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Variability of Heat Budget Parameters and Their Relation to Sea Surface Temperature over Central Equatorial Pacific Ocean

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Abstract

The Central Pacific Ocean (CPO) is an important area for the manifestation of El Niño/La Niña. In this paper, heat budget parameters over the CPO region (5˚N-5˚S; 120˚W-170˚W), and their relation with Sea Surface Temperature (SST) are examined with the National Centre for Environmental Prediction (NCEP) reanalysis data for the period 1979 to 2013. The heat budget parameters over CPO reveal that the seasonal change of NHF is observed with a minimum peak in March and maximum peak in December; the heat loss at the sea surface in winter is less than in summer. The variations in heat budget parameters are following El Niño and La Niña phenomena. The results reveal that the seasonal variation of net radiation and heat budget parameters are indicating decrease trend, whereas net heat flux shows an increasing trend. Sea Surface Temperature is having a positive correlation with net heat flux (0.43) and a negative correlation with net radiation (−0.61) and heat budget (−0.67). In the ENSO years, net radiation and heat budget are significant inverse relation with SST, whereas the net heat flux depicts is a positive correlation.

Subject Areas

Atmospheric Sciences

Keywords

Central Pacific Ocean, Heat Budget Parameters, SST, El Niño/La Niña, NCEP Reanalysis

1. Introduction

Solar radiation, which is stored in the ocean, regulates the earth's climate. Therefore, a compressive understanding of the variation of oceanic heat budget is having great significance in climate change. The area of equatorial Pacific Ocean is a sensitive part of global ocean dynamics, including the warming of the sea viz. Western Pacific Ocean warm pool, especially has a great influence on the climatic system. The best performance of ocean climate characteristics is the SST and ocean circulation. Ocean circulation plays a vital role in heat transport. Heat distribution affects the local and global climate. SST is one of the main indices to regulate the ocean's thermal state. Abnormal changes in ocean heat will be the source of variations in not only ocean circulation but also atmospheric circulation. Therefore, the study on heat parameters deepens the understanding of the SST over the equatorial Pacific Ocean.

The most important part of several research experiments was conducted for a better understanding of ocean-atmosphere interaction and its influence on circulation patterns. Tally [1] estimated the heat transfer values using the Bunker method over the Pacific Ocean [2]. Zhu and Yang [3] had shown in the ECMWRF reanalysis data that the air-sea heat exchange anomaly during El Niño in 1983 has a good relationship with the wind. Cayan [4] studied the abnormal changes of latent and sensible heat fluxes of the North Pacific and North Atlantic in relation to monthly mean atmospheric circulation and the SST anomaly. Yan [5] analyzed the characteristics of heat flux changes to get the distribution of heat balance in different months. Yan used the observational data during the 1998 South China Sea Monsoon Experiment and discussed the heat flux changes before and after the monsoon [6]. The sea surface net heat loss of Kuroshio and its extension area increased significantly in the 1990s due to latent and sensible heat fluxes [7].

The variation of equatorial Pacific Ocean thermal equilibrium state is related to the El Niño phenomenon, with further research, the thermal equilibrium state in the equatorial Pacific is bound to become a hot spot. The data that previous studies used are often too obsolete and may not be applicable to the research in recent years. The ocean is open fluid; the heat budget is going to affect the surrounding waters. The El Niño Modoki involves ocean-atmosphere coupled processes. The ENSO Modoki events significantly influence the temperature and precipitation over many parts of the globe in recent decades [8]. Therefore, in this paper, a compressive analysis of heat budget parameters in the Central Pacific Ocean (CPO), their relation, influence and impact on SST. It is well known that SST mainly depends on the heat budget such as net shortwave radiation (NSW), however this work has been done to find out which heat budget parameter influences the modifications on SST and has been verified and presented the relationship.

2. Area of Study and Data

The area of study is CPO ranging 5˚N-5˚S, 120˚W-170˚W. CPO is the important area for manifestation of El Niño Modiki in recent years. Due to El Niño, the circulation pattern is changing and leads to weakening of monsoon circulation, which leads to deficit in rainfall over Indian subcontinent during summer season [9] [10]. In order to a better understand the variations of surface heat flux, NCEP monthly reanalysis data [11] during El Niño and La Niña events are used for a period of 1979 to 2013. This study mainly refers to the most advanced COARE 3 calculation scheme, to understand the characteristics of CPO by using independent variables (wind speed, sea surface temperature and air temperature, sea and air relative humidity) to calculate heat flux.

3. Methodology

The latent heat flux (LHF) calculation:

$$\text{LHF} = \rho_a L_v C_l u \left(q_s - q_a \right) \tag{1}$$

where ρ_a is density of moist air, $\rho_a = 1.225\ \text{kg/m}^3$; L_v is Latent heat of evaporation, $L_v = 2.5 \times 10^6\ \text{J/kg}$, C_l is the air-sea moisture exchange coefficient, $C_l = 1.2 \times 10^{-3}$; u is the wind speed at 10 m layer of horizontal at sea; q_s and q_a denote the sea surface relative humidity and air relative humidity.

$$q_a = 0.622 \times \frac{e_a}{p - 0.387 e_a} \tag{2}$$

$$q_s = 0.98 \times q_{sae} \left(T_s \right) \tag{3}$$

where e_a is saturated vapour pressure; q_{sae} is the relative humidity when the temperature equal sea surface temperature; The constant 0.98, when salinity is 34, the vapour pressure of the sea will decrease, so the air-sea present unsaturated relative humidity, is reduced by 2%.

$$e_a = 6.11 \times 10^{\frac{7.5 T_a}{273 + T_a}} \tag{4}$$

The sensible heat flux (SHF) calculation:

$$\text{SHF} = \rho_a C_{pa} C_s u \left(T_s - T_a \right) \tag{5}$$

where C_{pa} is air specific heat at constant pressure, $C_{pa} = 1004.67$; C_s is the air-sea moisture exchange coefficient, $C_s = 1.0 \times 10^{-3}$; T_s is sea surface temperature; T_a is air temperature.

The surface heat budget (HB) can be given as follows

$$\text{NR} = \text{NSW} - \text{NLW}$$

$$\text{NHF} = \text{LH} + \text{SHF}$$

$$\text{HB} = \text{NR} - \text{NHF} \tag{6}$$

where, NSW is net shortwave radiation, NLW is net long wave radiation, LHF is latent heat flux, SHF is sensible heat flux, NR is net radiation, NHF is net heat fluxes. The main aim of this article is to find the relation between the heat budget parameters and SST. For this study, we are considering only atmosphere parameters, so advection term is not included in heat budget calculation.

4. Results and Discussion

4.1. Variations of Heat Budget Parameters over CPO

The spatial distribution of the climatological monthly heat budget over CPO for the period of 1979-2013 is depicted in **Figure 1**. The annual variation of the heat budget is higher during all months except from May to July. In general, the manifestation of El Niño starts in September and the heat budget is becoming higher until April. Heat budget variations are clearly observed in the annual cycle during El Niño depicted in **Figure 2** and in La Niña years given in **Figure 3**. The sea surface heat balance and components in CPO have obvious spatial distribution characteristics.

4.2. Seasonal and Interannual Variations

The monthly, seasonal and annual variations of NR (Net Radiation), NHF (Net Heat Flux), HB (Heat Budget) and SST (Sea Surface Temperature) over CPO are illustrated in **Figure 4** for the study period. In this article, the positive heat flux value means the ocean gain heat and the negative means the ocean loses heat. **Figure 4** reveals that HB and NR are having an inverse relation (−0.56 and −0.54) with SST, however, NHF is having positive relation with SST (0.27).From **Figure 4**, NR indicates the seasonal variation and higher values are attained in the autumn, however, spring and winter seasons illustrate lower values. During the study period, NR is indicating an increasing trend. The lowest NR (206 W/m^2) was observed in the spring season of 1990 and the maximum in the autumn season of 1999. NHF is showing a different scenario when compared with NR, the higher values are obtained at different seasons, however, NHF is indicating an increasing trend.

The minimum NHF (87 $W \cdot m^{-2}$) can be seen on autumn season of 1979 and maximum NHF (169 $W \cdot m^{-2}$) is in the autumn season of 2002. Higher and lower values of NHF reveal that the evaporation or heat transfer is different at different seasons and also depends on the El Niño/La Niña years. HB is showing a decreasing trend. Higher HB can be seen in the autumn and winter seasons and lower HB before 1997 in winter season. However lower values are in the summer season after 1997. As 1997 is a strong El Niño year, it changed the seasonal minimum from winter to summer.SST is ranging from 25.17˚C in the 1998 winter season to 29.01˚C in the winter season of 1997. SST variations in the winter season are the main to determine the El Niño/La Niña. The lower values of SST in the winter season indicating La Niña year, however the winter maximum in El Niño year. The relation between above mentioned parameters will be discussed in detail in further sections.

In normal years, southeast trade flourish in Pacific. Equatorial surface wind transport the warm surface water to the western Pacific, accumulate water to the western Pacific, so that the sea level rise and water temperature increase. When the southeast trade winds abnormal strengthen, the water in the equatorial eastern Pacific Ocean turn over strongly and have fewer precipitation anomaly. The

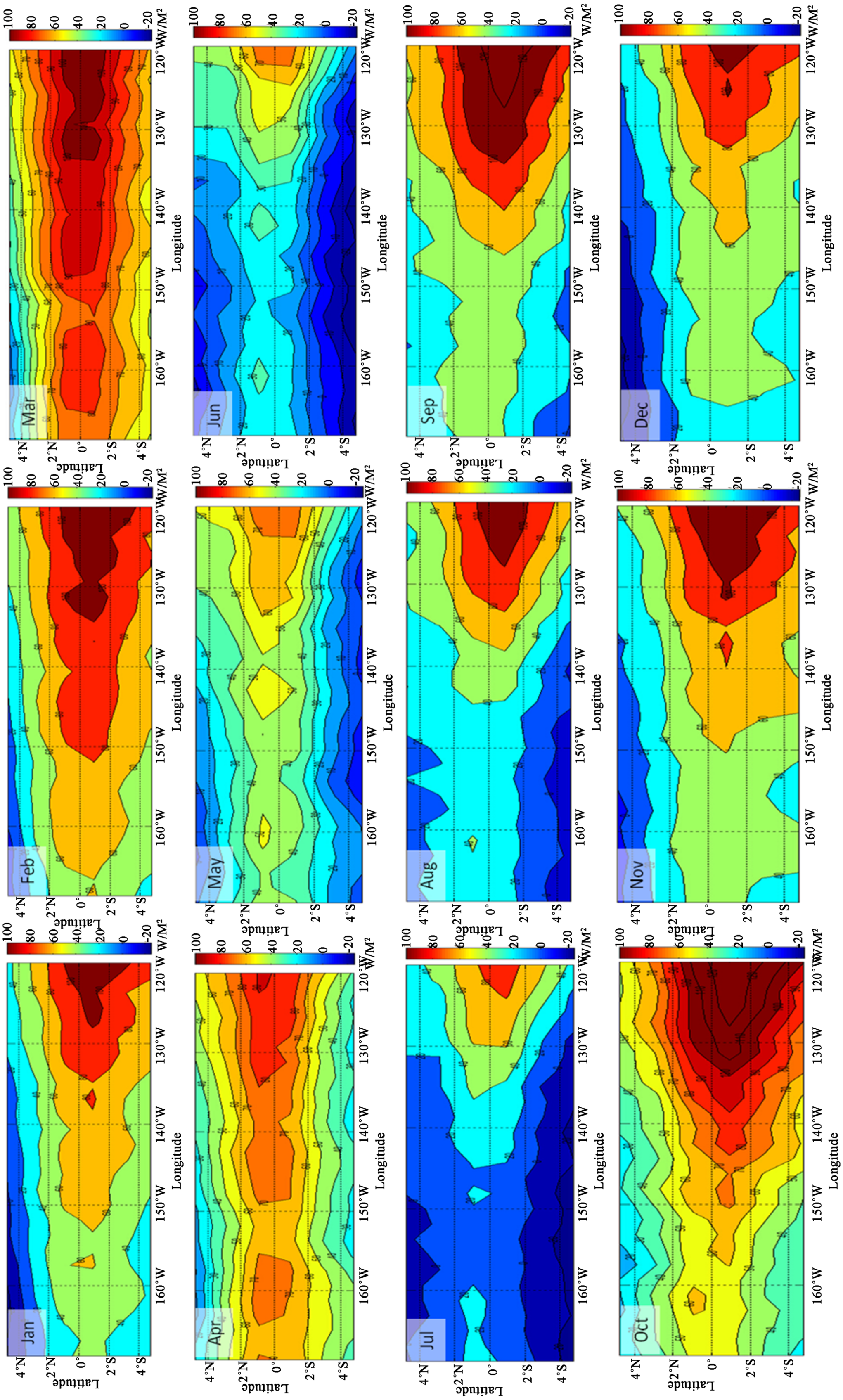

Figure 1. Climatology of monthly variations of heat budget over the Central Pacific Ocean.

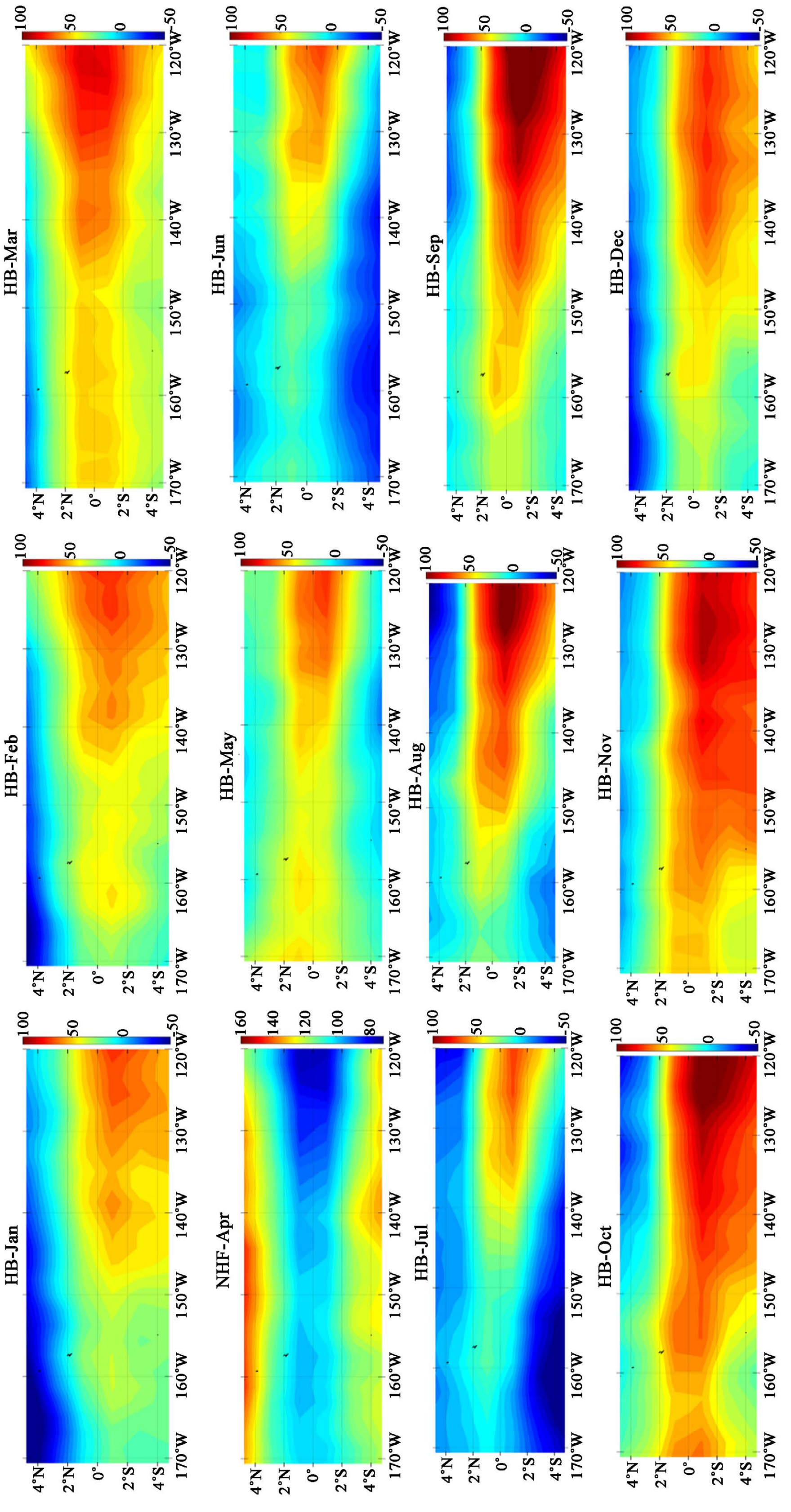

Figure 2. Climatology of monthly variations of heat budget over the Central Pacific Ocean during El Niño years.

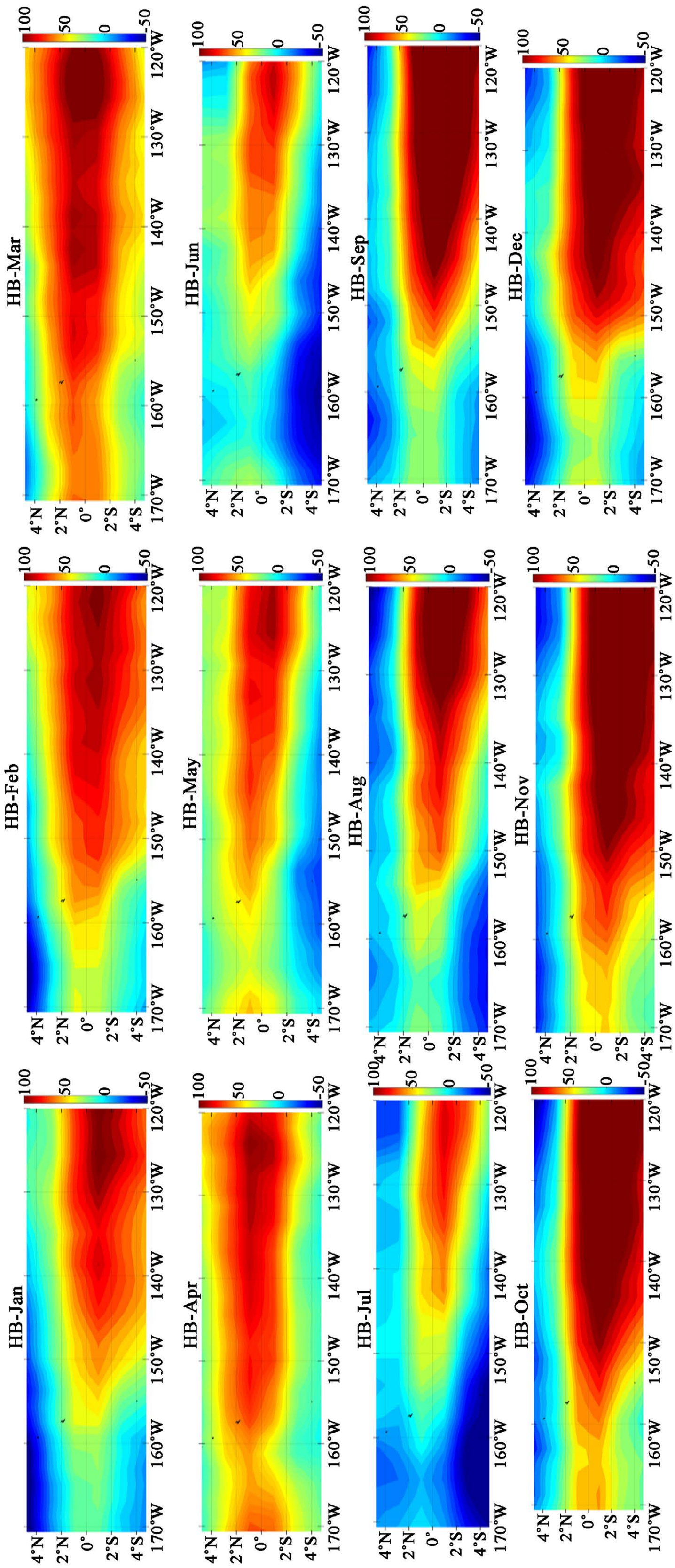

Figure 3. Climatology of monthly variations of heat budget over the Central Pacific Ocean during La Niña years.

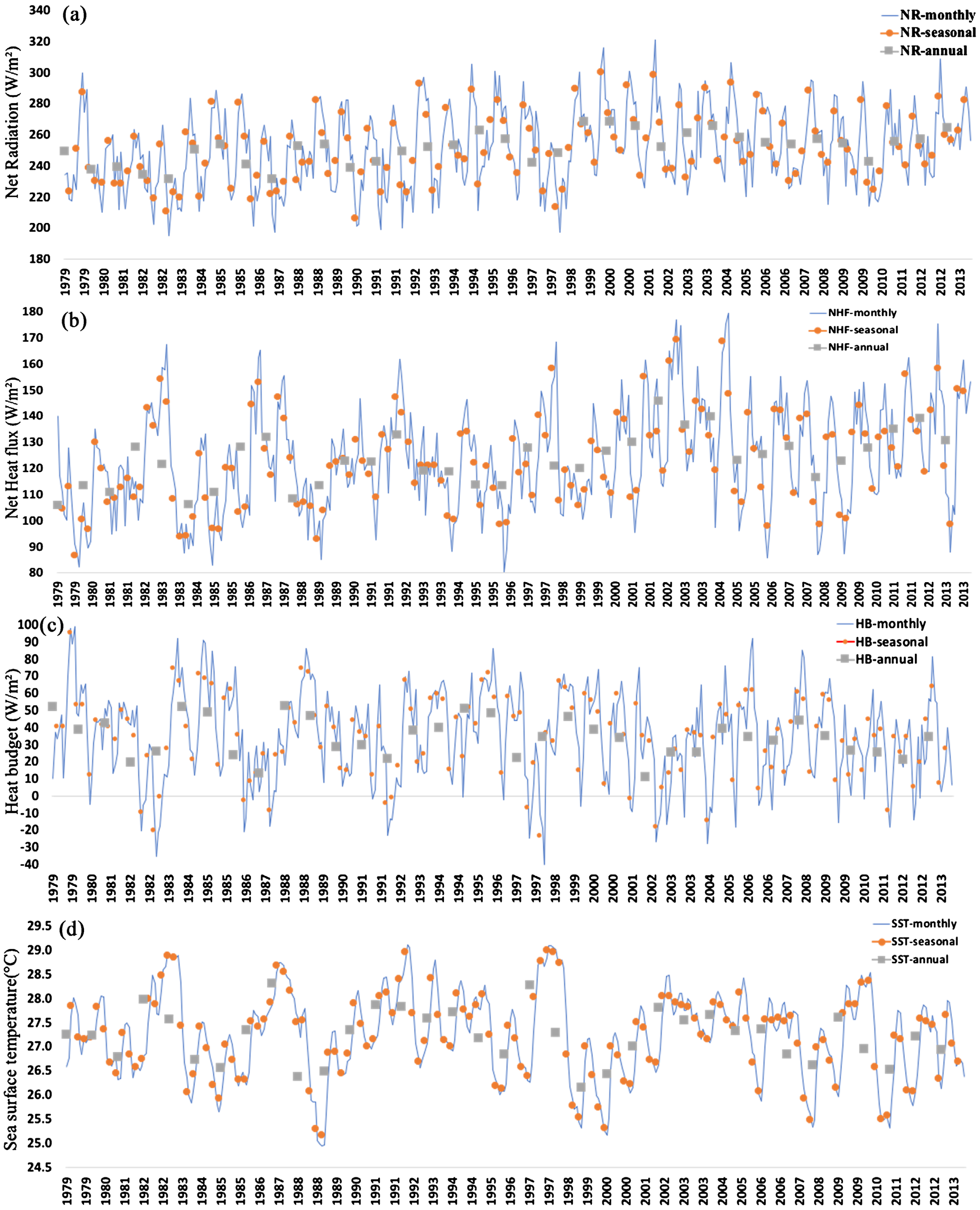

Figure 4. Variation of budget parameters at different scales for (a) Net Radiation ($W \cdot m^{-2}$); (b) Net Heat Flux ($W \cdot m^{-2}$); (c) Heat Budget ($W \cdot m^{-2}$); (d) Sea Surface Temperature (˚C).

temperature of equatorial western Pacific Ocean anomaly is high and more precipitation anomaly in La Niña events. But every a few years, the southeast trade winds is abated, the phenomenon which cold water turn over in eastern Pacific disappears, warm surface water reflux toward to east side. It result the temperature and sea level in the eastern equatorial Pacific sea surface rises. The cold ocean currents at coast of Peru and Ecuador turn into warm currents. At the same time, the drought climate change into the rainy weather, even causing flooding, this is El Niño.

The average heat budget of 2008 is 58.4 $W \cdot m^{-2}$, 59.1 W/m^2 in 2009, 59.8 W/m^2 in 2010, 50.4 $W \cdot m^{-2}$ in 2011 and 67.2 $W \cdot m^{-2}$ in 2012. The annual average heat budget in 2008-2009 gradually raise, sharp decrease in 2011, and increased in 2012. The average annual maximum value of heat budget is in 2012, the average minimum value of heat budget in 2011, differ 16.8 $W \cdot m^{-2}$. The spatial distribution of equatorial Pacific sea surface heat flux the heat budget of Nino 3.4 (160˚W-170˚W) in 2011 even appeared negative value, which means that the area is in a state of losing heat. From the analysis of the above, the year of 2011 is a typical La Niña year, and the year of 2012 is a typical El Niño year. So heat budget parameter variations also important to study about the El Niño/La Niña phenomena. One can understand the features with the heat budget parameters are influencing the walker circulation, which affecting the other circulations patterns. This study gives the variation of heat budget parameters over CPO.

4.3. Relation between SST and Heat Budget Parameters

Figure 5 divulges that NR and HB are having inverse relation with SST the correlation coefficients (CC) are −0.58 and −0.59 respectively, however NHF illustrate a positive relation with CC of 0.39. The relation between SST and NR, NHF and HB are clearly demonstrated that NR and HB are having inverse relation, where as NHF having positive relation with SST.

This indicates that, when NR increases SST becoming warmer and the evaporation increases and the transfer of heat is from Ocean to atmosphere leading to increase in NHF.

Table 1 presents the correlation of Heat Budget parameters during El Niño, Neutral and La Niña years During El Niño years, NR and HB having significant inverse relation and NHF is having a positive relation. During El Niño years, warm water prevails over this region. NHF is having relation with SST but it is not significant. Mainly the sensible heat flux is higher so NHF is higher. In the neutral years, NR having inverse relation which is not significant, however NHF having positive relation with SST and HB is having significant negative relation. Over the study region, higher temperature water appears which increases NHF and having significant relation with SST. In La Niña years, NR is dominant factor and having significant inverse relation with SST. However, HB is having inverse relation and NHF almost don’t have any relation with SST. This may be due to cooler SST prevails over the study area and higher NR needed to increase the temperature. The ocean and atmosphere temperatures are almost similar so

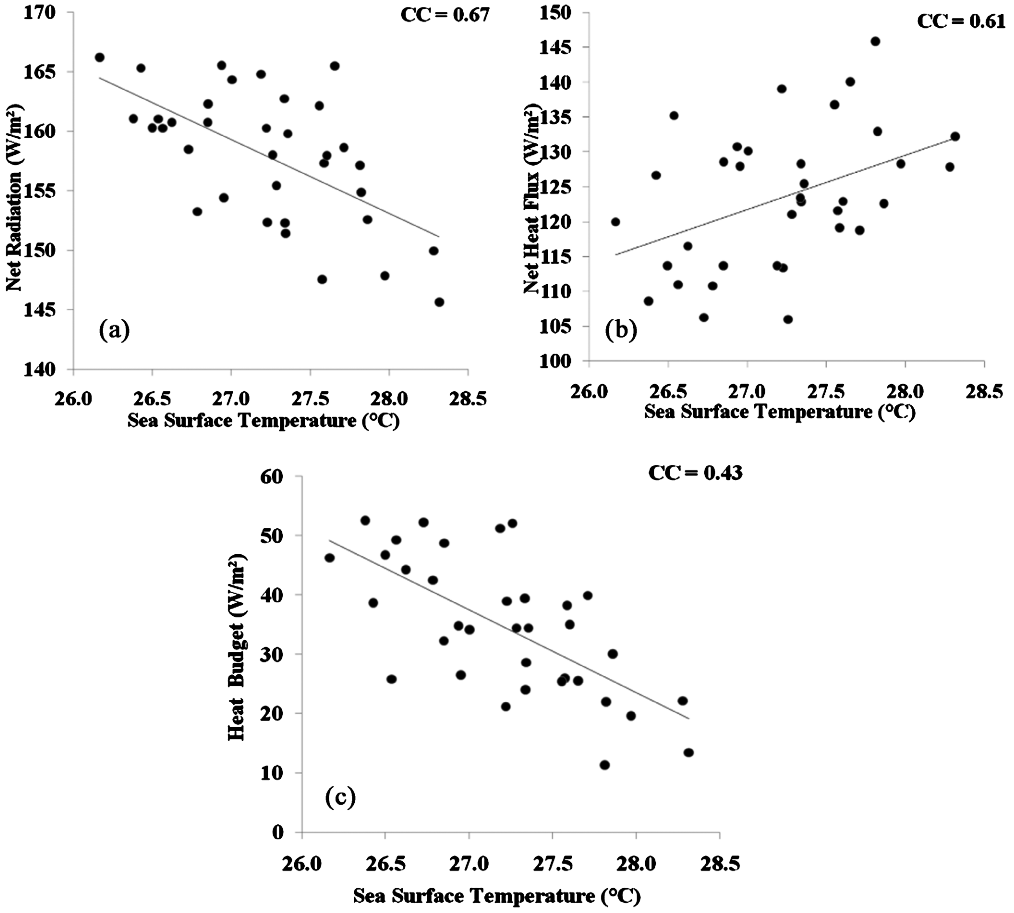

Figure 5. Association of SST with budget parameters of (a) net radiation and (b) net heat flux and (c) heat budget including the correlation coefficients.

Table 1. Correlation of Heat Budget parameters during El Niño, Neutral and La Niña years.

	NR	NHF	HB
El Niño	−0.65	0.39	−0.66
Neutral	−0.31	0.59	−0.78
La Niña	−0.63	0.05	−0.37
All years	−0.61	0.43	−0.67

the heat transfer will be less and due to lower SST, LHF is also low, so the NHF don't have any influence on SST modifications.

Table 2 provides the information about NR, NHF and HB in El Niño, La Niña and neutral years. when comparing El Niño and La Niña years with respect to neutral years, it is clearly seen that El Niño years indicate higher SST and NHF, lower HB and NR, however contrary to La Niña. The second source of annual variability in the surface meteorology and air-sea fluxes is the astronomical annual cycle in incoming SW radiation. The solar variability is a major contributor to the observed annual cycle in neat heat flux; the insolation decreases enough

Table 2. SST and Heat budget parameters range and average during ENSO Years.

		SST (˚C)	NR ($W \cdot m^{-2}$)	NHF ($W \cdot m^{-2}$)	HB ($W \cdot m^{-2}$)
El Niño	Avg	27.74	155.02	127.06	27.96
	Max	28.32	165.5	145.79	52.03
	Min	27.26	145.61	106	11.34
Neutral	Avg	27.12	158.69	122.81	35.88
	Max	27.82	165.54	139.07	49.26
	Min	26.5	151.4	110.78	21.18
La Niña	Avg	26.84	159.88	120.75	39.13
	Max	27.57	166.23	135.23	52.55
	Min	26.17	147.53	106.25	25.8

in austral winter so that the mean annual cycle illustrates ocean heat loss from early April to mid-August. SST variations are directly connecting with the air-sea interaction processes (heat budget parameters). LHF represents one of the two dominant components in energy exchanges between ocean-atmosphere. LHF mostly balances energy from shortwave radiation, the other important in air-sea heat exchanges. While shortwave radiation is associated with the direct warming process of the earth's surface. Latent heat exchange first occurs as a transfer of water vapour from ocean to atmosphere also called evaporation. Then by considering, water vapour release latent heat in the atmosphere and provides the energy to feed atmospheric circulation, particularly in tropical regions. The latent heat supply is a crucial driving force for tropical atmospheric circulation and is a very important input to numerical weather prediction models. Among the various heat exchanges, the LHF is the most variable on monthly time scales and cannot be resolved by the few available marine ship.

The points below 28˚C and above 29˚C were instrumental in reversing the trend. This peculiar behaviour of observed and satellite values is explained that the LHF increases with SST for SSTs below 27.5˚C, consistent with thermodynamic considerations [12]. However, at SSTs above 27.5˚C, LHF decreases with increasing SST because of dynamic interaction between the large-scale circulation and SST. When SST is high, the atmosphere becomes more convectively unstable. The resultant interaction between convection and large-scale circulation enhances the large-scale low-level convergence by mass continuity. In the center of the low level convergence the wind speed is low, yielding low LHF. The inverse trend observed for in situ data is in accordance with earlier observations and also due to the fact that SST seldom dropped below 27˚C over this region during summer and autumn. According to Muraleedharan and Pankajakehan [13] satellite underestimate colder (<28.5˚C) and warmer (>28.5˚C) SSTs and the process progressively increases on either side of the above threshold. SSTs falling below and above 27.5˚C have direct and inverse relationships with LHF respectively [12].

Local oceanic responses to the atmospheric forcing during the cooling episodes are explained through the composite fluctuations in SST, The phase relationships among the atmospheric forcing components in the composites confirm the results of the coherence calculations using a limited multiyear. This study emphasises the important effects of wind direction and speed on SHF variability. This finding is in tune with the study of Yu and Kao [14] which indicates the important role of winds in enhancing global evaporation in the past 5 decades. Taken together, winds are a critical player in the observed global variability of the air-sea heat exchange process of turbulent latent and sensible heat. SST is negatively correlated with LHF but positively correlated with solar radiation [15]. Variation of LHF was subjugated by variations in surface wind speed. The variation of solar radiation reflects the cloudiness in the free atmosphere, whereas that of surface LHD reflects the surface dynamic and the thermodynamic condition. The coupling between the two is apparently through convection. When convection occurs, clouds associated with the convective system block the solar radiation from reaching the surface, thus reducing the surface radiation. At the same time convection-generated cold, fry air and high wind on the surface, especially the latter act to enhance the surface evaporation [16] [17].

The stronger the convection, the larger the convective effects on surface wind LHF and solar radiation. On the other hand, clear sky and fair weather, lower surface winds and LHF (negative derivations from the mean). SST is generally warmer under clear skies and colder convective conditions. Short-time SST response to atmospheric forcing associated with convection, in which surface evaporation and SE cloud radiation forcing act cooperatively to affect SST variation. When the sky is clear (cloud), surface solar radiation is high (low), and the surface wind is weak (strong) thus LHF is low (high). As a result, the ocean experiences a net heating (cooling) which leads to an increase (decrease) of SST. Thus, both surface evaporation and NSW cloud radiative forcing provide a negative feedback on SST variation on such time scales. The variation of LHF at high SST is dominated by variations in wind speed, while changes in humidity deficit with SST are consistent with thermodynamic considerations. The decreases in wind speed with SST leads to relatively suppressed LHF at high SSTs on climate time scales, high SST leads to more convection, which enhance the low-level convergence and decreases surface wind, resulting the suppressed LHF in regions of convection. In the context of tropical SST, this interaction between convection and large-scale circulation has not received much attention in the phase and well explain seemingly contradictory results from different observational studies. Few measurements have interpreted that surface evaporation and cooling effects of convection has been emphasised by several researchers [9] [18] [19], when investigating the role of evaporative heat flux in regulating the SST. If the climatological effect of convection is to enhance the surface evaporation, one would expect evaporation is reason. Where there is abundance of convection, such as the western pacific warm pool. On the other hand, long-term observations and climatological data suggest that these regions dominated by low evaporation.

Although individual convective events can enhance the surface evaporation substantially on short temporal scales, the long-term average effects on convection is to suppress the surface evaporation at high SST due to its interaction with large-scale circulation [12] [20]. The HB is related with NR and NHF, however NR is related with NSW and NLW, and NHF is related with LHF and SHF. LHF is the main factor contributing for the SST fluctuations, even though there is a strong radiation coming from the sun and heating the surface of the ocean, due to strong evaporation LHF increases and the SST cooling will occur. However the heat transfer (SHF) between ocean and atmosphere is also contributing, but when compared with LHF, it is minimal.

5. Conclusions

The heat budget parameters over the Central Pacific Ocean and their relation with SST are investigated with the NCEP reanalysis data for the period 1979 to 2013. The following broad conclusions are drawn from this study:

- The seasonal variation of net radiation and heat budget parameters are depicting decreasing trend, whereas net heat flux shows an increasing trend over equatorial Pacific Ocean for the period 1979 to 2013.
- SST is having a positive correlation with net heat flux (0.43) and a negative correlation with net radiation (−0.61) and heat budget (−0.67).
- The Mean net radiation and heat budget are higher in La Niña whereas mean net heat flux is higher in El Niño.
- A significant inverse relation between SST and net radiation, and heat budget during El Niño years whereas in La Niña year, net radiation is the dominant factor and an inverse relationship with SST. In the neutral years, net heat flux depicts a positive relation and heat budget has a negative relation.

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Conflicts of Interest

The authors declare no conflicts of interest.

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