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Willy Anta Kusuma
*Physics Department, Faculty of Mathemathics and Natural Science, University of Sriwijaya, Palembang 30139, Indonesia*

Muhammad Nur
*Physics Department, Faculty of Mathemathics and Natural Science, University of Sriwijaya, Palembang 30139, Indonesia*

Mokhamad Yusup Nur Khakim
*Physics Department, Faculty of Mathemathics and Natural Science, University of Sriwijaya, Palembang 30139, Indonesia*

Iskhaq Iskandar
*Physics Department, Faculty of Mathemathics and Natural Science, University of Sriwijaya, Palembang 30139, Indonesia*, iskhaq@mipa.unsri.ac.id



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## Cover Page Footnote

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# Mixed-layer Heat Budget in Western and Eastern Tropical Pacific Ocean during El Niño Event in 2015/2016

Willy Anta Kusuma, Muhammad Nur, Mokhamad Yusup Nur Khakim, and Iskhaq Iskandar*

Physics Department, Faculty of Mathemathics and Natural Science, University of Sriwijaya, Palembang 30139, Indonesia

**E-mail: iskhaq@mipa.unsri.ac.id*

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## Abstract

Temporal variation of mixed-layer heat budget at two contrasting locations, namely, western Pacific (*warm water pool*) and eastern Pacific (*cold tongue*) during the extreme El Niño phenomenon in 2015/2016 is evaluated. Oceanic and atmospheric datasets, including sea surface temperature (SST), wind stress, shortwave radiation (SWR), longwave radiation, latent heat flux (LHF), and sensible heat flux are analyzed. A slight warming occurred in the eastern tropical Pacific associated with a positive SST anomaly, which reflected the weakening or reversal of the trade winds. Meanwhile, the western tropical Pacific exhibited a cooling tendency during the development phase of El Niño. Analysis of the mixed-layer heat budget shows that the net heat flux due to SWR and LHF significantly contributes to the warming of the eastern tropical Pacific. The contribution from horizontal advection was extremely small on both sides. The analysis shows that the residual term significantly contributes to cooling (warming) tendency observed in the western (eastern) tropical Pacific. This condition may suggest that residual process due to entrainment and diffusivity played an important role in the evolution of cooling (warming) process in the western (eastern) tropical Pacific.

*Keywords: air–sea interaction, climate change, El Niño, heat budget*

## Introduction

Air–sea interactions share an inseparable and important relationship in regulating the ocean heat budget, as reflected by variations in sea surface temperature (SST). Cronin and Sprintall [1], demonstrated that the warming of the ocean surface down to the base of the mixed layer is due to shortwave radiation (SWR) from sunlight, whereas the cooling process is due to longwave radiation (LWR) from the average global surface temperature, sensible heat flux (SHF) from the air temperature differences across the ocean surface, and latent heat flux (LHF) from the evaporation process. The heat balance generated by the air–sea interactions has become increasingly important and requires further observations to better evaluate this process, particularly during El Niño–Southern Oscillation events, which can significantly influence global climate change [2]. An El Niño event is usually associated with the weakening or reversal of the easterly trade winds in the Equatorial Pacific Ocean. This reversal of trade winds enhances downwelling Kelvin waves, shifting the warm pool (warm SST and high convection) to the eastern tropical Pacific. This condition results in relatively low and high rainfall in the western and eastern Pacific, respectively [3]. The abovementioned studies and other previous research on the Pacific Ocean heat budget have improved our understanding of oceanographic processes.

A recent study by Song and Yu [4] determined that heat flux diffusion, sun penetration, and zonal advection are the main factors that influence SST changes in the western Pacific. Meanwhile, in the eastern region, Pinker *et al*. [5] identified significant temporal (seasonal) variations in the LHF and SHF over the Pacific cold tongue. Pinker *et al*. [5] also suggested a relationship between SWR, which was affected by cloud cover, and LWR, which was affected by moisture. Furthermore, Abellan *et al.* [6] compared the mechanism of the 2015/2016 El Niño event with the 1997/1998 El Niño event and observed that the zonal winds along the equatorial Pacific during the 2015/2016 event had a lower intensity than those during the 1997/1998 event. However, they found significant meridional activity during the 2015/2016 event compared with that of the 1997/1998 event. The importance of the zonal and meridional winds have been reported by Guan *et al.* [7].

This study aims to evaluate mixed-layer heat balance in the warm pool and cold tongue regions during the evolution of the 2015/2016 El Niño event. The paper is organized as follows. The datasets and analytical methods are described in section 2. In section 3, heat balance of the mixed layer in the western and eastern equatorial Pacific during the 2015/2016 El Niño event are compared and discussed. The final section summarizes and concludes the main findings of this study.

## Data and Methods

The SST and wind stress data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). Both datasets have a daily temporal resolution and spatial resolution of 0.25° × 0.25° and cover the period from January 1, 1995 to December 31, 2016. The zonal and meridional current data were obtained from the Ocean Surface Current Analyses Real-time (OSCAR). The OSCAR data comprise ocean current flow observations at 15 m depth with a spatial resolution of 0.33° × 0.33°. It is available on the daily time series from January 1, 1995 to December 31, 2016. The daily time series of the atmospheric flux data containing SWR, LWR, SHF, and LHF, which were from the TropFlux project by ESSO-Indian National Centre for Ocean Information Services, are also used in this study. These atmospheric flux data have a spatial resolution of 1° × 1°. Furthermore, subsurface temperature and salinity data from in-situ observations obtained by the Tropical Atmosphere–Ocean (TAO) buoy array located at 137 °E, 2 °N, and 110 °W, 0° were used (Figure 1). The TAO provided temperature and salinity data from the ocean surface to 500 m depth. All spatial data used (i.e., SST, heat flux, winds, and ocean currents) covered the tropical Pacific Ocean.

First, the daily climatology for all parameters were calculated for the period from January 1, 1995 to December 31, 2016. The climatological values represent normal climate conditions in the Pacific Ocean. Then, the anomalies were calculated by subtracting these climatological values from the daily time series, followed by smoothing of the anomaly data using a 15 d running average. Note that the resulting SST anomaly values are being used for calculating Niño 3.4 index to describe the evolution of El Niño 2015/2016.

Following Iskandar *et al*. [8], we calculate the heat budget within the mixed layer during the 2015/2016 El Niño event as

$$\frac{\partial T}{\partial t} = \frac{Q_0 + Q_{pen}}{\rho C_p h} - h\bar{v}.\nabla T + R \quad , \qquad (1)$$

where $h$ is the thickness of the mixed layer, $\frac{\partial T}{\partial t}$ is the heat storage estimated by using ECMWF SST, $Q_0$ is net surface heat flux across the air–sea interface, $Q_{pen}$ is the heat loss due to SWR penetration below the mixed layer, $\rho$ is the density of sea water (1022.4 kg/m$^3$), $C_p$ is the heat capacity (3940 J/°C/kg), $R$ is a residual term, and $\bar{v}$ and $T$ are mixed-layer temperature and horizontal velocity, respectively. The three terms on the right-hand side represent the atmospheric heating, horizontal advection, and residual components. The atmospheric heating term captures how the atmospheric flux influences air–sea interactions, and the horizontal advection term captures how large-scale ocean currents influence the SST conditions. We assume that the residual term incorporates the parameters that could not be estimated from the data, which are inferred through nonlinear processes, such as vertical mixing from the bottom and vertical diffusivity. The mixed-layer thickness ($h$) was computed by density criterion in

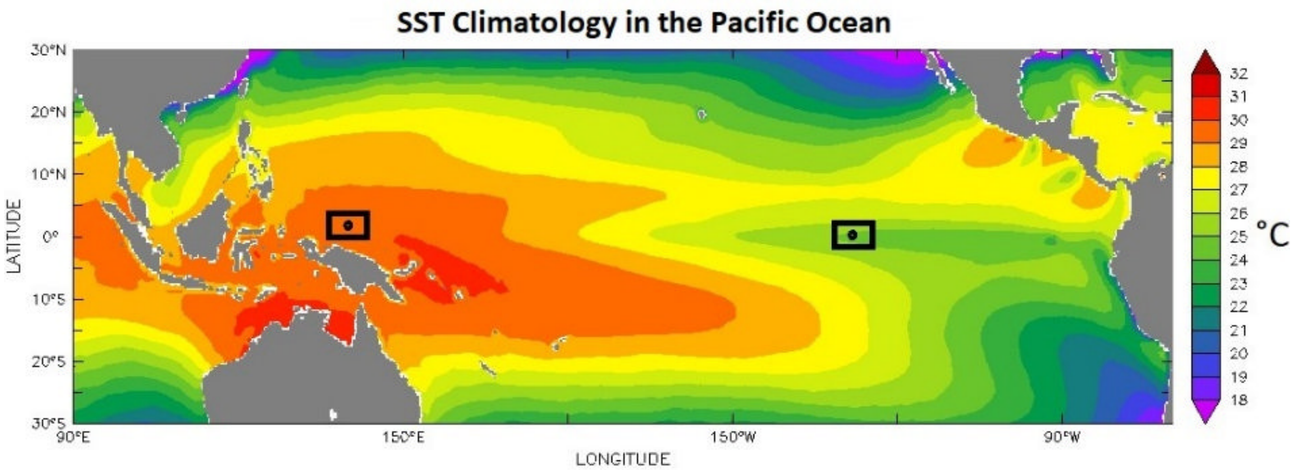


**Figure 1. Map of Mean Sea Surface Temperature during December–January–February season; Box for Calculating Heat Budget in the Western Region (140°–134° W, 0°–4° N) and that in the Eastern Region (113°–107°W, 2°S–2°N) are Shown with the Buoy Stations (dot) on 137° E, 2° N, and 110° W, 0°**

which the thickness is defined by specifying a density difference of 0.125 kg m$^{-3}$, and the density data from the TAO Buoy data, following Bosc *et al.*'s work [9]

Local storage in Eq. (1) was estimated using the SST data. We calculated $Q_0$ by summing the heat flux parameters across the air–sea interface as

$$Q_0 = (1-\alpha)Q_{SWR} + Q_{LWR} + Q_{LHF} + Q_{SHF}, \quad (2)$$

where $\alpha$ is the albedo with a constant value of 0.055 based on the work of Iskandar *et al.* [8], $Q_{SWR}$ is the incoming SWR heat flux, $Q_{LWR}$ is the LWR heat flux, $Q_{SHF}$ is the SHF, and $Q_{LHF}$ is the LHF. We defined $Q_{pen}$ as $Q_{pen} = -0.47Q_{SWR}\exp(-\gamma h)$ following Wang and McPhaden [10], with a gamma value of 0.004/m.

We estimated the horizontal advection based on Lee *et al.*'s work as follows [11]:

$$\overline{v}.\nabla T = \frac{(u_w \delta T_w) + (u_e \delta T_e)}{\Delta x} + \frac{(v_s\ \delta T_s) + (v_n\ \delta T_n)}{\Delta y} \quad ,(3)$$

where $u$ and $v$ are the zonal and meridional averaged velocity currents, respectively, calculated using the OSCAR data. $\delta T$ is the average SST difference between the boundary and average SST anomaly in the regions of interest. $\Delta x$ and $\Delta y$ are the distances along the zonal and meridional boundaries in the regions of interest, respectively. *w*, *e*, *s*, and *n* subscripts represent the western, eastern, southern, and northern boundaries of the regions of interest, respectively. We selected our regions of interest based on the SST characteristic in the western (warm pool region) and eastern (cold tongue region) Pacific. The western region is bounded by 140°–134°W, 0°–4°N, while the eastern region is bounded by 113°–107°W, 2°S–2°N.

## Results and Discussion

**Evolution of 2015/2016 El Niño Event.** The El Niño phenomenon was identified by examining the evolution of averaged SST anomaly within the region bounded by 170°–120°W and 5°S–5°N, which is known as the Niño 3.4 index. The daily time series of this index for the January 1, 2015–December 31, 2016 period is shown in Figure 2, Niño 3.4 Index. We identified the early evolution of the 2015/2016 El Niño event in May 2015, as indicated by the earliest positive deviation (highlighted in red in Figure 2). The peak evolution of the 2015/2016 El Niño event occurred in November 2015, when a positive deviation of 3 °C was observed. The 2015/2016 El Niño event lasted for 12 months, ending in April 2016.

Spatiotemporal variations of the SST and wind stress anomalies are shown in Figure 3. Consistent with Niño 3.4, we observed the weakening or reversal of the surface winds in the Equatorial Pacific by May 2015. This condition is the main factor in the warming process in the eastern tropical Pacific. The reversal of the trade winds into westerly wind anomaly generated downwelling equatorial Kelvin waves and reduced the upwelling in the eastern tropical Pacific. We observed increasing westerly wind activity followed by a warming SST anomaly in the eastern tropical Pacific by June 2015, whereas the western tropical Pacific experienced a continuous cooling tendency. These conditions continued in the following months, reaching their peak in November 2015. We identified a strong warming tendency in the eastern tropical Pacific that was defined by a positive SST anomaly in the eastern equatorial Pacific, with average values of up to 3 °C when the 2015/2016 El Niño event reached its peak in November 2015. This warming was associated with strong westerly wind burst events, which played an important role in maintaining

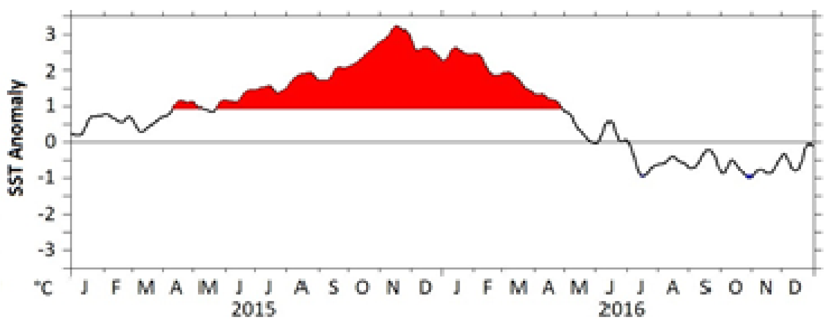


**Figure 2. Daily Time Series of Niño 3.4 Index for January 1, 2015–December 31, 2016 Period. The Niño 3.4 Index is Defined based on the Averaged SST Anomaly within the Region Bounded by 170°–120°W and 5° S–5°N. The Red Values Indicate the El Niño Event, whereas the Blue Values Indicate the La Niña Event. The Time Series was Smoothed Using a 15 d Running Average**

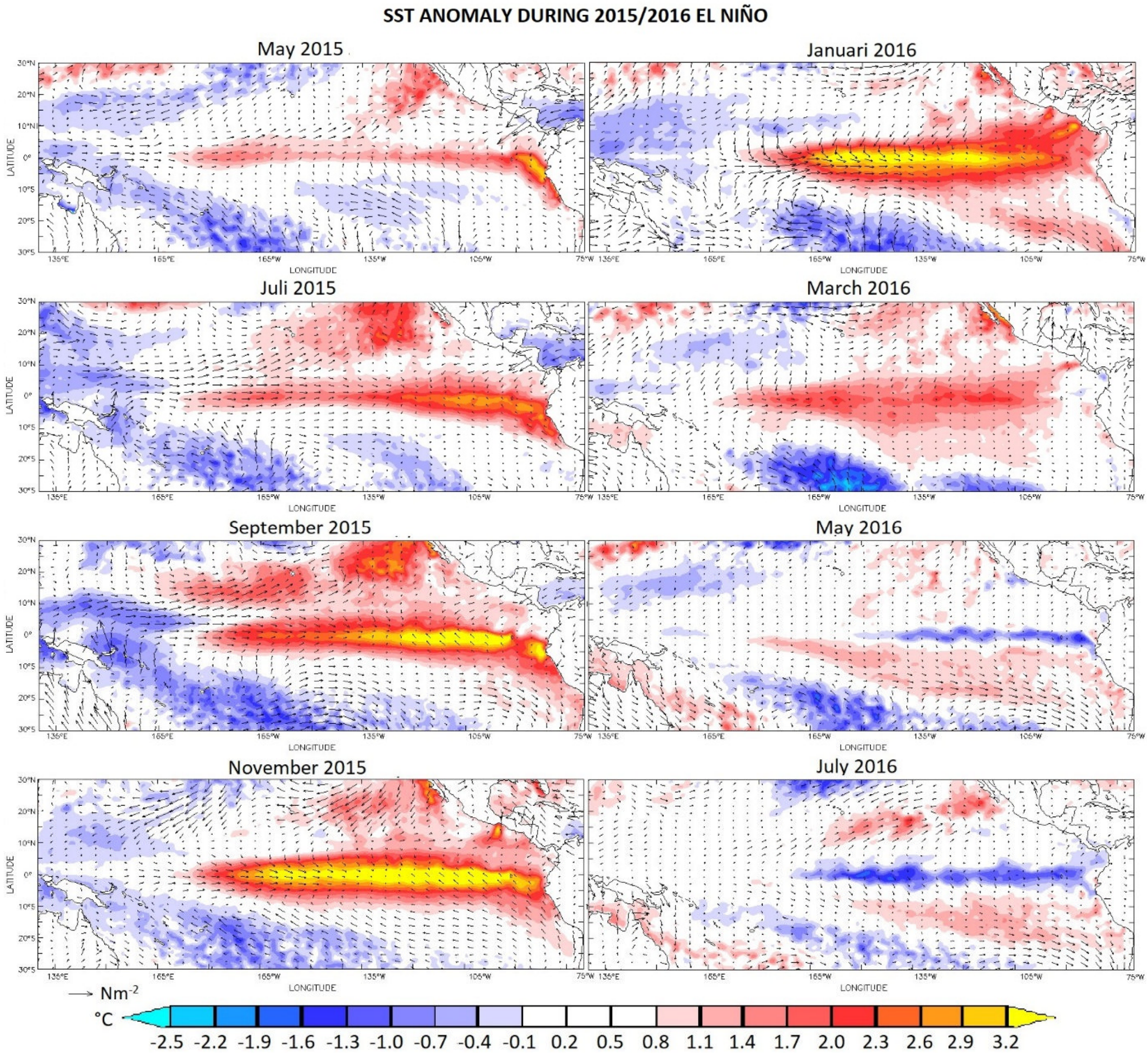


**Figure 3. Monthly SST (colors) and Wind Stress (Vectors) Anomalies. The Anomaly Values are Obtained by Subtracting the Mean Climatologies from their Monthly Values for the January 1, 1995–December 31, 2016 Period**

the warming tendency during the 2015/2016 El Niño event. The 2015/2016 El Niño event ended in May 2016, as indicated by the observed cooling tendency in the eastern equatorial Pacific. This cooling was likely related to the equatorial upwelling as the trade wind activity returned to its pre-El Niño conditions.

**Mixed-layer Depth Heat Budgets.** Figures 4**A** and 4**B** show the temporal variations of the mixed-layer heat balance for the January 1, 2015–December 31, 2016 period in the two regions of interest. The mixed-layer heat balance in the western Pacific exhibited a cooling tendency owing to the heat storage fluctuations from the early El Niño development in May 2015 to its mature phase in November 2015. This cooling tendency was closely related to a large reduction of the net heat flux during this period. During the mature phase of the 2015/2016 El Niño event, the cooling tendency in the western tropical Pacific was closely related to the cooling by the residual term as the heat flux tend to warm the ocean. The 2015/2016 El Niño event weakened by March 2016, characterized by a warming tendency. Note that the contribution from horizontal advection in this region was negligible.

In the eastern tropical Pacific, no significant heat changes were observed during the development phase of the 2015/2016 El Niño event from May to July 2015.

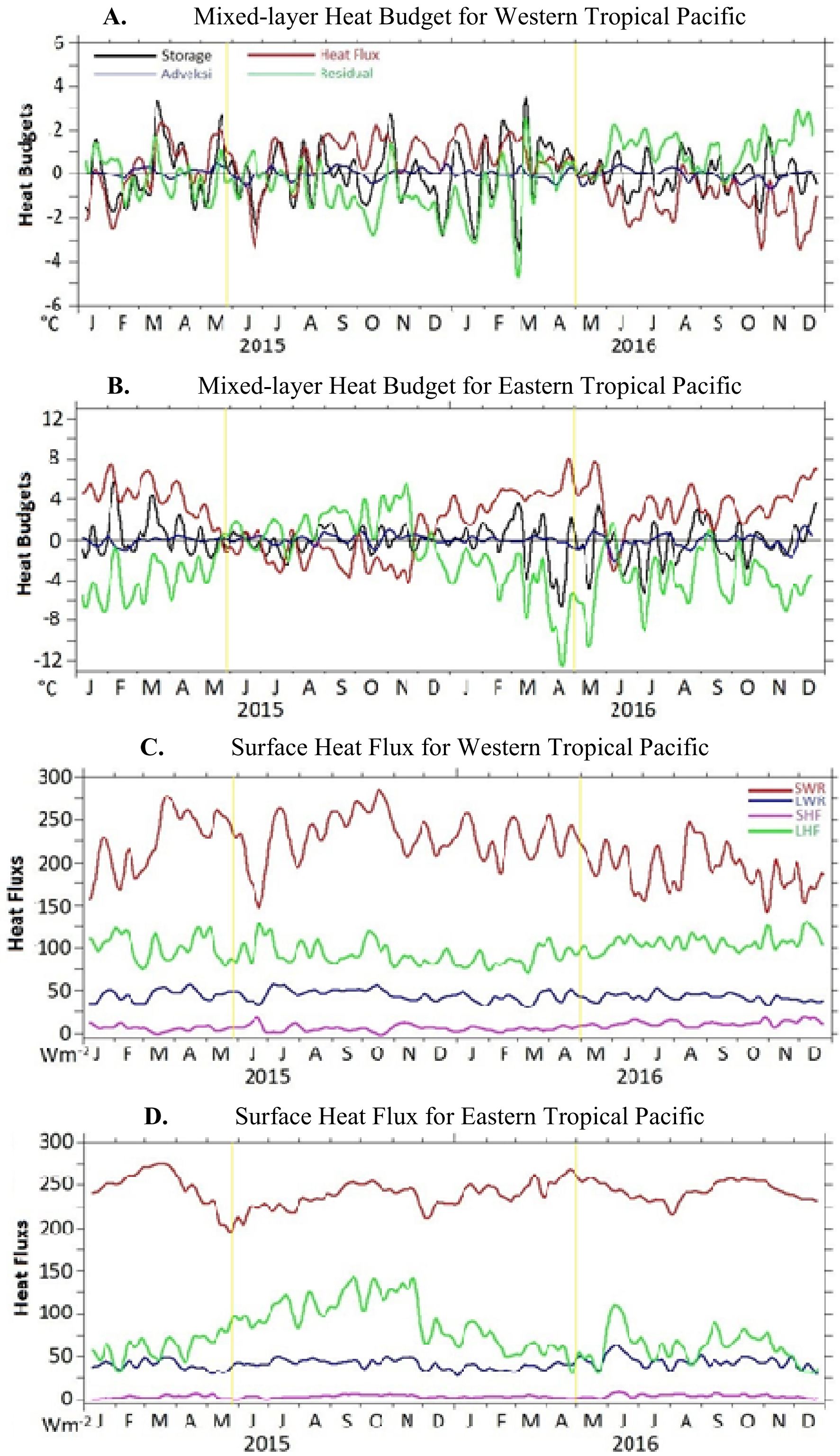


**Figure 4. Daily Time Series of A) Western and B) Eastern Pacific Heat Budgets. The Heat Budgets Contain Heat Storage (*Black*), Heat flux (*Red*), Horizontal Advection (*Blue*), and Residual (*Green*) Components. C) Western and D) Eastern Pacific Surface Heat Fluxes, i.e., SWR (*Red*), LWR (*Blue*), LHF (*Green*), and SHF (*Purple*). All Values in Figure 4 are Averaged Across the Regions Bounded by 0–4°N and 140°–134°W (Western Pacific), and 2°S–2°N and 113°–107°W (Eastern Pacific), Followed by Smoothing with a 15 d Running Average. The Development and Termination Phases of the El Niño Event 2015/2016 are Bounded by a Vertical Yellow Line**

The warming tendency induced by the residual term was balanced by the cooling tendency due to reduced surface heat flux (Figure 4**B**). A short warming occurred in August 2015 as the heat flux was significantly reduced and the residual term, which may be associated with downwelling Kelvin waves, tends to warm the eastern tropical Pacific. No significant change in the heat budget was observed during the mature phase of the event. During the termination of the event from March to May 2016, the residual term associated with strong upwelling cooled the eastern tropical Pacific although the surface heat flux tended to warm the ocean.

**Surface heat flux.** Figures 4**C** and 4**D** show the temporal variations of the heat flux parameters (e.g., SWR, LWR, LHF, and SHF). As indicated, SWR dominated the surface heat flux variations in the western and eastern tropical Pacific during the evolution of the 2015/16 El Niño event, with secondary contribution coming from the LHF. Note that both the SWR and LHF in the western tropical Pacific indicated high temporal variation during the evolution of the event and the surface heat flux greatly mimicked the SWR (Figure 4**A**). However, in the eastern tropical Pacific, only LHF showed high temporal variations and the changes in the surface heat flux followed the variations of the LHF.

**Horizontal advection**. The temporal variations in horizontal advection are shown in Figure 5, where the values shown in Figure 4 have been separated into their zonal heat and meridional heat components for the period from January 1, 2015 to December 31, 2016 in the two regions of interest. No significant advection activity (zonal or meridional) was observed in the western tropical Pacific (Figure 5A), which was expected due to the low current activity in this region. However, large fluctuations are observed in the eastern tropical Pacific (Figure 5**B**), with a peak in the zonal advection observed during the El Niño peak in November 2015. Strong zonal and meridional advection fluctuations are also observed after the end of the El Niño event in July 2016 (Figure 5**B**), suggesting that advection may play an important role in the cooling SST trends.

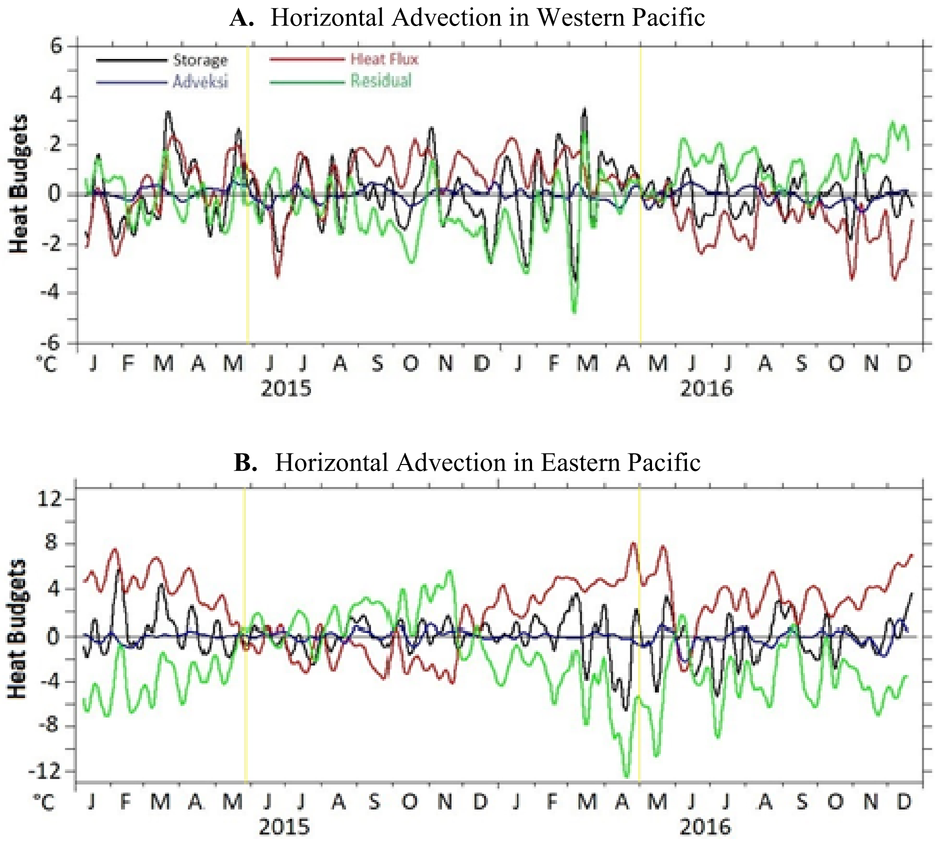


**Figure 5. Same as Figure 4 Except for Horizontal Advection in A) Western and B) Eastern Pacific. Note that the Horizontal Advection Contains Zonal (*Red*) and Meridional (*Blue*) Components. All Values in Figure 4 are Calculated Across the Regions Bounded by 0–4°N and 140°–134°W (Western Pacific), and 2°S–2°N and 113°–107°W (Eastern Pacific), Followed by Smoothing with a 15 d Running Average. The Development and Termination Phases of the El Niño 2015/2016 Event are Bounded by Yellow Vertical Lines**

## Conclusion

The analysis of the evolution of the El Niño 2015/2016 event shows that the trade wind variations along the equatorial Pacific have become the keys for the mechanism of warming and cooling SST anomaly in the eastern and western tropical Pacific. In addition, a significant heat flux contribution was observed for warming (cooling) SST in the eastern (western) tropical Pacific during the development phase of the El Niño event. The SWR was a major contributor to the surface heat flux variability in the western and eastern tropical Pacific. In the eastern side, the LHF also had a significant influence on the surface heat flux variations. Furthermore, the horizontal advection contributed to the mixed-layer heat budget only in the eastern tropical Pacific. A residual term (vertical entrainment) played an important role in the mixed-layer heat budgets in those two regions, especially in the eastern tropical Pacific during the termination phase of the El Niño event.

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