The effect of the wave-induced mixing on the upper ocean temperature in a climate model

HUANG Chuanjiang¹, QIAO Fangli¹*, SONG Zhenya¹

1. Key Laboratory of Marine Science and Numerical Modeling of State Oceanic Administration, First Institute of Oceanography, State Ocean Administration, Qingdao 266061, China

Received 20 July 2007; accepted 29 February 2008

Abstract
The significant underestimation of sea surface temperature (SST) and the temperature in the upper ocean is one of common problems in present climate models. The influence of the wave-induced mixing on SST and the temperature in the upper ocean was examined based on a global climate model. The results from the model coupled with wave-induced mixing showed a significant improvement in the simulation of SST and the temperature in the upper ocean compared with those of the original model without wave effects. Although there has still a cold bias, the new simulation is much closer to the climatology, especially in the northern ocean and tropical ocean. This study indicates that some important physical processes in the accurate simulation of the ocean may be ignored in present climate models, and the wave-induced mixing is one of those factors. Thus, the wave-induced mixing (or the effect of surface waves) should be incorporated properly into climate models in order to simulate or forecast the ocean, then climate system, more accurately.

Key words: surface wave, vertical mixing, SST, upper ocean temperature, climate model

1 Introduction
Surface waves are the most energetic and so one of the most important dynamical processes in the oceans, due to their strong effects on the exchanges of momentum, heat, and mass through the sea-air interface. The influence is very complicated, and our understanding of the dynamical processes involved remains rudimentary in spite of extensive efforts which have been devoted to in-situ observations and theories development during the past decades.

Wind energy input to surface waves which is estimated as 60 TW is the greatest source of mechanical energy in the global ocean (Wang and Huang, 2004). Numerical model results of our laboratory show its seasonal cycle within 43 ~ 82 TW (Teng et al., 2008). As a small-scale process, it is believed that surface waves affect the ocean and climate system mainly through regulating the vertical mixing in the upper ocean. In the past several decades, efforts have focused on the effect of wave breaking on the upper-ocean mixing (Mellor, 2003; Terray et al., 1996; Craig and Banner, 1994; Agrawal et al., 1992). However, the mixing induced by wave breaking is mainly limited in the near-surface zone within the upper few meters (Zhang et al., 2007;
Craig and Banner, 1994). Moreover, surface waves are not always breaking depending on their steepness, in that case, the circulation system is unaffected according to the above assumption.

In fact, besides wave breaking the interaction of surface waves with oceanic turbulence is a non-negligible source of turbulence kinetic energy. Turbulence and waves can interact in a variety of ways, in which the energy can transfer from the wave motion to turbulence associated with the attenuation of waves, and then enhance greatly mixing processes in the upper ocean (Teixeira and Belcher, 2002). On the basis of a theoretical analysis and ocean observations, Ardhuin and Jenkins (2006) pointed out that interaction of wave with oceanic turbulence can account for a significant fraction of energy losses of the wave field. However, the expression between the mixing coefficient and wave – turbulence interaction still does not appear.

From the Reynolds stress expression, Qiao et al. (2004) introduced a parameterization scheme of the vertical mixing coefficient induced by wave-turbulence interaction (wave-induced mixing or Bv hereafter) based on wave number spectrum. Bv is a function of the Stokes drift associated with wave motions, and independent of wave breaking (Qiao et al., 2008). Bv can affect more than 100 m which is much deeper than those achieved by wave breaking. On the basis of field observations in the East China Sea, Matsuno et al. (2006) validated that wave-induced mixing can penetrate through a great depth and is in good agreement with the argument of Qiao et al. (2004). Recently, Huang et al. (2007) pointed out that “a direct coupling between the traditional ocean general circulation model (OGCM) and a surface wave model (SWM) may provide a much better dynamical picture of the oceanic circulation”. All these suggest that wave – turbulence interaction is an important approach which wave energy affects the ocean interior.

So far, Bv has been successfully incorporated into some ocean and coastal circulation models, and explained some important phenomenon in the oceans. Using the Princeton ocean model (POM, Blumberg and Meller, 1987), Qiao et al. (2004) found that Bv can greatly improve the simulated temperature in the upper ocean in summer when it was coupled into the Mellor-Yamada turbulence closure scheme (Mellor and Yamada, 1982). Subsequent studies proved that Bv has an important effect on the summertime circulation in the Huanghai Sea (Xia et al., 2006) and coastal upwelling in the East China Sea (Qiao et al., 2006) because of the strong influence of vertical mixing on front processes. Huang et al. (2007) added wave-induced mixing to an implicit Richardson number-dependent mixing parameterization scheme developed by Hallberg (2000), model results show an important effect on the structure of the seasonal thermocline at middle and high latitudes and the ocean circulation. Lin et al. (2006) indicated that Bv is essential to produce the vertically uniform warm water column over a ridge in the central Bohai Sea.

Since the wave-induced mixing has an important effect on the upper ocean temperature and ocean circulation, these changes can modulate the atmosphere above through air-sea interaction. Subsequently the atmosphere can return its response to the ocean, thus form a feedback between the ocean and atmosphere. Song, Qiao, Lei et al. (2007) and Song, Qiao, Yang et al. (2007) have studied the effects of Bv on the climate system using a global coupled climate model. Their studies were mainly focused on the area of the Pacific Ocean, and the results showed that Bv can much improve the simulation of the cold tongue in the tropical Pacific Ocean and SST in the northern Pacific Ocean, where the former is regarded as a kind of tropical bias which is faced by all climate models without flux adjustment.

The influence of Bv on the global upper ocean
temperature was examined in this study using a global coupled climate model. The model linkages are discussed in Section 2. The results of experiments are discussed in Section 3. Section 4 is the conclusions.

2 Model linkages

The climate model FGCM-0 (Yu et al., 2002) is used in the present study, whose atmosphere component is from CCM3 developed by NCAR (Kiehl et al., 1998), and whose ocean component is L30T63 developed by LASG/IAP (Jin et al., 1999). These individual components are coupled with a flux coupler developed by Boville and Gent (1998), in which momentum fluxes and heat fluxes are directly exchanged between the ocean and atmosphere. However, the coupling of freshwater fluxes is not used, but replaced by the relaxation condition of sea surface salinity.

The ocean model L30T63 is 30 vertical layers in which 12 layers with equal depth are placed in the upper 300 m; its horizontal grid is the same as that of a T63 spectral atmospheric model with a resolution of 1.875° × 1.875°. The scheme developed by Pacanowski and Philander (1981, PP scheme hereafter) is used to parameterize the vertical mixing, and that proposed by Gent and McWilliams (1990) is used to parameterize the isopycnal mixing. The PP scheme is a Richardson number-dependent mixing parameterization in which the mixing coefficient is strongly influenced by the vertical shears of mean currents and the density gradients of seawater. At present the PP scheme has been widely used in the ocean general circulation models and climate models all over the world. However, it does not directly account for the effects of wind stress on vertical mixing, thus the effects of surface wave is not directly included.

The MASNUM global wave number spectral model (Yuan et al., 1992; Yang et al., 2005) coupled to the FGCM-0 is used to calculate Bv. The wave model receives wind flied from the atmosphere model through the flux coupler, and then calculates Bv based on the expression developed by Qiao et al. (2004). Subsequently, Bv is transferred to the ocean model through the coupler, and is added to the vertical mixing obtained from the PP scheme. Details of coupling processes can be referred to Song, Qiao, Lei et al. (2007).

Two numerical experiments were designed to evaluate the influences of the wave-induced mixing on the upper ocean temperature. The first experiment spun up the original FGCM-0 without Bv (Exp. N hereafter); the other spun up the FGCM-0 coupled with the MASNUM wave model, thus Bv was included in this experiment (Exp. W hereafter).

Both experiments have been integrated for 70 a from the cold start similar as Yu et al. (2002). Figure 1 shows time evolutions of global mean SSTs simulated in these two experiments. The SST in Exp. N deviates rapidly from the climatological SST in the first several years, while that in Exp. W does not exhibit an obvious tendency. On the whole, both experiments reach quasistationary states for the upper ocean after 20 ~ 30 a. The final 30 a data (i.e., 41 ~ 70 model year) were used to analyze the wave-induced mixing effects, and “annual-mean” is the mean of these 30 a data in this study.

![Fig. 1. Time evolutions of global mean SSTs simulated in Exp. N (blue line) and Exp. W (pink line), and that from the WOA01 climatology (black line).](image-url)
3 Experimental results

3.1 SST

Figure 2a shows the spatial distribution of annual-mean SST deviation simulated in Exp. N from the WOA01 climatological data (Conkright et al., 2002). Although no flux adjustments (Sausen et al., 1988) are used in the present climate model, Exp. N reproduces roughly the general features of SST in the global ocean. Nevertheless, there are some obvious defects. For example, SST is significantly underestimated in most of area, especially at middle and high latitudes of the Northern Hemisphere, with a maximal bias of 7.0 °C; however, SST is overestimated about 1.0 °C in the Southern Ocean. Yu et al. (2002) ascribed the SST bias to inaccurate simulations of sea ice. Moreover, poor simulations of the ocean circulation may also play an important role in the pattern of the SST bias (Randall et al., 2007). The simulated SST in Exp. N has also a warm bias about 1.0 °C in the southeast Pacific and Atlantic Oceans, which also appeared in other climate models which should be mainly associated with poor simulations of local wind stress, oceanic upwelling, and cloud amounts induced by insufficient model resolution (Randall et al., 2007).

The SST difference between Exp. W and Exp. N is shown in Fig. 2b. It shows that the simulated SST increases obviously in most of area when Bv is included, in which the maximal warm area is located in the northeast Pacific Ocean with a value of 3.0 °C. On the whole, the zonally averaged SST increases about 1.2 °C in the Northern Hemisphere (see Fig. 3). Although the SST is still colder than that of climatological data, it has shown a significant improvement compared with that in Exp. N. In addition, when wave-induced mixing is included, the simulated SST between the equator and 40°S turns to a little bit of warm bias from a cold bias of Exp. N, while the warm bias enhances further in the region of the Antarctic Circumpolar Current. The global annual-mean SST in Exp. N is colder about 1.2 °C than that of climatological data; however, it is very interesting that the global annual-mean SST in Exp. W is nearly agreement with that of climatological data although it is cooling in the Northern Hemisphere and warming in the Southern Hemisphere (see Fig. 1).

Figure 4 shows absolute mean deviations of SST (|SSTA| hereafter) in Exp. N and Exp. W from the WOA01 climatology. In the oceans north of 15°N, SSTA in Exp. W is about 2.0 °C, which is obviously smaller than that in Exp. N with a value of 3.0°C. It also indicates that the simulated SST in the northern ocean has a significant improvement by including Bv. In the tropical oceans, |SSTA| in Exp. W is about 1.0 °C, which is also smaller than that in Exp. N (about 1.5 °C). However, |SSTA| in the
oceans south of 15°S are 1.13 °C in Exp. W and 0.97°C in Exp. N, respectively, thus the deviation enhances slightly in the experiment with Bv.

As discussed above, the simulated SST improves greatly in most of area by including Bv. Recently, IPCC (Intergovernmental Panel on Climate Change) evaluated the ability of 23 climate models to simulate the present global climate system, and found that the cold SST bias in the northern oceans and the tropical ocean is one of the largest model system errors in the ocean component of climate models (Randall et al., 2007). This bias also presents in Exp. N without the wave-induced mixing. However, when Bv is included, the simulated SST increases obviously, in which zonally averaged SST warms about 1.2 °C and |SST| decreases about 1/3 in the northern oceans and the tropical ocean. Thus the cold SST bias in the original model of FGCM-0 has been much reduced, and the accuracy of the simulated SST has been significantly improved. It implies that some important physical processes in the ocean may be ignored in present climate models, and the wave-induced mixing is an important one of those factors.

3.2 Profiles of the upper ocean temperature

The cold bias of temperature in the upper ocean is another common problem of present climate models. Most of these 23 models evaluated by the IPCC showed cold biases of temperature in the upper ocean. However, at depths ranging from 200 to 3,000 m, the simulated temperatures were complicated, in which some models showed cold biases, while others showed warm biases (Randall et al., 2007).

Figure 5 shows the zonally averaged temperature deviations in Exp. N from the WOA01 climatology and Exp. W. The temperature in Exp. N is too cold within the uppermost kilometer compared with the climatology. The maximum cold bias is located at the depth of 200 m of 15°S with a value of 5.0 °C. The bias is about 4.0°C in the near-surface zone between 40° and 60°N, and decays with depth away from the surface. It can still reach 1.0 °C at the depth of 1,000 m.

When Bv is incorporated into the model, the upper ocean temperature increases obviously, in which the maximum warming with a value of 2.0 °C is located at a depth of 100 m between 15°S and 15°N. Moreover, the temperature increases about 1.5 °C in the near-surface zone north of 30°N.
Fig. 6. Deviations of the annual mean temperature within the upper 200 m simulated in Exp. N (blue line) and Exp. W (pink line) from the WOA01 climatology.

Temperature. The changes of the upper ocean temperature, especially changes of SST, are not spatially uniform in the global ocean, which can result in changes of sea level pressure and then the sea surface wind field. Changes of wind field can induce changes of the ocean circulation pattern. Moreover, changes of SST and wind field can also lead to changes of surface heat flux. On the other hand, both the ocean circulation and surface heat flux can return their responses to SST, then SST and the temperature in the upper ocean change further. Thus the simulation of the upper ocean temperature has been much improved by this kind of feedback.

4 Conclusions

The influence of the wave-induced vertical mixing (Qiao et al., 2004) on the upper ocean temperature was studied in the climate system based on the climate model of FGCM-0. Although the original climate model without wave-induced mixing can roughly reproduce the general pattern of the global upper ocean temperature, there have some obvious deviations. The uppermost error is the large cold bias of SST and temperature in the upper ocean in most are-
as of the global ocean. For example, the simulated SST at middle and high latitudes of the Northern Hemisphere is colder about 7.0 °C compared with the climatology.

Although there has still a cold bias, the simulation results have been much improved when Bv is incorporated into the model. In the model with wave-induced mixing the zonally averaged SST and the mean temperature within the upper 200 m increases about 1.2 and 1.0 °C, respectively, and absolute mean deviation of SST reduces about 1/3 in the northern ocean and the tropical ocean. Thus the cold SST bias in the original model has been relieved, so the simulation has been significantly improved.

It should be noted that although strong vertical mixing processes can transport a large amount of heat from the surface layer to subsurface, the simulated SST is warmer instead of cooler when Bv is included. This pattern is different with that obtained from sole ocean circulation models. This indicates that the influences of wave-induced mixing in climate models are different from those in ocean circulation models because of the strong air-sea feedback in the former. The detailed feedback mechanisms need further study.

References


Huang Chuanjiang, Qiao Fangli, Wei Zexun. 2007. Effects of wave-induced mixing under the mixed layer on the oceanic circulation. Manuscript submitted to Acta Oceanologica Sinica, in press


Oceanologica Sinica, in press
Song Zhenya, Qiao Fangli, Yang Yongzeng, et al. 2007. An improvement of the too cold tongue in the tropical Pacific with the development of an ocean wave coupled numerical model. Progress in Natural Science, 17(5); 576 ~ 583