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On Kuroshio Front Fluctuations in the East China Sea Using Satellite and In Situ Observational Data

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Fluctuations of the Kuroshio front in the East China Sea and their relation to variations of the Kuroshio stream around the Tokara Strait are investigated using consecutive satellite images, sea level data, as well as water temperature records from a Japan Meteorological Agency buoy station and a ferryboat which crosses the Tokara Strait. Meanders of the Kuroshio front with typical horizontal scales of 100 to 150 km and wave periods of 14 to 20 days are found to appear ubiquitously in the East China Sea. The front meanders originate upstream over the continental slope and evolve rapidly, while propagating downstream at speeds of 20 to 26 cm s^{-1}. Downstream southwest of Kyushu, the fully developed meanders sometimes take the form of warm filaments, and when the volume transport of the Kuroshio is large, they may develop into shed-off warm eddies. Previous observations based on ferryboat temperature records have revealed the repeated northward migration of a clear sea surface temperature (SST) front across the Tokara Strait. It is shown that this northward migration of the SST front corresponds to the passage of the Kuroshio front meanders across the Tokara Strait, and that the unclear southward migration of the SST front is due to the presence of mixed water behind each meander. The Kuroshio front meanders in the East China Sea are further found to be closely related to the north-southward movement of the entire Kuroshio stream in the Tokara Strait. A lag of about 10 days exists between the time the front meanders reach the Tokara Strait and the Kuroshio stream there shifts to its northernmost position.

1. INTRODUCTION

The Kuroshio originates from the Northern Equatorial Current and flows into the East China Sea (ECS; see Figure 1) through the passage east of Taiwan. Like its counterpart in the South Atlantic Bight, the Gulf Stream, the main stream of the Kuroshio in the ECS generally flows along the steep continental slope. Figure 2 shows the mean surface velocity pattern in the ECS averaged from GEK observations between 1953 and 1984. Except at the northern area of Taiwan where a part of the inflow Kuroshio water branches onto the continental shelf, we notice that the western edge of the Kuroshio, as indicated by a dashed line in Figure 1, approximately follows the 200-m isobath in the ECS. The Kuroshio leaves the continental slope around 128°E–129°E and 30°N and eventually flows out through the Tokara Strait into the southern sea area of Japan (see *Qiu and Imasato* [1990] for a more detailed discussion of the mean Kuroshio pattern in the ECS).

Although the mean Kuroshio path in the ECS is largely controlled by the bottom topography, recent observations have shown that low-frequency fluctuations of the Kuroshio are common at shelf break and slope regions. Based on water temperature records at a buoy station over the continental shelf (126°E, 28°20′N), *Shibata* [1983] found temperature fluctuations with a prominent period of 20 days. He attributed the fluctuations to Kuroshio front meanders that were often seen in satellite IR images. Using moored current meters at two sites along the 300-m isobath northwest of Okinawa Island, *Miyaji and Inoue* [1986] observed current fluctuations of the Kuroshio over a period of 71 days. They found that the dominant wave period of the fluctuations was between 10 and 20 days and that no clear phase lags existed between the the fluctuations of upper (100 m) and lower (290 m) water depths. Based on correlation analyses, they estimated the fluctuations to have a horizontal scale of 200 km and to propagate downstream at a speed of 20 cm s^{-1}. Mooring measurements were also carried out by *Sugimoto et al.* [1988] along and across the continental slope for a period of 1 month. The prominent wavelength and period of current fluctuations at a water depth of 300 m were observed to be 150 km and 11 days, similar to those found by *Miyaji and Inoue* [1986]. At a depth of 800 m offshore, they noticed the current fluctuations had similar wave periods of 11 to 14 days, but had larger wave lengths of 250 to 600 km. Further long-term mooring measurements covering more than 10 months have recently been carried out across the Kuroshio by *Mizuno et al.* [1989]. They found that both large-amplitude and small-amplitude current meanders were active during the 10-month mooring period and that the meander periods ranged from 5 to 30 days.

It is worth mentioning that the Kuroshio fluctuations in the ECS are not only important to the water mass exchange between the shelf water and the Kuroshio along the ECS shelf break, but can also be crucial to the Kuroshio variations south of Japan. For example, by analyzing sea surface temperature records measured from a ferry boat regularly crossing the Tokara Strait, *Nagata and Takeshita* [1985] found a well-defined temperature front migrating north and southward. Although the predominant periods of the fluctuations vary from year to year, they again appear in the 15 to 30 day range. The flow characteristics at the Tokara Strait have been shown in many regional models to be a crucial upstream condition in determining the Kuroshio variations south of Japan [e.g., *Sekine and Toba*, 1981; *Chao*, 1984; *Ya-*

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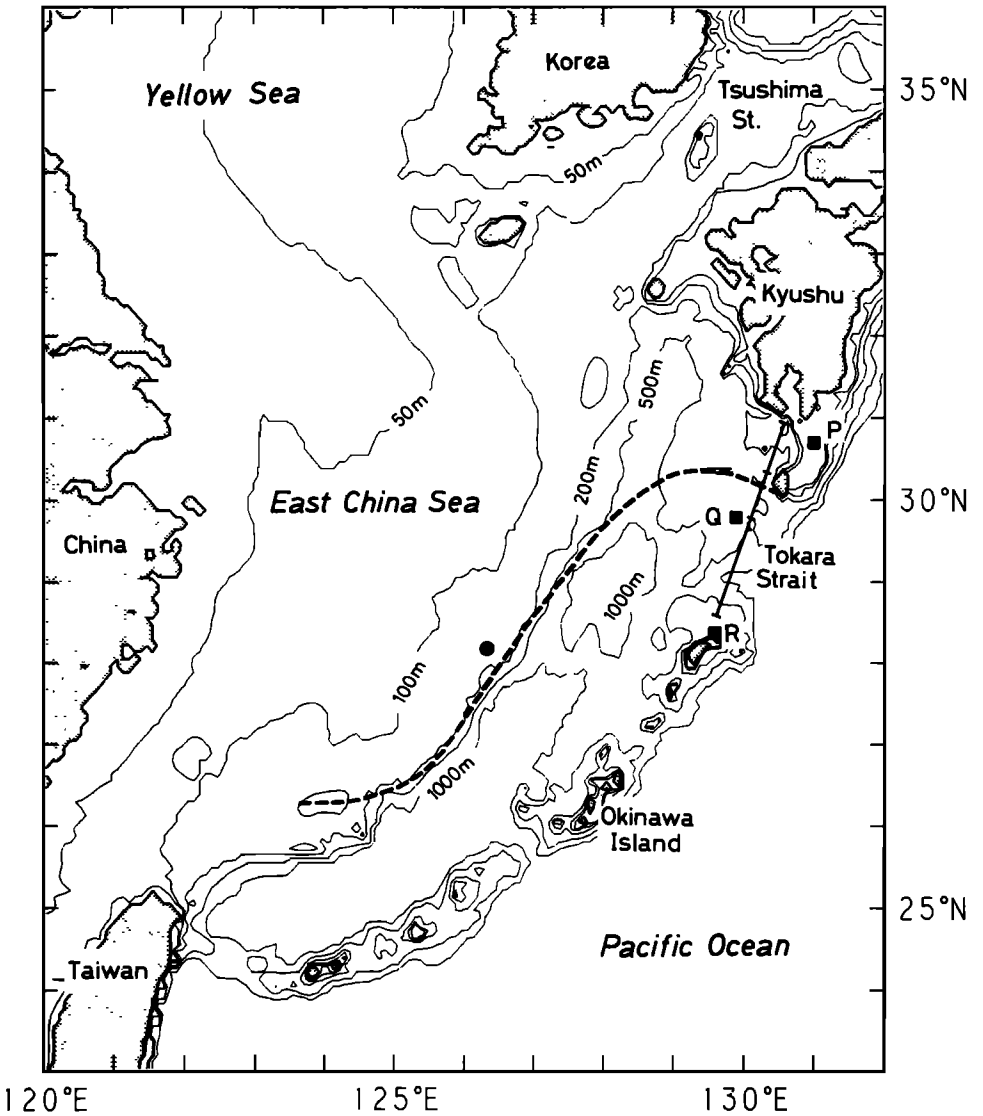

Fig. 1. Map of the East China Sea region. The dashed line indicates the mean western edge of the Kuroshio determined from the GEK observations (cf. Figure 2), and the solid circle over the continental shelf (126°20′E, 28°10′N) indicates the location of the JMA buoy station. Around the Tokara Strait, the solid line indicates the course of the ferryboat *Emerald-Amami*, and the black squares P, Q, and R indicate the locations of the tidal station Nishinoomote, Nakanoshima, and Naze, respectively.

suda et al., 1985; *Awaji et al.*, 1990]. In particular, *Awaji et al.* [1990] have shown that the fluctuation with a period of 30 days at the Tokara Strait strongly influences the sea conditions in shelf regions south of Japan. How the Kuroshio fluctuations at the Tokara Strait are related to the fluctuations that emerge upstream along the ECS shelf break is, however, not yet clarified.

Infrared images from NOAA satellites have been shown in many studies to provide useful information for surveying meso-scale processes of the ocean that have surface signals. In the ECS, satellite IR images have so far been used to determine horizontal wave patterns [*Shibata*, 1983; *Sugimoto et al.*, 1988] and to detect the split of the Tsushima Warm Current from the Kuroshio [*Huh*, 1982; *Muneyama et al.*, 1984]. However, studies based on consecutive satellite IR images have not yet been reported. This is primarily because it is rare to have clear skies for a period of days over the Kuroshio region in the ECS. In the present study, a sequence of relatively cloud-free satellite IR images over the ECS Kuroshio region were obtained from March to May 1986. Based on this sequence of satellite IR images, we first investigate the temporal and spatial evolution of the Kuroshio front fluctuations. Results derived from these satellite images are then compared with the water temperature records obtained at the ECS shelf break and across the Tokara Strait. By comparing the long-term temperature records with the sea level data around the Tokara Strait, we try to further clarify the relation between the Kuroshio fluctuations upstream along the shelf break and at the downstream Tokara Strait.

2. Satellite Observations of Kuroshio Front Meanders

Figure 3 shows a satellite IR image taken on March 5, 1986. In the image, darker tones indicate warmer waters, and brighter tones colder waters. Typical features of the

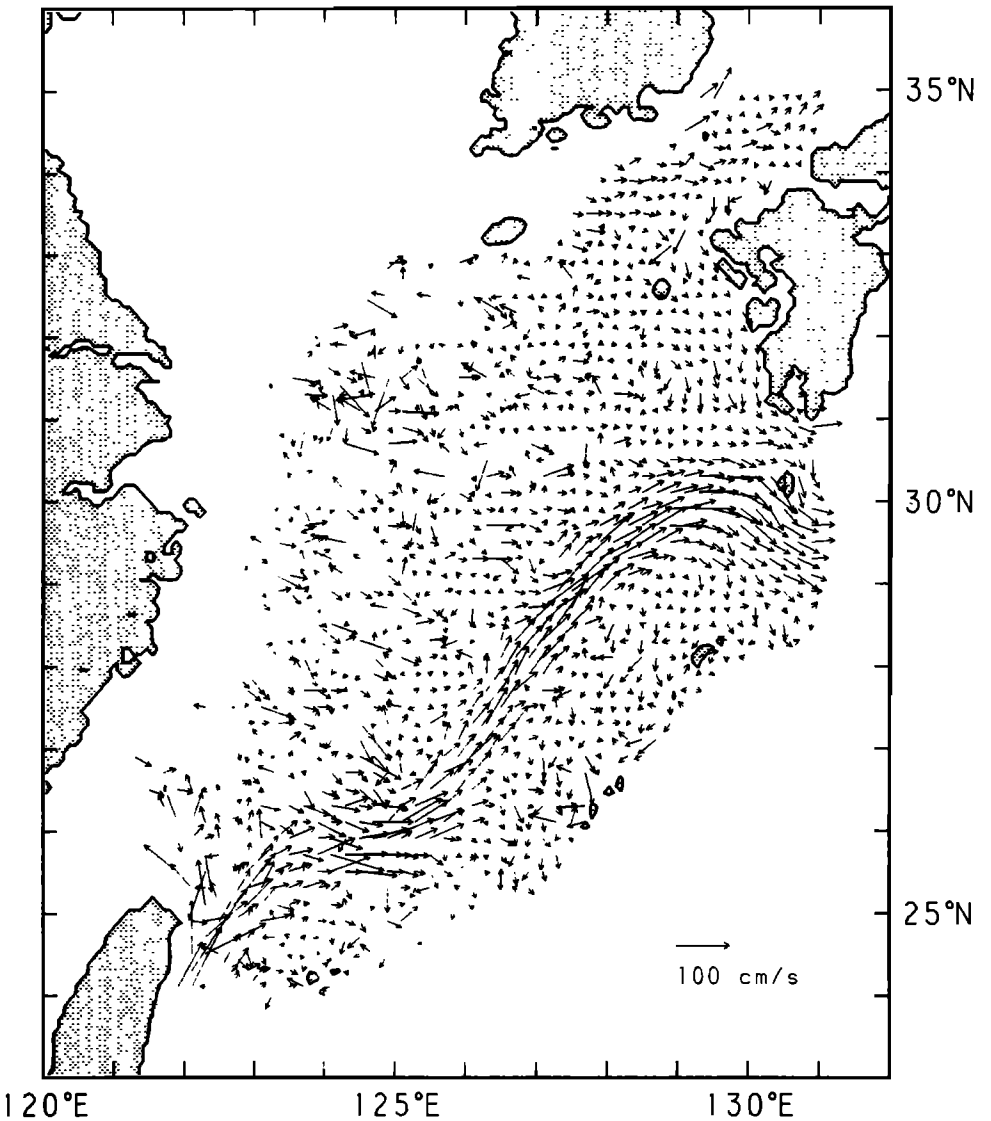

Fig. 2. Mean surface flow pattern in the East China Sea derived from the average of the GEK observations from 1953 to 1984 (see *Qiu and Imasato* [1990]).

sea surface temperature (SST) pattern during winter and spring seasons in the ECS can be seen in this image: The warm Kuroshio water exists offshore the shelf break, and a part of it also appears over the continental shelf north of Taiwan. The location of the Kuroshio water corresponds well to the flow pattern of the surface Kuroshio shown in Figure 2. Over the ECS continental shelf, a cold water tongue with a horizontal scale of 250 km protrudes from the Yellow Sea, where the water depth is shallow and intensive surface cooling occurs in winter due to prevailing northwest monsoons [e.g., *Guan and Mao*, 1982]. Along the coast of China there also exists a band of cold water whose origin is the runoff from the Yangtze and other rivers [*Beardsley et al.*, 1985]. Between these cold waters and the warm offshore Kuroshio stands an intermediate shelf water that can be regarded as a mixture between the coast-originated water and the Kuroshio water.

From Figure 3 we also notice that a sharp SST front, which corresponds well with the 20°C isotherm, appears between the intermediate shelf water and the Kuroshio water. Large-amplitude meanders with a typical horizontal scale of 150 km are seen along this SST front. In the following analysis, we refer to this SST front as the Kuroshio front and focus the discussion on its temporal and spatial fluctuations.

Figure 4 shows a sequence of the satellite IR images revealing the evolution of two front meanders from March 4 to March 12. Concerning the first meander situated around 126°30′E and 28°30′N on March 4, we find that on the following day this meander increased in amplitude and the amount of low-temperature shelf water engulfed into the Kuroshio on the upstream side of the meander increased. On March 6 (Figure 4*c*) the engulfment of the shelf water increased further and an isolated warm water mass started to form as the center of the meander moved downstream. On March 7 (Figure 4*d*) this warm water mass grew in size (about 90 km in diameter) and it was attached by only a thin piece of warm water to the main body of the Kuroshio. By March 12 (Figure 4*f*) the warm eddy had separated from the Kuroshio and can no longer be discerned in the SST pattern.

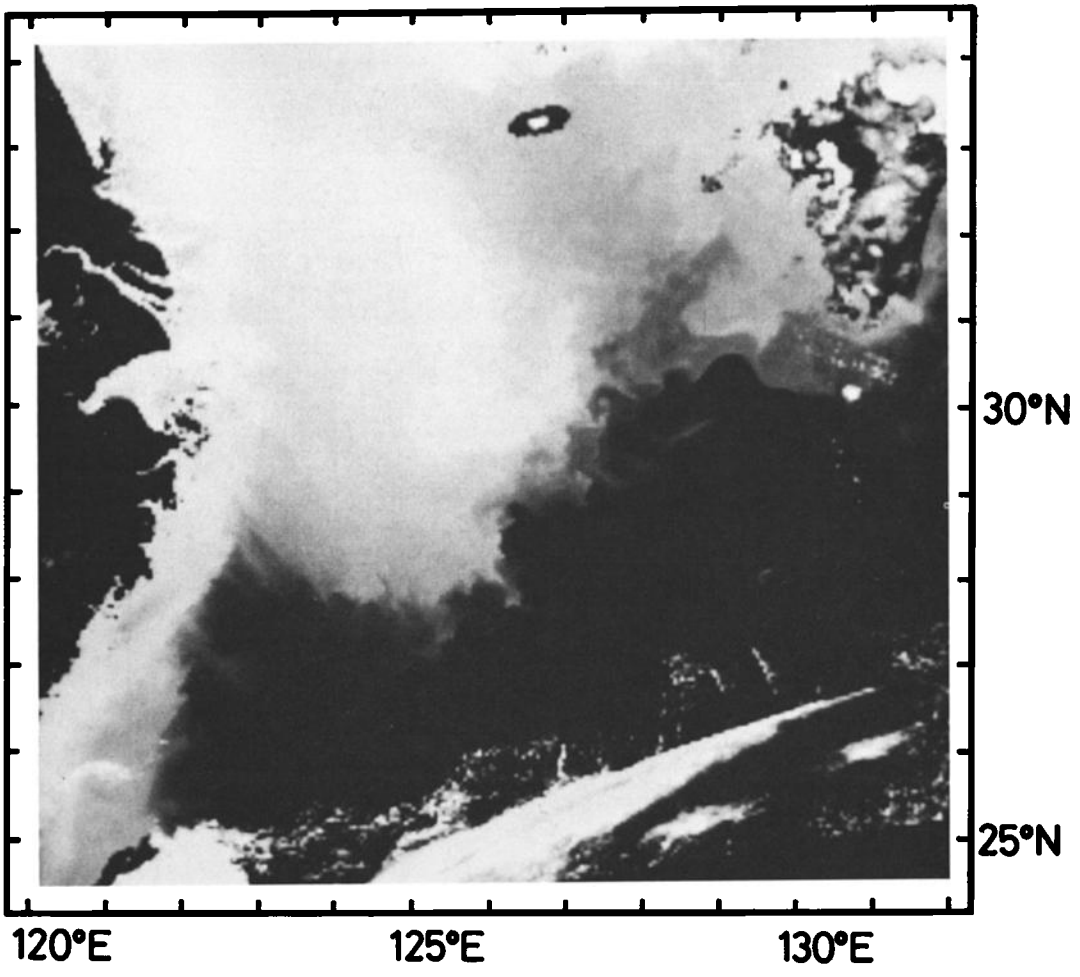

Fig. 3. Satellite IR image of the East China Sea taken by the NOAA 9 satellite at 1500 JST on March 5, 1986.

The other meander of the Kuroshio front, which was situated around 129°E and 30°30′N on March 5 (Figure 4*b*), took the form of a fully developed warm filament. This warm filament diffused rapidly between March 6 and 8. By March 12 the filament separated from the Kuroshio, though some of its influence can still be identified in the SST pattern southwest of Kyushu. A similar fully developed warm filament also appeared on April 12 at about the same location southwest of Kyushu (see Figure 5*h*). It is worth noticing that both the growth from the large meander to the warm filament (April 7–12; Figures 5*g*–5*h*) and the decay of the fully developed warm filament (March 5–8; Figures 4*b*–4*e*) occurred rapidly in the above two examples.

In Figure 5, we depict the temporal evolution of the Kuroshio front (solid lines) based on satellite IR images taken between March and April, wherein the Kuroshio front is defined by the isotherm that is consistent with the largest temperature gradient (in most cases being the 20°C isotherm). Also depicted in Figrue 5 is the mean western edge of the Kuroshio derived from GEK observations (dashed lines, cf. Figure 2). Comparison of the dashed and solid lines reveals that the observed fronts in the satellite images occur near the mean position of the Kuroshio front as determined by the GEK observations. From Figure 5 we clearly see a tendency for individual front meanders to propagate downstreamwards. In order to quantitatively determine the propagating speed of the front meanders, we hereafter define the location of each meander at the middle between the two points intersecting the dashed line (see arrows in Figure 5). We do not use the meander's apex as the center of the meander because it is often too distorted during the growth of the meandering.

In Figure 6 we plot the locations of the meanders (solid circles) as a function of time and the distance along the mean Kuroshio front. The vertical bars in the figure denote the horizontal extent of each meander along the mean Kuroshio front. By connecting the centers of the meanders, we find the downstream propagation of the Kuroshio front meanders is in the range of 20 to 26 cm s^{-1}. It is noteworthy that this propagating speed derived from the sequential satellite IR images agrees well with the values obtained by *Miyaji and Inoue* [1986] and by *Sugimoto et al.* [1988]: They estimated the phase speed of the Kuroshio meander to be about 20 cm s^{-1} based on correlations between mooring observations.

3. Comparison of Satellite and In Situ Water Temperature Observations

Over the ECS continental shelf, water temperatures have been observed at a buoy station since 1980 by the Japan Meteorological Agency [*Shibata*, 1983]. Since April 1984, the buoy station has been relocated to 126°20′E and 28°10′N,

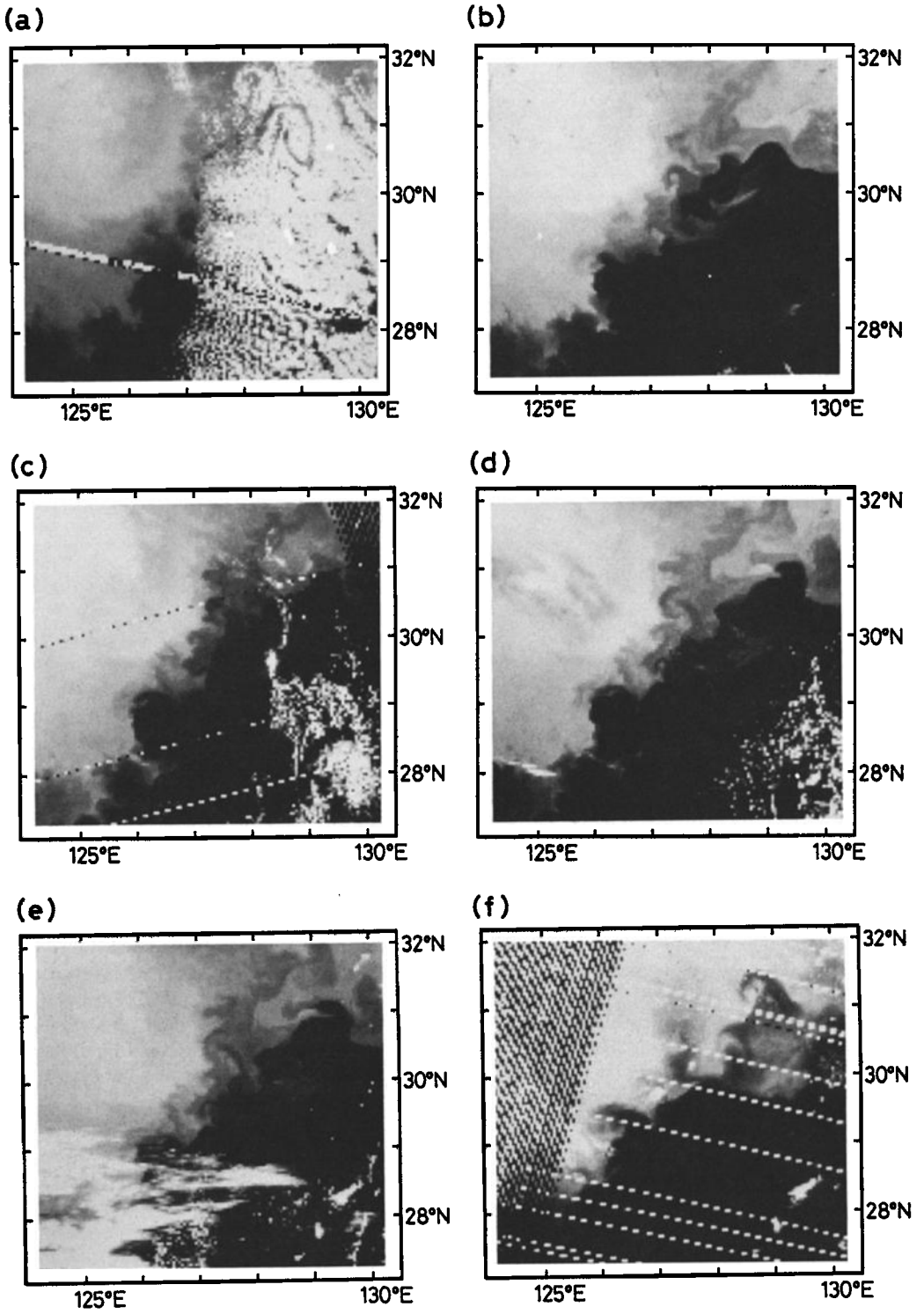

Fig. 4. Sequence of satellite IR images over the East China Sea Kuroshio region: (*a*) March 4 (at 0350 JST), (*b*) March 5 (1500), (*c*) March 6 (1820), (*d*) March 7 (1440), (*e*) March 8 (0310), and (*f*) March 12 (0750).

which is only about 30 km shoreward from the mean Kuroshio front (see the black circle in Figure 1).

Although the satellite IR images are useful in providing simultaneous SST information, consecutive cloud-free images over the warm Kuroshio region such as those obtained in Figure 5 are extremely rare. In order to further discuss the Kuroshio fluctuations in the time domain, in this section we will clarify the relation between the temperature fluctuations at the buoy station and the Kuroshio front fluctuations observed from satellite IR images. It is worth mentioning that the water temperature records of the JMA buoy are the only available long-term observational data for monitoring the Kuroshio fluctuations in the ECS (long-term mooring observations are now under way by Kyushu University [*Mizuno et al.*, 1989]).

Figure 7 shows the daily water temperature variations at the buoy station from December 1985 to May 1986. The temperature variations with a 1-year period have been re-

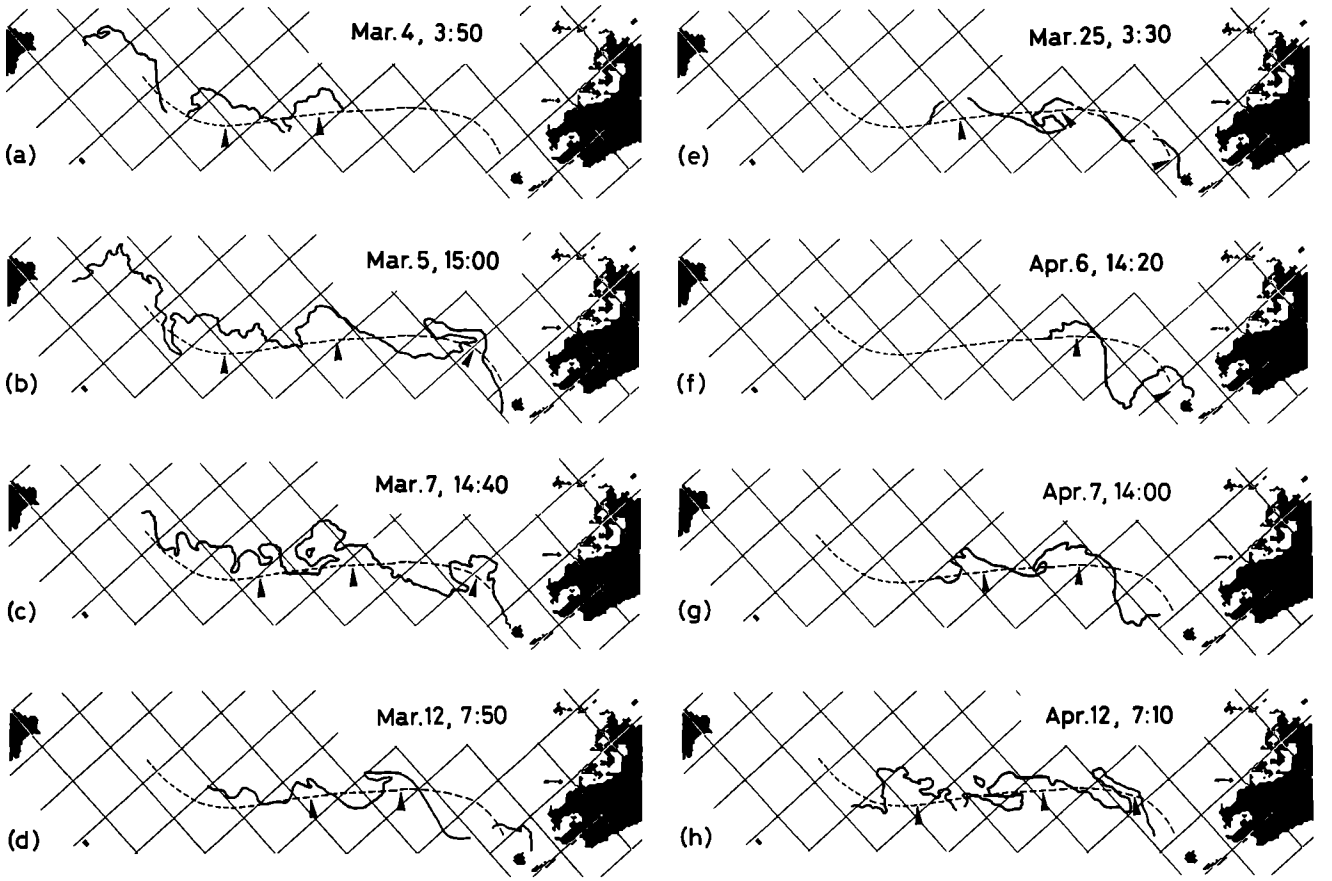

Fig. 5. Sequential evolution of the Kuroshio front deduced from the satellite IR images between March and April 1986 (solid lines). Portions covered by cloud are not shown. In each panel the dashed line shows the mean western edge of the Kuroshio (Figure 1), and arrows indicate the centers of individual front meanders.

moved, and the thick lines in the figure denote the variations after application of a 5-day running mean filter. In the low-pass filtered water temperature variations, four large peaks B, C, D, and E appeared between March 1 and April 15, during which period sequential satellite IR images were obtained. In Figure 6 we indicated the location of the buoy station by a thin dash-dotted line, and the four water temperature peaks B, C, D, and E by arrows. It is clear that each peak of the observed water temperature corresponds very well to the passage of the individual Kuroshio front meanders near the buoy station. At the buoy station of JMA, wind speeds and directions were measured at 7.5 m above the sea surface. Cross-correlation analysis shows that no significant relationship exists between the fluctuations of the water temperature and those of the wind. From these results, we conclude that water temperature fluctuations on time scales ranging from days to months observed at the JMA buoy station in winter and spring seasons accurately reflect Kuroshio front variabilities in the ECS.

From Figure 7 we further notice that the temperature fluctuations at depth 2 m (T0), 20 m (T1) and 50 m (T2) at the buoy station are visually well correlated. Cross-correlation analysis of the daily mean data in Figure 7 reveals that the correlation coefficients between T0 and T1, and between T0 and T2 are 0.91, and 0.77, respectively. This result suggests that the Kuroshio front meanders observed in the above satellite IR images are not confined to the sea surface, but have a vertical coherence scale at least 50 m deep.

Across the Tokara Strait, the surface (6 m deep) water temperature has been continuously observed by Kagoshima Prefectural Experimental Fishery Station by using the ferryboat *Emerald-Amami* [*Nagata and Takeshita*, 1985]. The ferryboat passes the Tokara Strait every 2 days on the course shown in Figure 1 by the solid line. In Figure 8 we show the temperature records observed by the ferryboat between March 1 and April 30, 1986. In the figure, arrows denote large temperature gradients that correspond to the Kuroshio front at the Tokara Strait. The mean position of the Kuroshio front, as can also be inferred from Figure 2, exists in the middle of the northern end (P) and the center (Q) of the strait. The other temperature front in Figure 8 which situates stably around the northern end of the strait corresponds to the boundary between the coastal and shelf waters.

The movements of the Kuroshio front in Figure 8 are very similar to those found by *Nagata and Takeshita* [1985], who analyzed the temperature records observed by the ferryboat between 1978 and 1981. For example, the northward migration of the Kuroshio front can be easily traced, while its southward migration is scarcely discernible. After having migrated north on March 9, March 27, April 4, and April 24, each front gradually weakened and was eventually replaced by a new front migrating from the south round point Q.

The physical explanation for these characteristics of the Kuroshio front at the Tokara Strait, however, is not yet clear. By incorporating the satellite information from the

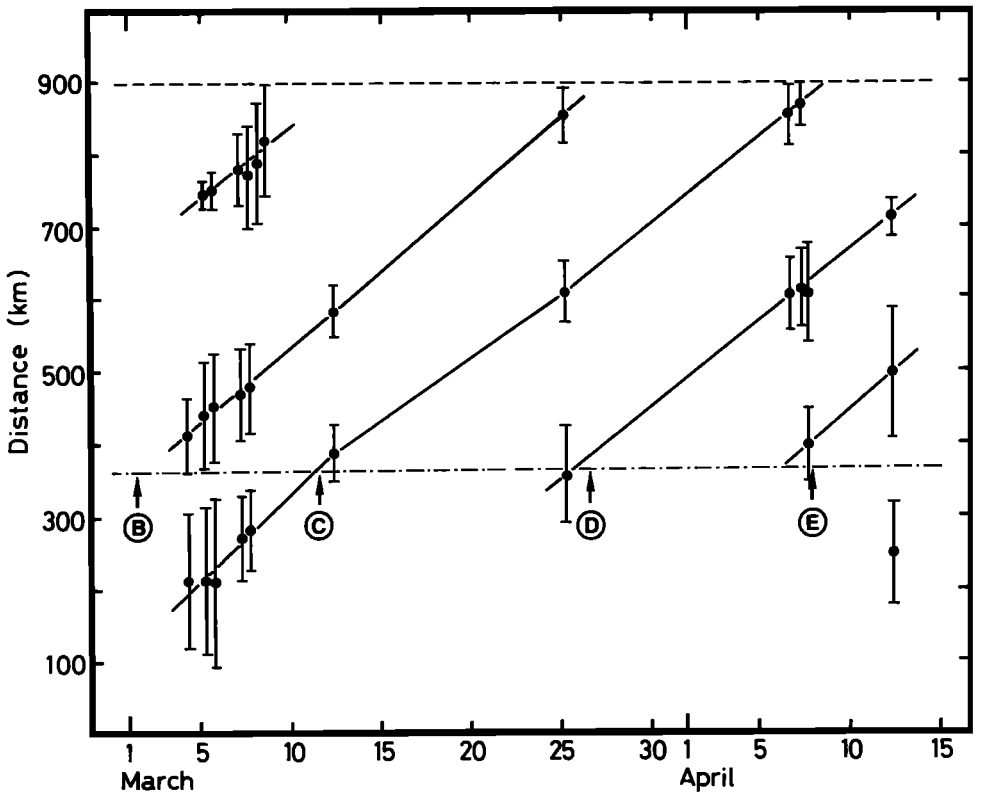

Fig. 6. Space-time plot of the movement of the Kuroshio front meanders, where black circles denote the centers of the front meanders, and vertical bars denote their extents along the mean Kuroshio front. In the figure, the thin dash-dotted line shows the location of the buoy station, and arrows B, C, D, and E indicate the four temperature peaks observed at the buoy station. The location of the Tokara Strait is indicated by a thin dashed line.

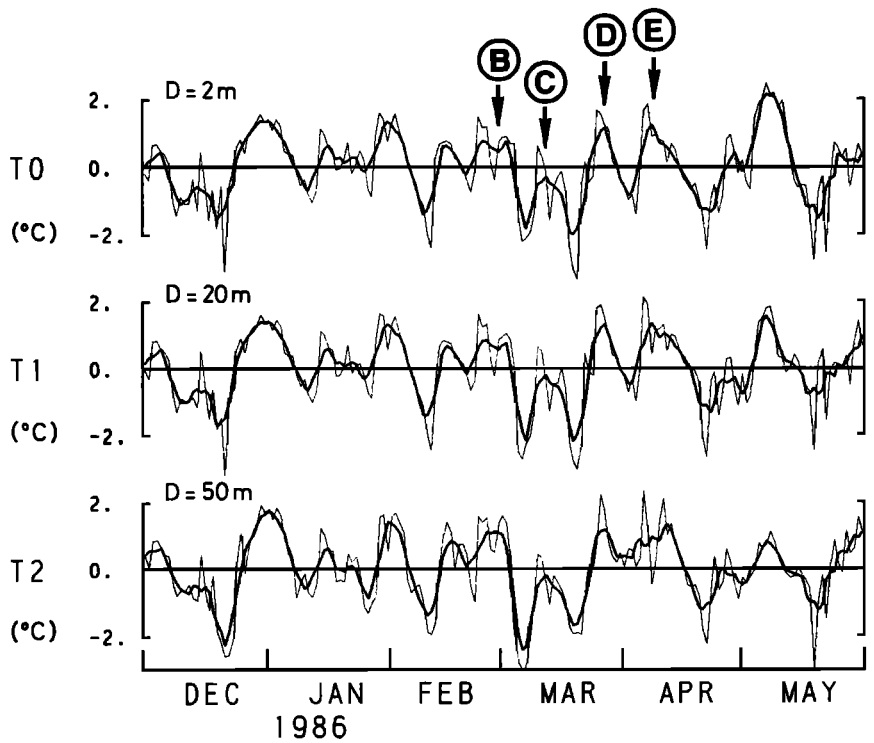

Fig. 7. Water temperature fluctuations observed at the JMA buoy station, where the thin lines show the daily mean fluctuations and the thick lines show those after a 5-day running mean procedure. Notice that temperature variations with a 1 year period have been removed from the data shown in the figure. The mean temperatures of T0, T1, and T2 over the period are 23.9°C, 23.3°C, and 21.6°C, respectively.

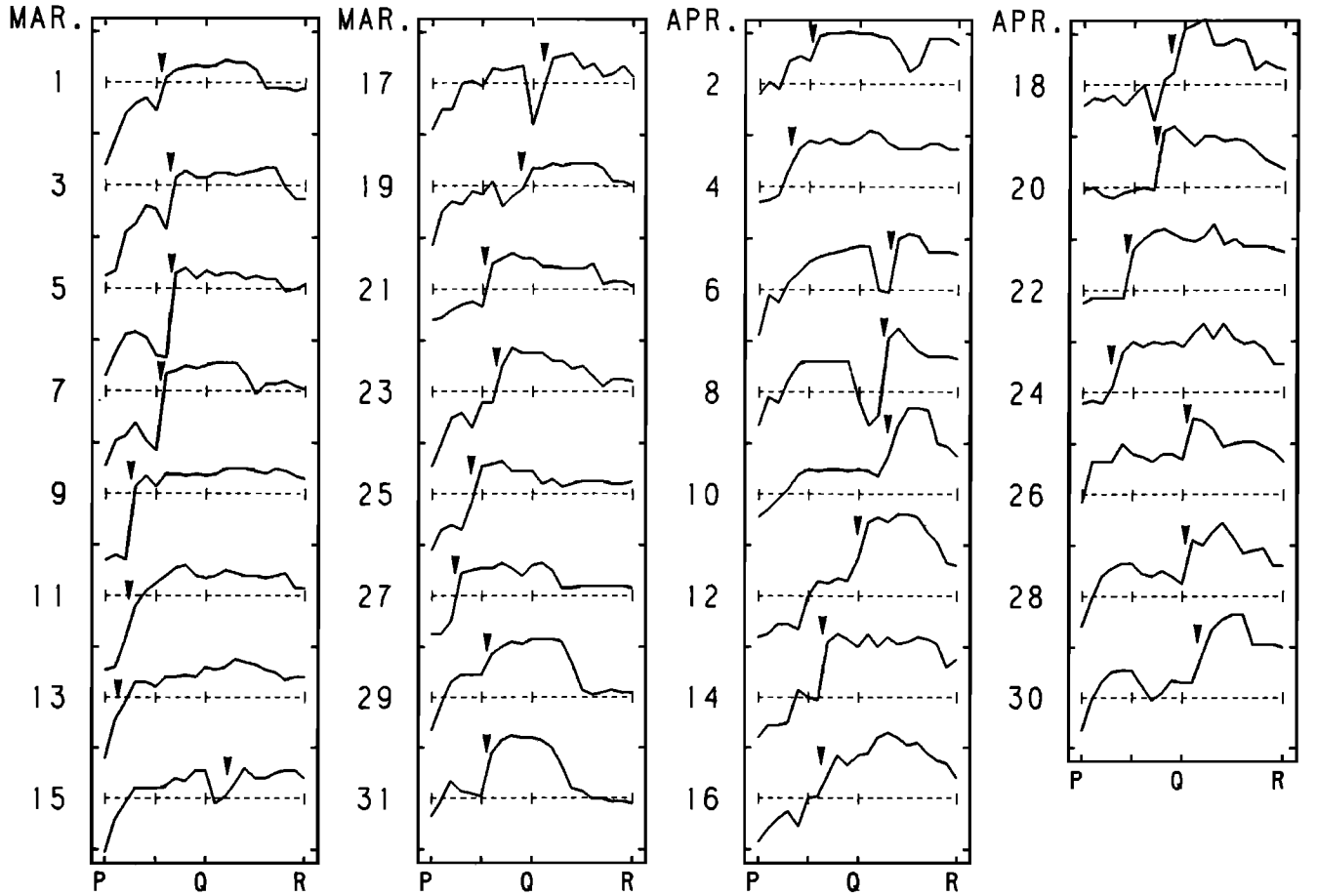

Fig. 8. Water temperature variations (at depth of 6 m) observed by the ferryboat *Emerald-Amami* across the Tokara Strait. Points P, Q, and R indicate the northern end, the middle, and the southern end of the strait, respectively (see Figure 1 for the course of the ferryboat). In each panel the center line shows 18°C and the vertical scales for the temperature are ±2°C. Arrows indicate the position where the large temperature gradient corresponds to the Kuroshio front.

last section, we can explain these characteristics as follows: First, we notice that the northward migration of the Kuroshio front observed on March 25, April 4 and April 24 corresponds to the arrival of the Kuroshio front meander B, C, and D at the Tokara Strait, respectively (see Figure 6, wherein the location of the Tokara Strait is denoted by the thin dashed line). Front meanders, as seen in the satellite IR images in Figure 4, generally have sharp temperature gradients and well-defined patterns on the downstream side, while the temperature gradients and patterns on the upstream side are always obscued by cold water engulfment. This asymmetry in temperature structures on the meanders' two sides results in the alternation of the front's clear northward and blurred southward migration at the Tokara Strait as observed in Figure 8.

4. Kuroshio Fluctuations at the ECS and Volume Transport Variations at Tokara Strait

In the previous sections we found that meanders of the Kuroshio front in the ECS increase in amplitude while propagating downstream at speeds of 20–26 cm s^{-1}. It was also found that these front meanders influence directly the SST distributions across the Tokara Strait. A new question here is whether these front meanders are related to the volume transport variations at the Tokara Strait. Although variations of the volume transport at the Tokara Strait have been pointed out by many former studies to be crucially important to the Kuroshio variabilities south of Japan, their origin and relation with the upstream Kuroshio fluctuations in the ECS have not yet been clarified.

In the present study, we try to clarify the relation by comparing the temperature data of the JMA buoy to the data of the sea level difference between Nishinoomote and Nakanoshima and between Nakanoshima and Naze (see Figure 1 for the locations of the three tidal stations). The sea level difference between Naze and Nishinoomote has been shown by *Kawabe* [1980, 1988] and *Rikiishi and Sasaki* [1988] to be a good index of the surface velocity and volume transport of the Kuroshio at the Tokara Strait. Based on their results, we regard the sea level difference between Nishinoomote and Nakanoshima and between Nakanoshima and Naze to represent the volume transport of the Kuroshio at the northern half and southern half of the Tokara Strait, respectively. In the following analysis we will focus the discussion on winter and spring seasons (December–May) when temperature fluctuations at the buoy station are prominent and correspond well to the Kuroshio variabilities. Since buoy data are only available from 1986 and 1987 after the tidal station Nakanoshima was set up in 1984, the discussion will be further confined to these 2 years.

In Figure 9 we show the temperature variations observed at the buoy station in the winter and spring of 1987. Compared with those of 1986 (Figure 7), we find that the temperature fluctuations are less regular and that the large-amplitude fluctuations are absent in the first 2 months of the period. In Figures 10 and 11 we show the time variations of the sea level difference from December 1985 to June 1986 and from December 1986 to June 1987, respectively.

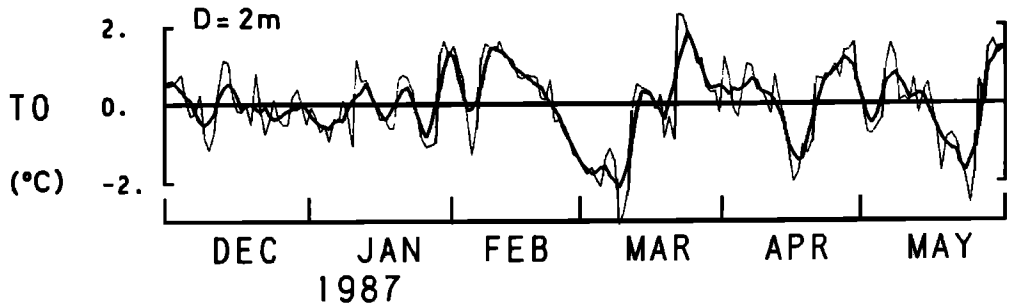

Fig. 9. Same as in Figure 7 except for water temperature variations from December 1986 to May 1987. The mean temperature over the period is 24.4°C.

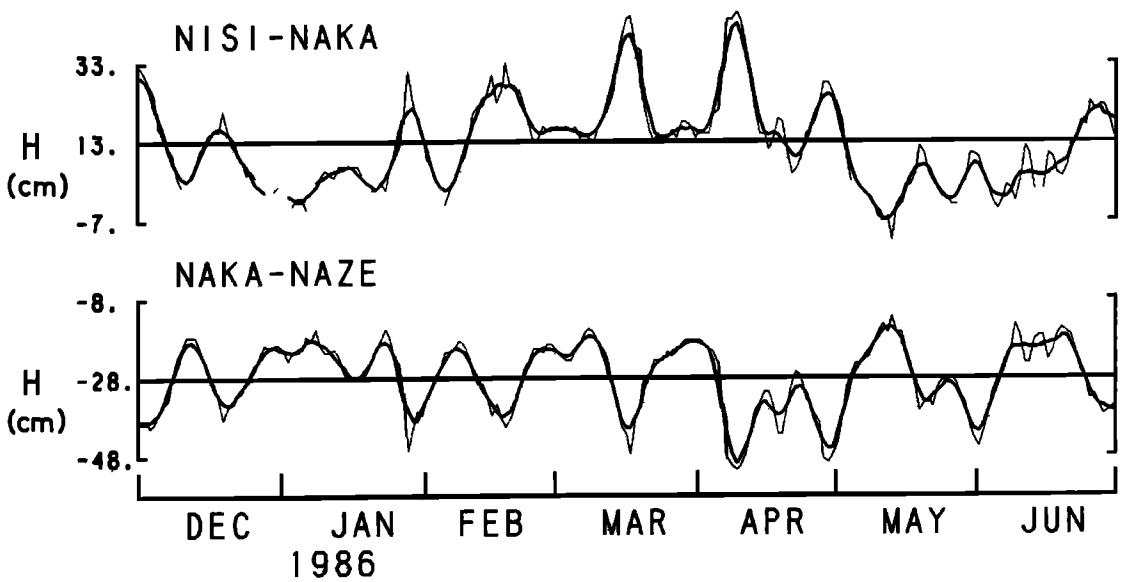

Fig. 10. Time series of sea level difference between Nishinoomote and Nakanoshima, NISI-NAKA, and between Nakanoshima and Naze, NAKA-NAZE (see Figure 1 for the locations of these tidal stations), from December 1985 to June 1986. Thin lines show daily mean values, and thick lines show values after application of a 5-day running mean filter.

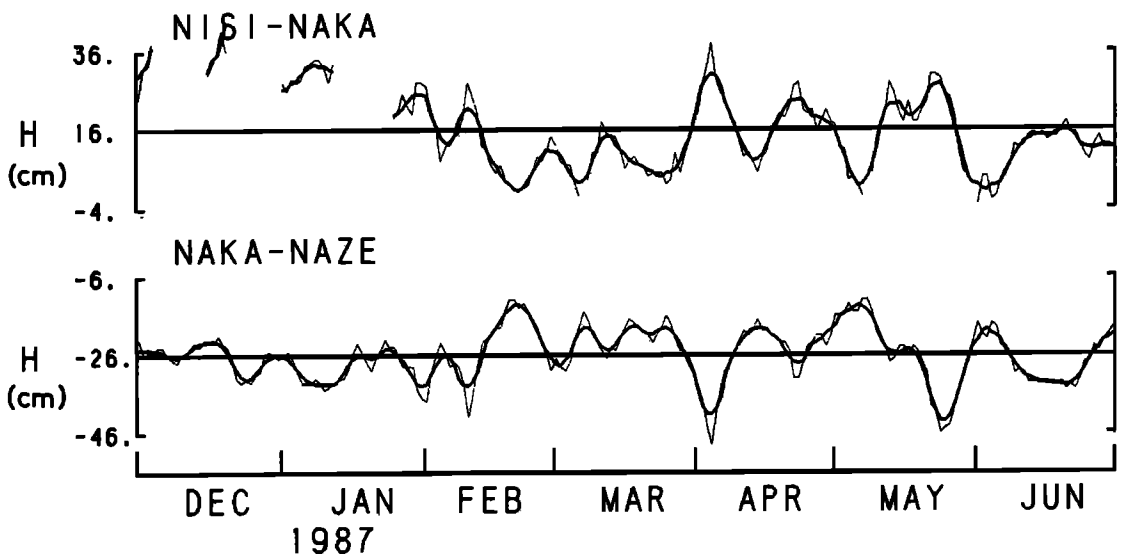

Fig. 11. Same as in Figure 10 except from December 1986 to June 1987.

In both figures we find a clear negative correlation between the sea level difference of Nishinoomote-Nakanoshima (P-Q) and that of Nakanoshima-Naze (Q-R) in fluctuations with periods of 15 to 20 days. The existence of this clear negative correlation indicates that the 15- to 20-day fluctuations appearing in Figures 10 and 11 are associated with the north-southward movement of the entire Kuroshio stream at the Tokara Strait.

In Figure 12 we calculated the cross-correlation coefficients between the fluctuations of the surface temperature at the buoy station and those of the sea level difference of Nakanoshima-Naze (Q-R). The correlation pattern is quite similar in both the 1986 and 1987 cases, with correlation peaks appearing when time lag is around 5, 15, and 37 days. Notice that the 37-day peak is the only physically relevent one in the present situation because it takes about 27 days for a front meander near the buoy station to reach the Tokara Strait (see Figure 6). In Figures 13*a* and 13*b* we superimposed the time series of the buoy's surface temperature upon those of the sea level difference of Nakanoshima-Naze with a time lag of 38 and 35 days, respectively. As shown in Figure 12, these two time lag values result in the maximum correlations for 1986 and 1987. Correspondence between the two time series is generally good, especially if we take into account that the propagating speeds of individual front meanders are not necessarily the same (see Figure 6).

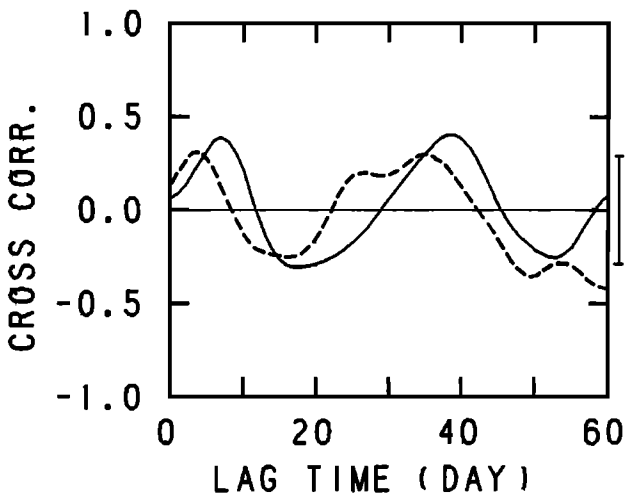

Fig. 12. Cross correlation between the temperature variations at the buoy station and the sea level difference variations of Nakanoshima-Naze. The solid line is obtained from data between December 1985 and June 1986, and the dashed line between December 1986 and June 1987.

The above results suggest that the volume transport variations associated with the north-south fluctuations of the Kuroshio stream at the Tokara Strait have their origins in the upstream Kuroshio front meanders in the ECS. Further observations, however, are necessary to reach a firmer conclusion. Cross-correlations between the buoy's temperature fluctuations and the fluctuations of the sea level difference between Naze and Nishinoomote (P-R) were also calculated, and we found no significant correlations between the two. This is of no surprise because the latter, representing the volume transport variations of the Kuroshio itself, is determined by the large-scale Sub-Tropical Gyre of the North Pacific.

Finally, it is worth noting that a time lag of about 10 days exists between the time the Kuroshio front meanders reach the Tokara Strait and the Kuroshio stream at the Tokara Strait shifts to its northernmost position. When the Kuroshio front meanders reach the Tokara Strait, we notice in Figure 5 that the meanders encounter the topographic protrusion of Kyushu and other islands to their north (cf.

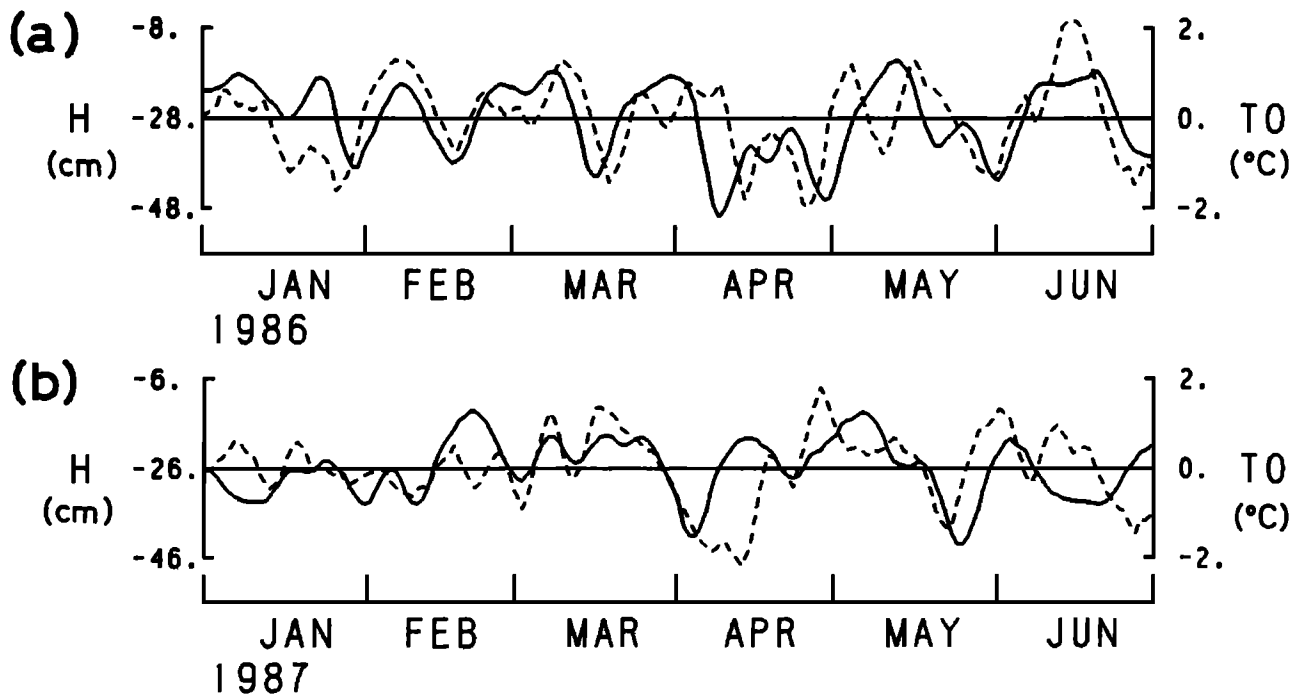

Fig. 13. Comparison between the time series of the buoy's suface temperature variations (dashed lines) and those of the sea level difference of Nakanoshima-Naze (solid lines). The temperature data have been lagged 38 days and 35 days in (*a*) 1986 and (*b*) 1987, respectively.

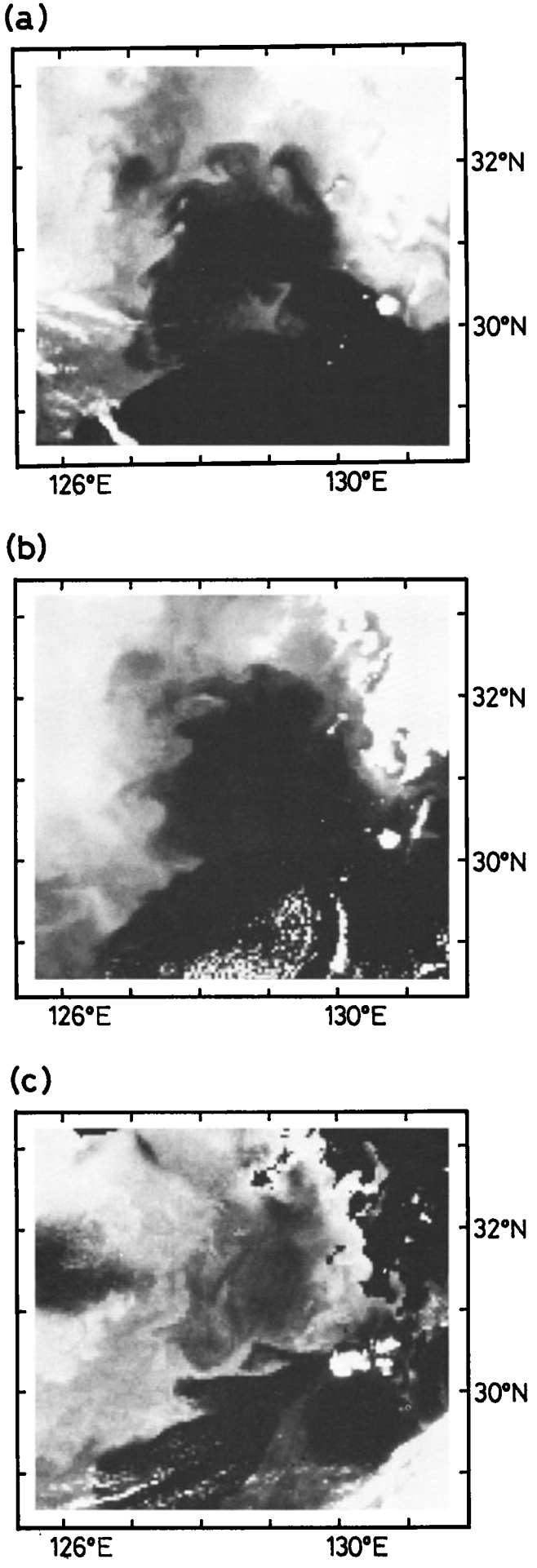

Fig. 14. Sequence of satellite IR images over the sea area southwest of Kyushu: (*a*) May 17 (at 0400 JST), (*b*) May 23 (0300), and (*c*) June 9 (1300).

isobaths around the Tokara Strait in Figure 1). We speculate that this encounter by the Kuroshio front meanders provokes the Kuroshio stream at the Tokara Strait to shift and that the delay in shifting to its northernmost position is due to the adjustment of the Kuroshio stream there. We will investigate this adjusting process of the Kuroshio stream in our future studies.

5. Shed-off Warm Eddies Southwest of Kyushu

The main flow of the Kuroshio in the ECS veers eastward around 128°30′E and 30°N (Figure 2). In the sea area southwest of Kyushu after the Kuroshio separates from the continental slope, most Kuroshio front meanders have large amplitudes (e.g., Figure 5). Besides the appearance of the fully developed warm filaments discussed in section 2, another outstanding feature of the Kuroshio front in this region is the emergence of large shed-off warm eddies.

In Figure 14 we show a sequence of three satellite images from May 17 to June 9, 1986, that capture a well-defined shed-off warm eddy. On May 17 the image shows that a great portion of warm Kuroshio water was fed into the eddy just west of the Tokara Strait. The anticyclonic rotation of this warm eddy can be inferred from the backward-breaking wave patterns of the surrounding colder water. On May 23 the horizontal scale of the warm eddy increased to about 180 km, and direct warm water supply from the Kuroshio was no longer clear. On May 22 and 23 the R/V *Yokomaru* of Seikai Regional Fisheries Research Laboratory carried out salinity-temperature-depth observations across the northern half of the eddy (along 31°30′N). In Figure 15 we depicted the vertical water temperature distribution observed by the vessel between 126°E and 130°E. It shows a typical temperature pattern for warm-core rings, and it is worth noting that the eddy reaches a depth greater than 200 m and that its size (~ 200 km) is that of the deep basin southwest of Kyushu. By June 9, the satellite IR image (Figure 14*c*) shows that the temperature difference between the water inside and outside the eddy has largely decreased, although it still remains recognizable with its horizontal size close to that on May 23.

Concerning the formation of warm eddies southwest of Kyushu, *Yamagata and Kamachi* [1989] recently proposed that the anticyclonic warm eddies are formed through the evolution of cyclonic eddies initially induced by the instability of the Kuroshio. Due to lack of satellite images and other observational data for the first half of May, we are unfortunately unable to compare the evolution of the warm eddy in Figure 14 with their numerical results.

Since not all the upstream meanders in the ECS evolve into shed-off warm eddies, it is of interest to investigate factors that might influence the formation of the shed-off wam eddies. Based on findings that about 27 days are neccesary for a front meander at the buoy location to reach the Tokara Strait (Figure 6), it is plausible that the warm eddy found in Figure 14 was induced by the front meander E after it propagated downstream and developed in amplitude. The temperature records in Figure 7, however, show no particular anomalous fluctuations for the meander E as compared

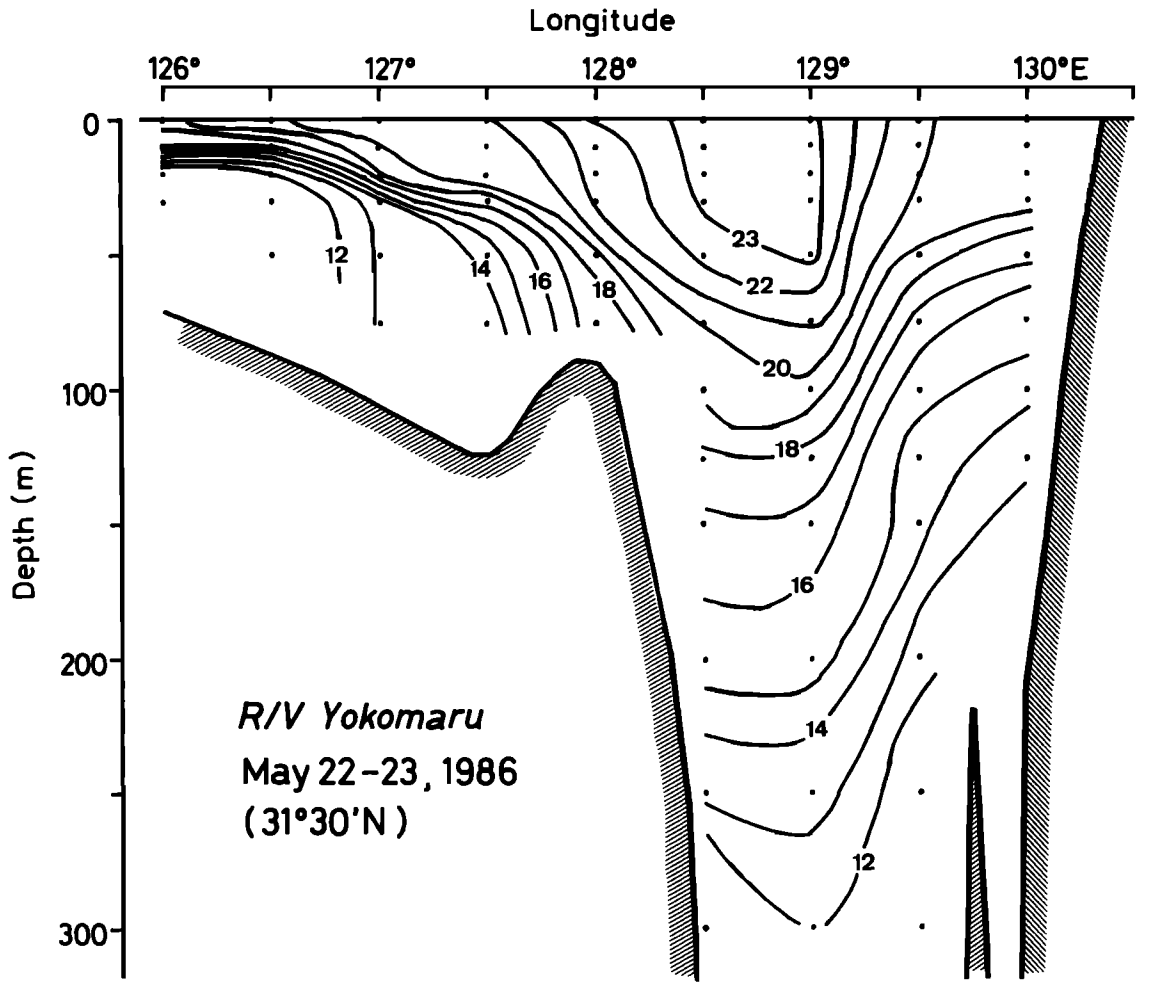

Fig. 15. Vertical temperature pattern observed by R/V *Yokomaru* along 31°30'N on May 22–23, 1986 (based on data report of KER, phase II, no.1 of Japan Oceanographic Data Center, 1988).

to its three preceding meanders. However, we do notice that the sea level difference across the Tokara Strait, which represents the Kuroshio transport in the upstream ECS, increased 20% in the middle of April (see Figure 16). Since the Kuroshio path curves sharply southwest of Kyushu (Figure 2), an increase in the volume transport can reinforce the inertial force of the Kuroshio there, consequently triggering shedding off of the warm eddy. The detailed mechanism of the eddy's shedding-off will be considered in our subsequent numerical studies.

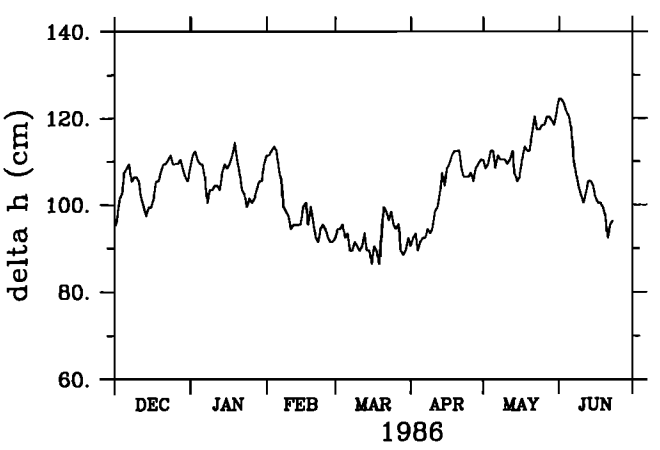

Fig. 16. Time series of daily mean sea level difference between Naze and Nishinoomote. The vertical scale in the figure includes the datum-line difference between the two stations using the value obtained by *Rikiishi and Sasaki* [1988].

6. Conclusions

Kuroshio front fluctuations along the East China Sea continental shelf, at the Tokara Strait, and southwest of Kyushu are investigated in detail by using satellite IR images, temperature records from the JMA buoy station over the continental shelf, and temperature records observed by the ferryboat *Emerald-Amami*, which crosses the Tokara Strait.

Based on consecutive satellite IR images between March and April 1986, we found that front meanders appear along the western edge of the mean Kuroshio. The meanders have typical horizontal scales in the range of 100 to 150 km and evolve rapidly while propagating downstream. From the movement of front meanders in the sequential satellite images, we determined the downstream propagation of the meanders to be at speeds of 20 to 26 cm s^{-1}.

Front meanders and warm filaments similar to those found in the present study have been frequently observed on the Gulf Stream front between Cape Canaveral and Cape Hatteras from both satellite observations [e.g., *Legeckis*, 1979] and field observations [*Lee et al.*, 1981; *Bane et al.*, 1981;

Brooks and Bane, 1981; *Lee and Atkinson*, 1983]. While the horizontal scales of the Gulf stream front meanders are similar to those in the Kuroshio (about 100 to 150 km), we notice that the downstream propagating speed and the prominent period of the front meanders in the Gulf Stream are 40–70 cm s^{-1} and 5–9 days, respectively. This propagating speed is double that of the Kuroshio (20–26 cm s^{-1}) and the prominent period is less than a half of the Kuroshio's (14–20 days). The energy source for these front meanders is likely the baroclinic or the mixed-type instabilities of the boundary current [e.g., *Orlanski and Cox*, 1973; *Luther and Bane*, 1985; *Oey*, 1988]. Comparing the bottom topography across the front regions of the Gulf Stream and the Kuroshio reveals that the shelf break in the Gulf Stream region is 60 m deep, much shallower than 200 m for the Kuroshio region. We conjecture that this difference in bottom depth causes the difference in propagation speed and period of the unstable waves between these two boundary currents.

After propagating downstream to the southwest of Kyushu, the fully developed meanders of the Kuroshio may take the form of shingle-like warm filaments or develop into shed-off warm eddies. In cases found in the present study, shingle-like warm filaments occurred when the volume transport of the Kuroshio in the ECS was small (from March to the middle of April), whereas a warm eddy formed during a period when the volume transport increased substantially (after the middle April). We speculate that the increase in volume transport may have reinforced the inertial effect of the Kuroshio southwest of Kyushu (where the path curves sharply) and, consequently, contributed to the shedding-off of the warm eddies.

Based on ferryboat observations, *Nagata and Takeshita* [1985] found that the Kuroshio front migrates rapidly northward across the Tokara Strait. By comparing the ferryboat observations with satellite data, we discovered that this northward front migration corresponds to the passage of the Kuroshio front meanders from the upstream ECS shelf break. Moreover, the blurred southward migration of the front seen in the ferryboat observations is found to be caused by the presence of mixed water on the upstream side of the front meanders.

Over the ECS continental shelf, temperature fluctuations observed at the JMA buoy station were found to accurately represent the movement of the Kuroshio front meanders. By comparing these temperature records with the sea level difference variations between Nishinoomote and Nakanoshima and Nakanoshima and Naze, we found good correlations between the appearance of the Kuroshio front meanders in the upstream ECS and the north-south fluctuations of the Kuroshio stream (in terms of the volume transport) at the Tokara Strait. It was also found that a time lag of about 10 days exists after the Kuroshio front meanders reach the Tokara Strait and before the Kuroshio stream shifts to its northernmost position. This time delay is possibly due to the adjustment of the Kuroshio stream around the Tokara Strait after the front meanders hit the topographic protrusion of Kyushu.

In the present study, we described the Kuroshio front fluctuations based on satellite images and in-situ observational data. While some characteristics, such as the downstream propagation of the meanders and the appearance of shingle-shaped warm filaments are commonly observed in other western boundary currents, the current fluctuations near the Tokara Strait where the Kuroshio interacts with the topographic protrusion of Kyushu and the shedding-off of warm eddies associated with the curvature of the current path are peculiar to the Kuroshio. In our forthcoming studies, we plan to physically explain these characteristics of the Kuroshio and to estimate their influence upon the neighboring sea regions.

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