A ‘self-adjustment’ mechanism for mixed-layer heat budget in the equatorial Atlantic cold tongue

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Abstract

Wind forcing is one of the most important sources for the oceanic energy cycle and is especially critical to the heat budget of surface mixed layer. The sensitivity of heat budget in the equatorial Atlantic cold tongue (EACT) region (5°S–5°N, 25°W–5°E) to wind forcing and the related mechanism are explored in this study. Based on the experiments forced by different wind forcing from both reanalysis and idealized datasets, it is revealed that the contribution ratio for each of the dominant physical processes in the heat budget is insensitive (the variations within 1% of the mean) to the variations in the local winds (the largest variation is about 20% of the mean) over the EACT region. Therefore, a ‘self-adjustment’ mechanism exists in the mixed-layer heat budget: as local zonal winds over the EACT region strengthen (weaken), both the cooling effects of turbulent mixing and the combined warming effects of surface net heat flux and zonal advection simultaneously increase (decrease) by nearly the same percentage and thus their contribution ratios are kept constant. Owing to the impact of meridional winds on each term of heat budget can be neglected, the above mechanism is also tenable under the situation when the local meridional winds change.

Keywords: self-adjustment; mixed-layer heat budget; wind forcing; equatorial Atlantic cold tongue

1. Introduction

The equatorial Atlantic cold tongue (EACT) region (5°S–5°N, 25°W–5°E) is characterized by a clear seasonal cycle of sea surface temperature (SST). During the boreal spring when the solstice is directly over the equator, the SST in the EACT reaches its maximum. During the boreal summer when the solstice moves away from the equator and the trade winds are strong (and thus the upwelling strengthens; Mitchell and Wallace, 1992), the SST decreases to its minimum. The seasonal variations of SST can reach 7 °C in the EACT region (Houghton and Colin, 1986). The EACT emanates from the African coast to nearly 20°W and reaches its minimum temperature at the equator near 10°W (Carton and Zhou, 1997). The variations of zonal SST gradient in the EACT region induced by the seasonal change of SST can further affect the intensity of African monsoon and the related precipitation (Okumura and Xie, 2004; Chang et al., 2006; Brandt et al., 2011; Meynadier et al., 2016). However, current earth system models (ESMs), and even some stand-alone ocean models cannot well reproduce the observed zonal SST gradient. Specifically, evident warm biases with amplitudes of 2 °C in ESMs and 1 °C in stand-alone ocean models exist over the cold tongue, which means the zonal SST gradient is seriously underestimated (Grodsky et al., 2012; Li and Xie, 2012; Richter et al., 2012; Richter, 2015). Furthermore, the biased EACT limits the use of ESMs as a tool for projecting the future changes in African monsoon and its related precipitation.

The variations of SST on different time scales in the EACT region are dominated by the heat budget in the mixed layer. In the heat budget, there are many terms arising from different processes, including air–sea interaction across the sea surface (the exchanges of latent and sensible heat fluxes), meridional advection, zonal advection, turbulent mixing, and entrainment. All the above physical processes can be affected by the wind forcing. Besides, there are many wind products, which differ from each other in terms of magnitude, directions, and spatiotemporal resolution. Existing studies have pointed out that large-scale ocean processes are sensitive to wind forcing (Liu et al., 1996; Fu and Chao, 1997). Cravatte and Menkes (2009) have reported that the mixed-layer heat budget over the equatorial Pacific cold tongue (EPCT) is very sensitive to different wind products. They found that the maximum SST difference over the EPCT region among the five simulations forced by different wind products reaches 1.8 °C; large differences can also be identified in the simulated vertical velocity over the Pacific cold tongue. Moreover, the contribution ratio of each physical process varies a lot among different simulations (surface net heat flux ranges from 23.4 to 26.9%, zonal advection
ranges from 22.4 to 26.1%, and the turbulent mixing ranges from 33.7 to 37.6%).

The aim of this study is to investigate the sensitivity of the heat budget in the EACT region to five different wind products, and idealized wind forcing with varying amplitudes in zonal or meridional direction, and explore the related mechanism. The article is organized as follows. Model description, data, experimental design, and the heat budget diagnosis method are introduced in the Section on Data and Methods. We analyze the sensitivity of the mixed-layer heat budget to different wind forcing, and propose a related mechanism in the Section on Results. Conclusions are given in the Section on Summary and Conclusion.

2. Data and methods

2.1. Model description

The model used is the Nucleus for European Modeling of the Ocean, Version 3.4 (NEMO3.4) framework (Madec, 2008) in its global configuration ORCA2, which includes the Ocean Parallélisé (OPA) oceanic general circulation model (Madec et al., 1998) and Louvain-la-Neuve Ice Model version 3 sea-ice model (Vancoppenolle et al., 2012). The nominal horizontal resolution of the model is $2^\circ$ with a meridional refinement to $0.5^\circ$ within $5^\circ$ of the equator. There are 31 vertical levels from the surface to the bottom (5000 m depth), with an interval of 10 m in the upper ocean above 150 m depth and gradually increasing to 500 m in the deep ocean.

2.2. Data

Input fields include 6-h horizontal winds, air temperature, and humidity at 10-m height, daily radiation (shortwave and longwave), and monthly total precipitation (rain and snow) and runoff. With the exception of horizontal winds, all the other variables are from the Common Ocean-ice Reference Experiment version II (CORE-II; Large and Yeager, 2009). The CORE-II forcing data was constructed based on the National Centers for Environmental Prediction and the National Center for Atmospheric Research reanalysis version 1 (NCEP-NCAR; Kalnay et al., 1996). During the construction process, the NCEP-NCAR data has been corrected based on multiple sources of high-quality observation data. Therefore, compared to NCEP-NCAR and many other reanalysis data, CORE-II has a higher reliability and has been used by many ocean models (Danabasoglu et al., 2014; Griffies et al., 2014). Five wind products are used as the external forcing of the ocean model: CORE-II, the 40-Year European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis model data (ERA-40; Uppala et al., 2005), the ECMWF Interim reanalysis data (ERA-Interim; Dee et al., 2011), NCEP-NCAR, and NCEP-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project Reanalysis data version 2 (NCEP-DOE; Kanamitsu et al., 2002). Basic information of the five wind products is listed in Table S1. All the five wind products have been interpolated to the model grid during their common time period, i.e. 1979–2001.

The area mean of wind speed and its zonal and meridional components over the EACT region during 1979–2001 for each product are shown in Table 1; the largest differences of them among the five products reach 21.5, 19.6, and 22.5% of the corresponding ensemble means, respectively. Specifically, NCEP-DOE and CORE-II have the winds with the largest magnitudes, while NCEP-NCAR has the winds with the smallest magnitude.

2.3. Experiment design

Three sets of sensitivity experiments were carried out after the model was spun up for 500 years. Each set includes five experiments. In the first set of experiments (the real wind RUNs), the wind forcing are from five wind products; these five real wind RUNs are named the same as the used wind products. In the second set of experiments (the idealized zonal wind RUNs), all the wind forcing are from the CORE-II with modifications to the amplitudes of the zonal winds over the EACT region. The ratio between the magnitude of the zonal winds in the idealized zonal wind RUN and the CORE-II RUN ranges from 80 to 100% with an interval of 5%. Here, the 100% idealized zonal wind RUN is identical to the CORE-II real wind RUN. Note that the standard deviation of the area-mean zonal winds over the EACT region is about 12.7% of the long-term mean (estimated as the average of five products). Therefore, the range of the variations in zonal winds of the second set of experiments is reasonable. Correspondingly, these five experiments are named as RUN_80U, RUN_85U, RUN_90U, RUN_95U, and CORE-II according to the ratios. The configurations of the third set of experiments (the idealized meridional wind RUNs) are similar to the second set of experiments except that the modifications are applied to the meridional winds. Note that the standard deviation of the area-mean meridional winds over the EACT region is about 11.7% of the long-term mean (estimated as the average of five products). The five experiments in this set are named as RUN_80V, RUN_85V, RUN_90V, RUN_95V, and CORE-II.

| Wind product | Wind speed (m s$^{-1}$) | $U$ (m s$^{-1}$) | $V$ (m s$^{-1}$) |
|--------------|-------------------------|-----------------|-----------------|
| CORE-II      | 5.07                    | -2.46           | 3.77            |
| ERA-40       | 4.59                    | -2.13           | 3.50            |
| ERA-Interim  | 4.55                    | -2.21           | 3.35            |
| NCEP-NCAR    | 4.26                    | -2.12           | 3.09            |
| NCEP-DOE     | 5.26                    | -2.57           | 3.88            |

Table 1. The area mean of wind speeds, and their zonal and meridional components over the EACT region ($5^\circ$–$5^\circ$N, $25^\circ$W–$5^\circ$E) during 1979–2001 for the five wind products: CORE-II, ERA-40, ERA-Interim, NCEP-NCAR, and NCEP-DOE.
2.4. The heat budget equation

To understand how the wind forcing affects the balance of heat budget in the mixed layer over the EACT region through its modulation on different physical processes, a diagnostic analysis of mixed-layer heat budget is performed based on the heat budget equation (Menkes et al., 2006):

$$\partial_t \langle T \rangle = \frac{Q_n}{\rho_0 C_p h} + \left( -\overline{\nu \partial_y T} \right) + \left( -\overline{\nu \partial_z h} \right) + \left( -\frac{\partial_y T}{h} \right) + \left( -\frac{K_v \partial_z T}{h} \right) + \left( \frac{1}{h} \left( \partial_t h + w_{(z=-h)} \right) \right) \left( \langle T \rangle - \overline{T_{(z=-h)}} \right) + \delta \left( E \right)$$

(1)

Here, the brackets indicate the vertical average of a quantity across the whole mixed layer; the overbars mean the monthly mean of a quantity; $u$, $v$, and $w$ are the zonal, meridional, and vertical velocities, respectively; $T$ is the temperature, $h$ is the mixed-layer depth (MLD), $K_v$ is the vertical mixing coefficient for tracers, $Q_n$ is the surface net heat flux, $\rho_0$ is the constant density ($1026$ kg m$^{-3}$), and $C_p$ is the constant pressure specific heat capacity ($4200$ J kg$^{-1}$ K$^{-1}$). Note that the MLD is defined by a density difference criterion, i.e. the density difference between the ocean surface and MLD is $0.05$ kg m$^{-3}$. The term on the left hand side of Equation (1) is the local variations in heat budget ($\langle T \rangle$). On the right-hand side of Equation (1), there are five terms (terms $A$–$E$). Term $A$ is the heat flux absorbed by the mixed layer (referred to as the surface net heat flux). Term $B$ represents the mean heat transported by meridional currents in the mixed layer (the meridional advection). Term $C$ represents the mean heat transported by zonal currents in the mixed layer (the zonal advection). Term $D$ represents the heating rate due to the vertical processes, which include the turbulent mixing ($D_1$) and the entrainment through the base of the mixed layer ($D_2$). Term $E$ is the residual error. The residual error is mainly originated from two aspects. The first aspect is the time average; the time step of the temperature/salinity process in the ocean model is $5760$ s. However, during the diagnosis of the mixed-layer heat budget, we used the monthly-averaged data, which means the time-average error is introduced. The second aspect is the choice of the MLD, which can be defined based on the temperature difference or density difference. In this study, the contribution ratio of residual error is about $1.2\%$, indicating that this term can be neglected in the following analysis. Note that the contribution ratio ($R$) for term $X$ is estimated as

$$R_X = \frac{|X|}{|A| + |B| + |C| + |D| + |E|}$$

(2)

Here, term $X$ is one of the five terms ($A$, $B$, $C$, $D$, and $E$) in Equation (1), and the term bracketed by two vertical bars represents the corresponding absolute value of this term.

3. Results

3.1. Mixed-layer heat budget in the EACT region under different wind products

Figure 1 illustrates each term and the corresponding contribution ratio for the mixed-layer heat budget over the EACT region in the first set of experiments, i.e. the five real wind RUNs. The warming effects are mainly dominated by two processes, i.e. the zonal advection (with a contribution ratio ranging from $33.5$ to $43.3\%$) and the surface net heat flux (ranging from $15.7$ to $16.5\%$). The warming effects are mainly counterbalanced by the cooling effects induced by the turbulent mixing (ranging from $44.9$ to $45.6\%$) in the vertical process. The meridional advection and entrainment also have cooling effects. However, the contribution ratios of these two processes are much smaller than the above three processes, which is consistent with the results over the tropical Pacific Ocean (Peter et al., 2006; Cravatte and Menkes, 2009). Therefore, in the mixed layer over the EACT region, the temperature variation is mainly modulated by three processes, i.e. turbulent mixing, zonal advection, and surface net heat flux.

Figure 1. (a) Each term (units: °C month$^{-1}$) in the heat budget over the EACT region (5°S–5°N, 25°W–5°E) for the first five real wind RUNs. (b) Same as (a), except for the contribution ratio of each term (units: %). Values of the three dominant terms are given in the colored histograms.
Remarkable differences can be observed in each of the above three terms among the five real wind RUNs (Figure 1(a)). The turbulent mixing term ranges from $-3.52$ to $-3.09 \, ^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.43 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 13.2% of the mean for the five RUNs. The zonal advection term ranges from 2.34 to 2.59 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.25 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 10.2% of the mean. The surface net heat flux term ranges from 1.07 to 1.27 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.20 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 17.4% of the mean.

By contrast, the varying amplitudes of the contribution ratios for the three terms among the five real wind RUNs are rather small (Figure 1(b)). Specifically, the varying amplitudes for the turbulent mixing, zonal advection, and surface net heat flux terms are 0.7, 0.8, and 0.8%, respectively, indicating that these three dominant terms are varying in proportion to each other.

3.2. Mixed-layer heat budget in the two sets of idealized wind experiments

Figure 2 shows each term and the corresponding contribution ratio for the mixed-layer heat budget over the EACT region in the second set of experiments, i.e. the five idealized zonal wind RUNs. The three dominant terms in this set of experiments are the same as those in the real wind RUNs. Distinct differences can also be observed in each of the three dominant terms among the five idealized zonal wind RUNs (Figure 2(a)). The turbulent mixing term ranges from $-3.40$ to $-2.91 \, ^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.49 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 15.5% of the mean for the five RUNs. The zonal advection term ranges from 2.25 to 2.58 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.33 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 13.6% of the mean. The surface net heat flux term ranges from 1.04 to 1.21 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.17 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 15.2% of the mean. As the magnitude of zonal winds increases (decreases), the cooling effect induced by the turbulent mixing intensifies (weakens), while the warming effects induced by the zonal advection and surface net heat flux also intensify (weaken) accordingly. Besides, the varying amplitude of the contribution ratio for each of the three dominant terms among the five idealized zonal wind RUNs is also comparatively small, which ranges from 0.3 to 0.7%.

Figure 3 displays each term and the corresponding contribution ratio for the mixed-layer heat budget in the third set of experiments, i.e. the five idealized meridional wind RUNs. This set of experiments also has the same three dominant terms as the above two sets of experiments. The varying amplitude of the contribution ratio for each of the three dominant terms among the five idealized meridional wind RUNs is also very small, which ranges from 0.2 to 0.3%. However, unlike the two previous sets of experiments, this set of experiments has a rather small varying amplitude in each of the three dominant terms. Specifically, the turbulent mixing term ranges from $-3.41$ to $-3.39 \, ^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.02 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 0.6% of the mean for the five RUNs. The zonal advection term ranges from 2.57 to 2.58 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.01 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 0.5% of the mean. The surface net heat flux term ranges from 1.19 to 1.21 $^\circ\text{C} \, \text{month}^{-1}$, the varying amplitude ($0.02 \, ^\circ\text{C} \, \text{month}^{-1}$) of which is about 1.7% of the mean. The above results indicate that the variations in meridional winds have neither an absolute nor a relative impact on the heat budget of the mixed layer over the EACT region.

Therefore, in the mixed-layer heat budget over the EACT region, there is a ‘self-adjustment’ mechanism,

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which can keep the contribution ratios of the three dominant terms in a quasi-balanced state under the local winds with different magnitudes.

### 3.3. The ‘self-adjustment’ mechanism

Figure 4 is a schematic diagram summarizing the relationship between the increase in the magnitude of local winds and the response in each of the three dominant processes, which include the turbulent mixing, zonal advection, and surface net heat flux. As the strength of local winds over the EACT region is intensified, the wind-driven vertical mixing (i.e. turbulent mixing) is enhanced and thus the SST over the EACT region is reduced (Table S2). Meanwhile, the strengthened zonal winds intensify the zonal velocity of the ocean currents, which further enhances the zonal advection over the EACT region. In response to the reduction in the SST, both the latent and sensible heat fluxes are reduced, indicating that the surface net heat flux is increased. The consistent enhancements of the three dominant terms under local winds with larger magnitudes keep the contribution ratio of each term at a constant level. The above relationship can be referred to as the ‘self-adjustment’ mechanism.

### 4. Summary and conclusion

The sensitivity of the mixed-layer heat budget over the EACT region to wind forcing is investigated in this study. Fifteen experiments including five real wind RUNs forced by different wind products, five idealized zonal wind RUNs forced by different intensities in zonal winds, and five idealized meridional wind RUNs forced by different intensities in meridional winds are carried out. Heat budget analysis in the mixed layer over the EACT region based on the 15 experiments confirms that there are three dominant terms, i.e. turbulent mixing, zonal advection, and surface net heat flux. The varying amplitudes of the three dominant terms are sensitive to the variations of zonal winds, but insensitive to the variations of meridional winds. Regardless of the variations in zonal winds and/or meridional winds, the contribution ratio for each of the three dominant terms is nearly kept as a constant. A ‘self-adjustment’ mechanism is employed to explain the quasi-balanced state of the three dominant terms.

It should be noted that similar study has been taken over the EPCT region by Cravatte and Menkes (2009). They found that the three dominant terms of the mixed layer over the EPCT region are the same as those dominant terms in this study. The varying amplitudes of the three dominant terms in their study are much larger (about four to six times) than those in our study. However, due to the fact that they only conducted the experiments forced with real winds, the above larger varying amplitudes cannot be attributed to the variations in the zonal winds as our study. Besides, the variation amplitudes of the contribution ratios in their experiments over the EPCT region are small (ranging from 3.5 to 3.9%), but much larger than those in our experiments over the EACT region (ranging from 0.7 to 0.8%). Therefore, the ‘self-adjustment’ mechanism is more applicable in the EACT region. More details about the similarities and dissimilarities of the heat budget between the EPCT region and EACT region can be referred to in Table S3.

Based on the ‘self-adjustment’ mechanism, only one dominant term in the heat budget over the EACT region is needed to be estimated, and the other two dominant terms can be easily deduced with a high accuracy. For example, we can estimate the zonal advection term first and then deduce the turbulent mixing term and surface net heat flux term, which can reduce the time used in the computational process and reduce the number of variables (only two variables are needed) used in the heat budget diagnosis. Besides, the finding of this work can be applied to the bias attribution in the ESMs. As the varying amplitudes of the three dominant terms are mainly sensitive to the zonal winds, more attention can be paid to the zonal winds than to the meridional winds when we diagnose the model bias over the EACT region.

However, due to the use of an ocean-only model, the feedback between the local winds and SST cannot be considered. In the future, coupled climate models or ESMs will be used to examine the ‘self-adjustment’ mechanism when the above feedback is considered.

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**Figure 4.** The schematic diagram for the relationship between the magnitude of wind speeds and different terms in the heat budget. The sign ‘+$r$’ indicates the increase/decrease or intensification/weakening in a variable or a process.
http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis .surfaceflux.html. NCEP-DOE reanalysis data was from http:// www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2 .html.

Supporting information

The following supporting information is available:
Table S1. Description of the five wind products used in the real
wind RUNs.
Table S2. The area-mean wind stress (units: N m$^{-2}$) and SST (units: °C) over the EACT region (5°S–5°N, 25°W–5°E) for the five real wind RUNs.
Table S3. Detailed information about the experiment design and
major results of Cravatte and Menkes (2009) and this study.

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