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A numerical study of Stokes drift and thermal effects on the oceanic mixed layer

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Abstract

This study explores the influence of Stokes drift and the thermal effects on the upper ocean bias which occurs in the summer with overestimated sea surface temperature (SST) and shallower mixed layer depth (MLD) using Mellor-Yamada turbulence closure scheme. The upper ocean thermal structures through Princeton ocean model are examined by experiments in the cases of idealized forcing and real observational situation. The results suggest that Stokes drift can generally enhance turbulence kinetic energy and deepen MLD either in summer or in winter. This effect will improve the simulation results in summer, but it will lead to much deeper MLD in winter compared to observational data. It is found that MLD can be correctly simulated by combining Stokes drift and the thermal effects of the cool skin layer and diurnal warm layer on the upper mixing layer. In the case of high shortwave radiation and weak wind speed, which usually occurs in summer, the heat absorbed from sun is blocked in the warm layer and prevented from being transferred downwards. As a result, the thermal effects in summer nearly has no influence on dynamic effect of Stokes drift that leads to deepening MLD. However, when the stratification is weak in winter, the thermal effects will counteract the dynamic effect of Stokes drift through enhancing the strength of stratification and suppress mixing impact. Therefore, the dynamic and thermal effects should be considered simultaneously in order to correctly simulate upper ocean thermal structures in both summer and winter.

Key words: mixed layer, cool skin layer, diurnal warm layer, Stokes drift

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1 Introduction

It is vital for ocean models to correctly reproduce the mixed layer depth (MLD) and sea surface temperature (SST), which are crucial for the air-sea interaction. SST is the lower thermal boundary condition and is usually determined by direct observation at a depth of 2–10 m under sea surface conducted by bucket thermometers of the buoy or the ship's cooling water intake.

On the other hand, it is well known that the temperatures at the sea surface are typically a few-tenths degrees Celsius cooler than the temperatures some tens of centimeters below (Fairall et al., 1996a). This layer is referred to as the cool skin layer, which is recognized as an important feature of the ocean viscous layer as a result of new satellite remote sensing methodologies emerging for air-sea flux estimates (Tu and Tsuang, 2005). The warm layer is a region in the upper few meters of the ocean where solar radiation has caused significant warming relative to the deeper mixed layer temperature. Warm layers occur during the day when temperature stratification caused by absorption of the solar radiation is sufficiently strong to suppress shear-induced mixing and can be of the order of 3 K, especially in summer (Halpern and Reed, 1976; Stramma et al., 1986; Fairall et al., 1996a; Soloviev and Lukas, 1997). Fairall et al. (1996a) indicated the peak afternoon warming is about 3.8°C at depth of 0.7 m for a clear day with 10-m wind speeds of 1 m/s. Ward and Donelan (2006) showed strong diurnal warming up to 4.6°C within the upper few meters based on the observation in the Gulf of California. Mattews et al. (2014) also found that the anomaly due to diurnal warm layer can reach to 0.8°C in the afternoon with a daily mean of 0.2°C. In practice, the depth measured SST is well below the cool skin layer and warm layer (Fairall et al., 1996a; Mellor and Blumberg, 2004; Wurl et al., 2019).

The turbulence closure scheme of Mellor-Yamada (Mellor and Yamada, 1982, hereinafter M-Y) is widely used in atmospheric and oceanic models. However, many studies indicated that MLD simulated by this kind of ocean models in summer is shallower although it is roughly consistent with observations in winter (Martin, 1985; Kantha and Clayson, 1994). Compared with the observations at ocean weather Station Papa, Martin (1985) showed that M-Y scheme underestimates the MLD and overestimates SST in summer. It is shown that insufficient mixing in the upper ocean during summer is a common problem of ocean circulation models, and there are no exceptions for models using M-Y scheme. This problem could not be corrected by adjusting the external air-sea flux parameterizations. For example, a reduc-

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tion of the surface heat flux will reduce SST in summer, but the simulated MLD will become too high. Many studies have investigated this problem by the inclusion of surface waves, wave breaking, Stokes drift or Langmuir turbulence (Kantha and Clayson, 1994; Huang et al., 2011; Wu et al., 2015; Chen et al., 2018).

Traditionally, most oceanic mixed layer models ignored the fact that the air-sea interface is a non-rigid, mobile surface with sustaining gravity wave motions. The upper ocean is influenced by all the attendant complex dynamics, including the turbulent kinetic energy injected near the surface by breaking waves and the kinetic energy input from Langmuir circulations (Kantha and Clayson, 1994; Min and Noh, 2004; Huang et al., 2011). The latter is associated with the Stokes drift, which is considered to be an efficient way to enhance both the dissipation rate and the turbulence energy in the upper ocean mixing. Craig and Banner (1994) ascribed the result of insufficient turbulence energy induced by ocean waves, especially the wave breaking, is the warm bias in summertime SSTs in the models. Mellor (2001) introduced a critical Richardson number to directly reduce the turbulence dissipation. As a result, the vertical mixing effect is enhanced and the simulated SSTs decreased in summer. Mellor and Blumberg (2004) further included wave breaking energetics to M-Y scheme to reduce the warm bias in the summer. Recently, many studies suggested that wave breaking-induced turbulence decays rapidly with distance from the surface and hence the overall effects on the mixed layer can be neglected (Kantha et al., 2014; Wu et al., 2015).

McWilliams et al. (1997) demonstrated the large potential impact of Langmuir turbulence on mixing in the oceanic mixed layer and Stokes-Coriolis force on Ekman turning in the upper ocean. Kantha and Clayson (2004) confirmed the importance of this additional source of energy to turbulent mixing in the oceanic mixed layer, which arises due to the action of Reynolds stresses on the shear of the wave-induced Stokes drift current. Ardhuin and Jenkins (2006) further suggested that the vertical shear of the wave-induced Stokes drift current behaves very similar to the vertical shear of the mean current, as far as the extraction of energy by the Reynolds stress is concerned. While the energy input to turbulence from Langmuir cells elevates the turbulent kinetic energy and mixing throughout the mixed layer, therefore, more effective in deepening the mixed layer (Kantha and Clayson, 2004; Min and Noh, 2004; Huang et al., 2011). It is now widely recognized that a mixed layer model must include Stokes production of turbulent kinetic energy (TKE) for a realistic simulation of properties in the mixed layer (Teixeira and Belcher, 2002; Kumar and Feddersen, 2017). For example, Smith et al. (2013) recognized the importance of including the Stokes drift in their ocean-wave coupled model.

In order to reduce the warm bias in the summertime, all of previous studies focused on how to enhance the vertical mixing effect through increasing TKE in the models. In this way, it is certain that it can deepen MLD and reduce the warm bias in summer. However, it also would more significantly deepen MLD in winter due to the high wind speed and low insolation. Therefore, it should be considered the other factors that reflect the different characteristics between summer and winter.

As mentioned above, in addition to the dynamic influence on the oceanic mixed layer, it is believed that the thermal effects on stratification are also important for vertical mixing. It has been known for decades that the upper few micrometers of the ocean are generally cooler by several tenths of degree compared to the well-mixed underlying water masses. This sea surface microlayer is called cool skin layer, in which the heat transfer is primarily conducted by molecular diffusion since turbulent motion is suppressed (Saunders, 1967; Katsaros et al., 1977; Paulson and Simpson, 1981; Wu, 1985; (Fairall et al., 1996b; Ward and Donelan, 2006; Alappattu et al., 2017; Wong and Minnett, 2018; Wurl et al., 2019). The skin SST (hereinafter $T_{\rm skin}$) is defined as the radiometric temperature measured across a very small depth of approximately 20 μm. The subskin SST (hereinafter $T_{\rm subskin}$) represents the temperature at the base of the thermal skin layer (~1 000 μm according to the definition in Donlon et al., 2002). According to Wurl et al. (2019), the temperature difference between the skin temperature and the underlying water at 1-m depth, $\Delta T = T_{\rm skin} - T_{\rm 1\,m}$ was generally negative with the median = −0.20°C, in which the positive values only occur at times with strong solar radiation (> 600 W/m^2) and low wind speeds (< 2 m/s).

The calculations of bulk fluxes are based on the empirical formula between the turbulent fluxes and the air-sea contrasts of wind, humidity and temperature. Logically, the proper temperature for the determination of sensible and latent turbulent heat fluxes as well as the upwelling longwave emission is $T_{\rm skin}$, which is the temperature of the water which is in direct contact with the atmosphere ((Fairall et al., 1996b). However, the radiometric measurements during field campaigns are not always available, thus a model is required to calculate $T_{\rm skin}$ from oceanographic and meteorological measurements (Tu and Tsuang, 2005).

Therefore, it is important to include the skin temperature for accurate calculation of latent, sensible, and net longwave heat fluxes, which needs to decouple $T_{\rm skin}$ from the conventional in situ bulk SST (hereinafter $T_{\rm bulk}$) measured at a depth of a few meters. In general, there is a large difference between $T_{\rm skin}$ and $T_{\rm bulk}$, which will significantly affect the calculation of air-sea fluxes. Accordingly, the cool skin and warm layer correction have been introduced into the standard bulk flux algorithm (COARE 3.0, (Fairall et al., 1996b). In order to correctly simulate the oceanic mixed layer, the vertical resolution in the model must be high enough to capture the thermal effects of the warm layer ((Fairall et al., 1996b; Tseng et al., 2015).

In this study, it will be investigated the dynamic effect of Stokes drift and thermal effects of the cool-skin and warm layer on the oceanic mixed layer. Section 2 provides a brief description of the model modification due to Stokes drift. The results for idealized forcing experiments and Ocean Weather Station Papa are presented in Section 3 and Section 4, respectively. Finally, Section 5 gives a summary and discussion.

2 Model modification due to Stokes drift

As shown by Sullivan et al. (2007), the wave influences are shown to be profound on both the mean current profile and turbulent statistics compared to a simulation without these wave influences and forced by an equivalent mean surface stress. The elevation spectrum of wind waves implies a mean Stokes drift profile $u_{\rm S}(z)$, which can be expressed as (Kenyon, 1969)

$$u_{\rm s}(z) = \frac{16\pi^2}{g}\int_0^{2\pi}\int_0^{\infty} f^3 S(f,\theta)\exp\left(\frac{8\pi f^2}{g}z\right)\cos\left(\theta-\theta_{\rm w}\right){\rm d}f{\rm d}\theta, \tag{1}$$

where $S(f, \theta)$ is the directional frequency spectrum of wind waves, f is frequency, g is the acceleration of gravity, z is the vertical coordination, and θ, $\theta_{\rm w}$ are the wave and wind directions, respectively. In general, the development of wind waves depends on wave age or fetch. For a given mean wind speed and sufficiently large fetch, the wave field comes into a fully-developed wind waves, which is independent of wave age or fetch. For simplicity, we just consider the situation of fully-developed wind waves. With wave dispersion relationship in deep water, the Stokes drift is reduced to (Kantha and Clayson, 2004)

$$u_s(z) = \frac{2\pi^3 H_s^2}{g T_s^3} \exp\left(\frac{8\pi^2}{g T_s^2} z\right), \tag{2}$$

where H_s and T_s are significant wave height and wave period of wind waves, respectively, which correspond to the fully-developed wind waves. They can be estimated by the empirical growth relations proposed by many studies. In this study, we choose the relationships suggested by Wilson (1965),

$$H_s = 0.030\,6 U_{10}^2, \\ T_s = 0.878 U_{10}. \tag{3}$$

Substituted Eq. (3) into Eq. (2), the Stokes drift can be expressed as

$$u_s(z) = 0.008\,8 U_{10} \exp\left(10.45 U_{10}^{-2} z\right). \tag{4}$$

This result is a little different from that of Harcourt and D'Asaro (2008), which is

$$u_s(z) = 0.017\,5 U_{10} \exp\left(45.44 U_{10}^{-2} z\right). \tag{5}$$

Equation (5) has a greater magnitude of Stokes drift at sea surface than Eq. (4), but it decreases more quickly with depth z than Eq. (4).

It has been shown that the influences of Stokes drifts are profound on both the mean current profile and turbulent statistics compared to a simulation without these wave influences. Following Sullivan et al. (2007), we have added the Stokes drifts into the mean current profile. In this way, the dynamic effect of Stokes drift on deepening oceanic mixed layer is included in our simulation. The Princeton ocean model (POM) is used to conduct a series of simulations with different model settings.

3 Experiments with idealized forcing

POM is a three-dimensional, primitive equation, numerical ocean model. We set the model domain as 30°S–60°N and 135°–155°W with a regular 0.5°×0.5° longitude-latitude grid. The bottom topography is obtained from ETOPO5, and the maximum water depth is set as 2 000 m. The internal time step used was 6 min.

It is evident that fine vertical resolution in the model is necessary to reproduce the warm layer (Fairall et al., 1996b; Tseng et al., 2015) . In order to show the influence of various resolutions in POM, we adopt two different vertical resolutions in the simulations. In experiment 1 (hereafter referred as EXP1), the vertical resolution from sea surface to depth of 100 m is set as 2 m, and 13 m from 100 m to 2 000 m. In experiment 2 (hereafter referred as EXP2), except the vertical resolution from sea surface to depth of 10 m is set as 1 m, the others are same as in EXP1. The additional level is placed at 0.5 m to capture the upper ocean warm layer. With the modification of Stokes drift, EXP1 and EXP2 are referred to as "EXP1-S" and "EXP2-S", respectively (Table 1). We used COARE 3.0 algorithm to calculate surface latent heat, sensible heat flux and ocean skin temperature. The experiments were tested for two types of idealized forcing in order to compare the MLD response to different forcing conditions. The forcing was chosen to represent two basic regimes: the surface heat input which tends to increase stratification with the smaller MLD, and the momentum flux input which tends to destroy the stratification with the greater MLD. The solar radiation fluxes are assumed as a sine function with the amplitudes 200 W/m² and 800 W/m², which represent the situations in winter and summer, respectively. The wind speeds U_{10} vary from 0 to 20 m/s at interval of 1 m/s.

Figure 1 is shown the comparison between EXP1 and EXP1-S, in which are both with low vertical resolution. It can be seen that SST will decrease when the Stokes drift is considered (Figs 1a, f). The changes in SST are attributed to the enhancement of turbulence kinetic energy. The influences of the Stokes drift are sensitive to the magnitude of wind speed and the property of the stratification. In low wind speeds, the turbulence kinetic energy caused by the Stokes drift is limited to a few meters above the upper level. As the wind speed increases, turbulence kinetic energy extends into much greater depth. The influence of Stokes drift is also dependent on the strength of the mixed layer stratification in the ocean. If the mixed layer is weakly stratified, the Stokes drift can affect deeper. With the same constant wind speed forcing, the turbulence kinetic energy caused by the Stokes drift extends into deeper when the amplitudes of the solar radiation decreases from 800 to 200 W/m² (Figs 1d, i). The surface heating weakens mixing process mainly because it enhances the stratification of the ocean. In case of low solar radiation, the stratification is weak and the enhanced turbulent energy can propagate effectively downwards, which means that the effect of Stokes drift is deeper in winter than in summer.

Figure 2 is illustrated the thermal effects of the skin layer and warm layer on the upper ocean during 24 h from the results of EXP2. The temperature of the cool skin layer is usually lower than the sublayer at a depth of 0.5 m. The solar radiation has caused significant warming near the surface and propagates download as it intensifies with increasing solar intensity. Under the light wind conditions, solar heating produces strong warming within a very thin surface layer. The warming peak occurs at noon, and exists until sunset. In the absence of mechanical mixing, the temperature due to solar heating at 2 m-depth can be increased by 2°C (Fig. 2). On diurnal and longer time scales, this difference is not very noticeable in the model results. At midnight, the upper ocean temperature is almost consistent. With solar radiation in-

Table 1. Summery of the experiments used in this study

Experiment	Vertical resolution	Stokes drifts	Idealized forcing		OWS Papa	
			Wind speed /m·s^{-1}	Amplitudes of the solar radiation /W·m^{-2}	Wind speed /m·s^{-1}	Solar radiation /W·m^{-2}
EXP1	low	no	0–20	200/800	observed	observed
EXP2	high	no	0–20	200/800	observed	observed
EXP1-S	low	yes	0–20	200/800	observed	observed
EXP2-S	high	yes	0–20	200/800	observed	observed

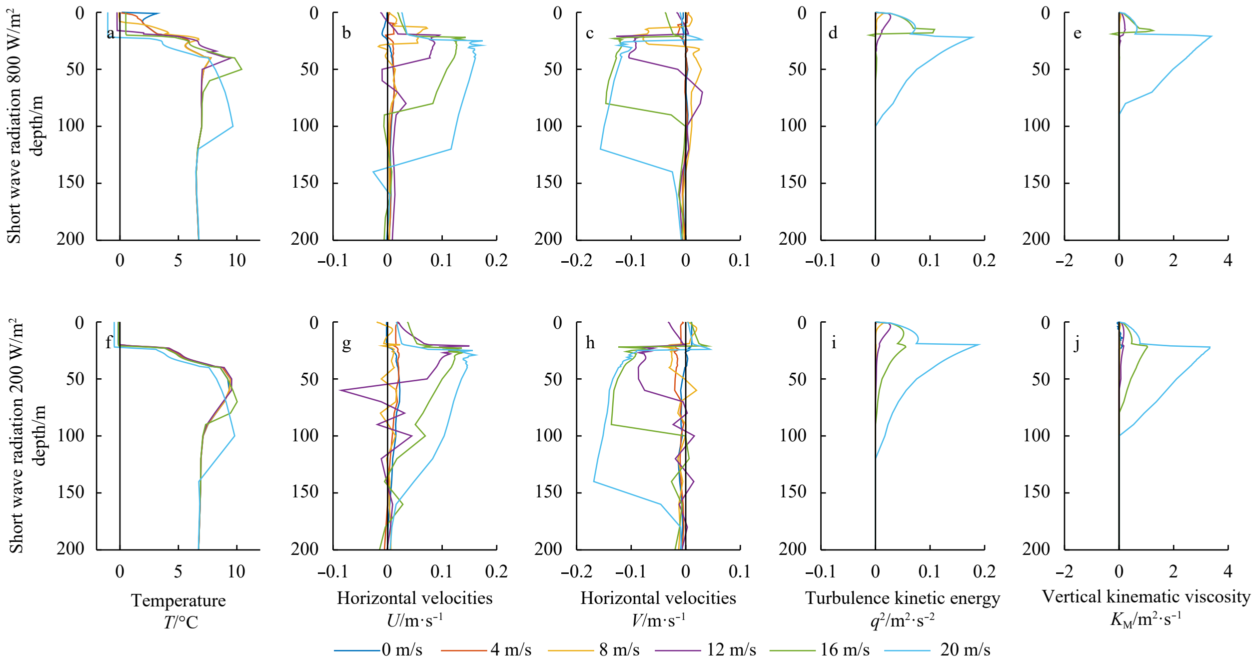

Fig. 1. The difference between experiment EXP1-S and EXP1 in the vertical structure of simulated. a, f. Temperature profile (T); b, c, g, h. horizontal velocities (U and V); d, i. turbulence kinetic energy (TKE, q^2); and e, j. vertical kinematic viscosity (K_M). The colors represent different wind speed, respectively. The top row shows the result forcing by high shortwave radiation 800 W/m² (a–e), the other row shows that forcing by low short wave radiation 200 W/m² (f–j).

creasing, the warming leads to a stably stratified surface layer. As shown in Figure 3, the temperature profile for wind speeds from 0 to 10 m/s with internal of 1 m/s. It is clear that the depth of the warm layer becomes deeper and its magnitude decreases with the increasing of wind speed.

In the diurnal warm layer, the temperature declines rapidly within a thin layer. The vertical structure of sea temperature in the upper ocean has a “double-thermocline structure”, which is a stably stratified surface layer. The double-thermocline structure gradually weakens with the increasing wind speed, and it disappears when wind speed is up to 9 m/s (Fig. 3). It also can be seen that the T_{skin} is lower than the temperature at depth of 0.5 m (Fig. 2). Therefore, there is a “cold-warm-cold” structure, which can hinder heat propagation downward. The structure is accompanied with warm layer in the upper oceanic layer, and we call it “blocking structure”. This blocking structure can hinder the heat from being transferred between the ocean and the atmosphere.

Figure 4 shows the comparison of different vertical resolution (EXP1, EXP2) without the dynamic effect of Stokes drift. The differences of the upper ocean temperature are generally confined to the upper 10 m of the ocean (Fig. 4). Clearly, there are no the blocking structure and the double-thermocline structure in EXP1. Compared to EXP1, the temperature profile of the upper ocean in EXP2 is more realistically simulated and the warm layer is correctly detected. Furthermore, the coarser the vertical resolution, the slower the temperature response to the surface heating . This is because the thicker layer needs more heat to alter the temperature. In the heating process, the surface heat is significant stored in the intensive diurnal warm layer. In the cooling process, comparing with EXP1, the blocking structure in EXP2 hinders the heat from transferring upwards. Consequently, the temperature in the upper few meters of the EXP2 is warmer than that in EXP1 (Fig. 4). It suggests that a fine vertical resolution is needed in order to capture temperature variations in the upper ocean.

To investigate the influence of Stokes drift and thermal effects on the depth of mixed layer, 0-20 m/s wind speeds are used in four experiments. The results for wind speeds of 7, 10, 12 and 15 m/s are shown in Figs 5 and 6, which correspond to the solar radiation of 800 W/m² and 200 W/m², respectively. The former represents the case in summer, and the latter represents the case in winter. With the increasing wind speed, the effect of Stokes drift can substantially affect the whole mixed layer. The enhanced turbulent energy mixes the surface warm water and transfer the heat downward. Therefore, the SST decreases with the deeped MLD (the black thick lines in Fig. 5). In Fig. 6, the diurnal variation amplitude of SST is relatively small with deeper MLD and smaller SST. When the wind speed is relatively weak (7 m/s), the depth of winter mixing layer is tens of meters deeper than that of summer. The influence of Stokes drift decreases gradually with the depth, which makes the influence of Stokes drift on the mixing layer depth is weaker under the low solar radiation than that under the high solar radiation. But with the increasing of wind speed (15 m/s), the difference of mixing depth caused by solar radiation decreases. At the same depth, Stokes drift has enhanced influence on the mixing depth under the condition of low solar radiation. Therefore, high wind speed and low solar radiation can contribute to enhance and deepen the influence of Stokes drift.

Forced by strong solar radiation and low wind speed, the upper layer of ocean shows a significant diurnal variation. Due to the existence of the cool skin layer and diurnal warm layer, the double-thermocline structure clearly exists. The cool skin layer acts as a hindrance to heat transfer between ocean and atmosphere. The cool skin layer and diurnal warm layer together effectively hinder the transfer of solar radiation downward. The

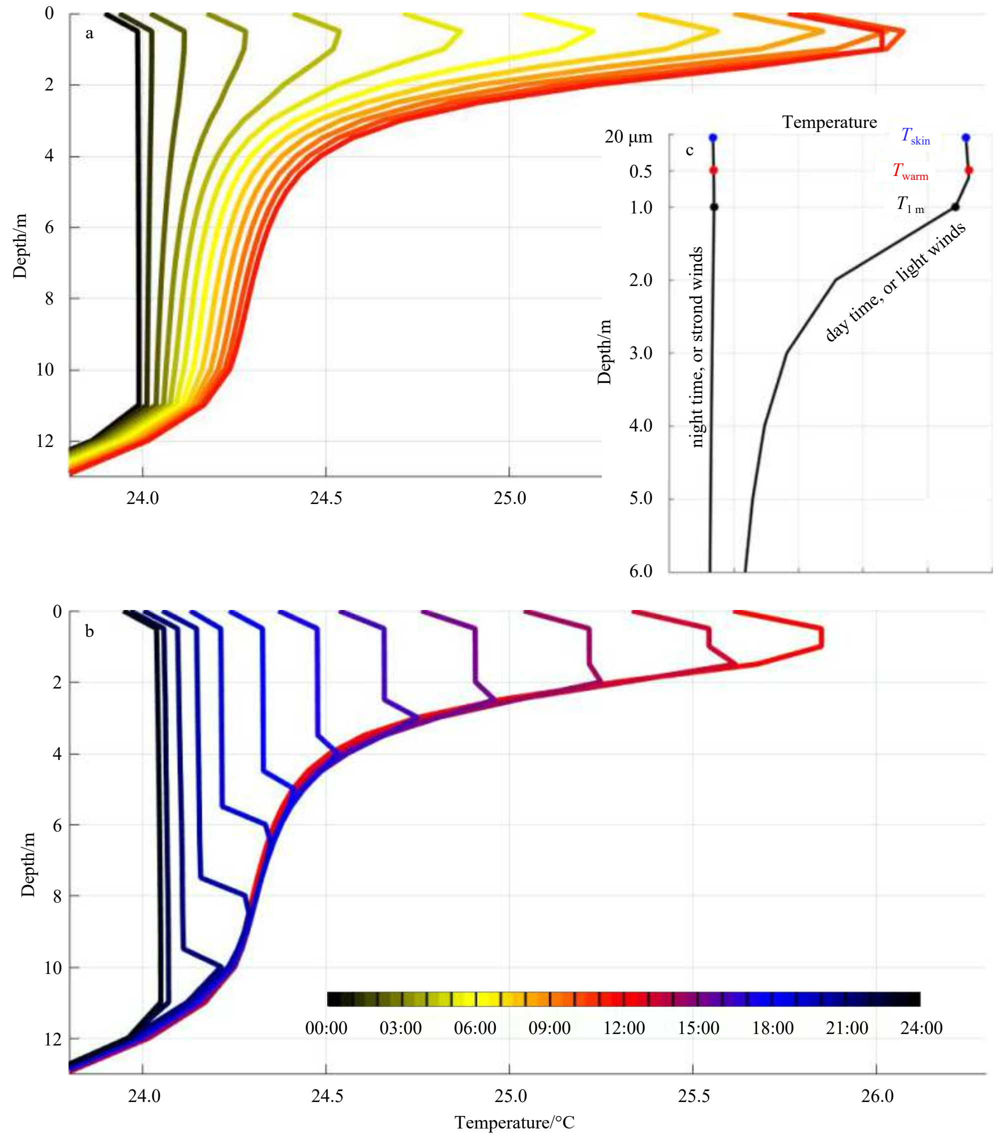

Fig. 2. The evolution of sea temperature profile with 2 m/s wind in high vertical resolution model result (EXP2) are shown. The colors represent temperature profile per 1 h, respectively.

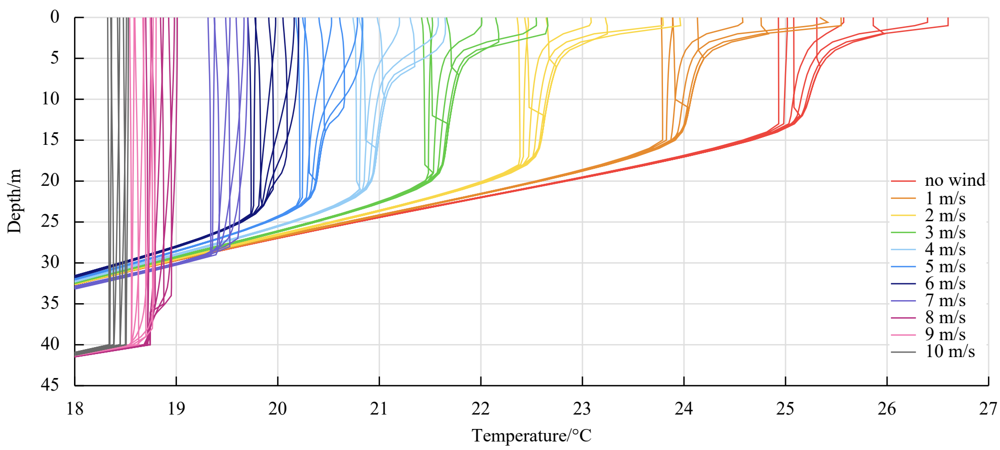

Fig. 3. The evolution of sea temperature profile per 3 h in high vertical resolution model result (EXP2) are shown. The colors represent the control experiments with wind speed from 0 to 10 m/s, respectively.

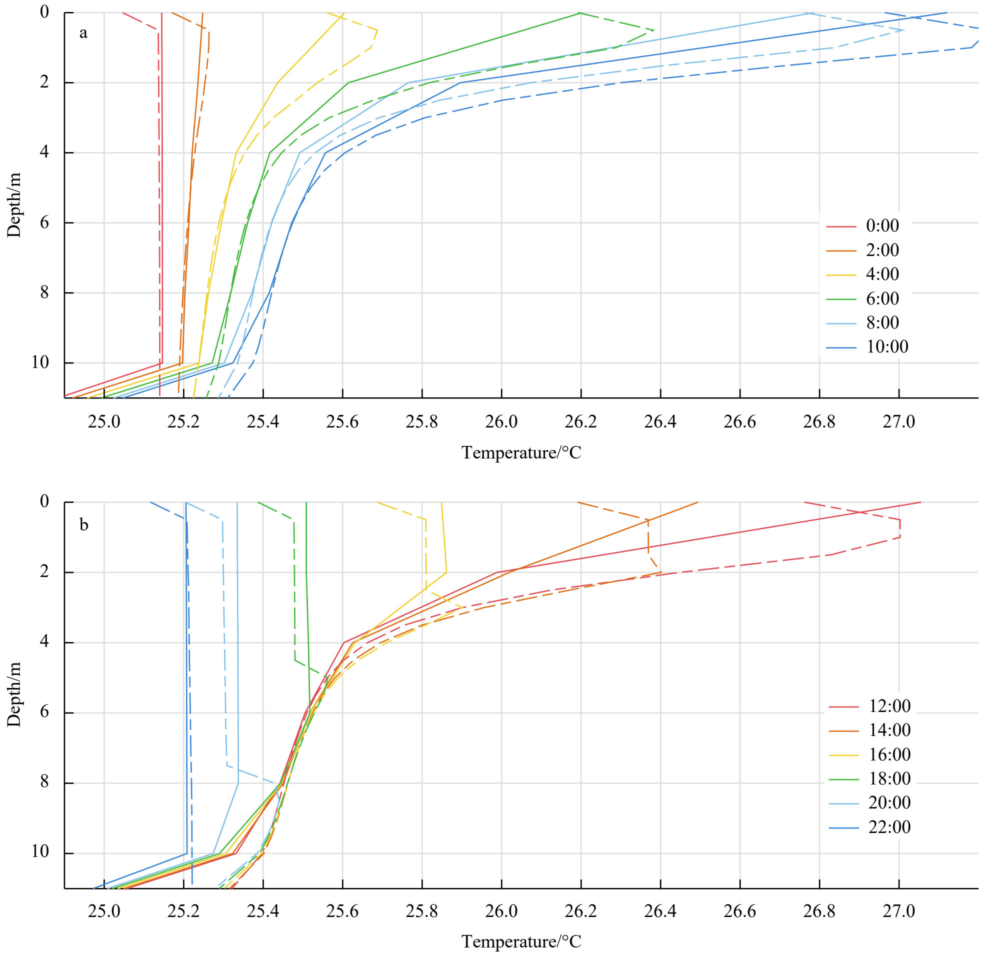

Fig. 4. The evolution of sea temperature profile in different control model result. The colors represent temperature profile per 2 h, respectively. Line: EXP1; and line with points: EXP2.

heat is captured by the diurnal warm layer. In other words, the heat of the solar radiation is actually accumulated in the blocking structure. In EXP1, without considering the existence of thermal effects, it is supposed that all solar radiation effectively enters the mixing layer, in which the shallower effect of solar radiation on the mixing layer is overestimated, and leads to the smaller MLD and warmer SST. When the wind speed increases or the solar radiation reduces, the stratification is weak. In this situation, the thermal effects tend to shallow the MLD. Due to the strong mixing, the warm layer cannot accumulate the heat into the surface stably. With the weak stratification, the cool skin layer prevents heat from being transferred upward. It depresses the turbulent kinetic energy of the upper mixed layer, and keep the intensity of the stratification. Therefore, the thermal effects can enhance the strength of stratification.When the wind speed increases to 15 m/s, the double-thermocline layer and blocking structure is collapsed due to the strong shear-induced mixing ascribed to the wind (Fig. 5).

In winter, the stratification in the upper ocean is weak due to the weak solar radiation and the strong wind speed. It seems that the increased mixing of Stokes drift will cause excessive mixing. However, the thermal effects can compensate for the weak stratification caused by the lack of solar radiation. The cool skin layer and diurnal warm layer increase the stratification, which inhibits the enhancement of turbulent energy induced by Stokes drift to some extent. In this way, it refrains from the problem of overmixing in winter.

4 Experiments at OSP

Since 1956, Ocean Station Papa (OSP) in the Gulf of Alaska at 50°N, 145°W has been in the site of open ocean research. The oceanography and meteorological measurements conducted on board by the Canadian weatherships. It is believed that the motion of the sea water around OSP is dominated by vertical physical processes and the advective effect can be neglected. Thus the data at OSP have been widely applied to evaluate the mixed layer models. We conduct the tests at OSP focusing on the seasonal evolution of the upper ocean thermal structure. The configurations are the same as those in Section 3.

In this section, the model is forced by observational data from January 1, 2012 to December 31, 2012. The horizontal resolution is 0.25° by 0.25°. The bottom topography is obtained from ETOPO5, and the maximum water depth is set as 2 000 m. The internal (external) time step is 30 min (60 s). The initial velocity is set to zero, and the initial temperature and the salinity profiles are adopted the data on January 1, 2012. Each experiment is run for one year, which is long enough to simulate of the mixed layer. The hourly data of the surface forcing are linearly interpolated into the model grid. The latent, sensible heat flux and sea skin temperature have been computed from the observed 10 m wind speed, the air temperature and the relative humidity using the advanced method of COARE3.0 bulk algorithm (Fairall et al.,

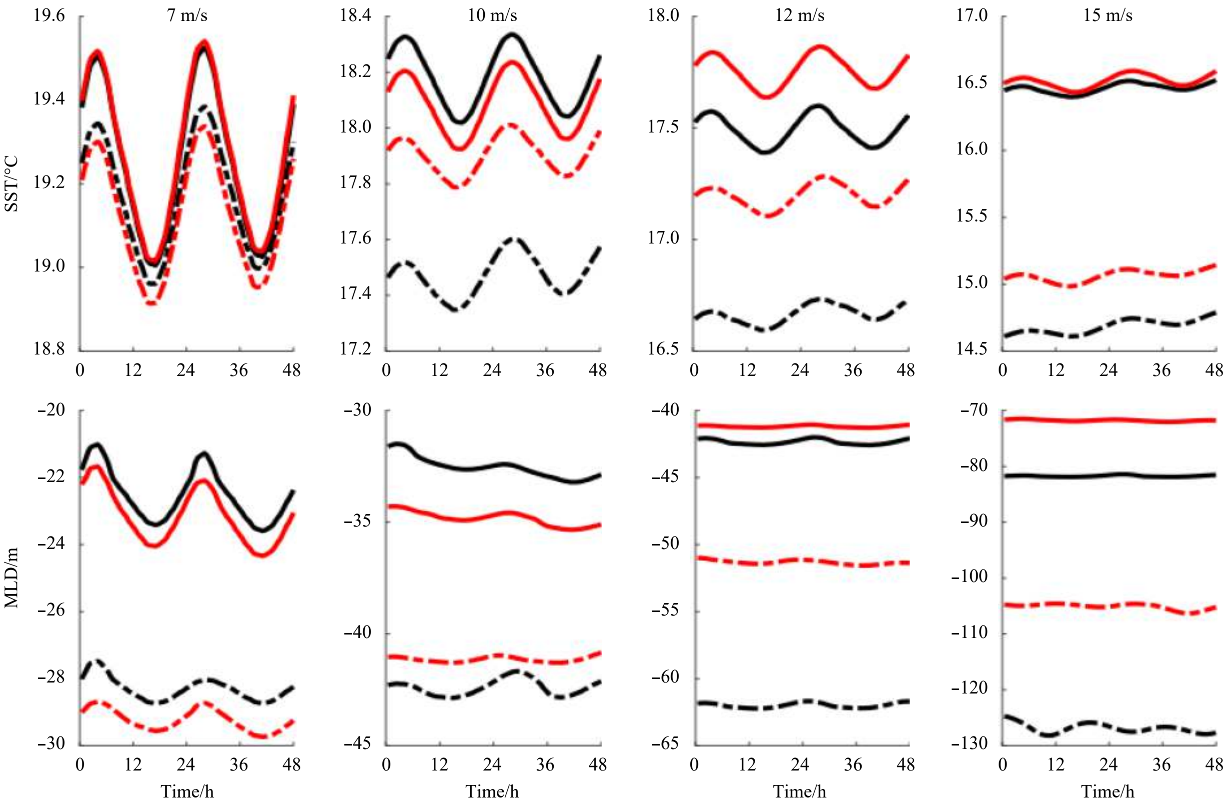

Fig. 5. The evolution of MLD and SST in two days with idealized forcing: 800 W/m² solar radiation and wind speeds from weak to strong. Solid black line: EXP1; solid red line: EXP2; black line with points: EXP1-S; and red line with points: EXP2-S.

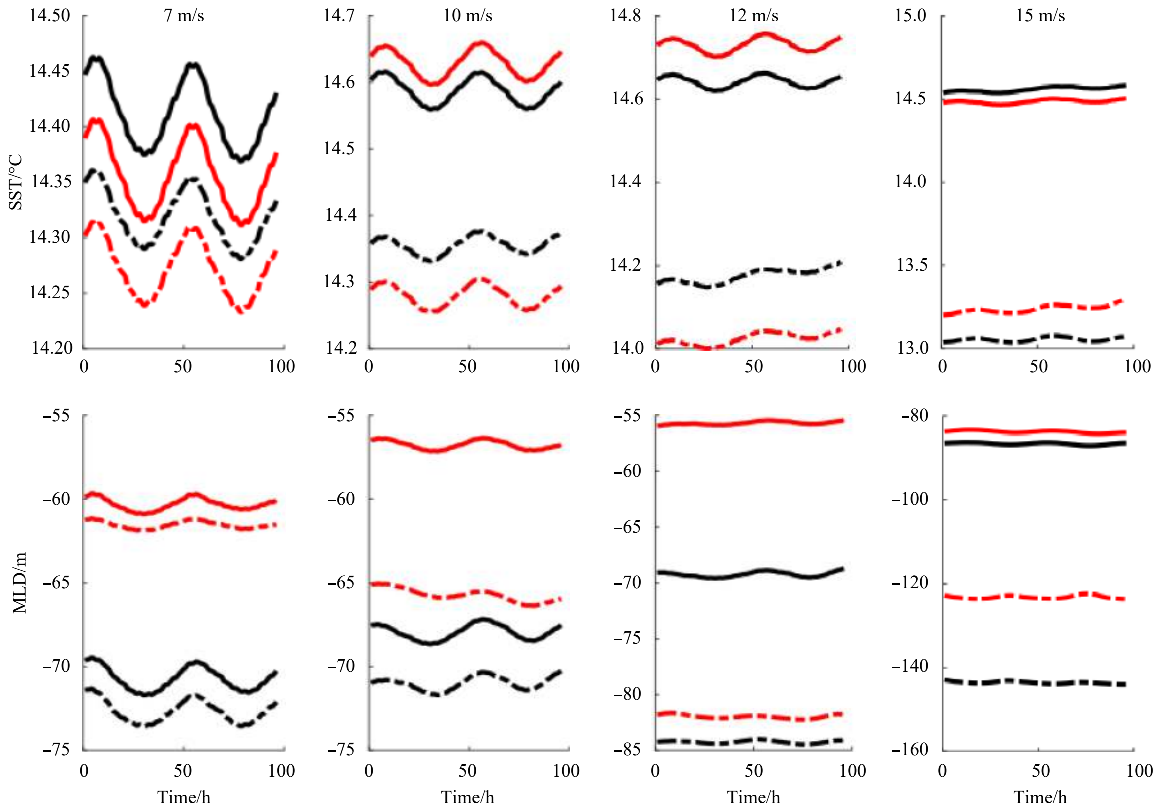

Fig. 6. The evolution of MLD and SST in two days with idealized forcing: 200 W/m² solar radiation and wind speeds from weak to strong. Solid black line: EXP1; solid red line: EXP2; black line with points: EXP1-S; and red line with points: EXP2-S.

1996b).

The observed and model predicted SST at depth of 1 m and MLD at OSP for the year 2012 are shown in Fig. 7. The MLD is defined as the depth at which the temperature becomes 0.2°C less than the SST. The observed MLD shows a drop of about 40 meters during the middle of January and a sudden increase at the beginning of April (Fig. 7b). Generally, the fluctuations of SST and MLD are controlled by surface forcing that is correctly demonstrated by the model. The EXP1 obtained the summer bias which is similar to that of Martin (1985). Although the results of EXP1 agree well with observations in winter, the simulated SST is warmer and MLD is shallower than the observations from July to August (Fig. 7). In contrast, In EXP1-S, the SST is well consisted with the observations. The improvement of SST in summer can also be seen in EXP2-S from Fig. 7a. However, in terms of MLD from January to April, there is a clear discrepancy between the EXP1-S and the observations. Because of the weak stratification and the heavy wind speed in winter, the over mixing can be expected from the result in EXP1-S (Fig. 7).

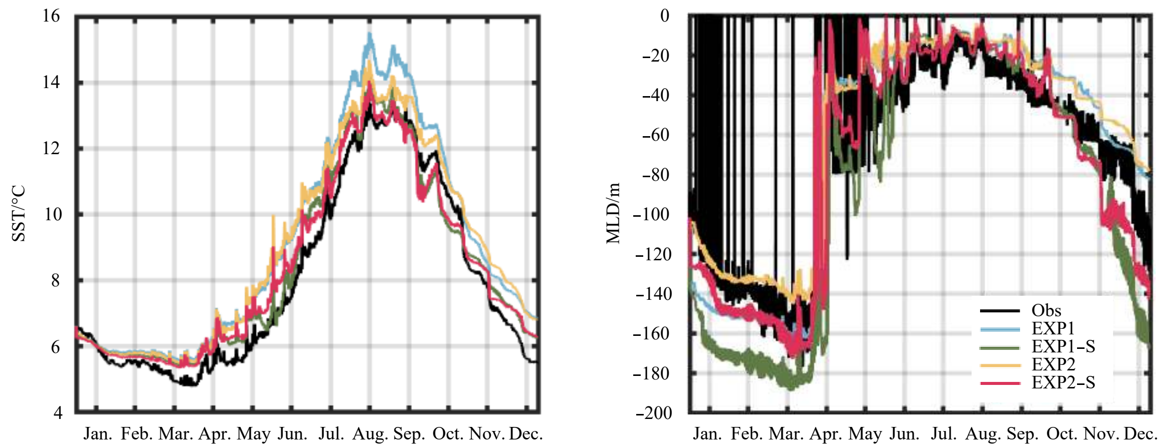

Fig. 7. Observed and simulated SST and MLD at Station Papa for 2012. Black line: observation; blue line: EXP1; green line: EXP1-S; yellow line: EXP2; and red line: EXP2-S.

Table 2 is listed the bias of SST and MLD of EXP1, EXP2, EXP1-S and EXP2-S compared with the observations. From Table 2, it can be seen that the simulated SST and MLD in EXP2-S are closest to the observations with the summer SST bias of only 0.48°C and MLD bias of 6.17 m. The simulated SST is overestimated about 2°C in EXP1, and the corresponding MLD is about 13 m shallower than the observations (Table 2). Figure 8 shows the iso-

Table 2. Difference between model and observed SST and MLD at Papa for 2012

Bias	EXP1	EXP2	EXP1-S	EXP2-S
Annual SST/°C	1.18	0.96	0.57	0.53
Summer SST/°C	1.98	1.21	0.64	0.48
Winter MLD/m	9.03	8.36	28.94	7.65
Summer MLD/m	13.11	12.11	8.05	6.17

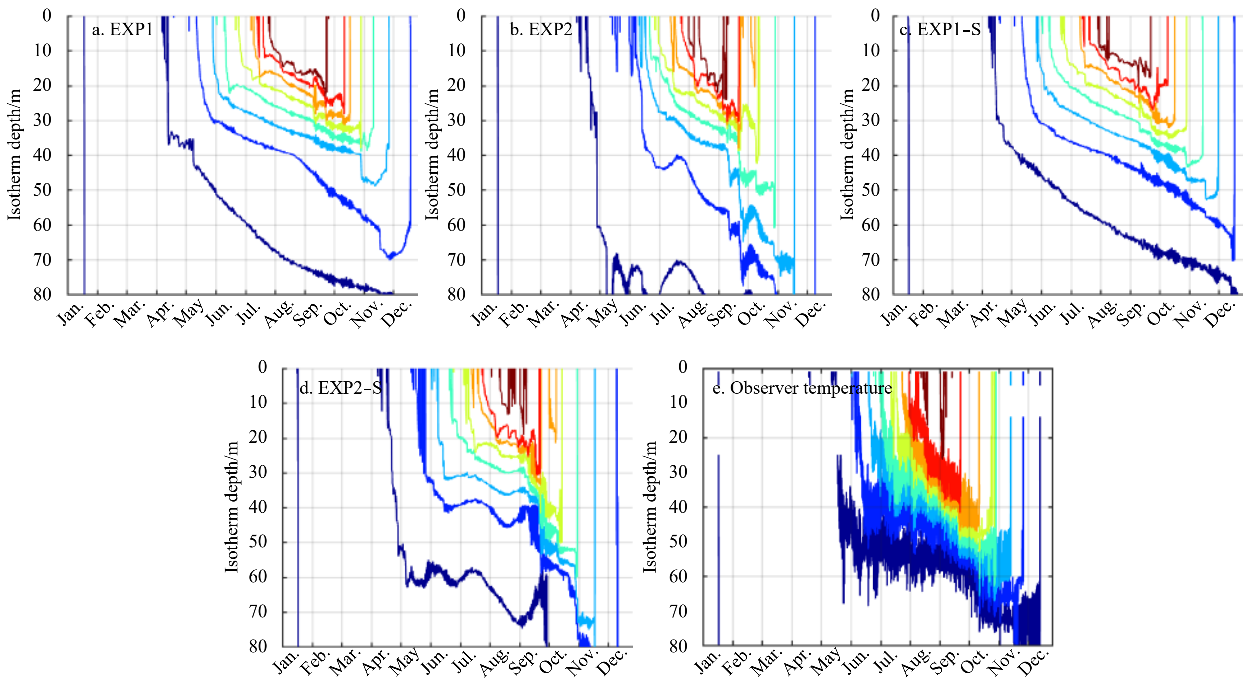

Fig. 8. Observed and simulated isotherm depth at Station Papa for 2012. a. EXP1, b. EXP2, c. EXP1-S, d. EXP2-S, and e. observation.

therm depths at OSP for the simulations and the observations. It is clear that the observed 13℃-isotherm is deeper and sharper than EXP1 (Fig. 8a). The EXP1-S tends to intense the turbulence and the vertical mixing. Strong mixing can transport a large amount of heat from the surface layer to the subsurface, resulting in a decrease in the surface temperature and an increase in subsurface temperature. The summer bias is associated with the cold subsurface temperature bias of 4℃ (Fig. 9). There is less warming accumulates above the MLD during the summer and significant warm bias under the MLD in both summer and winter (Fig. 9b). Although it is believed that the enhanced mixing contributes significantly to mixing in the ocean mixed layer, it is important to note that the effect of Stokes is deeper in winter. Excess heat is transferred to the deep ocean by Stokes in winter.

The most outstanding thermal effect is the enhanced stratification which prevents the heat from being propagated between ocean and atmosphere. While in summer (winter), the thermal effects decrease (increase) the net heat flux absorbed in the ocean. A reduction of the surface net heat flux improves the SST agreement in summer, but the simulated MLD will be too shal-

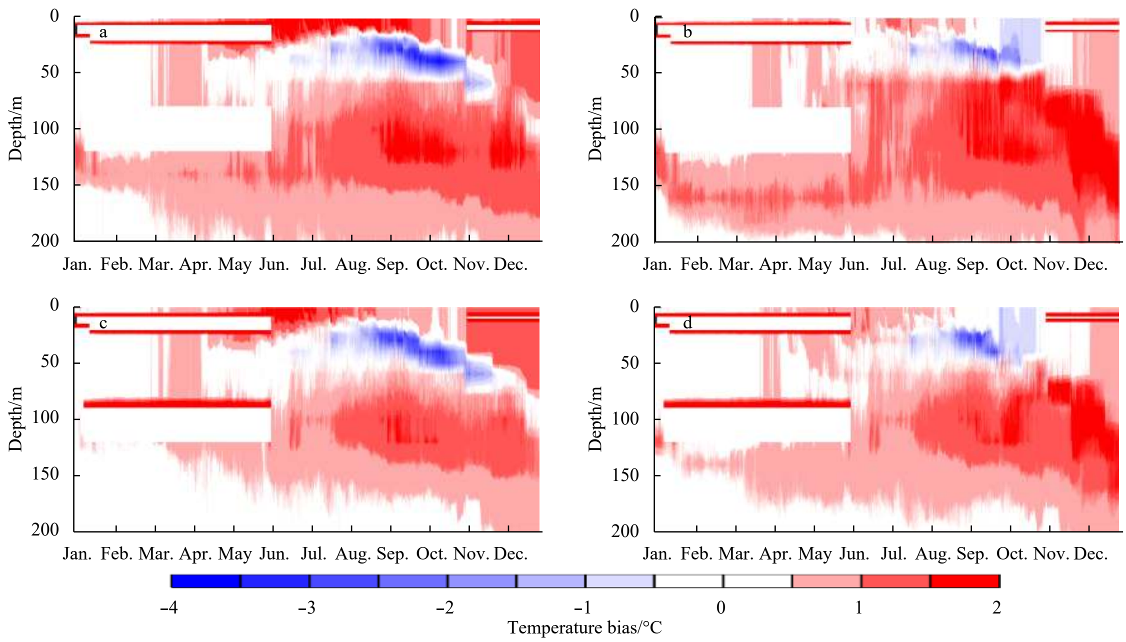

Fig. 9. Simulated temperature bias profile at Station Papa for 2012. a. EXP1, b. EXP1-S, c. EXP2, and d. EXP2-S.

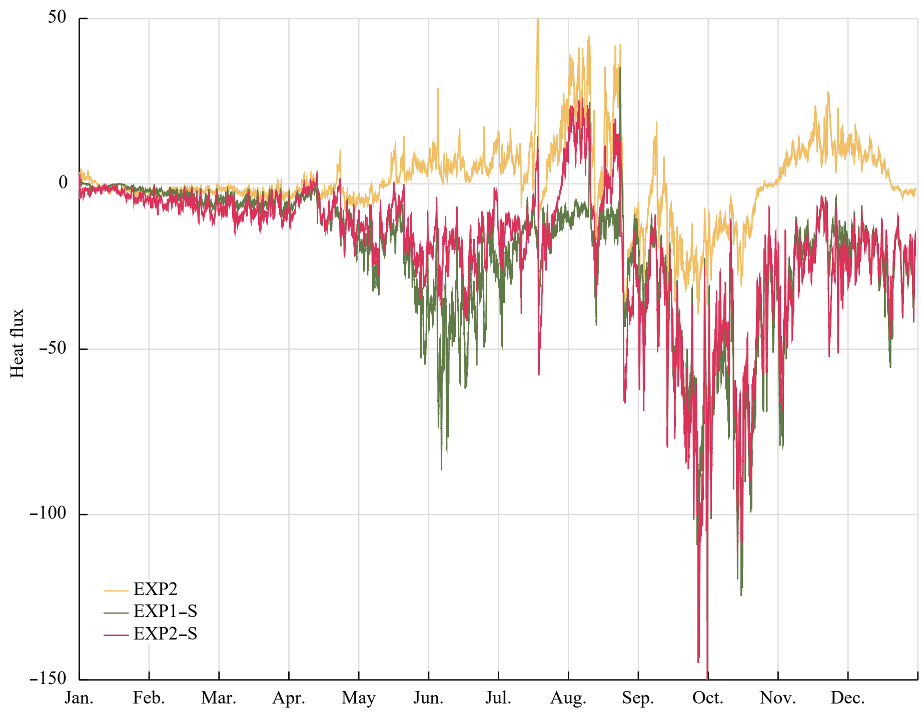

Fig. 10. The difference of the net heat flux released into the atmosphere compared with EXP1. Yellow line: EXP2; green line: EXP1-S; and red line: EXP2-S.

low (Fig. 10). The temperature can be simulated properly to include the thermal effects and the Stokes drift in EXP2-S. The shallowing of the MLD might be induced by inadequate mixing and overestimate of the surface heat flux during summer. In summer, the thermal effects accumulate the heat in the surface layer and result to reduce the net surface heat flux. The dynamic effect of Stokes drift enhances the turbulence kinetic energy and transfer the heat from surface to subsurface. These two factors can effectively solve the problem of insufficient mixing in the classic M–Y scheme and correct the summer simulated bias. In winter, the dynamic effect of Stokes drift due to the strong wind speed and weak stratification could mix much greater depths than in summer. However, the overestimated mixing can be effectively compensated by the thermal effects.

5 Summary

In order to improve the insufficient mixing in the ocean model in summer, the impact of Stokes drift, cool skin layer and warm layer are considered. Several simulation experiments are conducted through POM. It is shown that the Stokes drift can deepen the MLD and reduce the SST by enhancing the turbulence kinetic energy. In the case of low solar radiation, the effect of Stokes drift on the mixed layer is more significant compared with the case of high solar radiation at same wind speed. It will be improved the summer bias, and lead to a new bias in winter. We suggest that this contradict can be avoided by the inclusion of thermal effects of the cool skin layer and warm layer in the upper ocean.

The thermal effects of the cool skin layer and diurnal warm layer on the upper mixing layer is highly dependent on the magnitude of solar radiation and wind speed. In the case of low wind speeds and strong solar radiation, the heat accumulates in the diurnal warm layer. The double-thermocline structure and blocking structure can accumulate heat and prevent the heat from being transferred downwards. With the strong stratification, the thermal effects can enhance the influence of Stokes drift. But when the stratification is weak, the thermal effects can enhance the strength of stratification and counteract Stokes drift by suppressing excessive mixing effect. With strong winds and weak solar radiation, the effect of warm layer can be neglected while the cool skin effect on the net heat flux intensifies. Therefore, with the dynamic effect of Stokes drift and the thermal effects of skin layer and the warm layer together, POM can correctly simulate the SST and MLD either in summer or in winter.

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