A Modified Vertical Mixing Parameterization for Its Improved Ocean and Coupled Simulations in the Tropical Pacific

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ABSTRACT

Climate models suffer from significant biases over the tropical Pacific Ocean, including a too-cold cold tongue and too-warm temperature at the depth of the thermocline. The emergence of model biases can be partly attributed to vertical mixing parameterizations, in which there are great uncertainties in selections of functional forms and empirical parameters. In this paper, the impacts of two different vertical mixing schemes on the tropical Pacific temperature simulations are investigated using version 5 of the Modular Ocean Model (MOM5). One vertical mixing scheme is the widely used K-profile parameterization (KPP) scheme, and the other is a hybrid mixing scheme (the Chen scheme) by combining a Kraus–Turner-type bulk mixed layer (ML) model with Peters et al.’s shear instability mixing model (PGT model). It is shown that the Chen scheme works better than the KPP scheme for SST simulation but produces an exaggerated subsurface warm bias simultaneously. The better SST simulation can be attributed to the employment of the PGT model, which produces lower levels of shear instability mixing than its counterpart in the KPP scheme. Furthermore, a modified KPP scheme is presented in which its shear instability mixing model and constant background diffusivity are replaced by the PGT model and the Argo-derived background diffusivity, respectively. This new scheme is then employed into MOM5-based ocean-only and coupled simulations, demonstrating substantial improvements in temperature simulations over the tropical Pacific. The modified KPP scheme can be easily employed into other ocean models, offering an effective way to improve ocean simulations.

1. Introduction

Heat balance is particularly important in the tropical Pacific, where the fluctuation in SST has significant impacts on climate variability worldwide. Various ocean and coupled general circulation models (OGCMs and CGCMs) have been developed to better simulate the processes controlling the variability of SST, but large biases remain in many state-of-the-art models, including the too-cold cold tongue and too-diffuse thermocline on the equator (Zhang et al. 2006; Wang et al. 2014; Richter 2015; Zuidema et al. 2016). Many studies have been conducted to identify the origin of these biases, revealing that strong air–sea feedbacks in the tropics can amplify the small biases in individual oceanic and atmospheric submodels and generate pronounced drifts away from observations (Li and Xie 2014). On the atmospheric side, various factors have been identified, including too-weak alongshore wind and an underestimation of the stratocumulus deck along the western coast of South America (Ma et al. 1996; Colas et al. 2012). On the oceanic side, stubborn biases also exist in the ocean-only simulations. In particular, OGCMs, even driven by the best possible estimated atmospheric forcing fields, commonly produce SST biases that bear
a strong resemblance to those in coupled ocean–atmosphere simulations (Griffies et al. 2009), indicating that the ocean model component makes a great contribution to the SST errors in CGCMs. These SST biases are closely related to the way the thermocline effects on SST are represented in ocean models through vertical mixing processes (Zhang and Gao 2016; Gao and Zhang 2017).

Oceanic turbulent mixing plays a major role in the equatorial heat budget, and currently, great uncertainties exist in its parameterization for ocean model representations. In general, a vertical mixing parameterization primarily consists of three individual parts: a scheme for the upper boundary layer (Kraus and Turner 1967; Niiler 1977; Gaspar 1988; Chen et al. 1994; Large et al. 1994), a topographically enhanced mixing scheme for the abyss (St. Laurent and Garrett 2002; Simmons et al. 2004; Lee et al. 2006; Jayne 2009; Polzin 2009), and a constant background mixing representation (Zhang and Gao 2016; Peters et al. 1988; Pacanowski and Philander 1981; PGT scheme, Peters et al. 1988) and K-profile parameterization (KPP) scheme (Large et al. 1994). For Ri-dependent mixing models, mixing coefficients are negatively correlated with Ri, but their functional relationships are quite different. For example, compared with the PGT model, the PP model produces a weaker vertical mixing at low Ri but a more intense mixing at high Ri (Peters et al. 1988; Yu and Schopf 1997; Large 1998). In general, Ri-dependent mixing models work better in the regions where the shear instability mixing dominates, such as in the tropics, but cannot be used alone in the extratropics, where destabilizing buoyancy flux plays nonnegligible roles (Li et al. 2001). To fill this gap, the KPP scheme is developed and is currently widely used in ocean and climate modeling. This scheme expresses the profile of boundary layer diffusivity as the product of boundary layer depth, turbulent velocity scale, and vertical shape function. Below the boundary layer, vertical mixing is parameterized as the superposition of three processes: shear instability, internal wave breaking, and double diffusion. The KPP scheme has been employed in all the major OGCMs, with demonstrated improvements in ocean simulations. For example, Li et al. (2001) investigated the performances of the KPP scheme and the PP scheme in a Pacific OGCM, revealing that the KPP scheme works better than the PP scheme in both the tropics and the extratropics. Halliwell (2004) evaluated seven different vertical mixing schemes in the Hybrid Coordinate Ocean Model (HYCOM) and found that the KPP scheme had better performances than the KT ML models in the climatological simulations of the Atlantic Ocean.

The use of the KPP scheme is regarded as an improvement over other alternatives, but substantial model biases remain in the related ocean and climate modeling. Additionally, although the KPP scheme works better than the KT ML models (Halliwell 2004),
its comparisons with the Chen scheme have not been conducted. Thus, in this paper, we first evaluate the performances of the Chen scheme and KPP scheme using MOM5. Then, by examining the performances of each scheme, a modified KPP scheme is proposed. In this new scheme, the PGT model and the Argo-derived background diffusivity are used to replace the corresponding components in the original KPP scheme. Finally, this new scheme is employed into MOM5-based ocean-only and coupled simulations with an attempt to further improve SST simulations.

The paper is organized as follows. The KPP scheme, the Chen scheme, and the modified KPP scheme are briefly described in section 2. Section 3 describes the model configurations and model experiments. In section 4, comparisons between the two mixing schemes are presented and a modified KPP scheme is proposed. Using the new scheme, improved model performances are demonstrated in section 4. Finally, we discuss and summarize our results in section 5.

2. The vertical mixing schemes

a. The KPP scheme

The KPP scheme is proposed by Large et al. (1994); this scheme expresses the profiles of eddy viscosity and diffusivity as the product of oceanic boundary layer depth $h$, turbulent velocity scale $w_s$, and vertical shape function $G$:

$$ K_v = hw_s(\sigma)G(\sigma), \quad (1) $$

where $\sigma$ is a dimensionless vertical coordinate varying from 0 to 1 in the oceanic boundary layer. The $h$ is defined as the depth at which the bulk Richardson number ($R_i$) reaches a critical value ($R_i^c$):

$$ R_i^c(h) = \frac{[B_f - B(h)]h}{[V_r - V(h)]^2 + V_i^2(h)} = R_i^c, \quad (2) $$

in which the variables with subscript $r$ denote the corresponding properties at the near surface and $V_i$ is the turbulent velocity, whose effects are most important in pure convection with little or no mean shear. The turbulent velocity scale $w_s$ is dependent on convective velocity $w^* = (B_0 h)^{1/3}$ ($B_0$ is upward surface buoyancy flux) and friction velocity $u^* = (\tau \rho)^{1/2}$ ($\tau$ is wind stress and $\rho$ is seawater density). The shape function is a cubic polynomial $G(\sigma) = a_0 + a_1\sigma + a_2\sigma^2 + a_3\sigma^3$, in which the four coefficients are determined based on the boundary conditions. In the KPP scheme, the lower boundary condition is governed by the requirement that diffusivity and their vertical derivatives should be continuous. Therefore, mixing representations for the ocean interior can affect the estimated diffusivity in the whole boundary layer through a dependence of $G(\sigma)$ on the interior diffusivity and its vertical derivatives at the base of boundary layer. More descriptions can be found in Large et al. (1994). In this paper, more attention is paid to the vertical mixing processes below the boundary layer, including shear instability mixing and internal wave breaking.

In the KPP scheme, shear instability mixing for the ocean interior is parameterized as a function of $R_i$:

$$ \nu^v = \nu_0, \quad R_i < 0, $$

$$ \nu^v = \nu_0[1 - (R_i/R_{i0})^2]^p, \quad 0 < R_i < R_{i0}, $$

$$ \nu^v = 0, \quad R_{i0} < R_i, \quad (3) $$

where $\nu_0 = 5 \times 10^{-3} \text{ m}^2 \text{s}^{-1}$, $R_{i0} = 0.8$, and $p = 3$ (Large and Gent 1999). Diapycnal mixing away from the boundary layer is primarily driven by internal wave breaking and is typically scaled by background viscosity $\nu_m^w$ and diffusivity $\nu_m^v$. Based on the microstructure observations (Gregg 1987; Ledwell et al. 1993, 1998),

$$ \nu_m^w = 1.0 \times 10^{-4} \text{ m}^2 \text{s}^{-1}, $$

$$ \nu_m^v = 0.1 \times 10^{-4} \text{ m}^2 \text{s}^{-1}. \quad (4) $$

Background diffusivity determines the strength of vertical mixing within the thermocline and is important to heat transfers between the upper boundary layer and ocean interior. Thus, its value is critical to understand the energy budget of the ocean (Wunsch and Ferrari 2004). The constant diffusivity of $O(10^{-5})$ m$^2$s$^{-1}$ may be not adequate for uses as the background diffusivity in current OGCMs, because spatially varying diapycnal diffusivity has been reported by many studies (Polzin et al. 1997; Gregg et al. 2003; Whalen et al. 2012; Waterhouse et al. 2014). Particularly, microstructure measurements generally indicate that the diapycnal diffusivity can be reduced by one order of magnitude near the equator (Gregg et al. 2003; Thurnherr and St. Laurent 2011; Cheng and Kitade 2014; Liu et al. 2017). Thus, the effects of spatially varying diapycnal diffusivity need to be considered on SST and currents simulations (St. Laurent and Garrett 2002; Canuto et al. 2004; Harrison and Hallberg 2008; Jochum 2009; Melet et al. 2013; Furue et al. 2015; de Lavergne et al. 2016; Zhu and Zhang 2018a).

b. The Chen scheme

Chen et al. (1994) developed a hybrid mixing scheme by combining a KT-type ML model with Price’s dynamical instability model (Price et al. 1986). In this scheme, the KT-type ML model is used to describe the evolution of MLD (Niiler 1977):
where $h$ is the MLD; $\Delta b$ is the buoyancy jump across the base of the ML; $w_*$ is the entrainment velocity; $u_*$ is the friction velocity; $B_0$ and $J_0$ are nonpenetrating and penetrating components of the upward surface buoyancy flux, respectively; $h_p$ is attenuation depth of shortwave radiation, which can be calculated according to its empirical relationship with chlorophyll-$a$ fields (Zhang et al. 2011); $m_0$ is a parameter that is used to scale the wind stirring effect; and $n$ is a parameter to represent the ratio of entrainment buoyancy flux to surface buoyancy flux when convection occurs. The two parameters ($m_0$ and $n$) can be empirically determined based on observations. According to Davis et al. (1981), $m_0 = 0.4$ and $n = 0.18$ are taken in this study.

The term on the left-hand side of Eq. (5) is the potential energy required to lift the dense water and mix it through the ML under the condition of entrainment. The first term on the right-hand side is the TKE input by wind stirring. The second term represents the TKE changes induced by the nonpenetrating surface buoyancy flux, and the effect of the penetrating component is presented by the third term. The KT-type ML model is typically embedded into the layer ocean models with the uppermost model layer being prescribed as an ML. Nevertheless, its implementation into level ocean models is far from straightforward because the MLD can be located in different layers whose thickness is prescribed. Power et al. (1995) and Godfrey and Schiller (1997) proposed a method by which the Chen scheme was employed into MOM5. First, MLD is determined by the KT-type ML model. Then, if the model layers are fully within the ML, their eddy mixing coefficients are assigned to be $5 \times 10^{-3}$ m$^2$s$^{-1}$; for the model layers containing the bottom of the ML, the eddy mixing coefficients are reduced in proportion to the fraction of model layers occupied by the ML.

In the original Chen scheme, Price’s model (Price et al. 1986) was employed to describe the shear instability mixing in the ocean interior. However, this model can only be used to calculate tracer exchanges between two model layers rather than estimate the vertical eddy coefficients. Thus, in the MOM5, Price’s model is replaced by the modified PGT model (Peters et al. 1988) to describe the shear instability mixing:

\[
\nu_m = 6.75 \times 10^{-8} \text{Ri}^{-8} + 8.6 \times 10^{-4}(1 + 5\text{Ri})^{-2},
\]

\[
\nu_s = 2.03 \times 10^{-9} \text{Ri}^{-10} + 8.5 \times 10^{-4}(1 + 5\text{Ri})^{-3}.
\]

This model is derived from the 4.5-day mean profiles at $(0^\circ, 140^\circ W)$ in 1984. Thus, it cannot treat the high-frequency and small-vertical-scale motions, which have rather different dependencies on Ri (Richards et al. 2015) and are generally unsolved in ocean and climate modeling (Sasaki et al. 2012, 2013). Compared with that in the KPP scheme [Eq. (3)], the PGT model demonstrates a rapid increase of eddy coefficients when Ri $< 0.4$ (also see Fig. 7a below). Besides the great uncertainties in this slope, eddy coefficients go to infinity as Ri approaches zero. Therefore, for the practical applications in MOM5, eddy coefficients are bounded by $5 \times 10^{-3}$ m$^2$s$^{-1}$, roughly the maximum diffusivity observed by Peters et al. (1988). In the Chen scheme, background mixing coefficients are similar to those in the KPP scheme [Eq. (4)].

**c. A modified KPP scheme**

By comparing the performances of the KPP scheme and the Chen scheme in ocean-only simulations, we find that an improved SST simulation using the Chen scheme is realized by the employment of the PGT model, which produces a lower level of mixing than its counterpart in the KPP scheme. Therefore, a hybrid approach is proposed by replacing the shear instability mixing model in the KPP scheme by the PGT model. Ocean-only simulations are performed using this approach, and the model results demonstrate the advantages of using the PGT model in more accurately reproducing the observed cold tongue and equatorial thermocline. Based on these results, a modified KPP scheme is proposed in which its shear instability mixing model [Eq. (3)] and constant background diffusivity [Eq. (4)] are replaced by the PGT model [Eq. (6)] and the Argo-derived background diffusivity (Zhu and Zhang 2018a), respectively.

In the following, we begin our analysis by examining the performances of the KPP scheme and the Chen scheme using MOM5. The model configurations and model experiments are described below.

**3. Models and experiments**

The ocean-only simulations are based on the MOM5 (Griffies 2012), which is developed by the Geophysical Fluid Dynamics Laboratory (GFDL). This model has a horizontal resolution of 1°, with meridional resolution being progressively enhanced to $1/3^\circ$ equatorward of 30° latitude. It has 50 levels in the vertical with 10-m resolution in the upper 22 levels. More model details can be found in Griffies et al. (2009). The coupled simulations are based on the GFDL CM2.1 (Delworth et al. 2006), in which the oceanic component (MOM5) has the
identical configurations to the ocean-only simulations. The atmospheric component is the GFDL Atmospheric Model, version 2.1 (AM2.1), which has a horizontal resolution of 2.5° longitude × 2.0° latitude and 24 vertical levels. The oceanic and atmospheric components exchange fluxes every 2 h, and no flux adjustments are employed.

To evaluate the sensitivity of model solutions to vertical mixing schemes, two ocean-only forced experiments are conducted (an overview of experiments is provided in Table 1) using the corresponding vertical mixing schemes (denoted as the OCN_KPP run and OCN_Chen run, respectively). Each scheme has its own advantages. By investigating their performances in ocean-only simulations, a hybrid approach is proposed by replacing the shear instability mixing model in the original KPP scheme by the PGT model. This approach is then employed into a third experiment (denoted as OCN_Hybrid run) to test its improved performance.

In addition, more sets of experiments are performed, including the MOM5-based coupled simulations in which the modified KPP scheme is employed to examine the effects in the coupled context. The CPL_KPP run represents the coupled simulation using the original KPP scheme, whereas the experiments using the modified KPP scheme are denoted as OCN_MDF run for ocean-only simulation and CPL_MDF run for coupled simulation.

The ocean-only experiments are initialized using the January temperature and salinity fields from Steele et al. (2001) and are integrated for 30 years using the atmospheric climatological forcing fields from Large and Yeager (2009). Coupled experiments are run for 300 years using the values of greenhouse gases, aerosols, isolation, and land cover in 1990 (Wittenberg et al. 2006). The impacts of vertical mixing schemes on the model solutions are investigated based on the MOM5 outputs for the last 5 years and the CM2.1 outputs for the last 200 years. (All the results in this study can be reproduced using the model codes and input fields downloaded from https://github.com/mom-ocean/MOM5.)

### 4. Results

#### a. Comparisons between the OCN_KPP run and OCN_Chen run

Figure 1 demonstrates the observed and simulated annual-mean SST over the tropical Pacific. Compared with the observation (Fig. 1a), the simulated SST in the OCN_KPP run exhibits significant errors, including a cold bias over the eastern equatorial Pacific and a warm bias near the American continent (Fig. 1b). Pronounced improvements arise in the OCN_Chen run (Figs. 1c and 1d). In particular, the cold bias over the eastern equatorial Pacific is almost eliminated. The warm bias, however, remains in the southeastern tropical Pacific because it could be primarily induced by the coarse model resolution (Richter 2015; Zuidema et al. 2016).

The cold SST bias along the equator is accompanied with a subsurface warm bias (Fig. 2b), which is widely known as the problem of a too diffuse thermocline in the equatorial Pacific (Griffies et al. 2009). Although the Chen scheme works better in SST simulations over the KPP scheme, the subsurface warm bias is more significant in the OCN_Chen run (Figs. 2c and 2d). Especially in the eastern equatorial Pacific, regions with positive differences greater than 0.5°C nearly extend throughout the upper 200 m, implying that the local redistribution of heat by vertical mixing processes cannot solely explain the warming in both SST and subsurface temperature. Thus, oceanic processes off the equator can also make great contributions to the warm bias on the equator.

Temperature differences along 140°W are demonstrated in Fig. 3. Both runs (Figs. 3b and 3c) exhibit the warm biases off the equator, including a bias greater than 1°C in the band of 0°–15°S and up to an 8°C bias near 10°N. These subsurface warm biases can be transported equatorward through the subtropical cells (Fig. 4), contributing to the warm bias along the equator. Therefore, since the OCN_Chen run has the warmer biases off the equator (Fig. 3d), its subsurface warm bias along the equator (Fig. 2d) is exaggerated consequently. It is plausible that the SST warming over the eastern equatorial Pacific in the OCN_Chen run (Fig. 1d) is

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**Table 1. List of experiments.**

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Run</th>
<th>Vertical mixing scheme</th>
<th>Mixed layer model</th>
<th>Shear instability model</th>
<th>Background diffusivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCN_KPP</td>
<td>MOM5</td>
<td>KPP</td>
<td>KPP</td>
<td>KPP</td>
<td>10⁻⁵ m² s⁻¹</td>
</tr>
<tr>
<td>OCN_Chen</td>
<td>MOM5</td>
<td>KT-type model</td>
<td>KPP</td>
<td>PGT</td>
<td>10⁻⁵ m² s⁻¹</td>
</tr>
<tr>
<td>OCN_Hybrid</td>
<td>MOM5</td>
<td>KPP</td>
<td>KPP</td>
<td>PGT</td>
<td>10⁻⁵ m² s⁻¹</td>
</tr>
<tr>
<td>OCN_MDF</td>
<td>MOM5</td>
<td>KPP</td>
<td>KPP</td>
<td>PGT</td>
<td>Argo-derived</td>
</tr>
<tr>
<td>CPL_KPP</td>
<td>CM2.1</td>
<td>KPP</td>
<td>KPP</td>
<td>PGT</td>
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<td>PGT</td>
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caused by the upwelled warmer water. However, the mechanism for SST warming is not so straightforward. Specifically, a slightly reduced temperature trough (the reduction in the temperature difference around 50 m, 100°–150°W in Fig. 2d, where the contour of 0.5°C is disconnected) separates the warming in SST and in subsurface temperature, implying that the warming mechanism for the upper layer and the subsurface layer may be different.

To verify our hypothesis, a heat budget is performed:

\[
\frac{\partial T}{\partial t} = -\left(\frac{\partial T}{\partial x}u + \frac{\partial T}{\partial y}v + \frac{\partial T}{\partial z}w\right) + \left(\frac{\partial}{\partial z}k_r \frac{\partial T}{\partial z}\right) + \frac{1}{\rho_0 c_p} \frac{\partial I}{\partial z} + k_h \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right). \tag{7}
\]

The terms on the right-hand side, respectively, are total advection (horizontal advection plus vertical advection), vertical diffusion, and the residual term (penetrative shortwave radiation plus horizontal diffusion).
Figure 5 shows the differences in the heat budget terms between the two runs. Corresponding to the regions with subsurface warming (Fig. 2d), a positive difference in the advection term is found below 50 m (Fig. 5d). This is consistent with the conclusion stated above that the subsurface warming off the equator (Fig. 3d) is transported equatorward and contributes significantly to the equatorial subsurface warming in the OCN_Chen run (Fig. 4). The SST warming over the eastern equatorial Pacific is related to the positive difference in the vertical diffusion term above 50 m (Fig. 5e), implying a great discrepancy in vertical eddy diffusivities between the two runs.

To demonstrate this, annual-mean vertical eddy diffusivities (Kt) calculated from the KPP scheme and the Chen scheme are shown in Fig. 6. As expected, compared with those in the OCN_KPP run (Fig. 6a), the diffusivities around 100 m are reduced by up to an order of magnitude in the OCN_Chen run (Fig. 6c), resulting in a heat accumulation in the upper boundary layer and the consequent SST warming. Meanwhile, the diffusivities off the equator are elevated by up to two orders of magnitude in the OCN_Chen run (Fig. 6f), resulting in the consequent subsurface warming as seen in Fig. 3d.

Figure 6c reveals that substantial differences in vertical eddy diffusivities occur around 50–100 m and within the region of (100–200 m, 90°–120°W), corresponding to the flanks of the Equatorial Undercurrent (EUC) (Johnson et al. 2002). Thus, the discrepancy in vertical eddy diffusivities can be attributed to the different parameterizations for shear instability mixing. Figure 7a shows vertical eddy diffusivity from the PGT model [Eq. (6); solid line] and the shear instability mixing model in the KPP scheme [Eq. (3); dotted line] as functions of Ri. Although general features of the two schemes are similar with a reduced diffusivity for increasing Ri, the KPP scheme produces a significantly larger diffusivity in the range 0.3 < Ri < 0.8. Also, regions with Ri < 0.8 are shaded in Fig. 7b, which demonstrate a similar spatial pattern with the distribution of diffusivity differences (contours in Fig. 7b; also see Fig. 6c). Therefore, the SST warming in the OCN_Chen run can be attributed to the

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**Figure 3.** As in Fig. 1, but for the temperature along 140°W. The contour intervals are 2° in (a) and 1°C in (b)–(d).

**Figure 4.** Vertically averaged temperature differences over 100–200 m (OCN_Chen minus OCN_KPP; color) and mean currents from the OCN_KPP run (vectors).
employment of the PGT model, which produces a lower level of shear instability mixing than its counterpart in the KPP scheme.

Figure 6f reveals that substantial differences in the vertical eddy diffusivities also occur off the equator. However, vertical shear of horizontal currents is too weak to produce such diffusivity differences in these regions, implying that these differences could be caused by the parameterizations for the upper boundary layer. MLD is typically regarded as a strength indicator of upper boundary layer mixing. Figure 8 shows the observed and simulated annual-mean MLD over the tropical Pacific. Compared with the observation (Fig. 8a), the simulated MLD is generally overestimated in both runs. In particular, the overestimation is more significant in the OCN_Chen run (color in Fig. 8d), corresponding to the increased subsurface warm bias (contours in Fig. 8d). As indicated
in Eq. (5), the evolution of MLD in the Chen scheme is determined by the empirical parameter \( m_0 \), which scales wind-stirring effects in the KT-type ML model. The estimates of \( m_0 \) from observations are largely scattered (Gaspar 1988) and have great uncertainties. For example, using the upper-ocean observations over a 20-day period, Davis et al. (1981) gives the estimate of 0.4, which is typically applied in the Chen scheme. But the later studies find that \( m_0 \) is spatially and temporally varying (Martin 1985; Acreman and Jeffery 2007). Thus, in our previous study (Zhu and Zhang 2018b), \( m_0 \) is estimated through its inverse calculation from Eq. (5), the Argo dataset, and meteorological reanalysis data. We find that \( m_0 \) is spatially varying with values less than 0.4 arising in the northeastern and southeastern tropical Pacific. Therefore, the spatially constant \( m_0 \) originally specified in the OCN_Chen run indicates overestimations in these regions, leading to the deepening of the MLD. As a consequence, regions with large mixing coefficients \((5 \times 10^{-3} \text{ m}^2 \text{ s}^{-1})\) extend deeper than those in the OCN_KPP run (Fig. 6f), resulting in the positive temperature differences off the equator (Fig. 3d) and the equatorial subsurface warming below 50 m (Fig. 2d).

In this subsection, comparisons between the Chen and KPP schemes are made in terms of annual-mean temperature. Evidently, the Chen scheme works better than the KPP scheme in terms of SST simulation, but the subsurface warm bias is exaggerated simultaneously. The improvements in SST simulation can be attributed
to the employment of the PGT model, which is incorporated into the Chen scheme and generally produces weaker diffusivities compared with its counterpart in the KPP scheme.

b. A hybrid approach and its performance in the ocean-only simulation

Based on the results in the last subsection, it is natural to think that replacing the original shear instability mixing model by the PGT model can facilitate the KPP scheme to produce more realistic SST in ocean modeling, while avoiding the deterioration in subsurface temperature simulations. To further test this idea, an additional experiment is conducted (denoted as OCN_Hybrid run) and its performance is given in this subsection.

In the OCN_Hybrid run, the KPP scheme is employed but its shear instability mixing model is replaced by the PGT model. Figure 9 shows the improved performance in temperature simulations compared with the model solutions using the original KPP scheme. Vertical eddy diffusivities are reduced by nearly an order of magnitude around 50 m relative to those in the OCN_KPP run (Fig. 9a), demonstrating a similar result in the OCN_Chen run (Fig. 6c). Consequently, the cold SST bias in Fig. 1b is reduced by 0.3°C (Fig. 9b). In addition, the subsurface warming bias in the OCN_Chen run (Fig. 2d) does not appear in the OCN_Hybrid run (Fig. 9c), further confirming the assumption stated above that the subsurface warming along the equator originates from the overestimated MLD off the equator (Fig. 8d). In fact, the subsurface temperature is slightly reduced, resulting in a more realistic equatorial thermocline; this is consistent with the effect due to the vertical diffusion term (Fig. 5e). It is worth noting that the warm SST bias near the American continent is also reduced in the OCN_Hybrid run. Xu et al. (2014) found that the warm bias in the equatorial thermocline can propagate eastward via advection or Kelvin waves, contributing to the warm SST bias in the eastern boundary regions. Since the subsurface cooling arises in the equatorial thermocline (Fig. 9c), the warm SST bias in the southeastern tropical Pacific is alleviated correspondingly.

In this subsection, a hybrid approach is tested by replacing the shear instability mixing model in the KPP scheme with the PGT model. This approach is then employed into MOM5-based ocean-only simulations, resulting in great improvements in temperature simulations. However, the cold SST bias is only reduced by ~0.3°C using the PGT model, and there are still ~70% errors unaccounted for. The remaining SST bias can be related to the background diffusivity, which determines the strength of vertical mixing within the thermocline and is important to heat transfers between the upper boundary layer and ocean interior. Some previous studies have investigated the sensitivity of model performances to the changes in background diffusivity (Canuto et al. 2004; Harrison and Hallberg 2008; Jochum 2009; Sasaki et al. 2012, 2013; Furue et al. 2015; Jia et al. 2015), indicating that the spatial structure of background diffusivity is important to the tropical SST and thermocline simulations. However, background diffusivity is of great uncertainty and not well constrained because of the sparse microstructure observations. In particular, the values of the background diffusivity [Eq. (4)] typically specified in ocean and climate modeling are not consistent with the observations near the equator (Gregg et al. 2003; Thurnherr and St. Laurent 2011; Cheng and Kitade 2014; Liu et al. 2017), leading to the related errors in SST simulations (Jochum 2009; Zhu and Zhang 2018a). Thus, the Argo-derived background diffusivity is employed with an attempt to more realistically represent the background diffusivity in ocean and climate modeling.
c. The Argo-derived background diffusivity

To get a further improvement in SST simulations, the Argo-derived background diffusivity (Zhu and Zhang 2018a) is employed by replacing its counterpart in the KPP scheme [Eq. (4)]. In this subsection, the spatial pattern of the Argo-derived background diffusivity is briefly described.

The Argo-derived background diffusivity is estimated from the finescale parameterizations, which are proposed based on the midlatitude internal wave–wave interaction theory (McComas and Müller 1981; Henyey et al. 1986; Müller et al. 1986), by which the energy in the observed strain/shear variance on a vertical scale of 10–100 m is transferred to the scale on which the internal wave breaks, driving the diapycnal mixing in the ocean interior (Polzin et al. 1995; Kunze et al. 2006; Polzin et al. 2014). Furthermore, the strain-based finescale parameterization has been widely used to estimate the diapycnal diffusivity from the observations with the global coverage, such as the Argo profiles (Wu et al. 2011; Whalen et al. 2012). Figure 10a shows the estimated diapycnal diffusivity over the tropical Pacific. High diffusivity mainly arises in the northwestern and southwestern tropical Pacific, and low diffusivity mainly arises in the eastern tropical Pacific and the central equatorial Pacific. Similar to our previous study (Zhu and Zhang 2018a), only the regions with the diffusivity $<10^{-5}$ m$^2$ s$^{-1}$ are extracted and employed into ocean model. In addition, the background diffusivity within 2° latitude of the equator is prescribed with $10^{-6}$ m$^2$ s$^{-1}$; this is based on consideration that the finescale estimates near the equator are somewhat unreliable (Kunze 2017) and the observational evidence has shown the reduced diapycnal diffusivity of $O(10^{-6})$ m$^2$ s$^{-1}$ there. Note that the Argo-derived background diffusivity is time independent and varies only on the horizontal. Figures 10b and 10c illustrate the horizontal distributions of vertical eddy diffusivities at 2000 m from the OCN_KPP run and the following OCN_MDF run, respectively. Note that topographically enhanced mixing is considered in both experiments and the reduced mixing inferred from Fig. 10a is only considered in the OCN_MDF run.

In our previous study (Zhu and Zhang 2018a), we find that using the Argo-derived background diffusivity can improve the thermal structure simulations in the upper tropical Pacific. Particularly, subsurface warm bias is alleviated owing to the reduced diffusivity in the off-equatorial regions. It has been shown that, respectively, individual applications of the PGT model and the Argo-derived background diffusivity can improve the SST
simulations over the tropical Pacific. Therefore, it is natural to combine them together with an attempt to get a further improvement. In this subsection, a modified KPP scheme is described and its improved performances in ocean and climate simulations are demonstrated.

d. The modified KPP scheme

The modified KPP scheme is proposed in which its shear instability mixing model [Eq. (3)] and constant background diffusivity [Eq. (4)] are replaced by the PGT model [Eq. (6)] and the Argo-derived background diffusivity (Fig. 10), respectively. This new scheme is then employed into MOM5-based ocean-only and coupled simulations to demonstrate its improved performances.

Figure 11 demonstrates the improved performances in ocean-only simulations. It is obvious that the biases of the too-cold cold tongue and too-diffuse thermocline are substantially reduced. The cold SST bias is reduced by $-0.6^\circ \text{C}$, revealing an additive effect of the changes in the Ri-dependent scheme and background diffusivity. The subsurface warm bias along the equator is reduced by $-1.5^\circ \text{C}$, leading to a more realistic thermocline. It is worth noting that the temperature biases (Figs. 11a and 11b) and improvements (Figs. 11e and 11f) are of a similar spatial pattern but with opposite signs, further revealing the feasibility and effectiveness of this modified KPP scheme.

Furthermore, the modified KPP scheme is tested in the coupled simulations. The mechanism is straightforward in terms of processes at work, and hence the similar results should arise in the coupled simulations. However, the impacts on SST induced by vertical mixing are more complicated for coupled models. Figure 12 shows the impacts on coupled simulations. In general, SST biases in the CPL_KPP run (Fig. 12a) are similar to those in the OCN_KPP run, but the cold SST bias over the eastern tropical Pacific is large enough to extend to the western tropical Pacific via the Bjerknes feedback (Li and Xie 2014). Similar improvements in temperature simulations are also evident in the coupled simulation but are relatively weak (cold SST bias is reduced by $-20\%$) compared with those in the ocean-only simulation. Figure 13 shows the change in surface wind over the tropical Pacific. Although the response of wind to cold tongue warming is evident, the resultant Bjerknes feedback is not vigorous enough to enhance the warming in the ocean-only simulation (Fig. 11e). This result is different from some previous studies (Richards et al. 2009; Sasaki et al. 2013), in which SST changes in the ocean-only experiments tend to be amplified in the coupling experiments. It implies that the SST warming tendency in the eastern equatorial Pacific might be suppressed by the deficiencies in atmospheric models (Song and Zhang 2009) or coupled ocean–atmosphere processes (Luo et al. 2005).

5. Summary and discussion

This study investigates the impacts of two different vertical mixing schemes on the solutions of MOM5 over the tropical Pacific. One is the KPP scheme, and the other is the Chen scheme. In general, the Chen scheme...
works better than the KPP scheme for SST simulation; the cold tongue bias over the eastern equatorial Pacific is almost eliminated using the Chen scheme. However, the equatorial subsurface warm bias is exaggerated simultaneously. The results from heat budget analysis show that improvements in SST simulation can be attributed to the employment of the PGT model, which produces a lower level of shear instability mixing than its counterpart in the KPP scheme, resulting in a heat accumulation in the upper thermocline. The increased equatorial subsurface warm bias is induced by too-large $m_0$ and the resultantly deepened MLD off the equator. Based on the comparisons between the two vertical mixing schemes, a modified KPP scheme is proposed through replacing the shear instability mixing model and constant background diffusivity in the original KPP scheme with the PGT model and the Argo-derived background diffusivity, respectively. This new scheme is then employed into MOM5-based ocean-only and coupled simulations, demonstrating substantial improvements in temperature simulations over the tropical Pacific.

In our study, we have demonstrated the advantage of the PGT model in reproducing the observed cold tongue. In essence, the better performances can be attributed to the fact that the critical Ri ($Ri_0$) in the PGT model is smaller than that in the KPP model. The $Ri_0$ is the critical value below which eddy coefficients increase dramatically. Although it is not explicitly represented, $Ri_0$ in the PGT model is close to 0.3 (Peters et al. 1988), but $Ri_0$ in the KPP model is 0.8 [Eq. (3)]. To test the important role played by $Ri_0$, an additional experiment is conducted, in which forcing fields and configurations are identical to those in the OCN_KPP run, except that $Ri_0$ in the KPP scheme is assigned to be 0.3. The experimental results (Fig. 14) are similar to those in Fig. 9, revealing that reducing the $Ri_0$ in the KPP scheme has the same effects as employing the PGT model.

Furthermore, whether the PGT model could represent the realistic shear instability mixing in the ocean is still under debate. The PGT model is proposed by fitting a 4.5-day time series of microstructure measurements at $0^\circ$, $140^\circ W$ in 1984 (Peters et al. 1988), but the microstructure observations at the same location in 1991 are better fitted by the PP model or KPP scheme (Zaron and Moum 2009). Additionally, the relationship between vertical eddy coefficients and Ri may also depend on the local shear and external forcing (Zaron and Moum 2009). As a result, the PGT model derived from

![Figure 12](image-url)

**Fig. 12.** (a) SST biases and (b) temperature biases along the equator from the CPL_KPP run. Differences between CPL_MDF run and CPL_KPP run for (c) SST and (d) equatorial temperature. The contour interval is 0.5°C in (a) and (b) and 0.2°C in (c) and (d).

![Figure 13](image-url)

**Fig. 13.** Differences in SST (color; °C) and surface wind (vectors) between the CPL_MDF run and CPL_KPP run.
FIG. 14. As in Fig. 9, but for the annual-mean differences between the runs with $\alpha_0 = 0.3$ and $\alpha_0 = 0.8$ (OCN_KPP run).

the equatorial observations may not agree with the observations off the equator. Thus, it is premature to suggest the best shear instability mixing model, and more microstructure observations are required for further refinement. Also, deep-cycle turbulence above the thermocline (Smyth and Moum 2013; Pham et al. 2017) and finescale shear, which can be observed below the thermocline (Richards et al. 2015), can enhance turbulent mixing; model performances are improved when their effects are considered (Sasaki et al. 2012, 2013; Furue et al. 2015; Jia et al. 2015). Thus, the vertical distribution of background diffusivity is indeed important, and its influences need to be examined in our future studies.

In this study, we mainly focus on the improved performances of SST simulations, and the impacts on the tropical current system will be examined in further studies. In addition, we focus on the impacts on the mean ocean state in the tropical Pacific, which can influence the fidelity of simulated seasonal to interannual climate variability (Meehl et al. 2001; Xiang et al. 2012; Song et al. 2014). The effects on the seasonal and interannual variability will be a subject in our next study.

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