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The activity of double diffusive convection investigated through the density ratio distribution in the Mixed Water Region (MWR) off Joban-Kashima and Sanriku Coasts to the north-east of Honshu, Japan

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Abstract : The activity of double diffusive convection in the Mixed Water Region (MWR) off Joban-Kashima and Sanriku Coast is investigated by using CTD data obtained from 1996 to 2000 in September or October. More than 60% of fluid column down to 500db (σ_θ is almost above 27.0) are unstably stratified to double diffusive convection. However, the activity of double diffusive convection differs year by year, namely, in 1998 and 2000, double diffusive convection is active, but not in 1996, 1997 and 1999. Our results indicate that active double diffusive convection should occur intermittently in MWR year by year. In years when double diffusive convection is active, $\sigma_\theta=26.8$ surface which characterize the North Pacific Intermediate Water (NPIW) is sandwiched by the salt finger layers above and diffusive convection layers below. This suggests that double diffusive convection should modify a source water of NPIW originated at the further north region of MWR while its southward extension.

Keywords : *double diffusive convection, salt finger, diffusive convection, density ratio, Turner angle, modification of water mass, NPIW*

1. Introduction

In the area where surface evaporation exceeds precipitation (this area usually corresponds to the subtropical gyre, see figure 2 by SCHMITT, 1994), warm and salty layer usually lies above underlying cold and fresh layer with the net stratification being stable. In this case, salt finger convection should occur because of faster diffusion of heat than salt. On the other hand, oscillatory diffusive convection should occur in the lower layer in the sub-polar region where warm and salty layers frequently exists under cold and fresh water. These two convections are called as double diffusive convection (e.g. TURNER, 1973). The activity of double diffusive convection is well described by the density ratio or the TURNER angle defined as,

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$$\text{Density Radio } R_\rho = \frac{\alpha\overline{\theta_z}}{\beta\overline{S_z}}$$

$$\text{Turner Angle } Tu = \tan^{-1}\left(\frac{R_\rho+1}{R_\rho-1}\right), \qquad (1)$$

where $\overline{\theta_z}$ and $\overline{S_z}$ are mean vertical gradients of potential temperature and salinity, respectively. $\alpha = \frac{1}{\rho}\frac{\partial\rho}{\partial\theta}$, $\beta = \frac{1}{\rho}\frac{\partial\rho}{\partial S}$ are the thermal expansion and haline contraction coefficients, respectively. When R_ρ is larger than 1 (Turner angle ranges between 45° and 90°), salt finger convection occurs. When R_ρ is ranged between 1 and 2, convection is so active that salt and heat are efficiently transported downwards, but the downward transport of density due to salt exceeds than that of heat eventually results in the intensification of net density gradient. As for diffusive convection, R_ρ should be ranged between 1 and 0 (TURNER angle between −45° and −90°), and the activity of convection is also intensified as R_ρ becomes unity, and the net density gradient is also intensified. This curious behavior of double diffusive convection has a marked contrast to turbulent mechanical mixing in which stratification is eventually weakened or destroyed. Therefore, double diffusive convection has a potential to modify the water mass properties in the ocean in a different manner from that due to mechanical mixing.

In the region off Joban-Kashima and Sanriku coast, the Kuroshio and Oyashio directly contact each other. The Kuroshio and Oyashio Waters show a distinct contrast in water properties as characterized by relatively warm and salty Kuroshio and cold and fresh Oyashio waters. These two water masses are often intruded each other showing complicated fine and microstructures favorable for the onset of double diffusive convection (e.g. NAGASAKA *et al.*, 1995). Then, double diffusive convection should play a significant role in modification of water masses in this region. This region, called as the Mixed Water Region (MWR), has gathered attentions of physical oceanographers because the source water of North Pacific Intermediate Water (NPIW), having salinity value ranged 33.3PSU∼33.4PSU and potential density is $\sigma_\theta = 26.65$, should be modified to obtain its characteristics (33.8PSU∼34.1PSU and $\sigma_\theta = 26.8$) by some mixing processes in this region (TALLEY, 1993; TALLEY *et al.*, 1995). TALLEY and YUN (2001) proposed that cabbeling and double diffusive convection could explain the total increment of density ($\Delta\sigma_\theta = 0.15$). They used a simple T-S diagram analysis, and concluded that $\Delta\sigma_\theta = 0.07$ is increased by cabbeling and the rest by double diffusive convection. On the other hand, INOUE *et al.* (2003) investigated these mixing processes in more detail by using neutral surface analysis, and concluded that the total increments of density by cabbeling and double diffusive convection are almost the same and is about $\Delta\sigma_\theta = 0.03$, respectively. This value is almost half of that proposed by TALLEY and YUN (2001). Thus, the role of double diffusive convection in the MWR is still undetermined. This might be due to the lack of detailed knowledge on the activity of double diffusive convection in MWR.

In the present study, we try to investigate the activity of double diffusive convection in MWR off Joban-Kashima and Sanriku Coasts mainly through the statistical analysis using histogram plots of R_ρ (Tu) at various density surfaces. The data are described in section 2. The histogram and T-S diagram analysis are presented in section 3. Summary and discussion are given in section 4.

Table 1 Observations

Date	Instruments
15Oct. −17Oct. 1996	CTD, XBT
20Oct. −22Oct. 1997	CTD, XCTD
10Sep. −13Sep. 1998	CTD, XCTD
10Sept. −13Sep. 1999	CTD
10Sep. −12Sep. 2000	CTD

2. The data

The Research and Training Vessel Shinyo-Maru, Tokyo University of Fisheries is used to occupy the stations off Joban-Kashima and Sanriku Coasts located to the northeastern part of Honshu, Japan. All the observations are summarized in Table 1. Neil Brown Mark III CTD is used to detect oceanic structures down to 500db where σ_θ almost exceeds 26.8. Temperature and conductivity data are matched by using recursive filter to reduce the unwanted spikes. The remnant spikes or density inversions, which are not completely removed by this filter, are removed by eye. Salinities are calibrated with salinity measurements of bottle sampled salinities. These data are averaged to 1db intervals, and then running averaged over 11db bin. To obtain R_ρ defined in equation (1), the least square fit over 11db data is adapted to obtain temperature and salinity gradients. α and β are calculated from temperature and salinity data at a centered depth of 11db data bin by using EOS80. Tu is then calculated by using equation (1). An example of vertical profile of Tu obtained in October 1998 is shown in Fig. 1. Strong salt fingering (Circled, $1 < R_\rho < 2$) and diffusive convection layers (Squared, $0.5 < R_\rho < 1$) are piled up alternatively in the vertical showing interleaving layers originated from the Kuroshio and Oyashio Waters, and the strong mixing events are anticipated due to double diffusion. In the following analysis, Tu is divided at an one degree interval from $-90°$ to $90°$. The number of

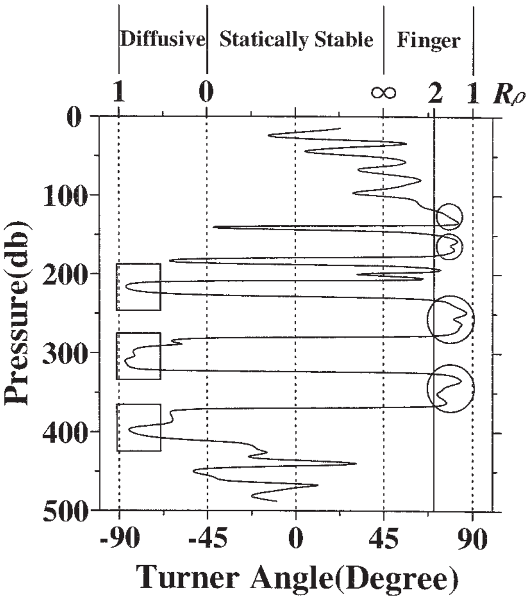


Fig. 1 Vertical profile of TURNER Angle in October 1998. TURNER Angle is shown at a lower horizontal coordinate, and corresponding density ratio R_ρ is at upper one. Diffusive ($-90° < Tu < -45°$, $0 < R_\rho < 1$), statically stable($-45° < Tu < 45°$, R_ρ : negative) and salt finger($45° < Tu < 90°$, $1 < R_\rho < \infty$) regimes are shown on top. A vertical solid line shows the boundary where $R_\rho = 2$ which separates the higher activity salt finger region($1 < R_\rho < 2$) from the lower one. Circled areas show the region for active salt finger, and squared ones for active diffusive convection.

Tu which falls into each one degree bin is counted, and is divided by the total data number to obtain the occurrence frequency.

3. Histogram and T-S diagram analysis

Histograms of $R_\rho(Tu)$ obtained from each observation are shown in Fig. 2 together with station plots. In each year, more than 60% water columns are unstably stratified to double diffusive convection, and in 1996, 1997 and 1999, modes of occurrence frequencies of R_ρ are found in the salt finger convection regime, but the value is about 4 suggesting that salt finger convection should occurs but is weak. On the other hand, in 1998 and 2000, we can found modes in both salt finger and diffusive convection regimes. The modes in salt finger regime are less than 2 in both years, and especially in 2000, a sharp peak exists near R_ρ is unity. This suggests that salt finger convection is so active in both years. The modes in diffusive regime are also near R_ρ unity suggesting diffusive convection is also active in these years.

Thus, the activity of double diffusive convection differs in each year. Then, we compare the histograms in 1997 and 1998 in more detail by plotting histograms at each σ_θ layer from $\sigma_\theta = 26.0$ to 27.0 at 0.1 σ_θ interval (Fig. 3a and 3b). Note that the occurrence frequency is calculated by dividing the total data number of each *Tu* within each layer (this number usually

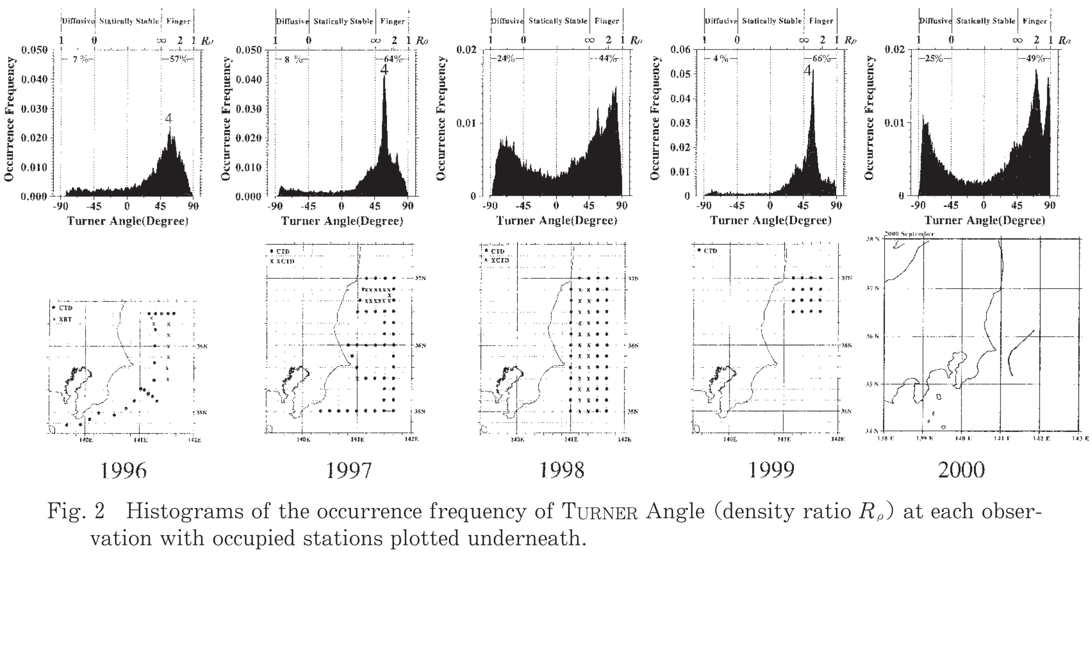


Fig. 2 Histograms of the occurrence frequency of TURNER Angle (density ratio R_ρ) at each observation with occupied stations plotted underneath.

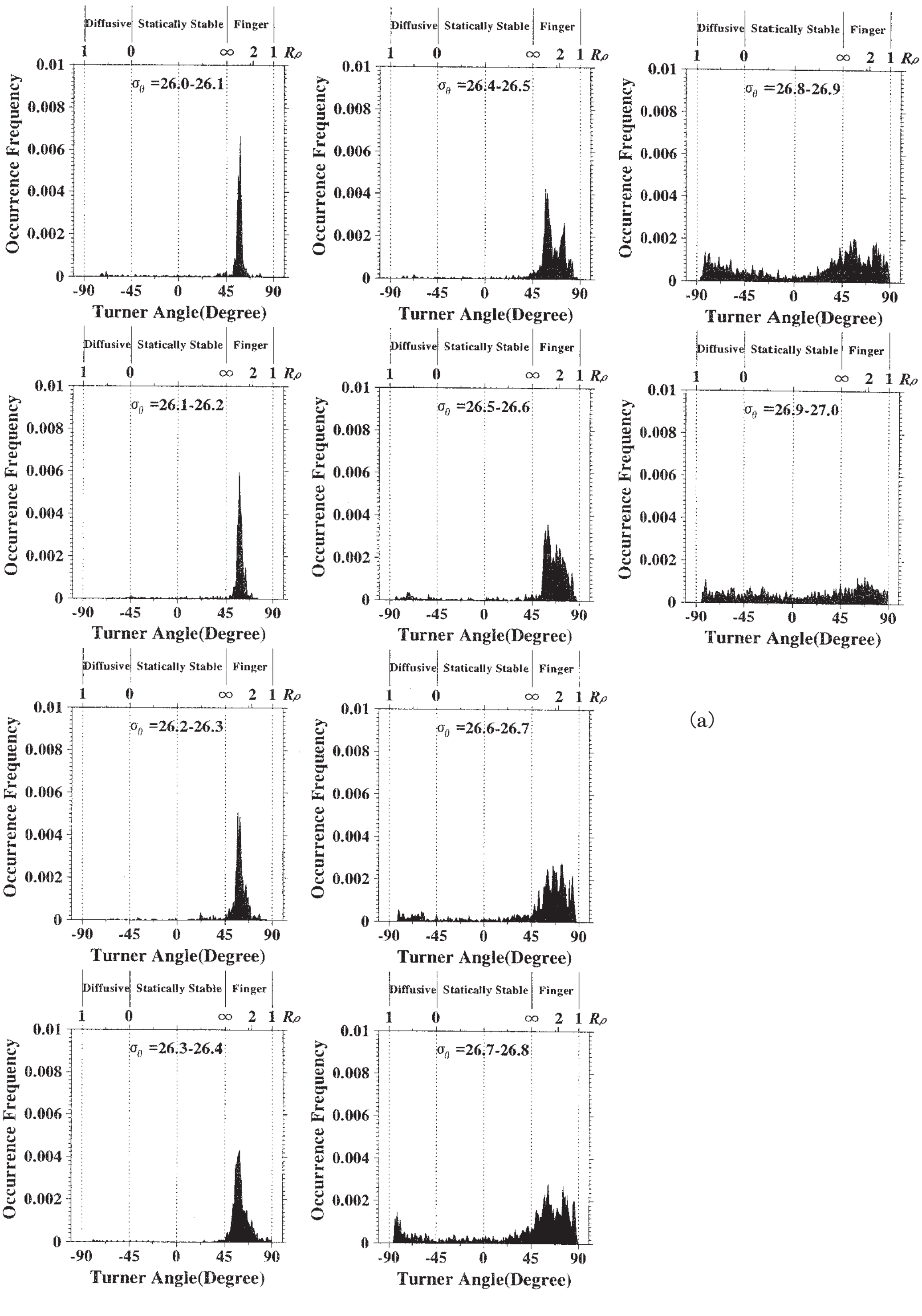
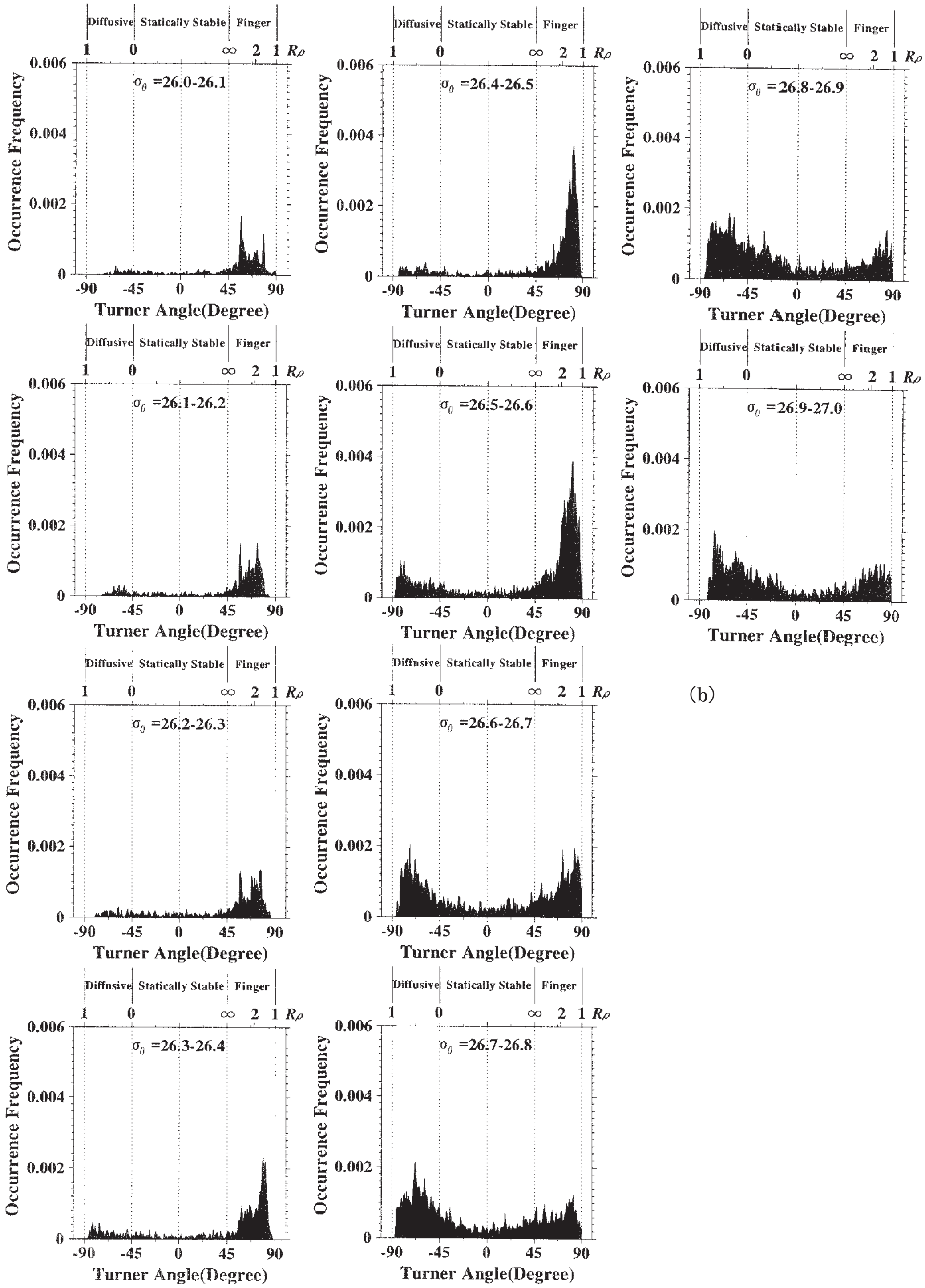


Fig. 3 Histograms of the occurrence frequency of Turner Angle (density ratio R_ρ) at each potential density surface in (a) 1997 and (b) 1998.


Diffusive
Statically Stable
Finger
1 0 ∞ 2 1 R_ρ
Occurrence Frequency
0.006
0.004
0.002
0
-90 -45 0 45 90
Turner Angle(Degree)
σ_θ =26.0-26.1
σ_θ =26.1-26.2
σ_θ =26.2-26.3
σ_θ =26.3-26.4
σ_θ =26.4-26.5
σ_θ =26.5-26.6
σ_θ =26.6-26.7
σ_θ =26.7-26.8
σ_θ =26.8-26.9
σ_θ =26.9-27.0

(b)

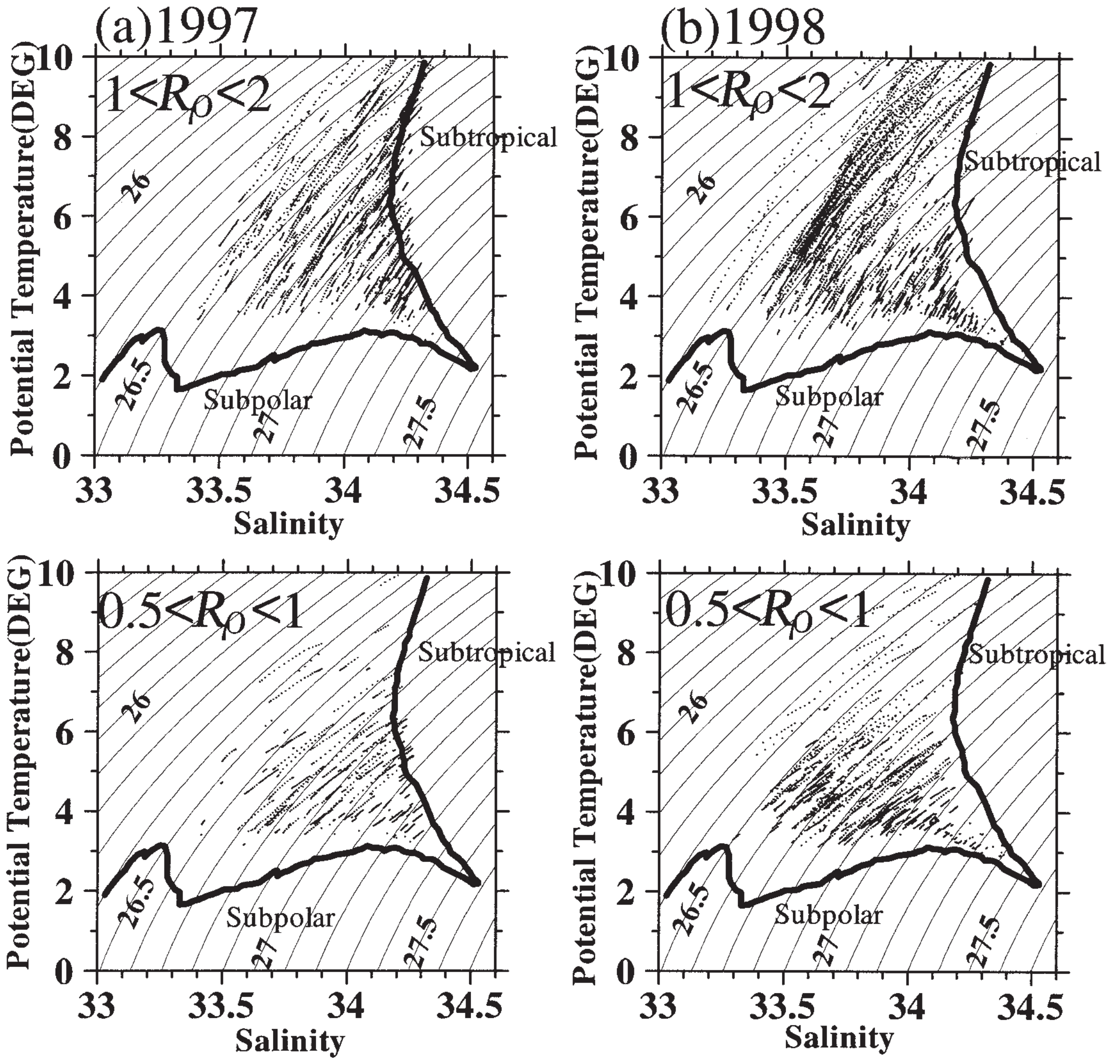


Fig. 4 T-S diagrams in (a) 1997 and (b) 1998. In upper two panels, conditionally sampled data which R_ρ distributed between 1 and 2 are plotted, and that between 0.5 and 2 in lower two panels.

differs between each layer) with the total data number of each observation. In 1997, a mode is clearly defined between $\sigma_\theta=26.0$ and 26.6 layers in the salt finger regime. R_ρ (Tu) of this mode is 4.3(58 degree) and is almost kept constant down to $\sigma_\theta=26.9$ surface, but its height diminishes. On the other hand, in the layer between $\sigma_\theta=26.4$ and 26.5, there appears another mode at $R_\rho=1.7$($Tu=75$degree). This mode is not clearly defined in the layers below, but exists down to $\sigma_\theta=26.9$ surface without changing its height. The heights of these two modes are almost comparable down to $\sigma_\theta=26.9$ surface. Therefore, in 1997, salt finger convection should exist, but is weak in the whole water columns as was seen in Fig. 2. The mode in the diffusive regime is not clearly defined, but exists in the layers below $\sigma_\theta=26.6$ surface.

In 1998, in the layers between $\sigma_\theta=26.0$ and 26.1, two modes exist at $R_\rho=5$ ($Tu=57$degree) and $R_\rho=1.5$ ($Tu=78$degree). The mode at a large value of R_ρ becomes not clear as σ_θ increases, but not so for that at smaller value of R_ρ. This latter mode forms a sharp pointed peak in the layers between $\sigma_\theta=26.3$ and 26.6, and R_ρ decreases its value slightly from $R_\rho=1.48$(Tu=79degree) to $R_\rho=1.27$(Tu=81 degree). Below this layer, the mode in the salt finger regime becomes less distinct, but that in the diffusive regime becomes clearly defined. The mode value in the layers between $\sigma_\theta=26.6$ and 26.7 is $R_\rho=0.42$ (Tu=−68degree) and that $\sigma_\theta=26.9$ and 27.0 is $R_\rho=0.6$ (Tu=−76degree), respectively. Therefore, salt finger convection should be active in the upper layers above $\sigma_\theta=26.7$ and 26.8 layers, and diffusive convection should be active below this layer. The same histogram plots were also done in 2000 observation (not shown here), and results support this conclusion.

We can see the same features in the T-S diagrams obtained in 1997 and 1998 in Fig. 4. In these figures, conditionally sampled data ($1<R_\rho<2$: active salt finger, $0.5<R_\rho<1$: active diffusive convection) are plotted together with typical water masses observed off Joban-Kashima and Sanriku Coast defined by TALLEY and YUN (2001). In 1997, the active salt finger layers are equally distributed over the wide range of σ_θ, and the active diffusive convection layers distribute mainly below $\sigma_\theta=26.5$. In 1998, however, the active salt finger layers also distribute in the same manner as in 1997, but, concentrates above $\sigma_\theta=26.7$ layer. The distribution pattern of active diffusive convection layers are almost same as in 1997, but are shifted towards the subtropical water mass.

4. Summary and discussion

We have investigated the activity of double diffusive convection in Mixed Water Region (MWR) off Joban-Kashima and Sanriku Coast where double diffusive convection should play a role in modification of the source water of North Pacific Intermediate Water (NPIW). CTD data obtained from 1996 to 2000 in September or October are analyzed by histogram plotting of occurrence frequency of density ratio R_ρ which can indicate the activity of double diffusive convection. We can summarize the main results as follows:

(1) More than 60% fluid column down to 500db (σ_θ is almost above 27.0) unstably stratified to double diffusive convection. The activity of double diffusive convection differs year by year. In 1996, 1997 and 1999, the mode value of R_ρ is greater than 4 suggesting salt finger convection is not active. We did not find the modes in diffusive convection regime in these years. In 1998, and 2000, however, the distinct modes were found in both salt finger and diffusive convection regimes. The mode values of R_ρ in salt finger convection in both years are less than 2, and those in diffusive convection regime is near unity suggesting salt finger and diffusive convections are active in these years.

(2) In years when double diffusive convection is active, salt finger convection prevails above $\sigma_\theta=26.7$ and 26.8 layers, and diffusive convection does below this layers.

The first result only indicates the year-to-year variation in the activity of double diffusive convection at the same season. There is a possibility that relatively short-term variation should exists in the activity of double diffusive convection. In fact, NAGASAKA *et al.* (1995) observed 2–3 days variation in the intensity of interleaving layers (several kilometer scales) possibly caused by double diffusive convection. Unfortunately, their observations were done by XBT, and no histogram analysis was made. However, the density ratio may change drastically according as the disappearance of interleaving layers. This point should be checked by the intense XCTD observation or long-term CTD Yo-yo/Tow-yo observation in future.

The latter result was also obtained by TALLEY and YUN (2001). As was mentioned in the introduction, they concluded that the half of density increment needed for the formation of NPIW is achieved by the efficient transports of density by double diffusive convection. Our results will partly support their result, but also indicate that this efficient mixing process by double diffusive convection should occur intermittently in MWR year by year. In fact, T-S diagram in 1998 shifted towards subtropical waters, but not so in 1997. This may indicate the intensification of southward intrusion of subarctic water into NPIW in 1998 and 2000 and the possibility of the efficient formation of NPIW in these years. The reason for this intermittency is not clear at present, but may be due to the southward extension of subarctic gyre relating to the wintertime wind condition in the Subarctic Region.

The existence of double diffusive convection in MWR has been anticipated by some authors (e.g. NAGASAKA *et al.*, 1995, YOSHIDA *et al.*, 1985), and may be confirmed by the present analysis. This convection should play a role in the modification of NPIW, but some other authors (e.g., YASUDA 1997) proposed a model in which isopycnal mixing is essential to the formation of NPIW. In their model, a source water of NPIW has already acquired its density at its formation site, and then achieves its minimum salinity through the mixing along isopycnal surface in MWR. Our results, however, also suggest that even if active double diffusive convection does not exist, slow vertical mixing due to salt finger would be present to transport salt and heat form overlying Kuroshio (Subtropic) Water to underneath Oyashio (maybe a source of NPIW or Subarctic) Water, and as a result, sufficient salt is acquired to form NPIW. In this case, the density increment due to salt finger should be negligible. This last discussion is so speculative and controversial one, and should be investigated in further detail in future.

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