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Seasonal changes of circulation in North Pacific by a MOM2 simulation

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Abstract : A Modular Ocean Model (MOM2) is used to simulate the circulation of the North Pacific, which is driven by climatological wind stress from HERLLERMAN and ROSENSTEIN (1983). The climatological temperature and salinity data (LEVITUS, 1982) is used as initial condition. After 8-years integration for annual forcing, monthly forcing is used to integrate the model for another 4-years.

The model results show that: (1) The Volume Transport (VT) of Kuroshio changes in the East China Sea from 27.5×10^6 m^3/s(SV) in winter to 32.9×10^6 m^3/s(SV) in summer, which is in contrast with that derived from Sverdrup relation. The North Equatorial Current (NEC) bifurcates at northernmost latitude in October and southernmost latitude in May, which influence the Kuroshio VT on PN section (near the Ryukyu Islands). This is caused by the seasonal shift of zeroline of wind stress curl over the southern part of the subtropical North Pacific. The vertical velocity difference is larger in summer, which also results in the a little larger VT of the Kuroshio on PN section in summer. (2) The Kuroshio bifurcates into two branches at the east of Taiwan. The main one flows northward into the East China Sea, and the other one flows northeastward to the region east of Ryukyu Islands. (3) There exists a permanent anti-cyclonic eddy south of Japan.

Key words : *Kuroshio, North Equatorial Current (NEC), seasonal change, wind stress curl*

1. Introduction

The seasonal change of the Kuroshio has been extensively studied, especially on PN section (near the Ryukyu Islands). About the Volume Transport (VT) of the Kuroshio across PN section, YUAN *et al.* (1994), using 11 cruises data from 1987 to 1994, got the result of 28.6×10^6 m^3/s. On average, the VT is strong in summer than in autumn. ICHIKAWA and BEARDSLEY (1993) used the hydrographic data from 1986 to 1989 and found that the VT of the Kuroshio west of the Ryukyu Islands equaled $27.6\pm3.7\times10^6$ m^3/s. Numerical models have also been used to explain the reason of a little larger VT of the Kuroshio on PN section in summer than that in winter, which is out of phase predicted by the Sverdrup Balance. KAGIMOTO and YAMAGATA (1997) used the POM model and found that the JEBAR (Joint Effect of BAroclinity and bottom Relief) effect is the main reason. By a 2-layer model SAKAMOTO and YAMAGATA (1996) proved that the role of JEBAR makes the total transport of the Kuroshio relatively insensitive to seasonal changes of winds as observed. Also by a 2-layer model SEKINE and KUTSUWADA (1994) proposed that some part of VT of western boundary current passes the eastern side of Nansei Islands in winter. In fact, the change in the Kuroshio VT is much influenced by the variation at the upstream side. Using a reduced gravity model and 20-years wind data, QIU and LUKAS (1996) found that the Kuroshio (at 20°N) has a seasonally minimum (maximum) VT in fall when the North Equatorial Current (NEC) bifurcates seasonally at the northernmost (southernmost) latitude which is influenced by the shift of wind stress curl of the North Pacific.

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The motivation of this paper is to find the influences of the seasonal shift of wind stress curl over the subtropical region to the seasonal change in VT of the Kuroshio on PN section. By a MOM2 simulation with seasonal wind and stratification, we found that the shift of the NEC bifurcation position caused change in the Kuroshio VT not only in the low-latitude but also in the mid-latitude such as on PN section. The summer stratification is also the reason of the larger Kuroshio VT on PN section in summer than in winter.

2. Ocean Model

A Modular Ocean Model (MOM2) is used to simulate the circulation of the North Pacific. The model domain is from 1° N to 61° N and from 120° E to 90° W. The grid size changes from 0.25 to 1 degree both in meridional and zonal directions, most fine in the Northwest Pacific. The model has 7 layers in vertical direction. The depths at the bottom of each level are 30 m, 60 m, 192.2 m, 694.0 m, 1794.0 m, 3492.1 m, 5560 m, respectively. All the four boundaries are closed. The ETOPO5, 1/12° world topography data set from the *National Oceanic and Atmospheric Administration* (1988), is smoothed to our model grid. On the north and south boundaries, sponge layers are adapted in which temperature and salinity are restored to the climatological values with the restoring time changing from 25 days outside to 75 days in the interior. Temperature and salinity are also restored on the surface boundary. Climatological wind stress data from HERLLERMAN and ROSENSTEIN (1983) is used. The climatological temperature and salinity data (LEVITUS, 1982) is used as the initial condition. The annual forcing is used to integrate the model from the rest state during 8-years. After that, monthly forcing is used to integrate the model for another 4-years. A seasonal equilibrium has reached for the upper layers. We have compared the results between hrizontal eddy viscosity (SMAGORINSKY, 1963) and constant eddy viscosity. Our result shows that the SMAGORINSKY scheme is more capable to simulate the mesoscale phenomena.

3. Computed results and discussion

3.1. Variation of NEC bifurcation position

Figure 1a and 1b show that the zeroline of wind stress curl shifts toward the southernmost latitude in May and northernmost latitude in October. By the Sverdrup relation, the NEC shifts seasonally (Figs.1c and 1d), and the shift of the NEC causes the seasonal change in the NEC bufurcation position at the western boundary (Fig.2a). QIU and LUKAS (1996) used the FSU (Florida State University) wind data and got the similar result. XU and YUAN (1995) used the TOGA data from 1986 to 1989 and found the same seasonal changes in the NEC bifurcation at the 130° E section.

3.2 East of Taiwan

The Kuroshio east of Taiwan separates into the two branches: the main brabch flows through the ridge northeastern of Taiwain and then flows along the continental slope of the East China Sea, and the other eastern branch flows east of the Ryukyu Islands. The two branches confluence together in the region south of Japan. Figures 3a and 3b show the velocity structure across the 23.125° N section in May and October at the 12th model years. The depth of 20cm/s velocity isoline reaches 600m in May but only 400 m in October. The maximum velocity reaches 92.1 cm/s in May and 69.0 cm/s in October. This means that the Kuroshio is intensified in the upper layer and the vertical difference is larger in summer than in winter. This is caused by the stratification effect in summer. SUN and KANEKO (1994) reported the similar measured phenomena. LIU *et al.* (1992) have pointed out that in winter the Ekman effect of the northeasterly monsoon caused the shallowing of the thermocline.

3.3. East China Sea

Figure 2b shows the variation of monthly mean VT of the Kuroshio on PN section. It is larger in May than in October. The VT in PN section is 31.0, 31.9, 32.1, 27.5 × 10^6 m^3/s in January, April, July and October respectively. KAGIMOTO and YAMAGATA (1997) got the similar result by POM simulation. Figures. 4a and 4b are the stream function of May and October

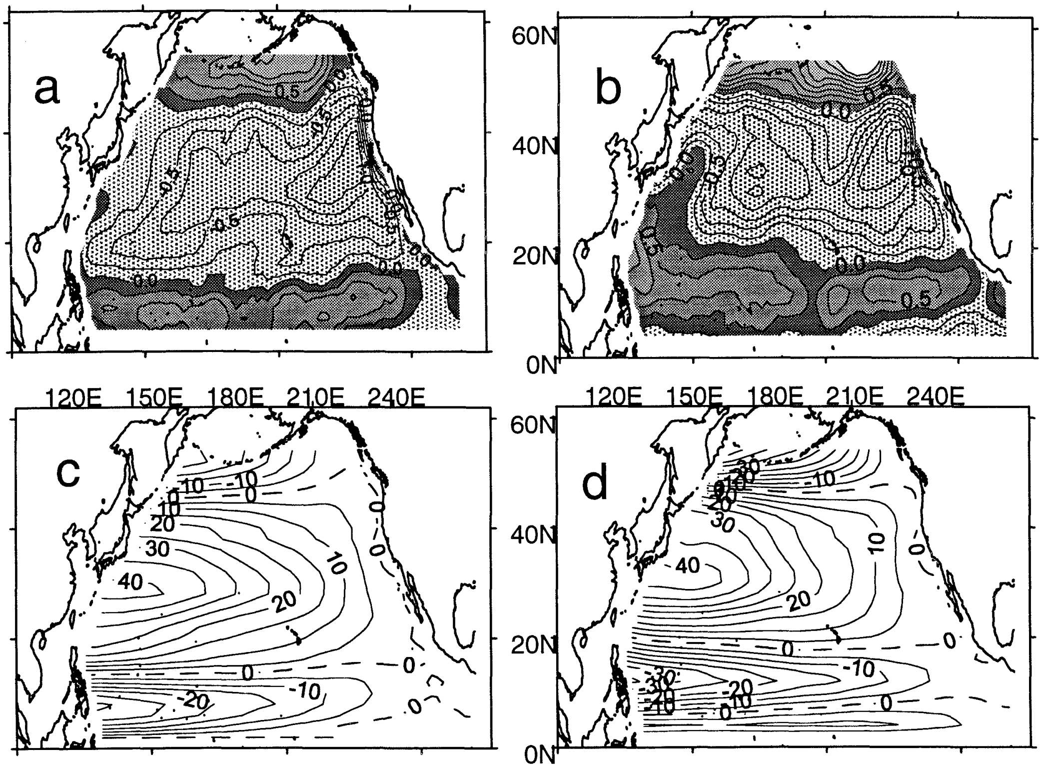

Fig. 1. Climatological wind stress curl from Herllerman and Rosenstein (1983) (CI=10^{-8} dyn/cm^3): (a) May and (b) October, and stream function from the Sverdrup Balance (CI=5×10^6 m^3/s): (c) May and (d) October.

respectively. Comparing the 60×10^6 m^3/s isoline in May with that in October, it is closer to Taiwan in May than in October. This means that the Kuroshio approaches the eastern coast of Taiwan with larger VT in May than in October, so that larger VT of the Kuroshio can flow into the Okinawa Trough through the ridge and cause a little larger VT of the Kuroshio on PN section in May than in October. This origin of this process is ascribed to the fact that NEC bifurcates at the southern latitude in May than in October. Therefore we propose that the wind stress curl and stratification are the main reasons of larger summer VT of the Kuroshio on PN section. When compared with the real measurement of VT of the Kuroshio, we shall be caution that the interannual changes also influence the VT of the Kuroshio significantly. Kawabe (1998) have reported that the variation of Kuroshio VT has 20-year period. Qiu and Lukas (1996) showed that the wind stress curl changing with the timescale of the El Niño Southern Oscillation (ENSO) can influence the Kuroshio VT.

3.4. South of Japan

There is a permanent anticyclonic eddy south of Japan. The VT reaches 115×10^6 m^3/s in winter (in January, not shown here) and 97.9×10^6m^3/s in October (Figure 4b). This is in consistent with the Sverdrup theory. Sekine and Kutsuwada (1994) has got the similar result by a 2-layer model.

4. Conclusions

In this paper, we have discussed the influence of the seasonal shift of wind stress curl to the Kuroshio VT variation on PN section. The seasonal shift of wind stress curl firstly causes the seasonal meridional shift of NEC bifurcation position, which can make the seasonal change in the Kuroshio VT east of Taiwain, and at last cause the seasonal change in the Kuroshio VT on PN section. It should be

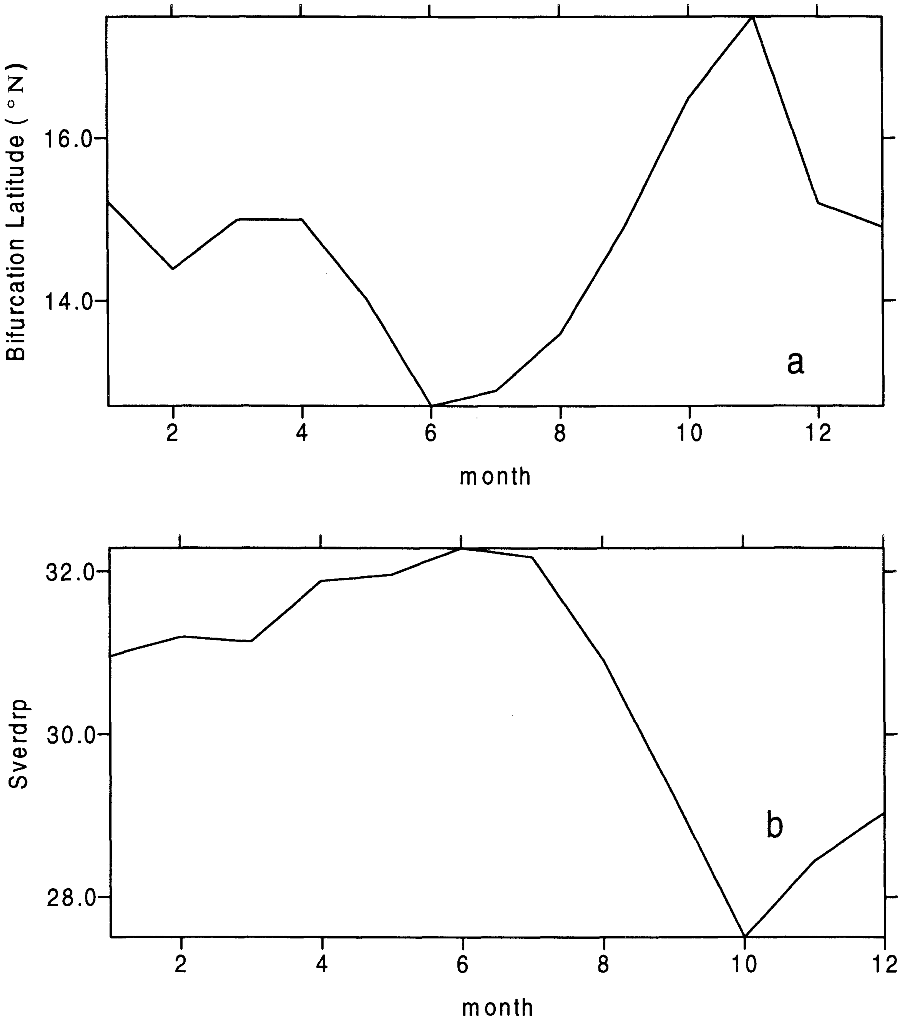

Fig. 2. (a) monthly change in the North Equatorial Current bifurcate position at the 125° E section,
(b) monthly change in Volume Transport at PN Section (unit: $10^6 m^3/s$)

mentioned that the interannual changes influence the VT of the Kuroshio significantly (QIU and JOYCE, 1992; KAWABE, 1998), and the mesoscale eddies influence the Kuroshio path and its VT frequently (YANG *et al.*, 1999). We got the following conclusion in this study:

1) On the 125°E section the NEC bifurcates at the northernmost latitude in October and southernmost latitude in May. This is caused by the seasonal shift of zeroline of wind stress curl over the southern part of subtropical North Pacific. This seasonal shift also causes the variation of VT of the Kuroshio in the East China Sea.

2) The vertical velocity difference is larger in summer. This is caused by stronger stratification in summer. This is one of the main reason of larger Kuroshio VT in summer.

3) The Kuroshio VT on PN section is 31.0, 31.9, 32.1, $27.5 \times 10^6 m^3/s$ in January, April, July and October respectively. The VT of the Kuroshio is strong in summer and weak in autumn.

4) The Kuroshio separates into the main branch and the eastern branch in the east of Taiwan.

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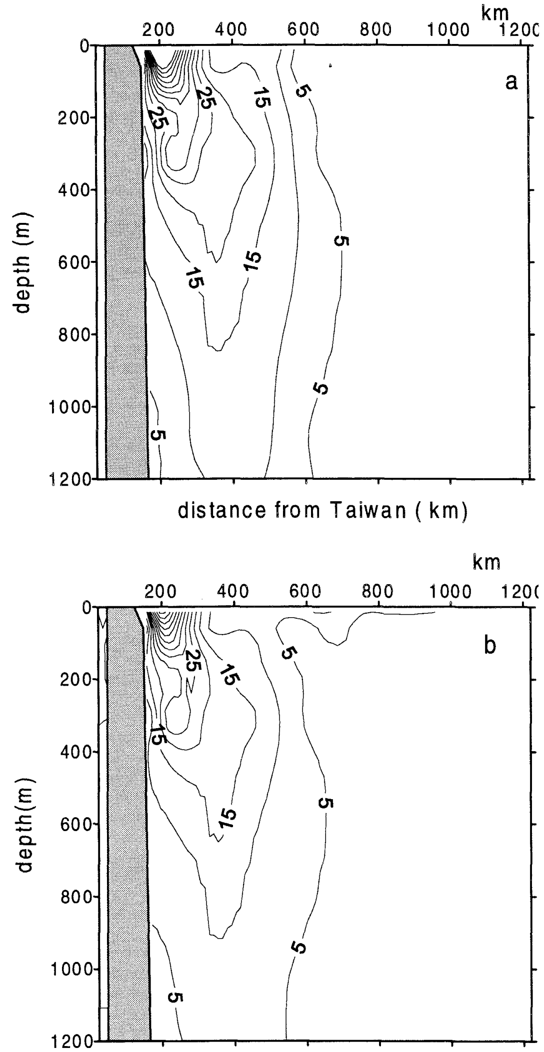

Fig. 3. Velocity structures at 23.125°N for 12 years integration: (a) May (Maximum velocity=92.1cm/s), (b) October (Maximum velocity=69.0 cm/s)

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References

Ichikawa, I. and R. C. Beardsley (1993): Temporal and spatial variability of volume transport of the Kuroshio in the East China Sea. Deep Sea Research. **40**, No.3, 580–605.

Kagimoto, T. and T. Yamagata (1997): Seasonal transport variations of the Kuroshio: An OGCM simulation. J. Physical Oceanography. **27**, 403–418.

Kawabe M.(1998): How important is the monitoring of decadal variation of Kuroshio for the ocean and atmosphere climate? Joint GCOS-GOOS WCRP Ocean Observations Panel for Climate (OOPC) 3rd session, France.

Herllerman, S., and M. Rosenstein (1983) Normal monthly wind stress over the world ocean with error estimate. J. Physical Oceanography. **13**,

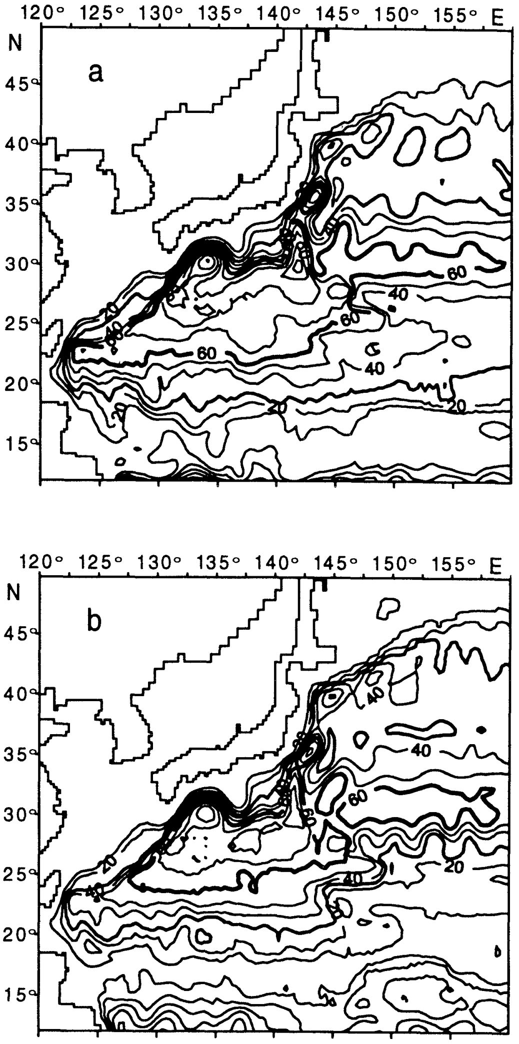

Fig. 4. Stream Function for 12-years integration (CI=10×10^6 m^3/s): (a) May, (b) October

1093–1104.

LEVITUS, S., (1982): Climatological atlas of the World Ocean NOAA Professional Paper No. 13 U.S. Government Printing Office, Washington D. C 173PP.

LIU, K–K., G.–C. GONG, C.–Z. ZHYU S.–C. PAI C.–L. WEI and S.–Y. CHAO (1992): Response of Kuroshio upwelling to the onset of northeast monsoon in the sea north of Taiwan: Observations and a numerical simulation. J. Geophysical Research. **97**, 12511–12516.

National Oceanic and Atmospheric Administration (1988): Digital relief of the surface of the Earth, Data Announce. 88–MGG–02, http://www.ngdc.noaa.gov / mgg / global / selttopo.html, Natl. Geophys. Data Cent., Boulder, Colo.

QIU, B., and T. JOYCE (1992): Interannual variability in the mid and low latitude western North Pacific. Journal of Physical Oceanography, **22**, 1062–1079.

QIU, B., and R. LUKAS (1996): Seasonal and interannual variability of the North Equatorial Current, the Mindanao Current and the Kuroshio along the Pacific western boundary. J. Geophysical Research. **101**, 12315–12330.

SAKAMOTO, T. and T. YAMAGATA (1996): Seasonal transport variations of the wind–driven ocean circulation in a two–layer planetary geostrophic model with a continental slope. J. Marine Res. **54**, 261–284.

SEKINE, Y., and K. KUTSUWADA (1994): Seasonal variation in volume transport of the Kuroshio south of Japan. J. Physical Oceanography. **24**, 261–272.

SMAGORINSKY, J. (1963): General circulation experiments with the primitive equations: I. The basic experiment. Monthly Weather Review, **91**, 99–164

SUN, X., and I. Kaneko (1994), Variations of Kuroshio during the period of 1989–1991. Proceedings of China_Japan Joint Symposium of the Cooperative Research on the Kuroshio, China Ocean Press. 41–61.

YANG, Y., C.-T. LIU, J.-H. HU, and M. KOGA (1998): Taiwan Current(Kuroshio) and impinging eddies. J. Oceanography , 1999, **55**, 609–617.

YUAN, Y., Z. PAN, I. KANEKO, and M. ENDOH(1994): Variability of the Kuroshio in the East China Sea and the currents east of Ryukyu Islands., Proceedings of China–Japan JSCRK, Qingdao, China Press, 121–144.

XU, D.-F., and Y.-C. YUAN (1995): The calculation of the circulation east of Philippine Sea. Oceanography in China. Vol. 5, 84–97.

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