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Ocean-atmosphere dynamics changes associated with prominent ocean surface turbulent heat fluxes trends during 1958-2013

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Abstract In this study three prominent features of ocean surface turbulent heat fluxes (THF) trends during 1958-2013 are identified based on the Objectively Analyzed air-sea Fluxes (OAFlux). The associated ocean-atmosphere dynamics changes are investigated based on data of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). First, the THF are enhanced over the mid-latitude expansions of the subtropical western boundary currents (WBCs). An intensified oceanic heat transport, forced by stronger near-surface zonal wind, is likely to be the cause of such THF tendency. Second, the THF are reduced over the tropical eastern Pacific Ocean, which is primarily caused by the decreasing near-surface wind speed and sea surface temperature (SST), associated with a local coupled ocean-atmosphere cooling mode. Finally, the THF are reduced over the northern tropical Atlantic Ocean, which is attributed to the decreasing air-sea humidity and temperature differences as a result of the convergence of near-surface air and the divergence of ocean currents (upwelling).

Keywords Turbulent heat fluxes trend · Western Boundary Currents · Tropical eastern Pacific Ocean · Northern Tropical Atlantic

1 Introduction

Turbulent heat fluxes (THF) consist of two components: latent heat flux (LHF) and sensible heat flux (SHF). LHF is the flux of heat from the ocean to the atmosphere that is associated with evaporation. SHF is the conductive heat flux from the ocean to the atmosphere. As the main form of air-sea heat exchange, THF are of particular interest for the comprehensive understanding of the coupled ocean-atmosphere interactions.

Several studies have addressed the THF trends and their associated mechanisms in different regions and for varying periods. As reported by Tomita and Kubota (2005), the THF have increased during the 1990s over the Kuroshio Oyashio extension region and reached their maximum during the past half century due to a pronounced warming in sea surface temperature (SST). By examining the variability of the tropical and subtropical LHF during 1989-2000, Liu and Curry (2006) found that the increasing LHF is primarily associated with a positive trend of near-surface wind speed. Zhang et al (2010a) showed that the LHF dampens the increase in SST caused by oceanic advection in the coastal China Seas during 1948-2006. Iwasaki and Kubota (2011) demonstrated that the LHF and freshwater flux were strengthened over the north-eastern subtropical Pacific during 1988-2005. Based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, Shaman et al (2010) pointed out that THF have increased over the Gulf Stream during 1948-2008 mainly due to higher storm frequency. The extreme THF events over the subtropical western boundary currents (WBCs), as described by Gulev and Belyaev (2012), have increased significantly during the same period. By analyzing the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF), Gao et al (2013) also found an increase in the LHF over the Kuroshio Current and Gulf Stream during 1988-2008. On the basis of investigating the relationship between SST and THF on different time scales, Gulev et al (2013) emphasized that on multi-decadal time scales, the ocean drives the atmosphere variability, whereas the opposite case is true for shorter timescales over the North Atlantic region (35^o-50^oN). Given all above results, investigating the THF variability is of crucial importance for understanding and evaluating the climate feedbacks and changes.

In this study we aim to assess the long-term changes of the coupled ocean-atmosphere dynamics by examining the prominent THF trends over the sea surface. The International Comprehensive Ocean-Atmosphere Data Set (ICOADS) is the longest and most extensive collection of surface marine meteorological data mainly from ships and buoys since 1662 (Woodruff et al, 2011). However, the ICOADS suffers serious spatial/temporal sampling problems and measurement uncertainties (Da Silva et al, 1994; Chou et al, 2004; Gulev et al, 2007). As pointed out in Gulev et al (2013), only the North Atlantic region was evaluated, where a large number of ship observations are available over a long period of time. Recent satellite-based data products could overcome the shortcoming of spatial/temporal sampling problems, but are insufficient to study the long-term climate variability due to a lack of temporal coverage, as the data sets only cover relatively short period from 1987 to today. These products include the GSSTF v3 (Chou et al, 2003), the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data (HOAPS) (Andersson et al, 2010), the Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations (J-OFURO) (Kubota et al, 2002) and the Ocean Surface Turbulent Flux (SeaFlux) (Liu et al, 2011; Clayson and Bogdanoff, 2013). The Objectively Analyzed air-sea Fluxes (OAFlux) are constructed from an optimal blending of surface meteorological variables from satellite retrievals and atmospheric reanalysis since 1958 (Yu and Weller, 2007; Yu et al, 2008). Compared with ICOADS and satellite data sets, OAFlux fulfill the requirement of both spatial and temporal coverage for this study.

The data sets used here, together with the method employed to identify the dominant factors for the THF trends are introduced in the next section. In Section 3.1, the prominent THF trends and their dominant factors are examined. We try to explore the physical mechanisms behind the THF trends in Section 3.2. Finally, discussion and conclusion are presented in Section 4 and 5, respectively.

2 Data and Method

2.1 Data

The OAFlux use the objective analysis to obtain optimal estimates of flux-related surface meteorology and then computes the global fluxes by applying the state-of-the-art COARE bulk flux algorithm 3.0 (Fairall et al, 2003). The surface meteorological fields used in OAFlux are mainly derived from satellite remote sensing and reanalysis outputs. Since the input data sources cover different periods and have different resolutions, OAFlux have several versions of THF products, i.e., monthly 1-degree resolution (1958 onward), daily 1-degree resolution (1985 onward), and daily 0.25-degree resolution (1987 onward). Different input data sources are blended in different versions of OAFlux. In this work, the monthly 1-degree resolution of OAFlux, spanning 1958-2013, is used to study the prominent THF trends. This version of OAFlux blend three atmosphere reanalysis (i.e., NCEP/NCAR, NCEP/DOE and ERA-40) and four satellite products (i.e., OISST, SSM/I, AMSR-E and QuikSCAT). Furthermore, it has validated against in situ flux measurements. Note that, before 1985, only atmosphere reanalysis data sets are blended in this version of OAFlux. After 1985, both satellite data and atmosphere reanalysis are synthesized (Yu and Weller, 2007; Yu et al, 2008).

Another set of data used in this work is the NCEP/NCAR reanalysis, which is a long-term data set based on a frozen global data assimilation and observational data from a variety of sources i.e., weather stations, ships, buoys, aircrafts, radiosondes and satellites (Kalnay et al, 1996). The NCEP/NCAR spans from 1948 to 2013 with a spatial resolution of T62 (approximately 210 km at the equator).

The monthly mean THF (positive-upward) along with flux-related input state parameters from the OAFlux data set, and the monthly mean atmosphere parameters (i.e., near-surface wind, sea level pressure, SST, surface air temperature, surface specific humidity) from the NCEP/NCAR data set are used in our study. The OAFlux are used to investigate the prominent THF trends, and the NCEP/NCAR is utilized to interpret the associated ocean-atmosphere dynamic changes. Besides, NCEP/NCAR data set also serves as a cross validation of the THF trends in OAFlux from the perspective of climate dynamics.

2.2 Method

The THF depend primarily on near-surface wind speed, air-sea humidity and temperature differences, as described in the COARE bulk flux algorithm 3.0 (Fairall et al, 2003):

$$LHF = \rho_a L C_E U_a (q_s - q_a) \tag{1}$$

$$SHF = \rho_a c_p C_H U_a (T_s - T_a) \tag{2}$$

where ρ_a is the surface air density, L is the latent heat of vaporization for water, c_p is the specific heat of air at constant pressure, C_E and C_H represent the bulk transfer coefficients for humidity and temperature, respectively. U_a stands for the near-surface wind speed. q_s and q_a are the surface saturation humidity and surface specific humidity, T_s and T_a are the SST and surface air temperature, respectively. Taking into account the effect of salinity, q_s is usually computed as $0.98q_{sat}(T_s)$, where q_{sat} represents the saturation humidity for pure water at T_s. In addition, T_a includes a correction from the measured surface air temperature T_z at the height z, using the adiabatic lapse rate γ, as $T_a = T_z + \gamma z$.

In order to identify the dominant factors that are responsible for the THF variability, we divide U_a, q_s, q_a, T_s and T_a into the climatological means and the anomaly terms ($U_a = \overline{U_a} + {U_a}'$, $q_s = \overline{q_s} + {q_s}'$, $q_a = \overline{q_a} + {q_a}'$, $T_s = \overline{T_s} + {T_s}'$, $T_a = \overline{T_a} + {T_a}'$). The overbar denotes the climatological mean and the prime denotes anomaly. Since the anomaly terms of each variable are much smaller than the climatological means (mostly less than 10%), equation (1) and (2) can be linearized by the same method as in Tanimoto et al (2003):

$$LHF' \approx \rho_a L C_E (L_{q_s} + L_{q_a} + L_{U_a}) \tag{3}$$

$$SHF' \approx \rho_a c_p C_H (S_{T_s} + S_{T_a} + S_{U_a}) \tag{4}$$

Here, LHF' and SHF' represent the anomalies of LHF and SHF, L_{q_s}, L_{q_a}, L_{U_a}, S_{T_s}, S_{T_a} and S_{U_a} refer to $\overline{U_a}{q_s}'$, $-\overline{U_a}{q_a}'$, $(\overline{q_s} - \overline{q_a}){U_a}'$, $\overline{U_a}{T_s}'$, $-\overline{U_a}{T_a}'$, $(\overline{T_s} - \overline{T_a}){U_a}'$, in equation (6) and (7) in Tanimoto et al (2003), respectively. L_{q_s}, L_{q_a}

and L_{U_a} can be treated as the respective contributions from ${q_s}'$, ${q_a}'$ and ${U_a}'$ to the total LHF anomaly. S_{T_s}, S_{T_a} and S_{U_a} represent the respective contributions from the ${T_s}'$, ${T_a}'$ and ${U_a}'$ to the total SHF anomaly.

Finally, we introduce two indices CL_X and CS_X to quantify the relative importance of the terms in equation (3) and (4) :

$$CL_X = \frac{|L_X|}{|L_{q_s}| + |L_{q_a}| + |L_U|} \tag{5}$$

$$CS_X = \frac{|S_X|}{|S_{T_s}| + |S_{T_a}| + |S_U|} \tag{6}$$

For equation (5), CL_X represents the relative importance of either the surface saturation humidity (in this case $X = q_s$), surface specific humidity (i.e., $X = q_a$)) or the near-surface wind speed (i.e., $X = U_a$). The denominator of the right side ($|L_{q_s}| + |L_{q_a}| + |L_U|$) stands for the total contribution of the three influencing factors to the LHF anomaly. By such definition, CL_X ranges from 0 to 1, and a larger CL_X indicates a more dominated contribution by the variable X to the LHF anomaly. If CL_X exceeds 0.5, the term X basically dominates the LHF anomaly. Therefore, we define the X with $CL_X > 0.5$ as the dominant factor causing the LHF anomaly. A similar definition applies to the SHF in equation (6) as well, and X in equation (6) represents the SST (T_s), surface air temperature (T_a), or the near-surface wind speed (U_a).

To interpret the long-term trends, all our analysis is based on annual mean values. However, we note that both the THF and the flux-related parameters have a seasonal variability. Finally, as the linearization of the bulk flux formulae no longer applies over high latitude (Liu et al, 1979; Bourassa et al, 2013), we only present the results between $50°S - 50°N$ in this work.

3 Results

3.1 Identification of prominent THF trends and associated dominant factors

The linear trends of THF from OAFlux, as depicted in Fig. 1a, exhibit three prominent features: 1) a significant increase in the THF occurs over the mid-latitude expansions of the primary subtropical WBCs (i.e., the Kuroshio Current, Gulf Stream, Agulhas Current, Eastern Australian Current and Brazil Current) with a magnitude of ~8-12 W/m^2 per decade; 2) a pronounced decrease in the THF happens over the tropical eastern Pacific Ocean at the rate of ~6-10 W/m^2 per decade; and 3) over the northern tropical Atlantic Ocean the THF reduce at a speed of ~4-6 W/m^2 per decade. These three prominent features of THF' are also observed in the LHF and SHF trends (Figs. 1b, 1c), with almost equivalent magnitudes for the former, and however, a less pronounced pattern for the latter, indicating an overwhelming contribution of LHF' to the THF trends.

To identify the dominant factors which are responsible for the prominent THF trends, we compute the trends of the q_s, q_a, T_s, T_a and U_a, respectively. The CL_X and CS_X are further calculated based on the climatology mean and linear trends of each parameter (see equations 5 and 6). The areas with $CL_X > 0.5$ and $CS_X > 0.5$ are marked with black crosses in Figs. 2 and 3.

The paths of the primary WBCs experienced a significant increase in SST (Figs. 2a and 3a), which constitutes the dominating cause of LHF' and SHF' over the same regions. Meanwhile, the surface winds over these regions have accelerated, contributing to enhancing the ocean heat loss over there. Over the tropical eastern Pacific Ocean, we observe a significant decrease in SST (q_s and T_s) and U_a, both of which together contribute to the decreasing LHF and SHF over the tropical eastern Pacific Ocean. Furthermore, the reduced LHF and SHF over the northern tropical Atlantic Ocean is primarily associated with an increases in surface specific humidity (q_a) and surface air temperature (T_a) (Figs. 2b and 3b).

Having described the patterns of THF trends and their contributors, we turn to the time evolution of these factors. Since the surface specific humidity (q_a) usually varies together with the surface saturation humidity (q_s), their contributions to the LHF anomaly are treated together as contribution from air-sea humidity difference ($L_{q_s} + L_{q_a}$). A similar assumption applies to the air-sea temperature difference (as $S_{T_s} + S_{T_a}$) in Fig. 4. We find that the increases in LHF and SHF over the WBCs mainly occur during 1970-2000. The air-sea humidity and temperature differences are the main drivers for the increases. For the tropical eastern Pacific Ocean, strong interannual variations of LHF and SHF are observed, which resemble the signal of the El Nino Southern Oscillation (ENSO). While, on long time scales, the weakening surface wind plays an equivalent role as the reduced air-sea humidity and temperature differences in the decreasing THF. Regarding the northern tropical Atlantic, a continuous decline of air-sea humidity difference depresses the ocean THF loss there.

3.2 Possible mechanisms for the THF trends

3.2.1 Increasing THF over the WBCs

WBCs transport a large amount of heat from the low latitudes to the mid and high latitudes, which contribute to the Earth's energy balance. The heat release from the WBCs is primarily in the form of THF. Fig. 3a describes the spatial distribution of SST trends during 1958-2013. It appears that there is an enhanced warming of the main WBCs, on a magnitude of ~0.2-0.3 K per decade consistent with Wu et al (2012). This is remarkably stronger than the globally averaged SST increase (0.17 K per decade) during the same period. As demonstrated in section 3.1, the enhanced SST warming greatly strengthens the THF loss over the WBCs, indicating an ocean controlled climate trend. The THF in turn has a damping effect on the SST (Cayan, 1992; Zhang and Mcphaden, 1995; Frankignoul and Kestenare, 2002). Moreover, from the perspective of ocean and atmosphere heat balance, increasing SST associated with enhanced THF loss implies that the heat transport by the WBCs has strengthened.

Fig. 5 presents the trend and climatology of near-surface zonal wind stress. On one hand, the westerly winds over the mid and high latitudes are stronger in intensity. On the other hand, over most of the tropical regions, the easterly winds also speed up, except for the tropical eastern Pacific Ocean. The pattern correlation coefficient between the trend and climatology zonal wind is 0.54, with a 95% confidence level (Student *t*-test), illustrating that the background surface wind circulation has strengthened in the latitude belts approximately between 10° to 65° in both hemispheres. Note that the stronger westerly winds are more pronounced over the Southern Hemisphere than that over the Northern Hemisphere.

According to the Sverdrup's theory of oceanic circulation, wind stress curl between the low latitudes and mid-latitudes is the main driver of the subtropical gyres. We compute the averaged wind stress curl over the corresponding subtropical gyres (as shown in Fig. 6a). It comes out that the magnitude of wind stress curl has increased over all the five subtropical gyres (as shown in Fig. 6b). The intensification of both the low latitude easterly and mid-latitude westerly (Fig. 5) would strengthen the subtropical wind stress curl, which forces stronger WBCs. Even though the intensification of zonal wind stress over the Northern Hemisphere is not significant, it could have an amplification effect over the WBCs through the ocean dynamic feedback. The WBCs in turn transport more heat and accelerate the THF loss over the mid-latitude expansions of these currents.

3.2.2 Decreasing THF over the tropical eastern Pacific Ocean

The decreased SST over the eastern tropical Pacific Ocean, as depicted in Fig. 7a, shows good agreement with the OAFlux (Fig. 3a). Such cooling limits the heat loss from ocean surface. Meanwhile, the cooling SST is coupled with a sinking air flow, accompanied by a positive SLP trend (shading in Fig. 7b) and a divergence tendency of near-surface winds (vectors in Fig. 7a and 7b). The divergence of near-surface winds over the eastern Pacific weakens the background easterly trade winds and reduces the wind speed there. The combined effects of both the decreased SST and the weakened wind speed suppress the ocean surface THF loss.

3.2.3 Decreasing THF over the northern tropical Atlantic Ocean

To investigate the negative THF trend over the northern tropical Atlantic Ocean, we present the trends of near-surface wind, and air-sea humidity and temperature differences in Fig. 8. During 1958-2013, there is a strengthening of easterly winds over the northern subtropical Atlantic and south-easterly winds near the equatorial Atlantic. Such wind anomalies tend to induce an Ekman divergence of the ocean current (upwelling) over the northern tropical Atlantic Ocean, which cools the ocean surface. By contrast, such pattern of wind trend results in a convergence of near-surface air at the same region, which provides a source of heat and water vapor from the adjacent area, contributing to the increases in the q_a (Fig. 2b) and T_a (Fig. 3b) there. Therefore, both the strengthening of easterly winds over the northern subtropical Atlantic and the intensified south-easterly winds near the equatorial Atlantic constitute the cause of the reduced air-sea humidity and temperature differences, which together suppress the ocean heat loss there.

4 Discussion

Due to the differences in the source of input variables, the formulation of bulk algorithms, and the changes in the observing system, uncertainties still remain in the THF data sets (Kalnay et al, 1996; Zeng et al, 1998; Moore and Renfrew, 2002; Curry et al, 2004; Yu et al, 2008; Santorelli et al, 2011; Brunke et al, 2011). Considering the existing uncertainties in the heat flux data sets, we only focus on the prominent THF trends in this work. The THF trends we have identified are consistent with other studies. For example, Yu et al (2008) showed that the increased LHF over the WBCs primarily occurs after the 1970s. Based on GSSTF data set, Gao et al (2013) reported that the maximum LHF increases occur over the

WBCs regions during 1988-2008. Additionally, their pattern of LHF trends also suggests that the LHF increases over the tropical Eastern Pacific and northern tropical Atlantic are relatively small compared to the overwhelming increase LHF over the tropical ocean surface (see Gao et al (2013) Figure 2).

In this study we interpolate the THF trends based on annual mean values. However, we emphasize that THF have seasonal variations, particularly over the mid and high latitudes. Yu et al (2008) pointed out that the THF over the WBCs increased mainly during wintertime, associated with increasing storm frequency (Shaman et al, 2010; Gulev and Belyaev, 2012). In our analysis, we also find that the near-surface wind speed over the WBCs has accelerated, which is likely linked with higher storm activities.

Computation of the trend of a certain variable is period-dependent, especially when the period is short. To assess the long-term changes of the coupled ocean-atmosphere dynamics, we choose a relatively long period (56 years, 1958-2013) to carry out this work. However, the presented trends do not necessarily represent continuous climate changes. They could also reflect climate variations on multi-decadal time scales. For example, the THF over the Kuroshio Current and the Gulf Stream increase primarily during 1970-2000 (as in Fig. 4). The variations seem to be associated with an increase of the Arctic Oscillation starting from the late 1960s to the 1990s, which manifests in stronger westerly winds over the North Hemisphere (Thompson and Wallace, 2000). But the Arctic Oscillation shifted towards a negative phase after the 1990s. Over the Southern Hemisphere, an increase of the Antarctic Oscillation is also observed, which explains the strengthening Southern Hemisphere westerly (Thompson and Wallace, 2000; Marshall, 2003).

The WBCs play a vital role in the climate over the adjacent mainland (Minobe et al, 2008; Kelly et al, 2010). Previously, the strengthening WBCs has been documented individually, for example, the Gulf Stream (Curry and McCartney, 2001), Kuroshio Current (Qiu and Joyce, 1992; Deser et al, 1999; Sato et al, 2006; Sakamoto et al, 2005) and the Eastern Australia Current (Cai et al, 2005; Qiu and

Chen, 2006; Ridgway, 2007; Roemmich et al, 2007; Ridgway et al, 2008). Curry and McCartney (2001) found that transport of the Gulf Stream has intensified after the 1960s. Sato et al (2006) and Sakamoto et al (2005) projected a stronger Kuroshio Current in response to global warming according to a high-resolution coupled atmosphere-ocean climate model. Based on long-term temperature and salinity observations from an ocean station off eastern Tasmania, Ridgway (2007) demonstrated that the East Australian Current had increased over the past 60 years. Beyond these studies on individual WBCs, our study suggests that the climate change over the WBCs is likely to be a systematic phenomenon over all ocean basins. As Wu et al (2012) also stressed, there was enhanced SST warming over all the WBCs. However, controversy still remains on the dynamic change of WBCs due to the uncertainty of the data set. According to a continuous observation from undersea telephone cables near 27° N in the Straits of Florida, DiNezio et al (2009) constructed a time series of transport of the Florida Current (part of Gulf Stream) since 1982. The time series suggest no indication of positive trend during the covering period (1982-2007).

Considering the tropical eastern Pacific, Cane et al (1997) and Zhang et al (2010b) observed a cooling mode of the Pacific cold tongue under global warming associated with an increased upwelling (Cane et al, 1997). Model experiments show that the cooling over the tropical eastern Pacific leads the ocean to an increased absorption of heat, contributing to the global warming hiatus in recent decades (Meehl et al, 2011; Kosaka and Xie, 2013). However, the cooling mode is very likely to collapse in the future, as suggested by the coupled climate models (Meehl et al, 2011). Regarding the northern tropical Atlantic Ocean, the trend of wind speed is very likely to be a stronger regime of the Intertropical Convergence Zone (ITCZ) which is characterized by a convergence of surface air and divergence of ocean currents.

The THF are related to the energy and water vapor transport from the ocean to the atmosphere. Prominent THF trends can be an indicator for the remarkable changes in the ocean and atmosphere dynamics. Besides the three identified THF trends in this paper, there are some other regions where THF trends are significant, i.e., the decreased THF over the northern subtropical central Pacific, the reduced THF over the southern subtropical eastern Pacific. These trends are also worth being investigated in the future. In addition, the seasonal dependence of THF trends and their corresponding impact factors are beyond the scope of this paper, which are of particular importance for understanding the mechanisms.

5 Conclusions

Based on the OAFlux data set, we have recognized three prominent ocean surface THF trends during 1958-2013, i.e., the enhanced THF over the mid-latitude expansions of subtropical WBCs, the reduced THF over the tropical eastern Pacific Ocean, and the reduced THF over the northern tropical Atlantic Ocean.

The dominant factors for these THF trends are identified by linearizing the bulk flux formulae. We find that over the WBCs, the THF are enhanced by the increasing SST. Such change is likely to be induced by intensified WBCs which are forced by a systemic stronger near-surface zonal wind stress in the latitude belts approximately between 10° to 65° in both hemispheres. Over the tropical eastern Pacific Ocean, the THF are reduced primarily through the decreasing near-surface wind speed and SST. The associated dynamic changes are found to be the divergence of near-surface wind coupled with a cooling ocean surface over the tropical Pacific Ocean. Over the northern tropical Atlantic Ocean, the reduced THF are primarily affected by the increasing surface specific humidity and air temperature, corresponding with a convergence of surface air and divergence of ocean currents.

This work proposes a novel way of exploring the changes of atmosphere-ocean dynamics by examining the trends of THF. As a next step, the associated dynamic changes will be investigated with more data sets and model scenarios.

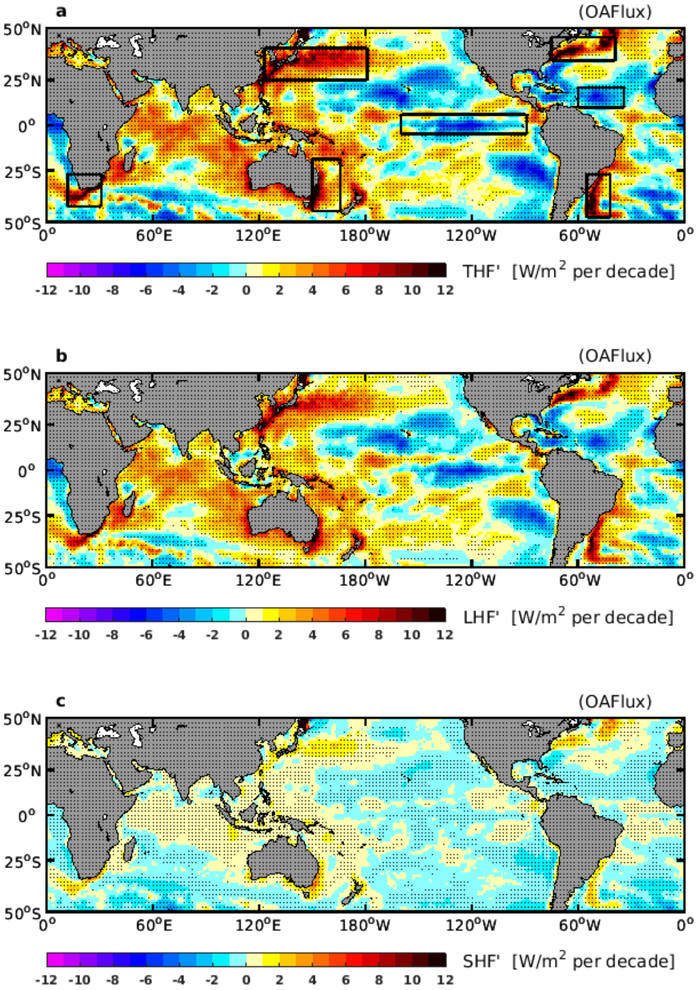

Fig. 1 Spatial distributions of trends in turbulent heat fluxes (THF'), latent heat flux (LHF') and sensible heat flux (SHF') in OAFlux data set. Stippling indicates regions where the trends pass the 90% confidence level (Student's t-test). The black rectangles locate the regions where we interpret the THF trends.

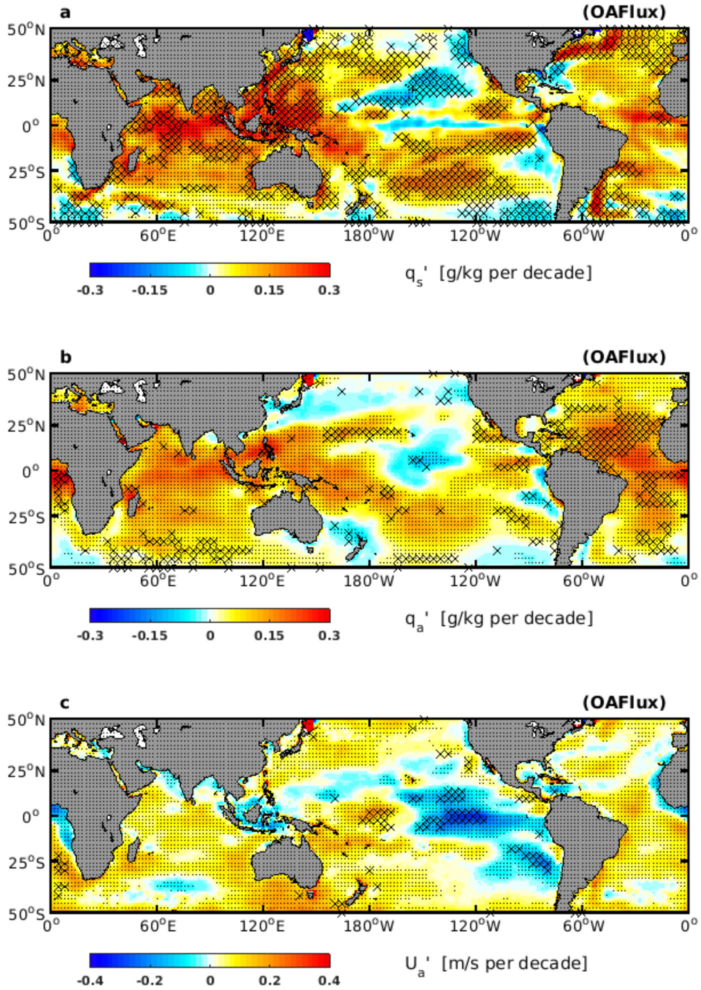

Fig. 2 As Figure 1, spatial distributions of the trends in surface saturation humidity ($q_s{}'$), specific humidity ($q_a{}'$) and wind speed ($U_a{}'$). The area with $CL_X > 0.5$ (see Equation 5) are marked with black cross.

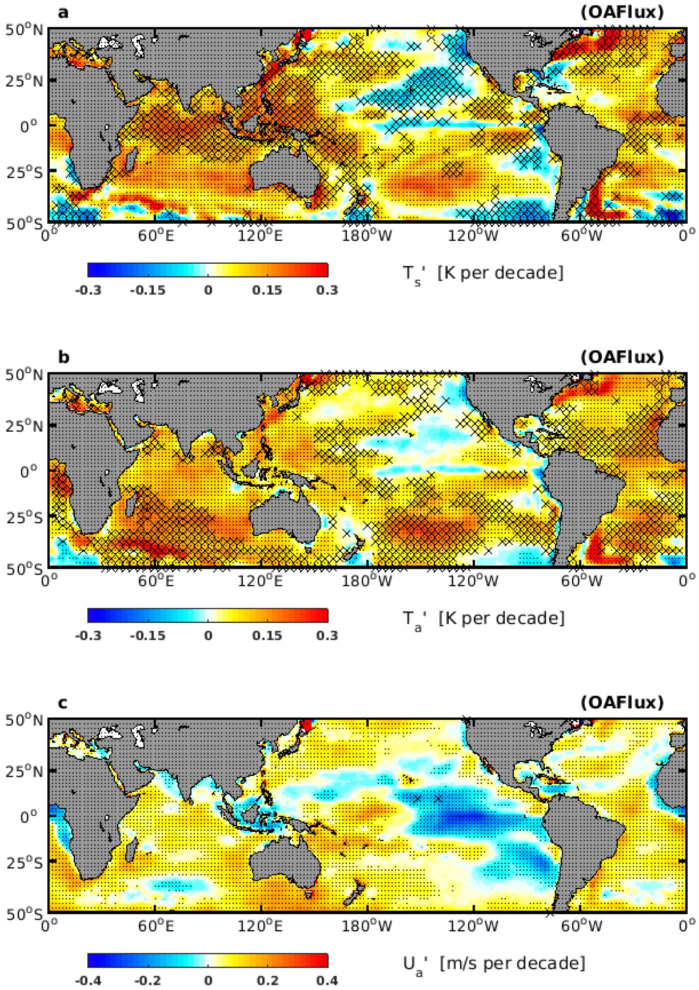

Fig. 3 As Figure 1, spatial distributions of the trends in sea surface temperature (T_s'), surface air temperature (T_a') and wind speed (U_a'). The area with $CS_X > 0.5$ (see Equation 6) are marked with black cross.

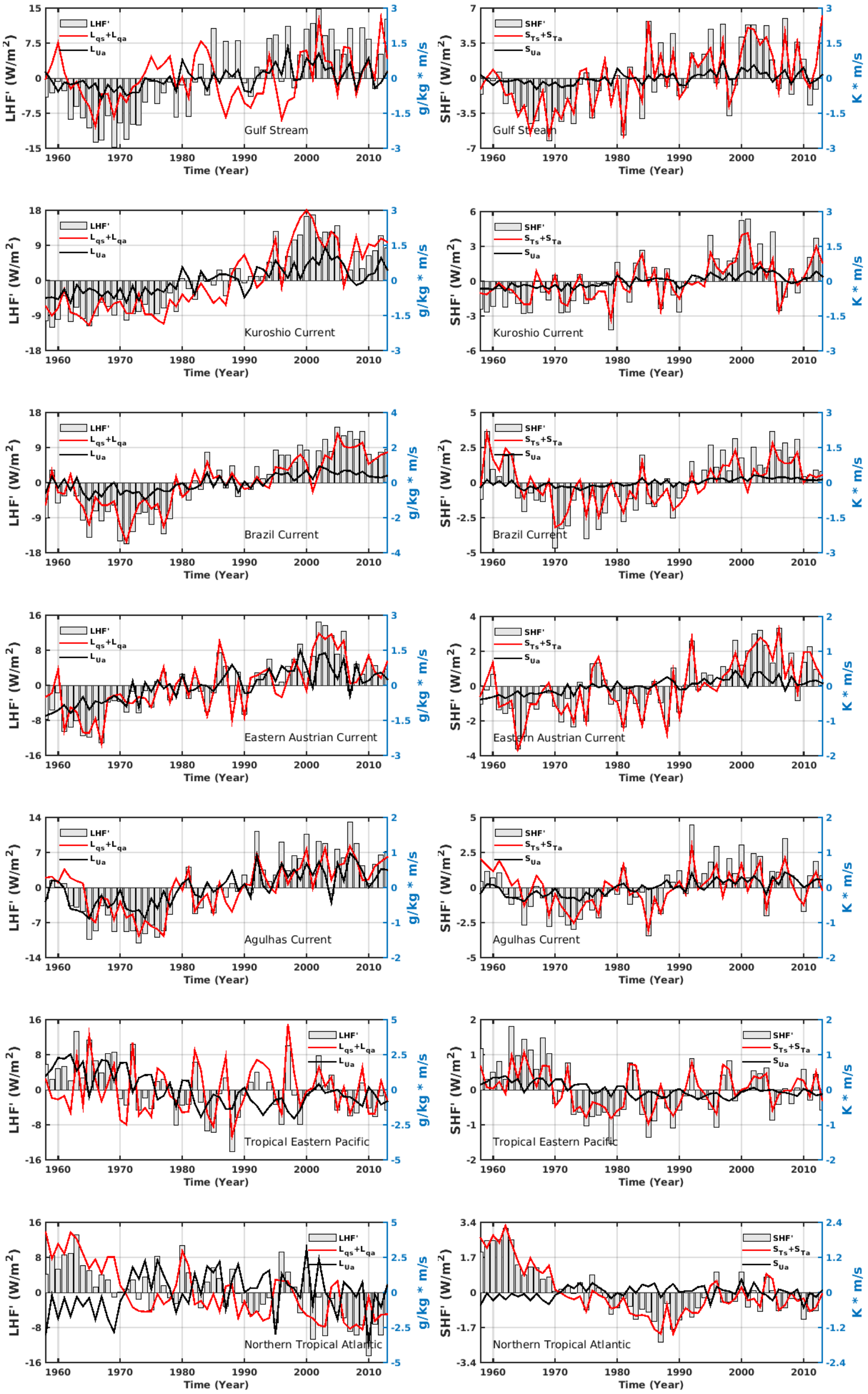

Fig. 4 Time series of area-averaged LHF and SHF anomalies (grey bar) and their corresponding contributors (red and black lines) over the identified regions (as shown in Figs. 1a).

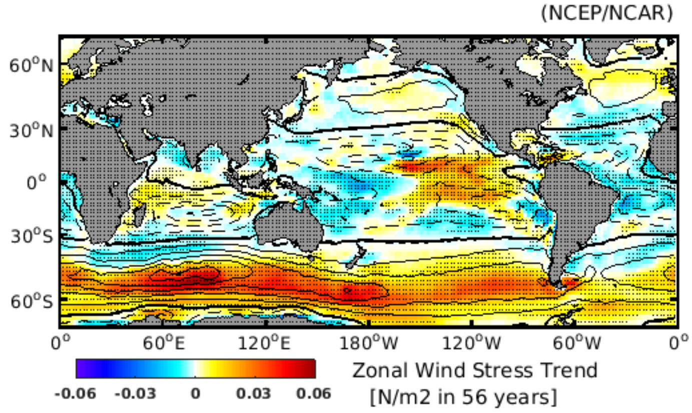

Fig. 5 Spatial distributions of the trend (shading, westerly-positive) and climatology (contours) of zonal wind stress. Easterly wind stress is in dash lines; westerly wind stress is in solid lines; zero zonal wind stress is bold.

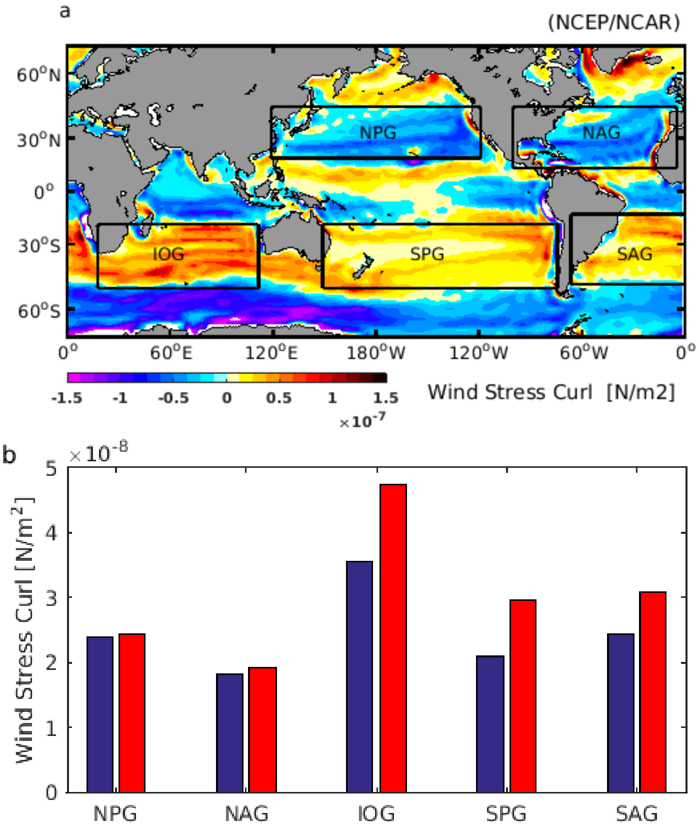

Fig. 6 a. Spatial distribution of the climatological ocean surface wind stress curl. The black rectangles locate the area where we compute the area-mean wind stress curl. b. Absolute values of area-mean wind stress curl over the corresponding subtropical gyres shown in the upper panel. Red and blue bars denote mean±trend/2. NPG stands for North Pacific Gyre, NAG stands for North Atlantic Gyre, IOG stands for India Ocean Gyre, SPG stands for South Pacific Gyre, SAG stands for South Atlantic Gyre.

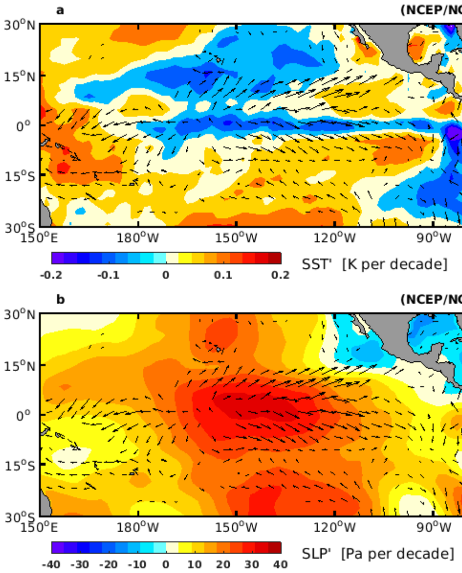

Fig. 7 Trends in surface wind (vectors), SLP (a, shading) and SST (b, shading) over the Pacific Ocean. We only show the wind trend above 90% confidence level (Student's *t*-test).

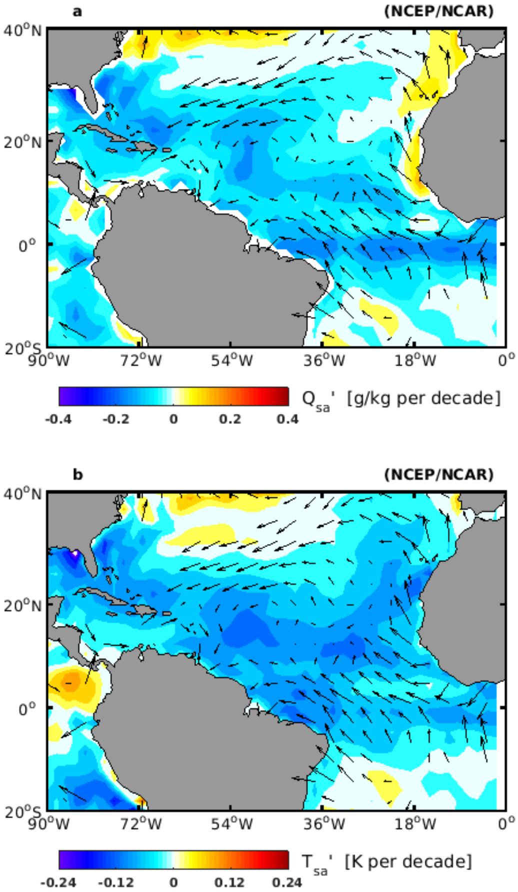

Fig. 8 Trends in surface wind (vectors), air-sea humidity difference (a, shading) and air-sea temperature difference (b, shading) over the Atlantic Ocean.

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