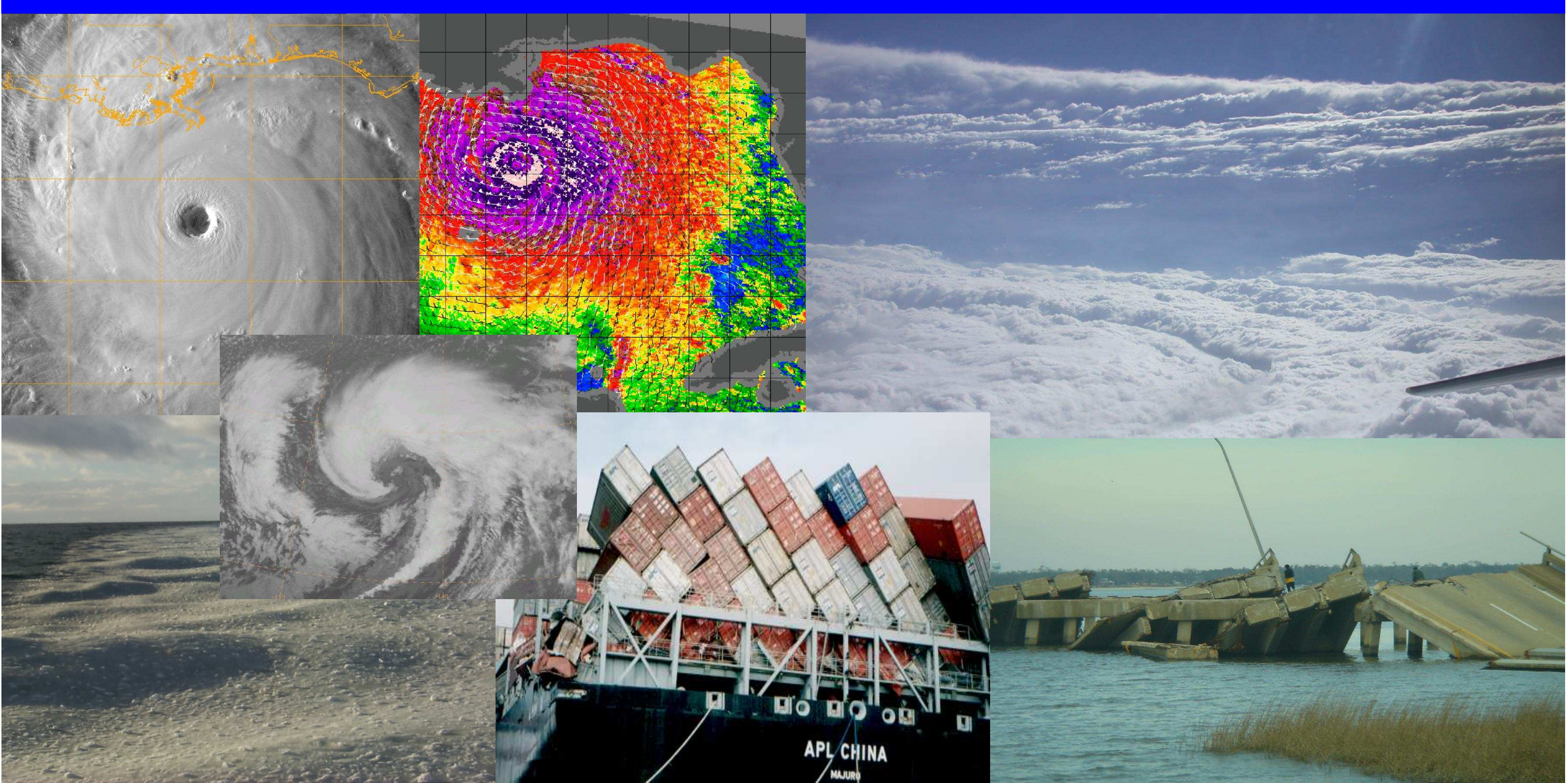
NOAA Operational Ocean Surface Vector Winds Requirements Workshop

National Hurricane Center
Miami, FL
June 5–7, 2006



NOAA Operational Satellite Ocean Surface Vector Winds Requirements Workshop Report

Convened at the

Tropical Prediction Center/National Hurricane Center
Miami, Florida
June 5–7, 2006

Acknowledgments

We thank Max Mayfield and Ed Rappaport for graciously inviting us to convene this workshop at the Tropical Prediction Center/National Hurricane Center. We also thank Richard Knabb and Michael Brennan for assisting with the workshop coordination and logistics. The following individuals also provided invaluable assistance in the preparation and editing of this report:

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Cover background: The ocean surface under hurricane force winds as seen from an altitude of 200 feet aboard the NOAA WP-3D N43F “Miss Piggy” during a flight in Hurricane Isabel, 2003. **Photos starting from top row from left to right:** Visible image from GOES of Hurricane Katrina, QuikSCAT ultra-high-resolution ocean wind speed image of Hurricane Katrina, view from inside the eye of Hurricane Isabel from the NOAA WP-3D N42RF “Kermit,” a GOES infrared image of a Pacific Ocean extratropical cyclone with hurricane force winds, the ice-ocean interface in the Ross Sea, damage sustained by the container ship APL China (over $100 million) in a hurricane-force extratropical storm that began as Typhoon Babs, Highway 90 in Biloxi, Mississippi, after Hurricane Katrina.

NOAA Operational Ocean Surface Vector Winds (OSVW) Workshop

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1 EXECUTIVE SUMMARY

Although satellite ocean surface vector wind (OSVW) data are revolutionizing operational marine weather warnings, analyses, and forecasts, critical but solvable gaps in OSVW capability remain leaving life and property at risk. This report from a workshop held June 5 to 7, 2006, at the Tropical Prediction Center/National Hurricane Center (TPC/NHC) in Miami, Florida, documents (1) the utilization and impact of presently available satellite OSVW data in the production and use of operational marine weather analyses, forecasts, and warnings at NOAA, (2) the OSVW operational requirements within NOAA based on actual experience and phenomena observed, and (3) a preliminary exploration of sensor/mission concepts that would be capable of meeting the requirements. Seven years after NOAA first began routinely utilizing satellite OSVW data, the nation still has no plans for an operational OSVW data stream that addresses the present and future satellite OSVW requirements of the National Oceanic and Atmospheric Administration (NOAA).

Near real-time measurements of ocean surface vector winds (OSVW), including both wind speed and direction from non-NOAA research satellites, are being widely used in critical operational NOAA forecasting and warning activities. Wind observations in near all-weather conditions from the NASA QuikSCAT mission (launched in June 1999) have been incorporated into daily operations at NOAA's Ocean Prediction Center (OPC) and Tropical Prediction Center/National Hurricane Center (TPC/NHC) since 2000. QuikSCAT data have been assimilated routinely for numerical weather prediction modeling at the National Centers for Environmental Prediction (NCEP) as well as numerous international weather centers such as the European Center for Medium-Range Weather Forecasting (ECMWF) since January 15, 2002. Also, the satellite vector winds have been provided through Advanced Weather Interactive Processing System (AWIPS) to coastal National Weather Service Weather Forecast Offices (WFOs) in the Western Region since 2000 and in the baseline AWIPS since April 2005.

Within the past few months, preliminary wind speed and direction measurements from the Naval Research Laboratory's (NRL) research WindSat instrument (launched in January 2003) are being provided to NOAA and to the Department of Defense (DoD) through the Fleet Numerical Meteorology and Oceanography Center (FNMOC). WindSat data are currently under evaluation and being compared to near real-time QuikSCAT measurements in NOAA, DoD, and interagency (e.g., Joint Typhoon Warning Center) operational activities.

This NOAA-sponsored workshop was held to:

- Document the operational utilization and impact of satellite surface wind speed and direction measurements; and
- Consider measurement accuracy, resolution, and coverage requirements for future NOAA operational ocean vector wind products in light of present experience from research missions and planned future advances in numerical weather

models, analytical techniques, and NOAA's global, regional, and storm warning and forecast requirements.

In addition, the workshop briefly examined the OSVW measurement requirements of the research community and surveyed mature and developing technologies that could form the basis for near-future operational NOAA OSVW observing systems. The workshop's participants included a broad range of 35 experts 35 representing NOAA (21), NASA (4), DoD (2), academia (4), and the private sector (4). The agenda and all presentations are available at the workshop Web site (http://manati.orbit.nesdis.noaa.gov/SVW_nextgen).

The workshop findings are summarized below:

1) QuikSCAT vector wind measurements are fully integrated, and heavily used, in the routine workflow of the national centers (OPC, TPC/NHC), JTWC, and coastal NWS Weather Forecast Offices. As well-validated WindSat products become available through national AWIPS and AWIPS, it is expected that these wind data will also be exploited by forecasters. In addition to their previously documented utility in global and regional numerical weather prediction, the QuikSCAT data have had major operational impact in:
    a) determining wind warning areas for mid-latitude systems (gale, storm, hurricane force); specifically, the availability of reliable, spatially extensive QuikSCAT measurements allowed the introduction of mid-latitude hurricane force wind warnings starting in late 2000.
    b) determining tropical cyclone 34-knot and 50-knot wind radii.
    c) tracking the center location of tropical cyclones, including the initial identification of their formation.
    d) identifying and warning of extreme gap and jet wind events at all latitudes.
    e) identifying the current location of frontal systems and high and low pressure centers.
    f) improving coastal surf and swell forecasts.

2) Nearly seven years of operational experience with the satellite vector wind data has highlighted the need for product improvements in the following areas to support the present needs of NOAA's operational forecasters and centers:
    a) Measurement accuracy and quality
        - Rain contamination leads to inaccurate retrievals in rainy conditions and an inability to measure maximum winds near the centers of tropical and extratropical (i.e., mid-latitude) cyclones.
        - Ambiguity (wind directional uncertainty) degrades the analysis of cyclone center locations.
        - Arbitrary limitations in retrieval algorithms leads to maximum reported speeds of 50 m/s (100 knots).
    b) Measurement spatial and temporal ("revisit") resolution and latency
        - 12.5- and 25-km resolution products cannot resolve important, specific, small-scale, high-wind-speed features near the centers of storms and cyclones, or small-scale gap winds near islands such as the Aleutians.

- The present 30-km land mask (designed to avoid land contamination of wind measurements) eliminates data within the critical near-shore areas of responsibility of most coastal WFOs.
- Insufficient revisit frequency from a single (albeit broad-swath) polar orbiting instrument makes timely (within 3 to 6 hours) wind data unavailable during some forecast cycles.
- Data retrieval is delayed during rapidly changing meteorological conditions (the QuikSCAT "near real-time" requirement of 180 minutes from data acquisition to product availability, developed prior to launch, has been found through operational experience to be too long).

c) Data product provisioning and training
   - QuikSCAT data are essentially unavailable in the operational gridded analysis products heavily used at WFOs, such as Local Analysis and Prediction System (LAPS), Mesoscale Surface Assimilation System (MSAS), and Advanced Regional Prediction System (ARPS) Data Analysis System (ADAS), hindering their even wider use in support of WFO and center operations. (Prior to April 2005, QuikSCAT data products were not yet available within the baseline AWIPS, and WindSat measurements are presently unavailable in AWIPS but are now available in NAWIPS workstations.)
   - NOAA operational satellite wind products have no user documentation.
   - Limited training materials are available for NOAA operational forecasters.

3) After much discussion, the workshop participants focused on the essential vector wind product requirements:
   - All-weather retrievals (i.e., accurate retrievals in rain)
   - Accuracy levied upon the selected 10-meter, 1-minute sustained wind as defined by operational requirements

     0–165 kt wind speed range:
       - 10–165 kt: speed +/- 2 kt and direction +/- 10 degrees (2 sigma)
       - 4–10 kt: speed +/- 2 kt and direction +/- 20 degrees (2 sigma)
       - 0–4 kt: speed +/- 2 kt
   - Revisit time interval (defined as the time interval between measurements at a particular point on the ocean surface): every 6 hours (1 to 3 hour goal)
   - Reduced product latency: 45–60 minutes from measurement to product availability (15 minute goal)
   - 2.5 km x 2.5 km grid spacing, which is defined as the spacing between unique wind vector retrievals (1 km x 1 km goal)
   - Unique wind vector grid cells to within 2.5 km of the coast (1 km goal)
   - Wind fields delivered into the operational environment, i.e., NAWIPS, AWIPS, and data assimilation systems
   - Product documentation/tutorial/training

These refined requirements:

a) ensure accurate measurements in the presence of extreme wind conditions such as those found in intense storms and cyclones by extending the upper wind speed limit to 165 kt, (in the Category 5 hurricane range) and requiring accurate measurements in the presence of rain;

b) increase the spatial resolution (decrease the characteristic dimensions) of individual measurements to allow definition of small-scale features in synoptic and mesoscale systems;
c) provide accurate vector wind measurements closer to the coast;
d) allow estimation of the required 1-minute sustained wind speed from the instantaneous spatially averaged wind measured by the spaceborne instruments; and
e) emphasize the overall operational requirement for an observing system (likely multiplatform) that satisfies revisit frequency requirements for measurements at every open-ocean location.

Workshop participants from the research community noted that the above refined operational requirements would result in data products that would significantly enhance the present research applications of the oceanographic, meteorological, and climate research communities.

Establishing an operational satellite OSVW data stream and closing the OSVW capability gaps will result in more accurate warnings, watches, and short-term forecasts; improved analyses, model initializations, and atmospheric forcing of ocean models; and a better understanding of coastal and oceanic phenomena. This will yield significant improvements in NOAA's operational weather forecasting, warning, and analyses capabilities.

2 Introduction

The operational use of satellite ocean surface vector wind (OSVW) observations has advanced considerably over the past 10 years. OSVW are now depended upon and used daily by operational weather centers around the world. Within NOAA's National Weather Service (NWS), the use of OSVW encompasses the warning, analysis, and forecasting missions associated with tropical cyclones, extratropical cyclones, fronts, localized coastal wind events (i.e., gap winds), surf, and swell.

Much has been learned about the importance and utility of satellite OSVW data in operational weather forecasting and warning by exploiting OSVW research satellites in near real-time. With oceans comprising over 70 percent of the earth's surface, the impacts of these data have been tremendous in serving society's needs for weather and water information and in supporting the nation's commerce with information for safe, efficient, and environmentally sound transportation and coastal preparedness. The satellite OSVW experience that has been gained over the past decade by users in the operational weather community allows for realistic operational OSVW requirements to be properly stated and justified for the first time.

2.1 Workshop Objectives and Goals

The workshop's objectives were to define and justify NOAA's operational ocean surface vector wind requirements and to investigate options and conceptual designs for a space-based sensor capable of addressing the unmet operational requirements of the NOAA community. The NOAA operational OSVW workshop that this report summarizes was a first step toward this objective.

The goals of this document are to:

- summarize the utilization and impact of current satellite ocean surface vector wind data in operational weather forecasting,
- define the actual operational ocean surface vector wind requirements within NOAA, and
- explore sensor/mission concepts using presently mature remote sensing technologies that would be able to meet these requirements

2.2 Near Real-Time Ocean Surface Vector Wind Measurements

Two research SVW missions are currently operating and providing timely data products for operational utilization at NOAA. QuikSCAT/SeaWinds, hereafter "QuikSCAT," (*Spencer et al., 1997*) and Coriolis/WindSat, or "WindSat," *(Gaiser, 2004)* employ different microwave remote sensing techniques to retrieve the SVW. However, their distinctions are not pertinent in defining NOAA's present operational SVW requirements.

QuikSCAT features most prominently in the following examples and experiences due in part to the near real-time availability of QuikSCAT products since February 2000 (*Hoffman and Liedner, 2005*). WindSat near real-time SVW data only became available in the beginning of 2006. A more detailed discussion of QuikSCAT, WindSat, and the techniques by which SVW information can be extracted from active and passive microwave instruments can be found in Appendix A. QuikSCAT and WindSat data are being processed and distributed operationally at the Navy's Fleet Numerical Meteorological and Oceanographic Center (FNMOC) and at NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). Near-real time data can be found at http://manati.orbit.nesdis.noaa.gov/quikscat, http://manati.orbit.nesdis.noaa.gov/windsat, and http://www.nrlmry.navy.mil/tc_pages/tc_home.html. Science-level QuikSCAT products and additional documentation can be found at http://podaac.jpl.nasa.gov/.

3 Utilization and Impact of Available Satellite OSVW Data in the Operational Weather Community

This workshop gathered meteorologists from the U.S. public and military operational weather forecasting community. The NWS was represented by the National Centers for Environmental Protection (OPC, TPC, NHC/TAFB, and the Environmental Modeling Center) and the regional headquarters (Alaska, Pacific, Western, and Southern regions). The DoD had representation via the JTWC (*Smith, 1995*). The combined areas of responsibility of the workshop participants cover a vast area that extends from the east coast of Africa, across the Indian, Pacific and Atlantic Oceans to the European coastline. This includes the North Atlantic and North and South Pacific Oceans as well as the coastal waters of the contiguous United States, Alaska, Hawaii, and Pacific Island Nations, as shown in Figure 1 (*OFCM, 2006*).

The NCEP EMC produces the atmospheric models used by the U.S. public and private weather enterprise as the primary source of forecast guidance. These models include the Global Forecast System (GFS), Global Ensemble Forecast System (GEFS), North American Mesoscale (NAM) model, the NOAA Wavewatch III ocean wave model and the recently introduced Real-Time Ocean Forecast System–Atlantic (RTOFS_ATL) ocean model (based on the University of Miami HYbrid Coordinate Ocean Model (HYCOM). OSVW are one of the important data sources assimilated into the NCEP global and mesoscale modeling systems (GFS and GEFS).

The mission of the National Weather Service (NWS) is to *provide weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters, and ocean areas for the protection of life and property and the enhancement of the national economy.*

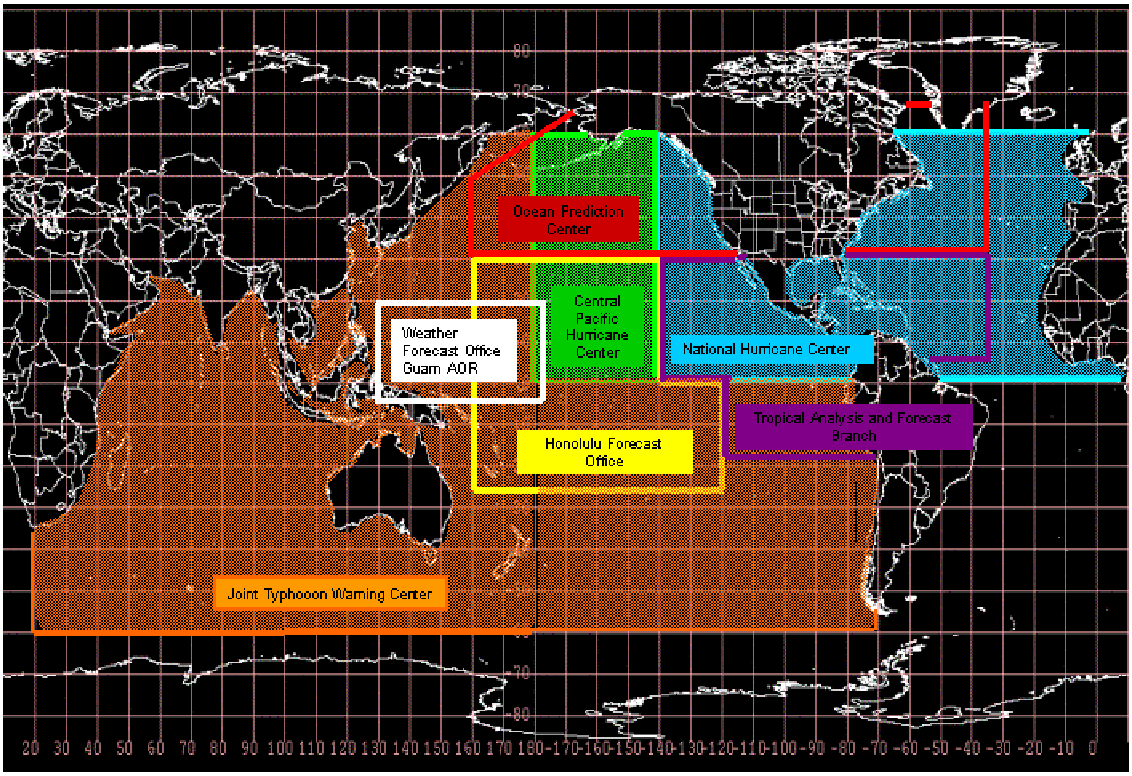


Fig 1. Map showing the combined areas of responsibility of meeting participants. Three centers, the OPC (red), TPC/TAFB (purple), and Honolulu Weather Forecast Office (yellow) share the United States high seas forecast responsibility as defined in the International Safety of Life At Sea (SOLAS) convention. The DoD Joint Typhoon Warning Center (orange), TPC/NHC (blue), and Central Pacific Hurricane Center (green) share the warning responsibility for tropical cyclones. Weather Forecast Office Guam (white) issues tropical cyclone public advisories for Micronesia.

3.1 Importance of Satellite OSVW

Remotely sensed OSVW from satellites are used by forecasters to help make wind warning and forecast decisions related to tropical and extratropical cyclones and other hazardous phenomena. NWS marine wind warnings and forecasts are used directly by mariners engaged in commerce, transportation, and recreation to make safe and economically efficient passages. Additionally, tropical cyclone warnings are utilized by emergency managers, government officials, and the general public to prepare for potential impacts from these systems. Remotely sensed OSVW help to fill the immense gaps inherent in the conventional ocean surface-based observation network. Remotely sensed OSVW often reveal small-scale characteristics of the wind field, which are used as a diagnostic tool in determining the development of potentially severe conditions, aid greatly in the determination of wind warning categories (severity), and help determine the radius of tropical storm force winds associated with tropical cyclones.

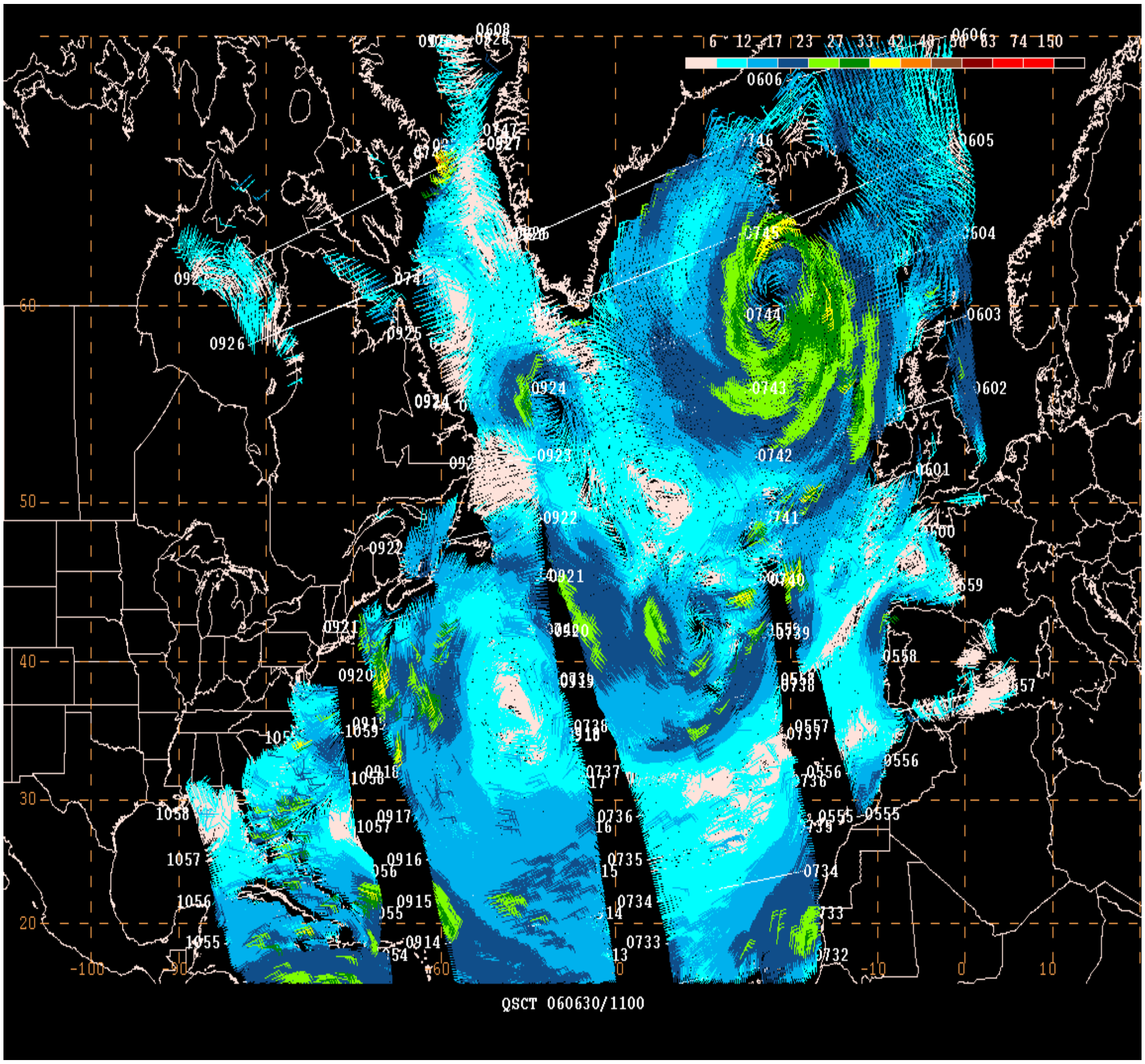


Fig 2. The near surface wind vector field as shown by the morning ascending QuikSCAT passes over the North Atlantic from 30 June 2006 as displayed on the NWS N-AWIPS workstations available at the OPC, TPC/NHC, and the Honolulu WFO. Wind speeds in knots are color coded according to legend.

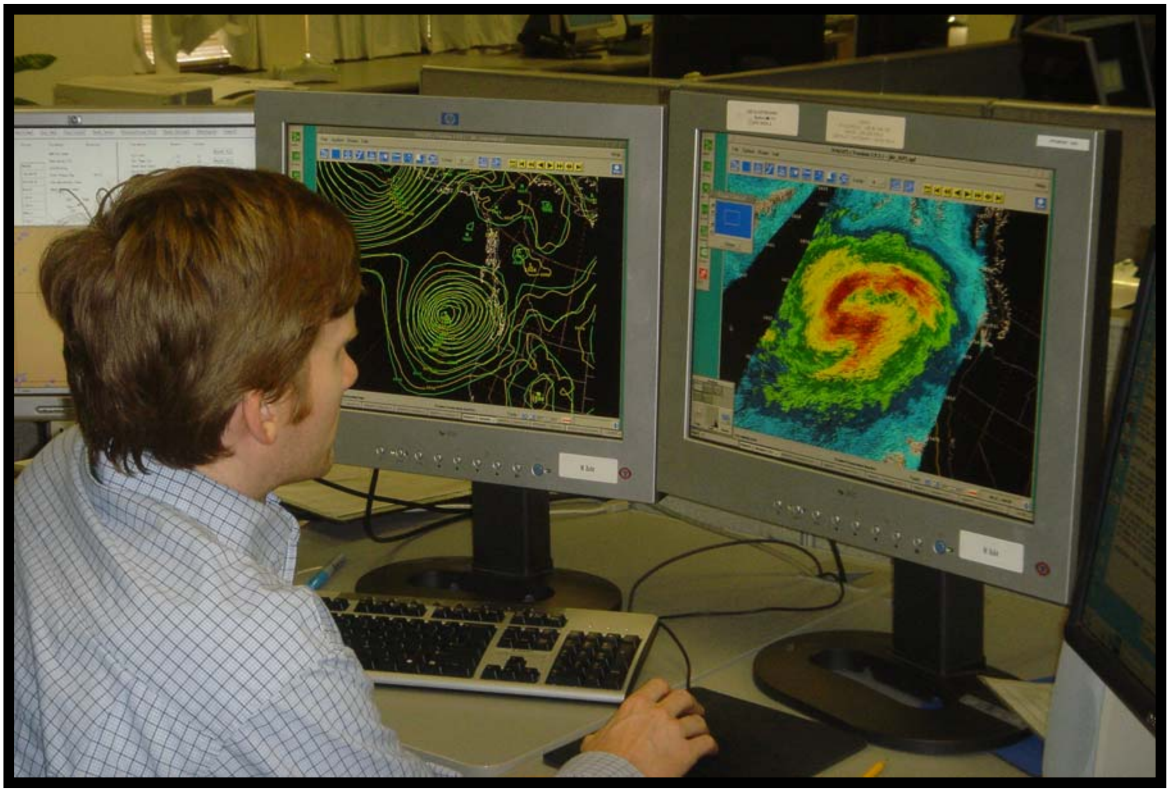


Fig 3. OPC forecaster Jim Clark using 12.5-km resolution QuikSCAT wind vectors to upgrade wind warnings for the Pacific offshore waters for Cape Flattery, Washington, to Cape Lookout, Oregon. The QuikSCAT pass shows the wind field of an entire ocean cyclone.

3.2 Utilization of Satellite OSVW

Remotely-sensed OSVW are a critical tool for the issuance of marine forecasts and warnings; tropical cyclone analysis, location, and warnings; identification and warning of coastal gap and jet winds; and public forecasts and warnings. These applications of satellite OSVW data are expanded upon in the following section.

3.2.1 Marine warnings and forecasts

- Short-term warnings and forecasts for high seas and offshore waters
- Observational source for surface analyses
  The use of scatterometer data for the daily surface analysis is crucial. One of our most important graphical products is the 6-hourly synoptic chart over our extensive area of responsibility (*Edson, 2006*).
  1. QuikSCAT OSVW data help to:
     - locate fronts and troughs
     - locate centers of high and low pressure
     - determine the category and extent of wind warning areas
       - Gale (34-47 kt)
       - Storm (48-63 kt)
       - Hurricane Force (64 kt or greater)

QuikSCAT is the first remote sensing instrument that can consistently distinguish extreme hurricane force conditions from less dangerous storm force conditions in extratropical cyclones. Due to the availability of QuikSCAT, OPC forecasters are now more likely to anticipate the onset of hurricane force conditions (*Sienkiewicz et al., 2006*).

2. The availability of satellite OSVW measurements greatly reduces the data void over the open oceans. The 1,800-km wide swath of the QuikSCAT scatterometer makes it possible for forecasters to view the entire circulation of tropical and extratropical cyclones within a single pass.

Since QuikSCAT OSVW have been available in near real-time in opertational NAWIPS workstations, the number of short-term wind warnings issued by OPC forecasters for the high seas waters have dramatically increased. Figure 4 shows the percent increase in the number of wind warnings by category issued by the OPC during the late fall of 2002. Available OSVW from QuikSCAT resulted in an increase in all warning categories issued. The greatest increase was observed for the stronger and more dangerous hurricane force warning categories (*Von Ahn et al*., *2004*).

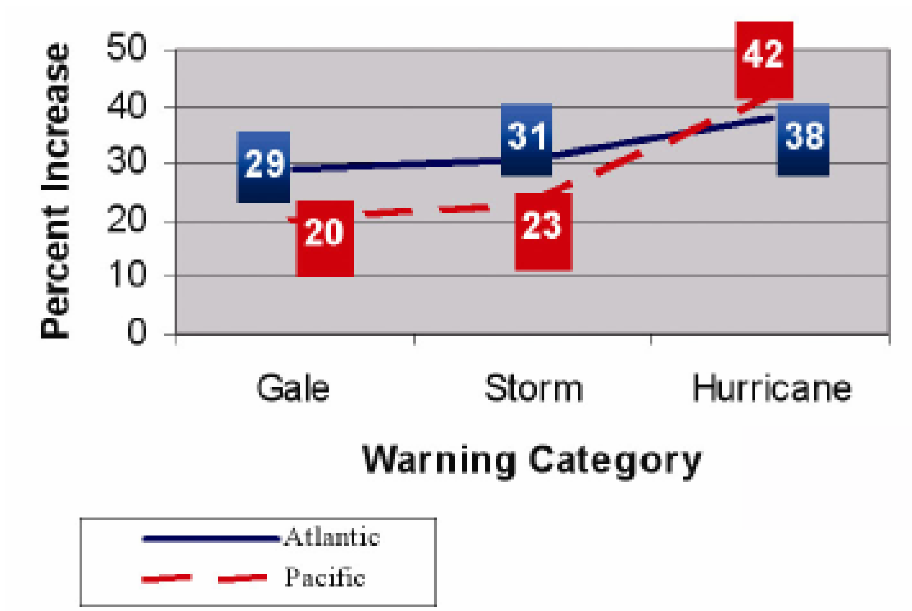


Fig 4. Percent increase in the number of wind warnings issued by OPC (from November 15 to December 15, 2002) as a function of warning type. Atlantic results are shown as a solid blue line and Pacific results as a dashed red line.

Hurricane force (HF) extratropical cyclones are a significant threat to safety at sea. Dangerous winds and waves associated with these extreme cyclones can cover vast ocean areas and result in the loss of lives and property. The economic impact is far reaching and can consist of loss or damage to cargo or a vessel, increased transit times, increased fuel usage, lost time due to vessel damage, and late delivery of perishable goods. Prior to QuikSCAT, there was no data source available to ocean forecasters that consistently *observed HF winds in extratropical cyclones. Merchant ships do occasionally report extreme conditions but not routinely enough for forecasters to be able to consistently differentiate the extreme HF cyclone from the more common Storm Force cyclone. QuikSCAT has given OPC forecasters this consistency* (*Von Ahn et al. 2004*).

The figure below provides an excellent example of the use of QuikSCAT OSVW in observing HF extratropical cyclones. The left panel of Figure 5 shows a GOES infrared (IR) satellite image overlaid with conventional ship and buoy observations, and the corresponding OPC surface analyses (with fronts and isobars) of an intense North Pacific winter ocean storm from 1800 UTC 01 Dec. 2004. The right panel of Figure 5 shows a 12.5-km QuikSCAT OSVW field of the same cyclone at approximately the same time. Wind speeds are color coded with red wind barbs depicting winds of hurricane force intensity. The conventional ship and buoy observations failed to suggest a cyclone of this intensity. The OPC forecaster upgraded the warning to hurricane force based solely on the QuikSCAT winds.

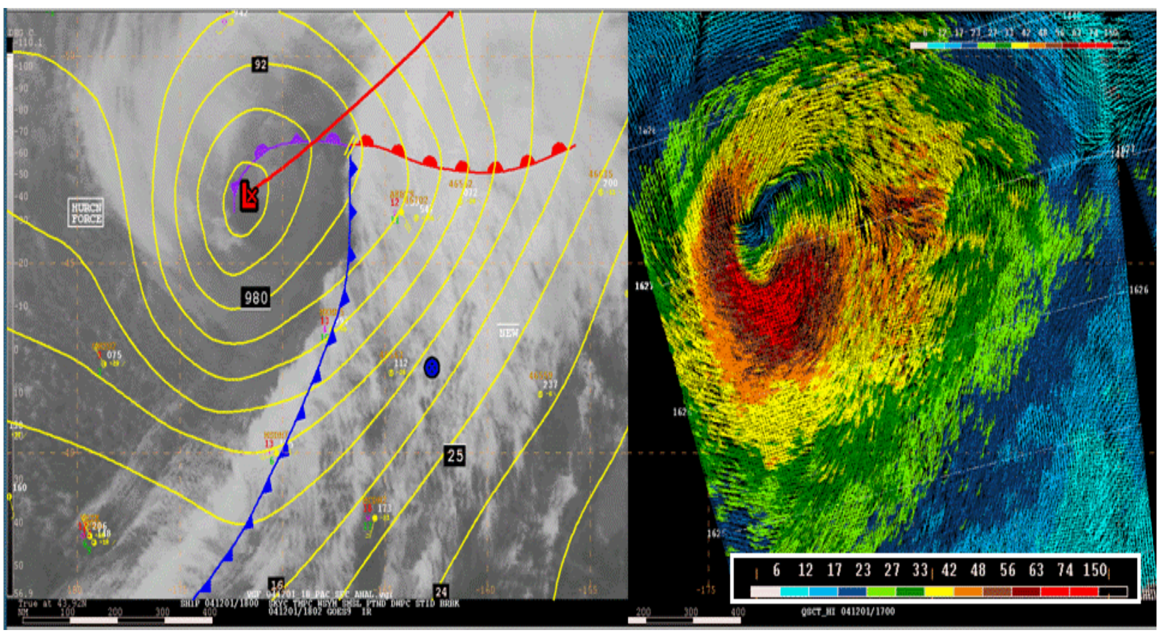


Fig. 5. Two-panel figure showing (left) the OPC surface analysis for 1800 UTC 1 Dec. 2004 for an intense North Pacific cyclone. Also shown are the GOES IR imagery and available ocean surface observations from ships of opportunity. The right panel displays the QuikSCAT 12.5-km resolution OSVW available to the OPC high seas forecaster as displayed on the operational NAWIPS workstations. Wind speed in knots is color coded according to the color bar shown in the lower right-hand side of the image. Red wind barbs indicate wind speeds of Hurricane Force intensity. The forecaster upgraded the warning category to hurricane force for this cyclone based solely on the strength of QuikSCAT winds (Von Ahn et al., 2004).

QuikSCAT OSVW have given OPC forecasters the ability to consistently observe winter ocean storms of hurricane force intensity. Figure 6 shows a five-year history of HF ocean storm activity in the North Atlantic and Pacific Oceans for the months of September through May from 2001 to 2006.

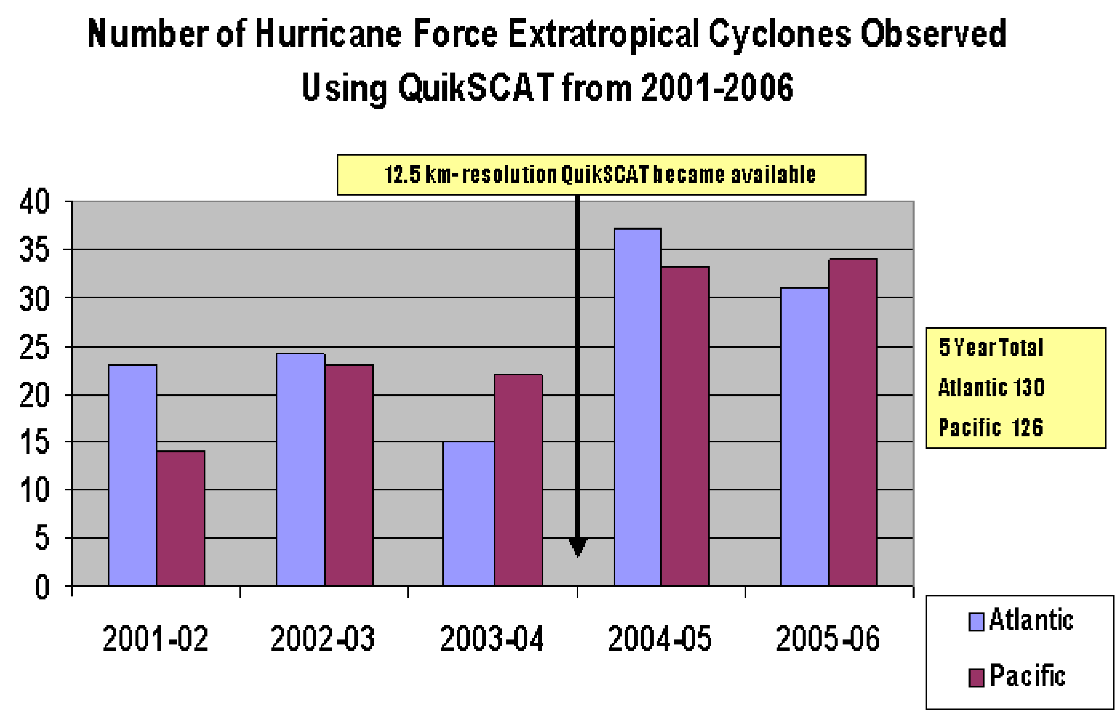


Fig. 6. The number of hurricane force winds (wind speed 64 kt or greater) observed using QuikSCAT OSVW for five winter seasons in the Atlantic (blue) and the Pacific (purple). For the first three seasons, only 25-km QuikSCAT OSVW were used. When the 12.5-km resolution QuikSCAT OSVW were introduced into the NAWIPS workstations, the total number of hurricane force storms observed by OPC increased, which can be attributed to the ability of the finer spatial resolution to capture the higher winds.

For the first three years of the study, on average 20 hurricane-force extratropical cyclones were observed in each ocean basin (21 in the Atlantic and 20 in the Pacific.) During the last two years the average number of hurricane-force storms increased dramatically (33 in the Atlantic, 34 in the Pacific). During the first three years only the standard 25-km resolution QuikSCAT OSVW were available to OPC forecasters. The final two years forecasters had both the 25 and 12.5 km QuikSCAT OSVW available to aid in the wind warning process. The 12.5 km QuikSCAT winds have less horizontal averaging and are able to detect smaller scale areas of stronger winds. This example illustrates that high-resolution OSVW result directly in more accurate warnings.

Complex sea surface temperature gradients associated with the Gulf Stream and shelf break front exist across the OPC mid-Atlantic and New England offshore zones. OSVW from QuikSCAT reveal significant wind speed gradients in the vicinity of these strong SST gradients. These wind gradients are most evident in the southerly flow in advance of an approaching frontal system. The wind speed pattern (of higher winds) tends to match the underlying SST pattern of warmer waters. Figure 7 is a four-panel from March 8, 2005, showing (a) QuikSCAT 12.5-km wind vectors color coded by wind speed according to the scale below the panel, (b) the difference in wind speed between 25-km QuikSCAT and the NCEP GFS 3-hour forecast 10-m winds, (c) three-day GOES SST composite valid March 8, and (d) the difference between the 0.9950 sigma layer wind speed (approximately 30 m above the ocean surface) from the 3-hour GFS and QuikSCAT 25-km wind speed.

In this example, clearly the QuikSCAT wind field pattern in (a) matches the SST pattern in (c) with gale (yellow) and near gale (dark green) conditions over the Gulf Stream waters and winds of 15 to 20 kt over the cooler waters. In (a), a patch of higher wind speeds coincide with a warm Gulf Stream ring in the upper left. Both (b) and (d) show the differences between the NCEP GFS near surface wind speeds used as guidance by forecasters and the QuikSCAT winds. The different fields show predominantly yellow and orange contours over the cooler waters representing an overforecast by as much as 6 to 8 kt by the GFS. Over the Gulf Stream and warm ring the difference in 10-m wind speeds in (b) show an underforecast of winds by the GFS of as much as 8 to 10 kt. The GFS 30-m wind speed difference in (d) agrees more closely with the winds over the warmer waters but grossly overestimates the wind speeds over the cooler waters. OPC forecasters have a variety of tools available to them to anticipate the impact of the underlying SST on the wind field and adjust the forecast accordingly.

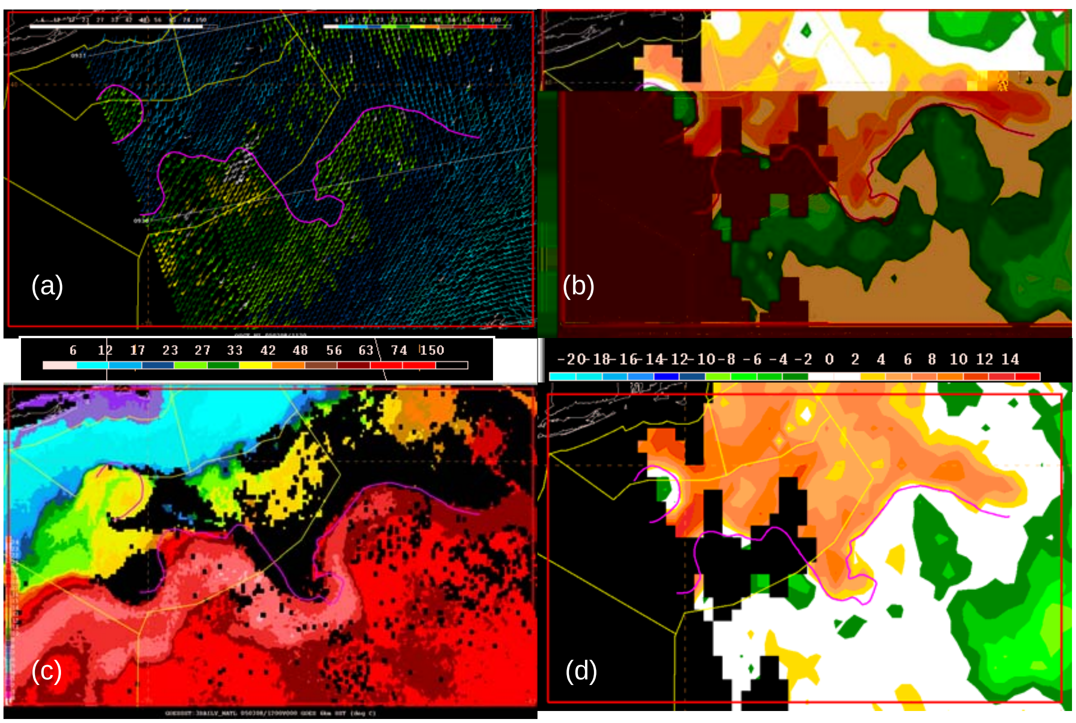


Fig. 7. Four-panel from March 8, 2005, showing (a) QuikSCAT 12.5-km resolution wind field for the waters southeast of New England and Long Island, (b) differences in wind speed (kt) between QuikSCAT 25-km and 3-hour forecast GFS 10-m winds, (c) 3-day GOES SST composite, and (d) 3-hour forecast GFS 30-m winds. In (b) and (d) differences are displayed according to the color scale above (d).

3.2.2 Tropical cyclone analysis and forecasting

Remotely sensed OSVW from QuikSCAT have also become an important tool for analysis and forecasting at the Tropical Prediction Center/National Hurricane Center (TPC/NHC), Central Pacific Hurricane Center (CPHC), the WFO Guam and JTWC. QuikSCAT wind speed and direction retrievals are utilized by the Hurricane Specialists Unit (publicly known as the NHC) in the analysis and forecasting of tropical cyclones in the North Atlantic and eastern North Pacific basins. The data are also used by TPC's Tropical Analysis and Forecast Branch (TAFB) in the issuance of marine forecasts, warnings, and analyses for large portions of the tropical North Atlantic and eastern Pacific oceans.

The mission of TPC/NHC is to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather, and by increasing understanding of these hazards. One of the most significant challenges in accomplishing this mission is the scarcity of data over the oceans. Winds from the QuikSCAT scatterometer have filled in some of these gaps since the data have been available in near real-time and have been integrated into the daily operations of both the NHC and TAFB since 2000. *(Brennan, 2006)*

QuikSCAT data have had a major impact in TC forecasting by providing estimates of:

- Tropical cyclone wind radii (maximum extent of 34- and 50-kt winds). The wide swath of retrieved winds from QuikSCAT is useful in determining the extent of 34-kt and occasionally 50-kt winds in tropical storms or hurricanes. NHC provides analyses and three-day forecasts of the maximum extent of the 34-kt and 50-kt winds in each full advisory package (nominally issued every 6 hours); 36-hour forecasts of the maximum extent of 64-kt winds are also provided, but QuikSCAT is typically not useful for determining 64-kt radii because of its spatial resolution limitations and the presence of significant precipitation that generally exists under these conditions. The information on wind radii from QuikSCAT is especially useful for tropical cyclones outside the range of aircraft reconnaissance and in the eastern North Pacific basin where reconnaissance missions are flown relatively infrequently.

  Accurate wind radii are critical to the both TPC/NHC, CPHC, and WFO Guam watch and warning process since they affect the size of tropical storm and hurricane watch and warning areas. Also, the timing of these watches and warnings is based in part on when 34-kt winds are expected to arrive at the coast. Wind radii analyses and forecasts are also important to the marine community, as the current and expected size and location of the 34-kt and 50-kt wind areas provide guidance to mariners seeking to avoid these hazardous wind conditions around a tropical cyclone *(Brennan 2006, Knabb 2006, Edson and Browning, 2006) (see Fig. 8).*

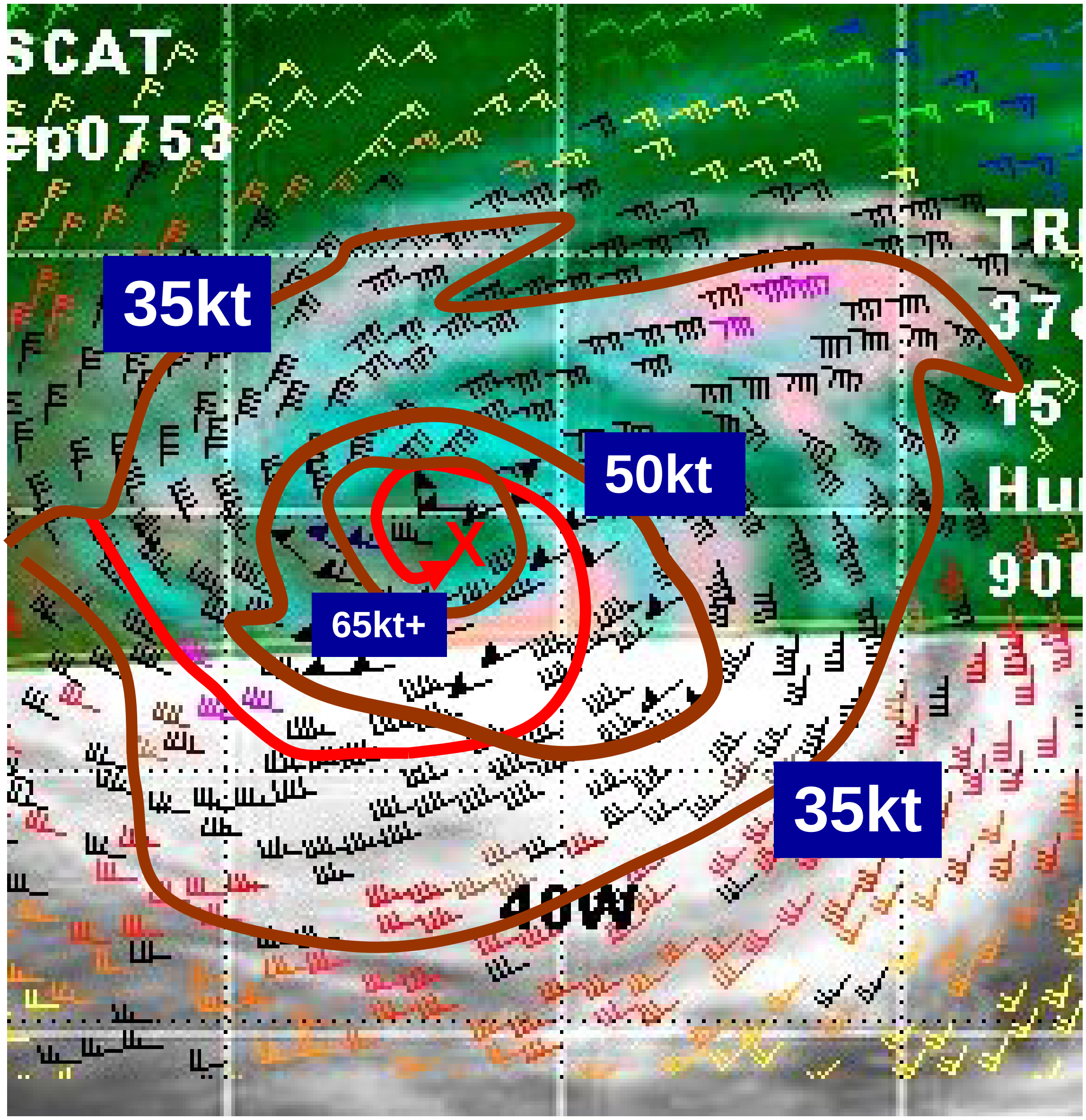


Fig 8. Hurricane Felix – Determination of outer wind radii using QuikSCAT wind vectors (*Edson*).

- Maximum wind speed in tropical storms and marginal hurricanes.
  - QuikSCAT data can be helpful in determining the intensity of tropical depressions, tropical storms, and some Category 1 or 2 hurricanes, although careful interpretation of the data by the forecaster is imperative.
  - In tropical cyclones of tropical storm or marginal hurricane intensity, QuikSCAT winds have shown some utility for estimating maximum sustained winds and compare favorably with reconnaissance flight-level wind data in some cases (Fig 9).

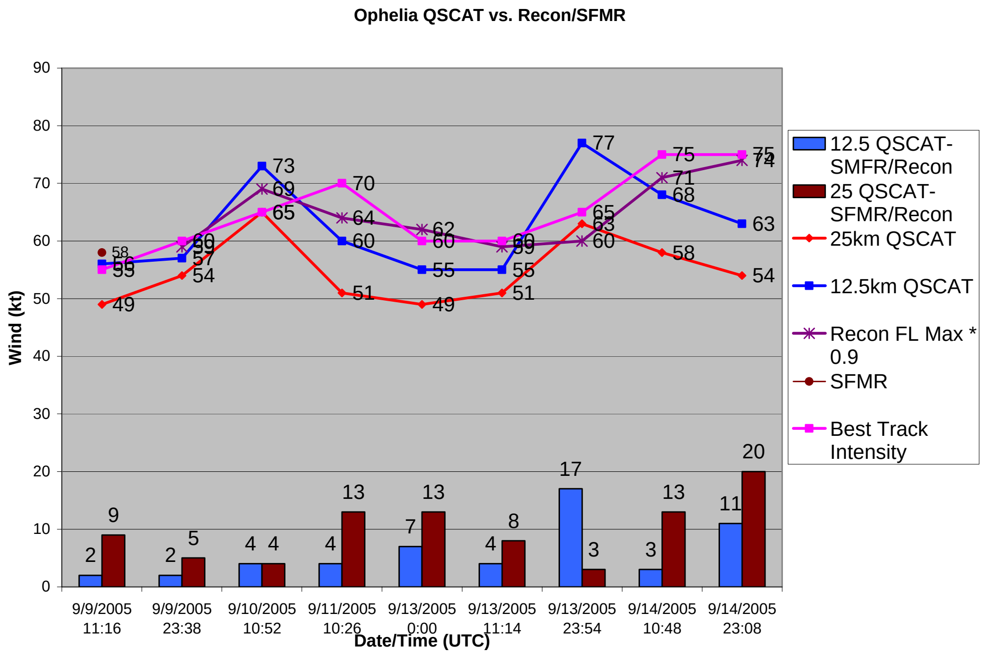
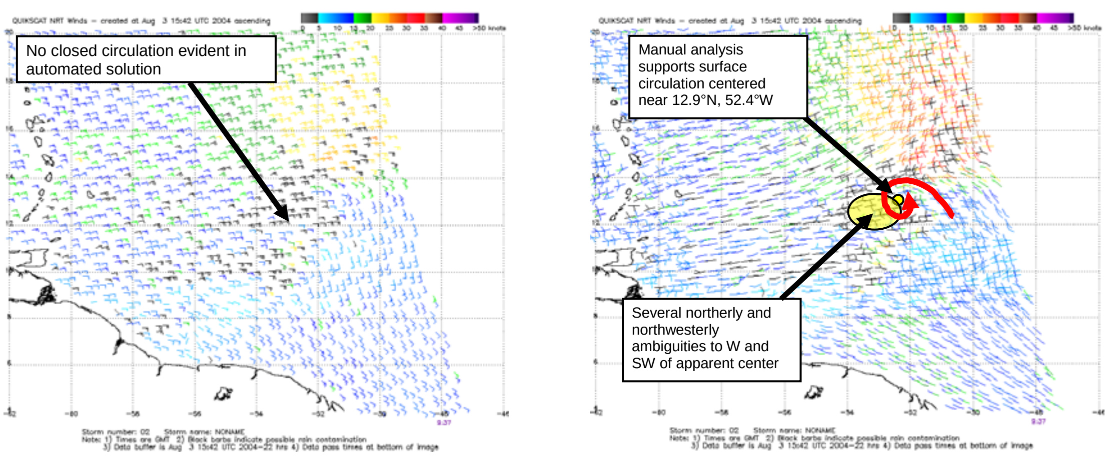


Fig 9. Time series of QuikSCAT wind maxima, maximum winds from stepped frequency microwave radiometer (SFMR), and maximum reconnaissance flight-level winds reduced by a factor of 0.9 in Hurricane Ophelia, per standard practice. Bar graphs indicate the absolute difference between the 12.5- and 25-km QuikSCAT wind maxima and the SFMR/aircraft maxima at that time.

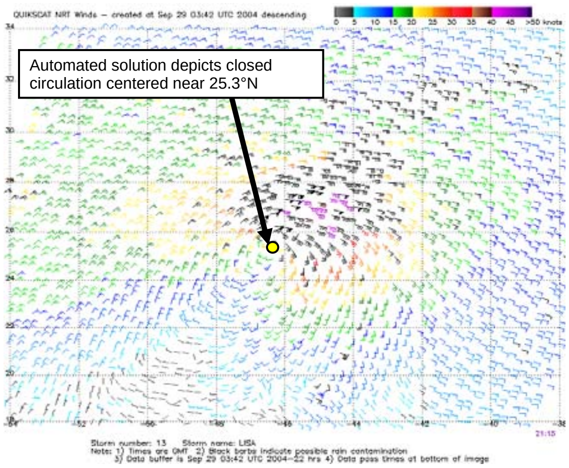
- Tropical cyclone center identification and location. Identification of a closed-surface wind circulation system is necessary to initiate advisories on a new tropical cyclone and to locate the center of mature tropical cyclones. Experience has shown that while automated wind direction solution from QuikSCAT is sometimes misleading, manual analysis of QuikSCAT ambiguities (alternative wind solutions) can often be used to identify early-stage closed circulations (Fig. 10) and to locate the centers of mature cyclones to precisions of a few tens of kilometres (Fig. 11).



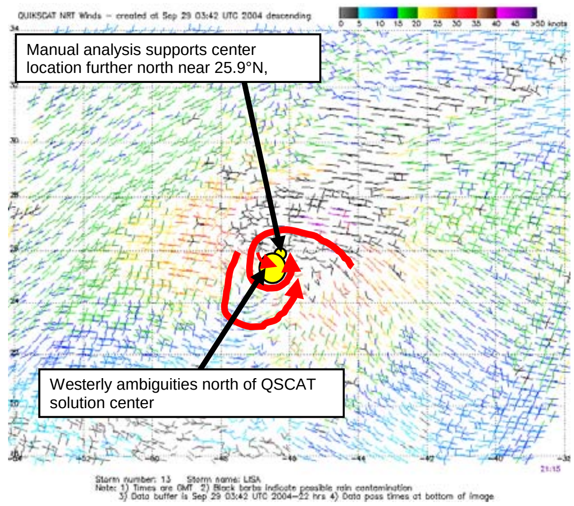
0937 UTC 3 August 2004 Advisories initiated on TD#2 (later Bonnie) partly based on this analysis.
Excerpt from TC Discussion:"IT IS DIFFICULT TO ASCERTAIN IF THE SYSTEM...AN ESPECIALLY FAST MOVING ONE...HAS A CLOSED CIRCULATION WITHOUT DATA FROM A RECONNAISSANCE PLANE. YOU COULD MAKE THE CASE THAT A SMALL CIRCULATION EXISTS USING QUICKSAT AMBIGUITY ANALYSIS."

Fig. 10. Early identification of a tropical depression using QuikSCAT ambiguity analysis.

- Positioning of tropical cyclones.



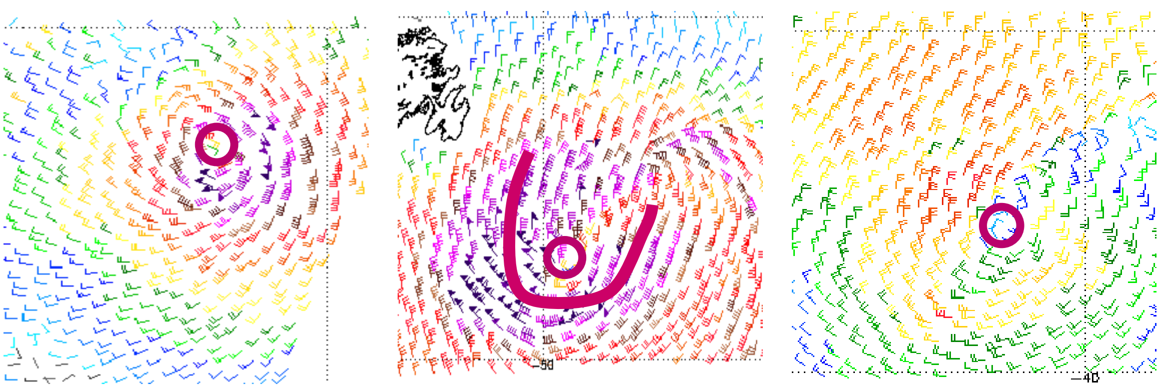
QuikSCAT wind vector solution for Hurricane Lisa at 2115 UTC 29 September 2005. The yellow dot indicates the approximate location of the center from the automated wind solution.



QuikSCAT ambiguities for Hurricane Lisa at 2115 UTC 29 September 2005. The small yellow dot indicates the approximate location of the center determined from manual ambiguity analysis shown in red lines.

Fig.11. Identification of storm center using all the retrieved ambiguities from QuikSCAT.

- Extratropical transition. QuikSCAT winds can help identify the expansion of the tropical cyclone wind field during the extratropical transition process (Fig. 12).



Tropical 28/09Z 115kts | **Extratropical transition 31/21Z 50kts** | **Extratropical 04/08Z**

Fig. 12. Hurricane Cindy – Extratropical transition observed in QuikSCAT winds (*Edson*).

3.2.3 Identification and warning of coastal gap and jet winds

- Identification and warning of gap wind events in the Eastern Pacific.
  - QuikSCAT winds have greatly improved the monitoring and forecasting of gap wind events, particularly in the Gulf of Tehuantepec (Fig 13). As noted by Cobb et al. (*2003*), prior to the availability of QuikSCAT data,

forecasters had to rely on occasional ship observations to verify gale or storm warnings in this region. Based on a study from 1999 through the present, 128 gale force wind events have been documented in the Gulf of Tehuantepec, with 29 of those events reaching storm-force magnitude (≥48 kt) (*Hugh Cobb, personal communication*). On average, gale-force winds occur 17 times during a cold season in the Gulf of Tehuantepec, with four storm-force events per season. Prior to the advent of QuikSCAT, the extent and magnitude of many of these high-wind events was unknown due to a lack of observations *(Brennan, 2006).*

- Since gap wind events are dominated by low-level cold advection and subsidence, rain contamination of QuikSCAT wind vectors is not a problem. The wide QuikSCAT swath is ideal for identifying the extent of 20 kt, gale force, and storm force winds, and for comparing to numerical model forecasts of wind distribution *(Brennan, 2006).*

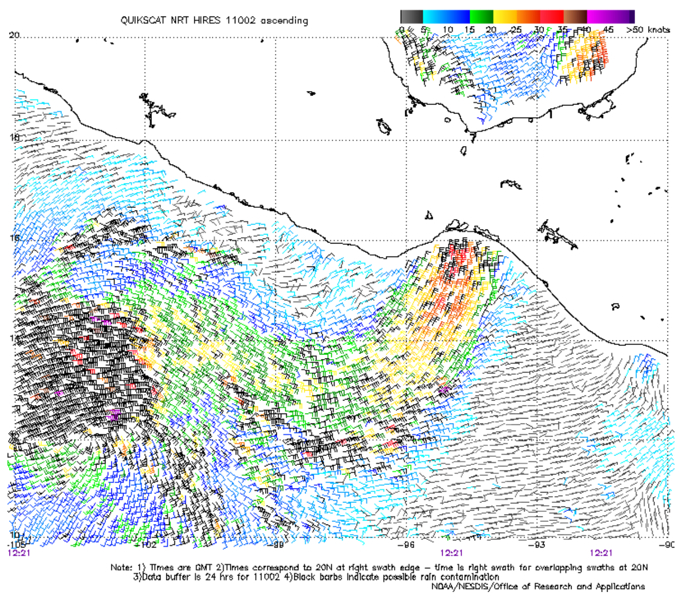


Fig. 13. Gale force winds in Gulf of Tehuanatepec revealed in high-resolution (12.5-km) QuikSCAT retrievals.

3.2.4 Public forecasts and warnings

- Remotely sensed ocean surface winds used as a diagnostic tool. Improved knowledge of upstream conditions over the oceans (lows, highs, wind maxima, fronts) gives both coastal and inland forecasters the ability to diagnose numerical model analyses and forecast fields for both coastal and land-falling events. This capability often results in changes of warning criteria and the forecast timing of the onset of hazardous conditions.
- Coastal jets in the lee of caps and points. Prior to QuikSCAT, the extent and impact of orographically induced jets and lee wakes were not well known (Fig 14).

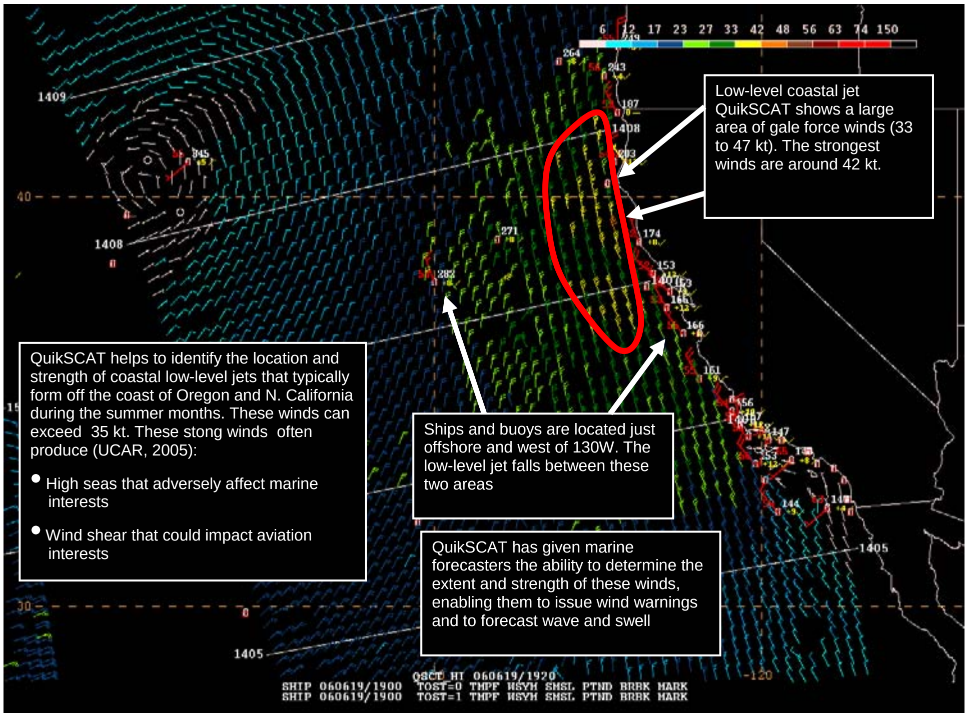


Fig. 14. Example of coastal low-level jet off the California coast as observed using the 12.5-km QuikSCAT pass from 1400 UTC 19 June 2006.

- Improved surf/swell forecasts. Detailed ocean surface winds give forecasters a detailed view of swell generation areas and the ability to better diagnose the quality of numerical wave model guidance. This supports the NWS's increased focus on rip current forecasting.

3.2.5 Numerical Weather Prediction

Satellite surface wind data improve numerical weather prediction (NWP) model forecasts in several ways. OSVW data

- contribute to the improved analyses of the surface wind field and, through the data assimilation process, of the atmospheric mass and motion fields in the free atmosphere above the surface.
- provide important verification data for NWP model forecasts.
- drive ocean models and surface wave models to calculate surface fluxes of heat, moisture, and momentum, and to construct surface climatology.

The use of scatterometer observations in data assimilation systems can extend their usefulness substantially and lead to improved sea level pressure analyses, improved upper air analyses of both wind and geopotential, and improved short- and extended-range numerical weather forecasts (*Atlas et al. (2), 2006*).

- Results from experiments in which QuikSCAT and/or WindSat OSVW data are assimilated also show a substantial increase in the ability to forecast storms over the oceans. Satellite OSVW data often provide indications of the formation of tropical cyclones earlier than other observing systems (Fig.15).

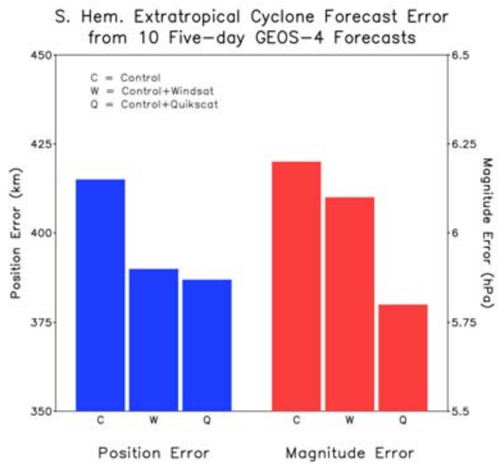


Fig. 15. Relative impact of WindSat and QuikSCAT data on 5-day GEOS-4 forecasts of cyclones. This figure shows a positive impact of OSVW data on cyclones. The impact of QuikSCAT is slightly larger than WindSat for cyclone position and significantly larger for cyclone magnitude. In the Northern Hemisphere (not shown), the impact is smaller and less consistent than for the Southern Hemisphere. The impact of QuikSCAT is substantially better than for WindSat (*Atlas et al. (1), 2006*).

- The assimilation of QuikSCAT data results in a substantial reduction of both magnitude and displacement errors with respect to the control run (Fig.16). The 60-hour forecast with QuikSCAT data is more accurate than the 24-hour forecast without QuikSCAT data. Following these initial experiments, QuikSCAT data began to be assimilated operationally in real time at NCEP and has been contributing substantially to the current accuracy of hurricane forecasting (*Atlas et al. (2), 2006*).

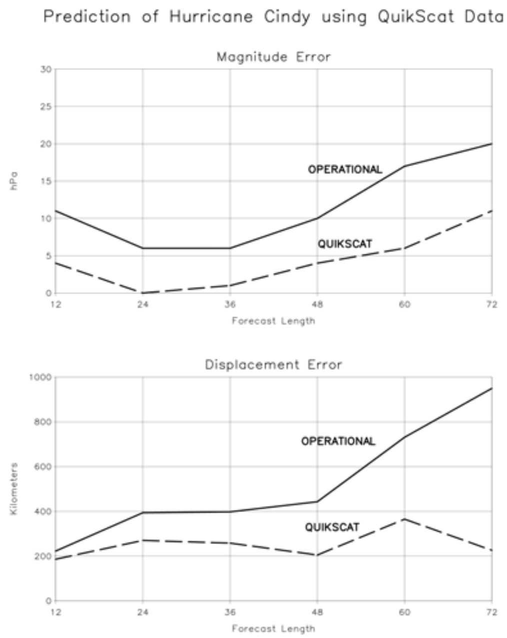


Fig. 16. The impact of QuikSCAT data in a test version of the NCEP operational data assimilation system. The magnitude and displacement errors of Hurricane Cindy from 1999 over a 60-hour period (*Atlas et al. (2), 2006*).

Chelton et al. 2006 illustrated the impact that the assimilation of QuikSCAT OSVW had on operational numerical weather prediction (NWP) models.

> *NCEP and ECMWF began assimilating QuikSCAT winds operationally on 13 and 22 January 2002, respectively. The resulting improvements in the accuracies of these NWP models during the first year of QuikSCAT data assimilation are evident from the statistics presented by Chelton and Freilich 2005. These accuracy improvements occurred abruptly after implementation of the QuikSCAT assimilation procedure in each model. This is evident, for example, from the time series of the global percentage of wind direction differences less than 20° between QuikSCAT and the two NWP models shown in* Figure 17. *Significant improvements in this measure of agreement between the different wind estimates occurred immediately after 13 January 2002 in the NCEP model and immediately after 22 January 2002 in the ECMWF model.*

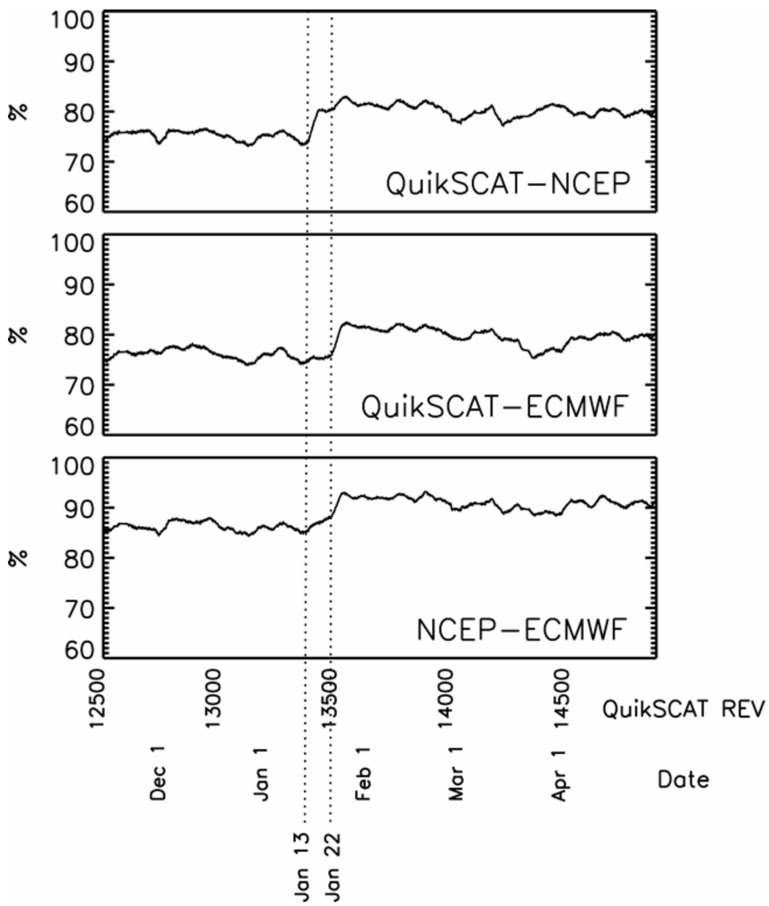


Fig. 17. (*Chelton et al., 2006*) Daily time series of the percentages of collocated winds with directional differences less than 20° between Nov. 15, 2001, and Mar. 1, 2002. The NCEP and ECMWF models began assimilating QuikSCAT winds on Jan 13, 2002 and Jan. 22, 2002, respectively. Comparisons of QuikSCAT vs NCEP winds (top), QuikSCAT vs ECMWF winds (middle), and NCEP vs ECMWF winds (bottom). The statistics were computed over the middle 1,600 km of the QuikSCAT measurement swath, excluding the near nadir measurements within ±125 km of the QuikSCAT ground track. Each time series was smoothed with a 4-day running average.

3.3 Workshop Participants Statements

The following quotes from several of the workshop presenters highlight the importance of a reliable and routine source of satellite ocean surface vector winds data in the operational environment.

Rick Knabb, Senior Hurricane Specialist, Tropical Prediction Center/National Hurricane Center, NOAA/NWS/NCEP, Miami, Florida:
"QuikSCAT has been a tremendous benefit to the Tropical Prediction Center."
"When QuikSCAT is gone, it will be like going back seven years in tropical cyclone analysis."
"Losing QuikSCAT would be like losing a limb, especially for Tropical Analysis and Forecasting Branch."

Hugh Cobb, Tropical Prediction Center/National Hurricane Center, NOAA/NWS/NCEP, Miami, Florida:
"QuikSCAT is our bread and butter."

Capt. Caroline Bower, Science Officer, Naval Pacific Meteorology and Oceanography Center (NPMOC)/Joint Typhoon Warning Center (JTWC), Pearl Harbor, HI:
"QuikSCAT plays a critical role in our tropical cyclone analysis and forecasting operations."

Roger Edson, Science and Operations Officer, NOAA/National Service Forecast Office in Guam:
"QuikSCAT has been absolutely vital for understanding the structure of tropical cyclones."

Joe Sienkiewicz, Chief (Acting), Ocean Application Branch W/NP42, Science Officer, NOAA/NWS/NCEP/OPC, Camp Springs, Maryland:
"Because of QuikSCAT, our ability to assess current conditions has never been better and our warnings never more accurate."

John Lovegrove, Meteorologist-in-Charge (MIC), NOAA/National Service Forecast Office, in Medford, Oregon:
"QuikSCAT has been instrumental in forecasting coastal jets. We didn't know they were out there before QuikSCAT."

Mark Freeberg, President of OCENS Inc., Seattle, Washington:
"We have thousands of users and QuikSCAT accounts for 15 percent of download of all wind products downloaded by these users."

4 Limitations of Current Systems

The experience acquired utilizing QuikSCAT measurements for almost seven years has clearly demonstrated the positive impacts of these data in the operational weather analysis, forecasting, and warning environment. The real-world experiences gained from exploiting the currently available research satellite missions has also revealed the limitations of the current satellite OSVW systems to the operational community. Understanding these limitations is just as important as understanding the positive impacts in identifying the present and future OSVW requirements of the operational weather community. Drawing upon the operational experiences to date, limitations of current OSVW missions and requirements for future missions are listed below:

- The inability to resolve maximum winds in the inner core of most hurricanes
  "It is necessary to have the capability to accurately measure all sustained wind speeds encountered in tropical cyclones, from zero up to 165 kts."(Knabb, 2006)
- The inability to resolve maximum winds in extratropical storms
  "We do not know how strong the maximum winds that occur in winter ocean storms are. We only know that hurricane force conditions exist. Ocean waves

respond to the square of the wind speed, therefore knowledge of the maximum wind speed (and direction) is needed for accurate wave predictions." (Sienkiewicz, 2006)

- Rain contamination and the resulting biases in retrieved wind speeds (Wiessman et. al., 2002). Co-located rain rate measurements are necessary to determine the influence of rain on the retrieved wind solution, where greatly reduced or even non-existent sensitivity to rain is desired to provide reliable wind speed and direction retrievals regardless of rain rate (no rain, light rain, or heavy rain). *(Brennan, 2006; Sienkiewicz et al., 2006).*
- Ambiguity removal errors that make QuikSCAT-derived tropical cyclone center locations unreliable and the determination of whether a circulation center exists in incipient systems difficult. Elimination of the directional ambiguity errors, is necessary for more accurate position fixing of the center of a tropical cyclone, and/or for determining if a closed circulation center exists at all (a key factor in determining whether or not cyclogenesis has occurred) *(Brennan, 2006; Edson, 2006; Bower, 2006.)*
- The long intervals between repeat passes of any single satellite—even the broad swath QuikSCAT—over any given region
  "Scatterometer instruments have been shown to increase forecasting accuracy by providing spatially extensive surface wind measurements that can be assimilated into numerical weather prediction (NWP) models, by providing researchers with the necessary data to establish more precise physical concepts of behavior, and by providing tropical cyclone forecasters with increased knowledge in the data-poor regions of the globe of position, outer wind structure, an approximate maximum intensity, genesis and early stage development, and the evolution of the outer winds during extratropical transition.

  An increase in global scatterometer coverage will provide more thorough input to the NWP assimilation process, fill in the remaining 10% gaps in daily satellite coverage over the tropical oceans, support the daily METWATCH and warning criteria of most tropical cyclone warning centers, thus providing opportunity for early detection, motion and positioning and increase the data base for the research community" (Edson, 2006).
- The time lag between the satellite overpass and data receipt. Reduce time of data receipt to, at most, a few minutes following the time of data collection by the satellite.
- Data limited by their spatial resolution
- The unavailability of near-shore data. Coastal regions that are the responsibilities of many WFOs are the *"area where most lives are lost."(Lovegrove, 2006).* With greater temporal/spatial resolution and more accurate wind speed and direction information, advisory or near-advisory conditions would be forecast with greater certainty and provide greater safety for boaters (*Lovegrove, 2006*).
- The slow implementation of data delivery in the operational environment such as NAWIPS, AWIPS and data assimilation. Offices across the country are equipped with surface analysis tools such as LAPS, MSAS, ADAS, etc. These tools should be improved to have capability to ingest OSVW measurements from satellites. This would improve substantially the quality of the analysis over water and the

usefulness of these tools when using them as part of the forecast and warning process and for populating grids (*Hinojosa, 2006; Stamus and Milliff, 2006*).

- The lack of documentation and training limits the use of data and their impact on operations. The training investment has been slim to none when the OSVW data are first made available. Initiatives/technologies like this appear on the Internet first and then only much later are products available in AWIPS. Even when available, only some forecasters use them. Satellite OSVW should be made part of the daily briefing procedure, but this has not yet been done, in part because of the lack of training (*Hinojosa, 2006; Stamus and Milliff, 2006*).

5 The Requirements and the Requirements Gap

5.1 NPOESS Integrated Operational Requirements

Current operational requirements for satellite ocean surface vector wind measurements are defined in Integrated Operational Requirements Document II (*IORD II, 2001*). These requirements represent the basis on which the National Polar-orbiting Operational Environmental Satellite Systems (NPOESS) architecture is to be designed.

The NPOESS Program is required to provide, for a period of at least 10 years, a remote sensing capability to acquire and receive in real time at field terminals and to acquire, store and disseminate to processing centers, global and regional environmental imagery and specialized meteorological, climatic, terrestrial, oceanographic, solar-geophysical and other data in support of Department of Commerce (DoC) mission requirements and Department of Defense (DoD) peacetime and wartime missions. The notional NPOESS architecture is based on a Cost and Operational Benefits Requirements Analysis of original IORD requirements conducted in 1996 (IORD II, 2001).

The IORD II, or Integrated Operational Requirements Document, defines two levels of operational requirements: threshold and objectives. The objective requirements represent the desired measurement performance. The threshold requirements, listed in the IORD II, refer to the minimum requirements to be achieved at any point where measurements are sensed and environmental data records (EDRs) are retrieved. These requirements were defined with the goal that the final output products for both DoD and DoC centers "*are accurate forecasts and analyses of environmental conditions to enhance various military and civilian operations. These forecasts are prepared using data from multiple systems, including NPOESS. DoC and DoD operational requirements are data values to be used as inputs to computer algorithms in order to create final forecast products for customers"(IORD II, 2001).*

5.2 NOAA's Operational OSVW Requirements

The operational needs and experience with the currently available satellite OSVW measurements presented during the workshop culminated in the formulation of new operational OSVW requirements. These requirements reflect the observational needs of

NWS and JTWC forecasters to prepare warnings and forecasts for a variety of meteorological and oceanographic phenomena observed over the oceans including tropical cyclones, extratropical ocean storms, areas of convection, gap flows, upwelling areas, topographically induced or enhanced jets, and island and mountain wakes. The spatial grid spacing reflects both the phenomena observed and the horizontal resolution of gridded forecasts now produced in operations by coastal NWS Weather Forecast Offices. The requirements include:

- All-weather retrievals (i.e., accurate retrievals in rain)
- Accuracy levied upon the selected 10-meter, 1-minute sustained wind as defined by operational requirements
  0-165kts wind speed range
    - 10–165 kts: speed +/- 2 kt and direction +/- 10 degrees (2 sigma)
    - 4–10 kts: speed +/- 2 kt and direction +/- 20 degrees (2 sigma)
    - 0–4 kts: speed +/- 2 kts
- Revisit time interval (defined as the time interval between measurements at a particular point on the ocean surface): every 6 hours (1 to 3 hour goal)
- Reduced product latency: 45 to 60 minutes from measurement to product availability (15 minute goal)
- 2.5 km x 2.5 km grid spacing, which is defined as the spacing between unique wind vector retrievals (1 km x 1 km goal)
- Unique wind vector grid cells to within 2.5 km of the coast (1 km goal)
- Wind fields delivered into the operational environment, i.e., NAWIPS, AWIPS, and data assimilation systems
- Product documentation/tutorial/training

5.3 Comparison of Current and New Requirements with Available OSVW Measurements

The IORD II threshold and objective requirements for OSVW EDRs were compared with:

- performances of currently operating sensors QuikSCAT and WindSat,
- projected performance from JPL study of a next-generation satellite instrument for measuring OSVW. This study is elaborated upon in Section 6 of this document, and
- new NOAA operational OSVW requirements as defined during the workshop and listed in Section 5.2.

The comparison is summarized in Table 5.3.1 It is important to note that the stated accuracies of the current satellite instruments QuikSCAT and WindSat are based on the current sensor performances, not their respective mission requirements. The comparison clearly shows that:

- Neither of the currently operational OSVW sensors satisfies the new operational OSVW requirements.

- New operational requirements
    - exceed IORD II threshold values in all categories.
    - are close to IORD II objectives for most of the categories.
    - exceed even the IORD II objectives for the wind speed measurements range.
- OSVW measurements produced by QuikSCAT
    - exceed IORD II thresholds in the requirement categories of measurement range, wind speed accuracy, resolution, and swath width.
    - fail to meet IORD II threshold requirements for satellite revisit time and measurement latency.
- OSVW measurements produced by the WindSat instrument
    - exceed the IORD II threshold for wind speed accuracy within the limited IORD II measurement range.
    - match the threshold level for directional accuracy for wind speeds higher than 6 m/s.
    - fail to meet the IORD II threshold level for spatial resolution and wind direction at wind speeds below 6 m/s.
    - do not meet time revisit and latency requirements since WindSat was the conical microwave imager sounder (CMIS) risk-reduction mission and, thus, not designed for it. However, even a single CMIS instrument in polar orbit will not meet the IORD II revisit/coverage requirements.

The new operational OSVW requirements are compared to current and future OSVW missions in Tables 5.3.1 and 5.3.2.

Table 5.3.1. Comparison of IORD II requirements and QuikSCAT and WindSat performance

		IORD-II Threshold	QuikSCAT	WindSat	IORD II Objective	New OSVW Requirements
Horizontal Cell Size		20km	25km / 12km operational 5km experimental	50km operational 35km experimental	1km	2.5km x 2.5km unique grid spacing 1km x 1km goal
Mapping Uncertainty		5km			1km	
Measurement Range		3-25m/s 0-360º	3-40m/s 0-360º	3-25m/s 0-360º	3-50m/s 0-360º	0-82.5m/s 0-360º
Measurement Accuracy	Speed	Greater of 2m/s or 10%			Greater of 1m/s or 10%	All wspd +/- 1m/s
	Direction	Wspd>5m/s ~20º	Wspd<3m/s >20º	Wspd>7m/s <20º	~10º	Wspd >5m/s ~10º
		Wspd<5m/s ~ 25º	Wspd >3m/s <20º	Wspd<7m/s <30º	~10º	Wspd<5m/s ~20º
Latency		90min	3h	5h	15min	45-60min 15min goal
Revisit Time		6h	18h	34h	1h	6h (1-3h goal)
Swath Width		1,700km	1,800km	1,000km		
Coastal Winds			30/20km of the coast	75km of the coast		2.5km of the coast

- (red) Worse than the IORD II threshold
- (yellow) IORD II threshold
- (green) Better than the IORD II threshold
- (blue) Worse than the IORD II objective
- (white) IORD II objective
- (purple) Better than the IORD II objective

Table 5.3.2. Comparison of IORD II requirements and CMIS, ASCAT, and JPL proposed next-generation measurements (*Accuracies of next-generation OSVW measurements are based on simulations)

		IORD-II Threshold	CMIS (Canceled)	ASCAT	Next-Generation OVWM	New OSVW Requirements
Horizontal Cell Size		20km	20km operational	50km operational 25km operational 12.5km experimental	1km-5km Ku-band 12.5km C-band <20km radiometer	2.5km x 2.5km unique grid spacing 1km x 1km goal
Mapping Uncertainty		5km				
Measurement Range		3-25m/s 0-360°	3-25m/s 0-360°	3-30m/s 0-360°	2-55m/s or greater	0-82.5m/s 0-360°
Measurement Accuracy	Speed	Greater of 2m/s or 10%	Greater of 2m/s or 10%	Greater of 2m/s or 10%	Wspd<7m/s <1m/s at 2km or <0.3m/s at 12.5km Wspd<15m/s <1.6m/s at 2km or <0.4m/s at 12.5km wspd~50m/s ~10m/s at 12.5km	All wspd +/- 1m/s
	Direction	Wspd>5m/s ~20°	~20°	<20°	<74° at 2km <28° at 12.5km	wspd >5m/s ~10°
		Wspd<5m/s ~ 25°	~ 25°	<25°	<24° at 2km <6° at 12.5km	Wspd<5m/s ~20°
Latency		90min	90min	45min	15min	45-60min 15min goal
Revisit Time		6h	19h	32h	18h	6h (1-3h goal)
Swath Width		1,700km	1,700km	2 x 500km 768km nadir hole	1,800km	

Worse than the IORD II threshold — IORD II threshold — Better than the IORD II threshold

Worse than the IORD II objective — IORD II objective — Better than the IORD II objective

6 Meeting the Next Generation Ocean Surface Vector Wind Requirements

As previously noted, the main objectives of this workshop were to

- Assess the operational utilization and impact of satellite OSVW measurements in weather forecasting, warning, and analysis; and
- Consider measurement accuracy, resolution, and coverage requirements for future NOAA operational ocean surface vector wind products in light of present experience from research missions, and planned future advances in the areas of numerical weather models, analytical techniques, and NOAA's global, regional, and storm forecast requirements.

The workshop briefly surveyed mature and developing technologies that could form the basis for near-future operational NOAA ocean surface vector winds observing systems. Concepts for a next-generation ocean vector winds instrument are being studied by JPL, and the performance characteristics of one promising approach are described below in section 6.2.

6.1 Meteorological Satellites

There are generally two classes of meteorological satellites being used today: geostationary and sun-synchronous near-polar orbiting satellites.

Geostationary satellites follow a circular orbit that is orientated in the plane of Earth's equator. These satellites are placed at a very high altitude (35,786 km) where the satellite's orbital period exactly matches the orbital period of Earth, so the satellite is always positioned over the same point on the equator. This makes geostationary satellites ideal for making repeated observations of a fixed geographical area centered on the equator. They can only view the whole earth disk below them, rather than a small subsection, and scan the same area very frequently (typically every 30 to 60 minutes), which makes them ideal for certain meteorological applications such as the cloud imagery seen on the television weather. However, geostationary satellites are unable to observe the polar regions and a network of five to six satellites is needed to provide global coverage. The geostationary orbit is ideal for images at the shorter wavelength (higher frequencies) found in the visible and infrared spectrum. The power and antenna size requirements for a microwave system to measure the Earth's surface from geostationary orbit is totally inadequate.

Polar-orbiting satellites operate in lower Earth orbits, where a typical polar-orbiting meteorological satellite is at an altitude of about 850 km. The lower altitude makes a polar-orbiting platform more suitable for the microwave frequencies needed to return OSVW. The antenna size and power requirements are realistically achievable for the moving platform with respect to the ocean surface supports the OSVW measurement technique. For reasons such as those mentioned above, the instruments for measuring OSVW are placed on polar-orbiting satellites. Therefore, we limit our consideration of next-generation instruments for measuring OSVW data to ones that will be placed on polar-orbiting satellites.

6.2 Current and Potential Future Ocean Vector Wind Measurement Systems: Status on Meeting the Next-Generation NOAA Requirements

The measurement of OSVW from space using microwaves has a long heritage and includes multiple measurement techniques, which can be broadly classified as active microwave scatterometry or passive polarimetric radiometry. Active scatterometers have a longer history, starting with the NASA NSCAT Ku-band scatterometer (*Freilich and Dunbar, 1999*), the NASA SeaWinds Ku-band scatterometer flown in the ADEOS-II and QuikSCAT missions, the ESA ERS-1 and ERS-2 C-band scatterometers (*Quilfen et al., 1999*), and the forthcoming ESA ASCAT C-band scatterometer (*Gelsthorpe et al., 2000*). Recently, high-resolution wind *speed* estimates have been demonstrated using C-band synthetic aperture radar (SAR), although wind *direction* determination using SAR is still experimental (*Beal et al., 2003*). Passive polarimetric radiometry measurements of OSVW have been demonstrated by the WindSat mission (*Gaiser et al., 2004*), which was a precursor to the now cancelled NPOESS CMIS instrument (see http://www.ipo.noaa.gov/Technology/cmis_summary.html for more information).

The result of the NOAA requirements workshop is that remotely sensed OSVW are highly desirable to both the operational and research communities. However, the capabilities of current instruments do not match the ultimate desires of the user community. A result of the workshop was the generation of a consensus set of desired measurement requirements that should become the goals for the design of future operational OSVW measurement systems. These requirements are summarized in Table 6.1.1 below.

The requirements in Table 6.1.1 are more stringent than the measurement characteristics of present or currently planned ocean vector wind measurement (OVWM) instruments. Table 6.1.2 summarizes some of the key measurement characteristics of present and planned OVWM systems, together with a summary of the advantages and disadvantages of each technique.

Parameter	NOAA Requirements	Next-Generation Performance
All-weather capabilities	Accurate retrievals in cloudy or rainy conditions	Retrievals under cloudy and rainy conditions
Wind Speed Range	2m/s - 82.5 m/s	2 m/s - 55m/s (or greater?)
Wind Speed Accuracy (10 m/ 1 minute)	1m/s (2σ)	**Wind speed <7m/s:** <1m/s (2σ) at 2km resolution; <0.3 m/s (2s) at 12.5 km resolution. **Wind speed <15m/s:** <1.6m/s (2σ) at 2km resolution; <0.4 m/s (2σ) at 12.5 km resolution. **Wind Speed ~50 m/s:** ~10 m/s (2σ) at 12.5 km resolution (C-band)
Wind Direction Accuracy (2m/s - 5m/s)	20^o (2σ)	74^o (2σ) at 2km resolution. 28^o (2σ) at 12.5 km resolution
Wind Direction Accuracy (5m/s - 83m/s)	10^o (2σ)	<24^o (2σ) at 2km resolution. <6^o (2σ) at 12.5 km resolution
Grid Horizontal Resolution	2.5 km (1 km goal)	1 km - 5km horizontal resolution. Grid spacing 2km
Coastal Coverage	2.5 km (1 km goal)	1 km - 5km horizontal resolution. Grid spacing 2km
Revisit Time	6 hours (1-3 hour goal)	**1 Platform:** ~18 hours. **2Platforms:** ~9 hours
Data Latency	45-60 minutes from measurement product availability (15 minute goal)	**1 Polar Ground Station:** ~90 minutes for data download, 15 minute latency. **2 Polar Nort/South Ground Stations:** ~45 minutes for data download, 15 minutes latency.

Table 6.1.1. NOAA OSVW measurement requirements and expected JPL-proposed (*Rodrigez at al, 2006*) next-generation ocean vector wind mission performance.

System	Measurement Method	Swath/Average time between measurements	Spatial Resolution	Measurement Advantages	Measurement Limitations
QuikSCAT	Ku-Band Scatterometer	1800km/ ~18hours	12.5 km/ ~5km experimental	High resolution, long heritage, well calibrated and validated	Limited coverage in rain, saturation for wind speeds ~40 m/s
WindSat	Multi-frequency polarimetric radiometry	950 km (Common Swath)/ ~34hours	30 km	Able to detect rain, SST, good ambiguity resolution	Low spatial resolution, unproven performance at low wind speeds and high wind speeds
CMIS	Multi-frequency polarimetric radiometry	1700 km/ ~19hours	20 km	Able to detect rain, SST, good ambiguity resolution	Low spatial resolution, unproven performance at low wind speeds and high wind speeds
ASCAT	C-band scatterometer	2 x 500 km swaths (768 km nadir hole)/ ~32 hours	50 km	Good performance at higher wind speeds and under rainy conditions	Low spatial resolution, worse performance at low wind speeds
SAR Winds	C-band scatterometer with SAR processing	500km achieved with single satellite ScanSAR/ ~64hours	~300 m	Very high spatial resolution, good performance at high winds	Wind direction estimation still experimental, swath limited to ~500 km
MeoScat	Ku-Band Scatterometer	2900km/ ~11hours	>10 km	Better temporal sampling	Limited spatial resolution, limited coverage during rain, saturation at high wind speeds
Next Generation OVWM	Ku-Band Scatterometer, C-band Scatterometer, Multi-frequency polarimetric radiometer	1800km/ ~18hours	1km-5km Ku-Band, 12.5 km C-band, <20 kmradiometry	Combines advantages from other techniques	Higher data rate than real aperture scatterometer or radiometers

Table 6.1.2. Comparison among different OSVW measurement systems and the next generation OVWM.

A comparison of Tables 6.1.1 and 6.1.2 shows that existing OVWM concepts fail to meet the next-generation NOAA operational requirements for measurement revisit time and measurement spatial resolution by almost one order of magnitude. The measurement accuracy goal is currently being met up to moderate wind speeds at the 1σ (68 percent) level, but may not meet the NOAA 2σ (95 percent) requirement, especially for very high wind speeds.

Meeting the temporal sampling requirements is not feasible using a single spaceborne platform, due to Earth's curvature limitations. As an illustration of the typical revisit time limitations of different OVWM concepts, we present in Figure 18 the spatial revisit characteristics of various platforms and platform combinations. It is clear from Figure 18 that meeting the NOAA requirement for six-hour revisit times will require at least two, and probably three, independent platforms. Since meeting the measurement requirement is impossible with a single platform, we concentrate on meeting the other NOAA requirements and assume that in order to satisfy the needs of its user community, the next-generation OVWM system will ultimately consist of multiple platforms, suitably coordinated to minimize the measurement repeat interval.

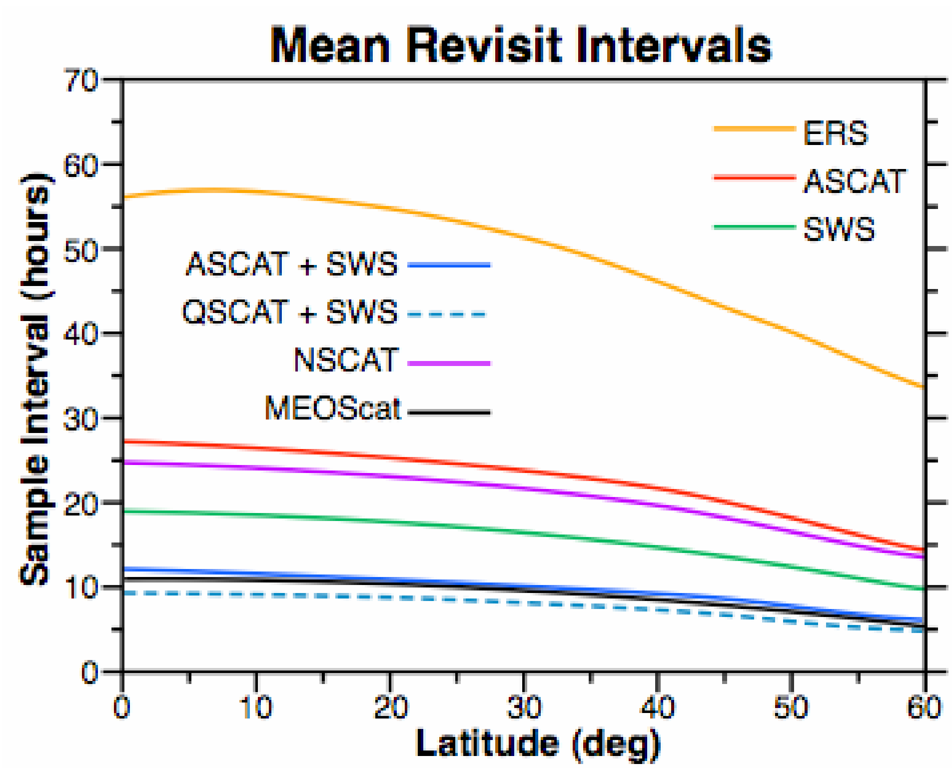


Fig. 18. Measurement revisit time for NSCAT (purple), ERS-1 and ERS-2 (orange), ASCAT (red), SeaWinds on ADEOS-II and QuikSCAT (SWS, green), and the MEOScat concept (black). Also shown are revisit times for combinations of two platforms.

In order to best meet the requirements set out in Table 6.1.1, while maintaining the high level of heritage and validation required for an operational mission with a moderate cost, we have decided to combine the best parts of the concepts shown in Table 6.1.2 into a single instrument, which we call the next-generation OVWM. This combination is feasible and cost effective due to the fact that all of the measurements can be made with a pencil-beam single-antenna reflector. This reduces the instrument cost significantly, while providing complementary measurements that are co-located (albeit with different spatial resolutions). The instrument concept includes both active and passive measurements. The components and the rationale for their inclusion are the following:

- **Ku-Band SAR Scatterometer:** Ku-band SAR scatterometry presents the only method for achieving high-resolution (1 km–5 km) spatial resolution with a moderate size antenna (2.5-m reflector).
- **C-Band Real Aperture Scatterometer:** C-band is required for minimizing rain effects, while providing accurate wind speed measurements at high wind speeds.
- **Multifrequency Polarimetric Radiometer Channels:** The inclusion of multiple radiometer channels is required for providing rain corrections and improving wind speed estimation and rain correction.

Simulated results of such a platform are compared to “reality” and the performance of the 12.5-km QuikSCAT output in Figure 19.

Finally, we conclude that the system proposed here, while not meeting all of NOAA’s next-generation requirements, is a cost-effective system for meeting many of them and providing a significant enhancement over current capabilities for those requirements which are not fully met. This combination of instrument and measurement heritage, moderate instrument cost, and a quantum increase in instrument performance make the next-generation concept presented here an attractive candidate for providing the first step towards an operational mission which will meet NOAA’s requirements.

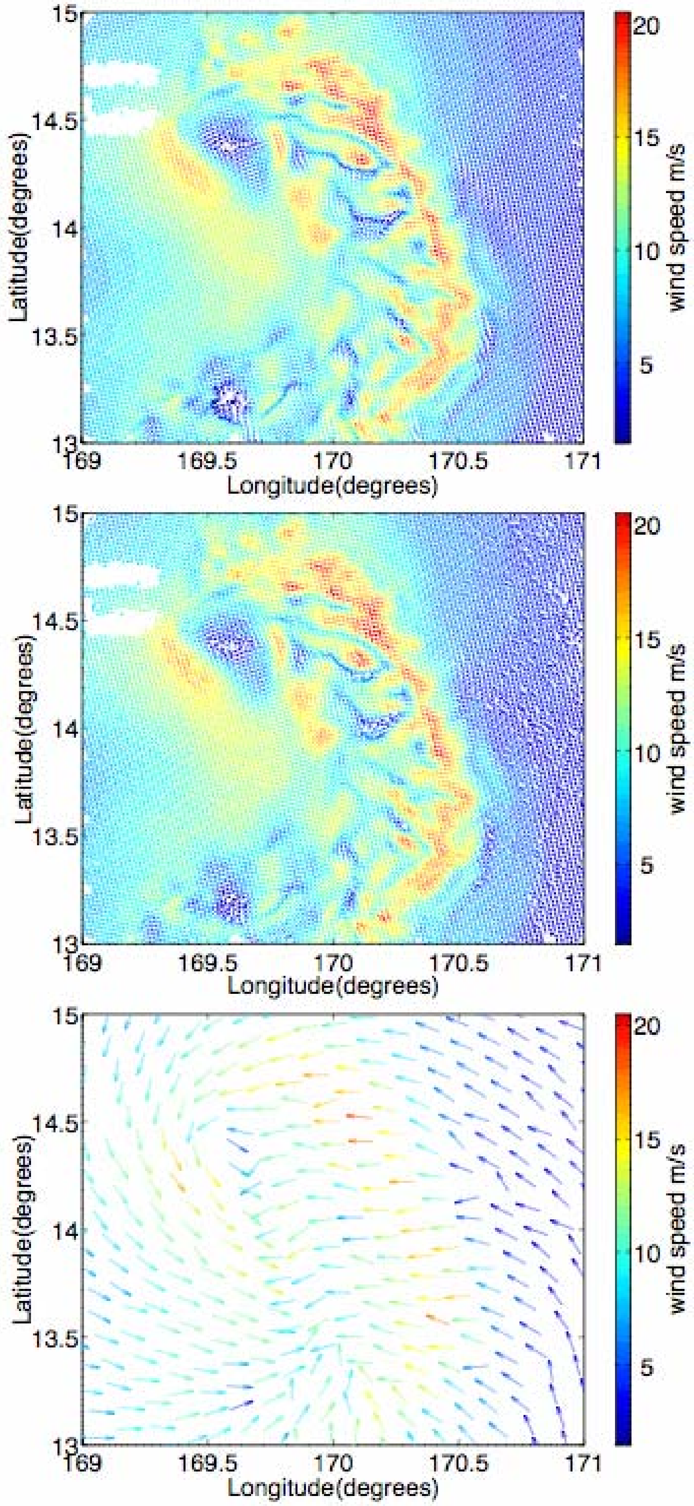


Fig 19: Ocean vector winds from a front produced by a squall. The top panel is the truth, the middle panel represents simulated results for the 2-km resolution OVWM system, and the bottom panel shows the capability of the present QuikSCAT system at 12.5-km resolution.

7 Summary

The NOAA workshop described here assembled a broad spectrum of users from NOAA's operational weather forecasting and warning communities to assess the operational utilization and impact of satellite ocean surface wind speed and direction measurements. While their operational roles and responsibilities were diverse, the fact that satellite ocean surface vector wind data were extremely valuable to their operational day-to-day responsibilities was unanimous. It was also clear that a gap exists between NOAA's actual OSVW requirements and those being provided by current and planned satellite missions. It was the strong consensus of the workshop participants that closing this gap was required to continue improvements in weather forecasting and warning capabilities. In summary:

- Satellite ocean OSVW fields are a critically important tool for the operational weather analysis, forecasting, and warning process within the marine environment.
- NOAA's operational requirements for OSVW data have advanced significantly over the past decade largely because of the real-world experiences gained by utilizing research satellite missions of opportunity.
- Present NOAA operational OSVW requirements are not met by present or planned satellite OSVW missions.
- NOAA's operational OSVW requirements are now closer to the OSVW objectives stated in the NPOESS IORD II, and the IORD II thresholds are no longer adequate to meet these operational requirements.
- NOAA's operational OSVW requirements are definitely largely achievable based on recent efforts by leading remote sensing scientists and engineers.

Eight years after NOAA first began utilizing QuikSCAT OSVW for operational use, and more than three years after the launch of WindSat, the nation still has no firm plans for operational acquisition of adequate OSVW data. Now is the time to develop and execute a plan that addresses NOAA's present and future operational satellite ocean surface vector wind requirements.

8 APPENDIX A

8.1 Scatterometer Wind Vector Measurements

Satellite scatterometers are non-imaging radar instruments that transmit microwave pulses and measure the signal backscattered from the ocean surface. Changes in the wind velocity cause variations in the amplitudes and directional characteristics of centimeter-scale ocean surface roughness, which in turn modifies the backscattered signal. The theory of wind retrieval from satellite scatterometer measurements is therefore based on the interaction of electromagnetic waves with rough surfaces. It has been established that backscattering of microwaves from the sea surface for moderate wind speeds and incidence angles is dominated by resonant or Bragg scattering, i.e., the incoming electromagnetic radiation is in resonance with ocean waves of comparable wavelength. These waves are usually in equilibrium with the wind stress, increasing amplitude (increasing backscatter) as the wind speed increases. The measured backscatter (and hence the inferred effective orientation of the centimeter-scale waves) tends to be larger in the upwind and downwind directions, and smallest at crosswind. Therefore observed backscatter contains information about wind ***velocity*—**both speed and direction (*Naderi et al., 1991*).

Scatterometer-derived winds have been available to the operational weather forecasting community for various periods over the last 10 years. The narrow, 500-km wide swath of the European Space Agency's European remote sensing satellites (ERS-1 and ERS-2) limited use of these measurements, since only about 40 percent of the ocean surface was covered each day, and the revisit intervals at most ocean locations were many days or more.

The situation improved in 1996, with the launch of the NASA Scatterometer (NSCAT) onboard Japan's Advanced Earth Observing Satellite (ADEOS-I) (*Naderi et al., 1991*). NSCAT made SVW measurements in two 600-km wide swaths (separated by a 329-km nadir gap) and provided 90-percent coverage of the world's ocean areas within a two-day period. NSCAT also provided a wide range of retrieved wind speeds that extended well into the storm force category (> 48 kt). For the first time, forecasters were able to examine direct measurements of wind velocities over entire storm systems and to differentiate between gale and storm force winds (*Atlas et al., 2001*). Unfortunately, due to a catastrophic power failure, the ADEOS-I satellite ceased operation on June 30, 1997.

In response to the loss of NSCAT, NASA launched the Quick Scatterometer (QuikSCAT) mission in June 1999, with a SeaWinds scatterometer onboard. The QuikSCAT near real-time winds were accessible shortly after launch through Internet access. In October 2001, QuikSCAT winds were introduced to the operational National Centers Advanced Weather Interactive Processing System (NAWIPS) workstations (*desJardins et al., 1991*). The QuikSCAT satellite is in its eighth year of operation and the spacecraft, instrument, and ground system continue to function well and are meeting

NASA's research mission requirements. The NASA budget provides for continuing the QuikSCAT mission through FY2007.

Prior to QuikSCAT, marine forecasters were forced to base warnings and forecasts over vast ocean areas on a limited number of conventional observations, on satellite-measured cloud patterns associated with storms, and on predictions from poorly initialized numerical models. Although QuikSCAT was not designed as an operational mission, marine forecasters, data assimilation, and numerical weather prediction centers use winds measured by SeaWinds routinely in support of NOAA operational responsibilities. Remotely sensed ocean vector winds from the SeaWinds scatterometer onboard the NASA QuikSCAT satellite have become an important tool for the issuance of marine forecasts, warnings, and analyses.

The availability of QuikSCAT winds has demonstrated both the utility and the limitations of ocean surface vector winds in an operational environment. An initial evaluation of these winds at TPC/NHC has shown promise, especially in terms of providing a spatially consistent wind field over the Tropics, of which large areas are typically void of surface observations. However, the limitations of QuikSCAT winds are clearly evident when the winds of greatest operational concern are typically accompanied by rainfall that can degrade the quality of QuikSCAT winds (Huddleston and Stiles, 2000; *Draper and Long, 2004*), greatly complicating the interpretation of these winds by operational forecasters. It is our hope that by describing the benefits and shortcomings of the current platform, future platforms will be designed to improve upon the strengths of QuikSCAT and address the problems and needs outlined here and elsewhere in the literature (e.g., *Atlas et al., 2001; Chelton et al., 2006; Von Ahn et al., 2006*).

For extreme conditions, theoretical studies (e.g., *Donelan and Pierson, 1987*) suggest a high-wind saturation (the point at which the backscatter stops increasing with an increasing wind speed) in deriving winds from backscatter. Such limitations have been recently documented from airborne observations spanning wind speeds up to 65 m/s for both C- and Ku-bands and H and V polarizations (*Esteban-Fernandez et al., 2006*). These measurements clearly show that the ocean surface backscatter presents a decreased sensitivity at hurricane force winds. It is thus important to note that unless the right frequencies and polarizations are used, increasing the spatial resolution of the scatterometer measurements may not necessarily result in higher wind speeds being retrieved due to the saturation effect. It should also be noted that higher-resolution measurements will also aid in seeing through precipitation events that often occur on the scales of a couple of kilometers, as well as reduce possible biases introduced by sampling over wind speed gradients.

Table 8.1 lists all OSVW products currently available for operational use in NAWIPS or via the Web from QuikSCAT scatterometry measurements, their respective accuracies and land mask applied.

Table 8.1. Details of QuikSCAT measurement characteristics, wind speed accuracy, data display capabilities, and land mask.

QuikSCAT – Ku-Band Scatterometer				
Resolution	10-m neutral stability wind spatially averaged over the footprint			
	Wind Direction	Wind Speed	Data Display	Land Mask
25 km (standard operational product)	Std<20º for wspd>3 m/s	Std ~1.2 m/s for 3-40 m/s	NAWIPS, AWIPS, Web access	30 km of the coast
12.5-km (high-res operational product)	Std<20º for wspd>3m/s	Std ~1.3 m/s for 3-35 m/s	NAWIPS, Web access	20 km of the coast
5-km (ultra-high-res experimental product)	Std ~26º	Std ~1.58 m/s	Web access	17 km of the coast

8.2 Radiometer Wind Measurements

Passive microwave sensors measure the naturally emitted microwave energy from the ocean surface, which is in general partially polarized assuming an off-nadir viewing geometry. A calm ocean surface is highly polarized, with most of the signal coming from the vertically polarized electromagnetic field. As the wind speed increases, the surface roughness increases and the polarization state changes. Therefore, changes in the polarization state can be directly related to changes in the wind field just above the surface.

The first broad-swath, operational measurements of ocean surface wind speeds were acquired by the Special Sensor Microwave/Imager (SSM/I) flying onboard the Defense Meteorological Satellite Program (DMSP) series of satellites. Over the past 15 years, the DMSP program has launched seven spacecraft with SSM/I instruments. Typically, two or three DMSP spacecraft are operating simultaneously in coordinated orbits, providing reliable measurements of ocean surface wind speed, sea ice concentration and age, and atmospheric parameters such as total precipitable water (TPW) and cloud liquid water (CLW). However the SSM/I was not designed to (and cannot) retrieve the wind direction. SSM/I winds also have an upper retrievable limit within the gale warning category (less than 48 kt, or 24.5 m s-1) (*Von Ahn et al., 2006*). Therefore, forecasters using SSM/I wind speeds can only distinguish between the lowest warning category and nonwarning winds. Perhaps a larger hindrance is that SSM/I is not able to retrieve wind speeds in areas of liquid cloud and precipitation, which are of very high interest to marine forecasters as they often contain high winds (*Atlas et al. 2001*).

The WindSat instrument aboard the Coriolis satellite was launched on January 6, 2003 (*Gaiser et al., 2004*). WindSat is the first fully polarimetric spaceborne microwave radiometer specifically designed to demonstrate the capability of retrieving the ocean surface wind speed and direction from space. At an altitude of 845 km in a near-polar orbit, WindSat renders fore and aft swath measurements at five frequencies: 6.8, 10.7, 18.7, 23.8, and 37 GHz. Three of these channels (10.7, 18.7, and 37 GHz) are fully polarimetric, and the other two are V and H polarized channels that were included to estimate the contributions of both the atmosphere and the sea surface temperature.

The thermal emission measured by microwave polarimetric radiometers is fully described by four component radiometric Stokes vector. The first two components of the full radiometric Stokes vector are brightness temperatures of the vertically and horizontally polarized field components, and the last two components are in-phase and quadratic covariance between vertical and horizontal field components.

The full characterization of the ocean surface emission polarization state by WindSat is achieved by measuring the four-component, modified, Stokes vector at the three fully polarimetric channels: 10.7, 18.7, and 37 GHz. This configuration of frequencies and polarizations had been selected based on the known dependence of a set of key geophysical parameters for which WindSat was designed to observe: total precipitable water and cloud liquid water, and surface parameters such as sea surface temperature, wind speed, and wind direction. Measured microwave thermal emission from wind-induced ocean surface roughness shows a small but distinct signature with the respect to the wind direction relative to the radiometer's azimuth angle, especially in the third (termed U and measured as the difference between +/- 45° polarized channels) and fourth (termed V and measured as a difference between left- and right-hand circular polarization channels) Stokes parameters.

Availability of V- and H-pol brightness temperature measurements acquired at multiple frequencies allows simultaneous retrievals of atmospheric (cloud liquid water, water vapor, and rain rate) and surface parameters (wind speed and see surface temperature). In combination with third and fourth Stokes measurements that carry information about wind direction, full OSVW retrieval from WindSat data is possible (*Jelenak et al., 2004; Bettenhausen et al., 2006*). Although the third and fourth Stokes signals are relatively weak, they are highly insensitive to the influence of the atmospheric absorption and emission caused by atmospheric water vapor and clouds. However, the effect of precipitation on third and fourth Stokes parameters is still not well understood and presents a topic of ongoing research.

Accurate knowledge of the model functions for wind speeds above 20 m/s is still very limited, and although initial results from WindSat observations have greatly stimulated the research in the field of passive polarimetry, a great deal of work still needs to be performed to better understand and refine the retrievals for high wind speeds and in the presence of rain. Recent work by Adams et al. (*2006*) presents a first evaluation of the current WindSat wind speed retrieval algorithms applied to tropical cyclones. The authors show how the algorithm, originally developed for nonprecipitable atmospheres and at ocean surface winds below 20 m/s, is severely affected by heavy cloud cover and precipitation, and present several cases where errors in excess of 20 m/s appear within the storms rain bands. They also point out that "it is doubtful that the wind speed retrieval will ever improve" with the current models and algorithms, and "hope that a new algorithm might be developed."

Table 8.2 lists current performances of 50-km resolution WindSat EDR product that is currently available for operational evaluation. Experimental WindSat EDR product with resolution of 35 km is currently under evaluation and its performances are still not well understood. However, relatively low resolution and unavailability of retrievals in coastal waters due to the land contamination of the measurements signal are limiting factors in operational usability of OSVW obtained from passive microwave measurements.

Table 8.2. Details of WindSat measurement characteristics, ocean EDR product accuracies, data display capabilities and land mask.

WindSat – Fully Polarimetric Microwave Radiometer							
	10-m neutral stability wind spatially averaged and under clear sky conditions (defined when clw<$0.2mm^2$)						
Resolution	Wind Speed (m/s)	Wind Direction (deg)	SST (C)	Cloud Liquid (mm)	Total Precipitable Water (mm)	Ocean Rain Rate (mm/hr)	Data Display
50 km (standard product)	Std~0.8 within (3-20) range	Std~25° for wspd<6 m/s Sdt~17° for wspd >6 m/s	0.7° for (5-32)° (when both 6.8ghz and 10.7ghz measurements available) ~0.9° (with only 10.7ghz available)	std~0.03 within (0-2) range	std~0.91 within (0-50) range	std~1 within (0-30) range	NAWIPS Web
	All retrievals are available within ~75 km off the coast						

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10 List of Acronyms

ADAS	Data Analysis System
ASCAT	(EUMETSAT) Advance Scatterometer
AWIPS	Advance Weather Interactive Processing System
CMIS	Conical Microwave Imager Sounder
CPHC	Central Pacific Hurricane Center
DMSP	Defense Meteorological Satellite Program
DoC	Department of Commerce
DoD	Department of Defense
ECMWF	European Center for Medium-Range Weather Forecasting
EDR	Environmental Data Record
EMC	Environmental Modeling Center
ESA	European Satellite Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GEFS	Global Ensemble Forecast System
GFS	Global Forecast System
GOES	Geostationary Operational Environmental Satellites
HF	Hurricane Force
HYCOM	HYbrid Coordinate Ocean Model
IORD	Integrated Operational Requirements Document
IR	Infrared
JTWC	Joint Typhoon Warning Center
LAPS	Local Analysis and Prediction System
MetWatch	Meteorological Watch program at NOCC
MSAS	Mesoscale Surface Assimilation System
NAM	North American Mesoscale Model
NASA	National Aeronautics and Space Administration
NAWIPS	National Advance Weather Interactive Processing System
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NOCC	Naval Oceanographic Command Center
NPMOC	Naval Pacific Meteorology and Oceanography Center
NPOESS	National Polar-orbiting Operational Environmental Satellite Systems
NRL	Naval Research Laboratory
NSCAT	NASA Scatterometer
NWRA	NorthWest Research Associates
NWS	National Weather Service
OPC	Ocean Prediction Center
OSU	Oregon State University
OSVW	Ocean Surface Vector Winds

OVWM	Ocean Vector Wind Measurements
RTOFS_ATL	Real Time Ocean Forecast System–Atlantic
TAFB	Tropical Analysis Forecast Branch
TC	Tropical Cyclone
TPC	Tropical Prediction Center
SAR	Synthetic Aperture Radar
SFMR	Step Frequency Microwave Radiometer
SOLAS	Safety of Life At Sea
SSM/I	Special Sensor Microwave/Imager
WFO	Weather Forecast Office