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Variation of the currents east of the Ryukyu Islands in 1998

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Abstract : Based on the CTD and wind data east of the Ryukyu Islands obtained in three cruises abroad by R/V Chofu Maru in 1998, the current velocities and volume transports are calculated by the modified inverse method. The northeastward Ryukyu Current over the slope east of the Okinawa Island and a southwestward current east of the Ryukyu Current are recognized to exist in February, April and July of 1998. There is a weaker southwestward countercurrent in the deep layer under the Ryukyu Current in February and July of 1998. Some warm or cold eddies in different scales, having direct influence on the Ryukyu Current, appear east of the Ryukyu Current in all the three cruises of 1998. The maximum velocity of the Ryukyu Current at Section OK is stronger in July, but weaker in February and April of 1998. The northeastward volume transports of the Ryukyu Current in February, April and July of 1998 are about 10×10^6, 3×10^6 and 8×10^6 m^3/s, respectively. The volume transport is smaller in April, partially due to the influence of a cyclonic eddy east of the Okinawa Islands. The calculated current velocities are in good agreement with those measured with vessel-mounted ADCP.

Key words : *Ryukyu Current, eddies*

1. Introduction

Hydrographic observation at OK line southeast of the Okinawa Island has been carried out by R/V Chofu Maru three (or four) times a year since 1993. The currents east of the Ryukyu Islands during 1992-1997 had been computed by use of the modified dynamic method and the modified inverse method in order to examine the seasonal and interannual variations of the Ryukyu Current before 1997 by LIU *et al.* (1998) and LIU *et al.* (2000). The northward Ryukyu Current often lies over the eastern slope of the Ryukyu Islands, while its velocity and volume transport (hereafter VT) have temporal variability. Weak current cores of the Ryukyu current can be identified still in the velocity distribution of OK line when the southward current east of the Ryukyu Islands was very strong in April of 1995 (LIU *et al.*, 1998). The Ryukyu Current was also found in all the three cruises (April, July and October) in 1997 (LIU *et al.*, 2000). The Ryukyu Current is stronger in summer and autumn, but weaker in spring, according to the statistical average of its maximum velocity (hereafter V_{max}) in 11 cruises during 1993-1996 (LIU *et al.*, 1998). Similar seasonal variation of the Ryukyu Current was also found in 1997 (LIU *et al.*, 2000). On the other hand, some eddies east of the Ryukyu Islands have direct influence on the Ryukyu Current, e.g., the stronger northward currents in summer and autumn of 1997 were partially attributed to the activities of warm eddies east of the Ryukyu Islands (LIU *et al.*, 2000).

The influence of eddies east of the Ryukyu Islands was much emphasized by NAKANO *et al.* (1998). They examined the temporal fluctuation of the geostrophic transport across the OK line from 1993 through 1997 and made a conclusion that no steady northeastward current was found in the east of the Ryukyu Islands. The structure of geostrophic velocity field varied correspondingly with the location of eddies (NAKANO *et al.*, 1998).

To examine the variation of the Ryukyu

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Table 1. Information about the observed data southeast of the Ryukyu Islands

Cruise	Sections	Observation period	Wind Speed(m/s)	Wind Direction(-)
9801	OK, L1, L2	1998.02.02-22	3.0	71
9804	OK, OE, OS	1998.04.26-29	3.4	146
9806	OK, OE, KR	1998.07.19-23	9.7	229

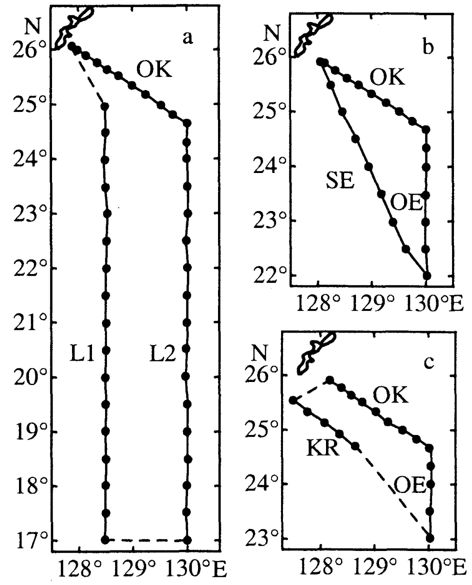

Fig. 1. Locations of CTD stations, sections and computation boxes in February (a), April (b) and July (c) cruises of 1998

Current and the effect of its adjacent eddies in 1998, we analyzed in this paper the CTD, ADCP and wind data east of the Ryukyu Islands obtained by R/V Chofu Maru in cruises 9801, 9804 and 9806 (see Table 1 and Fig. 1). Velocities and VTs of the currents east of the Ryukyu Islands are computed by the modified inverse method. Variation of the Ryukyu Current in 1998 is discussed in this paper, as well as interaction between the Ryukyu Current and its adjacent eddies.

2. Numerical computation and parameters

The modified inverse method (YUAN *et al*., 1998) has made the following four important modifications for the previous inverse model, i.e., (1) vertical eddy viscosity term in momentum equations, i.e., the flow is non-geostrophic, (2) vertical eddy diffusion term in the density equation, (3) an inequality constraint of heat transfer between atmosphere and ocean, and (4) β-effect. Computation boxes are shown in Fig. 1. In the computation by the modified inverse model mentioned above, each computation box is divided into five vertical layers with $\sigma_{t,p}$ values of 24.8, 26.0, 27.0 and 27.6 at the four interfaces. Due to lack of detailed wind data, a uniform wind field is assumed for each cruise and an average wind speed is obtained by vector averaging wind data observed at each CTD station during each cruise (see Table 1). Due to lack of heat flux data in this area, the heat inequality constraints will not be performed in the present study. Vertical eddy viscosity coefficient Az and vertical eddy diffusion coefficient K_v are taken to be 100 cm^2/s and 10 cm^2/s, respectively. An optimum reference level (ORL) of 2000 m is selected for the three cruises according to the empirical search method (FIADEIRO and VERONIS, 1983). In these computations, the following shallow water correction is adopted in the determination of the reference level: if the water depth of the station (H) is larger than the ORL, it is taken to be ORL, else it is taken to be H.

3. Computed results and discussion

3.1 Velocity distribution

The OK line is a northwest-southeastward section located southeast of the Okinawa Island. Hydrographic observations were conducted on February 2-4, April 26-27, and July 19-20, 1998. Velocity distribution at each section can be calculated by the modified inverse model. However, due to the limited pages, we will discuss the velocity distribution at Section OK only in these three cruises as follows.

In Fig. 2a (February, cruise 9801), there is a northeastward current (the Ryukyu Current) in the western part of Section OK. Its two current cores are located in the subsurface layer of computation points 4 and 5 and the middle layer of computation point 3. The two V_{max}

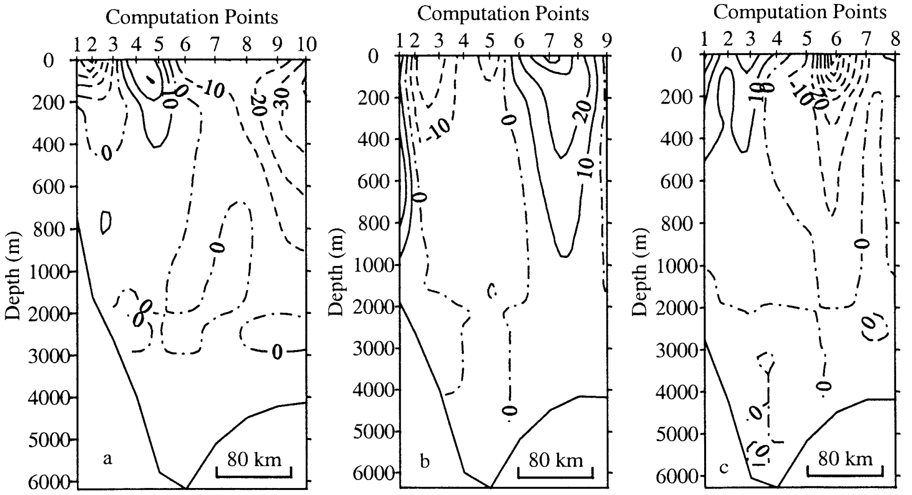

Fig. 2. Velocity distribution at Section OK in February (a), April (b) and July (c) of 1998 (cm/s; positive value: northeastward, negative value: southwestward)

values are 34 cm/s at 125 m level of computation point 5 and 15 cm/s at 700 m level of computation point 3, respectively. West of the Ryukyu Current, there is a stronger southward current in the surface layer west of computation point 3 near the Okinawa Island with its V_{max} of 59 cm/s in the subsurface layer of computation point 2. The area in the eastern part of Section OK is dominated mainly by a southward current. Distributions of geopotential anomaly referred to 1500 db show that there is an anticyclonic circulation southeast off the Okinawa Island (Figs. 3a, 3b, 3c). So both part of the Ryukyu Current and the eastern southwestward current make up a part of the anticyclonic circulation. The V_{max} of the southwestward current at computation point 3 and the northeastern current at computation point 7 are 28 and 43 cm/s in the surface layer, respectively. Both the velocities calculated by the modified inverse method and the geopotential anomalies are in good agreement with the currents measured with vessel mounted ADCP (Figs. 3a, 3b).

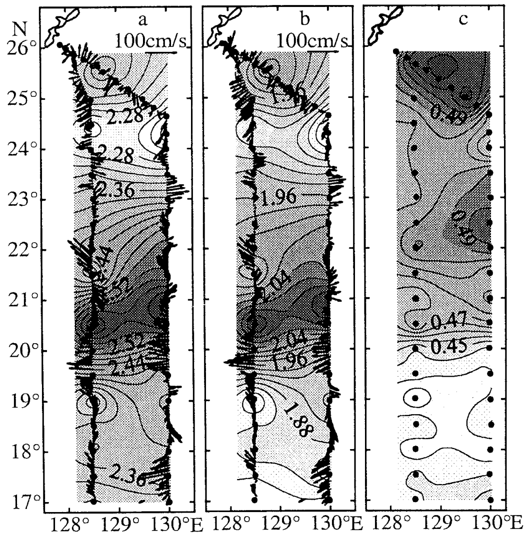

Fig. 3. Geopotential anomaly ($(10^{-2}\ m^2/s^2)$, ref. to 1500 db) and the currents measured with ADCP at 3 m (a), 97 m (b) and 800 m (c) levels in February of 1998

In Fig. 2b (April, cruise 9804), the Ryukyu Current is located at computation point 1 of Section OK near the Okinawa Island, with V_{max} of 31 cm/s at 600 m level. A southward current lies between computation points 2 and 5, and a northward current is located between computation points 6 and 8. Both of them make up the southern part of a cyclonic eddy, which can be identified from distributions of geopotential anomaly (Figs. 4a, 4b, 4c). This eddy has a large vertical extent, ranging from the surface to 1500 m depth or so. It seems that there is also an anticyclonic eddy at the southern part of Section SE south of Section OK.

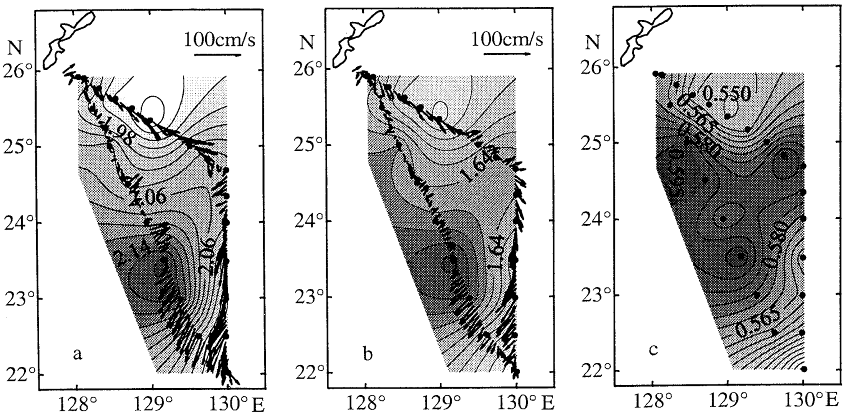

Fig. 4. Geopotential anomaly ($(10^{-2}\ m^2/s^2)$, ref. to 1000 db) and the currents measured with ADCP at 3 m (a), 97 m (b) and 800 m (c) levels in April of 1998

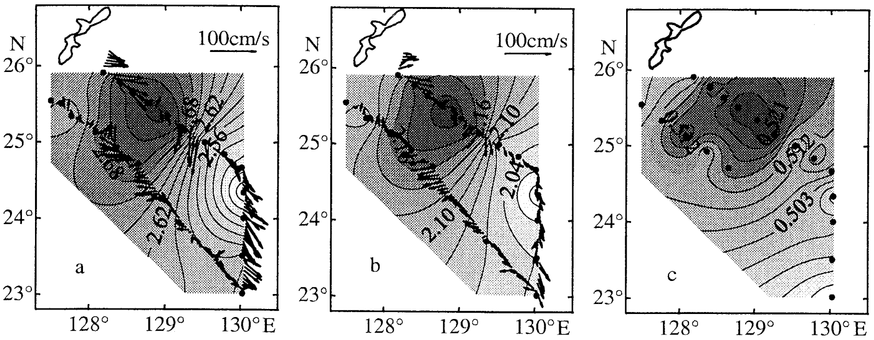

Fig. 5. Geopotential anomaly ($(10^{-2}\ m^2/s^2)$, ref. to 1500 db) and the currents measured with ADCP at 3 m (a), 97 m (b) and 800 m (c) levels in July of 1998

Temperature and salinity distributions (figures are not shown here) show that there are cold and warm water cores corresponding to the locations of the cyclonic and anticyclonic eddies mentioned above, respectively. Currents measured with ADCP at both 3 m and 97 m levels also confirm the above-mentioned two eddies and the Ryukyu Current (Figs. 4a, 4b). NAKANO *et al.* (1998) showed that a part of the high Sea Surface Dynamic Height (anticyclonic eddy) moved westward along 22° N and 25° N, and reached the area southeast of the Okinawa Island. These eddies affect the structure of geostrophic velocity field.

In Fig. 2c (July, cruise 9806), northeastward currents dominate the western part of Section OK. There are two northward current cores with V_{max} values of 42 and 29 cm/s at the surface layer of computation points 1 and 3, respectively. The eastern part of Section OK is dominated by a stronger southward current with V_{max} of 80 cm/s at 50m level of computation point 8. These two currents make up an anticyclonic eddy southeast off the Okinawa Islands, which can be identified from distributions of geopotential anomaly and ADCP currents (Figs. 5a, 5b, 5c). Horizontal temperature and salinity distributions (figures are not shown here) also show that there is a warm eddy southeast of Okinawa. This warm eddy shifts a little to the east in the deeper layer, and still exists at a depth of 1800 m or so. From Figs. 5 a, 5 b, 5 c, there is also a cyclonic flow in the eastern part of the computation area, which is to the southeast of the anticyclonic eddy mentioned above.

3.2 Variation of the Ryukyu Current

Calculated results indicate that there is a northeastward Ryukyu Current over the slope east of the Ryukyu Islands. Its V_{max} varies between 31～42 cm/s during the 3 cruises, which is similar to that in 1997 (LIU *et al.*, 2000). A southwestward current exists east of the Ryukyu Current in February, April and July of 1998, and a weaker southwestward countercurrent also exits in the deep layer under the Ryukyu Current in February and July of 1998. Some mesoscale warm/cold eddies appear east of the Ryukyu Islands in February, April and July of 1998, and they have direct influence on the Ryukyu Current. An anticyclonic eddy east of the Ryukyu Current strengthens the northward current, while a cyclonic eddy, weakens it. It is worthy to note that the sea surface height revealed by the altimetry data also show that there are active mesoscale eddies east of the Ryukyu Islands (NAKANO *et al.*, 1998).

The values of V_{max} of the Ryukyu Current at Section OK in February, April and July of 1998 were 34, 31 and 42 cm/s, respectively. As mentioned above, the Ryukyu Current may be weakened by the adjacent cyclonic eddy in April. The existence of the anticyclonic eddy east of the Ryukyu Current may partially account for the strengthening of the Ryukyu Current in July. However, the observed stations are far away from the Okinawa Island, and only a part of the Ryukyu Current near Okinawa is observed in both cruises 9804 and 9806. That is to say, the V_{max} values of the Ryukyu Current may be underestimated in the spring and summer cruises. Seasonal variation of the Ryukyu Current from spring to summer in 1998 is similar to that in 1997. The Ryukyu Current is also stronger in summer and weaker in spring of 1997. V_{max} at Section OK in spring and summer of 1997 were 25 and 47 cm/s, respectively (LIU *et al.*, 2000). It needs further investigation to identify whether the meso-scale eddies did cause the same seasonal variations of V_{max} in 1997 and 1998 or did not.

3.3 Volume transport

In the modified inverse computation, the total VTs flowing into and out from a computation box must be equal to each other. We will discuss the VT through Section OK and pay a special attention to the VT of the Ryukyu Current in each cruise as follows.

In February, the northeastward and southwestward VTs through Section OK are 12.0×10^6 and 21.8×10^6 m^3/s, respectively. It is very difficult to tell precisely the VT of the Ryukyu Current from the northward VT of the adjacent warm eddy, since it is not so simple as to draw a dividing line between the Ryukyu Current and the adjacent warm eddy. For a rough estimation, let's define the Ryukyu Current area in this cruise as the area between computation points 1 and 5 at Section OK in Fig. 2a, then the northward VT of the Ryukyu Current is about 10×10^6 m^3/s.

In April, the northeastward and southwestward VTs through Section OK are 19.3×10^6 and 11.2×10^6 m^3/s, respectively. The northward VT of the Ryukyu Current is about 3×10^6 m^3/s, which is smaller than that of 5×10^6 m^3/s in spring of 1997 (LIU *et al.*, 2000). The VT of the Ryukyu Current is a little underestimated due to the following two aspects: The observed stations are far away from the Okinawa Island, and only a part of the Ryukyu Current near Okinawa is observed in April. The small VT of the Ryukyu Current in spring can be also attributed to the influence of the cyclonic eddy east of the Okinawa Islands.

In July, the northeastward and southwestward VTs through Section OK are 11.7×10^6 and 15.9×10^6 m^3/s, respectively. The northeastward VT of the Ryukyu Current is about 8×10^6 m^3/s, which is smaller than that of 16×10^6 m^3/s in the summer cruise of 1997 (LIU *et al.*, 2000). This VT is also underestimated because only a part of the northeastward Ryukyu Current is observed due to the limited locations of the observed stations at the western end of Section OK near the Okinawa Island in this cruise as mentioned above.

4. Conclusions

Based on the CTD and wind data obtained by R/V Chofu Maru east of the Ryukyu Islands in 1998, the velocities and VTs of the currents east of the Ryukyu Islands are computed by the modified inverse method.

The calculated results indicate that the northeastward Ryukyu Current lies over the slope east of the Okinawa Island in February, April and July of 1998. A southwestward current also exists east of the Ryukyu Current in the three cruises of 1998, and a weaker southwestward countercurrent exits in the deep layer under the Ryukyu Current in February and July of 1998. Some warm or cold eddies in different scales appear east of the Ryukyu Current in all the three cruises of 1998, and they have direct influence on the Ryukyu Current.

The Ryukyu Current is stronger in July, but weaker in February and April of 1998 according to the maximum velocity of the Ryukyu Current at Section OK. The northeastward VT of the Ryukyu Current in February, April, and July of 1998 are about 10×10^6, 3×10^6 and 8×10^6 m^3/s, respectively.

Both the current velocities calculated by the modified inverse method and the distributions of the geopotential anomaly are in good agreement with the currents measured with vessel mounted ADCP.

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