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Spaceborne Scatterometer and Scientific Applications

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Introduction

Just a few decades ago, almost all ocean wind measurements came from merchant ships; the sparcity of which over the global ocean is well known. Today, many citizens believe that operational numerical weather prediction (NWP) 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, then we remember that NWP 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 and cloudy conditions, day and night. In this paper we will briefly describe satellite scatterometry and give an overview of some of the scientific applications

Principles of scatterometry

The scatterometer sends microwave pulses to the earth's surface and measure the backscattered power from the surface roughness. The roughness may describe characteristics of polar ice or vegetation over land. Over the ocean, which covers over three−quarters of the earth's surface, the backscatter is largely due the small centimeter waves on the surface. The idea of remote sensing of ocean surface winds was based on the belief that these surface ripples are in equilibrium with the local wind stress. Based on measurements in an aircraft experiment in the seventies, Jones et al. [1978], confirmed that, at incident angles greater than 20°, the backscatter coefficient increases with wind speed. They also demonstrated the anisotropic characteristics of the scattering. The backscatter depends not only on the magnitude of the wind stress but also the wind direction relative the direction of the radar beam. Because the backscatter is symmetric about the mean wind direction, observations at many azimuth angles are needed to resolve the directional ambiguity. The capability of measuring both wind speed and direction is the major uniqueness of the scatterometer. The past decade has seen continuous improvement to the coverage and resolution of ocean surface winds.

Scatterometer Missions

NASA launched a Ku−band (14.6 GHz) scatterometer on the Seasat Mission in June 1978. Four fan−beam dual−polarized antennas, oriented at 45° and 135° to spacecraft subtrack, illuminate two 500−km swaths, one on each side of the spacecraft, providing wind vectors at 50−km resolution. However, only one side was in operation most of the time, covering less than 40% of global ocean daily. The two orthogonal azimuth angles were not able to resolve the wind direction unambiguously. Seasat failed in October 1978.

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 the ERS−2 launched in 1996. The ERS scatterometers scan a 500−km swath on one side of the satellite, and measure at three azimuth angles, providing winds over only 49% 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 GH) scatterometer, was launched in 1996 on the Japanese spacecraft Midori. The six fan−beam antennas provide 600−km swaths on both sides of the spacecraft, covering 73% of global ocean at 25−km resolution daily. The unexpected destruction of the solar array caused the early demise of NSCAT, after returning 9 months of data.

NASA launched QuikSCAT, a Ku−band scatterometer with new design, 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. Uniformly gridded wind vectors from all these scatterometers can be accessed on line through http://airsea−www.jpl.nasa.gov/seaflux.

Detailed Structure of Tropical Cyclones

Scatterometers provide not only global synoptic coverage, but also detailed structure of marine weather systems, such as hurricanes and typhoons. Hawkins and Black [1983] validated the accuracy of wind retrieval at gale−force for Seasat. They were able to demonstrate that the advisories from hurricane centers consistently overestimate the radius of gale−force winds in tropical cyclones and wrongly portrait the symmetry of the wind distribution, when compared with scatterometer wind fields. Hsu and Liu [1996] were able to derive the gradient of geostrophic wind and pressure field around tropical cyclone Oliver, from ERS−1 scatteormeter winds using a boundary layer model and a gradient wind formula, and the results are more realistic than operational NWP. Liu and Chan [1999] studied the size distribution of tropical cyclones using the vorticity fields derived from ERS scatterometers. Liu et al. [1997] used both NSCAT winds and the integrated water vapor from the Special Sensor Microwave Imager (SSMI) to study the transition of Typhoon Tom from a tropical warm−core system to a mid−latitude baroclinic storm. Chu et al. [1999] showed that NSCAT winds associated with Typhoon Ernie generated more realistic ocean responses in an ocean general circulation model (GCM) than winds from operational NWP. Yueh et al. [2001] developed a special algorithm to retrieve wind vectors under the intense winds and high precipitation conditions of tropical cyclones.

Tropical cyclones are devastating when they are accompanied by strong winds and heavy rain. QuikSCAT and Tropical Rain Measuring Mission (TRMM) provide the opportunity to observe both wind and rain in typhoons prior to landfall. Liu et al.

[2000a] used the two sensors to demonstrate the interplay between the dynamics and the hydrologic balances of Hurricane Floyd. The high spatial resolution of ocean surface winds measured by QuikSCAT improves computation of moisture transport, the vertical profiles of moisture sink and diabatic heating, and the difference between evaporation and rain−rate at the surface. The results were validated by the observations of surface rain and rain profiles by TRMM.

In 1999, Hurricane Floyd caused the largest evacuation of citizens in U.S. history. Landfall of Hurricane Floyd on 16 September resulted in severe flooding and devastation in the Carolinas. The National Hurricane Center 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. QuikSCAT data were available to track the surface vortex all the way back to 2 September 1999 near the African coast [Liu, 2001]. Because such vortices, in their early stages, are too small to be resolved by operational NWP and have no clear cloud signal, the scatterometer, with its high spatial resolution, is the best mean (if not the only mean) of early detection of hurricanes and the study of their genesis. Early detection of tropical cyclones by QuikSCAT in the
1999 season was demonstrated by Katsaros et al. (2001).

Antarctic Wind−ice Interaction

The deficiencies of NWP models (caused by lack of knowledge and data) are most evident in the remote oceans around Antarctica. Here, spacebased wind measurements would have the strongest impact. Using monthly NSCAT data, Yuan et al. [1999] revealed three groups of intense storms (standing atmospheric waves) surrounding Antarctica, which are associated with three maxima of sea ice extent (SIE). The positions of the atmospheric waves and SIE shift together during Austral winter, thus supporting the postulation of positive feedback between wind pattern and the SIE maxima. The high−resolution QuikSCAT data show the persistence of this relation even in daily time scales [Liu, 2001]. The SIE 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 [X.Yuan, personal communication]. Scatterometers can monitor not only ocean surface winds, but also sea ice characteristics and extent.

El Nino Effects on Intraseasonal and Decadal Changes

Scatterometer data have help to monitor the Trade Winds, the collapse and strengthening of which are believed to cause El Nino and Southern Oscillation (ENSO). Liu *et al.* [1995] demonstrated the relation between westwind anomalies, propagation of Kelvin waves, and subsequent warming of the equatorial Pacific, through analysis of satellite data and simulation by ocean GCM. Liu et al. [1998] postulated ENSO teleconnection and multiscale interaction by relating intraseasonal westwind anomalies to the interannual phenomenon of ENSO, and to movement of the decadal temperature dipole off the coast of the U.S. The relation between ENSO and subtropical ocean temperature dipole was supported in a long−term (over 50 years) simulation by the UCLA coupled ocean−atmosphere model [Yu et al., 2000]. Chen et al. [1999] demonstrated scatterometer winds, when used as initial conditions, would drastically improve the ENSO forecasts. The relation between Asian cold surge and westwind anomalies was found to be governed by the movement of warm pool during ENSO, using scatterometer data [Yu et al., 2001]. The multiscale interaction related to ENSO will be summarized in this study.

Tropical Instability Waves

Tropical instability waves (TIW) were best observed by radiometers on geostationary satellites as meanders of the temperature front between the cold upwelling water of the Pacific equatorial cold tongue and the warm water to the north. The waves propagate westward, with periods of approximately 30 day, wavelength of 1100 km, and phase speeds of 0.5 m/s. Xie et al. [1998] identified TIW in the wind variations observed by the radar scatterometer on the European Remote Sensing (ERS−1) satellite. Using data from QuikSCAT and TRMM, Liu et al.[2000b] show that the wind vectors propagate with sea surface temperature and atmospheric water vapor in a coherent manner. The phase differences between oceanic and atmospheric parameters confirm the hypothesis that the coupling is caused by buoyancy instability and mixing in the atmospheric boundary layer. Hashizume et al. [2001] found similar coupling south of the equator in the Pacific and in North Atlantic, and TIW exerts influence in the Intertropical Covergence Zone. Polito et al. [2001] found current effect on scatterometer winds and meridional heat advection in TIW. In a 53−year long simulation by coupled ocean−atmosphere GCM. Yu and Liu [2001] described the seasonal and interannual ocean−atmosphere coupling of the TIW.

A Break in Trades from the western Pacific to Hawaii

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 knowledge 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.

The fine resolution of QuikSCAT also reveals, for the first time, a persistent wind pattern to the west, composed of alternate high and low winds streaks, and lines of positive and negative curl of wind stress (CWS) [Liu, 2001]. This pattern stretches a few thousand kilometers from the western side of the Hawaii Islands to beyond Wake Island in the western Pacific. The operational global NWP products (100−km spatial resolution) cannot resolve the mechanical wakes around the Hawaii Islands, and the long wake far to the west has never been clearly identified in NWP winds. The altimeter of Topex/Poseidon 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 western Pacific to the Hawaiian Islands. TRMM data reveal a narrow band warmer water and enhanced atmospheric convection (high cloud water) at the position of geostrophic current, probably resulted from heat advection from the west. QuikSCAT also observes surface wind convergence and vorticity associated with the warm water and convection.

The existence of eastward Subtropical Counter Currents in the western Pacific has been suggested by Japanese oceanographers and eastward Hawaiian Lee Currents have been observed near Hawaii by U.S oceanographers; the causes of these current systems have not been confirmed nor linked. Using QuikSCAT and TRMM, Xie et al. [2001] viewed this "long wake" as single system and postulated the it is sustained by positive ocean−atmosphere feedback. This narrow gap amidst westward flowing wind and current may have aided the ancient eastward migration of Polynesian across half of the Pacific.

Amazon and the Ocean Influence

Long and Hardin [1994] enhanced the spatial resolution of scatterometer observations to 4−5 km by signal processing techniques and mapped land vegetation. The map of backscatter power normalized to 40−degree incident angle over the Amazon produced from NSCAT data clearly distinguishes various vegetation, from tropical rain forest to woodland savanna, and to shrub. Areas of substantial commercial logging are revealed, as irregular woodland surrounded by homogenous rainforest is most interesting. By subtracting out the same normalized backscatter measured by the Seasat scatterometer 18 years ago, decadal changes are also revealed, including reservoir built and rainforest cleared/settled after Seasat.

Through climate model, Fu et al. [2001] postulated the teleconnection between SST (in the tropical Pacific and Atlantic) and precipitation in the eastern Amazon. The coupling of daily Amazon rainfall measured by TRMM and QuikSCAT winds over the Atlantic at various time lags has also been examined [R. Fu, personal communication]. The integrated water transport in the atmosphere and the ocean surface evaporation is being mapped over the Atlantic with observations from QuikSCAT and TRMM, using techniques developed by Liu [1993]. They are used to understand the moisture transport between the Atlantic and the Amazon basin the cross−equatorial wind−evaporation−SST feedback in the Atlantic; these are the possible physical mechanism of the teleconnection.

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