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Distribution of the density ratio in the North Pacific

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Abstract: We estimated the spatial distribution of the density ratio (R_ρ) in the upper 1000 db of the North Pacific from the WOCE data set. The mode value of R_ρ was equivalent to those reported in former studies (3∼4), meaning that the double diffusive convection is moderate or weak; however, the "hot spots" of double diffusive convection were found off eastern Hokkaido and at the formation region of the ESTMW (Eastern Subtropical Mode Water). The vertical eddy double diffusive flux of the density there is up-gradient, where the eddy diffusivity was negative: $-(9\sim8)\times10^{-5}\mathrm{m}^2/\mathrm{s}$ in the area off eastern Hokkaido and $-(8\sim4)\times10^{-5}\mathrm{m}^2/\mathrm{s}$ in the ESTMW region. This result means the importance of double diffusive convection to the water mass formation in certain regions. While lower R_ρ of the ESTMW region is related to the lateral mixed layer density ratio (R_L) estimated in the former studies, the mechanism maintaining large R_ρ in other regions still remains to be a topic of future study.

Keywords: *Density ratio, Mode Water, Vertical eddy diffusivity, Water mass structure*

1. Introduction

World ocean density ratio distributions were first investigated by INGHAM (1966). Here, the density ratio is defined as $R_\rho = \alpha\overline{\theta_z}/\beta\overline{S_z}$, where $\overline{\theta_z}$ and $\overline{S_z}$ are mean vertical gradients of potential temperature and salinity, respectively. $\alpha = \dfrac{1}{\rho}\dfrac{\partial\rho}{\partial\theta}$ and $\beta = \dfrac{1}{\rho}\dfrac{\partial\rho}{\partial S}$ are the thermal expansion and the haline contraction coefficients, respectively. The TURNER angle (Tu) is defined as a function of R_ρ, *i.e.*, $Tu = \tan^{-1}\left(\dfrac{R_\rho+1}{R_\rho-1}\right)$ (RUDDICK, 1983). When R_ρ is larger than 1 (Tu ranges between 45° and 90°), the salt finger convection occurs, and when R_ρ ranges between 1 and 0 (Tu ranges between −45° and −90°), the diffusive convection occurs. The activity of both type of convection is intensified as R_ρ becomes closer to unity. Especially when R_ρ ranges between 1 and 2, the salt finger convection is so active that salt and heat are efficiently transported downwards and that for R_ρ ranging between 0.5 and 1, the diffusive convection is active to transport heat and salt upward.

INGHAM (1966) showed that R_ρ is constant (≈ 2) in the main thermocline of the Central Waters in world ocean subtropical gyres. SCHMITT (1981, 1990) explained that salt finger convection is a major mechanism of the formation of the Atlantic Central Water maintaining such a constant value. Later on, mapping of R_ρ in the world ocean has been tried by FIGUEROA (1996) and YOU (2002) using the Levitus data set. FIGUEROA (1996) then pointed out that R_ρ in the main thermocline is less than 2 in most of the ocean except in the Central Waters in the North Pacific where R_ρ is larger than 3∼4.

The double diffusive convection occurs when relatively warm and salty water overlies cooler and fresher water, or vice versa. Such areas are generally found in various oceans; if a certain oceanic area has such lower values of R_ρ around unity, it should be called as a "hot spot" of double diffusive convection, where effective vertical mixing should take place.

It has been suggested that enhanced vertical

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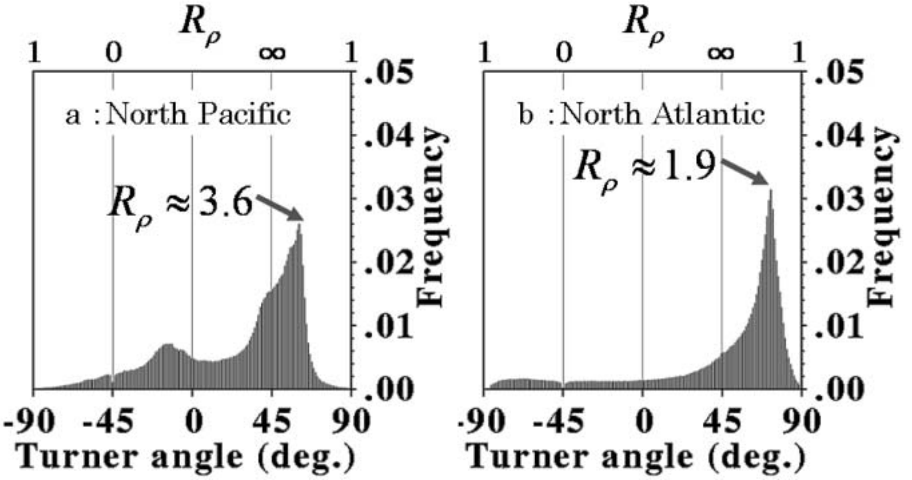


Fig. 1. The occurrence frequency of R_ρ in the upper 1000 db (a) in the North Pacific and (b) in the North Atlantic Oceans estimated from the WOCE data set.

mixing can produce significant effects on various large scale features of the ocean, and such effects have driven active studies and researches on this subject. BRYAN (1987) investigated the sensitivity of meridional overturning (MOT) and associated meridional heat flux by using a coarse resolution basin-scale model to K_V (the vertical eddy diffusivity of density). By varying K_V from 1×10^{-5} to 5×10^{-4} m^2/s, he reported that the magnitude of meridional mass transport in the model increased by an order of 4-fold. If, however, "hot spot" of double diffusive convection is ubiquitous in the world ocean, the effect of associated differential flux of heat and salt and negative flux of density may not be negligible. GARGETT and HOLLOWAY (1992) used the same model domain and forcing used by BRYAN (1987), but taking such a differential flux into account, with heat (T) and salinity (S) as separate fields having different diffusivities. By varying the ratio of diffusivity of S and T defined as $d = K_S/K_T$, they showed that the magnitude and the direction of MOT and the mean steady state distribution of T and S are sensitive to this parameter d.

Recent observations, however, revealed the enhanced vertical diffusivities over rough topography (*e.g.*, POLZIN *et al.*, 1997) due to the tidal effects near the boundary regions. If turbulent diffusivities are indeed enhanced in the deep ocean, such boundary mixing processes might affect the modification of water masses and the circulation pattern of world oceans (SAENKO and MERRYFIELD, 2005), and the relative importance of double diffusive convection will be smaller, given that R_ρ in the deep ocean are not significantly smaller than those in the upper ocean (YOU, 2002). The result of these observations may limit the effect of double diffusive convection in the deep ocean, but the double diffusive convection still remains important in the upper ocean where turbulent diffusivities are only of the order of 10^{-5} m^2/s and the diffusivities of T and S differ significantly (ST. LAURENT and SCHMITT, 1998).

Recently, the concept of lateral mixed layer density ratio (hereafter referred to as $R_L = \alpha \Delta T_L / \beta \Delta S_L$, where ΔT_L and ΔS_L are the horizontal temperature and salinity differences between the successive mixed layers several tens of kilometers apart) is introduced to explain the mechanism maintaining the main thermocline R_ρ value through the salt finger convection. These studies are motivated by the regulator theory proposed by STOMMEL (1993) and STOMMEL and YOUNG (1993). They found R_L over the basin scale is close to 2 in the temperature range between 7 and 17 °C and assumed a certain process, such as a random rainfall at sea surface controls the temperature and salinity field in the mixed layer to maintain this particular temperature and salinity

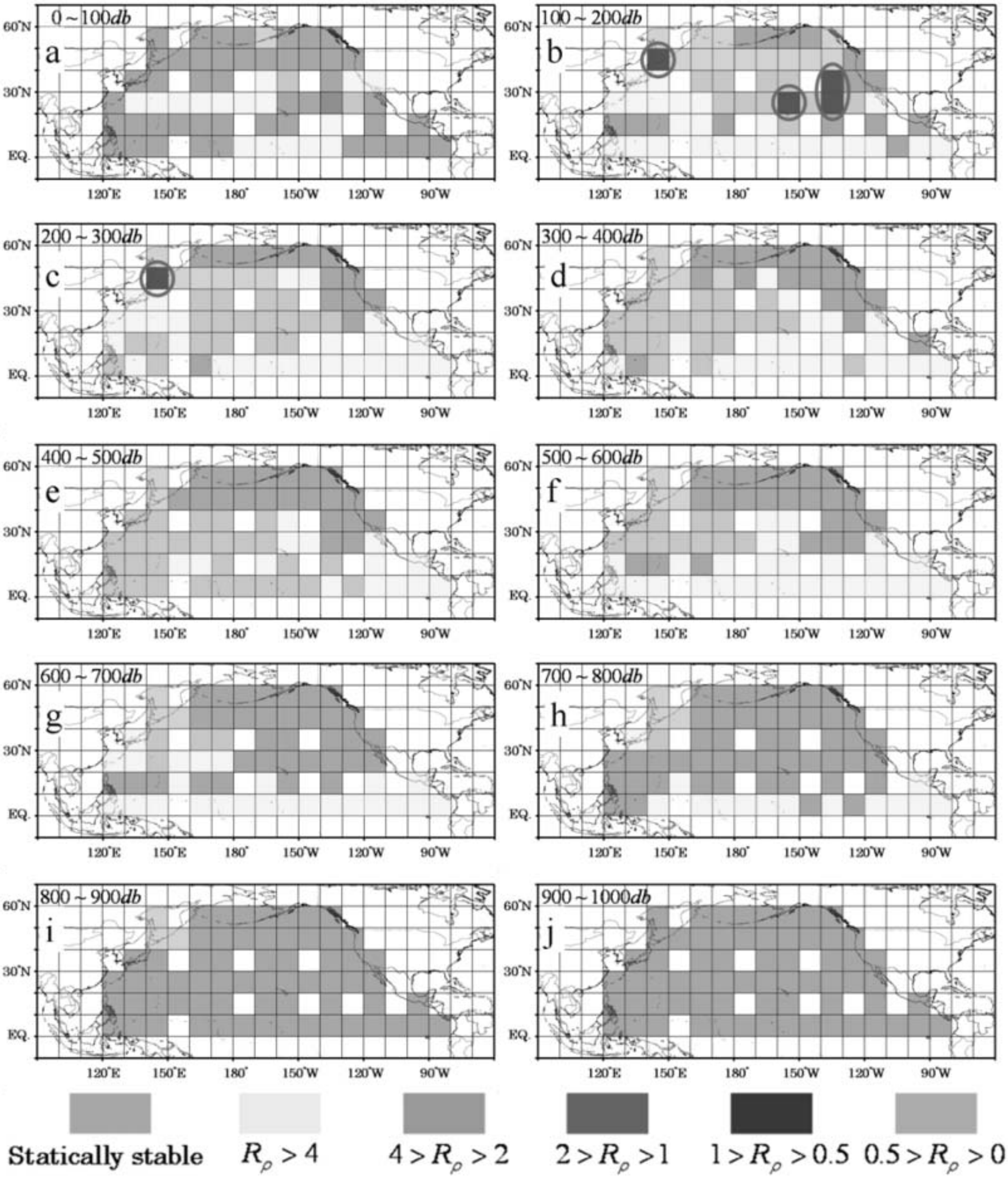


Fig. 2. Horizontal distributions of mode value of R_ρ in 10 degree boxes between the pressure surfaces. Open circles indicate the hot spots.

relation. Subsequently, Chen (1995) used the Levitus climatological data set to show R_L in the same temperature range is less than 2 which supports the Stommel's idea (Stommel, 1993). Rudnick and Ferrari (1999) investigated this lateral changes of temperature and salinity in the mixed layer in more detail in the Northeast Pacific, and obtained a surprising result that lateral changes in temperature and salinity are compensated in density at scales less than O (100 km), and a resulting R_L is close to unity. Ferrari and Young (1997)

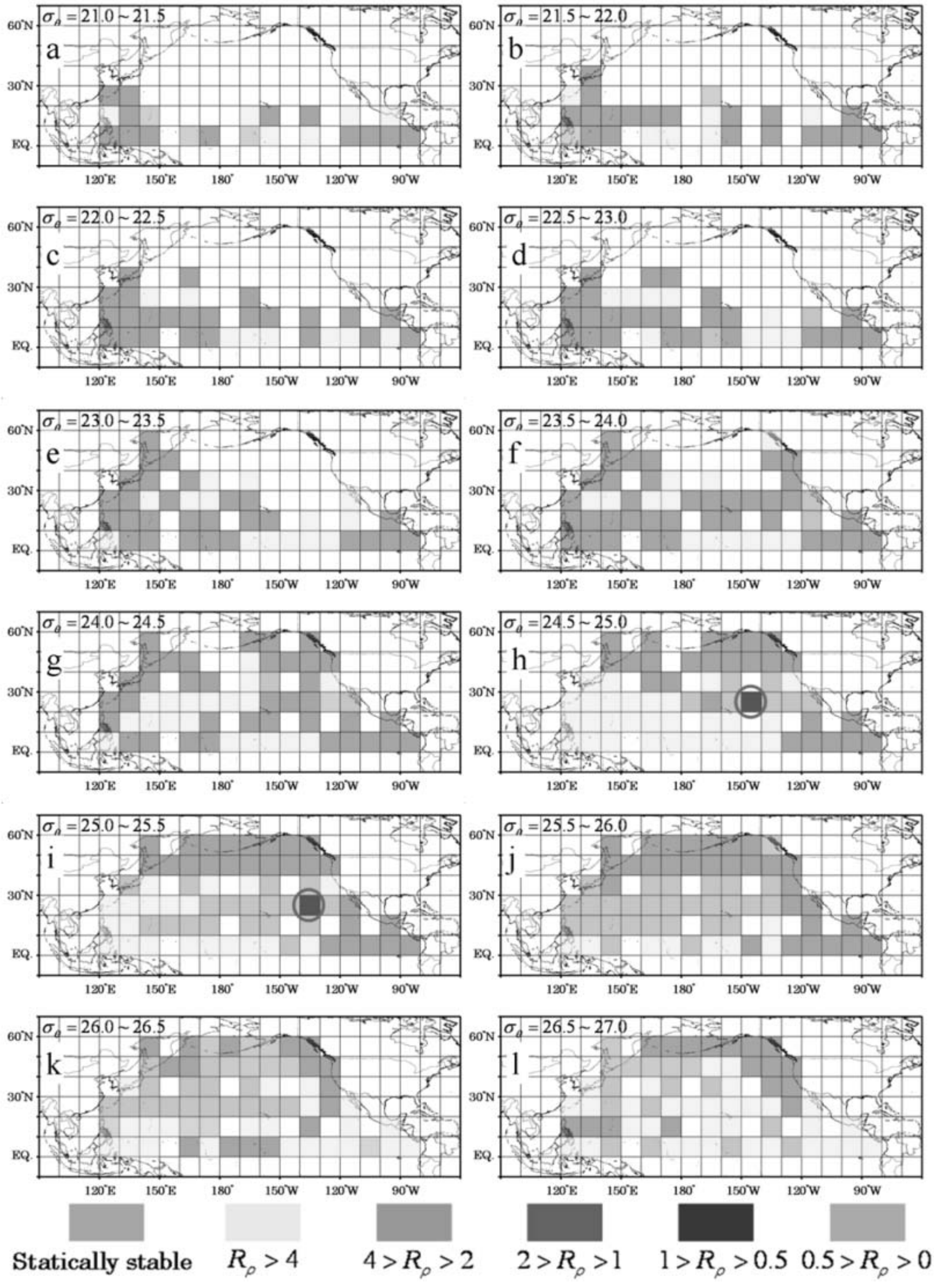


Fig. 3. Same as in Fig. 2, but for the designated sigma-theta surfaces. Open circles indicate the hot spots.

explained this low R_L by the slumping of slightly dense water in a surface layer of less dense water, and in the course of this slumping, horizontal density differences are easily disappeared to have R_L close to unity. This model, however, cannot explain the large scale R_L having the value of 2, and the R_ρ value also having 2 in the main thermocline. Recent idea of explaining this contradiction is given by SCHMITT (1999) that such density compensating temperature–salinity anomaly called as "spice" is consumed by the salt finger convection while the upper layer water being subducted, and the R_ρ is kept 2 in the main thermocline.

The problem raised here is the difference in the mode of R_ρ values between the North Pacific and the other oceans. The examples are shown in Fig. 1 for the WOCE data set (WOCE Global Data Ver.3, 2002, upper 1000 db) in the North Pacific (Fig. 1a) and in the North Atlantic (Fig. 1b). The mode in the North Atlantic is close to 2, while that in the North Pacific is larger than 3. This means that the salt finger convection is not so active in the North Pacific. Is this right? Are there no "hot spots" of double diffusive convection in the North Pacific? This higher value of R_ρ is usually explained by the fact that average salinity near a surface layer in the North Pacific is lower than that in the North Atlantic caused by strong evaporation over the entire Atlantic. However, this higher value of R_ρ could not be maintained by the mechanisms explained by the theories above. To solve this problem, we must know the basic water mass structures in the North Pacific through observing the detailed R_ρ distribution pattern. In the present study, the activity of double diffusive convection in the North Pacific is investigated through the R_ρ distribution in the upper 1000 db WOCE data set because, below this level, the stratification is usually highly stable.

2. Data processing

Before calculating R_ρ and Tu, all the WOCE CTD casts underwent several processes. Firstly, potential temperature (θ) and salinity were calculated and linearly interpolated at 1 db intervals. The CTD data sets stored at more than 2 db interval were removed for consistency of the quality of data. Secondly, temperature and salinity were vertically smoothed by 11 points (10 db) running mean. Lastly, vertical gradients were calculated by a 10 db least square fit. The α and β were calculated by differentiating equation of state (UNESCO, 1981) by temperature and salinity respectively. The occurrence frequencies of R_ρ values are estimated at each pressure interval (*e.g.*, 0〜100 db) or at each designated sigma–theta (hereafter σ_θ) interval (*e.g.*, 21.0〜21.5 σ_θ) and the peak values of the R_ρ are plotted at each 10 degree box in latitude and longitude to analyze the most favorable mode of double diffusive convection.

3. The horizontal distribution at the constant pressure and density surfaces

Shown in Fig. 2 are the horizontal distributions of R_ρ on pressure surfaces. In higher latitude region beyond 40°N, most fluid columns are stably stratified. In lower latitude region between the equator and 20°N in the layer from the surface to 800 db, the mode values exceed 4, suggesting the salt finger convection is not so active. On the other hand, in the mid–latitude (Subtropical Gyre) between 200 and 500 db, the mode values were between 2 and 4, suggesting the existence of weak salt finger convection. This is in contrast to the North Atlantic where the mode of R_ρ is less than 2.

Looking at the mode value distributions more precisely, we can see that the salt finger convection is active ($R_\rho<2$) in the shallower layer between 100 and 300 db in the area off eastern Hokkaido (40〜50°N, 140〜150°E) and in the eastern sub–tropical North Pacific (20〜30°N, 150〜130°W). These regions correspond to the region where the North Pacific Intermediate Water (NPIW) and the Eastern Subtropical Mode Water (ESTMW) are formed, respectively. The NPIW is defined as a thick salinity minimum around 26.7〜26.9 σ_θ in the western North Pacific (*e.g.*, QIU and JOYCE, 1992). The ESTMW is defined as a pycnostad (a minimum of potential vorticity) water around 24.0〜25.4 σ_θ in the eastern North Pacific (*e.g.*, HANAWA and TALLEY, 2001). Strong modification/formation of water masses are

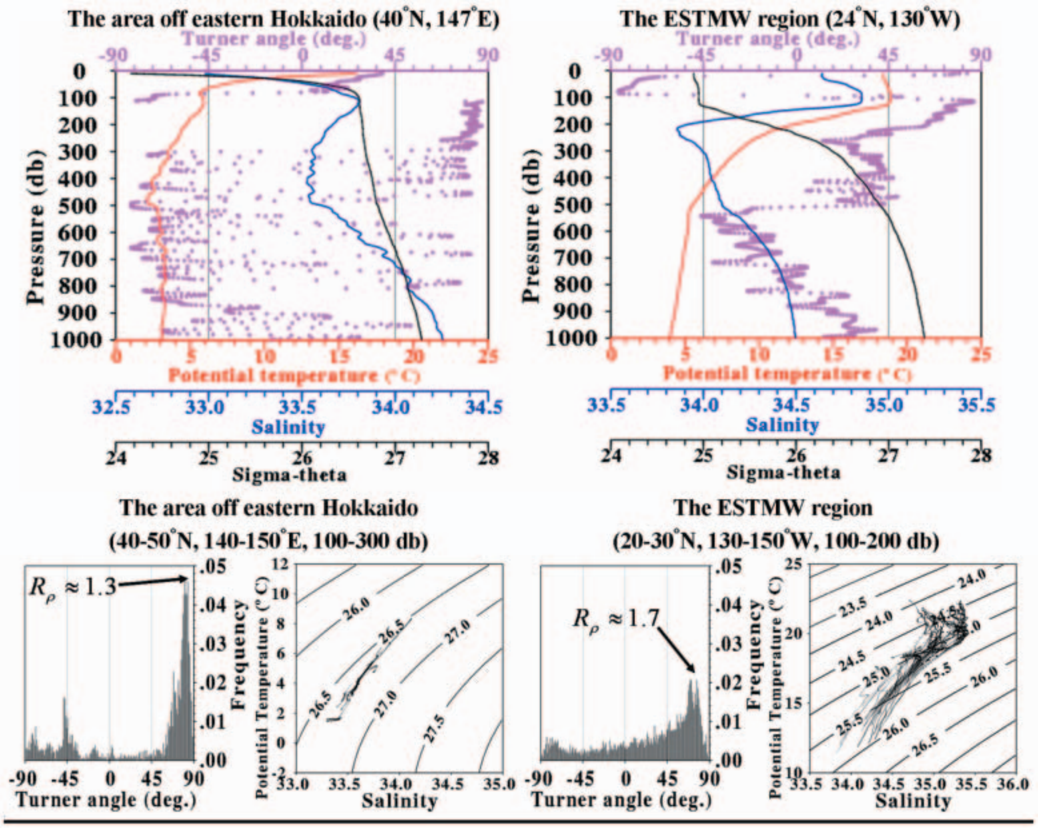


Fig. 4. (Upper two panels) : Examples of vertical profiles of potential temperature (red), salinity (blue), sigma-theta (black), and the TURNER angle (pink) at hot spots. (Bottom four panels) : Histograms of TURNER angle and -S diagrams plotted for the encircled regions shown in Figs. 2 and 3. Left two panels for the area off eastern Hokkaido (40–50° N, 140–150° E. 100–300 db), and right two for the ESTMW region (20–30°N, 130–150°W. 100–200 db).

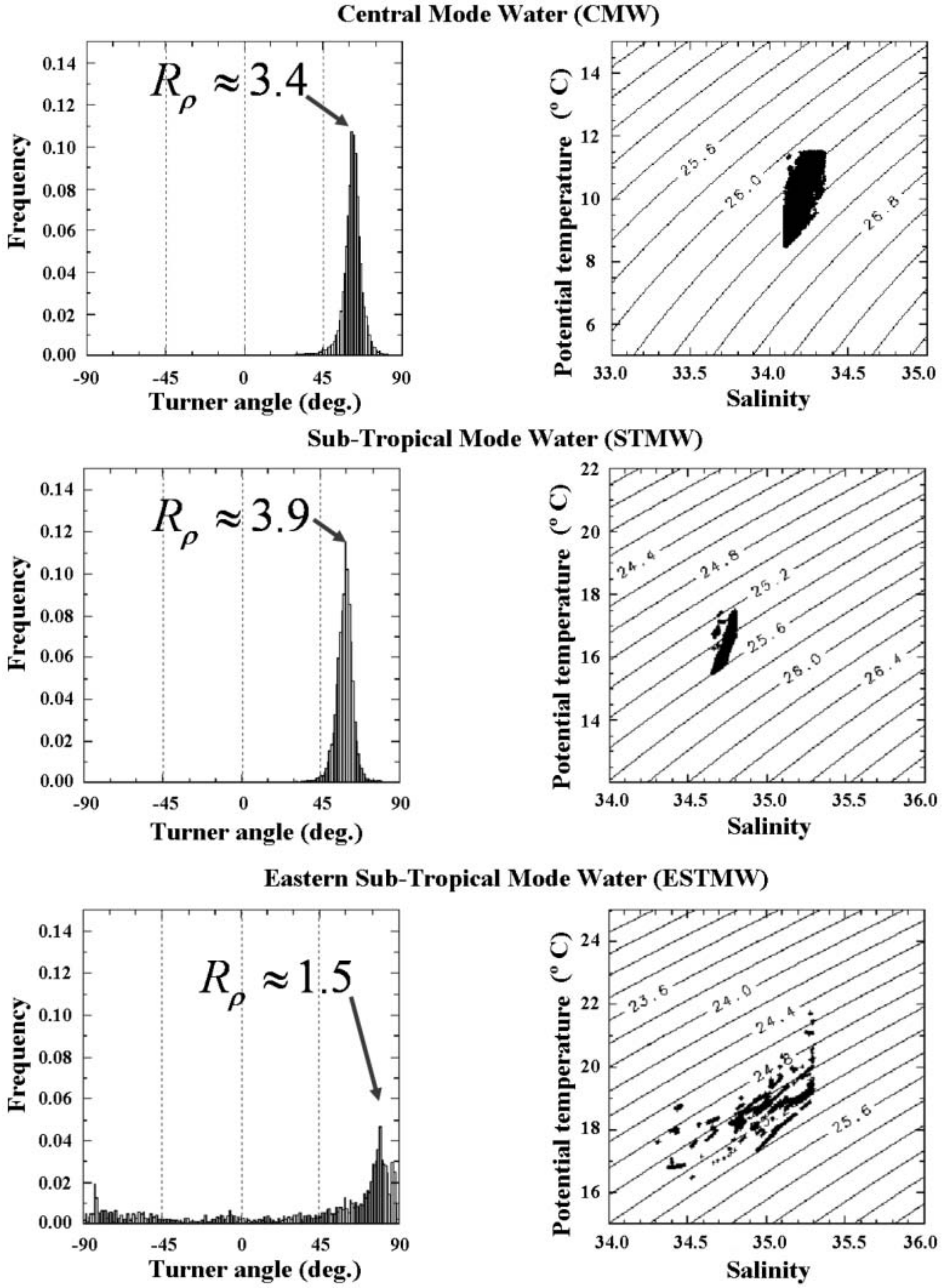
anticipated in these regions; then, these regions should be "hot spots" of salt finger convection, which should have an important role in the modification formation of these waters. In the area off eastern Hokkaido, weak diffusive convection is expected to occur in the layer below 300 db to 900 db.

R_ρ distributions on σ_θ surfaces (Fig. 3) show slight changes in the mode distribution from Fig. 2. In the shallower layers with σ_θ being less than 24.0, fluid layers are almost statically stable; however, the layers where σ_θ ranges between 25.0 and 26.5 in the sub–tropical gyre ($2<R_\rho<4$) suggest existence of weak salt finger convection. On the other hand, in the deeper layers in the high latitude, weak diffusive convection is anticipated.

Hot spots found in Fig. 2 are also found in density layers with σ_θ ranging between 24.5 and 25.0 in the eastern sub–tropical North Pacific, but as for in the area off eastern Hokkaido, hot spots become rather ambiguous and undetectable in presented density surfaces. The reason for this phenomenon will be discussed in the next section.

4. Hot spots

To see the vertical profile of R_ρ together with θ and S in the area off eastern Hokkaido (Fig. 4, top–left), in the layer between 100 and 300 db (at the top of thermocline), R_ρ is close to unity (Tu is close to 90°) suggesting the existence of strong salt fingering. However, in the layers deeper than 300 db, salt fingering and diffusive



Central Mode Water (CMW)

Sub-Tropical Mode Water (STMW)

Eastern Sub-Tropical Mode Water (ESTMW)

Fig. 5. Histograms of Turner angle and θ-S relationship for Central Mode Water (33〜40° N, 170〜150° W), for Subtropical Mode Water (20〜35° N, 120〜180° E) and for Eastern Subtropical Mode Water (20〜40° N, 120〜160° W). All of these Mode Waters are specified by core temperatures, salinities, and by potential vorticity ($<2.0\times10^{-10}\mathrm{m}^{-1}\mathrm{s}^{-1}$).

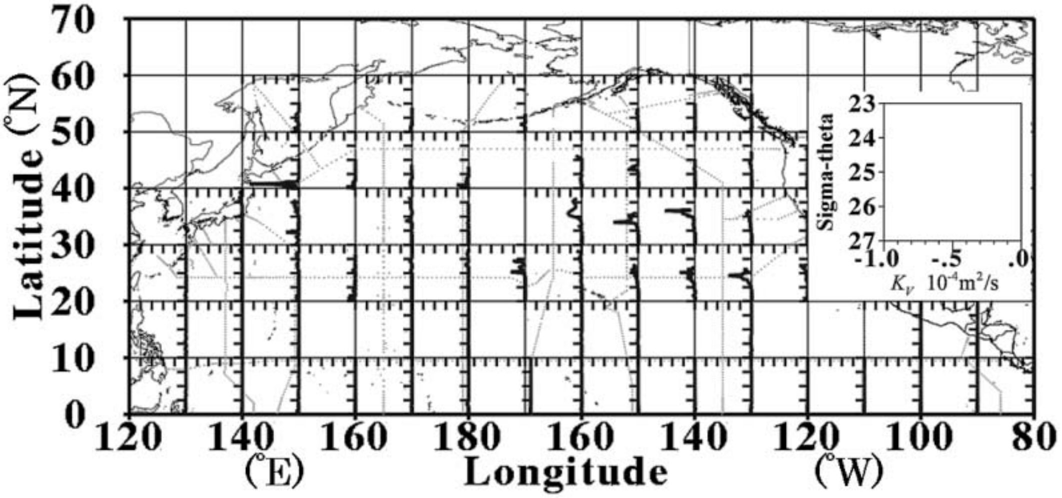


Fig. 6. Horizontal distributions of vertical eddy diffusivity of density in 10 degree boxes taking σ_θ for the vertical axis. See the inserted figure on the top right for reference.

convection layers are piled up alternatively suggesting the intrusive features possibly created by double diffusive convection (*e.g.*, RUDDICK and TURNER, 1979). Contrary to this, in the ESTMW region (Fig. 4, right), the salt finger convection favorable layer is found only in the layer between 100 and 200 db (at the top of thermocline), and in the deeper layers, the entire fluid column is stably stratified.

The occurrence frequency of R_ρ and θ–S relations in the area off eastern Hokkaido (Fig. 4, bottom– left) shows a sharp pointed peak in the salt finger convection regime ($45° < Tu < 90°$, $R_\rho \approx 1.3$). The θ–S relations aligned along an isopycnal line ($26.7\sigma_\theta$) also supports this low R_ρ value and it is showing that favorable layers of salt finger convection are confined to a narrow band in the density coordinate (around $26.6 \sim 26.7\sigma_\theta$) than in the pressure coordinate (100～300 db). It is, thus reasonable that hot spots found in pressure surfaces were rather ambiguous in density surfaces taking interval of $0.5\sigma_\theta$. A relatively small peak is found in the diffusive regime. This should be caused by the temperature inversions commonly observed in this region. As for in the ESTMW region (Fig. 4, bottom–right), a peak value of R_ρ is about 1.7, and this also suggests the occurrence of strong salt finger convection; however, the peak is not clearly defined but shows a flat distribution. The θ–S relations show a complicated structure contaminated by a certain surface process.

5. Mode Waters in the North Pacific

Two hot spots for double diffusive convection in the North Pacific show different features. Especially at the formation region of ESTMW, the θ–S relationship showed a complicated structure. It is thus worth comparing this region with other typical Mode Waters in the North Pacific, such as the Central Mode Water (CMW) and the Subtropical Mode Water (STMW), and discussing the processes to maintain the thermocline in the North Pacific in this section. The CMW is characterized as a pycnostad (minimum of potential vorticity) water centered at $26.2\sigma_\theta$ surface found at the western coast of the Kuril Islands to 150°W and between the Kuroshio Extension Front (approx. 33°N) and the Kuroshio Bifurcation Front (approx. 40°N) (SUGA *et al.*, 1997). The STMW is also a pycnostad water centered at $25.2\sigma_\theta$ surface found in the Kuroshio region to the International Date Line and is limited between 20°N and 40°N. As shown in Fig. 5, the mode values of R_ρ are 3.4 for the CMW and 3.9 for the STMW, respectively, suggesting the salt finger convection is not active. However, in the ESTMW region, the mode value is less than

2 (=1.5). This suggests that the mechanism proposed by SCHMITT (1999) works here indicating the importance of salt finger convection to form the ESTMW. This point is noted by FERRARI and RUDNICK (2000) at the same observation site, however, the mechanism of maintaining such large R_ρ in the other Mode Waters in the North Pacific is unclear. The salt finger convection is too weak in these locations to maintain large scale constant R_ρ values larger than 2 in the thermocline (FIGUEROA, 1996 also pointed out this).

6. Vertical diffusivity of density deduced by the formulation by ZHANG *et al.* (1998)

The important effect of double diffusive convection is the effective downward transport of density. In both types of convection, density gradient is intensified, that is, the sign of eddy diffusivity becomes negative. ZHANG *et al.* (1998) investigated this effect through parameterizing eddy diffusivities by R_ρ, and pointed out that meridional overturning cell was weakened and deeper temperature and salinity increased in the presence of double diffusive convection. Here, we use their parameterization, and show the horizontal distribution of vertical eddy diffusivity in Fig. 6. Profiles shown here are the averages of vertical diffusivity of density within each σ_θ surface (K_V) in respective boxes. "Hot spots" can be found in the σ_θ layer around 26.7 in the area off eastern Hokkaido and between in the ESTMW area, respectively. K_V was estimated as (9〜8) $\times 10^{-5}$m^2/s in the area off eastern Hokkaido and $-$ (8〜4) $\times 10^{-5}$m^2/s in the ESTMW area. These magnitudes are larger than the typical K_V value 1×10^{-5}m^2/s in the thermocline (ST. LAURENT and SCHMITT, 1998) by about an order, showing the importance of double diffusive convection to the water mass formation in respective region.

7. Summary and discussion

We investigated the water mass structure and detailed R_ρ distribution in the upper 1000 db of the North Pacific by using the WOCE data set. The “hot spots” of double diffusive convection were found in the area off eastern Hokkaido and in the Eastern North Pacific where the NPIW and the ESTMW are formed. Mode values of R_ρ in these regions are 1.3 and 1.7, respectively. The salt finger convection must be an important process for water mass madification formation in these regions. Although the favorable condition for the onset of salt finger convection was satisfied in most of the mid–latitude (the subtropical gyre) between 200〜500 db or between 25.0〜26.5σ_θ including the CMW and the STMW, the modes of R_ρ in these regions lie between 3 and 4, suggesting salt finger convection is not so active. The mechanism of maintaining large value of R_ρ in these regions is still unclear. This higher value of density ratio is usually explained by the fact that the average salinity near the surface layer in the North Pacific is lower than that in the Atlantic where the evaporation is so strong.

The subduction process causing inflow to the main thermocline occurs in winter when the surface mixed layers deepened through surface cooling. In this case, R_L estimated from the Levitus annual mean could not have direct connection with thermocline R_ρ, and the explanation presented by SCHMITT’s idea of “spice” holds true for the Atlantic, but not for the North Pacific except for ESTMW region as was shown in the present study. The observation field in the ESTMW region by RUDNICK and FERRARI (1999) was too limited to discuss the whole basin of the North Pacific; however, RUDNICK and MARTIN (2002) extended their analysis including the Indian and the Atlantic Oceans and concluded that this low value of R_L (≈ 1) is a common feature of all the oceans at the scales about O (3〜4km) where the mixed layer depth exceeds about 75 m. Therefore, in order to clarify the maintenance mechanism of thermocline R_ρ in the North Pacific, we must investigate winter time distribution of R_L more precisely in relation to the mixed layer depth. This problem will remain to be a topic of the future work.

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