ESTIMATING THE GEOSTROPHIC VELOCITY COMPONENT IN THE SEA SURFACE VELOCITY OBSERVED BY THE HF RADAR IN THE UPSTREAM OF THE KUROSHIO

Ryoko Tokeshi, Kaoru Ichikawa, Satoshi Fujii, Kenji Sato and Shoichiro Kojima

ESST, Kyushu Univ., tokeryo@riam.kyushu-u.ac.jp

ABSTRACT: The geostrophic current component is estimated from the sea surface velocity observed by the long-range High-Frequency Ocean Radar (HF radar) system in the upstream of the Kuroshio, by comparing with geostrophic velocity determined from along-track T/P and Jason-1 altimetry data. However, the sea surface velocity of the HF radar (HF velocity) contains not only the geostrophic current but also the ageostrophic current such as tidal current and wind-driven Ekman current. Tidal current component is first extracted by the harmonic analysis of the time series of the HF velocity. Then, the Ekman current is further estimated from daily wind data of IFREMER by applying the least-square method to the residual difference between the HF velocity and the altimetry geostrophic velocity. As a result, the Ekman current in the HF velocity is estimated as 1.32 % of the wind speed and as rotated 45° clockwise to the wind direction. These parameters are found almost common in the Kuroshio area and in the Open Ocean. After these corrections, the geostrophic velocity component in the HF velocity agrees well with the altimetry geostrophic velocity.

KEY WORDS: geostrophic velocity, wind-driven Ekman current, HF radar, satellite altimeter, the Kuroshio

1. INTRODUCTION

Studies of variations in the ocean have been drastically progressed by use of satellite altimetry. However, since the SSHA field is interpolated from along-track altimetry data during a period more than 10 days, fast-moving phenomena such as meanders of the Kuroshio cannot be well described by the SSHA field (Ichikawa *et al.*, 1995). Moreover, temporal anomaly field alone is not adequate to describe variations of the Kuroshio which has strong temporal-mean current.

Since July 2001, the sea surface current in the upstream region of the Kuroshio in the East China Sea has been monitored by a long-range HF radar developed by NICT, which has been confirmed to accurately measure surface velocity (Matsuoka *et al.*, 2003; Sato *et al.*, 2004). Since the HF radar data has higher resolution in space and time than the satellite altimetry and is not confined to temporal anomaly, the HF radar is considered to be more suitable to observe fast-moving variations of the Kuroshio, although the observation area is limited. Furthermore, combined use of the HF radar data with the satellite altimetry or ship hydrographic data would provide more comprehensive descriptions on variations of the Kuroshio by interaction with mesoscale eddies.

However, the HF velocity contains not only the geostrophic current component but also the ageostrophic current component such as tidal and wind-driven Ekman current. Those ageostrophic current components in the HF observations should be separated from the geostrophic currents that are measured by the altimetry or hydrographic observations.

The purpose of this study is therefore to remove the ageostrophic velocity components in the sea-surface velocity of the HF radar, and to estimate the geostrophic velocity component. To these aims, the HF velocity is compared with the geostrophic velocity component normal to the satellite subtrack calculated from the along-track altimetry data. Although the comparisons are limited on the subtrack and one-directional component, these velocity component determined from the along-track data has been reported to agree with *in situ* geostrophic velocity observations when it is spatially smoothed over the internal radius of deformation (Uchida *et al.*, 1998; Kashima *et al.*, 2003; Ito *et al.*, 2004).

The geostrophic velocity obtained by the altimetry data and the surface velocity measured by the HF radar, which are described in Section 2, are first compared in Section 3, and then a method to estimate the Ekman current is shown in Section 4. Those results are discussed and summarized in Section 5.

2. DATA

We use gridded vector HF velocity data for 3.5 years from July 2001 to January 2005, which are interpolated by NICT on a 7-km grid every 0.5 hours. In order to compare with the geostrophic velocity anomaly obtained by the altimetry, we calculate the HF velocity anomaly from the 3.5-year mean velocity (Fig.1a); outlier data away from the mean by five times of the standard deviation were removed. In Fig.1a, the Kuroshio is clearly recognized at the northern corner of the study area as a band of strong northeastward velocity.

In order to remove tidal components in the HF velocity, 11 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf, Sa and Ssa) and internal oscillations are first estimated by the harmonic analysis at each grid point. Except non-astrometrical constituents Sa and Ssa which are dominated by variations of ocean currents, the 9 constituents and the internal oscillations were extracted (Yanagi *et al.*,1997). Then the one-day mean velocity

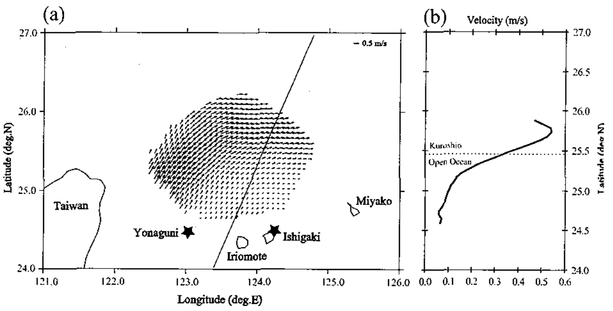

Figure1. Gridded 3.5-year mean velocity (a). The oblique line indicates the satellite subtrack used in this study. Profiles of the velocity component normal to this subtrack is extracted along the subtrack and plotted against the latitude (b).

anomaly is calculated from 0.5-hour velocity where outlier velocity over 3 times of the standard deviation is excluded, and no one-day mean is determined at a grid point if there are less than 24 samples in a day. Note that the removal of the Ekman current in the HF ageostrophic velocity will be described in Section 4.

We use the SSHA data along the satellite subtrack shown in Fig.1a observed every 10 day by T/P and Jason-1 altimeters. The altimeter products have been produced by Ssalto/Duacs and distributed by Aviso with support from Cnes (Ssalto/Duacs, 2004), in which tide and air pressure corrections have been applied. The SSHA from the same 3.5-year mean as the HF velocity is obtained on points along the satellite subtrack with 7-km interval. The geostrophic velocity anomaly v_{alt} normal to the satellite subtrack is calculated from the slope of the SSHA between adjacent points, which is defined as positive in the south-east direction. Since the altimetry geostrophic velocity anomaly v_{alt} is known to agree well with *in situ* velocity when it is smoothed over the internal radius of deformation (Ito *et al.*, 2004; Kashima *et al.*, 2003; Uchida *et al.*, 1998) which is about 40 to 60 km in this study area (Emery *et al.*, 1984; Dudley *et al.*, 1998), the SSHA is spatially smoothed over 40 km along the subtrack by the moving average in the Kuroshio and over 50 km in the open ocean.

For comparison with the geostrophic velocity v_{alt}, the gridded one-day mean HF velocity anomaly is interpolated to the observation point of SSHA along the satellite subtrack, and the HF velocity anomaly component V_{HF} normal to the subtrack is determined. Fig.1b shows the component normal to the subtrack for the 3.5-year mean vector velocity Fig.1a. To the north of 25.47°N, the stronger flow in the Kuroshio area is present, meanwhile weaker eastward mean flow is found in the Open Ocean area to the south of that latitude.

The wind data for the estimation of the Ekman current component used in Section 4 is obtained from CERSAT, at IFREMER, Plouzané, France, which is daily-mean vector velocity on a 0.5-degree grid. Then the temporal velocity anomaly from the same 3.5-year mean as the HF velocity is determined.

3. COMPARISON OF VELOCITIES

Along the satellite subtrack, V_{HF} is first compared with v_{alt} to examine influences of the ageostrophic current components included in V_{HF}; in order to examine spatial scales of V_{HF} and temporal dependency of ageostrophic current component, the comparisons are made for many combinations of various temporal smoothing scales of V_{HF} and various spatial smoothing of v_{alt}. In these comparisons, the root-mean-squared (rms) difference between V_{HF} and v_{alt} is calculated for all observation points along the satellite subtrack during 3.5 years in each area. Since root sum variances of V_{HF} and v_{alt} themselves tend to be smaller as increasing spatial or temporal smoothing scales, we define normalized difference as the rms difference divided by the corresponding root sum variance.

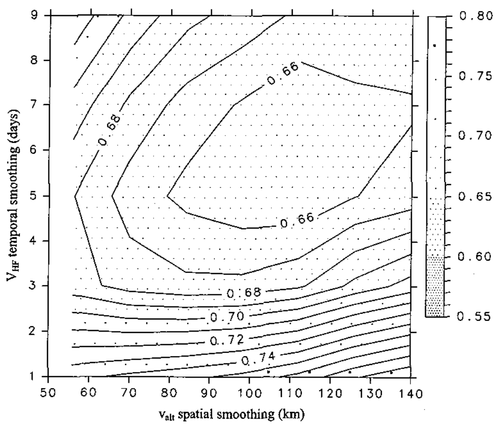

Figure2. The normalized difference between V_{HF} and v_{alt} in the Open Ocean area. Horizontal axis shows various spatial smoothing scale of v_{alt} and vertical axis shows various temporal smoothing scale of V_{HF}. The counter interval is 0.01.

The normalized difference does not change monotonously by increasing the spatial and temporal smoothing scales. Especially, in the Open Ocean area (Fig.2), a local-minimum normalized difference for a given temporal smoothing scale of V_{HF} is found only for temporal smoothing scales larger than three days. For the one-day mean V_{HF}, the normalized difference is especially larger than any other temporal smoothing scales, for all spatial smoothing scales of v_{alt}. This suggests that ageostrophic current component, such as wind-driven Ekman current, is dominant in the one-day mean V_{HF} in the Open Ocean area.

4. ESTIMATING THE HF GEOSTROPHIC VELOCITY

Since the wind-driven Ekman current is one of the largest factors in the ageostrophic current described in the previous section for the one-day mean in Fig.2, we estimate the Ekman current from the ageostrophic current as a wind-driven current component which linearly corresponds to the wind velocity. Namely, unknown speed factor and rotation angle of the Ekman current with respect to the one-day mean wind velocity are determined by the least square method which minimanize rms difference between the ageostrophic current and the Ekman current component normal to the satellite subtrack. These parameters are estimated independently in each area. Note that both wind velocity and estimated Ekman current are defined as the anomaly from the 3.5-year mean, as the same as V_{HF} and v_{alt}.

The estimated Ekman current is subtracted to produce the "Ekman-corrected" HF velocity v_{HF}. The accuracy of v_{HF} depends on whether the reference geostrophic velocity v_{alt} used in the estimation represents the unknown geostrophic current component in the HF observations which may be spatially smoothed. In the Kuroshio area, the normalized difference between v_{HF} and v_{alt} becomes smallest when the 70-km smoothed v_{alt} is used; for this case, the estimated speed factor and rotation angle of the Ekman current are 1.27% and 47.3° clockwise with respect to the one-day mean wind velocity. Meanwhile, in the Open Ocean area, the smallest rms difference occurs when the 56-km smoothed v_{alt} and used; the parameters are 1.47% and 38.5° for this case. The discrepancy of the spatial smoothing scales between two areas would be induced by different spatial smoothing scales in the HF measurements. In general, radar footprint size becomes larger as the distance from the radar site increases, and therefore the velocity measured by the HF radars would be averaged over a larger area, which is consistent with the lager smoothing scale of the reference geostrophic velocity v_{alt} in the Kuroshio area which is away from the radar sites. It should be noted, however, that the parameters obtained in both areas are similar, in spite of their independent estimations.

Based on the estimated parameters in each area, we select common parameters to both areas as 1.32% for the speed factor and 45.0° for the rotation angle, which are slightly weighted to the estimations in the Kuroshio area, accounting that the normalized difference in the Kuroshio area is more sensitive to the choice of parameters. These parameters are applied to the one-day mean wind velocity anomaly, and the estimated Ekman current component is subtracted from the V_{HF} to produce Ekman-corrected HF velocity v_{HF}. Normalized difference between v_{alt} and v_{HF} is calculated similarly to V_{HF} (Fig.3). Any value is smaller than corresponding one, not only for the one-day mean v_{HF} but also for the longer temporally averaged v_{HF}, due to removal of Ekman current induced by longer-period wind variations such as seasonal one. This improvement is especially remarkable in the Open Ocean area (Figs.2 and 3a) where geostrophic velocity is less dominant to the Ekman current than that in the Kuroshio area (Fig.4). However, in the Open Ocean area, the extremely larger normalized difference for the one-day mean v_{HF} also still remains after reduction of the Ekman current, suggesting presence of other ageostrophic current components only in the one-day mean v_{HF}. This will be discussed in the next section.

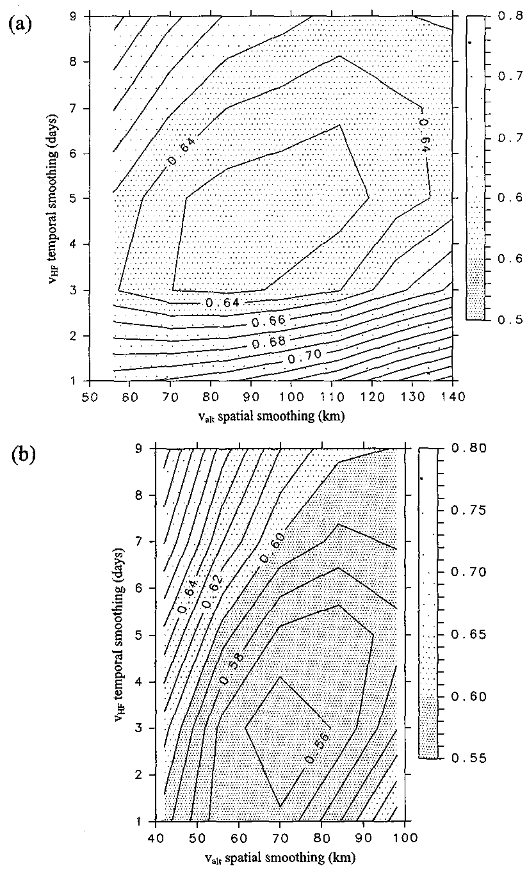

Figure3. The same as Fig.2 but the Ekman current component is removed from V_{HF}. In the Open Ocean area (a) and in the Kuroshio area (b)

5. SUMMARY AND DISCUSSIONS

Estimations of the Ekman current from wind velocity data have been reported in previous studies. For example, using 6-hour interval HF velocity data during passage of a typhoon, Matsuoka *et al.* (2003) estimated that the wind speed factor from 3.4 to 4.2% and the rotation angle from 35° to 39°, respectively. Meanwhile, following Niiler *et al.* (2003) who used along-track altimetry geostrophic velocity and two-day averaged surface drifter data, these parameters at 25°N correspond to 0.8% and 54°. The parameters obtained in this study for the one-day mean Ekman current is consistently situated between those two estimates. Quantitative comparisons are, however, difficult because the corresponding depths of those estimates are different; the Ekman current in Niiler *et al.* (2003) is at about 15 m where drogues of drifters are located, whereas the depth represented in the HF velocity is considered to be about 1.3 m for the HF radar (Matsuoka *et al.*, 2003). More detailed studies such as Yoshikawa *et al.* (2006) are necessary which account for vertical structure of the Ekman current.

After removal of the estimated Ekman current component in the HF velocity, the normalized difference between the daily mean HF velocity v_{HF} and the altimetry geostrophic velocity v_{alt} is improved. This improvement is confirmed also in the rms differences; 0.17 m/s difference with 70-km smoothed v_{alt} in the Kuroshio area and 0.19 m/s difference with 56-km smoothed v_{alt} in the Open Ocean area are reduced to 0.16 m/s and 0.18 m/s, respectively, after the removal of the Ekman current. However, even after the removal of the Ekman current, the rms difference for the one-day mean v_{HF} is still larger than that for the temporally-longer mean v_{HF}. This tendency is especially obvious in the Open Ocean area; the rms difference with the 56-km smoothed v_{alt} decreased from 0.18 m/s to 0.15 m/s by changing the one-day to three-day mean v_{HF}. In the Kuroshio area, the change of the difference with the 70-km smoothed v_{alt} by the three-day v_{HF} is from 0.16 m/s to 0.14 m/s. One possible reason for this residual difference is that the simple assumption is not adequate to linearly estimate the one-day mean Ekman current from the one-day mean wind velocity, but this cannot explain discrepancy between two area: More probable interpretation is that the ageostrophic current component other than the Ekman current remains in the one-day mean v_{HF} in the Open Ocean area. Since the beam footprint of the HF radar spreads wider as the distance from the radar site increases, the spatial smoothing scale intrinsic to the HF radar measurements also becomes large. In other words, spatial scales of the velocity structures measured by the HF radar would be smaller in the Open Ocean area where is closer to the radar sites, which could be smaller than the internal radius of deformation. Ageostrophic current components included in such small velocity structures in the Open Ocean area, would remain in the average over 24 hours which is slightly shorter than the period of inertial oscillation that is about 28 hours at this latitude, but they would be smoothed out in the 72-hour mean. Meanwhile, less ageostrophic current component is expected in the HF velocity away from the radar sites where the radar footprint size is considered to be larger than the internal radius of deformation. It is therefore concluded that the Ekman-corrected HF velocity v_{HF} in the Open Ocean area should be either spatially smoothed or temporally smoothed to determine geostrophic velocity.

The minimum normalized difference corresponds to the rms difference of 0.14 m/s in the Kuroshio area and 0.12 m/s in the Open Ocean area. These rms differences are regarded to be derived from the accuracy of the observations of the HF radar and geostrophic velocity themselves. For the HF radar velocity, accuracy of the single measurement is estimated to be 0.15 m/s by comparison with the surface velocity with in situ surface velocity at a moored buoy (Sato *et al.*, 2004). For the geostrophic velocity determined from along-track altimetry data, the accuracy is considered to be 0.16 m/s in the Kuroshio south of Shikoku (Uchida *et al.*, 1998) and 9.1×10^{-2} m/s in open ocean (Ito *et al.*, 2004).

Characteristic patterns of the normalized difference in Fig.3 are remarkably different between the Kuroshio area and the Open Ocean area, even if the one-day mean v_{HF} is excluded. An oblique area of smaller normalized difference exists from the lower left side to the upper right side of each panel; presence of the oblique area is reasonable since the spatial scale generally tends to be larger when the temporal scale increases. However, width of the area in the Kuroshio area is remarkably narrower than that in the Open Ocean area. This is considered to be caused by difference of sensitivity to over-smoothing or under-smoothing of v_{alt} in each area. In the Kuroshio area where distinct velocity structures with relatively small spatial scales exist, large difference would be produced if the velocity field v_{alt} is over-smoothed or under-smoothed than the true spatial scale of v_{HF}. Meanwhile, in the Open Ocean area where dominant spatial scale of the geostrophic velocity field would be larger, v_{alt} would stay similar even if it is slightly over-smoothed or under-smoothed.

In this study, we demonstrate that the HF geostrophic velocity v_{HF} results in the similar accuracy with the geostrophic velocity v_{alt} determined by the satellite altimetry. Although the comparisons in this paper are limited to the component normal to the satellite subtrack, the HF velocity can provide mapped vector velocity within the radar range. By using the mapped HF geostrophic velocity after proper corrections of ageostrophic current described in this paper, fast-moving phenomena such as interaction between the Kuroshio and meso-scale eddies are expected remarkably well described, which will be reported in another paper.

References from Journals:

Chelton D. B. *et al.*, 1998. *J. Phys. Oceanogr.*, **28**, 433-460.

Emery W. J. *et al.*, 1984. *J. Phys. Oceanogr.*, **14**, 294-317.

Ichikawa K., 2001. *J. Oceanogr.*, **57**, 55-68.

Ichikawa K. *et al.*, 2004. *J. Oceanogr.*, **60**, 365-374.

Ichikawa K., 1995. *J. Oceanogr.*, **51**, 729-740.

Ito S. *et al.*, 2004. *J. Oceanogr.*, **60**, 425-437.

Kashima M. *et al.*, 2003. *J. Oceanogr.*, **59**, 291-301.

Matsuoka T. *et al.*, 2003. 0-7803-7930-6/$17.00 (C) IEEE

P. P. Niiler *et al.*, 2003. *J. Geophys. Res.*, **108**(C6), 3193, doi:10.1029/2002JC001461.

QUIKSCAT SCATTEROMETER MEAN WIND FIELD PRODUCTS USER MANUAL, 2002. C2-MUT-W-03-IF, Ver.1.0

Sato K. *et al.*, 2004. *Bull. Coast. Oceanogr.*, **41**, 119-127 (in Japanese).

Ssalto/Duacs User Handbook, 2004. (M)SLA and (M)ADT Near-Real Time and Delayed Time Product. SALP-MU-P-EA-21065-CLS, Edition 1.2,

Uchida H. *et al.*, 1998. *J. Oceanogr.*, **54**, 115-122.

Yanagi T. *et al.*, 1997. *J. Oceanogr.*, **53**, 303-309.

Yoshikawa Y. *et al.*, 2006. *J. Geophys. Res.* (submitted to JGR)