Operational Use and Impact of

Satellite Remotely Sensed Ocean Surface Vector Winds

in the Marine Warning and Forecasting Environment

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ABSTRACT. In 2002, a National Oceanographic Partnership Program project was initiated with the ambitious objective of maximizing the use of currently and soon-to-be-available satellite ocean surface vector wind (OSVW) data, such as NASA's QuikSCAT scatterometer, in the operational weather forecasting and warning environment. This effort brought together people from the operational forecasting and satellite remote-sensing communities, academia, and the private sector. This diverse gathering of skill and experience yielded documentation of the impacts of these data in the operational short-term warning and forecasting environment of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service, improvement in the use of these data in the public and private sectors, and the transition of promising research results into the operational environment. This project helped create momentum that has continued to grow long after the formal effort ended; today, NOAA uses QuikSCAT operationally and is investigating how to best establish a sustained satellite OSVW observing capability.

INTRODUCTION

The ocean comprises over 70% of Earth's surface, which makes satellite remote sensing a logical and significant component of an overall effort to meet societal needs for weather and water information; support commerce with information for safe, efficient, and environmentally sound transportation; and provide information for better coastal preparedness. Ocean surface vector winds (OSVW) are crucial pieces of information needed to understand and predict the short-term and longer-term processes that drive our planet's environment. As the largest source of momentum for the ocean surface, winds affect the full range of ocean movement, from individual surface waves to complete current systems. Winds along the ocean surface regulate interaction between the atmosphere and the ocean via modulation of air-sea exchanges of heat, moisture, gases, and particulates. With the ocean covering almost three quarters of Earth's surface, this interaction has significant influence on global and regional climate.

On June 19, 1999, the National Aeronautics and Space Administration (NASA) launched QuikSCAT, a microwave radar system known as a scatterometer, specifically designed to retrieve OSVW over the global ocean (Jet Propulsion Laboratory, 2006). Prior to launch, NASA's Jet Propulsion Laboratory (JPL) and the National Oceanic and Atmospheric Administration's (NOAA's) National Environmental Satellite, Data, and Information Service (NESDIS) worked together to implement a near-real-time OSVW processing and distribution system at NOAA to allow QuikSCAT data to be used by the operational weather forecasting and warning communities around the world. Although QuikSCAT was not the first scatterometer launched into space (Naderi et al., 1991; Stoffelen and Anderson, 1993; Gelsthorpe et al., 2000; Verhof and Stoffelen, 2008), its reliability, high quality, relatively fine spatial resolution, and large daily geographical coverage resulted in its having the largest impact of any scatterometry mission in the operational marine weather forecasting and warning world (Jelenak and Chang, 2008).

In 2002, a National Oceanographic Partnership Program (NOPP) project was initiated to exploit the currently and soon-to-be-available satellite OSVW data in the operational weather forecasting and warning environment. This effort had three main objectives: (1) to quantify the impacts of QuikSCAT OSVW data in the operational short-term warnings and forecasts issued by the National Weather Service (NWS) Ocean Prediction Center (OPC) and National Hurricane Center (NHC), (2) to improve the use of satellite OSVW data in the public and private sector, and (3) to transition promising research products toward operational use. This project brought together people from the federal government, private industry, and academia and initiated what has become one of the most successful transitions of a research data stream (QuikSCAT OSVW) into operational use, where it continues to have a profound impact on marine weather warning and forecasting.

OPERATIONAL USE

In the United States, NWS is responsible for providing marine weather warning and forecast information, and it has international obligations to provide the same within its areas of responsibility under the umbrella of the World Meteorological Organization. Additionally, the US military provides marine weather forecasting and warning services to support military operations. A combination of the NWS areas of responsibility with those of the military's Joint Typhoon Warning Center (JTWC) provides coverage of much of the world's ocean (Figure 1).

With only a very limited number of open-ocean buoy and ship reports

available, remotely sensed satellite OSVW data are very important to accurate and systematic mapping of the global ocean wind field. QuikSCAT provides an almost complete OSVW map of the global ocean twice daily (Figure 2).

To be fully used by operational forecasters, experimental data sets such as QuikSCAT must be delivered in a timely fashion and made available for display on forecasters' operational workstations.

QuikSCAT vector winds were first introduced to NOAA forecasters in late 1999 via the near-real-time (NRT) QuikSCAT Web portal (http://manati. star.nesdis.noaa.gov/quikscat). This site provided forecasters with initial access to scatterometer wind data; however, its utility was limited to determining wind-warning categories. In early 2000, QuikSCAT wind data were made available as image files on National Center for Environmental Prediction (NCEP) National Centers Advanced Weather Interactive Processing System (N-AWIPS) workstations. However, these images were static, with no capability to turn rain-flagged data on and off or to change the colors assigned to wind-speed ranges.

The opportunity provided by the NOPP project significantly advanced display capability as forecasters worked with developers to optimize QuikSCAT displays on the N-AWIPS workstations. Ocean forecasters at OPC, NHC, and the Weather Forecast Office (WFO) in Honolulu can now view both the QuikSCAT 25-km and 12.5-km
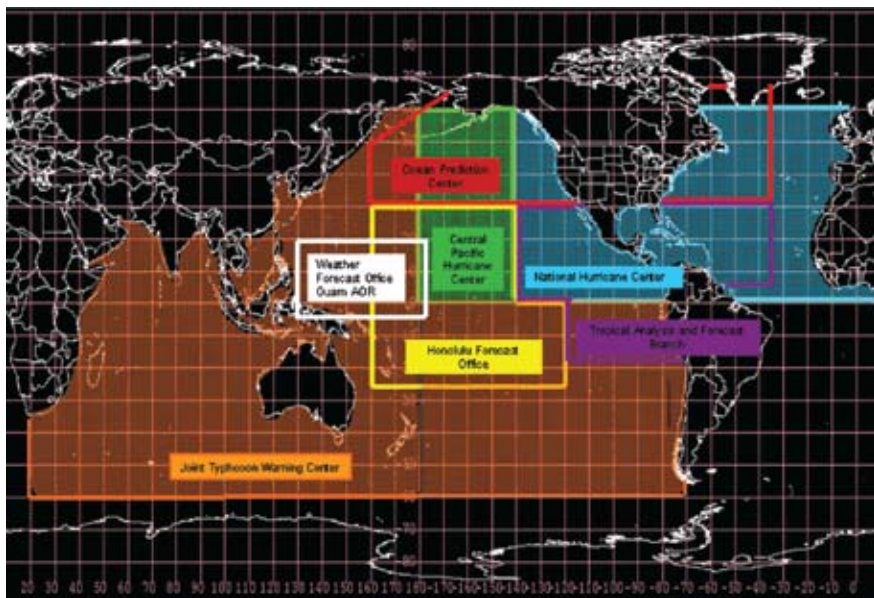

Figure 1. Map showing the combined areas of responsibility of all National Weather Service offices with marine warning and forecasting responsibilities, as well as the US military's Joint Typhoon Warning Center (JTWC). JTWC (orange), the National Hurricane Center (blue), and the Central Pacific Hurricane Center (green) share the warning responsibility for tropical cyclones.
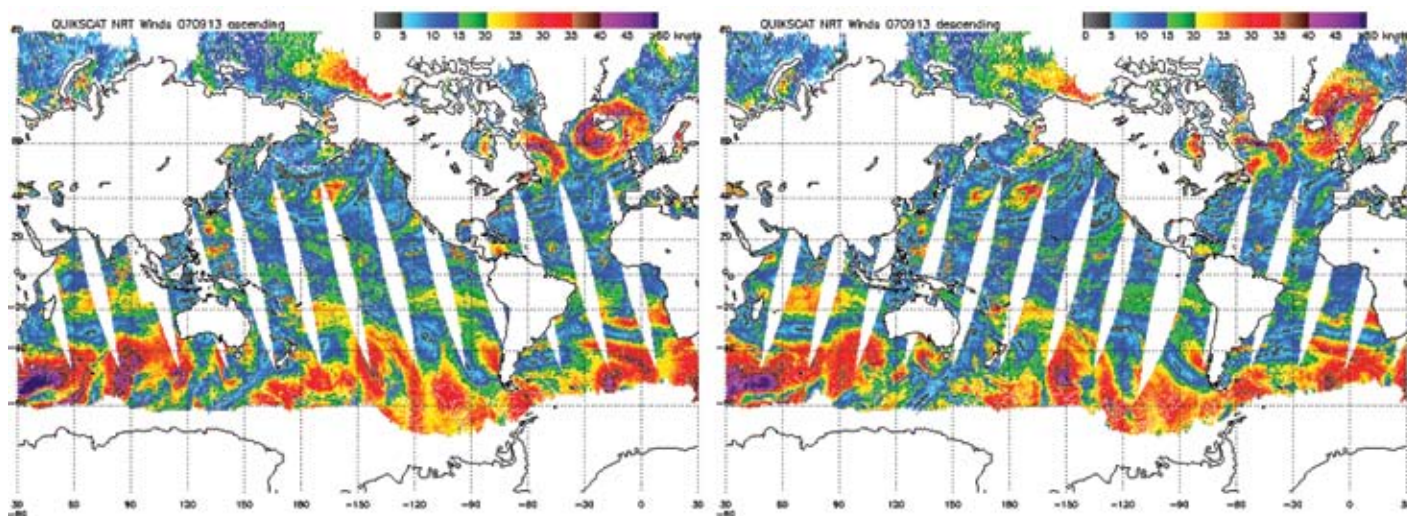

Figure 2. Typical daily coverage of ocean surface vector winds from NASA's QuikSCAT, resulting in 90% daily coverage of the world's ocean.

resolution wind fields, clearly display the data acquisition time, highlight potential areas of rain contamination, and customize the display to suit the forecaster and weather situation. Additionally, QuikSCAT vector winds have been provided through AWIPS to coastal WFOs in NWS's Western Region since 2000 and the rest of the WFOs since April 2005. This transition into AWIPS permitted the widest distribution of QuikSCAT data within NWS offices. The successful use of QuikSCAT by NOAA ocean forecasters is due in part to data quality but also to rapid data delivery and the comprehensive display capabilities built into the N-AWIPS software.

Our NOPP project provided an opportunity to place a person devoted solely to the transition of OSVW data from research to operations at both OPC and NHC. These unique positions created a bridge between the operational weather warning and forecasting world and the OSVW remote-sensing science/ engineering world. Direct interaction with forecasters not only helped the remote-sensing specialists to understand the products forecasters were using and allow for more effective use of new data, but forecaster feedback also helped those processing the data to focus resources on the issues and products that would prove most useful to the operational community.

The critical point in achieving proper feedback loops and maximizing the effective use of QuikSCAT data in the operational environment was the development and implementation of end-user training tools. The training investment was minimal at best when the QuikSCAT OSVW data were first made available. Very early on, we realized that the lack of documentation and training material significantly limited use of the data, and thus their impact on weather forecasting and warning products. To improve use of the data, unique QuikSCAT training presentations were created by combining the forecasters' and remote-sensing specialists' different experiences and knowledge of the data tailored for specific weather phenomena, with emphasis on tropical and extratropical cyclones. The training material provided background information on microwave remote sensing with active sensors in general, and QuikSCAT specifics such as scanning strategy, viewing geometry, and its strengths and weakness for OSVW retrieval. The material also reviewed geographic coverage, orbits, and data latency issues. Training sessions were conducted at various NWS centers and offices, which resulted in significant increases in the understanding and use of the data. Our experience in transitioning QuikSCAT data from research to operations taught us that user training and education are keys to a successful outcome.

Today, QuikSCAT OSVW data are used in the daily operations of all NWS offices with marine warning and forecasting responsibilities. Their uses include aiding decisions to initiate, continue, and terminate marine warnings, including advisories for tropical cyclones; adjustment of short-term marine forecasts for the intensity and geographic coverage of winds; identification of swell-generation areas for longer-term wave forecasts; identification of lows, highs, fronts, and convergence zones and examination of their intensity and trends; and real-time verification of numerical weather prediction analyses for winds, waves, and feature intensity.

OPERATIONAL USE OF QUIKSCAT DATA FOR TROPICAL CYCLONE WARNING AND FORECASTING

QuikSCAT OSVW have several uses in the tropical cyclone (TC) warning and forecasting mission of NHC, Central Pacific Hurricane Center, and JTWC. These data are used to help estimate intensity (maximum wind), especially for tropical storms, because QuikSCAT

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has limitations in retrieving the very high winds in hurricanes and typhoons due to system design and resolution, and the impact of rain (Brennan et al., in press). However, in TCs undergoing extratropical transition (e.g., Jones et al., 2003), QuikSCAT can provide valuable information on both the cyclone's intensity and wind field size, as the coverage of heavy rainfall is typically reduced near the location of maximum winds. The broad geographic coverage of QuikSCAT OSVW often provides the only consistent source of information for the analysis of 34-kt and 50-kt wind radii in TCs that are not sampled by aircraft reconnaissance (Figure 3). These wind radii are critical for defining ship avoidance areas and helping to refine the placement of coastal warnings. Emergency management officials often require that evacuation preparations be completed by the time that the 34-kt winds reach the local coastline.

The detection and location of surface circulation centers is another important use of QuikSCAT data, which have been used as justification to both initiate advisories for incipient cyclones and declare cyclones that no longer have well-defined centers dissipated. However, errors in the automated QuikSCAT wind solution, particularly in TCs, often require manual analysis of directional ambiguities for operational center fixing applications (e.g., Brennan et al., in press). Accurate TC center fixes are critical to determining the TC's initial position and motion, which are important for accurate TC track forecasting. Additionally, information on the location of the TC surface center relative to the cyclone's organized thunderstorm activity is vital to accurate satellite-derived intensity estimates; QuikSCAT is useful in this
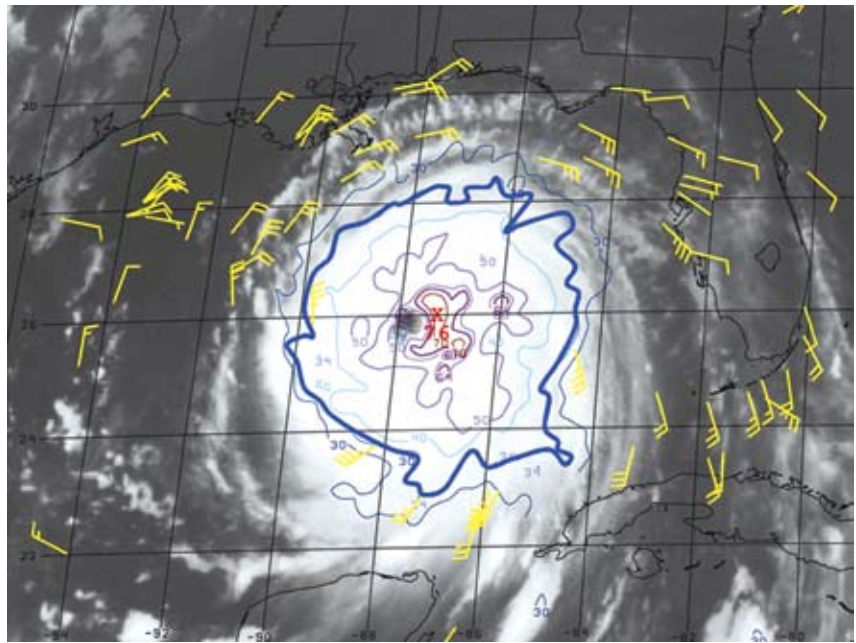

Figure 3. Thirty-four knot wind radii (blue line) as indicated by QuikSCAT in a pass over Hurricane Katrina (2005), with available ship and buoy observations (yellow barbs indicate wind speed in kt). The accuracy of the QuikSCAT analysis of the 34-kt radii in this situation provides forecasters with the confidence to use QuikSCAT for tropical cyclone 34-kt and sometimes 50-kt wind radii determination, especially in the open ocean where ship and buoy observations are sparse.
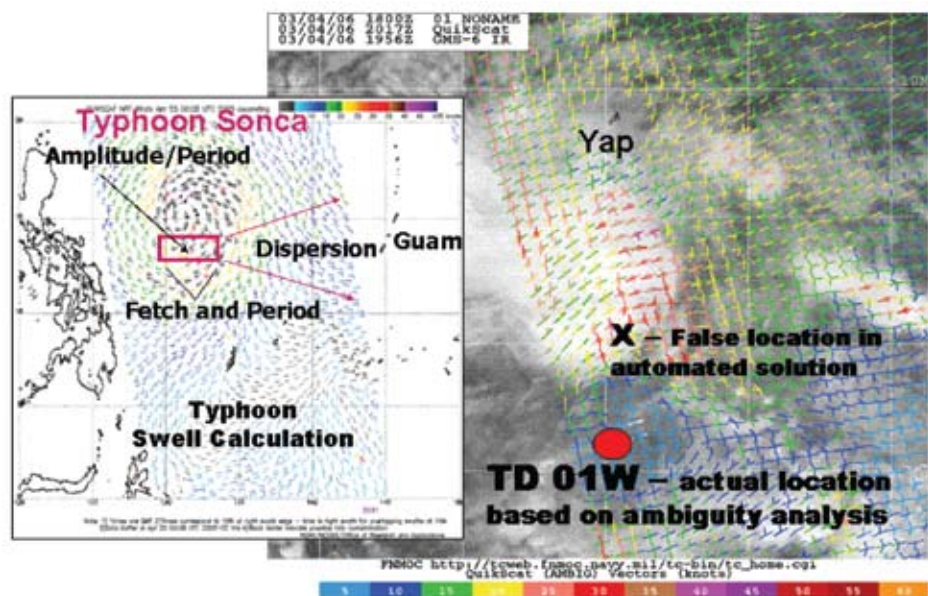

Figure 4. The broad swath of QuikSCAT winds allows forecasters to examine the character of swell generation regions in cyclones. Also, despite frequent errors in tropical cyclone (TC) center location in the automated QuikSCAT solution, manual analysis of directional ambiguities can be performed to locate the TC centers using all the possible QuikSCAT solutions. This tool has been essential for detection and center location of Pacific TCs not sampled by aircraft reconnaissance flights. *Courtesy of Roger Edson, Science and Operations Officer, NOAA/National Weather Service Office Guam*

application for TCs where the center is not easily seen in geostationary satellite imagery (Figure 4). Forecasters use QuikSCAT wind fields to determine potential swell generation associated with TCs as shown in the left image of Figure 4. In this example, forecasters can estimate fetch lengths, average wind speed, and dispersion pattern for swell.

The use of QuikSCAT at NHC has increased steadily since 2000, and has now reached the point where QuikSCAT is mentioned in 15–20% of NHC's tropical cyclone discussions in the Atlantic and East Pacific basins (Figure 5).

QuikSCAT winds are heavily used at NHC for daily marine analysis, forecasting, and warning activities. The best example of QuikSCAT's high impact is in the Gulf of Tehuantepec in the northeastern tropical Pacific, a region that is frequently impacted by strong, cold-season gap wind events that occasionally reach hurricane-force intensity (Figure 6). Prior to QuikSCAT, it was very difficult to obtain any information on wind intensity and coverage during these events. Using QuikSCAT data, a multi-year climatology of gale- and storm-force Tehuantepec events was constructed (Brennan et al., 2007), allowing NHC marine forecasters to identify forecast model biases and issue more accurate and timely warnings for these events.

OPERATIONAL USE OF QUIKSCAT DATA FOR THE DETECTION, WARNING, AND FORECASTING OF EXTRATROPICAL CYCLONES

Extratropical cyclones that reach hurricane force (HF) intensity are a significant threat to the safety of life at sea and a
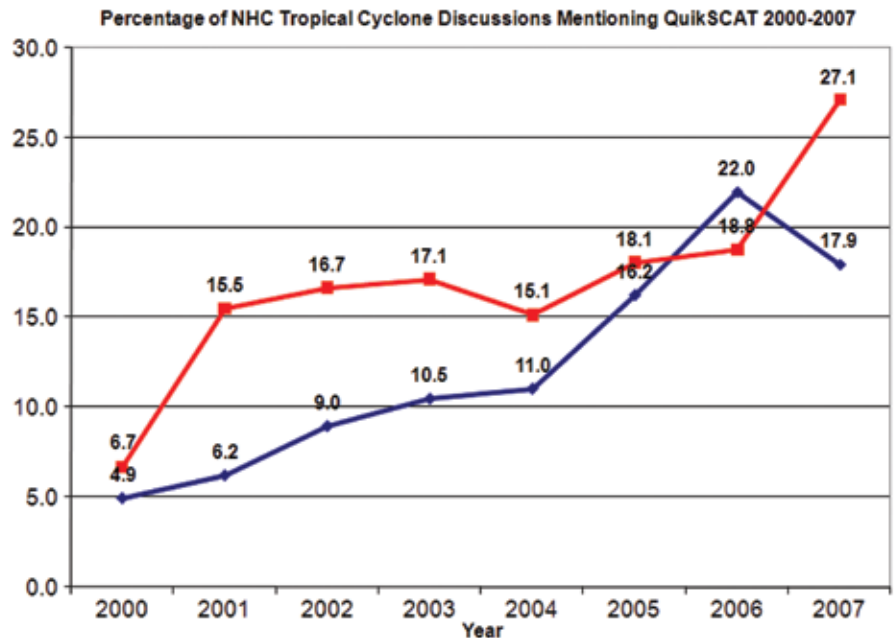

Figure 5. Percentage of Atlantic (blue) and East Pacific (red) tropical cyclone discussions issued by the National Hurricane Center that mention QuikSCAT (2000–2007).
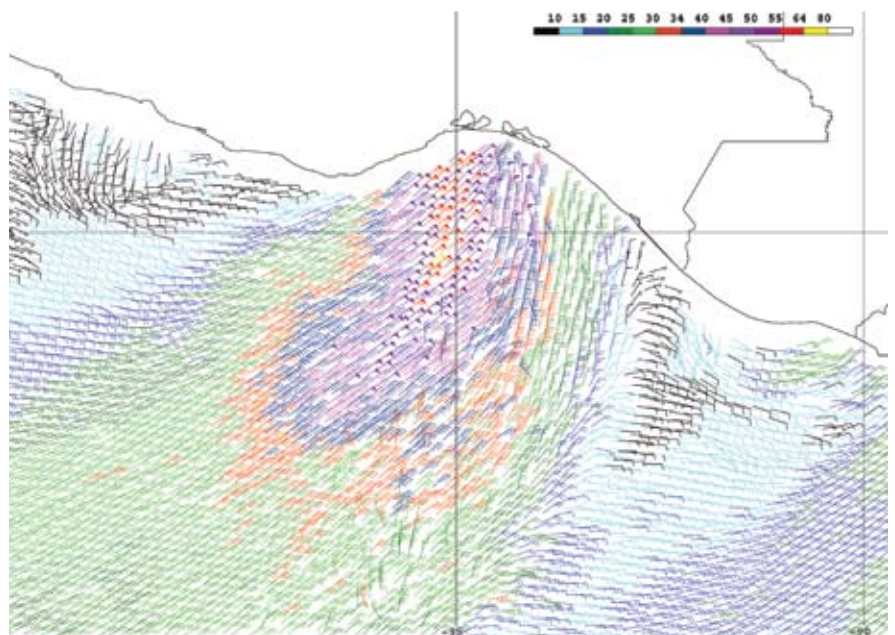

Figure 6. QuikSCAT 12.5-km-resolution wind retrievals in a hurricane-force Gulf of Tehuantepec gap wind event on November 22, 2006.

risk to cargo and vessels. Extratropical cyclones vary on scales from less than 100 km in diameter to 3,000 km or even 4,000 km in diameter and have an average life cycle of five days from genesis to death. These cyclones intensify explosively (see description in Sanders and Gyakum, 1980) and are called meteorological "bombs." Associated wind conditions can vary from only 10 to 20 kts to gale force (33 to 47 kts), storm force (48 to 63 kts), or hurricane force (> 63 kts). Winds of gale or greater force can extend over several million square kilometers of open ocean. At any given time, there can be as many as five to eight individual cyclones impacting the North Atlantic and North Pacific basins. In the main extratropical storm tracks of the North Pacific and the Atlantic, the forward speed of these cyclones during development can exceed 30 kts; the movement slows as the cyclones mature and the vortex deepens through the lower atmosphere.

OPC is responsible for issuing warnings and forecasts for the North Atlantic and North Pacific waters most frequented by these extreme ocean storms. OPC generates and issues marine warnings and forecasts, continually monitors and analyzes maritime data, and provides guidance on marine atmospheric variables for the purposes of protecting life and property, ensuring safety at sea, and enhancing economic opportunity. OPC warning bulletins are required to be received and monitored by all commercial vessels of 300 or more gross tons operating over the North Atlantic and North Pacific high seas and offshore waters. Customers include commercial mariners, fishermen, recreational sailors, the US Coast Guard, the

NOAA Emergency Response Division (formerly Hazardous Materials Response Division or NOAA HAZMAT), and the US military.

QuikSCAT ocean vector winds have revolutionized short-term warning and forecasting over the expansive ocean areas for which OPC is responsible. The 1800-km wide swath, large retrievable wind speed range, and rapid delivery of QuikSCAT data have changed the way forecasters make short-term warning and forecast decisions, especially those concerning the higher and more dangerous wind warning categories (Von Ahn et al., 2006). In essence, OPC forecasters have never before had such a high degree of situational awareness of weather conditions over the ocean.

The most significant impact of QuikSCAT OSVW on NWS operations has been the ability to routinely and consistently observe winds of HF intensity in extratropical cyclones. This new capability gave forecasters at OPC and NWS the confidence to introduce a new wind-warning category for extratropical cyclones of HF intensity in December 2000 (see Figure 7). Prior to QuikSCAT, only two warning categories existed for extratropical wind sources: gale (33 to 47 kts) and storm (≥ 48 kts). Under the two-tier warning system, the most severe storms were included in the rather common storm warning category, making it difficult to highlight and adequately warn for their severity. OPC forecasters had long been uncomfortable with this two-tier warning system, but required a consistent observing capability to divide the common occurrence of winds of 48 to 63 kts and the less-common and more dangerous winds in excess of 63 kts; QuikSCAT

winds provided that capability. The three warning categories are displayed on North Atlantic and North Pacific surface analyses that are broadcast via US Coast Guard radiofacsimile and are also available via the Internet at http://www.opc.ncep.noaa.gov/.

From fall 2006 through spring 2007, OPC identified and issued warnings for 115 separate extratropical cyclones that reached HF intensity (64 in the Atlantic and 51 in the Pacific; Figure 7). Although many of these cyclones spend their entire lives at sea, over the last several seasons, HF conditions produced by extratropical ocean storms have impacted the coasts of Alaska, the Pacific Northwest, and New England. For example, a mid-December 2006 extratropical cyclone caused widespread damage across Washington and Oregon and resulted in power outages to 1.5 million people (Figure 8). QuikSCAT winds have certainly raised the awareness of OPC forecasters as to the occurrence of HF intensity conditions. QuikSCAT has shown that HF winds in extratropical cyclones are: (1) much more frequent than thought; (2) occur most frequently in the late fall through winter months; (3) are short lived (on average 24 hours or less); (4) tend to occur in particular locations of the cyclone; and (5) can cover tens of thousands of square miles. HF cyclones occur across the heart of the North Atlantic and North Pacific great circle trade routes and can make landfall in areas such as Alaska, the Pacific Northwest, New England, and the mid-Atlantic coasts.

Prior to the QuikSCAT era, no additional warning category existed for the most damaging of extratropical cyclones. Figure 7 clearly shows forecaster reliance on QuikSCAT winds—as data
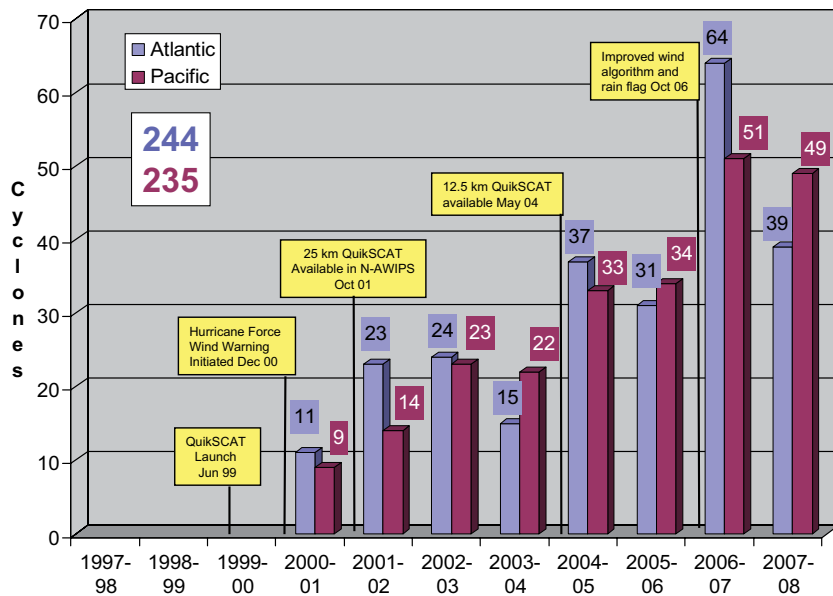
Figure 7. Bar graph showing the number of extratropical cyclones that reached hurricane force intensity for the eight cold seasons from December through May 2000–2001 and September through May 2001–2008. QuikSCAT winds are used heavily by forecasters to assess the wind conditions associated with extratropical cyclones. QuikSCAT milestones are shown by the yellow flags. Blue (maroon) bars show Atlantic (Pacific) cyclones. Total number of individual cyclones that reached hurricane force intensity is shown at left using the same color scheme.
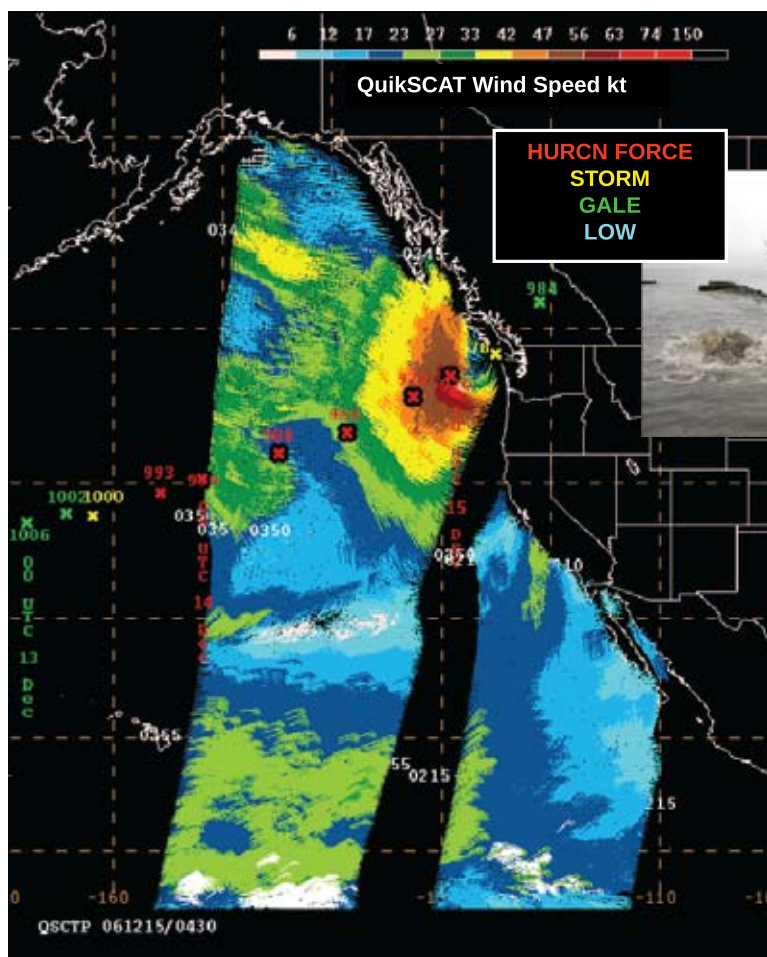
Hurricane Force Storm: Pacific North West: December 2006

Maritime extratropical cyclones can generate hurricane force winds and waves up to 100 ft, and are a significant threat to ocean and coastal commerce.

When they impact land they produce:
• strong winds
• high surf
• significant coastal flooding
• snow, rain, and blizzard conditions
• power outages

Figure 8. The 2006 "Hanukkah Eve" wind storm occurred on the evening of December 14 and extended into the morning of December 15. The storm blew down thousands of trees, knocked power out for close to 1.5 million customers, damaged hundreds of structures and homes, and injured dozens of people in the US Pacific Northwest and British Columbia, Canada. Hospitals treated 275 people for carbon monoxide poisoning following the storm.

availability increased, algorithms were improved, and higher resolution with less horizontal averaging was introduced, forecasters observed an increasing number of extratropical cyclones with HF conditions each season.

The loss of QuikSCAT would result in an 80% to 90% reduction in detection capability for HF winds from extratropical cyclones. To date, there is no other capability that provides the consistency in retrievable wind speed range and coverage for extreme winds as that available from QuikSCAT. Although the benefits of improved marine warning and forecasting for the coastal US regions seem clear, the need for accurate open-ocean warnings and forecasts might not be as obvious. However, ships sailing throughout the world's ocean transport more than 95% of US international trade by volume. During the last 50 years, commercial ships have doubled in size, waterborne commerce has tripled, and the number of small boats and recreational watercraft has increased. To keep ships on schedule and safe from dangerous ocean storms, the $200 billion global marine shipping industry increasingly relies on accurate marine warnings and forecasts (Kite-Powell, 2000). Accurate wind and wave information helps marine traffic avoid hazardous weather and keeps the costs of goods down, thus making products more affordable. Maritime commerce results in a contribution of $78.6 billion annually and generates nearly 16 million jobs; one out of six jobs in the United States is marine related (Year of the ocean: The U.S. marine transportation system, 1998).

As a result of QuikSCAT OSVW, today's marine warning and forecast services out to 48 hours (for HF cyclones) provide an estimated savings of $135 million annually to North Pacific and North Atlantic dry bulk and container shipping alone by minimizing storm exposure (Kite-Powell, 2008). In general, better information about the spatial and temporal occurrence of severe winds and waves allows adjustment of ships' routes to reduce exposure. In making decisions about route changes, ship operators must balance longer voyage times against expected (potential) losses due to storm exposure; more accurate forecast information can lead to better decision making.

Knowledge of the winds and waves over the ocean is important not only for maritime transportation but also for the fishing industry, offshore energy industries, search and rescue (SAR) efforts, and the accurate tracking and management of marine hazards such as oil spills. The two SAR events detailed below were supported by OPC, and illustrate how important QuikSCAT is considered for situational awareness of the ocean surface wind field:

First event: "On March 20 [2006], the OPC received a call from the US Coast Guard, Program Coordinator, Rescue & SARSAT [Search And Rescue Satellite Aided Tracking] Operations asking for assistance in determining the weather situation in the Red Sea where the *Al Salaam* ferry sank in Egyptian waters on February 2, 2006. The Coast Guard was responding to the International Maritime Organization, which asked the U.S. Government to conduct an investigation and produce a report on the chain of events leading up to the sinking. The Coast Guard noted that they had tried to obtain the information from several federal agencies but with no success. Although OPC does not analyze or forecast for that area, Dave Feit was able to pull together a combination of ship observations, QuikSCAT wind retrievals [Figure 9], and appropriate model data to provide the necessary information. The Coast Guard expressed appreciation for OPC's efforts." (Ocean Prediction Center, 2006)

Second event: "On February 16 [2007] the OPC received a call from NOAA HAZMAT requesting weather support for a factory ship for the Japanese whaling fleet, the *Nisshin Maru*, off Antarctica near 73.38 S and S 175.56 E. The support was requested to help the United States Coast Guard (USCG) assess the risk from an oil spill should it happen. OPC prepared a seven-day forecast for winds and seas at this location which was sent to NOAA HAZMAT. In addition, Joe Sienkiewicz, OPC Science and Operations Officer (SOO), provided QuikSCAT data and maps for the incident area to OPC forecasters. A total of two sets of forecasts were provided to HAZMAT who asked that OPC be prepared to continue to provide support, if needed. No further support to NOAA HAZMAT was required." (Ocean Prediction Center, 2007)

DEVELOPMENT OF NEW QUIKSCAT PRODUCTS AND THEIR TRANSITION TO OPERATIONS

This NOPP project also transitioned into the operational processing system a sophisticated enhanced resolution processing scheme developed by the Microwave Earth Remote Sensing Laboratory (MERS) at Brigham Young University. The MERS processing

An accurate measurement of wind speed and direction is of extreme importance in search and rescue, aircraft missions, and accident investigation (oil spills, ship sinking)

1500UTC 02 Feb

0200UTC 03 Feb

Two QuikSCAT passes on 02 and 03 Feb covered most of the Red Sea

There were no buoy or ship observations at the time of the sinking at 2200 UTC 02 Feb.

There was only one ship observation in the vicinity of the sinking that was reported 2 hours later at 0000 UTC 03 Feb.

Ship sank in this area

Duba: ferry left 1900*

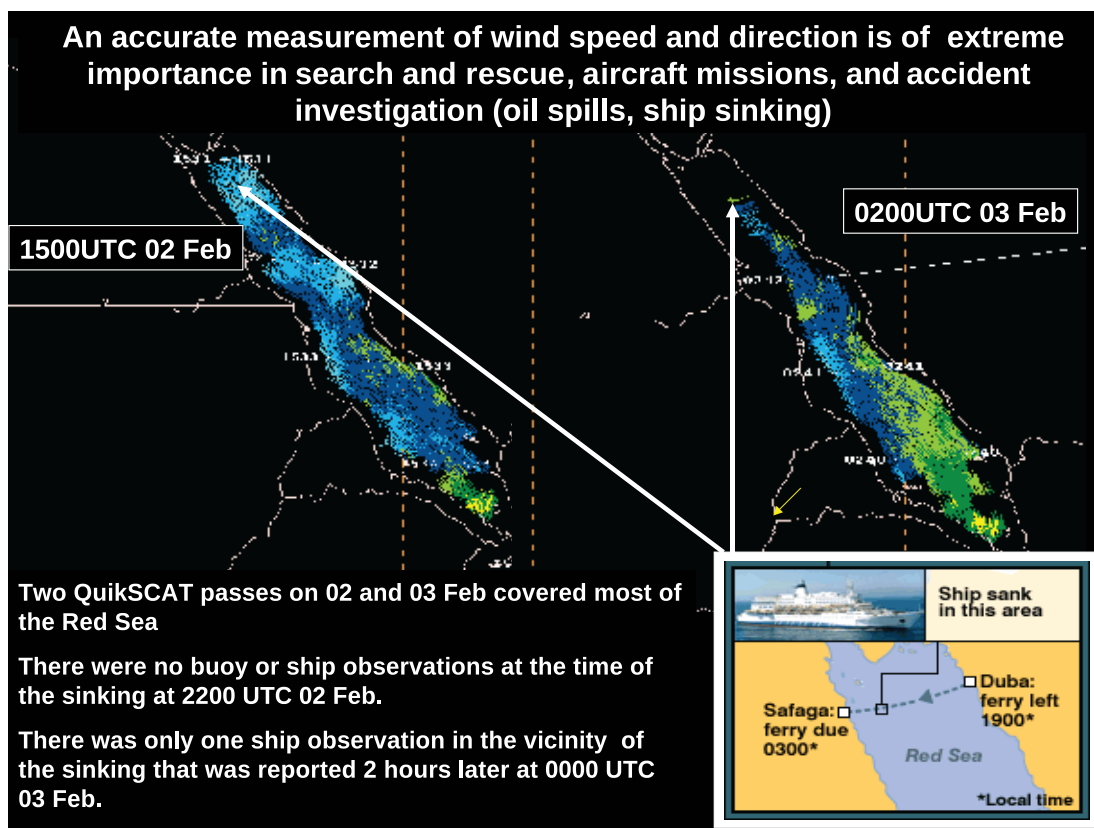Safaga: ferry due 0300*

Red Sea

*Local time

Figure 9. QuikSCAT provided measurements of wind speed and direction to help determine the cause for the sinking of a vessel in the Red Sea on February 2, 2006.

scheme produces ultra-fine- or ultra-high-resolution (UHR) wind speed and normalized radar-cross section (NRCS) images of Earth's surface from QuikSCAT (Long, 2004). These ultra-fine-resolution NRCS images reveal details of the wind structure in tropical cyclones, and together with the OSVW measurements have become an important tool in TC forecasting and warning, especially where aircraft reconnaissance is not available (Edson et al., 2002). The NOAA QuikSCAT NRT processing system now produces refined UHR, storm-centered, "postage-stamp" wind and NRCS products, which are posted to the NRT QuikSCAT storm page (http://manati.orbit.nesdis.noaa.gov/cgi-bin/

qscat_storm.pl) (see Figure 10, where a land distance flag was recently added; Owen and Long, 2008a; Plagge et al., 2008). A careful study of eight years of QuikSCAT data revealed that UHR wind retrieval can accurately locate hurricane centers compared with best track locations, even in early stages of development (Said and Long, 2008). MERS has developed an experimental UHR simultaneous wind/rain wind retrieval algorithm along with a new wind direction ambiguity removal algorithm, both of which are currently undergoing validation experiments (Williams and Long, 2006, 2008a,b; Owen and Long, 2008b).

USE IN THE PRIVATE SECTOR

In addition to government agencies exploiting QuikSCAT OSVW, there are also a surprising number of users in the private sector and the general public. We have received emails from a wide range of folks, including the meteorologist aboard an aircraft carrier, the surfing community, recreational and racing vessels, and the offshore wind farm industry. Through its WeatherNet system, OCENS Inc. (a participant in this NOPP-funded effort) made QuikSCAT OSVW data available to its market base, which includes sail and power cruising, ocean racing, commercial and sport fishing, tug and barge operations, and shipping.
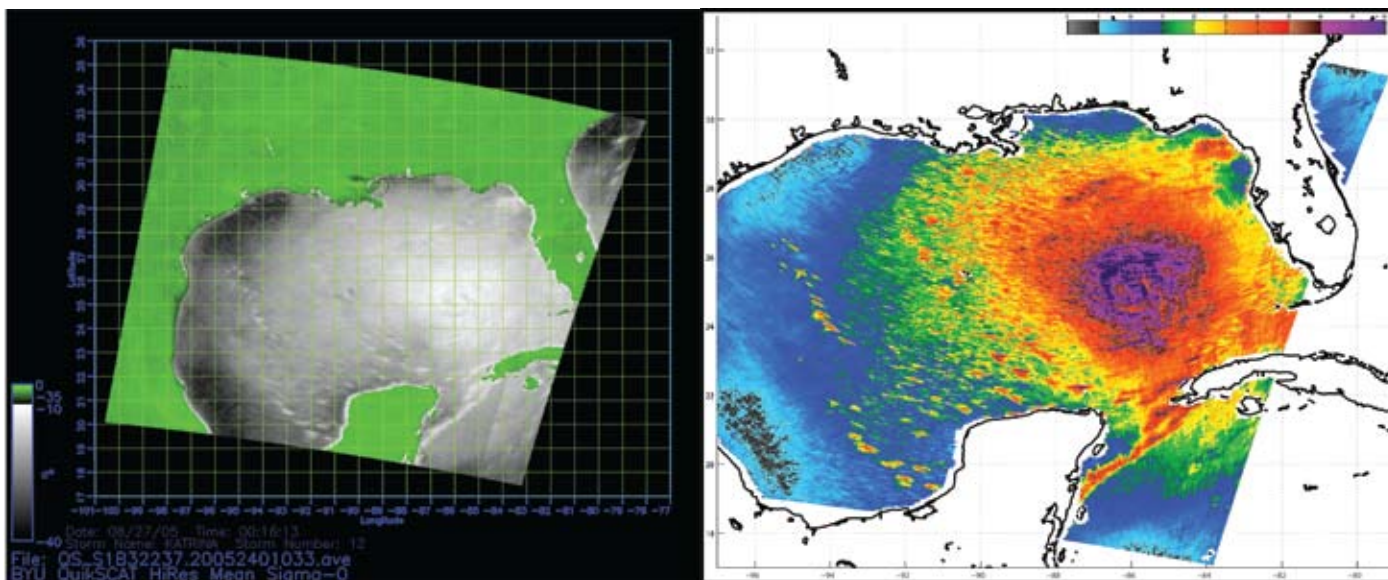
Figure 10. Early examples of ultra-high-resolution (UHR) processing of QuikSCAT data for Hurricane Katrina on August 27, 2005. (Left) UHR radar h-pol normalized radar-cross section image. High winds show up as lighter values, and lower wind speeds are darker. Land is colored green. (Right) QuikSCAT UHR wind speeds. Mesoscale structure and convective events are clearly visible.

Surveys conducted by OCENS found most user feedback was very positive. A broad set of their users found that the QuikSCAT data are most beneficial in areas where the weather is generally stable and the data are used to locate slight variations in wind patterns to enable optimum vessel routing. More advanced users have taken advantage of the availability of the QuikSCAT data to "tune" GRIB (GRIdded Binary) wind forecasts produced by the NWS Global Forecast System model and/or WaveWatch III models. Most notably, this practice was employed to startling success by the *Spirit of Sark*, a racing yacht participating in the Global Challenge Around-the-World Race, which is detailed in the following quote from an email received from Simon Bell, *Sark's* navigator:

Cold-Front Dissection: I have attached a GRIB-Explorer Screen-Shot for our first Brazilian-cold front (CF)

[shown in Figure 11].

*Using GRIB-Explorer we were able to calibrate our GFS Grib-file vs QuikSCAT and determine how far ahead/behind the GFS-Forecast was. From this, we could estimate our ETA at the Cold-Front. We were also able to "see" inside the Cold-Front and understand the structure of the Front and what conditions we could expect. We were able to see from the Screen-Shots that we could expect the wind to drop & back as we approached the CF and then jump to 30 kts from the SW at the Front. Using this info we flew our Spinnaker to **within 30 seconds** before the SW-Wind hit...and WOW did it hit.*

We were also able to understand the dynamics of the Cold-Front. The weather-forecasts reported a Cold-Front at Location XY heading SE and moving NE at 10knts. By observing the QuikSCAT Data over time, we understood that the situation was MUCH

more complicated! The N-side of the CF is driven by the NW-Wind and features on the N-Side therefore drift SE along the Cold-Front with this Wind. Then the whole Cold-Front does indeed Track NE...and combining this with the Drift we understood that features drift West! On the S-Side of the CF the opposite is true...features on the S-Side are driven by SE-Wind and therefore drift NW along the CF. Then with the whole Cold-Front Tracking NE...and combining this with the Drift we understood that features drift North! This helped us understand (too late) how to line-up on Gates thru the Cold-Front when one presented itself.

Spirit of Sark subsequently won the rugged Buenos Aires to Wellington Third Leg of the Global Challenge while making extensive use of QuikSCAT data acquired through WeatherNet and displayed in GRIB Explorer. Similar tuning techniques were employed by racers participating in
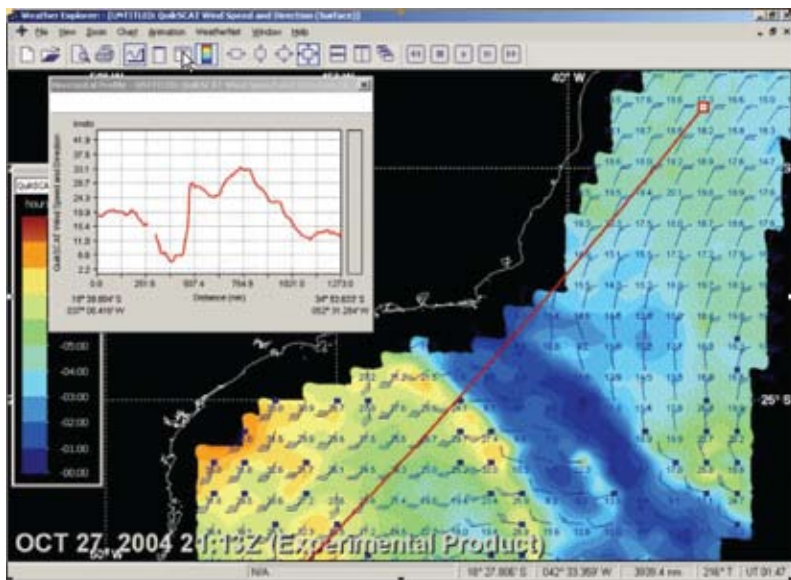
Figure 11. The GRIB-Explorer display of QuikSCAT wind vectors and wind speeds (color coded), depicting a cold front off the coast of Brazil on October 27, 2004.

the Newport–Bermuda, Annapolis–Bermuda, Pacific Cup, and Vic–Maui races during the summer of 2004. Better testimony to the benefits and utility of QuikSCAT data to the marine market would be difficult to find. Creating a means of enabling less technically proficient users to tune their wind forecasts en route with QuikSCAT information is an area of clear development opportunity.

LIFE AFTER NOPP FUNDING

The three years of NOPP support resulted in improved use of QuikSCAT OSVW data in the NWS operational environment, a measure of QuikSCAT impacts at the National Hurricane Center (NHC) and OPC. These years have also seen the transition of new QuikSCAT research products into operations and exploitation of these products by a commercial weather services company, which brought satellite OSVW data to

individual users. An equally important outcome of this project was the development of partnerships among the participants that continue to this day, and these partnerships have played a critical role in NOAA's pursuit of a QuikSCAT follow-on mission. Fortunately, we were able to sustain and build upon this effort with support from NOAA's Ocean Remote Sensing Program and Research to Operations (R2O) Program. Through the R2O program, the QuikSCAT OSVW impacts at local NWS Weather Forecast Offices were also captured (Millif and Stamus, 2008). With satellite OSVW data from QuikSCAT becoming such a well-used NWS tool, a workshop to define NOAA's operational OSVW requirements was held at NHC in Miami, Florida, in June 2006 (Chang and Jelenak, 2006). The primary goals of this meeting were to: (1) document the use and impact of presently available satellite OSVW data in operational marine weather

analysis, forecast, and warning activities at NOAA, (2) define the OSVW operational requirements within NOAA based on actual experience and phenomena observed, and (3) explore sensor/mission concepts capable of meeting the requirements. The desired outcome of the workshop was to help NOAA determine a course of action because there were no plans for a QuikSCAT follow-on mission.

Over the following year, the National Research Council (NRC) conducted a decadal survey of satellite observations in support of climate change monitoring, and listed as one of their recommendations the need for an advanced OSVW mission to replace the aging NASA QuikSCAT in order to provide key insights into ocean circulation and global heat transfer, and their impacts on Earth's climate (National Research Council, 2007). The NRC study also recommended that NOAA undertake this extended ocean vector wind mission (XOVWM) as a sustained operational capability.

In 2007, NOAA initiated an Analysis of Alternatives (AOA) type study to assess observing system options to mitigate or replace the current NASA QuikSCAT OSVW capability. OSVW AOA concluded that a sustained operational satellite OSVW capability should be designed to better address the operational weather forecasting and warning requirements through a more advanced observing system such as XOVWM identified in the 2007 NRC decadal survey described above.

Also in 2007, NOAA asked NASA JPL to conduct a NASA QuikSCAT follow-on mission study. The study showed that technology is currently available to improve scientific and operational

OSVW retrieval capability by an order of magnitude over that provided by QuikSCAT (Gaston and Rodriguez, 2008). The primary improvements are: finer horizontal resolution of surface wind estimates, decreased sensitivity to the effects of rain in the wind estimates, the ability to retrieve much higher wind estimates (> 50 m s^{-1}), and the ability to provide winds to within 5 km of the coast. In parallel, NOAA conducted a study assessing the impacts of both a QuikSCAT-equivalent and an improved OSVW capability, which resulted in the document *QuikSCAT Follow-On Mission: User Impact Study Report* (Jelenak and Chang, 2008).

Finally, NOAA is working with international partners to leverage scatterometry data from foreign satellites in an attempt to provide uninterrupted continuity of these data. Currently, the European Organisation for the Exploitation of Meteorological Satellites is flying an operational Advanced Scatterometer that will provide some OSVW data continuity, although it only provides approximately 55% of the coverage and twice as coarse spatial resolution wind retrievals as those provided by QuikSCAT. NOAA is also exploring access to data from Indian and Chinese satellites that will be launched in the next few years, as well as a partnership with the Japanese Exploration Space Agency (JAXA) to fly a QuikSCAT follow-on instrument as part of JAXA's Global Climate Observation Mission program.

CONCLUSION

Our NOPP project established personnel resources at OPC, NHC, and NESDIS that significantly strengthened existing collaborations. Because of this enhanced partnership, QuikSCAT OSVW data were transitioned in an optimal and efficient manner into the operational NWS environment. Quantifying the impacts of these data allowed us to better understand the value of this observing system capability. Additionally, we were able to determine and justify the actual operational weather warning and forecasting requirements for satellite OSVW, which will be important for the design of a QuikSCAT follow-on mission to continue this now routinely used OSVW capability. Academic and private sector partnerships were also enabled by our NOPP project. Working with Brigham Young University, we transitioned new QuikSCAT products into operations, and we expanded the use of QuikSCAT OSVW products in collaboration with OCENS Inc. The partnerships enabled by this NOPP opportunity had a significant role in the successful transition of QuikSCAT OSVW data into the operational environment at NOAA and beyond.

Ocean surface vector wind data received from NASA QuikSCAT have revolutionized operational marine weather warnings, analyses, and forecasting. QuikSCAT data give forecasters the ability to see the detailed wind field over vast ocean areas, to see the inner structure of ocean storms, and to identify areas of ocean wind wave generation. When issuing marine wind forecasts and warnings, these surface wind data give forecasters a higher level of situational awareness, providing a rich data source in areas not sampled by buoys and other wind platforms, ultimately resulting in improved forecasts and warnings. An impact study in the fall of 2002 by Von Ahn et al. (2006) demonstrated that the number of wind warnings issued for extratropical cyclones by OPC increased by 30% in the North Atlantic and 22% in the North Pacific when QuikSCAT winds were used in the forecast process. Based on this improved detection capability, OPC introduced a new warning category for hurricane-force winds in nontropical ocean storms in late 2000. For tropical cyclones, QuikSCAT data have become an important analysis tool at the National Hurricane Center, the Central Pacific Hurricane Center, and the Joint Typhoon Warning Center, providing information on the intensity of tropical depressions and tropical storms; improving the identification and analysis of TC center locations, especially in developing systems; and providing critical information on TC wind field structure, especially in data-sparse open ocean areas (e.g., Brennan et al., in press).

Today, QuikSCAT data are used around the world to help provide accurate marine weather warnings and forecasts. Users span government agencies, commercial companies (ship routing, offshore wind farms, weather information providers), and individual users (surfers, sailboat racers, recreational boaters). Satellite OSVW data from QuikSCAT impact many facets of daily life in marine and coastal communities. QuikSCAT OSVW data have successfully been transitioned to use in the operational environment. The next challenge will be to establish a sustained satellite OSVW observing capability that builds upon the knowledge gained from over nine years of QuikSCAT OSVW.

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