A case study of a cyclonic eddy structure observed in the south of the Kuroshio Extension by using profiling floats

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We deployed two profiling floats in the region south of the Kuroshio Extension in March 2000 as a preliminary study of the Japan ARGO project. Temperature and salinity profiles from the depth of 1500×10^{-4}Pa to the surface are reported every two and four weeks, respectively. Based on the float observations, together with altimeter data, we investigated water mass in the region and analyzed vertical structure of a cyclonic eddy, that advected the two floats from May through July 2000. The analysis showed that the eddy had typical character of the mesoscale eddy commonly seen south of the Kuroshio Extension region.

Keywords : Profiling float, ARGO project, cyclonic eddy

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1. Introduction

International meteorological and oceanographic organizations such as the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of UNESCO, and other related institutions have started conducting an international project that named ARGO. In the project about 3000 profiling floats will be deployed in the World Ocean in a few years, so that we will be able to construct a near real time monitoring system of ocean's upper and middle layer, with spatial and temporal resolutions of about 300km and ten days (The Argo Science Team, 2000 [1]).

In order to contribute the international ARGO project, a 5-year, inter-ministerial project of "The Establishment of Advanced Ocean Observation System" has started under "The Millennium Project" of the Japanese Government. The research group of Oceanic Variation in Subsurface and in the Middle Layer, Frontier Observational Research System for Global Change (FORSGC) has been established to achieve the goals of the 5-year project, in cooperation with the Ocean Observation and Research Department, Japan Marine Science and Technology Center (JAMSTEC). The project started in April 2000 and will be completed by the end of 2004. The project has been called as "Japan ARGO" or "J-ARGO".

FORSGC and JAMSTEC deployed two profiling floats in the region south of the Kuroshio Extension in March 2000, as a preliminary study of J-ARGO (Iwasaka et al., 2002 [2]). The aim is to see performance of the floats because we had little experience at the moment in using such profiling floats with temperature and salinity sensor. There were two major reasons that we chose the deployment region. One was that there were no strong currents there so that the floats had been expected to stay around the deployment point. The other reason was that the region was scientifically very interesting since there were several important water masses such as the North Pacific Subtropical Mode Water (NPSTMW) there. NPSTMW, a thermostad in the upper layer south of the Kuroshio and Kuroshio Extension with temperature range of 16-19°C (e.g., Suga, 1997 [3], Hanawa and Talley, 2001 [4]), is the most interesting and important water mass in the subsurface layer in the northwestern region of the subtropical gyre in the North Pacific.

In the present study, we will present some results of observations south of the Kuroshio Extension and try to reconstruct vertical structure of an eddy that advected the floats based on the float observation, in order to demonstrate how useful the profiling floats are for oceanographic observations.

2. Performance of the Profiling float

The profiling floats used in the present study are the Apex-type floats of Webb Research Co., with the CTP sensors of Sea Bird Electronics (SBE) Co. type 41. Parking depth of the floats is 1500×10^{-4}Pa, the maximum parking depth of this type of the float at this time. The float measures temperature and salinity at 58 levels from 1500×10^{-4}Pa to the sea surface (Table 1). One of the floats repeats its observation every two weeks and the other every four weeks. The specification of the

Table 1 Sampling layers of the floats used in the present study

Layer No.	Depth (×104Pa)	Layer No.	Depth (×104Pa)
0	deepest level	31	520
1	1500	32	500
2	1400	33	480
3	1300	34	460
4	1250	35	440
5	1200	36	420
6	1150	37	400
7	1100	38	380
8	1050	39	360
9	1000	40	340
10	975	41	320
11	950	42	300
12	925	43	280
13	900	44	260
14	875	45	240
15	850	46	220
16	825	47	200
17	800	48	180
18	780	49	160
19	760	50	140
20	740	51	120
21	720	52	100
22	700	53	80
23	680	54	60
24	660	55	40
25	640	56	20
26	620	57	10
27	600	58	5
28	580		
29	560		
30	540		

floats is not the same as that for ARGO project (The Argo Science Team, 2000 [1]) because the floats were deployed as a preliminary study for J-ARGO project. The period of two weeks was chosen arbitrarily but is appropriate for monitoring low frequency variability south of the Kuroshio Extension. The four-week-period was chosen for the second float in order to find out what would happen on the CTP sensor during the long-term observation because it was expected to have lifetime of more than 7 years. Hereafter, we will call the float of the 2-week-period cycle (WMO ID 29033) as Float-14 and that of the 4-week-period cycle (WMO ID 29032) as Float-28, respectively.

The two profiling floats were deployed on March 21st, 2000 at 30° 01'N, 143° 19'E, south of the Kuroshio Extension during the MR00-K02 cruise of R/V Mirai, JAMSTEC. Trajectories of the floats are shown in Fig. 1. They moved anti-clockwise from the deployment position until early August 2000. After that, however, both of them failed in surfacing because sea surface temperature (SST) there was so high that buoyancy of the floats was not enough for them to reach the sea surface. Float-28 began surfacing late October and Float-14 in December 2000. After they came back to observation, they have continued observation except for a short period in summer 2001 but they have shown small but not negligible biases on their salinity observations.

Accuracy of the salinity sensors on the floats is evaluated by comparing their observations with the CTD observations by R/V Mirai at deployment point and with those by S/V Tenyo of Japan Coast Guard in July 2000 in an area around the surfacing point of Float-28. At the beginning of the observation, mean differences between the float observation and those of the CTD data for salinity are -0.3×10^{-3}, and the root mean square of the difference is 1.7×10^{-3} for Float-14, and the average and

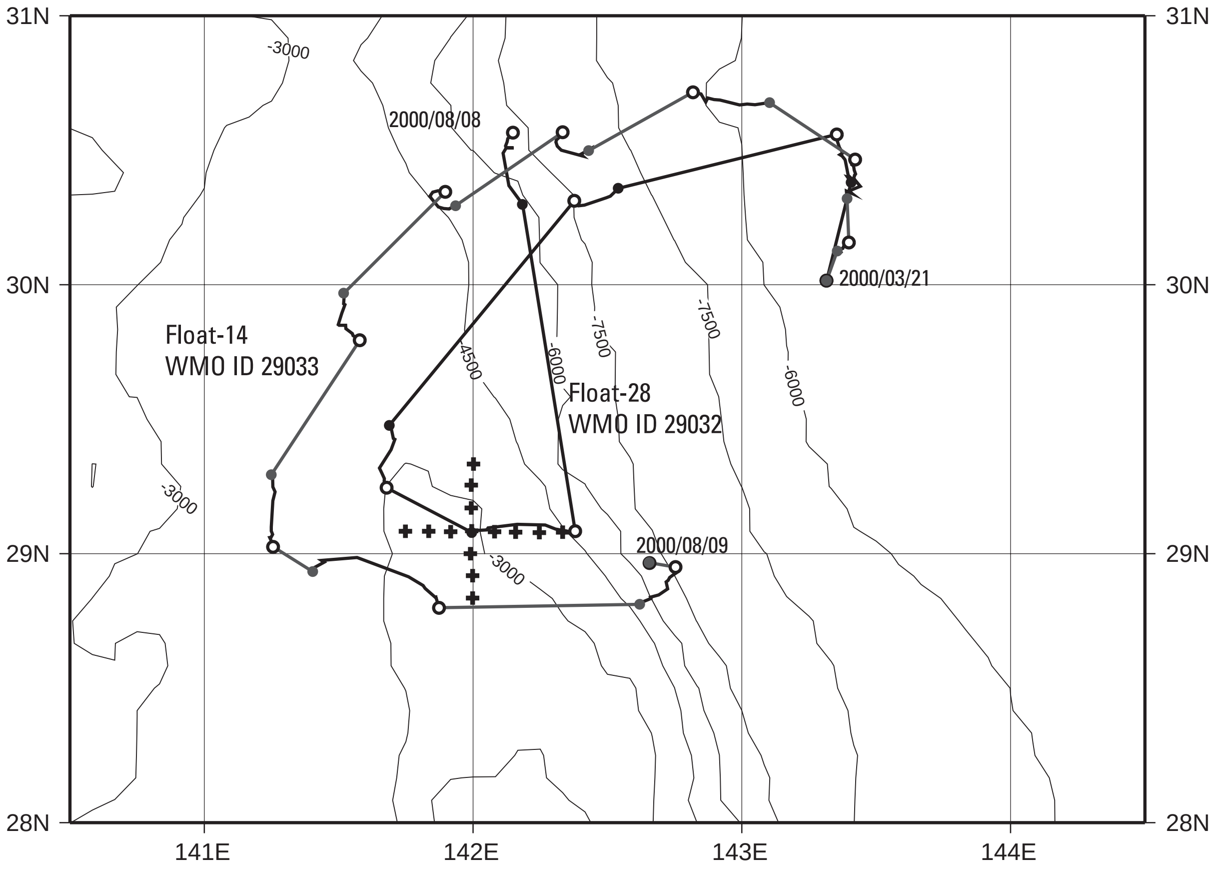

Fig. 1 Trajectories of the two floats from their deployment through the positions in early August. Small solid circles show the positions of the sinking positions and open circles indicate surfacing positions. Crosses indicate the CTD observation stations performed by S/V Tenyo. The figure is cited from Iwasaka et al. (2002) [2].

root mean square differences for Float-28 are -3.1×10^{-3} and 2.3×10^{-3}, respectively. About 4 months later, they still very good performance. That is, mean difference between the float observation and that by S/V Tenyo is 5.0×10^{-3} and root mean square difference between them is 7.7×10^{-3}, respectively for Float-14. For Float-28 average salinity difference between the CTD observation made by S/V Tenyo and that of the float is 0.3×10^{-3} and the root mean square difference is 0.4×10^{-3}, respectively (Iwasaka et al., 2002[2)]). Based upon the comparisons, we can conclude that the salinity sensors on the floats had performed very well from March through July and had enough accuracy (better than 0.01) for physical oceanographic purposes and for ARGO project. Thus, we do not apply any correction to the float observations obtained during the period.

However, as mentioned before, the floats failed in surfacing during high SST season. After that they showed some bias on the observed salinity values.

3. A case study of a cyclonic eddy structure

The two floats were moved anti-clockwise after the deployment until they failed in surfacing in early August 2000, as can be seen in Fig. 1. Based upon the data obtained by the two floats in the spring and early summer 2000, we investigated water mass distribution south of the Kuroshio Extension and the vertical structure of the cyclonic eddy that caught the floats from late April to early July 2000.

3.1. Data

Besides the float observations, CTD data by the R/V Mirai and that of S/V Tenyo were used in the present analysis.

TOPEX/Poseidon (T/P) altimeter data was used to see the sea surface height around the floats. We obtained the near-real time data of T/P altimeter from the WWW home page of National Environment Satellite, Data and Information Service (NESDIS), the National Oceanic and Atmospheric Administration (NOAA), U.S.A. The data was processed by applying a Gaussian window with a decorrelation time scale of 15 days, zonal and meridional decorrelation scales of 250km and 200km. The smoothed data was re-sampled to give 0.25-degree-by-0.25-degree grid data set. This data is used to examine the relation between the float trajectories and sea surface height.

3.2. Water mass south of the Kuroshio Extension

Figures 2 and 3 show time-depth cross sections of temperature and salinity from April through July 2000 observed by Float-14 and Float-28, respectively. In April, mixed layer was developed to the depth of about 300m. A seasonal thermocline began to develop in May in upper 100m layer. The thirmocline became sharpened as season progressed. NPSTMW (16-19°C) appeared in upper 300m in spring but became thinner in early summer when the floats were to the south of their deployment point.

Contour lines of temperature and salinity show wavy feature, i.e., the contour lines was raised in May and early July while those was lowered in June. Clmatology of the temperature and salinity fields, e.g., World Ocean Atlas 98 (a product of National Oceanographic Data Center, NOAA, U.S.A,), does not show such wavy character in the time-depth cross sections along the float trajectories. Taking sigma-theta as a vertical coordinate instead of depth (pressure), neither temperature nor salinity fields show wavy features in their time-sigma-theta cross sections (figures are not shown). This suggests the wavy character be not due to the distribution of different water masses, but to dynamical change in the structure there.

All the observations from April through July are plotted as a T-S diagram in Fig. 4. Except for surface and salinity minimum layers, the points distribute almost on a single curve. Typical water masses in the region can be seen on the T-S diagram, such as NPSTMW, North Pacific Central Water, North Pacific Central Mode Water, and so on.

3.3. A cyclonic eddy structure

The floats moved anti-clockwise from May through July (Fig. 1), drawing almost parallel, anti-clockwise arcs. Float-14 always moved along the outer arc. Average speed of the movement is estimated to be $0.30 ms^{-1}$ for Float-14 and $0.42 ms^{-1}$ for Float-28 at the sea surface according to the surface float positions reported from the ARGOS system. Average speed at the drifting level is estimated to be $0.03 ms^{-1}$ for Float-14 and $0.05 ms^{-1}$ for Float-28, respectively.

These facts suggest that a cyclonic eddy caught the floats during the period. In order to confirm that, we compared the float trajectories with sea surface height maps that derived from T/P altimeter data.

The cyclonic eddy that caught the floats was first clear-

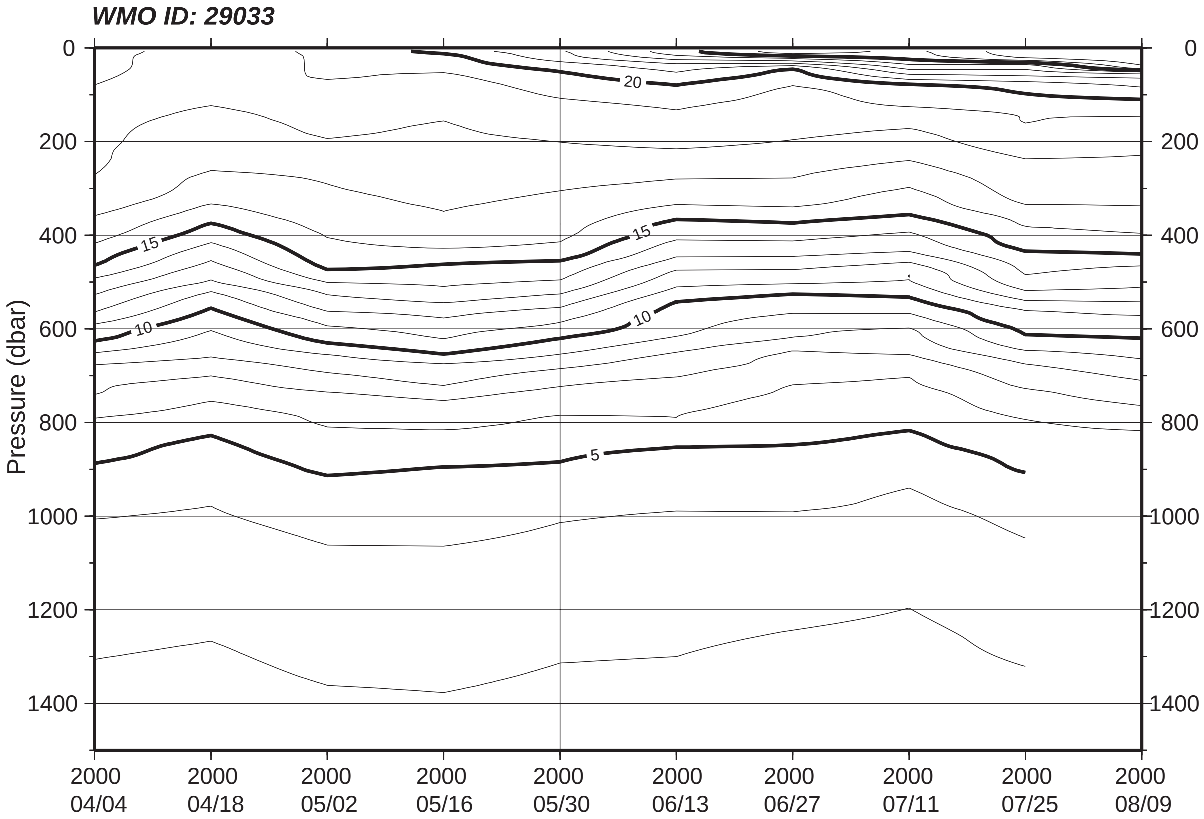

Fig. 2a Time-depth cross section of the temperature for Float-14.

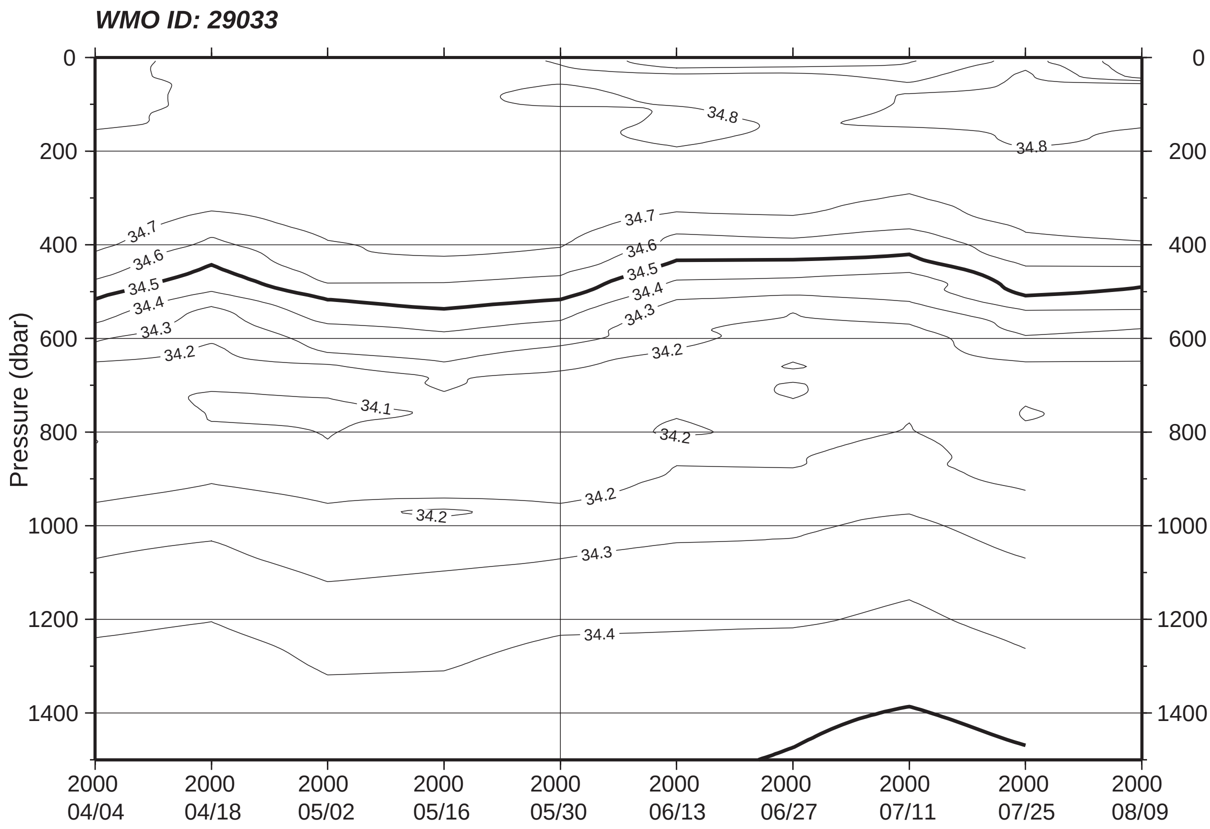

Fig. 2b Same as Fig.2a, except for salinity.

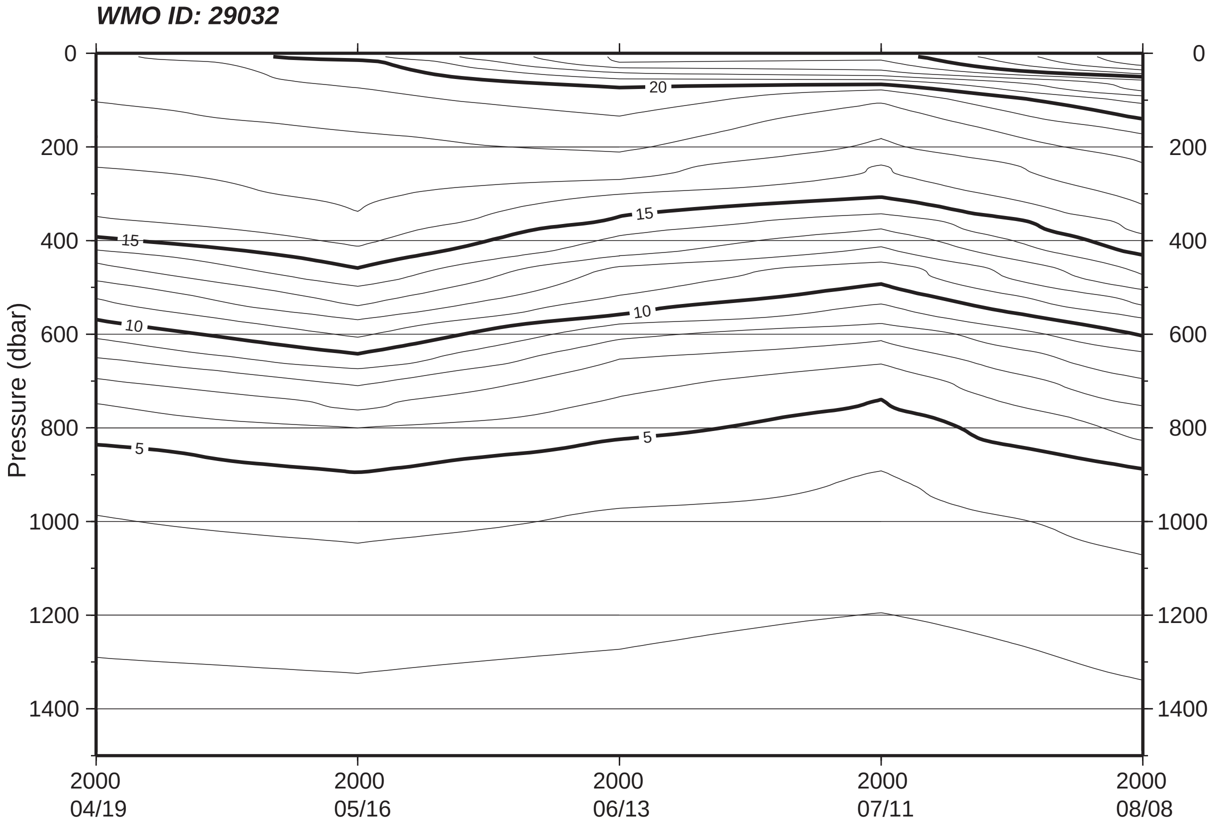

Fig. 3a Same as Fig.2a, except for Float-28.

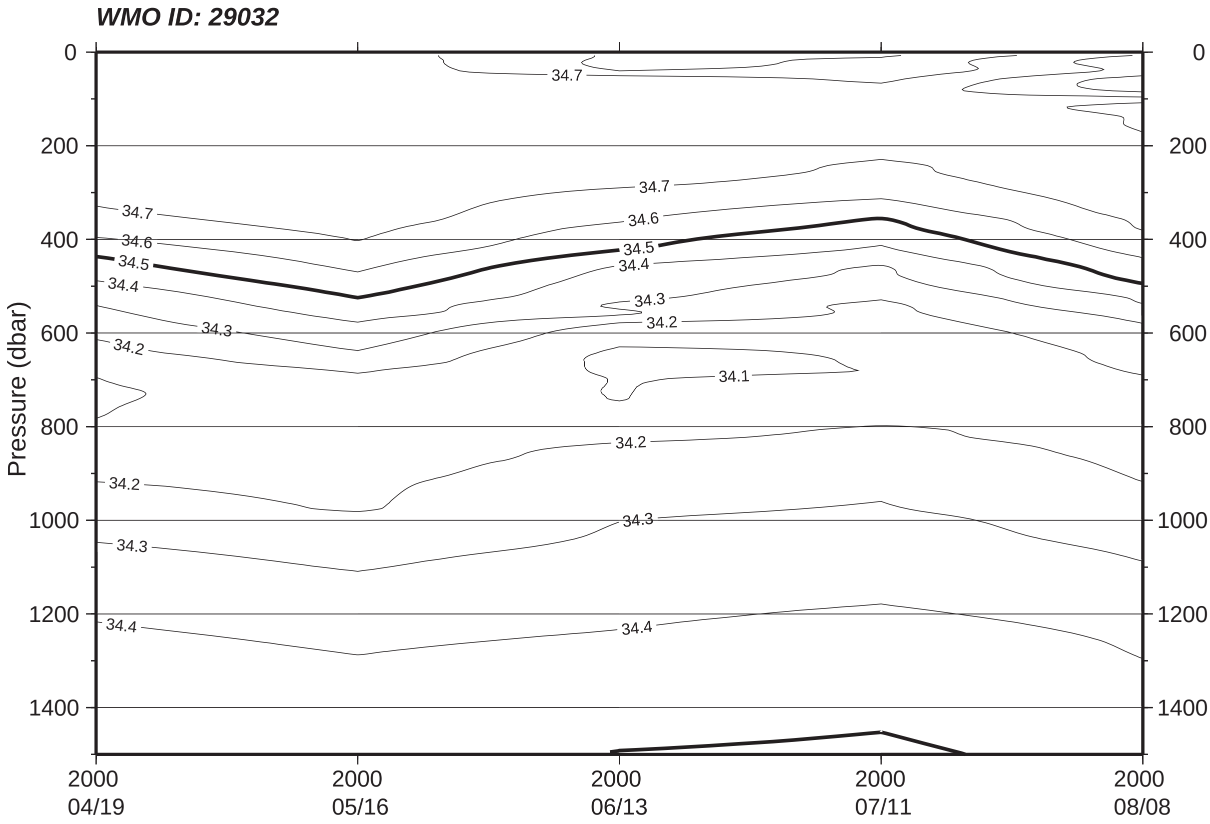

Fig. 3b Same as Fig.2a, except for salinity.

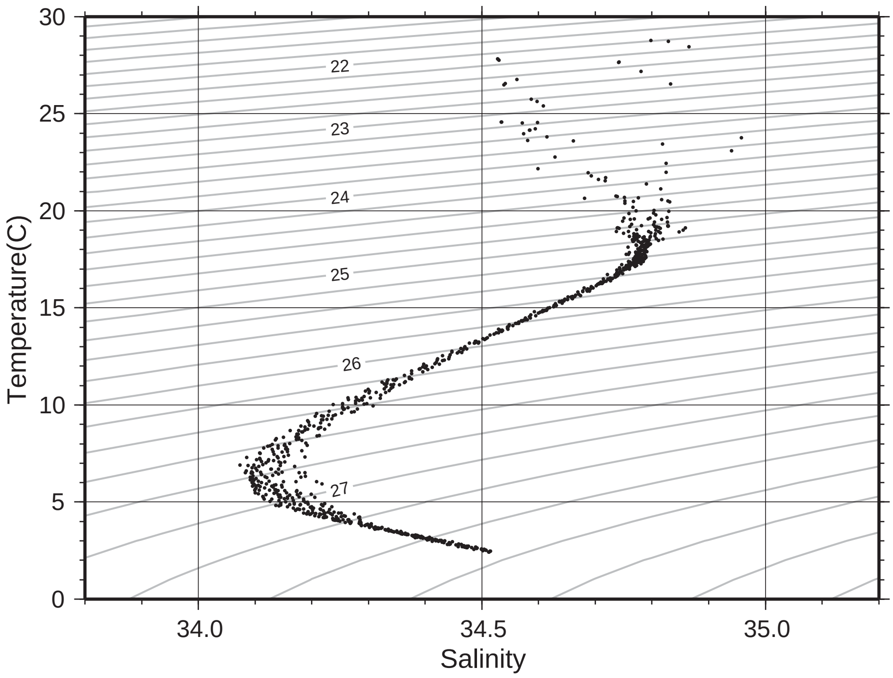

Fig. 4 T-S diagrams of all observations obtained by the two float before August 2000.

ly seen on the T/P map in middle of May 2000. Center of the eddy first located around 29°N, 143°E, then it moved slowly to the west as the eddy became intensified until middle of June. The eddy became weaker as it approached to the Izu-Ogasawara ridge and disappeared in early August. The two floats first located in the northern flank of the eddy in early May. They moved to the northwest of the eddy in late May. In June, they located in the western flank of the eddy. In early July, the floats approached to the center of the eddy from the southwestern flank.

In order to summarize the behavior of the eddy and relative positions of the floats to the eddy, we show Figure 5. This shows the time-longitude cross section of the sea surface height anomaly based on T/P altimeter data, in the latitudinal belt of 29°N-30°N, from 135°E to 155°E and from February 29th through August 22nd. The latitudinal belt was chosen because the floats stayed in the zone during the period. In the figure, dots denote longitudes of the surfacing points of each float. As can be seen in the figure, a negative anomaly appeared in April between 141°30E and 145°E and expanded to the west until late June. The anomaly disappeared in middle of July in the latitudinal band. The floats were on the western side of the negative anomaly from May through July.

We also referred to the maps of sea surface height produced by the Stennis Space Center, the U. S. Naval Research Laboratory based on T/P, ERS-1 and GOF altimeter (http://www7320.nrlssc.navy.mil/altimetry/) by using MODULAR OCEAN DATA ASSIMILATION SYSTEM (MODAS; http://www7320.nrlssc.navy.mil/modas/). The general character of the eddy described above can be seen in the maps, too.

Differences seen in temperature and salinity observed at the same level between the two floats can be explained by assuming that Float-28 was advected closer to the center of the cyclonic eddy than Float-14. That is, temperature and salinity observed by Float-14, the outer float, is higher by about 0.2-0.8K in temperature and about 0.02-0.08 in salinity at each level above 800×10^{-4}Pa depth. Below the level, temperature observed by the outer float is slightly higher by up to 0.2K. Salinity values observed by the outer float just below the salinity minimum layer showed larger than those by the inner float, by up to 0.02, but below about 1000×10^{-4}Pa depth, differences in salinity between the floats did not show general tendency. These differences are consistent with temperature and salinity structure of typical cyclonic eddy (e.g., Ebuchi and Hanawa, 2000[5)]). Time change of the temperature and salinity profiles observed by the floats can also be explained by time change of relative positions of the floats and center of the eddy. That is, as the floats approached the center from May, main thermo-

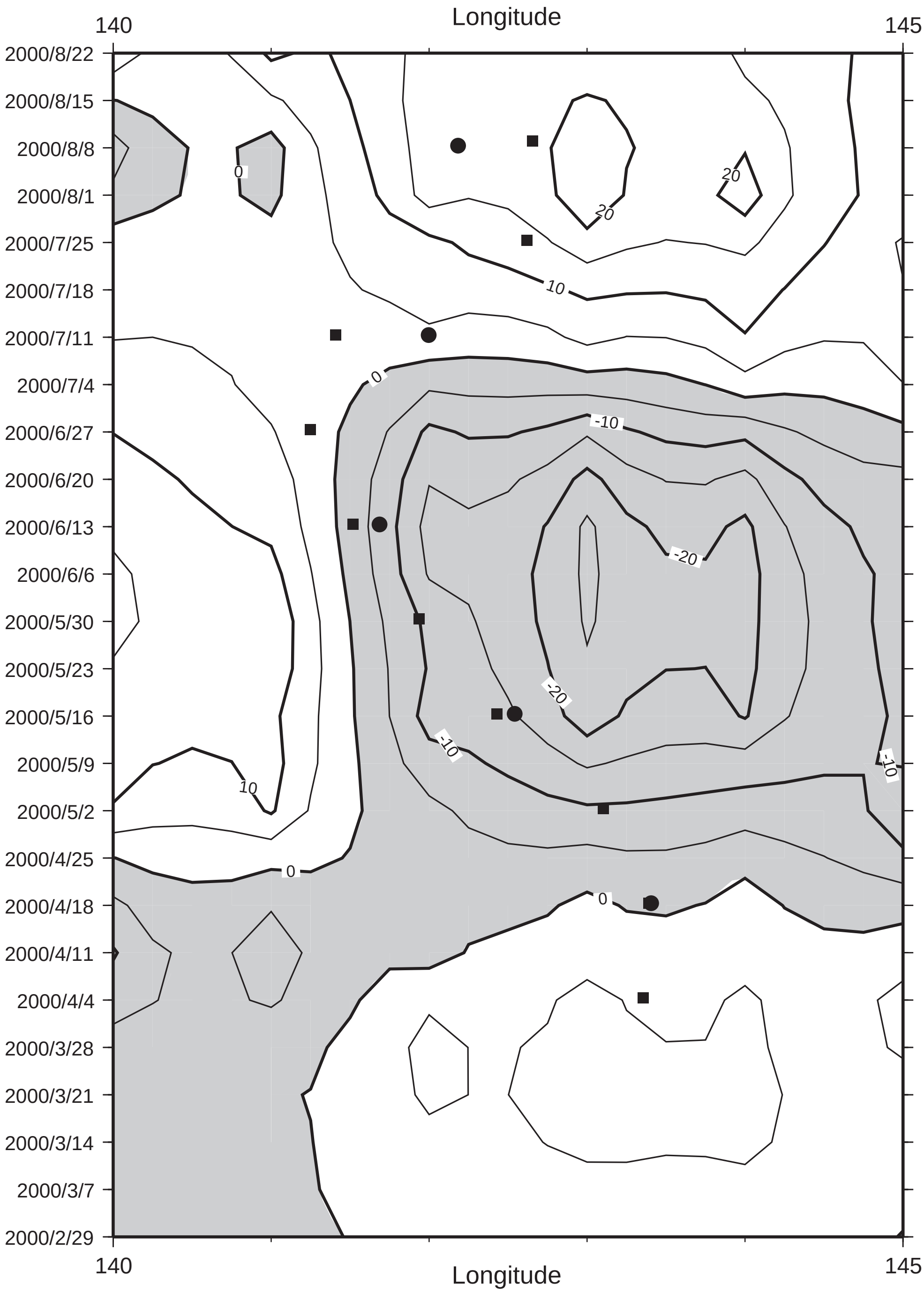

Fig. 5 Time-longitude diagram of the TOPEX/Poseidon altimeter data in the latitude belt of 29-30° N. Solid square denotes the positions of Float-14 and solid circle, Float-28, respectively.

cline and salinity minimum layer became shalower until middle of July when the floats were closest to the center.

In order to see the structure of the eddy that caught the floats, we try to reconstruct the structure of the eddy based on the observation by the floats and S/V Tenyo.

We assumed that, 1) the eddy had a central symmetry structure and 2) the structure did not change from May to July. Of course these assumptions are not really true about the eddy but we employed them as a first order approximation of the eddy structure so that we could draw the structure based on insufficient number of observations.

In the analysis, we identified the center of the eddy based on the sea surface height anomaly maps and computed the distance between the center and the float or hydrographic observation positions. We also referred to the MODAS maps. We sorted the observed vertical temperature and salinity profiles in ascending order of the distance. Here, vertical profiles of the temperature and salinity obtained by the floats were interpolated into every 1×10^{-4}Pa, by applying the Akima method (Akima, 1970[6]). CTD data obtained by S/V Tenyo were also used. Then, we computed average temperature and salinity every 1×10^{-4}Pa depth every 20km-bin. After that, we applied a median filter, of which window width is 10×10^{-4}Pa, to the composite profile in each 20km-bin in order to eliminate spiky noise.

Resultant composite structure of the cyclonic eddy is shown in Figs. 6a and 6b. General characters of the eddy

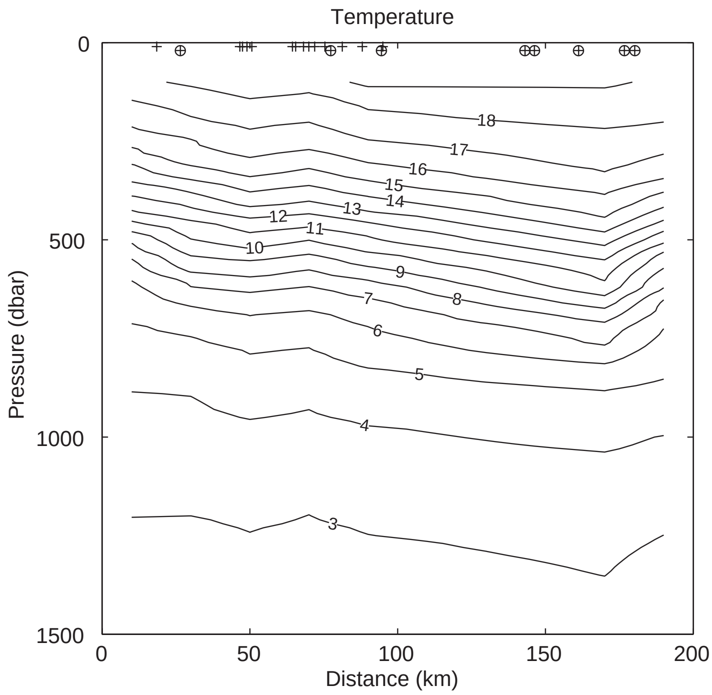

Fig. 6a　Composite structure of the cyclonic eddy along the radius for temperature.

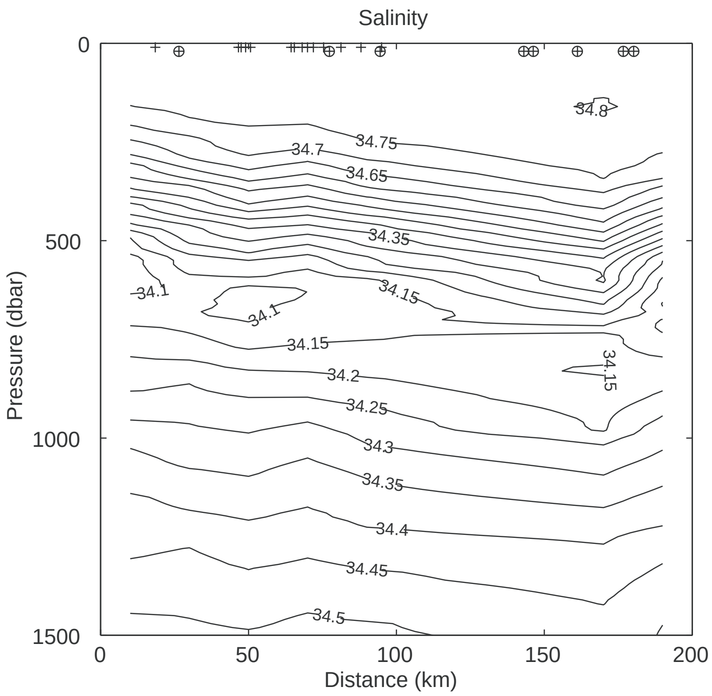

Fig. 6b　Same as Fig.6a, except for salinity.

are that, the eddy shows vertically coherent structure from surface to the depth of 1500×10^{-4}Pa, in other words, baloclinic structure, in both temperature and salinity. Contour lines of temperature and salinity slope toward outside. Radius of the eddy is about 160 km. Except for the upper 100×10^{-4}Pa depth, average horizontal temperature gradient increases with depth, from 1.0 to 2.7×10^{-6}km^{-1} from 150×10^{-4}Pa through 400×10^{-4}Pa, then it takes almost similar values in the layer of 400-600$\times10^{-4}$Pa. Below the layer, the gradient decreases with depth to 0.26×10^{-6}km^{-1} as one reaches to the depth of 1000×10^{-4}Pa. Positive horizontal salinity gradients, i.e., salinity increases toward outside, are seen in upper 700×10^{-4}Pa depth, with maximum gradient of about 2.0×10^{-6}m^{-1} at about 450×10^{-4}Pa level. Below 1000×10^{-4}Pa level, horizontal salinity gradient is negative. Maximum value is about -7.5×10^{-7}m^{-1} at about 1000×10^{-4}Pa and it decreases with depth to about -2.0×10^{-7}m^{-1}.

Tangential geostrophic velocities relative to 1500×10^{-4}Pa in the cross-section are also computed. Generally, cyclonic flows are evident, except for the bin 60km apart from the center, where horizontal gradients of both temperature and salinity are opposite to those in the rest of the region in the composite structure. The speed is more than 0.5ms^{-1} in upper 200×10^{-4}Pa layer within 100km from the center. The speed is larger than the float drifting speed at the surface. Because the drifting speed at the parking depth is not negligible (about 0.05ms^{-1}) as mentioned above, the geostrophic speed at the surface layer is 1.5 or 2 times larger than the drifting speed difference between the surface and the 1500×10^{-4}Pa level.

Comparing to the synoptic eddy structure described by Ebuchi and Hanawa (2000)[5], in which they reconstructed the eddy structures based upon the satellite altimeter data, XBT and ADCP data obtained along the Tokyo-Ogasawara line, the composite structure of the cyclonic eddy is generally similar, except for some differences. That is, the horizontal scale and temperature and salinity structures in the vertical cross section are generally similar to each other but there is some unrealistic part in the composite structure in the present study. Geostrophic speed at the surface layer estimated in the present study is about twice as large as that obtained in Ebuchi and Hanawa (2000)[5]. Difference in the structure and current speed between them is mainly due to insufficient number of vertical profiles around the eddy to reconstruct the vertical structure and due to the assumption for the composite analysis in the present study.

5. Summary and discussion

We deployed two profiling floats in the region south of the Kuroshio Extension in March 2000. They have been reporting vertical profiles of temperature and salinity from 1500×10^{-4}Pa to the surface every two and four weeks, respectively. Performance of the floats was very well for at least first 4 months after the deployment.

Based on the float observations we investigated water mass in the region. We also analyzed vertical structure of the cyclonic eddy, that advected the two floats from May through July 2000. The analysis showed that the eddy had typical character of the synoptic eddy commonly seen south of the Kuroshio Extension region.

The results shown in the present study clearly demonstrate how useful and cost-effective the profiling floats with temperature and salinity sensor are in oceanographic observation for upper and middle layers. Considering the quality of the observation and the lifetime, total cost of the float observation is estimated equivalent to, or even lower than that of XCTD. Shortcoming of the float observation is that we can not control the observation position after the deployment.

One major problem in the float observation is maintenance of accuracy of the salinity sensor. But deterioration of the salinity sensors on the float seems very small compared to the CTD sensors installed on the surface mooring buoys such as TRITON (Kudorda and Amitani, 2000[7]).

We are very sure that in the near future profiling floats will be one of the major, important observation tools in physical oceanography, especially for monitoring purposes although there are some problems mentioned above. Profiling float is, however, not suitable for observation near shore and strong current regions except for the Antarctic Circumpolar Current. XCTD and XBT are still very useful for such regions. For research purpose, very precise and accurate observations by research vessels are needed. The precise and accurate observations in the open sea are also desirable for calibration of the sensors on the profiling floats. Research vessels are also needed to sample water, deploy and retrieve moorings, observe current and so on. Moorings will be used for observation of deep sea and for monitoring at fixed position.

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References

1) The Argo Science Team, Report of the Argo Science Team 2nd Meeting (AST-2) March 7-9, 2000, Southampton Oceanography Centre, Southampton, U.K., (2000)

2) Iwasaka Naoto, Suga Toshio, Takeuchi Kensuke, Mizuno Keisuke, Takatsuki Yasushi, Ando Kentaro, Kobayashi Taiyo, Oka Eitarou, Ichikawa Yasuko, Miyazaki Motoki, Matsuura Hiroshi, Izawa Takashi, Yang Chan-Su, Shikama Nobuyuki, and Aoshima Momoko, Pre J-ARGO: Experimental observation of upper and middle layers south of the Kuroshio Extension region by using profiling floats, *J. Oceanography*, 58, in press. (2002)

3) Suga, T., Climatology and variability of North Pacific Subtropical Mode Water as revealed by Hydrographic data analysis. *Umino Kenkyu (Oceanography in Japan)*, 6, 371-382, (1997)

4) Hanawa, K. and L. Talley, Mode Waters. p. 373-386. In *Ocean Circulation and Climate*, ed. by G. Siedler, J. Church and J. Gould, Academic Press, New York, (2001)

5) Ebuchi, N., and K. Hanawa, Mesoscale eddies observed by TOLEX-ADCP and TOPEX/POSEIDON altimeter in the Kuroshio Recirculation region south of Japan, *J. Oceanogr*., 56, 43-57, (2000)

6) Akima, H., A new method of interpolation and smooth curve fitting based on local procedures, *J. Associ. Comput*. Mach., 17, 589-602, (1970)

7) Kuroda, Y. and Y. Amitani, TRITON: New ocean and atmosphere observing buoy network for monitoring ENSO. *Umino Kenkyu (Oceanography in Japan)*, 10, 157-172, (2001)

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