Interannual Variations of Water Temperature and Salinity along the 137°E Meridian

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Analyses were performed on hydrographic data gathered along the 137°E meridian by the R/V Ryofu Maru of the Japan Meteorological Agency (JMA). Distributions were obtained of the mean and standard deviation of water temperature and salinity along the section. Relationships between interannual variations of these variables and wind forcing were examined. A correlation analysis revealed that temperature change, which occurred in the equatorial region of the western North Pacific accompanied by El Nino and La Nina events, reached about 20°N with the inclination of isotherms across the north equatorial current fluctuating around 20°N. Empirical orthogonal function (EOF) analysis of the winter water temperatures in the section was performed to extract variations following El Nino and La Nina events as the first mode and those corresponding to decadal changes of sea surface temperature (SST) in the North Pacific as the second mode. Interannual variations in the area of the North Pacific tropical saline water (NPTSW) and the North Pacific intermediate water (NPIW) along the section correspond well to interannual variations of the wind-stress curl minimum (negative value) in the area southeast of Japan. A remaining problem is to quantitatively evaluate the lag times of the variations to the wind-stress curl variation. In the equatorial region of the section, the northward extension of saline water is weak, and negative water temperature anomalies have often occurred in connection with El Nino events since the latter half of the 1970s. These changes may be part of the decadal variation of the North Pacific.

1. Introduction

Since 1967, the Japan Meteorological Agency (JMA) has been carrying out winter oceanographic surveys along the 137°E meridian, from the southern coast of Japan to the area off the New Guinea coast using the R/V Ryofu Maru. Beginning in 1972, both winter and summer surveys have been conducted. This project was initiated in 1967 as part of the Cooperative Study of the Kuroshio (CSK), sponsored by the Intergovernmental Oceanographic Commission, Unesco.

The surveys have been routinely conducted in the second half of January and in July for the purpose of:

1) detecting the long-term variation of oceanic conditions in the western North Pacific connected with climate change, and

2) monitoring background marine pollution.

The observation line was set along the Shikoku, the West Mariana, and the West Caroline Basins in order to obtain data undisturbed by islands and submerged mountains. The typical distance between neighboring hydrographic stations is 60 nautical miles, except for 40 nautical
miles in the Kuroshio region from 34°N to 30°N, and 30 nautical miles in the equatorial region from 8°N to 1°S. Deep hydrographic observations to depths of 4000 m or 5000 m were conducted for every 5 degrees, from 30°N to the equator.

Conductivity-temperature-depth (CTD) observations were initiated in the summer of 1988, replacing reversing thermometers and Nansen bottles. The observational elements gathered consist of currents, water temperature, salinity, dissolved oxygen, nutrients, pollutants, phytopigments, zoo- and phyto-planktons. Greenhouse effect gases as related to the problem of global warming have been included in the list of observational elements since 1989.

Observations south of 3°N have not been taken since 1987, and those in the Kuroshio region were not conducted at all in 1970, and only partly made in 1968.

Masuzawa (1967) described the distributions of temperature, salinity and oxygen, the results of current measurements and geostrophic transport, and also analyzed water masses associated with the 1967 survey of the section. Masuzawa (1968) compared the temperature, salinity, and geopotential anomaly observed in 1968 with those of the prior year, and showed the surface geopotential topography referred to 1000 db surface, indicating the north equatorial current (NEC), the north equatorial countercurrent (NECC), and the Mindanao eddy. Masuzawa and Nagasaka (1975) analyzed hydrographic data observed along the section from 1967 to 1972, and reported a large variability of temperature, salinity, and steric height in the surface layer, suggesting a relationship of these varying quantities to El Nino events and atmospheric changes over the North Pacific.

Qiu and Joyce (1992) analyzed hydrographic data of the 137°E section observed from 1967 to 1988. They displayed the mean distribution of temperature, salinity, and potential density to a depth of 5000 m, and the geostrophic velocity referred to 1000 db. They also described the relationship between variations in the area occupied by the North Pacific intermediate water (NPIW) of the section and the meandering of the Kuroshio, differences in surface dynamic heights between El Nino Southern Oscillation (ENSO) years and non-ENSO years, and the relationship among interannual variations of geostrophic transport of the NEC, NECC, and the Sverdrup transport.

In the present paper, an analysis is performed on the hydrographic data gathered along the 137°E meridian by the R/V Ryofu Maru of the JMA during the period from 1967 to 1987. The interannual variations of water temperature and salinity along the section are analyzed. Furthermore, the relationship among these variations and the wind forcing are discussed. The characteristic of this paper is that variability of salinity and water temperature is discussed in connection with wind forcing, while Qiu and Joyce (1992) treated the relationship between wind forcing and geostrophic transport that is an integrated state, not the distribution of properties.

2. Data Set

The 137°E oceanographic data obtained by the R/V Ryofu Maru are processed in the following manner:

1. Values of temperature and salinity at each observation point are interpolated to every 10 m of depth by the application of a cubic spline.
2. These vertically interpolated data are then linearly interpolated in the horizontal at each level between neighboring stations to obtain values for every 30 nautical miles.
3. The gridded values of temperature and salinity are used to create distributions for all observations.

If any abnormal values are found, such as those exhibiting very large extremes, the original
data are checked, appropriate corrections are made, and the data processing is repeated.

The seasonal mean oceanographic dataset compiled by Levitus (1982) is used to examine how the vertical distributions of temperature and salinity in the meridional section extend horizontally and how they are related to the distributions in the zonal-vertical sections.

Wind stress curl data over the North Pacific presented by Kutsuwada and Teramoto (1987) are used to examine the effects of wind stress on the variations of the NPTSW and NPIW. The monthly wind stress was calculated from the weather reports compiled by JMA and given on 2° × 2° quadrangles in the North Pacific. Anomalous data were removed from the original data set through three-standard deviation test. In the calculation, they use the air density which is a function of month and latitude, and the drag coefficient which varies depending on wind velocity and air-sea temperature difference.

The author used the wind stress data set of tropical Pacific Ocean prepared by Stricherz et al. (1992) to investigate relationships between variations of tropical temperature and salinity in the 137°E section and the tropical wind. The wind stress data are given on a 2° × 2° grid for the region from 30°N to 30°S, 120°E to 70°W based on the Comprehensive Ocean-Atmosphere Data Set (COADS) CMR5 data. A drag coefficient of 1.4 × 10⁻³ and an air density of 1.2 kg m⁻³ are used. A three-standard-deviation test is used to eliminate extremes.

3. Oceanographic Features and Wind Field

3.1 Oceanographic features

The 137°E meridian is located in the westernmost part of the subtropical gyre and intersects the current system of the gyre. Figure 1 displays the mean geostrophic velocity referred to 1000 db, averaged over the 21 winter observations from 1967 to 1987. In the figure, shading indicates westward currents. The section crosses, in sequence from the north, the Kuroshio (eastward), the Kuroshio countercurrent (westward), the subtropical countercurrent (eastward, from 27°N to

Fig. 1. Latitude-depth section at 137°E of the mean geostrophic velocity (cm s⁻¹) referred to 1000 db, averaged over the 21 years of winter observations from 1967 to 1987. The regions of westward current (negative values) are shaded.
26°N), the broad north equatorial current (westward) centered in the region from 12°N to 9°N and the north equatorial countercurrent (eastward, from 8°N to 3°N).

A characteristic of the temperature field in the western Pacific is that it has a pool of warm water with temperature higher than 28°C in the surface layer of the equatorial region and relatively warm water in the intermediate layer south of Japan (the western edge of the subtropical warm gyre). (Figures are not shown here.)

Figure 2 shows the mean winter sea surface salinity, based on the dataset of Levitus (1982). The saline region with values greater than 35.0 psu is termed the North Pacific tropical saline water (NPTSW), found between 20°N to 30°N, and 140°E to 135°W in the North Pacific. The NPTSW counterpart in the South Pacific is the South Pacific tropical saline water (SPTSW), being more saline than the NPTSW with salinities of greater than 36.0 psu. The region of the SPTSW extends from 15°S to 30°S, and 155°W to 100°W. A saline region with values greater than 35.0 psu outside of the SPTSW, crosses the equator to the north and reaches Australia to the west. The region extends westward to 160°E along the equator on the sea surface and reaches the coast of New Guinea Island in the subsurface layer. (The figure is not shown here.)

Figure 3 shows the zonal-depth section of the mean winter salinity along the 20°N parallel. The highest value of saline water is found in the region between 170°E and 180°, from the sea surface to a depth of 100 m. The NPTSW is mainly formed in this region and spreads eastward and westward in the subsurface layer, lying at depths shallower than the depth of the isopycnal surfaces of $\sigma_\theta = 25.0$. On the other hand, less saline waters with values less than 34.2 psu extend from near 140°E at a depth of 600 m to 140°W at 200–600 m, displaying a salinity minimum along the isopycnal surface of $\sigma_\theta = 26.7$ west of 160°W. This water mass is termed the North Pacific...
Fig. 3. Longitude-depth section along 20°N of the zonal mean winter salinity (psu). The contour interval is 0.1 psu and the regions more saline than 35.0 psu and less saline than 34.2 psu are shaded. Based on the oceanographic dataset by Levitus (1982).

Fig. 4. Latitude-longitude distribution of the mean winter salinity minimum (psu) over the North Pacific. The contour interval is 0.02 psu. Based on the oceanographic dataset by Levitus (1982).
intermediate water (NPIW).

Figure 4 displays the horizontal distribution of the mean winter minimum salinity values which give the salinity in core water of the NPIW. The minimum values appear at depths of about 750 m in the western portion and 400 m in the eastern portion along the isopycnal surface of \( \sigma_t = 26.7 \) or 26.8. The NPIW has its origin in the subarctic region of the North Pacific, and is assumed to spread into the subtropical region through isopycnal mixing and advection processes (Reid, 1965). In Fig. 4, the tongue-shaped distribution of low salinity water extending southwestward in the northeastern Pacific indicates the intrusion of subarctic water into the subtropical region. The tongue-shaped distribution east of Japan reflects the state of the relatively saline
NPIW gradually becoming less saline through isopycnal mixing with subarctic water as it advects eastward. The westward extension of isohalines south of Japan indicates the existence of the less saline NPIW southeast of Japan.

3.2 Characteristics of wind field

Figure 5 shows the mean vertical component of the wind stress curl for January, averaged over the 23 years from 1961 to 1983, based on the dataset by Kutsuwada and Teramoto (1987). The subtropical gyre is driven by the negative wind stress curl in the shaded region, from 10°N to 33°N. The wind stress curl has a minimum negative value southeast of Japan, which is formed by the northwesterly winter wind, being conspicuous in January and February. Presently, the minimum negative value of wind stress curl (–|curl_zτ|max in the Fig. 16) is adopted as an index representing the wind field south of Japan.

The NPTSW is considered to be formed under the climatological condition that evaporation exceeds precipitation. Therefore, it is necessary to examine the water budget of the sea surface, in particular, evaporation minus precipitation, to investigate the interannual changes of the NPTSW. Unfortunately, the present analysis does not have access to a dataset of precipitation and evaporation over the ocean. It cannot be done here for the reason to analyze the effect of net evaporation on the variation of the NPTSW.

Figure 6 shows the shaded area of wind stress curl minimum (see Fig. 5), the region of the NPTSW on the sea surface enclosed by the 35.0 psu isohaline (see Fig. 2), the region of the NPIW at an intermediate depth indicated by the isohalines of 34.1 and 34.2 psu (dashed lines, see Fig. 4), and the 137°E meridian exhibiting the ranges of the NPTSW and NPIW appearances in the section. The central area of the NPTSW is shown by the 35.4 psu isohaline. The area of wind stress curl minimum is located to the northwest of the NPTSW.

4. Mean and Standard Deviation of Water Temperature and Salinity

Although the mean and standard deviation of temperature and salinity were separately calculated for winter and summer observations, only the results of the winter observations are shown here, since the results for summer are similar.

4.1 Mean and standard deviation of temperature

Figure 7 shows the mean temperature averaged over the 21 years of winter observations from 1967 to 1987. The isotherms sharply deepen between 33°N and 32°N, crossing the Kuroshio. The isotherms are deepest near 31°N and gradually become shallower southward, being shallowest between 8°N and 7°N. The seasonal thermocline at depths of 100 m to 200 m is separated from the main thermocline near 500 m north of 15°N. Both thermoclines join between 13°N and 5°N, where the thermocline is very sharp.

Figure 8 displays the standard deviation (SD) of winter temperatures. The Kuroshio exhibits a bimodal path, that is, a straight path and a large meandering path south of Japan, resulting in a large SD between 33°N and 30°N at depths of 200 m to 750 m. Here, the SD is greater than 2°C and reaches a maximum of 3.96°C. Another large SD of more than 2°C is found between 14°N and 3°N at depths of 50 m to 200 m, with an especially large maximum SD of 3.52°C south of 7.5°N in the region of the north equatorial countercurrent. This large SD is brought by El Nino and La Nina events. Relatively large SDs of more than 1°C extend along the seasonal and main thermoclines.
Fig. 7. Latitude-depth section at 137°E of the mean water temperature (°C) averaged over the 21 years of winter observations from 1967 to 1987. The contour interval is 1.0°C.

Fig. 8. Latitude-depth section at 137°E of the standard deviation of water temperature (°C) over the 21 years of winter observations from 1967 to 1987. The contour interval is 0.2 for values up to 1.0°C and 1.0 for values greater than 1.0°C. The regions greater than 2°C are shaded.
Fig. 9. Latitude-depth section at 137°E of the mean salinity (psu) averaged over the 21 years of winter observations from 1967 to 1987. The contour interval is 0.1 psu and the regions more saline than 35.0 psu and less saline than 34.2 psu are shaded.

Fig. 10. Latitude-depth section at 137°E of the standard deviation of salinity (psu) over the 21 years of winter observations from 1967 to 1987. Contours are shown at every 0.2 psu for values less than 1.0 psu, and at 1.8 and 2.0 for values greater than 1.0 psu.
4.2 Mean and standard deviation of salinity

Figure 9 presents the distribution of the mean winter salinity. The NPTSW appears in the subsurface layer between $18.5^\circ$N and $13^\circ$N at depths of 100 m to 200 m. The saline water in the equatorial region (SWER) is found south of $4.5^\circ$N at depths between 80 m to 300 m, with salinity values of greater than 35.0 psu. The NPIW forms a layer of minimum salinity of less than 34.2 psu, extending from $28.5^\circ$N and depths of 850 m to $20^\circ$N and 550 m. The water of less than 34.5 psu found between $14^\circ$N and $5^\circ$N in the layer shallower than 80 m is part of the low salinity zone between $10^\circ$N and $20^\circ$N shown in Fig. 2, resulting from excess precipitation. The salinity is almost uniform, exhibiting values of 34.5 to 34.6 psu south of $3.5^\circ$N at depths of more than 500 m, and between $3.5^\circ$N and $10^\circ$N at depths of more than 200 m.

Figure 10 displays the winter distribution of the standard deviation of salinity. Large values of SD over 1.0 psu are found between $33^\circ$N and $30^\circ$N at depths of 150 m to 600 m, induced by changes in the path of the Kuroshio. The layer at depths shallower than 100 m and the northern part of the SWER have large SDs of over 2.0 psu. These large SDs are produced by the interannual changes in precipitation and the northward extension of the SWER, respectively.

5. Statistical Analysis of Temperature

It was shown in Section 4 that the field of water temperature exhibits great variability, in conjunction with the path fluctuations of the Kuroshio and the occurrence of El Nino and La Nina events.

In this section, correlation analysis and empirical orthogonal function (EOF) analysis are conducted for winter water temperatures along the $137^\circ$E section.

Fig. 11. Latitude-depth section at $137^\circ$E of the simultaneous correlation of winter water temperatures from 1967 to 1987. The correlations are taken about the point +A in the figure. The contour interval is 0.2°C and negative correlations are shaded.
5.1 Correlation analysis

Figure 11 shows the cross section of simultaneous correlations of the winter temperatures calculated about the point at 6.5°N, 130 m depth (the symbol +A in the figure) where the standard deviation is greatest, except for the Kuroshio region, as seen in Fig. 8. According to the t-distribution test, the coefficient of simple correlation \( r_{\alpha} \) at the significance level \( \alpha \) of 0.05 is 0.4329 for sample number \( n \) of 21 (21 years from 1967 to 1987). It can be said that with the critical rate of 5% that temperature at the place where the absolute value of correlation is higher than 0.4329 fluctuates correlatively with the one at the point A in Fig. 11.

The correlation is positive over almost the entire region south of 19.5°N to at least as deep as 1400 m. This means the temperature in the region changes in phase with the temperature fluctuation around the point +A, caused by the vertical displacement of the thermocline, accompanied by El Nino and La Nina events. Though it is not statistically significant, the lower layer (depths of 300 to 650 m and 800 to 1200 m) in the NECC has negative correlations, meaning that isotherms in this layer move in the opposite direction to the thermocline around the point +A during El Nino and La Nina events. It can be inferred that these isotherm movements in the opposite direction, strengthen the lower current of the NECC during El Nino events by sharpening the inclination of isotherms and weaken it during La Nina events.

Though it is not statistically significant, the correlation takes the opposite sign north and south of 19.5°N. If temperature changes are brought about by the vertical displacement of isotherms, this opposite sign means opposite vertical movement of the isotherms north and south of 19.5°N. This movement suggests that the isotherms in the NEC change their own inclination back and forth around 19.5°N.

5.2 EOF analysis

Empirical orthogonal function (EOF) analysis was applied to the winter temperature dataset, limited to the range from 29°N to 3°N, and from the surface to 900 m for this analysis, due to the completeness of the data. The range is shown in Fig. 14 by enclosing with dashed lines. The large temperature changes between 30°N and 33°N associated with the meandering Kuroshio are excluded from the analysis, owing to the limitations of the dataset.

The total number of grid-points on the 137°E section used for the EOF analysis is 513 (vertically 19 × southward 27). The number of sample \( n \) is 21 (21 years from 1967 to 1987), and 513 EOFs need to be calculated to express completely the total variance of all grid-points.

Significance of each EOF (principal component) can be judged from the criterion proposed by Overland and Preisendorfer (1982). According to their paper, in the principal component analysis (PCA) of random data, proportions of first, second and third principal components (PC) are 10.45%, 9.29% and 8.57%, respectively, in case of sampling number \( n = 20 \) and the number of calculated PC, \( P = 100 \). Those proportions decrease when \( P \) and \( n \) increase. In this EOF analysis, \( n = 21 \), \( P = 513 \) and proportions of first, second and third EOFs are 20.9%, 13.2% and 8.0%, respectively. Comparing those proportions, it can be concluded that first and second EOFs are significant because they have larger proportions than noise level, but it is not clear whether the third EOF is significant or not.

Figure 12 displays the distribution of eigenvectors, for (a) the first mode (EOF1) and for (b) the second mode (EOF2). The EOF1 explains 20.9% of the total variance. The shaded regions with values less than −7 are found at 7°N to 14°N, and depths between 50 m to 150 m, and 4°N to 6.5°N between 400 m to 700 m. These regions correspond to those of high positive correlation, north of and below the point +A in Fig. 11.
The EOF2 explains 13.2% of the total variance. The shaded region, from 14°N to 26°N, has positive values and covers most of the NEC region, except for its main current area (see Fig. 1). Positive values are especially large in the lower layer of the NEC, north of 20°N.

The time coefficients \( f_1 \) for EOF1 and \( f_2 \) for EOF2 are shown in Fig. 13. Durations of the El Nino and La Nina events, and the Kuroshio meandering are shown at the bottom of the figure. Values of \( f_1 \) are positive during El Nino event years, and negative in La Nina event years, although there are some discrepancies in 1977, 1980, and 1981 in this relationship. The time coefficient \( f_1 \) yields large negative eigenvectors in the shaded areas of Fig. 12(a) during El Nino and large positive eigenvectors during La Nina event years that correspond to large negative and positive temperature anomalies, respectively. Consequently, it can be considered that EOF1 represents temperature changes associated with El Nino and La Nina events.

The time coefficient \( f_1 \) takes an especially large value in the winter of 1973 in Fig. 13. It is...
Fig. 13. Fluctuation of time coefficients $f_1$ (upper) and $f_2$ (lower) from the EOF analysis for the same data as shown in Fig. 12. El Nino, La Nina, and Large Kuroshio meander events are also shown (bottom).

Fig. 14. Latitude-depth section at 137°E of the water temperature anomaly (°C) for January 1973. The contour interval is 1°C and the regions of negative anomaly are shaded. EOF analysis is conducted for the region enclosed with dashed lines.
necessary to examine characteristics in the distribution of water temperature and salinity in the 137°E section at that time. Figure 14 shows the cross section of the water temperature anomaly for the winter of 1973. Negative anomaly occupies most of the region south of 30°N. Comparing it with Fig. 7, it is found that very large negative anomalies appear along the thermocline between 7°N and 15°N, where the isotherms decline downward toward the north. Figure 15 shows the cross section of the salinity anomaly for the winter of 1973. Comparing this figure with Fig. 9, it is found that the anomaly is negative above the core of the layer of salinity minimum except for the surface layer, and positive below the core. Considering this salinity anomaly distribution, together with the vast extension of negative temperature anomaly, it can be concluded that the oceanic structure characterized by temperature and salinity distribution became shallower over the entire region south of 30°N during the winter of 1973. This phenomenon deserves special mention.

The time coefficient f_2 remains negative until 1976 and positive afterward. This means that the temperature in the shaded region in Fig. 12(b) exhibits a long-term variation, having negative anomalies until 1976 and positive anomalies afterward. This long-term variation in EOF2 can be regarded as part of the decadal change of the North Pacific. For example, Tanimoto et al. (1993) displayed the distribution of the first mode (EOF1) eigenvectors for various time scales in the EOF analysis of sea surface temperature (SST) in the North Pacific. In the decadal time scale, the distribution of eigenvectors for EOF1 had a vast positive region that occupied most of the North Pacific north of 25°N. The time coefficient was positive from 1970 till 1976, and negative from 1977 to 1985, and corresponds well to f_2 in Fig. 13 in the inverse phase. This means that the temperature in the shaded region of Fig. 12(b), that is, the major portion of the NEC in the 137°E section, was lower when the SST in the North Pacific was higher from 1970 until 1976,
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and higher when the SST was lower from 1977 until 1885.

Kitoh (1991) pointed out a decadal change in the zonal-mean zonal wind which is closely related to the SST variation in the tropical western Pacific, with a meridional shift of the East Asian subtropical jet contributing to this decadal change. In connection with this decadal change in the atmosphere, the Oyashio (the cold current east of Hokkaido) is apt to shift remarkably southward (Sekine, 1988a, b), while the Kuroshio tends to have a large meandering path (Sekine, 1993) after 1975. Another characteristic in the decadal change is the high frequency of occurrence of El Nino events, compared to La Nina events after 1976, as shown in Fig. 13.

Thus, it can be concluded that the EOF2 of winter temperatures in the 137°E section reflects those decadal changes in the North Pacific described above.

![Temporal variations in the minimum negative wind stress curl southeast of Japan (upper curve, 10^{-7} N m^{-3}), and areas of the NPIW (middle curve, 10^6 m^2) and NPTSW (lower curve, 10^6 m^2) along the 137°E section. The thin solid lines indicate the year to year variations, the thick solid lines the four year running means.](image)

Fig. 16. Temporal variations in the minimum negative wind stress curl southeast of Japan (upper curve, 10^{-7} N m^{-3}), and areas of the NPIW (middle curve, 10^6 m^2) and NPTSW (lower curve, 10^6 m^2) along the 137°E section. The thin solid lines indicate the year to year variations, the thick solid lines the four year running means.
6. Effect of Wind on Changes in Temperature and Salinity

So far, the characteristics of interannual variations in temperature and salinity have been described. This section examines the variations of the wind indices mentioned above, and areas of the NPTSW and NPIW measured over a mesh of 0.5 degrees in the horizontal and 25 m in the vertical. Furthermore, the relationships among changes of temperature, the SWER, and the eastward component of wind stress $\tau_x$ in the equatorial region are examined.

The vertical velocity at the bottom of Ekman layer $w_H$ resulting from divergence of the Ekman layer, is given by $(\rho f)^{-1} \text{curl} \, \vec{f}$, provided that the $\beta$ term $\beta \tau_z/((\rho f)^2)$ is negligible. Negative values of curl, $\vec{f}$, lead to convergence of the Ekman layer, downward velocity $w_H$, and the intensification of the anticyclonic circulation of the ocean around the area of wind stress curl minimum. Therefore, it can be expected that strong negative wind stress curl will result in the forcing of the surface saline water in the NPTSW region into the subsurface layer and advecting the saline water westward, resulting in the expansion of the NPTSW area in the 137°E section. Further, it will force the area of the NPIW in the section to increase through the intensification of westward advection of less saline water in the intermediate layer.

The minimum negative wind stress curl, the area of the NPIW, and the area of the NPTSW as function of time are shown in the upper, middle and lower portion of Fig. 16, respectively. The symbols “○” and “▲” designate values for each observation. The thick solid lines represent the four year running mean of each variable, expressing temporal trend. It should be noted that negative values of wind stress curl are upward in the abscissa (right) in the upper portion of the figure.

According to the basic concept mentioned above, it is assumed that maximums or minimums in the areas of the NPIW and NPTSW correspond to minimums or maximums in the wind stress curl just prior to their occurrence. The year and month of the appearance of maximum and minimum in temporal trend are summarized in Table 1. The numerals in parentheses in Table 1 are the lag years. The temporal trend of the NPTSW corresponds well to that of wind stress curl, having its minima and maxima with a lag of 0-1 year and 2 years to the maxima and minima in the wind stress curl, respectively.

We cannot consider that the temporal trend of the NPIW varies simultaneously with the wind stress curl in inverse phase, because strongest negative wind stress curl induces maximum anticyclonic circulation and bring fresher NPIW from the east causing wider area of the NPIW in the 137°E section. In the temporal trend of the NPIW, the maxima lag by 3 to 4 years in 1971 and 4.5 years in 1982, while the minima lag by 6.5 years.

Next, the relationships between interannual variations of temperature, salinity, and the eastward component of wind stress are examined in the equatorial region.

### Table 1. Year and month of the appearance of the maximum and minimum in the temporal trend of each variable, with lag values in parentheses.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Minimum</th>
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<td>Jul. ’77 (6.5)</td>
<td>-Jul. ’82 (4.5)</td>
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Fig. 17. Temporal variations in the area of saline water in the equatorial region (SWER) $A_{ss35}$ (upper curve, $10^6$ m$^2$), maximum (positive) or minimum (negative) water temperature anomalies $\Delta T_{\text{max}}$ between 4°N and 8°N along the 137°E section (middle curve, °C) and the eastward component of wind stress $\tau_x$ averaged over the region 3°N to 3°S, 124°E to 180°F (based on the wind dataset by Stricherz et al., 1992) (lower curve, dyne cm$^{-2}$). The thin lines represent the year to year variation, while the thick curves in the middle and upper portion of the figure are four year running means. The thick curve in the lower trace is a 6 month running mean. El Nino and La Nina events are also shown (bottom).
Figure 17 shows the area of the SWER ($S \geq 35.0$) $A_{S \geq 35}$ in the upper portion of the figure, the maximum temperature anomaly $\Delta T_{\text{max}}$ (maximum of the absolute value) between 4°N and 8°N of the section in the middle portion, the eastward component of wind stress $\tau_x$ regionally averaged between 3°N and 3°S, and 124°E and 180°, based on the wind dataset by Stricherz et al. (1993) in the lower portion, and the duration of El Nino and La Nina events at the bottom. Smoothed curves represent the four year running mean for $A_{S \geq 35}$ and $\Delta T_{\text{max}}$, and the 6 month running mean for $\tau_x$.

In general, positive temperature anomalies appear and La Nina events occur when westward stress is large. On the other hand, negative temperature anomalies occur with El Nino events when the westward stress is small. El Nino does not occur from January 1980 until January 1981 when the negative temperature anomaly is large. The values of $\Delta T_{\text{max}}$ exhibit a temporal trend with positive values before January 1976 and negative values from July 1977 until July 1982.

Values of $A_{S \geq 35}$ also exhibit a temporal trend that decreases after July 1976. These temporal trends in $\Delta T_{\text{max}}$ and $A_{S \geq 35}$ bounded in 1976, can be caused by the temporal trend in $\tau_x$, which has small absolute values from January 1976 until March 1981, being similar to the variation of the time coefficient $f_2$ shown in Fig. 13. This implies that such temporal trends in $\Delta T_{\text{max}}$ and $A_{S \geq 35}$ in the equatorial region may be part of the oceanic and atmospheric decadal change in the North Pacific.

7. Discussion

Iida and Shinohara (private communication) found, from the meridional distributions of the zonal mean eastward component of the wind stress and latent heat flux, that the area of the sea-surface salinity maximum in the NPTSW was nearer to the position of maximum Ekman pumping than to that of the maximum latent heat flux. They also pointed out that the convergence of the Ekman layer played a more important role in the downwelling of the NPTSW in the surface layer into the subsurface layer, than the formation of dense water by evaporation. This may support existence of the relationship in variations between NPTSW and wind stress curl like the one indicated in this paper.

As for the formation of the North Pacific Intermediate Water (NPIW), several theories are presented recently. Okhotsk Sea water is the origin of the NPIW, and outflow water from the Okhotsk Sea obtains the density of 26.8–27.6$\sigma_\theta$ owing to ice formation and vertical mixing at the Bussol’ Strait (north of Urup Island) (Talley, 1991). Talley (1993) concluded that NPIW is formed as a salinity minimum in the northern part of the mixed water region (MWR) between the Kuroshio and Oyashio, through intrusion of cold fresh Oyashio water into saltier subtropical water influenced by the Kuroshio, warm core rings and the Tsugaru Warm Current, and erosion of the minimum from the top by vertical mixing. It is suggested that formation of the newest (freshest) NPIW occurs when the Oyashio introduces fresh subpolar water to the MWR (Talley et al., 1995).

Fukasawa et al. (1992) identified flow paths of the NPIW using inverse method. The paths are along the subtropical gyre as a whole, and consist of six branches. They showed three shortcut routes from the northern side to the southern side of the gyre around 170°E, 160°W and 140°W.

These studies indicate that the NPIW south of Japan is supplied with water transported on the shortcut route around 170°E from the source region (the MWR) as well as water traveled long way along the subtropical gyre. The shortcut transport implies the possibility of changes in the NPIW south of Japan corresponding to changes in the wind field in the western North Pacific.

It was shown in Section 6 that the change in the area of the NPIW in the 137°E section
corresponds well to the change in the winter wind stress curl minimum southeast of Japan, with a lag of 3 to 6.5 years.

On the other hand, Qiu and Joyce (1992) showed that the central position of the NPIW in the 137°E section moved southward, over the same distance as the amplitude of the meander, and its area decreased when the Kuroshio had a large meandering path. They suggested that the area of NPIW in the 137°E section would be reduced by the blocking of westward transport of the NPIW by the large meander of the Kuroshio, which induced weakening of the Kuroshio countercurrent.

Figure 18 shows the sections of potential density $\sigma_\theta$ (left) and geostrophic velocity referred to 1000 db (right) along the 137°E meridian superimposed with the region of the NPIW for the summer of 1978 (upper panels) and the summer of 1981 (lower panels) when the area of the NPIW in the section was smallest and largest, respectively. In the potential density section for the summer of 1981, the area of the NPIW in the summer of 1978 is also shown by the shaded area enclosed by the dotted trace. When comparing these figures, differences in the oceanic conditions between the two years can be summarized as follows:

(a) The NPIW is bounded by the 26.6$\sigma_\theta$ and 27.8$\sigma_\theta$ surfaces in the summer of 1978, but extends over those isopycnal surfaces during the summer of 1981. The extension thickens the NPIW.
(b) The region of the NPIW in the summer of 1978 is divided by the eastward current around 26°N to 27°N, which makes the area narrow.

(c) The southward displacement of the trough of isopycnals near 30°N, owing to the large meander of the Kuroshio in the summer of 1978, leads to the southward displacement of the northern end of the NPIW, and results in a decrease in the area of the NPIW. On the other hand, the NPIW extends northward over the trough of potential density in the summer of 1981, which takes a more northward position due to the straight path of the Kuroshio. The extension widens the NPIW.

(d) The westward velocity near the southern part of the NPIW is stronger in the summer of 1981 than in the summer of 1978. The broader area of the southern part of the NPIW in the summer of 1981 may be brought about by the transport of a larger quantity of less saline water from the east.

These results suggest that the large meander of the Kuroshio evidently contributes to the reduction in the area of the NPIW by the southward shift of its northern boundary, as was pointed out by Qiu and Joyce (1992). In addition, the strength of the anticyclonic circulation southeast of Japan is closely related to the area of the NPIW, by changing the thickness of the NPIW and the westward transport of less saline water.

Absolute values of temperature anomalies in the equatorial region are largest in the zone between 4°N and 8°N, where the thermocline is shallowest and sharpest (see Figs. 7 and 8). The thermocline is sufficiently sharp in the equatorial region that the ocean can be approximated by a two layer model with the thermocline as the interface. In the two layer model, the internal radius of deformation around the equator is defined by $a_e = (c_1/2\beta)^{1/2}$, where $c_1$ is the phase velocity of the internal wave given by $c_1 = (g'\rho_1 h_1)^{1/2}$, $g'$ the reduced gravity, and $h_1$ the thickness of the upper layer.

The values $h_1 = 150$ m, $\rho_1 = 1023.0$ kg m$^{-3}$ (for the upper layer), $\rho_2 = 1026.0$ kg m$^{-3}$ (for the lower layer) yield $c_1 \approx 2$ m s$^{-1}$. The values of $c_1$ and $\beta = 2.289 \times 10^{-11}$ m$^{-1}$s$^{-1}$ lead to $a_e = 200$ km (about two degrees in latitude).

The equatorial Kelvin wave is meridionally trapped within the distance of $a_e$ from the equator. Considering that $a_e$ is about 200 km and that the maximum temperature anomalies appear between 4°N and 8°N (about 400–800 km from the equator), it is clear that most of the large temperature anomalies are not induced by the equatorial Kelvin wave.

As was shown in Fig. 17, the variation $A_{S35}$ and $\Delta T_{max}$ are out of phase. This may reveal the relationship between the vertical and horizontal movements of water in the equatorial western Pacific. The variation of $A_{S35}$ and $\Delta T_{max}$ are mainly caused by the horizontal movement of saline water in the equatorial region and the vertical displacement of the thermocline, respectively.

Thus, the problem remains to reveal the three-dimensional motion in the surface and subsurface layer in the equatorial western Pacific, induced by the rapid change of westward trade winds, especially rapid weakening.

8. Conclusions

It was found from correlation analysis of winter water temperatures along the 137°E section that temperature fluctuations in the equatorial region, accompanied by El Nino and La Nina events, reach to about 20°N. Also, the isotherms in the north equatorial current change their meridional inclination around 20°N. In the EOF analysis of winter water temperatures, changes accompanied by El Nino and La Nina events are retrieved as the first mode, while variations corresponding to decadal changes in the North Pacific SST are found in the second mode.
The areas of the NPTSW and the NPIW in the 137°E section change, corresponding well to the variation of the wind stress curl minimum southeast of Japan, with lags of 0 to 2 years and 3 to 6.5 years, respectively. It can be considered that changes in the Ekman pumping and anticyclonic circulation by wind stress curl southeast of Japan, resulted in these area variations, but it is necessary to quantitatively estimate the relationship, including the lag times.

Temporal trends in $A_{S\geq35}$ and $\Delta T_{\text{max}}$ in the equatorial region clearly correspond to the decadal change in the North Pacific. Changes in $A_{S\geq35}$ and $\Delta T_{\text{max}}$ over a shorter time scale are left as problems, such as what kind of wave is generated and the structure of the three-dimensional motion when abrupt changes in wind occur in the equatorial western Pacific to bring about the observed changes in $A_{S\geq35}$ and $\Delta T_{\text{max}}$.

Clarification of the mechanism for the abnormal conditions during the winter of 1973, when almost the entire oceanic structure became shallower in the 137°E section should also be examined in future studies.

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