Freshwater Flux and Ocean Chlorophyll Produce Nonlinear Feedbacks in the Tropical Pacific

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ABSTRACT

Various forcing and feedback processes coexist in the tropical Pacific, which can modulate El Niño–Southern Oscillation (ENSO). In particular, large covariabilities in chlorophyll (Chl) and freshwater flux (FWF) at the sea surface are observed during ENSO cycles, acting to execute feedbacks on ENSO through the related ocean-biology-induced heating (OBH) and FWF forcing, respectively. At present, the related effects and underlying mechanism are strongly model dependent and are still not well understood. Here, a new hybrid coupled model (HCM), developed to represent interactions between the atmosphere and ocean physics–biology (AOPB) in the tropical Pacific, is used to examine the extent to which ENSO can be modulated by interannually covarying anomalies of FWF and Chl. HCM AOPB-based sensitivity experiments indicate that individually the FWF forcing tends to amplify ENSO via its influence on the stratification and vertical mixing in the upper ocean, whereas the OBH feedback tends to damp it. While the FWF- and OBH-related individual effects tend to counteract each other, their combined effects give rise to unexpected situations. For example, an increase in the FWF forcing intensity actually acts to decrease the ENSO amplitude when the OBH feedback effects coexist at a certain intensity. The nonlinear modulation of the ENSO amplitude can happen when the FWF-related amplifying effects on ENSO are compensated for by OBH-related damping effects. The results offer insight into modulating effects on ENSO, which are evident in nature and different climate models.

1. Introduction

El Niño–Southern Oscillation (ENSO) is the strongest interannual signal in the climate system, consisting

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of a warm phase (El Niño) and a cold phase (La Niña). ENSO arises from the so-called Bjerknes feedback, which involves interactions between the sea surface temperature (SST), wind, and thermocline (Bjerknes 1969). Multiple other multiscale processes coexist in the Earth system of the tropical Pacific, including ocean-biology-induced heating (OBH) and freshwater flux (FWF) forcing (Murtugudde et al. 2002; Zhang and Busalacchi 2009). The roles played by various forcings and feedbacks in ENSO

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modulations have been extensively investigated, with a focus on climatic factors (Hu et al. 2014; Zhu et al. 2014). For example, large interannual variations in FWF at the sea surface have been observed in the western–central equatorial Pacific during ENSO cycles, which not only represents a response to ENSO but also produces a feedback onto ENSO (e.g., Zhang and Busalacchi 2009). As currently understood, ENSO induces FWF anomalies that force anomalies of sea surface salinity (SSS) and buoyancy flux, affecting stratification and vertical mixing in the upper ocean. These processes act to modulate SST and thus ENSO. A positive feedback on ENSO can be illustrated in association with interannually varying FWF forcing in the tropical Pacific (Fig. 1a; Zhang et al. 2012). In addition, the role of variable vertical mixing as a positive feedback on ENSO has recently been discussed in observations (Moum et al. 2013) and models (Gnanadesikan et al. 2017). These studies indicate that mixed layer modulation by stratification can play an important role in the heat budget.

On the bioeffect side, the existence and variations of chlorophyll (Chl) modulate the penetration of solar radiation in the upper ocean, inducing differential heating between the mixed layer (ML) and subsurface layers; this in turn acts to regulate the stratification and vertical mixing in the upper ocean and further modulate SST and ENSO (e.g., Zhang et al. 2009). Both positive and negative feedbacks have been shown for chlorophyll impacts on ENSO, depending on the region involved and whether the impact is associated with time-mean heating (Anderson et al. 2009) or variability (Zhang 2015a). For example, a negative feedback is associated with variability in the local Chl-induced heating (Zhang 2015b); thus, this apparently distinguishes between the positive remote feedback associated with Chl-induced mean heating in the gyres and negative feedback associated with mean heating in the marginal zones described in Anderson et al. (2009).

As a result, either positive or negative feedbacks can be involved in the Chl-induced heating effects on the climate system (Fig. 1b). While physical factors affecting ENSO have been extensively examined in the tropical Pacific, OBH feedback effects on ENSO are still not well understood (e.g., Miller et al. 2003). Indeed, large uncertainties exist in representing biofeedback processes in various models; the induced bioeffects on the climate remain elusive and are strongly model dependent (Timmermann and Jin 2002; Marzeion et al. 2005; Wetzel et al. 2006; Lengaigne et al. 2007; Anderson et al. 2009; Gnanadesikan and Anderson 2009; Jochum et al. 2010; Heinemann et al. 2011; Park et al. 2014a,b). Furthermore, interactions between FWF forcings and OBH feedback are expected because they both can modulate the stratification and vertical mixing in the upper ocean and thereby affect SST. However, their collective modulating

FIG. 1. A schematic diagram illustrating processes involved in (a) FWF forcing and (b) OBH feedback. In (a), as a response to SST variability, FWF anomalies directly force sea surface salinity (SSS) and buoyancy flux Q_B anomalies, acting to modulate density, the depth of the mixed layer (MLD), stratification, and vertical mixing in the upper ocean, which affect SST. In (b), as a response to ENSO, a change in Chl concentrations corresponds to perturbations in penetration depth H_p , which directly modify the penetration of sunlight in the upper ocean, with differential heating between the ML and subsurface layers [Q_{pen} is the penetrative part through the base of the ML; Q_{abs} is the absorbed part within the ML]. The induced differential heating in the vertical direction acts to modify the stratification, vertical mixing, and entrainment of subsurface waters into the ML, which affect SST.

effects on ENSO are neither clearly demonstrated nor well understood.

In this work, we use a new hybrid coupled model (HCM) that has been developed to represent interactions between the atmosphere and ocean physics–biology (AOPB) in the tropical Pacific (Zhang et al. 2018a,b). First, the ocean’s biophysics interactions are taken into account using an ocean–biology model to predict Chl, which is then used to directly modulate its effects on the penetration of solar radiation in the upper ocean; previously, we used a statistical model to represent this biological effect (Zhang et al. 2011). Second,

a hybrid coupled model is constructed to represent ocean–atmosphere interactions by coupling an ocean general circulation model (OGCM) with empirical models, which are used to determine the interannual anomalies of wind stress and freshwater flux (Zhang and Busalacchi 2009; Zhang et al. 2012). The HCM AOPB can adequately depict ENSO cycles, and the effects of related FWF forcing and OBH feedback on ENSO are clearly seen when these processes are included individually or collectively in the tropical Pacific. Then, the HCM AOPB is used to investigate the ways ENSO can be modulated by OBH feedback and FWF forcing. To understand the nature of these combined modulating effects on ENSO, a series of sensitivity experiments are performed using the HCM AOPB with different intensities represented for interannual covariabilities of OBH feedback and FWF forcing. The direct heating effects and mechanism are analyzed to demonstrate how ENSO can be modulated by these two processes. Some specific questions are to be addressed in detail: Does ENSO amplitude linearly increase or decrease with the intensities of FWF forcing and/or OBH feedback? Can the interactions between these two processes lead to nonlinear modulations of ENSO and why?

This paper is organized as follows. Section 2 describes the model used and the experimental design. The overview of the model performance is presented in section 3 and followed by section 4 for demonstrating the modulating effects on ENSO. Section 5 provides the summary and discussion.

2. Model descriptions and experimental designs

In this work, an HCM of the atmosphere and ocean (representing the climate system) is combined with an ocean-biology model to represent the bioclimate interactions in the tropical Pacific. The model is briefly described in this section, and a more detailed description for various ocean components is presented in Zhang et al. (2018a) and of empirical atmospheric models for wind stress and FWF is given in the appendix.

a. The model used

Figure 2 shows the HCM of the AOPB, which is used to represent the FWF–climate and bioclimate interactions in the tropical Pacific. The HCM consists of an OGCM and a simplified representation of the atmosphere (wind stress τ , freshwater flux, and heat flux). The OGCM is the reduced gravity, primitive-equation, sigma-coordinate model of Gent and Cane (1989) and has been widely used in tropical ocean–atmosphere modeling studies (e.g., Murtugudde et al. 2002; Wang et al. 2009a; Zhang et al. 2012). This ocean model is coupled with a statistical wind stress model to form a hybrid coupled model (Zhang et al. 2012).

Within the context of such an HCM, the total wind stress forcing to the ocean can be divided into a climatological part τ_{clim} and an interannual anomaly part τ_{inter} . Similarly, the total freshwater exchange between the atmosphere and ocean ($\text{FWF} = P - E$; where P stands for precipitation and E stands for evaporation) is separated into a climatological part (FWF_{clim}) and an interannual anomaly part ($\text{FWF}_{\text{inter}}$). The heat flux is estimated using an advective atmospheric mixed-layer (AML) model (Seager et al. 1995). The climatological parts (τ_{clim} and FWF_{clim}) are prescribed using their long-term seasonally varying fields from observations; the interannual anomalies (τ_{inter} and $\text{FWF}_{\text{inter}}$) are calculated using empirical models constructed by the singular value decomposition (SVD) analysis technique, which is described in the appendix.

Moreover, an ocean-biology model is coupled with the climate system to represent biological processes. As detailed in Wang et al. (2015), the ocean-biology model consists of 12 components, including 6 nutrients [nitrate, silicon, ammonium, dissolved inorganic carbon (DIC), dissolved oxygen, and dissolved iron] and 6 biological components [large and small sizes of phytoplankton (P_L and P_S), large and small sizes of zooplankton (Z_L and Z_S), and large and small sizes of detritus (D_L and D_S)]. Additionally, some diagnostic variables are introduced in the model. For example, phytoplankton carbon biomass (mol N m^{-3}) is converted to mol C m^{-3} according to the Redfield ratio ($\text{C:N} = 6.625$), and chlorophyll concentrations are then calculated using the ratio between phytoplankton biomass and chlorophyll, which is called the C:Chl ratio. The ratio between phytoplankton biomass and chlorophyll (C:Chl) is not fixed, which depends on light, temperature, and nutrients (nitrate and iron) as detailed in Wang et al. (2009b).

These components are coupled to form an HCM AOPB in the tropical Pacific (Fig. 2). The strength of coupling and feedback is regulated by three coupling parameters, which allow the wind stress, freshwater flux, and chlorophyll concentration fed to the ocean to vary as

$$\tau = \tau_{\text{clim}} + \tau_{\text{inter}} = \tau_{\text{clim}} + \alpha_{\tau} \tau'(\text{SST}_{\text{inter}}),$$

$$\begin{aligned} \text{FWF} &= \text{FWF}_{\text{clim}} + \text{FWF}_{\text{inter}} = \text{FWF}_{\text{clim}} \\ &+ \alpha_{\text{FWF}} \text{FWF}'(\text{SST}_{\text{inter}}), \quad \text{and} \end{aligned}$$

$$\text{Chl} = \text{Chl}_{\text{clim}} + \text{Chl}_{\text{inter}} = \text{Chl}_{\text{clim}} + \alpha_{\text{Chl}} \times (\text{Chl} - \text{Chl}_{\text{clim}}),$$

in which several scalar parameters, α_{τ} , α_{FWF} , and α_{Chl} , are introduced to represent wind-forcing intensity (the so-called relative coupling coefficient), FWF forcing intensity, and the Chl-induced feedback intensity, respectively. Note that in the reference run, Chl is directly estimated from the ocean-biology model, and in various

FIG. 2. A schematic diagram illustrating the HCM used to represent interactions between the AOPB in the tropical Pacific. The HCM AOPB consists of an ocean-biology model, an OGCM, and statistical atmospheric models to calculate interannual anomalies of wind stress and freshwater flux (FWF), respectively. The total wind stress τ is separated into a climatological part τ_{clim} and an interannual anomaly part τ_{inter} , written as $\tau = \tau_{\text{clim}} + \tau_{\text{inter}}$. Similarly, the total FWF, which is represented by precipitation P minus evaporation E at the sea surface, is also separated into a climatological part (FWF_{clim}) and an interannual anomaly part ($\text{FWF}_{\text{inter}}$), written as $\text{FWF} = \text{FWF}_{\text{clim}} + \text{FWF}_{\text{inter}}$. In addition, the ocean-atmosphere system is coupled to an ocean-biology model that has 12 components, including 6 nutrient and 6 biological components, which produces the Chl field. The Chl concentration simulated from the ocean-biology model is used to represent the effects on the penetration of solar radiation in the upper ocean. The Chl field is used to estimate penetration depth H_p , thus linking ocean biology to ocean physics. In this simplified coupled system, the climatological fields (SST_{clim} , FWF_{clim} , etc.) are prescribed as seasonally varying; the interannual anomalies of τ_{inter} and $\text{FWF}_{\text{inter}}$ are determined from their corresponding empirical models, and those of Chl are estimated from the ocean-biology model. The HCM AOPB is used to demonstrate the individual and collective effects of the interannually varying FWF and Chl in the tropical Pacific.

sensitivity runs, Chl can be expressed as $\text{Chl} = \text{Chl}_{\text{clim}} + \alpha_{\text{Chl}} \times (\text{Chl} - \text{Chl}_{\text{clim}})$ in which α_{Chl} is used to represent the Chl-induced feedback intensity, and Chl_{clim} is the climatological field. So, α_{Chl} can be varying and can even be chosen as $\alpha_{\text{Chl}} > 1$. Choosing such a large value would assume that the model underpredicts observed chlorophyll variation. Experiments indicate that when α_{Chl} is chosen as $0 < \alpha_{\text{Chl}} < 1$, the impacts are very weak. When α_{Chl} is chosen as larger values ($\alpha_{\text{Chl}} > 1$), we see some cases in which the total Chl field can become negative at the surface. If this happens, we simply set the total Chl field to be its Chl_{clim} field.

At each time step, the OGCM calculates interannual anomalies, which are then used to calculate the interannual anomalies of τ and FWF using their corresponding empirical models. These interannual anomalies are then added onto their prescribed climatological fields to force the ocean. The ocean-biology model is used to depict Chl concentrations; then, a corresponding penetration depth

H_p can be estimated to represent the effect of Chl on the incoming solar radiation in the upper ocean, which affects the thermodynamics in the ocean (Zhang et al. 2011). Thus, interactions between the atmosphere and ocean physics and biology are represented. As previously examined by Zhang et al. (2012), coupled behaviors sensitively depend on the relative coupling coefficient α_τ ; that is, the wind stress anomalies from the τ_{inter} model can be further scaled by this parameter. Several tuning experiments are performed using different values of α_τ to examine the ways that coupled interannual variability can be sustained in the HCM. It is found that using a value of $\alpha_\tau = 1.3$ can produce sustainable interannual variability in the HCM. In this paper, experiments are all performed using the HCM with α_τ being taken as $\alpha_\tau = 1.3$.

The OGCM domain covers the tropical Pacific basin from 120°E to 76°W and from 30°S to 30°N. The horizontal resolutions of the model varied: zonal resolutions were 1° in the central basin and gradually increased to

0.4° at the western and eastern boundaries, and meridional resolutions ranged from 0.3° to 0.6° between 15°S and 15°N and decreased to 2° at the northern and southern boundaries. Sponge layers are imposed near the model's southern and northern boundaries (poleward of 20°S/N). The OGCM is initiated from the *World Ocean Atlas (WOA01)* temperature and salinity fields and is integrated for 20 years using atmospheric climatological forcing fields. The coupled bioclimate experiment is then started from this OGCM spinup run, with an imposed westerly wind anomaly for 8 months (Zhang et al. 2018b). Thereafter, the evolution is determined solely by the coupled interactions in the system, and the coupled model is integrated for 30 years, arbitrarily denoted as model year 2301. As shown in Zhang et al. (2018b), this model can depict the interannual oscillations associated with ENSO. The related FWF and OBH experiments, which started from the end of the 30-yr coupled run, are performed from model years 2301 to 2330.

b. Experimental design

The model is used to represent bioclimate and FWF–climate couplings in the tropical Pacific. In this study, we focus on the modulating effects on ENSO induced by interannual variations in FWF and Chl, which can be represented individually or collectively in the HCM AOPB. Two corresponding scalar parameters, α_{FWF} and α_{Chl} , are introduced to represent intensities of FWF forcing and OBH feedback, respectively; also, the relative coupling coefficient α_τ is introduced to represent wind stress anomaly intensity in response to SST anomalies. Testing indicates that using values of $\alpha_\tau = 1.3$, $\alpha_{\text{FWF}} = 0.0$, and $\alpha_{\text{Chl}} = 0.0$ leads to HCM simulations that have reasonable interannual variations. The values of α_{FWF} and α_{Chl} can be varied to represent the related forcing and feedback intensities. The ranges over which α_{FWF} and α_{Chl} can vary are tested from 0.0 (correspondingly, no interannually varying FWF or OBH effects) to 2.5 (strong effects) in the model experiments.

Sensitivity experiments with varying α_{Chl} and α_{FWF} values (representing variable forcing and feedback intensities) are performed to illustrate the feedback effects associated with the interannually covarying FWF and OBH in the tropical Pacific. In a climatological run, denoted as FWF_{clim}–CHL_{clim} ($\alpha_\tau = 1.3$, $\alpha_{\text{FWF}} = 0.0$, and $\alpha_{\text{Chl}} = 0.0$), freshwater flux and Chl are both considered to be climatologically varying only, with their interannual effects being not taken into account. Then, FWF and OBH are alternatively assumed to be interannually and/or climatologically varying, thus allowing their feedback effects on ENSO to be examined individually or collectively. FWF_{inter}–CHL_{clim} denotes a set of runs in which the interannually varying FWF

forcing effect is activated (α_{FWF} is varying and $\alpha_{\text{Chl}} = 0.0$); FWF_{clim}–CHL_{inter} denotes a set of runs in which the interannually varying OBH feedback effect is activated ($\alpha_{\text{FWF}} = 0.0$ and α_{Chl} is varying); FWF_{inter}–CHL_{inter} denotes a set of runs in which the effects of both interannually covarying FWF and Chl are taken into account (both α_{FWF} and α_{Chl} are varying). The FWF_{inter}–CHL_{inter} run with values of $\alpha_\tau = 1.3$, $\alpha_{\text{FWF}} = 1.0$, and $\alpha_{\text{Chl}} = 1.0$ is referred to as a reference feedback run, in which both effects are included with reasonable intensities ($\alpha_{\text{FWF}} = 1.0$ and $\alpha_{\text{Chl}} = 1.0$). Choosing a large α_{FWF} value (e.g., $\alpha_{\text{FWF}} > 1$) means that the model simulations underestimate the true FWF variability in the HCM.

c. Observational and reanalysis data used

Various observed and reanalysis data are used to specify climatological fields, to construct the empirical model for τ_{inter} and FWF_{inter}, and to validate model simulations. SST fields are from Reynolds et al. (2002). Monthly mean wind stress data are from the ERA-Interim (Dee et al. 2011). Monthly precipitation P data are from the Global Precipitation and Climatology Project (GPCP; Adler et al. 2003); monthly evaporation E fields are obtained from the objectively analyzed air–sea fluxes (OAFlux; Yu and Weller 2007). The P and E data are used to derive FWF fields over the period 1979–2016 (defined as $P - E$; the FWF field is positive when there is a flux from the atmosphere to the ocean). In addition, surface chlorophyll datasets are obtained from the GlobColour project from 1998 to 2016, which supplied continuous datasets for merged level 3 ocean color products [including the SeaWiFS, MODIS, Medium-Resolution Imaging Spectrometer (MERIS) and VIIRS sensors; Maritorena et al. 2010].

3. Overview of the model performance

Results from the reference run ($\alpha_{\text{FWF}} = 1.0$ and $\alpha_{\text{Chl}} = 1.0$) are presented in this section to demonstrate its performance; some related observations are used to validate the model simulations.

Figure 3a illustrates interannual SST anomalies from the reference run. As is also evident from our previous HCM-based modeling studies (Zhang 2015c), the HCM AOPB constructed in the tropical Pacific can capture the main coupled ocean–atmosphere processes in a balanced way, such that ENSO cycles can be adequately depicted. In particular, the model captures a pronounced interannual oscillation, with a dominant standing pattern of SST variability on the equator (Fig. 3a). Also, the model can adequately depict the mean ocean physical and

FIG. 3. Interannual anomaly fields along the equator simulated from the reference FWF_{inter}-CHL_{inter} run with $\alpha_{FWF} = 1.0$ and $\alpha_{Chl} = 1.0$: (a) SST, (b) FWF, and (c) Chl. FWF_{inter}-CHL_{inter} is a run in which the related FWF forcing and OBH feedback are included in the simulations. The HCM is integrated for more than 100 years; for clarity, only the model years from 2301 to 2320 are plotted. The FWF field is positive when there is a net FWF from the atmosphere to the ocean at the sea surface. The contour interval is 0.5°C in (a), 30 mm month^{-1} in (b), and 0.02 mg m^{-3} in (c).

biological climatologies in the tropical Pacific, as compared with observations.

The empirical models are used to determine interannual variabilities of wind stress and FWF (Zhang and Busalacchi 2009; Zhang et al. 2009, 2011), and the ocean-biology model is used to determine Chl variability. As shown in Figs. 3b and 3c, large interannual anomalies of FWF (Fig. 3b) and Chl (Fig. 3c) coexist in the western-central equatorial Pacific during ENSO cycles. El Niño events (warm SST anomalies) are characterized by positive FWF anomalies and low Chl concentration in the central equatorial Pacific; La Niña events (cold SST anomalies) are characterized by negative FWF anomalies and high Chl concentration.

Since the effects of the FWF- and OBH-induced feedbacks on modulating ENSO are derived from the HCM, the HCM performance is critically important in realistically capturing ENSO evolution as observed in

nature. Some quantitative model validations are presented in Figs. 4 and 5 for some interannual anomaly fields and in Table 1 for the standard deviations of some interannual anomaly fields. Model validations indicate that the simplified HCM can depict reasonably well the mean ocean climatology and interannual variability in the tropical Pacific relative to observations. For example, the space-time evolution features of interannual variability simulated in the HCM compare well with those observed.

However, it seems obvious that the HCM has biases in simulating ENSO relative to observations. Because both stochastic atmospheric forcing and changes in the pattern of atmospheric response to those in Niño-3.4 SSTs are not included in the HCM, the simulated ENSO is quite regular. The spatial patterns of SST variability in the model simulations are somehow distinct from the observed features. Interdecadal shifts of response functions

FIG. 4. Time series of anomalies for the Niño-3.4 SST and Niño-4 zonal wind stress (a) from observations and the ERA-Interim and (b) from reference FWF_{inter}-CHL_{inter} run. Observational or reanalysis data are shown for the period of 1998–2016.

have been reported in fully coupled models (Russell and Gnanadesikan 2014), an effect that cannot be captured in our shorter, data-constrained HCM. Moreover, the spatial pattern of SST variability from the HCM simulation shows the central Pacific (CP) type of El Niño, whereas the observed SST shows the canonical El Niño. In terms of ocean biological fields, one bias is in the structure of the spatial pattern of ENSO-related chlorophyll anomalies in the model, which seems biased toward the central tropical Pacific, whereas in nature they are more confined to the eastern tropical Pacific.

4. ENSO modulations

More results are analyzed from the HCM-AOPB-based simulations with different representations of FWF and OBH. Figure 6 shows the simulated SST fields along the equator obtained from various model experiments, for example, the FWF_{clim}-CHL_{clim} simulation, in which interannually varying FWF forcing and OBH feedback are both excluded. Examples for the commonly used Niño-3.4 SST series are shown in Figs. 4 and 7 from the model simulations.

The effects of FWF forcing and OBH feedback on ENSO amplitude and oscillation period can be clearly

seen in Figs. 3–7. Figure 8 displays the standard deviations of Niño-3.4 SST anomalies from some selected experiments, which are intended to illustrate the magnitude of interannual variability for El Niño and La Niña events. So, we can interpret large values as amplified El Niño–La Niña cycles and the opposite for small values, respectively. In addition, the commonly used Niño-3.4 SST series are used to quantify the dominant time scales of the ENSO (Fig. 9). There is a statistically significant increase in the energy and period of interannual variability associated with the coupling FWF effects and also a statistically significant decrease of the both with the additional coupling of chlorophyll being included.

The results of observations and simulations are quantitatively compared in Table 1 in terms of the standard deviations of some selected interannual anomalies. In the following, more sensitivity experiments with varying intensities of FWF forcing and OBH feedback are performed to demonstrate their combined effects on ENSO.

a. The OBH feedback effect

One set of experiments is denoted as FWF_{clim}-CHL_{inter}, in which Chl is assumed to vary interannually, whereas FWF forcing is prescribed to follow a seasonally varying

FIG. 5. Time series of anomalies for the Niño-4 Chl and Niño-4 FWF from (a) observations and (b) the reference $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{inter}}$ run. Observational or reanalysis data are shown for the period of 1998–2016.

climatology. Examples for SST anomalies simulated are shown in Figs. 6b, 7, and 8. Compared to $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$ (Fig. 6a), the ENSO amplitude is reduced when interannually varying OBH feedback is explicitly included in $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{inter}}$.

The processes involved in the OBH feedback have been illustrated in Fig. 1b (also see Zhang 2015a), and the effects on the penetration of solar radiation in the upper ocean have been assessed. A corresponding negative feedback loop can be traced in association with the effects of interannual variations in Chl. During El Niño events, for example, a drop in Chl concentrations in the

western-central equatorial basin causes deeper penetration of sunlight in the upper ocean, with more heating occurring in the subsurface layers but less in the ML, thus inducing a differential heating between the ML and subsurface layers. The induced differential heating in the vertical direction acts to weaken stratification and destabilize the upper ocean and to enhance the vertical mixing and entrainment of subsurface waters into the ML. Thus, the OBH alters ocean dynamical processes and exerts an influence on SST in such a way that the intensity of El Niño events is reduced. The situation during La Niña is similar to that during El Niño, but in

TABLE 1. The standard deviations of selected anomaly fields observed and simulated in the four HCM AOPB-based experiments. Model results are calculated from model year 2301 to 2350; the corresponding observations are calculated as follows: SST ($^{\circ}\text{C}$) from NOAA OISSTv2 during 1982–2016; FWF (mm month^{-1} ; defined as P minus E , where P is from the GPCP, version 2.3, analysis and E is from the OAFflux, version 3) during 1982–2016; Chl (mg m^{-3}) is from the GlobColour project during 2000–16. Shown are SST in the Niño-3.4 region and FWF and Chl in the Niño-4 region.

	Obs	$\text{FWF}_{\text{clim}}\text{-OBH}_{\text{clim}}$	$\text{FWF}_{\text{clim}}\text{-OBH}_{\text{inter}}$	$\text{FWF}_{\text{inter}}\text{-OBH}_{\text{clim}}$	$\text{FWF}_{\text{inter}}\text{-OBH}_{\text{inter}}$
Niño-3.4 SST	0.95	0.66	0.51	0.97	0.80
Niño-4 FWF	62.9	0	0	85.84	74.07
Niño-4 Chl	0.02	0	0.02	0	0.03

FIG. 6. Interannual SST anomalies along the equator simulated in (a) $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$ (the climatological run), (b) $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{inter}}$ ($\alpha_{\text{FWF}} = 0.0$ and $\alpha_{\text{Chl}} = 1.0$), (c) $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$ ($\alpha_{\text{FWF}} = 1.0$ and $\alpha_{\text{Chl}} = 0.0$), and (d) $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{inter}}$ ($\alpha_{\text{FWF}} = 1.0$ and $\alpha_{\text{Chl}} = 1.0$). The contour interval is 0.5°C .

the opposite sense. During a La Niña event, an increase in Chl concentrations in the western–central equatorial basin leads to sunlight being more trapped within the ML and penetrating less throughout the base of the ML (less heating in the subsurface layers), which stabilizes the stratification and weakens vertical mixing in the upper ocean. These processes act to warm SSTs so that La Niña is weakened. Therefore, the OBH effects serve as a negative feedback onto the ENSO, whose amplitude decreases as the intensity of OBH feedback increases.

In the model simulations, changes in α_{Chl} have direct effects on the amplitude of SST variability (Fig. 10a). As

mentioned above, the parameter of α_{Chl} is introduced to represent the OBH feedback intensity. An inverse relationship exists between the biofeedback intensity α_{Chl} and ENSO amplitude (Fig. 10a). The larger the value of α_{Chl} prescribed in the model is, the stronger the OBH feedback is, and the smaller the ENSO amplitude is. In addition, the ENSO amplitude decreases with α_{Chl} in a nonlinear way. When α_{Chl} is low and the OBH feedback effects are weakly represented, the ENSO amplitude is not strongly affected. When α_{Chl} reaches a certain value, there is a sharp decrease in the ENSO amplitude; this is clearly evident when α_{Chl} increases from 1.5 to 2.0 (Fig. 10a).

FIG. 7. Time series of the SST anomalies in the Niño-3.4 region simulated from $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$, $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{inter}}$, and $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$.

The extent to which ENSO is modulated by the OBH feedback can be analyzed in detail. Symbolically, the interannual variability of Chl can be written as $\text{CHL}_{\text{inter}} = \alpha_{\text{chl}} \times \text{ENSO}$ amplitude. (Note that the $\text{CHL}_{\text{inter}}$ field in the HCM is produced by an ocean-biology model; here, the relationship between the ENSO amplitude simulated in the HCM and the intensities of OBH feedback represented is explicitly expressed for analysis purpose.) This expression indicates that the intensity of Chl variability is determined by two factors in the model simulations: A direct one associated with α_{chl} and an indirect one associated with ENSO amplitude. A change in α_{chl} directly leads to a change to Chl, thus modulating the ENSO amplitude due to the OBH feedback, which indirectly affects the intensity of Chl variability. Because Chl-induced feedback tends to damp ENSO, the ENSO amplitude is inversely proportional to α_{chl} . Correspondingly, an increase in the OBH feedback intensity α_{chl} can be envisioned to have direct and indirect effects on Chl variability as follows. An increase in α_{chl} in model experiments (i.e., a stronger OBH feedback) produces a direct increase in Chl variability. Then, the increased Chl variability acts to strongly damp ENSO because of the OBH feedback; the weakened ENSO in turn gives rise to a decrease in Chl variability, which represents an indirect effect due to the increased α_{chl} . Thus, an increase in α_{chl} leads to a direct (increasing) effect on Chl variability that tends to be opposite to the indirect effect due to the weakened ENSO. Furthermore, the inverse relationship between α_{chl} and the ENSO amplitude is nonlinear because the ENSO amplitude does not vary linearly with α_{chl} as indicated in Fig. 10a.

b. The FWF forcing effects

Next, we focus on FWF forcing effects. The second set of experiments is denoted as $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$, in which FWF forcing is assumed to vary interannually, whereas Chl is prescribed to follow a seasonally varying

climatology. Examples of the simulated SST anomalies are shown in Figs. 6c and 7–9. Compared with $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$ (Fig. 6a), the ENSO amplitude is enhanced in $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$ when the interannually varying FWF forcing is explicitly included.

The processes involved in FWF forcing have previously been described (Fig. 1a; also see Zhang and Busalacchi 2009 and Zhang et al. 2012). FWF anomalies directly force SSS anomalies, which modulate density, the depth of the mixed layer (MLD), the buoyancy flux Q_B , and the thickness of the barrier layer; these directly affect the stratification and vertical mixing in the upper ocean. By affecting these ocean dynamical processes, FWF forcing acts to modulate SST and ENSO in a substantial way. A corresponding positive feedback loop can be traced in association with interannual FWF anomalies. During El Niño, for example, a positive FWF anomaly observed in the western–central equatorial Pacific is accompanied by a negative SSS anomaly. The positive FWF anomaly enhances the negative SSS anomaly, which decreases the surface density in the western–central equatorial basin. The induced changes in density (i.e., the mixed layer is less dense) enhance stratification and stabilize the upper ocean, leading to weakened vertical mixing. Additionally, the positive FWF anomaly tends to increase the negative buoyancy flux anomaly and make the ML shallower, which weakens the entrainment of colder subsurface waters into the mixed layer. These FWF-induced ocean dynamical processes exert a direct influence on SST, such that El Niño events are enhanced by a positive FWF anomaly, leading to a positive feedback onto El Niño events. The train of causation during La Niña is similar to that during El Niño, but in the opposite sense. Therefore, the FWF forcing effects serve as a positive feedback onto ENSO, and ENSO amplitude increases as the intensity of FWF forcing increases.

More experiments with different FWF forcing intensities are performed, and their results are shown in

FIG. 8. Zonal sections of the standard deviations for the equatorial (5°S–5°N) SST anomalies for $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$, $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{inter}}$, $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$, and $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{inter}}$ (colored solid lines) and observation (dotted line).

Fig. 10b. It is evident that FWF forcing acts to amplify ENSO, with a positive feedback relationship between FWF forcing and ENSO amplitude (Fig. 10b). In general, the ENSO amplitude is proportional to the FWF forcing intensity (as indicated by α_{FWF}). The larger the α_{FWF} value is, the stronger the FWF forcing represented in the model is, and the larger the ENSO amplitude is.

The degree to which ENSO is modulated by FWF forcing can be analyzed in detail. Symbolically, FWF variability represented in the HCM can be written as $\text{FWF}_{\text{inter}} = \alpha_{\text{FWF}} \times \text{ENSO amplitude}$. This expression indicates that FWF variability depends on two factors in the model simulations: α_{FWF} itself and the ENSO amplitude. In various experiments with varying α_{FWF} , a change in α_{FWF} directly leads to a change to FWF, which modulates the ENSO amplitude and thus indirectly affects the FWF variability. Because the FWF variability acts to amplify ENSO, the ENSO amplitude is proportional to α_{FWF} . The effects of increased FWF forcing can be derived as follows. An increase in α_{FWF} (i.e., a stronger FWF forcing) leads to a direct increase in FWF variability. Then, the increased FWF variability acts to amplify ENSO, which in turn gives rise to a further increase in FWF variability, indicating an indirect effect due to the increased α_{FWF} . Thus, an increased α_{FWF} leads to a direct (increasing) effect on FWF variability, which tends to be enhanced by an indirect effect due to the enhanced ENSO. In this FWF forcing case, an increased α_{FWF} leads to stronger FWF variability, executing a strong amplifying effect on ENSO, which further increases FWF variability, indicating a non-linear modulating effect. This amplifying effect is thus different from the reducing effect due to OBH feedback (i.e., an increase in α_{Chl} leads to strong Chl variability, which damps ENSO more strongly).

c. The combined effects

Then, the third set of experiments is performed, denoted as $\text{FWF}_{\text{inter}}\text{-OBH}_{\text{inter}}$, in which the interannual

FIG. 9. Wavelet power spectra for the Niño-3.4 SST anomalies calculated from the $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{clim}}$, $\text{FWF}_{\text{clim}}\text{-CHL}_{\text{inter}}$, $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{clim}}$, and $\text{FWF}_{\text{inter}}\text{-CHL}_{\text{inter}}$ simulations, as well as from SST observations. The dot-dashed line is the 95% significance level for these simulations, assuming a white noise process.

covariabilities of FWF forcing and OBH feedback are collectively taken into account. Figures 3–5 illustrate the anomalies of SST, FWF, and Chl simulated from the reference feedback run ($\alpha_{\text{FWF}} = 1.0$ and $\alpha_{\text{Chl}} = 1.0$). Accompanied with ENSO-related SST anomalies (Fig. 3a), FWF (Fig. 3b) and Chl (Fig. 3c) exhibit large interannual variations over the western–central equatorial Pacific. Coherent well-defined patterns and relationships can be seen between these anomaly fields. For example, El Niño conditions (Fig. 3a) are characterized by a warm SST anomaly in the central–eastern equatorial regions, accompanied with a positive FWF anomaly (Fig. 3b) and a negative Chl anomaly (Fig. 3c) over the western–central equatorial Pacific. In response to ENSO cycles, interannual covariabilities of FWF and Chl also execute a feedback onto ENSO.

These FWF and Chl anomalies not only represent a response to ENSO but also execute a feedback onto ENSO. When these effects are present in the HCM experiments, the FWF forcing and OBH feedback are expected to modulate ENSO. As demonstrated in previous modeling studies (e.g., Zhang et al. 2012; Zhang 2015a), these two processes tend to modulate dynamic processes in the upper ocean (i.e., ocean density, stratification, and vertical mixing), which exert an influence on SST, a field that directly induces changes in the atmosphere. The HCM AOPB is then used to represent the interactions between the atmosphere and ocean physics–biology system in the tropical Pacific, with FWF forcing and OBH feedback explicitly included.

The large anomalies of FWF observed in the western–central equatorial Pacific have amplifying effects on

FIG. 10. The effects of FWF forcing and OBH feedback on the ENSO amplitude revealed by the HCM AOPB-based 24 sensitivity experiments. Shown are the standard deviations of the Niño-3.4 SST anomalies: (a) as a function of the OBH feedback intensities on the horizontal axis (as represented by $\alpha_{\text{Chl}} = 0.0, 1.0, 1.5$, and 2.0), with different color lines indicating varying FWF forcing intensities (as represented by $\alpha_{\text{FWF}} = 0.0, 0.5, 1.0, 1.5, 2.0$, and 2.5) and (b) as a function of the FWF forcing intensities on the horizontal axis (as represented by $\alpha_{\text{FWF}} = 0.0, 1.0, 1.5, 2.0$, and 2.5) with different color lines indicating varying OBH feedback intensities (as represented by $\alpha_{\text{Chl}} = 0.0, 0.5, 1.0, 1.5$, and 2.0). Note that the observed standard deviation of the Niño-3.4 SST anomalies is 0.95°C (Table 1). Some dashed lines are arbitrarily plotted to indicate the nonuniformly changing effects.

ENSO, whereas those of Chl have damping effects. These two processes can interact with each other when they are collectively taken into account in model simulations. Corresponding feedback loops can be traced in association with the interannual anomalies of FWF and OBH, which are described above for each individual effect (Fig. 1). In general, the larger the FWF variability

is, the stronger the FWF forcing is, and the stronger the amplifying effect on ENSO is. In contrast, the larger the Chl variability is, the stronger the OBH feedback is, and the stronger the damping effect on ENSO is. Therefore, the way ENSO is modulated (an increase or decrease in ENSO amplitude) is determined by the relative dominances of these effects associated with FWF forcing and OBH feedback. When the OBH-related damping effect dominates, the ENSO amplitude decreases; in contrast, when the FWF-related amplifying effect dominates, the ENSO amplitude increases. Furthermore, it can be envisioned that at some balanced points where the amplifying effects on ENSO due to FWF forcing offset more or less the damping effects due to OBH feedback, no obvious modulation can be seen in ENSO amplitude.

These qualitative and intuitive arguments for the possible combined effects are confirmed by sensitivity experiments using the HCM AOPB with different intensities of each effect represented for FWF forcing and OBH feedback. The results of a series of 24 experiments are illustrated in Fig. 10. The simulations indicate that individually, the FWF forcing tends to enhance (prolong) the ENSO amplitude (period) through its effect on the stratification and vertical mixing in the upper ocean, whereas the OBH feedback tends to reduce (shorten) it through its effect on the penetrative solar radiation, further affecting the stratification and vertical mixing. As demonstrated above, ENSO simulations are sensitively dependent on the intensities of each individual effect represented in the model.

Again, α_{Chl} and α_{FWF} are conveniently used to represent the intensities of OBH feedback and FWF forcing, respectively. Individually, an increase in α_{Chl} (α_{FWF}) corresponds to an increase in the intensity of OBH feedback (FWF forcing), which has damping (amplifying) effects on ENSO. Collectively, when these two processes are taken into account together, their compensated effects occur in terms of ENSO modulations in model simulations. An increase in α_{FWF} has two-edged effects. Directly, an increase in FWF variability has an amplifying effect on ENSO. Indirectly, the enhanced ENSO leads to large Chl variability and strong negative OBH feedback, which has a large damping effect on ENSO, leading to a weakened ENSO. Similarly, an increase in α_{Chl} has two effects. Directly, its increase leads to an increase in Chl variability, which has a damping effect on ENSO. Indirectly, the weakened ENSO leads to weak FWF variability, which has a weakened amplifying effect on ENSO. In this case, an increase in OBH feedback leads to an ENSO amplitude that is reduced by both the enhanced OBH feedback and weakened FWF forcing and thus ENSO can be damped much strongly.

The combined effects of these two processes lead to ENSO modulations that are different from those induced individually by FWF forcing effect or OBH feedback effect alone. When these two processes occur collectively, the effects induced by one can be compensated for by another. As a result, the ENSO amplitude modulated is not linearly proportional to the intensities of the FWF forcing or OBH feedback represented in the model (Fig. 10). For example, the ENSO depicted in the model can have the same amplitude but with differently represented intensities for the coexisting FWF forcing and OBH feedback. For instance, the ENSO amplitude simulated at $\alpha_{\text{Chl}} = 1$, $\alpha_{\text{FWF}} = 2.5$ can have nearly the same level to that when taking $\alpha_{\text{FWF}} = 1.0$, $\alpha_{\text{Chl}} = 0.0$.

Furthermore, some surprising cases emerge in which an increase in the FWF intensity actually corresponds to a decrease in the ENSO amplitude (Fig. 10b). For example, under weakly represented OBH feedback cases [its effect is not included ($\alpha_{\text{Chl}} = 0.0$) or its intensity is weakly represented as taking $\alpha_{\text{Chl}} = 1.0$], the ENSO amplitude increases as α_{FWF} increases (green and red lines in Fig. 10b). When the OBH feedback increases to a certain intensity (say, $\alpha_{\text{Chl}} = 1.5$ and $\alpha_{\text{Chl}} = 2.0$), the ENSO amplitude can be modulated in a nonlinear way: The ENSO amplitude does not increase linearly with increases in α_{FWF} (purple and blue lines in Fig. 10b). For example, the ENSO amplitude actually decreases when α_{FWF} increases from $\alpha_{\text{FWF}} < 1.5$ to $\alpha_{\text{FWF}} > 1.5$ when the OBH feedback is represented by certain intensity at $\alpha_{\text{Chl}} = 2.0$ (green line in Fig. 10b). Thus, there may exist a threshold for α_{FWF} at which the ENSO amplitude reaches a local maximum at $\alpha_{\text{FWF}} = 1.5$ and $\alpha_{\text{Chl}} = 2.0$, and then unanimously decreases with either a decrease or increase in α_{FWF} . At certain intensity of the OBH feedback, its damping effects on ENSO can exceed the amplifying effects due to FWF forcing, and the ENSO amplitude can decrease even though FWF forcing increases.

A schematic diagram is shown in Fig. 11 to explain this situation, which can be attributed to the double-edged impacts of the FWF forcing on ENSO. An intensifying FWF forcing enhances ENSO amplitude, but it also increases Chl variability, which thus intensifies the OBH-related damping effect on ENSO. Thus, there can be situations in which an increased FWF forcing corresponds to a weakened ENSO (i.e., the signs of the FWF effects on ENSO can be even reversed from an increase to a decrease in the ENSO amplitude due to the OBH effect). This indeed happens in a different combination of modeling experiments in which varying intensities of the FWF or Chl effects are specified using feedback parameters (α_{FWF} and α_{Chl}). Therefore, the net combined effects can either enhance or weaken ENSO, depending on the

FIG. 11. A schematic diagram illustrating possible net outcomes of combined effects on ENSO amplitude that are induced by FWF forcing and OBH feedback. Individually, FWF forcing tends to have an amplifying effect on ENSO amplitude. Correctively, when the OBH feedback coexists at a certain intensity, the amplifying effect of FWF forcing on ENSO can be compensated by damping one induced by OBH feedback. So, ENSO amplitude can be either increased or decreased in the model experiments, depending on the relative dominance of these two processes in coupled models.

relative dominance of the OBH-feedback-related damping effect or FWF-related amplifying effect. If the former is stronger than the latter, the ENSO amplitude is modulated to be decreased.

These experiments clearly illustrate that ENSO modulations are sensitively dependent on the ways FWF forcing and OBH feedback are represented in the model. When their combined effects are collectively taken into account, ENSO can be modulated in a nonlinear way. Sensitivity experiments reveal some situations (for example, the green line in Fig. 10b between $\alpha_{\text{FWF}} = 1.5$ and $\alpha_{\text{FWF}} = 2.0$) in which the amplitude response is not linear. In particular, the OBH effect with certain intensities can lead to a decrease in ENSO amplitude even though FWF forcing is increased. Evidently, modulating effects induced by their combined effects differ from those individually induced by FWF forcing or OBH feedback alone.

d. Insight into the modulating effects on ENSO

ENSO modulations are clearly evident in nature and various coupled model simulations, which can be attributed to various forcings and feedbacks in the tropical Pacific. Understanding how ENSO is affected by these processes in the tropical Pacific is a crucial problem in climate dynamics and ENSO-induced climate predictions. For example, several previous studies with more complex models have also investigated the feedback from ocean biology onto interannual variability in the tropical

Pacific (Wetzel et al. 2006; Lengaigne et al. 2007; Anderson et al. 2009; Jochum et al. 2010; Heinemann et al. 2011; Park et al. 2014a). Large uncertainties exist in representing OBH feedback in these different models, and yet there are large differences in the related modulating effects on ENSO. For example, the ENSO amplitude is decreased when the OBH feedback is included in some studies (an indication of a negative feedback; e.g., Zhang et al. 2009; Jochum et al. 2010), whereas it is increased in others (an indication of a positive feedback; e.g., Wetzel et al. 2006; Heinemann et al. 2011). The reasons for these intermodel differences are still not well understood. Additionally, the mechanisms for the way SST is modulated by OBH feedback are in debate. For example, Timmermann and Jin (2002) argued that SST modulations are realized through a direct heating effect on SST within the mixed layer (a direct thermal effect). In this study and our previous studies (e.g., Zhang 2015a), however, ENSO modulations are realized through an indirect effect via ocean dynamical processes: Ocean-biology-induced feedback acts to produce a differential heating between the ML and subsurface layers, which alters the stratification and the vertical mixing in the upper ocean, leading to changes in SST and in the atmosphere (Fig. 1b).

Results from this study offer a clue to explain the intermodel differences in ENSO modulations induced by OBH feedback. As illustrated in Fig. 11, the net outcomes of the compensated effects under the combined influences of FWF forcing and OBH feedback can be very different or even opposite. Individually, ENSO amplitude increases (decreases) with increasing intensities of FWF forcing (OBH feedback). When OBH feedback is not included, an increase in FWF forcing acts to enhance ENSO amplitude, depending on their relative dominance. When OBH feedback is included and comes into play, its damping effect tends to counteract the FWF-related amplifying effect, and ENSO amplitude can be decreased or increased. When the OBH-related damping effect on ENSO is weaker (greater) than the FWF-related amplifying effect, the ENSO amplitude is modulated to be increased (decreased). In particular, as indicated in some model simulations, it is possible that an increase in FWF forcing can even cause a decrease in ENSO amplitude when the amplifying effect on ENSO due to the FWF forcing is weaker than the damping effect due to the OBH feedback. Therefore, whether ENSO amplitude is modulated to be increased or decreased depends on the relative dominance of the related FWF forcing and OBH feedback effects represented in models.

Large uncertainties exist in model representations of these FWF forcing and feedback effects over the tropical Pacific, which can be clear sources for biases in

ENSO simulations. The results obtained from this simple modeling study provide guidance to understand the related modulating effects on ENSO in other comprehensive climate models. In particular, the revealed relationships between ways ENSO is modulated and the intensities of FWF forcing and OBH feedback are represented in models can be used to interpret how biases are produced in ENSO simulations. For example, many current climate models do not explicitly include the OBH feedback; then, the associated damping effect by the OBH feedback does not exist, leading to the FWF-related amplifying effect that is not adequately compensated for. As such, ENSO amplitude simulated can be much too strong as indicated in some climate models (Wang et al. 2005; Kang et al. 2014, 2017). In addition, FWF forcing in many climate models tends to be depicted too strong as indicated by the so-called double intertropical convergence zone (ITCZ) problem (e.g., Lin 2007), implying that its amplifying effects on ENSO can be overestimated. Because the amplifying effects induced by FWF forcing tend to be compensated for by OBH-related damping effects, these two processes must be collectively represented in a balanced way in models. Otherwise, if the OBH feedback is not adequately included as in many climate models, the effects induced by FWF forcing are not offset by OBH feedback. Therefore, model biases can be produced in ENSO simulations due to misrepresentations of these natural forcing and feedback processes in the tropical Pacific.

The natural coupled atmosphere and ocean physics–biology system in the tropical Pacific is also influenced by global warming. As has been observed, long-term changes in FWF and Chl coexist in the tropical Pacific in the changing climate. For example, an enhanced water cycle is associated with an increase in FWF forcing to the ocean (e.g., Zhang and Wu 2012; Kang et al. 2014), which is expected to exert an amplifying effect on ENSO; also, Chl concentration is observed to decrease in the tropical Pacific (e.g., Boyce et al. 2010; Uz et al. 2017), whose related OBH feedback can have damping effects on ENSO. However, possible ENSO modulations by such long-term changes in Chl and FWF and the related feedback on global warming remain poorly understood (Behrenfeld et al. 2006). Understanding how ENSO can be modulated by these processes in the context of global warming is an important challenge facing the scientific community (e.g., Collins et al. 2010). HCM-based sensitivity experiments with varying intensities of FWF and OBH effects are conducted. These simplified HCM AOPB-based analyses and results from this paper provide insight into processes and mechanisms for a better understanding of ENSO diversities and modulations that are seen in nature and comprehensive Earth system models.

The insight into the modulating effects and underlying processes gained from this study can be used to interpret how ENSO may be modulated by long-term changes in the FWF forcing and OBH feedback over the tropical Pacific that may be induced by global warming.

5. Conclusions and discussion

Large interannual covariabilities of Chl and FWF are observed in the western–central equatorial Pacific during ENSO cycles, acting to not only represent a response to ENSO but also produce a feedback onto ENSO. For instance, various modeling studies have indicated that ocean-biology-induced heating feedback can exert significant influences on the climate system in the tropical Pacific. In addition, FWF forcing can have an amplifying effect on ENSO. Thus, active bioclimate and FWF–climate interactions coexist in the region. However, the nature of their combined interactions and modulating effects on ENSO are neither well illustrated nor well understood. Here, a newly developed hybrid coupled model (HCM) for atmosphere and ocean physics–biology (AOPB) is used to illustrate how ENSO can be modulated collectively by the effects of FWF forcing and OBH feedback, whose intensities are represented by α_{FWF} and α_{Chl} , respectively. A series of sensitivity experiments are performed using the HCM AOPB with their varying intensities. It is demonstrated that the amplitudes and time scales of ENSO can be substantially affected by interannually varying FWF forcing and OBH feedback. Individually, ENSO amplitude increases (decreases) when the FWF forcing (OBH feedback) intensity increases. A positive feedback is associated with the FWF forcing, acting to enhance interannual variability and lengthen time scales; the stronger the FWF forcing is, the stronger its amplifying effects on ENSO are. In contrast, a negative feedback is associated with the OBH feedback, acting to reduce interannual variability and shorten time scales; the stronger the OBH feedback is, the stronger its damping effects on ENSO are.

Collectively when these two processes coexist, the FWF-induced amplifying effect on ENSO tends to be compensated for by the OBH-related damping effect. Thus, the net outcomes of their combined effects on ENSO differ from those induced individually. The interactions between these two processes cause nonlinear modulations of the ENSO amplitude. For example, the ENSO amplitude in the model simulations does not unanimously vary with the intensities of FWF forcing or OBH feedback. There exist situations in which the ENSO amplitude can be decreased even though the FWF-

related amplifying effect on ENSO is increased. This can occur when, at certain intensities, the damping effects due to OBH feedback can override the amplifying effects due to FWF forcing. These results indicate that because of the compensated effects of FWF forcing and OBH feedback, ENSO amplitude can be modulated to be increased or decreased, depending on the relative dominance of these two processes represented in a model.

There are apparent interplays involved in FWF forcing and OBH feedback in terms of their effects on ENSO. Given that FWF affects stratification and vertical mixing in the upper ocean, this clearly impacts ocean biology and hence penetration of solar radiation on ENSO time scales. For example, an increase in FWF leads to a decrease in SSS, which enhances water-column stratification with reduced vertical mixing; these processes tend to reduce vertical fluxes of nutrients and result in a reduction in Chl. In terms of OBH feedback, a reduction in Chl concentration over the western–central equatorial Pacific (which occurs during El Niño) causes penetrative solar radiation to be absorbed less within the mixed layer, but more penetrated into the subsurface layers; the produced differential heating between the ML and subsurface layers reduces the stratification with enhanced vertical mixing, which affects SST and thus the atmosphere, including precipitation and FWF. Right now, how the FWF-induced processes directly affect marine ecosystems and Chl concentration and hence penetrating radiation has not been examined in detail. Those complicated interplays need to be carefully addressed with more focused experiments performed using the developed HCM AOPB to trace the influence loops and quantify the interplays between one another.

The modulating effects on ENSO induced by the FWF forcing and OBH feedback are examined using the HCM. There are possible biases in the modeling framework used in this paper. For example, one apparent bias in the HCM simulations is that ENSO-related variability is too regular. In reality, there is clear asymmetry in intensity, duration, and spatial patterns between cold and warm phases of ENSO (Kessler 2002; Okumura et al. 2011; Hu et al. 2014; Timmermann et al. 2018). This is partly because the influence of climate noise is not taken into account in the model. In fact, the statistical atmospheric representations for interannual anomalies of wind stress and FWF preclude the occurrence of random wind and freshwater flux events from other climate and weather phenomena that might reduce or obscure the positive or negative feedback effects noted here. More specifically, in terms of SST variability, the HCM indeed has systematic biases in simulating ENSO compared with observations. For instance, the spatial patterns in Fig. 3a are highly distinct from the observed

features. In particular, Fig. 3a shows that the largest amplitude of the interannual SST anomalies appears in the central Pacific at approximately 180°–160°W, although observation shows that the strongest SST variability with typical ENSO events appears in the eastern tropical Pacific. In terms of ocean biological fields, one bias is in the structure of the spatial pattern of ENSO-related chlorophyll anomalies in the model, which seems biased toward the central tropical Pacific, whereas in nature they are more confined to the eastern tropical Pacific. This might have artificially enhanced the negative feedbacks associated with the ocean biology since the atmosphere is more sensitive to SST anomalies in the central equatorial Pacific. So, the biases in the simplified HCM simulations and disagreements with observations may influence conclusions qualitatively. These issues need to be carefully analyzed in the future.

Numerical experiments are performed using the HCM simulations in which the FWF forcing and OBH feedback intensities are explicitly represented with empirical parameters that are variable. Here, we demonstrate that the amplitudes and oscillation periods of ENSO can be modulated by FWF forcing and OBH feedback. However, the combined effects induced by interannual variations in FWF and OBH rely on only one model simulation, which can be highly model dependent. Indeed, there is uncertainty in the represented amplitudes of the FWF forcing and biofeedback to SST changes, which is indicated by the feedback strength factors (α_{FWF} and α_{CH}). In addition, ENSO also exhibits other properties that can be modulated, including seasonal phase locking and asymmetries during ENSO cycles. For example, observed SST variability exhibits strong asymmetries during ENSO cycles, including evolution between El Niño and La Niña events. Preliminary examinations using the HCM simulations indicate that there is no clear evidence for any asymmetries that arise from the feedbacks, like La Niña being damped more strongly than El Niño because of non-Gaussian biological behaviors. Nevertheless, these issues have not been carefully addressed and need to be further explored in this context of the modulating effects on ENSO associated with the freshwater flux positive feedback. Also, the modulating effects on ENSO need to be validated using other models; the approach presented in this paper can be used in other modeling studies.

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APPENDIX

Empirical Atmospheric Models Used

Interannual anomalies of wind stress and FWF (τ_{inter} and $\text{FWF}_{\text{inter}}$) are calculated using empirical models constructed from historical data by the singular value decomposition (SVD) analysis technique (Zhang and Busalacchi 2009; Zhang et al. 2009), which is briefly described in this appendix.

a. An empirical model for interannual wind stress variability

The interannual anomaly model for wind stress τ adopted in this work is a statistical one, which can be symbolically written as $\tau_{\text{inter}} = F_{\tau}(\text{SST}_{\text{inter}})$, where τ_{inter} and $\text{SST}_{\text{inter}}$ are interannual anomalies of τ and SST, and F_{τ} represents the relationships between interannual variations in τ and SST.

The F_{τ} function is estimated using the SVD analysis of the covariance matrix that is calculated from time series of monthly mean $\text{SST}_{\text{inter}}$ and τ_{inter} fields. In this work, a combined SVD analysis is performed based on the covariance among anomalies of SST, zonal, and meridional wind stress components (Zhang et al. 2003, 2005, 2006). In time, the SVD analysis is performed using historical $\text{SST}_{\text{inter}}$ and τ_{inter} data over the 1963–96 period (34 years).

Based on this SVD analysis, an empirical model for τ_{inter} can be constructed to relate interannual variations in wind stress to those in SST, representing a dominant wind–SST coupling in the tropical Pacific. As understood, interannual wind responses to a given SST anomaly are sensitively dependent on seasons during ENSO evolution, and so the seasonality in the wind response to SST variability needs to be taken into account in constructing the τ_{inter} model. To this end, the SVD analyses are performed separately for each calendar month, thus yielding 12 seasonally varying submodels for January, February, and so on (e.g., Zhang et al. 2004; Zhang and Busalacchi 2005). Thus, given an SST anomaly, interannual wind response can be calculated according to the constructed τ_{inter} model. In consideration of the sequence of the singular values and the

reconstruction testing of the τ_{inter} fields from SST anomalies, the first five leading SVD modes are retained in the empirical τ_{inter} model for having its reasonable amplitude.

b. An empirical model for interannual FWF variability

$\text{FWF}_{\text{inter}}$ is also determined by an empirical model relating interannual freshwater flux variability with SST anomalies. This is based on the fact that interannual freshwater flux anomalies over the tropical Pacific are dominated by the ENSO signal. For example, interannual variations in freshwater flux closely follow those in SST during ENSO evolution. During El Niño, a warm SST anomaly is related to an increase in P (a positive freshwater flux anomaly into the ocean). During La Niña, a cold SST anomaly is accompanied with a negative freshwater flux anomaly (a net loss of freshwater from the ocean), which is primarily attributed to a deficit in P . Thus, a coherent pattern exists between interannual variations in SST and freshwater flux over the tropical Pacific, with a dominant SST control on freshwater flux.

The satellite-based P and E data are used to empirically parameterize interannual FWF (P minus E) variability in the tropical Pacific (Zhang and Busalacchi 2009). We adopt a statistical method to construct a feedback model for interannual freshwater flux variability ($\text{FWF}_{\text{inter}}$) as a response to ENSO-induced SST anomalies. To determine optimized empirical modes of their covariability, an SVD analysis is performed using historical SST and freshwater flux anomaly fields during the period of 1979–2008 (a total of 30 years). Then, an empirical model for $\text{FWF}_{\text{inter}}$ can be developed using the derived spatial eigenvectors of the SVD modes (e.g., Zhang and Busalacchi 2009). The seasonality is taken into account by constructing seasonally dependent models for $\text{FWF}_{\text{inter}}$. The SVD analyses are performed separately for each calendar month, and thus the $\text{FWF}_{\text{inter}}$ model consists of 12 different submodels, one for each calendar month (e.g., Zhang et al. 2003). In consideration of the sequence of the singular values and the reconstruction testing of the freshwater flux anomaly fields from SST anomalies, the first five leading SVD modes are retained for the empirical model to have reasonable amplitude in estimating $\text{FWF}_{\text{inter}}$ fields. Thus, given an SST anomaly, interannual freshwater flux anomalies can be empirically determined in association with ENSO.

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