SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

doi: 10.1007/s11430-010-0022-2

Autumn intensification of the Ryukyu Current during 2003–2007

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Received November 14, 2008; accepted September 24, 2009

Inverse calculations using data from 16 repeat hydrographic transects collected from April 2003 to June 2007 have yielded velocity structures and volume transports (VTs) of the Ryukyu Current in the region east of the northern Ryukyu Islands. The inverse calculation results show that the Ryukyu Current is dominated by a subsurface velocity core with maximum velocities from 15.1 to 80.0 cm/s, whose positions vary between 110 and 600 dbar and 27.2°–28.2°N along the transect. The mean velocity exhibits a subsurface velocity core with a maximum value of 24.6 cm/s at 326 dbar depth, a VT of 14.0 Sv (1 Sv $\equiv 10^6$ m^3/s), a vertical dimension of 800 m, and a horizontal dimension of 60 km. The seasonal mean velocities show that the Ryukyu Current is stronger in autumn than in other seasons. It is suggested that this seasonal variation is coincident with the intensification of the anticyclonic eddy south of Shikoku, Japan.

Ryukyu Current, inverse technique, subsurface maximum velocity core, volume transports, seasonal variation

Citation: Zhu X H, Huang D J, Guo X Y. Autumn intensification of the Ryukyu Current during 2003–2007. Sci China Earth Sci, 2010, doi: 10.1007/s11430-010-0022-2

The possibility of a northeastward current over the eastern slope of the Ryukyu Islands was pointed out first by Worthington and Kawai [1], and was named the "Ryukyu Current" (RC) by Wang and Sun [2]. In the region southeast of Okinawa Island, the northeastward volume transport estimated by inverse methods varies from 3 to 28 Sv (1 Sv $\equiv$ 10^6 m^3/s) [3–6]. A 270-day (November 2000 to August 2001) mean of northeastward volume transport referenced to 2000 dbar, using data from pressure-sensor-equipped inverted echo sounders and an ADCP mooring, was estimated to be 6.1 Sv [7].

Ichikawa et al. [8] moored current meters at 3–4 stations along a section southeast of Amami-Ohshima Island to measure the RC. They estimated a value of ~16 Sv as 4.5-year (from January 1998 to July 2002) mean of northeastward volume transport in the upper 1500 m and found, for the first time, a subsurface RC core with a maximum mean velocity of 23 cm/s at 600 m depth. Using an inverse technique on hydrographic section datasets collected in September 1987 and December 2000, Nakano et al. [9] and Zhu et al. [10] showed a snapshot of the RC having a northeastward current core at depths of 300–500 dbar. Recently, the absolute geostrophic velocity distributions were presented by Nagano et al. [11] and Zhu et al. [12]. Despite the above progress in the studies on the RC southeast of Amami-Ohshima Island, the answer to a fundamental issue, the seasonal variation of the RC velocity structure and net volume transport (NVT), remains unclear.

Using an inverse technique, we estimate the RC velocity structure and the related volume transport along 16 repeat hydrographic sections collected during 2003–2007. Our objective is to confirm the mean flow structure of the RC east of the northern Ryukyu Islands and to clarify its seasonal variation.

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1 Data and inverse technique

The sixteen repeat hydrographic surveys were performed along four sections including the AE, AA, ASUKA, and TK lines by the Japan Meteorological Agency (JMA) from April 2003 to January 2007 (Figure 1). Maximum CTD cast depths were near-bottom for the TK line and the shallow-water stations along the other sections, and about 2000 dbar for deep-water stations. The hydrographic surveys were carried out mainly by the *R/V Chofu-Maru* of the Nagasaki Marine Observatory, JMA, or by other research vessels of the JMA.

The merged Sea Surface Height Anomaly (SSHA) maps at 7-day intervals were downloaded from Archiving Validation and Interpretation Satellite Oceanographic Data (website: www.aviso.oceanobs.com).

The inverse technique developed by Wunsch [13] is applied to the computational box enclosed by the four hydrographic sections, the Japanese coastline, and the Ryukyu Islands (Figure 1). The water column is divided into five potential density layers along the following σ_θ isopycals: 25.00, 26.00, 27.00, 27.50, and 27.65 (depths of about 200, 500, 900, 1400, and 1900 m). The water masses are assumed to be conserved in these five layers, and the salt masses are assumed to be conserved in all layers except for the top one. The equation system including the mass and salt conservation equations can be written in the form

$$A \times b = -\Gamma, \tag{1}$$

where A is a 9×46 matrix, b is an unknown 46-element vector of reference velocities at 46 station pairs, and Γ is a 9-element vector of the initial imbalances of mass and salt; the reference level is at 2000 dbar or the deepest common level. The inverse solution is obtained by the "tapered least squares" method described by Wunsch [13] and Zhu et al. [10].

2 Velocity

The inverse results provided four sections of absolute geostrophic velocity for each cruise. Of these, the currents along TK and ASUKA lines are well known [14, 15] and the AA line is not important to this study. Therefore, we focus only on the AE line (Figure 1). Figure 2 shows the absolute geostrophic velocity obtained from the inverse results for 16 observations from April 2003 to June 2007 along the AE line. The RC is clearly visible as an energetic northeastward velocity core whose speed is between 15 and 80 cm/s. The position of its core changes not only in the

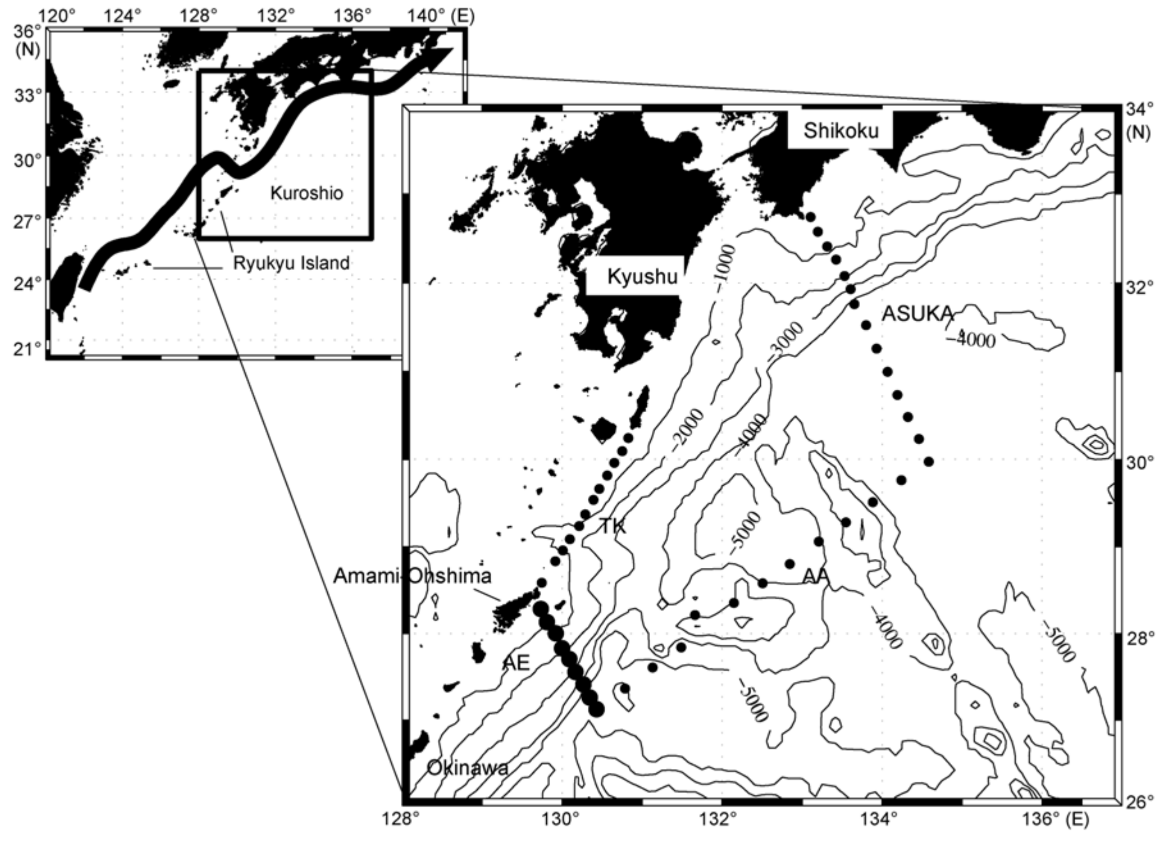

Figure 1 Location map of hydrographic stations. Solid circles indicate CTD stations. 'AE', 'AA', 'ASUKA', and 'TK' are the names of the four hydrographic sections. Bathymetric contours are in m.

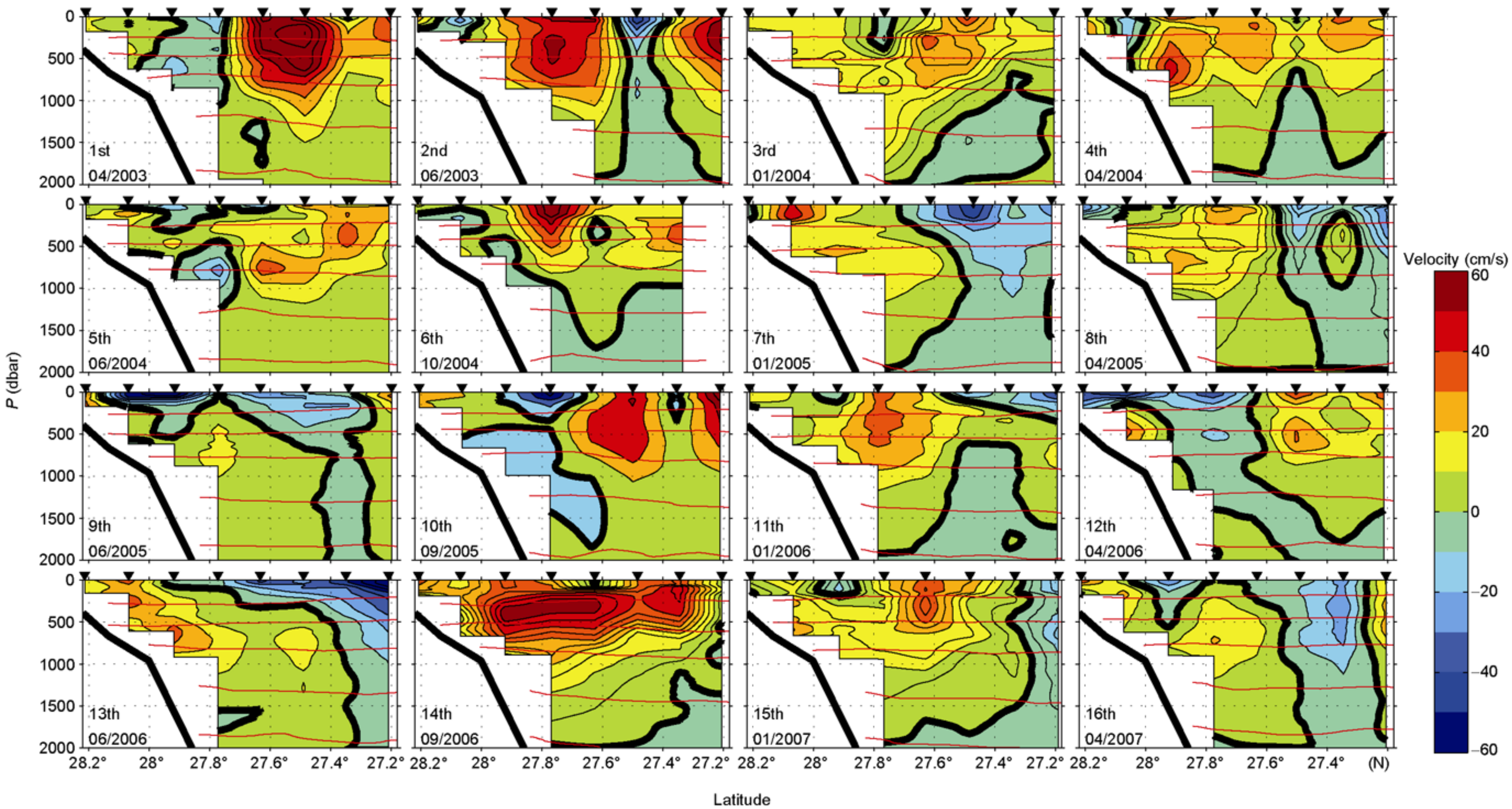

Figure 2 Absolute geostrophic velocity along the AE line. Black contours filled with color indicate current velocity with 10 cm/s intervals. Positive values indicate northeastward velocity. Red contours indicate the five potential density layers in the inverse calculation. Thick contours show 0 velocity. Inverted triangles indicate the locations of inverse computational points. The cruise number and period (month/year) of the hydrographic survey are shown in the bottom-left corner of each panel.

horizontal but also in the vertical. For example, the RC core can be very close to Amami-Ohshima Island (as on the 4th and 13th cruises), and can move offshore south of 27.6°N (as on the 1st, 10th and 15th cruises). The position of subsurface maximum velocity can appear near the surface at 110 dbar (10th cruise) or at about 600 dbar (4th, 5th, 8th, and 12th cruises). The subsurface maximum velocity varies from 15.1 cm/s (9th cruise) to 80.0 cm/s (14th cruise). Sometimes the RC appears as a single core (1st, 11th and 15th cruises), and at times, as multiple cores (4th, 5th, 6th, 7th, 8th, 12th and 14th cruises).

To examine seasonal variations of the flow structure and its mean state, the absolute geostrophic velocities from 16 cruises were averaged by season (Figure 3). The four seasons are divided by following the JMA rule, i.e., January, April, June, and September-October correspond to winter, spring, summer, and autumn, respectively. The seasonally averaged absolute geostrophic velocity clearly shows a closed subsurface maximum velocity core in all seasons. The velocity core becomes weak in summer and strong in autumn. The maximum velocities are 23.4, 22.9, 20.1, and 46.8 cm/s for winter, spring, summer, and autumn, respectively. Among four seasons, the RC is the strongest in autumn (Figure 3(d)), which seems to be caused by the 14th cruise's contribution (Figure 2). However, even when this cruise is excluded in the averaging calculation for autumn, the maximum velocity is 44.9 cm/s, which is still the strongest among four seasons.

The mean absolute geostrophic velocity for all seasons also forms a closed subsurface velocity core with a maximum value of 24.6 cm/s (Figure 3(e)). The maximum velocity core is located at 326 dbar and 27.62°N along the AE line, where the water depth is nearly 2700 m.

The vertical profiles of the velocity averaged horizontally at the whole AE line in four seasons (Figure 3(f)) exhibit subsurface maximum peaks around 200 to 700 dbar, and remain almost zero at 2000 dbar. These profiles are almost the same in winter, spring, and summer, but increase significantly in autumn, which occurs only above the 700-dbar depth. According to these profiles, the RC has a feature of strong baroclinicity.

3 Volume transport

We estimated the northeastward volume transport (NEVT) and net volume transport (NVT) across the AE line in the upper 2000-dbar layer (Figure 4(a)). The NEVT/NVT vary from 6.8/0.3 to 35.4/35.0 Sv, and their means (± standard deviations) are 18.7/14.0 (±10.9/8.8) Sv. The NEVT/NVT exhibit seasonal variation with the maximum values (26.7/23.9 Sv) in autumn and almost the same values in other seasons (very small second maximum values (17.6/12.5 Sv) in spring) (Figure 4(a)). If the values of 14th

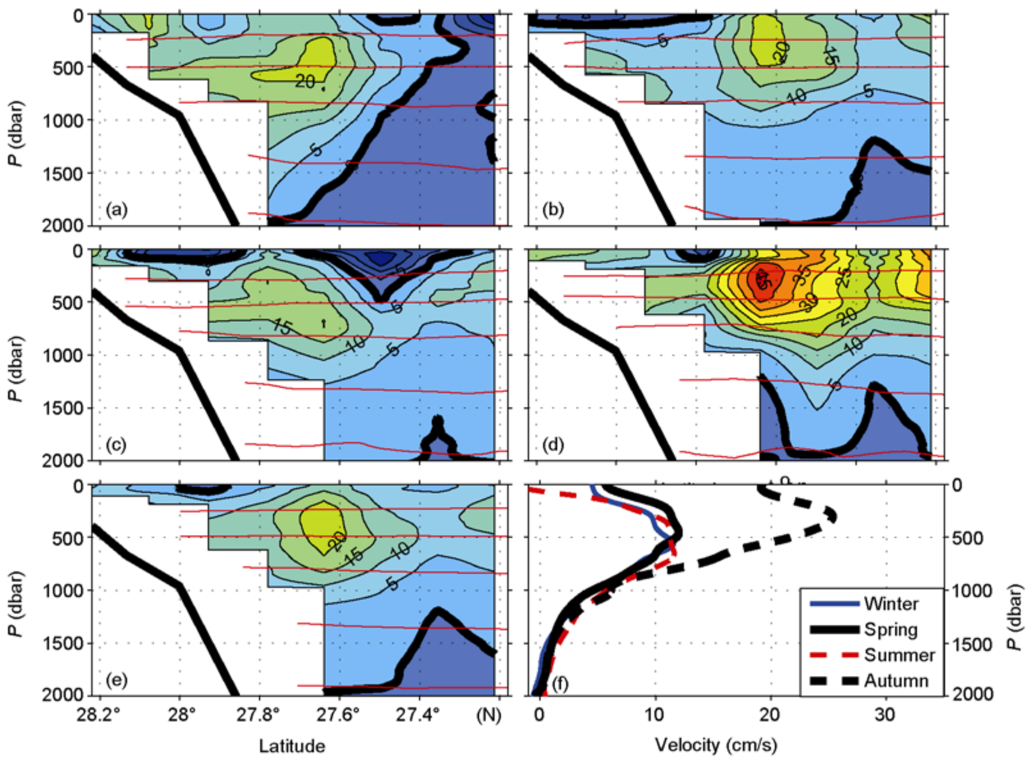

Figure 3 Mean absolute geostrophic velocity along the AE line for winter (a), spring (b), summer (c), autumn (d), and all seasons (e). Black contours filled with color indicate current velocity with 5 cm/s intervals. Red contours indicate the five potential density layers in the inverse calculation. Positive values indicate northeastward velocity. (f) Mean velocity profiles for each season.

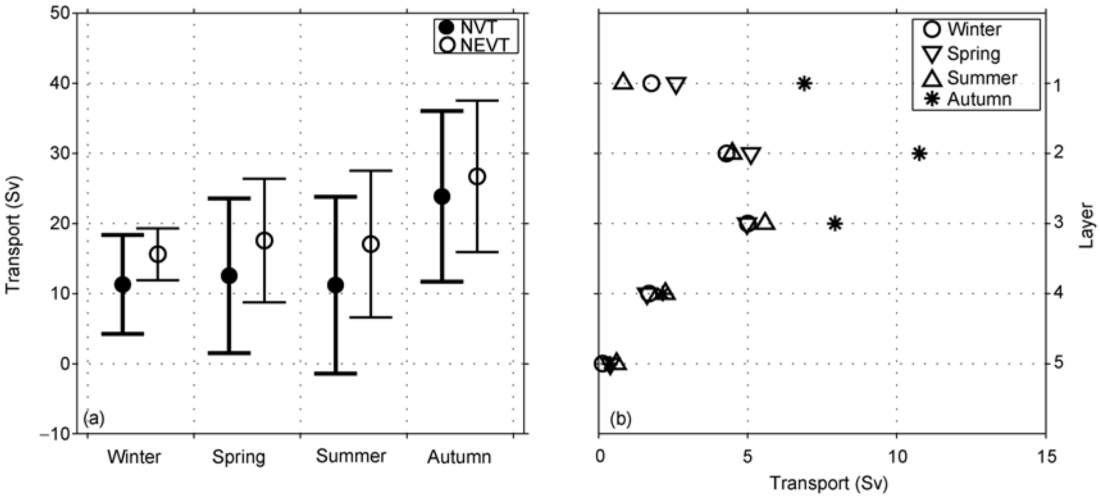

Figure 4 (a) Mean northeastward volume transport (NEVT) and net volume transport (NVT) along the AE line for each season. The error bars indicate the standard deviations. (b) Mean NVT along the AE line for the five potential density layers in the inverse calculation.

cruise are excluded in the calculation, the autumn means of the NEVT/NVT are 22.4/18.3 Sv, which still remain the largest one among the four seasons.

To examine the volume transport in different layers, the mean NVT in the five potential density layers across the AE line are calculated (Figure 4(b)). The mean NVT exhibits a subsurface maximum in layer 2 whose depths are from about 200 to 500 dbar and remains almost zero in layer 5. The NVTs are almost the same within each layer in winter, spring, and summer, and increase significantly in autumn. The increase of NVT in autumn occurs only in the upper three layers (upper 900 dbar). The mean NVT in the upper 1000 dbar accounts for about 91% of the total NVT in the upper 2000 dbar, resulting from the strong baroclinicity structure of velocity (Figure 3(f)).

4 Summary and discussion

With inverse calculations based on 16 repeat hydrographic data from April 2003 to June 2007 along four sections, we have presented the seasonal variations of flow structure and VT of the RC in the region east of northern Ryukyu Islands. The RC is dominated by a subsurface core structure with maximum speed varying from 15.1 to 80.0 cm/s. The positions of the subsurface velocity maximum vary between 110–600 dbar and 27.2°–28.2°N along the AE line. The mean velocity calculated over 16 cruises exhibits a closed subsurface velocity core with a maximum speed of 24.6 cm/s, a vertical dimension of 800 m, a horizontal dimension of 60 km, and VT of 14.0 Sv. The seasonally averaged velocity shows that the RC is the strongest in autumn and almost the same in other seasons. The mean VTs of the RC for winter, spring, summer, and autumn are 11.3, 12.5, 11.2, and 23.9 Sv, respectively. The vertical profile of mean VT exhibits a subsurface peak around 200–600 dbar and is almost zero in the deep layers, indicating that the RC is dominated by a baroclinic structure.

The present study shows that the RC is the strongest in autumn. This feature has also been identified in the previous studies. Using the modified inverse method with hydrographic data, Yuan et. al. [4], Liu et al. [16] and Liu and Yuan [5] reported that the RC is the strongest in autumn during 1987–1997, except for 1996, in the region southeast of Okinawa. Using the 12-year NVT time series derived from satellite data calibrated with in situ transport measurements, Andres et al. [17] also confirmed the annual cycle of the NVT in the region southeast of Okinawa, in which the maximum NVT occurs in autumn (October-November) and the standard deviations of NVT are quite large. However, these studies have not revealed the cause why the RC is intensified in autumn.

To explain why the RC is the strongest in autumn, we checked monthly QuikSCAT wind stress curl and wind speed vector for the four months during the observation period (figures not shown here). The comparison of wind curl and wind speed with the RC suggests that the RC does not response simply to the variation in local wind field. This feature is similar to the response of Kuroshio NVT across the ASUKA line to wind as pointed out by Isobe and Imawaki [18].

The SSHA map shows a high SSHA around the region south of Shikoku, Japan (Figure 5). It is expected that the presence of an anticyclonic eddy south of Shikoku, corresponding to the high SSHA, can increase the NVT across the AE line through its clockwise recirculation. However, it also raises an issue why the high SSHA occurs in this region only in autumn. To answer this question and to find the quantitative relation between the NVT and the anticyclonic eddy south of Shikoku, the work with the help of a numerical model is necessary.

From the SSHA distribution, it is known that the autumn

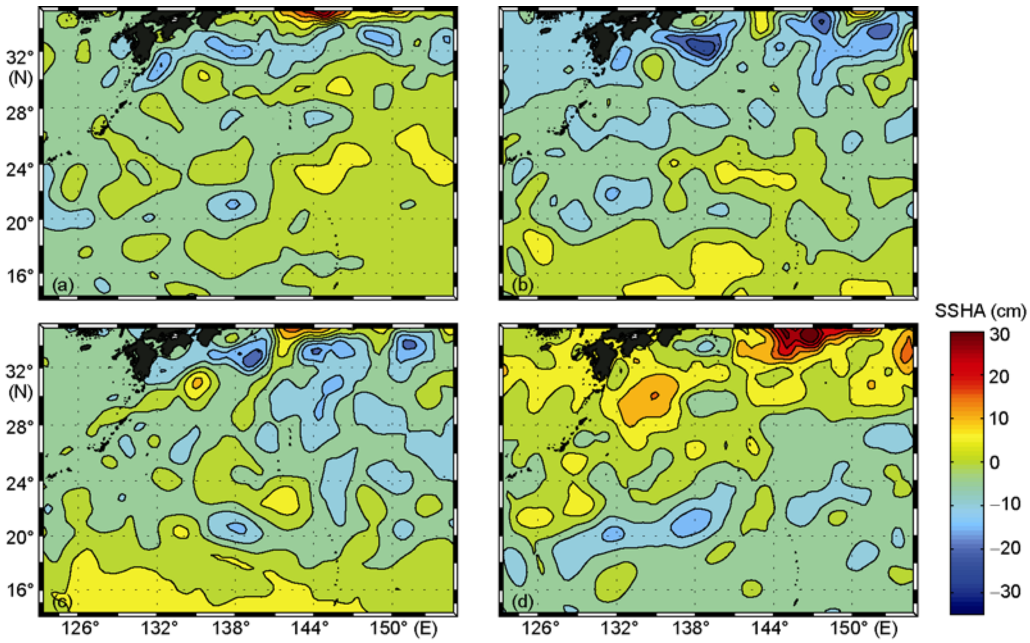

Figure 5 Mean sea surface height anomaly (SSHA) map for each season during 2003–2007. (a) Winter; (b) spring; (c) summer; (d) autumn.

increase in NVT is coincident with the intensification of Kuroshio recirculation south of Shikoku. However, the Kuroshio NVT or the through flow across the ASUKA line did not increase in autumn. In fact, the seasonal variation in the Kuroshio transport through the ASUKA line is very small during the period from 1992–2001 [19] and during our observational period (results not shown here). Therefore, the Kuroshio transport into the Kuroshio Extension region does not necessarily increase in autumn.

Along the same AE line, Ichikawa et al. [8] estimated a value of ~16 Sv as the mean of NVT in the upper 1500 m, and also showed that an unclosed subsurface RC core with a maximum speed of 23 cm/s at 600 m depth using the 4.5-year mooring data from 1998–2002. In the present study, the mean transport of 14.0 Sv and the mean subsurface maximum speed of 24.6 cm/s are very similar to those reported by Ichikawa et al. [8]. However, the mean NVT vertical structure given by present study is not a linear function with depth (Figure 6). On the other hand, Ichikawa et al. [8] showed a nearly linear relation between the NVT and depth (see Figure 10 in Ichikawa et al. [8]). We note that there was actually no current meter data between 600 m depth and the surface layer in the observations of Ichikawa et al. [8] and deduce that the nearly linear relation between the NVT and depth in Ichikawa et al. [8] may be caused by vertically linear interpolation.

The NVT profile in the present study shows a nonlinear structure with large seasonal variation in the upper 600 dbar. The mean NVT in the upper-600-dbar layer reaches 11.4 Sv, about 65% of that in the upper-1500-dbar layer, which can be obtained from Figure 6. These results indicate that with simple linear interpolation it is difficult to obtain an accurate velocity profile and corresponding VT for the upper 600 m in this region.

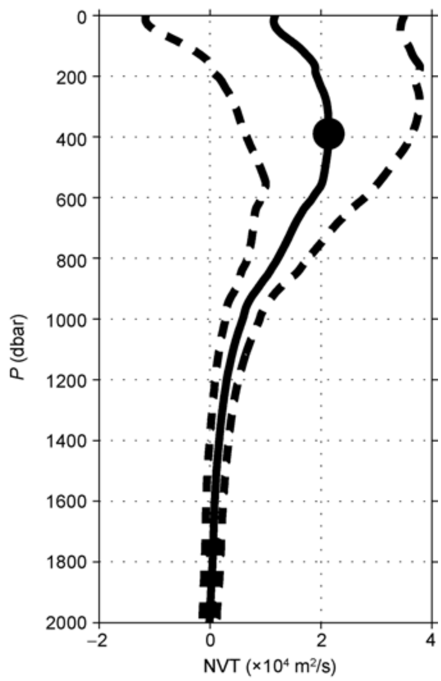

Figure 6 Vertical profiles of mean net VT per unit depth estimated at every 1 dbar of depth. Solid circle indicates the subsurface maximum. The broken lines indicate the mean ± the standard deviations.

The subsurface maximum structure of NVT obtained in this study is different from that in the ASUKA line [19], that in the East China Sea [17] and that of the region southeast of the Okinawa Islands [20], in which the NVTs in the upper 1000 dbar are proportional to the surface volume transport. The latter can be then estimated from satellite sea surface height anomaly difference (ΔSSHA) across the current. Therefore, our result that there is no linear relation between the NVTs in the surface layer and those in the subsurface layer (Figure 6) indicates a difficulty for monitoring the NVT through the entire water column with the satellite ΔSSHA across the RC in the region southeast of Amami-Ohshima.

Using inverse methods based on the hydrographic transect data, Nakano et al. [9] and Zhu et al. [6] presented a similar absolute geostrophic velocity structure to the present study for the same region in September 1987 and fall 2000, respectively. However, the absolute geostrophic velocity structures in 2002, obtained by Nagano et al. [11], are significantly different from the results in this study and those in Nakano et al. [9] and Zhu et al. [6]. As commented by Zhu et al. [12] (see also Nagano et al. [21] for the reply), the presence of unrealistic strong deep currents in Nagano et al. [11] is likely to be a problem. Therefore, more direct measurements of currents are desirable in the future.

The hydrographic data were provided by the Japan Meteorological Agency (JMA). We thank Dr A. P. Cracknell of the University of Dundee for his valuable comments and manuscript revising. Two anonymous reviewers are acknowledged for their critical comments and valuable suggestions on the manuscript. This work was supported by National Natural Science Foundation of China (Grant Nos. 40776021, 40706018), National Basic Research Program of China (Grant No. 2006CB400603), National High Technology Research and Development Program of China (Grant No. 2006AA09Z102), and JSPS KAKENHI (Grant No. 21310012).

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