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Tsushima Current Mode Water (TCMW)

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Abstract

The Tsushima Current Mode Water (TCMW) can be defined as a water mass characterized by a thermostad ranging from 4 to 10°C and lying between the seasonal and main thermoclines in the Japan Sea. Seasonal and interannual variations of TCMW are described based on the published hydrographic thermal maps. In cooling season, a thick mixed layer of TCMW covers a wide area in the southern part of the Japan Sea, i.e., from the polar front along 40°N to the south. During heating season, this TCMW is mainly contained in a core water of warm eddies in the Tsushima Current region. The drastic structural changes of these eddies are brought in the following wintertime due to the strong vertical convection. Thus, TCMW seems to lose its original properties every winter. Thermal maps during recent eight years (1983-1990) suggested the large interannual variations of the TCMW formation rate and its properties.

Key words: Tsushima Current Mode Water (TCMW), Japan Sea, thermostad

Introduction

The subtropical Mode Water (STMW) in the North Pacific is widely distributed in the subsurface layer of the northwestern subtropical gyre. To clarify the formation rate of STMW and its properties is very important for understanding the mechanisms of air-sea heat exchange through the sea surface, e.g., Hanawa (1987), Suga et al. (1989). This STMW is characterized by vertical homogeneity of water properties and is formed due to the evolution of wintertime vertical convection. Its formation regions correspond to the area where the ocean releases the large amount of heat to the atmosphere, i.e., around the Kuroshio and the Kuroshio Extension. Such heat-loss area of ocean also extends to the Asian marginal seas, e.g., the Japan Sea and the East China Sea (Iwasaka and Hanawa, 1990), so that we can expect the similar formation of particular homogeneous water mass in such areas.

The Japan Sea is connected to the neighboring seas only through the shallow straits with depth less than 150 m, i.e., the Tsushima/Korea, Tsugaru and Soya Straits (Fig. 1(a)). Warm water which enters through the Tsushima/Korea Strait flows northeastward and flows out through the Tsugaru and Soya Straits (Fig. 1(b)). The offshore extension of warm water bordered by the polar front in the Japan Sea contains several warm eddies, e.g., Kn, Ks, Y, O and N in Fig. 1(b) which were shown by Isoda and Nishihara (1992) as the long-term mean typical locations of warm eddies. The flow area associated with this warm water from the polar front to the south has been called as the Tsushima Current region. Figures 2(a) and (b) show the vertical sections of seasonal mean temperature in summer and winter along A-A′ line, adopted from Ogawa (1983, his Fig. 3) and along B-B′ line, adopted from Minami et al. (1987, his Fig. 3), (as for their locations see Fig. 1(a)), respectively. Along A-A′ line, water temperature in both seasons never becomes lower than about 10°C except for bottom water near the Korean coast. Many Japanese and Korean oceanographers have pointed out that this bottom cold water is caused by an outflow from the Japan Sea to the East China Sea, e.g., Lim and Chang (1969), Hahn (1979), Ogawa (1983), Byun and Chang (1984), Isoda and Yamaoka (1991) and Isobe et al. (1994). Namely, warm water more than 10°C always inflows into the Japan Sea through the Tsushima/Korea Strait. Therefore, the water less than 10°C in the Japan Sea must be formed somewhere within the Japan Sea itself. At the winter section along B-B′ line, a prominent thick mixed layer with water temperature less than 11°C evolves just south of the polar front and reaches a depth of 150-200 m depth. At summer section along B-B′ line, the water mass characterized by a thermostad lying between the seasonal (50-100 m depth) and main thermoclines (150-200 m depth) can be seen. A temperature of about 4-10°C characterizes this thermostad water. According to the similar definition of STMW

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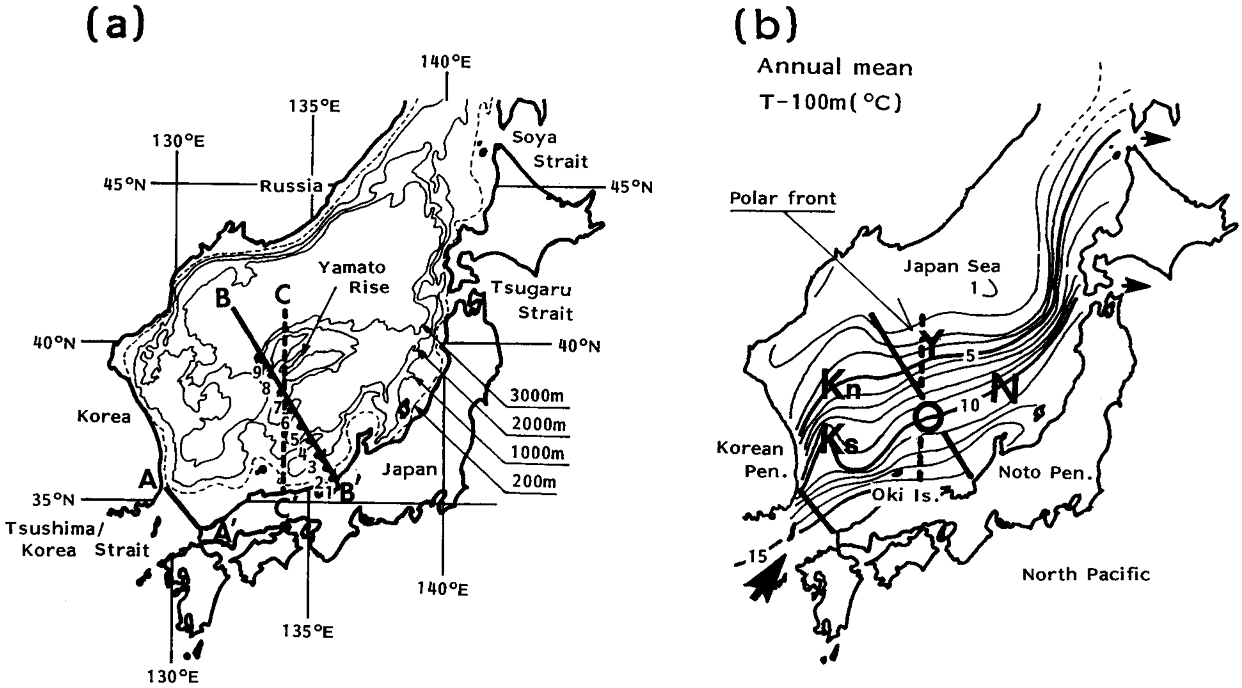


Fig. 1. (a) Bathymetric chart of the Japan Sea. A–A′ and B–B′ lines show the observation lines for the vertical sections of seasonal mean temperature. C–C′ line over the Yamato Rise is the monitor line as for the TCMW formation. (b) Annual mean thermal map at the depth of 100 m. Y, O, N, Kn and Ks indicate the typical locations of warm eddies, which were presented by Isoda and Nishihara (1992).

(Masuzawa, 1969), we propose to call this thermostad water mass in the Tsushima Current region as the Tsushima Current Mode Water (TCMW).

Miyazawa and Abe (1960) already reported that the sinking of surface water in late winter seems to form TCMW, though they called its water as the "Japan Sea Central Water". After their study, however, there have been no studies for elucidating where TCMW is really formed and how this water is transported within the Japan Sea, because almost studies during resent three decades have focused on the dynamics for path of the Tsushima Current, e.g., the meandering path, two branches or three branches.

We believe that the formation process of TCMW is important from the viewpoint of dynamics on the surface circulations in the Japan Sea, because TCMW is renewed every winter due to the vertical convection and covers a wide area in the Tsushima Current region as discussed in this paper. The purpose of the present study is to describe the seasonal and interannual variations in TCMW based on the published hydrographic thermal maps.

Seasonal variation of the TCMW zone

Figure 3 shows the climatological temperature distributions in the Japan Sea at the depths of 0, 100, 200 m for each season. The TCMW zone were redrawn from the "Marine Environmental Atlas II—Northwestern Pacific Ocean" compiled by JODC (1978). In these panels, stippled, blackened and shaded areas indicate 4–6, 6–8 and 8–10°C zone, respectively. This drawing manner is similar to that adopted by Hanawa (1987) for the STMW distributions in the North Pacific.

In winter, the TCMW zone at the sea surface (0 m depth) extends from the polar front along 40°N southward to about 37°N. The pattern of the sea surface TCMW zone is almost the same as that at the depth of 100 m. These temperature distributions imply the existence of a thick mixed layer of TCMW in winter. Such zone is defined as the wintertime outcrop/formation area of TCMW. It is also found that the TCMW zone in winter occupies a wide area south of the polar front along 40°N, i.e., the area more than a half of the Tsushima Current region. The sea surface TCMW zone abruptly migrates northward in spring and almost disappears from summer to autumn due to the sea surface heating. Thus, TCMW mass formed in winter is completely masked by the warm surface layer except for winter season.

It is interesting that the thermal maps at the depth of 100 m show the two stagnant positions of TCMW distributions in all seasons. One stagnant position is the point-a, which indicates the northern limit of the polar front being corresponded well with the location of warm eddy-Y (see Fig. 1(b)). Isoda and Nishihara

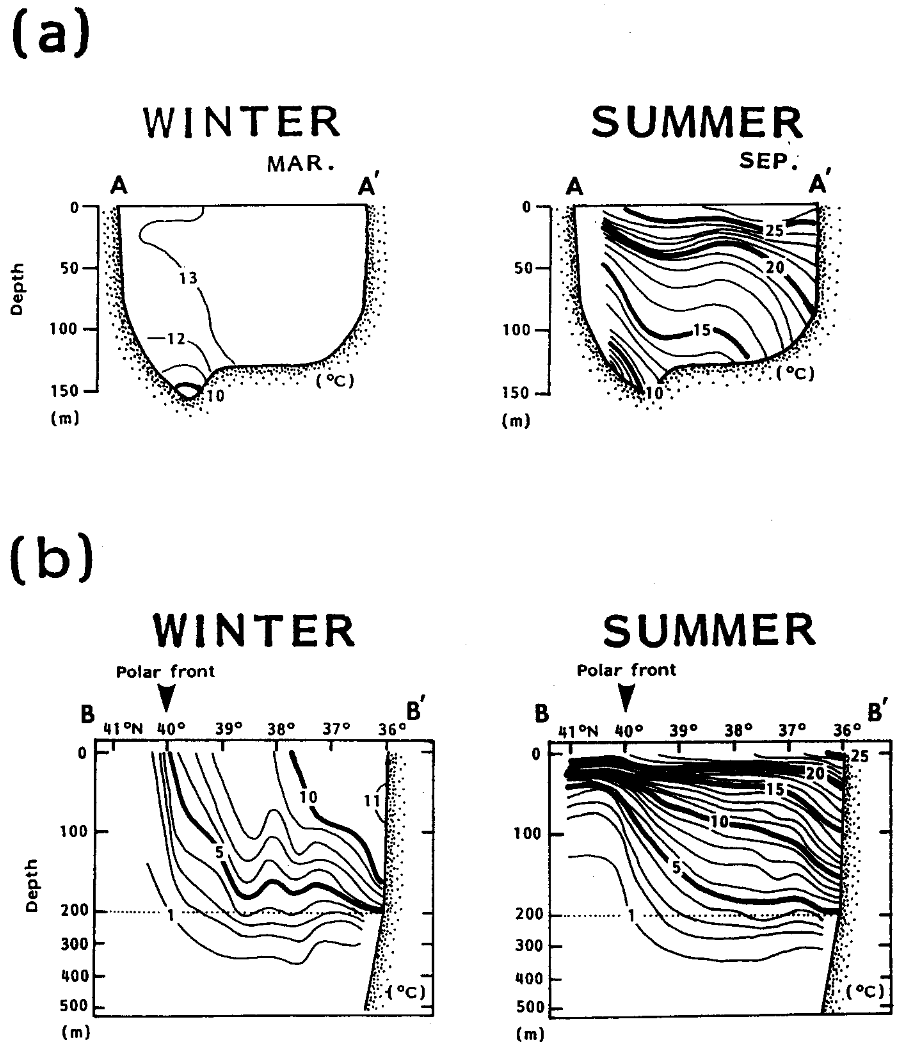


Fig. 2. Vertical sections of seasonal mean temperature in summer and winter (a) along A–A′ line adopted from Ogawa (1983, his Fig. 3) and (b) along B–B′ line adopted from Minami et al. (1987, his Fig. 3), respectively.

(1992) showed that warm eddy-Y seems to be affected by the bottom topography and stably exits above the Yamato Rise. The other is the point-b at the northern (or Korean) side of the Tsushima/Korea Strait. This means that warm water more than 10°C is the source of inflow water from the Tsushima/Korea Strait as mentioned in the introduction. The TCMW zone at the depth of 100 m has the widest area from winter to spring and its area decreases from summer to autumn. The extension of inflow water more than 10°C has also the following seasonality. From winter to summer, inflow water extends northeastward along the Japanese coast as the coastal boundary current, whereas TCMW occupies the area off the Korean coast from winter to summer. The northward extension of inflow water along the Korean coast occurs in autumn.

At the depth of 200 m, the TCMW zone stagnates retaining almost the same pattern and forms a large warm water pool area at the southeastern Japan Sea in all seasons, which corresponds to the region from O to N in Fig. 1(b). Isoda (1994a) showed that, on the average, several warm eddies move parallel to the Japanese coast from the Oki Islands to the Tsugaru Strait without an exact boundary between O and N areas. Namely, this large warm water pool is apparent as the result of the long-term trajectory of these warm eddies. The another warm water pool exists around warm eddy-Ks shown in Fig. 1(b), though its water temperature is less than 4°C. Therefore, we can speculate that TCMW will be mainly contained in a core water of warm eddy and advected from its formation area to other regions due to the movement of their warm eddies.

Interannual variation of TCMW from 1983 to 1990

The heat flux through the sea surface varies considerably from year to year, so it is expected that both the formation rate and the property of TCMW also vary

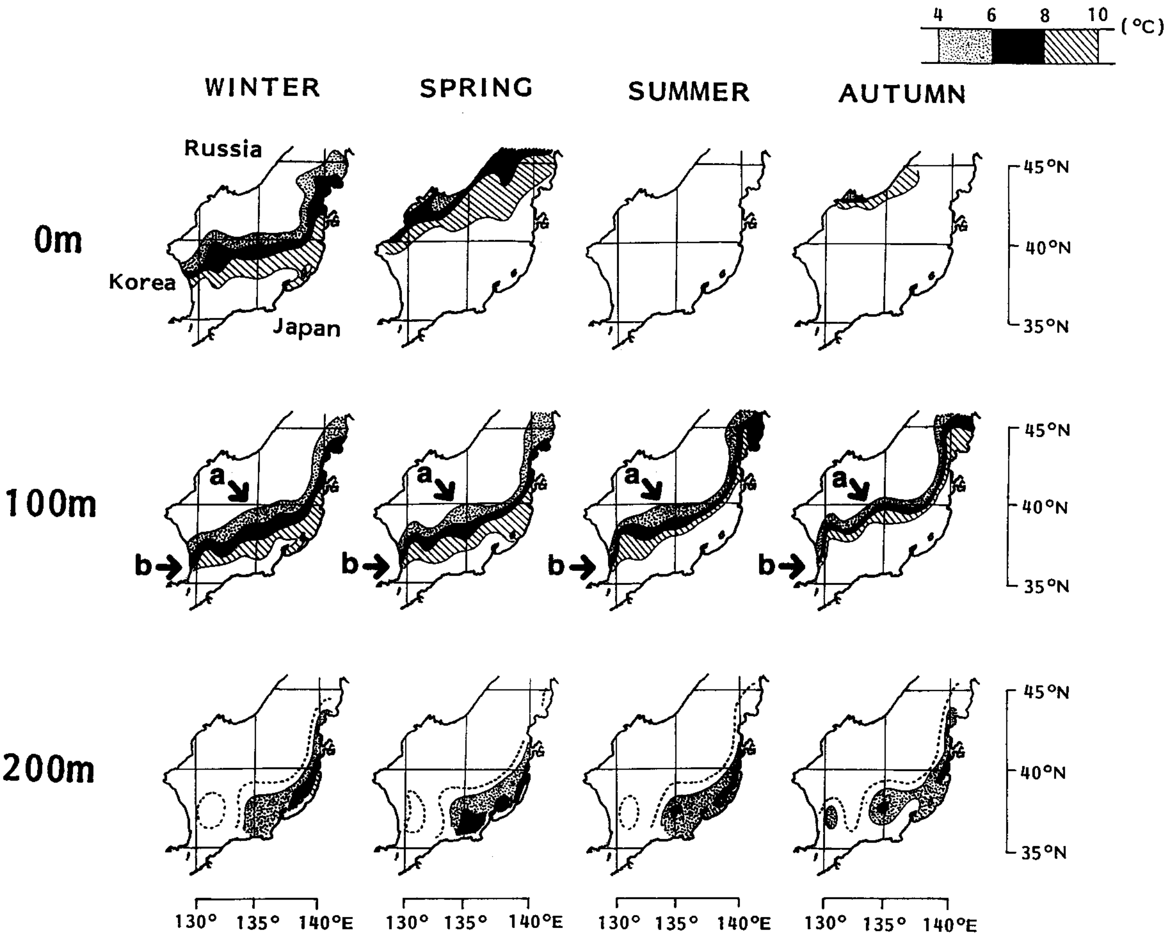


Fig. 3. Climatological temperature distributions of the TCMW zone fro depths of 0, 100 and 200 m for each season. These were redrawn from Marine Environmental Atlas II—Northwestern Pacific Ocean" of JODC (1987). Stippled, blackened and shaded areas indicate the 4-6, 6-8 and 8-10°C zone, respectively. Dotted lines in the panel of 200 m depth indicate 3°C contour lines.

simultaneously. Isoda (1994b) examined the long time series of wintertime sea surface temperature (SST) data in the Japan Sea, and discussed the interannual variability of subsurface waters. Figure 4 shows the time series of SST in winter from 1971 to 1990 averaged Stns. 1 to 7, adopted from Isoda (1994b, his Fig. 5). In the present study, we used thermal maps during 1983 to 1990 whose period corresponds to the years from relative cold winter to warm winter.

Since the amount of subsurface temperature data has increased in summer, we can examine spatial changes in the subsurface temperature distributions. Figure 5 shows the monthly TCMW zone at the depth of 100 m in August from 1983 to 1990. These maps were redrawn from "Monthly Water Temperature Map at the depth of 100 m" of "The Ten-Day Marine Report" routinely published by JMA (1983-1990). These figures show that the TCMW zone distribution is much more complicated than the averaged picture in summer (Fig. 3). The individual shape of TCMW in Fig. 5 is changed by the synoptic variability of some warm and cold eddies. The extension of the TCMW zone differs from year to year, especially east of the Noto Peninsula. The period from 1983 to 1986 is thought to be that when the larger evolution of TCMW could be expected. From 1987 to 1990, inflow waters more than 10°C extended along the Japanese coast and a narrow band of TCMW existed at its northern boundary.

To present more clearly the seasonal and interannual variations of the TCMW zone, we obtained the positions of TCMW isotherms from the monthly thermal maps at the depth of 100m along C-C′ line shown in Figs. 1(a) and 5. Since the northern limit of the TCMW zone in the vicinity of the point-a in Fig. 3 is relatively stable as mentioned in the previous section, the TCMW isotherms along C-C′ line is expected to monitor the temporal variations in the area of TCMW. Figure 6 shows the time-latitude diagram of the TCMW zone along C-C′ line. The polar front indicated by about 4°C isotherm was located around 40°N. Area of

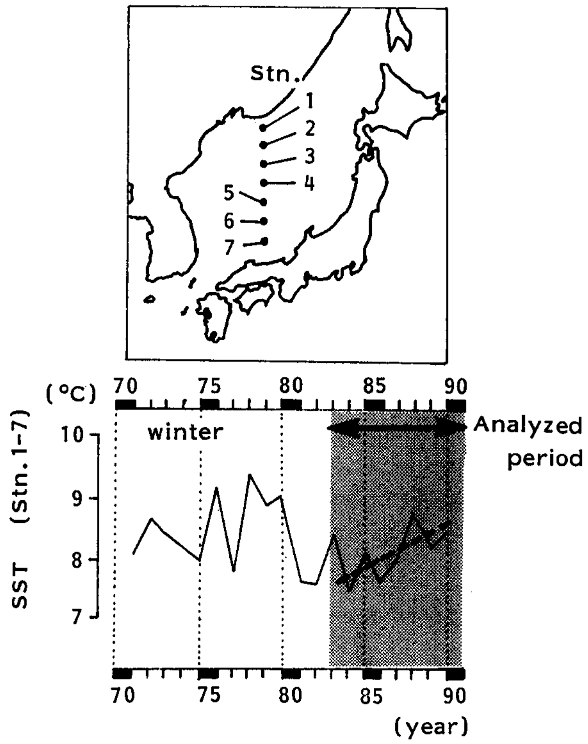


Fig. 4. The time series of SST in winter averaged from Stns. 1 to 7, adopted from Isoda (1994b).

detected TCMW was relatively widened from spring to summer. This TCMW must have been formed in the previous winter because no mixed layer develops in spring and summer. In cold winters from 1983-1984 to 1986-1987, it can be speculated that the ocean released the large amount of heat to the atmosphere so that the large amount of TCMW might be formed within the Tsushima Current region.

Examples of core water in a warm eddy

Isoda and Nishihara (1992) showed that warm eddy movements in the Tsushima Current region are not random, but warm eddies are generally found in the following three major regions; [Y] area on the Yamato Rise, [Ks and Kn] area off Korean coast and [O and N] area along the Japanese coast as shown in Fig. 1(b). The maps of monthly TCMW zone at the depth of 200 m were redrawn from the routine thermal maps issued by JMSA (1993, 1984, 1989 and 1990). The Japanese hydrographic data used for drawning the vertical sections of temperature were obtained from Maizuru Marine Observatory (1983, 1984, 1989 and 1990). Unfortunately, since the hydrographic data off the Korean coast cannot be easily used, the structural

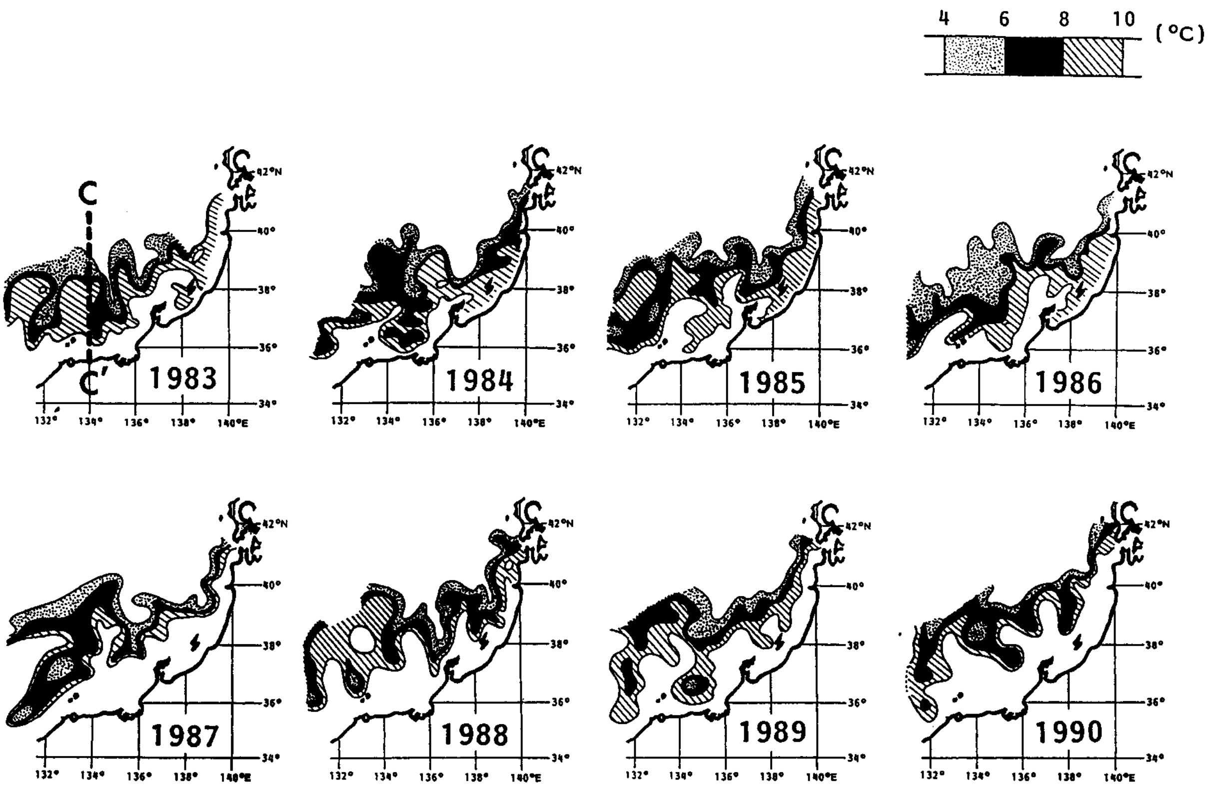


Fig. 5. The monthly TCMW zone at the depth of 100 m in August for 8 years from 1983 to 1990. The zone were redrawn from "Monthly Water Temperature Map at the depth of 100 m" of "The Ten-Day Marine Report". The representation is the same as that of Fig. 3.

change of warm eddies–Ks and Kn due to the wintertime vertical convection was not verified in the present study.

Warm eddy-Y on the Yamato Rise

As we can see from Fig. 6, the region of TCMW in the vicinity of the polar front can be expected to be the area where TCMW was formed every winter. The routine observation of B–B′ line (for locations at Stns. 1–9 see Fig. 1(a)) made it possible to investigate the seasonal evolution of the warm eddy-Y structure on the Yamato Rise. Figure 7 shows the seasonal variations of vertical sections of water temperature along B–B′ line from February 1983 to October 1984. The changes of vertical features of the mixed layer imply that the frontal structure at the northern limit of the TCMW formation area seems to be associated with warm eddy-Y on the Yamato Rise. Warm eddy-Y disappeared in February 1983 and 1984 and this drastic structural change of warm eddy-Y seems to be brought by the wintertime vertical convection. TCMW during heating season was contained in a core water of warm eddy-Y.

Warm eddies in the O and N area

We investigated two specific examples for the structural change of warm eddy exerted by severe winter cooling (1983–1984) or not (1989–1990). The extreme wintertime deepening of the mixed layer might occur from 1983 to 1984, while for two years of 1988 and 1990 the area forming TCMW was very narrow from 38°N to north (see Fig. 6). During cold winter from 1983 to 1984, warm eddy could be detected around the Noto Peninsula and moved eastward with an average speed of about 1 cm s^{-1} (Fig. 8(a)). During warm winter from 1989 to 1990, warm eddy was nearly stationary northeast of the Oki Islands, but moved slightly eastward (Fig. 8(b)). We used water temperature data of sections off the Noto Peninsula and off the Oki Islands shown by thick lines D1–D3 in Fig. 8(a) and E1–E3 in Fig. 8(b), respectively. These sections seem to be located at the central part of each warm eddy.

The size and shape of a warm eddy little changed in both winters. However, their core temperatures increased, i.e., 6–7°C to 9–10°C during cold winter in 1983–1984 (see sections D1 and D2 in Fig. 8(a)), from 8–9°C to 11–12°C during warm winter in 1989–1990 (see sections E1 and E2 in Fig. 8(b)). The surface warmer water formed during heating season would be entrained into an eddy due to the vertical mixing in winter. Such mechanism may explain the increase in a core temperature of warm eddy. It is suggested that a core water of warm eddy in O and N area is renewed every winter as well as a warm eddy-Y and its original properties are also lost during one year due to the wintertime vertical convection.

The difference between cold and warm years is clear as follows. After cold winter, a homogeneous core water at the section D3 in Fig. 8(a) is seen to have been capped by a new seasonal thermocline more than 10°C, which is created by the advection of inflow water and the sea surface heating. After warm winter, the shape of a core water at the section E3 in Fig. 8(b) becomes unclear. Presumably, a core water of warm eddy may be interacted with inflow warm water, because its core temperature was more than 10°C whose property was the same as that of inflow water. This is an example of interannual variation of interactions between inflow water and warm eddy due to the difference of TCMW formation.

Discussion and conclusion

Based on the published hydrographic thermal maps, seasonal and interannual variations of TCMW in the Japan Sea are described. In cooling season, the mixed layer of TCMW with a thickness of 150–200 m extends a wide area of the Tsushima Current region from the polar front along 40°N to the south. This TCMW is generated by the wintertime vertical convection and is mainly contained in a core water of warm eddies during heating season. However, the drastic structural changes of these warm eddies are brought in the next winter. It should be noticed that this renewal depth (150–200 m) is remarkably shallower than that of STMW (300–400 m) in the Kuroshio Extension region (Hanawa, 1987). It may be considered that the inflow and outflow water depths at the shallow straits may limit the vertical spreading of the Tsushima Current water masses to less than 150–200 m depth. Therefore, TCMW readily seems to lose its original properties every winter. Thermal maps during eight years from 1983 to 1990 suggested the large interannual variations of the TCMW formation rate and its properties. In cold winters from 1983–1984 to 1986–1987, the ocean might release the large amount of heat to the atmosphere so that the large amount of TCMW was formed. The difference between cold and warm winter years was also seen as the different interactions between inflow water from the Tsushima/Korea Strait and warm eddies near the Japanese coast.

Thus, the present study suggests that seasonal change of the Tsushima Current in the Japan Sea is caused not only by that of volume transport through the straits but also by the seasonal redistributions of water masses related with the TCMW formation. In other words, TCMW mass is considered as a large heat reservoir in

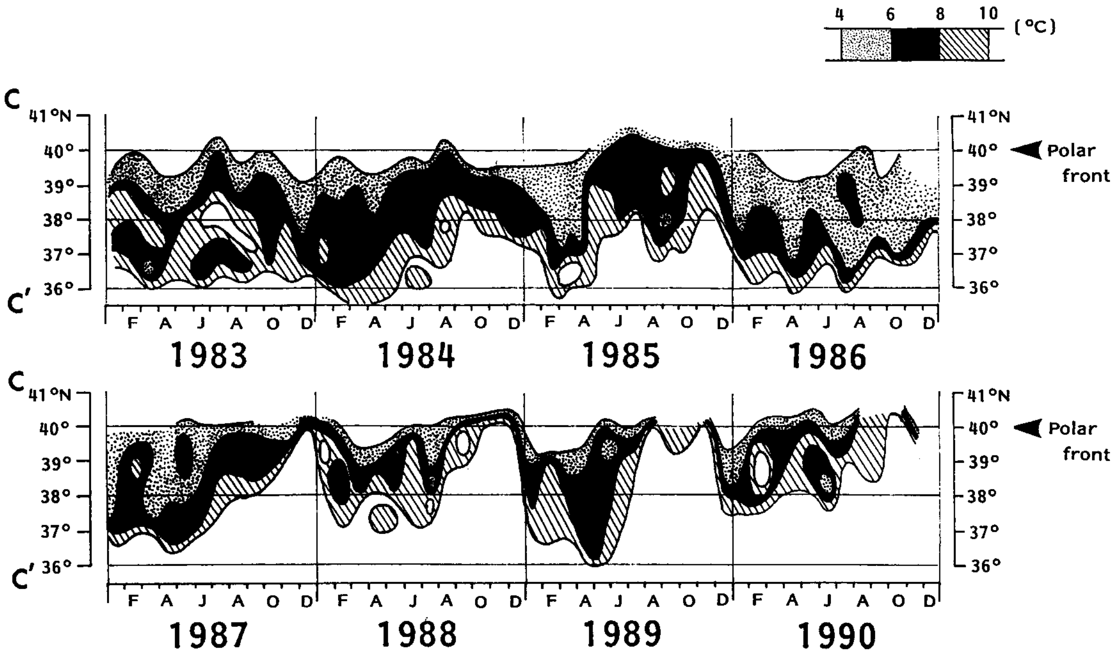


Fig. 6. The time-latitude diagram of the TCMW zone at the depth of 100 m along C–C′ line (for location see Fig. 1(a)). The representation for the stippled, blackened and shaded areas are the same as that of Fig. 3.

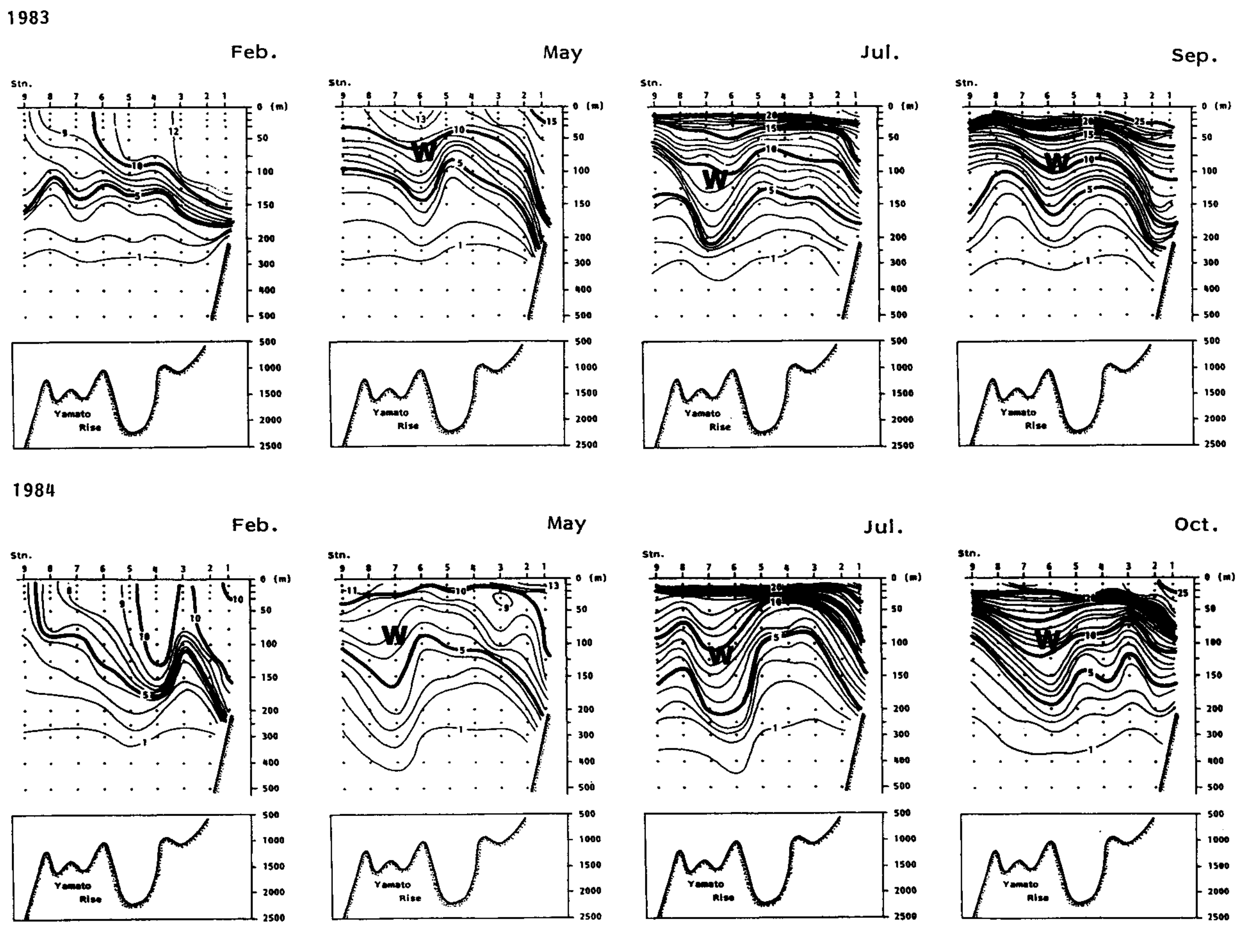
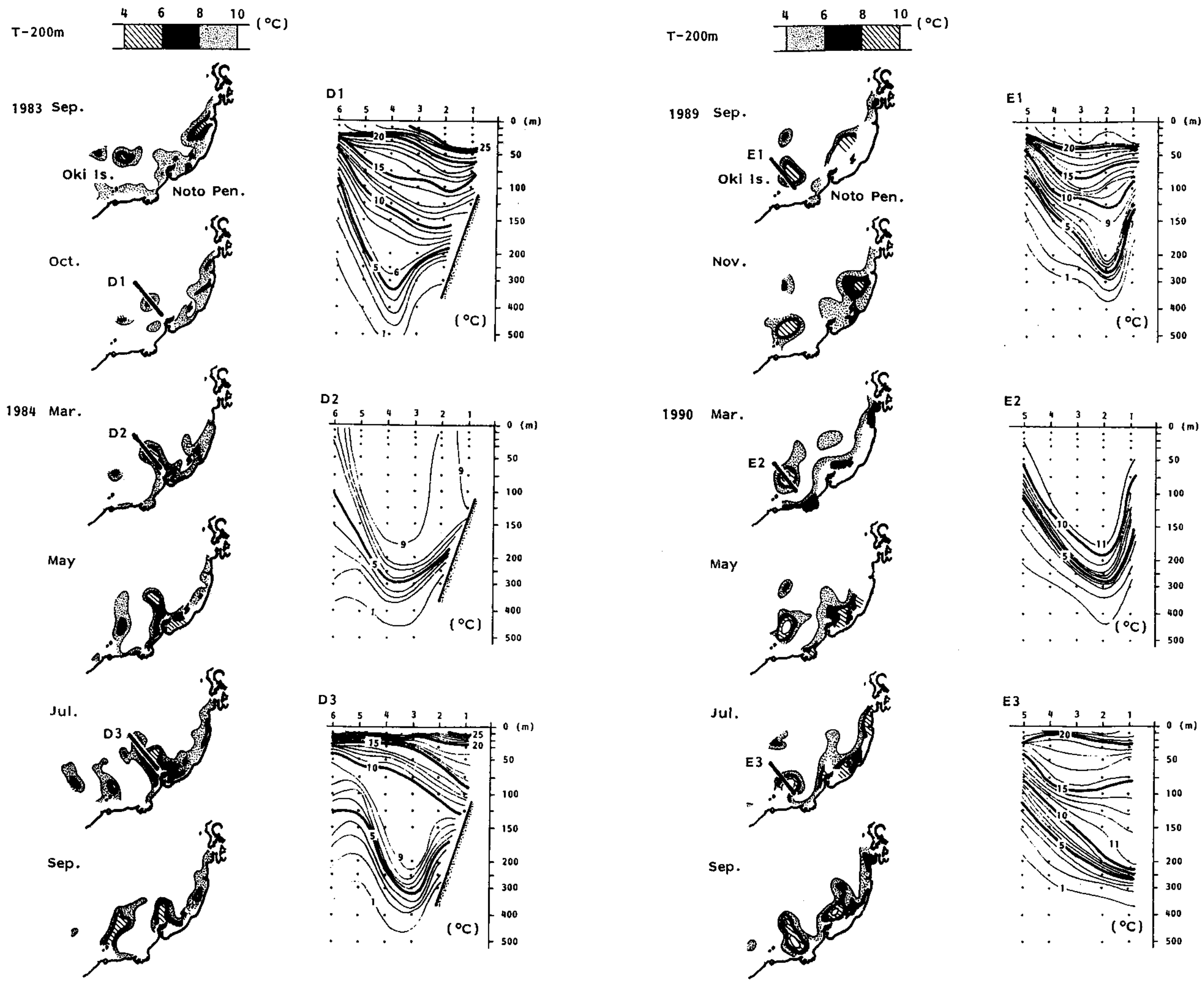


Fig. 7. The vertical sections of water temperature at Stns. 1-9 along B-B′ line (for location see Fig. 1(a)) from February 1983 to October 1984.



(a) (b)

Fig. 8. The monthly TCMW zone at the depth of 200 m (a) from September 1983 to September 1984 and (b) from September 1989 to September 1990. Vertical temperature cross-sections of (a) D1, D2 and D3 around warm eddy off the Noto Peninsula, and (b) E1, E2 and E3 around warm eddy off the Oki Islands. The zones were redrawn from "Quick Bulletin of Oceanic Condition" routinely compiled by JMSA (1983, 1984, 1989 and 1990). The representation is the same as that of Fig. 3.

the Japan Sea and, therefore, the controller in the circulation system of the Tsushima Current. In our future study, the dissipation or diffusion process of TCMW will be made clearer through investigating water masses properties at the downstream area of the Tsushima Current, i.e., off west coast of Hokkaido and at the outflow area of the Tsugaru and Soya Straits.

Senjyu and Sudo (1993) pointed out that the another thermostad water mass of the "upper portion of the Japan Sea Proper Water (UJSPW)" is also formed by the wintertime convection in the northern area of the polar front. The past studies called it as the "Japan Sea Itermediate Water", which is characterized by the minimum salinity layer and temperature less than 1°C. In the Tsushima Current region, this water with a thermostad of more than 300 m in thickness exists below the main thermocline. This implies that UJSPW is advected from the northern shallow formation area to the deep layer in the south of the polar front. Therefore, it is suggested that UJSPW formed especially in severe winter can memorize its properties for a long time. To clarify the evolution and extension of both TCMW and UJSPW will be very important subject to know the relationship between subsurface and abyssal circulation systems in the Japan Sea.

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