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# A critical evaluation of the upper ocean heat budget in the Climate Forecast System Reanalysis data for the south central equatorial Pacific

**Hailong Liu**[1,5], **Xiangcui Liu**[1,2], **Minghua Zhang**[3] **and Wuyin Lin**[4]

[1] State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, People's Republic of China
[2] Graduate University of the Chinese Academy of Sciences, Beijing, People's Republic of China
[3] Institute for Terrestrial and Planetary Atmospheres, Stony Brook University, State University of New York, Stony Brook, NY, USA
[4] Atmospheric Sciences Division, Brookhaven National Laboratory, Upton, NY, USA

E-mail: lhl@lasg.iap.ac.cn (Hailong Liu)

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**Abstract**
Coupled ocean–atmospheric models suffer from the common bias of a spurious rain belt south of the central equatorial Pacific throughout the year. Observational constraints on key processes responsible for this bias are scarce. The recently available reanalysis from a coupled model system for the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data is a potential benchmark for climate models in this region. Its suitability for model evaluation and validation, however, needs to be established. This paper examines the mixed layer heat budget and the ocean surface currents—key factors for the sea surface temperature control in the double Inter-Tropical Convergence Zone in the central Pacific—from 5°S to 10°S and 170°E to 150°W. Two independent approaches are used. The first approach is through comparison of CFSR data with collocated station observations from field experiments; the second is through the residual analysis of the heat budget of the mixed layer. We show that the CFSR overestimates the net surface flux in this region by 23 W $m^{-2}$. The overestimated net surface flux is mainly due to an even larger overestimation of shortwave radiation by 44 W $m^{-2}$, which is compensated by a surface latent heat flux overestimated by 14 W $m^{-2}$. However, the quality of surface currents and the associated oceanic heat transport in CFSR are not compromised by the surface flux biases, and they agree with the best available estimates. The uncertainties of the observational data from field experiments are also briefly discussed in the present study.

**Keywords:** double ITCZ, heat budget, CFSR

## 1. Introduction

The double ITCZ bias in coupled ocean–atmosphere models (Mechoso *et al* 1995), which refers to two rainfall belts symmetric to the equator all year round, accompanied by corresponding maximum in sea surface temperature (SST), is still a pervasive problem. It has been shown to exist in almost all climate models participating in the most recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) models (Lin 2007). Figure 1 shows the observed distribution of SST and the simulation from the

[5] Address for correspondence: No. 40 Hua Yan Li, Beijing 100029, People's Republic of China.

 

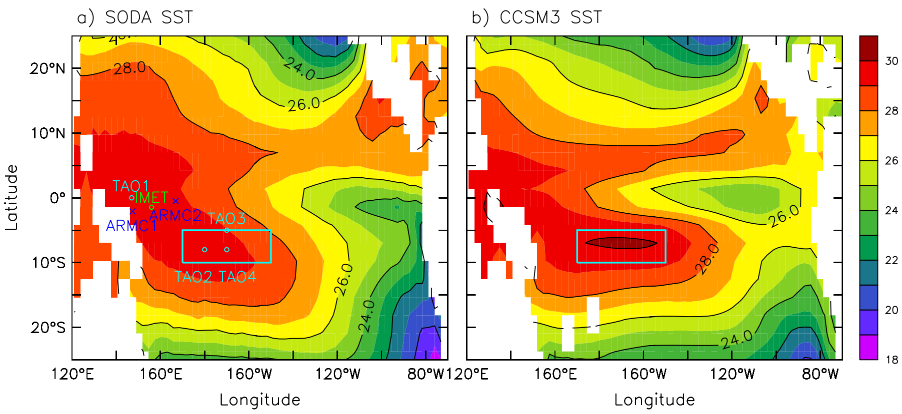


**Figure 1.** Annual mean sea surface temperature (in degrees Celsius) for (a) SODA (1993–2004) and (b) CCSM3.0. The locations of two ARM TWP sites, TAO buoys and IMET buoy during TOGA-COARE are all labeled in (a). The cyan boxes (from 5°S to 10°S and 170°E to 150°E) denote the targeted domain in the present study.

Community Climate System Model version 3.0 (CCSM3.0). There is now evidence that the ITCZ south of the equator in the central equatorial Pacific and that in the eastern Pacific are caused by different reasons (Yu and Mechoso 1999, Zhang *et al* 2007, Song and Zhang 2009, Liu *et al* 2011). In this study, we focus on the region of the spurious rain band in the central equatorial Pacific (from 5°S to 10°S and 170°E to 150°W, which is represented by the cyan boxes in figure 1) where the anomalous deep convection can evoke remote atmospheric responses. We refer this region to as the South Central Equatorial Pacific (SCEP).

Progress to eliminate the double ITCZ bias in coupled models has been extremely slow. This is at least partly due to the lack of high-quality observational data that are critical to the characterization of the coupled feedbacks between the atmosphere and ocean in addition to their dynamic and thermodynamic states over the tropical Pacific. The atmospheric or oceanic reanalyses have been very useful in evaluating models, but abundant caveats have been shown in the literature to caution against the quality of these products for specific types of applications. Recently, the National Centers for Environmental Prediction (NCEP) released a new reanalysis data, called Climate Forecast System Reanalysis (CFSR) (Saha *et al* 2010), which was produced by a global coupled seasonal forecast system, with higher resolution than what have been available before. It has also been found that CFSR is considerably more accurate than the previous NCEP global reanalysis. Potentially, this coupled system reanalysis may have unprecedented value in evaluating coupled climate models. How accurately this improved reanalysis can characterize the atmosphere–ocean feedbacks still strongly depend on the quality and sampling density of the ingested data and the internal model physics. Over the SCEP, few conventional atmospheric balloon sounding measurements exist in the assimilation process, but the ocean buoy array (McPhaden *et al* 1998) and satellite data provide some constraints to the coupled assimilation system. In order to use the CFSR to validate coupled climate models, however, the quality of the reanalysis product needs to be first assessed. The purpose of this paper is to evaluate the heat budget and the ocean currents of the upper ocean over the SCEP in the CFSR using independent observations. Recent observed and modeled studies of the upper ocean heat budget associated with the double ITCZ bias have been done, but primarily in the southeastern tropical Pacific (e.g. Colbo and Weller 2007, Toniazzo *et al* 2009, De Szoeke and Xie 2008, De Szoeke *et al* 2010, Colas *et al* 2011).

This paper is organized as follows. Section 2 describes the reanalysis and the observational data. Section 3 presents the evaluation of CFSR. Section 4 is a summary.

## 2. Data sets

The atmospheric reanalysis in CFSR has a global horizontal resolution of T382 (approximate 38 km) and 64 layers in the vertical, while the oceanic data has a horizontal resolution of 0.5° (approximate 55 km in tropics) and 40 layers in the vertical (Saha *et al* 2010). In the analysis procedure, six-hourly guess fields are first generated by the atmosphere–ocean–land–sea ice coupled model, rather than the atmosphere only model alone like the previous NCEP reanalysis. A three-dimensional variational analysis is then performed to statistically weight the observations and the first guess to produce the reanalysis. The CFSR is available from 1979 to the present, when the satellite radiances data are available.

To evaluate the CFSR, we use measurements at locations adjacent to the study domain from two Atmospheric Radiation Measurement Program's Tropical Western Pacific (ARM TWP) sites, one on Los Negros Island in Manus (2.0°S, 147.4°E) established in 1996, the other on Nauru Island (0.5°S, 166.9°E) established in 1998. They are referred to later as ARMC1 and ARMC2 respectively. We also use data from four tropical atmosphere–ocean (TAO) buoys (McPhaden *et al* 1998). The buoy located at (0° 147°E), referred to as TAO1, is close to the ARMC1 site at (2°S, 147°E); the other three buoys, referred to as TAO2 (8°S 180°), TAO3 (5°S 170°W) and TAO4 (8°S 170°W), are all located in the target domain. Additionally, we use the Woods Hole Oceanographic Institution Improved Meteorological instrument (WHOI IMET) surface mooring deployed in the center of the intensive flux array (IFA) at

(1.45°S, 156°E) during the Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment Intensive Observation Period (TOGA-COARE IOP, 1 November 1992–28 February 1993) (Weller and Anderson 1996). The locations of these sites are all labeled in figure 1(a). These *in situ* observations of the surface solar radiation have not been used for assimilation in CFSR.

In a previous study (Liu *et al* 2010), we derived an upper ocean heat budget after assessing seven objective analyses of surface fluxes and four ocean data assimilation products over the central equatorial Pacific. The derived heat budget of the upper ocean in Liu *et al* (2010) is used as the observational reference to evaluate CFSR in present study. Based on temporal stability, Liu *et al* (2010) also concluded that Simple Ocean Data Assimilation (SODA) version 2 (Carton and Giese 2008) is among the more reliable ocean products in terms of climatological heat budget. The monthly data from SODA is also employed to evaluate the ocean currents.

To be consistent with Liu *et al* (2010), the monthly mean data from CFSR are used to compute the heat budget in the present study. Because the study domain is primarily located in the warm pool, the heat transport due to the mesoscale eddy is believed to be minor. This hypothesis was also briefly demonstrated by Liu *et al* (2010) using daily data. Following Liu *et al* (2010), four terms are explicitly computed in the heat budget of the SCEP: the temperature tendency, the zonal and meridional heat transports, and the net surface heat flux. The sum of the rest terms, the entrainment, the horizontal diffusion, the vertical diffusion, and the eddy heat fluxes, is the residual term. The assimilation increments are also included in the residual term. The closure of the mixed layer heat budget of the ocean data analysis system at NCEP has been systematically examined by Huang *et al* (2010). Their results suggested that the heating sources and sinks due to ocean data assimilation have only a minor impact on the climatological heat budget.

## 3. Results

Over the tropical oceans, the dominant surface energy fluxes are the solar radiation and latent heat fluxes. We first evaluate these two heat components and then the overall heat budget of the upper ocean.

Figure 2(a) shows the monthly mean surface net downward shortwave radiation at ARMC1 and the collocated TAO buoy (TAO1). Results from ARMC1 and TAO1 track each other very well with mean values of 194 and 197 W m$^{-2}$. The sound cross-validation suggests the robustness of the observational datasets. Figure 2(b) compares the monthly mean net surface solar radiation fluxes at the ARMC1 site in CFSR against the ARM measurements. It is seen that CFSR is systematically larger than the ARM or TAO measurements. Over the period of 1997–2007, the mean values are 248 in CFSR versus 195 W m$^{-2}$ in ARMC1, an overestimation of about 50 W m$^{-2}$. Here, 5.5% is used as the ocean surface albedo to compute the net surface solar radiation. A decrease of the albedo from 5.5% to 5.0, which is at the low end of available albedo estimates (Jin *et al* 2004), in the calculation

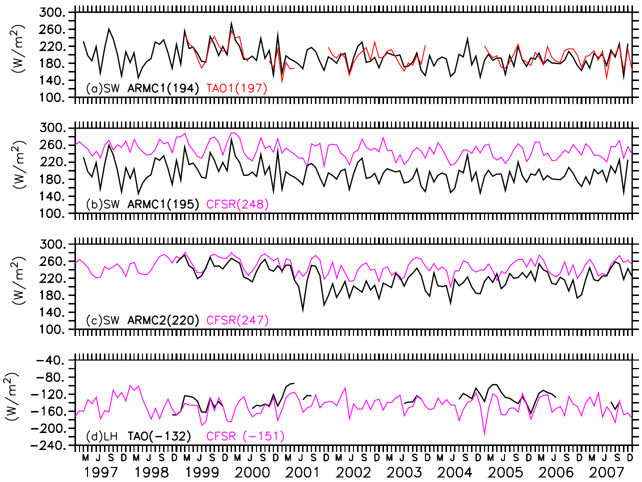


**Figure 2.** (a) The monthly mean net surface shortwave radiations (in W m$^{-2}$) for the measurement of ARMC1 (thick black) and nearby buoy TAO1 (red). The monthly mean net surface shortwave radiations at (b) the ARMC1 site and (c) the ARMC2 site (thick black) compared with CFSR at the same locations (purple). (d) The monthly mean latent heat flux (in W m$^{-2}$) for three TAO buoys (TAO2, TAO3 and TAO4) mean (thick black) and CFSR averaged in the same location (purple). The numbers in the parenthesis in (a) and (d) are time mean when TAO buoys have observations. The numbers in (b) and (c) show the time mean over 1997–2004 and 1999–2004, respectively.

would increase the ARM value by only 1 W m$^{-2}$. This change is too small to explain the differences.

The comparison at AMRC2 site is shown in figure 2(c). It is seen that the shortwave flux in the CFSR is also systematically larger than the ARM measurements, although the interannual variabilities track the measurements well. The overestimation is 27, 247 W m$^{-2}$ versus 220 W m$^{-2}$. The relatively smaller overestimation at ARMC2 than that at ARMC1 is consistent with the lower SST and less cloud at ARMC2 (figure 1(a)). The location of ARMC2 being near the boundary of the warm pool makes it less ideal to cross evaluate the data, but the overall larger shortwave radiation for CFSR than the field program data can also be seen at this site.

Because the deep convection moves eastward from the maritime continent during the warm event of the ENSO cycle, the solar radiations at ARM sites also exhibit interannual variabilities; the high value is 209 W m$^{-2}$ (246 W m$^{-2}$) for ARMC1 (ARMC2) during 1999–2000 and the low value is 188 W m$^{-2}$(213 W m$^{-2}$) during 2001–7 when the three moderate warm events occur. The low value (200 W m$^{-2}$) can be also found during 1997–8 at ARMC1 site. However, the interannual signals in CFSR are not as clear as that in the observations, which warrants a separate study.

There is also overestimation of the surface latent heat flux in CFSR. Figure 2(d) shows the mean latent heat fluxes averaged over the three TAO buoy sites in CFSR and in buoy measurements. It is seen that CFSR overestimates latent heat flux, 151 W m$^{-2}$ versus 132 W m$^{-2}$, by 19 W m$^{-2}$.

The discrepancies in the CFSR surface shortwave and latent heat flux also appear in the comparison of CFSR values against TOGA-COARE measurements at the same location.

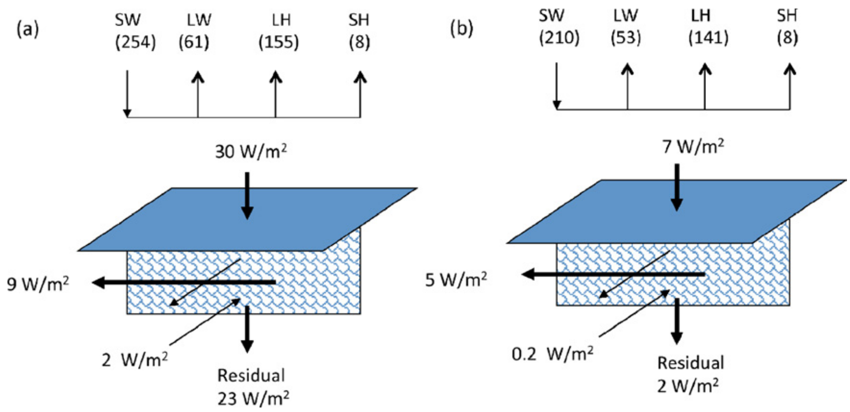


**Figure 3.** The schematic diagrams of the upper mixed layer heat budget and components of surface heat flux over the SCEP for (a) CFSR and (b) the result derived by Liu *et al* (2010).

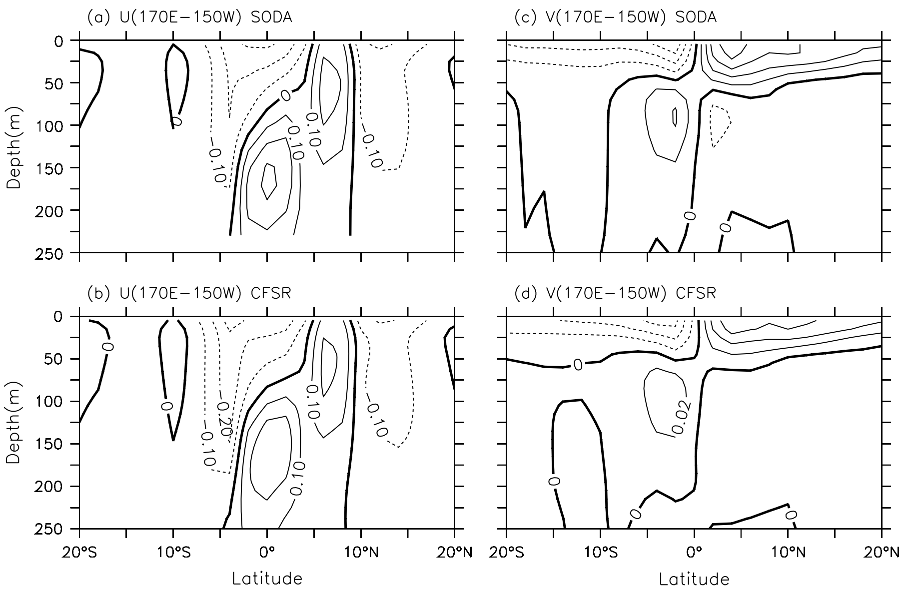


**Figure 4.** The zonal currents (in m $s^{-1}$) averaged in the SCEP (between 170°E and 150°W) for (a) SODA and (b) CFSR. (c) and (d) are same as (a) and (b), but for the meridional currents.

Shortwave radiation in CFSR is 228 W $m^{-2}$ versus 195 W $m^{-2}$ in TOGA-COARE, an overestimation of 33 W $m^{-2}$; latent heat flux in CFSR is 116 W $m^{-2}$ versus 108 W $m^{-2}$ in TOGA-COARE data, an overestimation of 8 W $m^{-2}$. Curry *et al* (2004) however computed a latent heat flux of 120 W $m^{-2}$ rather than the IMET value of 108 W $m^{-2}$, a difference of 12 W $m^{-2}$ when they used the same flux algorithm of Fairall *et al* (1996) but with winds for a 0.5° × 0.5° grid box. If the Curry *et al* (2004) value were used, CFSR would be underestimated by 4 W $m^{-2}$. Because TOGA-COARE only spanned four months from November 1992 to February 1993, the above comparison is subject to large impact from differences in temporal and spatial samplings.

For the overall heat budget, figure 3(a) shows the sources and sinks of heat of the upper ocean from 5°S to 10°S and 170°E to 150°E in CFSR. The upper ocean or the mixed layer is defined in the present study as the depth of isotherm that is 0.5 °C colder than the SST. It is at about 80 m at the SCEP. This budget is compared with observational estimates derived in Liu *et al* (2010) shown in figure 3(b). It is seen that the net downward heat flux at the surface in CFSR is larger than that in Liu *et al* (2010) by 23 W $m^{-2}$. This overestimation is mainly due to the even larger overestimation of net shortwave radiative flux of 44 W $m^{-2}$, compensated by an overestimation of surface latent heat flux of 14 W $m^{-2}$. Additionally, 7 W $m^{-2}$ of the overestimated shortwave radiation is offset by the overestimation of the surface longwave radiation.

Figure 3 also shows that heat transport by the ocean currents in CRSR is within 5 W $m^{-2}$ of the best estimate, which is primarily from SODA. The two products used similar oceanic measurements, but are driven by different atmospheres. The prevailing surface wind in this region is southeast trade wind. In the zonal direction, the easterly drives a westward surface current, the south equatorial current (SEC). Figures 4(a) and (b) compare the zonal current in SODA and CFSR. The two products agree well with each other. Since ocean water temperature in this region is higher than that to its east (figure 1), the SEC transports cold water to cool the study region (figure 3). In the meridional direction, the surface poleward Ekman currents are mainly restricted to the upper 50 m; the meridional currents below 50 m are equatorward as required by mass continuity. Figures 4(c) and (d) show that the meridional current in SODA and CFSR. The two also agree very well with each other.

Therefore, an inference of the biases in the CFSR surface fluxes also can be made by using the budget residual of the mixed layer ocean in figure 3. The large residual flux suggests that the energy is not balanced in the CFSR; a larger sink is needed to offset the large downward flux at the surface.

## 4. Summary and discussion

The above analysis demonstrated that in CFSR the surface downward heat flux over the SCEP is overestimated by 23 W $m^{-2}$, and this overestimation is attributed to an even larger overestimation of shortwave radiation by 44 W $m^{-2}$, offset by an overestimated surface latent heat flux by 14 W $m^{-2}$. However, the quality of surface currents and the associated heat transport in CFSR are not compromised by the surface flux biases, and are as good as the available best estimates.

Our conclusion on the surface energy fluxes was drawn based on two independent approaches. The first is through comparison of CFSR data with collocated station observations from ARM TWP sites, TAO buoys, and TOGA-COARE, which all point to the same biases. The second is through the residual analysis of the heat budget of the mixed layer. The budget in the CFSR cannot be closed without introducing a large heat sink of about 20 W $m^{-2}$.

In the CFSR, surface fluxes are largely calculated through physical parameterizations rather than observational constraints. This is especially true in surface radiation, which is significantly impacted by clouds. Given the magnitude of the overestimated surface flux, it can be safely argued that clouds in CFSR are underestimated over the SCEP. Further comparison of the total cloud amount against the products of International Satellite Cloud Climatology Project (ISCCP) D2 does show a negative differences center exceeding 30% just above the SCEP (figure 5). The latent heat flux is largely determined by surface atmospheric winds, sea surface temperature, and surface air humidity. Both surface winds and surface humidity over the SCEP are strongly affected by convective and boundary layer parameterizations. In contrast, ocean currents are constrained by temperature and salinity measurements through the direct assimilation of these variables, which ensures better quality than that in the surface heat fluxes. CFSR is therefore a unique product to study the coupled ocean–atmospheric system. Our analysis points to both caveats and values in the product, which will be important to the investigation of the double ITCZ problem in climate models. It also points to the need to explicitly constrain the surface heat fluxes using observations in the data assimilation process.

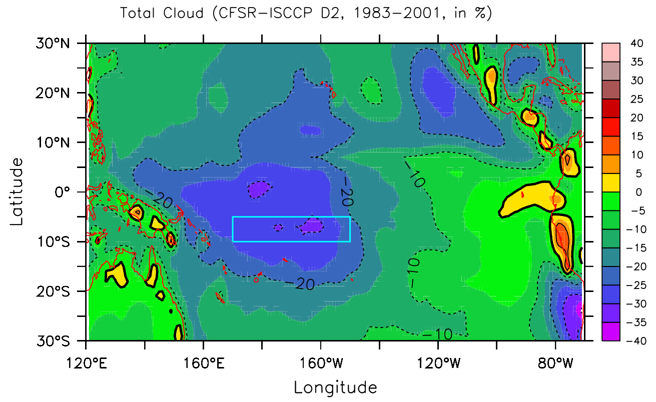


**Figure 5.** The difference of annual mean total cloud (in percentage) between CFSR and ISCCP D2 during 1983–2001.

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