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Temporal and spatial variations in the Bottom Cold Water on the shelf off San'in coast, Japan

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Abstract: The main thermocline off San'in coast in the Japan Sea intersects a gentle slope on the shelf. A large displacement of this thermocline from the shelf edge to the inshore region has been frequently observed from accumulated hydrographic observation data. Such a displacement means the evolution of a cold-water region over the shelf, which is called the Bottom Cold Water (BCW). In order to clarify the temporal and spatial variations in the BCW, we analyzed a time series of the bottom-water temperature data from December 1980 to December 1982, measured by a submarine telephone cable on the shelf between Japan and Korea.

We found that intense evolutions of the BCW over the shelf occur 6 to 9 times in a year, rather than seasonal variations of the BCW. Although such events sometimes are followed by a few cycles of oscillations, they show eastward phase propagations of 7 to 10 cm s^{-1} at a typical wavelength of a few hundreds of kilometers. These characteristics may identify such motions as bottom-trapped Rossby waves originating from disturbances around the wastern entrance of the Tsushima/Korea Strait.

1. Introduction

The Japan Sea is a marginal sea of the North Pacific Ocean and is a semi-enclosed basin with its depth reaching more than 3000m. The Tsushima Current flowing into the Japan Sea through the Tsushima/Korea Strait forms three branches off the San'in coast in the Japan Sea as shown in Fig.1(a). Fig.2 shows horizontal current profiles by ADCP at 10m, 50m, and 100m depth, vertical distributions of temperature along Section A off Hamada (for location see Fig. 1(b)), and wind vectors at Hamada in summer 1988 (a) (ISODA and MURAYAMA, 1990) and summer 1989 (b)(ISODA *et al.*, 1992). Both observations were carried out under a light wind with speed of less than 1 m s^{-1}. Nevertheless, observation (a) exhibits a large displacement of the main thermocline from the shelf edge to the inshore region, while observation (b) shows that the thermocline intersects the shelf edge. Thus, it seems that the large displacement of the thermocline shown in observation (a) cannot be explained by using the coastal upwelling theory in the wind-forced regions. In addition, it can be seen that the positions and shapes of the flow on the shelf may be also largely affected by the location of the main thermocline.

The large displacement of the main thermocline around the shelf edge means the evolution of a cold water region over the shelf, which is called the Bottom Cold Water (hereafter referred to as the BCW). For a long time, this BCW has been believed to exist over the shelf off San'in coast. This was based on the results of accumulated hydrograpghic observations (e.g. UDA, 1931; YAMASAKI, 1969; MORIWAKI and OGAWA, 1988, 1989; ISODA and MURAYAMA, 1990). However, the detailed horizontal structure of the BCW, its variation period, and the possible cause of such variations are not yet clarified, because such an irregular phenomenon as the BCW in time and space cannot be detected from the monthly or bi-monthly hydrographic observations.

A submarine telephone cable lies on the shelf between Japan and Korea as shown in Fig. 1(b), The bottom-water temperatures along the submarine cable were measured for the purpose of

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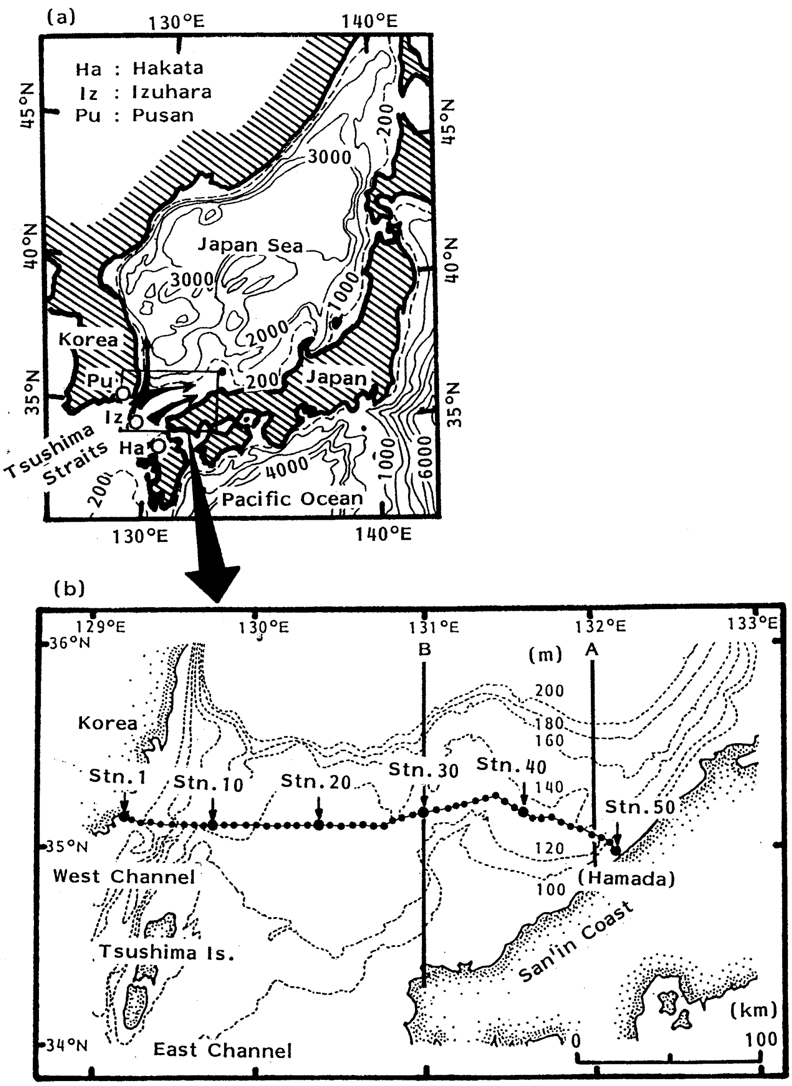

Fig. 1 (a) Map of the Japan Sea. The three branches around the Tsushima/Korea Strait are shown schematically by heavy arrows. Locations of the tide-gaugestations are shown by open circles. (b) Bathymetric chart from 100m to 200m depth on the shelf off San'in coast, showing locations of bottom-water temperature stations along the submarine cable. A and B indicate the observation lines.

maintenance and inspection. The cross-shelf (or nearly north-south) migration of the BCW front, which is the thermal front at the southern end of the BCW, can be inferred from these temperature data, because the BCW front moves just over the submarine cable as shown in Fig.2. Such continuous data in time and space on the shelf are scarce and are very valuable. We analyzed two-year temperature data along the submarine cable. The characteristics of the seasonal and the short-term variations in the BCW distribution over the shelf are described in this paper.

2. Data

The observation sites of bottom-water temperature on the shelf off San'in coast are shown in Fig. 1(b). The temperature sensor is installed in a repeater on the sea bottom for amplifying the signal. There are 50 repeaters arrayed on the submarine cable.

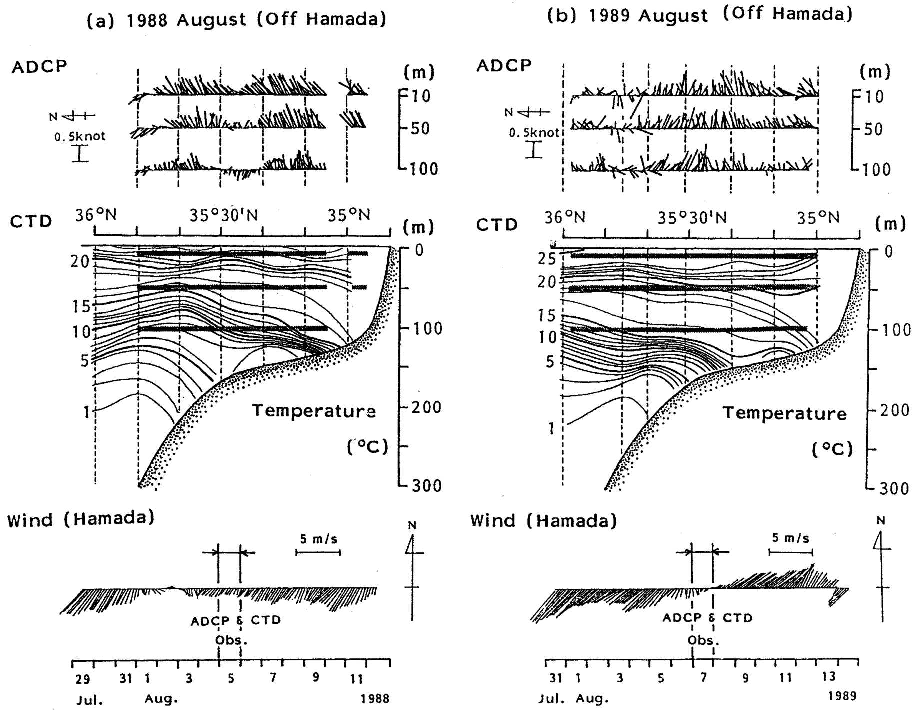

Fig. 2. Horizontal current profiles deduced from ADCP at 10m, 50m, and 100m depth (upper), vertical distribution of temperature (middle) across Section A in Fig.1(b), and time series of 24-hour running mean wind vectors during 2 weeks at Hamada (lower) on 5 August 1988 (a) from ISODA and MURAYAMA (1990) and 7 August 1989 (b) from ISODA *et al.* (1992). Three heavy horizontal lines in the middle panel indicate the observed depths and regions of ADCP.

Two-year temperature data at one week intervals from December 1980 to December 1982 were analyzed in this study. However, water temperatures at Stn.24 were not observed throughout the entire period due to some mechanical trouble. The missing time series data for Stn. 24 were constructed by linear interpolation of values at adjacent stations. Data were not taken at all stations from 23 December 1980 to 27 January 1981 and from 8 September to 15 September 1981. Hydrographic temperature data measured by the Fisheries Agency Japan (1985, 1986) at Shimane, Yamaguchi, and Fukuoka Prefectural Fisheries Experiment Stations in 1981 and 1982, are used to understand the spatial distributions of the BCW.

Since the shelf off San'in coast is directly connected to the Tsushima/Korea Strait, the flow variations on the shelf might be monitored by those in the Strait. Flow variations in the Tsushima/Korea Strait are investigated by examining sea-level differences across the Strait (e.g. KAWABE, 1982). Daily mean sea-level data from 1981 to 1982 are available at Pusan (Hydrographic Office of the Republic of Korea) and at Izuhara and Hakata (Japan Maritime Safety Agency). The positions of these tidal stations are also shown in Fig. 1(a). Since the momentum balance normal to the flow direction may be geostrophic, it can be expected that variations of sea-level difference between Hakata and Izuhara and those between Izuhara and Pusan reflect the variations of surface velocity in the East and West Channel of the Tsushima / Korea Strait, respectively. From the variations of sea level difference in both channels, the cross-shelf flow structure on the shelf will be roughly inferred.

3. Data analysis

Seasonal variations in the BCW

Fig. 3 shows the temporal variation in tem-

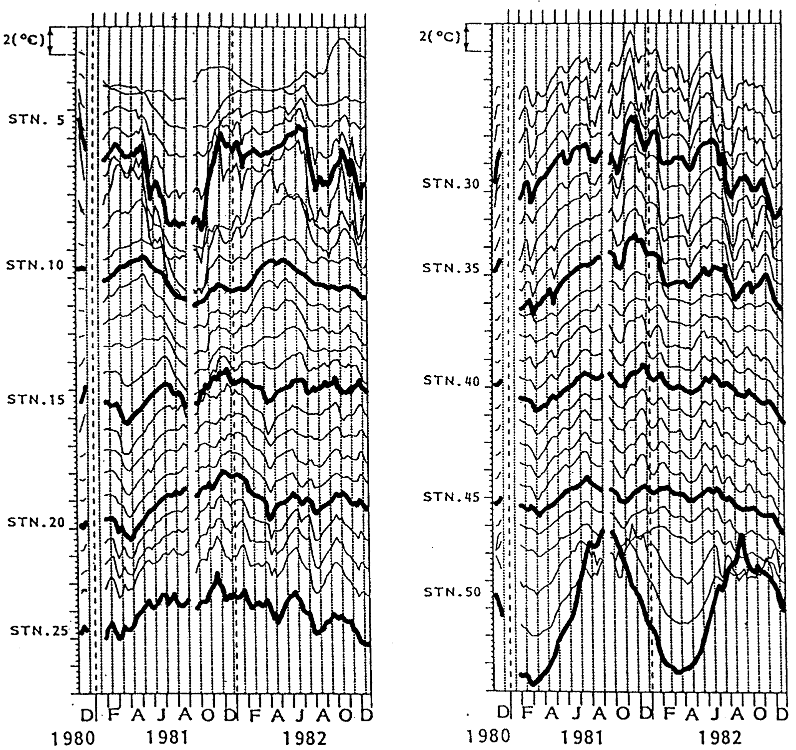

Fig. 3. Temporal variations in temperature from Stn.1 to Stn.50. Interval between dotted (broken) lines denotes a period of 4 weeks (1 year).

perature at each station. It is found that the shelf along the submarine cable can be divided into the following three regions based on the difference in the patterns of seasonal variation. Region (1) from Stn.1 to Stn.15, which corresponds to the entrance of the West Channel, has the maximum temperature in winter and the minimum in summer. Region (2) from Stn.16 to Stn.47 does not have a dominant seasonal variation, but has significant year-to-year variation with the maximum temperature in winter 1981. Region (3) from Stn.48 to Stn.50 may be considered as the region where the near-shore branch of the Tsushima Current exists and has a large seasonal variation with the maximum temperature in summer and the minimum in winter. Thus, the change of the seasonal cycle near the Japanese coast demonstrates completely opposite signs from that near the Korean coast.

The seasonal variation of sea-level difference between Izuhara and Pusan is very large while that between Hakata and Izuhara is small (KAWABE, 1982). It is considered that sea-level difference in the West Channel represents volume transport of the Tsushima Current rather than that in the East Channel. Then, temporal variations at Stn.5 in the region (1) and at Stn.50 in the region (3) are compared with the 21-day running mean of the difference in daily mean sea-level between Izuhara and Pusan, and each relationship is shown in Fig. 4. The variations of sea-level difference may indicate that the volume transport of the Tsushima Current is small from January to May and increases considerably from June to August. After reaching a maximum from August to October, the transport gradually decreases.

The seasonal changes of temperature at Stn. 5 occur rather rapidly. The large temporal gradients of temperature are seen in June and November, whereas the temperature in the other months tends to be relatively constant. It is suggested that the large spatial temperature gradient region, i.e. the BCW front, passes through the entrance of that West Channel in June and November. Therefore, we may conclude that

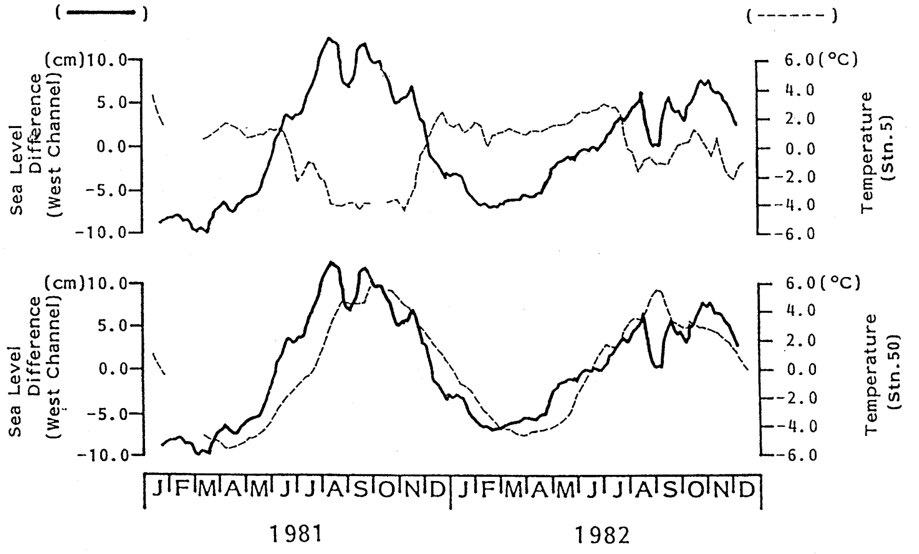

Fig. 4. The 21-day running mean of difference in daily mean sea-level between Izuhara and Pusan, i.e. at the West Channel, is indicated by heavy lines. Dashed lines show seasonal variations of bottom-water temperature at Stn.5 (upper) and Stn.50 (lower).

BCW front shifts southward (northward) along the Korean coast as corresponding to the increase (decrease) of volume transport in June (November). Such seasonal flow variation around the West Channel has also been indicated from the current measurements (BYUN and SEUNG, 1984) and the hydrographic data analysis (OGAWA, 1983; ISODA, 1989; ISODA and YAMAOKA, 1991).

It can be seen that the shape of the temperature variation at Stn.50 is roughly sinusoidal, and nearly the same as the variation patterns of sea-level difference. The correlation between the variation characteristics of the water temperature and those of sea-level difference suggests that the height of the water column along the Japanese coast increases when the water temperature near the Japanese coast increases. Such characteristics of the Tsushima Current may demonstrate the structure of the coastal boundary current, which may be strongly trapped along the Japanese coast (HANAWA, 1984; ISODA and YAMAOKA, 1991).

Short-term variations of the BCW

It is evident from Fig. 3 that the short-term variations are very pronounced only in the region (2). These variations look somewhat periodical in nature with a period of several tens of days. Their up/down-peak times are not the same among stations and tend to shift slightly from the Korean side's stations to the Japanese ones. To enhance such horizontal propagation characteristics of short-term variations, we calculated the temporal temperature gradient (TTG) within one week period at each station, i.e. temperature values of week $n+1$ minus those of week n at each station. The results together with bottom topography along the submarine cable line are shown in Fig. 5. The lateral axis in this figure is the distance from Pusan to Hamada the and time advances downward. Positive TTG values denote an increase of water temperature and negative values (blacked) denote a decrease. That is, the black color areas correspond to the BCW evolutions. Its propagation features are displayed by shaded arrows. From this figure, the following characteristics are evident: i) The BCW with the short-term variations may not be developed over the whole shelf all at once, but is often continuous and complex, presumably as a result of meander events closely spaced in space or time. There are, however, occasions starting with a relatively intense burst of motion, sometimes followed by a few cycles of oscillations as in

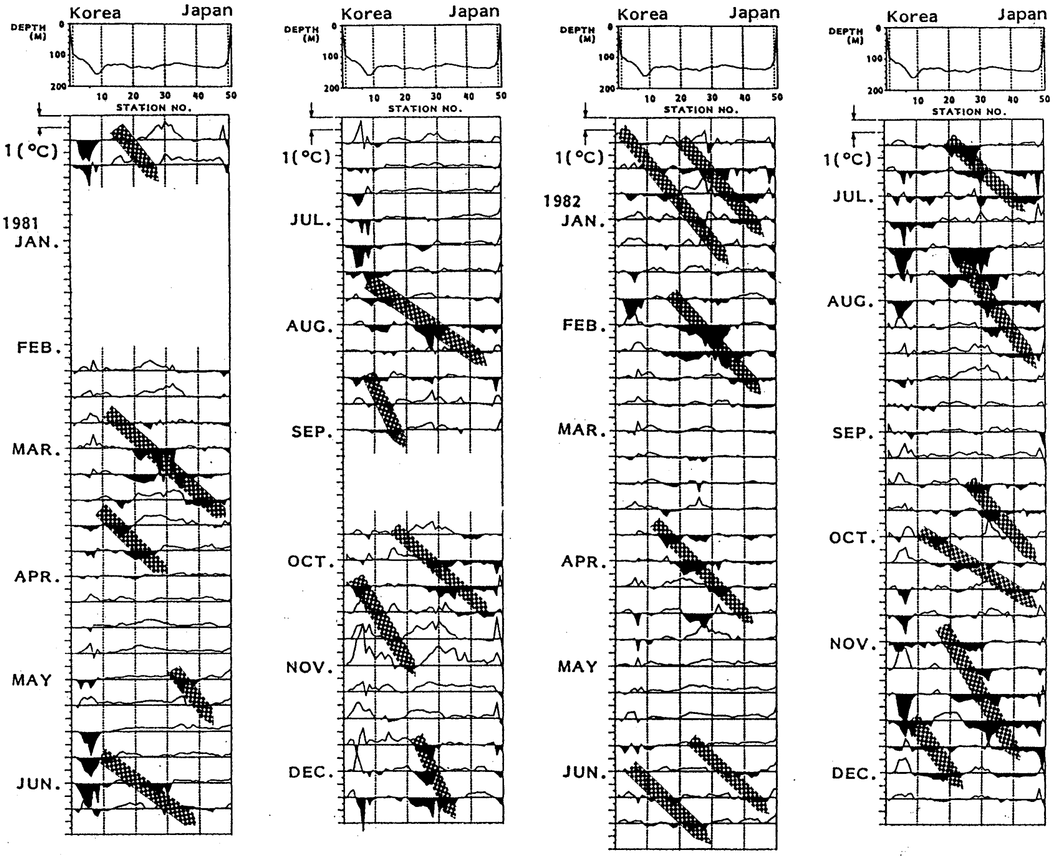

Fig. 5. Temporal temperature gradient (TTG) within one week at each station. Positive TTG values denote an increase of water temperature and negative values (blacked) a decrease. The shaded arrows display the propagation features of Bottom Cold Water evolution, which correspond to the blacked TTG areas. The bottom topography along the submarine cable line is shown in the upper part of each panel.

February to March in 1981, November to December in 1981, June in 1982, and November in 1982. Such events occurred 6 to 9 times in a year; the time scale of variations can be regarded as having periods of 40 to 60 days.

ii) It is inferred from reading the horizontal distribution of TTG variations that the horizontal scale of meandering along the shelf is approximately a few hundred kilometers.

iii) The phase of variations has moved gradually eastward. The area of phase propagation begins around the western entrance of the Tsushima / Korea Strait. The averaged eastward phase speed is estimated to be 7 to 10 cm s^{-1}; the phase propagates over about 170 km in 3 to 4 weeks in the region (2).

The synoptic pattern of the BCW can be drawn by using the convetional hydrographic observation data of the Fisheries Agency Japan, because these data were obtained during several days at the beginning of each month and, in addition, the BCW has very slow variations in time as mentioned above. Near-bottom (and 200m depth) horizontal temperature distributions on (and off) the shelf are shown in Fig. 6(a) for 1981 observations and in Fig. 6(b) for 1982 observations with the TTG distributions. That is, Fig.6 shows the horizontal distribution of the line where the main thermocline intersects the bottom slope, a feature of the BCW front. Three TTG distributions shown in each figure were also taken at nearly the same time as the corresponding hydrographic observations. At first sight, considerable spatial variations of the

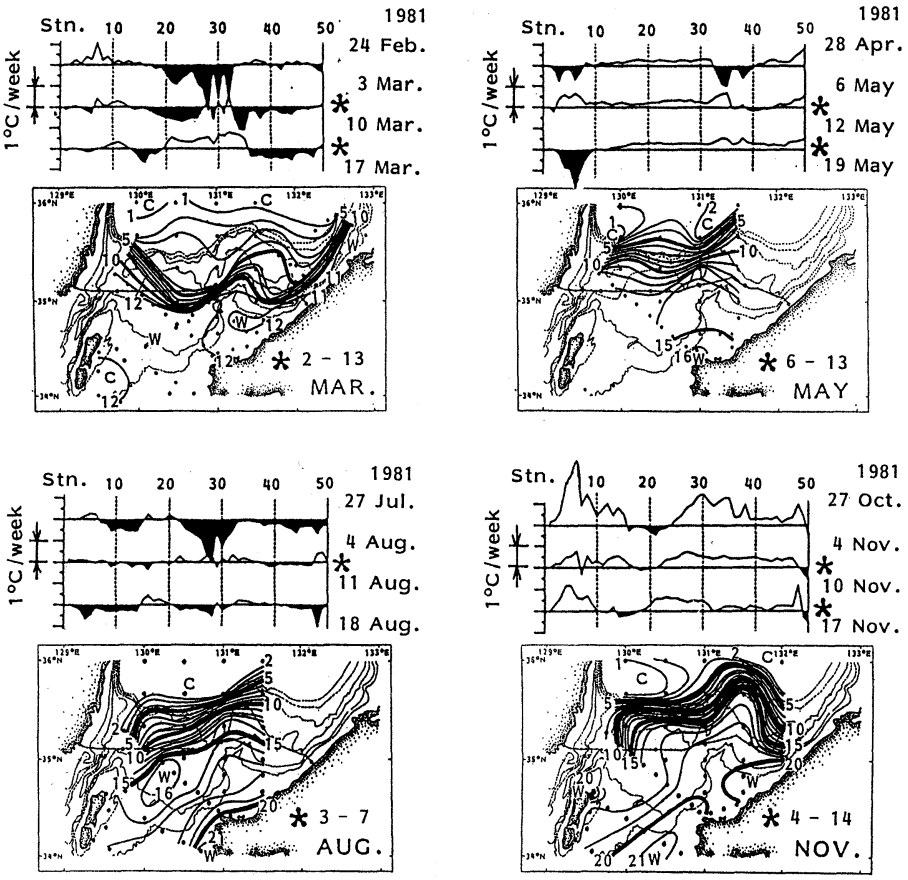

Fig. 6. Near-bottom (and 200m depth) horizontal temperature distributions, i.e. the feature of the BCW front, on (and off) the shelf for 1981 observations (a) and 1982 observations (b). The three TTG distributions shown in the upper part of each panel were taken at nearly the same time as the corresponding hydrographic observations.

BCW front are noted. From a comparison of horizontal temperature distributions at the same month in 1981 and in 1982, we cannot find the seasonal characteristics of the flow patterns. For example, there is a large meandering path in March 1981 and August 1982, but a flow along the shelf edge in March 1982 and August 1981. Although a meandering path can be seen in November in 1981 and 1982, the shapes of meandering differ from each other.

We can detect large meanders of these BCW fronts with the cross-shelf amplitude of 50 to 100 km in March and November 1981, and in August and November 1982. Such southward evolution of the BCW front corresponds to the boundary between positive and negative TTG value areas. This situation means that the southward depression will propagate eastward with time. On the other hand, a similar meander is not clear in May and August 1981, in March and May 1982, and then spatial TTG variations at those times are surely small. From these characteristics, it is clear that the short-term variations shown in Figs.3 and 5 are caused by the cross-shelf migrations of the wave-like BCW front on the shelf.

Next, to see the short-term variations of the geostrophic current in the Tsushima / Korea Strait, we calculate the cross-correlation analysis between sea-level differesnces in the West and East Channels. The statistical period is 512($=2^9$) days (from 11 April 1981 to 4 septem-

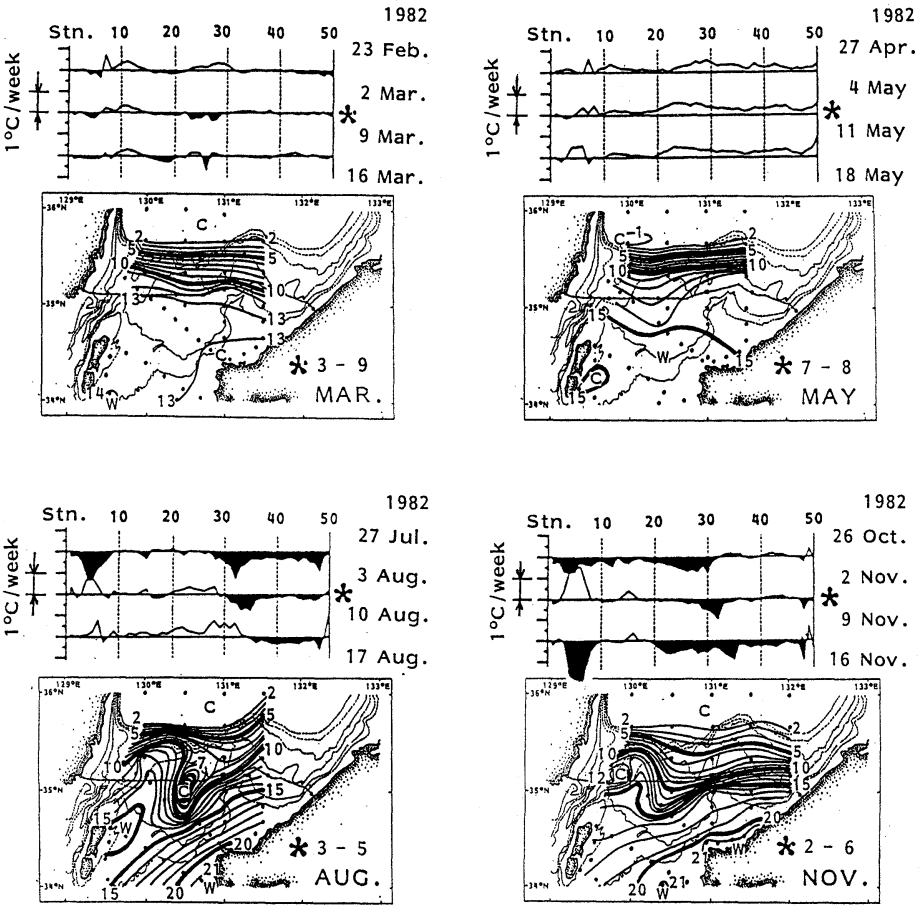

Fig. 6(b)

ber 1982) and the result is shown in Fig. 7. Hence, the Nyquist frequency is 0.5 cpd and the degree of freedom is 4. A common conspicuous spectral peak with a good correlation (95 % confidence limits of coherence-squared value is about 0.43) is seen at a period of a 50 days and its frequency band roughly coincides with that of the BCW variations. It is found that the phase difference of flow between both channels is surprisingly out of phase, although those channels are adjacent to each other (see in Fig. 1).

We will then investigate the relation between the variations of flow and water temperature by applying bandpass-filtering methods, although the statistical period is too short to analyze the data statistically. In Fig. 8, we superimposed the bandpass-filtered anomaly time series for the variations in both channels of sea level difference (thick lines) and temperature at Stn.35 (dashed lines) with a period of 42 to 63 days. Here, Stn.35 is situated on the central shelf off the San'in coast and its amplitude is relatively large. It is found that both variations of the flow and water temperature tend to be large for the same period from summer to winter 1981, although the phase of both variations cannot be discussed due to the slow variations of the BCW with relatively short wavelength. Besides, time series of sea-level show that the pattern of variations between the East and West Channels is surely opposite. Thus, it is inferred that flow structures with short-term variation have relatively small spatial scale in the cross-shelf direction and are out of phase between the coast and the shelf edge.

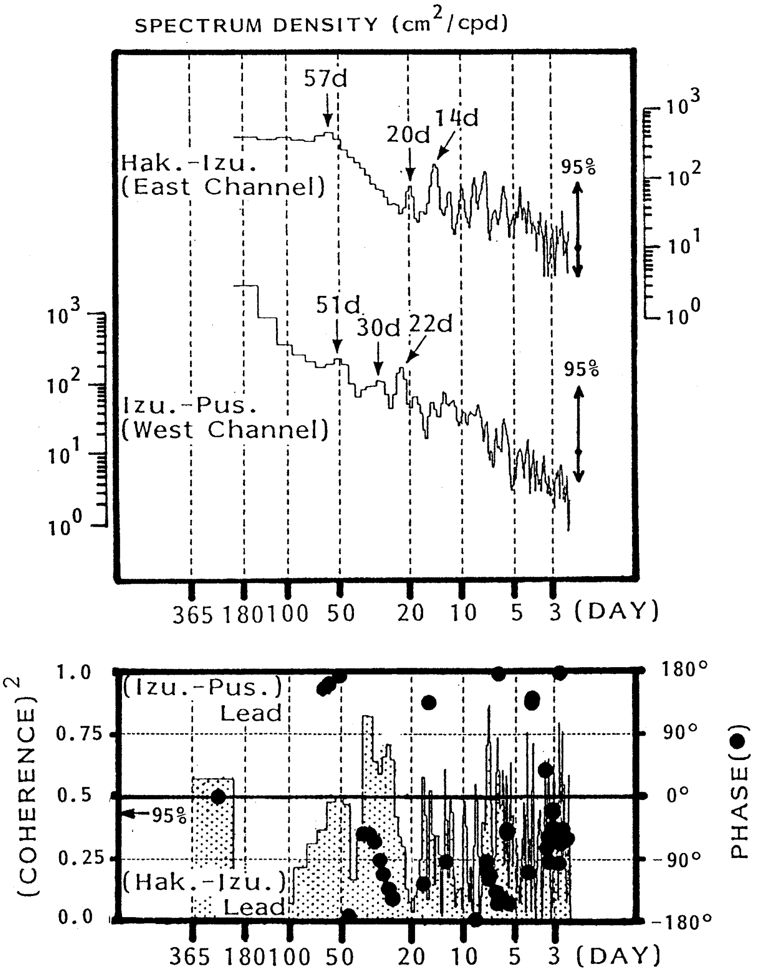

Fig. 7. Cross-spectrum between sea-legvel difference at the West and East Channel using 512-day data from 11 April 1981 to 4 September 1982. Phase values with more than 0.43 coherence squared are shown by solid circles.

4. Conclusion and discussion

By using the bottom-water temperature data observed along the submarine cable, we analyzed the characteristics of temperature variation in time and space on the shelf off San'in coast. Only the water temperature close to the Korean coast and the Japanese coast has the dominant seasonal variation. The BCW front shifts into the Tsushima/Korea Strait along the Korean coast corresponding to the increase of inflow volume transport of the Tsushima Current. This behavior may be due to the development of baroclinic structure in summer. Bottom-water temperature near the Japanese coast is strongly affected by seasonal water characteristics of the Tsushima Current. On the other hand, the water temperature on the shelf off San'in coast has no dominant seasonal variation, but has significant year-to-year variation. Besides, the following interesting behaviors of the BCW are superimposed on such year-to-year variations. Intense evolutions of the BCW over the shelf off San'in coast occur 6 to 9 times in a year, having periods of 40 to 60 days, sometimes followed by a few cycles of oscillations. Such events show eastward phase propagation with a phase speed of 7 to 10 cm s^{-1}, a typical wavelength of a few hundreds kilometers and cross-shelf amplitude

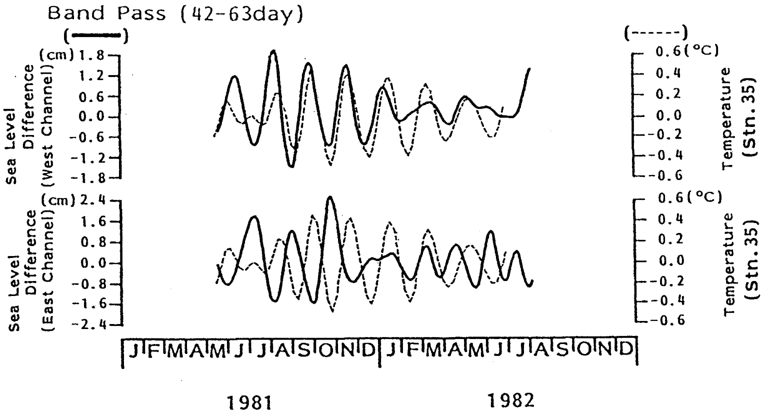

Fig. 8. The bandpass-filtered anomaly time series for the range of 42–63 day period. The heavy lines in the upper and lower panel are sea-level difference at the West and East Channel, respectively. The dashed lines in both panels show variations in water temperature at Stn.35 located at the center of the submarine cable.

of 50 to 100 km distance.

Finally, to investigate the type of such observed waves, the theoretical dispersion relations of free waves off San'in coast are compared with the observed data. ISODA *et al.* (1991) showed that the phase speed of external and internal Kelvin waves which could exist at the shelf off San'in coast were estimated as about 1400 m s^{-1} and 1.6 m s^{-1}, respectively. Besides, if the observed wave may be regarded as a barotropic shelf wave, it must be a higher-mode wave, 5th higher or 6th or mode wave, with many nodes in the cross-shelf direction (ISODA *et al.*, 1991). However, the observational data shown in Fig. 6 deny the possibility of such higher-mode waves. Therefore, it may be difficult to explain the observed wave by the gravity wave or shelf wave of barotropic mode.

Next, we shall consider the topographic Rossby wave affected by a stratification, because the main thermocline has existed around the shelf edge throughout the year as shown by the present study. The wave equation and wave dispersion relation of the topographic Rossby wave by Rhines' theory (RHINES, 1970) are as follows.

$$p=A\exp(i(kx+l_n y+\omega t))\cosh(\mu z) \qquad (1)$$

$$\tanh(\mu H)=-\frac{N^2\alpha k}{f\omega\mu} \qquad (2)$$

$$\text{where} \quad \mu=N\,(k^2+l_n^2)^{1/2}/f \qquad (3)$$

Here x and y are Cartesian coordinates directed along-shelf and across-shelf, respectively, z the vertical coordinate directed upward from the sea surface, p the pressure, α (=40m/100 km =0.0004) the bottom slope gradient, $f=8.5\times10^5$ s^{-1} the Coriolis parameter, H(=120m) the mean depth, ω the wave frequency, k the along-shelf wavenumber, $l_n=2n\pi/L$ (L is the shelf width and n=1,2,3,..) the cross-shelf wavenumber, and N^2 the Brunt-Väisälä frequency. From eqs. (1) and (3), it is found that such a wave tends to be a bottom-trapped mode (large μ at (1)) in the case of strong stratification (large N^2), short wavelength (large k) or higher-mode wave (large l_n).

The density data were collected from the observed data by Fisheries Agency Japan in March and September 1981 along Section B in Fig.1. March is the season of vertical mixing in winter, and September is the season with the development of the seasonal thermocline. Using these data we calculated the variation in Brunt-Väisälä frequencies and the corresponding theoretical dispersion curves for the first three modes. The profiles of density, the Brunt-Väisälä frequency, and dispersion curves are shown in Fig. 9 for each month. For the purpose of comparing the theoretical curves with the observations, we shall use the Brunt-Väisälä frequency value near the shelf edge, i. e. $N^2=3.0\times10^{-3}$ s^{-1} in March and $N^2=10.0\times10^{-3}$ s^{-1} in September, and the observed wave's ω-k region as

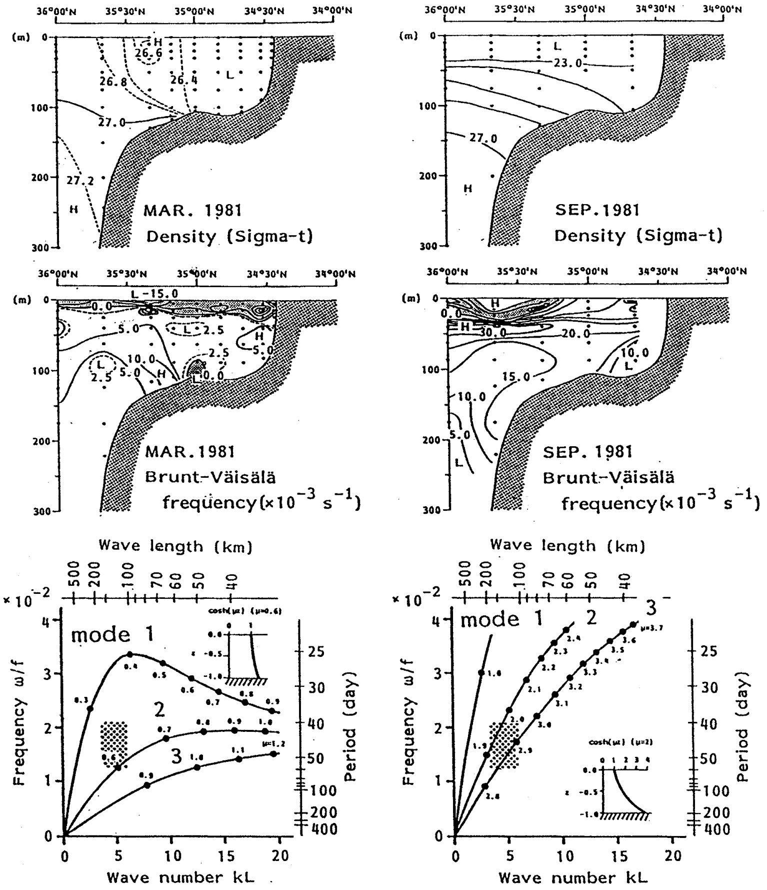

Fig. 9. Density (upper) and Brunt-Väisälä frequency (middle) profiles along Section B in Fig. 1(b). Lower panels denote dispersion curves of the first three modes for the profile given by eqs (2) and (3) (adapted from RHINES, 1970). The vertical profiles of cosh (μz) which is calculated using the value at each shaded area corresponds to that of the current. Shaded areas denote the observed ω-k relation.

denoted by the shadow area in the dispersion curves. It may be possible that the observed wave can be explained by the 2nd or 3rd mode bottom-trapped Rossby wave in both months. It is suggested that the alongshore flow component in the cross-shelf direction is out of phase between the coastal area and the shelf edge area, when the short-term variations of the BCW are passing off San'in coast. Such a result would also coincide with that inferred from the analysis of sea level differences in the Tsushima/ Korea Strait.

As for the primary mechanisms responsible for the BCW evolution, we cannot believe that its evolution always occurs when upwelling-favorable winds prevail. This is because most of the wind energies in the southwestern area of the Japan Sea area are concentrated around several-day periods. The annual mean BCW front, i.e. the main thermocline, is situated along the shelf edge and hits the topographic protrusion of the Korean peninsula (MORIWAKI and OGAWA, 1989), and the water characteristics of the Tsushima Current on the shelf have large seasonal change in temperature and salinity (OGAWA, 1983; MORIWAKI and OGAWA, 1988). From the above characteristics, we speculate that the short-term variations of the BCW will be generated by a kind of geostrophic adjustment process between inner and outer shelf around the Korean coastal area or by the baroclinic instability process of the Tsushima

Current. In our forthcoming studies, we plan to investigate the low-frequency changes of sea conditions off the Korean coast and to physically explain the generation mechanism of the BCW variations.

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