Journal of Oceanography
Vol. 49, pp. 231 to 245. 1993

Fluctuation in Volume Transport Distribution Accompanied by the Kuroshio Front Migration in the Tokara Strait

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(Received 22 June 1992; in revised form 4 September 1992; accepted 11 September 1992)

A relation between migration of the Kuroshio front and fluctuation of distribution of volume transport in the Tokara Strait was described, using sea level records at five tide gauge stations around the strait and data which were composed of sea surface temperature, XBT casts, sea surface salinity and velocities at 20 m, 75 m and 150 m depths taken en route a ferryboat. The Kuroshio front extends to about 150 m depth. The sea surface salinity and the horizontal velocities abruptly change at the front. There is a good correlation in a period range from half a month to two months between the migration of the front, which is not only at the surface but also in the subsurface, and the sea level fluctuation at Nakano-shima. A northward migration of the front with a period range from 17 to 50 days decreases the transport in the southern strait between Naze and Nakano-shima but increases in the northern strait between Nakano-shima and Sata-misaki. The northward migration intensifies inflow into Kagoshima Bay and the Ohsumi Branch Current. Correlation between the transport in the northern strait and the Ohsumi Branch Current is significant in the period range from 30 to 50 days. In this significant period range, the former leads the latter by about 3 days.

1. Introduction

The Kuroshio, which flows northeastward along the continental slope in the East China Sea (ECS), leaves the continental slope west of Yaku-shima and turns to southeastward. Eventually, it flows out through the Tokara Strait into the Pacific Ocean. The Tokara Strait is a convenient sea area for monitoring of the Kuroshio transport because of the following 2 reasons. First, the strait is geographically constrained by Amami-ohshima and Sata-misaki. Secondly, it is surrounded by five tide gauge stations which distribute fitting for the monitoring (Fig. 1).

On the way of the Kuroshio course in the ECS, a front between the Kuroshio and shelf waters forms over the continental slope. The front is well defined by sea surface temperature (SST) from late autumn to early summer. By analysing the SST measured by a ferryboat regularly crossing the Tokara Strait, Nagata and Takeshita (1985) found the Kuroshio front migrating between Nakano-shima and Sata-misaki with a period range from 15 to 30 days. However, they supposed that the period varied from year to year.

Recently, by analysing sequence of satellite infrared images over the Kuroshio region in the ECS during the period from March 4 to April 12, 1986 and water temperature fluctuation observed at a buoy station on the shelf edge northwest of Okinawa, Qiu *et al.* (1990) found a progressive meander of the Kuroshio front with a typical horizontal scale of 100 to 150 km and with a period of 14 to 20 days. The meander propagated downstream at a speed of 20 to 26 cm/s and eventually arrived at the Tokara Strait. In that study, they pointed out that the northward

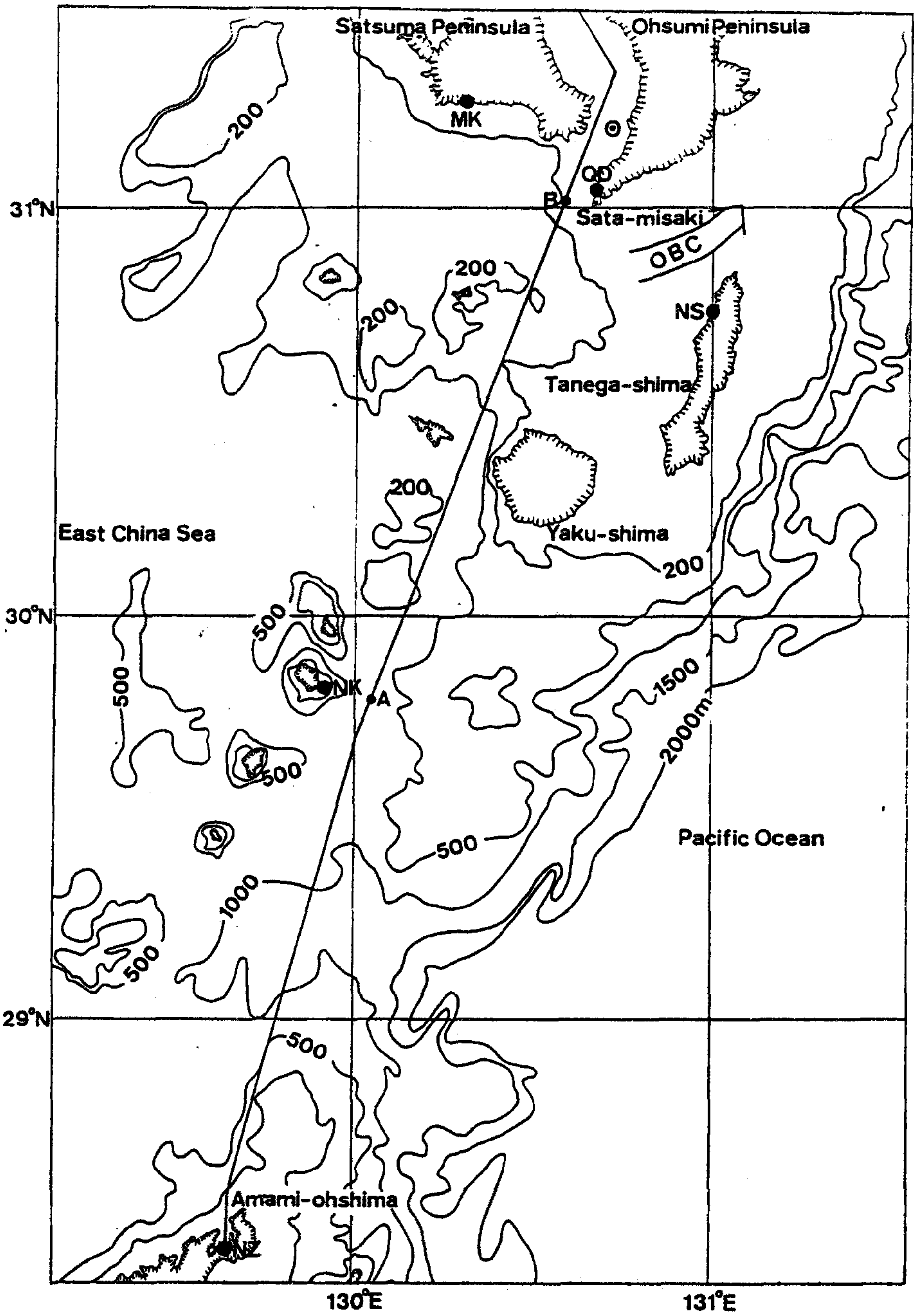

Fig. 1. Map of the Tokara Strait region. The line from Kagoshima to Naze indicates a course of the ferryboat Naminouemaru. The line on the course between A (29°47′ N, 130°06′ E) and B (31°04′ N, 130°37′ E) was occupied by R/V Hakuhoumaru for the measurements of SST, SSS and Velocities. The mark ⊙ indicates the location of the bouy station for measurements of velocity and temperature. The sites of the five tide gauge stations, Naze (NZ), Nakano-shima (NK), Nishino-omote (NS), Ohdomari (OD) and Makurazaki (MK) are indicated by black circles. The typical location of the Ohsumi Branch Current is shown by an arrow.

migration of the front was resulted by the Kuroshio front meander passing through the Tokara Strait and produced fluctuation of transport between Naze and Nakano-shima. The latter result shows that distribution of volume transport in the Tokara Strait is possible to vary depending on the front migration.

In a period from summer to autumn, detecting the front by the SST is difficult, because of its uniformity. However, there may be a front in subsurface layer. Migration of the subsurface front may reflect on fluctuation of sea level. For an indirect evidence, vertical extensions of horizontal velocity distribution and a temperature section near the front will be described, using results of observations on boards of the R/V Hakuhoumaru (Ocean Research Institute, University of Tokyo) and of a ferryboat called Naminouemaru (Ohshima Un-yu, Co., Ltd.). Then, we will show statistically significant time scale of fluctuation in the distribution of the volume transport assessed from the sea level records.

If the fluctuation of volume transport in the northern strait between Nakano-shima and Sata-misaki is accompained by the front migration, the mean surface flow pattern and geographical constraint to the Kuroshio in the strait show that the migration of the front plays important roles in a water exchange of Kagoshima Bay and in fluctuation of the Ohsumi Branch Current (OBC) between Ohsumi Peninsula and Tanega-shima (Fig. 1). We can find envidences for the important roles in time series of velocity and temperature measured at the mouth of Kagoshima Bay and in fluctuation of sea level difference between Nishino-omote and Ohdomari shown by Sakurai (1985). In this paper, we will reproduce his figure and show relations of the front migration with the water exchange of Kagoshima Bay and the fluctuation of the OBC.

Predominant time scale of the fluctuation of volume transport in the northern strait relates to a frequency of the intensity in the inflow into Kagoshima Bay and of the OBC. So, the time scale will be statistically shown by using the sea level records at the tide gauge stations around the northern strait. A phase relation between the fluctuations of the volume transport in the northern strait and of the volume transport of the OBC will be also shown.

2. Data and Analysis

The five tide gauge stations are sited at Naze, Nakano-shima, Nishino-omote, Ohdomari and Makurazaki (Fig. 1). Since the Kuroshio and the OBC flow among those stations, the transport fluctuations of the two currents may be estimated from fluctuations of surface slope obtained from the sea level records at those stations, assuming the geostrophic balance (Rikiishi and Sasaki, 1988). The sea level records for 3 years from 1985 through 1987 will be analyzed referring to the SST measured every two days on the course of the Naminouemaru.

The sea level data were provided by the Japan Oceanographic Data Center. The barometric pressure data, which were necessary for the barometric correction on them, were obtained from the Monthly Report of Meteorological Observation. The SST data were provided by the Kagoshima Prefectural Fisheries Experimental Station which installed an automatic-recording thermometer on a hull of the ferryboat Naminouemaru.

Daily mean sea level at each station was calculated from hourly one eliminated the tidal components by the 25 hours running mean and corrected for barometric pressure based on the hydrostatic approximation. The filter is rather simple but has higher efficiency to eliminate the main components of the tide. Actually, the amplitude contractions of the main four components, M_2, S_2, K_1 and O_1, are $2.26 \times 10^{-4}, 0, -1.17 \times 10^{-4}$ and 2.26×10^{-3}, respectively. The largest amplitude among them resulted from the filtering process is only 0.44 mm of O_1 at Ohdomari.

The spectrum analysis by the Fast Fourier Transform method was applied to the time series of the daily mean sea levels and its differences between the two tidal stations of the total of five stations. In this analysis, the degrees of freedom are 16.

To describe vertical extent of the front, XBT casts were made every about 10 miles parallel with the SST measurement on the board of the Naminouemaru from December 8 to 9, 1990. Other observations, which were composed of the SST, sea surface salinity (SSS) and current profile, were made on board of the R/V Hakuhoumaru on 23 January 1991.

3. Structure of the Front

Figure 2 shows a comparison of sea level fluctuation at Nakano-shima with the SST fluctuation at a site on the course of the ferryboat east of the island during the period from 1 January 1985 to 31 December 1987. In this figure, we notice that a period range from 15 to 60 days predominates in the sea level fluctuation for all seasons. Sharp troughs both in the SST and in the sea level occur at the same time in winter and spring. The sharp trough of the SST reflects the temperature front existing south of Nakano-shima. Since the SST is uniform during summer and autumn, indication of the front by the SST is difficult. But there may be the front in a subsurface. Migration of the subsurface front is supposed to appear on the sea level fluctuation of that period range.

Figure 3 shows a comparison between the SST and a temperature section observed by XBT

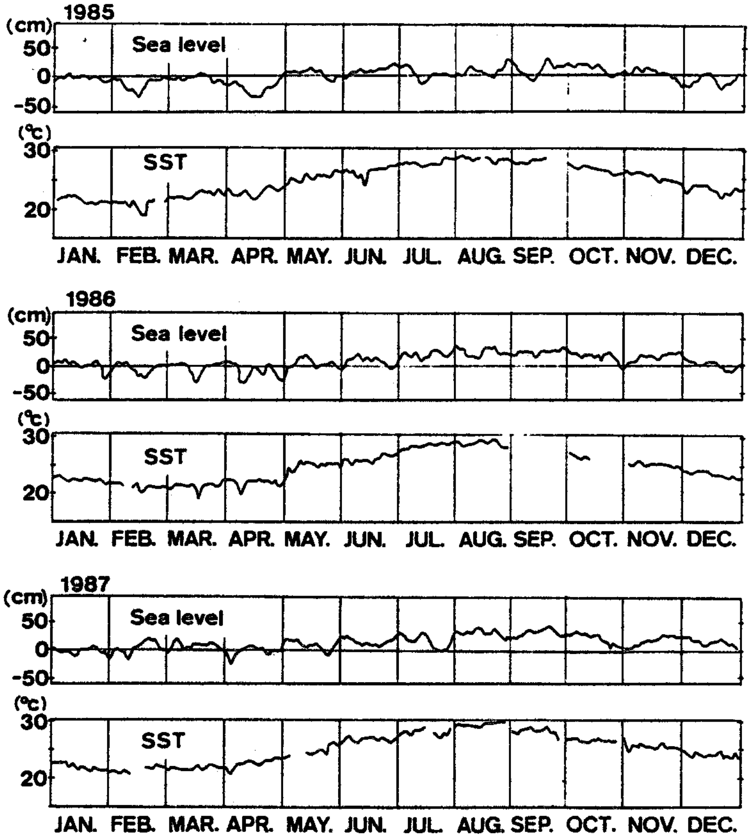

Fig. 2. SST at a site on the ferryboat course east of Nakano-shima and sea level at the island.

casts on the board of the Naminouemaru. We can find three SST fronts in this figure. Isotherms near the fronts slope southwestward from the sea surface into a depth of a hundred and several ten meters. The isotherms in the layer from 150 to 200 m depth are nearly horizontal and parallel to each other. Such a distribution of isotherms of a temperature section crossing the Tokara Strait may be usual in the season from late autumn to early summer (Akiyama and Ameya, 1991). Consequently, the northward migration of the front accompanies the northward shift of warm water which has about 150 m thickness.

In Fig. 4, SST, SSS and horizontal velocities at 20 m, 75 m and 150 m depths are compared with each other. These data were measured on board of the R/V Hakuhoumaru on her course from a beginning point A sited about 13 miles east of Nakano-shima to an end point B at the mouth of Kagoshima Bay (Fig. 1). Her course lies approximately along the course of the Naminouemaru. Absolute value of the velocity gradually decreases with depth. However, the velocities at the

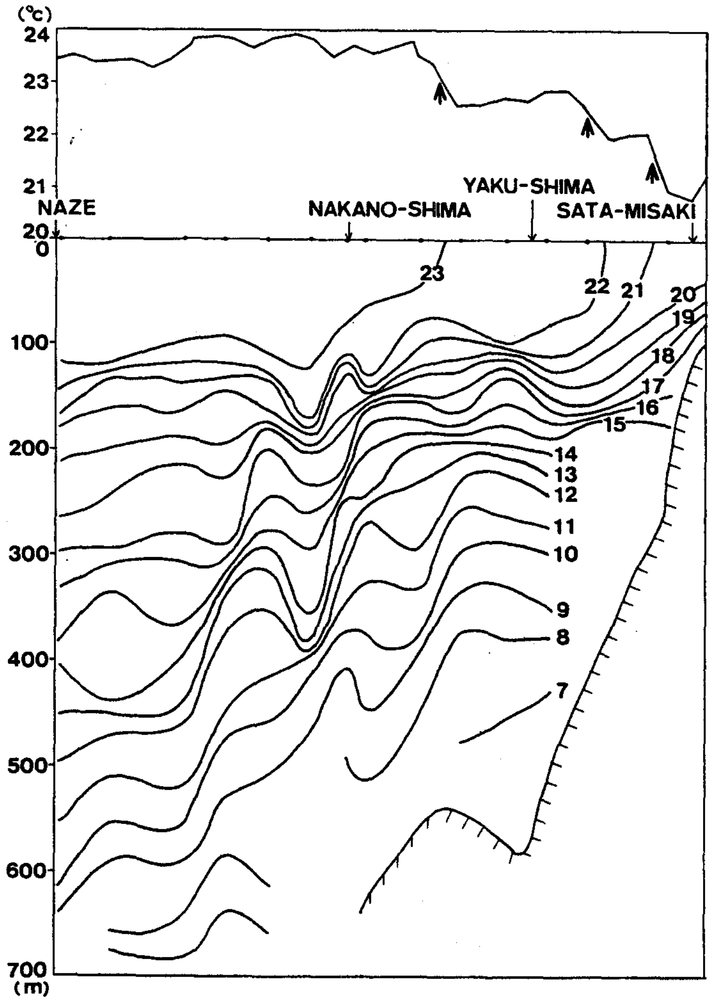

Fig. 3. A temperature section and SST along the course of the Naminouemaru. Fronts are indicated by arrows.

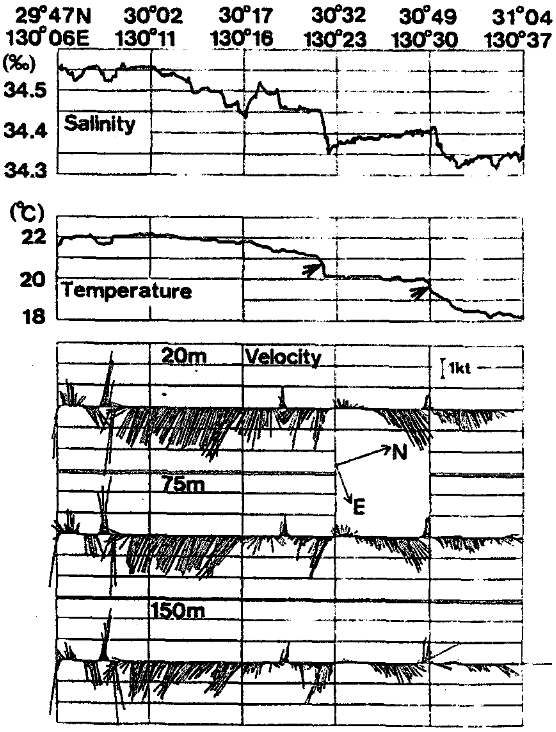

Fig. 4. SST, SSS and velocities at 20 m, 75 m and 150 m below the sea surface measured by R/V Hakuhoumaru on the half northern course of the Naminouemaru (see Fig. 1). Base lines in the stick diagrams are crossing the eastward at an angle of 70°40′.

three depths are nearly parallel to each other. The SSS distribution is approximately parallel to the SST one except around a trough of the SSS near the site (30°17.6′ N, 130°16.9′ E).

Horizontal distributions of the velocities, the SST and the SSS strongly relate to each other. The velocities rather steeply increase toward southwest at the front. The high speed zone exists southwest of the surface front but not at the front. This suggests that the velocity distribution considerably depends on a subsurface density distribution. The dependence may be recognized in the front deepening toward the southwest (Fig. 3).

4. Distribution Fluctuation of the Volume Transport in the Tokara Strait

A southern boundary of the Kuroshio in the Tokara Strait may be at a northern end of Amami-ohshima. However, its northern boundary, which is indicated by the front, is migrating from south to north. The front sometimes migrates from Nakano-shima to Sata-misaki. The distribution of the Kuroshio transport may vary according to the migration of the Kuroshio front. If such a shift of the Kuroshio happens keeping the quasi geostrophic balance, the migration reflects on sea level fluctuation. Actually, the relations among the SST east of Nakano-shima, the sea level at the island Nakano-shima and the velocity distribution around the front suggest the geostrophic balance for the migration. Using the sea level records, we will show a range of predominant time scale in the distribution fluctuation of the transport in the Tokara Strait.

Figure 5 shows the sea level fluctuations at four tide gauge stations during 3 years from 1985

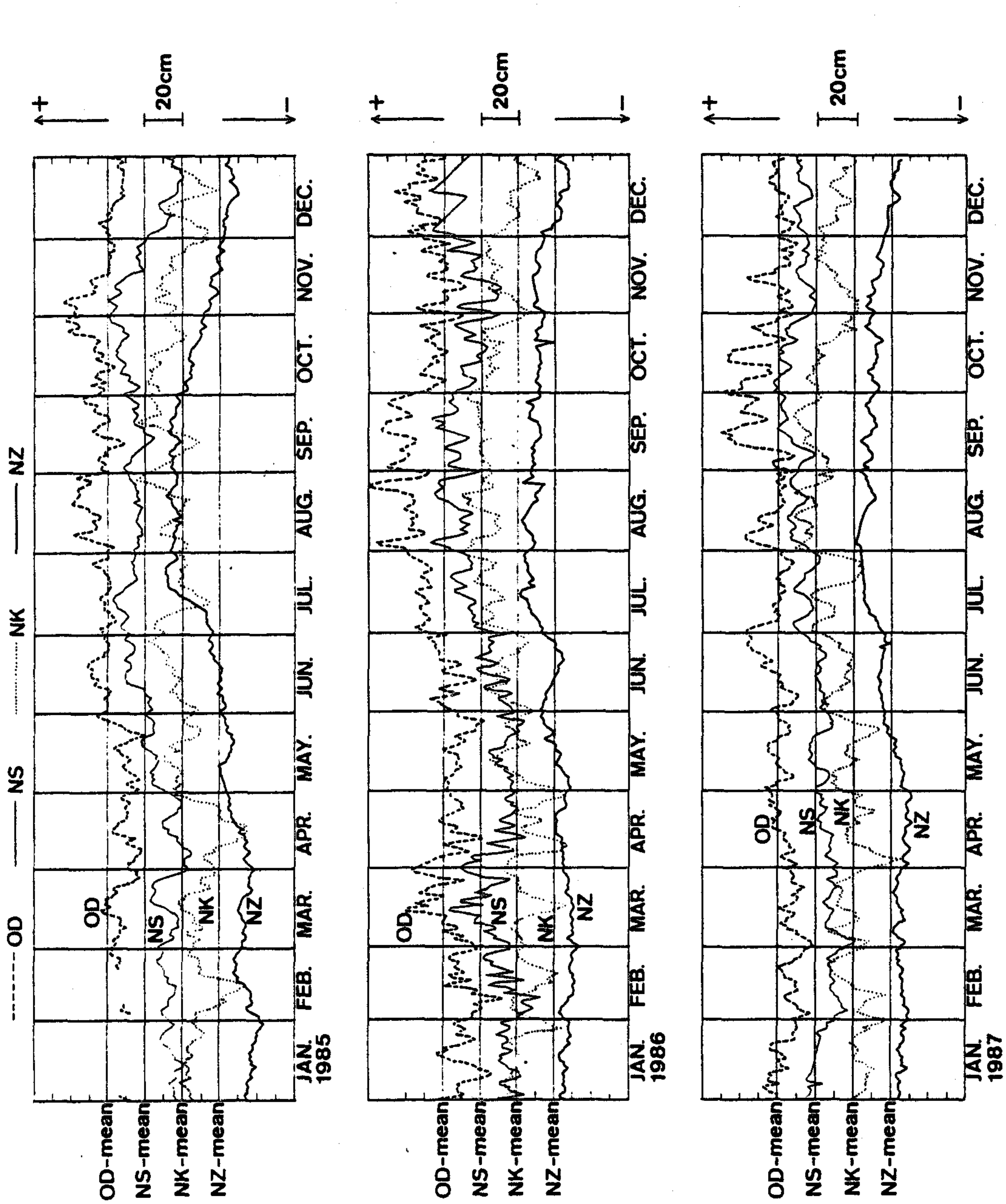

Fig. 5. Sea level fluctuations at the four tide gauge stations. NZ: Naze, NK: Nakano-shima, NS: Nishino-omote and OD: Ohdomari.

through 1987. Seasonal variation can be found in the fluctuations at all stations. However, Naze differs from the other stations in time of the highest sea level in the seasonal variation. The highest sea level at Naze occurs in July. On the other hand, the highest sea level at other stations occurs from September through November. This corresponds to the result of Kawabe (1988). He shows that the maximum velocity of the Kuroshio assessed from the sea level difference between Naze and Nishino-omote occurs in July. Such a maximum transport was also found in July in a seasonal variation of the Florida Current (Schott *et al.*, 1988).

The northern 2 stations, which are located at Nishino-omote and Ohdomari, resemble in predominance of shorter period fluctuations and in phase each other. However, Naze and Nakano-shima differ in predominant time scale from the northern 2 stations. Furthermore, they differ from each other. At Nakano-shima, the time scale from 15 days to two months is predominant. The fluctuations with such a time scale in winter and spring is accompanying the SST fluctuations mentioned above (Fig. 2).

There is a repeating oscillation in the sea level at Nakano-shima during 3 months from end of January to end of April 1986 (Figs. 2 and 5). A period of the oscillation is about 22 days. The period and the term are equal to those of sea level difference between Naze and Nakano-shima found by Qiu *et al.* (1990). So, the oscillation of the difference reflects mainly the sea level oscillation at Nakano-shima and also the distribution fluctuation of the transport in the Tokara Strait reflects mainly on the sea level fluctuation at Nakano-shima.

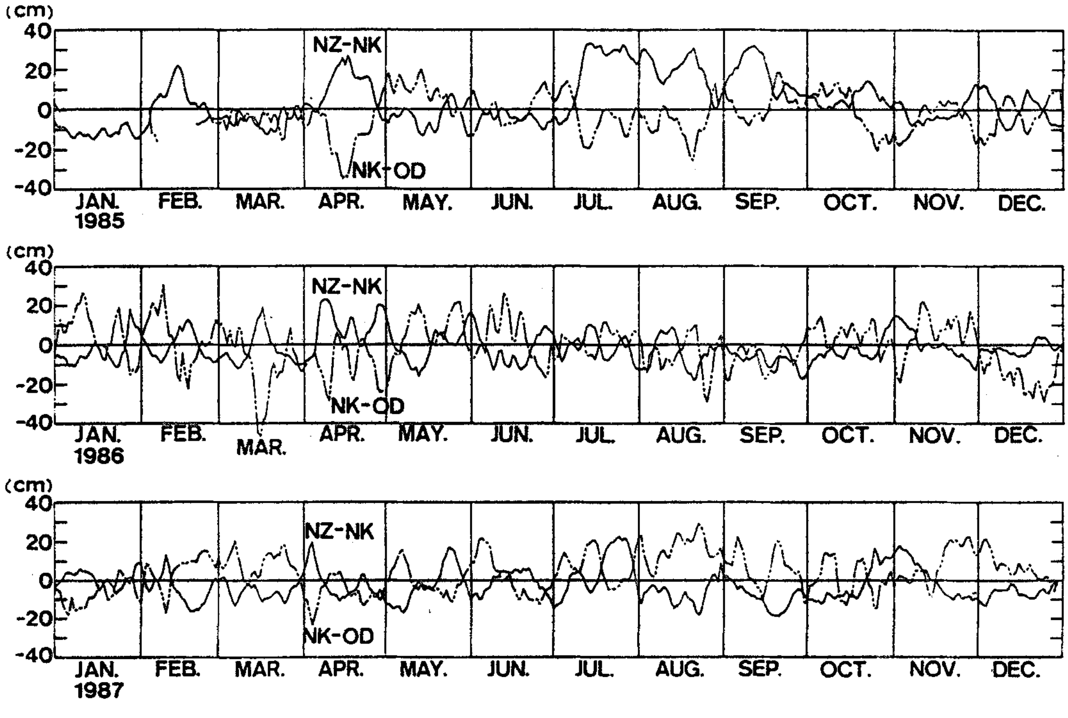

Fig. 6. Comparison of fluctuations of the sea level difference. The sea level difference between Naze and Nakano-shima is compared with that between Nakano-shima and Ohdomari. The mean difference is designated by 0 cm. NZ-NK: sea level difference between Naze and Nakano-shima, and NK-OD: sea level difference between Nakano-shima and Ohdomari.

In Fig. 6, the sea level difference between Naze and Nakano-shima is compared with that between Nakano-shima and Ohdomari. We can find in this figure that the sea level difference between Naze and Nakano-shima is clearly out of phase to that between Nakano-shima and Ohdomari. Such a relation of the out of phase was already found in the sea level differences from Naze to Nakano-shima and from Nakano-shima to Nishino-omote in the season from autumn through spring in 1986 and 1987 (Qiu *et al.*, 1990). This means that the transport between Naze and Nakano-shima decreases by the increase of that north of Nakano-shima. Though such a clear relation of the out of phase is derived from what the sea level at Nakano-shima is used in the two time series compared with each other, a significant time scale of the relation is worthy of statistically representing.

Figure 7 shows coherences squared and phase differences between the two sea level slopes from Naze to Nakano-shima and from Nakano-shima to Ohdomari, respectively. The phase difference is distributed around 180° in a period range from 17 days to 50 days where the coherence are significant. There is another coherence rise peaked at a period of 13.1 days. The coherence rise may be caused from the M_f tidal component whose period is 13.66 days, because the phase of this component at Naze leads those at the other tide gauge stations by about 200° and the amplitudes of the sea level differences between Naze and Nakano-shima and between

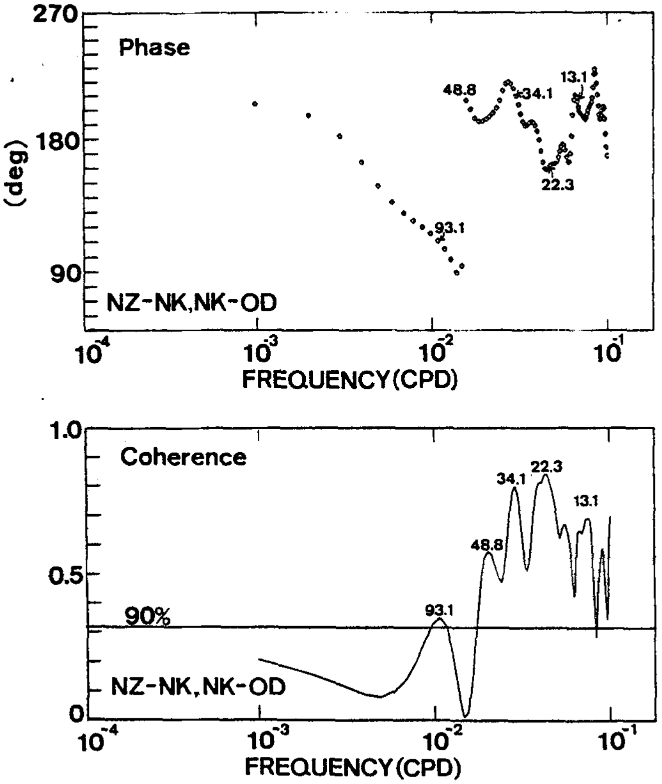

Fig. 7. Coherences squared and phase differences between the two sea level differences from Naze to Nakano-shima (NZ-NK) and from Nakano-shima to Ohdomari (NK-OD). Numbers at peaks of coherence squared show periods in a unit of day. Phase leads at the peaks are indicated by the same numbers.

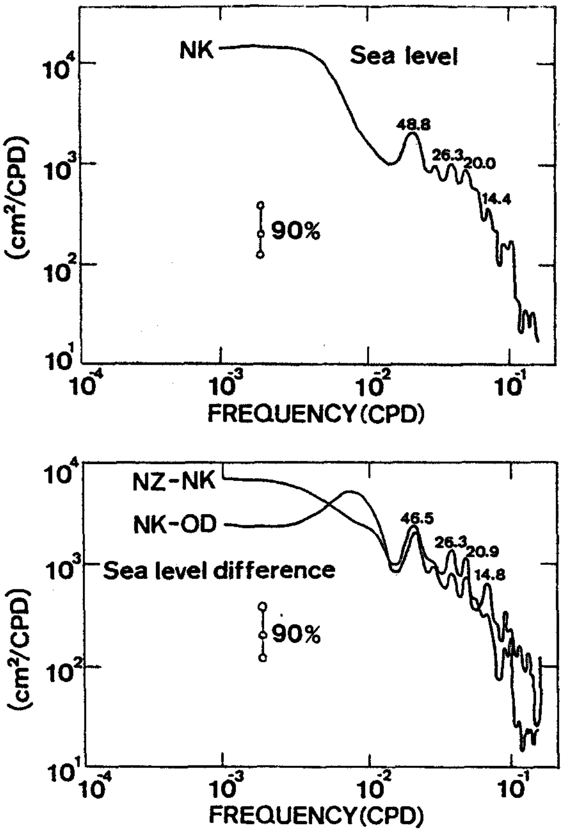

Fig. 8. Power spectra (cm^2 day) of sea level fluctuation at Nakano-shima (upper panel) and of sea level differences between Naze and Nakano-shima (NZ-NK) and between Nakano-shima and Ohdomari (NK-OD) (lower panel). Numbers at peaks of power spectrum show periods in a unit of day.

Nakano-shima and Ohdomari are about 2 cm and 2 mm, respectively (Japan Hydrography Department, 1992). We may disregard the fluctuations with the period range, because those do not relate to the front migration. The significant time range from 17 to 50 days is nearly equal to that of the Kuroshio front migration in the Tokara Strait (Nagata and Takeshita, 1985; Akiyama and Ameya, 1991). The distribution caused by the front migration is thought to be mainly reflected in the sea level fluctuation at Nakano-shima, because energy densities of the sea level fluctuation at Nakano-shima and of the slope fluctuations from Naze to Nakano-shima and from Nakano-shima to Ohdomari relatively concentrate at nearly the same period range (Fig. 8).

5. Effects of the Migration to Kagoshima Bay and to the OBC

Analysing velocity and water temperature records at a buoy station near the mouth of Kagoshima Bay from 13 February to 15 March 1980, Sakurai (1985) found water temperature rising and falling according to inflow and outflow, respectively. The result shows that the Kuroshio front migration in the Tokara Strait plays an important role in the water exchange of Kagoshima Bay. Because of another interesting phenomenon in a figure of his article which is concerning the migration of the front in the Tokara Strait and the transport fluctuation of the OBC, the figure will be reproduced from his article.

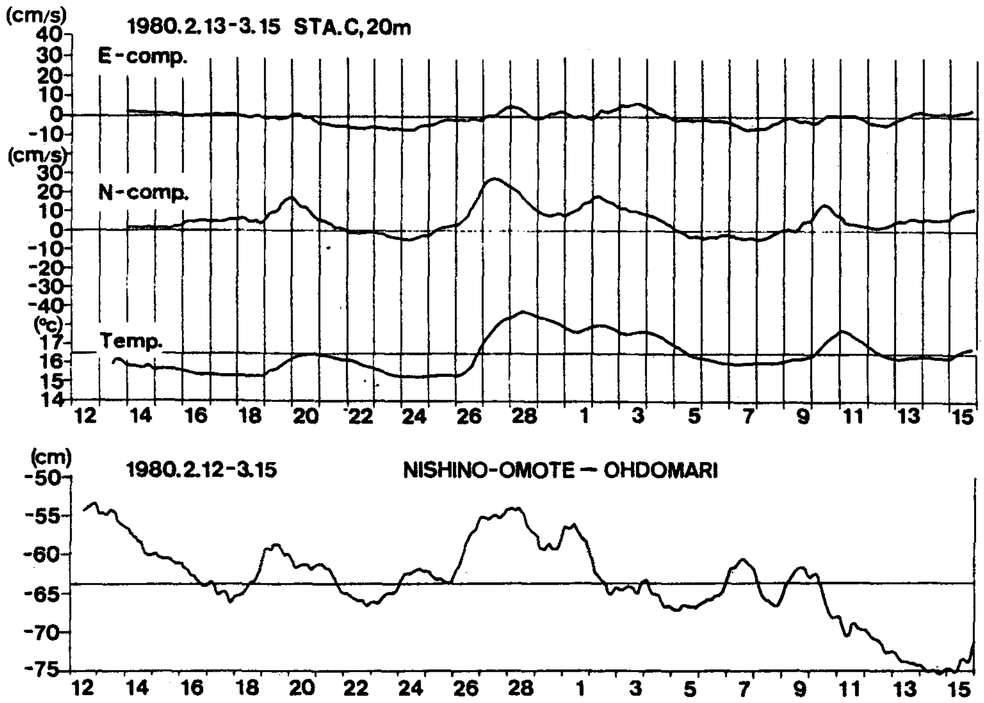

Fig. 9. Comparison of temperature and velocity fluctuations at the mouth of Kagoshima Bay (upper panel) with fluctuation of the sea level difference between Nishino-omote and Ohdomari (lower panel) (reproduced from Coastal Oceanography of Japanese Islands, 1985).

Figure 9, which originates in Sakurai's article, shows fluctuations of temperature and velocity at 20 m below the sea surface near the mouth of Kagoshima Bay on its axis and fluctuation of sea level difference between Nishino-omote and Ohdomari (Fig. 1). The north component of velocity has a wider range than the east one. This is due to the configuration near the mouth of Kagoshima Bay which elongates from south to north (Fig. 1). Inflow into the bay is made by the northward current. In the season when the measurements were made, temperature was uniformly distributed from the sea surface to about 100 m depth, but rose sharply from the mouth to the south. Then, the inflow would be generally denoted by a rise of temperature at the mouth.

Correspondence between the two time series of the north component and of the temperature is generally good (Fig. 9). A dominant temperature rise happened on the days from 26 to 28 February and the resulted higher temperature continued into 4 March. The period of the temperature rising happened together a northward migration of the Kuroshio front in the Tokara Strait shown in a space-time diagram of the SST produced by Nagata and Takeshita (1985). That is, the northward shift of the Kuroshio front in the Tokara Strait causes the inflow into the Kagoshima Bay.

Figure 9 gives another interesting information concerning to the fluctuation of the OBC. The sea level difference between Nishino-omote and Ohdomari increased at approximately same period from 26 to 28 February when the north component was accelerating and the temperature rising. The correspondences among them can be found in other periods. This shows that the northward shift of the Kuroshio front in the Tokara Strait strengthens the OBC.

6. Relation between Transport Fluctuation of the OBC and the Kuroshio Front Migration

The northward migration of the Kuroshio strengthens the inflow into Kagoshima Bay and the OBC. A significant time scale of the strengthening will be statistically described. This will be shown by phase relation between the two fluctuations of the transport in the northern strait and of the OBC. In this case, we may also assume the geostrophic flow on the OBC. Then, we substitute a sea level slope from Nishino-omote to Ohdomari for the transport of the OBC.

Figure 10 shows coherences squared and phase differences between the two sea level slopes from Nakano-shima to Ohdomari and from Nishino-omote to Ohdomari. The phase difference is positive when the phase of the former slope leads to that of the latter. The coherence is significant in the period ranges from 30 to 50 days and from 11 to 15 days. We also disregard the fluctuations with the latter period range. In the former period range, the phase lead is 20° to 50°. The significant coherence may result from what the sea level fluctuation at Ohdomari reflects on both fluctuations of the two sea level slopes. However, it can be avoided in this case.

The transport fluctuation in the northern strait between Nakano-shima and Sata-misaki may be approximated by the fluctuation of sea level slope from Nakano-shima to Makurazaki (Fig.

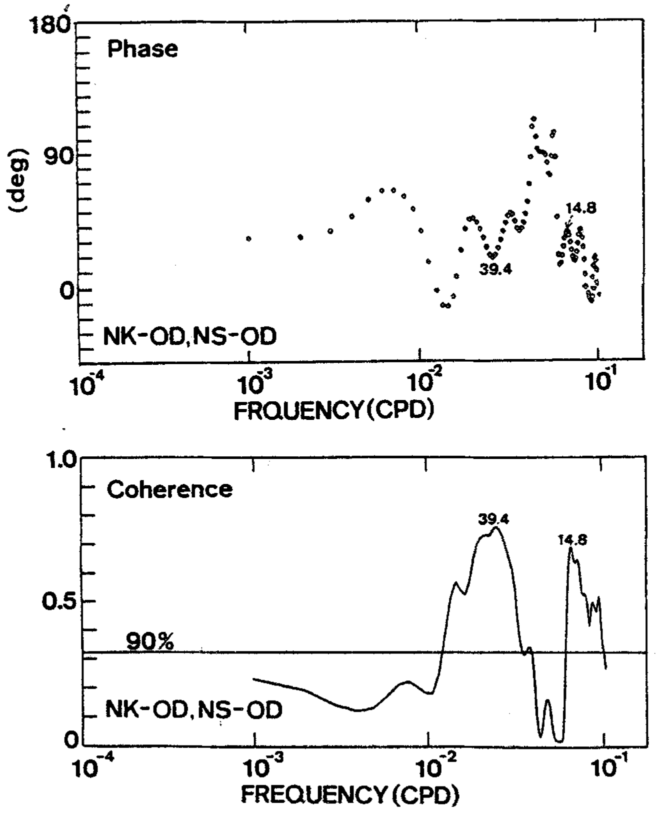

Fig. 10. Coherences squared and phase differences between the two sea level differences from Nakano-shima to Ohdomari (NK-OD) and from Nishino-omote to Ohdomari (NS-OD). Numbers at peaks of coherence squared show periods in a unit of day. Phase leads at the peaks are indicated by the same numbers.

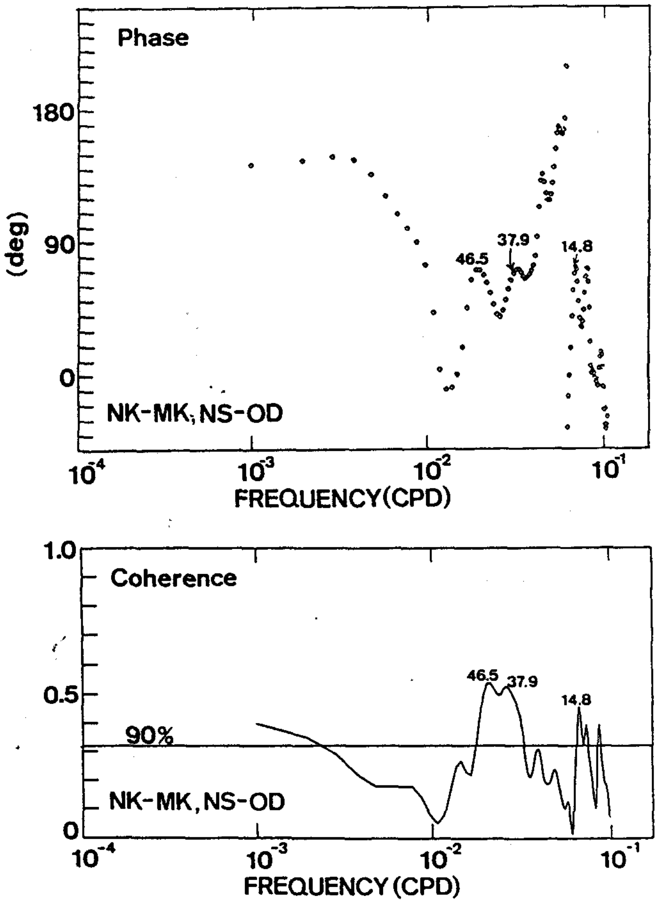

Fig. 11. Coherences squared and phase differences between the two sea level differences from Nakano-shima to Makurazaki (NK-MK) and from Nishino-omote to Ohdomari (NS-OD). Numbers at peaks of coherence squared show periods in a unit of day. Phase leads at the peaks are indicated by the same numbers.

1). Figure 11 shows coherences squared between the two sea level slopes from Nakano-shima to Makurazaki and from Nishino-omote to Ohdomari and phase leads of the former to latter. We can also find high coherence in the nearly same period range mentioned above, although the coherence rise is not so high as that case. The phase of the transport fluctuation between Nakano-shima and Makurazaki leads that of the OBC by 40° to 70° in the period range where the coherence is significant.

The coherence peaks take place at a period of about 40 days in the either cases (Figs. 10 and 11). In this period, the transport between Nakano-shima and Ohdomari leads that of the OBC by about 30°. Then, the phase relation shows that the transport fluctuation of the OBC with that period lags behind that between Nakano-shima and Ohdomari by about 3 days.

7. Conclusion

The Kuroshio front in the northern strait between Nakano-shima and Satamisaki extends to about 150 m below the sea surface. The SSS and the horizontal velocities abruptly change at the SST front. The high speed zone of the Kuroshio lies just south of the front. So, the northward migration of the front accompanies the high speed zone and the water mass of the Kuroshio. Then, the migration intensifies inflow to Kagoshima Bay and the OBC.

The sea level fluctuation at Nakano-shima closely relates to the front migration and to the volume transport distribution in the Tokara Strait. Sea level rising at the island responds to the northward migration of the front.

The fluctuation of the eastward transport in the southern strait between Naze and Nakano-shima is out of phase to that in the northern strait between Nakano-shima and Ohdomari in the period range from 17 to 50 days where the phase relation is significant. The fluctuation of the volume transport distribution with the period range results from the front migration. The northward migration increases the volume transport in the northern strait but decreases in the southern strait.

The fluctuation of the transport in the northern strait significantly correlates to that of the OBC in the period range from 30 to 50 days. In the period range, the former leads the latter by about 30°. This means that the transport of the OBC increases after about 3 days from the time when that in the northern strait increases. Akiyama and Ameya (1991) showed that it took 7 to 10 days for the front migration from Nakano-shima to Sata-misaki. Referring to their estimation for the migration speed, the volume transport of OBC increases after the front reaches to Yakushima.

The front migration may be an aspect of a meander of the Kuroshio originated on the shelf edge of the East China Sea (Qiu *et al.*, 1990). But the front migration is not always caused by such a progressive meander. By consecutive satellite infrared images from 15 to 20 April 1988, a meander from the ECS to the Tokara Strait, which was composed of some tongues intruding from the Kuroshio region into the shelf water and vice versa, did not progress (Maeda *et al.*, 1992). The tongues were gradually intruding into another water mass at nearly same place. In the case of the consecutive images, a shelf water tongue from the continental shelf west of Yakushima was gradually stretching east and increasing its width. Finally, it reached to Yakushima and its northern boundary attained to Sata-misaki. In this stage, we can find a new temperature front on the course of the ferryboat.

Acknowledgements

The authors wish to express their gratitude to the crew members of the ferryboat Naminouemaru of Ohshima Un-yu Co., Ltd. and R/V Hakuhoumaru of the Ocean Research Institute of the University of Tokyo for their kind cooperation for the observation from their vessels. They also want to express their special thanks to the Kagoshima Prefectural Fisheries Experimental Station for providing the ferryboat temperature data and to the Japan Oceanographic Data Center for providing the sea level data. They further express their thanks to Miss N. Morizono for drawing the figures and typing the manuscript. This study was supported by the grant (No. 02640319) from the Ministry of Education, Science and Culture, Japan.

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