Ocean Biology-Induced Climate Feedback Effects on Interannual Variability in the Tropical Pacific: A Missing Process in the NCEP CFS

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ABSTRACT

Satellite-based ocean color measurements indicate clear evidence for bio-climate interactions in the tropical Pacific associated with El Niño-Southern Oscillation (ENSO). Recent data analyses and modeling studies have demonstrated that ocean biology can potentially affect the climate in the tropical Pacific through the penetration depth of solar radiation in the upper ocean ($H_p$), a field serving as a link between the climate system and the marine ecosystem. However, most global climate models, including the NCEP CFS, have not adequately taken into account ocean biology-induced heating effects. In particular, interannually varying effect of $H_p$ on the heat budget has not been included. Therefore, the ocean biology-induced feedback (OBF) to the physics and the corresponding coupled bio-climate interactions are still missing in the NCEP CFS. It is very unlikely that in the near-term the CFS will include a comprehensive ocean biogeochemical model to resolve interannual $H_p$ variability. Furthermore, great difficulties still exist in capturing interannual $H_p$ variability using physical and biological ocean models. For example, current comprehensive and time-consuming ocean biogeochemistry models still cannot realistically depict interannual $H_p$ anomalies during ENSO cycles. A cost-effective parameterization is clearly needed to take into account the ocean biology-induced heating effect on the upper ocean; a key is to explicitly capture interannual $H_p$ variability which is dominantly forced by ENSO in the tropical Pacific.

Over the past decade, remote sensing has led to significant advances in physical understanding, interpretation and modeling efforts of ocean biology-related effects on the climate. In particular, the time series of remotely sensed ocean color data and associated products have revolutionized how the impacts of climate variability and change on ocean biology can be understood and quantified both globally and regionally. $H_p$ can be now accurately derived using chlorophyll content data that are available from ocean color imagery since Sep. 1997, providing an opportunity for characterizing its variability and quantifying its coherent relationships with physical fields (SST and sea level). Previously, an empirical model for interannual $H_p$ variability has been derived using a singular value decomposition (SVD) analysis from historical satellite observations, which allows for a non-local, SST-dependent, and spatially-temporally varying representation of $H_p$ variability and heating effects. As a test bed, the effects of ocean biology-induced climate feedback on interannual variability in the tropical Pacific are examined by incorporating the derived empirical $H_p$ model into a hybrid coupled ocean-atmosphere model. It is shown that the OBF has significant effects on ENSO amplitude and oscillation periods. Applications of the empirical $H_p$ model to the NCEP CFS to represent OBF are discussed.

1. Introduction

Sunlight is the original energy source for the Earth’s ocean, atmosphere, land and biosphere. Its shortwave radiation part can pass through the atmosphere relatively unimpeded and reach the Earth’s surface, about 70% of which is covered by the ocean. The incoming irradiance is attenuated in the upper ocean due to pure water and due to biogenic components. Mathematically, the attenuation of incoming solar radiation follows an exponential decline with depth in the upper ocean (e.g., Paulson and Simpson 1977).
The penetrative solar radiation and induced heating effects on the upper layers of the ocean are controlled by different processes in the climate system and the marine ecosystem. One factor is associated with ocean biology. For example, the way in which incident solar radiation is absorbed in the mixed layer can be significantly impacted by total phytoplankton biomass and its vertical distribution. When biological activities are strong, the incoming solar irradiance attenuates strongly in the vertical with more heating being trapped in the mixed layer. When biological activities are weak, the incoming solar irradiance penetrates deeper and can directly heat subsurface layers, at the expense of the reduction of the heating in the mixed layer. Thus, the existence and variation of phytoplankton biomass can modulate the vertical penetration of solar radiation in the upper ocean (Chavez et al. 1998, 1999; Strutton and Chavez 2004). It has been demonstrated that ocean biology-induced heating can be an important contributor to the heat budget near the equator in the tropical Pacific (e.g., Lewis et al. 1990; Strutton and Chavez 2004).

Ocean biology-induced heating effects can be quantitatively represented by the penetration depth of solar radiation in the upper ocean ($H_p$), a field linking the climate system to the marine ecosystem (e.g., Murtugudde et al. 2002; Ballabrera-Poy et al. 2007). This field, indicating perturbations in ocean biology, exerts a direct influence on the penetrative solar radiation in the upper ocean, resulting in a differential heating in the vertical between the mixed layer and subsurface layers below, which can further lead to changes in the oceanic density field, the stability, the mixed layer depth (MLD), and vertical mixing and entrainment of subsurface cold water into the mixed layer. These oceanic processes, directly or indirectly modulated by biological conditions, can affect SST which in turn potentially feeds back to the atmosphere in the tropical Pacific where mixing and entrainment are major contributors to changes in SST. This ocean biology-induced feedback (OBF) presents additional effects on the physical system in the tropical Pacific, leading to coupled bio-physical interactions (Zhang et al. 2009).

Over the past decades, remote sensing has led to significant advances in physical understanding, interpretation and modeling efforts of ocean biology-induced effects on the climate. In particular, the time series of remotely sensed ocean color data and associated products have revolutionized how the impacts of ocean biology on climate variability and change can be understood and quantified both globally and regionally (e.g., McCain et al. 1998). Satellite ocean color data are now available since 1997, which can be used to characterize basin-scale variability pattern of ocean biology and quantify its relationship with physical parameters. However, previous studies have demonstrated great sensitivities of ocean and coupled simulations to $H_p$ specifications (e.g., Nakamoto et al. 2001; Murtugudde et al. 2002; Marzeion et al. 2005; Manizza et al. 2005; Wetzel et al. 2006; Lengaigne et al. 2007; Anderson et al. 2007; Ballabrera-Poy et al. 2007; Zhang et al. 2009). In particular, the effects of interannual $H_p$ variability on simulations of the mean climate and its variability in the tropical Pacific are strikingly model dependent and even conflicting.
$H_p$ can be now derived using chlorophyll content data that are available from ocean color imagery (e.g., McCain et al. 1998; Nakamoto et al. 2001; Murtugudde et al. 2002 and Ballabera-Poy et al. 2003). Thus, satellite ocean color data-derived $H_p$ fields can be used for ocean and coupled ocean-atmosphere modeling studies. To account for the effects of interannual $H_p$ variability, an empirical parameterization for interannual $H_p$ response to physical changes induced by ENSO has been developed (Zhang et al. 2010). The developed $H_p$ model has been implemented into a hybrid coupled model (HCM) of the tropical Pacific and the effect on interannual variability has been examined (Zhang et al. 2009). These results are presented below.

2. Data and models

(1) The $H_p$ fields derived from satellite ocean color data

Current high quality ocean color data can resolve biology-related signals in the ocean (e.g., McClain et al. 1998), providing an opportunity for describing interannual variability in ocean biology and its coupling with physics. Following Murtugudde et al. (2002) and Ballabera-Poy et al. (2007), the monthly $H_p$ fields are derived from remotely sensed chlorophyll from September 1997 to April 2007. Figure 1a illustrates the annual mean structure of the derived $H_p$ field in the tropical Pacific (also see Murtugudde et al. 2002 and Ballabera-Poy et al. 2003, 2007). Seasonal variations are shown in Ballabera-Poy et al. (2007). The areas of small attenuation depth ($<19$ m) correspond to those of elevated biological activity in the coastal and equatorial upwelling regions. The Beer-Lambert law implies that regions with the smallest attenuation depth correspond to those where downwelling solar irradiance is absorbed the fastest. On interannual time scales, $H_p$ also exhibits a basinwide signal across the tropical Pacific, which is clearly dominated by El Niño and La Niña events. A map of the standard deviation of interannual $H_p$ variability is shown in Fig. 1b. The biology-related interannual $H_p$ variability is most pronounced over the central region. The standard deviation of $H_p$ in the Niño 4 and Niño3 regions estimated from the ocean color data (Fig. 1b) is 1.14 m and 0.76 m. As $H_p$ exhibits a clear spatial and temporal structure across the tropical Pacific basin, it exerts an influence on the penetrative solar radiation and heat balance of the mixed layer in the equatorial Pacific (e.g., Lewis et al. 1990).

In the tropical Pacific, large interannual anomalies are evident in the SST and $H_p$ fields (Figs. 2a-b), with their coherent co-variability pattern during ENSO cycles. For example, large-scale SST anomalies are generated by ENSO. The response in ocean biology is quick and almost simultaneous, as represented in the $H_p$ fields whose interannual variations follow SSTs closely in the tropics (Figs. 2a-b). Clearly, both SST and $H_p$ fields are simultaneously responding to the dynamical changes associated with ENSO; the ocean biology induced feedback impacts on SST can provide additional coupled bio-physical interactions which need to be

![Fig. 2](https://example.com/fig2.png)
adequately taken into account in modeling. Since SSTs represent the forcing in terms of coupling to the atmosphere, we use SST fields to derive a feedback model relating interannual \( H_p \) variability to SST forcing.

(2) An empirical model for the attenuation depth of solar radiation (\( H_p \))

We analyze the SST-\( H_p \) relationship on interannual time scales using SVD methods which allow to determine their statistically optimized empirical modes from their historical data (e.g., Zhang et al. 2006). The analysis period is from September 1997 to April 2007 and the analysis domain is confined to the tropical Pacific from 25\(^\circ\)S to 25\(^\circ\)N and from 124\(^\circ\)E to 76\(^\circ\)W. The first five SVD modes explain about 54.7\%, 10.2\%, 7.0\%, 3.7\%, and 3.3\% of the covariance. The spatial structure of the first derived SVD mode illustrates coherent patterns of interannual SST and \( H_p \) anomaly fields in the tropical Pacific (figures not shown).

Then, an empirical \( H_p \) model can be constructed using the derived spatial patterns of the SVD modes (see Zhang and Busalacchi (2009a) for a detailed example). Considering the sequence of the singular values and the reconstructions of interannual \( H_p \) variability from SST anomalies, only the first two SVD modes are retained (the inclusion of higher modes does not change the results significantly).

Figure 2c exhibits one example of the \( H_p \) anomalies calculated using the empirical \( H_p \) model from the given SST anomalies (Fig. 2a). The model captures the large-scale interannual \( H_p \) variability during the ENSO evolution. However, as compared with the original field (Fig. 2b), the amplitude is systematically underestimated by a factor of about 2. Since some variance is always lost inevitably due to only some limited SVD modes retained in the empirical model, an amplification factor (\( \alpha_{H_p} \)) is introduced to rescale its amplitude back to match what is derived from the ocean color data (Fig. 2b).

Note that the SST and \( H_p \) fields used for computing the SVD modes-based model are varying at the interannual timescale only, and the derived model is for estimating interannual \( H_p \) anomalies in the tropical Pacific associated with ENSO. Our previous efforts along these lines specified \( H_p \) in an uncoupled manner with physical parameters (e.g., Murtugudde et al. 2002 and Ballabrera-Poy et al. 2007). Here \( H_p \) is a physical state-dependent parameter that allows for a feedback from ocean biology to the climate system and their active interactions during ENSO cycles, an approach taken by Timmermann and Jin (2002) to examine the ocean biology effect on climate.

(3) The hybrid coupled ocean-atmosphere model

A hybrid coupled model (HCM) for the tropical Pacific ocean-atmosphere system has been developed at ESSIC (Zhang et al. 2006). Fig. 3 illustrates a schematic for the HCM. Its ocean general circulation model (OGCM) is a primitive equation, sigma coordinate model whose details can be found in Murtugudde et al. (2002). The OGCM domain covers the tropical Pacific basin from 25\(^\circ\)S to 25\(^\circ\)N and from 124\(^\circ\)E to 76\(^\circ\)W, with the horizontal resolution of 1\(^\circ\) in longitude and 0.5\(^\circ\) in latitude, and 31 layers in the vertical. The atmospheric wind stress anomaly (\( \tau_{\text{inter}} \)) model is also constructed empirically from the SVD analysis,
specifically relating $\tau_{\text{inter}}$ variability to large-scale SST anomalies ($SST_{\text{inter}}$). The attenuation depth of solar radiation ($H_p$) in the upper ocean is written as $H_p = H_p + \alpha_{\text{Hp}} \cdot H'_p,$ consisting of the prescribed climatological part ($H_p$) and its interannual part ($H'_p$). The former is prescribed from a long-term annual mean field (Ballabrera-Poy et al. 2007) and the latter is calculated from the SST$_{\text{inter}}$ anomalies. A scalar parameter, $\alpha_{\text{Hp}},$ is introduced to represent the OBF strength. More recently, anomalous freshwater flux forcing has been also included in the HCM to take into account the freshwater flux-induced positive feedback in the tropical Pacific climate system (Zhang and Busalacchi 2009b).

3. Impacts of the OBF on interannual variability in the HCM

A control HCM run was performed in which interannual $H_p$ variability is not allowed to feedback to SST in the HCM. As shown in Zhang and Busalacchi (2009b), the model can simulate interannual oscillations well. Next, we perform a series of runs in which the $H_p$-SST relationship derived from satellite data is included to take into account the OBF and interactions between ocean biology and physics (Fig. 4), with all the other model settings exactly the same as the control run. Note that the seasonally varying SST climatology ($SST_{\text{clim}}$) fields specified to compute large-scale SST$_{\text{inter}}$ anomalies are all the same, which are determined from the forced OGCM climatological simulations.

Varying values of $\alpha_{\text{Hp}},$ representing the OBF strength, are tested to investigate its effect on interannual variability. Simulations with $\alpha_{\text{Hp}}=0.0$ are analyzed in Zhang and Busalacchi (2009b). One example of simulated SST anomaly fields is shown in Fig. 4 for two feedback runs with $\alpha_{\text{Hp}}=2.0$ and $\alpha_{\text{Hp}}=3.0$, respectively.

A striking feature is that the coupled models depict a pronounced interannual oscillation, with a dominant standing pattern of SST variability on the equator. As is well understood, the positive feedback associated with the wind-SST-thermocline coupling sustains interannual variability in the coupled system. When the OBF is taken into account, the effects can be clearly seen on the amplitude and oscillation periods of interannual variability (Fig. 4). The SST anomalies are weaker in the OBF runs, and become even weaker as the OBF is intensified. Moreover, runs with the OBF explicitly included exhibit clear phase differences as well. For example, a phase lead starts to show up clearly in year 30 due to an earlier transition from the warm to cold phases in the $\alpha_{\text{Hp}}=3.0$ run. As such, the inclusion of the OBF causes a clear change in the oscillation periods. This can be more clearly seen in the power spectra estimated from the Niño3 SST indices (figures not shown): the interannual variability has a sharp peak at 4.2 years in the $\alpha_{\text{Hp}}=2.0$ run, but
has shifted toward higher frequency band in the $\alpha_{hp}=3.0$ run, with two enhanced power peaks at 4.2 years and at 3.6 years, respectively. These results indicate that the ocean biology induced feedback effects tend to shorten the persistent time scales of SST anomalies. In addition, the irregularity is evidently large in the no and weak OBF runs (e.g., the year 32 in Fig. 4), but is significantly reduced in the $\alpha_{hp}=3.0$ run due to the damping OBF effects on the system. Also, there is a change in the annual phasing of ENSO events, especially the peak season shifting from winter to summer. Some of these effects are not seen in Timmermann and Jin (2002) who used a simpler coupled model and a simpler formulation of the feedback.

The effects can be further quantified. The standard deviation (std) of Niño3 (Niño4) SST anomalies is 0.76°C (0.85°C) in the control run ($\alpha_{hp}=0.0$); it is reduced to 0.65°C (0.78°C) in the $\alpha_{hp}=2.0$ run, and to 0.59°C (0.69°C) in the $\alpha_{hp}=3.0$ run, respectively. Relative to the control run, these values represent a decrease of the amplitude by 14% (8%) in the $\alpha_{hp}=2.0$ run and by 22% (19%) in the $\alpha_{hp}=3.0$ run. Also, the std of the zonal wind stress in the Niño4 region is 0.19 dyn cm$^{-2}$ in the $\alpha_{hp}=0.0$ run; it decreases to 0.17 dyn cm$^{-2}$ in the $\alpha_{hp}=2.0$ run (a reduction by 11%) and to 0.15 dyn cm$^{-2}$ in the $\alpha_{hp}=3.0$ run (a reduction by 21%). Thus, a significant fraction of the SST and surface wind variability can be attributed to the OBF effect in our model simulations.

A heat budget analysis has been preformed to understand processes by which the OBF is affecting interannual variability. When the OBF is included, the induced feedback acts to reduce the cooling effect of the vertical mixing and entrainment during La Niña (i.e., less cooling), but increase their cooling effect during El Niño (i.e., less warming). This indicates that the inclusion of the OBF effects acts to counteract the positive SST-wind-thermocline feedback, leading to a weakening SST variability during ENSO cycles.

These results can be explained in terms of a negative feedback between ocean biology and climate system as follows. ENSO cycles are characterized by SST anomalies over the equatorial regions, which induce a biological response, as represented by large interannual $H_p$ variability. During La Niña when SSTs...
are low in the eastern and central tropical Pacific, $H_p$ is negative and the solar radiation attenuates with depth strongly in the vertical. More solar heating is thus trapped in the mixed layer (ML), with less penetration downward into the subsurface. The direct effects are to add the solar heating more in the surface layer but less in the subsurface layers. The induced differential solar heating in the vertical acts to enhance the stratification and thus stabilize the upper ocean, with reduced mixing and entrainment of subsurface waters. These oceanic processes tend to weaken the cold SST anomalies generated by La Niña, with the wind-feedbacks favoring further reduction in upwelling and SST cooling. The effects on El Niño can be also seen but with opposite sense. As a result, the inclusion of the OBF in the HCM induces additional oceanic processes that act to counteract the positive SST-wind-thermocline feedback, thus reducing the strength of interannual variability.

4. An application to the NCEP CFS

At present, ocean models have considerable difficulty in representing biogeochemical processes. For example, current comprehensive ocean biogeochemistry models still cannot realistically depict interannual $H_p$ anomalies during ENSO cycles. Indeed, capturing the ocean biology-related $H_p$ responses to physical anomalies requires realistic parameterizations of relevant physical and biogeochemistry processes both in the ocean, which are difficult to achieve at present. As a result, the bio-effects have not been included in coupled models currently used for real-time ENSO predictions. Due to the large amplitude and the demonstrated significant ocean biology-induced climate effects (e.g., Zhang et al. 2009), interannual $H_p$ anomalies are expected to have roles in modulating the mean climate and ENSO in the coupled atmosphere-ocean system of the tropical Pacific.

Currently, the NCEP CFS has not taken into account biological components to represent the bio-feedback to the physical system (e.g., Wang et al. 2005; Saha et al. 2006). It is very unlikely that in the near-term the CFS will include a comprehensive ocean biogeochemical model to resolve interannual $H_p$ variability (In its recent release, the GFDL MOM 4 has the capability to handle geographically varying penetrating radiation; that is, a fixed chlorophyll climatology and $H_p$ is specified without accounting for interannually varying effects). Therefore, ocean biology-induced feedbacks from the marine ecosystem to the physical system and the corresponding bio-climate coupling are missing (e.g., Behringer 2007). The demonstrated interannual $H_p$ effects on the large-scale mean state and seasonal-to-interannual climate

![Fig. 6 Interannual SST (left) and $H_p$ (right) anomalies along the equator simulated from the GFDL MOM3 (1/3°x1° in tropics, 1°x1° in extratropics, 40 layers), forced by observed atmospheric data (see Zhang et al. 2001). The $H_p$ variability is obtained by using the empirical $H_p$ model from the corresponding SST anomalies. The contour interval is 1°C for SST and 0.5 m for $H_p$.](image)
variability have not been taken into account. As a result, the roles of ocean biology in tropical biases and ENSO modulation are not known; the potential for improving ENSO simulation and prediction has not been explored.

Apparently, the missing bio-climate coupling in the NCEP CFS may well be a problem. Considering the lack of realistic $H_p$ representations in the state-of-the-art NCEP CFS and considering the potential role of ocean biology in modulating mean climate and ENSO, we deem it important to include and understand the bio-effects in the CFS. Clearly, a key to addressing all these problems is how to realistically capture interannual $H_p$ variability associated with ENSO.

The derived empirical $H_p$ model can be embedded into the NCEP CFS to parameterize ocean biology-induced heating effects on the penetrative solar radiation in the upper ocean, making a direct contribution to the improvement in its oceanic component (Fig. 5). For example, the empirical $H_p$ model derived using the SVD analysis technique has been tested to calculate an $H_p$ response to interannual SST variability from an output of the GFDL OGCM simulation (Zhang et al. 2001). The OGCM is the version 3 of the GFDL MOM (Pacanowski and Griffies 1998), a finite-difference treatment of the primitive equations of motion using the Boussinesq and hydrostatic approximations in spherical coordinates. The vertical mixing scheme is the nonlocal K-profile parameterization of Large et al. (1999). The domain is that of the Pacific Ocean between 60°S and 65°N (Zhang et al. 2001; Zhang and Zebiak, 2002, 2003, 2004). The zonal resolution is 1.0°; the meridional grid spacing is 1/3° between 10°S and 10°N, gradually increasing to 1.0° at 30°N and 30°S and fixed at 1.0° in the extratropics; there are 40 levels in the vertical, with 17 levels in the upper 450 m, forced by prescribed atmospheric data during the periods 1949-2000. Interannual SST anomalies along the equator simulated are shown in Fig. 6a. The interannual $H_p$ variability is obtained by using the empirical $H_p^{97-07}$ model from the corresponding SST anomalies. Using the simulated interannual SST anomalies as an input to the empirical $H_p$ model, interannual $H_p$ anomalies can be estimated (Fig. 6b). Large $H_p$ anomalies and coherent $H_p$–SST relationships are evident in association with ENSO. The effects on the penetrative solar radiation are expected in the ocean simulation. Further modeling experiments are underway to investigate the impacts of ocean biology on large-scale mean climate and its variability and predictability in the tropical Pacific. In particular, the benefits for ENSO simulation and prediction will be quantified. As demonstrated in the hybrid modeling study (Zhang et al. 2009), ocean biology in the tropical Pacific is expected to contribute to the modulation of the mean climate and ENSO through the penetrative effect on solar radiation, leading to an improved climate forecast in the NCEP CFS.

References


