Mixing characteristics of the subarctic front in the Kuroshio-Oyashio confluence region

Zhu Ke-Lan\(^a,1,\)*, Chen Xi\(^b,1\), Mao Ke-Feng\(^b,\)*, Hu Dong\(^c\), Hong Sen\(^d\), Li Yan\(^b\)

\(^a\) Army of PLA, Beijing, China  
\(^b\) College of Meteorology and Oceanography, National University of Defense Technology, Nanjing, China  
\(^c\) Army of PLA, Beijing, China  
\(^d\) Army of PLA, Beihai, China

Received 17 October 2017; accepted 23 July 2018  
Available online 11 August 2018

**KEYWORDS**  
Kuroshio—Oyashio confluence region; Subarctic front; Mixing; Turbulent eddy diffusivity; Thermal diffusivity

**Summary**  
This paper analyzes the mixing characteristics of the Subarctic Front (SAF) in the Kuroshio-Oyashio Confluence Region based on temperature, salinity, and current data obtained from surveys and remote sensing in June 2016. The frontal zone of the observed area is at 145°–151°E, 38°–41°N. The front is distributed between 25.5°–26.7°N in a band pattern inclined from north to south and is deeper in the south. The region shallower than 200 m and distributed along the isopycnal of 25.9°–26.1°N has the strongest horizontal temperature and salinity gradients, and the largest of the former can reach over 0.7°C/km. Diapycnal mixing of the SAF is mainly turbulent; it is stronger in the north than in the south. The region with stronger turbulence (\(K_r > 10^{−3.5}\) m\(^2\)/s) is distributed mainly in water layers within and under the front (26.1°–26.7°N), showing that the SAF is shallower in the north and deeper in the south along the front. Symmetric instability may be the main factor causing strong turbulent mixing in the frontal zone. Double diffusion mixing is stronger in the south than in the north; the region with stronger double diffusion (\(K_u > 10^{−4.5}\) m\(^2\)/s) is distributed mainly in water layers within and above the front (25°–26.5°N) on the southern side of the SAF. These water layers are dominated mainly by “salt-fingerling” double diffusion, with only a few water layers dominated by “diffusive layering” double diffusion mixing in middle and lower waters deeper than 300 m.

© 2018 Institute of Oceanology of the Polish Academy of Sciences. Production and hosting by Elsevier Sp. z o.o. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
1. Introduction

Ocean fronts, which are the boundaries of different water masses, are distributed along coastal regions and in the open ocean (Nagai et al., 2015a). They appear as sudden changes in ocean water temperature, salinity, density, and velocity. Recent studies have shown that frontal zones are the source of some water masses; for example, the North Pacific Intermediate Water (NPIW) is formed in the Subarctic Front (SAF) region (Hasunuma, 1978). A variety of marine phenomena such as diapycnal mixing (Nagai et al., 2015a), water mass formation and subduction (Nagai et al., 2015a; Pollard and Regier, 1992; Rudnick, 1996), and lateral mixing and cabbeling (Thomas and Shakespeare, 2015) also occur in these regions.

Diapycnal mixing generated from turbulence and double diffusion is of great importance in causing thermohaline intrusions and forming water masses (Pollard and Regier, 1992; Ruddick and Kerr, 2003; Ruddick and Richards, 2003; Stern, 1967), and is also an important mechanism affecting the physical properties of seawater and the intensity of thermohaline circulation (MacKinnon and Gregg, 2003a; Wunsch and Ferrari, 2004). In addition, diapycnal mixing greatly affects the maintenance and variation of ocean fronts (Wang and Li, 2012).

There have been several global studies of mixing at ocean fronts. Some observations have indicated that turbulent dissipation is stronger near the surface and extends deeper at the warm side of the frontal zone (Dewey and Moun, 1990). Nagai et al. (2009, 2012) believe that near-inertial internal waves and front formation strengthen turbulent mixing; from an observation in 2015, they found that the turbulent kinematic dissipation rate of the Kuroshio thermocline is 10−100 times higher than that of a typical thermocline and that it is accompanied by a near-inertial internal wave velocity shear at the isopycnal direction (Nagai et al., 2015b). D’Asaro et al. (2011) believe that strong air-sea interaction in the Kuroshio Extension Region could strengthen turbulent mixing in the upper layer of the frontal zone.

Double diffusion may have a strong influence on the formation of water masses in the frontal zone. Yuan and Talley (1996) believed that the NPIW is related to the “salt-finger” function of Oyashio water of the mixing layer of SAF in winter. In addition, Nagai et al. (2015a) observed thermohaline intrusions (caused by near-inertial internal waves and sub-inertial flows) under the principal axis of the Kuroshio front and indicated that the sub- and near-inertial motions would strengthen the double diffusion, which then would enhance the diapycnal mixing.

The Kuroshio-Oyashio Confluence Region (KOCR; 142°−160°E, 35°−40°N; Sugimoto and Hanawa, 2011; Sugimoto et al., 2014) is located where the northern branch of the Kuroshio Extension (KE) intersects with the Oyashio Current. The anticyclonic eddy in the southern part of this region takes warm, salty KE water to the north (Itoh and Yasuda, 2010). Thus, the water in the south maintains the characteristics of the KE and the cyclonic eddy in the north brings cold, fresh Oyashio water to this region and forms the SAF (143°−171°E, 37°−43°N; Kitano, 1974; Sugimoto et al., 2014; Uda, 1963) with significant differences in thermohaline characteristics.

Currently, studies on the SAF focus mainly on variations in its characteristics and its response to the atmosphere. Yuan and Talley (1996) discovered that regions, where the horizontal temperature and salinity gradients of the SAF are high, are located mainly at 40°−44 N, with the temperature front in the west stronger than that in the east. Nakamura and Kazmin (2003) indicated that changes in low-frequency sea surface temperatures (SSTs) would result in the SAF changing from north to south and cause the long-term change in a temperature front dominated by a 10-year cycle (Nakamura et al., 1997). In addition, some numerical studies showed that weather- and planetary-scale atmospheric fields could respond to changes in the intensity of the SAF (Kwon and Deser, 2007; Nakamura et al., 2010; Sampe et al., 2010; Taguchi et al., 2009).

However, there are few studies on diapycnal mixing in the SAF, and no explicit conclusions have been drawn regarding its mixing characteristics. Therefore, this paper analyzes the temperature, salinity, current structure, and diapycnal mixing characteristics of the SAF in the KOCR, and discusses the reason for strong turbulence in the SAF region based on observations from a cruise from June 1 to 2, 2016.

This article is organized as follows. In Section 2, we introduce the data and observation information. In Section 3, we analyze the temperature, salinity, and current in the SAF region and the structural characteristics of the SAF. In Section 4, we analyze the mixing characteristics of the SAF region and in Section 5, we discuss the mechanism of strengthening turbulent mixing in the same. Finally, in Section 6, we present our conclusions.

2. Field experiments and data analysis

2.1. Observations of the subarctic front (SAF) in the Kuroshio—Oyashio confluence region (KOCR)

The absolute dynamic topography (ADT), sea surface temperature (SST), and sea surface geostrophic flow system of waters surrounding the SAF from June 1 to 2, 2016, based on satellite altimeter (Archiving Validation and Interpretation of Satellite Oceanographic data, AVISO) and Optimum Interpolation Sea Surface Temperature (OISST) records (Reynolds et al., 2007), are shown in Fig. 1a. Shipboard observations were carried out in the region between 146.75°−148.75°E and 38°−40°N (Fig. 1b). The ADT in this region is high in the south and low in the north; the ADT of the Kuroshio Extension, in the south of the frontal zone, can reach above 1.4 m but that of Oyashio, in the north, is only around 0.3 m. This presents an ADT variation of about 1 m in the frontal zone. The SST in the southern Kuroshio Extension is over 20°C while that of Oyashio is below 10°C, resulting in a temperature gradient of up to 0.1°C/km. There are also many eddies in the surrounding regions; cyclonic eddies are located mainly in the Oyashio area, anticyclonic eddies are located mainly in the sea near the Kuroshio Extension, and there is an obvious anticyclone in the southeastern part of the observed area.

Thus, we organized the cruise into six sections so that we could observe all the structural characteristics of the front. The average length of sections S01−S03 was about 70 km, and that of sections S04−S06 (Fig. 1c) was about 12 km. Fourteen Expendable Conductivity-Temperature-Depth (XCTD) observation stations (XCTD-1, Tsurumi-Seiki Co. Ltd., Japan) with a sampling frequency of 25 Hz and vertical resolution of
0.14 m were deployed along Section S01; fifteen and thirteen of these were deployed, respectively, along Section S02 and Section S03, at horizontal intervals of about 8 km. Further parameters of the XCTD stations are shown in Table 1. For intensive observations within the frontal zone, we deployed 16, 11, and 11 XCTD observation stations along Sections S04—S06, respectively, with horizontal intervals of 3 km. Further details of each section are shown in Table 2.

### 2.2. Data and methods

#### 2.2.1 Processing the vessel survey data

The XCTDs provided good quality deep temperature and salinity data. However, the temperature profiles also showed distinct spectral spikes at 5 and 10 Hz, which is a common phenomenon in XCTD profiles from subtropical and subpolar waters (Gille et al., 2009). Five-point smoothing was used to

---

**Table 1** Some parameters of the TSK XCTD-1 sensor used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>−2°C to 35°C</td>
<td>0.02°C</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0—60 mS/cm</td>
<td>0.03 mS/cm</td>
</tr>
<tr>
<td>Depth</td>
<td>0—1000 m</td>
<td>5 m or 2%, whichever is greater</td>
</tr>
</tbody>
</table>

**Table 2** Details of sections S01—S06. “Number of stations” refers to the number of Expendable Conductivity-Temperature-Depth stations deployed along each section.

<table>
<thead>
<tr>
<th>Section</th>
<th>Location</th>
<th>Heading</th>
<th>Number of stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>S01</td>
<td>147.6°—148.58 E, 38.62°—39.55 N</td>
<td>Northwest to southeast</td>
<td>14</td>
</tr>
<tr>
<td>S02</td>
<td>147.37°—148.12 E, 38.25°—39.15 N</td>
<td>Southeast to northwest</td>
<td>15</td>
</tr>
<tr>
<td>S03</td>
<td>147 E, 38.1°—38.97 N</td>
<td>North to south</td>
<td>13</td>
</tr>
<tr>
<td>S04</td>
<td>146.92 E, 38.18°—38.5 N</td>
<td>South to north</td>
<td>16</td>
</tr>
<tr>
<td>S05</td>
<td>146.85 E, 38.35°—38.57 N</td>
<td>North to south</td>
<td>11</td>
</tr>
<tr>
<td>S06</td>
<td>146.8 E, 38.33°—38.6 N</td>
<td>South to north</td>
<td>11</td>
</tr>
</tbody>
</table>
remove this disturbance and retain the authenticity of the data as much as possible according to the method in Gille et al. (2009).

The current data were obtained through observations with 38k and 150k Shipboard Acoustic Doppler Current Profilers (SADCPs) (Teledyne RD Instruments, United States of America; further parameters shown in Table 3) at intervals of 0.16 km and vertical resolutions of 24 m and 8 m. To obtain higher quality flow field data, we merged and processed the data from both SADCPs.

2.2.2 Parameterization
To understand the mixing characteristics of SAF, this paper uses the Thorpe method to calculate turbulent eddy diffusivity (K_{th}) and quantify turbulent mixing; calculates the thermal diffusivity (K_{th}) and analyzes the diapycnal mixing characteristics caused by double diffusion with two thermohaline parameterizations; and calculates the Turner Angle (\theta_T) to analyze the double diffusion characteristics of the frontal zone.

a. Thorpe scale method
The dissipation rate \epsilon of turbulent energy is calculated using the Thorpe scale \delta_T in the formula \epsilon = c_1 \delta_T^2 N^2 (Thorpe, 2005), where \delta_T is the root mean square of distance moved after formation of stable density profiles due to the rearrangement of sea water mass points on the actual density profile; c_1 = (L_0/L_T)^2 where the value of c_1 in this study is 0.64 and L_0 is the Ozmidov scale (L_0 = \langle e \rangle^{1/2} N^{-3/2}) (Dillon, 1982); and N^2 is the cubic value of buoyancy frequency given by N^2 = (\frac{\partial p}{\partial z} / \rho_0) \delta_T^{5/2}.

The resolution of the data also affects the calculation of the Thorpe scale. Galbraith and Kelley (1996) believe that about five sample points are needed to accurately identify turbulence overturns; therefore, turbulence overturns of vertical scale (H_{min}) greater than 5 \delta_T (where \delta_T is the vertical resolution) are effective. Therefore, H_{min} < 5 \delta_T are removed. Galbraith and Kelley (1996) also point out that H_{min} should be greater than 2 \frac{\delta_T}{\sqrt{\epsilon/\nu}}.

These calculations to find \epsilon are needed to determine the eddy diffusivity K_{th}, which uses the formula K_{th} = \Gamma N^2 (Osborn, 1980) where \Gamma is a mixing efficiency of 0.2.

b. Thermohaline parameterization
The diapycnal mixing of the SAF caused by double diffusion is used to calculate the thermal diffusivity K_{th}; the k-profile parameterization (KPP) scheme (Fedorov, 1988) for the region of the front with a density ratio of 0 < R_\sigma < 1 and the scheme from Radko et al. (2014) for the region of the front with a density ratio of R_\sigma > 1.

For the former, K_{th} = 0.909 \exp((4.60 \exp[-0.54(R_\sigma^{-1} - 1)]) where v is the molecular viscosity of seawater (1.8 \times 10^{-7} m^2/s in this paper) and R_\sigma is the density ratio \frac{\rho_2}{\rho_1} when \rho_2 is the vertical potential temperature gradient after smoothing; \rho_1 is the vertical salinity gradient after smoothing; a = (-\rho^{-1} \frac{\partial \rho}{\partial \psi}) is the thermal expansion coefficient of seawater; b = (-\rho^{-1} \frac{\partial \rho}{\partial S}) is the salinity contraction coefficient; and \rho is the seawater potential density. When 0 < R_\sigma < 1, the thermohaline stratification of the water is favorable for "diffusive layering" (DL) (Kelley et al., 2003); when R_\sigma > 1, the thermohaline stratification of the water is favorable for "salt fingering" (SF) (Stern and Turner, 1969).

In a region with a density ratio R_\sigma > 1 K_0 = F_0k_1 \gamma, \quad F_s = a(R_\sigma - 1)^{-0.5} + b, \quad \gamma = a_2 \exp(-b_2 R_\sigma) + c_2, \quad a_2 = 135.7, \quad b_2 = -62.75, \quad b_3 = 2.709, \quad b_4 = 2.513, \quad \text{and} \quad c_2 = 0.5128.

c. Turner angle
Density ratio R_\sigma is not as intuitive as Turner angle \theta_T although it can also be used to analyze the double diffusion characteristics, thus this paper uses the Turner Angle to analyze the double diffusion characteristics. \theta_T is calculated using the formula \theta_T = tan^{-1}[(\psi_{\psi}) + (\psi_\beta}], \quad (\psi_{\psi} - (\psi_\beta)] where the parameters are the same as density ratio (R_\sigma). When \theta_T > 45, conditions are favorable for diffusive layering; when 45 < \theta_T < 90, they are favorable for salt fingering; when 45 < \theta_T < 45, there will be no double diffusion in the water body; and if \theta_T gets close to ±90, the double diffusion intensity increases.

2.2.3 Diagnosis parameters
The gradient Richardson number (RI), potential vorticity (q), and effective Coriolis parameter (f_{eff}) are required to measure the Kelvin–Helmholtz instability (KI), symmetric instability (SI), and near-inertial internal waves (NIWs).

a. The gradient Richardson number (RI)
The RI is calculated using the formula \text{RI} = N^2 / (u_z^2 + v_e^2), where u_z and v_e represent the vertical shear of zonal and meridional velocity of the SADCP. When \text{RI} < 0.25, there is KI in the water; when 0.25 < \text{RI} < 1, there is SI in the water instead (Stone, 1966).

b. Potential vorticity (q)
The q is calculated using the Ertel potential vorticity formula (Hoskins, 1974; Jing et al., 2016), expressed as follows:

q = q_v + q_h, \quad q_v = (f + \zeta) N^2 \quad q_h = -\nabla_s b^2 / f.

where q_v and q_h represent the vertical and horizontal components, respectively; f stands for the Coriolis parameter; \zeta = \nabla \times \mathbf{u} and represents the relative vorticity; N^2 = -g \partial \phi / \rho_0 \partial z is the square of the buoyancy frequency; b = g \partial \phi / \rho_0 \partial \phi represents buoyancy; g is gravitational acceleration; \alpha_0 is the potential density after smoothing and \rho_0 is the reference density (1024 kg/m^3). When q < 0, there is SI in the water (D’Asaro et al., 2011).

c. The effective Coriolis parameter (f_{eff})
NIWs can initially be determined using the effective Coriolis parameter (f_{eff}), calculated by Jing et al. (2017) as follows:

f_{eff} = \sqrt{(f + \zeta)^2 - \frac{\nabla_s^2 + \nabla_\phi^2}{4}}.

### Table 3

<table>
<thead>
<tr>
<th>SADCP type</th>
<th>Maximum measured depth (m)</th>
<th>Bin (m)</th>
<th>Frequency (kHz)</th>
<th>Sampling layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>38 kHz</td>
<td>1000</td>
<td>24</td>
<td>0.4</td>
<td>40</td>
</tr>
<tr>
<td>150 kHz</td>
<td>400</td>
<td>8</td>
<td>1.5</td>
<td>45</td>
</tr>
</tbody>
</table>

*Notes:*
- \text{RI} is the root mean square of distance moved.
- K_{th} is the thermal diffusivity.
- RI is the gradient Richardson number.
- q is the potential vorticity.
- f_{eff} is the effective Coriolis parameter.
where $\zeta = v_x - u_y$ is the relative vorticity (with $v_x$ and $u_y$ still representing the vertical shear of the zonal and meridional velocity of the SADCP) and $S_y = v_x + u_y$ is the shear strain. As the front zone is assumed to be geostrophic, and thus horizontally nondivergent, $S_y = 2u_x = -2v_x$.

Kunze (1985) pointed out that a region of strong positive vorticity ($f_{\text{eff}} > f$) can be a barrier to reflect NIWs with inherent frequencies of $\omega < f_{\text{eff}}$, while a region with weak effective Coriolis parameter ($f_{\text{eff}} < f$) can trap NIWs.

3. Structural characteristics of the SAF

In this section, we use Section S02 as an example with which to understand the structural characteristics of SAF, and analyze the temperature, salinity, and currents in this region based on 65 thermohaline profiles from XCTDs S01–S06 and current data from 38k and 150k SADCPs obtained on a cruise conducted from June 1 to 2, 2016.

3.1. Hydrographic characteristics of SAF waters

The temperature, salinity, and current distributions of the observed area are shown in Fig. 2a, b, c, f. There is cold and fresh Oyashio water in the northern part of the SAF and warm and salty KE water in the south. The former mainly appears in the region less dense than 26.5 $\sigma_T$ with the potential temperature of $<10^8$ C, but the surface water is warm and fresh with temperatures $>11^8$ C and salinity of about 32.5. KE water mainly appears in the region less dense than 26.3 $\sigma_T$ with the potential temperature of $>15^8$ C and salinity above 34. In addition, there is a clear low saline layer (with a salinity of 33–33.5) between 26.5–26.9 $\sigma_T$ that originated from Oyashio; Hasunuma (1978) and Talley (1993) consider that this low saline layer belongs to the NPIW.

The background current in SAF region heads eastwards, which is roughly consistent with the direction of flow in the Kuroshio Extension Region (Fig. 1a). The flow velocity is higher in the southern part of the frontal zone (up to 2 m/s) than in the north (about 0.3 m/s). The weak, shallow (less than 200 m) southward flow at 38.3$^8$N (Section S02, Fig. 2f) is caused by the east wing of an anticyclonic eddy (Fig. 1a) in the southern part of the frontal zone. Section S01 and Sections S03–S06 of the front have structural characteristics similar to Section S02; the difference is that Sections S03–S06 are obvious westward zonal currents caused by the significant effect of the west wing of an anticyclonic eddy (Fig. 1a).

3.2. Structural characteristics of the SAF

The horizontal gradient of the water temperature is shown in Fig. 2d. The front is distributed between 25.5 and 26.7 $\sigma_T$ in a band pattern inclined from north to south. As the depth increases, the front moves southwards; the mean horizontal width of the front is about 20 km and it can reach up to 25 km at locations 100 m deep. The narrowest part is only 13 km at a location 50 m deep. In the vertical direction, the front is shallower than 400 m but deepens southward. The region with the highest front intensity (horizontal temperature and salinity gradient) is shallower than 200 m, and the temperature gradient there can reach over 0.7 $^8$C/km. The intensity gradually weakens as depth increases. The structural characteristics of the horizontal salinity gradient (Fig. 2e) are consistent with those of temperature gradient (Fig. 2d), but the intensity is only 1/8 that of the temperature gradient. In this text, the term “SAF” refers mainly to the temperature front, and we take a horizontal ship-measured temperature gradient of $>0.2^8$C/km as the front zone.
4. Characteristics of mixing in the SAF region

As shown in Nagai et al. (2009, 2015a, 2015b), there is strong and turbulent mixing and double diffusion in the Kuroshio front. The SAF, which is geographically close to it, has a large temperature gradient; however, there are few studies on its mixing characteristics. Therefore, to understand the mixing characteristics of the SAF, this section takes Section S02 as an example and uses the Thorpe method to calculate the turbulent eddy diffusivity ($K_u$) of the frontal zone, thereby analyzing the turbulent mixing in the region. In this section, we calculate the thermal diffusivity ($K_u$) of the frontal zone to analyze the diapycnal mixing characteristics caused by double diffusion with thermohaline parameterizations and use the Turner Angle ($Tu$) to analyze the double diffusion characteristics of the same area.

4.1. Distribution of turbulence and double diffusion mixing in the frontal zone

4.1.1 Characteristics of turbulent mixing

The characteristics of the distribution of $K_u$ in Section S02 are shown in Fig. 3a; $K_u$ ranges from $10^{-6}$ to $10^{-3}$ m$^2$/s, and is quite low ($<10^{-5}$ m$^2$/s) for water layers less dense than 26.1 $\sigma_t$. North of 38.4$^\circ$ N, waters with low $K_u$ are located mainly in areas shallower than 50 m; south of this latitude, waters with low $K_u$ may be as deep as 200 m, possibly related to strong mechanical stirring within the KE region and the shallow sea. These waters can be mixed evenly by mechanical stirring, which could lower the Thorpe displacement and thus result in a small $K_w$ value.

There is strong turbulence in water layers below the 26.1 $\sigma_t$, and $K_u$ is greater than $10^{-5}$ m$^2$/s where the strong turbulent mixing region ($>10^{-3}$ m$^2$/s) is distributed mainly in water layers of 26.1–26.7 $\sigma_t$. South of 38.4 N, the strong turbulent mixing region gradually becomes deeper and can reach up to 400 m at 38.3$^\circ$N. The strong turbulent mixing region is distributed mainly along the front (Fig. 2d) and, north of 38.4 N, in waters under the front deeper than 50 m. It is located both in and under the front at depths greater than 150 m in the south. And in waters south of 38.3$^\circ$N, the strong turbulence region can reach 26.9 $\sigma_t$. The characteristics of the distribution of $K_u$ in other sections are similar to the ones here.

4.1.2 Characteristics of double diffusion mixing

The characteristics of the distribution of $K_u$ in S02 are shown in Fig. 3b. The $K_u$ of the frontal zone is located between $10^{-6}$ and $10^{-4}$ m$^2$/s, which is generally lower than $K_w$. The water layers at 25–26.1 $\sigma_t$ have a high $K_u$ ($>10^{-4.5}$ m$^2$/s), unlike the upper layer in which the $K_u$ value is lower. Waters with $K_u$ values $>10^{-4.5}$ m$^2$/s are located mainly in regions less dense than 26.5 $\sigma_t$, both within and above the front (25–26.5 $\sigma_t$), and waters with high $K_u$ ($>10^{-4.5}$ m$^2$/s) are distributed along the front in a manner similar to $K_u$. As the front deepens continuously from north to south, waters with higher $K_u$ also deepen to up to 400 m. Therefore, diapycnal mixing caused by double diffusion takes place mainly above the front, especially in the upper sea less dense than 26.1 $\sigma_t$.

The distribution of $Tu$ in the frontal zone (Fig. 4) shows that water layers above 26.5 $\sigma_t$ with high $K_u$ values would promote the development of SF-type double diffusion, while those denser than 26.5 $\sigma_t$ would promote the development of DL-type double diffusion. Therefore, in areas of the sea that are less dense than 26.5 $\sigma_t$, especially those in the upper sea less dense than 26.1 $\sigma_t$, SF is the key factor causing diapycnal mixing. In water layers denser than 26.5 $\sigma_t$, the “thermohaline staircase” (Schmitt et al., 1987) can be observed although $K_u$ is quite low at depths greater than 300 m. This indicates that the diapycnal mixing of these layers, which are concentrated mainly in the NPIW layer, is caused by DL-type double diffusion although there are also a few instances of SF-type double diffusion.

4.2. Characteristics of mixing in different regions of the SAF

To further analyze the relationship between turbulent and double diffusion mixing, and the characteristics in different regions of the frontal zone, we select all stations in Section S02 to calculate the mean values of $K_w$ and $K_u$ at 30–560 m, which are about $10^{-4.1}$ m$^2$/s and $10^{-5.1}$ m$^2$/s, respectively; from this, we know that the diapycnal mixing of Section S02 is

![Figure 3](image-url)  
*Figure 3* Logarithmic distribution of eddy diffusivity $K_u$ (a) and $K_w$ (b), both in m$^2$/s in S02; gray lines are isopycnal contours ($\sigma_t$) and black dashed lines are the locations of the front (horizontal temperature gradient $> 0.2$ C/km).
generally turbulent. In addition, $K_r$ is weak in the south and strong in the north, while $K_u$ is strong in the south and weak in the north (Fig. 5). This means that in the southern part of the SAF, $K_r$ is lower (about $10^{-4.2}$ m$^2$/s) than in the middle (about $10^{-4.1}$ m$^2$/s) and in the north (about $10^{-4}$ m$^2$/s). Similarly, $K_u$ is higher (about $10^{-5}$ m$^2$/s) in the southern part of the SAF than it is in the middle (about $10^{-5.1}$ m$^2$/s) and northern (about $10^{-5.2}$ m$^2$/s) regions. The other regions also show such characteristics.

To understand the mixing characteristics in the southern, middle, and northern regions of the SAF in detail, we select stations 15, 21, and 28 as three typical representative profiles from Section S02. These three stations are located at 148.58°E, 38.25°N; 147.80°E, 38.64°N; and 147.42°E, 39.09°N. We also calculate the buoyancy frequency, $T_u$, and $R_i$ for $K_u$ and $K_r$; all of these are shown in Fig. 6.

Station 15, located in the southern part of the SAF, has a relatively high temperature, salinity, stable stratification, and $R_i$ value; its middle and upper layers can promote SF-type double diffusion, while its middle and lower layers can promote DL-type double diffusion. The distribution of $K_u$ and $K_r$ shows that the former is significantly higher than the latter in the waters shallower than 200 m, so diapycnal mixing is caused mainly by SF-type double diffusion. As the depth increases, the $K_r$ values gradually increase to $10^{-3}$ m$^2$/s in waters deeper than 200 m while $K_r$ remains at $10^{-5}$ – $10^{-4}$ m$^2$/s, indicating that diapycnal mixing is caused mainly by turbulent mixing in waters deeper than 200 m.

Station 21, located in the middle of the frontal zone, has stable stratification and the temperature and salinity fall rapidly with increasing depths due to the effect of Oyashio. The water layer of this station is not conducive to generating SF-type double diffusion, but it is conducive to generating DL-type double diffusion; $K_u$ is about $10^{-5}$ m$^2$/s and $K_r$ is between $10^{-5}$ and $10^{-3}$ m$^2$/s. Therefore, diapycnal mixing is caused mainly by turbulent mixing.

Station 28, located in the northern part of the frontal zone, has characteristics similar to Station 21 except for its potential temperature-salinity scatter, which is mainly concentrated in regions cooler than 4°C. The characteristics of $T_u$ for this station show that strong turbulent mixing occurs here; there are many water layers not favorable for double diffusion ($-45 < T_u < 45$°). The mean values of $K_u$ and $K_r$ are about $10^{-5}$ m$^2$/s and $10^{-4}$ m$^2$/s, indicating that the diapycnal mixing is caused mainly by turbulence.

These results show that the characteristics of mixing vary in different regions of the SAF. Although the diapycnal mixing is caused mainly by turbulence, there is obvious double

**Figure 4** Distribution of the Turner angle ($T_u$) (Ruddick, 1983) of the section S02. The gray contour lines are isopycnal and the black dashed lines represent the location of the front with a horizontal temperature gradient $>0.2$ °C/km.

**Figure 5** Mean values (30–560 m) and standard deviations of $K_u$ (m$^2$/s, black solid line) and $K_r$ (m$^2$/s, gray solid line) of all stations in Section S02. The areas between the vertical gray dotted lines represent the southern, middle, and northern regions of the SAF, respectively (each with a horizontal sea surface temperature gradient $<0.08$ °C/km). The black and gray dotted lines are the trend lines of the least square fit of $K_u$ and $K_r$, respectively.
diffusion in the southern part of the SAF. The diapycnal mixing in waters shallower than 200 m is caused mainly by SF-type double diffusion. The depth increases the turbulence functions which are gradually strengthened and diapycnal mixing is caused mainly by turbulence. In the middle and northern part of the SAF, the diapycnal mixing is caused mainly by turbulence; diapycnal mixing caused by double diffusion is weak, making conditions more favorable for the development of DL-type double diffusion.

5. Discussion

By analyzing the mixing characteristics of the SAF, we found that diapycnal mixing is dominated mainly by turbulent mixing in the frontal zone; the $K_r$ near the front can reach $10^{-4}$–$10^{-3}$ m$^2$/s, which is 1–2 magnitudes higher than in the open ocean. We use S02 and S03 as examples to discuss the strengthening mechanism of turbulent mixing in the SAF region.

The shear or Kelvin–Helmholtz instability (KI) and symmetric instability (SI) can strengthen turbulent mixing (D’Asaro et al., 2011); the latter can also effectively extract kinetic energy from the geostrophic frontal jet and feed a turbulent cascade to dissipation. Here, we measure this instability using the gradient Richardson number ($Ri$) and potential vorticity ($q$).

The $Ri$ and $q$ of Section S02 are shown in Fig. 7a and b. The region in which $0.25 < Ri < 1$ basically corresponds to those in which $q < 0$; these are concentrated in the water layers near the front where 25.5–26.7 $\sigma_{pi}$, indicating that SI occurs in these layers. The negative value region of $q$ corresponds, simultaneously, to the strong turbulent mixing region; thus, the strong turbulent mixing ($K_r \geq 10^{-3.5}$ m$^2$/s) of water layers near the 26.1–26.7 $\sigma_{pi}$ front at Section S02 is closely related to SI. However, there is a large difference between Section S03 (Fig. 7d and e) and Section S02. The values of $q$ corresponding to other regions with strong turbulent mixing are basically greater than 0 (Fig. 7e); the exception is the relationship between strong turbulence and SI near 38.15°N and 38.4°N at 26.5–26.7 $\sigma_{pi}$, which indicates that SI is not the main reason for the increased turbulence in Section S03. The horizontal temperature gradient and logarithmic distribution of $K_r$ in Section S03 are presented in Fig. 8a and b, respectively.

In addition, near-inertial internal waves (NIWs) may also strengthen the turbulent mixing (Whitt and Thomas, 2013). As shown by the characteristics of the effective Coriolis parameter ($f_{eff}$) in Section S02 (Fig. 7c), the water layers at 25.5–26.7 $\sigma_{pi}$ near the front are basically located at the NIWs barrier layers with $f_{eff} > 1.2f$, further indicating that NIWs are not the main factors strengthening the turbulent mixing.
of Section S02, except in areas on the southern side of 38.3°N. Section S01 is similar to Section S02; at the front in Section S03 (Fig. 7f), there is an obviously high $K_r (\geq 10^{-3.5} \text{m}^2/\text{s})$ and low $Ri (\leq 0.25)$ in areas shallower than 200 m north of 38.5°N and deeper than 150 m north of 38.4°N. At the same time, these KI regions have a fine vertical spatial continuity and scale structure, and $f_{\text{eff}}$ is generally lower than $f$. The results suggest that NIWs may be a possible reason for KI, which strengthens turbulence, in these two regions.

Thus, the strong turbulence in the water layers at 26.1–26.7 $\sigma_0$ and 26.5–26.7 $\sigma_0$ in Sections S02 and S03 near 38.15°N and 38.4°N, respectively, is closely related to SI. The turbulent mixing in Section S03 may be strengthened by KI. In Sections S01 and S02, SI may be the main reason for the strengthened turbulent mixing in the frontal zone. Lastly, NIWs could be the factors causing KI in the front at areas shallower than 200 m north of 38.5°N and deeper than 150 m north of 38.4°N.

Figure 7  Characteristics of $Ri$, $q$ (s$^{-1}$), and $f_{\text{eff}}$ ($f$) in Sections S02 and S03. In (a), the $Ri$ of S02 is given in logarithmic form in the region within the closed black contour lines, (b)–(c) is where $Ri \leq 0.25$, and the $q$ and $f_{\text{eff}}$ distribution of S02, respectively, are seen, (d)–(f) illustrate the $Ri$, $q$, and $f_{\text{eff}}$ distributions of S03, respectively, with the gray lines showing isopycnal contours ($\sigma_0$) and black dashed lines representing the locations of the front (horizontal temperature gradient $> 0.2^\circ \text{C/km}$).

Figure 8  (a) Horizontal temperature gradient [°C/km] and (b) logarithmic distribution of $K_r$ [m$^2$/s] for Section S03; gray lines are isopycnal contours ($\sigma_0$) and the black dashed line in (b) represents the location of the front (horizontal temperature gradient $> 0.2^\circ \text{C/km}$).
6. Conclusion

This paper presents the results of studies on the mixing characteristics of the SAF in the KOCR, and analyzes of the temperature, salinity, current structural characteristics, and mixing characteristics of the SAF. Using data from cruising observations and the AVISO and OISST satellite altimeter datasets to calculate parameters such as the Turner number ($T_u$), turbulent eddy diffusivity ($K_e$), thermal diffusivity ($K_t$), and gradient Richardson number resulted in the following conclusions:

1. There is cold and fresh Oyashio water in the northern part of the SAF, and warm and salty Kuroshio Extension water in the southern region. The SAF is located between 25.5 and 26.7 $\sigma_t$ in a band pattern inclined north to south. As the depth increases, the front moves southward with a gradually weakening intensity. The background current is eastward, with a high and low flow velocity, respectively, in the south and north. There are numerous eddies in the waters around the SAF.

2. Diapycnal mixing in the SAF zone is mainly turbulent, and it is stronger in the north than in the south of the frontal zone. The region with strong turbulence ($K_e > 10^{-4.5}$ m$^2$/s) is distributed mainly in water layers within and under the front (26.1–26.7 $\sigma_t$) and it is shallow in the north and deep in the south. The region with strong double diffusion ($K_e > 10^{-4.5}$ m$^2$/s) is distributed mainly in water layers (25–26.5 $\sigma_t$) within and above the front, in the southern part of the SAF, with a depth gradient similar to that of turbulence. These water layers are dominated mainly by salt-finger double diffusion, while the middle and lower regions deeper than 300 m also have a few layers dominated by diffusive-layering double diffusion mixing.

3. Symmetric instability may be the main factor strengthening turbulent mixing in the frontal zone, but shear instability causes it in other zones. Shear instability within the front in regions shallower than 200 m north of 38.5°N, and in layers deeper than 150 m north of 38.4°N in Section 503, may be related to near-inertial internal waves.

Acknowledgments

This work was supported by the National Natural Science Foundation of China, No. 11572351 and the Province Natural Science Foundation of Jiangsu, China, No. BK20150711. We thank all the crew members who participated in the ship cruising observation in May–June 2016.

References


