P5.2 VORTICITY-BASED DETECTION OF TROPICAL CYCLOGENESIS

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1. INTRODUCTION

Tropical cyclogenesis (TCG), although an already well researched area, remains a highly debatable and unresolved field. While considerable attention has been paid to tropical cyclone formation, little attention has focused on observational studies of the very early stages of TCG, otherwise referred to as the genesis stage. In the past, the early stages of TCG were unverifiable in surface observations, due to the paucity of meteorological data over the tropical oceans. The advent of wide swath scatterometers helped alleviate this issue by affording the scientific community with widespread observational surface data across the tropical basins. One such instrument is the SeaWinds scatterometer, aboard the QuikSCAT satellite, which infers surface wind speed and direction. Launched in 1999, this scatterometer has encouraged various studies regarding early identification of tropical disturbances (Liu et al. 2001; Katsaros et al. 2001; Sharp et al. 2002). These studies, though operational in intent, hypothesized the potential for SeaWinds data to be applied towards research applications (i.e., genesis stage research). The main goal of this study is to develop an objective technique that will detect the early stages of TCG in the Atlantic basin using SeaWinds data.

Liu et al. (2001), Katsaros et al. (2001), and Sharp et al. (2002) demonstrated the ability to identify tropical disturbances, systems too weak to be classified as tropical cyclones by the National Hurricane Center (NHC). Each technique utilized surface wind data obtained by the SeaWinds scatterometer. However, the criteria that defined their identification method differed. Sharp et al. (2002) employed vorticity as his detection condition, whereas Liu et al. (2001) and Katsaros et al. (2001) relied upon closed circulations apparent in the scatterometer data. Using a threshold of vorticity over a defined area, Sharp et al. (2002) identified numerous tropical disturbances and assessed whether or not they were likely to develop into tropical cyclones. Detection was based on surface structure, requiring sufficiently strong vorticity averaged over a large surface area. Unlike Sharp et al. (2002), Katsaros et al. (2001) and Liu et al. (2001) concentrated on disturbances that would develop into classified tropical cyclones. They examined surface wind patterns and looked for areas of closed circulation, successfully detecting tropical disturbances before designation as depressions. These studies illustrated the usefulness of SeaWinds data towards tropical disturbance detection, with the intent of improving operational activities. The early identification of surface circulations presented in these studies suggests an opportunity to detect the early stages of TCG, setting the basis for this paper.

The detection technique described herein has the potential for applications in the scientific and operational communities. In operational applications, the forecasting community can implement the detection technique as an additional observational tool. In doing so, the technique can enhance the current observing system employed to identify and monitor tropical weather systems, thereby reducing the time forecasters spend examining the tropics for incipient systems. In research applications, identification of the early stages of TCG can enhance understanding in regions where little research has been conducted due to the prior inability to conclusively locate tropical disturbances. This study focuses on the Atlantic basin, but the detection technique can be applied to other tropical regions, such as the Pacific basin, after adjusting the threshold values to account for regional differences in TCG mechanisms.

The ability to detect the early stages of tropical cyclogenesis provides an opportunity to classify tropical disturbances in the Atlantic basin based on the source of initial cyclonic vorticity maximum. Following categorization by Bracken and Bosart (2000) these sources include disturbances associated with: (i) monsoon troughs or the intertropical convergence zone (Riehl 1954, 1979), (ii) an easterly wave (Carlson 1969; Burpee 1972, 1974, 1975; Reed et al. 1977; Thorncroft and Hoskins 1994 ab), (iii) a stagnant frontal zone originating in the midlatitudes (Frank 1988; Davis and Bosart 2001), (iv) mesoscale convective

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systems (MCSs; Bosart and Sanders 1981; Ritchie and Holland 1997; Simpson et al. 1997; Bister and Emanuel 1997; Montgomery and Enagonio 1998), and (v) upper-level cut-off lows that penetrate to lower levels (Avila and Rappaport 1996). Among these, our research in the Atlantic basin affords the possibility to investigate cases associated with easterly waves. Of great interest is the prospect to examine the connection between a cold-core wave disturbance in the tropical easterlies and a warm-core tropical cyclone, which remains an unresolved issue in TCG research (Bourassa personal communication 2005). Easterly waves are of great importance since approximately 63% of tropical cyclones in the Atlantic basin originate from African easterly waves (Avila and Pasch 1992).

Another fundamental issue with tropical cyclone genesis involves the development of surface circulation during the pre-WISHE (Wind Induced Surface Heat Exchange) stage (Bourassa personal communication 2005). The fine details of the pre-WISHE process cannot be resolved with SeaWinds data. However, SeaWinds data does allow for an observationally based estimate of vorticity available at the surface prior to the pre-WISHE stage, which is needed for numerical model initializations.

2. DATA

2.1 *Scatterometer Data*

The geophysical model function that is used in this study is the Ku2001 product developed by Remote Sensing Systems (RSS). The Ku2001 product is currently the most accurate GMF for most meteorological conditions (Bourassa et al. 2003). It performs far better near nadir, swath edges, and rain than either the science quality product from Jet Propulsion Laboratory (JPL) or the near real-time product from NOAA/NESDIS.

The Ku-2001 product more accurately characterizes the wind direction dependence of σ^o at low winds and exhibits a flatter σ^o versus wind speed response at high winds. This improved vector wind retrieval algorithm provides a fully integrated stand-alone rain flag and the capability to retrieve winds up to 70 m/s (Wentz et al. 2001). The scatterometer winds are calibrated to equivalent neutral winds at a height of 10 meters above the local mean water surface (Bourassa et al. 2003).

2.2 *GOES Imagery*

GOES-8 and GOES-12 infrared images are obtained from the NOAA/NESDIS Comprehensive Large Array-data Stewardship System (CLASS) for our 15 tropical cyclone cases during the 1999-2004 hurricane seasons. Images are acquired approximately every three hours and compiled into separate animations, with a forward-in-time progression. The purpose of these animations is to provide a means of verification for each tropical disturbance position and continuity of the track (i.e. track assessment). The GOES data allow cloud features to be tracked between the relatively sparse QuikSCAT overpasses.

3. METHODOLOGY

3.1 *Detection Technique*

The vorticity-based detection technique used in this study is a variation of the method developed by Sharp et al. (2002). This technique calculates relative vorticity within the SeaWinds swaths and applies a mean vorticity threshold over a specified spatial area (Sharp et al. 2002). Different criteria are utilized than those of Sharp et al. (2002), permitting identification of tropical disturbances prior to classification as a tropical cyclone by the NHC.

The spatial scale for averaging vorticity within the SeaWinds swaths is a 100 km by 100 km area. Individual vorticity values are calculated from wind observations at the center of each grid cell defined by 4 [2 x 2] adjacent scatterometer vectors through determining the circulation around each box and then dividing through by the area (Sharp et al. 2002). This method enables the vorticity to be calculated at the same spatial density as the wind observations. In each calculation a minimum of 3 wind vectors out of the 4 in a square are required (if only 3 wind vectors exist, the square becomes a triangle). The wind vector data that is used in this approach includes rain-flagged data. Incorporation of rain-flagged data can affect the vorticity calculation, generating noise. The noise that results is usually small when compared to the vorticity signal; although, in some instances it is comparable and therefore the position of the vorticity signature is questionable. For these instances, the detection technique is pinpointing down the general area of the vorticity signature and though not what is desired, the detection technique still proves effective.

The criteria that define the detection technique consist of three components. The thresholds used in these criteria are greatly reduced as compared to those of Sharp et al. (2002). The criteria defined require that within the specified spatial scale (100 km by 100 km area) the average vorticity must exceed a minimum vorticity threshold, the maximum rain-free wind speed must exceed a minimum wind speed threshold, and that these conditions be met in at least 80% of the cells within 50 km of the vorticity points being tested. If all three of these criterions are met then the system under consideration is deemed to be a tropical disturbance. In general, if the three conditions are fulfilled the system does not necessarily develop into a tropical cyclone. However, all of the 15 cases used in this study will develop into tropical cyclones as a result of our initial selection.

3.2 *Threshold Determination*

The threshold values defined in our detection technique are determined using research-quality SeaWinds data for 15 tropical cyclones during the 1999-2004 Atlantic hurricane seasons. In preliminary examples we applied a speed and vorticity threshold of 4.0 ms^{-1} and $2.0x10^{-5}$ s^{-1}, respectively. Results showed that 65 overpasses fit these criteria; however, some of the vorticity signatures identified were indistinguishable from noise (i.e., false alarms). Therefore, it was determined that these threshold values were too small. To reduce the number of false alarms found in our preliminary example, a categorical score is computed for a range of vorticity and wind speed thresholds to determine appropriate values.

The categorical score considered in this study is the probability of detection (POD), which evaluates the effectiveness of detection techniques. It is defined as:

$$POD = \frac{H}{H + M} \quad (1)$$

where H is the number of hits and M is the number of misses. The POD score measures the ability of our technique to accurately identify tropical disturbances in the correct locations. A score of 1 indicates perfect detection, whereas a score of zero represents random detection.

In order to test this method, a POD plot is produced that assesses the contributions from both wind speed and vorticity thresholds in regards to our preliminary example (Figure 1). This plot illustrates that low threshold values yield a higher probability of detection, whereas high thresholds yield a lower probability of detection. As previously mentioned a POD score of 1 is most desirable since it represents perfect detection; however, the test cases include two conditions that were indistinguishable from noise. Therefore, the POD range deemed appropriate in our threshold determination is between 95% and 99%. Through analysis, the 96% POD contour is chosen based on its large gradient and high sensitivity area, as well as its reduction of false alarms. Threshold values associated with this contour include a vorticity and wind speed threshold of $5.0x10^{-5}$ s^{-1} and 6.3 ms^{-1}, respectively. Utilization of these values within our detection technique shows that 62 overpasses meet our criteria.

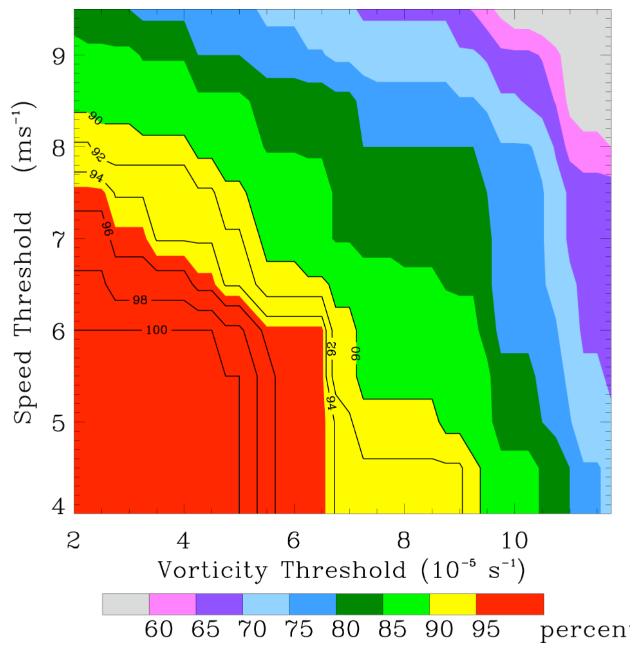

Figure 1. Probability of Detection graph.

3.3 *Track Assessment*

QuikSCAT's approximately twice-daily coverage of the Atlantic basin, as well as it's four-day repeat cycle proves problematic in regards to identification of tropical disturbances. As previously mentioned, 65 QuikSCAT overpasses identify tropical disturbances that fulfill the detection technique's criteria. Though substantial in number, the time period between these overpasses is anything but adequate, with a range from 11 to 36 hours. These temporal gaps may not be a problem for detection of existing tropical cyclones; however, they are significant for identification of tropical disturbances associated with the early stages of TCG. Gaps between detection generate uncertainty regarding a system's track in time and positioning.

GOES infrared images are used to provide supplementary observational guidance in the form of track assessment. GOES animations are created for our 15 cases to validate each tropical disturbance's track and position through cloud cover analysis. Animations are made with a backward and forward-in-time progression.

4. RESULTS

Results for the 15 tropical cyclones during the 1999-2004 Atlantic hurricane seasons are illustrated in Table 1. These systems are chosen because their coverage is adequate for reasonable study in the Atlantic basin. Ten of the 15 tropical cyclones originate as tropical waves off the coast of Africa (i.e., African easterly waves). These include Floyd (1999), Debby (2000), Nadine (2000), Jerry (2001), Dolly (2002), Danny (2003), Isabel (2003), Juan (2003), Nicholas (2003), and Alex (2004). The other five cases originate from sources other than tropical waves, such as upper-level cut-off lows and stagnant frontal zones. These include Florence (2000), Michael (2000), Karen (2001), Noel (2001), and Gustav (2002).

Table 1. Results for 15 tropical cyclones during the 1999-2004 Atlantic hurricane seasons. The last column signifies the hours elapsed between the NHC initial classification and our earliest tropical disturbance identification (i.e., tracking time).

Storm	Year	Tracking Time
Floyd	1999	46
Debby	2000	95
Florence	2000	67
Michael	2000	38
Nadine	2000	50
Jerry	2001	101
Karen	2001	19
Noel	2001	62
Dolly	2002	53
Gustav	2002	25
Danny	2003	38
Isabel	2003	101
Juan	2003	26
Nicholas	2003	64
Alex	2004	79

Tropical disturbances associated with the early stages of TCG are found for these cases within a range of 19 hours to 101 hours before classification as tropical cyclones by the NHC (Table 1). The average tracking time for these systems is approximately 58 hours, where tracking time is defined as the time elapsed between the NHC initial classification and our earliest tropical disturbance identification. Some examples of the technique in identifying the early stages of TCG are illustrated in Figures 2 and 3. These figures illustrate spatially averaged vorticity signatures that are overlaid with solid black contours, which signify the locations where the detection technique's criteria are met. Each example illustrates an apparent surface circulation.

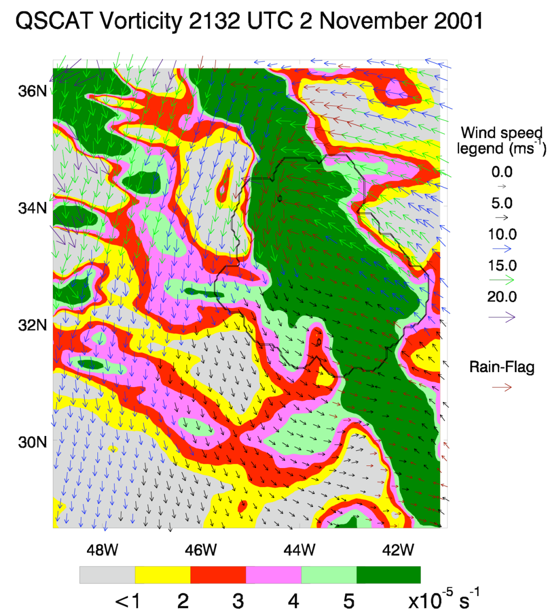

Figure 2. Noel, 26 hours before classification as a TC. The vorticity signature shown is associated with the non-tropical occluded low that produced Noel.

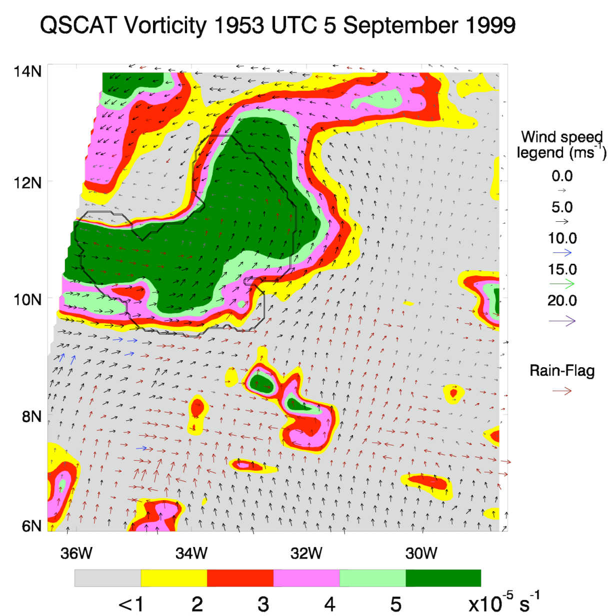

Figure 3. Floyd, 46 hours before classification as a TC. The vorticity signature shown is associated with the easterly wave that spawned Floyd.

5. CONCLUSIONS

A vorticity-based detection technique is developed to identify and monitor tropical disturbances associated with the early stages of TCG in the Atlantic basin. Detection is based on visual inspection of GOES infrared images, as well as, surface structure. From a sampling of 15 tropical cyclones during the 1999-2004 hurricane seasons the technique identifies tropical disturbances approximately 19 to 101 hours before classification by the NHC. Herein the minimum tracking time is associated with pre-TC Karen (2001); whereas, the maximum tracking time is associated with pre-TC Jerry (2001) and pre-TC Isabel (2003). Smaller tracking times are associated with systems that develop from sources other than easterly waves, such as upper-level cut-off lows and stagnant frontal zones. Reasoning behind the shorter tracking times stems from land interference, which QuikSCAT lacks the ability to resolve. Larger tracking times correspond to cases that originate from African easterly waves. Therefore, focus is primarily concentrated on such cases, due to approximately 63% of all Atlantic tropical cyclones being associated with tropical waves.

Overall results for the 15 cases prove very successful. Therefore, the vorticity-based detection technique described herein is an effective tool in identifying and monitoring tropical disturbances in the genesis stage. Based on these conclusions it is reasonable to assume that this technique could be useful to scientific and operational communities.

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