Can we obtain sea-surface flow information from satellite scatterometer winds ?

Kyung-Ae Park, Peter Cornillon[1], Jong Yul Chung, and Kuh Kim
School of Earth and Environmental Sciences, Seoul National University, Korea
[1]Graduate School of Oceanography, University of Rhode Island, USA

Abstract

A satellite scatterometer is a microwave radar sensor used to measure the backscattering at a sea surface. This instrument transmits radar pulses to the sea surface and measure the radar energy reflected back towards the source. Changes in wind velocity make sea surface roughness change and then affect on backscattered power. This gives us information of sea surface wind speed. Directions of wind vectors are acquired by multiple, collocated, and nearly simultaneous measurements. It should be noted that the scatterometer observes not the wind directly but the wind stress vector relative to the surface current. This suggests the possibility that the satellite scatterometer winds can include the effect of the surface current. This study shows the evidence that scatterometer measure surface wind stress, not surface winds and presents the velocity structure of oceanic warm and cold eddies.

1. Introduction

Scatterometers are radars used in oceanography to estimate vector winds at the ocean surface. They rely on reflected energy from capillary waves to estimate the wind speed and on multiple looks at different azimuthal angles to obtain a measure of the wind direction. The reflected energy from the various radar beams of the scatterometer are combined in an empirically derived model function to obtain the vector winds. To date four scatterometers have flown on satellites (SEASAT, ERS-1, ERS-2 and ADEOS) providing near global coverage every few days for the period during which the missions were operational.

Because capillary waves, the primary scatterers, are quite short they do not penetrate more than a few centimeters beneath the ocean surface, hence the wind vector is estimated relative to the movement of the upper meter or so of the water column. The effects of wind waves have, to a large extent, been accounted for in the model function since the model function has been empirically derived. This is not the case for ocean currents. The wind vector returned by the scatterometer is in fact the vector difference of the surface wind from the ocean surface current. In the following we demonstrate this with scatterometer (NSCAT and QuikSCAT) (JPL, 1998) data by examining the wind vector field over Gulf Stream rings.

Warm and cold core rings are ideal to study this effect both because of their large surface currents and because their horizontal spatial scales are large compared with the scatterometry footprint, but small compared with horizontal scales in the atmosphere. In addition, the velocity structure within horizontal warm core rings is relatively well known as a result of numerous research programs to study them and the water through which they move. Gulf Stream warm core rings result from meander crests that detach from the Gulf Stream. Surface currents in warm core rings are similar in magnitude to surface currents in the Gulf Stream, order 1 m/s at their maximum (Joyce and McDougall 1992). The inner core of the ring, which extends to approximately 50 km, the width of the Gulf Stream, is nearly in solid body rotation. The rate of rotation of warm core rings and their horizontal structures may be affected primarily by interactions with the Gulf Stream or the continental shelf after the ring has formed and to a lesser extent by dissipation within the ring. Figure 1 shows an example of a warm core ring as seen in the satellite-derived Sea Surface Temperature (SST) field of 10 June 1997 along with NSCAT winds measured on 10 June 1997.

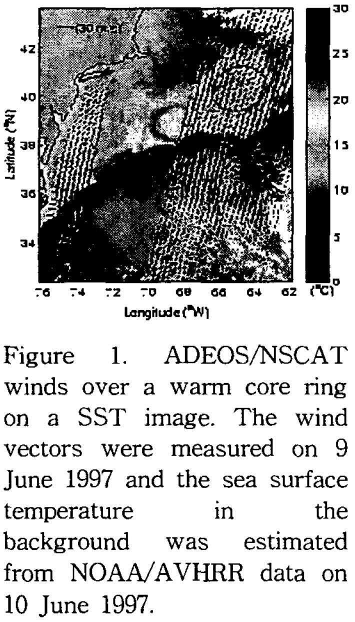

Figure 1. ADEOS/NSCAT winds over a warm core ring on a SST image. The wind vectors were measured on 9 June 1997 and the sea surface temperature in the background was estimated from NOAA/AVHRR data on 10 June 1997.

Of particular interest to this study is that regardless of the direction from which the wind is blowing, the surface current of the ring will be in the direction of the wind on one side of the ring and opposed to this direction on the other side of the ring assuming of course that the wind does not change direction significantly from one side of the ring to the other.

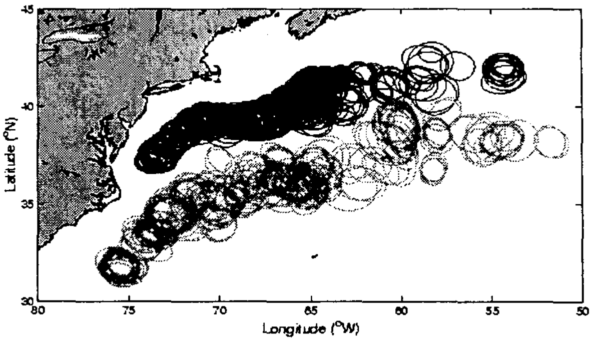

Figure 2. The location of Gulf Stream warm (black) and cold (gray) core ring observations used in this study. Each ellipse represents a fit to the outer contour of a ring observation manually digitized from an AVHRR-derived SST field.

2. Data Selection and Analysis

Three data sets were used in this study: AVHRR (Advanced Very High Resolution Radiometer)-derived SST fields (Cornillon et al 1987), 25 km NSCAT and QuikSCAT vector winds and Acoustic Doppler Current Profiler (ADCP)-derived ocean currents.

Data from two satellite-borne scatterometer missions have been used for this study: NSCAT (September 1996 through June 1997), and QuikSCAT (July 1999 through April 2000). The spatial resolution of both scatterometers is 25 km and the temporal sampling, although irregular depending on latitude and scatterometer design, is on the order of once per day at mid-latitude. The data used were obtained from the Jet Propulsion Laboratory in Pasadena, California. The uncertainty of the NSCAT data is on the order of 1.3m/s and 20° for wind speeds ranging from 1m/s to 18m/s (Freilich, 1999). The uncertainty of QuikSCAT is thought to be similar.

The SST data were used to select scatterometer passes that covered a ring as well as to locate the center of the ring. Gulf Stream rings are clearly visible in satellite-derived SST fields under cloud free conditions. For this study daily SST fields were used to locate the warm rings for the duration of the scatterometer mission. Initially all images in which a ring was clearly visible (i.e., not obscured by clouds) and not interacting with the Gulf Stream were identified. The locations of all digitized rings are shown in Figure 2; 439 warm core ring observations were made in the Slope Water north of the stream and 260 cold core ring observations were made in the Sargasso Sea south of the stream.

An accurate determination of a ring center is of importance because most of procedures herein to derive the azimuthal component of ring velocity are supposed to be performed in a rotating coordinate system based on a ring centroid. To do this, the ring boundary was first digitized by following thermal front surrounding the ring on a sea surface temperature image and the location coordinates were then subsequently retrieved in terms of latitudes and longitudes. The ring center was obtained by fitting an ellipse in a least square sense to the ring periphery determined subjectively. From each fitted ellipse, the orientation angle of ring as well as major and minor axis length were evaluated. The mean eccentricity of the rings is relatively so high about 0.5558 that we deployed an elliptic regime for deriving azimuthal velocity of a ring rather than a circular approach. In order to extract ring speeds from the scatterometer data we assume that the vector wind in the absence of the ring changes slowly over the area covered by the ring. Under such conditions, the residual wind vector field obtained by removing the background mean wind from the observed wind may yield the ring velocity field. For this study the background mean field was defined as mean of wind vectors right over a ring excluding the outside region. Clearly the assumption that the background wind field changes slowly will not always be the case. For example, in the vicinity if storms or meteorological fronts one would expect there to be large changes in the vector wind field over relatively short horizontal distances.

In order to eliminate such events from further analyses additional conditions should be imposed on the scatterometer winds. However, it is not easy to know whether wind vectors are in poor situation not enough to derive ring velocities because the meteorological condition and air-sea interactions over a warm core ring have not been well observed and studied. Accordingly, we devised a poor wind pass rejection procedure to testify if each wind is in bad condition violating our basic assumption as described earlier. The hypothesis to find good wind passes laying in a good atmospheric and oceanic situation is that the conditions could be defined from a statistical common characteristics of wind vectors in a well-made training data set of the scatterometer passes, even though we do not have any actual knowledge on the wind vectors in stable or unstable atmospheric conditions. To find a common divisor of various wind fields free from possible uncertainty sources, we developed an iterative procedure to define criteria. Those criteria are primarily composed of wind statistics around the rings and SST differences between a ring

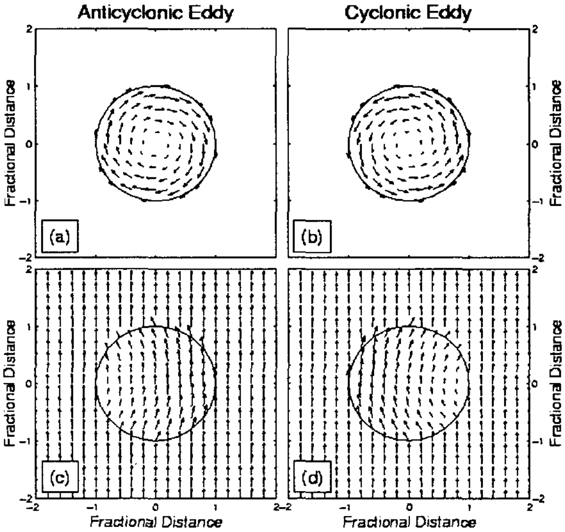

Figure 3. Examples of scatterometer-observed winds over warm-core ring and cold-core ring.

inside and outside. The criteria involved in the wind statistics are mainly a wind vector uniformity check and a curvature check both in a wind direction and a speed within a given sampled region including inside and outside area of a warm core ring. Detailed description and thresholds for the criteria are not listed herein and see Park and Cornillon (2002).

The residual wind fields were in satellite coordinates. To facilitate further analysis of these fields, each was transformed to a ring centered coordinate system. The azimuthal direction of ring velocity was defined as a rightward direction on a line tangential to the ellipse periphery and the radial direction was taken as an outward direction passing through a wind vector position from a ring center.

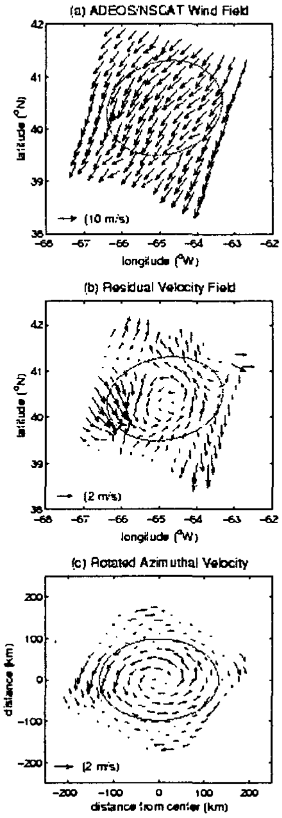

Figure 4. Procedure of deriving azimuthal velocity from scatterometer winds. (a) Original wind vectors, (b) residual velocity field demeaned by a mean wind vector for the ring inside, and (c) azimuthal velocities in a rotated and ring-centered coordinate system.

3. Results

3.1 Derivation of Azimuthal Ring Velocity

Figure 3 shows an schematic diagram of scatterometer observed winds. Figure 3a and 3b show general patterns of anti-cyclonic currents over the WCR and cyclonic currents over the CCR. In the outside region, it was assumed that there were no flows to visualize the pattern more clearly. The maximum speed was given to about 1 m/s at the boundaries based on the azimuthal velocities from scatterometer data. When winds blow from the south to the north over the rings, scatterometers are expected to measure backscattering that has been increased or decreased on either side by the effect of the current (Figure 3c and 3d).

As an example of sequential procedures as explained previously, the wind vector field on 9 June 1997 was selected and shown in Figure 1. The original wind field (Figure 4a) blows southwestward with a mean speed of about 7.7 m/s and the overall wind vectors are nearly uniform with a small rms variability of wind directions about 5.9°, However, those winds over a ring inside region are apparently deflected from the mean wind direction as compared with an outside area. This may be an indication of interactions between the original wind field and ring currents in scatterometer measurements. As well shown in Figure 4b, the residual wind vectors demeaned by a background wind field evidently rotate anti-clockwise of which the directions should be reversed to understand the original warm core ring velocity. In order to decompose these residual vectors into azimuthal and radial components, the coordinate system was rotated by a rotation angle of the ellipse itself. The azimuthal components in Figure 4c are surprisingly similar to those of an ideal warm core ring velocities in negative azimuthal velocity directions and their speed distribution. The velocities are predominantly small near the ring center and gradually increasing within a range of less than 2 m/s as goes to the ring edge.

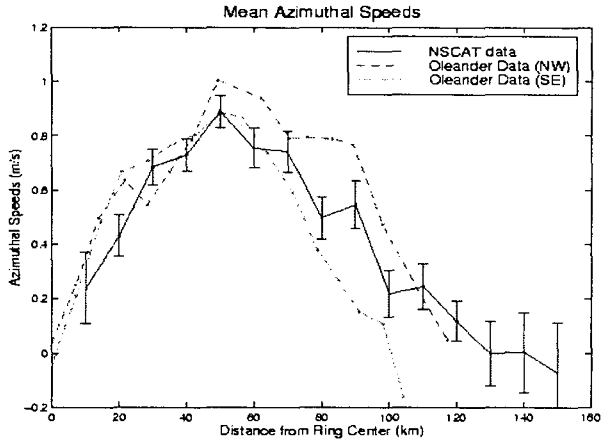

Figure 5. Comparison of scatterometer-derived azimuthal velocities of warm core rings with in-situ observations from ADCP equipped on the Oleander. The dashed and dashdotted curves correspond to a northern half and a southern half of the cruise section of the Oleander across a warm core ring, respectively.

3.2 Azimuthal Ring Currents

The azimuthal component of the residual wind velocity was obtained as a function of radial distance from the ring center for each fourteen residual fields. These observations were binned in equal area bins of every 10 km interval from the ring center and averaged. The resulting averages as well as the standard error of the mean are presented in Figure 5.

The Oleander, a container ship that sails from New York to Bermuda once a week, has been equipped with an ADCP for the past 5 years. The ADCP azimuthal components of the current and those derived from the scatterometer are in excellent agreement. The asymmetry of the two profiles across the ring center is thought to result from perturbations in the ring velocity on the southeastern side of the ring due to the ring-stream interaction. The scatterometer-derived azimuthal currents, a solid curve, shows a good coincidence in several aspects with the ADCP observations. First of all, the maximum velocities of the three curves are found at nearly same distance of about 50 km. Secondly, the maximum azimuthal velocities are similar that those in the northwestern and the southeastern profile are 1.0 m/s and 0.88 m/s and scatterometer-derived velocity is about 0.89 m/s. Thirdly, the slope of the scatterometer-derived curve to the maximum velocity are similar to the two observational curves.

Figure 6 shows the azimuthal velocities from scatterometer observation over warm and cold eddies. This was done for the whole wind passes of NSCAT and QuikSCAT without any applying the wind pass rejection criteria. Nevertheless, the two cases clearly show a reverse direction, that is, anticyclonic direction over warm core ring and cyclonic direction over cold core ring. This may be an excellent evidence on the principle of the scatterometer observation.

4. Conclusion

Scatterometer-derived wind vector over warm core and cold core ring have been used to emphasize that the fact that scatterometers measure surface wind stress, not surface winds. Wind stress is determined by, among other factors, the difference between surface winds and surface currents. Surface winds on the other hand are defined relative to a fixed location, for example the winds measured at a fixed mooring. This distinction is important when considering both ocean and atmospheric modeling efforts because the boundary condition needed in these efforts is wind stress not vector winds. The present methodology is limited however in the case of single passes due to noise in the scatterometer field. On the other hand, assuming that the errors from one pass to the next are random, combining a number of passes of the same ring allows for a good representation of at least the azimuthal currents in the ring.

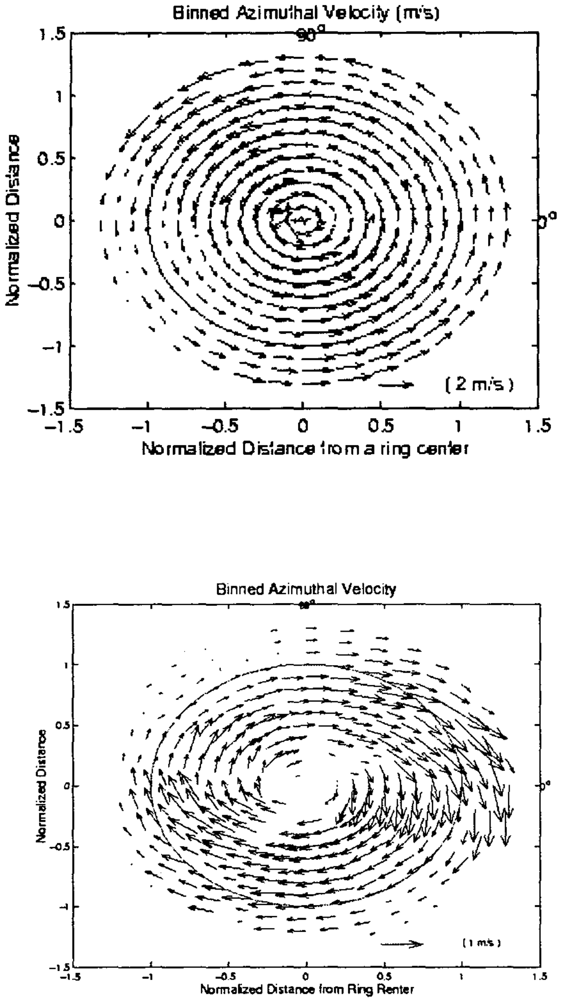

Figure 6. Azimuthal speeds of cold and warm core rings derived from QuikSCAT and NSCAT wind vectors.

Acknowledgements

This study was performed with support from the National Aeronautics and Space Administration as part of the SeaWinds programs. Recent handling of the scatterometer data was, in part, supported by the Brain Korea 21 Project through the School of Earth and Environmental Science, SNU, Korea.

References

Cornillon, P., C. Gilman, L. Stramma, O. Brown, R. Evans, and J. Brown, Processing and analysis of large volumes of satellite derived data. *J. Geophys. Res.*, 92, 12993-13002, 1987.

Park K. A. and P. Cornillon, Warm and cold core ring velocity structure using NSCAT scatterometer data. in preparation for submitting to *J. Geophys. Res.*, 2002.

Joyce, T. and T. McDougall, Physical Structure and temporal evolution of Gulf Stream warm core ring 82B. *Deep Sea Res.* 39 (Suppl. 1), S19-S44, 1992.

JPL, Science data product (NSCAT-2) user's manual ver. 1.2, overview & geophysical data products, 1998.