Subtropical Mode Water in the 137°E Section

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ABSTRACT

The subtropical mode water (STMW) in the North Pacific Ocean has been investigated based on the data of long-term observations along the 137°E meridian, which have been performed by the Japan Meteorological Agency since 1967 for winter and since 1972 for summer. STMW cores were identified as vertical potential vorticity minima, and examined by the use of apparent oxygen utilization as an indicator of the age of STMW.

The main results can be summarized as follows. 1) A major part of the STMW appearing in the summer (or the winter) sections is the water formed in the immediately previous winter, its age being half a year (or one year). 2) Within half a year after its formation the STMW can be advected to the 137°E section only as far south as about 26°N and as far as about 23°N within one year. 3) Typical potential temperature in summer was higher than in winter, with salinity higher and potential density lower. 4) Less STMW was observed during the period of the typical large meander of the Kuroshio in the later 1970s. 5) The salinity of STMW was relatively low before 1981; it increased considerably in the summer of 1981 and has since showed a slowly decreasing trend.

1. Introduction

One of the most remarkable water masses in the world's oceans can be found in the subsurface layer of the western part of the subtropical gyre of both the North Pacific and the North Atlantic oceans. This particular water mass, which is characterized by vertical homogeneity of water properties with wide distribution, is known as the Subtropical Mode Water for the North Pacific (henceforth abbreviated to STMW, Masuzawa 1969, 1972) and as the Eighteen Degree Water for the North Atlantic (henceforth 18°Water, Worthington 1959). The vertical homogeneity of STMW/18°Water comes from its deep wintertime convective formation, which occurs near the northwestern edge of the subtropical gyre (Worthington 1959, 1972, 1977; Masuzawa 1969, 1972; Talley and Raymer 1982; Hanawa 1987). Its wide distribution throughout the western part of the subtropical gyre reflects the fact that STMW/18°Water is carried away from its formation area by lateral advection (Worthington 1959; Masuzawa 1969; McCartney 1982).

Since the evolution of wintertime vertical convection essentially depends on air-sea interactions, the renewal of STMW/18°Water varies with the conditions not only of the ocean but also of the atmosphere. Worthington (1972) discussed the air–sea heat flux as a cause of 18°Water formation. Indeed, the formation/outcrop regions of STMW/18°Water (Worthington 1959; Masuzawa 1969, 1972; Fieux and Stommel 1975; Hanawa 1987) correspond to the areas where the ocean releases the largest amount of heat to the atmosphere (Hsiung 1985). This heat flux varies considerably from year to year (Zhao and McBean 1986), so it is expected that both the formation rate and the properties of STMW/18°Water vary correspondingly. Talley and Raymer (1982) examined the long time series of hydrographic data taken at the *Panulirus* station near Bermuda, and discussed the interannual variability of 18°Water.

It is considered that STMW/18°Water can be a useful tracer for the subsurface circulation of the subtropical gyre because of its wide advective distribution, despite its limited formation which is confined both spatially and temporally. McCartney (1982) showed that the basic distribution of 18°Water has a simple relationship to the warm water (>17°C) circulation proposed by Worthington (1976), using several sections across the North Atlantic.

Figure 1 shows the acceleration potential, relative to 1000 db, on the surface where the thermosteric anomaly equals 240×10^{-8} m^3 kg^{-1} (σ_t = 25.60 kg m^{-3}) for summer (May–October), adapted from Tsuchiya (1982, his Fig. 2). In the low latitudes of the North Pacific, this surface lies in the main thermocline. In the western subtropical North Pacific, it lies within the thermostad of STMW. The area where the vertical separation between 16° and 19°C isotherms is greater than 150 m, adapted from Tsuchiya's (1982) rendition of Masuzawa (1972), is also shown in Fig. 1. Hanawa (1987) examined the wintertime outcrop area of STMW and pointed out that the outcrop/formation region of STMW was immediately offshore of the Kuroshio mainly east of Japan. Moreover the extension

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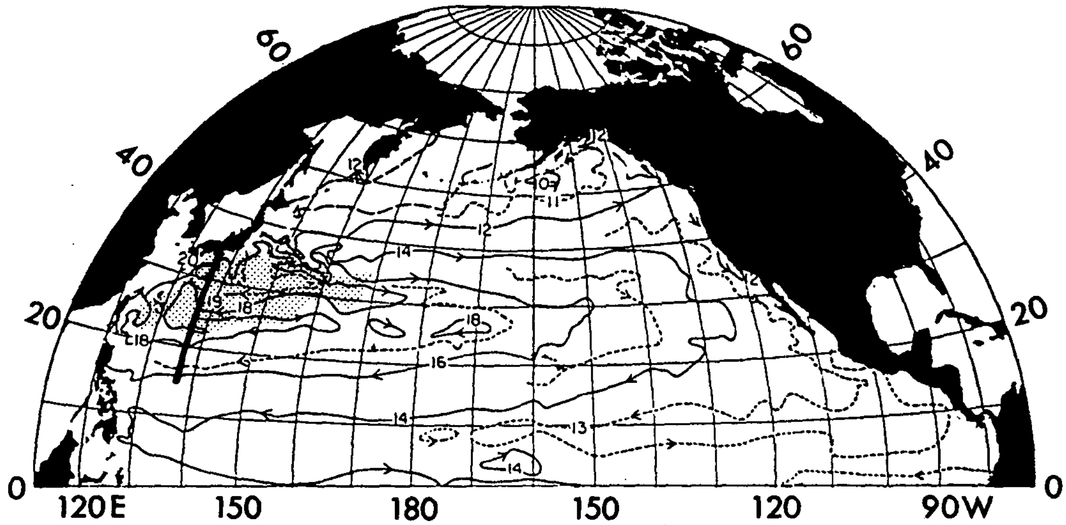

FIG. 1. Acceleration potential (unit in $m^2 s^{-2}$) relative to 1000 db on the surface where thermosteric anomaly equals $240 \times 10^{-8} m^3 kg^{-1}$ for summer (May–October), adapted from Tsuchiya (1982, his Fig. 2). The stippled area indicates the region where the vertical separation between 16° and 19°C is greater than 150 m, adapted from Tsuchiya's (1982) rendition (his Fig. 11) of Masuzawa (1972, his Fig. 13). The thick line shows the part of the 137°E meridian used in this study.

of STMW seems to correspond to the southwestward flow illustrated by the contours in Fig. 1.

In the present study, we used data from the section along 137°E shown in Fig. 1 by the thick line. The observations provide data of fairly uniform quality over a long period. Although this section seems to be located somewhat west of the main part of the STMW formation region, STMW can be advected to this meridian by the Kuroshio Countercurrent. Therefore, it follows that spatial distribution and properties of STMW in this section will be determined not only by the formation process but also by the advective–diffusive process following its circulation pattern. The purpose of this study is to describe the spatial distribution and properties of STMW in summer and winter sections including their interannual variations, and also to relate them to the formation, circulation and dissipation processes.

The remainder of this paper is organized as follows. The data and analytical methods used in this study are explained in section 2. Spatial distribution and typical properties of STMW both in summer and in winter are summarized for the whole series of observations in section 3. Interannual variations of spatial distribution and water properties of STMW are discussed in section 4. Section 5 gives discussion of circulation and dissipation of STMW. Section 6 presents conclusions.

2. The data and analytical methods

a. The data used

The data used in this study are the hydrographic observations along the 137°E meridian, performed every winter since 1967 and every summer since 1972 by the R/V *Ryofu Maru* belonging to the Japan Meteorological Agency (Masuzawa, 1967; Masuzawa and Nagasaka 1975; Andow 1987). Each section consists of 40–50 serial stations from Japan to New Guinea, which are spaced 60 miles apart for the latitude range of 8° to 32°N and 30–40 miles for the remainder, with no significant exception. The sampling depths are at standard depths without significant exception.

b. Analytical tools

A water mass formed by deep convection such as STMW is characterized by a pycnostad, i.e., a minimum in the vertical potential density gradient. Hence, a potential vorticity (PV) minimum is a useful tracer for STMW if relative vorticity can be neglected, according to quasi-geostrophic theory. McCartney (1982) used this tracer to illustrate the subtropical recirculation system of "mode water". Talley and Raymer (1982) showed the circulation and changing properties of 18°Water, identifying an 18°Water core by its vertical PV minimum. In the present paper, a finite-difference form of the PV, i.e.,

$$PV = (f/\rho)(\Delta\sigma_\theta/\Delta z)$$

was calculated for each interval between the adjacent Nansen bottles, where f is the Coriolis parameter, $\Delta\sigma_\theta$ the potential density difference, and Δz the depth interval.

Another tool used in this study is apparent oxygen utilization (AOU), which is the difference in oxygen concentration of a water parcel from its saturated value.

AOU has a tendency to increase due to the consumption of oxygen by organic processes at all times after isolation from the atmosphere. Ebbesmeyer and Lindstrom (1986) computed the age of a parcel of 18°Water as the time required for the AOU to have occurred since the parcel's last exposure to the atmosphere. Their age calculations were made using the apparent oxygen utilization rate (AOUR) given by Jenkins (1980).

The errors in potential density, AOU and PV are as follows. Temperature errors are of the order of ±0.01°C and salinity errors are smaller than ±0.01. Dissolved oxygen errors are of the order of ±0.03 ml l^{-1}. The resulting errors in potential density and AOU are smaller than ±0.01 kg m^{-3} and of the order of ±0.03 ml l^{-1}, respectively. Errors in PV, since they depend on bottle intervals, are of the order of 60×10^{-14}, 30×10^{-14} and 15×10^{-14} cm^{-1} s^{-1} for the bottle intervals of 25, 50 and 100 m, respectively.

Figure 2 shows examples of vertical profiles for both the PV and AOU obtained at 29°N in the summer of 1985. Here PV is calculated for each bottle interval and is represented by a vertical bar. The PV-minimum layer lies between the depths of 170 and 400 m and is centered between 200 and 250 m, where PV is considerably smaller than 200×10^{-14} cm^{-1} s^{-1}. The value of PV in the main thermocline below the PV-minimum layer is a little higher than this value and, in the seasonal thermocline above the PV-minimum layer, is much higher. Layers with a PV lower than 200×10^{-14} cm^{-1} s^{-1} generally represent STMW because most of the main thermocline in the region of our interest has a PV higher than this value (compare McCartney 1982).

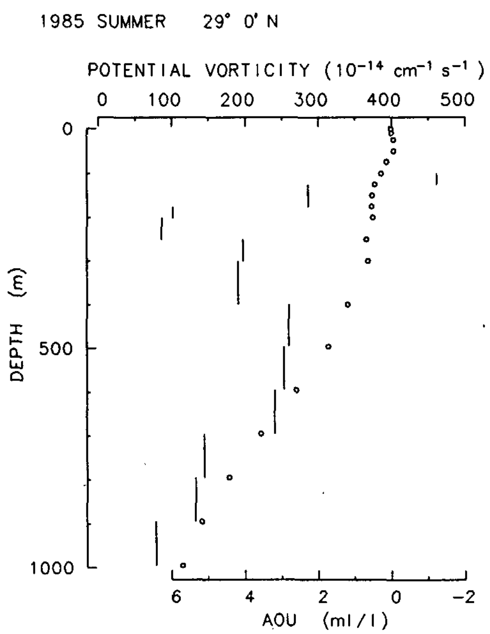

FIG. 2. Vertrical profiles of potential vorticity (vertical bars) and AOU (open circles) obtained at 29°N, 137°E in summer 1985.

AOU is lower than 1.0 ml l^{-1} above 300 m, while it increases rapidly from the main thermocline downward.

c. *STMW as a thermostad*

The potential temperature θ sections for summer 1986 and winter 1987 are shown in Fig. 3. The Kuroshio is near 33°N in both sections. We will define the Kuroshio axis as the intersection of the 15°C isothermal surface and the 200 m surface, following the traditional way (e.g., Kawai 1972; Taft 1972). The axis is located at 33°20′N in the summer section and at 32°40′N in the winter section. The Kuroshio had a nearly straight path along the Japanese coast when these sections were observed.

The stippling identifies layers with a PV lower than 200×10^{-14} cm^{-1} s^{-1}. The summer section contains a distinct thermostad, which extends from the Kuroshio south to 25°N, the water of the thermostad being called STMW. The depth and θ ranges of STMW in the section are from 100 to 400 m and from 15° to 19°C, respectively. It can be seen that the depth, θ and thickness of STMW are different from one latitude to another.

In the winter section, the surface mixed layer reaches a depth of 150 m around 30°N and 100 m around 25°N. Its θ is higher than 20°C at all latitudes. The observation along 137°E in winter is usually made in the latter two weeks in January, while the winter convective mixed layer in this area usually does not complete its evolution until March (see Hanawa and Hoshino 1988), i.e., the mixed layer in the winter section is still developing. Therefore, the section can not provide information about the STMW being newly formed that winter. The thermostad corresponding to STMW indicated by stippling, lies above the main thermocline and is separated from the local mixed layer by a strong thermocline. Its depth and θ ranges are from 200 to 400 m and from 14 to 18°C. This subsurface thermostad must have been formed in previous winters because no nearby mixed layer ever develops by January to form such a thermostad.

In fact, the wintertime sea surface temperature never becomes lower than 18°C south of the Kuroshio at this longitude (see Hanawa 1987). Therefore, the major part of STMW in the 137°E section must have been advected from the remote formation region.

d. *Area distribution of θ and AOU*

Bivariate area distribution in the 137°E section according to water classes defined by intervals of θ and AOU was prepared (e.g. Fig. 4). For the latitude range from the Kuroshio axis to 20°N, the total area per bivariate class 0.2°C × 0.1 ml l^{-1} in all of the sections dealt with was calculated using AOU and θ profiles interpolated linearly. It was assumed that each station represents a lateral extent confined by the two mid-

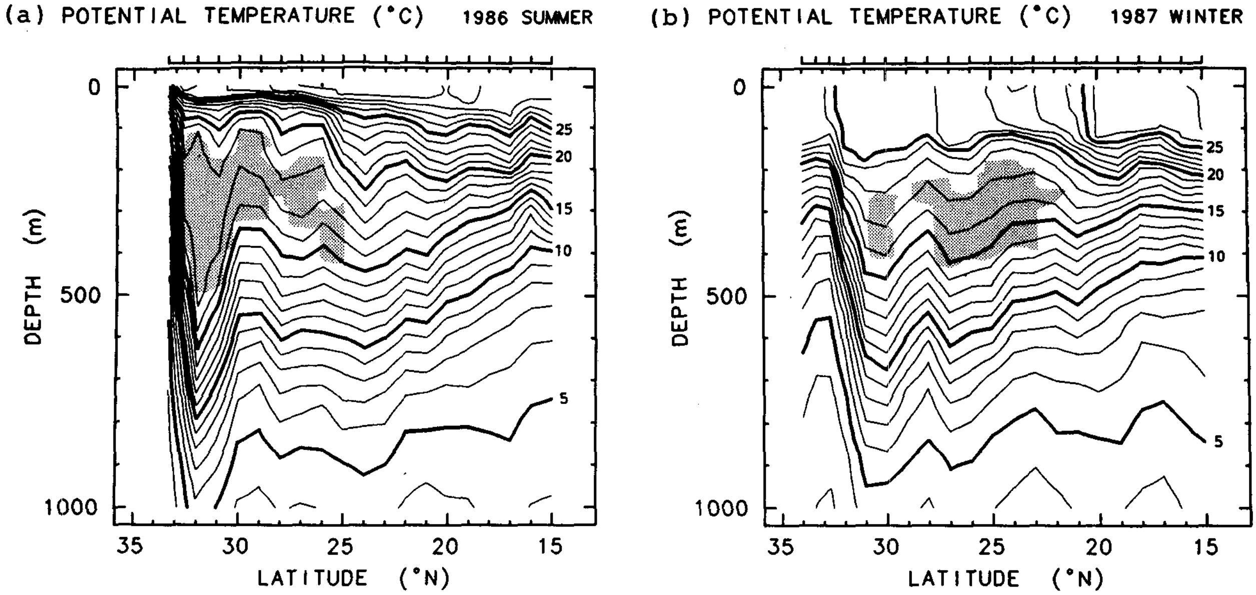

FIG. 3. θ sections along 137°E made by the R/V *Ryofu Maru* in (a) summer 1986 and (b) winter 1987. The stippled areas represent layers whose potential vorticity is lower than 200×10^{-14} cm^{-1} s^{-1}.

points between that station and the next station. For the winter sections, the areas in the mixed layer and in the subsurface layer were calculated separately. The summer sections have no mixed-layer water in the above specified range below 20°C. Here, the mixed layer depth was defined as the depth where θ equals sea surface temperature minus 1°C.

The area distributions for summer and winter are quite similar for θ below about 16.5°C. A single linear ridge (henceforth called the main ridge) extends from low θ and high AOU to high θ and low AOU. Above ~16.5°C, the summer and winter ridges bend to become nearly parallel to the θ axis with the summer ridge system reaching lower AOU values than does the winter ridge.

Figure 4 shows contour maps of area distribution of θ and AOU in the ranges extending somewhat beyond those of STMW. For summer, at θ higher than 17°C, a predominant ridge runs almost along the AOU value of 0.6 ml l^{-1}. A weaker, secondary ridge branches off the main ridge around 17°C and runs along the AOU value of 1.0 ml l^{-1}. In the winter subsurface diagram,

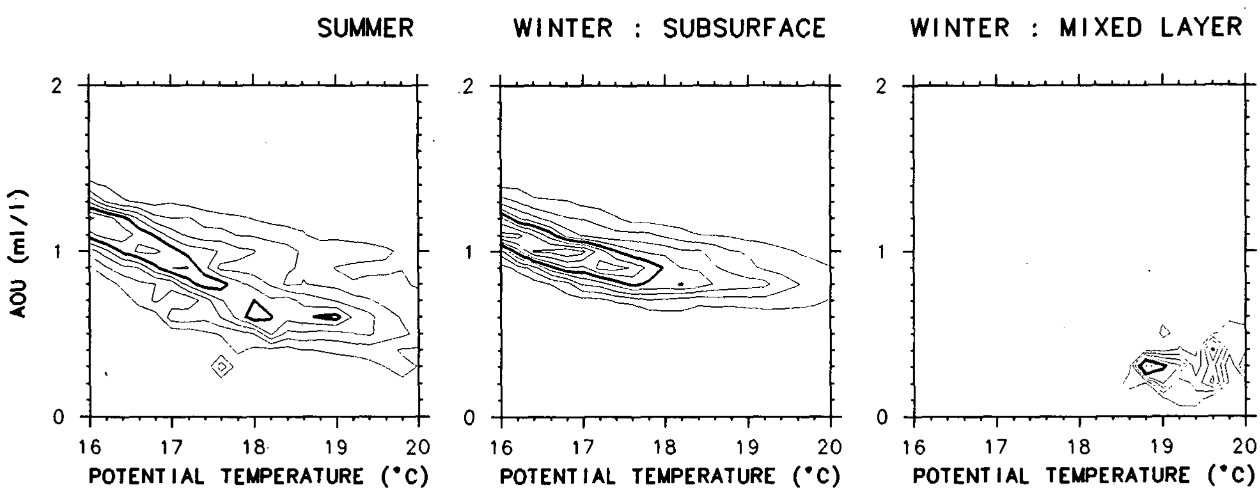

FIG. 4. Distribution of area along 137°E in each bivariate θ-AOU class 0.2° C × 0.1 ml l^{-1} for all sections which were taken in summer from 1972 to 1986 and in winter from 1973 to 1987, within the θ range of 16° to 20°C and the latitude range of south of the Kuroshio axis to 20°N. No diagram is given for the summer mixed layer because its temperature is above 20°C. Contour lines are drawn for each 10 km^2 of area with thickening for each 50 km^2.

a single ridge lies along the AOU value of 0.8 ml l^{-1}. The mixed layer water in winter has θ values higher than 18.6°C and AOU values around 0.3 ml l^{-1}, which are distinctly lower than those of the predominant summer ridge. It should be emphasized that the AOU of the mixed layer water is not zero. Actually, Suga and Hanawa (1989) showed that AOU is 0.2–0.35 ml l^{-1} in the mixed layer of the Kuroshio Extension region east of Japan, where the thick and cold mixed layer exists and the main part of STMW is formed.

The AOU of the mixed-layer water is established almost independently of θ in the ocean region of interest, as mentioned just above. Since the water of θ lower than 20°C is definitely below the seasonal thermocline during the heating season, it cannot undergo significant heating. Therefore, the ridges parallel to the θ axis for θ higher than about 17°C show that the AOU of that water has increased after isolation from the atmosphere, evidently as a result of organic processes.

Jenkins' (1980) estimates of AOUR values for the subtropical North Atlantic permit us to discuss the age of surface and subsurface water. The value for a near-surface layer (roughly from 100 to 300 m in depth) is of the order of 0.5 ml l^{-1} yr^{-1}. For the θ range higher than about 17°C, this value corresponds well to the intervals between the AOU values of two summer ridges and between those of the mixed layer and the winter ridge. Furthermore, the difference in AOU between the predominant summer ridge and the winter ridge is about one half of the annual AOUR value given by Jenkins (1980), i.e., about 0.25 ml l^{-1}. Hence a reasonable interpretation of area-distribution patterns based on annual reestablishment of an AOU near 0.3 ml l^{-1} in the winter surface layer is as follows. The age of water constituting the predominant ridge in the summer diagram is half a year; that of the secondary ridge one and a half years; that of the ridge of the subsurface water in winter one year; and that of the mixed-layer water virtually zero.

3. Ensemble analysis of STMW cores

The concept of "STMW core" is useful in specifying properties of STMW. In this section, we will define a STMW core and deal with the two sets of the cores observed in summer from 1972 to 1986 and in winter from 1973 to 1987. Since they can be regarded as ensembles of both summer and winter cores, the typical features of STMW will be studied on the basis of these data.

a. Definition of a STMW core

As seen in Fig. 3, STMW exhibits quite a wide range of θ at each station, although its main character is vertical homogeneity. Talley and Raymer (1982) identified an 18°Water core with the vertical PV minimum in order to discuss the variability of 18°Water. We define a STMW core in a similar manner requiring that it lie in a *layer* of minimum PV, taking the lowest-PV layer when more than one minimum is found. However, since only a *layer* can be specified on the basis of the available discrete samples, we stipulate further that the core is at the depth where the AOU is smallest, that is, where the most recently ventilated water lies.

Even a *core* defined in the way given above may have a property whose value differs significantly from that usually associated with STMW. In order to eliminate such cases, we took a thickness as the depth interval between two isotherms which are 0.5°C below and above θ at the PV-minimum depth and required that the thickness be 50 m or more. The success of this criterion is illustrated in Figs. 5a–b where the thickness associated with each PV minimum observed in the region south of the Kuroshio axis and north of 15°N is plotted against PV. The figures show that PV derived from the potential-density difference between adjacent bottles has less sensitivity to the thickness and, therefore, less effectiveness in identifying STMW cores as the center of a thermostad, where the thickness is below 50 m. Further, in the scatter diagrams of the thickness versus θ and salinity for all PV minima, shown in Figs. 5c–f, the points for the thickness greater than 50 m lie in fairly narrow ranges of θ (from 15° to 20°C) and salinity (from 34.6 to 35.0) with only a few exceptions. These ranges correspond very well to the characteristics of STMW described by Masuzawa (1969, 1972). Thus we can safely define a true STMW core by imposing the additional requirement that the layer bounded by θ of 0.5°C above and below the value at the core be 50 m or more.

As an example, Fig. 6 shows STMW cores meeting all of the above conditions as they appear in the sections for θ, salinity, potential density and AOU encountered in the summer of 1981.

b. Age of STMW cores deduced from AOU

The AOU values of STMW cores are plotted against latitudes in Fig. 7 in order to examine the spatial distribution of STMW cores in the following subsection. Histograms give the corresponding univariate distributions. At this point we will consider only the AOU histograms. Summer STMW cores have AOU values generally lower than those of winter cores. The histograms show modes at the ranges of 0.55–0.65 ml l^{-1} and 0.85–0.95 ml l^{-1} for summer and winter, respectively. According to the discussion of Fig. 4 (section 2d), these modal distributions imply that the major parts of summer and winter STMW are half a year old and one year old, respectively. In addition, the AOU values of summer cores are scattered more widely than those of winter cores. The AOU range for summer extends from the modal level to the higher side. It is wide enough to include AOU of the secondary ridge representing water which was formed one and a half years

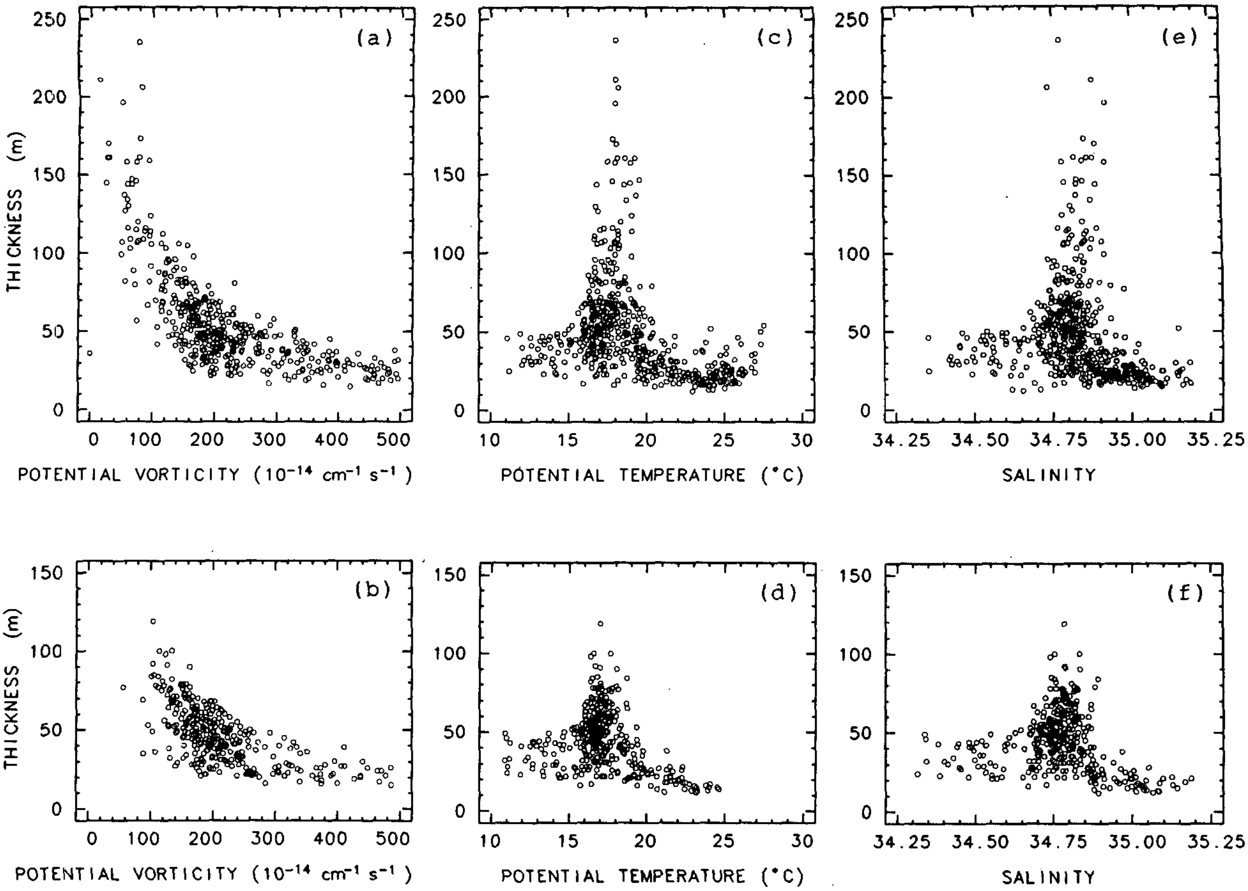

FIG. 5. Scatter diagrams of the thickness vs potential vorticity (a–b), θ (c–d) and salinity (e–f) for each potential vorticity minimum. The thickness is taken as the depth interval between two isotherms which are 0.5° below and above θ at the potential-vorticity-minimum depth. The data were obtained in summer from 1972 through 1986 (a, c, e) and in winter from 1973 through 1987 (b, d, f).

ago (Fig. 4). On the other hand, the AOU range of winter cores is confined well within the neighborhood of the modal level. The rather narrow range of winter cores can include AOU values corresponding to only a single age of STMW; there is no apparent sign of two-year-old STMW. This aspect of the distribution suggests that STMW is renewed or mixed into the main thermocline and loses its original properties within, at most, two years from its formation.

Since water around the secondary summer ridge (Fig. 4) must have suffered diapycnal mixing for a longer time than water around the predominant summer ridge, the former is less likely to lie in a thick thermostad and so be identified as a STMW core. Hence it does not cause another peak in the frequency distribution of AOU of summer STMW cores. Moreover, because of the sparsity of the sampling depths, a given sample may not lie at the core of STMW but near its upper or lower boundary where mixing with waters of the main or seasonal thermocline has occurred. The sample AOU may therefore differ considerably from the true core value, which can moderate the sharpness of the peak corresponding to new summer cores. Nevertheless we can draw some distinctions, preferring to distinguish only cores of new summer STMW which are distinctly half a year old. We regard a STMW core whose AOU is lower than 0.75 ml l^{-1} as a new core because this value separates the part of considerably higher elevation along the predominant summer ridge along the AOU value of 0.6 ml l^{-1} from the other (Fig. 4). (We call the rest of summer cores "the other summer cores.") This criterion may be too low to exclude only cores which have an age of one and half years or more. It will, however, enable us to make a comparison between distinctly new summer cores and winter cores, which is one of the most interesting concerns to us. The characteristic width of the consequent distribution of a new core's AOU is 0.3 ml l^{-1}, which corresponds approximately to the variability of initial AOU values deduced from the AOU of the mixed layer (see Fig. 4).

c. Characteristics of spatial distribution of STMW cores

Histograms for the latitude of cores are shown in Fig. 7. The number of cores for each latitude represents

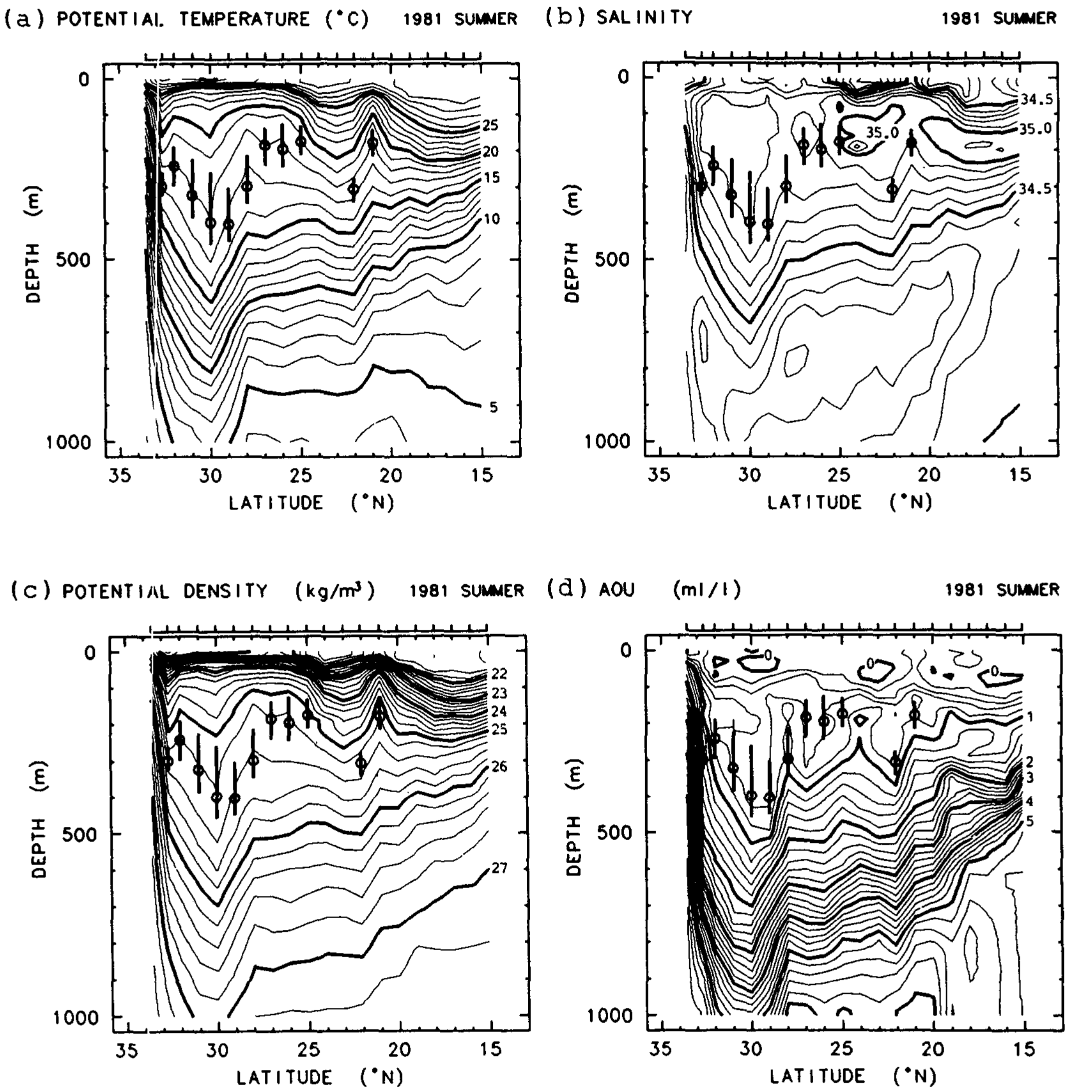

FIG. 6. STMW cores (open circles) with their thickness (vertical bars) superimposed on (a) θ, (b) salinity, (c) potential density and (d) AOU sections along the 137°E meridian in summer 1981.

the probability that STMW is present at that latitude, since the spacing of stations was nearly the same for all surveys during the 15 years. It is seen that STMW cores appeared almost every summer in the latitude range 29° to 26°N. The presence of STMW becomes infrequent gradually from 30° to 32°20′N, while it becomes infrequent abruptly south of 26°N. At 24° and 23°N, STMW was detected in less than half of 15 summers, and south of 23°N, almost no STMW was found in summer. Moreover, the presence of the new cores shown by stippling on the histogram is remarkably confined between 32° and 26°N. In winter, STMW appears most frequently at 29° and 27°N. The frequency decreases abruptly north of 29°N, while it decreases gradually from 26° to 23°N.

Figures 8 and 9 show latitude–depth diagrams and latitude–thickness diagrams, respectively, for STMW cores. In summer new cores (closed circles) lie mainly between 120 and 220 m depth, while in winter core depths lie between 200 and 320 m. The thickness of the new cores in summer can be larger than 100 m north of 26°N, while the thickness of the winter cores is smaller than 100 m at almost all latitudes.

d. Typical properties of STMW cores

Scatter diagrams plotting the AOU of STMW cores against θ, salinity, and potential density are shown in Fig. 10. Each diagram is supplemented by a histogram of each property; stippled portions of the histograms of Fig. 10 represent new summer cores. In summer, typical properties of new and the other cores are considerably different. That is, the other cores have lower θ, lower salinity and higher potential density. In particular, the distribution of θ is clearly bimodal; the

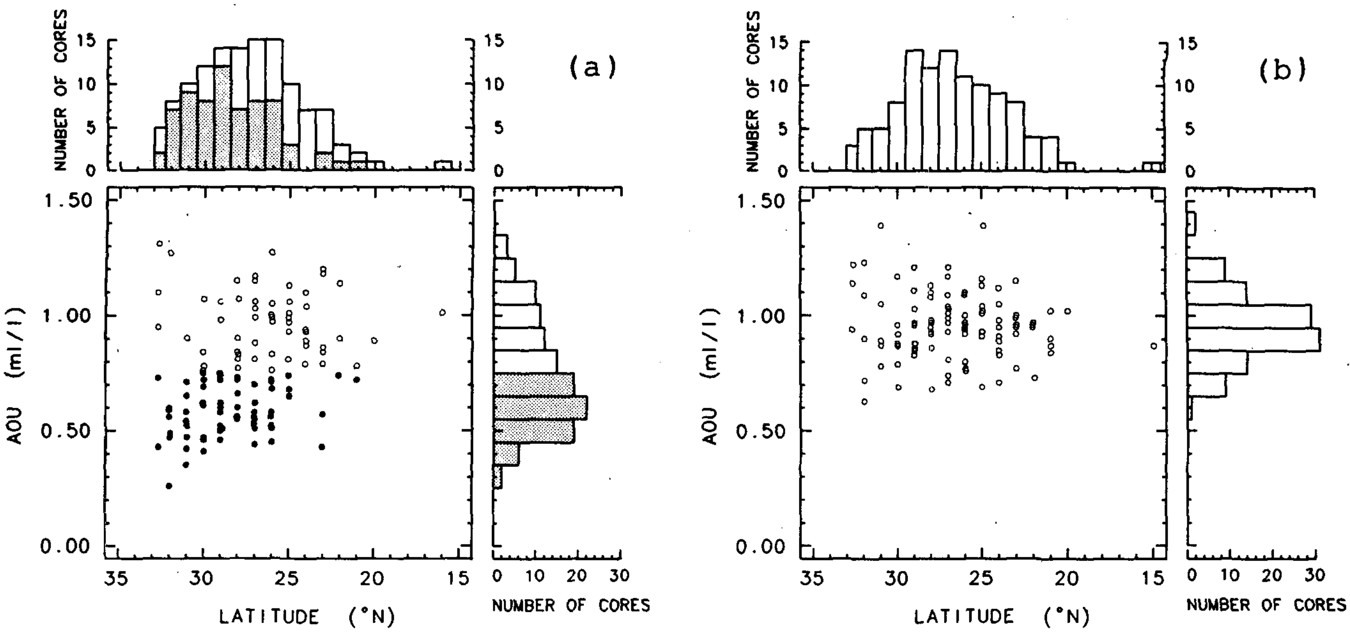

FIG. 7. Scatter diagrams of AOU vs latitude for all STMW cores obtained along the 137°E meridian in (a) summer from 1972 through 1986 and (b) in winter from 1973 through 1987, with histograms of their latitude and AOU. Closed circles on the diagrams and stipple on the histograms represent new summer cores whose AOU is lower than 0.75 ml l^{-1}.

higher mode corresponds to new cores and the lower one to the other cores. In winter, the properties of STMW cores are well defined compared to those in summer. Generally, winter values lie between those of new and the other summer cores, or close to those of the other summer cores.

Figure 11 shows θ–S diagrams for both (a) summer and (b) winter. The summer new cores (closed circles)

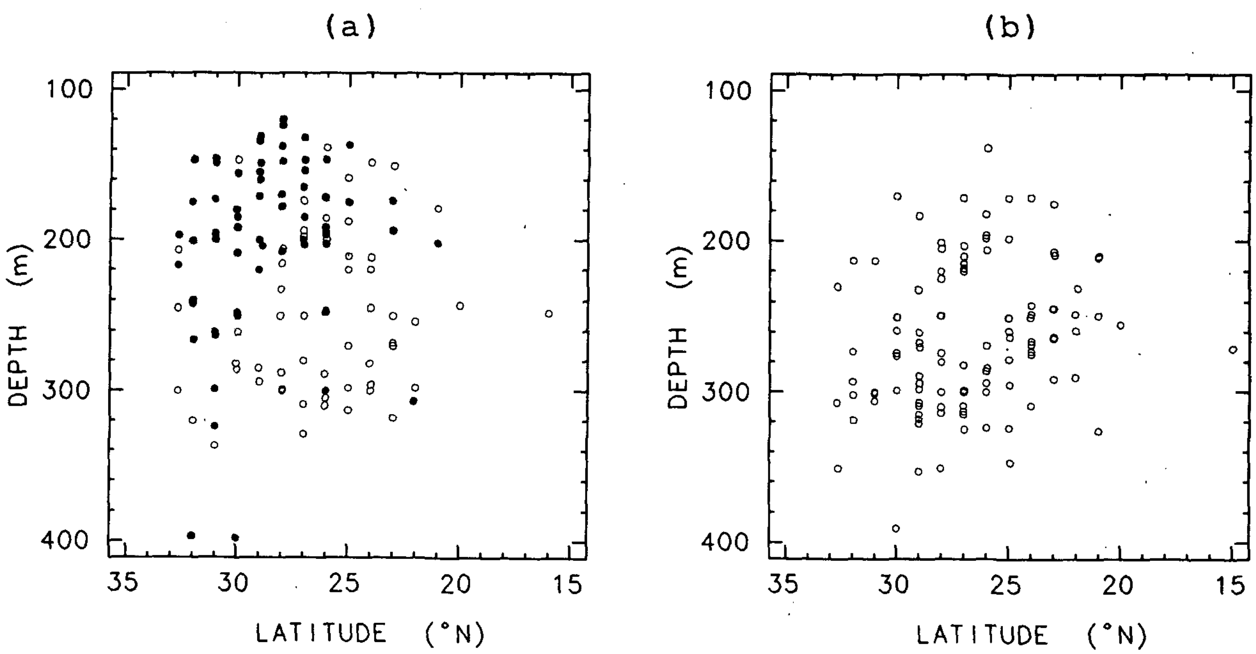

FIG. 8. As in Fig. 7 except for depth vs latitude. Closed circles represent new summer cores whose AOU is lower than 0.75 ml l^{-1}.

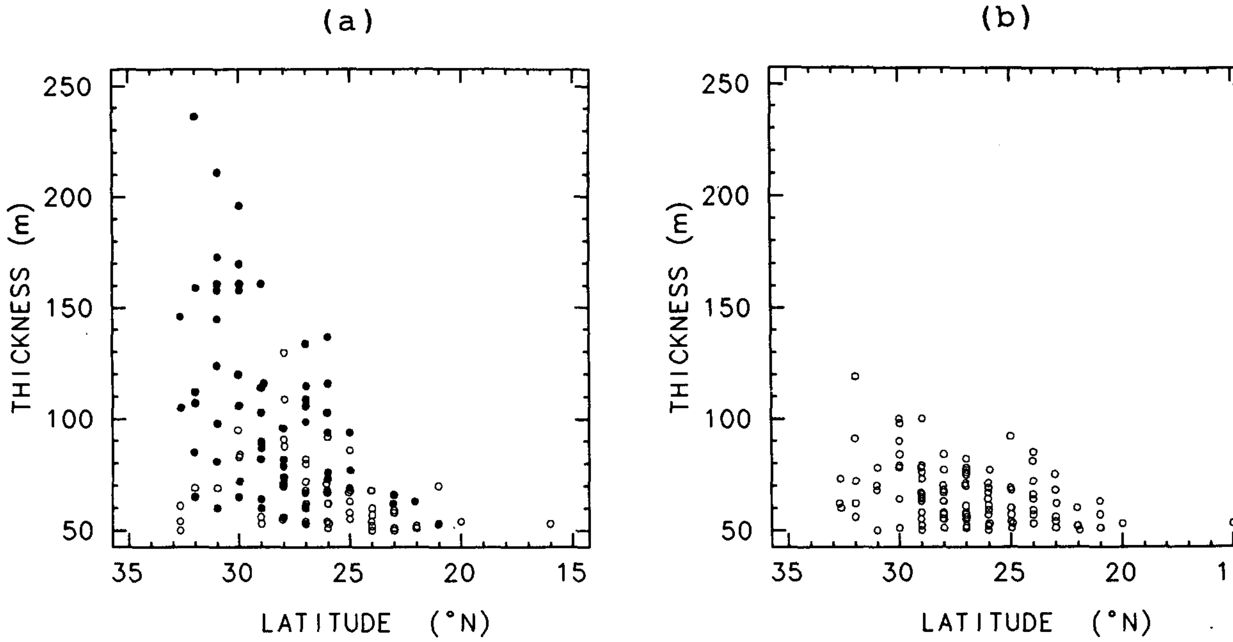

FIG. 9. As in Fig. 8 except for thickness vs latitude.

are scattered so widely that they show less correlation between θ and salinity than do the other summer cores and the winter cores.

4. Interannual variations of STMW

a. Spatial distribution of STMW

Figure 12 shows the spatial distribution of STMW cores for (a) each summer from 1972 to 1986 and (b) each winter from 1967 to 1987. Squares represent cores whose thickness is larger than the mean value, where the mean thickness is 90 m for summer cores and 65 m for winter cores. Solid symbols for summer cores represent cores whose AOU is lower than 0.75 ml l^{-1}. The location of the Kuroshio axis, indicated by a horizontal bar, shows that the current flowed with a stable large meander from summer 1976 to winter 1979.

In that period, the number of detected STMW cores was relatively small, especially in summer 1977 and winter 1978 and 1979. The STMW cores disappeared not only at latitudes north of the axis but also at the lower latitudes during the period. The number of cores was also small in the winters of 1968, 1974 and 1981. This seems to result partly from the lack of stations in 1968 and from the erosion of STMW due to the intense development of the surface mixed layer in 1974 and 1981. No core with AOU lower than 0.75 ml l^{-1} was sampled in the summer of 1976. The incidence of cores of above average thickness shows considerable variability: high in the summers of 1981, 1984 and 1986 and in the winters of 1967, 1971, 1975, 1985 and 1987; low in the summers of 1975, 1977 and 1980 and in the winters of 1976, 1977 and 1979. This variability is not surprising in view of the expected variability of the formation condition and the Kuroshio system.

b. Properties of STMW

Figure 13 shows the interannual variation of the properties of STMW cores. The values for each summer or winter are averaged over (a) low-AOU (less than 0.75 ml l^{-1}) cores for each summer and (b) all cores for each winter. Twice a standard deviation for each mean value is shown by a vertical bar. The properties varied with the approximate amplitudes of 1.5°C, 0.1 and 0.5 kg m^{-3} for θ, salinity and potential density in summer, while the amplitudes are rather small in winter.

The salinity of STMW seems to have a slow variation over a long period. For summer it was relatively low before 1981, while it increased in 1981 and then had a decreasing trend, with an exceptionally low value in 1983. The corresponding trend is also apparent for winter; the salinity of STMW increased in 1982 and then decreased slowly with one exception, the winter of 1984. There was another high-salinity period before the 1972 winter. There is no apparent trend of θ or potential density which depends strongly on θ. Although the standard deviations are large compared with the amplitude of the interannual variation, θ was relatively high in the summers of 1973, 1978 and 1983, while the corresponding variation is not clear for winter.

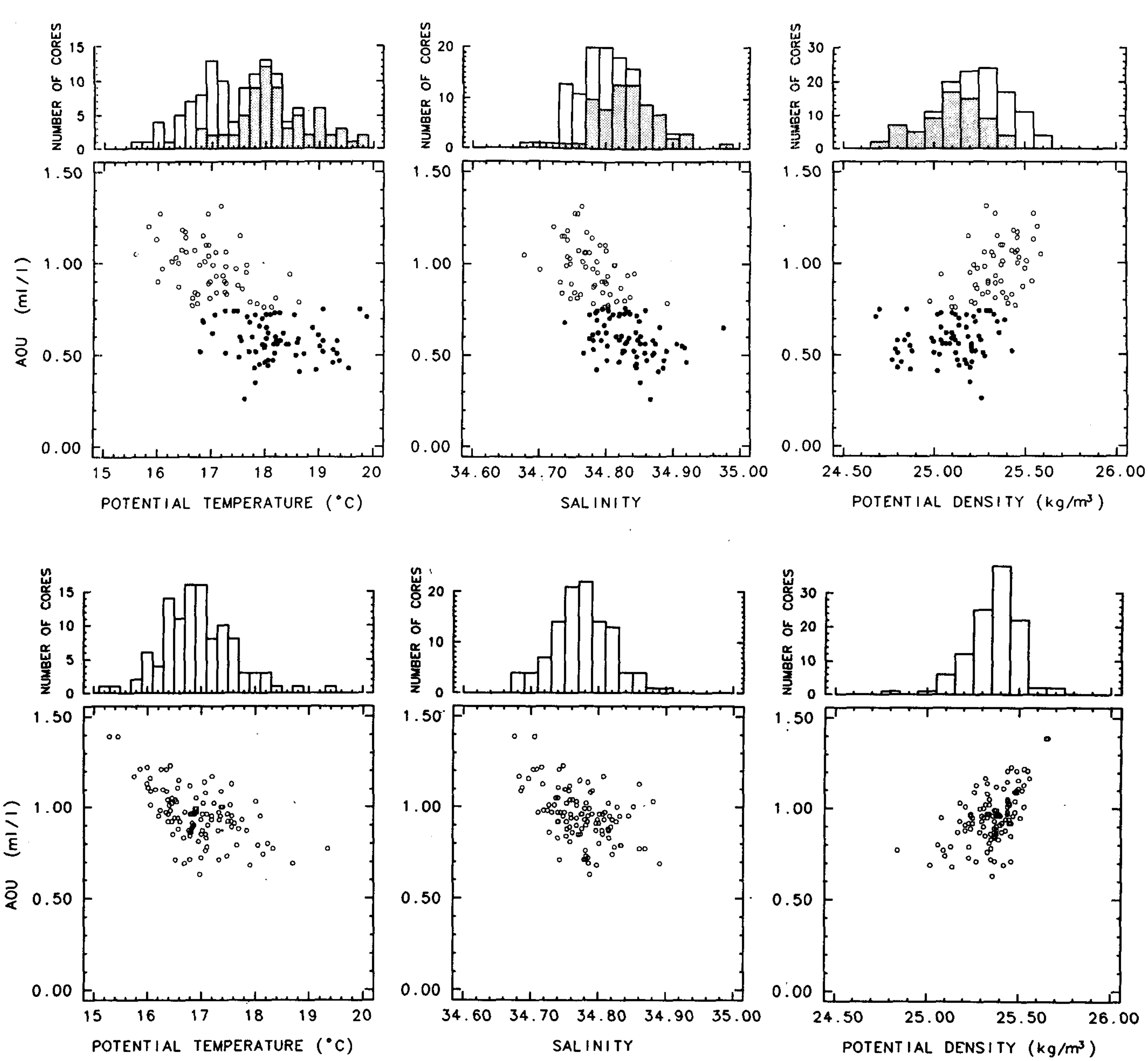

FIG. 10. Scatter diagrams of AOU vs θ, salinity and potential density for all STMW cores obtained in summer from 1972 to 1986 (upper panels) and in winter from 1973 to 1987 (lower panels). Each diagram is supplemented by a histrogram of each property. Closed circles on the diagram and stipple on the histograms represent new summer cores whose AOU is lower than 0.75 ml l^{-1}.

We computed lag correlations between the mean properties of each summertime STMW and those of the previous-winter, the following-winter and the next-summer, where summertime STMW refers to that of AOU lower than 0.75 ml l^{-1}. For salinity, we found that the correlation was remarkably high between the summer STMW and the following winter (Fig. 14), while it was low for the other two cases. This implies that interannual variation of salinity appears first in summer STMW, a situation consistent with the fact that the summer STMW is newer than the winter STMW.

5. Discussion of circulation and dissipation of STMW

The typical features of the spatial distribution and the typical properties of STMW obtained in the preceding sections (mainly in section 3) provide information about the circulation and dissipation of STMW. Discussion will be based on the premise that the main

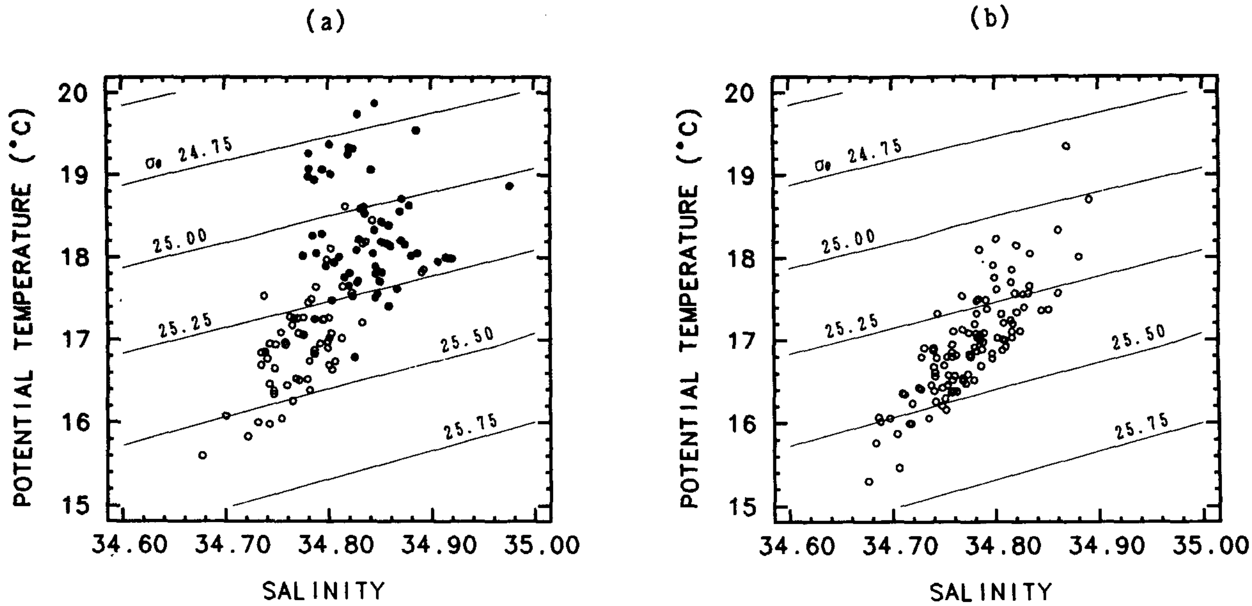

FIG. 11. Scatter diagrams of θ vs salinity with σ_θ contours plotted for all STMW cores obtained (a) in summer from 1972 to 1986 and (b) in winter from 1973 to 1987, with the same representation as in Fig. 8.

part of the STMW formation region is just south of the Kuroshio Extension (around 145°E) according to Hanawa's (1987) analysis of the wintertime outcrop area of STMW. Furthermore, by taking account of earlier suggestions (Masuzawa 1969, 1972; McCartney 1982), we also make the premise that the westward/southwestward flowing Kuroshio Countercurrent carries STMW to the 137°E section.

According to the characteristics of the spatial distribution of STMW cores shown in Fig. 7, new STMW formed in a given winter can be advected only as far south as about 26°N in the 137°E section by the following summer (after half a year) while it can be advected, along a path farther from the central ridge of the Kuroshio recirculation system, as far south as about 23°N by the following winter (after a year). Flow along an outer portion of the recirculation would probably be slower and also the associated advection path to the more southern portion of the 137°E meridian longer. Therefore, it is reasonable that the latitude at 137°E to which STMW originating in a given winter can be advected moves gradually southward. In addition, the half-year-old STMW appearing in summer lies at a shallower depth (Fig. 8) and also has a greater thickness (Fig. 9) than the one-year-old water in winter.

The relationship between the above features of the circulation of STMW and the seasonal variability of the Subtropical Front (Yoshida and Kidokoro 1967; Uda and Hasunuma 1969; White et al. 1978) is noteworthy. White et al. (1978) used all available hydrographic data to calculate mean monthly zonal relative geostrophic flow (0/200 db) for the region of the subtropical front in the western North Pacific in order to specify the seasonal variation of the location and the strength of the front associated with the subtropical countercurrent. They showed that the strength of the front is greatest in spring and summer and weakest in autumn and winter. Additionally, they showed that the western portion of the front, which crosses the 137°E meridian, tends to be located farther north when it is stronger. As for the western portion, the front is stronger and farther north when a thick layer of new STMW has been advected to just north of the front, while the front is weaker and farther south when STMW has been advected to lower latitudes in smaller thicknesses. This fact implies that STMW may contribute to the maintenance of the front.

The difference between typical properties of new summer cores and those of winter cores can be related to another aspect of the circulation of STMW. Since the distribution of sea surface temperature over the outcrop area of STMW has large spatial variability (Hanawa 1987), it is suggested that each STMW should originally have individual properties dependent on the place where it is formed. Hence, new STMW appearing in summer and that appearing in winter is possibly advected from different regions of STMW formation. We should examine the spatial variability of the STMW formation region in order to relate the character of the properties of STMW to its circulation more clearly in the future.

The widely scattered distribution of the θ–S characteristics of new summer cores (Fig. 11a) suggests that properties of newly formed STMW change greatly from

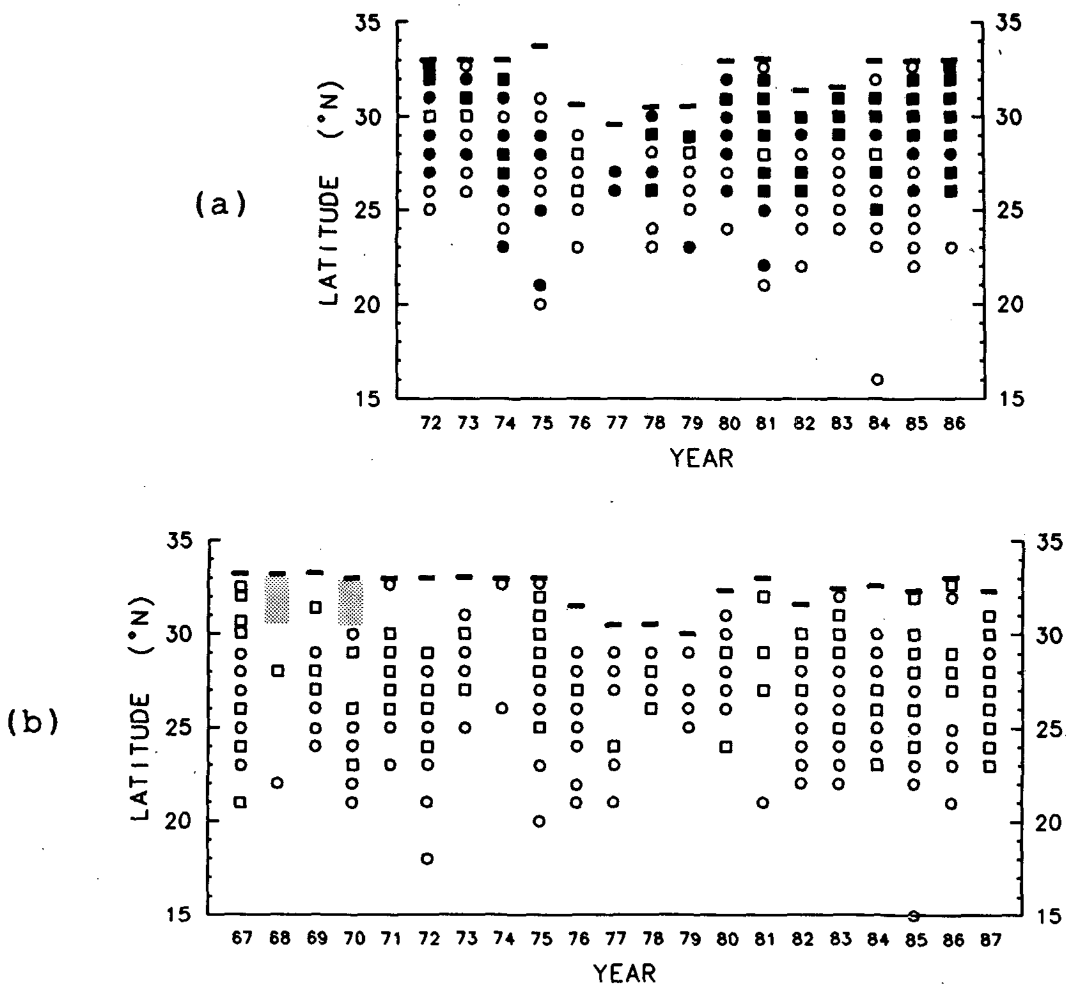

FIG. 12. Latitude of observed STMW cores vs years for (a) each summer from 1972 to 1986 and (b) each winter from 1967 to 1987. Squares represent cores whose thickness is larger than the mean values: 90 m for summer and 65 m for winter. Solid symbols for summer cores represent cores of AOU lower than 0.75 ml l^{-1}. Horizontal bars show the Kuroshio axes. Stippling indicates lack of stations.

year to year as a result of variations of the formation conditions, such as source-water properties and air–sea heat fluxes. On the other hand, those of winter cores are distributed compactly (Fig. 11b). STMW in the winter sections could have undergone rather large diapycnal mixing with the main thermocline water as a result of longer residence time. This mixing possibly reduces the dispersiveness of the properties of STMW because the water in the main thermocline probably has extremely small temporal and spatial variability as compared with STMW.

6. Conclusions

The AOU values of the ensembles of STMW cores indicate that the major part of STMW appearing in both summer and winter is formed in the immediately previous winter: the modal age for summer is one-half year while for winter it is one year. It was also indicated that the STMW formed in a given winter is renewed or mingled with the main thermocline and so loses its original properties within two years of its formation. In addition, it was suggested that STMW formed in a given winter can be advected to the 137°E meridian only as far south as about 26°N within half a year, while it can be advected as far south as about 23°N within one year. This character of advection seems to be associated with the seasonal variation of the subtropical front. Typical values of θ, salinity and potential density of the STMW appearing in summer (winter) are 17.5°–19.1°C (15.9°–17.7°C), 34.77–34.89 (34.71–34.83) and 24.75–25.35 kg m^{-3} (25.05–25.55 kg m^{-3}). It is further suggested that STMW encountered in winter has undergone stronger diapycnal mix-

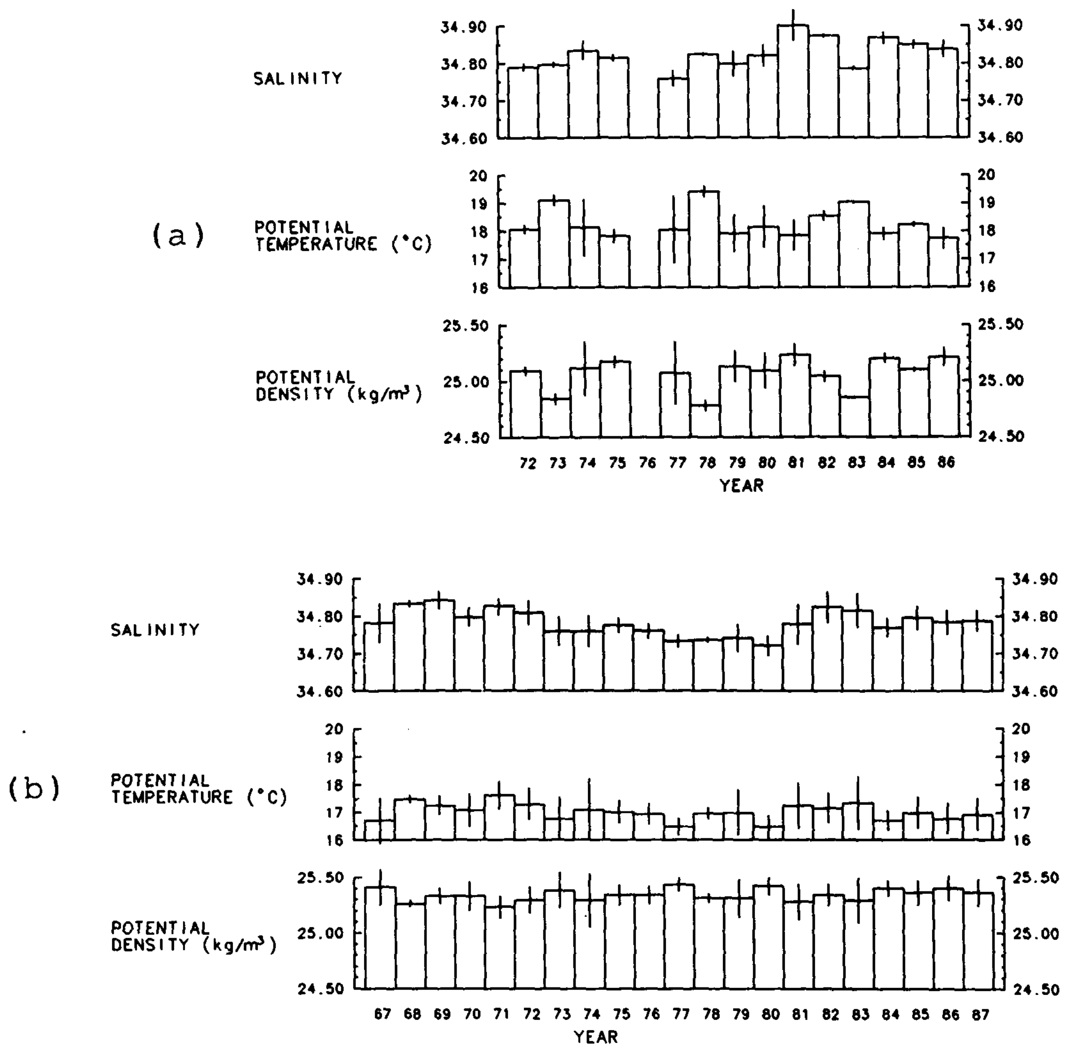

FIG. 13. Salinity, θ and potential density of STMW for (a) each summer and (b) each winter, averaged over low-AOU (lower than 0.75 ml l^{-1}) cores for each summer and all cores for each winter. Twice a standard deviation for each mean value is shown by a vertical bar.

ing with the main thermocline water than has the new summer STMW.

Less STMW was observed during the period of the Kuroshio's large meander, especially in the summer of 1977 and the winters of 1978 and 1979. Large regions where the STMW was quite thick were observed in the summers of 1981, 1984 and 1986 and in the winters of 1967, 1971, 1975, 1985 and 1987, while such regions were small in the summers of 1975, 1977 and 1980 and in the winters of 1976, 1977 and 1979. The salinity of STMW was relatively low before 1981, while it increased in the summer of 1981 and has since had a slowly decreasing trend; the change in salinity appeared first in summer.

We have inferred several aspects of the circulation, dissipation and formation of STMW from the main features, both of the spatial distribution and of the properties of STMW along the 137°E meridian. Further clarification of its circulation requires the examination of data from a whole region of the western North Pacific. The dissipation process of STMW will be made much clearer through investigating the seasonal and the main thermocline waters along with STMW over the subtropical gyre. Since we have examined the sections along the single meridian, i.e., the 137°E meridian, and these sections do not include the main part of the STMW formation region, we cannot fully deal with its formation process and its influence on the subtropical gyre. Clarification of such a process and its influence requires the examination of variations of both the air–sea heat flux over the formation region and the Kuroshio with regard to its mass transport and its water properties, along with the investigation of the subsurface water throughout the gyre.

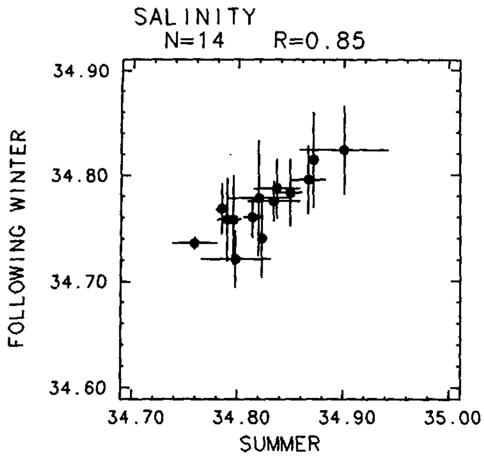

FIG. 14. Correlation between mean salinity of each summer STMW from 1972 to 1986 and that of the following winter, where summer STMW refers to that of AOU lower than 0.75 ml l^{-1}. Horizontal or vertical bars indicate twice a standard deviation for each mean salinity. R and N refer to a correlation coefficient and a number of samples, respectively.

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REFERENCES

Andow, T., 1987: Year-to-year variation of oceanographic sub-surface section along the meridian of 137°E. *Oceanogr. Mag.*, **37**, 47–73.

Ebbesmeyer, C. C., and E. J. Lindstrom, 1986: Structure and origin of 18°C water observed during the POLYMODE Local Dynamics Experiment. *J. Phys. Oceanogr.*, **16**, 443–453.

Fieux, M., and H. Stommel, 1975: Preliminary look at feasibility of using marine reports of sea surface temperature for documenting climatic change in the Western North Atlantic. *J. Mar. Res.*, **33**(Suppl.), 83–95.

Hanawa, K., 1987: Interannual variations in the winter-time outcrop area of Subtropical Mode Water in the western North Pacific Ocean. *Atmos.-Ocean,* **25,** 358–374.

——, and I. Hoshino, 1988: Temperature structure and mixed layer over the Izu Ridge. *J. Mar. Res.*, **46,** 683–700.

Hsiung, J., 1985: Estimates of global oceanic meridional heat transport. *J. Phys. Oceanogr.*, **15,** 1405–1413.

Jenkins, W. J., 1980: Tritium and He^3 in the Sargasso Sea. *J. Mar. Res.*, **38,** 533–569.

Kawai, H., 1972: Hydrography of the Kuroshio Extension. *Kuroshio—Its Physical Aspects,* H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 235–352.

Masuzawa, J., 1967: An oceanographic section from Japan to New Guinea at 137°E in January 1967. *Oceanogr. Mag.,* **19,** 95–118.

——, 1969: Subtropical mode water. *Deep-Sea Res.,* **16,** 463–472.

——, 1972: Water characteristics of the North Pacific Central Region. *Kuroshio—Its Physical Aspects,* H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 95–127.

——, and K. Nagasaka, 1975: The 137°E oceanographic section. *J. Mar. Res.,* **33,** 109–116.

McCartney, M. S., 1982: The subtropical recirculation of Mode Waters. *J. Mar. Res.,* **40**(Suppl.), 427–464.

Suga, T., and K. Hanawa, 1989: Characteristics of the mixed layer along the Kuroshio and the formation area of Subtropical Mode Water. To be submitted to *J. Mar. Res.*

Taft, B. A., 1972: Characteristics of the flow of the Kuroshio south of Japan. *Kuroshio—Its Physical Aspects,* H. Stommel and K. Yoshida, Eds., University of Tokyo Press, 165–216.

Talley, L. D., and M. E. Raymer, 1982: Eighteen degree water variability. *J. Mar. Res.,* **40**(Suppl.), 752–775.

Tsuchiya, M., 1982: On the Pacific upper-water circulation. *J. Mar. Res.,* **40**(Suppl.), 777–799.

Uda, M., and K. Hasunuma, 1969: The eastward Subtropical Countercurrent in the western North Pacific Ocean. *J. Oceanogr. Soc. Japan,* **25,** 201–210.

White, W. H., K. Hasunuma and H. Solomon, 1978: Large-scale seasonal and secular variability of the Subtropical Front in the western North Pacific from 1954 to 1974. *J. Geophys. Res.,* **83,** 4531–4544.

Worthington, L. V., 1959: The 18° water in the Sargasso Sea. *Deep-Sea Res.,* **5,** 297–305.

——, 1972: Negative oceanic heat flux as a cause of water-mass formation. *J. Phys. Oceanogr.,* **2,** 205–211.

——, 1976: On the North Atlantic circulation. *Johns Hopkins Oceanographic Studies,* No. 6, The Johns Hopkins University Press, 110, pp.

——, 1977: The intensification of the Gulf Stream after the winter of 1976–1977. *Nature,* **270,** 415–417.

Yoshida, K., and T. Kidokoro, 1967: A subtropical counter-current in the North Pacific—An eastward flow near the subtropical convergence. *J. Oceanogr. Soc. Japan,* **23,** 88–91.

Zhao, Y. P., and G. A. McBean, 1986: Annual and interannual variability of the North Pacific ocean-to-atmosphere total heat transfer. *Atmos.-Ocean,* **24,** 265–282.