Effect of the Prandtl number in the parameterization of vertical mixing in an OGCM of the tropical Pacific

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[1] Inclusion of the Prandtl number variation with stratification in a vertical mixing scheme helps to improve the simulation of the tropical Pacific using an ocean general circulation model (OGCM) significantly, by mitigating various persistent problems of the OGCM such as the warm and cold biases in the central and eastern equatorial Pacific, the too weak and deep Equatorial Undercurrent and the insufficient zonal slope of the thermocline. It also makes the distributions of temperature and zonal velocity along the equator more realistic. A similar test with a different vertical mixing scheme supports the generality of the results. **Citation:** Noh, Y., Y. J. Kang, T. Matsuura, and S. Iizuka (2005), Effect of the Prandtl number in the parameterization of vertical mixing in an OGCM of the tropical Pacific, *Geophys. Res. Lett.*, *32*, L23609, doi:10.1029/2005GL024540.

1. Introduction

[2] Significant progress has been made last decades in the simulation of the tropical Pacific using an ocean general circulation model (OGCM) in association with ENSO simulation. Nonetheless, most existing OGCMs still suffer from several persistent deficiencies; for example, the warm and cold biases of the sea surface temperature (SST) in the eastern and central Pacific, a too strong Southern Equatorial Current (SEC) and equatorial upwelling, a too diffused thermocline with insufficient zonal slope, a too weak Equatorial Undercurrent (EUC), the westward shift of the cold tongue, etc. [e.g., *Stockdale et al.*, 1998].

[3] Since vertical mixing plays a critical role in determining the structure of the tropical ocean, numerous efforts have been made to improve the performance of the OGCM by improving its parameterization [*Pacanowski and Philander*, 1981; *Rosati and Miyakoda*, 1988; *Blanke and Delecluse*, 1993; *Chen et al.*, 1994; *Schneider and Müller*, 1994; *Halpern et al.*, 1995; *Reason*, 1996; *Yu and Schopf*, 1997; *Large and Gent*, 1999; *Li et al.*, 2001; *Noh et al.*, 2002]. However, it has been difficult to obtain a vertical mixing scheme that performs well universally, as the ocean mixed layer in the different ocean regions is often controlled by different dynamics. For example, the vertical mixing scheme by *Pacanowski and Philander* [1981], tuned for the shear-dominated tropical ocean, causes too shallow a mixed layer depth (MLD) in the extratropical ocean [*Li et al.*, 2001].

[4] Meanwhile, *Peters et al.* [1988] found from the observation of the equatorial turbulence that the eddy diffusivity K_h decreases faster than the eddy viscosity K_m with increasing stratification, thus increasing the turbulent Prandtl number Pr (=K_m/K_h). Recently, *Noh* [2004] showed using the one-dimensional model that the parameterization of Pr has significant effect only in the ocean mixed layer dominated by shear production. As a result, its inclusion substantially suppresses the excessive downward transport of heat and momentum in the tropical ocean, whereas it hardly affects the extratropical ocean [see *Noh*, 2004, Figures 1 and 3].

[5] Therefore, in this paper, we investigated how the inclusion of the effect of Pr in the vertical mixing scheme affects the simulation of the tropical Pacific using the OGCM.

2. Model

[6] For the vertical mixing scheme, we used the Noh model [*Noh*, 1996, 2004; *Noh and Kim*, 1999; *Noh et al.*, 2002, 2004]. In the new version of the model, the parameterization of the influence of stratification on Pr is given in the form of

$$\mathrm{Pr} / \mathrm{Pr}_0 = (1 + \beta \mathrm{Rt})^{1/2}, \qquad (1)$$

with $\beta = 0.5$ under the stable condition (Rt > 0) [*Noh*, 2004]. Here $\mathrm{Rt} = (Nl/q)^2$, where q and l are velocity and length scales of turbulence, and Pr_0 is the value of Pr in the absence of stratification. The effect of Pr is taken into account in some vertical mixing schemes [*Blanke and Delecluse*, 1993; *Pacanowski and Philander*, 1981], but neglected in many widely used schemes [e.g., *Mellor and Yamada*, 1982; *Large et al.*, 1994; *Chen et al.*, 1994]. In order to investigate the effect of Pr, we examined two different versions of the Noh model, which will be referred as NMIX_B (β = 0) and NMIX_O (β = 0.5). Here K_h, calculated by $K_h = K_m/\mathrm{Pr}$, becomes smaller in NMIX_O than in NMIX_B with stratification, while K_m remains equivalent in both cases.

[7] The OGCM used in this study is GFDL MOM 2.2 [*Pacanowski*, 1996]. Horizontal resolution is 1.125° in longitude and 0.5625° in latitude, and there are 37 vertical levels with 25 levels in the upper 400 m, as in the case of *Kawamura et al.* [2001]. The model domain covers the Pacific basin from 35.5°S to 65°N. The lateral mixing coefficients are given by $A_M = 2 \times 10^3$ m^{2}s^{-1} and $A_H = 1 \times 10^3$ m^{2}s^{-1}, as suggested by *Maes et al.* [1997]. The

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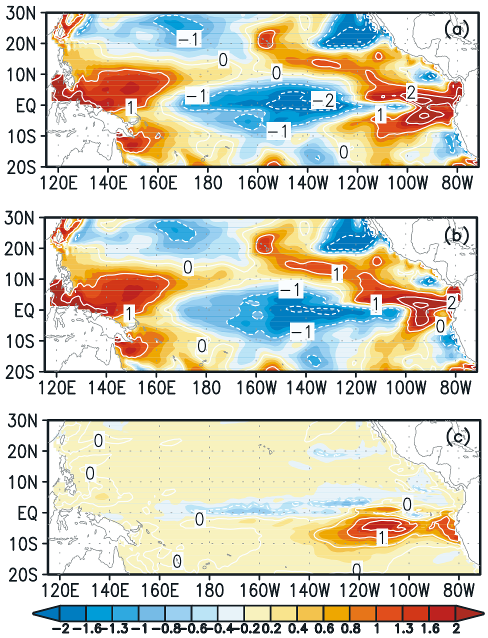

Figure 1. (a) Annual mean SST anomaly of NMIX_B (Contour interval is 1°C). (b) Annual mean SST anomaly of NMIX_O. (c) Difference of the annual mean SST (NMIX_B − NMIX_O).

penetrative solar radiation is prescribed for moderately clear Jerlov type IB water [*Paulson and Simpson*, 1977].

[8] The model was started from the state of rest with climatological temperature and salinity distributions of *Levitus* [1982], and forced by the wind stress climatology of *Hellerman and Rosenstein* [1983]. For the heat and freshwater fluxes at the sea surface, the combined boundary condition using both the climatological flux and the restoring term was used, similar to the work of *Noh et al.* [2002], which enables us to assess the predictability of SST. The reanalysis data from NCEP were used for the climatological fluxes. The model was integrated for 10 years, during which the upper layer of the ocean reaches equilibrium.

3. Results

[9] Figure 1 shows the annual mean SST anomalies from NMIX_B and NMIX_O, together with the difference of SST between them. The cold bias in the central Pacific and the warm bias at the eastern Pacific still appear in both NMIX_B and NMIX_O, but the magnitude of the anomaly decreases in NMIX_O in both the central and eastern Pacific. This means that, in the case of NMIX_O, the zonal gradient of SST is larger and the coldest water is found closer to the eastern coast. Meanwhile, the disagreement between NMIX_B and NMIX_O is mainly limited to the tropical ocean, as expected from *Noh* [2004].

[10] The distribution of zonal velocity along the equator reveals that the SEC is too thick and the EUC is too deep and weak in the central Pacific in NMIX_B, whereas the SEC is thinner and the EUC is shallower and stronger in NMIX_O in closer agreement with observation (e.g., TOGA-TAO data) (Figure 2). Moreover, the peak velocity of the SEC is located at the central Pacific, and the EUC becomes very weak east of 110°W in NMIX_B. In NMIX_O, however, the peak velocity of the SEC is shifted toward the eastern Pacific, and the EUC remains strong east of 110°W, consistent with observation [*Carton et al.*, 2000].

[11] The temperature distribution along the equator from NMIX_B suggests that the stratification in the lower part of the mixed layer (∼50–100 m) of the central Pacific almost vanishes due to excessive mixing near the thermocline, the zonal gradient of SST in the eastern Pacific is much smaller than observation [*Levitus*, 1982], and the stratification becomes very weak below the thermocline near the eastern coast (Figure 3). These symptoms are alleviated substan-

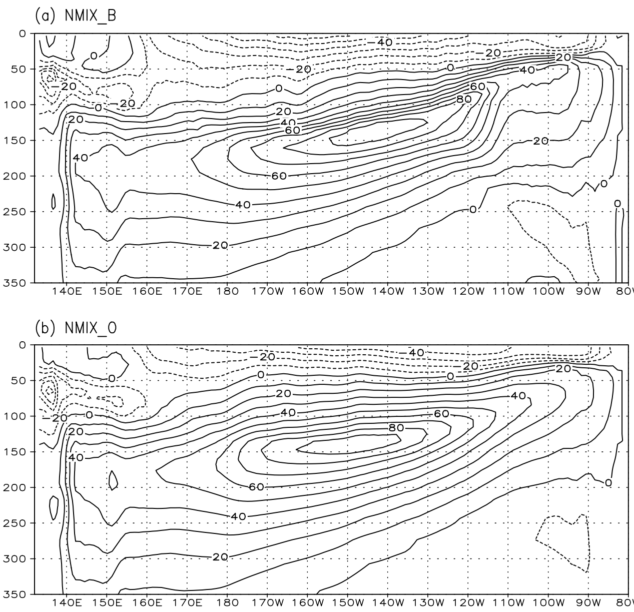

Figure 2. Annual mean zonal current distribution along the equator (Contour interval is 20 cms^{-1}): (a) NMIX_B and (b) NMIX_O.

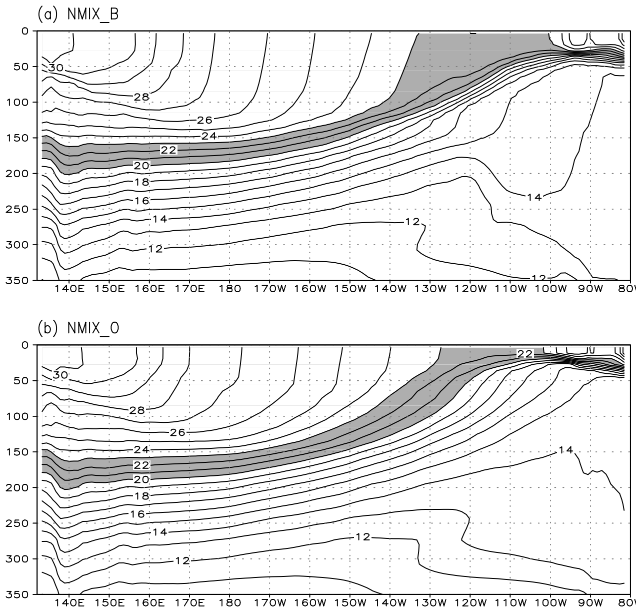

Figure 3. Annual mean temperature distribution along the equator (Contour interval is 2°C, and the area between 20–23°C is shaded.): (a) NMIX_B and (b) NMIX_O.

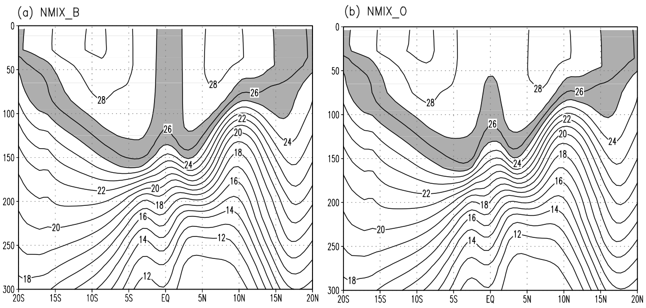

Figure 4. Annual mean temperature distribution along 180°E (Contour interval is 1°C, and the area between 23–27°C is shaded.): (a) NMIX_B and (b) NMIX_O.

tially in NMIX_O. Moreover, the zonal slope of the thermocline is increased in NMIX_O, as evidenced by the slope of isothermal lines of 20–23°C in the eastern Pacific.

[12] The discrepancies between two experiments can be understood by the presence of too strong subsurface mixing in the absence of the effect of Pr (NMIX_B), as suggested by *Noh* [2004]. In the central Pacific, too strong subsurface mixing makes the SEC too thick in NMIX_B, which makes upwelling exist too deep and thus brings up colder water to the surface. It is manifested by the temperature distribution in the meridional cross-section (Figure 4). The vertical velocity field along the equator also shows a deeper upwelling region in NMIX_B than in NMIX_O (not shown). In addition, the increase of SST in the central Pacific in NMIX_O may be attributed to the reduced downward diffusion of heat from the sea surface with smaller K_h as well. The overestimation of MLD, owing to the excessive subsurface mixing, makes the EUC deeper and weaker in NMIX_B. Note that the EUC is determined by the balance between zonal pressure gradient and vertical mixing [*Philander*, 1990].

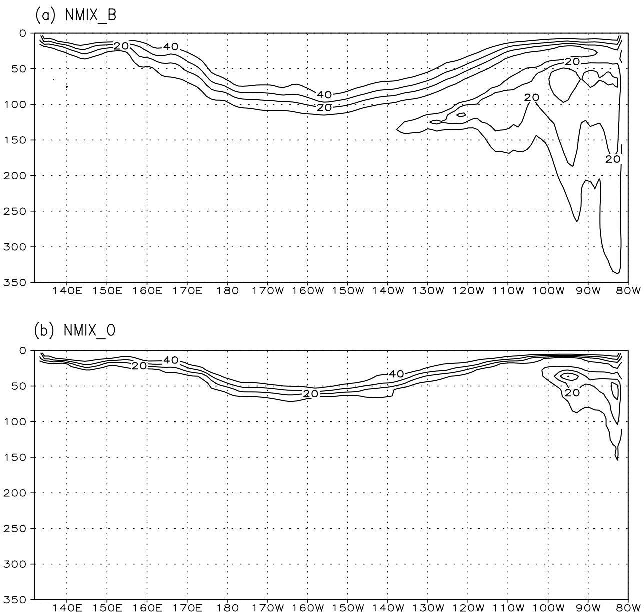

Figure 5. Annual mean distribution of K_h along the equator (Contour interval is 10 cm^{2}s^{-1}): (a) NMIX_B and (b) NMIX_O.

[13] On the other hand, in the eastern Pacific, excessive friction by larger K_m below the thermocline suppresses the coastal upwelling in NMIX_B, and it leads to the weaker SEC in the eastern Pacific. It causes the SST to be too warm, especially south of the equator. Note that the presence of the North Equatorial Countercurrent makes the SST insensitive to the intensity of coastal upwelling, north of the equator. The westward velocity of the SEC in the eastern Pacific from NMIX_O is found to be larger than that from NMIX_B by as much as 0.16 ms^{-1} (not shown).

[14] Indeed, the distributions of K_h along the equator show clearly that not only the mixing penetrates deeper in the central Pacific but also it becomes anomalously large below the thermocline near the eastern coast in NMIX_B, although the near surface mixing intensities are equivalent to each other (Figure 5). The distributions of K_m are closer to each other, but its much larger value below the thermocline near the eastern coast is still observed in NMIX_B (not shown). Note also that K_m is proportional to K_h in NMIX_B, since Pr is constant.

4. Concluding Remarks

[15] In this paper, we have shown that the inclusion of the variation of Pr with stratification in a vertical mixing scheme helps to improve the simulation of the tropical Pacific significantly.

[16] In the present case, the effect of Pr appears only in the tropical ocean (see Figure 1), contrary to the effect of Ri that is globally applied. Besides, the simultaneous reduction of K_m and K_h, while keeping Pr constant, causes the stronger and shallower SEC, and it leads to the increase of the cold bias in the central Pacific by stronger upwelling [*Schneider and Müller*, 1994; *Li et al.*, 2001; *Noh et al.*, 2004].

[17] In order to examine the generality of the present result regarding the effect of Pr, we performed a similar experiment with *Pacanowski and Philander*'s [1981] vertical mixing scheme, in which Pr is parameterized by $1 + b\mathrm{Ri}$ with $b = 5$ and $\mathrm{Ri} = (N/S)^2$. We compared the cases $b = 0$ and 5 (PPMIX_B and PPMIX_O, respectively). A very similar pattern was obtained in the difference between two experiments, as shown in Figure 6.

[18] The wind stress by *Hellerman and Rosenstein* [1983] is known to overestimate the easterly wind stress along the equator, which increases the cold bias in the central Pacific [*Stockdale et al.*, 1998]. We also carried out the OGCM experiment with the NCEP wind stress in order to investigate the sensitivity to the wind stress. In this case, the cold bias in the central Pacific is weaker and the warm bias in the

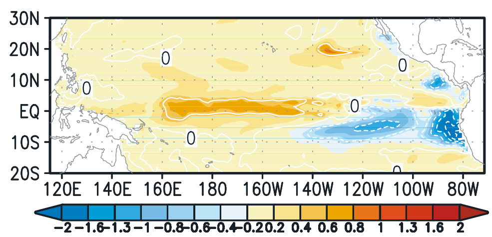

Figure 6. Difference of the annual mean SST (PPMIX_B – PPMIX_O) (Contour interval is 1°C).

eastern Pacific is stronger than shown in Figure 1, owing to the weaker wind stress, but the SST difference between NMIX_B and NMIX_O reveals the same pattern (not shown).

[19] Finally, it should be mentioned that there have been attempts to correct the tropical SST biases by improving other processes such as lateral mixing, horizontal resolution, and momentum coupling between the ocean and atmosphere [*Richards and Edwards*, 2003; *Jochum et al.*, 2005; *Luo et al.*, 2005], although the significance of these effects has yet to be appraised.

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