), but it is unlikely that this trend is of any statistical significance.

3.3.3 Geographic Distribution of Verified Events

The CEs generally are located throughout in the Atlantic Basin wherever cyclogenesis climatologically occurs, including the Cape Verde region, subtropical Atlantic, Gulf of Mexico, and the Caribbean Sea. Disallowing for overlap, 53% (47%) of events are primarily east (west) of 60°W. While the CEs themselves range across the whole Atlantic Basin, this is not necessarily true within each classification bin. As shown in Figure 3.13, the CEs are unevenly distributed between the two regions, with 15 (19) Type 1, 16 (4) Type 2, and 5 (9) Type 3 events in the eastern (western) half of the Atlantic. These figures correspond to 41% Type 1, 44% Type 2, and 15% Type 3 classification in the eastern half of the Basin, and 59% Type 1, 13% Type 2, and 28% Type 3 classification in the western half.

Not surprisingly, over 80% of Type 2 events are registered in the eastern half of the Atlantic Basin, where observational density remains quite poor in the middle part of the 20th

Century [Vecchi and Knutson, 2008]. As shown by the preponderance of eastern Atlantic Type 2 CEs in Figure 3.9, many of these cases involve tropical waves in the Cape Verde region that have very strong reanalysis signatures on order of $3-4\sigma$. While the available ship reports were often consistent with the existence of a TC near the 20CR thickness anomaly location, there were simply too few observations to make a credible case for Type 3 classification. For this reason, it is not surprising that a majority of the Type 3 cases are in the Gulf (3 CEs), Caribbean (2 CEs), or southwestern North Atlantic (4 CEs). Ship traffic and land observations in these regions are denser and more reliable, and the time integration of prior observations increases representation quality even during times of no observations. While there may be a smaller “pool” of missing TCs in these areas, there is also a much greater likelihood that the observational density will be sufficient to render a meaningful judgment on the CEs that are resolved.

To summarize, observational verification of the reanalysis-derived CEs was successful, yielding a strong case for addition to BT in one out of approximately five tries in the test seasons. This was accomplished with no *a priori* consultation with or input from ongoing BT reanalysis projects. However, selected results have subsequently been confirmed independently, and the HURDAT project researchers are actively consulting the output from this project. While there is some ambiguity and randomness inherent to the methodology, independent expert verification of some results along with the temporal and geographic presentation of the results, suggests a high confidence that the technique can reliably and effectively locate prospective TCs in the pre-satellite era. To provide more detail on the process by which CEs are binned and categorized, several case studies of events with differing levels of ground-truth observance are subsequently presented. Thus, Chapter 4 will shift the focus away from macro-measures of reanalysis model performance and to specific applications of the methodology in the context of operational revisions to TC climatology.

Figure 3.1: Normalized 300-850 hPa thickness anomaly in version 2 of the 20th Century Reanalysis for the North Atlantic Basin for 0000 UTC 18 October 1958, in σ . Figures 3.1, 3.2, and 3.3 show reanalysis output at 0000 UTC 18 October 1958. Note that while several local thickness anomaly maxima exceeding 2σ are observed in this figure, inspection of vorticity, MSLP, and streamline data in Figures 3.2 and 3.3 demonstrate that only the anomalies in the central Atlantic and western Gulf of Mexico are associated with potential surface cyclones and are considered CEs.

Figure 3.2: Same as Figure 3.1, except plot shows relative vorticity at 850 hPa, shaded in units of 10^{-5} s^{-1} and MSLP contoured for each 2 hPa from the 20CRv2.

Figure 3.3: Same as Figure 3.1, except plot shows 850 hPa streamlines from 20CRv2.

Figure 3.4: Major historical data sources added to ICOADS Release 2.5 [Woodruff *et al.*, 2010]. Horizontal green lines illustrate the time range of the original data sources. The annual numbers of reports are plotted as curves, blue for the previous R2.4, and red for R2.5. For clarity, the vertical scale is truncated at 9 million reports per year. Note the steady increase in annual reports during the 1950s.

Figure 3.5: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of the 20CR, overlaid with wind direction, wind speed, and surface pressure and temperature observations from all available ICOADS ship reports at 0000 UTC 18 October 1958. The upper left corner of each ship observation is the wind direction and wind speed in kt. The upper right corner is the surface temperature in $^{\circ}\text{C}$. The lower left corner are the last three digits of surface pressure in hPa (e.g., 1015.4 hPa is denoted 154). Synoptic time of the observation is in the lower right corner.

Figure 3.6: Cyclone phase space diagram [Hart 2003] showing the thermodynamic evolution of the candidate event between 1200 UTC 16 October 1958 and 0000 UTC 19 October 1958. This figure plots lower-level thermal wind on the x-axis and upper-level thermal wind on the y-axis, with the intensity of the cyclone represented by the size of the dot.

Figure 3.7: Same as Figure 3.6, except plotting low-level thermal wind against storm-relative thickness asymmetry.

Figure 3.8: Mean normalized thickness anomaly in 20CRv2 by CE classification type, with 95% confidence bounds.

Figure 3.9: Track map for all 1951-1958 Atlantic hurricane season “missing TC” CEs identified in 20CRv2, by classification type.

Figure 3.10: Track map for Type 3 1951-1958 Atlantic hurricane season “missing TC” CEs identified in 20CRv2, with individual event information.

1951- 1958 Atlantic Basin Candidate Events by Day of Occurance

Figure 3.11: Frequency of total candidate event occurrence by day for the 1951 through 1958 Atlantic Basin hurricane seasons. The black line represents raw daily totals. The aqua and red lines represent 20-day centered moving averages for all candidate events and Type 3 events, respectively.

Figure 3.12: Count of Atlantic candidate event types per calendar year for 1951-1958.

Figure 3.13: Verification of candidate event types in the Eastern and Western Atlantic Basins.

Table 3.1: Type 3 candidate events in the North Atlantic Basin for 1951-1958 hurricane seasons, with average thickness anomaly and key ship observations from ICOADS. Bold entries indicate events that have been recommended by the HURDAT project for inclusion in BT.

Candidate Event Dates	Location	Avg. Thickness Anomaly	Key Observations
15-17 July 1952	Gulf of Mexico	2.25	31 kt wind, 1007 hPa SLP reading
25-30 September 1952	Eastern Atlantic	2.3	Multiple west wind obs, 1005 hPa SLP
11-16 July 1953	Western Atlantic	2.35	Well-defined closed circulation, 40 kt wind
Late September 1953 (pre-Hurricane Gail)	Eastern Atlantic	N/A	25 kt winds, possible closed circulation
18-23 June 1954	Western Atlantic	1.72	Closed circulation from wind obs, 40 kt wind
14-18 September 1954	Gulf of Mexico	2.5	1005 hPa SLP, large area of 20-25 kt winds
5-10 September 1955	Gulf of Mexico	1.92	1008 hPa SLP, 25 kt winds, closed circulation
14-19 October 1956	Western Atlantic	1.55	996 hPa SLP, 55 kt wind, large area of gales
5-10 October 1957	Eastern Atlantic	2.31	23 kt west wind, 1006 hPa SLP
17-19 October 1957	Eastern Atlantic	1.75	31 kt wind observation, 1006 hPa SLP
1-5 November 1957	Caribbean Sea	1.68	32 kt wind, 10 kt west wind, 1005 hPa SLP
22-30 August 1958	Eastern Atlantic	1.81	28 kt SW wind with 1006 hPa SLP
Early October 1958 (pre-Hurricane Janice)	Caribbean Sea	N/A	25 kt wind and well-defined closed circulation
16-19 October 1958	Western Atlantic	1.29	58 kt wind, multiple 35 kt winds, 999 hPa SLP

Table 3.2: 1951-1958 North Atlantic Basin candidate event counts, by month and classification.

	June	July	August	September	October	November	Totals
Type 1	5	8	7	8	3	3	34
Type 2	3	2	7	5	3	0	20
Type 3	1	2	1	4	5	1	14
Totals	9	12	15	17	11	4	68

CHAPTER FOUR

CASE STUDIES

No matter how successful the performance of reanalysis-derived TC candidate event identification algorithm is in aggregate, revising and improving the TC climatology must be performed one case at a time. To more thoroughly demonstrate the process by which individual CEs are evaluated and classified by the 20CR, observations, and the synoptician, complete case studies of five CEs are presented. These cases were chosen because they cleanly represent some of the major analytical outcomes that are the end result of assessing a CE or historical TC. The possibilities detailed in this chapter are: negative evidence for the possible presence of a TC (Type 1 CE), not having enough observational data to make a determination (Type 2 CE), positive and compelling evidence for the possible presence of a TC (Type 3 CE), evidence for extending the track of a recorded cyclone beyond its current known positions, and evidence for merging and combining the tracks of two extant BT cyclones. Each of these types of case studies are represented in the 1951 through 1958 period within the northern Atlantic Basin.

4.1 Null Case: Candidate Event #1, July 1952

By far the most common outcome of the observational verification process is that the CE does not represent a credible addition to BT climatology. This result occurred in 50% (34/68) of the CEs identified by the 20CRv2 during the 1951 through 1958 hurricane seasons. This type of event was nearly equally common in the western and eastern halves of the Atlantic Basin. For a Type 1 classification to occur, there needs to be sufficient ground truth to demonstrate to a high degree of confidence that there is no TC associated with the 300-850 hPa thickness anomaly in the reanalysis. The density of ship reports required to meet this threshold varies from case to case based on the strength of evidence in the observations, but often even a small number of reports can be reasonably conclusive when they show very high surface pressures, little or no turning in the 10-m windfield, or very light surface winds. Individual data points are also considered in the

context of nearby observations to correct for poorly calibrated instruments that demonstrate persistent biases. While this study did not attempt to systematically correct for these biases, an awareness in the accuracy of archival ship reports informs the CE classification process.

CE #1 of the 1952 hurricane season moves generally westward from the northern Bahamas to the central Gulf of Mexico between 0000 UTC 1 July and 0000 UTC 5 July. This case exhibits a symmetrical and fairly high-amplitude thickness anomaly in the western Atlantic and Gulf of Mexico, but is determined through careful synoptic analysis to be unsupported by dense sea- and land-based observation platforms. Originating in a diffuse area of thickness anomalies that covers much of the Atlantic east of Florida in late June of 1952, CE #1 first becomes distinct in the thickness fields as a 1.5σ anomaly centered several hundred miles east of Melbourne, Florida at 0000 UTC 1 July. While Figure 4.1 shows that a SLP of 1010.5 hPa is observed near 28° N, 79° W, the surface windfield is very light (on the order of 5 to 10 kts) over south Florida and the Bahamas. Additionally, anti-cyclonic turning in the surface windfield is evident, with generally easterly or southeasterly winds along 25° N and southerly or southwesterly winds north of 30° N. Over the course of the 1 July, as the thickness anomalies increase to 2σ , westerly winds advance down the Florida peninsula. This is consistent with a weak stationary front or surface trough stalling over South Florida. Surface winds remain light, with a maximum speed of 16 kts near Bimini at 1200 UTC, and observed SLP from the ship reports remains between 1016 and 1018 hPa.

The thickness anomaly in the reanalysis continues to become better defined and more symmetric on 2 July and is centered very near 26° N 80° W at 1200 UTC. However, winds in the vicinity of the maximum remain less than 10 kts and are consistent with a weak surface trough. Occasional wind observations in excess of 30 kts are located north of 30° N due to an increasing pressure gradient as a surface high strengthens over the Eastern Seaboard. Seabreeze fronts are also observed on both the East Coast and Gulf Coast of Florida on 2 July, which are less likely to occur if there is a dominant synoptic feature like a TC in the vicinity. The surface trough slides westward overnight and 2σ thickness anomalies are centered in the eastern Gulf of Mexico near 26° N, 85° W at 1200 UTC 3 July as shown in Figure 4.2. However, the surface windfield remains light and chaotic in the region of the lowest SLP (1015 hPa). At 0000 UTC 4 July, west, southwest, and northeast wind observations are found in fairly close proximity to one another near 26° N, 87° W. However, the very light wind speeds of less than 10 kts and high SLP

suggest that either outflow boundaries from disorganized convection or an extremely weak mesoscale vortex are more likely explanations for these observations than the presence of a TC. The maximum thickness anomalies continue to weaken and become increasingly elongated west-to-east as the CE moves more rapidly northwest on 4 July. Figure 4.3 shows that by 1800 UTC, the suggested center from the 20CR is near 27° N, 90° W, accompanied by a broad area of 15-25 kt easterly winds with surface pressures in excess of 1016 hPa. There is no evidence for a surface circulation, and the thickness anomalies dissipate in the central Gulf early on 5 July.

CE #1 of the 1952 hurricane season is a good example of a case that is easily classified as a Type 1 event. While the 20CRv2 resolves tropospheric thickness anomalies that often exceed 2σ and are compact and symmetrical, there are no surface observations to support the existence of a TC anywhere in the vicinity of South Florida or the eastern Gulf of Mexico between 1 July and 5 July. Winds near the purported center are generally very weak, and surface pressures remain quite high over the lifetime of the CE. While a very weak surface circulation may exist briefly on 3 July and early on 4 July, there is no evidence to suggest that the vortex is sufficiently organized to merit TC classification. Additionally, since observational density is high over Florida and the Gulf, it is unlikely that more ship reports would dramatically change the results of this case study. Thus, CE #4 is classified as Type 1.

Subsequent to the results of this research being shared with the HURDAT project team, Andrew Hagen performed an independent study of 1952 CE #4, which concluded that “no gales or low pressures were recorded during the entire tropical portion of the lifetime of this system.” Therefore, it was not recommended for addition to the BT database [*Hagen*, personal communication 2010], confirming the negative results of this study. While the surface pressure and surface wind fields in the 20CR remained broadly consistent with ship observations, the modeled thickness anomalies did not correspond to a TC. Although the 20CR is nudged by assimilated surface data, it still is “capable” of producing spurious TCs. It is important to remember that real-world tropical waves and pre-genesis disturbances also produce positive anomalies in tropospheric thickness. Without sufficient observational evidence, these features will be are classified as Type 1 events, as is CE #4 during the 1952 hurricane season

4.2 Indeterminate Case: Candidate Event #4, September 1953

The second most common outcome of the verification process is that there are simply not enough reliable observations in the ICOADS or ISD databases to reach a meaningful conclusion as to whether the CE does or does not likely represent a missing real-world TC, i.e., a Type 2 classification. These CEs account for about 30% of all verified anomaly events. As noted in Section 3.3.3, Type 2 events mostly are found in the eastern half of the Atlantic Basin, where there were few ship tracks in the mid-20th Century. These CEs often presented strong thickness anomalies in the 20CR, and the observations that did exist suggested the presence of a TC. However, the observations often did not offer conclusive evidence of a closed circulation, making a Type 2 classification necessary.

One such CE is candidate event #4 of the 1953 hurricane season, which was active in the eastern tropical Atlantic between 0000 UTC 21 September and 1200 UTC 26 September. Candidate #4 first emerges from a monsoon trough early on 21 September, with a 300-850 hPa thickness anomaly of over 2σ centered near 7° N, 36° W as shown in Figure 4.4. Unfortunately, there is only one ship report within hundreds of miles in any direction from the CE. However, this observation (near 8° N, 35° W) is intriguing since it reports light due southerly winds, possibly indicating an incipient circulation center or amplified tropical wave axis just to its west. Even more interestingly, SLP with this report is approximately 1007 hPa, which is low enough to be consistent with a developing TC. This ship continues to be the only relevant observation throughout the day on 21 September, with winds increasing to southerly at 10 kts and pressure dropping to 1006 hPa as the thickness anomaly moves slowly west-northwest.

Even less information is available on 22 September to assess CE #4, since the continued west-northwesterly motion to near 10° N, 41° W by 1800 UTC leads to increased separation from the first ship. Another vessel far to the northeast of the CE reports easterly trade winds at about 15 kts. At 1200 UTC 23 September, the CE becomes much stronger in the 20CR thickness anomaly fields, with maximum normalized anomalies exceeding 3σ centered near 12° N, 42° W (see Figure 4.5). This occurs despite the nearest ship observation being located over 300 miles from the proposed center of circulation. Nonetheless, the 1008.5 hPa SLP observed at this distance may indicate that continued intensification is occurring. There are no further relevant observations on 23 September, and ships also remain distant from the anomaly maximum on 24

September as it moves slowly west-northwest. Once again, peripheral SLP observations remain quite low, generally 1010 hPa or less.

Early on 25 September, the 20CR thickness anomalies begin to elongate along 16° N, while a 27 kt sustained northeasterly wind observation is located well north near 22° N, 41° W. Still, there are no records of ships anywhere near the CE, which continues northwest over the day on 25 September. Figure 4.6 shows that by 0000 UTC 26 September, the 20CR analyzes the event as a weakening open trough along 18° N, 48° W which is beginning to merge with a broader region of warm thickness anomalies to its south and west. As was the case during the entire life of CE #4, there still are no observations from the southern semicircle of the possible circulation. The reanalysis model loses the CE by 1200 UTC 26 September north and east of the Lesser Antilles.

CE #4 of the 1953 hurricane season is a frustratingly elusive case. Despite over 36 consecutive hours of warm thickness anomalies exceeding 3σ in the 20CR fields, an examination of all available ship reports from ICOADS did not reveal any observations that would unambiguously demonstrate the presence of a TC in the vicinity of these anomalies. However, there are two points to consider: first, there were several observations, especially of surface pressure, that were impressive considering the likely distance to a theoretical TC's center. Second, there were no observations that were truly inconsistent with the presence of a real TC near where the 20CR resolves a modeled storm. Examining the very empty synoptic charts, it is easy to imagine that additional data points could realistically lead to either a positive or negative finding. However, until further observations emerge and provide more information on the case, this study finds that no empirical determination can be made with confidence, resulting in a Type 2 designation.

4.3 New Cyclone Case: Candidate Event #4, October 1958

The events of most interest to TC climatologists are those that verification demonstrates have the best chance of representing real world missing storms, also known as Type 3 cases. CE #4 of the 1958 hurricane season is the event selected to demonstrate the criteria needed to achieve this classification. This event moves generally north-northeast from Hispaniola to

Newfoundland between 0000 UTC 16 October and 0000 UTC 19 October. It first appears in the thickness anomaly plots as an elongated area of 1σ warm anomalies north and east of Puerto Rico at 0600 UTC 16 October. As shown in Figure 4.7, this anomaly is accompanied by an analyzed sub-1010 hPa low near 24° N, 68° W, at 1200 UTC that is confirmed by several ship observations near or below 1010 hPa. There are also three wind observations at this time exceeding 30 kts, including a 38 kt sustained east-northeasterly wind near 28° N, 68° W. A light west wind is also observed near 21° N, 71° W. Finally, cyclone phase space plots show a shallow, symmetric warm core structure within the 20CR on 16 October. Therefore, it is possible that a tropical or subtropical cyclone developed as early as 1200 UTC 16 October 1958, although the surface observations are not unambiguous at this time due to the possible existence of a trough axis extending to the southwest of the proposed surface center.

As the cyclone continued northeast on the evening of 16 October and early on 17 October, surface observations continue to show a vigorous circulation that is elongated southwest to northeast, even as SLP observations continue to fall to 1004 hPa near 28° N, 66° W at 0600 UTC 17 October, while a large area of winds exceeding 30 kts is located west, north, and northeast of the estimated circulation center. Maximum normalized thickness anomalies continue to increase to over 1.5σ by 1200 UTC 17 October, which is co-located with a 34 kt sustained wind out of the south near 30° N, 62° W. At the same time, the phase space diagrams in Figures 4.8 and 4.9 show increasing thermal asymmetry and a shallower warm core, which possibly indicates a somewhat subtropical cyclone structure within the 20CR. Nevertheless, the cyclone continues to intensify quickly on the evening of 17 October, with a pressure of 999.7 hPa and southeast winds of 40 kts near 34° N, 61° W, northeast winds sustained at 58 kts just to the north, and a number of wind observations supporting a less elongated closed circulation. These observations are displayed graphically in Figure 4.10.

At 0000 UTC on 18 October, a SLP observation of 999.9 hPa is coupled with a 58 kt sustained wind report out of the southwest near 35° N, 60° W. Another 27 kt west wind report just to the south indicates that the low-level circulation center of a vigorous tropical or subtropical cyclone is likely nearby. Early on 18 October, gale force winds expand outward to up to 250 miles from the surface center as the cyclone begins to interact with an extratropical low over eastern Canada (see Figure 4.11). Phase space data indicate that the transition of the CE to a non-tropical, cold core cyclone within the 20CR is complete by 1200 UTC 18 October. This is

supported by the decoupling of the warm thickness from the surface circulation on the synoptic maps. The CE is last tracked as a rapidly deepening extratropical low over Newfoundland at 0000 UTC on 19 October.

To summarize, the case for adding 1958 CE #4 to the Atlantic BT database is fairly compelling. In addition to approximately one dozen observations of sustained winds exceeding tropical storm force and of up to 58 kts as well as several sub-1000 hPa SLP reports, there is strong evidence to support a tightly closed surface circulation on the 17 October and early 18 October. While ambiguity remains regarding the thermodynamic evolution of the low, both phase space and thickness anomaly data suggest that the CE was at least partially tropical in nature. Therefore, this CE preliminarily satisfies the *Landsea* [2008] criteria for possible inclusion in BT pending further study, and is placed on the short list of 14 CEs from the original 68 to be the very highest priority for examination by the HURDAT project group.

4.4 Track Extension Case: Hurricane Janice, October 1958

Applications of the 20CR reanalysis technique are not limited to simply affirming or denying the hypothesis that a reanalysis-derived CE represents a real world TC. The method can also be used to evaluate the position and intensity records for pre-satellite era TCs, which the L04 demonstrates are very often incomplete and in need of revision. Although suggesting modifications to existing BT cyclone tracks is not the primary goal of this research, there were 11 cases in the 1951 through 1958 hurricane seasons for which a significant and persistent thickness anomaly either preceded or followed the track of a known cyclone. As mentioned in Section 4.1, pre-TC disturbances and waves also possess warm cores; so this in itself is not evidence for extending the TC track without support from historical ship reports. In two of these cases, observational data suggests that an expansion of the BT track may be warranted, pending further review.

Hurricane Janice in early October of 1958 is the case that is selected to represent this application of the study methodology. The currently accepted BT position data for Janice is given in Figure 4.11, showing the storm's known track beginning in the Northwestern Caribbean Sea at 0600 UTC 5 October, followed by generally northeastward motion over the Bahamas and

then the open Atlantic with intensification to Category 1 hurricane status on 7 October. Transition to an extratropical cyclone occurs over the open north Atlantic at 0000 UTC 12 October. The precursor disturbance to Janice is first noted in the 20CR thickness fields as a large area of 1.5σ anomalies near Hispaniola on 2 October. While this feature is accompanied by a surge in the easterly trade winds to 25 kts, and there is a SLP report of 1007.4 hPa near 17° N, 69° W, there is no evidence to suggest that anything other than some turning in the low-level windfield is occurring in the central Caribbean at that time. (This same ship reports a 1006 hPa SLP at 1200 UTC, but this seems too low when compared with other ship observations and may be biased low.) Still, a 33 kt sustained wind from the southeast is noted at 1800 UTC near 16° N, 70° W, showing that while a closed circulation is not yet present on 2 October, a very vigorous tropical wave axis is present.

Figure 4.12 shows the pre-Janice disturbance at 0000 UTC 3 October. While the strongest thickness anomalies are located (along with winds of 25-30 kts) in the vicinity of Jamaica, the 20CR closes off a 1008 hPa SLP contour on the strength of multiple ship reports of 1007 hPa in the southern Caribbean Sea, where an easterly-to-northerly turning in the surface windfield is noted along 80° W. This hints that surface organization is beginning to occur north of Panama. Throughout the day on 3 October, the wave axis slows to a stop in the western Caribbean, as west winds in Panama indicate that a weak surface vortex may have developed near 11° N, 79° W by 1800 UTC. Figure 4.13 at 0000 UTC 4 October displays a west wind observation near 11° N, 80° W, along with a large area of 25-30 kt east winds continuing south of Cuba and a large area of 1.5σ anomalies covering the Northwestern Caribbean. There are a large number of 1007 and 1008 hPa pressure observations, suggesting that the low is continuing to deepen and become better organized. While observations are sparse for much of the day on 4 October, it is apparent from the information available that the developing surface center is moving between north and north-northwest to near 17° N, 83° W by 1800 UTC while near gales continue over Cuba.

At 0000 UTC 5 October, Figure 4.14 shows that both surface observations and 20CRv2 thickness anomalies are in good agreement with the placement of a TC near 18° N, 82° W. A northwesterly wind report of 15 kts with a surface pressure of 1007 hPa at 17.5° N, 83° W and a broad area of east and southeasterly winds exceeding 25 kts north and west of Jamaica support this conclusion. Subsequent to the arrival of an Air Force reconnaissance aircraft early on 5

October, advisories were initiated by the National Hurricane Center at 0600 UTC (*NHC* 1958). Based on the totality of the observational study and evidence suggesting the existence of a closed circulation on the 4th, it is likely that the TC developed at least 6 h and very possibly 18 h prior to the initiation of position and intensity data in the currently existing BT database. While the possible changes to BT indicated by this case study are marginal, it does demonstrate the potential of the 20CR methodology to signal events where track extensions to existing TCs in the pre-satellite era may be merited.

4.5 Merging Cyclones Case: Hurricane Gail/TS #11, September 1953

Although this final application of the technique is unlikely to be used frequently, it can potentially correct the serious error of a single historical TC being listed twice in the BT dataset. While such cases likely are uncommon, there is such an occurrence during the study timeframe, as first noted by the HURDAT project team [*Hagen*, personal communication 2010]. (This is the only one of the five case studies that was performed with prior knowledge of a preliminary external BT revision, and was analyzed by the 20CR technique at the specific request of the HURDAT reanalysis team.) The BT currently has Hurricane Gail developing on 2 October 1953 at 0600 UTC in the eastern tropical Atlantic and dissipating along 50° W at 1800 UTC 5 October. Concomitant with Gail is Tropical Storm #11 which is active between 0600 UTC 5 October and 0000 UTC 9 October north and east of the Lesser Antilles. Historical tracks of these “two” TCs are found in Figure 4.15. Note that TS #11 originates a mere several hundred miles northwest of Gail early on 5 October. While not unprecedented, it is unusual for tropical cyclogenesis to occur in such close proximity to another established TC, especially since Gail is analyzed at hurricane intensity on 4 October and would be expected to induce strong horizontal and vertical wind shear over any disturbances in its vicinity. This reasoning leads to suspicion of the BT’s solutions for Gail and TS #11.

This verification case is distinct from the previous four cases since it involves two known TCs in the 20CR. This situation dramatically changes how the storms are resolved in the reanalysis because an estimated MSLP is directly assimilated into the model as an “observation.” Therefore, Figure 4.16 shows an extremely strong (4σ) localized thickness anomaly maximum at

0000 UTC 4 October near 13° N, 44° W in association with the BT observation for Hurricane Gail. However, the ship observations themselves indicate that the true center may lie several degrees to the north. This assessment is also supported by the 20CR thickness anomaly fields, which are very asymmetrical with a large area of 2σ anomalies extending well north of Gail. While there are few surface observations in the vicinity on 4 October, the SLP fields and thickness anomalies in the 20CRv2 become increasingly elongated. Another key observation is that the reanalyzed center of Gail begins to be located several degrees northeast of the BT position. Figure 4.17 shows the 1800 UTC fields, with 4σ anomalies reaching as far north as 21° N. This uncertainty in the analysis is a strong indication that the 20CR is deeming the BT-derived observations unrealistic and substituting a more likely scenario.

This trend continues on 5 October when the 20CR resolves a single TC moving northwest approximately halfway between the BT position data for Gail and TS #11. Unfortunately, there remain no ship reports nearby to help refine this position estimate. However, those wind and pressure observations that are available are more consistent with a single slow-moving and large TC rather than two systems. By 0000 UTC 6 October, the 20CR has essentially “settled in” to the BT position estimate, placing a symmetric thickness anomaly very close to 19° N, 44° W (see Figure 4.18). This is only about 2 degrees away (or one 20CR gridpoint) from the BT position. Over the next 24 hours, the 20CR track gradually asymptotes toward the BT track data for TS #11, with no further serious deviations for the remainder of its existence.

While ground truth data is scarce, the 20CR is extremely skeptical of Best Track’s two-storm initial solution. At no point during the lifetimes of both Hurricane Gail and Tropical Storm #11 are there two distinct anomaly maxima. Additionally, despite assimilating the dubious BT SLP observations for “both” cyclones into the 20CRv2, the reanalysis model places SLP minima well away from the BT tracks and maintains a single contiguous center on 4-6 October that is similar to the new unified Gail/TS #11 track proposed by the HURDAT project shown in Figure 4.19. The 20CRv2 assessment of the synoptic situation in the eastern Atlantic Ocean in early October 1953 increases confidence in the TC track merger hypothesis and has subsequently been used by the HURDAT group to propose to the Best Track Change Committee that TS #11 be combined with the track data for Hurricane Gail [*Hagen*, personal communication 2010].

Normalized 300–850hPa Thickness Anomaly (sigma) and MSLP (hPa; contoured) for 1952070100

Figure 4.1: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of 20CR, overlaid with wind direction, wind speed, and surface pressure observations from all available ICOADS ship reports at 0000 UTC 1 July 1952. This plot shows candidate event #4 of the 1952 hurricane season. For all such figures in Chapter 4, the upper left corner of each ship observation is the wind direction. The upper right corner is the wind speed in kt. The lower left corner are the last three digits of surface pressure in hPa (e.g., 1015.4 hPa is denoted 154). Synoptic time of the observation is in the lower right corner.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1952070312

Figure 4.2: Same as Figure 4.1, but for 1200 UTC 3 July 1952.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1952070418

Figure 4.3: Same as Figure 4.1, but for 1200 UTC 3 July 1952.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953092106

Figure 4.4: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of 20CR, overlayed with wind direction, wind speed, and surface pressure observations from all available ICOADS ship reports at 0600 UTC 21 September 1953. This plot shows candidate event #4 of the 1953 hurricane season.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953092312

Figure 4.5: Same as Figure 4.4, but for 1200 UTC 23 September 1953.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953092600

Figure 4.6: Same as Figure 4.4, but for 0000 UTC 26 September 1953.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958101612

Figure 4.7: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of 20CR, overlayed with wind direction, wind speed, and surface pressure observations from all available ICOADS ship reports at 1200 UTC 16 October 1958. This plot shows candidate event #4 of the 1958 hurricane season.

Figure 4.8: Cyclone phase space diagram [Hart 2003] showing the thermodynamic evolution of candidate event #4 between 1200 UTC 16 October 1958 and 0000 UTC 19 October 1958. This figure plots lower-level thermal wind on the x-axis and upper-level thermal wind on the y-axis, with the intensity of the cyclone represented by the size of the dot.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958101718

Figure 4.9: Same as Figure 4.7, but for 1800 UTC 17 October 1958.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958101812

Figure 4.10: Same as Figure 4.7, but for 1200 UTC 18 October 1958.

Figure 4.11: Best-Track position and intensity data for Hurricane Janice, active between 0600 UTC 5 October 1958 and 0600 UTC 13 October 1958. Maximum sustained wind is denoted by line color. Courtesy: UNISYS (<http://weather.unisys.com/hurricane/atlantic/1958/index.html>).

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958100300

Figure 4.12: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of 20CR, overlaid with wind direction, wind speed, and surface pressure observations from all available ICOADS ship reports at 0000 UTC 3 October 1958. This plot shows the precursor disturbance to Hurricane Janice.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958100400

Figure 4.13: Same as Figure 4.12, but for 0000 UTC 4 October 1958.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1958100500

Figure 4.14: Same as Figure 4.12, but for 0000 UTC 5 October 1958.

Figure 4.15: Overlaid Best-Track position and intensity data for Hurricane Gail, active between 0600 UTC 2 October 1953 and 1800 UTC 5 October 1953, and TS #11, active between 0600 UTC 5 October 1953 and 0000 UTC 9 October 1953. Sustained wind from BT is denoted by line color. Courtesy: UNISYS (<http://weather.unisys.com/hurricane/atlantic/1953/index.html>)

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953100400

Figure 4.16: Normalized 300-850 hPa thickness anomalies (shaded, in σ) and MSLP (contoured at an interval of 2 hPa) in version 2 of 20CR, overlaid with wind direction, wind speed, and surface pressure observations from all available ICOADS ship reports at 0000 UTC 4 October 1953. This plot shows the thickness anomaly associated with Hurricane Gail and TS #11.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953100418

Figure 4.17: Same as Figure 4.16, but for 1800 UTC 4 October 1953.

Normalized 300–850hPa Thickness Anomaly (sigma) and
MSLP (hPa; contoured) for 1953100600

Figure 4.18: Same as Figure 4.16, but for 0000 UTC 6 October 1953.

Figure 4.19: Hypothetical track map of the merged Hurricane Gail/TS #11 TC. Source: Unisys/HURDAT [*Hagen*, personal communication 2010].

CHAPTER FIVE

THE EASTERN PACIFIC BASIN

Successes in the objective identification of Atlantic Basin CEs that are subsequently shown in ICOADS data to be possible TCs offers strong evidence that the current technique can suggest meaningful revisions to the existing TC climatology. With nearly 30% of the CEs for which sufficient ship reports exist (Type 1 and Type 3 events) found to be potentially missing TCs, the technique may enhance the efficiency of existing efforts such as the HURDAT project by directing their resources towards areas most likely to yield changes to the BT. In addition, Chapter 4 demonstrated the versatility of the study's technique in a number of synoptically distinct case studies. These results raise the question of whether the study method is broadly applicable to other TC basins and timeframes outside of the 1951-1958 hurricane seasons. This chapter will address this question of spatial extension of the method by applying the 20CR technique to the East Pacific Basin.

Despite accounting for approximately one-fifth of total annual TC activity globally, the historical record of TC activity in the eastern North Pacific Basin is woefully inadequate. As record-keeping only begins in 1949, the resulting biases in climatology have led to difficulties in establishing long-term global trends in cyclone activity and accurately quantifying risk to an even greater extent than the incomplete Atlantic TC records. This area of sparse data is caused by several factors. First, unlike the Atlantic Basin, where the general direction of storm propagation is towards populated land areas and common cyclone tracks are intersected by shipping routes, common cyclogenesis regions in the eastern Pacific Basin (EPAC) are lightly observed, and storms typically move away from landmasses. Therefore, despite the fact that the Eastern Pacific warm pool is the most prolific producer of TCs per unit area in the world [*Cronin et al.*, 2002], the climatological record for the EPAC begins nearly 100 years after a comparable database for the North Atlantic. Real-time satellite coverage was not reliably available for the full EPAC Basin until the 1970s. Track and intensity information are also extremely fragmentary for the first several decades of the dataset, with Figure 5.1 showing a strong increase in observed TC activity coinciding with the beginning of satellite imagery availability in 1971. These

characteristics make the Eastern Pacific Basin an ideal test for whether it is possible to successfully apply the 20CR methodology to other TC basins.

To accomplish this test, 300-850 hPa layer thickness climatology was calculated for the EPAC using an abbreviated version of the process described in detail in Chapter 2. TC-masked means and variances were calculated for the 20CRv1 and 20CRv2 over the region 0 - 30° N, 80 - 160W, where the vast majority of EPAC cyclogenesis occurs. Subsequently, existing climatological storm tracks are used to assess the mean normalized response of layer thickness to TC passage, as in Section 2.2. Figure 5.2 shows the normalized response in the 20CRv2 to TC passage in the Eastern Pacific. Compared with a similar plot for the North Atlantic Basin (Figure 2.6), the morphology of the response curves are similar, although the magnitude of peak response is reduced by approximately 40% in the EPAC. This is likely due to the overall lower quality of the climatological database in this basin, since there is no effort comparable to the HURDAT project currently active in the EPAC. Nonetheless, these results show that the 20CR reanalysis resolves TCs as warm-core cyclones and lends credibility to using the 20CR as a tool to search for TC CEs in the EPAC.

With the reanalysis climatology in hand, plots of 20CRv2 normalized thickness anomalies, estimated SLP, low-level vorticity, and low-level windfield were made for each 12-hour period between June 1 and November 30 for the 1951-1958 EPAC hurricane seasons, as done for the Atlantic Basin. These maps were analyzed in accordance with the guidelines described in Section 3.1, resulting in the identification of 49 CEs during the period. These 49 CEs represent 13 existing BT cyclone track extensions and 36 potential “missing TC” events. Observational verification of these 49 events in the ICOADS database using individual maps was performed each six hours over the life of each CE. Results yielded a distribution of 17 Type 1, 24 Type 2 events, and 8 Type 3 events. These values represent approximately 35%, 49%, and 16% of the total number of CEs, respectively. Included in Type 3 are both events in which a potential “missing TC” is identified by the 20CR (4 CEs) and those for which evidence for a track extension to an existing cyclone may be warranted (4 CEs). The 49 CEs are distributed fairly proportionately to the overall seasonal climatology as shown in Table 5.1, with peak CE occurrence during August and September.

The observational verification of the EPAC CEs exhibits significantly greater ambiguity than the results for the Atlantic Basin, in which the 68 CEs between June of 1951 and November

of 1958 consisted of 34 Type 1, 20 Type 2 events, and 14 Type 3 events, or 50%, 29%, and 21%, respectively. The increased prevalence of Type 2 events in the EPAC is not surprising since ship traffic in the EPAC development region is less much dense than the Atlantic Basin. Figure 5.3 shows an example of the challenges of verifying a thickness anomaly CE in the open Eastern Pacific. With the nearest surface observation many hundreds of miles northwest of the reanalysis-indicated surface center, this event was classified as a Type 2. Brief descriptions of all 49 CEs can be found in Appendix B.

The “hit rate” of one Type 3 CE per season during the 1951 through 1958 EPAC hurricane seasons is less than might be expected. Given that aggregate seasonal activity during the 1950s lags well behind the long-term climatological average of 15 TCs per year (see Figure 5.1), it stands to reason that there are a greater number of “missing storms” to be found in the EPAC than the Atlantic for these years. However, the methodology did not locate large numbers of Type 3 events, likely for some combination of several possible reasons. First, the aforementioned paucity of ship reports in the EPAC during hurricane season suggest no relevant observations exist for some TCs; thus, these TCs will never be added to the BT. Second, for several years in the middle of the decade, persistent negative thickness anomalies covered much of the main development region, making it difficult to identify CEs. Finally, as a proof-of-concept and given the limitations, the synoptic analysis was less exhaustive and more error-prone than performed for the Atlantic Basin. Still, the 20CR was able to successfully identify a non-trivial quantity of CEs for which a solid case can be made proposing addition to EPAC TC climatology. Suggestions for modifying the study technique that may rectify these errors and improve the efficacy of the method are discussed in the next chapter.

Figure 5.1: Seasonal activity in the East Pacific Basin for the years 1948 through 2008, categorized by tropical storm, hurricane, and major hurricane intensity. Dashed lines are individual yearly totals, and the solid lines indicate 10-year trailing moving averages for each bin.

Figure 5.2: Normalized 300-850 hPa thickness anomalies for sixty days centered on TC passage in version 2 of 20CR for the 1948 to 2008 East Pacific Basin hurricane seasons. Results are categorized by the maximum sustained wind at TC passage as tropical storms (17 to 32 m s^{-1}), minor hurricanes (33 to 49 m s^{-1}), and major hurricanes ($\geq 50 \text{ m s}^{-1}$), along with the number of six-hourly TC position points in Best Track belonging to each bin.

Table 5.1: 1951-1958 Eastern Pacific Basin candidate event counts, by month and classification.

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CHAPTER SIX

CONCLUSIONS AND FUTURE WORK

Initial results from the 1951-1958 East Pacific hurricane seasons are not as robust as those from the Atlantic Basin due to inferior data availability and observational density. However, as in the Atlantic Basin, the 20th Century Reanalysis was able to identify a potential missing TC or track extension in about 30% of the cases for which there were sufficient observations to make a determination (8 of 25 Type 1 or Type 3 cases). Therefore, while the first foray into revising the climatology of a non-Atlantic Basin did not yield dramatic changes to BT, as a proof-of-concept it demonstrates that the methodology is not specific to one basin and can successfully be ported to other cyclogenesis regions. As such, the result opens the door for many possible future applications of the reanalysis methodology described. This chapter offers a brief summary of the research project and concludes with thoughts on future improvements, extensions, and applications of the study technique that may yield a broader understanding of TC climatology.

6.1 Summary

This project has attempted to develop an empirical and at least partially objective method to rapidly identify the events in the pre-satellite era that are most likely to merit addition to the BT TC database. This goal was undertaken with the idea of providing both active operational support to extant TC reanalysis projects such as the HURDAT project and to yield a technique that independently is capable of proposing revisions to the climatological record. To briefly summarize the study methodology, an investigation of the characteristic signatures of TC passage in the newly-released 20CR dataset reveals that TCs are accompanied by significant and consistent anomalies versus local climatology in 300-850 hPa layer thickness. These cases of warm anomalies in the deep tropics were next identified in the 20CR and filtered by thermodynamic structure, which yielded approximately 60 candidate cases in the Atlantic Basin for the 1951 and 1958 test seasons in which persistent warm-core anomalies did not correspond

to an existing BT cyclone. Verifying these events using synoptic observations from the ICOADS database of historical ship observations and cyclone phase space diagrams further narrows the number of potential additions to Best Track in this time frame to roughly one dozen, or between one and two per year. Finally, several detailed case studies representing the range of possible outcomes of the verification process with respect to single CEs showed that the potential revisions were warranted by available information.

The current successes in locating “missing TCs” in the Atlantic Basin indicate that historical reanalysis datasets are a useful tool in focusing and directing efforts to improve the climatological database of historical TCs. Not only did this technique identify numerous candidates for addition to Best-Track, several of these selections have already been positively assessed by the HURDAT reanalysis project and formally recommended for addition to the climatological record. These results, along with those from a quick but promising look into the East Pacific Basin, suggest that the 20th Century Reanalysis in concert with comprehensive observational datasets can act as a powerful lens into the past that could eventually enhance the interpretation of long-term trends in seasonal activity and aid our ability to answer key questions regarding the nature and causation of TCs.

6.2 Future Work

The most obvious future direction for this research is to apply the 20CR technique globally to all basins in which TC development occurs. Outside the Atlantic and Eastern Pacific, for which the datasets are maintained by the NHC, climatological records are often incomplete, divided between various forecasting agencies that disagree on track and intensity data, and riddled with systemic errors [*Knapp et al.*, 2010], with the IBTraCS project only recently codifying these sources in a single database. In the Western Pacific and Indian Oceans, climatological data extends only as far back as 1945. Additionally, satellite coverage was not available for these basins prior to 1979, meaning that there also are potentially a large number of missing TCs after the beginning of recordkeeping. While the amount of information that can be added to IBTrACS is dependent on the density and quality of observations in ICOADS, a first look at TC climatology for the Indian and Pacific Oceans between 1886 through 1944 is feasible

using the methodology developed here. Furthermore, the reanalysis could improve the quality of records in these basins between 1945 through 1978. By the same token, verifying reanalysis CEs for the years 1886 through 1910 in the Atlantic Basin may also yield additional missing TCs, since the HURDAT project studied these years prior to the development of the more comprehensive ICOADS dataset. Standardizing the beginning date of climatological records across all ocean basins, even with imperfect observational verification, would provide extremely valuable information for those seeking to better quantify and predict long-term trends in TC activity and whether such changes are cyclical or anthropogenic in nature.

The results from the Atlantic and East Pacific Basins are promising and suggest a panoply of new directions for future research. However, the limitations of these results point out areas in which the methodology can be improved or modified. One potential improvement is the process by which CEs are identified. In the current iteration, CEs are identified manually by a synoptician inspecting a three-panel map of the basin, plotting thickness anomalies, SLP, vorticity, and streamlines every 12 hours. Although this process worked well for eight hurricane seasons in two basins, it would likely be excessively time-consuming over four additional basins and the nearly 100 years that require climatological revision. One of the major advantages of the 20CR-based methodology is that it is both more efficient and more thorough than case-by-case reanalysis. Thus, additional efforts to more fully automate the CE identification process would benefit the efficacy and usefulness of the method by allowing the synoptician to focus on the observational verification process. Another problem is that by plotting absolute normalized thickness anomalies, it is more difficult to identify CEs in years in which there is a cold interannual bias in the 300-850 hPa thickness fields. In these years, like 1954 and 1955 in the EPAC, even lows that are well-organized in the low-level vorticity and streamline fields do not have normalized thickness anomalies exceeding 1 or 1.5 σ and thus do not meet the definition of a CEs. Modifying the thickness anomaly criteria to correct for an interannual bias or measuring thickness anomalies relative to the background field could increase the method's ability to identify promising CEs. This could potentially bring the number of missing TCs found by the 20CR/ICOADS methodology closer to the potential maximum number that can be found.

A final speculative idea could extend the method even further, but require extensive testing before results could be confidently deemed meaningful. This approach would extend the work of *Emanuel* [2010] by investigating whether there is a relationship between the number and

intensity of TC-like events appearing within the 20CR and aggregate measures of confirmed seasonal activity. In order for this idea to demonstrate merit, it would be necessary to show that annual CE counts have a statistically significant relationship with satellite era seasonal TC activity, when climatology is more trustworthy. If such a relationship is found, it would be powerful because it would allow at least a rough estimate of net seasonal activity in each basin to be backed out of the CE frequency data. Even with a very broad range of uncertainty, these activity estimates would be very valuable for investigations into the interannual variability of TC activity and fundamental questions of the broader role of TCs in climate.

APPENDIX A

DESCRIPTION OF ATLANTIC BASIN CANDIDATE EVENTS, 1951-1958

As described in Chapter 3, Type 1 CEs are those that demonstrate fairly conclusively that there is no TC associated with the thickness anomaly from reanalysis. Type 2 events are those for which there are too few surface observations in the vicinity to come to a meaningful judgment, and Type 3 events reflect those for which surface observations generally support that a closed circulation, warm core, and strong winds are associated with the anomaly at some point in the CE window.

1951: 5 Type 1, 2 Type 2, 0 Type 3

1. 6/29/00Z-7/2/00: Tropical wave stalls and gradually becomes better defined in the Bay of Campeche by 6/29, large area of 2sd, closed 1008 hPa contour, +vort. Slow NW motion and 3sd contour on 6/30. Crosses Mexican coast near 22N 97W on 7/2.

Verification: No relevant obs in BoC 6/29; 1009slp 23n 96w 6/30/00z but obs seem trough-like, no closed circ; 1009slp in BoC 30/18z, moves onshore 7/1. TYPE 1.

2. 7/15/00Z-7/19/00Z : Tropical wave approaches Lesser Antilles on 7/15 with sig anoms. 2sd anoms and +vort near PR on 7/16 with more cyclonic turning. Crosses Cuba on 7/18 and weakens, lost in GoM on 7/19.

V: Straight NE trades 7/15, pressures 1015slp, 10-15 ne winds in PR 7/16/00z, 1013 press, wave axis near Hisp 7/16/12z, clearly no closed circ 7/17-18, merges w trough 7/18/12z. TYPE 1.

Tropical Storm Baker: Possible track extension to 8/1 near 17N 50W.

V: No evidence prior to classification. TYPE 1.

3. 8/16/00Z-8/23/12Z: Tropical wave w cyclonic turning south of 14N along 48W. Elongated area of

sig anoms. Near 16N 60W on 8/19/00Z. NW movement to near 23N 68W on 8/21, remains analyzed as open wave, some pressure reflection. Recurves and centered near 28N 68W on 8/23, crosses near Bermuda with extratropical transition (?) on evening of 8/23.

V: 25kt E trades well N 8/16/12z, no evidence of circ though sparse obs 17-18; wave axis crosses LA 8/19/12z with some turning but no circ, 1012slp; 1011slp but light winds 8/20/12z, non-tropical low develops with W winds 32n 65w 8/21/12z moving past Bermuda. TYPE 1.

4. 8/23/12Z-8/29/00Z: Sig anoms 2sd+ embedded in large area of +anoms, centered near 10N 52W, +vort sub 1012 pressures and cyclonic turning on 8/23. Crosses Lesser Antilles and near 13N 62W with little change in structure. General WNW movement and near western end of Haiti on 8/27, sub 1010, high amplitude turning and 2sd+ anoms. Probably near Cozumel on 8/29/00Z, signal moves inland into Central America.

V: TW with NE/SE wind and 1011slp along 54w on 8/24 12z winds of 27kt near 13n 60w, lt. NW winds in Trinidad, 1011slp; 1008slp Trinidad 18z; E 25kt and 1009slp 13.5n 64w 25/6z; 13kt N wind, 1009slp 25/18z; 1008slp 14n 68w 26/00z; cyclonic turning near Jamaica 8/27/12z, large area of NE trades in Carib around 20kt w 1010slp; some NW winds in Honduras and Nicar as center nears C, 1008slp but weak winds 28/12z. TYPE 2.

5. 9/26/00Z-10/1/12Z: Small area of sig anoms in Southern Caribbean near 13N 80W with small closed circulation and open 1008 hpa contour. Feature drifts south and west on 9/27 to near 12.5N 82W with no change in intensity. Lingers near Costa Rica until 10/1, may or may not be related to genesis of TS How on 9/28.

V: lt E, NE, SW winds in S Carib 26/12, some 1008slp reports 9/27 but no clear center, lt NW winds on Nic coast 27/12z; 20kt S wind 28/00z; lt W winds and 1004 slp in Costa Rica 12z; pressures rise 9/29 as winds become variable in S Carib, gradual slackening of winds through 10/1. TYPE 1.

6. 10/16/12Z-10/22/00Z: Large, well-defined circulation with closed 1010 low and 2sd anoms in far eastern Atlantic near 11N 23W on 10/16. Moves slowly WNW and deepens to 1008 and 3sd on 10/18 near 13N 27W. Slowly weakens through 10/21 near 15N 38W. Absorbed by front along 40W on 10/22.

V: WNW 13 kt winds and 1007 slp on 16/18z; 1005slp 17/6z 14n 22w; 22kt, 24kt winds in CVI

17/12z, few obs 10/18, 25 kt E wind 15n 25w; lt w wind 9n 31w 19/12z, no obs 10/20, 10kt NNW wind 1010slp 21/00z, elongates in no obs region 10/22. TYPE 2.

1952: 6 Type 1, 1 Type 2, 2 Type 3

1. 7/1/00Z-7/5/00Z: Low pressure develops over northern Bahamas on 7/1 after slow separation from front on 7/1. Turning in sfc windfield. Crosses S Florida on 7/3 with cc analyzed. Lost on 7/5 near 25N 90W.

V: High SLP and trough-like wind 7/1, v weak vortex may be near WPB 2/18z, 1013 slp, weak wind/high pres 7/3 as lowest slp moves into EGoM, chaotic/weak windfield 18z, 27kt Se wind 4/12z but no CC and high pres. TYPE 1.

2. 7/15/12Z-7/17/00Z: Tropical wave enters Bay of Campeche on 7/15. Deepens to sub-1008 closed circulation centered near 27N 96W by 7/16 12Z, thickness anomalies over 3sd present. Inland over S. Texas by 7/17 00Z, estimated landfall Kenedy County.

V: 22 kt NW ind 20N 96W 15/18z, 1009slp; 1007 slp 16/00z; 31 kt SE wind 26.5n 92w 06z, lt W wind Brownsville; NW wind TX coast, s wind and 1008slp offshore, circ near 27.5N 95W, several 25kt obs to east, onshore near Corpus Christi 18z, multiple 1007slp onshore 18/00z. TYPE 3.

3. 8/1/00Z-8/6/00Z: CV wave with cc analyzed near 11.5N 25W on 8/1. CC and closed 1012 contour w 2sd+ anomalies centered near 12N 38W on 8/3/00Z. Large area of anomalies with 3sd max, open wave along 52W by 8/5/00Z. Signature lost nearing Lesser Antillies on the 6th.

V: Few obs 8/1, SW 15kt wind 8n 32w w 1010slp 2/18z; more lt W wind south of 9N 3/18z, 1010slp; lt NW wind 11n 45w 1010slp 4/6z; 15kt E wind 4/12z 12n 46w; open wave crosses LA 8/5-6. TYPE 2.

4. 8/15/12Z-8/18/00Z: Sig anoms near 15N 27W on 8/15 with cc. Generally WNW movement with gradual weakening, lost near 17N 40W on 8/18/00Z.

V: No evidence of closed circ near CV 8/15, 13kt W wind 10n 25w but 1015 slp 16/00z, few obs but consistent with weak open wave. TYPE 1.

5. 9/2/12Z-9/7/00Z: Tropical wave with sig anoms near 20N 73W on 9/2. Transits Cuba on 9/3.

Centered in Yucatan Channel with closed circulation on 9/5/00Z, pressures 1010 hPa. Weak reflection in Bay of Campeche on 9/7.

V: No evidence of circulation near Cuba 9/3, not much turning in sfc windfield 9/4, slp generally 1012, straight E winds in NW Carib 4/12z and 9/5, no evidence even for TW on 9/6. TYPE 1.

6. 9/10/00Z-9/13/00Z: Closed circulation, closed 1012 contour and large area of positive vorticity centered near 17N 50W on 9/10. Moves WNW to near 20N 61W on 9/12/00Z. Sheared apart north of PR on 9/13.

V: Lt SE winds with questionable 1008slp near 20n 52w 9/10/06z; lt SW wind 20n 54w 10/12z; E trades only 11/00z-18z; SW 16kt wind with 1008slp 17n 60w 12/00z but E trades in N LA 06z-18z no reflection 9/13/00z. TYPE 1.

Hurricane Dog: possible eastward track extension on 9/24-9/26.

V: No evidence for track extension. TYPE 1.

7. 9/25/12Z-9/30/00Z: High-amplitude TW with large area of 2sd+ anoms south of CV near 10N 24W on 9/25. Deepens with cc and 1010 CL on 9/26, 1006 CL with large area of +vort and 3sd deviations centered near 13N 29.5W on 9/27/00Z. Impressively well defined. Moves slowly north and spins down on 9/28-29, lost near 18N 32W on 9/30.

V: N, WNW winds near 12n 25 w 13kt, 9/25/12z, s wind 19kt 14n 18w, 1007slp 18z; 1008slp w 13kt SW wind 12 25w, 28kt NNE CV 26/00z; WNW 5kt 1006slp 20/06z, possible circ near 14n 25w 12z, 1005.8slp; 24kt SW wind 18z 14n 27w, 1006 slp well E of center 27/06z, 1005slp with 18kt N wind 15n 30w 27/12z, weakens and moves N 9/28, occasional NW wind reports 9/28-29 but obs. TYPE 3.

8. 10/03/00Z-10/6/00Z: Low gradually separatates from frontal zone and becomes warm-core on 10/03 near 24N 52W. Closed circulation and 1014 contour with 3sd+ anoms. Moves slowly NW to 25N 55W, merges with front on 10/6.

V: Lt winds and very elongated circ 10/3, high slp, no evidence for a TC 10/4, troughlike on 10/5, frontal merger 10/6. TYPE 1.

1953: 2 Type 1, 4 Type 2, 1 Type 3

1. 6/28/00Z-6/29/12Z: Large area of sig anoms in western Gulf of Mexico with general cyclonic turning along 95W on 6/28. Possibly moves inland over South Padre Island late on 6/29.

V: General area of circ 27n 94w, large area of 1010slp, several south winds 20-25kt, W winds onshore 6/29/18z, 32kt E ind 29n 94w at 29/6z. TYPE 2.

2. 7/11/12Z-7/16/00Z: Sig anoms in Florida Staits with +vort and closed 1012 contour near north coast of Cuba on 7/11. Better resolved on 7/12 with closed circ and 1010 closed, 2sd anoms moving past SE FL coast. Near 28N 77W on 7/13/12Z with 3sd anoms, large closed circulation. 1008 closed near 30N 76W at 7/14/00Z. Moves rapidly NE on 7/15 to near 38N 70W on 7/15/12Z and loses tropical characteristics in Canadian Maritimes on 7/16.

V: Weak circ possible near 25n 82.5w 7/11/18z, 1009slp in Keys and 22kt SW winds MIA, WSW wind EYW; 1006slp near Lk. Okeechobee, N/S/E/W winds all reposted 12/06z with circ inland over S FL; S wind 30kt 28n 78w, circ emerges near MLB 12z, CC near 28n 78w 13/00z; 29n 76w, 1005slp 30n 77w 6z; 30kt E wind 30n 76w 12z; 14/00z 1004slp, est center 30n 74, several 30kt wind obs, circ near 32n 74w 6z; 30kt ob 12z, windfield starts to broaden NE; near 34n 74w, 37n 73w 15/06z, 3 30kt obs, gales expand as ET begins 12z, 40kt ob co-located with 1010slp 15/18z. TYPE 3.

3. 8/24/12Z-8/28/12Z: Sig anoms south of the CV near 12N 26W with closed circulation analyzed on 8/24. WNW movement to near 15N 35W on 8/26. Low becomes elongated to the north due to interaction with trough on 8/27, recurves along 40W on 8/28.

V: 1010slp W wind 16kt along 13n 24/12z; W wind and NE winds in close proximity near 16n 27w 25/00z; 1009sslp 6z, pressures rise to 1012slp but W wind 11n 32w 26/00z, weak circ near 16n 32w eased on NE, NW, and SE winds 12z but only max 17kt winds; no evidence of closed circulation 27/12z-28. TYPE 1.

Hurricane Dolly: Sig anoms and closed circulation analyzed as early as 9/5/12Z near 13N 52W.

V: Pressure 1009 no evidence of CC on 9/6, west wind on 9/6/18z, 1005slp in Carib on 9/7/6z. TYPE 2.

Hurricane Edna: Sig anoms centered near 10N 42W on 9/11/12Z.

V: NW wind on 9/12/06z, 1012slp, 25kt winds but sparse obs. TYPE 2.

4. 9/21/00Z-9/26/12Z: Turning embedded in ITCZ with sig anoms 2sd+ near 8N 35W on 9/21/00Z w closed 1012 contour. Slow wward movement to near 10N 42W on 9/23/00Z w 1010 closed contour and closed circ analyzed, 3sd anoms. turn north begins on 9/24 to near 14N 45W on 9/25/00Z, weakens and turns NE on 9/26 to last position 22N 43W on 9/26/12Z.

V: 5 kt S wind 8n 35w 21/00z with 1007slp, 10kt 6z, 1006slp 18z, few obs 9/22 but 10kt SE wind with 1006slp 13n 36w, no obs nearby 9/23 but 1008slp far N of analyzed center around 17n 38w, no obs 9/24 but pres 1010 in all directions at a distance; 25kt NE wind near 22n 40w 25/00z; W wind 10kt, 1010 25/18z near 23n 44w, W wind 24n 45w 26/06z 1012slp, no evidence after that ob. TYPE 2.

Hurricane Gail: Sig anoms near 10N 27W with closed circ. Anoms 3sd+ on 10/2/00z, 1010 closed contour and strong +vort near 13N 32W.

V: 25kt wind, possible closed circ near 10n 27w on 9/30. TYPE 3.

5. 11/3/00z-11/5/00z: Weak cyclonic turning with stationary frontal boundary and sig anoms near 22N 62W on 11/3. Low moves slowly ENE and then NE and is lost on 11/5.

V: Cyclonic turning in LL windfield 11/3/00z along 62w but 1012slp, no closed circ; N and S winds about 10kt along 55w 4/12, 1012slp, elongated and diffuse 11/5/00z. TYPE 1.

1954: 4 Type 1, 1 Type 2, 2 Type 3

1. 6/1/12Z-6/3/12Z: Modest cyclonic turning with 2sd sig anoms between SE FL coast and N Bahamas on 6/1. Low moves rapidly NE to near 30N 68W by 6/2/12Z. Passes just south of Bermuda and loses tropical characteristics on 6/3.

V: Low near 30n 75w 6/1/12z, 25kt E wind, 1010slp but clear front extends to SW, 1006slp 6/2/00z, absorbed 6/3. TYPE 1.

2. 6/18/12Z-6/23/12Z: Small area of 1.5 sd anoms near Andros Is. with closed 1012 contour and +vort in FL Straits on 6/18. Circulation enters SE Gulf near 25N82W on 6/19, crosses Tampa to

Daytona Beach on 6/20 with large area of positive vorticity and closed 1010 contour. Moves slowly NE to near 30N 75W on 6/22. Absorbed by front east of mid-Atlantic on 6/23.

V: 1010slp near 25n 84w, W wind 10-15kt in Keys 6/18/18z, N/W/S/NE wind obs, strongest wind 20kt, circ near Naples? 19/12z, 1009.5slp and 17kt S wind near WPB; 1008slp at MLB 20/00z, circ probably just offshore, NW, WSW, E winds max 23kt; 20/18z 1006slp 28n 80w, 27kt NE wind 28.5n 79w, large area of 20-25kt, circ near 29n 77w 21/12z, front approaches and windfield spreads out 18z, 30kt well north, merging w front 6/22 as gales develop off NC max sust 40kt possibly subtropical. TYPE 3.

Tropical Storm Barbara: Sig anoms and closed circ near Apalachicola on 7/25/12Z.

V: 1010 low possibly onshore in N FL on 7/25 and 7/26. TYPE 1.

3. 7/30/00Z-8/2/00Z: Sig anoms 2sd+ with +vort and cyclonic turning along 64W south of 22N. Moves quickly WNW into Turks and Caicos on 7/31, signal becomes diffuse over northern Bahamas on 8/1 and is gone by 8/2.

V: No evidence of CC 7/30 modest turning and trades to 20kt, SE 30kt winds 7/30/18z with 1012slp, 1010slp 31/00z; turning but no circ in Bahamas 8/1, high pressures at sfc. TYPE 1.

Hurricane Dolly: Sig anoms over N Lesser Antilles on 8/29/12Z.

V: 1007 and 18kt winds on 8/30 but few obs. TYPE 2.

4. 9/14/12Z-9/18/00Z: Tropical wave crosses Yucatan on 9/14, splits into n (Bay of Campeche) and s (Gulf of Tehuantepec) vort maxes with large area of sig anoms elongated n/s on 9/15. Circulation becomes better defined in W Gulf on 9/16/12Z near 25N 95W with 3sd anoms. Crosses Gulf coast near TX/MX coast on 9/18/00Z.

V: Wave axis over Yucatan 9/14-15; NW wind 15kt, 1008slp 19.5n 91w 16/00z; broad circ covers full GoM 06z, area of 20-25kt winds SE 25n 88w, too few obs to close off circ; W west in BoC, 1007slp 16/12z center 26n 93w?; SE 33kt winds 27n 88.5w, 1005slp 26.5n 93w 17/00z, NW wind at Brownsville 17/6z, 1007sslp, inland 17/18z. TYPE 3.

Tropical Storm Gilda: Some evidence to suggest wward track extension into BoC on 9/28 and 9/29.

V: No evidence of closed circulation prior to BT cyclogenesis. TYPE 1.

1955: 6 Type 1, 8 Type 2, 1 Type 3

1. 6/1/12Z-6/4/00Z: Low analyzed near 23N 73W on 6/1. Closed circulation analyzed 23N 74W on 6/2/00Z. Sig anomalies near 28N 68W 6/3/00Z. ET transition 6/4 in N ATL.

V: 6/2/12z WSW and ENE winds but light, clear trough and cold-core nature. TYPE 1.

2. 6/30/00Z-7/1/12Z: Easterly wave with sig anoms along 57W south of 14N on 6/30. Through S Leewards on 7/1, lost on 7/2.

V: 25kt E trades but no closed circ. TYPE 1.

3. 7/2/00Z-7/9/00Z: Diffuse area of sig anoms between 40-50W south of 15N on 7/2. Wave axis with LL vort along 50W (pos titled) on 7/4. Anoms cross Antilles on 7/6, centered over Jamaica on 7/8, lost over Yucatan on 7/9. Surface reflection weak in streamlines.

V: 1009slp on 7/3/12z, few obs and no evidence of a closed circ; 25kt NE wind 7/5, straight trades no lower than 1012slp 7/6 stays clear TW through the period. TYPE 1.

4. 7/11/00Z-7/12/12Z: Diffuse area of sig anoms along 40W south of 15N on 7/11. Weak reflection in pressure and streamlines. Washes out east of LA on 7/12.

V: 1011slp 7/11/06z, WSW 7kt wind 18z far from anoms may be brief circ but few obs. TYPE 2.

5. 7/28/00Z-8/2/00Z: Sig anoms on 7/28 centered near 18N 48W. Anomalies deepen on 7/29 and 7/30 near 22N 60W with modest support in pressure and wind fields. Stalls NE of Puerto Rico on 7/31 and 8/1 with more streamline curvature. Anomalies weaken and dissipate moving N into open Atlantic near 27N 65W on 8/2.

V: Light W wind and 1013slp well S of anoms 7/28/00z, few obs 7/29-30, light winds and no evidence of circulation 8/1. TYPE 1.

Connie: 8/2/12Z: Sig anoms centered near 11.5N 42W on 8/2 associated with amplified wave axis 24 hours before classification. Analyzed initial position well SW of BT.

V: SW winds but few data points, may be need to reposition in BT. TYPE 2.

6. 8/8/12Z-8/13/12Z: Well-organized, high amplitude wave with sig anoms centered 13N 22W. CC analyzed on 8/8. Slow W motion through 8/10, anoms b/w 1-1.5sd. Vortex slowly weakens and is lost along 40W on 8/13.

V: N 20kt, 1009slp in CV 8/8/18z, 15kt WNW win; large area of light W winds 8/9, 1010slp; weak circ if any 8/10, no obs 8/11-8/12. TYPE 1.

7. 8/18/00Z-8/19/12Z: Sig anoms on 8/18 near 17N 37W. Modest in pressure/wind reflection. Lost on 8/19.

V: No observations anywhere nearby. TYPE 2.

Edith: 8/20/12Z: Sig anoms centered 14N 50W on 8/20.

V: 1007slp on 8/20, nearly stationary until formation. TYPE 2.

8. 8/25/12Z-8/29/00Z : SAs centered along 11N 28W. Elongated CC analyzed. Moves slowly W while weakening, along 42W on 8/29.

V: 1007slp on 8/25/18z 10n 21w, well e of anoms; no obs 8/26, few 8/27-8/28, no evidence of a TC but too sparse to be conclusive. TYPE 2.

9. 9/5/00Z-9/10/12Z: Sig anoms along SE FL with sfc circ analyzed. Feature drifts in FL Straits on 9/6 w 2sd+ anoms. Slow N motion across C FL by 9/8, nearly stationary through 9/10 when it moves NW and inland.

V: General area of 1012slp with cyclonic turning over FL on 9/5/12z, weak low in FL Straits 18z, W winds 10kt 23n 82.5w, 1011 6/00z, winds 10-15kt, 1010 6/12z, closed circ near 25n 82w?; 24kt Sw wind 18z, low near 25.5n 83.5w 9/7/00z, 1008slp, possibly approaching Tampa 7/12z; inland near Lk Wales 18z, near St Augustine 8/6z, NS until 9/9, pressures rise as circ winds down over N FL. TYPE 3.

10. 9/20/00Z-9/26/12Z: Large area of strong (2sd+) anoms centered near 12N 25W on 9/20. 1008hpa closed low analyzed with large surface circulation. Feature propagates WNW to near 16N 42W on 9/22. CC and closed low remain, near 22N 48W on 9/24. Captured by trough along 55W on 9/26.

V: 1006slp, 20kt E wind 13n 24w 20/00z; W winds far S 18z; S, SSW, E, SE winds but no obs to

close off a circ 9/21, 10kt N winds 22/06z, 1010slp; 1009 15kt, 18z; 1008slp w 18kt E wind 23/06z; 1007slp with 30kt ENE wind 12z 21 45w; 25kt SW 1009slp 24/06z; 5kt NW 18z but E winds nearby; 10kt W wind possible circ 23n 50w on 25/00z; 25kt 12z; circ continues to be plausible 9/26 near 30n 55w, ET 9/26 late. TYPE 2.

11. 9/24/00Z-10/3/00Z: Area of strong (2sd+) anoms centered near 13N 25W on 9/20. Sub-1008mb and CC analyzed. Moves NW to near 18N 33W on 9/26. Weakens and along 44W on 9/28. Moves SW and intensifies with 2sd+ anoms appearing along 50W near 15N on 9/30. Anoms near northern LA on 10/2 with minimal pressure/wind reflection.

V: 1006/7slp, 20kt NE winds, W winds far south near 6n 28w on 24/6z, few obs 9/25-26, 1013 in vicinity on 9/27, 1010slp SW of circ 28/06z, no evidence of circulation, 1009.8slp 29/06z 1008slp and 10kt N winds 29/18z at 10n 50w, few obs nearby 9/30, no evidence of closed circulation 10/1-2. TYPE 2.

12. 10/3/12Z-10/13/12Z: Sig anoms 2sd+ embedded in MDR wide region of 1sd+ anoms. Turning in sfc windfield and modest pressure reflection. Slow wwrld movement with 3sd+ anoms near 13N 45W by 10/8. Near Martinique on 10/10, CC analyzed. Lost near n coast of Venezuela on the 11th, reappears in S Carib on 10/12 as 1008hPa closed low. Lost over NW Carib on 10/13 as front approaches.

V: No obs 10/3-5, stright E trades 10/6-7, 1011slp far removed from anoms 10/8, no obs in the vicinity of the "center"; 1005slp and 10kt E wind 9n 55w 9/6z, 25kt NE wind with suspicious 1010slp 12z, no evidence of CC 10/10/00z, 1006slp and NNE wind 10n 60w 6z; no CC 11/00; 1006slp 15n 81w possibly weak circ near 13n 80w on 10/12 with several W wind ob; 14n 81w possible CC but weak winds, moves inland over Nicaragua on 13/00z. TYPE 2

13. 11/22/00Z-11/24/12Z: ST/T low develops in open Atlantic near 24N 47W on 11/22 closed sub 1010 low analyzed. Sig anoms 2sd+ move ENE and loses tropical (WC) characteristics by 11/24 near 26N 40W.

V: Trough-like appearance on 11/22/12z, frontal until dissipation. TYPE 1.

1956: 5 Type 1, 2 Type 2, 1 Type 3

1. 6/6/12Z-6/9/00Z: Sig anoms on 6/6/12Z over central Bahamas near 23N 75W. Elongated circulation moves north and then rapidly NE on 6/7 to near 33N 73W with 1008 closed contour by 12Z. ET transition along 70W s of 40N on 6/9.

V: 6/6 some W wind components but only 1012slp and 15kt winds; clear trough-like structure on 6/7-8. TYPE 1.

2. 7/31/00Z-8/1/12Z: TW with 2sd anoms along 55W s of 14N on 7/31, open 1012 contour. Lost over n Leewards on 8/1.

V: Trade winds blow straight through area on 7/31 and 8/1. TYPE 1.

3. 8/16/12Z-8/20/00Z: Small area of sig anoms w closed 1014 contour near 18N 62W on 8/16. Nw movement to near 24N 68W on 8/18. Lost on 8/20 near 20N 70W.

V: 25kt NE winds 16/12z but 1015slp, no evidence of CC 8/17, TW analyzed in sfc windfield on 8/18-19. TYPE 1.

4. 8/31/12Z-9/4/00Z: Small area of sig anoms w closed 1010 contour, strong +vort and closed circ on 8/31 near 14N 26W. Slow WNW motion to near 17.5N 30W on 9/2 with slow weakening. Opens to TW on 9/4 near 20N 40W.

V: 20kt N winds, 1006slp in CV on 8/31/12z, CC but weak winds 9/1, spins down on 9/2 and clearly an open wave by 9/3. Too few obs to know windfield during CC phase. TYPE 2.

5. 9/9/00Z-9/13/00Z: Large area of 2sd sig anoms south of CVI on 9/9. Slow WNW motion to near 14.5 32W on 9/11/00Z, closed circ and 1010 contour. Weakens to open wave along 40W on 9/13.

V: 1006.8slp 12n 24w 9/6z, NW and NE winds 15-20kt broad circ possible 10/00z W 13kt wind 8n 29w; 28kt SE winds on 10/6; N, NE, SE, SW, W at 18z, 24kt W, 1009slp, few obs thereafter on 9/11-9/12. TYPE 2.

6. 10/13/00z-10/14/00z: Low may briefly have attained tropical/subtropical characteristics near Bermuda on 10/13.

V: Non-tropical and trough-like; gale force winds but clearly baroclinic. TYPE 1.

7. 10/14/00z-10/19/00Z: Large sfc trough over central Bahamas on 10/14. 1008 closed low near Andros on 10/15, closed circ but only weak 1sd thick anoms. Just E of west palm beach on 10/16/00Z, 1006 closed low. Near 30N 80W on 10/17/00Z, 1002 closed, 2sd thick anoms. Just E of Wilmington on 10/18/00Z, absorbed by front near 38N 70W on 10/19. A large, well-organized and -resolved system. Interesting case study.

V: 10/14/00z 45 kt NE winds with nontropical gale center, 1003slp over Keys on 15/12z; massive area of gale force winds to 55kt 16/00z; lowest pres 998hpa on 17/00z as strongest winds approach co-location with lowest pressures; 17/12z 45kt and 996 and appearance of at least subtropical structure on 10/17-18, ET transition occurs on 10/19. TYPE 3.

8. 11/17/00Z-11/19/12Z: Sig anoms centered near 26N 74W on 11/17 with strong cyclonic turning and open 1014 contour. Slow wward motion to near 26N 76W on 11/18/00Z, thick anoms increase to 2sd+, NE motion on 11/19 near 29N 71W at 12Z with loss of warm core thereafter.

V: TW and 1013 slp on 11/17/00z, 20-25kt obs in NE quad 6z 1012slp 25n 75w; S winds 26kt and 1012slp 17/18z, still no evidence of CC; sfc winds weak 11/18z and only cyclonic turning in WF with generally high surface pressures. TYPE 1.

1957: 2 Type 1, 3 Type 2, 3 Type 3

1. 6/11/00z-6/13/00z: Low separates from front in open Atlantic near 30N 52W, embedded in very large area of 3sd thick anoms also containing TS #1 to the west. Eward motion, closed 1012 contour, near 30N 45W on 6/12/00z. Loses warm-core near 32N 42W on 6/13.

V: 30kt NE wind, 1010 press, evidence of closed circ on 6/11 22kt W wind report, but appears frontal with relatively few obs; weakens in low ob area on 6/12-13. TYPE 2.

2. 7/28/12Z-7/29/12Z: Closed circulation with small area of sig anoms near 12N 40W. Opens to tw on 7/29.

V: 1010 pressure on 7/28/12z, but generally very few obs over short life cycle. TYPE 2.

3. 9/25/12z-9/28/00z: Thick anoms 2sd along trough from Freida to east Cuba on 9/25. ENE motion to near 29N 60W on 9/27/12z, loses warm core on 9/28.

V: Weak circ possible 9.26 near 27n 70w, more likely trough associated with Frieda to N and E.

TYPE 1.

4. 9/30/00z-10/01/00z: Sig anoms, closed circ and 1012 contour near 13N 48W on 9/30. Weakens to open wave.

V: 5kt SSW wind on 9/30, 22kt E wind and 1009slp but no evidence of closed circulation in sfc windfield on 6z. TYPE 1.

5. 10/5/12z-10/10/12z: Sig anoms with well-defined tropical wave near 12N 27W on 10/5. Slow NW motion to near 14N 28W on 10/6/12z, closed 1010 contour. Nward motion along 30W to around 18N on 10/8, 3sd thick anoms. System remains nearly stationary and spins down through 10/10 near 20N 30W.

V: 1010slp and 10kt wind W at 5/12z; 1007slp and tight couplet of ENE/NW winds; W at 18kt with 1006slp on 6/18z; 23kt W winds on 7/6z; consistent w CC but few obs on 10/7-8; 25kt wind well E on 10/9/12z, weakens 10/10. TYPE 3.

6. 10/14/12z-10/17/00z: Sig anoms in the Bay of Campeche along trough and open 1008 contour on 10/14. open 1004 contour on 10/15 at 12z with 2sd thick anoms. Closed 1006 contour near 22N 95W on 10/16/12z. Inland over central Mexico on 10/17.

V: Generally low pressures in vicinity but few obs nearby. TYPE 2.

7. 10/17/00z-10/19/12z: Sig anoms near 17N 45W with closed circulation and 1012 contour. Drifts west to near 16N 50W by 10/19 and weakens to open wave on 10/20. Possible precursor to TS #8 but this is ambiguous from synoptic charts.

V: Light WNW wind, 1011 pres 17/00z; N, E, W winds 12z but weak winds; 1006slp 18z, 17kt N winds at 18/00z 31kt SE wind 1008slp ad west winds, obs sparse on late 18th, 27kt NE wind w 1010slp at 19/6z, 24kt 12z. TYPE 3.

8. 10/31/00z-11/5/00z : Area of sig anoms near 15N 61W in the Lesser Antilles. Closed circ on 11/1 over USVI and closed 1010 contour. Little motion with modest intensification possible through 11/3. Slow north motion to near 20N 65W and loss of warm core on 11/5.

V: Light W winds, 1008slp on 31/06z, evidence for broad, weak circulation; 1/6z 32kt SE wind 20n

62, continued evidence of broad circ through 11/2, pressure 1010 or less, W wind 10kt w 1007slp 3/6z; 1006slp and 24kt 3/12z, 30kt 3/18z; 1005slp and 20kt W wind 4/18z but losing tropical appearance. TYPE 3.

1958: 3 Type 1, 1 Type 2, 3 Type 3

1. 7/21/12z-7/24/00z: Small area of sig anoms with analyzed TW along 67W s of 23N on 7/21. Located near central Bahamas on 7/22/12z with small vortmax. Lost on 6/23 near WPB.

V: 7/22/06z NW winds in SE Cuba of 22kt but surface pressures are high and there is no other evidence of a circulation in the sfc windfield. TYPE 1.

2. 8/22/12Z-8/30/00z: 2sd thick anoms south of CVI on 8/23 est near 12.5 28W with closed circ and 1010 contour, strong +vort. Slow wward motion to near 14N 34W on 8/25/00z. Open wave analyzed on 8/27 near 15N 49W but 2sd anoms still analyzed. N motion on 8/28 near 23N 50W on 8/29/00z. Last warm-core position near 29N 51W on 8/30, weakening rapidly.

V: 1007slp and 25kt winds on 8/23/00z; 1006slp at 6z with S, NE, E winds; 18z 1007slp and SW wind at 28kt; 13kt W wind 13kt 12n 30w at 8/24/00z; 1007slp 06z, 22kt SW wind 12z, W winds reports continue through 8/26 and obs support open wave 8/27-8/30, plausible TC on 8/23-8/26. TYPE 3.

Tropical Storm Gerda: Some evidence that TS Gerda re-develops in BoC on 9/17 or 9/18. NS thickness anoms linger for several days, sfc analysis ambiguous.

V: Not promising, lt winds pressures 1010 possibly crosses coast in N MX on 9/19 or 9/20. TYPE 1.

Hurricane Janice: Sig thickness anomalies first appear over Mona Passage on 10/2, generally move west and expand through 10/5.

V: 1007kt pressure and 25kt winds on 10/2, closed circulation on 10/4 near 12.5N 81.5W with clear support for track extension coming from a number of surface observations. TYPE 3.

3. 10/4/12z-10/7/00z: 1sd anoms with +vort and closed 1014 contour near 20N 50W on 10/4. Signal intensifies and expands to 2sd+ on 10/6/00z near 25N 48W with closed circ. Moves n and lost on 10/7.

V: 1010slp on 10/4/12z, 10 and 21kt winds possible weak circ on 5/6z but obs do not close off and no closed circulation seems likely as pressures rise on 10/6. TYPE 1.

4. 10/16/12z-10/19/00z: Possibly subtropical low in the vicinity of 25N 65W on 10/16 moving quickly NE, closed 1010 contour. Deepens to closed 1006 contour and large +vort area centered near 32N 63W on 10/17/12z. Closed 998 contour and powerful vortmax, warm core still indicated by thickness anomalies near 40N 55W on 10/18/12z, ET transition on 10/19. Interesting case study due to intensity of cyclone analyzed.

V: Strong evidence for at least a subtropical and possibly transitioning to fully TC as numerous observations of 40-60kt winds are found, with clear closed circulation; possible troughing to SW away from low and may be entangled with front is only ambiguity. TYPE 3.

5. 10/17/12z-10/23/00z: Cyclonic turning with sig anoms in BoC near 21N 95W on 10/17 at 00z. Intensifies and near 25N 93W on 10/18/00z, open 1012 contour. Seems to lose tropical characteristics while crossing Florida from Cedar Key to St. Augustine early on the 19th, but reacquire warm core on 10/20 at 00z over Gulf Stream near 32N 76W with closed 1000 contour and circ. Deepening rapidly. Stalls/splits with one piece of energy taken NE and analyzed closed circ stalls south of Ob on 10/21 near 34N 75W, closed low and contours persist into 10/22 but without analyzed warm core. Drifts inland over SC on 10/23

V: NW 23kt wind on 18/00, 27kt 12z, 35kt w 10kt W wind and 1007slp, but possible frontal nature, seems to acquire waem core on 10/20 but windfield remains broad with several 40kt obs, appearance remains frontal 10/20-23. Uncertainty about thermal structure. TYPE 2.

APPENDIX B

BRIEF DESCRIPTION OF EAST PACIFIC BASIN CANDIDATE EVENTS, 1951-1958

1951:

1. 6/24/00-6/26/12: Near 18N 110W. TYPE 1.
2. 6/28-7/1 TS #3: Track extension centered near 21N 115W. TYPE 1.
3. 8/1-8/4: 15N 140W. TYPE 2.
4. 8/20-8/23: Possible track extension prior to formation of TS #6 12N 95W. TYPE 1.
5. 9/6-9/10: 12N 105W, could be precursor to TS #7. TYPE 3.
6. 10/4-10/7: 15N 105W. TYPE 1.
7. 10/10-10/13: 15N 130W. TYPE 2.
8. 11/3: 24N 110W. TYPE 1.

1952

1. 6/19-6/20: 12N 105W. TYPE 2.
2. 7/8-7/16: 12N 125W, approaches Hawaii on 7/15 20N 155W. TYPE 2.
3. 8/14-8/16: 18N 110W. TYPE 2.
4. 8/26-9/1: 15N 125W. TYPE 3.

5. 9/13-9/15: Extension of H#5 back to near 15N 100W. TYPE 3.

6. 10/06-10/10: 13N 115W. TYPE 1.

7. 10/10-10/13: east extension of H#7 to 12N 108W. TYPE 2.

1953

1. 6/21/00-6/24/12: 25N 120W. TYPE 1

2. 6/29/12-7/2/12 : 9N 95W to 12N 110W. 30 kt wind 7/1/12z but no close circ. TYPE 2.

3. 7/30/12-8/1/00 : 12N 135W. TYPE 2.

4. 8/23/00-8/24/12 : 12N 105W, precursor to TS #1. TYPE 1.

5. 9/6/00 - 9/9/00: 15N 112W, precursor to TS #2. TYPE 2.

6. 9/22/00 - 9/27/12: 10N 105W. TYPE 1.

7. 9/27/00 - 10/02/00: 12N 95W to 15N 103W, precursor to TS #4? TYPE 2.

1954

1. 6/30/12-7/7/00: 12N 105W to 17N 130W. TYPE 2.

2. 7/18/00 -7/19/12: 21n 120w, possible successor/extension to ts#3. TYPE 1.

3. 9/13/12 - 9/15/00: 13n 106w, precursosr to ts #7. TYPE 1.

4. 9/19/00 - 9/21/00 : 13n 98w, precursor to ts #8. TYPE 2.

1955

1. 8/3/00 - 8/6/12: 18n 115w to 21n 126w. TYPE 2.

2. 8/22/12 - 8/24/12 : 12n 127w to 10n 135w. TYPE 2.

3. 8/28/00 -9/1/00 : 25n 120w. TYPE 1.

4. 9/23/12 - 9/26/12: 9n 85w. TYPE 1.

1956

1. 7/6/12 -7/8/12 : 12n 105w, precursor to ts#5. TYPE 3.

2. 9/8/00 - 9/12/00 : 10n 90w, precursor to ts #10. TYPE 2.

3. 10/11/00 - 10/14/12: 9n 100w to 18n 110w. TYPE 2.

1957

1. 6/15/12 - 6/18/00: 16n 110w. TYPE 1.

2. 6/22/00 - 6/26/00 : 12n 103w to 18n 120w. TYPE 2.

3. 7/3/00 - 7/5/00: 11n 117w to 12n 123w. TYPE 2.

4. 7/6/12 - 7/11/12: 7n 85w to 8n 98w. TYPE 3.

5. 7/28/00 - 8/3/12: 16n 108w to 15n 138w. TYPE 3.

6. 8/20/00 - 8/23/00: 11n 136w to 18n 160w, off map. TYPE 2.

7. 9/11/00 - 9/17/00: 10n 94w to 15n 100w, possible precursor to TS#6. TYPE 3.

8. 11/01/00 - 11/05/12: 16n 108w. TYPE 1.

1958

1. 6/2/12 - 6/5/12: 10n 112w to 12n 120w. TYPE 2. (one ob)

2. 7/5/00 - 7/14/00: 14n 95w to 16n 135w. TYPE 2.

3. 7/11/00 - 7/12/12 : 8n 90w. TYPE 1.

4. 8/27/00 - 9/2/12: 10n 110w to 15n 140w. TYPE 2.

5. 9/15/12 - 9/22/00 : 15n 105w to 23n 108w. TYPE 3.

6. 10/12/12 - 10/14/00: 12n 102w, precursor to ts#12, also possible track extension out to Hawaii on 10/22. TYPE 2.

7. 10/16/00 - 10/19/12: 8n 93w to 18n 114w. TYPE 1.

8. 10/25/00 - 10/28/12: 10n 102w. TYPE 2.

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BIOGRAPHICAL SKETCH

Ryan Truchelut was born and raised in Orlando, FL, spending much of his childhood competing in high school and club track and cross country. In 2008, he graduated from Princeton University *summa cum laude* with a degree in Geosciences. During his undergraduate career, Ryan was perhaps best known for writing over 100 “Weather Guy” newspaper columns, a body of work that remains a landmark achievement in pseudo-journalistic zaniness.

To the surprise of absolutely no one, Ryan has chosen to make a career out of his lifelong obsession with extreme weather. In the process of finishing a master’s thesis on hurricane climatology at Florida State University, he is working towards a doctorate in meteorology, as well as providing operational forecasting for an agricultural commodities firm. Otherwise, Ryan continues to enjoy his traditional assortment of certifiably nerdy hobbies, including coin collecting, banjo picking, birdwatching, analog media of both Polaroid film and vinyl record varieties, and of course, exploring America’s vast natural and novelty value wonders with his fiancée, Erica.