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Interannual SST variations to the north and south of the polar front in the Japan Sea

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Abstract: Interannual variations of the sea surface temperature (SST) in the Japan Sea and its relationship with the inflow variations of the Tsushima Current were investigated by using 20 years (1971–1990) long, 1° grid SST data along the 134° E meridian and sea level difference data across the Tsushima/Korea and Tsugaru Straits. The SST is closely related to the formation of a thin surface layer in summer, and of a thick mixed layer in winter. Therefore, the winter SST is suitable for research of the long-term variability of subsurface waters to the north and south of the polar front in the Japan Sea. Interannual SST variations in winter have two dominant periods: decadal and 2–4 years period.

The SST variation with decadal period is predominant in the area north of the polar front and seems to be correlated to the inflow variation of the Tsushima Current. The SST variation with 2–4 years period tends to appear almost simultaneously throughout the polar front and to its north and south, and has no significant correlation to the inflow variations of the Tsushima Current. It may be influenced by the outbreaks of the Asian winter monsoon.

1. Introduction

The Tsushima Current carries heat and water mass northward through the Tsushima/Korea Strait and creates the warm subsurface layer throughout the basin south of the oceanic thermal front, i.e. the polar front in the Japan Sea (Fig.1(a)). This warm current is known to exhibit large variability not only with seasonal period but also with various interannual periods. TOBA *et al.*(1982) showed that the Tsushima Current is caused by the sea level difference between the East China Sea and the sea east of the Tsugaru Strait and exhibits large interannual variations as well as apparent seasonal ones. By using coastal SST data, WATANABE *et al.* (1986) found that two kinds of SST variations with 10 and 6 years period are dominant along the Japanese coast. Based on hydrographic surveys from 1953 to 1982, NAGANUMA(1985) suggested that variations with a 6-year periodicity are found to be related to the flow patterns of the Tsushima Current. MIITA and TAWARA(1984) showed that a 6- to 7-year periodicity of water temperature is also predominant at the Tsushima/Korea Strait.

Thus, the previous studies were based on water temperature data in the Tsushima Current region, i.e., the region south of the polar front. Water temperature variations north of the polar front are not well understood yet. Our poor knowledge of the northern area oceanography is a serious problem, because the Tsushima Current system associated with the density structure is related to the contrast between the cold northern and the warm southern waters across the polar front. It is important to clarify the relation between both waters for understanding not only the horizontal circulations in the Japan Sea, but also the polar front genesis.

Unfortunately, long-term continuous hydrographic data of the Russian sea area are not available. A useful approach to studying the thermal structure of the northern Japan Sea is to focus on the SST variations, which reflect the ocean conditions due to the development of the surface mixed layer in winter. The Japan Meteorological Agency (JMA) has collected SST data with ship and satellite observations and averaged them over a 1° grid. If no data are available in a 1° box, the JMA calculates the weighted mean of the 5 data at the nearest

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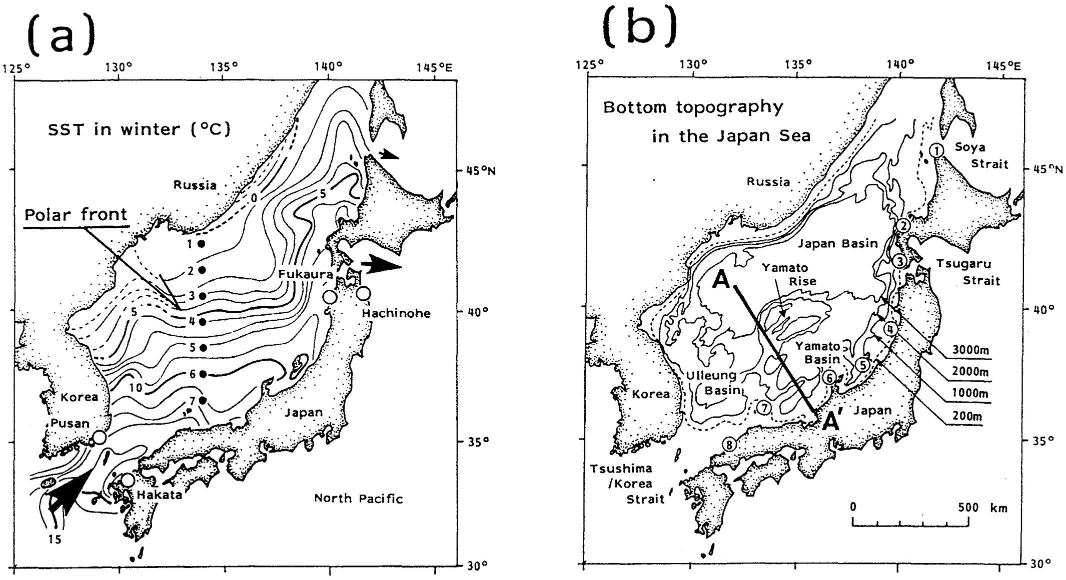

Fig. 1 (a) Seasonal mean thermal map in winter at the surface layer (JODC, 1978) and the grid points of SST (●) and sea level (○). (b) Bathymetric chart of the Japan Sea. A–A' line shows CTD observation line of the Maizuru Marine Observatory. Numerals in open circles show the station numbers of the coastal SST observation (WATANABE *et al.*, 1986).

sites with a weight w defined by $w=exp(-(d/200km)^2)$ (d: distance) and uses it as the monthly mean in that box. This procedure is applied to not a few boxes in the northern Japan Sea, particularly in winter months. However, poor spatial and temporal density of available data do not make nonsense of the study on the northern Japan Sea, if confined into comparison of the regional characteristics on both sides of the polar front rather than concerned with general description of hydrography in the individual region. The purpose of the present study is to describe interannual SST variations, and to find the relation between the north-south water mass variations and the inflow variations of the Tsushima Current.

2. Data

SST data

Figures 1(a) and (b) show the mean SST distribution in winter (JODC, 1978) and the bottom topography, respectively. Surface isotherms in the central Japan Sea tend to be directed zonally and the polar front is formed along about 40° N latitude. ISODA *et al.*(1991) revealed that a part of the front corresponds with the location of a warm eddy above the Yamato Rise. ISODA and NISHIHARA(1992) showed that this warm eddy seems to be affected by the bottom topography and stably exists above the Yamato Rise throughout the year. Therefore, the SST variation in the meridional direction passing through the Yamato Rise is useful for describing the north-south thermal structures on both sides of the polar front. In this context, we use monthly mean SST data along 134° E meridian (JMA, 1971–1990) for recent 20 years. Grid points 1 to 7 are defined for the analysis as shown in Fig. 1(a).

Sea level data

Yearly mean sea level data at Hakata, Fukaura and Hachinohe by the Geographical Survey Institute, Ministry of Construction, Japan (1991) and at Pusan by the Hydrographic Office of the Republic of Korea (1970–1991) are collected. Locations of these tidal stations are indicated by the open circles in Fig.1(a). Variations of the inflow volume transport or surface current velocity through the Tsushima/Korea Strait and the outflow through the Tsugaru Strait are investigated by examining the sea level difference between Hakata and Pusan and

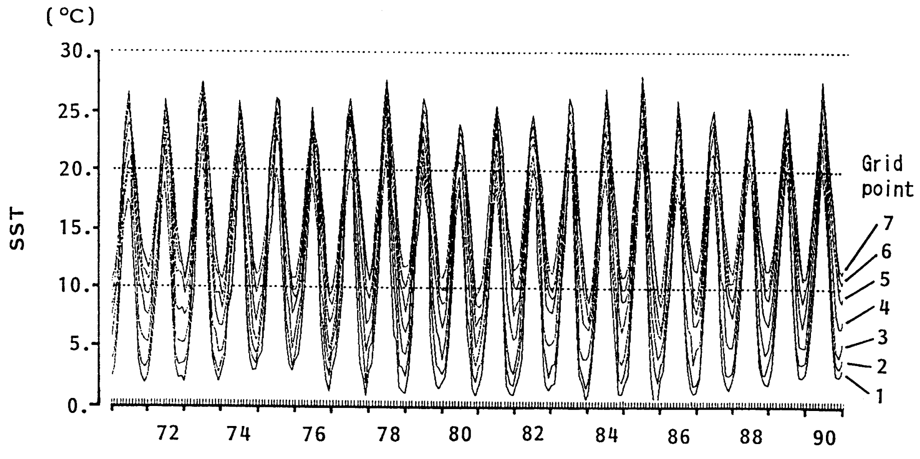

Fig.2. The time series of the monthly mean SST from grid points 1 to 7 for 20 years (1971–1990).

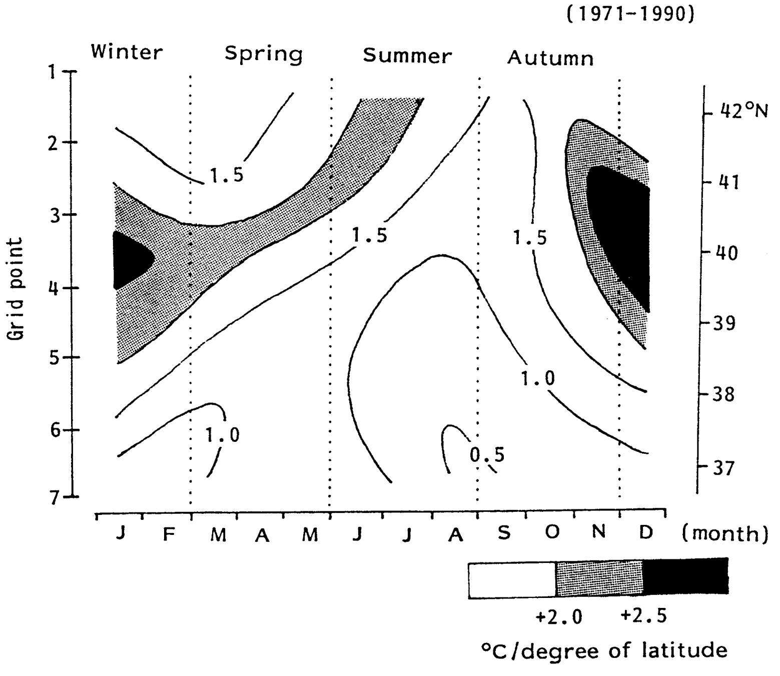

Fig. 3. The 20 years averaged time (seasonal)-latitude diagram of the southward gradient of the monthly mean SST along 134°E meridian.

between Fukaura and Hachinohe, respectively.

3. Characteristics of the seasonal SST variation

Figure 2 shows the time series of monthly mean SST during 20 years at grid points 1 to 7. One remarkable feature is a significant seasonal signal, e.g., maximum in summer and minimum in winter. The other is that the envelopes of the maximum and minimum SST indicate interannual features. The summer SST is significantly higher in 1973, 1978, 1985 and 1990 than in the other years, while the winter SST is higher from 1971 to 1976 and 1986 to 1990 than from 1977 to 1985.

A time-latitude diagram of SST front averaged over 20 years is drawn in Fig.3 for studying

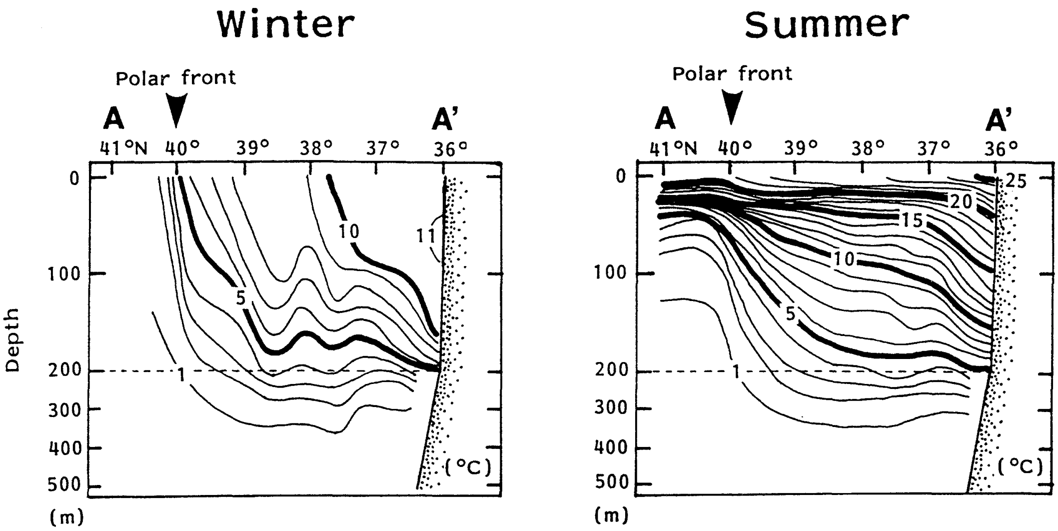

Fig. 4. Seasonal mean vertical sections of water temperature in winter and summer along A–A' line in Fig.1 (b) (Minami *et al.*, 1987).

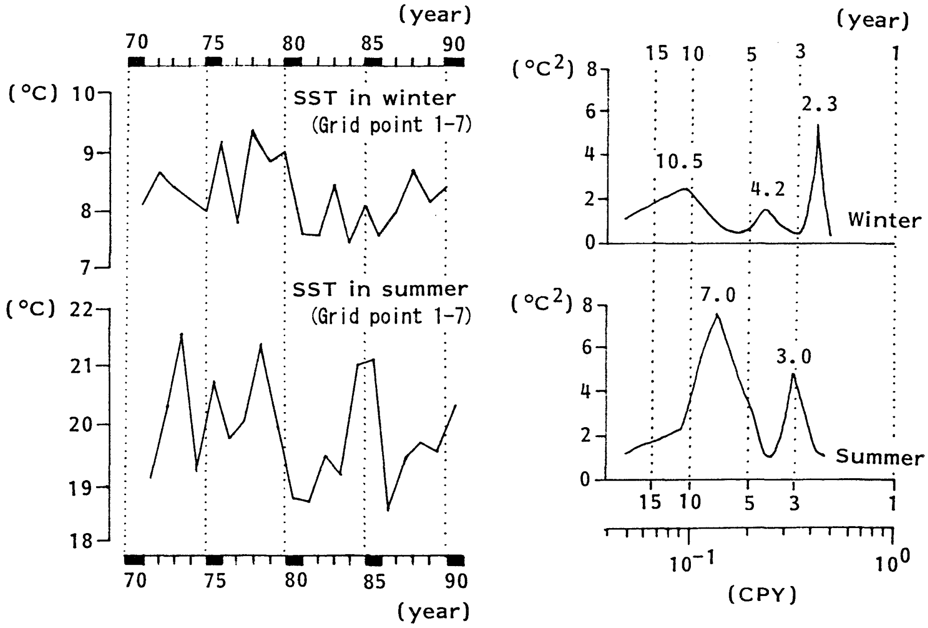

Fig. 5. The time series of SST in winter and summer averaged over grid points 1 to 7 and the SST spectra for both seasons.

the seasonality of the SST. The SST front is defined as the band where the SST gradient is sharper than 2.0℃/degree of latitude on the monthly mean. In the heating season from March onwards, the thermal frontal zone gradually migrates northward as a result of warming of surface water and disappears in August. In the cooling season from October onwards, the zone width abruptly increases at latitudes from 39 to 42° N. From December to February, the thermal frontal zone stagnates around 40° N. Figure 4 is redrawn from seasonal mean maps obtained from hydrographic measurements in 1964–1983 by the Maizuru Marine Observatory

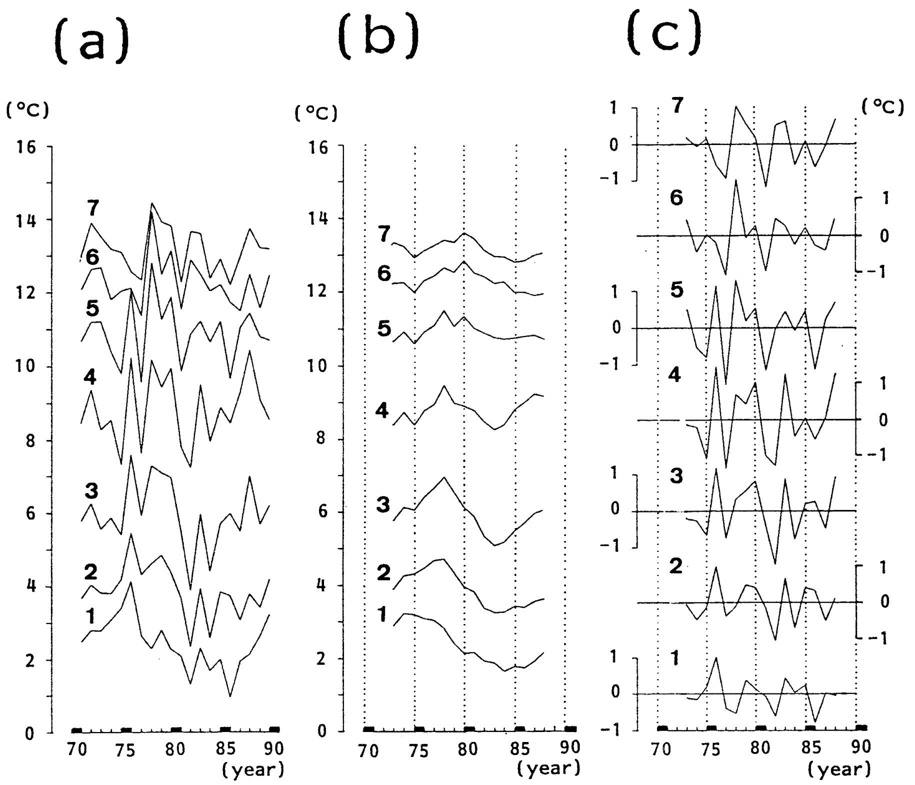

Fig. 6. Time series of SST raw data in winter (a) and those of low-passed (b) and high-passed (c) SST data with the 7-year running mean filter.

(Minami *et al.*, 1987). It shows the vertical sections of water temperature in winter and summer along A–A' line in Fig. 1(b). The summer SST is closely related to the formation of a thin surface layer, whereas the winter SST is strongly affected by subsurface waters due to the deepening of the surface mixed layer. It is also found that the polar front stably exists around 40° N in both seasons. From these figures, we can regard the stagnated thermal SST front at 40° N in Fig. 3 as the wintertime outcrop area of the polar front. Therefore, the SST distribution in winter will give us information on characteristics of the subsurface waters. In the present study, we analyze the wintertime SST data averaged over December to February to describe the interannual variations of the north-south thermal structure in the Japan Sea.

Before the analysis of the winter SST data, we describe the characteristics of temporal winter and summer SST fluctuations. Figure 5 shows the time series of SST in winter (December to February) and summer (June to August) averaged over grid points 1 to 7 and their SST spectra. The Maximum Entropy Method (MEM) was used because of advantage of treating the present short-length time series. It is clear that SST variations with 2–4 years and 10 years period (hereafter referred to as the decadal variation) are prevailing in winter, whereas those with 3 years and 7 years period are dominant in summer. It can be said that the decadal periodicity is a cooling-season mode and the 7-year periodicity is a heating-season mode which is restricted in a thin surface layer.

4. Interannual variations of the SST in winter

In the SST spectrum in winter, we detect two remarkable spectral peaks around 2–4 years and about 10 years. In the following analysis, we divide the data into two categories with these two periods by using the 7-year running mean filter. Figure 6 shows the time series of the raw SST data in winter (a), their low-passed SST data

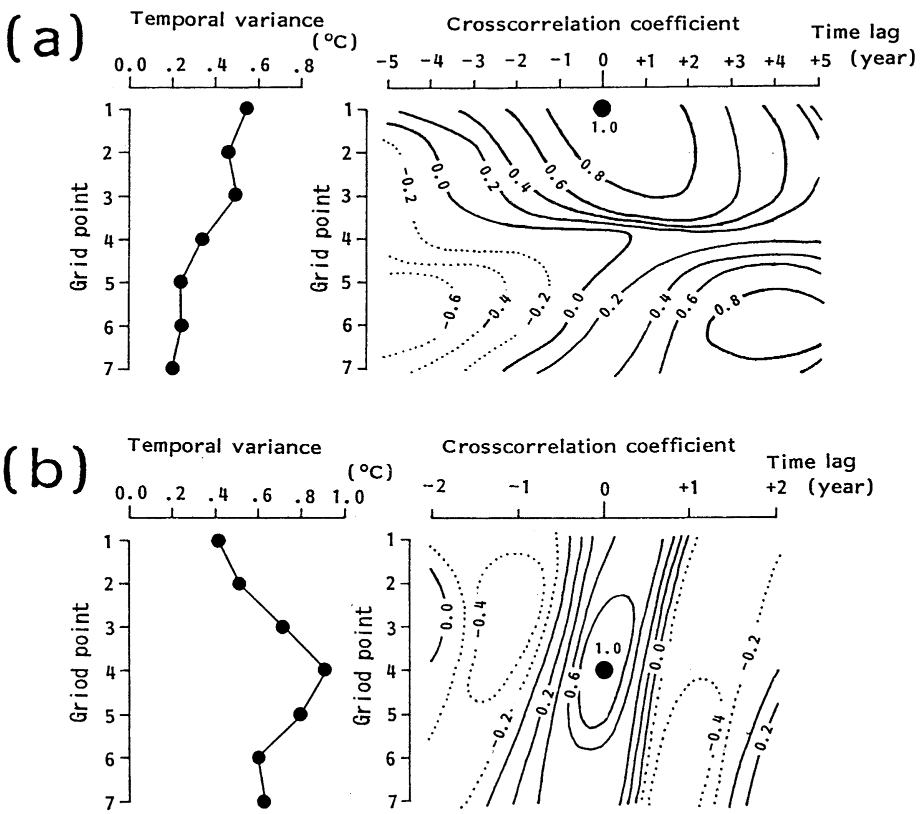

Fig. 7. Temporal SST variance at each grid point (left panels) and cross-correlation coefficients between a grid point with the maximum variance and the other grid points for 1972–1988 (right panels); (a) decadal variation and (b) 2–4 years variation.

(b) and the high-passed SST data (c) at each grid point. It is evident that the decadal SST variation is larger at the northern grid points (Fig.6(b)) and the SST variation with 2–4 years period exhibits a wavy pattern common to all grid points (Fig. 6(c)). We apply the cross-correlation analysis to each SST variation in order to extract the dominant spatial / time variation patterns.

Figure 7 shows the cross-correlation coefficients among the time series at all grid points for the two periods. The amplitude of temporal SST variance at each grid point indicates the spatial predominance. The distribution of cross-correlation coefficients represents time lags between a grid point with the maximum variance and the other grid points. The significant signal with decadal period is found in the area north of the polar front (grid points 1 to 3) with a distinct time lag of 3–4 years to the south (Fig. 7(a)). However, we cannot verify this time lag because the data is not long enough to discuss the decadal variation in detail. The SST signal with 2–4 years period is relatively strong around the polar front (grid points 3 to 5) with a small time lag less than 1 year to the north (Fig. 7 (b)).

5. Relationship between the north-south SST variations and the inflow variations of the Tsushima Current

Figure 8 shows the time series of SST variation with decadal period and yearly mean sea level differences at the entrance (Hakata–Pusan) and exit (Fukaura–Hachinohe) straits. Surprisingly, the decadal signal of the sea level difference is dominant rather than the signal with several years period. Furthermore, the dominant SST variation at grid points 1 to 4 appears to be negatively correlated with the sea

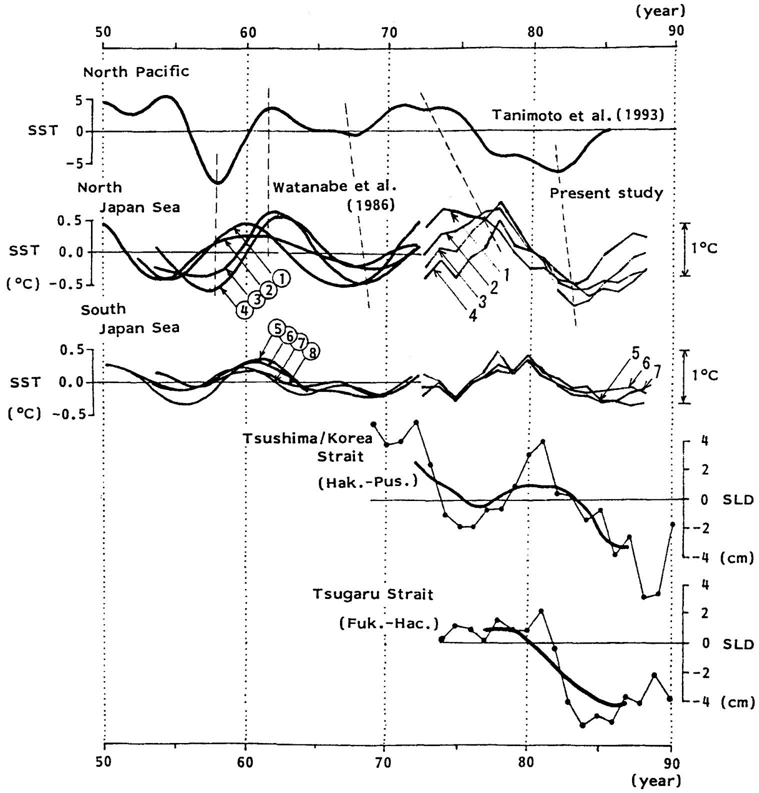

Fig. 8. Time series of decadal SST variations over the North Pacific (after Tanimoto *et al.*, 1993) along the Japanese coast (after Watanabe *et al.*, 1986) and along 134°E meridian (present study). Lower two figures show the interannual variations of yearly mean sea level differences at the Tsushima/Korea and Tsugaru Straits. Heavy lines show the 7-year running means of the sea level difference.

level differences, especially across the Tsushima/Korea Strait. It seems that the year of increasing (decreasing) inflow volume transport or surface current velocity through the Tsushima/Korea Strait corresponds to that of decreasing (increasing) SST in the northern Japan Sea.

Watanabe *et al.*(1986) obtained SST signals with a similar time scale by use of SST data from 1950 to 1972 at coastal stations shown in Fig.1(a), and showed the SST variation pattern at northern grid points is different from that at southern grid points, as redrawn in the middle panels in Fig.8. Tanimoto *et al.*(1993) indicated that the dominant decadal SST variability over the North Pacific is associated with the Pacific/North American(PNA) anomaly pattern in the troposheric circulation. The time coefficients of their decadal mode (the 1st mode of Empirical Orthogonal Function (EOF)) are also redrawn at the top panel in Fig.8. The variation pattern of their time coefficients is similar to that of the SST in the northern Japan Sea with a time lag of several years. It is worthwhile to note that the SST variation in the Japan Sea with decadal time scale may be influenced, either directly or indirectly, by the ocean-atmosphere interactions over the North Pacific.

Figure 9 shows a time series of the Asian winter monsoon index (MOI) redrawn from Bingham *et al.*(1992), the SST variation with 2–4 years period averaged over grid points 4 to 7 and the sea level differences at the entrance and exit straits, respectively. The SST variation coincides well with the MOI. This result shows that stronger outbreaks of cold air in winter are responsible for the lower SST period. However, there is no significant relationship between this SST variation and the inflow variation of the

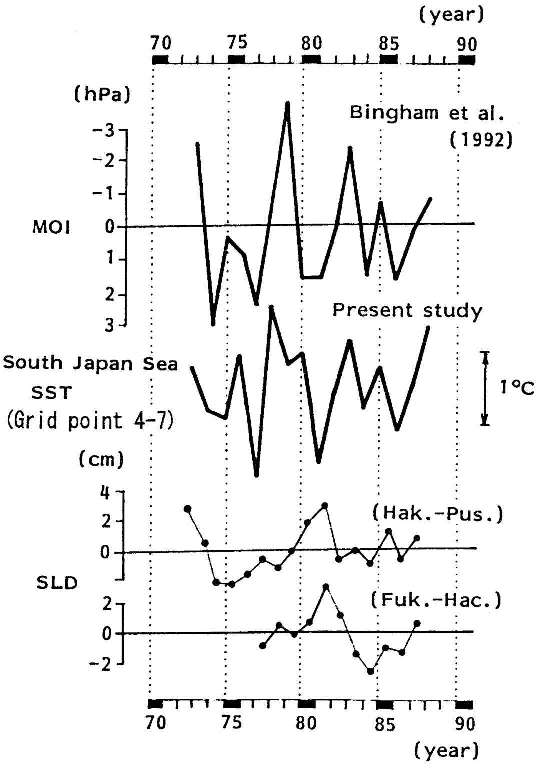

Fig. 9. Time series of MOI in winter (after BINGHAM *et al.*, 1992), and of variation with 2–4 years period averaged over grid points 4 to 7. Lower two figures show the interannual variations of yearly mean sea level difference at the Tsushima/Korea and Tsugaru Straits, which are high-passed with the 7-year running mean filter.

Tsushima Current with the same time scale.

6. Conclusions and discussion

In the present study, we have investigated the interannual SST variations in the Japan Sea and their relationship with the inflow variations of the Tsushima Current. The analysis of the seasonal SST variation confirms that the SST in winter is strongly affected by prominent thick mixed waters and, therefore, is useful to studying the interannual variations of subsurface waters in the Japan Sea. Interannual SST variations in winter have decadal and 2–4 years periods.

The SST variation with decadal period is especially dominant in the northern area of the polar front in the Japan Sea and seems to be correlated to the inflow variation of the Tsushima Current. This variation is, in turn, related to the large-scale SST variation over the North Pacific, though the linkage mechanism is still unclear (and out of the scope of the present study). The SST variation with 2–4 years period tends to appear almost simultaneously throughout the polar front and to its north and south, and has no significant correlation to the inflow variation of the Tsushima Current. The strengthening of the Asian winter monsoon is responsible for the remarkable SST decrease.

These facts suggest that the interannual variations of the eastward mean flow of the Tsushima Current is closely related with those of the SST difference between both sides of the polar front. In the decadal variation, the large north-south difference of the SST increases the eastward density flow in the polar frontal region, both of which correspond to increasing inflow from the Tsushima/Korea Strait. On the other hand, the inflow variation with 2–4 years period disappears because of the small north-south SST difference. Thus, the different ocean response depending on interannual periodicity will be an important physical aspect of the Tsushima Current system associated with the north-south density structure.

The variations with 6–7 years period were generally found in the previous studies mentioned in the introduction, but in the present study were not detected as sharp SST signal in winter. This may be primarily due to the difference of the analyzed data: namely the previous studies used the summer hydrographic data (NAGANUMA, 1985) or monthly mean anomaly SST data (WATANABE *et al.*, 1986), and were concerned with the east-west patterns of the Tsushima Current along the Japanese coast. Since the variation with 6–7 years period is seen in a thin summer surface layer, the primary energy source of it may be the heat stored in the surface layer in summer. To clarify this variation and its mechanism, further studies on the water mass formation along the Tsushima Current will be needed in relation to the atmospheric heating.

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References

BINGHAM, F. M., T. SUGA and K. HANAWA (1992): Comparison of upper ocean thermal conditions in the western North Pacific between two pentads: 1938–42 and 1978–82. J. Oceanogr., **48**, 405–425.

Geographical Survey Institute, Ministry of Construction, Japan (1991): Tables and graphs of annual mean sea level along the Japanese coast 1894–1990. 83pp.

Hydrographic Office of the Republic of Korea (1970–1991): Technical reports. Results of tidal observation (1969–1990).

ISODA, Y. and M. NISHIHARA (1992): Behavior of warm eddies in the Japan Sea. Umi to Sora, **67**, 53–65. (in Japanese)

ISODA, Y., S. SAITOH and M. MIHARA (1991): SST structure of the polar front in the Japan Sea. *In*: Oceanography of Asian Marginal Seas, Elsevier Oceanogr. Ser., 54, (ed. K.Takano), Elsevier, Amsterdam, 103–112.

Japan Meteorological Agency (1971 – 1990): The ten-day marine report.

Japan Oceanographic Data Center [JODC] (1978): Marine Environment Atlas, Northwestern Pacific Ocean II (seasonal and monthly). Japan Hydrogr. Association, Tokyo, 147pp.

MIITA, T. and S. TAWARA (1984): Seasonal and secular variations of water temperature in the East Tsushima Strait. J. Oceanogr. Soc. Japan, **40**, 91–97.

MINAMI, H., Y. HASHIMOTO, Y. KONISHI and H. DAIMON (1987): Statistical features of the oceanographic conditions in the Japan Sea. Umi to Sora, **62**, 163–175.

NAGANUMA, K. (1985): Fishing and oceanographic conditions in the Japan Sea. Umi to Sora, **60**, 89–103. (in Japanese)

TANIMOTO, Y., N. IWASAKA, K. HANAWA and Y. TOBA (1993): Characteristic variations of sea surface temperature with multiple time scale in the North Pacific. J. Clim., **6**, 1153–1160.

TOBA, Y., K. TOMIZAWA, Y. KURASAWA and K. HANAWA (1982): Seasonal and year-to-year variability of the Tsushima-Tsugaru Warm Current System with its possible cause. La mer, **20**, 41–51.

WATANABE, T., K. HANAWA and Y. TOBA (1986): Analysis of year-to-year variation of water temperature along the coast of the Japan Sea. Prog. Oceanogr., **17**, 337–357.