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Effects of Freshwater Flux (FWF) Forcing on Interannual Climate Variability in the Tropical Pacific

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ABSTRACT

The impacts of freshwater flux (FWF) forcing on interannual variability in the tropical Pacific climate system are investigated using a hybrid coupled model (HCM), constructed from an oceanic general circulation model (OGCM) and a simplified atmospheric model, whose forcing fields to the ocean consist of three components. Interannual anomalies of wind stress and precipitation minus evaporation, (P-E), are calculated respectively by their statistical feedback models that are constructed from a singular value decomposition (SVD) analysis of their historical data. Heat flux is calculated using an advective atmospheric mixed layer (AML) model. The constructed HCM can well reproduce interannual variability associated with El Niño-Southern Oscillation (ENSO) in the tropical Pacific.

HCM experiments are performed with varying strength of anomalous FWF forcing. It is demonstrated that FWF can have a significant modulating impact on interannual variability. The buoyancy flux (Q_B) field, an important parameter determining the mixing and entrainment in the equatorial Pacific, is analyzed to illustrate the compensating role played by its two contributing parts, one is related with heat flux (Q_T) and the other with freshwater flux (Q_S), respectively. A positive feedback is identified between FWF and sea surface temperature (SST) as follows. SST anomalies, generated by El Niño, non-locally induce large anomalous FWF variability over the western and central regions, which directly influences sea surface salinity (SSS) and Q_B, leading to changes in the mixed layer depth (MLD), the upper ocean stability, the mixing and the entrainment of subsurface waters. These oceanic processes act to enhance the SST anomalies, which in turn feedback to the atmosphere in a coupled ocean-atmosphere system. As a result, taking into account anomalous FWF forcing in the HCM leads to an enhanced interannual variability and ENSO cycles. It is further shown that FWF forcing is playing a different role from heat flux forcing, with the former acting to drive a change in SST, while the latter being representing a passive response to the SST change. This HCM based modeling study presents clear evidence for the role of FWF forcing in modulating interannual variability in the tropical Pacific. The significance and implications of these results are further discussed for physical understanding and model improvements of interannual variability in the tropical Pacific ocean-atmosphere system.

1. Introduction

The ocean is a key player in climate variability and predictability on various time-space scales. Largely driven by atmospheric forcing, the induced physical changes in the ocean can feedback to the atmosphere by which the principal oceanic quantity felt is sea surface temperature (SST). Numerous studies have identified roles of various forcings and feedbacks in the climate system, including the Bjerknes feedback (*e.g.*, Bjerknes 1969), the wind-evaporation-SST (WES) feedback (*e.g.*, Xie and Philander 1994), the SST-solar radiation feedback (*e.g.*, Waliser *et al*. 1994), and others. In the past, most studies have emphasized the forcing and feedback effects of atmospheric *wind* and *heat flux* on the coupled ocean-atmosphere system. Another less focused atmospheric forcing component to the ocean is freshwater flux (FWF) which has direct

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effects on ocean salinity, an important variable in climate and the water cycle. While sea surface salinity (SSS) has no direct and immediate influence on the atmosphere, its variations can be forced by atmospheric FWF perturbations, which can further modify the oceanic density fields, the mixed layer depth (MLD), the mixing and entrainment, all of which can affect SST. For example, FWF forcing and its related salinity effect have been demonstrated to play an important role in climate variability in the North Atlantic, being recognized as a driving force for the thermohaline circulation and its fluctuations (*e.g.*, Schmitt *et al*. 1989).

In the tropical Pacific, a predominant role of wind forcing has been demonstrated in interannual climate variability associated with ENSO, involving a feedback loop among the SST, winds and the thermocline (*i.e.*, the Bjerknes feedback). The associated interannual changes in SST induce coherent fluctuations in the atmospheric circulation, including precipitation (P) and evaporation (E), whose interannual variabilities have been well documented in association with ENSO (*e.g.*, Xie and Arkin 1995;Yu and Weller 2007). These large variations of P and E are reflected in those of freshwater flux.

Over the tropical Pacific region, the major contribution to interannual variations in FWF comes from a net difference between P and E, with a dominance of the former over the latter. Indeed, associated with ENSO, interannual FWF variability shows a close relationship with SST in the tropical Pacific. During El Niño, SSTs are warm in the central and eastern equatorial Pacific, accompanied by an increase both in P and E in the central basin. Due to the dominance of P over E, a warming is associated with a positive FWF anomaly (an anomalous flux into the ocean). During La Niña, cold SST anomalies are accompanied by a reduction both in P and E in the central basin. The resultant FWF anomaly is negative (an anomalous loss of freshwater from the ocean). Thus, interannual variations in FWF present a non-local positive correlation with SST during ENSO cycles. This is contrasted to those in heat flux which have been demonstrated to have a negative correlation with SST (*e.g.*, Barnett *et al.* 1991; Wang and McPhaden 2001).

Recent studies indicate that FWF forcing and its directly related changes in salinity can play an active role in maintaining the Pacific climate and its low-frequency variability through their effects on the horizontal pressure gradients, the stratification, and the equatorial thermocline. Clearly, FWF forcing and its related feedback need to be taken into account in modeling studies due to its large interannual anomalies induced by ENSO.

At present, FWF forcing has not been adequately represented in simplified models. In most previous modeling studies, the effects of FWF forcing have been demonstrated mostly in forced ocean-alone experiments. For example, idealized anomalous FWF forcing fields are perpetually prescribed to examine the response of the ocean (*e.g.*, Reason 1992; Yang *et al.* 1999; Huang and Mehta 2004, 2005). Since the ocean-atmosphere is not coupled, there is no feedback from the changes in the ocean induced by FWF forcing to the atmosphere. Various coupled ocean-atmosphere models for the tropical Pacific have been developed for use in ENSO-related modeling studies, including intermediate coupled models (ICMs), hybrid coupled models (HCMs), and coupled general circulation models (CGCMs). However, FWF forcing has not been adequately represented in most state-of-the-art coupled models. For example, FWF has not been even included in most ICMs and HCMs used for simulation and prediction of ENSO (*e.g.*, Zebiak and Cane 1987; Barnett *et al.* 1993; Syu *et al.* 1995; Zhang *et al.* 2003, 2005, 2006; Zhang and Zebiak 2004). In CGCMs, the FWF forcing is included, but has not been realistically simulated. In particular, the so-called double ITCZ (the intertropical convergence zone) problem is still a big challenge to CGCM simulations in the tropical Pacific; most models tend to have excessive precipitation over the ITCZ in the tropical Pacific. This deficiency in precipitation simulation is reflected in the FWF field, resulting in large and systematic biases that affect the ocean. In addition, large uncertainties exist in observational estimates of P and E from different sources and products. Thus, FWF forcing remains a challenge to be represented realistically in diagnostic analyses and coupled modeling studies.

Indeed, previous modeling studies have mostly focused on the roles of atmospheric forcing components of *winds* and *heat flux* in the coupled ocean-atmosphere system of the tropical Pacific; FWF forcing and its related salinity effect on climate variability have not been getting much attention. In addition, its effects have been examined *mostly* in ocean-only modeling studies. In a coupled ocean-atmosphere system, changes in SST induced by FWF forcing can feedback to the atmosphere. But, these have not been clearly illustrated in a coupled ocean-atmosphere context. Although CGCMs include the FWF forcing, its impact on interannual variability has rarely been diagnosed explicitly. Furthermore, FWF-induced feedback can also influence the strength of other forcings and feedbacks in the coupled system. For example, the changed SSTs induced by FWF forcing can modulate heat flux forcing which has been demonstrated to provide a negative feedback to interannual SST variability in the tropical Pacific. Then, what are the net effects of these related feedbacks on interannual variability? Moreover, ENSO has been observed to change significantly from one event to another. Many factors have been identified that can modulate ENSO amplitude (*e.g.*, Zhang and Busalacchi 2005; Zhang *et al.* 2008). As demonstrated in previous forced ocean-only simulations, FWF forcing can induce large changes in SST, indicating the potential for modulation of ENSO. However, the extent to which FWF forcing can play a role is not known.

In this work, a hybrid coupled modeling approach is taken to isolate the influences of anomalous FWF forcing on salinity and interannual variability in the tropical Pacific. The HCM developed at ESSIC (Zhang *et al.* 2006) consists of a layer ocean general circulation model (OGCM) and an empirical atmospheric model for interannual wind stress variability. In particular, as with wind forcing component, an additional empirical model has been developed to take into account interannual FWF variability that is explicitly related to SST anomalies. The FWF model is constructed from a SVD of the covariance matrix that is calculated from time series of monthly mean SST and (P-E) fields. Then, using this empirical (P-E) model, a FWF anomaly can be estimated from a given SST forcing, which can be included in the HCM to account for its related possible feedback. In addition, heat flux in the HCM is calculated using an advective atmospheric mixed layer (AML) model developed by Seager *et al.* (1995). Thus, the HCM has three atmospheric forcings to the ocean: wind stress, heat flux and freshwater flux, respectively. In this study, our focus is on the roles of anomalous FWF forcing in modulating interannual variability.

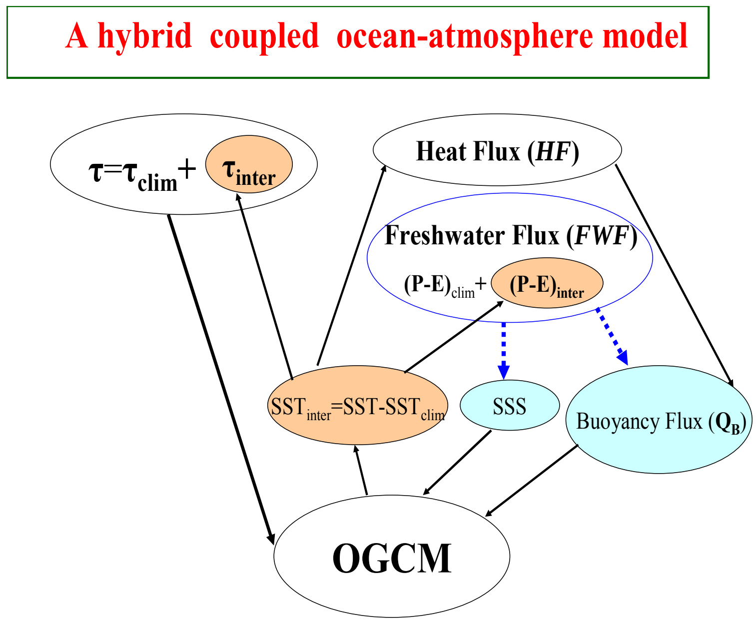

Fig. 1 A schematic diagram illustrating a hybrid coupled model (HCM) for the tropical Pacific ocean-atmosphere system, consisting of an OGCM and a simplified atmospheric model, whose forcing fields to the ocean include three components: wind stress, freshwater flux and heat flux, respectively. The total wind stress (τ) consists of prescribed climatological wind stress (τ_{clim}) from observations and its interannual anomalies (τ_{inter}) associated with large scale SST anomalies (SST_{inter}); the total freshwater flux (FWF), represented by precipitation minus evaporation (P-E), consists of prescribed climatological freshwater flux [$(P-E)_{clim}$] and its interannual anomalies [$(P-E)_{inter}$]; heat flux (HF) is calculated using the Seager *et al.* (1995) advective atmospheric mixed layer (AML) model. Empirical submodels for $\boldsymbol{\tau}_{inter}$ and $(P-E)_{inter}$ fields are constructed using a singular value decomposition (SVD) analysis. Buoyancy flux (Q_B) is calculated from the heat flux and freshwater flux to force a mixed layer model which is embedded in the OGCM. Climatological SST ($\mathbf{SST}_{clim}$) fields are specified from a spinup run of the OGCM forced by observed climatological atmospheric fields.

2. Model descriptions

Figure 1 shows a schematic of the various components of a HCM, recently developed at ESSIC (Zhang et al. 2006). The HCM consists of a layer OGCM and a simplified atmospheric representation of three forcing fields to the ocean, including the two empirical submodels for interannual wind stress and FWF variability, respectively. For more details, see Zhang and Busalacchi (2009).

3. The effects of anomalous FWF forcing

The HCM will be used to examine the effects of FWF forcing on interannual variability in the tropical Pacific. When the FWF forcing is included in the HCM (Fig. 1), the total FWF exchange between the atmosphere and ocean can be written as: FWF = $(P\text{-}E)_{clim} + \alpha_{FWF} \bullet (P\text{-}E)_{inter}$, in which its climatological part, $(P\text{-}E)_{clim}$, is specified (the P_{clim} is from observation; the E_{clim} is estimated from simualted SST_{clim} fields using the advective AML model). Its anomalous part, $(P\text{-}E)_{inter}$, is calculated using the SVD-based empirical model from interannual SST anomalies. The coefficient, α_{FWF}, represents the strength of the anomalous FWF forcing. A standard run is performed with interannual $(P\text{-}E)_{inter}$ forcing (α_{FWF} = 1). Basically, the HCM with α_{FWF} = 1 can quite well produce the mean ocean climatology and its interannual oscillations with about 4-year period (Fig. 2). We then perform two more HCM experiments using the identical OGCM that is coupled to the same SVD-based atmospheric wind stress and (P-E) models, but with differing α_{FWF} values to represent the strength of anomalous FWF forcing: a climatological FWF forcing run (α_{FWF} = 0.0; the $(P\text{-}E)_{clim}$ run) and an enhanced FWF forcing run (α_{FWF} =2.0).

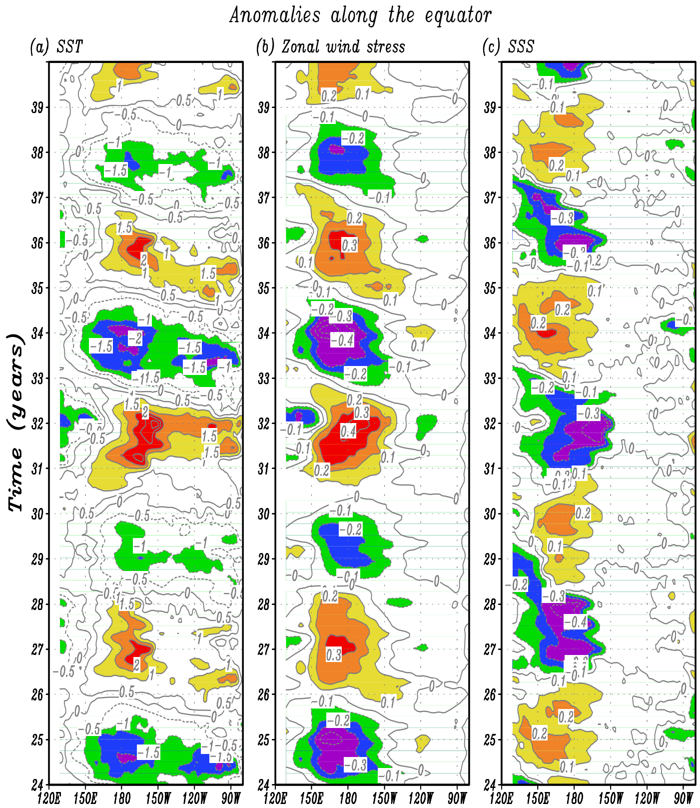

Fig. 2 Anomalies along the equator simulated from the HCM with the interannual FWF forcing: (a) SST, (b) zonal wind stress, and (c) SSS. The contour interval is 0.5 °C in (a), 0.1 dyn cm^{-2} in (b), and 0.1 psu in (c), respectively.

Nino4 region	α_{FWF}= 0.0 (Clim run)	α_{FWF}= 1.0 (Standard run)	α_{FWF}= 2.0 (Enhanced run)
SSS	0.11	0.16	0.28
SST	0.76	0.85	0.97
MLD	5.6	6.7	9.0
τ	0.16	0.19	0.23
Q_T	1.49	1.72	1.95
Q_S	0.0	0.65	1.58
Q_B	1.49	1.24	1.08
Nino12 SST	0.53	0.57	0.64
Nino3 SST	0.67	0.76	0.92

Table 1 The standard deviation of some selected anomaly fields from the HCM simulations with the climatological (α_{FWF} = 0.0), the standard (α_{FWF} = 1.0) and enhanced (α_{FWF} = 2.0) FWF forcings, respectively. Shown at the Niño4 region are for SSS, SST, MLD, zonal wind stress (τ), buoyancy flux (Q_B) and its heat flux part (Q_T) and freshwater flux part (Q_S). Also shown in the last two rows are for SST at the Niño12 and Niño3 sites. The unit is: psu for SSS, °C for SST, meter for MLD, dyn cm^{-2} for τ, 10^{-6} Kg s^{-1} m^{-2} for Q_B and Q_T and Q_S, respectively.

The effects of anomalous FWF forcing on some selected variables are quantified in Table 1. As analyzed above, the relationships among interannual anomaly fields indicate a positive effect of FWF forcing on SST during ENSO cycles. In the standard $(P\text{-}E)_{inter}$ run (α_{FWF} =1.0), the positive feedback between SST and FWF is included in the HCM simulation. The FWF anomalies induce additional ocean processes in such a way to reinforce the warming during El Niño and cooling during La Niña, respectively. The enhanced SST anomalies further increase interannual variability in the coupled system. When the positive SST-FWF relationship is not included as in the climatogical FWF forcing run (α_{FWF} = 0.0), these additional oceanic effects that could be induced by the FWF forcing are disabled, and there is no positive feedback. As a result, the simulated interannual variability in the α_{FWF} = 0.0 run is weakened as compared with that in the α_{FWF} = 1.0 run. When the anomalous FWF forcing is enhanced as represented in the α_{FWF} = 2.0 run, its obvious direct effects are to increase the temporal variability of SSS and MLD in the central basin. Also, it increases the compensating effect of Q_S on Q_T, with a net reduction in Q_B variability. All these processes tend to cause more warming during El Niño and more cooling during La Niña, which acts to reinforce SST variability during ENSO cycles. As the positive feedback is exaggerated, a stronger interannual variability emerges. Clearly, the oceanic processes induced by the FWF forcing and the related feedback act in such a way to enhance the strength of ENSO cycles.

4. Concluding remarks

Most previous modeling studies have focused on the roles of atmospheric forcing components of *winds* and *heat flux*; FWF forcing and its related salinity role in coupled climate variability have not received much attention. Furthermore, the effects of FWF forcing have been examined mostly in *forced ocean-only* modeling studies. In this work, the impacts of FWF forcing on salinity and interannual variability are examined in a hybrid coupled ocean-atmosphere context in which climatological atmospheric forcing fields of wind and FWF are specified, while their anomaly parts can be added on or off separately or collectively.

We have designed various experiments using the HCM with differing strengths of anomalous FWF forcing. Three cases are considered. In a standard simulation, the climatological and anomalous FWF fields are both taken into account [i.e., FWF = $(P\text{-}E)_{clim}+(P\text{-}E)_{inter}$]. The constructed HCM can well reproduce interannual variability associated with ENSO in the tropical Pacific. Two more sensitivity experiments are then performed using the HCM with the climatological forcing only [i.e., FWF = $(P\text{-}E)_{clim}$] and an enhanced FWF forcing run [i.e., FWF = $(P\text{-}E)_{clim}+ 2.0\bullet(P\text{-}E)_{inter}$], respectively.

Interannual variability in the tropical Pacific is predominantly driven by wind-induced feedback; simulations with climatological FWF forcing still show large interannual variability of SSS and SST in the tropical Pacific with basic feature unchanged. This indicates that wind forcing is of primary importance for dynamics of interannual variability in the tropical Pacific climate system. However, a significant effect can be seen, arising from anomalous FWF forcing. Quantitatively, taking the $(P\text{-}E)_{inter}$ run as a standard, the SST variance at the Niño3 site can be reduced by about 12% in the climatological FWF forcing run, but enhanced by 21% in the enhanced FWF forcing run; the variances for SSS and zonal wind stress at the Niño4 site are reduced by about 31% and 16% in the climatological FWF run, but enhanced by 16% and 75% in the enhanced FWF forcing run, respectively. Thus, anomalous FWF forcing can modulate interannual variability in a substantial way.

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