EARLY DETECTION OF TROPICAL CYCLONES USING SEAWINDS-DERIVED VORTICITY

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The SeaWinds instrument on *QuikSCAT* provides a new tool for identifying systems that have the potential to develop into tropical cyclones.

Tropical cyclone (TC) detection has vastly improved over the days when meteorologists had to watch their barometers and the skies for prediction. The additional use of reconnaissance aircraft, which began in 1944 (Anthes 1982), helped to determine the structure and development of TCs. In these aircraft, scientists look for evidence of a closed low-level circulation center as well as persistent, organized thunderstorm activity (C. W. Landsea 2000, personal communication). Later, visible and infrared satellite images were also analyzed and a technique was developed to classify tropical cloud systems (Dvorak 1975, 1984). Currently, the National Hurricane Center (NHC) uses a combination of the above resources and several new resources, including the SeaWinds scatterometer on the *QuikSCAT* satellite (Katsaros et al. 2001).

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Prior to the advent of scatterometer-based ocean surface vector wind observations, routine surface wind observations near a TC were found only by ships of opportunity, buoys, reconnaissance airplane dropsondes, or by coastline observation stations and their Doppler radar systems (Tuttle and Gall 1999). Satellite-borne scatterometers have been useful in monitoring the location and intensity of TCs (Hsu and Liu 1996; Katsaros et al. 2001). With the advent of the European Remote Sensing satellite system (*ERS-1* and *ERS-2*), spatial and temporal resolution of surface vector wind observations were much better than before, but they were often impractical for use as an early detection tool because of insufficient sampling. The National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) had sufficient accuracy (Bourassa et al. 1997) and more than double the coverage; however, NSCAT coverage was still insufficient for this task. The SeaWinds scatterometer has improved spatial coverage and temporal resolution, and we will show that it can be used as an early detection tool.

Earlier detection of TCs would be beneficial in many areas. Earlier notice would give the public and maritime interests more time to prepare for a potential future threat. Earlier detection allows scientists more time to plan research missions into storms [e.g., using the National Oceanic and Atmospheric Administration (NOAA) Gulfstream-IV jet aircraft]. In research applications, it also allows the study of determining what promotes tropical cyclogenesis.

The detection algorithm described herein is based on vorticity, which is different than what NHC uses to define a TC. It is also different from the technique used by Katsaros et al. (2001), which identifies closed circulations in the scatterometer data. We chose our technique because of the clear signal given by TCs in average vorticity fields (e.g., Fig. 1). Our technique does not incorporate persistence; NHC considers persistence of organized convection in determining if a TC exists. The statistics for how early a system is detected before NHC classification are based on the first time a signal is detected for a given system.

The thresholds for our detection algorithm are based on observations during the 1999 Atlantic hurricane season (see section titled *Methodology*). During the time of *QuikSCAT*'s operation in 1999 the Atlantic basin had 14 TCs (i.e., tropical depressions, tropical storms, and hurricanes). Based on the thresholds derived from that season, 9 of the TCs had signals that were detected an average of 26 h before the NHC classified the systems as depressions (see section titled *Results*). In the case of TC Emily, the detection algorithm found a vorticity signal 72 h before the NHC classified the system as a TC. The other 5 TCs of that season are not detected early for several reasons, which will be described (see section titled *Results*). The detection algorithm is implemented on two datasets from the 2000 Atlantic hurricane season (see section titled *Application to the 2000 Atlantic Hurricane Season*): research-quality SeaWinds data and near-real-time (<3-h delay) data. The technique found signals for 7 of 18 TCs early for the research-quality data, whereas it found signals for 3 of 12 TCs early for the near-real-time data.

DATA. Scatterometers are unique among satellite remote sensors in their ability to determine surface wind speed and direction. Microwaves are scattered by short water waves (capillary and ultra gravity waves), which respond quickly to changes in winds. The backscatter cross section (the fraction of transmitted energy that returns to the satellite) is a func-

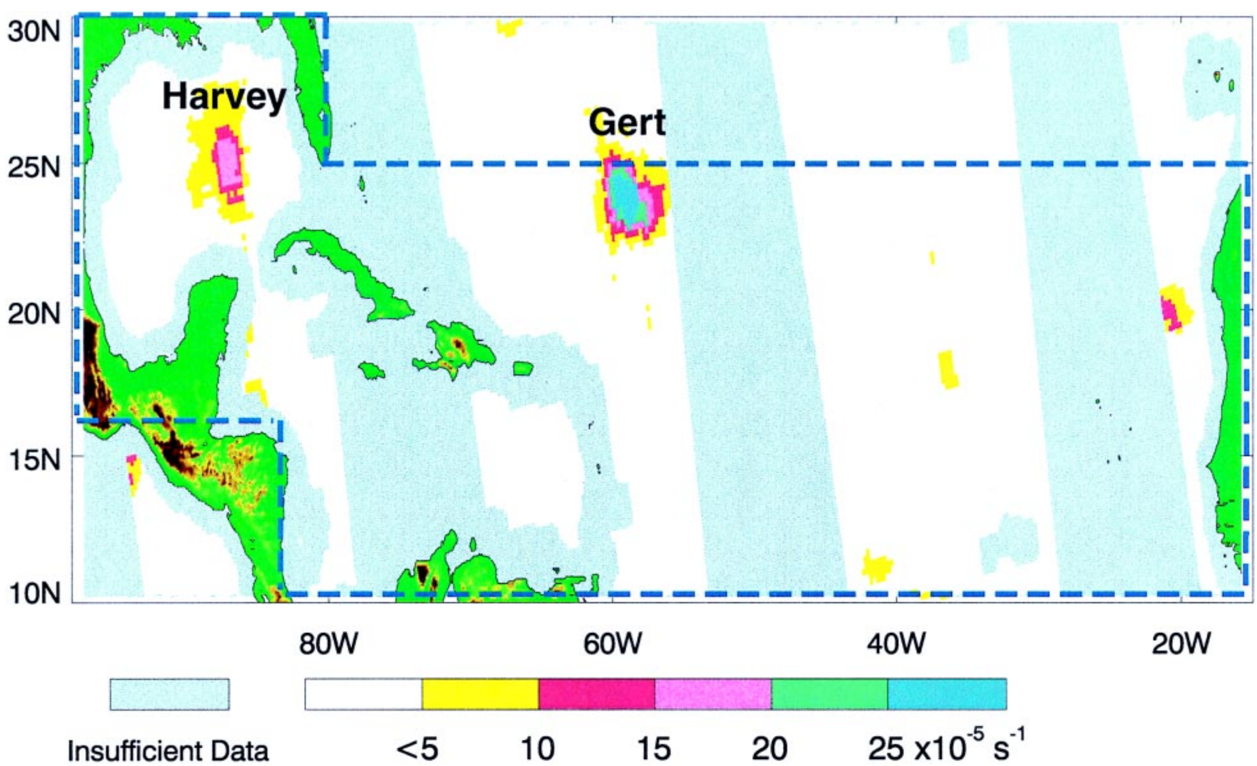

FIG. 1. Vorticity field example from ascending swaths on 19 Sep 1999. Vorticity (see background color scale) is calculated from the scatterometer winds and then averaged over a 175 km by 175 km box within the swaths. The gray regions represent areas where the average vorticity was not calculated. Hurricane Gert and Tropical Storm Harvey give a clear signal in this field.

tion of wind speed and wind direction relative to the orientation of the scatterometer (Wentz and Smith 1999). Scatterometers operate by acquiring spatially and temporally collocated measurements of backscattered power from different viewing geometries. The known relationship between the cross section, wind velocity, and viewing geometry is then used to estimate wind speed and direction (Naderi et al. 1991; Wentz and Smith 1999). The SeaWinds scatterometer uses a new radar design with two conically rotating pencil beams. These beams have incidence angles of 46.25° and 54°. The inner beam has a radius of 707 km, and the outer beam has a radius of 900 km. Individual footprints are binned into 25 × 25 km cells, with up to 76 cells across the satellite swath. This geometry results in relatively accurate observation between 200 and 600 km from nadir, with the greatest uncertainties farthest away from nadir as well as very close to nadir (Bourassa et al. 2002, hereafter BLOS).

The relationships between the backscatter cross section and satellite-relative wind direction, for fixed wind speed and incidence angle, are sinusoidal (Naderi et al. 1991; Wentz and Smith 1999). Consequently, the measure of misfit for the satellite relative wind direction is sinusoidal in wind direction, which typically results in one to four local minima (see Naderi et al. 1991 for detailed discussion). Ideally, the best fit corresponds to the correct direction. Noise in the observed backscatter cross sections can alter the dependence of the misfit on relative wind direction, and thereby cause incorrect directions (also known as aliases) to be chosen. A median filter is applied to each of the ambiguous directions to determine which ambiguity is selected (Shaffer et al. 1991). This process requires an initial guess at the correct ambiguity, which is chosen from the direction (of the two most likely ambiguities) that is the closest match to the direction from the National Centers for Environmental Prediction (NCEP) 2.5° analysis. F. J. Wentz et al. (2001, personal communication) are experimenting with using scatterometer data to provide the first guess field, which will eliminate any biases added by using a separate analysis.

Rain was not considered a serious problem for the ERS or NSCAT scatterometers; however, rain can have a substantial influence on SeaWinds observations. Rain influences radar returns through three processes: backscatter off of the rain, attenuation of the signal passing through the rain (Moore et al. 1999), and modification of the surface shape by raindrop impacts (Bliven et al. 1993; Sobieski and Bliven 1995; Sobieski et al. 1999). The influence of these considerations on the accuracy of winds is a function of scatterometer design. Rain has a greater influence at large incidence angles (the beam interacts with more rain), and for Ku band (NSCAT and SeaWinds) rather than C band (*ERS-1/2*). Modeling these problems is a concern of ongoing research. The rain flag used in this study is the multidimensional histogram (MUDH) flag (Huddleston and Stiles 2000), which is based on a probability space determined from 4 of 6 parameters that are sensitive to rain. MUDH rain flags are in the research-quality dataset available from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory as well as the near-real-time data available through NOAA. Recent research (Weissman et al. 2002) has shown that rain is not as large a problem for the wind speeds we are studying (i.e., 10–20 m s^{-1}), unless in the presence of intense rains typical of the core of mature TCs. A modified rain flag, to be used in tropical systems, is being developed.

Scatterometers actually determine "equivalent neutral wind speeds" (Liu and Tang 1996; Verschell et al. 1999) at a height of 10 m above the local mean water surface, which differ from wind speeds that would be measured by anemometers after adjustment to a height of 10 m. These differences are a function of atmospheric stratification, and are usually <0.5 m s^{-1} (hereafter equivalent neutral winds will be referred to as winds). Comparisons of the research-quality *QuikSCAT* winds (QSCAT-1 algorithm) to research vessel observations (BLOS) found the accuracy varied across the swath, with average uncertainties in speed of 0.45 m s^{-1} and in direction of 5° for correctly chosen ambiguities. Most of the errors in ambiguity selection occurred for vector wind, $|\mathbf{V}|$, less than 4 m s^{-1}, with a much smaller fraction for $4 < |\mathbf{V}| < 6$ m s^{-1}, a nearly negligible fraction for 8 m $s^{-1} < |\mathbf{V}| < 12$ m s^{-1}, and a small, but nonnegligible fraction for $|\mathbf{V}| > 12$ m s^{-1} in the near-nadir part of the swath (BLOS). The near-real-time data (which is also based on the QSCAT-1 algorithm) has degraded accuracy due to assumptions in the processing, and the accuracy of the product is yet to be determined.

METHODOLOGY. Tropical cyclones have areas of positive near-surface vorticity ranging in size from 100 to 1000 km (Liu and Chan 1999; Ahrens 1998). A vorticity-based detection tool should account for the vorticity feature's spatial extent and magnitude. SeaWinds observations of the 1999 Atlantic hurricane season are used to develop an objective technique for detection of TCs. This technique applies a mean vorticity threshold over a given spatial area. Vorticity is calculated within the SeaWinds swaths rather than from a regularly gridded product (typically called a level 3 product) in anticipation of using the technique operationally with the near-real-time data. Ideally, the existence of a TC could then be confirmed by the NHC using satellite pictures of the area to look for persistent, organized convection (i.e., the second half of the definition of a TC).

The spatial scale for averaging vorticity is a 7-point (175 km) by 7-point box centered on the swath points. Individual vorticity values are calculated at the center of each 2 by 2 box of wind observations by determining the circulation around the box and then dividing by the area. A minimum of 3 wind vectors out of 4 in a square is required for the calculation (i.e., if only 3 wind vectors exist, the square becomes a triangle). This approach allows the vorticity to be calculated at the same spatial density as the wind observations. All wind vector data are used in these calculations (i.e., the rain-flagged data are not removed). The inclusion of rain-flagged data likely modifies the vorticity calculation; however, the noise that results by including these data is small compared to the signal. The average is then calculated from these individual vorticity values. For an average to be made, we choose to require that at least 44 (about 90%) of the 49 vorticity observations exist (i.e., not be missing). This limits the technique's ability in areas close to land and on the edge of the swaths. The test then has three components:

1) The average vorticity in the 7-point by 7-point box must exceed the subjectively determined minimum threshold vorticity (10×10^{-5} s^{-1}).
2) The maximum rain-free wind speed within the box must exceed a certain minimum wind speed (10.0 m s^{-1}).
3) The above two criteria must be met at least 25 times (i.e., approximately an area of 15,000 km^2) within a 350 km by 350 km area.

If the above criteria are met, then a potential TC is identified. These threshold numbers are subjectively determined using the research-quality SeaWinds data for the 1999 Atlantic hurricane season (the near-real-time product was not available at that time). Storms from that season had to be directly "hit" by the *QuikSCAT* swath (i.e., the storm center could not be within 150 km of the edge of the swath) and their central circulation pattern had to be clear of any landmasses to be considered in our determination of a threshold. Due to the small sample of swaths that fit these criteria (40 swaths), the thresholds might be too large, but are good for lowering the false alarm rate for 1999.

The domain used to develop this technique is the Gulf of Mexico, the Caribbean Sea, and the tropical Atlantic in the latitude band from 10° to 25°N (the dashed region in Fig. 1). Points north and south of this band are excluded because they are climatologically unfavorable origin points for TCs, and TCs did not develop there in the 1999 season. Test runs farther north are also susceptible to misidentifying midlatitude frontal systems in the latter months of the hurricane season.

RESULTS. Our vorticity-based test is applied for the time *QuikSCAT* began operating (20 July) to the end of the 1999 Atlantic hurricane season (30 November). Of the around 1,100 swaths that passed through the domain during that period, the test identified a total of 96 swaths containing potential systems. Some storms had multiple hits: for example, TC Emily (Fig. 2a) had five hits. Most of the identified systems are NHC-classified TCs (Table 1). The probability of detection (POD)—the number of times a system was detected early or during its existence divided by the total number of times *QuikSCAT* passed over an existing system—was 0.82. The false alarm rate (FAR)—the sum of the last four rows in Table 1 divided by the sum of all rows in Table 1—was 0.33. The critical success index (CSI)—the number of times systems were detected early or during their existence divided by sum of the number of detected systems ($N = 96$) and the number of times *QuikSCAT* passed over a developed system and our algorithm did not detect it (14)—was 0.58.

Of the 14 TCs that occurred in the 1999 season during the time *QuikSCAT* was operating, 9 were identified before the NHC classified them as tropical depressions (Table 2). TC Lenny, in addition to being detected early, had the distinction of being the only storm identified after the NHC classified it as dissipated (listed as a closed circulation in Table 1). The average early detection time for these 9 storms was 26 h before the NHC classified them as TCs.

Tropical Cyclone Emily was identified 72 h before the NHC classified it as a TC (the earliest detection relative to NHC identification). The NHC classified Emily as a TC at 2100 UTC on 24 August 1999 with a center of circulation of 11.9°N, 54.0°W. At that time, it was immediately named a tropical storm, based on aircraft reconnaissance reports. *QuikSCAT*'s image of Emily (Fig. 2a), 72 h earlier, has a small tight circulation centered at 11.5°N, 46.7°W. Around the circula-

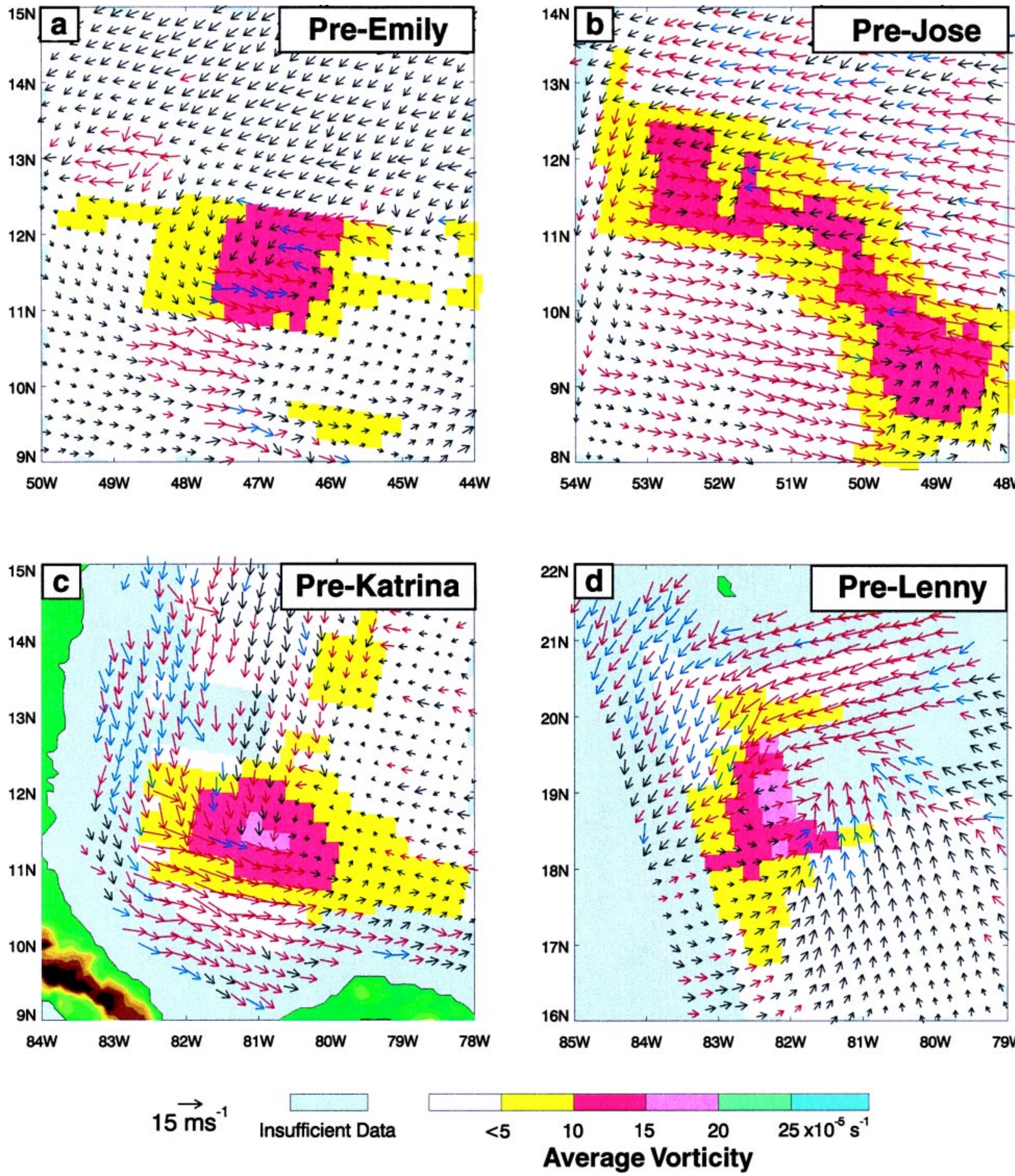

FIG. 2. Sample of the systems that were detected early by our vorticity algorithm. The background color represents spatially averaged vorticity (as in Fig. 1.). Wind speed is proportional to reference arrow length given in bottom left. Black (blue) arrows represent wind speeds less (greater) than 10.0 m s^{-1}. Red arrows indicate data flagged by the MUDH rain flag. (a) Emily, 72 h before the NHC classified it as a TC (2102 UTC 21 Aug 1999). (b) Jose, 24 h before the NHC called it a TC (2103 UTC 16 Oct 1999). (c) Katrina, 45 h before the NHC called it a TC (2334 UTC 26 Oct 1999). (d) Lenny, 34 h before the NHC called it a TC (1043 UTC 12 Nov 1999).

tion, some rain-free wind vectors have wind speeds greater than 10 m s^{-1} and one had winds to tropical storm force. The only negative factor for this system was that the convection was highly variable [this and all further convection information comes from NHC (2001)].

Table 1. Classification of the systems that were detected by the vorticity-based test for the 1999 Atlantic hurricane season.

Reason an identified system passed the test	Percentage of systems passing test ($N = 96$)
NHC-classified TC	52.1
Early detection of NHC-classified TCs	14.6
Closed circulations (possible TCs)	13.5
Tropical waves or ITCZ	12.5
Fronts	3.1
Other	4.2

Tropical Cyclone Jose was identified 24 h before the NHC classified it as a TC. According to SeaWinds (Fig. 2b), an elongated circulation existed in the location where Jose would form. Thunderstorm activity was also getting better organized at this time. The wind speeds around the system were relatively weak (around 10 m s^{-1}).

Tropical Cyclone Katrina was identified 45 h before its NHC classification as a TC. Katrina formed from the remnants of an old frontal boundary, and at the time of the satellite overpass (Fig. 2c), thunderstorms were beginning to concentrate about a low pressure area. According to *QuikSCAT* (Fig. 2c) a weak low-level closed circulation was located near 11.5°N, 81.0°W. The strongest winds in the circulation were located west of the center. In this region the wind speeds were mostly above 10 m s^{-1} with one rain-free speed above tropical storm force.

Tropical cyclone Lenny was identified 34 h before the NHC classified it as a TC. It was identified as a broad area of low pressure as early as 8 November, but convection around the system was poorly organized. A reconnaissance aircraft investigated the system on 12 November and did not find a well-defined surface circulation center. The *QuikSCAT* data (Fig. 2d) indicated that a circulation was forming around 19°N, 82°W. In addition, rain-free wind speeds indicated that winds of 10–15 m s^{-1} were located in the north semicircle of the system.

Five other TCs [Floyd, Gert, Tropical Depression (TD) 11, TD 12, and Irene] were identified by the vorticity-based test before the NHC classified them as TCs. Of the remaining five storms, only TC Harvey was identified as soon as *QuikSCAT* passed over it (i.e., the previous overpass of the system was before the NHC classified it as a TC). The question of how often *QuikSCAT* passes over developing tropical systems is a key factor in determining the usefulness of *QuikSCAT* in this application. During the 1999 Atlantic hurricane season, *QuikSCAT* passed over a tropical system either once every 12 h (84% of the time), once every 24 h (7%), or once every 36 h (9%). The inclusion of data from another SeaWinds scatterometer, expected to be operational in mid-2003, should provide more frequent coverage of tropical systems.

Tropical cyclones Bret, Cindy, Dennis, and TD 7 were not identified by *QuikSCAT*'s first overpass of the systems. The reasons, made clear upon reviewing the SeaWinds data, are that either there was interference with land, ambiguity selection errors (often rain related), or the data suggested no closed surface circulation in the area that the NHC said the center existed. The vorticity-based test failed 3 times to pick up TD 7 (the first time is shown in Fig. 3a), and an examination of each swath revealed that each of the factors listed above contributed to the lack of a vorticity signal.

Table 2. Early detection times (in hours) relative to the NHC's initial classification time (i.e., the time when the system first reached the criteria used by the NHC) for the 1999 Atlantic hurricane season during the time of *QuikSCAT*'s operation. Five TCs were not identified before the NHC's initial classification time.

Storm	Relative detection time
Emily	72
Floyd	13
Gert	20
TD 11	20
TD 12	6
Irene	3
Jose	24
Katrina	45
Lenny	34

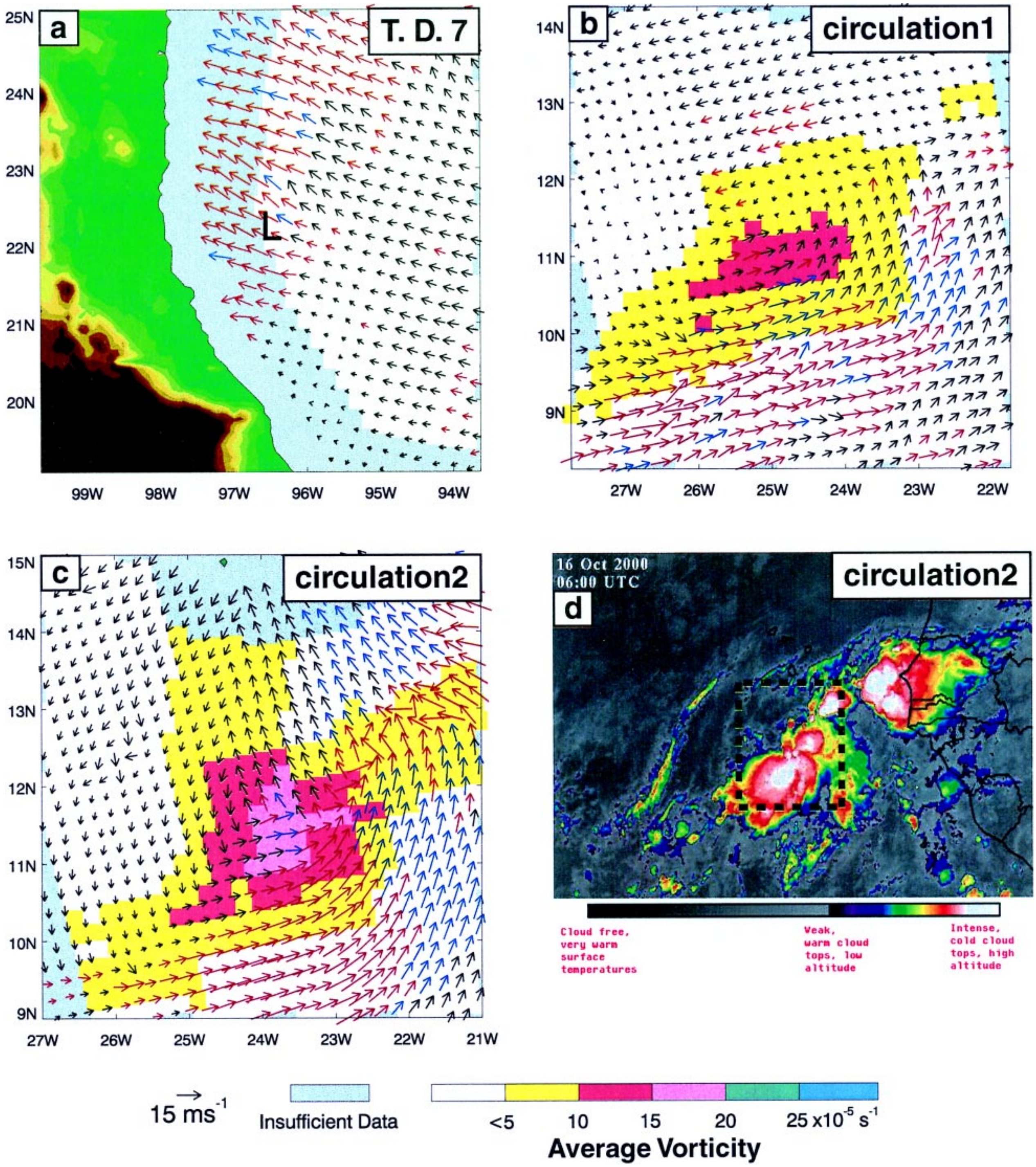

Fig. 3. As in Fig. 2, but for more complicated comparisons. (a) Tropical Depression Seven (0050 UTC 6 Sep 1999). The "L" represents the center of circulation, according to the NHC. This event did not pass our vorticity-based test. (b) An area that was identified by the vorticity-based test and was not classified as a tropical depression by the NHC (0745 UTC 3 Aug 1999). (c) Another area that passed the vorticity-based test and was not classified as a TC by the NHC (0704 UTC 16 Oct 2000, near-real-time dataset). (d) A Meteosat image taken an hour earlier before the system in (c). The dashed box indicates the area covered in (c).

In addition to the TCs classified by the NHC, our vorticity-based detection technique identified seven separate closed circulations. In one case (Fig. 3b) the winds on the south side of the system match the wind definition for a TC given by NHC. Along with this case, three other circulations could have been classified as tropical depressions depending on the organization of the thunderstorm activity in the system. The other three circulations appear to be related to frontogenesis because they occurred late in the season and because they developed north of 20°N.

Our results from the 1999 Atlantic hurricane season suggest that this vorticity-based technique should perform well when applied to the 2000 season. In addition, the 2000 season offers an opportunity to test the algorithm with a near-real-time dataset, which could be used operationally by the NHC.

APPLICATION TO THE 2000 ATLANTIC HURRICANE SEASON.

Research-quality dataset. The threshold values derived from the 1999 Atlantic hurricane season were applied to the available data for the 2000 season. Most of the identified systems have closed circulations (i.e., they are among the first three categories listed in Table 3). The detection technique finds 7 of the TCs (Table 4) an average of 27 h before the NHC classified them (17 h if you remove the outlier of TC Ernesto). The reduction in early warning involved in the latter case is probably due to the inclusion of *QuikSCAT* data in the NHC's determination of a closed circulation. Intergovernmental storm discussions from the 2000 season frequently referred to *QuikSCAT*'s use, especially in determining closed circulations in the far eastern Atlantic: an area that is not practical for the use of aircraft reconnaissance. The POD for these data was 0.70, whereas the FAR was 0.43. The CSI was 0.46, which is less than for the 1999 data because of the larger percentage of misidentified fronts in the 2000 data.

Tropical cyclone Ernesto had the greatest early detection time. Ninety-two hours before the NHC classified it as a depression, a closed circulation appeared in the far eastern Atlantic at approximately the longitude Ernesto would have been in this stage of its development [according to the storm reports archived by the NHC (2001)]. However, the system was not identified by our technique in the observations from the next three overpasses. This is because this vortex lost its organization before redeveloping farther west in the Atlantic.

Eleven TCs were either identified after the NHC classified them as depressions or were never identified. Four TCs (TD 4, Florence, Leslie, and Michael) first developed outside of our domain. In each case, the TC developed just off the east coast of Florida, which is north of 25°N in the Atlantic. During the development of this technique, this region was avoided because of the number of fronts that made their way through this area and the consequential increase in the false alarm rate. TCs Gordon and Helene (which existed first as TD 12, became an open wave, and then regenerated) developed too close to the Yucatan peninsula; consequently, our algorithm did not identify them until after the NHC did. The second *QuikSCAT* overpass identified TC Beryl after it was classified by the NHC. The first overpass suggested that no closed circulation existed in the area identified by the NHC. The TC Chris was never identified for the same reason.

Our vorticity detection technique found six closed circulations not classified as depressions by the NHC. One case (Fig. 3c, shown as it was found by the

TABLE 3. Classification of the systems that are identified by the vorticity-based test for the 2000 Atlantic hurricane season for the research-quality data and for the near-real-time data (starting 18 Aug 2000).

Reason an identified system passed the test	Percentage of systems passing test (research-quality data *N*=61)	Percentage of systems that passed test (near-real-time data *N*=38)
NHC-classified TC	45.9	28.9
Early detection of NHC-classified TCs	11.5	10.5
Closed circulations (possible TCs)	11.5	15.8
Tropical waves or ITCZ	14.8	15.8
Fronts	14.8	26.3
Other	1.6	2.6

near-real time dataset) was a circulation that had just come off of Africa. A well-defined circulation is apparent. An infrared satellite image taken close to the time of the *QuikSCAT* swath (Fig. 3d) shows that organized thunderstorm activity appeared to be in the area. However, this activity did not persist, and the system quickly lost its circulation. This is similar to the findings of Carlson (1969) and Frank (1971) that some systems can move off the west coast of Africa with a closed circulation; however, they usually decay within 12 to 24 h. Four other circulations (not shown) were classified as potential TCs, but their convection lacked persistence. The other detected circulation was likely associated with frontogenesis.

The detection algorithm did not perform as well in the 2000 season as it had in the 1999 season. The main reason for this is the increased misidentification of fronts in the data. There are a couple of possible ways to correct this problem. A subjective way would be to analyze detected systems visually (i.e., with other synoptic datasets) to determine if a front exists. A possible objective way would be to analyze the deformation fields in the data, because fronts are usually associated with areas of deformation. A reduction in the number of fronts identified by the algorithm would make the results for the 2000 season comparable to the 1999 season.

Table 4. Early detection times (in hours) relative to the NHC's initial classification time for the 2000 Atlantic hurricane season. For the research-quality data 11 TCs were not identified before the NHC's initial classification time, and for the near-real-time data, 10 TCs were not identified earlier.

Storm	Relative detection time (research-quality data)	Relative detection time (near-real-time data)
TD 1	9	N/A
TD 2	20	N/A
Debby	13	13
Ernesto	92	—
Joyce	13	13
Keith	10	—
Nadine	35	35

Near-real-time dataset. The near-real-time dataset used in this study became available on 18 August 2000. Compared to the research-quality data, a smaller percentage of the identified systems are closed circulations (any of the first three categories in Table 3), and a larger percentage are termed misidentified fronts. For this reason the FAR and CSI became 0.61 and 0.33, respectively; whereas, the POD was 0.68. Despite this increased inaccuracy, the vorticity-based test still identifies 3 of the TCs early, which is 2 less than found in the research-quality data for the same time period. The reason they are not identified by the near-real-time dataset is probably due to assumptions made in the rapid processing that lead to ambiguity selection errors. These errors would propagate into the calculation of the vorticity, which could reduce the value of the vorticity calculated. A possible correction for this would be to establish lower vorticity thresholds in the near-real-time dataset; however, lower thresholds would increase the false alarm rate.

Improved vorticity thresholds can be developed with more near-real-time data. We did not receive near-real-time data until 18 August 2000, and even then, an error in retrieving the data caused us to miss about 10% of the data. The effectiveness of this technique will improve as the quality of the near-real-time data improves. For example, a new geophysical model function (Ku 2000; F. Wentz and D. Smith 2000, personal communications) has been shown (BLOS) to be more accurate than the model function (QSCAT-1) used for the near-real-time product. Increases in processing power should also reduce the negative impacts of the assumptions used to produce the near-real-time product. Furthermore, reductions in rain-induced errors in speed (Weissman et al. 2002) and direction (Stiles and Yueh 2002) will also improve the accuracy of the scatterometer-derived vorticity.

SUMMARY. A vorticity-based detection algorithm is developed to identify potential TCs in the Atlantic hurricane basin. We use the research-quality data from the 1999 hurricane season to subjectively determine vorticity and wind thresholds for that season. The test is then applied to the 2000 hurricane season, and it is also applied to near-real-time data.

The results show that the vorticity in scatterometer winds can be used as an early detection tool for potential TCs. When this technique is applied to the research-quality dataset for the 2000 season, the vorticity-based test finds vorticity signals for 7 of 18 TCs an average of 17 h before the NHC classified them as TCs (27 h if we include the early detection time for TC Ernesto, 92 h). When applied to the near-real-time dataset, for a shorter period of data, the vorticity-based test found signals for 3 of 12 TCs an average of 20 h before the NHC classified them as TCs. The inclusion of data from the future SeaWinds scatterometer on the Global Change Observation Mission (GCOM) satellite should provide more frequent coverage of tropical systems, which could potentially further improve the early detection of these signals.

Scatterometer-based detection techniques should not be the only approach for TC detection. The scatterometer-based technique is sometimes much better than conventional approaches; however, there are cases where the conventional methods are better. Our intent is to provide an objective technique that can be used operationally to supplement the conventional techniques. The technique does not perform well near the edge of the *QuikSCAT* swaths or near landmasses. However, if a system is close to land, it should be easy to identify by conventional methods. Furthermore, this technique needs to be used in conjunction with visual inspection or additional tests to eliminate false alarms.

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