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Characteristics of Variations of Water Properties and Density Structure around the Kuroshio in the East China Sea

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Quarterly data of CTD at the PN line in the East China Sea during 1988–94 were analyzed to examine the variations of water properties and density structure in relation to the Kuroshio. The Kuroshio flows over the continental slope at the PN line. Water properties in the surface layer less than 100 db change greatly and show a clear seasonal cycle, while those in the subsurface layer are much less variable. The small isobaric variations in the subsurface layer are almost due to the vertical movement of isopycnals, on which the water properties vary little. The subsurface variations of salinity, temperature and isopycnal depth are classified into four groups occurring in the four regions, divided vertically by the middle of the main pycnocline and horizontally by the offshore edge of the Kuroshio, named Groups 1 (upper Kuroshio), 2 (upper offshore region), 3 (lower Kuroshio), and 4 (lower offshore region). The difference in averaged isopycnal depth between Groups 1 and 2 (3 and 4) is highly correlated with the vertical shear of the Kuroshio velocity in the upper (lower) pycnocline. The isopycnal depth of Groups 1 and 3 has little annual cycle (with large intraseasonal variations in Group 3), while that of Groups 2 and 4 shows a clear seasonal variation with the minimum in fall. As a result, the Kuroshio velocity is smallest in fall almost every year, although the amplitude of seasonal variation and the season of maximum velocity are different from year to year. Interannual variations of isopycnal depth are characterized by a large amplitude of Group 2 and an opposite phase between Groups 3 and 4, so that the variations of difference in isopycnal depth between Groups 1 and 2 and Groups 3 and 4, i.e., the upper and lower shear of the Kuroshio velocity, are comparably significant.

Keywords:
· Kuroshio,
· East China Sea,
· water properties,
· isopycnal depth,
· seasonal variation,
· interannual variation.

1. Introduction

The Kuroshio flows into the East China Sea through the passage east of Taiwan and flows out through the Tokara Strait south of Kyushu (Fig. 1). The current axis of the Kuroshio in the East China Sea is located at the continental slope with much less variability than that in the southern region of Japan where the Kuroshio takes a large-meander path and a non-large-meander path alternately, with a primary period of about twenty years (Kawabe, 1985, 1987; Yamashiro *et al*., 1993). Hydrographic observations in the East China Sea have been made at several sections by the Japanese agencies. In particular, long-term data are taken at the PN (Pollution Nagasaki) line northwest of Okinoerabushima by the Japan Meteorological Agency. They are quite useful for examining water masses and density structure around the Kuroshio in the East China Sea.

Water masses in the East China Sea are very different between the onshore and offshore sides of the Kuroshio (Nitani, 1972; Sawara and Hanzawa, 1979; Chen *et al*., 1994). Water on the onshore side of the Kuroshio, namely in the continental-shelf region, is formed by a mixing of fresh water discharged from rivers such as the Huanghe (Yellow River) and Changjiang (Yangtze River), low-salinity water in the Yellow Sea, and saline water on the offshore side of the Kuroshio, so that salinity in the shelf region is much lower than that offshore of the Kuroshio. The seasonal cycle of the fresh-water supply from the Changjiang (minimum in January and maximum in July) strongly influences the water properties in the shelf region (Beardsley *et al*., 1985; Chen *et al*., 1994); salinity near the sea surface in the shelf region changes seasonally in an opposite phase to water temperature, namely maximum in winter and minimum in summer (Kondo, 1985). Similar seasonal variations are seen near the sea surface in the Kuroshio and on its offshore side, associated with an offshore extension of the low-salinity water which is largest in summer and smallest in winter.

Fujiwara *et al*. (1987) and Hinata (1996) calculated the long-term means of salinity and temperature in each season

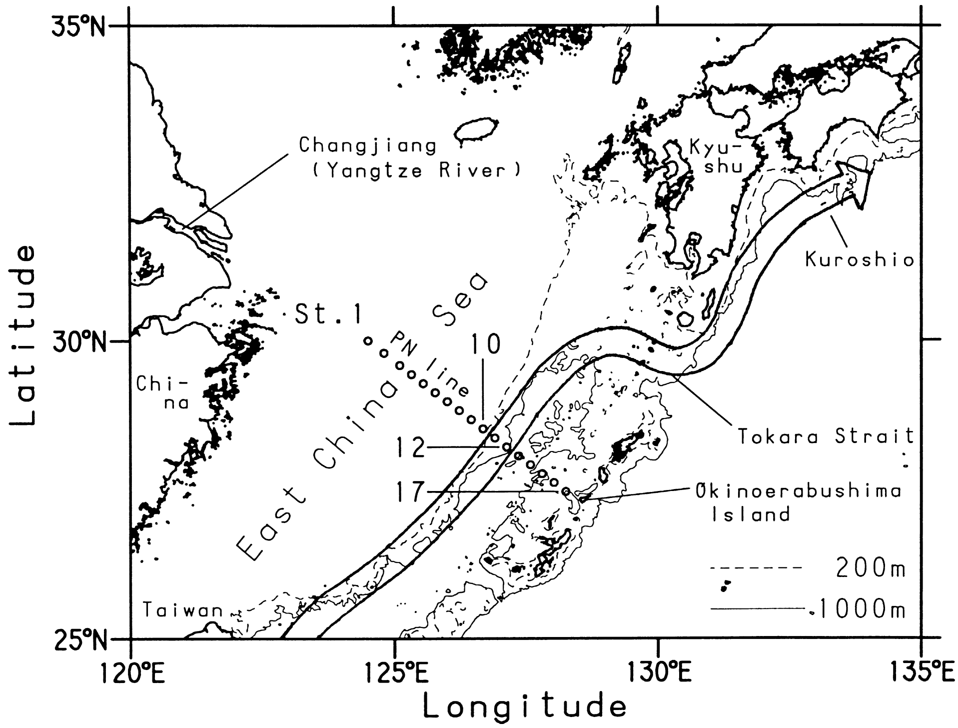

Fig. 1. CTD stations at the PN line (circles) and the typical path of the Kuroshio (arrow).

at the PN line during 1972–81 and 1972–93, respectively. They indicated that seasonal variations at depths greater than 200 m are much smaller than those in the shallower layer. Hinata (1996), however, showed that seasonal variations are significant at depths of 200–600 m on the offshore side of the Kuroshio, and salinity and temperature are at a minimum in fall. The layer of 200–600 m corresponds to a main thermocline and to a value lying between a maximum and a minimum of salinity. Water masses in the Kuroshio and on its offshore side are characterized by a salinity maximum at 23.9–24.9σ_t at depths of 100–250 m, a salinity minimum at 26.8σ_t at 500–700 m, and a main thermocline between them (Nitani, 1972; Masuzawa, 1972). The water in the salinity maximum is a modified North Pacific Tropical Water, formed originally at the sea surface by strong evaporation at 20–30°N in the central region of the North Pacific. The water in the salinity minimum is a modified North Pacific Intermediate Water, formed originally in the mixed-water region between the Kuroshio and Oyashio fronts east of Japan.

Seasonal variations of velocity and volume transport of the Kuroshio in the East China Sea have been studied by several authors. Fujiwara *et al*. (1987) and Hinata (1996) showed that the volume transport of the Kuroshio at the PN line referred to 700 db averaged seasonally during 1972–81 and 1973–93 is clearly at a minimum in fall. Yamashiro *et al*. (1990) showed that the seasonal mean transport at the PN line referred to GEK velocity during 1972–86 is at a maximum in summer and at a minimum in fall. Kawabe (1988) examined sea-level difference between Naze and Nishinoomote at the Tokara Strait from 1965 through 1983, and showed that the long-term mean semimonthly velocity of the Kuroshio is at a maximum in July and at a minimum in the second half of October with a sharp decrease in August and September. Thus the velocity and transport of the Kuroshio show a maximum in summer and a minimum in fall on the long-term average. However, the seasonal variation is different from year to year, and the only feature found every year is a weak velocity from September to December (Masuzawa, 1960; Taft, 1972; Kawabe, 1988).

Water properties near the sea surface in the East China Sea have been well examined in terms of seasonal variations. On the other hand, water properties in subsurface and deep layers have not been well clarified. In the present paper we re-examine the seasonal variations of water properties in a surface layer, and primarily study the characteristics of water properties and density structure in a subsurface layer and their relation to the velocity of the Kuroshio. Attention is paid to the variations in depth of isopycnals, which are directly related to variations of salinity and temperature as well as geostrophic velocity of the Kuroshio.

In the hydrographic observations at the PN line, CTD has been used since spring 1987 instead of Nansen bottles. The vertically continuous data of salinity and temperature from CTD make it possible to describe the vertical distributions and gradients of water properties accurately. We analyze the quarterly CTD data at the PN line during 1988–94. The data used in this paper are explained in Section 2. The characteristics of seasonal variations of water properties are examined in Section 3. Variations in depth of isopycnals and their relation to the Kuroshio velocity are studied for periods of one year and less in Section 4 and for interannual periods in Section 5. Summary and conclusions are given in Section 6.

2. Data

We used quarterly CTD data at nineteen stations at the PN line from summer 1987 to spring 1995 obtained by the Nagasaki Marine Observatory, the Japan Meteorological Agency (Fig. 1). The observations were made in each season, actually in January, April, July and October. We will call them winter, spring, summer and fall, respectively. We analyzed the data for seven years from 1988 through 1994. The data in 1987 and 1995 were used only for calculating one-year running means. The analysis is done in terms of the annual and shorter-term variations and the interannual variations. One-year (four-data) running means of the CTD data were calculated for the interannual variations, and were subtracted from the CTD data for the annual and shorter-term variations.

Seventeen stations of CTD are located with an interval of 15 nautical miles, and were numbered Sts. 1, 2, ..., 17 southeastward. The observations were made at two more stations at the center of Sts. 9 and 10 and Sts. 12 and 13, called Sts. 9.5 and 12.5, respectively. Stations 1–10, Sts. 11–12, and Sts. 12.5–17 are located in the continental-shelf region, the continental-slope region, and the offshore deep-water region with water depth of about 1000 m, respectively.

The Nagasaki Marine Observatory calibrated and edited the CTD data with an interval of one decibar (salinity, in-situ temperature, and pressure). We calculated potential temperature and density referred to 0 db and geostrophic velocity from the CTD data. Salinity data at St. 12 in summer 1987 were questionable, and were determined from temperature data with the averaged salinity–temperature relation at St. 12 in summer during 1988–94. No CTD observation was made at St. 16 in spring 1991, and the salinity and temperature data were interpolated with those at Sts. 15 and 17.

Geostrophic velocities between Sts. 12 and 17 were calculated referred to 700 db following previous calculations by the Japan Meteorological Agency. In the continental-slope region between Sts. 10 and 12, in-situ density was linearly extrapolated along isobars, and the reference level for geostrophic velocity was assumed at the middle of water depths of the two adjacent stations. In the continental-shelf region between Sts. 1 and 10, the reference level was assumed to be the shallower bottom between the two adjacent stations.

3. Characteristics of Seasonal Variations of Water Properties

Figure 2 shows seasonal distributions of geostrophic velocity, potential temperature (θ), salinity (S) and potential density (σ_θ) at the PN line averaged during 1988–94. A northeastward flow faster than 20 cm·s^{-1} exists along the continental slope between Sts. 10 and 14, having the maximum at the sea surface between Sts. 11 and 12. This current is the Kuroshio. The locations of the strong current core and axis of the Kuroshio do not change between seasons on the seasonal average.

The main thermocline is between 8°C and 21°C at depths of about 150–550 db in the Kuroshio and 150–700 db in the offshore region (Fig. 3). The thermocline shallows sharply in the Kuroshio, hits the continental slope, and does not exist in the shallow continental-shelf region. The halocline and pycnocline show almost the same spatial change as the thermocline. The θ-S relation in the thermocline offshore of the Kuroshio is almost linear and steady especially around the middle of the thermocline, as shown in Masuzawa (1972) and Chen *et al*. (1994) (Fig. 4).

The maximum and minimum salinity is found at the top and bottom of the thermocline, respectively. Salinity reaches greater than 34.80 at depths of 100–250 db with the maximum on an isopycnal of 24.5σ_θ, and reaches the minimum less than 34.35 on an isopycnal of 26.7σ_θ which is at a depth of 700 db between Sts. 14 and 17, shallower to the west, and at 550 db at St. 12 (Figs. 2–4). The salinity maximum ends at St. 13 in the Kuroshio associated with the inclined halocline along the continental slope, while the salinity minimum penetrates into the Kuroshio and reaches the slope. The salinity at the minimum is especially low on the slope side west of St. 15, while salinity less than 34.3 does not exist at Sts. 16–17 on the seasonal average.

3.1 Surface layer

Seasonal variations of water properties are quite large at depths less than 100 db, resulting in the large standard deviations shown in Fig. 5. Salinity and temperature in the surface layer less than 100 db are almost uniform in winter, become less saline and warmer in spring and summer, and form a significant seasonal halocline and thermocline in summer. Then a mixed layer develops at depths less than 40 db in fall and to 100 db in winter. Temperature in the surface layer is at a minimum in winter, with a second minimum in spring, and at a maximum in summer, while salinity changes seasonally in an almost opposite phase to temperature, as indicated by Kondo (1985). As a result, correlations between salinity and temperature are large negatives at depths less than 100 db (Fig. 5(c)). Seasonal variations in the surface layer are particularly large in the continental-shelf region (Fig. 4).

In winter, salinity, temperature and density are vertically uniform, so that the contours run vertically except near

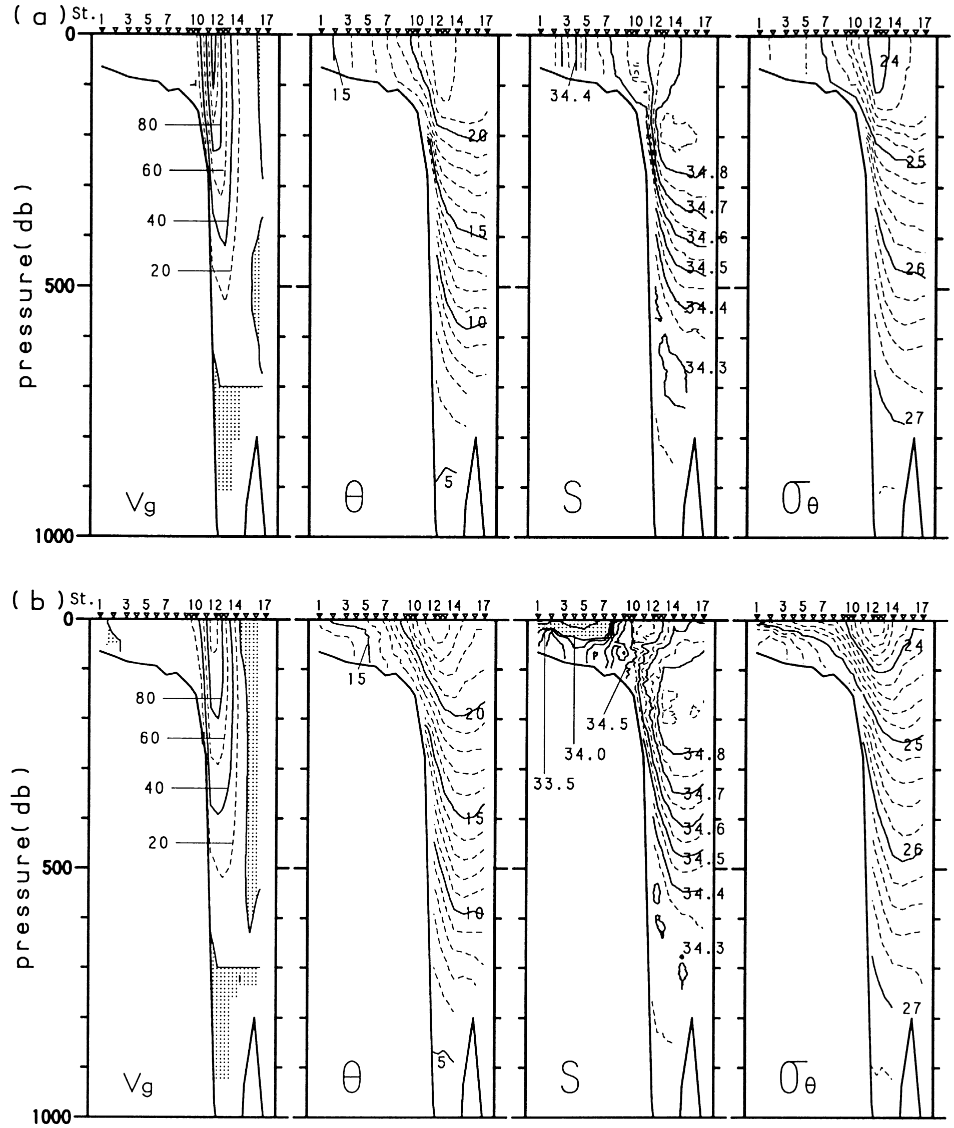

Fig. 2. Distributions of geostrophic velocity (V_g) (cm·s^{-1}), potential temperature (θ) (°C), salinity (S) and potential density (σ_θ) at the PN line in winter (a), spring (b), summer (c) and fall (d), averaged during 1988–94. Positive values in the leftmost panels indicate northeastward velocities, and negative values are shaded. Salinity less than 34.0 is shaded, and the contour interval for less than 34.0 in (b) and (c) is 0.5. Inverted triangles on the top of each panel represent the CTD stations.

the Kuroshio axis (Fig. 2). Salinity is almost uniform on the offshore side of St. 14, while it decreases westward on the onshore side. Sea surface temperature (SST) is at a maximum of 22.5°C at St. 12 and decreases to the both sides; a warm low-density core, usually called a warm core, clearly exists near the sea surface just offshore of the Kuroshio axis.

In spring, low-salinity water less than 34.0 extends eastward to St. 7 on the average in a thin shallow layer less than about 40 db in the shelf region. Kondo (1985) mentioned that the seasonal halocline in the East China Sea due to the fresh-water supply from the Changjiang is formed at depths less than 40 m. This low-salinity water is warmer than the lower-layer water whose salinity, temperature and density are still vertically uniform, like winter conditions. SST is at a maximum at St. 12 with a larger value of 24.7°C, and the warm core develops further.

In summer, low-salinity water less than 34.0 in the shallow layer extends to the farther east and reaches St. 11. On the other hand, water more saline than 34.6 extends westward on the bottom of the shelf at Sts. 7–10. As a result, isohalines are rather horizontal. SST is at a maximum at St. 12 like winter and spring conditions with a much larger value of 29.5°C, but isotherms are much more horizontal with a very thin warm core. The seasonal thermocline

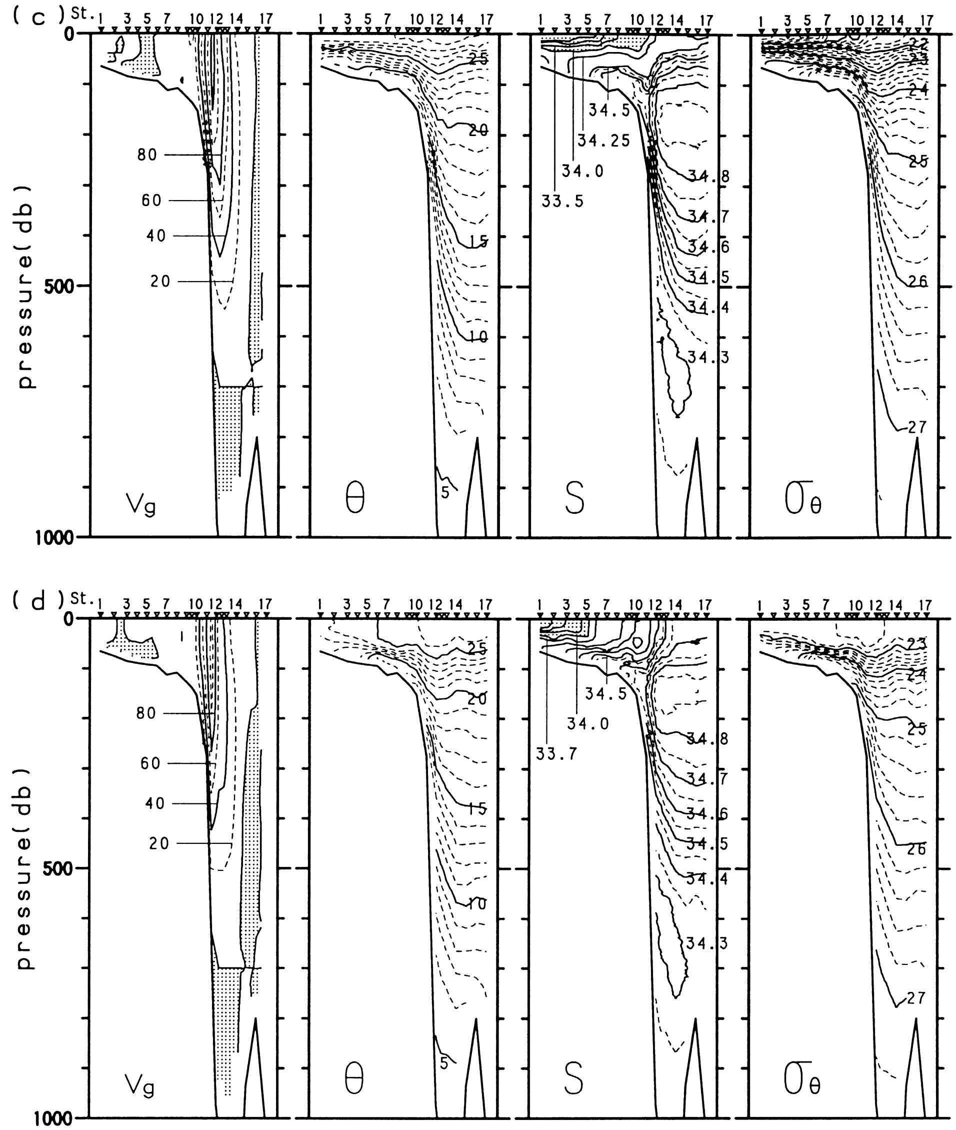

Fig. 2. (continued).

develops at depths between 10 db and 60 db in the shelf region and down to 150 db in the offshore region of the Kuroshio. The seasonal pycnocline develops in the seasonal thermocline and extends toward the sea surface due to the shallow halocline.

In fall, the horizontal extension of the low-salinity shallow water decreases, and the water less than 34.0 is limited to the west of St. 5. A vertical mixing forms a mixed layer at depths less than 40 db; the upper part of the seasonal thermocline and pycnocline disappears, while the lower part remains. SST is still at a maximum at St. 12 with 26.4°C, but the warm core, in particular its offshore edge, is not clear; nevertheless, the contour of 26.2°C forms the warm core between Sts. 11 and 14. Hinata (1996) showed the warm core greater than 27.0°C between Sts. 11 and 14 in fall. A difference of 0.8°C in the warm-core temperature between the present study and Hinata (1996) may be due to the difference in the analysis period.

3.2 *Subsurface layer*

Seasonal variations of salinity and temperature in the subsurface layer at depths greater than 100 db are much smaller than those in the surface layer (Fig. 3). The subsurface variations at Sts. 12 and 12.5 in the Kuroshio are quite large at depths of 100–300 db and small at depths greater than 400 db, while those at Sts. 13–17 on the offshore side of the Kuroshio are significant in the whole part of the main thermocline. Standard deviations of salinity and temperature in Figs. 5(a) and 5(b) show the same characteristics as Fig. 3, except for relatively large standard deviations at 300–500

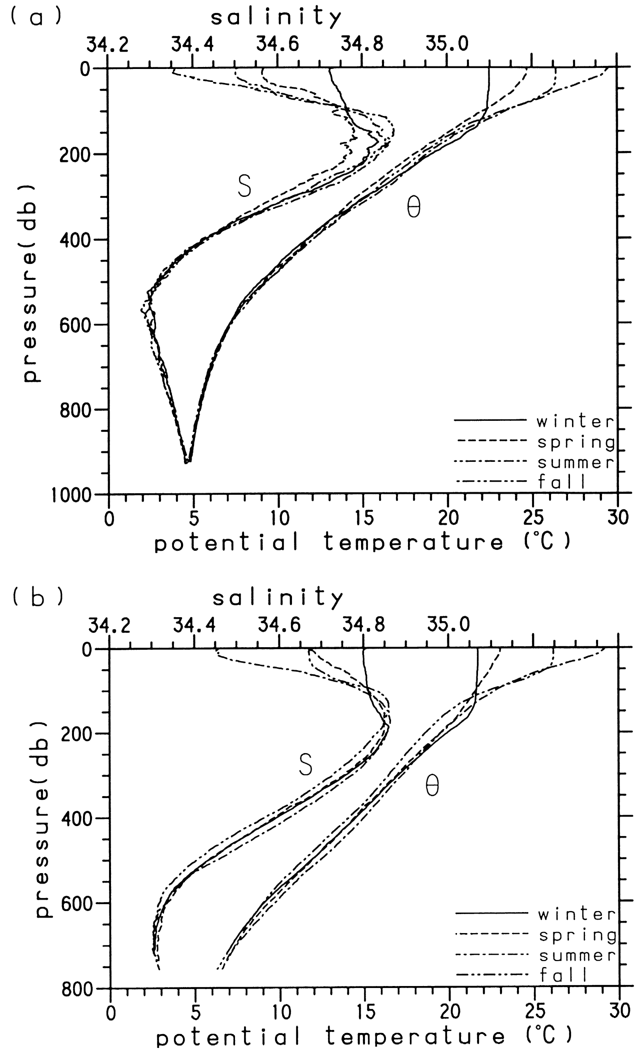

Fig. 3. Vertical profiles of salinity and potential temperature averaged seasonally during 1988–94 at Sts. 12 and 12.5 (a) and Sts. 13–17 (b).

db at Sts. 12 and 12.5, which are mainly due to the variations with a shorter term than annual, as clarified in Section 4 as the characteristics of Group 3.

Seasonal variations in the subsurface layer have a different tendency from those in the surface layer. Salinity and temperature are positively correlated to each other in the main thermocline (about 150–700 db) with a maximum coefficient of nearly 1.0 around the middle of the main thermocline (about 300–400 db) (Fig. 5(c)). The phase of the subsurface variations is different between the Kuroshio (Sts. 12 and 12.5) and its offshore region (Sts. 13–17) (Fig. 3). At depths of 100–300 db in the Kuroshio, salinity and temperature are at a minimum in spring, and are at a maximum in summer in the deep part and in fall for salinity and winter for temperature in the shallow part. On the other hand, salinity and temperature in the whole main thermocline offshore of the Kuroshio are at a minimum in fall and at a maximum mostly in summer. The minimum in fall at depths of 200–600 m on the offshore side of the Kuroshio was pointed out by Hinata (1996).

The subsurface variations are further examined in terms of the characteristics on isopycnals. At depths above the middle of the main thermocline at 25.7σ_θ, salinity at Sts. 11–12.5 occupies a larger range than that at Sts. 13–17, and the θ-S curves at Sts. 11–12.5 disperse more in all seasons (Fig. 4). Such large dispersion of θ-S curves in the Kuroshio is shown in Sawara and Hanzawa (1979) and Chen *et al.* (1994) for several sections in the East China Sea. As a result, standard deviations of salinity and temperature on isopycnals less than 25.7σ_θ at Sts. 11–12.5 are much larger than those at Sts. 13–17 (Fig. 6).

Except for less than 25.7σ_θ at Sts. 11–12.5, standard deviations of salinity and temperature have a maximum at 26.5–26.7σ_θ around the salinity minimum and a minimum at 25.7σ_θ around the middle of the thermocline in the Kuroshio and its offshore region (Sts. 12–17), and have a second maximum at 24.5σ_θ around the salinity maximum in the offshore region of the Kuroshio (Sts. 13–17). The maximum standard deviations are different between Sts. 12–14 (the Kuroshio and its just offshore region) and Sts. 15–17 (further offshore region), since the magnitude at Sts. 12–14 is larger, and the corresponding density is 26.7σ_θ at Sts. 12–14 and about 26.5σ_θ at Sts. 15–17.

Thus, the amplitude of variations of water properties on isopycnals changes vertically in association with the structure of salinity and temperature. The minimum amplitude occurs at the middle of the thermocline, and the variations are divided into four groups at Sts. 11–12.5 and Sts. 13–17 in the upper thermocline and at Sts. 12–14 and Sts. 15–17 in the lower thermocline.

Another important property is that the standard deviations of temperature on isopycnals are much smaller than those on isobars at all depths at all stations, and those of salinity around the middle of the thermocline (25.7σ_θ, 300–400 db) are also much smaller (Figs. 5 and 6). Salinity and temperature in the subsurface layer vary little on isopycnals. Furthermore, the θ-S plots show a linear relation between salinity and temperature in the main thermocline, decreasing as density increases (Fig. 4), and salinity and temperature on isobars are positively correlated to each other in the thermocline (Fig. 5(c)). These imply qualitatively that the variations of salinity and temperature on isobars are due to vertical movement of isopycnals on which the water properties are almost constant. Then, the variations of salinity and temperature at 400 db, St. 15 were calculated from the variations of density with the mean σ_θ-S and σ_θ-θ relations at St. 15 (Fig. 7). The results are almost the same as the observations. It is concluded that the isobaric variations of salinity and temperature in the subsurface layer are almost due to the vertical movement of isopycnals.

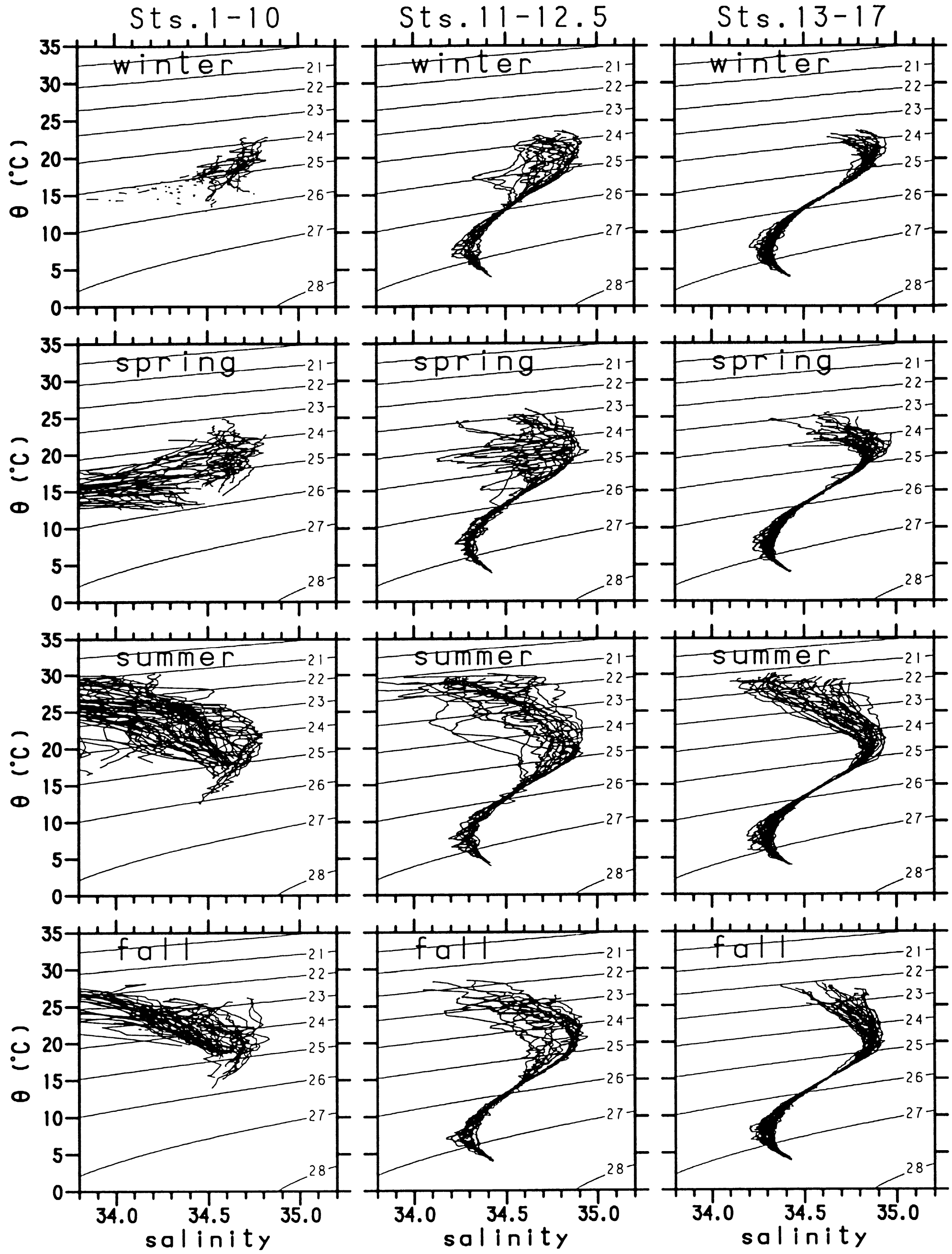

Fig. 4. Potential temperature–salinity diagrams in each season for all the observations during 1988–94 at Sts. 1–10 (left), Sts. 11–12.5 (middle), and Sts. 13–17 (right). Potential density is shown by thin lines in each diagram.

4. Annual and Shorter-Term Variations in Depth of Isopycnals

4.1 Variations of isopycnal depth

Figure 8(a) shows standard deviations of the annual and shorter-term variations in depth (pressure) of isopycnals. Isopycnals of 24.6σ_θ and more exist in all the observations, together with 24.2σ_θ and 24.4σ_θ at Sts. 12 and 12.5, while no isopycnal exists at Sts. 1–10 in the shelf region. The standard deviations have two maxima exceeding 25 db; one lies on isopycnals less than 24.8σ_θ at Sts. 14–17, and the other is between 25.8σ_θ and 26.6σ_θ at Sts. 12–13. They correspond to the salinity maximum offshore of the Kuroshio and the lower pycnocline in the Kuroshio, respectively. Vertical variations of isopycnals are large in these areas.

Correlations of the vertical movements of isopycnals

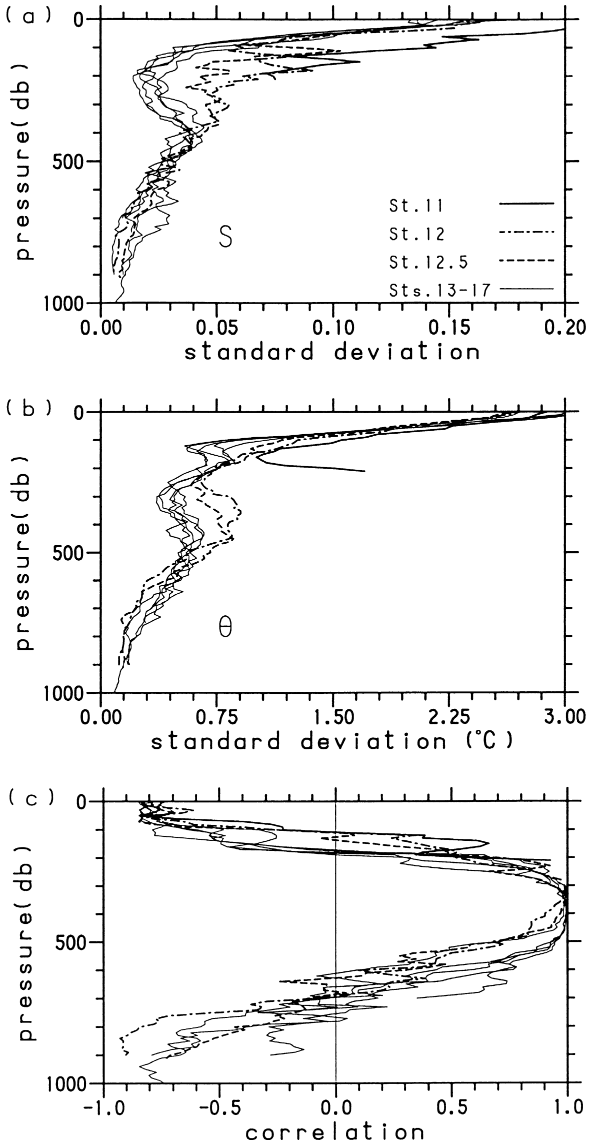

Fig. 5. Standard deviations of the annual and shorter-term variations of salinity (a) and potential temperature (b) on isobars at Sts. 11–17 during 1988–94, and correlation coefficients between them (c).

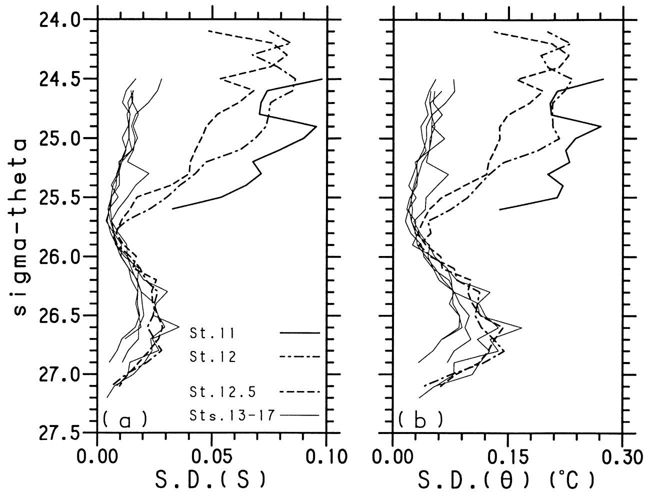

Fig. 6. Standard deviations (S.D.) of the annual and shorter-term variations of salinity (a) and potential temperature (b) on isopycnals at Sts. 11–17 during 1988–94.

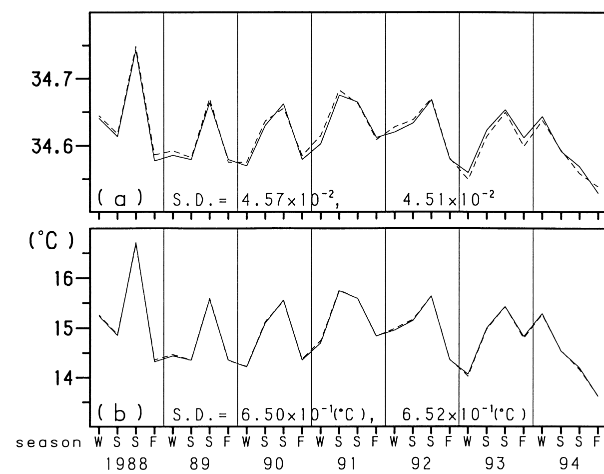

Fig. 7. (a) Variations of salinity during 1988–94 on an isobar of 400 db at St. 15 (dashed line) and those estimated from the density at 400 db with the mean density-salinity relation (solid line). The mean relation was obtained by fitting all the density-salinity plots during 1988–94 at depths between 375 db and 425 db at St. 15 to a linear equation with the least squares method. The standard deviations (S.D.) of both the curves are shown at the bottom of the panel. The right one is for the estimated variations. (b) Same as (a) but for potential temperature.

with that of four reference isopycnals—25.2σ_θ at Sts. 12 and 15 and 26.2σ_θ at Sts. 12 and 16—are shown in Fig. 9. The reference isopycnals are selected from the four regions in the upper and lower pycnoclines in the Kuroshio and its offshore region which show different variations of water properties on isopycnals (Section 3). The isopycnal of 26.2σ_θ at St. 12 shows the maximum standard deviation in Fig. 8(a) and changes its depth most actively at the PN line. When we take a correlation coefficient of 0.7 as a criterion of high correlation, the movement of this isopycnal is highly correlated with those of isopycnals in the lower pycnocline and the salinity minimum at Sts. 12–13 as well as in the upper pycnocline at St. 11; the high-correlation region extends to a confined area along the continental slope. High correlations with 26.2σ_θ at St. 16, 25.2σ_θ at St. 15, and 25.2σ_θ at St. 12 are located in the lower pycnocline at Sts. 15–17, in the upper pycnocline at Sts. 14–16, and in the upper pycnocline at Sts. 12 and 12.5, respectively. Each of the

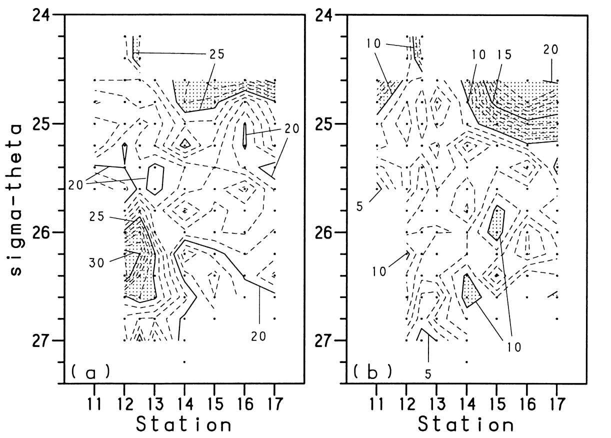

Fig. 8. Standard deviations (db) of isopycnal depth (pressure) at Sts. 11–17 during 1988–94 for the annual and shorter-term variations (a) and the interannual variations (b). Dots show the isopycnals observed throughout the period from summer 1987 to spring 1995. Values larger than 25 db in (a) and 10 db in (b) are shaded.

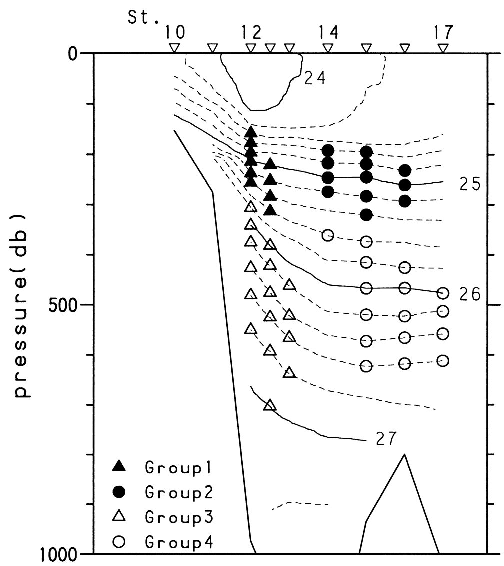

Fig. 10. Isopycnals of Groups 1–4 defined by the correlation higher than 0.7 in Fig. 9. This is shown on the distribution of mean potential density in winter.

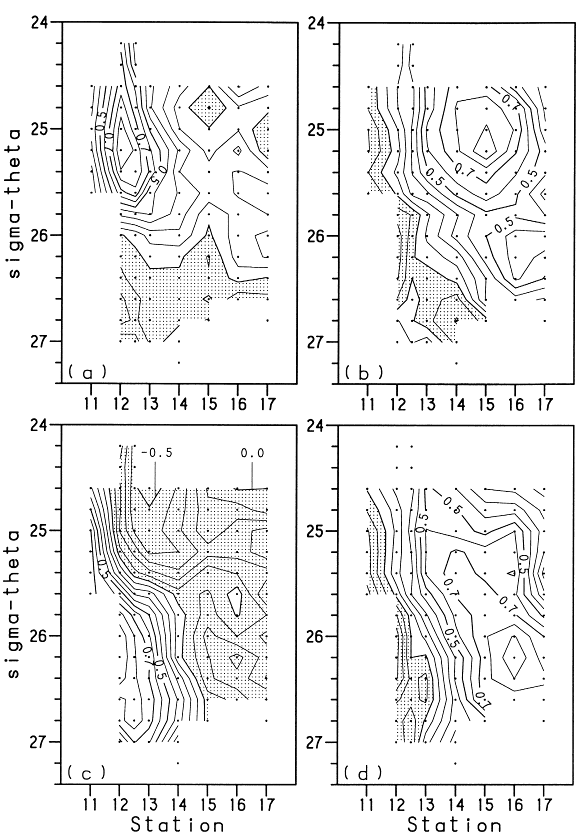

Fig. 9. Same as Fig. 8 but for correlation coefficients of the annual and shorter-term variations in depth of isopycnals with 25.2σ_θ at St. 12 (a), 25.2σ_θ at St. 15 (b), 26.2σ_θ at St. 12 (c), and 26.2σ_θ at St. 16 (d). Negative values are shaded.

high-correlation regions is confined zonally within less than three stations and vertically to the upper or lower pycnocline. The zonal extension is especially small for the correlation with 25.2σ_θ at St. 12. It should be noted that negative correlations are not significant with magnitude smaller than 0.4, except those around the salinity maximum at Sts. 12.5–14 reaching –0.58 at 24.6σ_θ in Fig. 9(c).

Thus the high correlations are located in the four small zonal bands in the pycnocline in the Kuroshio and its offshore region: 24.4–25.6σ_θ at Sts. 12–12.5 in Fig. 9(a), 24.6–25.4σ_θ at Sts. 14–16 in Fig. 9(b), 25.8–27.0σ_θ at Sts. 12–13 in Fig. 9(c), and 25.2–26.6σ_θ at Sts. 14–17 in Fig. 9(d). The high-correlation regions almost cover the PN section, and the isopycnal movement at the PN line—the variations of density structure around the Kuroshio—is characterized by the four groups: Groups 1–4 in Fig. 10. The isopycnals of 25.0–25.6σ_θ at St. 11 in Fig. 9(c) are highly correlated with 26.2σ_θ at St. 12, but are not included in Group 3 since they are located in the upper pycnocline and are further onshore. Those of 25.2σ_θ and 25.4σ_θ at St. 14 in Fig. 9(d) are not included in Group 4 because they overlap with Group 2. Groups 1 and 2 are located in the upper pycnocline, while Groups 3 and 4 are in the lower pycnocline. Groups 1 and 3 are in the Kuroshio, while Groups 2 and 4 are in its offshore region. Groups 3 and 2 correspond to the most and secondary active areas of the isopycnal movement, respectively.

Figure 11 shows the annual and shorter-term variations in depth of isopycnals of Groups 1–4. The isopycnal depth of Group 4 shows a clear seasonal variation; it increases monotonously from fall to the next summer every year,

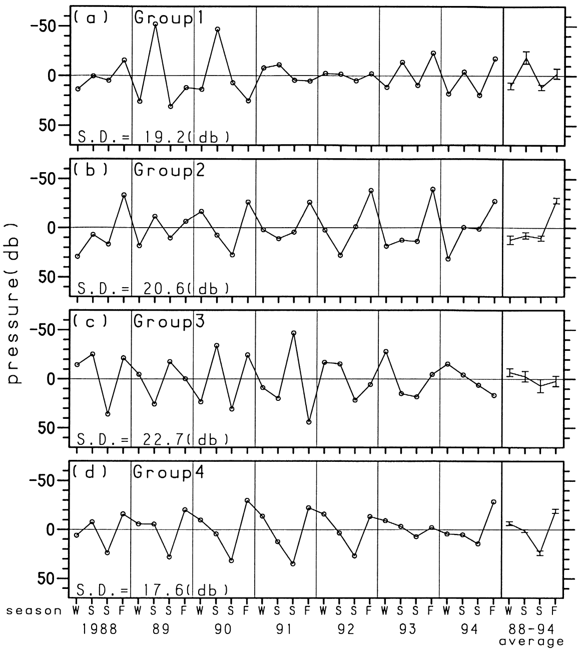

Fig. 11. Annual and shorter-term variations during 1988–94 of isopycnal depth (pressure) averaged for Groups 1–4 (a–d). The curves on the rightmost side are the seasonal averages with the 99% confidence intervals. The standard deviation (S.D.) of the group is shown at the left bottom of each panel.

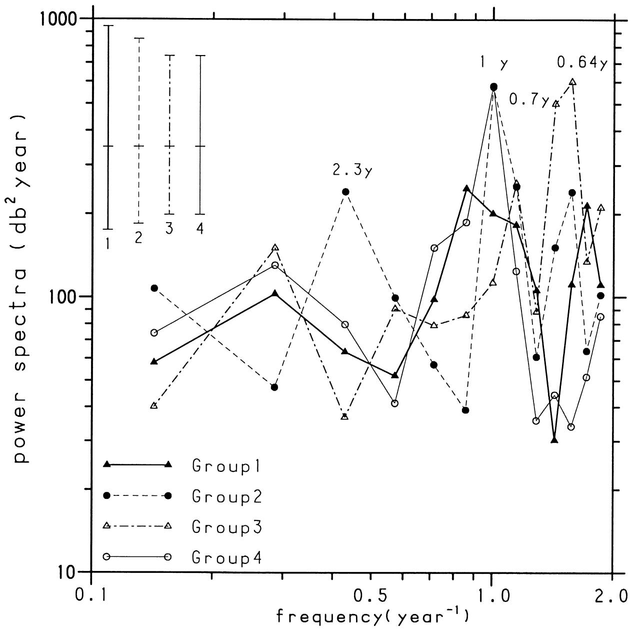

Fig. 12. Power spectra of variations in isopycnal depth (pressure) averaged for Groups 1–4 during 1988–94. Vertical bars on the upper-left corner show the 99% confidence intervals.

although the amplitude is different from year to year. The seasonal average of the depth is particularly large in summer and small in fall. The deep isopycnals in summer cause maximum salinity and temperature on isobars at depths of 300–600 db on the offshore side of the Kuroshio (Fig. 3(b)). The depth of Group 2 is smallest in fall almost every year, and the average in fall is much smaller than those in the other seasons. The depth in winter to summer is not significantly different on the seasonal average. The shallow isopycnals in fall are common to Groups 2 and 4. This causes minimum salinity and temperature in fall on isobars in the main thermocline offshore of the Kuroshio.

The annual variation of isopycnal depth is dominant only in Groups 2 and 4, namely in the offshore region of the Kuroshio (Fig. 12). Group 3 in the Kuroshio has a large peak of power spectrum at 0.64–0.7 year and no peak at one year. Therefore, the seasonal average of Group 3 does not show any significant difference between seasons. The variations in isopycnal depth of Group 1 is much smaller than those of the other groups except for two quite small values in spring of 1989 and 1990, which make the long-term average in spring smaller than those in the other seasons.

The variation in isopycnal depth of Group 3 is little correlated with those of Groups 2 and 4 with coefficients of –0.13 and 0.01, respectively. Correlations of Group 1 with the other groups are also low (less than 0.3). Thus, the annual and shorter-term variations of isopycnal depth in the Kuroshio are clearly different from those in the offshore region of the Kuroshio.

4.2 Relation to current velocity of the Kuroshio

A difference in isopycnal depth between Groups 1 and 2 (Groups 3 and 4) may be related to a gradient of isopycnals and, in turn, a vertical shear of current velocity of the Kuroshio in the upper (lower) pycnocline. As a matter of fact, the differences in isopycnal depth of Groups 2 minus 1 and Groups 4 minus 3 are highly correlated with the geostrophic velocities at 150 db referred to 300 db and at 300 db referred to 700 db between Sts. 12 and 15 with coefficients of 0.97 and 0.96, respectively (Fig. 13). Therefore, the variations of vertical shear of velocity in the upper and lower pycnoclines are exactly shown by the isopycnal gradients between the groups.

The geostrophic velocity at 150 db referred to 300 db is largest in spring and smallest in fall almost every year (Fig. 13(a)). The small velocity in fall is associated with the small isopycnal depth of Group 2. The geostrophic velocity at 300 db referred to 700 db includes significant variations with periods less than one year and the seasonal cycle—large in summer and small in fall—which are related to the isopycnal depth of Groups 3 and 4, respectively (Fig. 13(b)).

The geostrophic current at 150 db between Sts. 12 and 15 occupies the offshore side of the Kuroshio from the current axis at 150 db and almost shows the variation of the Kuroshio velocity (Fig. 2). The geostrophic velocity at 150

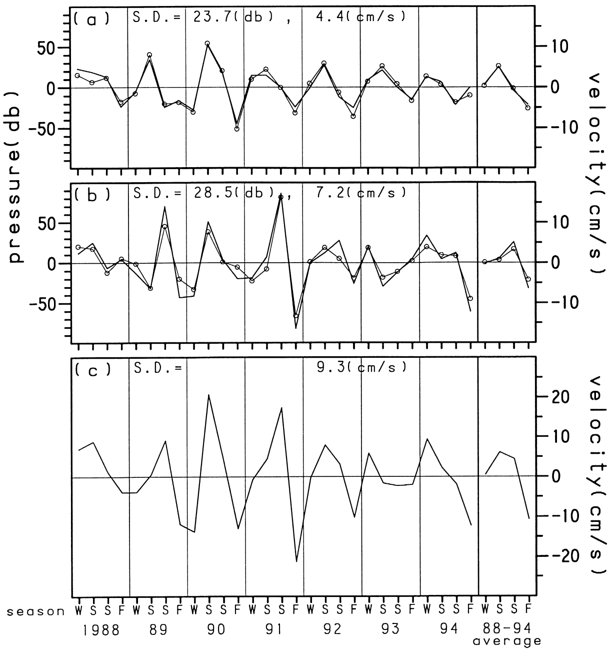

Fig. 13. (a) Annual and shorter-term variations during 1988–94 of the difference in isopycnal depth (pressure) of Groups 2 minus 1 (thin line with circles) and geostrophic velocity at a depth of 150 db referred to 300 db between Sts. 12 and 15 (thick line). The standard deviations (S.D.) of both the curves are shown at the top of the panel. The curves on the rightmost side are the seasonal averages. (b) Same as (a) but for the difference in isopycnal depth of Groups 4 minus 3 and geostrophic velocity at 300 db referred to 700 db. (c) Annual and shorter-term variations of geostrophic velocity at 150 db referred to 700 db.

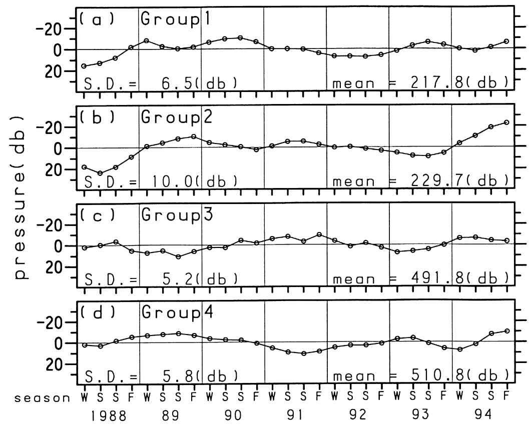

Fig. 14. Interannual variations of the anomaly from the long-term average during 1988–94 in isopycnal depth (pressure) averaged for Groups 1–4 ((a)–(d)). The average and standard deviation are shown at the bottom of each panel.

db referred to 700 db in Fig. 13(c)—the sum of the velocities in Figs. 13(a) and 13(b)—is largest in various seasons except fall: winter in 1993 and 1994, spring in 1988, 1990 and 1992, and summer in 1989 and 1991; the seasonal variation is different from year to year. However, the velocity is smallest in fall every year except in winter 1990, and the seasonal average in fall is much smaller than those in the other seasons. This confirms the conclusion of Taft (1972) and Kawabe (1988). The seasonal average of this velocity during 1988–94 is largest in spring, but the averages in spring and summer are not significantly different. This is due to the difference in the seasonal variation of velocity between the upper and lower pycnoclines; the seasonal average is largest in spring in the upper pycnocline and summer in the lower pycnocline.

5. Interannual Variations in Depth of Isopycnals and Velocity of the Kuroshio

Interannual variations of isopycnal depth are smaller than the annual and shorter-term variations, less than half in most of the section (Fig. 8). Standard deviations of the interannual variations are greater than 15 db on isopycnals less than $25.0\sigma_\theta$ at Sts. 15–17, corresponding to the salinity maximum in the offshore region of the Kuroshio. The standard deviations offshore of the Kuroshio on almost all isopycnals are larger than those in the Kuroshio. This is consistent with the result of Kawabe (1988) that interannual variations of sea level on the offshore side of the Kuroshio are much larger than those on the onshore side.

Interannual variations of salinity, temperature and depth on subsurface isopycnals have similar properties to those of the annual and shorter-term variations shown in Figs. 6 and 9. The interannual variations, therefore, are averaged for the four groups defined in Section 4 (Fig. 14). Group 2 corresponds mostly to the maximum area of vertical movement of isopycnals in Fig. 8(b); the variation in isopycnal depth of Group 2 is much larger than those of the other groups, having a large peak of power spectrum at a period of 2.3 years (Fig. 12). The variations of the groups are not correlated with larger coefficients than 0.5, except for a negative correlation between Groups 3 and 4 with a coefficient of –0.63.

The difference in isopycnal depth between Groups 1 and 2 (Group 2–Group 1) is highly correlated with the geostrophic velocity at 150 db referred to 300 db between Sts. 12 and 15, called $V_{150/300db}$ hereafter, with a coefficient of 0.82 (Fig. 15(a)). The variation with a period of 2.3 years is dominant in the $V_{150/300db}$ due to the isopycnal depth of Group 2.

The difference in isopycnal depth of Groups 4 minus 3 is highly correlated with the geostrophic velocity at 300 db referred to 700 db, $V_{300/700db}$, with a coefficient of 0.92 (Fig. 15(b)). The amplitude of the difference of Groups 4 minus 3 is significant because of the opposite phase of isopycnal movement between the groups, and is comparable to that of

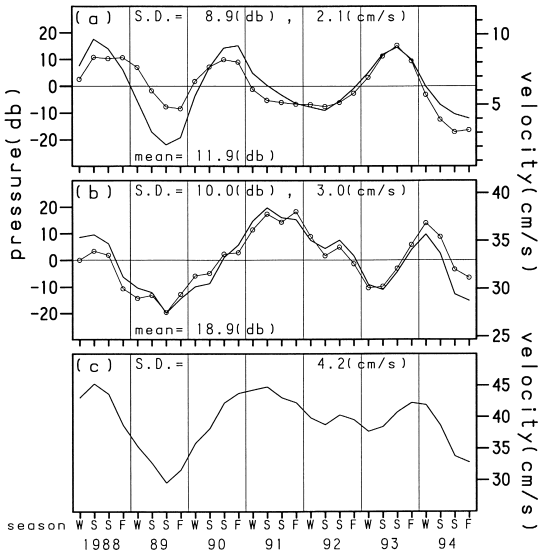

Fig. 15. (a) Interannual variations during 1988–94 of the difference in isopycnal depth (pressure) of Groups 2 minus 1 (thin line with circles) and geostrophic velocity at a depth of 150 db referred to 300 db between Sts. 12 and 15 (thick line). Anomalies from the long-term average are shown for the difference in isopycnal depth, and the average is shown at the bottom of the panel. The standard deviations of both the curves are shown at the top of the panel. (b) Same as (a) but for the difference in isopycnal depth of Groups 4 minus 3 and geostrophic velocity at 300 db referred to 700 db. (c) Interannual variations of geostrophic velocity at 150 db referred to 700 db.

Groups 2 minus 1, although the isopycnal movement of Groups 3 and 4 is much smaller than that of Group 2.

The variations of $V_{150/300db}$ and $V_{300/700db}$ during 1988–90 are similar and characterized by a maximum in 1988 and a minimum in 1989. As a result, the variation of geostrophic velocity at 150 db referred to 700 db, $V_{150/700db}$, is similar to them (Fig. 15(c)). On the other hand, the variations of $V_{150/300db}$ and $V_{300/700db}$ from 1990 to 1994 are different, as the $V_{150/300db}$ is at a maximum in 1990 and 1993 and at a minimum in 1992, while the $V_{300/700db}$ is at a maximum in 1991 and 1994 and at a minimum in 1993. The phase during 1991–93 is rather opposite, and accordingly the variation of $V_{150/700db}$ during 1991–93 is small.

As a result, the $V_{150/700db}$ has a maximum in spring 1988, small maxima in spring 1991 and in fall 1993 to winter 1994, clear minima in summer 1989 and fall 1994, and a small minimum in spring 1992 to spring 1993. The variations of the $V_{150/700db}$ during 1988–92 are similar to those of the surface velocity of the Kuroshio south of Kyushu and, in particular, the volume transport of the Kuroshio estimated from sea-level data by Kawabe (1995), which have maxima in 1988 and 1990–91 and minima in 1989 and 1992. The geostrophic velocity at 150 db is highly correlated with the volume transport of the Kuroshio in interannual time scales.

6. Summary and Conclusions

The hydrographic data of CTD at the PN line in the East China Sea during 1988–94 were analyzed to examine the variations of water properties and density structure in relation to the Kuroshio. The data were taken quarterly in January (winter), April (spring), July (summer) and October (fall) by the Nagasaki Marine Observatory, the Japan Meteorological Agency. The CTD stations are located in the continental-shelf region (Sts. 1–10), the continental-slope region (Sts. 11 and 12), and the offshore region with water depth of about 1000 m (Sts. 12.5–17).

The Kuroshio flows along the continental slope between Sts. 10 and 14 with the current axis between Sts. 11 and 12. The warm core exists just offshore of the surface axis of the Kuroshio with the maximum sea surface temperature at St. 12.

The temporal variations of water properties are very different between the surface and subsurface layers which are defined as less and greater than 100 db. Water properties in the surface layer change greatly and show a clear seasonal cycle. The present analysis reconfirmed that salinity in the surface layer is at a maximum in winter and at a minimum in summer with an almost opposite phase to water temperature, due to the seasonal cycle of an extension of low-salinity shallow water (less than 34.0) from the continental side.

Water properties in the subsurface layer are much less variable than those in the surface layer. The subsurface variations of salinity and temperature on isobars are almost due to the vertical movement of isopycnals, on which the water properties are much less variable than those on isobars.

Variations of salinity and temperature on isopycnals are especially small around the middle of the main pycnocline at $25.7\sigma_\theta$, and are relatively large in the upper and lower pycnoclines. The variations in the upper pycnocline are largest around the salinity maximum at $24.5\sigma_\theta$ and different in amplitude between the Kuroshio (Sts. 11–12.5) and its offshore region (Sts. 13–17). The variations in the lower pycnocline are largest around the salinity minimum at $26.7\sigma_\theta$ with different amplitude and corresponding density between Sts. 12–14 and Sts. 15–17. Similar spatial difference is seen in the variations in depth of isopycnals. Thus, the variations in the subsurface layer are classified into four groups occurring in the four regions, divided vertically by the middle of the pycnocline and horizontally by the offshore edge of the Kuroshio: Group 1 (upper Kuroshio), 2 (upper offshore region), 3 (lower Kuroshio), and 4 (lower offshore region) (Fig. 10).

The depth of isopycnals in the offshore region of the Kuroshio (Groups 2 and 4) shows a significant seasonal variation with a dominant annual cycle and the clear minimum in fall. The isopycnal depth of Group 2 is not significantly different among the seasons except fall, while that of Group 4 increases monotonously from fall to the next summer every year. As a result, salinity and temperature on isobars are at a minimum in fall in Groups 2 and 4 and at a maximum in summer in Group 4. The isopycnal depth of Group 1 is much less variable than those of the other groups, while that of Group 3 has the largest variation among the groups and is characterized by dominant intraseasonal variations with periods of 0.64–0.7 year.

The difference in averaged isopycnal depth of Groups 2 minus 1 (Groups 4 minus 3) is highly correlated with the vertical shear of the Kuroshio velocity in the upper (lower) pycnocline. The vertical shear of velocity in the upper pycnocline is largest in spring and smallest in fall almost every year. The small velocity shear in fall is associated with the small isopycnal depth of Group 2. The velocity shear in the lower pycnocline shows a seasonal cycle, large in summer and small in fall, and shorter-term variations with periods of 0.64–0.7 year in relation to the isopycnal depth of Groups 4 and 3, respectively. As a result, the velocity of a main part of the Kuroshio is smallest in fall almost every year, although an amplitude of the seasonal variation and the season of maximum velocity are different from year to year, which confirms the conclusion of Taft (1972) and Kawabe (1988).

Interannual variations in depth of isopycnals are much smaller than (a half to a fourth of) the annual and shorter-term variations, but are significant and characterized by (1) the variations of Group 2 are largest among the groups with a dominant period of 2.3 years, and (2) the variations of Groups 3 and 4 are highly correlated to each other in an opposite phase. Owing to the characteristics (2), the variations of difference in isopycnal depth between Groups 3 and 4 are comparable to those between Groups 1 and 2, although the variations in isopycnal depth of Groups 3 and 4 are small (nearly half of Group 2).

The vertical shear of velocity in the upper pycnocline has a dominant period of 2.3 years in relation to the isopycnal depth of Group 2. The interannual variations of velocity shear in the lower pycnocline are similar to those in the upper pycnocline during 1988–90 but different later with a rather opposite phase during 1991–93. The velocity of a main part of the Kuroshio is highly correlated with the the volume transport of the Kuroshio shown by Kawabe (1995) on interannual time scales.

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References

Beardsley, R. C., R. Limeburner, H. Yu and G. A. Cannon (1985): Discharge of the Changjiang (Yangtze River) into the East China Sea. *Contin. Shelf Res.*, **4**, 57–76.

Chen, C., R. C. Beardsley, R. Limeburner and K. Kim (1994): Comparison of winter and summer hydrographic observations in the Yellow and East China Seas and adjacent Kuroshio during 1986. *Contin. Shelf Res.*, **14**, 909–929.

Fujiwara, I., Y. Hanzawa, I. Eguchi and K. Hirano (1987): Seasonal oceanic conditions on a fixed line in the East China Sea. *Oceanogr. Mag.*, **37**, 37–46.

Hinata, T. (1996): Seasonal variation and long-term trends of the oceanographic conditions along a fixed hydrographic line crossing the Kuroshio in the East China Sea. *Oceanogr. Mag.*, **45**, 9–32.

Kawabe, M. (1985): Sea level variations at the Izu Islands and typical stable paths of the Kuroshio. *J. Oceanogr. Soc. Japan*, **41**, 307–326.

Kawabe, M. (1987): Spectral properties of sea level and time scales of Kuroshio path variations. *J. Oceanogr. Soc. Japan*, **43**, 111–123.

Kawabe, M. (1988): Variability of Kuroshio velocity assessed from the sea-level difference between Naze and Nishinoomote. *J. Oceanogr. Soc. Japan*, **44**, 293–304.

Kawabe, M. (1995): Variations of current path, velocity, and volume transport of the Kuroshio in relation with the large meander. *J. Phys. Oceanogr.*, **25**, 3103–3117.

Kondo, M. (1985): Oceanographic investigations of fishing grounds in the East China Sea and the Yellow Sea—I. Characteristics of the mean temperature and salinity distributions measured at 50 m and near the bottom. *Bull. Seikai Reg. Fish. Res. Lab.*, **62**, 19–66 (in Japanese with English abstract).

Masuzawa, J. (1960): Statistical characteristics of the Kuroshio current. *Oceanogr. Mag.*, **12**, 7–15.

Masuzawa, J. (1972): Water characteristics of the North Pacific Central Region. p. 95–127. In *Kuroshio—Its Physical Aspects*, ed. by H. Stommel and K. Yoshida, Univ. Tokyo Press, Tokyo.

Nitani, H. (1972): Beginning of the Kuroshio. p. 129–163. In *Kuroshio—Its Physical Aspects*, ed. by H. Stommel and K. Yoshida, Univ. Tokyo Press, Tokyo.

Sawara, T. and Y. Hanzawa (1979): Distribution of water type in the East China Sea. *Umi to Sora*, **54**, 135–148 (in Japanese with English abstract).

Taft, B. (1972): Characteristics of the flow of the Kuroshio south of Japan. p. 165–216. In *Kuroshio—Its Physical Aspects*, ed. by H. Stommel and K. Yoshida, Univ. Tokyo Press, Tokyo.

Yamashiro, T., A. Maeda, M. Sakurai and H. Ichikawa (1990): Mean velocity distribution and transport of the Kuroshio referred to GEK surface velocity in the East China Sea. *Umi to Sora*, **66**, 181–190 (in Japanese with English abstract).

Yamashiro, T., A. Maeda and M. Sakurai (1993): Mean position and deviation of the Kuroshio axis in the East China Sea. *Umi to Sora*, **69**, 125–134 (in Japanese with English abstract).