

Sensitivity of equatorial Pacific Ocean circulation To solar radiation absorbed by phytoplankton

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ABSTRACT

Sensitivity experiments conducted with the MIT ocean general circulation model reveal the potential influence of solar radiation absorbed by phytoplankton on the thermal structure and currents of the equatorial Pacific Ocean. In the model, vertical attenuation of solar radiation is parameterized as a function of chlorophyll pigment concentration, the major variable affecting turbidity in the euphotic zone. To isolate turbidity effects, the model is run from 1948 to 2001 with either a constant minimum pigment concentration of 0.02 mgm^{-3} during the entire period or spatially and temporally varying pigment concentration from the Sea-viewing Wide Field-of-view Sensor during 1997-2001. The two model runs are compared for 2001, a relatively normal year following the strong 1997-1998 El Niño and subsequent La Niña. Due to phytoplankton-radiation forcing, equatorial sea surface temperature is decreased by 0.3K on average annually between 100W and 160W, but the negative temperature change is more pronounced in sub-surface layers, reaching -1.5K at 110W. In that region, heat trapping by phytoplankton causes the mixed layer to shallow and isotherms to shoal toward the equator, generating geostrophic currents that enhance the south equatorial current. These surface currents diverge north and south of the equator as they progress westward, creating equatorial divergence, convergence at the level of the equatorial undercurrent, and upwelling, explaining the change in thermal structure. The equatorial undercurrent is strengthened by as much as 4 cms^{-1} at its core. The findings support previous results obtained with the MHI Ocean isoPYCnal general circulation model and pigment concentration from the Coastal Zone Color Scanner. They indicate that biology-induced buoyancy may play a significant role in the equatorial Pacific Ocean circulation and suggest the existence of a biophysical feedback mechanism that contributes to maintaining the cold tongue in the eastern equatorial Pacific Ocean, with implications for inter-annual variability associated with El Niño.

Keywords: Ocean circulation, numerical modeling, remote sensing, Equatorial Pacific, ocean color, phytoplankton

1. INTRODUCTION

The equatorial Pacific Ocean is a complex environment, with both horizontal advection and upwelling affecting biological processes (Chavez and Barber, 1987¹; Pena et al., 1994²; Murray et al., 1994³; Friedrichs and Hofmann, 2000⁴). The biological activity is asymmetric around the equator, with much larger productivity north of the equator.

This asymmetry is associated with the Inter Tropical Convergence Zone (ITCZ), located north of the equator most of the year. Maximum biological activity north of the equator is caused by the ITCZ wind stress generating Ekman transport divergence. Equatorial upwelling generates higher biological activity in the eastern Pacific. This feature is well known, and is evident in a large data set analyzed by Pena et al. (1994²). On inter-annual time scales, fluctuations in equatorial Pacific Ocean chlorophyll are tightly coupled to local thermocline variations associated with El Niño events

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(Chavez et al., 1999⁵). The anomalous warming of the equatorial Pacific Ocean affects the marine ecosystem at all trophic levels (Barber and Chavez 1983⁶, 1986⁷; Sharp and McClain, 1993⁸; Blanchot et al., 1992⁹; Leonard and McClain, 1996¹⁰).

Both dynamical forcing and biological productivity of the equatorial Pacific Ocean occur on a wide range of spatial and temporal scales. In many cases, the forcing and resultant productivity are episodic rather than part of a regular oscillation. For example, there is considerable biological activity associated with Rossby waves and upwelling Kelvin waves (Kessler, 1990¹¹; Bidigare et al., 1996¹²; Foley et al., 1997¹³). After the 1982-1983 El Niño it was noted that the reduced production in the eastern Pacific Ocean was caused by a remotely forced downwelling Kelvin wave. If the thermocline is too deep, upwelling will not bring nutrient-rich water from below the thermocline into the euphotic layer (Barber and Chavez, 1983⁶; Friedrichs and Hoffman, 2000⁴). Conceptual models developed from observations in the eastern tropical Pacific (Barber and Chavez, 1983⁶; 1986⁷) have suggested that Kelvin waves are the primary agents affecting biological productivity, because upwelling favorable winds are maintained in this region. This biological activity can be modeled, at least partially, in ocean general circulation models (OGCMs) using high-resolution satellite ocean-color sensor data such as Sea-viewing Wide Field-of-view Sensor (SeaWiFS).

The expression of upper ocean biological processes is patchy in time and space, due to the highly non-linear nature of the biophysical system (Steele, 1978¹⁴). This phenomenon has been observed in SeaWiFS chlorophyll data (Murtugudde et al., 1999¹⁵; Signorini et al., 1999¹⁶). The dynamic nature of the patchiness in the equatorial Pacific Ocean needs to be quantified and understood. The long-term continuous monitoring (color, surface height) available from satellite sensors offers the opportunity to examine the variability of the ocean surface on time scales of a few days to years, and space scales of a few kilometers to basin scales.

The upper-ocean vertical motions along the equator in the Pacific Ocean and their relation to chlorophyll distribution was examined by Halpern and Feldman (1994¹⁷) with satellite measurements of phytoplankton abundance and OGCM simulations of vertical velocity. However, in OGCM simulations biology is generally neglected or crudely taken into account. Solar radiation is either absorbed at the surface assuming the ocean as “black” or is decaying with a constant attenuation depth. Schneider and Zhu (1998¹⁸) compared these two methods and determined that a global attenuation depth yielded a more realistic SST seasonal cycle in the equatorial Pacific. Previously, Lewis et al. (1990¹⁹) had argued, based on in situ measurements of heat fluxes, that ocean transparency in the western Pacific Ocean might explain SST overestimation by OGCMs that assume that all solar radiation is absorbed at the surface. In the real ocean, however, the presence of phytoplankton modifies attenuation depth, and phytoplankton biomass, hence solar penetration, is variable in space and time.

Recently, using satellite ocean-color imagery, absorption of solar radiation by phytoplankton was incorporated in OGCMs to study effects of space- and time-varying biology on Equatorial Pacific circulation. In Nakamoto et al. (2001²⁰) model runs with either spatially and seasonally varying absorption or a constant attenuation depth of 23 m (clearest waters) were compared. The simulations revealed systematically lower SST in the eastern Equatorial Pacific. In Murtugudde et al. (2002²¹) the spatial pattern of attenuation depth in a tropical ocean model was specified and the results were contrasted with those obtained using a constant attenuation depth of 17 m, the global mean value. It was argued that the problem of a colder than observed cold tongue in the eastern Equatorial Pacific could be remedied by using an accurate solar heating parameterization. In these studies, the heating changes due to phytoplankton resulted in dynamical changes, such as anomalous currents and upwelling. The impact on climate, locally and remotely, is expected to be significant, as suggested by the NCAR Community Climate Model (CCM-3) simulations of Shell et al. (2003²²). Potential feedbacks in inter-decadal climate variation are summarized in Miller et al. (2003²³).

The situation in the Equatorial Pacific, as indicated by the simulations of Nakamoto et al. (2001²⁰), is intriguing. A lower SST was predicted all year near 110-120W, with a peak of -2.6 K in May-June. This feature may not be explained by local changes in buoyancy. It was also obtained in model runs that considered not only the impact of phytoplankton on ocean physics, but also the response of phytoplankton to the modified nutrient supply and light availability (Manizza et al., 2005²⁴). Nakamoto et al. (2001²⁰), on the one hand, suggested that biology-induced westward currents produced significant mass flux toward the equator and a strengthening of the equatorial undercurrent, resulting in enhanced

upwelling. Murtugudde et al. (2002²¹), on the other hand, argued that using the appropriate attenuation depth weakens the stratification in the region, providing natural re-stratification of the water column. This resulted in a deeper mixed layer, weaker currents, reduced divergence, and higher SST. The eastern Pacific warming might be further enhanced by the Bjerknes feedback (Timmermann and Jin, 2002²⁵; Marzeion et al., 2005²⁶). Further investigation is needed, however, to precise the mechanisms at work and quantify effects that can be compared with observations.

In this context, the study's goal is to explore further the role of biology, more precisely absorption of solar radiation by phytoplankton, in the dynamics of the equatorial Pacific Ocean. Our starting hypothesis, based on previous numerical simulations, is that the presence of phytoplankton in the upper oceanic layers, by modifying buoyancy, plays a significant role, in an indirect if not direct way, in the variability of the Equatorial Pacific Ocean on seasonal to inter-annual time scales. Specifically, the study aims at confirming the effect of space- and time-varying phytoplankton on currents and thermal structure reported previously and at identifying the mechanisms, local or remote, by which they are maintained or modified. The objective is also to conclude on whether biology forcing should be included explicitly in the modeling of seasonal and inter-annual variability of the equatorial Pacific Ocean.

2. NUMERICAL EXPERIMENTS

The approach is basically to run an OGCM with and without explicit parameterization of solar radiation penetration by phytoplankton. The difference between results of the two types of runs yields biological effects. Pigment concentration is specified at each time step from satellite data, not predicted. The effects of nutrients and biological production are implicitly taken into account, even though biogeochemical processes are not included explicitly, since phytoplankton distribution is the result of those processes. Of course, by prescribing phytoplankton abundance our approach does not have any predictive capability to assess feedbacks on ocean biology. This important aspect is beyond the scope of this sensitivity study, which essentially aims at quantifying effects of realistic phytoplankton-radiation forcing.

The OGCM is a version of the MITGCMUV, a primitive equation model developed at MIT (Marshall et al., 1997a²⁷, 1997b²⁸). MITGCMUV has been used successfully in a variety of configurations including small-scale convection and global-scale ocean simulations. Some of the experiments are summarized in Marshall et al. (1997b²⁸). The model has 23 z-coordinate vertical levels with the top eight layers set to 10m, 10m, 15m, 20m, 25m, 35m, 50m, and 75m. The horizontal domain covers latitudes from -80 to 80 degrees, with a uniform grid resolution of 1 degree in both latitude and longitude directions. The model incorporates a KPP mixing scheme along with Redi-Gent-McWilliams sub-grid mixing schemes. Ocean bottom topography is based on the 2-minute resolution global sea floor topography derived by Smith et al. (1997²⁹).

External forcing at the ocean surface is accomplished using NCEP re-analysis data sets for 1948-2001. They consist of twice-daily wind stress components, daily evaporation minus precipitation, daily short wave heat flux, and daily total heat flux excluding the short wave heat flux (i.e., long wave and turbulent components). The temperature in the top layer of the model is restored towards Reynolds monthly mean temperature with a relaxation period of one month, and sea surface salinity is nudged to Levitus monthly climatology with the same relaxation period. The temperature and salinity in the lower layers are dynamically prognosticated without such a constraint.

Solar radiation penetration is parameterized according to Morel and Antoine (1994³⁰). This allows computation of the heating rate profile as a function of surface phytoplankton pigment concentration, as determined from satellite ocean-color imagery. The pigment concentration is assumed constant vertically. This treatment is sufficient, since at depth the residual radiant energy is low. (This assumption will be further discussed in Section 3.) Figure 1 shows, for the visible part of the solar spectrum (wavelengths of less than $0.75 \mu\text{m}$), solar transmittance as a function of depth for various pigment concentrations in the range $0\text{-}20 \text{ mgm}^{-3}$. Paulson and Simpson's (1977³¹) values for clear waters are also displayed. The transmittance profiles are strongly affected by the presence of phytoplankton. About 30% of the visible light is transmitted below 20 m in the case of pure seawater, but only 0.01% when the pigment concentration is

20 mgm^{-3} . Paulson and Simpson's (1977³¹) values correspond roughly to Morel and Antoine's (1994³⁰) values for a pigment concentration of 0.02 mgm^{-3} , although significant differences exist below 30 m, i.e., a higher transmittance with Paulson and Simpson's (1977³¹) formula.

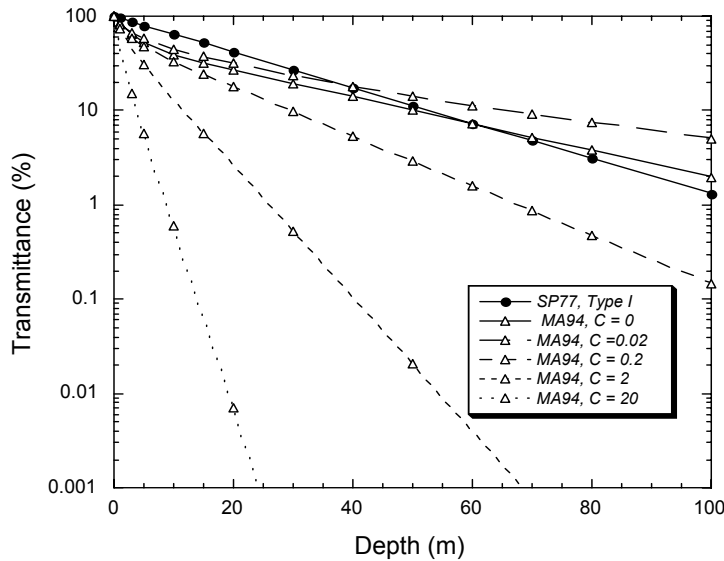


Figure 1. Vertical profiles of solar radiation transmittance in the ultraviolet and visible (wavelengths less than 0.75 μm) for various values of pigment concentration, C . The parameterization of Morel and Antoine (1994³⁰), MA94, is used in the computations. The profiles obtained with Paulson and Simpson's (1977³¹) formula, SP77, are displayed for comparison.

Two types of runs were performed, a clear water control run with a minimum pigment concentration of 0.02 mgm^{-3} (CTRL/C002), and a turbid water chlorophyll run with space and type varying pigment concentration derived from satellite data (CHL). In both runs, Morel and Antoine's (1994³⁰) parameterization was used, unlike in the study of Nakamoto et al. (2001²⁰), which used Paulson and Simpson's (1977³¹) formula in the control run and Morel and Antoine's (1994³⁰) parameterization in the chlorophyll run. This procedure eliminates uncertainties associated with crossover of vertical heating rate profiles. Furthermore, using the same scheme in both types of experiments guarantees that the heating rate due to downwelling solar irradiance at a given depth, location, and time in the ocean model is always higher in CHL than in the CTRL, making more straightforward the analysis of the biology-induced ocean response. CTRL was performed for 54 years from 1948 to 2001, starting with the ocean at rest, and CHL from 1998 to 2001 with SeaWiFS-derived pigment concentration. The restart conditions at the model start time of January 01, 1998 in CHL were specified using the model status at the end of 1997 obtained in the 54-year CHL. Because of the time-dependent nature of the NCEP re-analysis data set, the initial conditions used in CHL might not represent a cyclostationary state in the upper ocean after 50 years of the CTRL simulation. Compared with the study of Nakamoto et al. (2001²⁰), twice daily or daily NCEP fields were used as external forcing instead of climatological monthly mean fields. These authors also used pigment concentration climatology from the Coastal Zone Color Scanner (1978-1986) instead of the more accurate SeaWiFS data. Furthermore, the Ocean IsoPYCnal (OPYC) model in Nakamoto et al. (2001²⁰) resolves the mixed layer explicitly, whereas the mixed layer depth of the z-coordinate MITGCMUV is diagnosed.

3. RESULTS AND DISCUSSION

The output of CHL is compared with the output of CRTL for annually averaged values of temperature, mixed layer depth, and currents. The comparison is made for 2001, the last year of the model runs, a year relatively normal following the strong 1997-1998 El Niño and subsequent la Niña. The results are presented in terms of differences between CHL and CRTL values and, therefore, give the effect of space and time varying, biology-induced ocean transparency, hence solar radiation penetration, on equatorial Pacific circulation and thermal structure, with respect to the clearest water case.

Figure 2 displays the surface temperature difference between CHL and CRTL in the Pacific, between 30S and 30N, (top) and the vertical profile of temperature along the equator, between the surface and 220m. Away from the coast, surface temperature is generally increased in the entire horizontal domain, by 0.1 to 0.5K, except in a relatively narrow latitude band along the equator between 180 and 100W, where temperature is decreased by up to 0.4K. This cooling due to the presence of phytoplankton is even more pronounced at depth along the equator, with differences reaching -1.5K at 40 m at 110W. The vertical domain along the equator exhibits negative differences almost everywhere, except in the most eastern and most western regions above 40m. The surface cooling is not expected, since phytoplankton trap heat near the surface. Moreover, the mixed layer depth is decreased everywhere in the tropical Pacific (Figure 3, top), even along the equator where the negative temperature differences occur (Figure 3, bottom). This suggests that the thermal structure in the upper layers may not be governed by local buoyancy in the central equatorial Pacific, but rather by remote processes in which advection should play a role.

The situation can be explained by examining the zonal velocity differences in the surface layer (Figure 4, top) and sub-surface, namely 65 m (Figure 4, bottom). In the surface layer, due to phytoplankton-radiation forcing a westward flow is generated north and south of the equator that enhances the south equatorial current. This westward flow, reaching about 4 cm s^{-1} , is associated with a shoaling of the isotherms toward the equator, presumably due to the longitudinal gradient of chlorophyll concentration toward the equator in both hemispheres (not shown here). The resulting slope implies a pressure gradient force toward the equator and this pressure force induces westward geostrophic motion in both hemispheres. The surface currents diverge as they progress westward, creating equatorial divergence, convergence at the level of the equatorial undercurrent, and upwelling, explaining the change in thermal structure (negative temperature difference). The equatorial undercurrent is enhanced by as much as 4 cm s^{-1} at its core (Figure 5). This change, however, is relatively small compared with the actual speed of the current, about 80 cm s^{-1} . In the eastern part of the equatorial Pacific, where chlorophyll concentration is large and mixed layer shallow, the zonal gradient of chlorophyll concentration might contribute to increase the eastward pressure force. Therefore geostrophic motion toward the equator would be induced, reducing the Ekman drift and upwelling and giving rise to an eastward current that weakens the south equatorial current (Figure 4). It is also possible that in this region of shallow thermocline, the increase in undercurrent flow (eastward) is felt in the surface layers (Figure 5, top left panel), offsetting biologically induced geostrophic flow (westward).

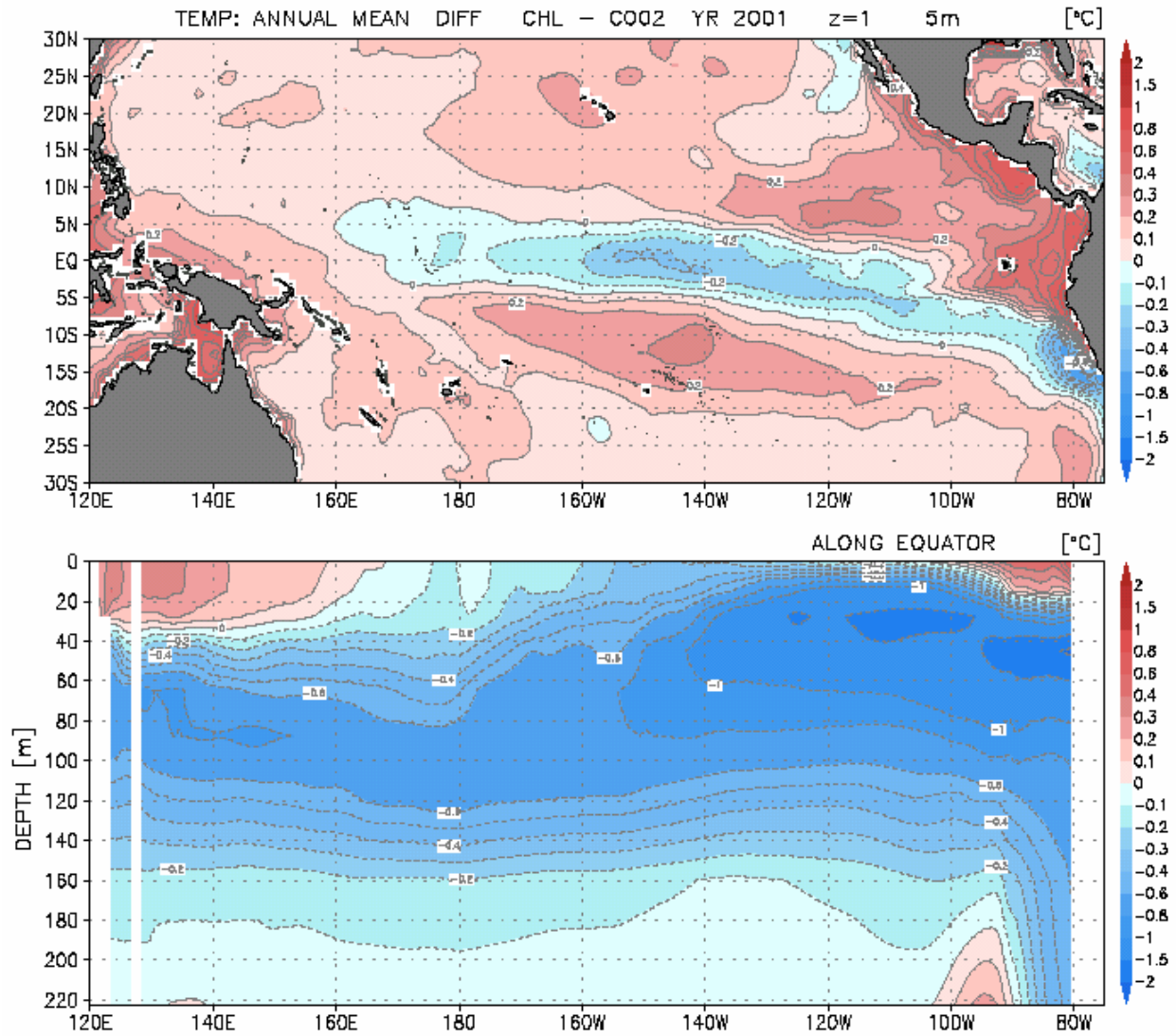


Figure 2. Temperature difference between model runs with and without phytoplankton-radiation forcing. (Top) Surface Temperature in the tropical Pacific. (Bottom) Vertical temperature cross-section along the equator.

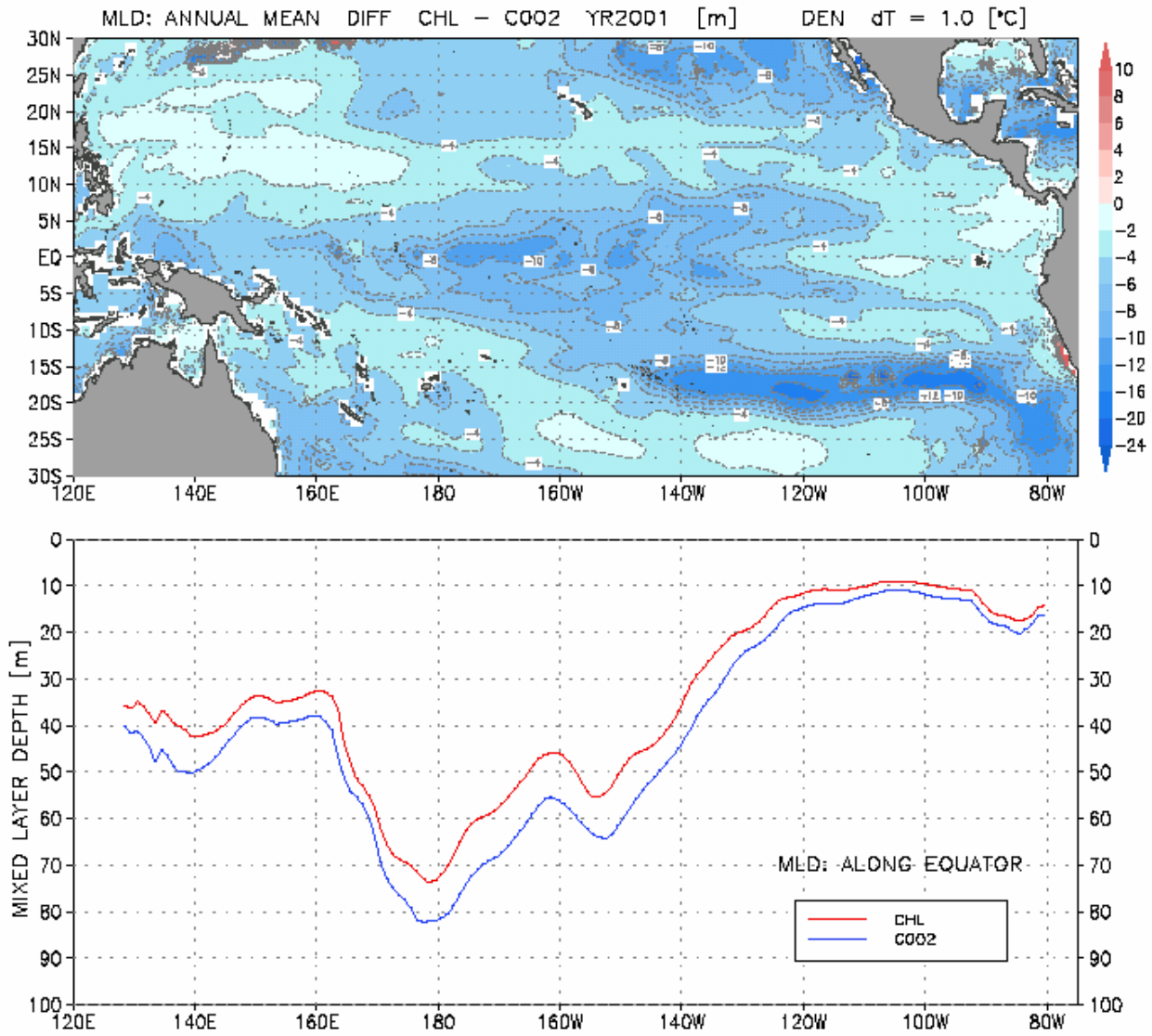


Figure 3. (Top) Mixed layer depth difference between model runs with and without phytoplankton-radiation forcing in the tropical Pacific. (Bottom) Mixed layer depth with and without phytoplankton-radiation forcing along the equator (red and blue curves, respectively).

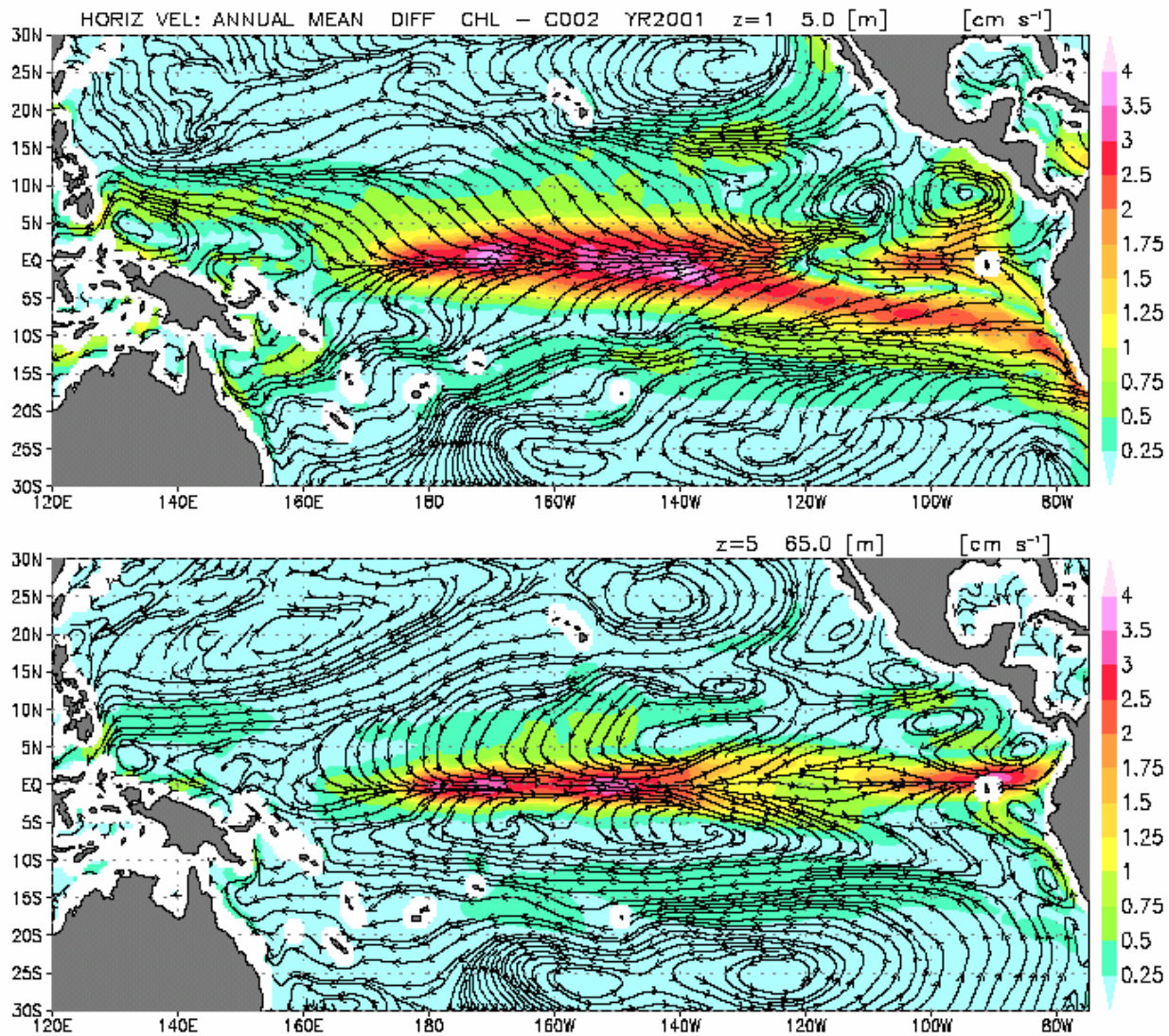


Figure 4. Horizontal velocity difference between model runs with and without phytoplankton-radiation forcing in the tropical Pacific at 5 m depth (top) and 65 m depth (bottom).

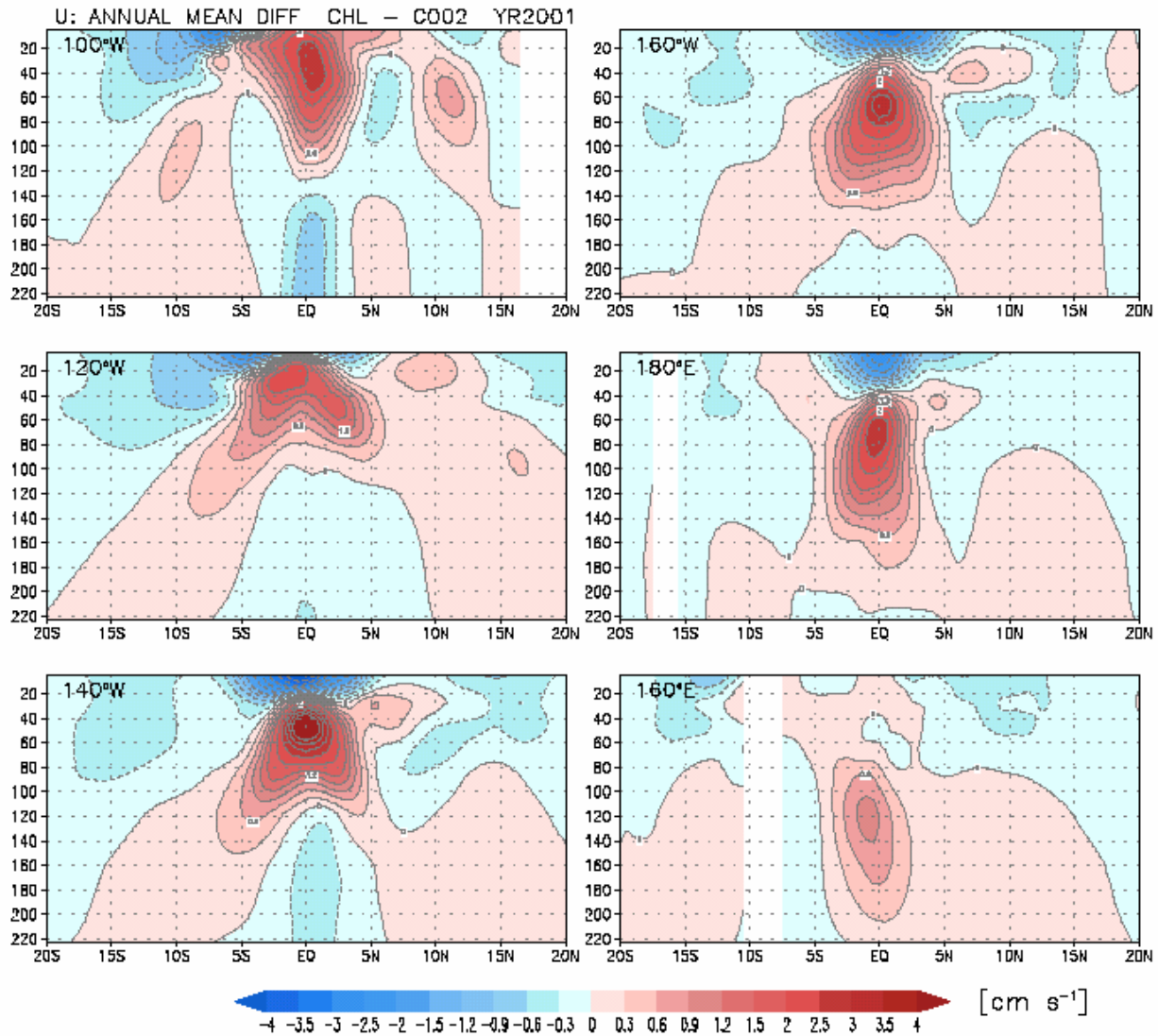


Figure 5. Vertical profile of zonal velocity difference across the equator, from 20S to 20N, at various longitudes.

The changes in currents and thermal structure described above are in agreement, at least qualitatively, with the findings reported by Nakamoto et al. (2001²⁰) and Manizza et al. (2005²⁴), who used different OGCMs in yet similar numerical experiments. They confirm the significant (direct and indirect) role of biology-induced buoyancy on the equatorial Pacific Ocean circulation. In particular, the central equatorial Pacific is cooler due to water transparency.

Since Manizza et al. (2005²⁴) included interactions between phytoplankton and their environment, i.e., the response of biology to changes in nutrients and light availability, their results in view of ours suggest that these interactions are not a governing factor, compared with the direct radiation forcing, in the equatorial Pacific.

Our findings, however, disagree with the conclusions of Murtugudde et al. (2002²¹), Timmermann and Jin (2002²⁵), and Marzeion et al. (2005²⁶). These authors argued that in the eastern equatorial Pacific solar radiation absorbed below the mixed layer at the level of the deep chlorophyll maximum produces a deepening of the mixed layer. This biologically-induced deepening is associated with a weakened south equatorial current, reduced upwelling, and hence a warmer eastern equatorial Pacific. We note in this respect that, between 160 and 140W, where our simulations give the maximum negative temperature differences at the surface, the mixed layer depth is about 50m (Figure 3) and chlorophyll concentration 0.3 mgm⁻³. In these conditions, only a few percent of the surface radiation would penetrate deeper layers (Fig. 1), and even a large amount of phytoplankton at depth would not affect the heating profile significantly. The situation is definitely different in the eastern part of the equatorial Pacific, where the mixed layer depth is shallow (about 10m, see Figure 3). The ideas put forward by Marzeion et al. (2005) have merit in this region, even though the vertical change in chlorophyll concentration, i.e., 0.2 to 0.4 mgm⁻³ over the first 50m, is not dramatic. Incorporating the vertical distribution of chlorophyll concentration in our simulations might enlarge the warming area in the eastern Pacific. However, other mechanisms may predominate as mentioned above, in which the zonal gradient of chlorophyll concentration drives an eastward pressure force, or in which the enhanced equatorial undercurrent offsets biologically induced westward geostrophic currents.

Timerman and Jin (2002²⁵) and Marzeion et al. (2005²⁶) further hypothesized that the biologically induced eastern Pacific surface warming would be strongly enhanced by the so-called Bjerknes feedback in which weaker trades are generated through differential heating of the atmosphere. We agree that the Bjerknes feedback would be effective, but to amplify the cooling of the central equatorial Pacific. In this case, a negative surface temperature difference would increase the zonal gradient of surface temperature and enhance the Walker circulation, with stronger trade winds producing stronger equatorial upwelling, thereby pumping cold water to the surface.

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