2B.4 GLOBAL INDENTIFICATION OF PREVIOUSLY UNDETECTIED TROPICAL CYCLONES IN NOAA/CIRES 20TH CENTURY REANALYSIS DATA

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1. INTRODUCTION

Prior to the advent of the satellite era, limited *in situ* synoptic observations led to an indefinite number of tropical cyclones (TCs) remaining undetected in global tropical basins. This era of poor confidence in climatological data extends until roughly the mid-1960s in the Atlantic Basin and the late-1970s in most other global tropical basins. TCs that were not observed via land, ship, or aircraft observations prior to those years were not identified operationally and therefore are not a part of the consensus TC climatology. While prior studies [*Vecchi and Knutson* 2008, *Chang and Guo* 2007, *Landsea et al.*, 2008] confirm that this historical undersampling exists, there remains considerable disagreement regarding its magnitude in existing literature. This disparity has led to difficulties in interpreting long-term trends in tropical cyclone activity as well as ambiguities regarding the potential existence of multi-decadal oscillations in tropical cyclone count. These uncertainties hamper the ability of public and private interests to accurately quantify and manage the risks tropical cyclones pose to coastal communities both now and in the future.

Previous research made use of the NOAA/CIRES 20th Century Reanalysis [*Compo et al*., 2011], a new reanalysis dataset that assimilates only surface-based observations and extends back in time to the late 19th Century, to develop a scheme that identified previously unknown Atlantic Basin potential cyclones in the pre-satellite era [*Truchelut and Hart* 2011]. Synoptic verification using historical surface ship observations from the ICOADS dataset as well as supplemental observations from land-based platforms showed the reanalysis-derived set of candidate events effectively identified around 1.5 such cases per year for the 1951-1958 Atlantic Basin hurricane seasons as well as several cases per year suggestive of significant track extensions to existing cyclones.

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This research expands the scope of the original methodology in both spatial and temporal dimensions by using a filtering algorithm that dramatically improves the efficiency and speed with which candidate events are identified in the NOAA/CIRES 20th Century Reanalysis dataset. This scheme was first applied to the Atlantic Basin to test its efficacy against a set of manually verified pre-satellite era seasons. The method was then applied to the Atlantic, East Pacific, West Pacific, and North Indian Oceans for the years 1891-1979.

2. METHODOLOGY

Truchelut and Hart [2011] details the process by which the NOAA/CIRES 20th Century Reanalysis was adapted for use as tool to aid study of historical TCs. Briefly, mean and variance climatology of an array of layer thicknesses was taken from the reanalysis. Using normalized thickness anomalies, it was shown that thickness of the 300 to 850hPa layer is a useful proxy for warm-core cyclones consistent with *Hart* [2003]. The 300-850hPa thickness layer showed a statistically significant response to TC passage, demonstrating that the reanalysis is capable of resolving TC structure to the first order.

Given that TCs were shown to have a particular thermodynamic signature in the reanalysis , searching for TC-like events that do not correspond to a known cyclone was therefore possible. Using the 1951-1958 Atlantic Basin hurricane seasons as a test case, spatial plots of 300-850hPa thickness anomalies, and mean sea level pressure, low-level vorticity, and streamlines from the reanalysis were first manually searched for signatures consistent with a TC. The initial set of 57 candidate events was subsequently verified using the ICOADS [*Woodruff et al*., 2011] database of historical ship observations, revealing 12 of these cases could plausibly be “missing TCs” consistent with the criteria defined in *Landsea et al.* [2008]. Tracks of these 57 candidate events are shown in Figure 1.

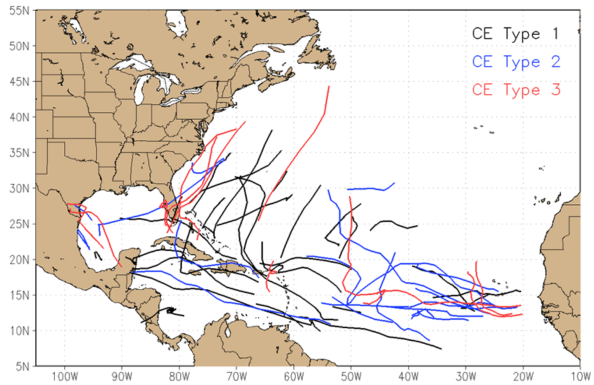

Figure 1. Track map for all 1951–1958 Atlantic hurricane season candidate events identified in the 20th Century Reanalysis. Type 1 events are unlikely to be tropical cyclones, Type 2 cases are ambiguous, and Type 3 events are those most likely to be "missing TCs." Position data is determined every six hours from reanalysis sea level pressure fields.

While this manual methodology was successful in identifying plausible TC candidate events in the test seasons, the technique was also quite time-consuming. In order to make the process more expeditious and thus expand its temporal and spatial applicability, this research project endeavored to develop an automated process to recruit the initial set of candidate events. This algorithm incorporates the synoptic variables used as criteria in the manual technique, applying critical threshold values to 300-850hPa normalized thickness, sea level pressure, and 850hPa vorticity. Over 3750 combinations of threshold values for these variables were tested for the 1951-1958 Atlantic Basin hurricane seasons in order to maximize the proportion of the known candidate events identified while keeping the overall number of events low for the purposes of synoptic verification.

In addition, several other criteria are applied to reduce the number of baroclinic and non-tropical features identified by the algorithm. These include forcing the SLP to be the minimum value within a 12-degree box, constraining vorticity and thickness anomaly maxima to be within 6 degrees of the SLP minimum, establishing a maximum value of allowable 600-900hPa baroclinicity, and constraining vorticity at the point of maximum thickness to be positive. The algorithm also allows the thickness anomaly requirement to be met by the local maximum exceeding a certain value relative to its local environment.

The reanalysis gridpoints that meet these standards are grouped geographically and temporally into discrete candidate events. The signature of the candidate event is tracked for two days before and two days after registering a hit in the algorithm, with interpolation of these points producing an estimated track for the event. Finally, duplicate or overlapping candidate events are removed or combined, respectively. The resulting set of tracks and their respective synoptic variables are then subjected to the identical manual synoptic verification process using land and sea-based *in situ* observations as used in the first methodology.

3. TESTING THE CANDIDATE ALGORITHM

While the major advantages of using an automated means of identifying TC candidate events are that the scheme can identify interesting events for observational verification more quickly and objectively than manual synoptic analysis, it does so at the cost of transparency. Therefore, it is important to test the algorithm against other objective means of identifying "missing TCs." The algorithm is here tested against the methodology from *Truchelut and Hart* [2011].

3.1 *Verification against Manual Identification*

The first test of the candidate event detection algorithm is how it performs relative to manual identification of candidate events in the 1951-1958 Atlantic Basin hurricane seasons. As the algorithm is a formalization of the manual search critieria applied successfully to these seasons, ideally the automated and manual methods will produce comparable numbers of candidate events. Because the threshold values were selected based on the synoptic characteristics of the most likely manually-identified "missing TCs," it is known that the algorithm will "find" most of the likely "missing TCs" during this period, but the number of other known candidate events that are located by the algorithm is a meaningful test.

After running the tuned candidate event search algorithm on the 1951-1958 Atlantic Basin hurricane seasons, the manual and automatically generated sets of candidate events were compared for cases that appeared in both sets. Of the 57 candidate events identified manually, 34 cases were also identified by the search algorithm (out of 76 total candidate events automatically identified, or 9.5 per year). The number of events located by the algorithm broken out by the observational classification type of candidate event is shown in Figure 2.

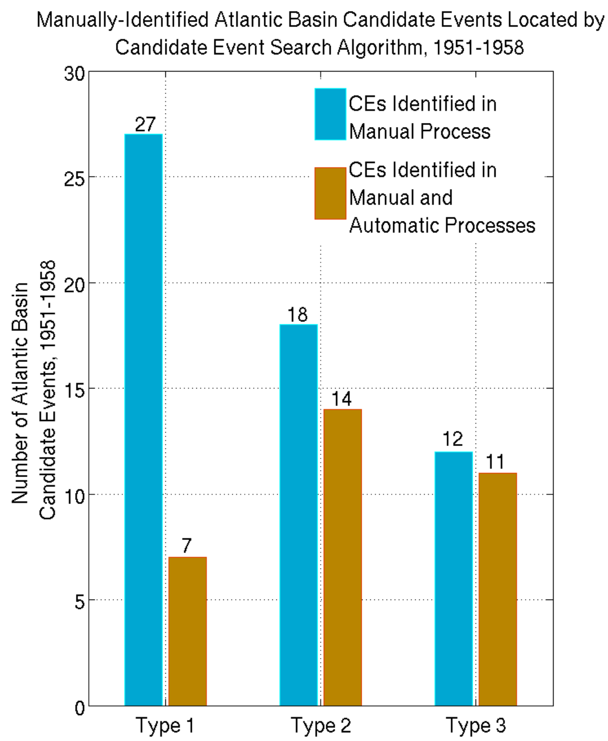

Figure 2. Quantity of each candidate event type found using the manual process compared with the quantity found in both the manual process and the algorithmic method. As determined by in situ observations, Type 1 events are unlikely to be tropical cyclones, Type 2 cases are ambiguous, and Type 3 events are those most likely to be "missing TCs."

Figure 2 shows a clear trend of increasing chance of identification by the algorithm with greater likelihood of the candidate event being a "missing TC." While the automated method locates just 25% of the Type 1 events that are likely not TCs, it finds over 75% of Type 2 cases where no determination can be made and over 90% of likely "missing TC" Type 3 events. This filtering of weak cases demonstrates that the algorithm adds value to the verification process by discriminating in favor of possible TCs while keeping the overall number of candidate events small enough to allow synoptic analysis of each case. It is also worth noting that several of the 42 candidate events identified by the algorithm but not the manual process appear to be credible cases for further investigation, pointing to the subjectivity and imperfection of the manual technique itself.

4. EXPANDING TC CLIMATOLOGY

As the algorithm was shown to be successful in identifying the candidate events most likely to be "missing TCs" in the 1951-1958 Atlantic hurricane seasons, the algorithmic process was applied to both the remaining pre-satellite era years in the Atlantic and to all pre-satellite years in the other Northern Hemisphere tropical basins.

4.1 *Atlantic Basin*

Thanks to the work of the HURDAT Project, a thorough synoptic reanalysis of Atlantic hurricane seasons through 1953 has been completed [*Hagen et al.,* 2011]. Therefore, the 1959-1966 seasons are the final eight years predating regular satellite coverage that have not been rigorously re-assessed and are a natural starting point to operationally test the candidate event-locating algorithm. The same set of critical threshold values and data processing procedures that were used for the 1951-1958 seasons were applied to 1959-1966, resulting in a set of 61 total candidate events, or roughly 7.5 events per year. Observational verification of these cases using ICOADS data yielded the classification of 37 of the candidate events as Type 1 (61%), 16 as Type 2 (26%), and 8 as "missing TCs," Type 3 (13%).

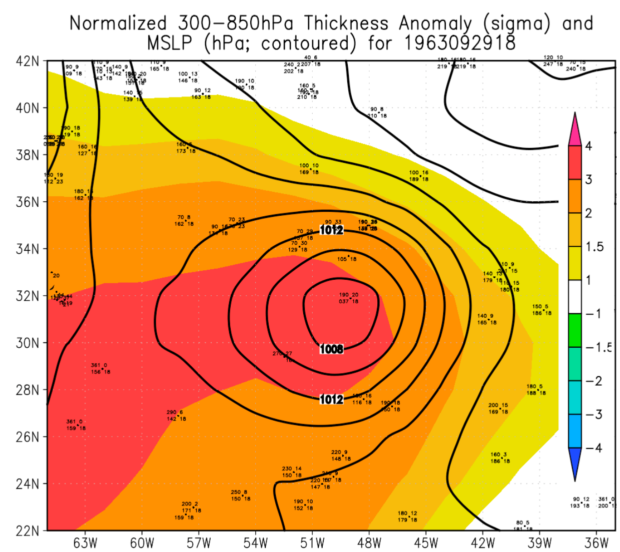

Figure 3. Normalized 300-850hPa thickness anomalies and sea level pressure from the 20th Century Reanalysis, plotted with ship observations of wind speed, direction, and sea level pressure for 1800UTC 29 September 1963. The event plotted is 1963 Candidate Event #13, located in the Central Atlantic Ocean.

An example of a Type 3 event is shown in Figure 3. This candidate event, a warm-core cyclone that evolved from a mid-latitude system, was tracked by the algorithm as a strong signal for several days, and shown by the observations plotted in Figure 3 to have a closed circulation, sustained gale force winds, and a minimum central pressure lower than 1004hPa. This evidence makes a strong case for the eventual addition of this candidate event to TC climatology, and a similar case can be made for 7 other candidate events between 1959 and 1966. The addition of roughly one "missing TC" per year in these years is consistent with the expected seasonal activity adjustment found in *Landsea* [2007].

4.2 *Global Basins*

While research is still ongoing, early results show promising indications that the automated event locator algorithm can successfully identify credible "missing TC" candidates in global tropical basins. In order to extend the technique to other basins, 300-850hPa thickness layer mean and variance climatology was calculated for each basin, and the algorithm was run and candidate event data was processed following the same method as the Atlantic studies. The critical threshold values used were also the same as for the Atlantic because they represent normalized quantities, with the exception of sea level pressure. Because ambient pressures tend to be lower in basins other than the Atlantic, the pressure criterion was reduced in accordance with the basin's mean zonally averaged sea level pressure during the local tropical cyclone season.

Running the algorithm in the East Pacific, North Indian, and West Pacific basins for the pre-satellite era years of 1891-1979 yielded a total of 509, 569, and 1742 discrete candidate events (5.7, 6.4, and 19.6 per year), respectively. These totals are roughly in line with the basins' overall relative levels of TC activity.

5. CONCLUSION

The algorithmic process demonstrated success in locating credible candidate events in the Atlantic and other basins, both measured against an earlier manual technique and observational verification. This result indicates that automated methods may be used to construct a quantitative and objective estimate of global TC candidate counts for decades prior to the advent of climatological records. While necessarily limited by the resolution of reanalysis products, and with the caveat that synoptic verification has not yet been performed on all of the candidate events identified, the algorithm is able to quickly identify potential missing TCs with an accuracy nearing that of the manual technique. These findings suggest that reanalysis models are a useful means of efficiently and effectively adding new information to the tropical cyclone climatological record and are a promising basis upon which to improve our understanding of long-term trends in tropical cyclone activity.

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