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QuikSCAT's SeaWinds facilitates early identification of tropical depressions in 1999 hurricane season

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Abstract. Far from land and surface ship observations, most tropical depressions are identified by examining images from geostationary satellites for the presence of rotation of the convective cloud masses. During the 1999 hurricane season, surface wind vectors obtained by the SeaWinds scatterometer on the QuikSCAT satellite for the tropical Atlantic and Caribbean Sea were examined to test the hypothesis that developing tropical depressions (TDs) could be observed with this satellite sensor, before identification by the traditional means. QuikSCAT was able to detect the presence of closed circulation in the surface winds before the systems were designated as depressions. The satellite's unprecedented large swath width of 1800 km allows twice a day observation of most of the tropical oceans. SeaWinds data can, therefore, provide valuable guidance that are an important addition to the tools available to the tropical cyclone forecasting community.

Introduction

The SeaWinds instrument on QuikSCAT is a Ku-band radar with ancestry in the Seasat scatterometer [e.g., *Jones et al.*, 1982; *Katsaros and Brown,* 1991] and the NASA scatterometer, NSCAT [*Naderi et al.*, 1991], on the Advanced Earth Observing Satellite I (ADEOS I). The QuikSCAT mission [*Graf et al.*, 1998] was a recovery mission to compensate for the loss of NSCAT, due to the failure of the power supply of ADEOS I. NSCAT provided global surface winds from September 1996 through June 1997, but, unfortunately, the instrument's life span missed the Atlantic hurricane season. However, NSCAT did observe a major typhoon in the Pacific Ocean [*Liu et al.*, 1997].

A scatterometer works on the principle that electromagnetic radiation transmitted toward the sea surface is scattered back towards the emitting antenna. The intensity of the backscattered radiation at Ku-band is proportional to the amplitude of the centimeter-scale roughness at the sea surface, which is commensurate with the emitted radar wavelength. These small-scale waves are generated by the local wind stress on the sea. For a given wind speed, the backscattered power varies as a function of cos 2Φ, where Φ is the azimuth angle between the look direction and the wind direction. Thus, by measuring the backscattered power from the ocean surface at several azimuth angles, the wind speed and direction may be retrieved, but multiple solutions or "ambiguities" are possible due to the 2Φ functional form.

Scatterometer data from the European Space Agency's C-band instrument on the European Remote Sensing (ERS) satellites 1 and 2 (launched in 1991 and 1995, respectively) have 50-km resolution and 500-km swath widths, which rarely cover an entire tropical cyclone. However, 20 orbits from ERS-1 selected for complete coverage of tropical cyclones were processed at 25-km resolution for study of the value of the higher resolution. ERS-2 is still operating in 2000. Previous U.S. scatterometers were side-looking fixed beam sensors covering 500-km swaths on both sides of the satellite subtrack, but with a 400-km wide gap between them. SeaWinds has two conically scanning radar pencil beams at incidence angles of 47° (H-pol) and 52° (V-pol) and provides 25-km resolution. It has an 1800-km wide continuous swath and can, therefore, completely cover most tropical cyclones.

QuikSCAT data were released to both the science and operational communities on February 1, 2000. The data set used in this study had not been officially released at the time of this demonstration project. The National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data and Information Service (NESDIS) has the responsibility for the near real-time processing and distribution of SeaWinds data for the operational community, and graphics of the near real-time data are available to the general public at http://manati.wwb.noaa.gov/quikscat/.

Two approaches were taken to evaluate the usefulness of QuikSCAT data for studying tropical disturbances. The first approach was based on the hypothesis that the QuikSCAT wind vectors would give an early indication of cyclonic rotation in the surface wind field. Closed circulation in the surface wind is one of the attributes that differentiates a developing tropical cyclone from an open wave. Historically, hurricane forecasters identify potentially developing tropical cyclones by the rotation seen in cloud images obtained from geostationary satellites (GOES East over the tropical Atlantic Ocean). Some previous work indicates that tropical cyclone vorticity first develops at mid-levels where latent heat is released and is transmitted downwards [*Bosart and*

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Sanders, 1981; *Ritchie and Holland,* 1997]. The release of latent heat as an energy source of hurricanes is discussed in detail by *Malkus and Riehl* [1960].

A second approach in evaluating the usefulness of QuikSCAT data in the study of tropical cyclones was to incorporate its scatterometer-derived wind field into the real time surface analyses provided by the Atlantic Oceanographic and Meteorological Laboratory's (AOML) Hurricane Research Division (HRD). These analyzed wind fields are primarily derived from data obtained by reconnaissance aircraft during penetrations into hurricanes [*Powell et al.,* 1998] and also utilize surface winds from dropsondes, winds from an airborne microwave radiometer, and other available surface wind data.

A weather system must have a substantial region of convection and "a definite organized surface circulation" to be classified as a tropical depression [*NOAA Office of the Federal Coordinator for Meteorological Services and Supporting Research,* 1997]. Due to the westward translation of the air in the tradewind region, approximately a 10 m/s westerly (eastward) wind south of the center of circulation is required to confirm that there is a bona fide tropical depression embedded in the tradewinds. We relax the criteria for this study and look simply for a consistent pattern of closed circulation.

Surface observations to assess wind speed and direction in the tropical Atlantic are rarely available from ships, buoys, or land stations and this has resulted in the dependence on observations of rotation in the satellite-observed cloud mass. Since clouds at higher levels may obscure the low-level cloud motions and delay detection of rotation, the working hypothesis for the 1999 hurricane season's demonstration project was that the vorticity might first be detected in the surface winds seen by QuikSCAT.

Methods

The QuikSCAT Science Data User's Manual, available at the Physical Oceanography Distributed Active Archive Center (PODAAC) web site (http://podaac.jpl.nasa.gov/), provides relevant details for the science level data and the near real-time data used in this study (http://manati.wwb.noaa.gov/quikscat/). The SeaWinds data are retrieved at a resolution of 25 km by 25 km with a landmask that extends 30 km off the coast to eliminate land effects. Details on the wind direction ambiguity removal process can be obtained at the above referenced web sites and at http://www.aoml.noaa.gov/rsd/satellite. Errors in the wind vector directions are often found at the edge of the swath, and Ku-band scatterometers are known to have wind retrieval errors related to rain contamination. However, no rain flag was applied to the data in the demonstration project. Since then, *Huddleston and Stiles* [2000] have used various measurement parameters to calculate a "probability of contamination" index for QuikSCAT data. Their multidimensional histogram (MUDH) rain flag is now available with releases of QuikSCAT data.

There were 12 named storms during the 1999 Atlantic hurricane season (Table 1). The first two storms, Arlene and Bret, occurred before SeaWinds data were available for this study. Column 2 in the table gives the date and time when the National Hurricane Center (NHC) first identified the named systems as TDs. Four of these TDs became tropical storms (Arlene, Emily, Harvey, and Katrina), and the other eight eventually developed into hurricanes.

Table 1. Study results for tropical cyclones of the 1999 Atlantic Ocean and Caribbean hurricane season. The last column lists the lead time SeaWinds' swath would have provided, if received in real time.

Storm Name	Date Classified by NHC	Circulation First Seen by QuikSCAT	Time of QuikSCAT Pass (UT)	Lead Time (hours)
Arlene	11 Jun	N/A	--	--
Bret	18 Aug	N/A	--	--
Cindy	19 Aug	19 Aug	20:18	--
Dennis	24 Aug	24 Aug	10:48	--
Emily	24 Aug	23 Aug	9:27	35
Floyd	07 Sep	05 Sep	19:53	49
Gert	11 Sep	10 Sep	19:27	19
Harvey	19 Sep	18 Sep	0:25	33
Irene	13 Oct	13 Oct	11:34	3
Jose	17 Oct	16 Oct	21:09	24
Katrina	28 Oct	27 Oct	10:43	34
Lenny	13 Nov	11 Nov	23:41	45

For this study, the SeaWinds data were examined during the 1999 hurricane season from August to November and from 0° to 25°N in the tropical Atlantic, Caribbean, and Gulf of Mexico for the presence of closed circulation in the surface wind fields. Our strategy involved examining the regions upstream of the named TDs, 12, 24, 36, and 48 hours (approximately) prior to their being designated TDs. Even with an 1800-km swath and using both ascending and descending passes, the SeaWinds instrument does not cover all longitudes in one day. Therefore, the upstream positions of some of these TDs occurred in coverage gaps on some occasions.

During any given hurricane season a number of weather systems within the tropics exhibit closed circulation for a time with no further development. We also examined SeaWinds data in the tropical Atlantic Basin and Gulf of Mexico for the presence of these non-developing systems.

Results

Figure 1 shows an example of a wind field obtained in Hurricane Floyd at its peak intensity. This figure also illustrates the complete coverage of this large storm (~1000 km diameter) by the new scatterometer swath design of SeaWinds.

Figure 2a shows the QuikSCAT surface wind field of the system that became Tropical Storm Emily on the day when it was designated a tropical depression. Figure 2b displays the GOES image of the pre-Emily system on the same day. Figures 3a and 3b similarly show the QuikSCAT data at the precursor stage of the depression that became Tropical Storm Katrina and an infrared GOES image 4 hours later. Figures 3a and 3b also reveal a broad center of circulation and good agreement between the convective activity visible on the GOES infrared image and the highest winds detected by QuikSCAT.

Table 1 lists the dates of official designation of systems as tropical depressions by NHC and the date and time when SeaWinds data first show a closed surface circulation. The QuikSCAT time of detection does not assume that all of the World Meteorological Organization (WMO) criteria for a TD were necessarily present. The lead time that QuikSCAT

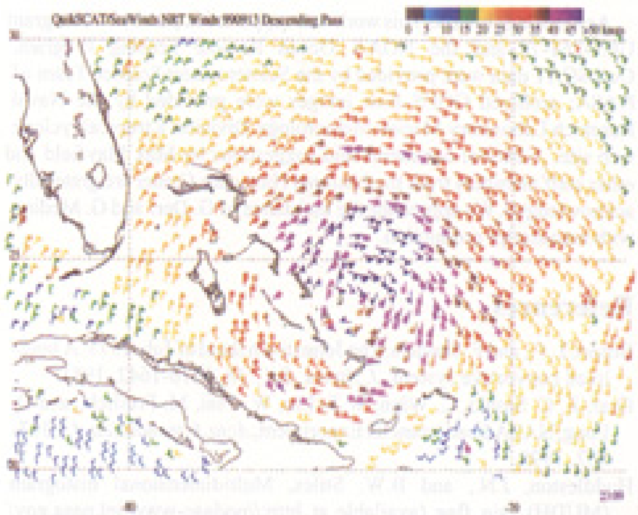

Figure 1. An example of a SeaWinds wind field of Hurricane Floyd at its peak intensity on September 13, 1999. This figure also illustrates the complete coverage of the storm (~1000 km diameter) by the new swath design of SeaWinds.

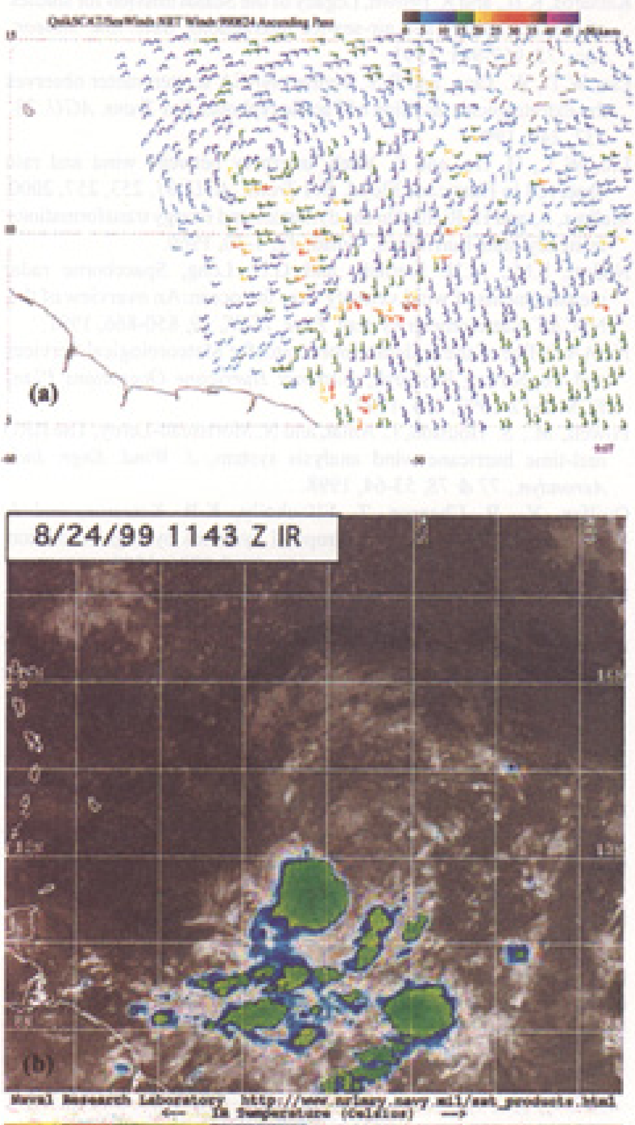

Figure 2. (a) Scatterometer wind vectors from the SeaWinds instrument obtained ~9:07 UTC on August 24, 1999. The wind field reveals closed circulation in the tropical depression that eventually became Hurricane Emily. (b) GOES visible image combined with infrared false color that was obtained within hours of the QuikSCAT wind field shown on Figure 2a.

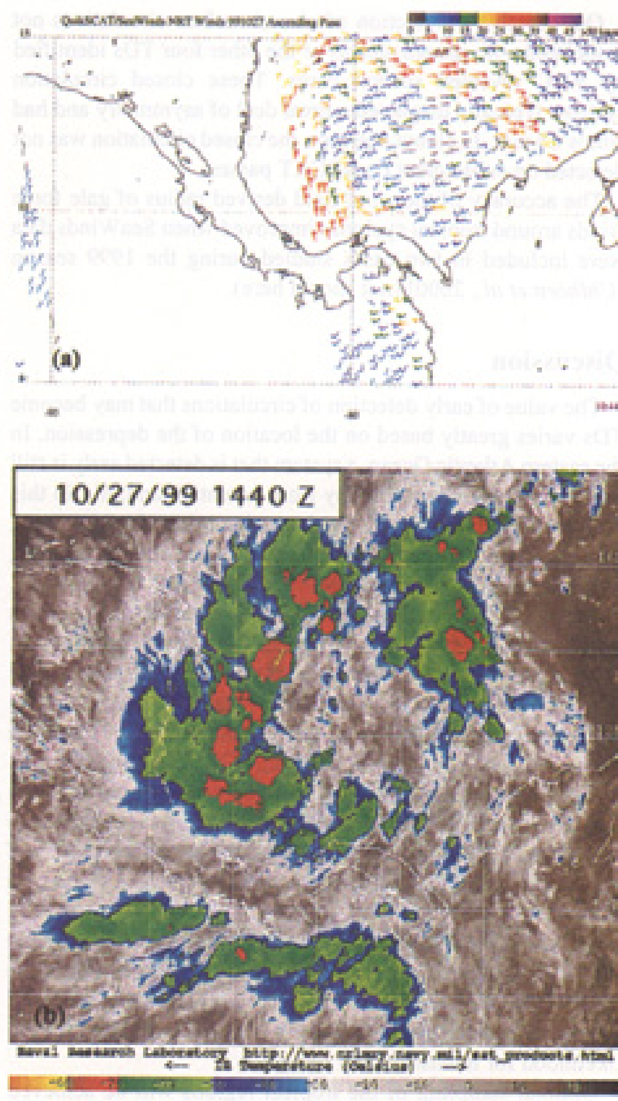

Figure 3. (a) SeaWinds wind field at 10:44 UTC on October 27, 1999 over the tropical cyclonic circulation that developed into Tropical Storm Katrina. (b) GOES infrared image of the same area approximately 4 hours later. The exact time is labeled on the figure.

provides in these cases is seen in the last column. In some cases, the westerly winds south of the centers of circulation were relatively weak (<10 m/s); however, we observed closed circulation in eight of the "tropical depression precursors" (49 hours for Hurricane Floyd) before these systems were officially designated TDs. The large variability in QuikSCAT's lead time for identification of closed circulation is due, in part, to the incomplete longitudinal swath coverage by a single polar-orbiting satellite.

Our search for detection of closed surface circulations not associated with named storms or the other four TDs identified by NHC revealed several cases. These closed circulation systems typically displayed a great deal of asymmetry and had winds ≤5 m/s. In all but one case, the closed circulation was not detected on subsequent QuikSCAT passes.

The accuracy of the wind field derived radius of gale force winds around tropical cyclones improved when SeaWinds data were included in two cases studied during the 1999 season [*Uhlhorn et al.*, 2000] (not shown here).

Discussion

The value of early detection of circulations that may become TDs varies greatly based on the location of the depression. In the eastern Atlantic Ocean, a system that is detected early is still perhaps a week or more away from potential landfall. In this case, early detection may not be as important for increasing warning time to coastal zone residents as it is to shipping interests and to studying the elements that affect cyclogenesis. However, early detection would better enable NHC and others to strategically plan the use of limited flight hours, dropsondes, and human resources. Of course, the greatest value would be derived from the improved lead time that could be used to warn and mobilize authorities to save lives and property. This could be particularly important in the Gulf of Mexico, where storms can develop rapidly and make landfall as hurricanes within a few days of their identification as TDs. Aircraft reconnaissance and other data sources aid forecasters, but in remote regions of the Pacific and Indian Oceans the value of QuikSCAT may be even greater.

QuikSCAT's 1800-km wide swath also provided valuable information about the ambient surface wind fields in which the storms were embedded. The surrounding winds are important elements in determining the storm's motion, its size, and its likelihood for intensification.

Optimal sampling of the tropical regions will be achieved with two scatterometers of SeaWinds design on satellites in orbits that are interleaved. A second SeaWinds instrument, which could provide complete tropical ocean coverage, is scheduled for launch aboard the ADEOS II satellite in the near future. A study of Hurricane Floyd by *Liu et al.* [2000] combined QuikSCAT winds with the Tropical Rainfall Measuring Mission (TRMM) data and provided insight into the interplay between wind and rain in tropical cyclones.

Conclusions

In summary, QuikSCAT shows promise as an aid to early identification of potential tropical depressions in the Atlantic Ocean, the Caribbean, Gulf of Mexico, and probably other tropical regions as well. QuikSCAT detected early closed surface circulation in eight of the 12 named storms that developed during the 1999 Atlantic hurricane season. The system of rapid distribution of processed swath-oriented wind fields via the web by NESDIS allow these data to provide practical and timely support to forecasters.

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