Surface Heat Flux Induced by Mesoscale Eddies Cools the Kuroshio-Oyashio Extension Region

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Abstract  Sea surface temperature (SST) is a key player in the air-sea interaction, influencing storm tracks, atmospheric circulation, and climate modes. Although prevailing theories attribute variations of large-scale SST to atmosphere forcing and ocean internal dynamics, we find that sea surface heat flux anomalies induced by mesoscale eddies exert significant influences on the upper-ocean heat budget in the Kuroshio-Oyashio extension region. Despite making nearly no contribution to the net heat exchange at the air-sea interface, the eddy-induced heat flux anomalies weaken the thermal stratification in the upper ocean and result in pronounced sea surface cooling. The underlying dynamics is the efficient dissipation of eddy potential energy by eddy-induced heat flux anomalies. This makes the conversion of eddy potential energy to eddy kinetic energy significantly reduced, corresponding to a weaker eddy-induced restratification flux. The finding complements the existing theories on large-scale SST dynamics and has important implications for understanding extratropical climate variability.

Plain Language Summary  Sea surface temperature (SST) plays a fundamental role in the air-sea interactions. At large scales (~1,000 km), it is traditionally thought that the atmospheric forcing drives the midlatitude SST variability. At mesoscales (~100 km), it is an ocean-driven scenario where pronounced SST anomalies carried by ocean eddies exert an imprint on the atmospheric boundary layer. In this study, we find that such ocean mesoscale-atmosphere (OME-A) interactions have a significant influence on the large-scale SST in the Kuroshio-Oyashio extension region, complementing the existing views on the large-scale SST dynamics. This is because the eddy-induced heat flux anomalies damp the SST anomalies and thus available potential energy of eddies. Correspondingly, the conversion of eddy available potential energy to kinetic energy is significantly reduced in presence of OME-A interactions, resulting in less heat transported from the subsurface to the surface region.

1. Introduction

The ocean and atmosphere are a highly coupled system with the sea surface temperature (SST) playing a fundamental role in their coupling (Kushnir et al., 2002; Kwon et al., 2010). Dynamics of SST in the extratropical region have been extensively studied in the past few decades. In the canonical theories, variations of extratropical SST at large scales (~1,000 km) are primarily explained by atmospheric forcing and basin-scale oceanic processes (Alexander, 2010; Frankignoul, 1985; Kwon et al., 2010). On seasonal and shorter time scales, large-scale SST anomalies (SSTAs) are modulated by changes in the air-sea heat flux (Frankignoul & Kestenare, 2002), especially in winter when cold and dry air outbreaks move from continents to the warmer sea surface (Xue et al., 1995). On longer time scales, the contribution of heat advection due to geostrophic and Ekman currents becomes important (Dong & Kelly, 2004; Nakamura et al., 1997; Qiu, 2000). In addition, due to the seasonal evolution of mixed layer depth and entrainment, SSTAs form in one winter can reemerge in the following winter (Alexander & Deser, 1995). This reemergence can be nonlocal in the presence of strong advection (Sugimoto & Hanawa, 2005).

Recent studies also reveal the essential role of oceanic eddies in the large-scale SST budget in the extratropical region (Nurser & Zhang, 2000; Su et al., 2018). Eddies produce a significant upward heat transport peaking in the subsurface region associated with the conversion of eddy potential energy (EPE) to eddy kinetic energy.
Both CTRL and FILT simulations consist of an ensemble of
(Large & Yeager, 2009). computed based on the bulk formula with the ocean surface current's impact on the wind stress included conditions. The WRF initial condition is obtained from NCEP of October 2003, 2004, 2005, 2006, and 2007. For each ensemble pair, CTRL and FILT share the same initial well as wind stress from the atmosphere model hourly. The heat, freshwater SSTA variability. Therefore, the OME direction) is applied to the ROMS simulated SST before being provided to WRF at each coupling step (No 15° (longitude) × 5° (latitude) half width (the cutoff wavelength is 16° in zonal direction and 6° in meridional direction) is applied to the ROMS simulated SST before being provided to WRF at each coupling step (No filter is performed on ocean surface currents), making the atmosphere unable to “feel” the mesoscale SSTA variability. Therefore, the OME-A EPE feedback is largely suppressed in FILT and the difference between CTRL and FILT allows us to evaluate the impact of OME-A EPE feedback on the large-scale SST. More details on the configuration of CRCM can be found in Ma et al. (2016).

2. Materials and Methods

2.1. Experimental Design

The twin simulations (CTRL and FILT) in the North Pacific are devised using the Coupled Regional Climate Model (CRCM) developed at Texas A&M University (Ma et al., 2016). CRCM includes the Weather Research and Forecasting (WRF) Model as the atmospheric component and the Regional Ocean Modeling Systems (ROMS) as the oceanic component, both having the horizontal resolution of 9 km. The ocean model provides SST and surface current velocity to the atmosphere model and receives updated heat and freshwater fluxes as well as wind stress from the atmosphere model hourly. The heat, freshwater fluxes, and wind stress are computed based on the bulk formula with the ocean surface current's impact on the wind stress included (Large & Yeager, 2009).

Both CTRL and FILT simulations consist of an ensemble of five 6-month integrations, initialized on the 1st of October 2003, 2004, 2005, 2006, and 2007. For each ensemble pair, CTRL and FILT share the same initial conditions. The WRF initial condition is obtained from NCEP-II reanalysis, whereas the ROMS initial condition is obtained from a 6-year spin-up run using CORE-II data set as the atmospheric forcing. The 6-month integration is short enough to rule out the remote influences through planetary waves (Qiu & Chen, 2005), isolating the SST change due to the local OME-A EPE feedback. Moreover, as demonstrated in section 3, it is still long enough to allow the response of EPE and SST to the OME-A EPE feedback to reach a roughly stable state. The winter season is chosen, because the OME-A interaction is strong during that time.

The FILT ensemble is conducted with the same settings as the CTRL except that a low-pass Loess filter with 15° (longitude) × 5° (latitude) half width (the cutoff wavelength is 16° in zonal direction and 6° in meridional direction) is applied to the ROMS simulated SST before being provided to WRF at each coupling step (No filter is performed on ocean surface currents), making the atmosphere unable to “feel” the mesoscale SSTA variability. Therefore, the OME-A EPE feedback is largely suppressed in FILT and the difference between CTRL and FILT allows us to evaluate the impact of OME-A EPE feedback on the large-scale SST. More details on the configuration of CRCM can be found in Ma et al. (2016).

2.2. Heat Budget Analysis

To discuss the thermal condition of the upper ocean, we perform the heat budget analysis:
The term on the left hand side of equation (1) is the change rate of heat, which is balanced by terms on the right-hand side of equation (1). The terms on the right-hand side in sequence are the heat advection by large-scale background flows, the horizontal eddy heat transport convergence, the vertical eddy heat transport convergence (referred to as the vertical mixing), and the residue term. The residue term does not have a clear dynamical interpretation but would be zero if large-scale motions are obtained using a time or zonal mean as in the classical eddy-mean flow interaction theories rather than the spatial filter we use. Because it has no counterpart in the classical eddy-mean flow interaction theories, it is referred to as the residue term. The residue term is found to be an order of magnitude smaller than the other terms and can be neglected. The horizontal mixing is dropped in equation (1) as the horizontal diffusivity is set as zero in CRCM simulations.

2.3. Mesoscale Temperature Anomaly Variance Budget

In order to evaluate the OME-A EPE feedback’s impact on the eddy energy budget, the mesoscale temperature anomaly variance budget (see Text S2 for the detailed derivation) regarded as a proxy for EPE budget is performed:

$$<\frac{\partial}{\partial t}\left( \frac{1}{2} \mathbf{u}' \mathbf{u}' \right) > = -<\mathbf{v}\cdot\frac{1}{2} \mathbf{u}' \mathbf{u}' > -<\mathbf{u}_h \mathbf{T}' \cdot \mathbf{v}_h \mathbf{T} > -<\mathbf{w}' \mathbf{T}' \cdot \mathbf{T} > -<\mathbf{T}' \frac{\partial}{\partial z} \left( \frac{Q'}{\rho_0 C_p} \right) > ,$$

$$-<\mathbf{u}' \mathbf{T}' \cdot \mathbf{v} \mathbf{T} > + <\mathbf{T}' \mathbf{u} \mathbf{v} \mathbf{T} >$$

The term on the left-hand side of equation (2) is the tendency of mesoscale temperature anomaly variance determined by the production and destruction processes on the right-hand side. The first term on the right-hand side is the advection of mesoscale temperature anomaly variance. The second term is the horizontal eddy temperature transport acting on the temperature gradient of mean flows. It denotes the energy conversion from available potential energy of mean flows (MPE) to EPE (von Storch et al., 2012), referred to as the MPE-EPE conversion. The third term is the vertical eddy temperature transport acting on the background thermal stratification associated with the conversion of EPE to EKE (referred to as the EPE-EKE conversion). The fourth term is the dissipation through vertical mixing (referred to as the vertical dissipation). The last two terms have no clear dynamical meanings and referred to as the residue term. Again, the dissipation through horizontal mixing is dropped here as the horizontal diffusivity is set as zero in CRCM simulations. The OME-A EPE feedback contributes to the budget through the vertical dissipation term as evidenced by its decomposition into the surface term and the interior dissipation term:
The surface term \(-\mathcal{T} \mathcal{Q} \big|_{z=0}\), representing the OME-A EPE feedback, is negative in CTRL as a result of eddy-induced heat flux anomalies (Figure 1b) but is much reduced in FILT (Figure S2).

2.4. Statistical Analysis

The error bar of the ensemble mean difference (CTRL-FILT) in this study is defined as \([X - 3\sigma_e, X + 3\sigma_e]\) with \(X\) the sample mean difference and \(\sigma_e\) its standard error:

\[
X = \frac{1}{n} \sum_{j=1}^{n} x_j, \quad \sigma_e = \sqrt{\frac{\sum_{j=1}^{n} (x_j - X)^2}{n-1}}/\sqrt{n}, \quad n = 5, \quad (4)
\]

where \(x_j\) is the difference between CTRL and FILT of the \(j\)th ensemble member.

3. Results

3.1. Difference of SST Between CTRL and FILT

Figure 1a shows the ensemble mean SST difference between CTRL and FILT averaged for the last 90 days of the simulations when the SST difference seems to become roughly stable (Figure 1e). There is a systematic sea surface cooling in CTRL compared to FILT. The SST difference between CTRL and FILT is generally less than 0.5°C in the North Pacific basin except in the KOE region where the value can reach up to 2°C locally. In the KOE region, the relative cooling in CTRL is most evident in the upper 50 m and the signal attenuates rapidly as the depth increases (Figure 1c). Such surface-intensified cooling in CTRL corresponds to a
weakened thermal stratification measured by the vertical temperature gradient. Indeed, the thermal stratification in the upper 100 m is systematically weaker in CTRL than in FILT with its vertical mean value in CTRL only 60% of that in FILT (Figures 1d and 1f). The largest temperature difference in the KOE region coincides well with the strongest OME-A EPE feedback (Figure 1b). Such coincidence implies that the surface cooling in CTRL might result from the OME-A EPE feedback.

To test this hypothesis, a heat budget analysis for the KOE region is performed based on the last 90-day diagnostic output from CRCM. In both CTRL and FILT, there is a dominant balance in the upper ocean between the cooling caused by the vertical mixing and the warming by the vertical eddy heat transport convergence (Figures 2a and 2b), with the remaining terms playing a minor role. The former is a result of strong surface heat release from the ocean to the atmosphere in the winter time, while the latter is due to the upward eddy heat transport associated with the conversion of EPE to EKE (Figure 2d). This vertical eddy heat transport, peaking around 50 m, acts to restratify the upper ocean and plays a crucial role in resisting the surface cooling caused by the heat release in the upper ocean.

It is evident from the heat budget difference between CTRL and FILT that the reduced thermal stratification and decreased SST in the KOE region in CTRL are primarily attributed to the change of the vertical eddy heat transport convergence which causes more cooling near the sea surface (Figure 2c). In presence of the OME-A EPE feedback, the vertical eddy heat transport is significantly weakened, with a maximum reduction of 49 ± 11 W m⁻² around 30 m (Figure 2d). Their difference (CTRL-FILT) corresponds to a

Figure 2. Heat budget in the KOE region. The heat budget averaged over the KOE region in (a) CTRL, (b) FILT, and (c) CTRL-FILT. The red line denotes the vertical eddy heat transport convergence. The blue line denotes the vertical mixing. The yellow line denotes the heat advection by large-scale background flows. The pink line denotes the horizontal eddy heat transport convergence. The purple line denotes the change rate of heat. The grey line denotes the residue. Time-mean (d) vertical eddy heat transport, (e) vertical turbulent heat transport, and (f) turbulent vertical diffusivity in CTRL (denoted by blue lines) and FILT (denoted by red lines) in the KOE region. Note that the ROMS does not output the turbulent vertical diffusivity at the sea surface (Haidvogel et al., 2008). The grey shading indicates the error bar with detailed descriptions in section 2. All values shown here are the ensemble mean and only the values in the last 90-day model integration are used for the computation of time mean.
destratification flux (the opposite of a restratification flux), contributing to the weakened thermal stratification and cooled sea surface in CTRL.

The difference of the vertical eddy heat transport convergence is largely balanced by the difference of the vertical mixing (Figure 2c) so that an equilibrium state of the upper ocean temperature difference between CTRL and FILT can be established. The advection by large-scale flows and the horizontal eddy heat transport convergence play the secondary if not negligible roles with their total contribution less than 25%. Compared to FILT, the vertical mixing in CTRL results in less cooling near the sea surface but more cooling in the deeper region (Figure 2c). The vertical mixing difference between CTRL and FILT is not due to the change of the area-mean heat flux at the air-sea interface but mainly results from the differed decay rate of vertical turbulent heat transport in the ocean. The net heat loss at the sea surface averaged over the KOE region is 271 W m$^{-2}$ in CTRL, fairly close to 258 W m$^{-2}$ in FILT (Figure 2e). Their difference, 13 ± 20 W m$^{-2}$ is not significantly different from zero, suggesting that the surface heat flux anomalies induced by mesoscale eddies do not directly make significant contribution to the net heat exchange at the air-sea interface. However, the vertical turbulent heat transport decays more slowly with depth in CTRL than in FILT (Figure 2e) as a result of enhanced turbulent vertical diffusivity in CTRL (Figure 2f), making the near-surface (deeper) region less (more) cooled. The difference of the vertical turbulent heat transport results in a restratification flux which largely compensates the destratification flux caused by the difference of the vertical eddy heat transport mentioned above. In the surface ocean boundary layer, the intensity of small-scale turbulence is basically determined by the sea surface buoyancy flux (dominated by heat flux), wind stress magnitude, vertical shear, and stratification (Large et al., 1994). It is found that the larger turbulent vertical diffusivity in CTRL is mainly attributed to the weakened stratification with the first three factors playing a negligible or countering role (Figure 3). Therefore, the change of the vertical mixing is unlikely to be directly caused by the OME-A interaction but is an indirect result of it through its impact on the vertical eddy heat transport and further on the stratification.
3.2. Impact of OME-A EPE Feedback on the Vertical Eddy Heat Transport

As demonstrated in section 3.1, the reduction of vertical eddy heat transport leads to the sea surface cooling and weakened thermal stratification in CTRL. In this subsection, we attempt to understand the underlying dynamics responsible for the reduced vertical eddy heat transport. In FILT, the atmosphere is unable to “feel” the mesoscale SSTA variability so that the OME-A EPE feedback is largely suppressed. Meanwhile, the mesoscale SSTA’s imprints on surface wind and their feedback on Ekman pumping (Chelton et al., 2004; Gaube et al., 2015) are also filtered out. We find that the latter related transport variation at the base of the Ekman layer (Thomas & Ferrari, 2008) is unlikely to account for the difference of computed vertical eddy heat transport between CTRL and FILT (see Text S1 and Figure S3 for details, Thomas & Ferrari, 2008). It thus implies that the weakened vertical eddy heat transport in CTRL might be due to the OME-A EPE feedback. To confirm this conjecture, a mesoscale temperature anomaly variance (closely related to the mesoscale EPE) budget over the KOE region during the last 90-day model integration is performed (Figure 4).

In both CTRL and FILT, there is in general a balance between the production and destruction terms of mesoscale temperature anomaly variance on the right-hand side of equation (2), with negligible tendency of mesoscale temperature anomaly variance. The production is achieved primarily through the advection and MPE-EPE conversion, while the destruction results mainly from two processes: the vertical dissipation and EPE-EKE conversion. The OME-A EPE feedback has a profound influence on the mesoscale temperature anomaly variance budget in the upper 150 m. In CTRL, the vertical dissipation averaged in the upper 150 m is more than twice as large as that in FILT. The enhanced vertical dissipation is mainly due to the OME-A EPE feedback with the contribution from the interior dissipation negligible. The advection, MPE-
EPE conversion, and EPE-EKE conversion all respond significantly to the OME-A EPE feedback and work in concert to balance the intensified destruction of mesoscale temperature anomaly variance in CTRL. In particular, the mean EPE-EKE conversion in the upper 150 m is reduced by 29% in CTRL, compensating ~34% of the enhanced dissipation. This leads to a weakened vertical eddy heat transport in CTRL, lending supports to our hypothesis.

4. Conclusions and Discussion

These results from the high-resolution regional climate model experiments reveal the important role of OME-A EPE feedback in shaping the upper ocean thermal stratification, providing a new perspective on the large-scale SST dynamics and complementing the existing theories. Through damping the EPE, the eddy-induced surface heat flux anomalies reduce the EPE-EKE conversion, leading to a weakened eddy restratification flux. The latter weakens the thermal stratification in the upper ocean and results in sea surface cooling.

Although this study focuses on the KOE region, similar impacts of OME-A interaction on SST are expected to hold in other regions with strong mesoscale eddy activities and air-sea interactions. In addition, the results of this study have important implications for modeling biogeochemical processes in the ocean. In the presence of OME-A EPE feedback, small-scale turbulence in the upper ocean is significantly enhanced due to the weakened stratification. This could further affect the light exposure of phytoplankton and supply of nutrients into the euphotic zone, the two key factors controlling the primary production (Levy et al., 2012). Therefore, the OME-A EPE feedback may be important in maintaining the upper-ocean ecosystem that controls the ocean's storage of carbon and regulates the carbon dioxide level in the atmosphere (Ducklow et al., 2001).

Conflict of Interests

The authors declare no competing financial interests.

Data and Materials Availability

The data, analysis codes, and information about model configuration used in our study are publicly available from Figshare repository (http://doi.org/10.6084/m9.figshare.11402691).

References


