Scatterometer Missions and Scientific Applications

W. TIMOTHY LIU and WENQING TANG
MS 300-323, Jet Propulsion Laboratory, 4800 Oak Grove Drive,
Pasadena, CA, 91109, USA.
Tel: (1) 818-354-2394; fax: (1) 818-393-6720; email:liu@pacific.jpl.nasa.gov

ABSTRACT

The past decade has seen continuous improvement to the coverage and resolution of ocean surface winds measured by spacebased microwave scatterometers. The large coverage of the scatterometer makes it the best instrument to provide global synoptic view of ocean surface wind vectors and the high spatial resolution also provides details structure of small marine storms. The principles of scatterometry and the scatterometer missions are summarized. Two examples of recent scientific applications making use of the improved capabilities are described. One application is the genesis of Atlantic hurricanes out of the monsoon shear zone off African coast, and the other is the relation between moisture advection from the ocean and rainfall in the Indian subcontinent. Future scatterometer technology is also discussed.
Keywords: scatterometer, winds, remote sensing, hurricanes, rain

1. 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 to 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. At incident angles greater than 20°, the backscatter coefficient increases with wind speed. The backscatter depends not only on the magnitude of the wind stress but also the wind direction relative to the direction of the radar beam. The capability of measuring both wind speed and direction is the major uniqueness of the scatterometer. Because the backscatter is symmetric about the mean wind direction, observations at many azimuth angles are needed to resolve the directional ambiguity. The past decade has seen continuous improvement to the coverage and resolution of ocean surface winds.

2. UP IN SPACE

The European Remote Satellite (ERS)-1 and -2 provided nine years of continuous wind data starting 1991, covering 40% of the global ocean daily. The backscatters measured have 50-km spatial resolution but are sampled at 25 km. The National Aeronautics and Space Agency (NASA) Scatterometer (NSCAT) covered 77% of global ocean at 25-km resolution daily. The unexpected destruction of the solar array caused the early demise of NSCAT in June 1997, after returning 9 months of data. NASA launched QuikSCAT in 1999. It 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. Instead of the fan-beam antennas used by all the scatterometer before, QuikSCAT uses pencil-beam antennas in a conical scan and has a continuous 1,800-km swath. In one decade, daily wind vector coverage increases from 41%, to 77%, then to 93%, and spatial resolution improves from 50km, to 25 km, and to 12.5 km. A review of scatterometer mission and applications is given by Liu [2002].

3. OUT OF AFRICA

In 1999, the National Hurricane Center declared Floyd a tropical depression (east of the West Indies) on 7 September. As shown in Fig. 1, QuikSCAT data were able to track the surface vortex all the way back to the shear zone in the monsoon trough off the African coast on September 2, 1999, almost a week earlier [Liu,

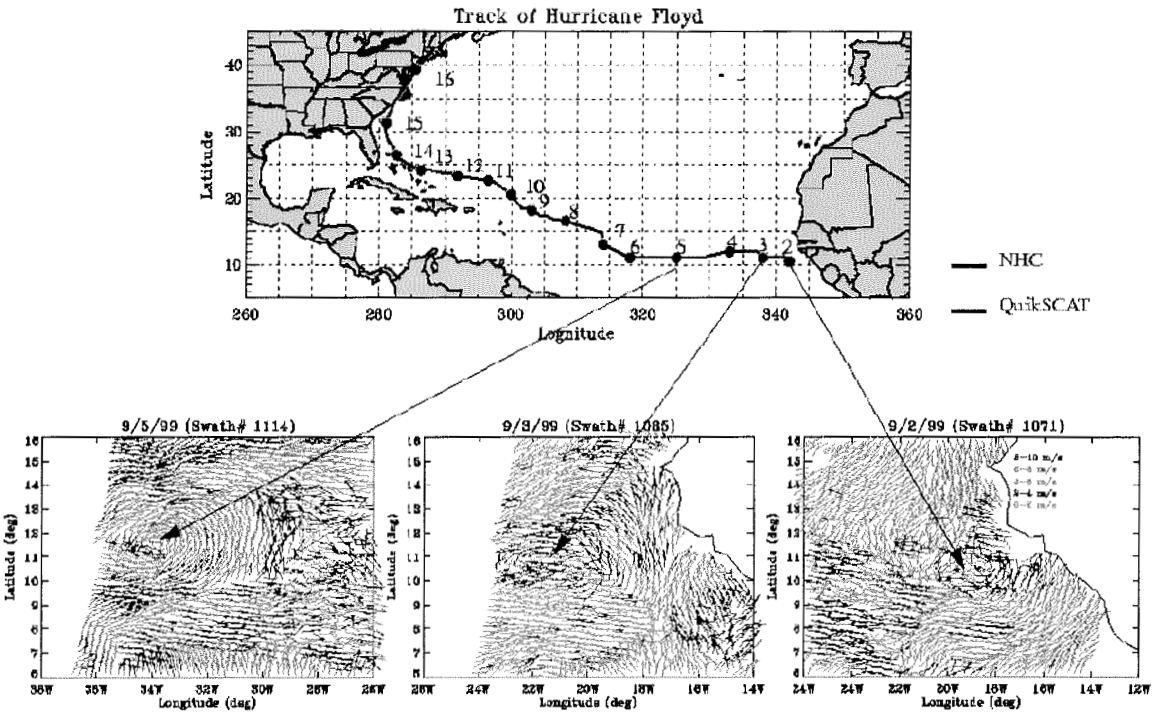

Fig. 1 Track of Hurricane Floyd issued by the National Hurricane Center and revealed by QuikSCAT

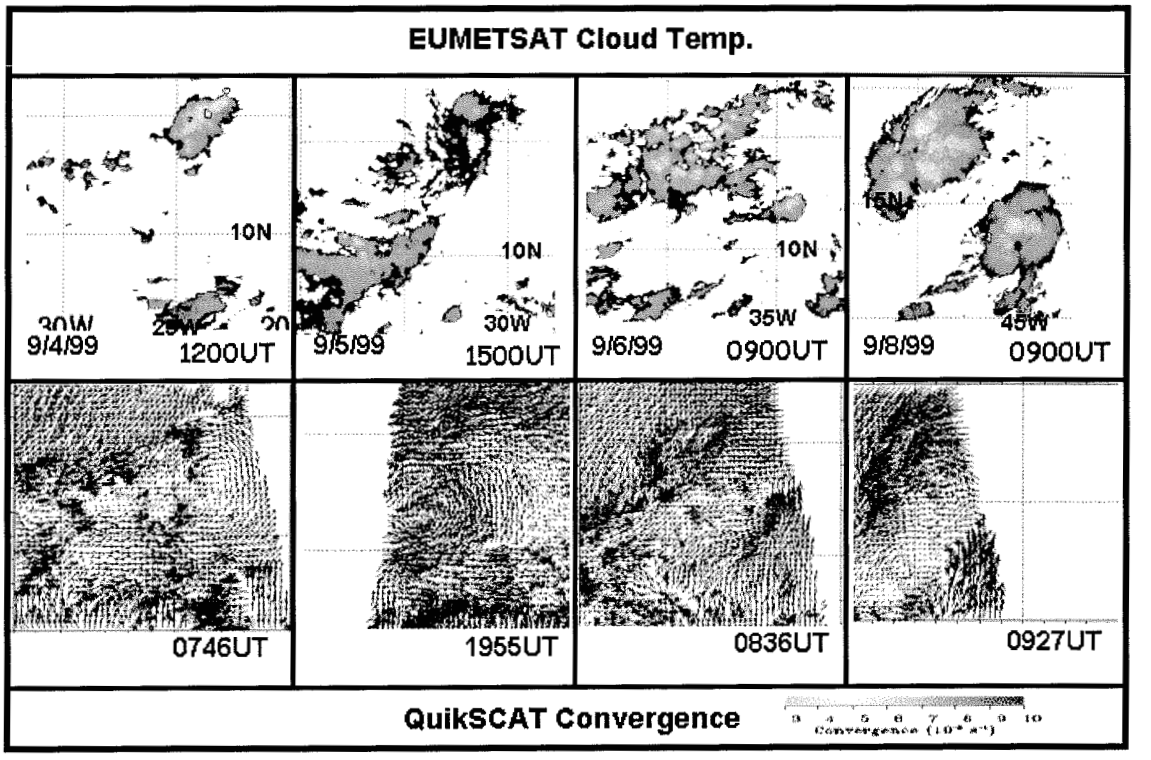

Fig.2 Comparison of EUMETSAT infrared images (top) and QuikSCAT surface wind vectors and convergence for the vortex that evolved into Hurricane Floyd.

2001]. Cyclogenesis (starting of the hurricane heat engine) requires sufficient inertial stability in the atmosphere, as reflected in a small Rossby radius of deformation, to retain the heat released by cumulus convection. A current theory [e.g. Simpson et al., 1997] suggests that the stability is achieved by mid-level vortex merging. After merging, the resultant mid-level vortex strengthens and thickens to reach the surface. The surface circulation, in turn, will feed moisture and ocean energy into the cyclone. In the early stages, the scattered cloud patterns revealed by weather satellite (Fig. 2) do not appears to be related to surface vortex and cannot dispel the doubt on whether surface vortex plays any role in the mid-level vortices merging that happens much later in the genesis of Floyd. A careful examination of the distribution of surface wind convergence, however, show that, even at the early stages, the cloud patterns (mid-level vorticity) are collocated with surface wind convergence associated with the surface wind vortex (Fig. 2). The high resolution surface wind vectors from QuikSCAT provide a good opportunity for a more objective examination of the relation between surface circulation and mid-level vorticity, in the genesis of hurricanes[Ritchie et al., 2002].

4. INTO INDIA

The vertically integrated moisture transport (**MT**) is

$$\mathbf{MT} = \frac{1}{g}\int_0^{p_s} q\,\mathbf{u}\,dp$$

where g is the acceleration due to gravity, p_s is the pressure at the surface, q and **u** are the specific humidity and wind vector at pressure level p. The computation of **MT** requires measurement of the vertical profiles of wind vector and humidity in the atmosphere, which traditionally come from aerological (rawindsondes) data. Over oceans, rawindsonde data are sparse. Liu (1993) proposed a method to estimate **MT**, using surface wind vector measured by the scatterometer and the vertically integrated water vapor (W) measured by microwave radiometer.

The method uses an equivalent velocity $\mathbf{u_e}$ defined by

$$\mathbf{u_e} = \mathbf{MT}/W$$

where

$$W = \frac{1}{g}\int_0^{p_s} q\,dp$$

The equivalent velocity is the depth-averaged wind velocity weighted by humidity.

Since W can be accurately measured by both the operational Special Sensor Microwave Imager (SSM/I) and Tropical rain Measuring Mission (TRMM) Microwave Imager (TMI), the problem of measuring **MT** is essentially the determination of $\mathbf{u_e}$. Spaceborne scatterometer could measure surface wind vector $\mathbf{u_s}$ over global ocean. We have developed a quantitative relation between $\mathbf{u_s}$ and $\mathbf{u_e}$. The varibility of humidity profile has been extensively studied by Liu et al. (1991) and the dominant mode of variability was found to peak at the top of the boundary layer. Heta and Mitsuta (1993), using W derived by Liu (1987) from the microwave radiometer on Nimbus-7

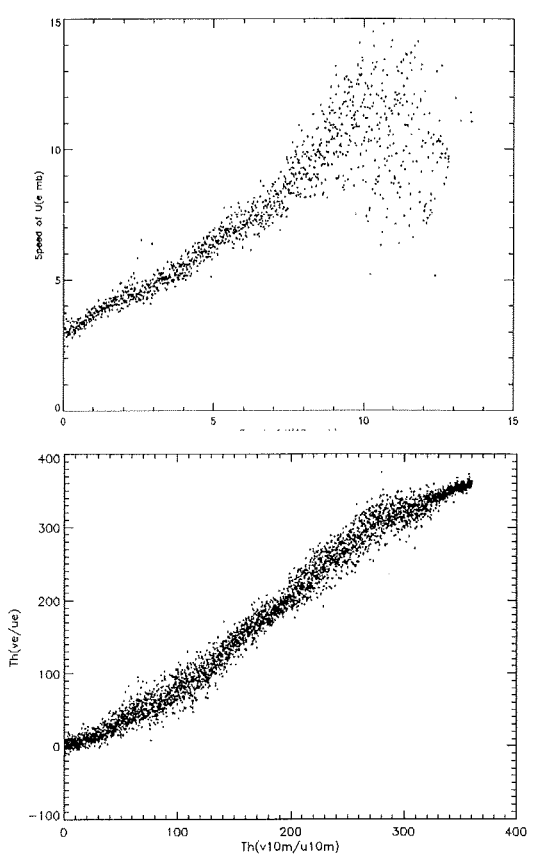

Fig. 3. Relation between the equivalent velocity for moisture transport and the 10-m wind velocity, from ECMWF data.

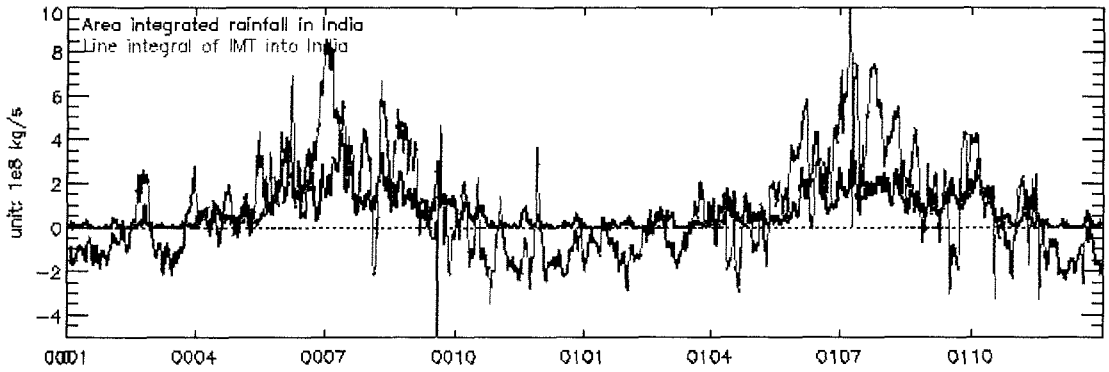

Fig.4 Line integral of vertically integrated moisture advection across the Indian coastlines of Arabian Sea and Bay of Bengal (blue) and the area integrated rainfall in India (black).

and using 850 mb cloud drift winds as $\mathbf{u}_e$, have satisfactorily estimated E-P in the tropical Pacific. The top of the boundary layer is approximately at 850 mb and wind at this level is closely related to surface level wind through similarity relations [e.g., Brown and Liu, 1982]. In the past, oceanographers used to get ocean surface wind stress by multiplying the geostrophic winds (derived from pressure gradient) by a constant factor and tuning them by a constant angle. Fig. 3 shows the close relation between $\mathbf{u}_s$ and $\mathbf{u}_e$ derived from ECMWF data. Statistical models between $\mathbf{u}_e$ and the 10 m level winds have been developed from ECMWF data using both multivariate regression and neutral network. The models have been validated with global rawinsonde data over oceans. The moisture advection from the Arabian Sea and Bay of Bengal is clearly related to the precipitation over the Indian subcontinent in Fig. 4. The moisture transport across the coastal lines into the subcontinent was estimated using QuikSCAT surface wind and TRMM integrated water vapor. To the first order, there is general agreement between the seasonal cycle of moisture advection and Indian rainfall, taking into consideration the northern boundary is not closed.

5. TOWARDS THE FUTURE

One of the drawbacks of present scatterometers is the wind-direction ambiguity. The backscatter is a cosine function of the azimuth angle. In a recent experiment, it was demonstrated the correlation between co-polarized and cross-polarized backscatter is a sine function of azimuth angle. By adding a receiver of cross-polarized backscatter to the scatterometer on QuikSCAT, the directional ambiguity problem can be mitigated [Tsai et al., 2000]. 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 wind direction. With polarimetric scatterometer, we can achieve uniform retrieval accuracy across the entire swath.

QuikSCAT is a real-aperture system which employs only range discrimination technique and the spatial resolution is limited by the antenna size. The present instrument uses a 1-m antenna, but we may have to double or triple the diameter to get sufficient spatial resolution. Another way to achieve higher resolution is to add synthetic aperture techniques to discriminate the illuminate scene in both range and Doppler, as proposed by Spencer et al. [2002] and others.

Historically, scatterometers of the European Space Agency (ESA) used the C-band (5 GHz), but NASA prefers the Ku-band (14 GHz). A higher frequency is more sensitive to shorter surface waves. The Ku-band is more sensitive to wind variation at low winds but is more subjective to atmospheric effects and rain contamination. There have been calls for multi-frequence scatterometer, which is sensitive to various part of ocean surface wave spectrum, for more than a decade [e.g. Huang et al., 1984]. It may mitigate the shortcomings of either C-band or Ku-band scatterometers.

ACKNOWLEDGMENT

This study was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration (NASA). It was jointly supported by the Ocean Vector Winds, Physical Oceanography, and Tropical Rain Measuring Mission Programs of NASA. Hal Pierce and Liz Ritchie kindly provided the Eumetsat cloud pictures.

REFERENCES

Brown, R. A., and W. T. Liu, 1982: An operational large-scale marine planetary boundary layer model. J. Appl. Meteor., 2, 261-269.

Heta, Y. and Y. Mitsuta, 1993: An evaluation of evaporation over the tropical Pacific Ocean as observed from satellites. J. Appl. Meteor., 32, 1242-1247.

Huang, N. E., C. L. Parsons, S.R. Long, and L.F. Bliven, 1984: A new type of overshoot phenomenon in wind wave development and its implications in remote sensing of the ocean. J. Geophys. Res., 89, 3679-3687.

Liu, W. T., 1987: El Niño atlas, Nimbus-7 microwave radiometer data. JPL Publication 87-5, Jet Propulsion Laboratory, 68pp.

Liu, W. T., 1993: Ocean Surface Evaporation. Atlas of Satellite Observations Related to Global Change, R.J. Gurney, J. Foster, and C. Parkinson (eds.), Cambridge University Press, Cambridge, 265-278.

Liu, W.T., 2001: Wind over troubled water. *Backscatter*, **12**, No. 2, 10-14

Liu, W.T., 2002: Progress in scatterometer application, *J. Oceanogr.*, **58**, 121-136.

Liu, W. T., W. Tang, and P. P. Niiler, 1991: Humidity profiles over ocean. J. Climate, 4, 1023-1034.

Ritchie, E., J. Simpson, W.T. Liu, C. Veldon, K. Brueske, and J. Halvorsen, 2002: A closer look at hurricane formation and intensification using new technology. *Coping with Hurricanes*. Chapter 12, R. Simpson, M. Garstang, and R. Anthes (eds.), Amer. Geophys. Union, in press.

Simpson, J., E. A. Ritchie, G. J. Holland, J. Halverson, and S. Stewart, 1997: Mesoscale Interactions in Tropical Cyclone Genesis. *Mon. Wea. Rev.*, 125, 2643-2661.

Spencer, M.W., W.-Y. Tsai, and D. G. Long, 2002: The application of combined range/Doppler discrimination techniques for high resolution measurements with a spaceborne pencil-beam scatterometer. Trans. Geoscience Remote Sensing, IEEE, in press.

Tsai, W.-Y., S. Nghiem, J. Huddelstgon, M. Spencer, B. Stiles and R. West, 2000: Polarimetric scatteromometer: a promising technique for improving ocean surface measurements from space. *IEEE trans. Geosci. Remote Sensing*, **38**, 1903-1921.