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A numerical estimation of the impact of Stokes drift on upper ocean temperature

ZHANG Xiaoshuang[1], WANG Zhifeng[2], WANG Bin[3], WU Kejian[2]*, HAN Guijun[1], LI Wei[1]

[1] Key Laboratory of Marine Environmental Information Technology, National Marine Data and Information Service, State Oceanic Administration, Tianjin 300171, China
[2] Ocean University of China, Qingdao 266100, China
[3] National Ocean Technology Center, State Oceanic Administration, Tianjin 300112, China

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Abstract
The impact of Stokes drift on the mixed layer temperature variation was estimated by taking into account an advective heat transport term induced by the Stokes drift in the equation of mixed layer temperature and using the oceanic and wave parameters from a global ocean circulation model (HYCOM) and a wave model (Wave Watch III). The dimensional analysis and quantitative estimation method were conducted to assess the importance of the effect induced by the Stokes drift and to analyze its spatial distribution and seasonal variation characteristics. Results show that the contribution of the Stokes drift to the mixed layer temperature variation at mid-to-high latitudes is comparable with that of the mean current, and a substantial part of mixed layer temperature change is induced by taking the Stokes drift effect into account. Although the advection heat transport induced by the Stokes drift is not the leading term for the mixed layer temperature equation, it cannot be neglected and even becomes critical in some regions for the simulation of the upper-ocean temperature.

Key words: sea surface waves, Stokes drift, mixed layer temperature

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1 Introduction

Recently, there have been widespread concerns over the impact of the sea surface waves on the large-scale circulation patterns, such as the vertical mixing and advective transport effect. Qiao et al. 2004 and Qiao et al. 2008 analyzed the contribution of the sea surface waves to the oceanic vertical mixing. Their results suggested that the wave-induced mixing was important to the formation of upper ocean thermocline. Li et al. (2008) studied the influence of the Stokes drift on the upper ocean mixed layer, they pointed that the Stokes drift was the main source of the vertical vorticity in the ocean mixed layer and could substantially affect the whole mixed layer through the Coriolis-Stokes forcing and Langmuir circulations.

Moreover, the previous studies have stressed the role of Stokes transport in the upper ocean advective transport. The advective transport induced by sea surface waves could change the upper ocean current system in the rotating ocean (Longuet-Higgins, 1953, 1960; Kenyon, 1970; Weiber, 1983; Jenkins, 1986). In addition, on the large horizontal scale, the contribution of the sea surface waves to the Sverdrup transport could reach the same magnitude as that produced by the wind-driven current at the mid-to-high latitudes (Mcwilliams, 1999). Lane (2006) incorporated the radiation-stress and vortex-force induced by the sea surface waves into the motion equation to establish the dynamic connection between the sea surface waves and mean current. In this study, the vortex-force was justified to be the dominant wave-averaged effect on the mean current, and the Stokes drift had resemble contribution with the mean current to the tracer advective transport. Furthermore, Wu and Liu (2008) investigated the driving effect of the sea surface waves on the oceanic large-scale motion from the viewpoint of energy. It is found that the ratio of the energy input induced by the Stokes drift to the total input energy into the Ekman-Stokes layer could be larger than 10% at high latitudes. The ratio can even reach 22% in the area of the Antarctic Circumpolar Current (ACC). Moreover, the sea surface waves also have important impact on the ocean heat flux, sea surface temperature, and other phenomena in the upper ocean (Deng et al., 2009).

Collectively, the sea surface waves not only influence the oceanic circulation system through volume and energy transports but also impact the temperature and other physical processes in the upper ocean. Zhang and Wu (2012) demonstrated the importance of the Stokes drift on the upper ocean temperature by using reanalysis data sets (SODA, NCEP/NCAR and ECWMF). They found that the differences in data sources and spatial resolutions may induce unexpected errors in the estimations. Beyond that, the spatial (different sea areas) and temporal variation characteristics of the temperature advection induced by the Stokes drift were not analyzed in the paper (Zhang and Wu, 2012). In this study, the hybrid

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*Corresponding author, E-mail: kejianwu@ouc.edu.cn

coordinate ocean model (HYCOM) ocean circulation model (Large et al., 1994; Bleck, 2002; Chassignet et al., 2003) and Wave Watch III (WWIII) (Cavaleri and Malanotte-Rizzoli, 1981; Chalikov and Belevich, 1993; Tolmas, 2009) will be employed to provide the oceanic and surface wave data to estimate and analyze the spatial and seasonal variations of the temperature advection induced by the Stokes drift.

2 Theoretic analysis and model

2.1 *The mixed layer temperature equation*

The upper ocean thermodynamics equation (Stevenson and Niller, 1983) in the absence of horizontal heat diffusion can be presented as:

$$\frac{\partial T}{\partial t}+\vec{V}\cdot\nabla T+w\frac{\partial T}{\partial z}=\frac{1}{\rho c_{\mathrm{p}}}\frac{\partial Q}{\partial z}+\frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right), \tag{1}$$

where ρ represents the seawater density; c_{p} denotes the specific heat capacity per unit volume; T stands for the seawater temperature; t is the time; Q indicates the sea surface net heat flux; $\vec{V}$ is the horizontal velocity vector; w is the vertical velocity; $\nabla=\left(\frac{\partial}{\partial x},\frac{\partial}{\partial y}\right)$ represents the horizontal gradients; and K is the vertical heat diffusion coefficient.

Integrating Eq. (1) from the sea surface to the depth $-h$ with respect to z gives, the following temperature equation for the upper ocean:

$$\frac{\partial\overline{T}}{\partial t}=\frac{Q_0-Q_{-h}}{\rho c_{\mathrm{p}}h}-\overline{\vec{V}}\cdot\nabla\overline{T}-\nabla\cdot\left(\int_{-h}^{0}\vec{V}'T'\mathrm{d}z\right)-\frac{\overline{T}-T_{-h}}{h}w_{\mathrm{e}}, \tag{2}$$

where

$$w_{\mathrm{e}}=\frac{\partial h}{\partial t}+\vec{V}_{-h}\cdot\nabla h+w_{-h};$$

$$\overline{T}=\frac{1}{h}\int_{-h}^{0}T\mathrm{d}z,\ \overline{\vec{V}}=\frac{1}{h}\int_{-h}^{0}\vec{V}\mathrm{d}z;$$

$$T'=T-\overline{T},\ \vec{V}'=\vec{V}-\overline{\vec{V}};$$

in which w_{e} represents the velocity of traveling the h-plane, $\overline{T}$ and $\overline{\vec{V}}$ are the average temperature and horizontal velocity in the upper ocean (0–h depth) respectively; and T' and $\vec{V}'$ denote the perturbations of $\overline{T}$ and $\overline{\vec{V}}$.

If the value of h is chosen as the mixed layer depth or a shallower depth, Eq. (2) can be evaluated as the mixed layer temperature equation and the sea surface temperature (SST) variation equation. The l.h.s of Eq. (2) is the change rate of the average temperature. The r.h.s of Eq. (2) include the effects of the net heat flux (1st term), the advective heat transport (2nd and 3rd terms), and the vertical turbulence (the last term).

Currently, the advective heat transport only considers the effect of the mean current in the upper ocean, but it does not include the effect of Stokes drift. As we know, the Stokes drift has a significant influence on the mean current field. For the wave tracer (Lane, 2006),

$$\nabla\cdot c^{\mathrm{w}}\vec{u}^{\mathrm{w}}=\vec{u}^{\mathrm{St}}\cdot\nabla c, \tag{3}$$

where c represents the tracer; the superscript "w" indicates the wave; $\vec{u}^{\mathrm{w}}$ and $\vec{u}^{\mathrm{St}}$ denote the velocity of the wave transport and Stokes drift, respectively. The divergence of the wave tracer flux equals the mean tracer advection that is induced by the three-dimensional Stokes velocity. The advective equation that combines the effects of the mean current and sea surface waves can be formulated as:

$$\frac{\partial c}{\partial t}=-\left(\vec{u}+\vec{u}^{\mathrm{St}}\right)\cdot\nabla c. \tag{4}$$

The Stokes drift makes a similar contribution to the tracer advective transport, as compared to the mean current. It is reasonable to conclude that the advective transport of the Stokes drift cannot be neglected in the advective heat transport term of Eq. (2). Therefore, the current mixed layer temperature equation has a deficiency by failing to consider the advective heat transport effect of the Stokes drift.

According to the above analysis, it is reasonable and necessary to introduce the advective heat transport effect induced by the Stokes drift into Eq. (2). The new mixed layer temperature equation is

$$\begin{aligned}\frac{\partial\overline{T}}{\partial t}=&\frac{Q_0-Q_{-\mathrm{h}}}{\rho c_{\mathrm{p}}h}-\overline{\vec{V}}\cdot\nabla\overline{T}-\overline{\vec{V}}_{\mathrm{St}}\cdot\overline{T}-\\&\nabla\cdot\left[\int_{-\mathrm{h}}^{0}\left(\vec{V}'+\vec{V}_{\mathrm{St}}'\right)T'\mathrm{d}z\right]-\frac{\overline{T}-T_{-\mathrm{h}}}{h}w_{\mathrm{e}},\end{aligned} \tag{5}$$

where

$$\overline{\vec{V}}_{\mathrm{St}}=\frac{1}{d_{\mathrm{St}}}\int_{-d_{\mathrm{St}}}^{0}\vec{V}_{\mathrm{St}}\mathrm{d}z,$$

$$\vec{V}_{\mathrm{St}}'=\vec{V}_{\mathrm{St}}-\overline{\vec{V}}_{\mathrm{St}},$$

in which $\overline{\vec{V}}_{\mathrm{St}}$ represents the average Stokes drift velocity over the Stokes depth; $\vec{V}_{\mathrm{St}}'$ stands for the perturbation term for $\overline{\vec{V}}_{\mathrm{St}}$; and d_{s} denotes the Stokes depth.

In the mixed layer, both the current velocity gradient and the temperature gradient are insignificant, so the magnitude of the fourth term in r.h.s of Eq. (5) can be taken as a minor term relative to other terms. In order to simplify the calculation, the term is ignored in the following parts. The third term in r.h.s of Eq. (5) is the advective heat transport effect of the Stokes drift. The seawater density ρ=1 025 kg/m^3, and the specific heat c_{p}=3 944 J/(kg·°C).

2.2 *The dimensional analysis*

The four terms impacting the temperature variation are defined as T_{q}, T_{c}, T_{St} and T_{w}, respectively. Here, T_{q} is the heat flux term, T_{c} and T_{St} represent the advective heat transport terms induced by the mean current and Stokes drift, respectively, and T_{w} is the vertical turbulence term. The magnitudes of these terms are expressed as follows:

$$O\left(T_{\mathrm{q}}\right)=O\left(\frac{Q_0-Q_{-h}}{\rho c_{\mathrm{p}}h}\right)=O\left(\frac{Q}{\rho c_{\mathrm{p}}H}\right), \tag{6}$$

$$O(T_c) = O\left(\overline{\vec{V}} \cdot \nabla \overline{T}\right) = O\left(\frac{UT}{L}\right), \quad (7)$$

$$O(T_{St}) = O\left(\overline{\vec{V}}_{St} \cdot \nabla \overline{T}\right) = O\left(\frac{U_{St}T}{L}\right), \quad (8)$$

$$O(T_w) = O\left(\frac{\overline{T} - T_{-h}}{h} w_e\right) = O\left(\frac{TW}{H}\right). \quad (9)$$

Considering the zonal characteristic of the Stokes drift, the dimensional analysis could be calculated separately in two parts, including the mid-to-high latitudes (30°–80°S, 30°–80°N) and the low latitudes (30°S–30°N). At the mid-to-high latitudes, the magnitudes of the sea surface heat flux (Q), the mixed layer depth (H), the mean current velocity in the mixed layer (U), the average Stokes drift velocity in the Stokes depth (U_{St}), the average temperature in the mixed layer (T), the horizontal distance (L), and the velocity traveling on the h-plane (W_e) are 10 W/m^2, 10 m, 0.01 m/s, 0.01 m/s, 10°C, 10^5 m and 10^{-5} m/s, respectively. The magnitudes of T_q, T_c, T_{St} and T_w (°C/s) are

$$O(T_q) = 1\times10^{-6},$$

$$O(T_c) = 1\times10^{-6},$$

$$O(T_{St}) = 1\times10^{-6},$$

$$O(T_w) = 1\times10^{-5}.$$

Obviously, T_{St} has the same magnitude as T_q and T_c, while the value is one order of magnitude lower than T_w. At mid-to-high latitudes, the vertical turbulence effect is the most significant term, and T_{St} is comparable with T_q and T_c. Therefore, the advective heat transport effect induced by the Stokes drift is negligible at mid-to-high latitudes. At the low latitudes, the magnitudes of Q, H, U, U_{St}, T, L, and W_e are 10 W/m^2, 10 m, 0.01 m/s, 0.001 m/s, 10°C, 10^5 m and 10^{-5} m/s, respectively. The magnitudes of T_q, T_c, T_{St} and T_w (°C/s) are

$$O(T_q) = 1\times10^{-6},$$

$$O(T_c) = 1\times10^{-6},$$

$$O(T_{St}) = 1\times10^{-7},$$

$$O(T_w) = 1\times10^{-5}.$$

The magnitude of T_{St} is one (two) order(s) of magnitude lower than T_q and T_c (T_w). Therefore, the vertical turbulence effect is also the most significant term at the low latitudes, but the importance of the advective heat transport effect induced by the Stokes drift reduces.

To sum up, the advective heat transport effect induced by the Stokes drift is a minor term at low latitudes, but it is significant at mid-to-high latitudes that can reach the same magnitude as T_q and T_c. The result justifies the importance of the Stokes drift for the upper ocean temperature variation. Consequently, it is necessary to do the quantitative calculation for T_{St}, T_q, T_c and T_w to analyze the importance and the spatial-temporal characteristics of these effects.

2.3 *Model*

The ocean circulation model HYCOM (hybrid coordinate ocean model) is employed to provide the climatological temperature, current velocity, sea surface net heat flux, and mixed layer depth data; the wave model WWIII is employed to provide the wave field data.

The calculation area extends from 75°S to 83°N and 0° to 360° at longitude. For the HYCOM, the resolution is 1°×cosφ in latitude and 1° in longitude. The vertical mixing parameterization scheme used in the model is KPP (K-profile parameterization) scheme. There are 28 vertical levels with an intensified vertical resolution in the upper ocean mixed layer. The potential density of these levels are 1 013.50, 1 014.50, 1 015.50, 1 016.50, 1 017.50, 1 018.50, 1 019.50, 1 020.25, 1 021.00, 1 021.75, 1 022.50, 1 023.25, 1 024.00, 1 024.70, 1 025.28, 1 025.77, 1 026.18, 1 026.52, 1 026.80, 1 027.03, 1 027.22, 1 027.38, 1 027.52, 1 027.64, 1 027.74, 1 027.82, 1 027.88 and 1 027.92 kg/m^3. The model reaches stabilization after 30 a integrating. The data of last year are used for the analysis in this study. For the WWIII, the horizontal resolution is 0.5°×0.5°. The frequency extension and frequency increment factor are 0.041 77–0.405 6 Hz and 1.1, respectively. The number of frequencies is 25.

The atmospheric force and topography used in these two models are the climatological data set from COADS (including the wind speed and wind stress at 10m height above the sea surface, the humidity and specific humidity of air, net shortwave and long wave radiation fluxes) and DBDB2 topography data with 2′ resolution.

3 The contribution of the Stokes drift to the mixed layer temperature variation

3.1 *The Stokes drift*

For the single-frequency deep-water gravity waves, the Stokes drift velocity (Phillips, 1977) can be expressed as:

$$\vec{U}_{St} = U_{ss} e^{2kz} \vec{k}\ ,\ U_{ss} = a^2 \sigma k\ , \quad (10)$$

where, U_{ss} represents the velocity of the sea surface Stokes drift; $\vec{k}$ is the unit wavenumber vector; k denotes the wave number; and σ is the wave frequency. The Stokes drift can also be expressed by the significant wave height H_s and the average period T,

$$\vec{U}_{St} = U_{ss} e^{\frac{8\pi^2 z}{gT^2}} \vec{k}\ ,\ U_{ss} = \frac{2\pi^3 H_s^2}{gT^3}\ . \quad (11)$$

The Stokes depth is defined by

$$d_{St} = \frac{1}{2k}\ . \quad (12)$$

The typical value of the Stokes depth varies from 5 to 10 m.

The global distribution of the Stokes depth is given in Fig. 1. The value of the Stokes depth varies from 3 to 17 m. The Stokes depth in the eastern ocean is obviously deeper than that in the western ocean. Chen et al. (2002) used the satellite altimeter data and statistical methods analyzing the spatial distribution characteristics of the wind wave and the swell in the global

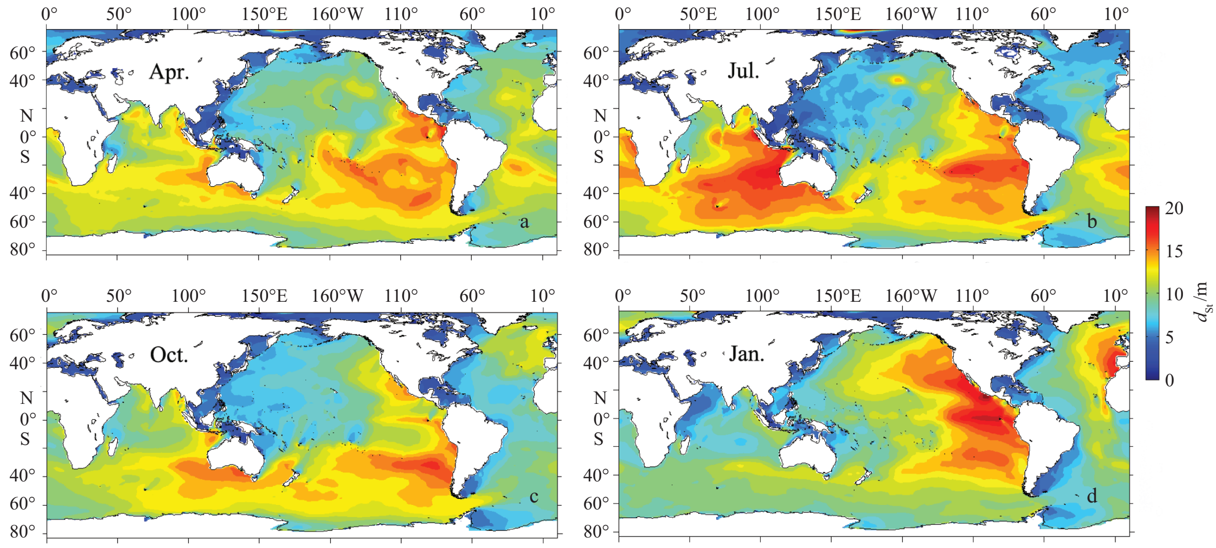

Fig.1. The global distribution of the Stokes depth for April (a), July (b), October (c), and January (d).

ocean. This study concluded that the swell in the eastern ocean is much stronger than that in the western ocean. They defined the phenomenon as "swell pool". Zhang et al. (2011) used three new indexes (wind-wave correlation coefficient, wave age, and swell index) analyzing the spatial distribution characteristics of the wind wave and swell in the global ocean, which demonstrated the existence of the "swell pool".

Because the swell predominates in the eastern ocean, the average wave period (the wavenumber in unit length) in the eastern ocean is longer (smaller) than that in the western ocean. According to Eq. (12), these features cause a deeper Stokes depth in the eastern ocean.

Figure 2 displays the average velocity of the Stokes drift within the Stokes depth. The most significant feature is the zonal distribution. The averaged velocity at mid-to-high latitudes is much larger than that at low latitudes. The maximum appears in the westerlies in the Northern and Southern Hemispheres.

3.2 *The advective heat transport effect induced by the Stokes drift*

The third term in the r.h.s of Eq. (5) is the contribution of the Stokes drift to the mixed layer temperature variation, which can be expressed as:

$$T_{\rm St} = \overline{\overline{V}}_{\rm St} \cdot \nabla \overline{T} = u_{\rm St} \frac{\partial \overline{T}}{\partial x} + v_{\rm St} \frac{\partial \overline{T}}{\partial y} \,. \tag{13}$$

The data simulated by the HYCOM and WWIII are used to calculate $T_{\rm St}$ according to Eq. (13). The global spatial distribution characteristics of the annual mean $T_{\rm St}$ is presented in Fig. 3. The

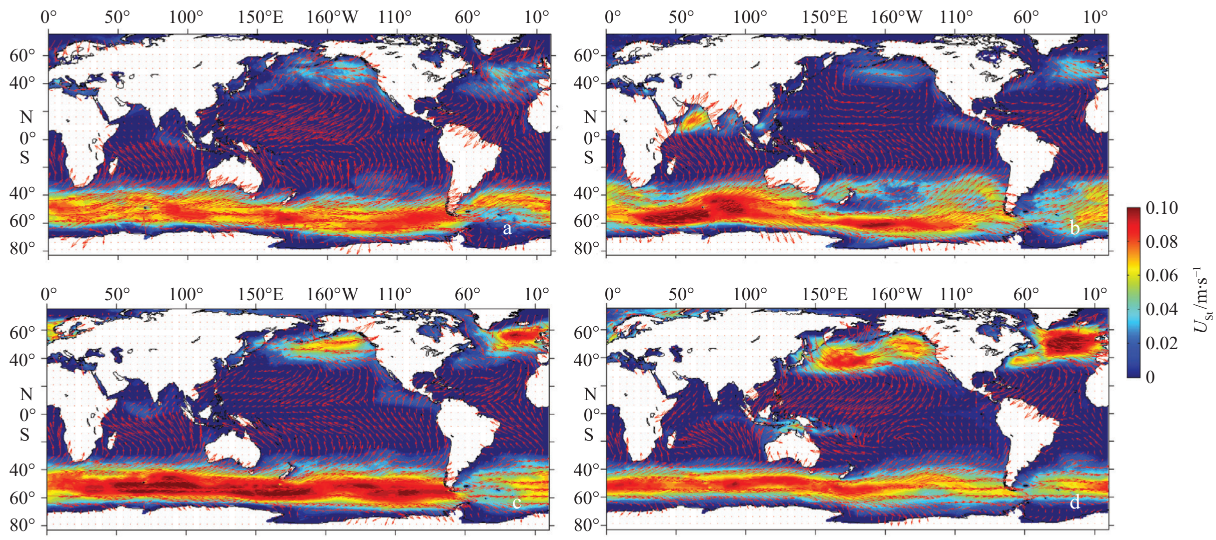

Fig.2. The same as Fig. 1, but for the average Stokes drift velocity in the Stokes depth.

contributions of the Stokes drift at mid-to-high latitudes are larger than those in low latitudes. In the Northern Hemisphere, the positive and negative contributions coexist; the maximum absolute value of T_{St} is 0.08×10^{-6} °C/s (0.2°C per month) at the high-latitude Pacific and 0.2×10^{-6} °C/s (0.5°C per month) at high-latitude Atlantic. In the Southern Hemisphere, the positive and negative contributions also coexist; the maximum absolute value 0.23×10^{-6} °C/s (0.6°C per month) occurs in the westerlies. At low latitudes, the average value of T_{St} is about 6.5×10^{-9} °C/s (0.1°C per month). The coexistence of positive and negative T_{St} is caused by the fact that the value of T_{St} is not only related to the direction and magnitude of the Stokes drift velocity but also related to the meridional and zonal temperature differences. Figure 4 shows the global distribution of T_{St} that is determined by u_{St} and v_{St}. The coexistence of the positive and negative T_{St} is mainly induced by the effect of v_{St} and the meridional temperature differences. The effect of v_{St} is significant in the eastern ocean where the swell plays a dominant role. Most values of the effect induced by u_{St} are positive (negative) in the area of ACC (high latitudes of the Northern Hemisphere).

The distributions of T_{St} in different seasons are presented in Fig. 5, while the averaged absolute values of T_{St} in different oceans and different seasons are shown in Table 1. The seasonal variation of T_{St} in the Pacific and Atlantic are not significant. T_{St} values show larger seasonal differences in the Indian Ocean, where they are significantly affected by the monsoon. The values of T_{St} in the northern Indian Ocean in summer are much larger than that in the other three seasons. In the area of the ACC, the values of T_{St} are much larger than those in other areas in the whole year that the annual mean value of T_{St} can reach 0.0992×10^{-6} °C/s (0.26°C per month).

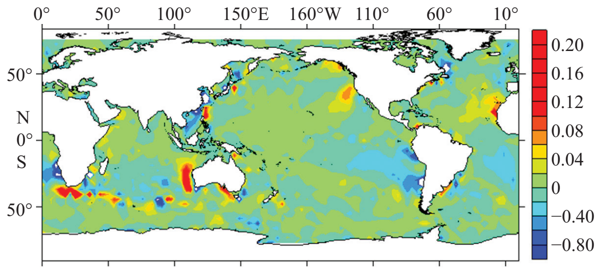

Fig.3. The global spatial distribution of annual mean T_{St}.

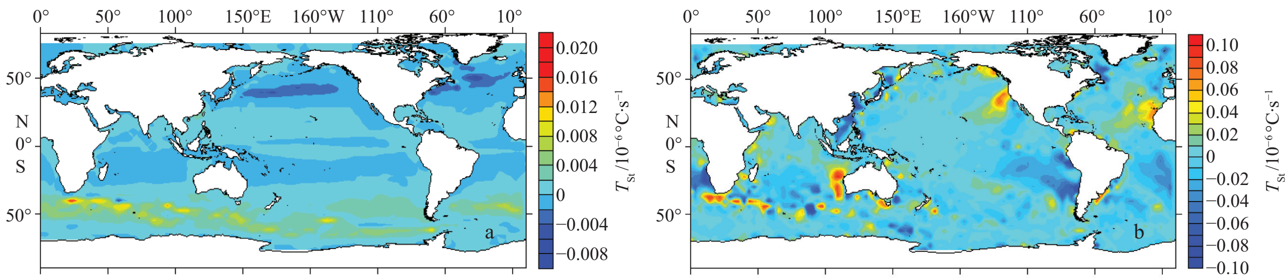

Fig.4. The distribution of the annual mean T_{St} in the direction of u (a) and v (b).

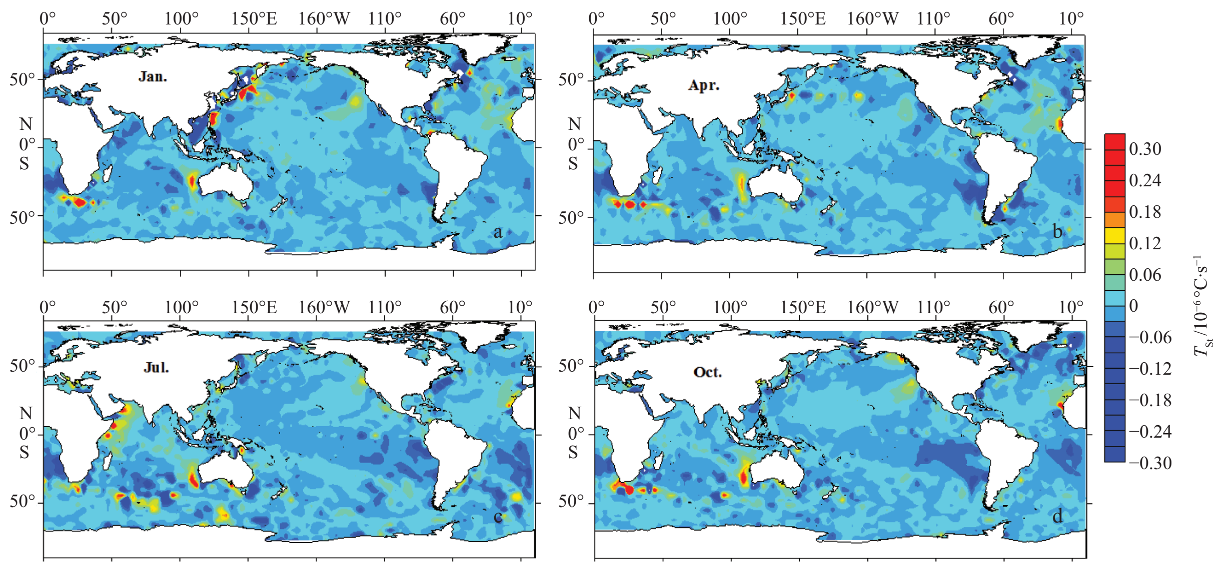

Fig.5. The global spatial distribution of T_{St} for January (a), April (b), July (c), and October (d).

Table 1. The average absolute values of T_{St} (10^{-6} °C/s) in different oceans and different seasons

	Latitude range	Longitude range	Apr.	Jul.	Oct.	Jan.	Annual mean
Pacific Ocean	70°N–40°S	120°E–60°W	0.033 9	0.024 5	0.033 4	0.047 6	0.037 8
Atlantic Ocean	70°N–40°S	70°W–20°E	0.045 0	0.039 6	0.055 6	0.078 6	0.058 3
Indian Ocean	25°N–40°S	20°–120°E	0.018 2	0.034 0	0.024 5	0.037 5	0.029 7
ACC	40°–60°S	0°–360°	0.087 0	0.105 6	0.118 2	0.072 9	0.099 2
Global	70°N–60°S	0°–360°	0.048 8	0.055 4	0.060 6	0.054 6	0.057 2

3.3 *The importance of the advective heat transport effect induced by the Stokes drift*

The contributions of the advective heat transport induced by the mean current (T_c), the heat flux term (T_q), and the vertical turbulence term (T_w) can be estimated by:

$$T_c = \overline{\vec{V}} \cdot \nabla \overline{T} \,, \tag{14}$$

$$T_q = \frac{Q_0 - Q_{-h}}{\rho c_p h} \,, \tag{15}$$

$$T_w = \frac{\overline{T} - T_{-h}}{h} w_e \,. \tag{16}$$

The change ratio of the temperature without (T_{t1}) and with (T_{t2}) considering the Stokes drift effect can be estimated by the following formulas:

$$T_{t1} = T_q - T_c - T_w \,, \tag{17}$$

$$T_{t2} = T_q - T_c - T_{St} - T_w \,. \tag{18}$$

According to these formulas, all the values of T_c, T_q, T_w, T_{t1} and T_{t2} could be estimated. By comparing T_{St} with other terms, the importance of T_{St} can be analyzed. The zonal mean values of T_{St} and T_c are showen in Fig. 6, where the blue and red curves represent the values of T_c and T_{St}, respectively. T_c has three peaks happening at the equator, 40°S, and 40°N (see the blue curve). The maximum (0.34×10^{-6} °C/s (0.88°C per month)) appears around 40°S. T_{St} values also exhibit a peak around 40°S (see the red curve). T_{St} and T_c are comparable in high latitudes. Figure 7 shows the ratio of the zonal mean T_{St} and T_c. The curve is symmetrical in the Northern and Southern hemispheres, that is, the values at high latitudes are larger than those at low latitudes. The maximum ratio (50%) occurs at 64°S. The average ratio is 40% (30%) in the area of 40°–60°S (40°–70°N). The average ratio at the low latitudes also can reach to 20%.

The ratios of T_{St} and T_{t1} in different areas and different seasons are shown in Table 2. The annual mean ratio in the area of the ACC is the largest (9.68%) among all places, and the global mean ratio is 5.91%. The values in the ACC have an obvious seasonal variation, such that the values in July and October are larger than those in January and April. On the contrary, the ratios at mid-to-high latitudes in Northern Hemisphere in January and April are larger than those in July and October. The ratios in the area around the equator are small.

To sum up, the effect of the advective heat transport induced by the Stokes drift is significant compared with the effect induced by the mean current. The importance of the Stokes drift on the mixed layer temperature variation is almost equivalent to that of the mean current. The global (ACC) annual mean change ratio of the mixed layer temperature induced by T_{St} is 5.91% (about 10%). Although the advective heat transport effect induced by the Stokes drift is not the leading term (the leading term is the vertical turbulence term T_w), it cannot be neglected for the simulation of the mixed layer temperature variation.

4 Summary and discussion

This paper analyzes the effect of sea surface waves on the mixed layer temperature variation through the theoretic analysis and quantitative estimation. The classical mixed layer temperature equation is modified in this paper by introducing the effect of the Stokes drift into the advective heat transport term. Then, dimensional analysis is conducted. The results show that

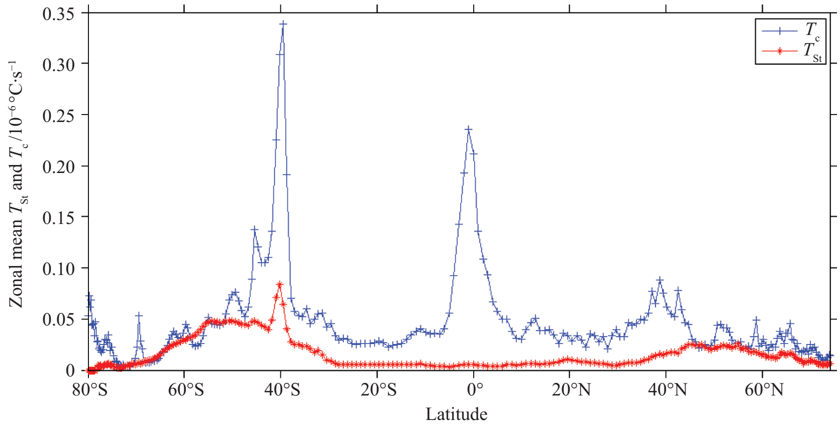

Fig.6. The zonal mean values of T_{St} and T_c.

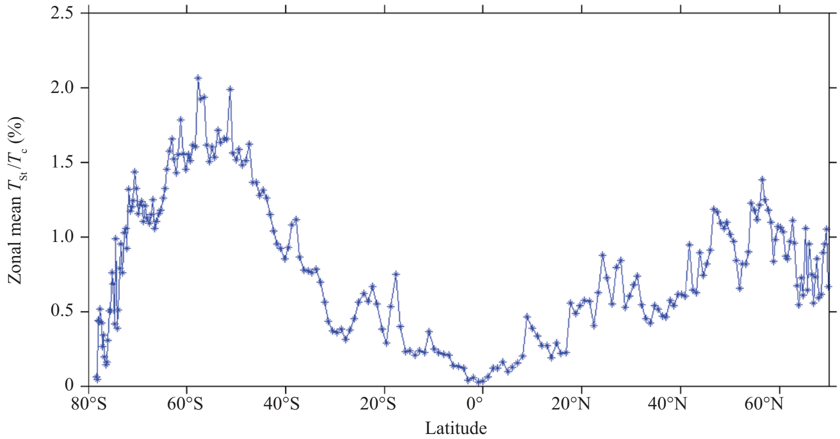

Fig.7. The zonal mean ratios of T_{St} to T_c.

Table 2. The average ratios (%) of T_{St} to T_{t1} in different ranges and different seasons

	Apr.	Jul.	Oct.	Jan.	Annual mean
40°–60°S	5.34	16.96	14.54	1.96	9.68
40°–60°N	8.53	3.41	4.32	7.92	6.26
40°N–40°S	3.91	3.28	2.88	2.29	3.08
Global	5.89	6.75	6.93	4.05	5.91

the contribution of sea surface waves to the mixed layer temperature variation is significant and could reach the same magnitude with the mean current at mid-to-high latitudes. However, the contribution of sea surface waves is not obvious at low latitudes, where it can be ignored.

Further, the data simulated by the HYCOM and WWIII are used to calculate the terms T_q, T_{St}, T_c and T_w in the mixed layer temperature equation quantitatively. The distribution characteristics of T_{St} are similar in the Pacific and Atlantic Oceans, and the values at mid-to-high latitudes are larger than those at low latitudes. The values in the area of the ACC are large throughout the whole year and have obvious seasonal variation. The main reason for this is the seasonal variation of the sea surface wind field. In the Indian Ocean, the value of T_{St} is small. Comparing this to other terms in the mixed layer temperature equation emphasizes the importance of the advective heat transport induced by the Stokes drift. The mean ratio of T_{St} to T_c is 40% in the ACC, and the maximum is 50%. The ratio is relatively small at low latitudes, but it can reach 20%. Thus it can be seen that the sea surface waves and mean current have equivalent importance for the mixed layer temperature variation. The change ratio of the mixed layer temperature induced by the Stokes drift is 9.68% in the ACC, 6.26% at mid-to-high latitudes of the Northern Hemisphere, and 5.91% of the global mean value. Although the Stokes drift-induced advective heat transport is not the leading term (the leading term is the vertical turbulence term T_w), its effect cannot be neglected for the simulation of the mixed layer temperature variation. So it is necessary and important to consider the advective heat transport effect induced by the Stokes drift into the mixed layer temperature equation, the simulation of upper ocean temperature and climatology research.

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References

Bleck R. 2002. An oceanic general circulation model framed in hybrid isopycnic – Cartesian coordinates. Ocean Modeling, 4(1): 55–88

Cavaleri L, Malanotte-Rizzoli P. 1981. Wind wave prediction in shallow water: theory and applications. Journal of Geophysical Research, 86: 10961–10975

Chalikov D, Belevich M Y. 1993. One-dimensional theory of the wave boundary layer. Boundary-Layer Meteorology, 63: 65–96

Chassignet E P, Smith L T, Halliwell G R, et al. 2003. North Atlantic simulations with the hybrid coordinate ocean model (HYCOM): impact of the vertical coordinate choice, reference pressure, and thermobaricity. Journal of Physical Oceanography, 33: 2504–2526

Chen G, Chapron B, Ezraty R, et al. 2002. A global view of swell and wind sea climate in the ocean by satellite altimeter and scatter meter. Journal of Atmospheric and Oceanic Technology, 19: 1849–1859

Deng Zengan, Xie Lian, Liu Bin, et al. 2009. Coupling winds to ocean surface currents over the global ocean. Ocean Modelling, 29: 261–268

Jenkins A D. 1986. A theory of steady and variable wind- and wave-induced currents. Journal of Physical Oceanography, 16: 1370–1377

Kenyon K E. 1970. Stokes transport. Jounal of Geophysical Research, 75: 1133–1135

Lane E M. 2006. Wave-current interaction: a comparison of radiation-stress and vortex-force representations. Journal of Physical Oceanography, 37: 1122–1141

Large W G, McWilliams J C, Doney S C. 1994. Ocean vertical mixing: a review and a model with a nonlocal boundary layer parameterization. Reviews of Geophysics, 32: 363–403

Li Shuang, Song Jinbao, Sun Qun. 2008. Effect of Stokes drift on upper ocean mixing. Acta Oceanologica Sinica, 27: 11–20

Longuet-Higgins M S. 1953. Mass transport in water waves. Philosophical Transaction of the Royal Society, A245: 535–581

Longuet-Higgins M S. 1960. Mass transport in the boundary layer at a free oscillating surface. Journal of Fluid Mechanics, 8: 293–306

McWilliams J C, Restrepo J M. 1999.The wave-driven ocean circulation. Journal of Physical Oceanography, 29: 2523–2540

Pillips O M. 1977. The dynamics of the upper ocean. Cambridge: Cambridge University press, 336

Qiao Fangli, Yang Yongzeng, Xia Changshui, et al. 2008. The role of surface waves in the Ocean mixed layer. Acta Oceanologica Sinica, 27(3): 30–37

Qiao Fangli, Yuan Yeli, Yang Yongzeng, et al. 2004. Wave-induced mixing in the upper ocean: Distribution and application in a global ocean circulation model. Geophysical Research Letters, 31: L11303

Stevenson J W, Niiler P P. 1983. Upper ocean heat budget during the Hawaii-to-Tahiti shuttle experiment. Journal of Physical Oceanography, 13: 1894–1907

Tolmas H L. 2009. User manual and system documentation of WAVE WATCH III TM version 3.14. Technical note MMAB contribution

Weber J E. 1983. Steady wind- and wave-induced currents in the upper ocean. Journal of Physical Oceanography, 13: 524–530

Wu Kejian, Liu Bin. 2008. Stokes drift-induced and direct wind energy inputs into the Ekman layer within the Antarctic Circumpolar Current. Journal of Geophysical Research, 113: C10002, doi10.1029/2007JC004579

Wu Kejian, Yang Zhongliang, Liu Bin et al. 2008b. Wave Energy Input into the Ekman Layer. Science in China Series D: Earth Sciences (in Chinese), 51(1): 134–141

Zhang Jie, Wang Weili, Guan Changlong. 2011. Analysis of the global swell distributions using ECMWF re-analysis wind wave data. Journal of Ocean University of China, 10(4): 325–330

Zhang Xiaoshuang, Wu Kejian. 2012. The influence of Stokes drift on the alteration ration of temperature in the oceanic mixed layer. Journal of Ocean University of China, 42(9): 1–6