Official Magazine of the AMRS Association

WaterObserver.org Spring/Summer 2001 / US$6.95

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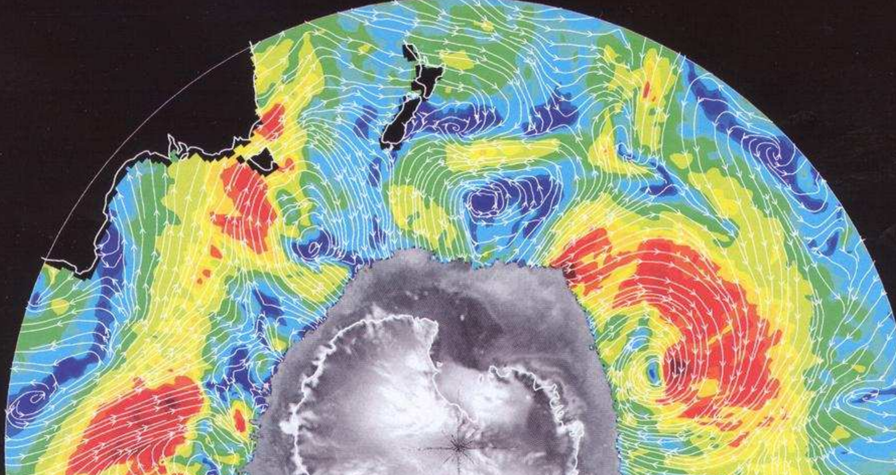

PLUS • Remote Sensing of Inland and Coastal Waters

Wind Over Troubled Waters

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Sailors understand both the importance and the difficulty in getting information on wind over oceans. Just a few decades ago, almost all ocean wind measurements came from merchant ships. Textbooks still describe global ocean wind distribution in sailor's terms: the calms of the doldrums and horse latitudes, the steady trade winds, and the ferocity of the Roaring Forties.

Today, there is a belief that operational numerical weather prediction will give us all the wind information we need, until a hurricane suddenly intensifies and changes course, or the delay of monsoon brings drought, or the Pacific trade wind collapses before an El Nino.

When prediction fails and disaster hits, we remember that numerical weather prediction depends on models which are limited by our knowledge of the physical processes and the availability of data.

Spaceborne microwave scatterometers are the only proven instruments that will give us real measurements of ocean surface wind vector (both speed and direction) under clear

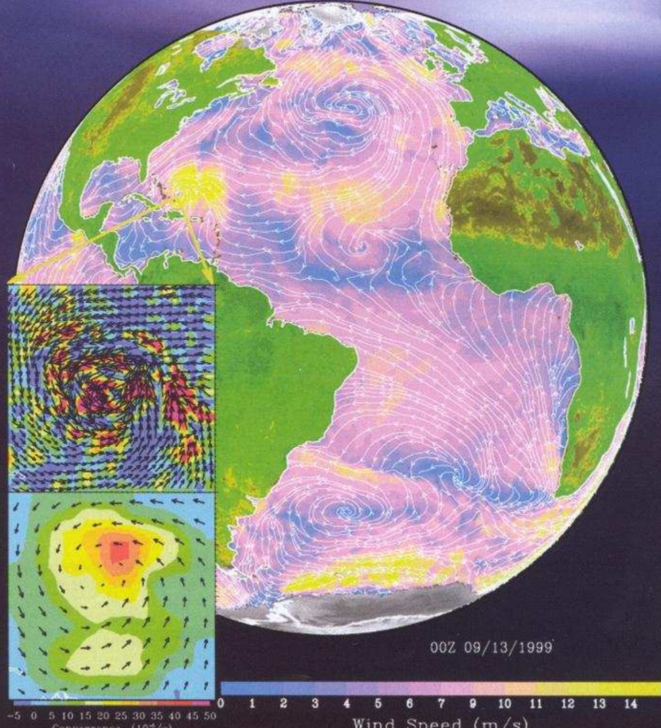

Figure 1. *White streamlines indicating wind direction are superimposed on the color image of wind speed, derived from objective interpolation of the observations by Quikscat. Normalized backscatter coefficients measured by the same instrument over land and Antarctica are also added. In the inserted figures, black arrows representing wind vectors are superimposed on the color image of wind convergence, derived from Quikscat (upper) and from Eta model (lower).*

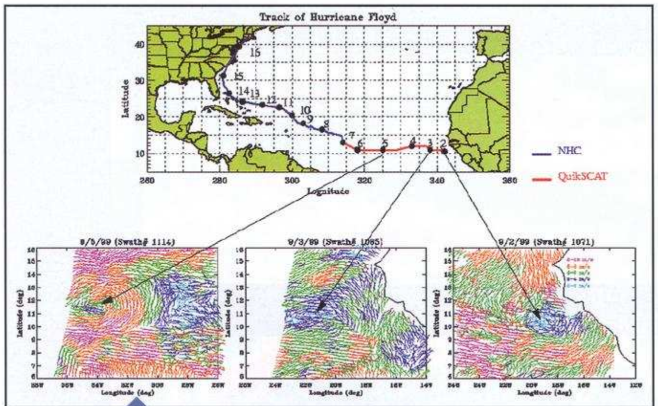

Figure 2. *Track of Hurricane Floyd issued by the National Hurricane Center and revealed by Quikscat.*

and cloudy conditions, day and night. They give us not only a near-synoptic global view, but details not possible using numerical weather prediction models. Such coverage and resolution are crucial to understanding and predicting the changes of weather and climate.

Hurricane Floyd

All the global, classical wind features displayed in Figure 1 were produced from one day of observations by the scatterometer on the Quikscat satellite, clearly demonstrating its capability for global coverage. The North Atlantic is dominated by a high pressure system, whose anticyclonic (clockwise) flow creates strong winds blowing parallel to the coast of Spain and Morocco, implying strong coastal upwelling in the ocean. Hurricane Floyd, with its high winds (yellow) is clearly visible west of the Bahamas. Tropical depression Gert is forming in the tropical mid-Atlantic (as an anticlockwise spiral) and will develop into a full-blown hurricane later. Because the atmosphere is largely transparent to microwaves, Quikscat was able to cover 93% of the global oceans, under both clear and cloudy conditions, in a single day.

Quikscat's ability to cover a large surface area in a relatively short period of time results in the synoptic view of the ocean. The spatial resolution of its data also provides detailed descriptions of small and intense weather systems, like Hurricane Floyd. The insert in Figure 1 shows that Quikscat's 12.5 km spatial resolution allows the delineation of surface wind convergence associated with the multiple rain bands of Hurricane Floyd. The insert also shows that the winds from the Eta model are not even close to being able to resolve such rain bands. Eta is a regional numerical weather prediction model producing operational wind products with the highest available spatial resolution (40 km). Wind convergence is important because it feeds water vapor to the hurricane; as the water vapor rises, it condenses, releases latent heat, and fuels the hurricane.

On 13 September 1999, Hurricane Floyd turned north. Its strength and proximity to the Atlantic coast caused the largest evacuation of citizens in U.S. history. Landfall of Hurricane Floyd three days later resulted in severe flooding and devastation in the Carolinas. The National Hurricane Center had declared Floyd as a tropical depression on 7 September 1999. Two days earlier, Quikscat had already revealed the surface vortex (close circulation) with wind speed meeting the criterion of tropical depression (Figure 2). Quikscat data were available to track the surface vortex all the way back to 2 September 1999 near the African coast. Because such vortices, in their early stages, are too small to be resolved by operational numerical weather prediction, and have no clear cloud signal, the scatterometer, with its high spatial resolution, is the best means, if not the only means, of early detection of hurricanes and the study of their genesis.

The Hawaiian Islands

The subtropical Pacific should be monotonous. The trade winds blow steadily from east to west, and so flows the North Equatorial Current. Only the Hawaiian Islands break this steady flow. According to conventional theories and observations, the wind wakes caused by the islands should dissipate within 300 km downstream, and should not be felt in the western Pacific. By sacrificing temporal resolution for high spatial sampling, the wind wake, consisting of low winds behind the islands and the strong winds through the gaps, are clearly visible in Quikscat data, within 300 km west of the islands (Figure 3). The fine resolution of Quikscat also reveals a persistent wind pattern to the west, composed of alternate high and low wind streaks, and lines of positive and negative curl of wind stress. This pattern stretches a few thousand kilometers from the western side of the Hawaiian Islands to beyond Wake Island in the western Pacific. The operational global numerical weather prediction products (100 km spatial resolution) cannot resolve the mechanical wakes around the Hawaiian Islands, and the 'long wake' far to the west has never been clearly identified in numerical weather prediction winds.

Wind stress curl usually creates higher and lower sea levels and geostrophic currents in the ocean. The Topex/Poseidon altimeter [a joint U.S. / France altimetry satel-

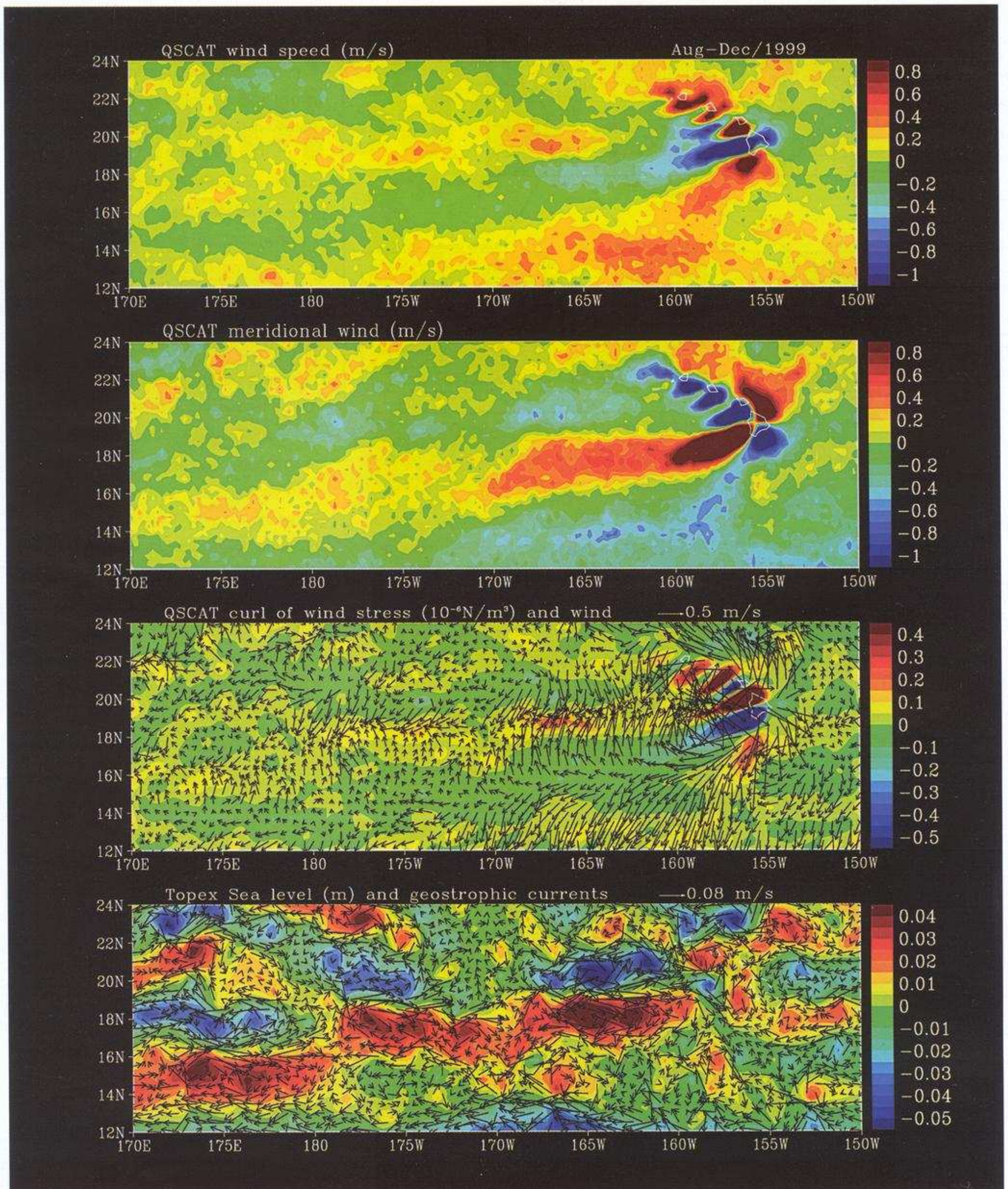

Figure 3. *Wind speed, meridional wind component, and wind vector superimposed on curl of wind stress derived from the first five months of QuikSCAT observations are shown with the sea level and geostrophic current changes derived from Topex/Poseidon observations over the same period. The meridional running-mean representing the large scale gradient has been removed from the data.*

lite - ed.] shows bands of positive and negative sea level changes, implying cyclonic and anticyclonic current gyres with an eastward geostrophic current between them at 19° N; the current should be continuous from the western Pacific to the Hawaiian Islands. Data from the TMI sensor [a microwave sensor on the U.S. / Japan Tropical Rainfall Measuring Mission satellite - ed.] reveal a narrow band of warmer water and enhanced atmospheric convection (high cloud water) at the position of the geostrophic current, probably resulting from heat advection from the west. Quikscat also observes surface wind convergence and vorticity associated with the warm water and convection. The long wake revealed by Quikscat may be sustained by positive feedback between the ocean and the atmosphere. This narrow gap amidst westward flowing wind and current, which may have aided the ancient eastward migration of Polynesia across half of the Pacific, has never been viewed by a single system until now.

Antarctica

The deficiencies of numerical weather prediction models, which are caused by lack of knowledge and data, are most evident in the remote oceans around Antarctica. Here, space-based wind measurements would have the strongest impact. Quikscat reveals three groups of intense storms (standing atmospheric waves) surrounding Antarctica, which are associated with three maxima of sea ice extent, as shown in Figure 4. The positions of the atmospheric waves and sea ice extent shift together during Austral winter, thus supporting the postulation of positive feedback between wind pattern and the sea ice extent maxima. The sea ice extent maxima provide favorable conditions for cyclogenesis in the open ocean. The wind-ice coupling appears to be most prominent during the La Nina episodes (1996 and 1999) covered by Nscat and Quikscat, and during Austral winters. The figure demonstrates the capability of scatterometers in monitoring not only ocean surface winds, but also sea ice characteristics and extent.

Scatterometer Missions

The principles of scatterometry have been described in many publications. A summary is given at http://airsea-www.jpl.nasa.gov/scatterometer.html. The past decade has seen continuous improvement to the coverage and resolution of ocean surface winds.

A C-band (5.3 GHz) scatterometer was launched on the first European Remote Sensing (ERS-1) satellite in 1991, and it was followed by an identical instrument on ERS-2, launched in 1996. The ERS scatterometers scan a 500 km swath on one side of the satellite, providing winds over 41% of the global ocean daily. The backscatters have 50 km spatial resolution but are sampled at 25 km.

Nscat, the NASA Ku-band (13.9 GHz) scatterometer, was launched in 1996 on the Japanese spacecraft Midori. The six fan-beam antennas provided 600 km swaths on

Figure 4. *See magazine cover for image. The gray scale image shows various kinds of ice in Antarctica. The landmass is outlined by the white line. The gray area outside the landmass is occupied by sea ice. Outside of the ice, white streamlines representing wind directions are overlaid onto the color image of wind speed distribution. The map (including both ice and wind) was produced from one day of Quikscat observations.*

both sides of the spacecraft, covering 77% of the global ocean at 25 km resolution daily. The unexpected destruction of the solar array caused the early demise of Nscat, after returning nine months of data.

NASA launched Quikscat, a Ku-band scatterometer, in 1999. It uses pencil-beam antennas in a conical scan and has a continuous 1,800 km swath that covers 93% of the global ocean in a single day. The standard wind product has 25 km spatial resolution, but special products with 12.5 km resolution for selected regions have been produced. The superior coverage offered by Quikscat over previous scatterometers is obvious in Figure 5. Uniformly gridded wind vectors from all these scatterometers can be accessed on line through http://airsea-www.jpl.nasa.gov/seaflux.

Requirements and Perspectives

Advances have been made with the four scatterometers launched in the past decade, but continuous effort is still needed to meet scientific requirements. The time scales of the inertial period in the mid-latitude oceans, and diurnal changes in tropical oceans, set the highest frequency requirements for measuring ocean surface wind. Record length requirements are set by the importance of continuous and consistent records over the life cycles of climate anomalies, from interannual to decadal.

Spatial resolution requirements have been largely driven by the resolution of hurricane structure and coastal ocean upwelling. Even from the vantage point of space, no single polar orbiting instrument can monitor ocean surface winds with sufficient resolution, coverage and frequency, nor can any single instrument be expected to operate for the long period needed to acquire climate-relevant time series. To meet these needs, a constellation of scatterometers is required.

A scatterometer identical to Quikscat is scheduled to be launched in February 2002, on the Japanese spacecraft ADEOS-2. If there is sufficient overlap between the operations of the two identical scatterometers, the importance of high frequency wind forcing on the ocean can be demonstrated.

The European Space Agency is planning to launch a series C-band dual-swath advanced scatterometer (Ascat) on their operational polar meteorological platform "METOP", starting in December 2005. It is crucial that the U.S. maintains the wide swath scatterometers after ADEOS-2 for continuous monitoring of high frequency ocean surface winds. A sensible way should be sought to move space-based scatterometers from research to operational agencies, while preserving the continuity and quality of a long data record.

All wind retrievals from past and present scatterometers suffer, at various degrees, from ambiguities in wind direction because of the sinusoidal relationship between the backscatter and wind direction. To mitigate the problem, radar measurements of the same area are made in different azimuth angles (angles between the wind and radar beam). Although Quikscat has a continuous scan, the azimuth angles are too close together at the outer swath and too far apart near nadir, hampering selection of correct wind direction. Wind fields from operational numerical weather prediction have usually been used as initial field for the iterative direction-choosing procedures (nudging). The dependence of retrieved wind directional error on the nudging fields, however unlikely, has yet to be vigorously examined.

Rain drops in the atmosphere cause attenuation of backscatter return, and they also distort the ocean surface. Due to insufficient validation data, the relationship between backscatter and wind vector under heavy precipitation is less well established.

Slight modification of the Quikscat instrument to receive cross-polarized backscatter, in addition to co-polarized ones will provide polarimetric capability that theoretically will eliminate the directional ambiguitiy problem. Wind vectors can then be retrieved with uniform accuracy across the swath independent of nudging wind field. Polarimetric scatterometry also has the potential of separating the rain effect in the atmosphere from that at the ocean surface, allowing improved wind retrieval under rainy conditions. It also does not require full circular scan and may ease the accommodation requirement on operational spacecraft. ■

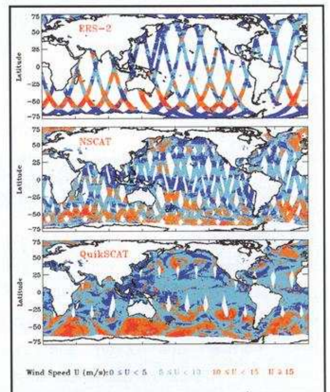

Figure 5. *Typical daily coverage by the scatterometer on ERS-2 (upper), Nscat (center) and Quikscat (lower).*

Acknowledgments

This study was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration. Xiaosu Xie and Hua Hu of JPL helped in data analysis and in preparation of all the figures. The high resolution winds over Hurricane Floyd and the backscatter data over land and ice were produced by Simon Yueh of JPL and David Long of Brigham Young University. Figures 3 and 4 are preliminary results of joint studies by the author with Shangping Xie of University of Hawaii and Xiaojun Yuan of Columbia University respectively. Simon Yueh and Wu-yang Tsai of JPL kindly advised on polarimetric scatterometry.