

## Phytoplankton influences on tropical climate

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Received 6 May 2002; accepted 15 July 2002; published 6 December 2002.

[1] We study the effect of ocean biology on tropical surface temperatures using a simplified coupled atmosphere-ocean model. It is shown that moderate phytoplankton blooms, occurring e.g. during La Niña conditions, lead to a vertical redistribution of heat in the surface layers and an associated surface layer warming of about  $20 \text{ W/m}^2$ . The positive air-sea coupling in the eastern equatorial Pacific plays an important role in amplifying this signal, thereby damping La Niña conditions. This temperature-regulating feedback acts as a biological thermostat within the surface ocean and influences also the amplitude and asymmetry of the El Niño-Southern Oscillation. **INDEX TERMS:** 1620 Global Change: Climate dynamics (3309); 4522 Oceanography: Physical: El Niño; 4504 Oceanography: Physical: Air/sea interactions (0312); 4855 Oceanography: Biological and Chemical: Plankton; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics. **Citation:** Timmermann, A., and F.-F. Jin, Phytoplankton influences on tropical climate, *Geophys. Res. Lett.*, 29(23), 2104, doi:10.1029/2002GL015434, 2002.

### 1. Introduction

[2] The El Niño-Southern Oscillation (ENSO) phenomenon is the strongest global mode of natural interannual climate variability. It originates from an instability of the tropical Pacific coupled atmosphere-ocean system [Neelin *et al.*, 1998]. ENSO influences climate conditions worldwide, resulting in drought or flood conditions and anomalously warm or cold conditions in many localities, with consequences for both, human and ecological systems [Glantz, 1996]. Fortunately, ENSO can be predicted to a certain degree of accuracy several seasons in advance [Latif *et al.*, 1998] using climate models of different complexity as well as statistical methods. These predictions provide the basis for developing strategies that help to mitigate ENSO-related climate impacts on agriculture, fishery, water management, and other relevant societal areas.

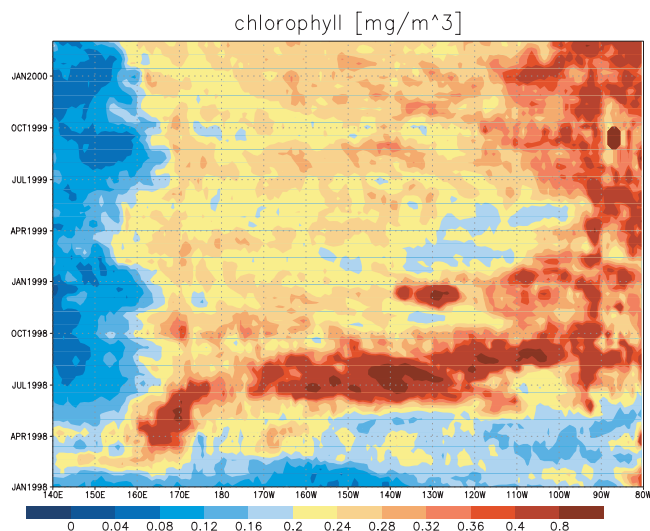
[3] Recent advances in understanding Pacific climate dynamics have paved the road for new areas of research: This paper studies the effect of ocean biology on tropical climate dynamics, and in particular on the ENSO phenomenon. New satellite instruments such as the Sea-Viewing Wide Field-of-View Sensor [McClain *et al.*, 1998] (SeaWiFS) monitor the physical and biological state of the tropical Pacific with an unprecedented accuracy. These new data have been used [Nakamoto *et al.*, 2001; Murtugudde *et al.*, 2002] to assess the effect of ocean biology on

the average surface-layer temperatures in the equatorial Pacific. Lewis *et al.* [1990] argued that ocean biology might have a significant influence on the western equatorial Pacific heat budget. They propose that these changes might also affect ENSO variability. Photosynthetically active phytoplankton, one of the main agents in upper ocean biology, contains chlorophyll that absorbs solar light within the upper ocean. This leads to a change of the vertical profile of absorption of solar light and thus to an enhanced radiant heating of the ocean surface layer [Lewis *et al.*, 1990; Sathyendranath *et al.*, 1991]. At the same time ocean biology is strongly influenced by interannual climate variations in the tropical Pacific [Chavez *et al.*, 1998, 1999; Leonard and McClain, 1996]. Phytoplankton blooms in the eastern equatorial Pacific tend to occur during La Niña conditions, whereas El Niño conditions are characterized by low chlorophyll concentrations. This leads to a significant interannual modulation of the chlorophyll concentrations within the upper ocean, in particular for those El Niño/La Niña transitions that are mainly controlled by oceanic upwelling.

[4] Our study focuses on the question how tropical climate variability and in particular ENSO are influenced by upper ocean biology. This question is studied by using a simplified ENSO model that also accounts for ocean mixed-layer processes, atmospheric boundary layer physics and the climate dependence of equatorial upper ocean chlorophyll concentrations.

### 2. The Physical Model

[5] The dynamical ENSO model used here is similar to Jin's nonlinear recharge model [Jin, 1998]. The main difference in our new model is the incorporation of a simplified mixed layer scheme that is based on a well-justified [Schopf and Cane, 1983; Fu and Wang, 2000] quasi-equilibrium assumption for entrainment and buoyancy. Furthermore, the new model computes surface heat fluxes explicitly using bulk formulae [Louis, 1979; Hanawa and Toba, 1987] and empirical relationships [Wang *et al.*, 1995] between surface air temperatures and sea surface temperatures (SST) as well as between anomalous cloud cover and SST anomalies. The mixed layer heat budget is decomposed into a dynamical term, accounting for zonal and meridional temperature advection, a surface-layer heating term that originates from the shortwave, longwave, latent and sensible heat fluxes. The shortwave heating term captures also the modified absorption of the photosynthetically available part of the incoming light due to chlorophyll. The light attenuation coefficient is directly computed from the upper ocean chlorophyll concentrations using standard simple parame-



**Figure 1.** Longitude-time diagram of the equatorial Pacific SeaWiFS chlorophyll  $\alpha$  concentrations [ $\text{mg}/\text{m}^3$ ].

terizations [Morel, 1988] that are suitable for our simplified atmosphere-ocean model.

[6] The climate-dependence of chlorophyll concentrations  $chl$  [ $\text{mg}/\text{m}^3$ ] in the eastern equatorial Pacific is parameterized in a very simple way. In the western tropical Pacific chlorophyll concentrations are kept constant. The  $chl$  in the eastern equatorial Pacific depends on the local temperature  $T_e$  based on  $chl = -\alpha(T_e - T_r) + 0.05$ , where  $T_r = 30^\circ\text{C}$  is the radiative-convective equilibrium temperature. This parameterization mimics the gross effect of a rather complex interaction between phytoplankton, zooplankton, nutrients, and iron. The iron content is one crucial limiting factor for primary production in the eastern tropical Pacific [Price *et al.*, 1994; Frost, 1996] and in surface waters it is strongly controlled by equatorial upwelling. The later is determined by wind stress that is influenced by equatorial SST anomalies. Thus, on long timescales (several months) an equilibrium relationship between chlorophyll concentration and sea surface temperature anomalies is expected<sup>1</sup>.

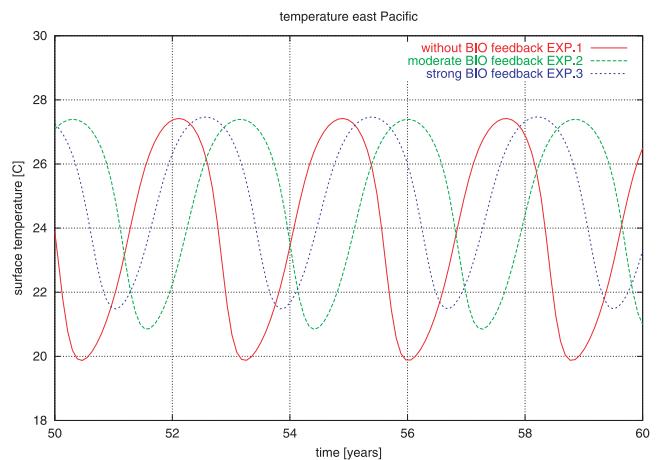
[7] Figure 1 displays a time-longitude plot of the equatorial Pacific surface chlorophyll concentrations measured by SeaWiFS. We observe that the peak and decline phase of the strong El Niño event 1997/1998 are characterized by low chlorophyll concentrations of about  $0.1\text{--}0.2 \text{ mg}/\text{m}^3$ , whereas significantly higher concentrations can be seen for the subsequent lingering La Niña event. The chlorophyll data fields as well as the observed Niño 3 SSTA (not shown) are used to derive the empirical relationship between  $chl$  and  $T_e$ . The massive short-term phytoplankton bloom during the summer 1998 that was triggered by tropical instability waves (TIW) [Chavez *et al.*, 1998] is not included in our biological parameterization.

### 3. The Influence of Ocean Biology on ENSO

[8] Three different experiments were performed.

[9] First experiment: The simplified coupled atmosphere-ocean-mixed layer model is integrated for several decades

<sup>1</sup> Here the fast dynamics of the physically controlled biological system is disregarded.



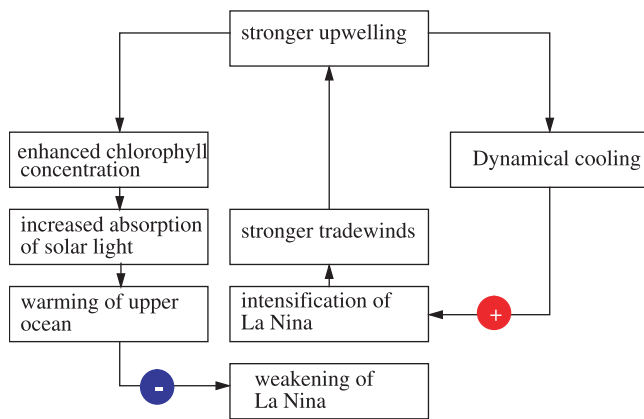
**Figure 2.** Simulated temperatures in the eastern equatorial Pacific for clear water (red), a moderate biological feedback (green) and a strong biological feedback (blue).

treating water as “clear water” with a typical light attenuation depth<sup>2</sup> of 23 m. The result presented in Figure 2 shows an ENSO oscillation with a period of about 3 years. The temperature amplitude (El Niño minus La Niña) amounts to about 7 K. The simulated ENSO cycle is robust against reasonable changes of the model parameters. Both the mean and interannual variability of the mixed layer depth in the western and eastern equatorial Pacific are simulated (not shown) reasonably well [Wang and McPhaden, 1999, 2000], given the simplicity of the model. During La Niña conditions the mixed layer depth in the eastern equatorial Pacific amounts to about 25 m. During El Niño conditions typical mixed layer depths are 40 m. The penetrative radiation at the base of the mixed layer attains values of  $40 \text{ W}/\text{m}^2$  and  $12 \text{ W}/\text{m}^2$ , respectively.

[10] Second experiment: Instead of the “clear water” assumption we employ a temperature-chlorophyll relation using  $\alpha = 0.02 [1/^\circ\text{C}]$ , thereby mimicking a moderate influence of ENSO on ocean biology. In Figure 2 we observe an increase in La Niña temperatures by about one degree Celsius. El Niño is hardly affected by ocean biology, because low chlorophyll concentrations and deep mixed layers accompany warm temperatures in the eastern equatorial Pacific. The associated penetrative radiation flux at the base of the mixed layer is virtually the same as in the first experiment. During La Niña it is reduced to about  $27 \text{ W}/\text{m}^2$ . This adds an extra radiant heating of  $0.35^\circ\text{C}/\text{month}$  to the mixed layer heat budget and thus reduces La Niña amplitudes. The heating originates from the presence of biology rather than from changes in the mixed layer depth.

[11] Third experiment: We choose  $\alpha = 0.04 [1/^\circ\text{C}]$ , such as to mimic a strong biological-physical coupling in the equatorial Pacific. As compared to the first experiment La Niña events are warmer by about  $1.5\text{--}2^\circ\text{C}$  (Figure 2). Again El Niño temperatures and the ENSO period remain largely unaffected. Light attenuation due to ocean biology also influences the depth of the eastern equatorial mixed layer. A small reduction of the mixed layer depth by about 5 m is simulated in the eastern Pacific, when a strong

<sup>2</sup> The attenuation depth is defined as the depth for which the incoming visible solar light is damped to about 37%.



**Figure 3.** Schematic of the positive Bjerknes atmosphere-ocean feedback (right loop) and the negative biological feedback (left loop) in the eastern equatorial Pacific.

biological sensitivity is assumed (not shown). During La Niña conditions the effect of solar light absorption in waters rich in chlorophyll leads to an additional mixed layer heating of about  $0.55^{\circ}\text{C}/\text{month}$  as compared to the “clear” water case. In comparison with the first experiment  $20\text{ W}/\text{m}^2$  less radiation leave the base of the mixed layer, a value that is confirmed by observational studies [Lewis *et al.*, 1990].

#### 4. Discussion and Summary

[12] These experiments clearly illustrate that ocean biology has an influence on the simulated ENSO variability. Changes of light attenuation within the mixed layer due to chlorophyll affect El Niño and La Niña in an asymmetric way. The asymmetry of this negative feedback will contribute to the observed skewness [Burgers and Stevenson, 1999] of the ENSO probability distribution. This effect is associated with an overall warming of the eastern equatorial Pacific mean state and a reduction of the simulated ENSO amplitude.

[13] The interplay between dynamical and biological feedbacks is illustrated in Figure 3. A La Niña state is amplified by the so-called Bjerknes feedback: An initial eastern equatorial cold anomaly generates stronger trades through differential heating in the atmosphere. Enhanced trade winds produce stronger equatorial upwelling, thereby pumping cold water from the subsurface to the surface. On the other hand strong upwelling, associated with La Niña conditions, enhances chlorophyll concentrations in the upper ocean. This leads to an increased trapping of solar light within the biologically active mixed layer and a subsequent warming. The Bjerknes feedback can further amplify the biogenic surface layer warming, an effect that is missed in forced ocean experiments. In contrast to classical bio-climate feedback hypothesis [Charlson *et al.*, 1987] invoking oceanic phytoplankton, Dimethyl-Sulfide (DMS), and tropical clouds, the negative biological feedback described here limits tropical cooling rather than climate warming.

[14] The climate of the Last Glacial Maximum (about 20 thousand years ago) was characterized by stronger Pacific trade winds [Chuey *et al.*, 1987], increased equatorial

upwelling and steeper thermocline slopes [Andreasen and Ravelo, 1997]. We speculate that associated increases of the biogenic productivity and thus enhanced chlorophyll concentrations might have regulated tropical climate. Translated to the greenhouse-warming situation where some models predict an increase of eastern equatorial Pacific temperatures and a decrease of the zonal temperature contrast along the equator [Timmermann *et al.*, 1999], the biological thermostat is expected to become less effective and a weak acceleration of tropical climate change might be the consequence. The suggested negative feedback might have also implications for regional climate changes, associated with tropical instability waves that occur preferentially during La Niña conditions and that are associated with large chlorophyll concentrations.

[15] Further studies using dynamical biological models and more complex coupled atmosphere-ocean models are required to shed more light onto the details of the biothermostat hypotheses proposed here and onto how an inclusion of ocean biology might improve tropical climate simulations and ENSO predictions.

[16] **Acknowledgments.** This paper was sponsored by the German Science Foundation (DFG) and the National Science Foundation (NSF). We thank A. Oschlies, R. Murtuguade, M. Lewis and A. Miller for their valuable comments that helped to improve the manuscript.

#### References

- Andreasen, D., and A. C. Ravelo, Tropical Pacific Ocean Thermocline Depth Reconstructions for the Last Glacial, *Paleoceanography*, *12*, 395–414, 1997.
- Burgers, G., and D. B. Stevenson, The “normality” of El Niño, *Geophys. Res. Lett.*, *26*, 1027, 1999.
- Charlson, R. J., J. O. Lovelock, M. O. Andrea, and S. G. Warren, Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate, *Nature*, *326*, 655, 1987.
- Chavez, F. P., P. G. Strutton, and M. J. McPhaden, Biological-physical coupling in the equatorial Pacific during the onset of the 1997–98 El Niño, *Geophysical Research Letters*, *25*, 3543–3546, 1998.
- Chavez, F. P., P. G. Strutton, G. E. Friederich, R. A. Feely, G. C. Feldman, D. G. Foley, and M. J. McPhaden, Biological and chemical response of the equatorial Pacific Ocean to the 1997–98 El Niño, *Science*, *286*, 2126–2131, 1999.
- Chuey, J., D. Rea, and N. Piasis, Late Pleistocene paleoclimatology of the central equatorial Pacific: A quantitative record of eolian and carbonate deposition, *Quat. Res.*, *28*, 323, 1987.
- Coale, K. H., S. E. Fitzwater, R. M. Gordon, K. S. Johnson, and R. T. Barber, Control of community growth and export production by upwelled iron in the equatorial Pacific Ocean, *Nature*, *379*, 621–624, 1996.
- Frost, B. W., Phytoplankton bloom on iron rations, *Nature*, *383*, 475–476, 1996.
- Fu, X., and B. Wang, A coupled modeling study of the seasonal cycle of the Pacific cold tongue, Part I: Simulation and sensitivity experiments, *J. Climate*, *14*, 765–779, 2000.
- Glantz, M., *Currents of Change: El Niño's impact on climate and society*, Cambridge University Press, 1996.
- Hanawa, K., and Y. Toba, Critical examination of estimation methods of long-term mean air-sea heat and momentum transfers, *Ocean-air Interactions*, *1*, 79, 1987.
- Jin, F.-F., A Simple Model for the Pacific Cold Tongue and ENSO, *J. Atmosph. Sci.*, *55*, 2458–2469, 1998.
- Latif, M., D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, J. O'Brien, A. Rosati, and E. Schneider, Predictability and Prediction, *J. Geophys. Res.*, *103*(C7), 14,375–14,393, 1998.
- Leonard, C. L., and C. R. McClain, Assessment of interannual variation (1979–1986) in pigment concentrations in the tropical Pacific using the CZCS, *Int. J. Remote Sensing*, *17*, 721–732, 1996.
- Lewis, M. R., M.-E. Carr, G. C. Feldman, W. Esias, and C. McClain, Influence of penetrating solar radiation on the heat budget of the equatorial Pacific, *Nature*, *347*, 543–546, 1990.
- Louis, J. F., A parametric model of vertical eddy fluxes in the atmosphere, *Bound. Layer Meteor.*, *17*, 187–202, 1979.

- McClain, C. R., et al., Science quality SeaWiFS data for global biosphere research., *Sea Techn.*, 39, 10–16, 1998.
- Morel, A., Optical modeling of the upper ocean in relation to its biogenous matter content (case 1 waters), *Journal of Geophysical Research*, 93, 10,749–10,768, 1988.
- Murtugudde, R., J. Beauchamp, and A. Busalacchi, Effects of Penetrative Radiation on the Upper Tropical Ocean Circulation, *J. Climate*, 15, 470–486, 2002.
- Nakamoto, S., Kumar, S. Prasanna, J. M. Oberhuber, J. Ishizaka, K. Muneyama, and R. Frouin, Response of the equatorial Pacific to chlorophyll pigment in a mixed layer isopycnal ocean general circulation model, *Geophys. Res. Lett.*, 28, 2021, 2001.
- Neelin, J. D., D. S. Battisti, A. C. Hirst, F. F. Jin, Y. Wakata, T. Yamagata, and S. E. Zebiak, ENSO theory, *J. Geophys. Res.*, 103(C7), 14,261–14,290, 1998.
- Price, N. M., B. A. Ahner, and F. M. M. Morel, The equatorial Pacific Ocean: Grazer-controlled phytoplankton populations in an iron-limited ecosystem, *Limnol. and Oceanogr.*, 39, 520–534, 1994.
- Sathyendranath, S., A. D. Gouveia, S. R. Shetye, P. Ravindran, and T. Platt, Biological control of surface temperature in the Arabian Sea, *Nature*, 349, 54–56, 1991.
- Schopf, P. S., and M. A. Cane, On equatorial dynamics, mixed layer physics, and sea surface temperature, *J. Phys. Oceanogr.*, 13, 917–935, 1983.
- Timmermann, A., M. Latif, A. Bacher, J. Oberhuber, and E. Roeckner, Increased El Niño frequency in a climate model forced by future greenhouse warming, *Nature*, 398, 694–696, 1999.
- Wang, B., T. Li, and P. Chang, An intermediate model of the tropical Pacific Ocean, *Journal of Physical Oceanography*, 25, 1599–1616, 1995.
- Wang, W., and M. J. McPhaden, The surface layer heat balance in the equatorial Pacific Ocean, Part I: Mean seasonal cycle, *J. Phys. Oceanogr.*, 29, 1812–1831, 1999.
- Wang, W., and M. J. McPhaden, The surface-layer heat balance in the equatorial Pacific Ocean. Part II: Interannual variability, *J. Phys. Oceanogr.*, 30, 2989–3008, 2000.
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