

Mixed layer warming by the barrier layer in the southeastern Indian Ocean

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Abstract

The southeastern Indian Ocean is characterized by the warm barrier layer (BL) underlying the cool mixed layer water in austral winter. This phenomenon lasts almost half a year and thus provides a unique positive effect on the upper mixed layer heat content through the entrainment processes at the base of the mixed layer, which has not been well evaluated due to the lack of proper method and dataset. Among various traditional threshold methods, here it is shown that the 5 m fixed depth difference can produce a reliable and accurate estimate of the entrainment heat flux (EHF) in this BL region. The comparison between the daily and monthly EHF warming indicates that the account for high-frequency EHF variability almost doubles the warming effect in the BL period, which can compensate for or even surpass the surface heat loss. This increased warming is a result of stronger relative rate of the mixed layer deepening and larger temperature differences between the mixed layer and its immediate below in the daily-resolving data. The interannual EHF shows a moderately increasing trend and similar variabilities to the Southern Annular Mode (SAM), likely because the mixed layer deepening under the positive SAM trend is accompanied by enhanced turbulent entrainment and thus increases the BL warming.

Key words: barrier layer, mixed layer, entrainment heat flux, high-frequency variability, southeastern Indian Ocean

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1 Introduction

The oceanic barrier layer (BL) is defined as the intermediate region between the base of the uniform density mixed layer and the isothermal layer, when the isothermal layer is deeper than the mixed layer due to the salinity structure or temperature inversion (Lukas and Lindstrom, 1991; Sprintall and Tomczak, 1992). The BL is a widespread phenomenon over the global oceans. It has been well studied in tropical areas (Agarwal et al., 2012; Foltz and McPhaden, 2009; Murtugudde and Busalacchi, 1999; Qu et al., 2014; Wang and Liu, 2016), but less explored in the high latitude due to sparse observations. Nonetheless, the Southern Ocean has been shown as one of the most prominent BL regions (De Boyer Montégut et al., 2007; Pan et al., 2018). Strong seasonal BLs mainly occur in the southeastern Indian Ocean and southeastern Pacific during wintertime (Fig. 1). The BL in the former area is featured by a strong temperature inversion induced by the subduction of the warm Subantarctic Mode Water (SAMW) (Pan et al., 2018).

The BL insulates the mixed layer from the entrainment cooling or even could lead to a warming effect on the mixed layer heat budget. In the tropical oceans, the reduction of mixed layer cooling can have a significant impact on tropical cyclone intensification (Balaguru et al., 2012a; Neetu et al., 2012; Rudzin et al., 2018; Yan et al., 2017). In the Southern Ocean, wind-driven entrainment plays a dominant role in supplying nutrients from subsurface water to eutrophic zone on time scales of less than 10 d and promoting the phytoplankton growth (Carranza and Gille, 2015).

Traditionally the entrainment process is one of the major mechanisms for the mixed layer cooling in the Southern Ocean, particularly in winter (Dong et al., 2007). The significance of the entrainment impacts on the mixed layer heat and salinity budget is also found to modulate sea ice variability on the long-term time scale (Close and Goosse, 2013). The entrainment effect will be reversed in the BL regions where the entrainment warming can offset the mixed layer heat loss in winter, which may have non-negligible feedback on the air-sea interaction like in the tropics.

The heat flux induced by entrainment processes is deduced from the mixed layer heat budget equation. Among all heat budget terms, the entrainment heat flux is usually subjected to large uncertainties, which can be attributed to two kinds of problems: methodology and data. The calculation of entrainment heat flux (EHF) involves the temperature difference between the mixed layer average and the mixed layer base. The latter is hard to be determined with the real data so the common practice is to use a fixed temperature difference, or the temperature difference between a fixed depth difference beneath the mixed layer base. Various threshold numbers have been used for both methods in previous studies (Table 1). However, a careful justification for this subjective choice remains unexplored.

The entrainment mixing is a small-scale process with strong seasonality. Due to the paucity of observations in the Southern Ocean, the available observation datasets such as Argo can only provide monthly or seasonal fields, i.e., capture the large-scale and part of the mesoscale processes. However, the high-fre-

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Table 1. The EHF calculations based on various definitions

No.	Definition of ΔT	Reference
1	$\Delta T = 1^\circ\text{C}$	Qiu and Kelly (1993)
2	$\Delta T = 0.75^\circ\text{C}$	Swenson and Hansen (1999)
3	$\Delta T = 0.2^\circ\text{C}$	Dong and Kelly (2004)
4	$\Delta T = T_{\text{ml}} - T_5$	Qu (2001); Girishkumar et al. (2013)
5	$\Delta T = T_{\text{ml}} - T_{10}$	Qu (2003); Close and Goosse (2013)
6	$\Delta T = T_{\text{ml}} - T_{20}$	Yasuda et al. (2000); McPhaden (2002)

Note: T_N is the temperature at the depth of N (unit in m) below the mixed layer base. T_{ml} is the mixed layer average temperature.

quency forcing may provide a significant portion of energy input and regulate the short-term mixed layer variability in the Southern Ocean (Lin et al., 2018). With the glider observations, du Plessis et al. (2022) showed that 1–10 d mixed layer variability is responsible for the buoyancy loss resulted mainly from the entrainment. Recent studies also revealed that the high-frequency submesoscale (0.1–10 km) processes may have a significant contribution to the vertical heat fluxes, especially in the Southern Indian Ocean (Siegelman et al., 2020; Su et al., 2018). Thus, the actual BL-induced warming may be underestimated using the monthly data without considering the high-frequency variations.

Given the paucity of observation data in the Southern Ocean, here we intend to investigate the aforementioned two problems by reconciling a more accurate EHF calculation that is suitable for the gridded dataset with the traditional threshold methods and comparing the EHF between the monthly and daily outputs. The BL-induced warming is then quantitatively estimated with an emphasis on the high-frequency contribution. Section 2 describes the dataset and calculation methods. The results are presented in Section 3, and a brief conclusion follows in Section 4.

2 Data and method

2.1 Southern Ocean state estimates (SOSE)

The data used in this study is obtained from the SOSE reanalysis dataset (Mazloff et al., 2010). SOSE dataset assimilates a large volume of *in-situ* measurements including the Argo floats, ship-board CTD, and XCTD profiles, etc. It has a horizontal resolution of $(1/6)^\circ \times (1/6)^\circ$ and 42 vertical layers spanning from 2005 to 2010. The model is driven by 6-hourly atmospheric forcing from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis, so the results contain the daily variability due to high-frequency forcing. The output provides both monthly and daily resolved data, and thus facilitates evaluating the high-frequency contribution in the entrainment processes.

2.2 Calculation of the BL thickness

The calculation of barrier layer thickness (BLT) is based on the method presented in De Boyer Montégut et al. (2007), where the mixed layer depth is calculated using the density threshold:

$$\Delta\rho = \rho(T_{10} + \Delta T, S_{10}, P_0) - \rho(T_{10}, S_{10}, P_0), \quad (1)$$

With the 10 m reference depth and $\Delta T = 0.2^\circ\text{C}$, the isothermal layer depth is defined as the depth at which the temperature decreases by 0.2°C from the reference depth. The BLT is then calculated as the difference between the mixed layer and isothermal layer depths. This definition has been widely used in the world ocean including the Southern Ocean (e.g., Balaguru et al., 2012b; Bosc et al., 2009; Pan et al., 2018; Qiu et al., 2012).

2.3 Calculation of the entrainment heat flux

The mixed layer heat budget equation is expressed as:

$$\frac{\partial T_{\text{ml}}}{\partial t} = \underbrace{\frac{Q_{\text{net}}}{\rho C_p h}}_{\text{atmospheric forcing}} - \underbrace{\left(u_{\text{ml}} \frac{\partial T_{\text{ml}}}{\partial x} + v_{\text{ml}} \frac{\partial T_{\text{ml}}}{\partial y} \right)}_{\text{horizontal advection}} - \underbrace{\frac{\Delta T}{h} w_e}_{\text{entrainment}}, \quad (2)$$

where T_{ml} is the mixed layer average temperature, Q_{net} is the external heat, ρ is the seawater density, C_p is the specific heat capacity, h is the mixed layer depth, ΔT is the temperature difference between T_{ml} and the temperature at the mixed layer base, and the entrainment velocity w_e is defined as:

$$w_e = \frac{\partial h}{\partial t} + \left(u_{-h} \frac{\partial h}{\partial x} + v_{-h} \frac{\partial h}{\partial y} \right) + w_{-h}, \quad (3)$$

where the subscript $-h$ indicates the mixed layer base. The positive entrainment velocity ($w_e > 0$) indicates an entrainment process while it is set to be zero for otherwise (in this study we consider the entrainment processes only). The entrainment velocity can be decomposed into three terms: the local change of mixed layer depth, the lateral induction, and the vertical advection (Eq. (3)). As discussed in Kim et al. (2006), contributions from the last two advective terms can be unambiguously calculated from the model outputs, but the entrainment heat flux due to local mixed layer depth change ($\Delta T \partial h / \partial t$) is subjected to errors if using ad hoc schemes. To this end, Kim et al. (2006) proposed a new calculation for this term from a heat balance perspective (hereafter K05).

For an entrainment process, the mixed layer depth changes from $h^{(n)}$ to $h^{(n+1)}$ and the average temperature from $T^{(n)}$ to $T^{(n+1)}$ from the time $t^{(n)}$ to $t^{(n+1)}$. Regardless of other processes, the heat balance during the consecutive time step can be written as:

$$T^{(n)} h^{(n)} + T_b^{(n)} (h^{(n+1)} - h^{(n)}) = T^{(n+1)} h^{(n+1)}. \quad (4)$$

After some algebra, Eq. (4) becomes

$$\frac{T^{(n+1)} - T^{(n)}}{\Delta t} = - \frac{T^{(n)} - T_b^{(n)}}{h^{(n+1)}} \cdot \frac{h^{(n+1)} - h^{(n)}}{\Delta t}, \quad (5)$$

where $T_b^{(n)}$ is the mixed layer base temperature.

There are two differences between the new calculation and the traditional one. One is that the mixed layer depth in the entrainment heat flux term is using the next step value $h^{(n+1)}$. The other is that the mixed layer base temperature is taken as the average over the mixed layer depth difference ($h^{(n+1)} - h^{(n)}$) at the current time step, i.e.,

$$\Delta T_{\text{exact}} = T^{(n)} - T_b^{(n)}. \quad (6)$$

3 Results

3.1 Comparison of different EHF calculations

Figure 1 shows the seasonal BL patterns in the southeastern Indian Ocean deduced from the SOSE dataset. The data are illustrated only from May to October since the BL is very weak in the other half year. The BL phenomenon peaks in June and July with a maximum around 300 m. Thick BLs exhibit a roughly zonal distribution aligned between 40° – 55°S , 100° – 160°E . Generally speaking, the seasonal variations and patterns well agree the character-

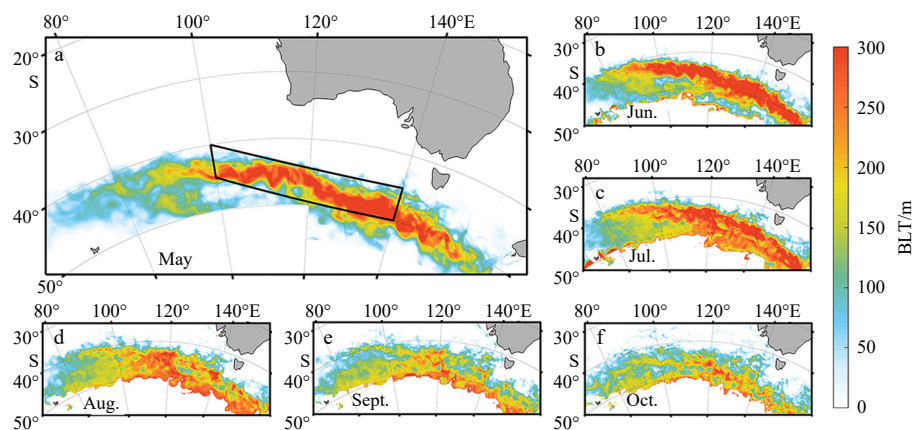


Fig. 1. The barrier layer thickness (BLT) distribution in the southeastern Indian Ocean from May to October. The black box indicates the barrier layer (BL) area for the subsequent analysis.

istics of the Argo-deduced BL (Pan et al., 2018). The BL formation in the southeastern Indian Ocean stems from the subduction of the warm SAMW, and therefore the BL in this region is characterized by an inverse temperature profile, which can lead to a unique warming effect on the mixed layer from the bottom. In the following, we will concentrate on a strong BL subregion for further analysis (Fig. 1a).

As mentioned in Section 1, various methods have been proposed for the EHF calculation. Figure 2 compares the seasonal variation of the EHF between the K05 and the traditional threshold methods in the BL months. All the methods produce the same temporal variation of the EHF, though the magnitudes are subject to large differences. The mixed layer warming induced by the BL starts in May, reaches the peak in July, and finally dies out in September. The results from the fixed depth difference methods are closer to the K05 with very limited deviations, while the EHF from fixed temperature difference methods are very sensitive to the definition and thus have relatively large biases. Among all threshold values, the fixed depth difference of 5 m below the mixed layer depth is suggested for this area if we want to continue using the threshold methods. It is noteworthy that this definition may be not the best one for other regions. In fact, the performance of a fixed threshold method varies significantly over the entire Southern Ocean and thus no single threshold value is omniscient. The K05 method should be

preferred for a large area or the basin-wide oceans.

To examine the spatial difference between methods, we choose a moderately-performed definition of 20 m depth difference. As shown in Fig. 2, this threshold tends to overestimate the entrainment warming approximately by $0.05^{\circ}\text{C}/\text{month}$. The EHF distribution is roughly consistent with the BL pattern each month. By comparison, the overestimates are nearly homogeneous over the entire barrier layer region (Fig. 3). The difference is only slightly larger during the strong warming months. It should be noted that there are also negative EHF at the flanks of the BL region, which results from the normal BL structure, i.e., the isothermal layer is deeper than the density-based mixed layer and no inverse temperature occurs. Overall, the warming effect still plays a dominant role in the BL regions.

3.2 BL-induced warming from high-frequency contributions

The entrainment is a process induced by small-scale turbulence with the occurrence over a much longer time scale. It is thus expected that the cumulative effects of the high-frequency entrainment variability may have a significant difference from the monthly average. Figure 4 demonstrates the EHF calculated using the monthly and daily SOSE data. The EHF difference between them emerges from June to August. The daily EHF warming has a much larger fluctuation and the magnitude can reach as high as $0.25^{\circ}\text{C}/\text{month}$, nearly double the monthly warming. Even at the lower end of the fluctuation, the daily EHF is roughly the same as the monthly EHF during the strong BL months. In winter, the surface net heat loss is the only dominant term in the mixed layer heat budget of the Southern Ocean, while the other effects are secondary (Dong et al., 2007). However, when considering the high-frequency variability of the mixed layer, we found that the EHF warming in the BL regions is comparable to the surface air-sea heat fluxes, particularly in August when the warming can even surpass the surface cooling (Fig. 4b). This means that the heating from the underlying BL can compensate the mixed layer heat loss from the surface almost over the whole winter. This unique warming effect could not be discerned if neither the BL nor the high-frequency variability is accounted for. In spring, i.e., a transitional season, both the EHF and surface net heat fluxes are reduced to very small values. Their magnitudes are still comparable with ups and downs on both effects.

Equation (5) indicates that the EHF is composed of the relative variation of the mixed layer depth $(1/h) \partial h / \partial t$ and the tem-

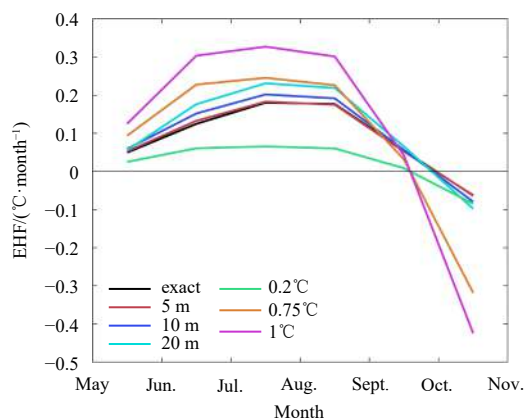


Fig. 2. The entrainment heat flux (EHF) seasonal variation from May to October calculated by K05 method (exact) and different threshold methods listed in Table 1.

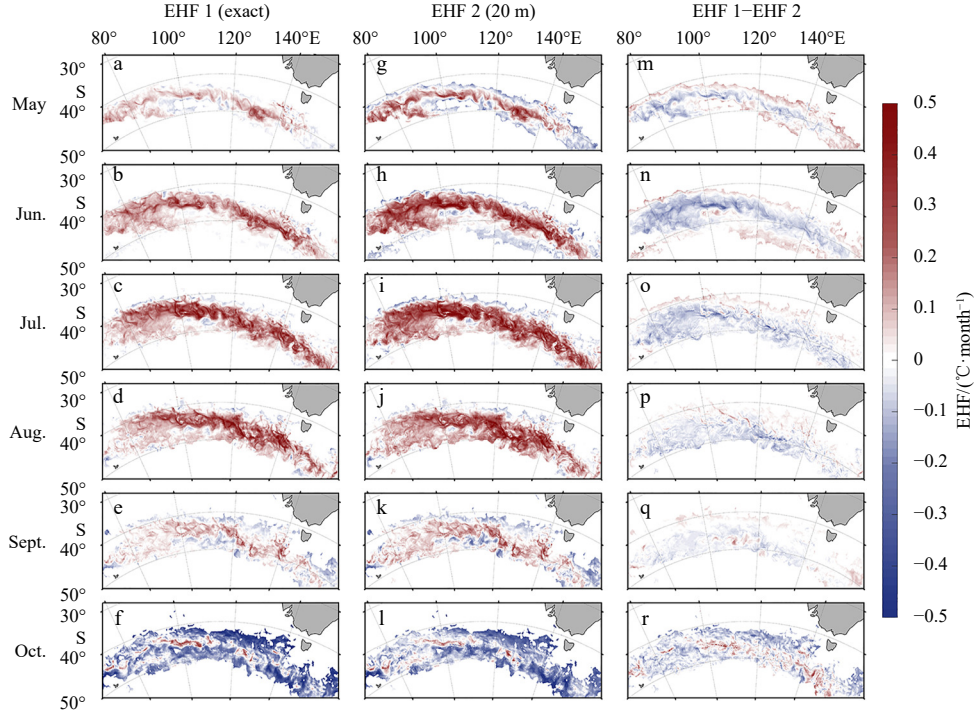


Fig. 3. Spatial distributions of the entrainment heat fluxes (EHFs) from May to October using K05 method and the 20 m depth difference threshold method.

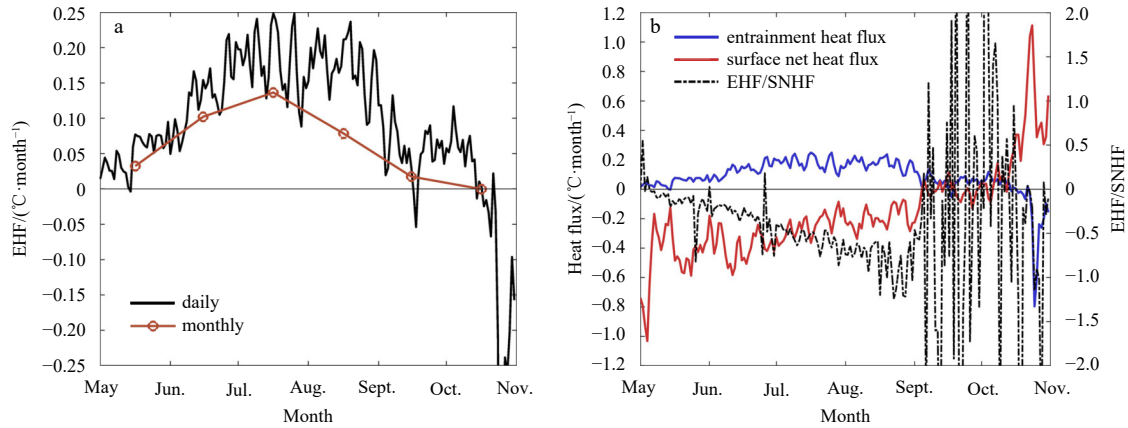


Fig. 4. Seasonal entrainment heat flux (EHF) warming calculated from daily (black) and monthly (red) Southern Ocean state estimates (SOSE) data (a) and comparison between the daily EHF warming (blue) and the surface net heat flux (SNHF) cooling (red) (b). The black dashed line represents the ratio between the EHF and SNHF.

perature difference between the mixed layer average and the mixed layer base ΔT . Figure 5 examines the seasonal contributions from these two terms using daily and monthly data respectively. The variation of the temperature difference is mainly due to the decrease of the average mixed layer temperature. Thus, it is of no surprise that the monthly temperature difference is greater than the daily difference, simply because the monthly data have a longer time interval (Fig. 5a). If we assume that the mixed layer temperature decreases linearly within a month, then the daily temperature change would be much smaller than the temperature difference from the daily data. Moreover, the daily-resolved mixed layer variability is also much larger than the monthly one (Fig. 5b), which again highlights the importance of the high-frequency component of the mixed layer variability. The BL region in the southeastern Indian Ocean is located on the course of the

strong Antarctic Circumpolar Current (ACC). The high-frequency variation may stem from the rich meso- and submeso-scale processes associated with the ACC within the mixed layer. Previous studies revealed the significant vertical heat advection induced by submesoscale in the southern Indian Ocean (Su et al., 2018). Here we emphasize that the small-scale turbulent entrainment processes can also make great contributions to the mixed layer heat content.

3.3 Interannual variability of the BL-induced warming

On the interannual scale, the EHF in the BL period has more complicated variability. The daily EHF has a relatively larger fluctuation than the monthly EHF, and there is no significant correlation between them (Fig. 6). The EHF anomalies are not negligible compared with the seasonal warming in Fig. 4, indicating

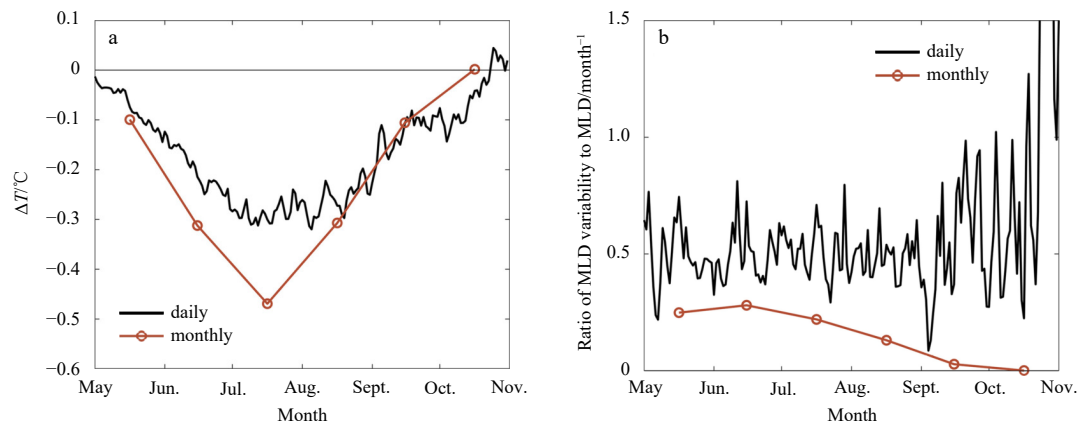


Fig. 5. The temperature difference between the mixed layer average and the mixed layer base (a); the daily and monthly relative variation of the mixed layer depth (MLD) (b).

that the EHF is subject to large interannual variability. Sallée et al. (2010) pointed out that the Southern Ocean mixed layer depth has a zonally asymmetric response to the Southern Annular Mode (SAM) and the SAM index is positively related to the mixed layer depth anomalies in the southeastern Indian Ocean. The forcing mechanism is attributed to the anomalous northward cold wind associated with the SAM that leads to a buoyancy loss over the southeastern Indian Ocean. This implies a possible linkage between the EHF and SAM via mixed layer deepening. During

positive SAM phase, the anomalous negative heat fluxes decrease the mixed layer temperature. It is possible to amplify the temperature difference ΔT with the underlying warm water, or to increase the mixed layer depth by convective mixing. Either effect or both together may enhance the EHF. Owing to the limited length of the SOSE data, it is difficult to evaluate the correlation between the EHF and SAM variability. However, we indeed found that the annual EHF deduced from the daily but not monthly data has a very similar trend and variation to the SAM index during this six-year period (Fig. 7). As the EHF is related to the small-scale mixing, the rapid change of mixed layer depth may not be well captured by the monthly data. This is also the reason why the contribution of the entrainment mixing is often taken as secondary, as most available datasets for the Southern Ocean are monthly resolved including the observation-based gridded data and global reanalysis (e.g., Dong et al., 2007; Screen et al., 2010). It should be noted again that the link should be further examined with a longer daily-resolved dataset. This cross-scale interaction between the climate signal and turbulent mixing is an interesting question that warrants investigating in the future study.

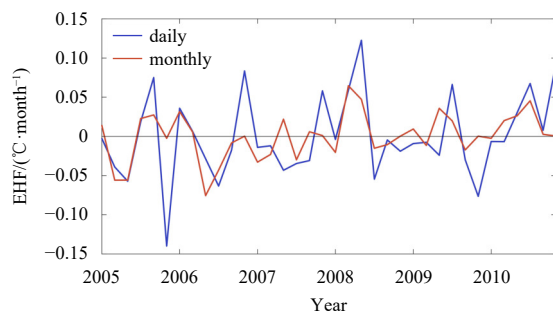


Fig. 6. Interannual variation of the entrainment heat flux (EHF) anomaly from May to October.

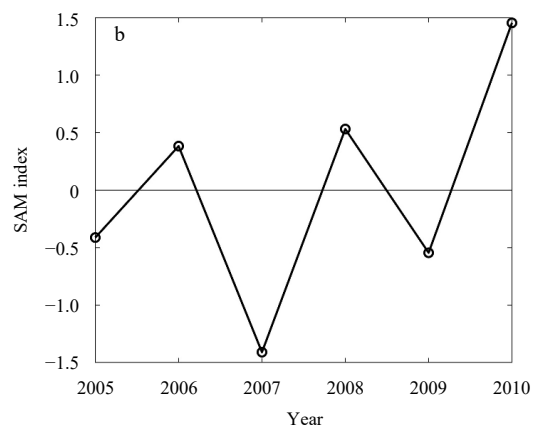
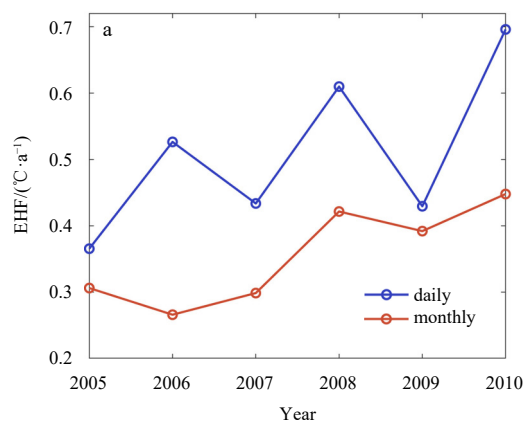


Fig. 7. Annual variation of entrainment heat flux (EHF) deduced from the daily and monthly Southern Ocean state estimates (SOSE) data (a) and the annual observation-based Southern Annular Mode (SAM) index obtained from <https://legacy.bas.ac.uk/met/gjma/sam.html> (b).

4 Discussion and conclusions

In this study, we attempted to give a more accurate evaluation of the entrainment-induced mixed layer warming in the BL region of the southeastern Indian Ocean. Two problems are iden-

tified and subsequently tackled. On one hand, by comparison with a bulk method adapted to the model data (K05), we found that the traditional EHF calculation is found to be good enough if choosing the temperature difference with a threshold of fixed 5 m below the mixed layer base. On the other hand, the high-frequency variability of the mixed layer resolved in the daily data can contribute to the mixed layer warming nearly twice as much as the monthly data. This result indicates that the cumulative effect of a small-scale process like turbulent entrainment may be very significant and cannot be simply parameterized by the mean properties.

The similarity of the SAM and EHF shows a possible linkage between the large-scale forcing and the small-scale response through the change of mixed layer depth. However, their monthly time series do not have such a good correlation. Multiple processes may impact the EHF variability due to the large-scale forcing. As mentioned in Section 3.3, the increase of the mixed layer depth is mainly forced by the anomalous air-sea heat fluxes associated with the SAM. The surface heat loss could also modify the mixed layer temperature and thus increase the contrast with the BL temperature. This dual effect absorbs the heat from the BL to compensate for the mixed layer heat loss from the surface at the interannual scale. However, these processes may be complicated by seasonal variability. For example, the positive SAM in spring can facilitate the mixed layer deepening in fall as revealed by Li et al. (2019).

In addition, since the EHF is related to the BL temperature, the interannual variability of the BL, i.e., the subducted SAMW, may also impact the rate of the mixed layer warming. During the past two decades, both the volume and density of the SAMW have been undertaking significant change during past decades and their variabilities are layer-dependent (Hong et al., 2020). Kolodziejczyk et al. (2019) presented that the volume changes of these water masses explain most of the ocean heat content interannual variability. It is therefore anticipated that the BL properties could very probably play a part in the SAM-EHF relationship at the interannual scale.

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