THE APPLICATION OF SCATTEROMETER WINDS AT NOAA

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ABSTRACT

The National Oceanic and Atmospheric Administration (NOAA) of the United States is responsible for providing High Seas wind warnings for a large portion of the Northern Hemisphere oceans. Wind warning categories are defined by the Beaufort Scale and consist of GALE (17.2 to 24.4 m s^{-1}), STORM (24.5 to 32.6 m s^{-1}) and HURRICANE FORCE (32.7 m s^{-1} or greater) for non-tropical sources of wind and TROPICAL STORM (17.2 to 32.6 m s^{-1}) and HURRICANE (32.7 m s^{-1} or greater) for tropical events.

This paper will give an overview of NOAA's experience with QuikSCAT winds at both the Ocean Prediction (OPC) and Tropical Prediction Centers (TPC). To be used effectively in the forecast process, data must be consistently delivered to the forecasters in a timely manner and displayed in a comprehensible fashion.

Near real-time scatterometer derived winds from the NASA QuikSCAT satellite have proven to be extremely useful to NOAA forecasters. In a recent survey, ten percent of all short-term wind warnings issued by the OPC were determined using QuikSCAT winds. QuikSCAT winds were also used to more accurately place half to two thirds of all weather features on manual ocean surface analyses.

QuikSCAT with its wide swath and large retrievable wind range is the first data set to consistently observe winds well into the Hurricane Force category in extratropical cyclones. Based on QuikSCAT winds OPC forecasters are now able to detect and better understand Hurricane Force extratropical cyclones. QuikSCAT's impact on tropical cyclone analysis and forecasting has been less dramatic. QuikSCAT is used routinely to determine the outer radius of Tropical Storm Force winds. Heavy rain and scale effects limit the capabilities of QuikSCAT to estimate the intensity and determine if a developing tropical cyclone has closed off a circulation. However, forecasters at the TPC have examined the climatology of Gulf of Tehuantepec gap winds using QuikSCAT and have been able to improve wind forecasts.

Large sea surface temperature (SST) gradients exist over the mid-Atlantic coastal and offshore waters of the U.S. QuikSCAT has revealed that large wind speed gradients often coincide with these SST gradients. OPC forecasters now factor in low-level stability when making wind forecasts. The overall impact of QuikSCAT on marine forecasting in NOAA has been very positive. QuikSCAT winds in fact have revolutionized the ocean forecasters ability to assess near surface winds over vast ocean areas.

1. INTRODUCTION

NOAA has weather warning and forecast responsibility for the world's ocean areas between 35 degrees West to 160 degrees East longitude and from 25 degrees South to 67 degrees North latitude. Wind warning categories are based on wind speed as defined in the Beaufort Scale (Bowditch, 1977): GALE (17.2 to 24.4 m s^{-1}), STORM (24.5 to 32.6 m s^{-1}) and HURRICANE FORCE (32.7 m s^{-1} or greater) for non-tropical sources of wind. For tropical cyclones two warning categories are used: TROPICAL STORM (17.2 to 32.6 m s^{-1}) and HURRICANE (TYPHOON) (32.7 m s^{-1} or greater). NOAA ocean forecasters in the past relied on very sparsely distributed ship and buoy observations to make warning decisions. Often one or two observations could be found in synoptic scale weather systems. Today, QuikSCAT derived ocean vector winds have become a very heavily relied source of data upon which NOAA forecasters make accurate warning decisions and determine the frontal structure and wind field distribution of weather systems. Earlier papers such as Atlas et al., 2001 have focused on the use of scatterometer winds in numerical weather prediction. This paper will solely focus on the application of scatterometer winds on the human analysis and forecast process. NOAA display capabilities will be discussed in section 2. A variety of applications of QuikSCAT vector winds are the subject of section 3. A summary will be given in section 4.

2. DISPLAY CAPABILITIES

In order for experimental data sets such as QuikSCAT to be fully used by operational forecasters these data must be both timely in delivery and able to be displayed comprehensibly on forecaster operational workstations. QuikSCAT vector winds were first introduced to NOAA forecasters in late 1999 via an internal webpage. This gave forecasters initial access to the scatterometer winds, however, the utility was limited to only being able to determine wind warning categories. In 2000, QuikSCAT winds were made available in the National Center for Environmental Prediction (NCEP) N-AWIPS (National Centers Advanced Weather Interactive Processing System) workstations as image files. This was the first attempt at integrating QuikSCAT winds into the Ocean Prediction Center work environment. Images were static with no capability to turn rain-flagged data on and off or change colors of wind speed ranges.

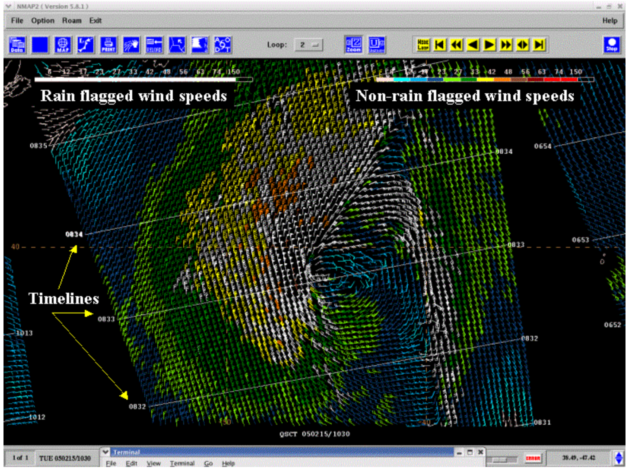

Figure 1. QuikSCAT display of a North Atlantic winter cyclone as viewed in the operational NOAA N-AWIPS workstations. Wind speeds in knots are colored coded as shown by the color bar in the upper right. Rain-flagged wind vectors are shown in white. Timelines at one-minute intervals indicate the data acquisition time.

In the fall of 2001, the NOAA NESDIS Office of Research and Applications established an operational data flow of the Near-Real Time (NRT) QuikSCAT winds. Requirements for N-AWIPS display options for QuikSCAT winds were submitted to the NCEP Computing

Development Branch. As part of the requirements and developmental processes, forecasters work with developers to tailor display capability to maximize utility. As a result of the early experiences with display capabilities at the Ocean Prediction Center and the requirements process, QuikSCAT displays have been optimized on the N-AWIPS workstations. As shown in Fig. 1, ocean forecasters at the OPC, TPC and Honolulu Weather Forecast Office today are able to view QuikSCAT winds in both 25 and 12.5 km resolutions, display timelines that clearly state data acquisition time, highlight potential areas of rain contamination, and customize the display to suite the forecaster and weather scenario. The successful use of QuikSCAT by NOAA ocean forecasters is due in part to the quality of the data itself but also to the rapid delivery of the the data and the comprehensive display capabilities built into the N-AWIPS software.

3. APPLICATIONS OF QUIKSCAT

QuikSCAT ocean vector winds have revolutionized short-term forecasting over expansive ocean areas. After receipt of a QuikSCAT swath, forecasters no longer have to fill in the gaps between sparse observations from ships of opportunity and buoys. The 1800 km wide swath, large retrievable wind speed range, and rapid delivery of QuikSCAT has changed the way forecasters make short-term warning and forecast decisions. In a recent survey of NOAA Ocean Prediction Center forecasters ten percent of wind warning decisions were made using QuikSCAT. The greatest impact was seen to be with the higher and more dangerous wind warning categories. In essence, short-term wind warnings have never been more accurate. This is due to the ability of QuikSCAT to differentiate between wind warning categories of Hurricane, Storm, and Gale Force. In addition to warning decisions QuikSCAT is used to assess the current state of the atmosphere and locate features such as fronts, highs and lows. In the same survey of OPC forecasters, 50 (Atlantic) and 68 (Pacific) percent of weather features were located on synoptic analyses using QuikSCAT. The remainder of this section will discuss a variety of applications of QuikSCAT winds in marine forecasting.

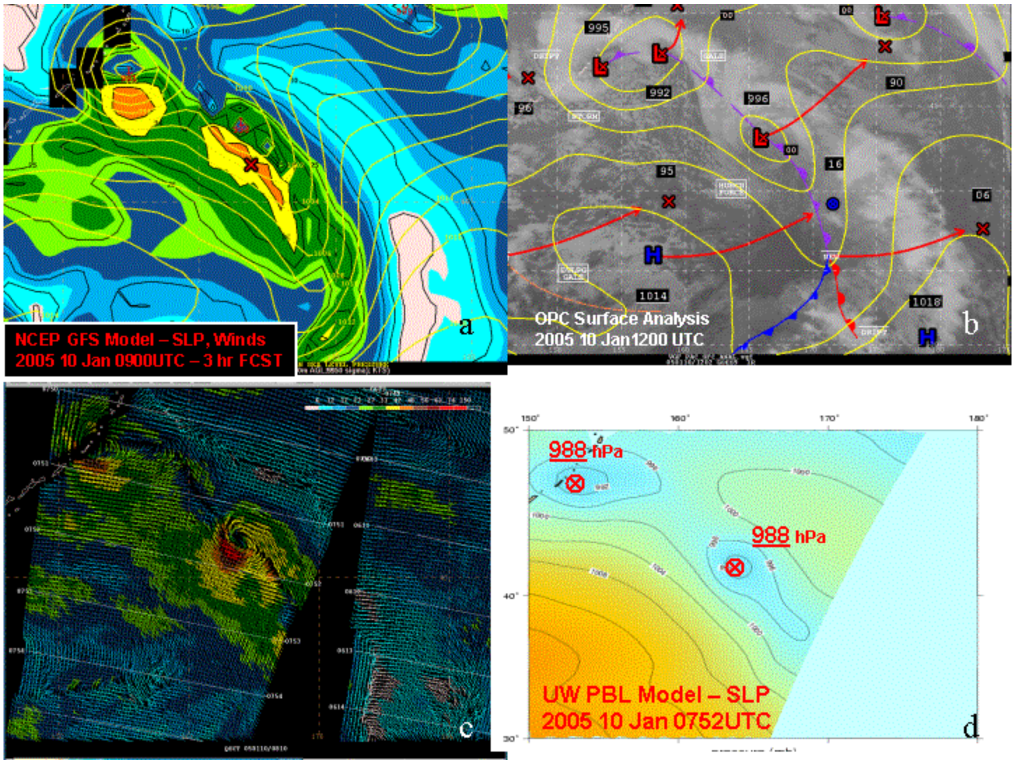

Figure 2. Four panel showing (a) 3 hr forecast from the NCEP GFS model of sea-level pressure (yellow lines) and wind speed (color filled contours) valid 0900 UTC 10 January 2005, (b) IR satellite image and 0600 UTC 10 January 2005 OPC Surface Analysis, (c) 12.5 km QuikSCAT winds, and (d) University of Washington PBL model retrieved sea-level pressure field. In (d) the location and central pressure from the PBL model are shown in red.

a. QuikSCAT as a diagnostic

Accessibility of QuikSCAT winds in NOAA operational workstations gives forecasters the ability to compare a variety of observations, satellite imagery, numerical model forecast fields with QuikSCAT winds. QuikSCAT has thus become a favored data set for forecasters to assess the quality of numerical model analyses and forecasts. As an example QuikSCAT 12.5 km wind speeds and NCEP Global Forecast System (GFS) winds are compared in Fig. 2 for 10 January 2005 for a North Pacific cyclone. In Fig. 2a, 10 m wind speeds from the GFS are contoured using the same scale as the QuikSCAT winds in 2c. The OPC surface analysis for 0600 UTC 10 January 2005 is shown in Fig. 2b. The QuikSCAT image in Fig. 2c shows a very small yet intense cyclone with winds in excess of 32 ms^{-1} (red wind barbs). In Figure 2a, the NCEP GFS 3 hour forecast of 10m wind speeds and isobaric pattern show a significantly weaker cyclone with maximum wind speed of only 20 m s^{-1}. An X in 2a shows the cyclone position depicted by QuikSCAT. Not only was the cyclone in the GFS short-term forecasts too weak with maximum winds but the center was also displaced significantly too far to the north. OPC forecasters chose to warn for extreme winds and upgraded the warning to Hurricane Force from Gale warning and adjusted the expected track for the storm farther to the south. In this case QuikSCAT winds were successfully used as a diagnostic to assess short-term numerical model forecasts.

In Fig. 2d, the sea-level pressure (SLP) field in hPa as derived from QuikSCAT wind field using the inversion method and the University of Washington (UW) Planetary Boundary Layer (PBL) Model as described by Patoux and Brown (2003). The retrieved SLP field suggests that the eastern cyclone was approximately 10 hPa deeper (988 versus 998 hPa) than the 3-hour forecast from the NCEP GFS model suggested. The derived SLP field shown here was calculated in a post analysis mode. The OPC with help from the UW PBL Group is in the process of setting up the process to derive SLP, vorticity, and convergence from QuikSCAT winds in real-time using the UW PBL Model to improve both SLP and frontal analyses and further increase QuikSCAT's use as a diagnostic of numerical guidance fields.

b. Hurricane Force extratropical cyclones

The large retrievable wind speeds from QuikSCAT has given OPC forecasters the ability to distinguish between strong Storm Force and dangerous Hurricane Force winds in association with extratropical cyclones. This large retrievable wind speed range and wide swath make QuikSCAT an excellent tool to consistently detect dangerous winds in cyclones. QuikSCAT winds have certainly raised the awareness of OPC forecasters as to the occurrence of Hurricane Force conditions.

For the purposes of this study a cyclone was deemed to attain hurricane force status if OPC forecasters issued a hurricane force warning. Warning decisions are based primarily on QuikSCAT but also on conventional ship and buoy observations. The staff of the OPC Ocean Applications Branch have then tracked and catalogued all extratropical cyclones that obtained Hurricane Force strength over the North Pacific and Atlantic Oceans from October 2001 through March 2005 as shown in Table 1.

Winter Season	**Atlantic**	**Pacific**
2001-2002	22	15
2002-2003	23	22
2003-2004	15	22
2004-2005	37	31

Table 1. The number of Hurricane Force extratropical cyclones observed by OPC forecasters in each ocean basin during the winter seasons from the fall 2001 to spring 2005.

On average between 15 to 23 extreme cyclones were observed over each ocean basin during the months of October through April for the years 2001 through 2004. For the first three years of this study only the 25 km resolution QuikSCAT winds were used. These numbers increased dramatically during the most recent winter season. The 2004-2005 season forecasters had the 12.5 km QuikSCAT winds available in the N-AWIPS workstations. The 12.5 km winds are noisier than the 25 km due to less averaging between cells. The reduced horizontal averaging also yields higher winds. Of course this brings into question the validity of detection of Hurricane Force conditions by either the 25 km and 12.5 km resolution QuikSCAT winds and is beyond the scope of this paper.

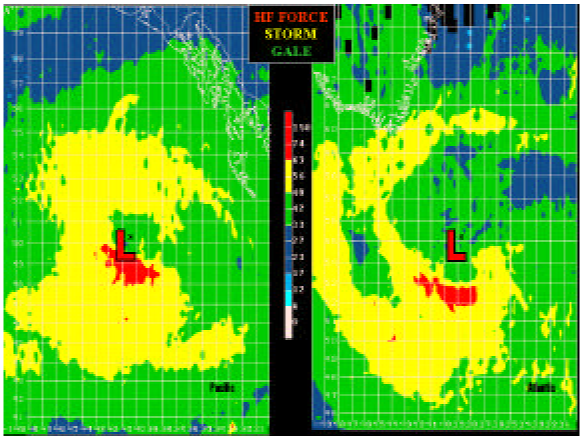

Figure 3. Composites of maximum winds for Hurricane Force extratropical cyclones for the North Pacific (left panel) and North Atlantic (right panel) for cyclones from 2003-04. The composites were created using 5 QuikSCAT passes for the North Atlantic and 11 passes over the North Pacific. The red filled contours show areas of Hurricane Force winds, yellow Storm force, and green Gale force winds.

However, what have we learned through QuikSCAT concerning Hurricane Force (HF) extratropical cyclones? HF extratropical cyclones are winter phenomena occurring between October and March. One Atlantic cyclone was observed in the month of April. HF cyclones are most frequent in the North Pacific in December and in January over the North Atlantic. HF cyclones tend to be explosive deepeners based on the definition by Sanders and Gyakum (1980). The average minimum central pressure is similar for both the North Pacific and North Atlantic at 965 to 970 hPa. However, we observed a larger range of central pressures in the North Atlantic than the Pacific. The North Atlantic appears to be able to produce deeper cyclones than the North Pacific and also sustain HF conditions at higher central pressures. The deeper cyclones are most likely due to the overall low-level baroclinicity of the western North Atlantic. The high central pressures may be due to the topographic impacts on the low-level flow caused by the high terrain of Greenland. HF conditions tend to be short lived on the order of less than 24 hours and occur in the mature cyclone near the time of minimum central pressure. Although HF cyclones are indeed the result of baroclinic instability they tend to become shallow warm core seclusions in maturity. Composites of maximum winds from QuikSCAT from 5 different North Atlantic and 11 North Pacific HF cyclones are shown in Fig. 3. Both composites show HF conditions to be found in a crescent shaped arc south of the mature cyclone center. This region in a cyclone is typically on the cold side of the occluded or bent back front, has a deep mixing depth, and has little vertical wind shear.

c. Tropical applications

Although QuikSCAT has been extremely useful to observe Hurricane Force extratropical cyclones it has been used with less success for tropical cyclones. HF conditions tend to occur in extratropical cyclones in rain-free areas of areas of shower activity. Unfortunately, in tropical cyclones often the highest winds are coincident with very heavy precipitation near the eye wall. The radar signal is the attenuated by the heavy precipitation and the relatively small-scale of tropical cyclones (compared to the 25 km foot print of QuikSCAT) make it near impossible to detect the highest winds and structure of a tropical cyclone. However, the NOAA Tropical Prediction Center does indeed use QuikSCAT winds in their daily tropical cyclone responsibility and marine forecast responsibility. QuikSCAT has been useful to estimate the radii of both 17 m s^{-1} and 24 m s^{-1}. The four retrieved ambiguities from QuikSCAT can also be used to estimate whether an area of disturbed weather in the tropics has developed a closed surface circulation.

Precipitation contamination and its impact on wind retrievals remains a problem for QuikSCAT winds in both the tropics and lower mid-latitudes. To help mitigate this problem it is hoped that future scatterometers be accompanied with microwave rain rate detection instruments.

The marine warning and forecast responsibility of the TPC includes the eastern Pacific and western Atlantic. Mountain gaps in Central America in the Pacific and passages between mountainous islands in the Caribbean Sea impact the low-level wind flow. QuikSCAT has given forecasters of the TPC Tropical Analysis and Forecast Branch the ability to study gap flows such as the Gulf of Tehuantepec and Gulf of Papagayo and the Mona and Windward Passages. Perhaps the most significant of these is the Gulf of Tehuatepec where QuikSCAT has often shown winds well into storm force. These strong winds occur when a strong cold front races south along the eastern face of the Rocky Mountains through the United States and then Mexico. Continental air spills into the Pacific through the gap in the mountains north of the Gulf of Tehuantepec. QuikSCAT has given TPC forecasters the ability to both observe and forecast the onset and intensity of these events.

d. Winds near sea surface temperature gradients

Wind gradients have been observed by aircraft observations across the sea surface temperature (SST) gradients of the Gulf Stream as described by Sweet el al., 1981. Calmer winds and seas were found over the cooler shelf waters with rougher seas and higher winds over the warm Gulf Stream waters. Sweet et al., 1981 suggested that differences in low-level static stability

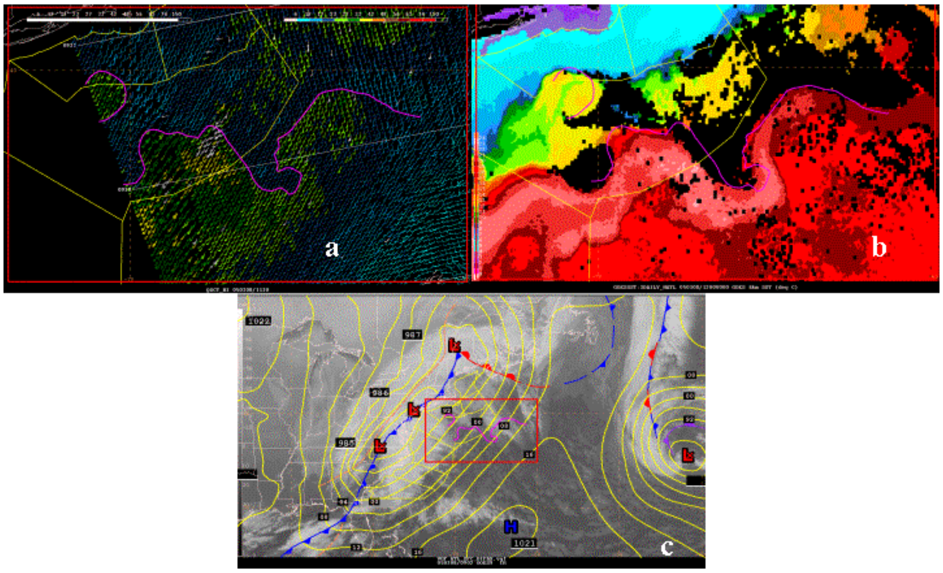

Figure 4. Three panel image showing (a) QuikSCAT 12.5 km winds, (b) GOES 3-day SST composite, and (c) OPC surface analysis from 1200 UTC 8 March 2005. The red box in (c) highlights the areas shown in (a) and (b). The purple line in all images delineates the wind speed gradient illustrated by QuikSCAT.

accounted for the observed wind speed differences. QuikSCAT with its wide swath is an excellent tool to observe near surface winds near the complex SST gradients of the U.S. shelf, slope and Gulf Stream waters. An example from QuikSCAT of southerly flow from 8 March 2005 is shown in Fig. 4. The left panel shows the 12.5 km QuikSCAT winds for 0930 UTC 8 March and the right panel a 3-day GOES SST composite to illustrate ocean features. Although a uniform pressure gradient existed over the Gulf Stram and Shelf waters QuikSCAT revealed a significant wind gradient. Over the Gulf Stream winds were as high as 18 m s^{-1} and to the north over cooler waters winds were as low as 5 m s^{-1}. The purple contours in Fig. 4a. delineate the sharp wind gradient. In comparing Fig. 4a to 4b one can see that the wind gradient nearly matches the SST gradient of the North Wall of the Gulf Stream. One can even see the strong winds of 13 m s^{-1} over the warm eddy to the northwest of the Gulf Stream. In essence QuikSCAT winds bolster the conclusions of Sweet et al., 1981 that low-level stability due to the underlying SST impacts the wind distribution in the vertical. OPC forecasters now have a variety of numerical guidance tools to anticipate the low-level stability and potential for both stratification and strong vertical momentum transfer.

e. Other applications

The OPC produces gridded QuikSCAT winds hourly. These gridded wind fields at 1/3 degree resolution are available via the Internet and can be downloaded by mariners at sea using satellite communication systems. The gridded QuikSCAT winds are then used by mariners to make a variety of short-term routing and sail handling decisions. Initially the gridded QuikSCAT winds were composited over time to include 9 hours of the most recent data. At the request of the recipient customers (and with some hesitation on the part of OPC) the compositing time was increased to 32 hours. The longer compositing time made sure that all gaps of data were filled. As meteorologists the hesitation to potentially have the customer looking at data 24 hours old or older is obvious. Interestingly, most sailors would rather have old data than no data at all and in many parts of the world such as in the trades this is a valid request. Meteorologists display the QuikSCAT winds highlighting wind speeds (color coding) while sailors color code QuikSCAT winds by age of the data. QuikSCAT is now used directly by end customers to make short-term decisions.

4. SUMMARY

The availability of QuikSCAT winds has indeed dramatically improved NOAA ocean forecasters ability to assess wind conditions over the vast open oceans. One could even say that QuikSCAT has revolutionized the oceanic wind warning and short-term warning process. The success of QuikSCAT in NOAA operations is due to the relatively rapid data delivery (between an hour to 2 hours of data acquisition), the wide 1800 km swath of QuikSCAT and large retrievable wind speed range. The wide swath, in particular, makes QuikSCAT winds repeatable over specific features of interest, a capability that did not exist with earlier scatterometers. Ten percent of short-term warning decisions are based exclusively on QuikSCAT. The success of QuikSCAT in NOAA operations is also due to the display capabilities developed within NCEP. QuikSCAT is indeed fully integrated into the operations of the OPC and TPC.

In this paper it has been shown that QuikSCAT is an excellent diagnostic and is used to assess numerical model initial conditions and short-term forecasts. NOAA forecasters are able to confidently distinguish between strong Storm force and extreme Hurricane Force conditions and warn mariners appropriately. QuikSCAT winds are used to accurately locate fronts, highs, lows, and troughs. The significance of SST on the near-surface wind has been revealed over the complex waters of the Gulf Stream. Forecasters now have tools based on numerical guidance to help anticipate significant wind gradients across SST gradients. Today's numerical weather prediction models fail to forecast such wind speed gradients.

QuikSCAT wind fields have been less useful with tropical cyclones due to both precipitation contamination and sampling size. QuikSCAT is not useful to estimate the maximum wind speeds of a tropical cyclone. Hopefully future instruments will address the tropical cyclone problem and rain contamination. QuikSCAT winds are useful to determine the outer radius of tropical storm force winds.

Much of this discussion focuses on the use of wind speed and not the full wind vector although locating frontal features and highs and lows relies on the full wind vector. The OPC over the next several months intends to expand the use of QuikSCAT winds by using the UW PBL Model to retrieve derived fields such as sea-level pressure, vorticity, and convergence. This process will indeed require the full ocean wind vector. It is anticipated that deriving such fields in real time from QuikSCAT will enhance the use of QuikSCAT as a diagnostic.

Sanders (1990) discussed sea-level pressure and features analyses over oceanic regions. A portion of the title stated “In search of the sea truth”. To summarize QuikSCAT has given NOAA ocean forecasters the best sea truth to date.

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