

# Biological-physical coupling in the central equatorial Pacific during the onset of the 1997-98 El Niño

Francisco P. Chavez and Peter G. Strutton

Monterey Bay Aquarium Research Institute, Moss Landing, California

Michael J. McPhaden

Pacific Marine Environmental Laboratory, Seattle, Washington

**Abstract** Perturbations to phytoplankton biomass associated with the onset of the 1997-98 El Niño event are described and explained using physical and bio-optical data from moorings in the central equatorial Pacific. The physical progression of El Niño onset is depicted, from reversal of the trade winds in the western equatorial Pacific, through eastward propagation of equatorially trapped Kelvin waves and advection of waters from the nutrient-poor western equatorial warm pool. Fluctuations in chlorophyll and quantum yield of fluorescence are tightly coupled to thermocline variations.

## Introduction

Equatorial upwelling, driven by the trade winds that blow from east to west, results in sea surface temperatures (SST) in the central and eastern equatorial Pacific that are abnormally cool for a tropical ocean. This upwelling makes the equatorial Pacific the largest natural source of carbon dioxide to the atmosphere (Feely *et al.*, 1987), accounts for one fifth of the global supply of nitrate to the ocean surface (Chavez and Toggweiler, 1995) and therefore has consequences not only for global climate, but also for biogeochemical cycles (Chavez and Barber, 1987; Feely *et al.*, 1987). Low rates of phytoplankton productivity (Chavez and Barber, 1987) and hence new production (Dugdale *et al.*, 1992) contribute to the maintenance of a positive gradient of carbon dioxide between ocean and atmosphere.

Approximately every three to seven years, equatorial Pacific SST becomes anomalously warm in association with El Niño, a phenomenon with global climatic implications (Rasmusson and Wallace, 1983). While the physical and climatic consequences of El Niño are relatively well understood, the biological consequences in the equatorial Pacific are still poorly determined. In this report we present a time series of bio-optical measurements collected during the onset of the 1997-98 El Niño, a particularly strong event. We present evidence for strong physical-biological coupling and suggest that during onset of the 1997-98 El Niño primary production in the equatorial Pacific was regulated by remotely forced thermocline variations through the supply of upwelled iron.

## Methods

Our current understanding of the physical processes associated with El Niño has been facilitated by the Tropical Atmos-

phere Ocean (TAO) array. The array consists of approximately 70 moored buoys across the equatorial Pacific Ocean (McPhaden, 1995). These buoys record surface wind velocity, SST, surface air temperature, relative humidity, and ocean temperature down to 500 m. Data are transmitted daily, enabling near real-time monitoring and prediction of basin scale physical changes associated with El Niño.

In December 1996 bio-optical instrumentation was installed on moorings located at 0°, 155°W and 2°S, 170°W. The data presented are from 0°, 155°W. The instruments used for our analysis consisted of a Biospherical PRR-620 (downwelling irradiance at 412, 443, 490, 510, 555, 656 nm and PAR) on the top of the buoy tower, two Biospherical MCP-200s (downwelling irradiance at 490 nm) at 10 m and 30 m, and a Biospherical PRR-600T2 (downwelling irradiance at 412, 443, 490, 510, 555, 656 nm and PAR, and upwelling radiance at 412, 443, 490, 510, 555, 670 and 683 nm) at 20 m. A copper shutter system, for bio-fouling protection, covered the optical sensors of the Biospherical PRR-600T2. The shutter opened on command prior to each measurement and remained closed between measurements. Comparison of data (not shown) from the sensors at 10 and 30 m, not protected from bio-fouling, with the 20 m sensor confirmed the effectiveness of the shutter system.

Data were recorded at 10-minute intervals from 0600 to 1800 local time. Dark values were recorded at local midnight. The 10-minute data from 1000 to 1400 local time were averaged, resulting in one data point each day. Downwelling irradiance at 3 m above the surface and at 20 m depth were used to calculate the diffuse attenuation coefficient at 490 nm ( $K_{490}$ ), which was then converted to a mean chlorophyll concentration for the upper 20 m of the water column (Morel, 1988). The resulting time series of chlorophyll concentration was used as the basis of our investigation into phytoplankton population dynamics. Primary productivity ( $\text{mg C m}^{-2} \text{ day}^{-1}$ ) was calculated from a regression between measured surface chlorophyll and primary productivity (Model I,  $r^2=0.64$ ,  $n=56$ ) (<http://www1.whoi.edu/jgofs.html>). The concentration of nitrate in surface waters was estimated from a quadratic relationship between temperature and nitrate derived by Chavez *et al.* (1996b).

The intrinsic growth rate ( $k$ ) of the phytoplankton population was calculated from net growth and grazing. The equatorial Pacific is a microbial loop dominated system (Chavez *et al.*, 1996a) so we have ignored contributions by net phytoplankton and macro-zooplankton. The growth coefficient was calculated as  $\mu = \ln(\text{Chl}_{t+1}/\text{Chl}_t)[\text{day}^{-1}]$ . Micro-zooplankton grazing rate was estimated from a relationship between chlorophyll and grazing rate for the equatorial Pacific (Landry *et*

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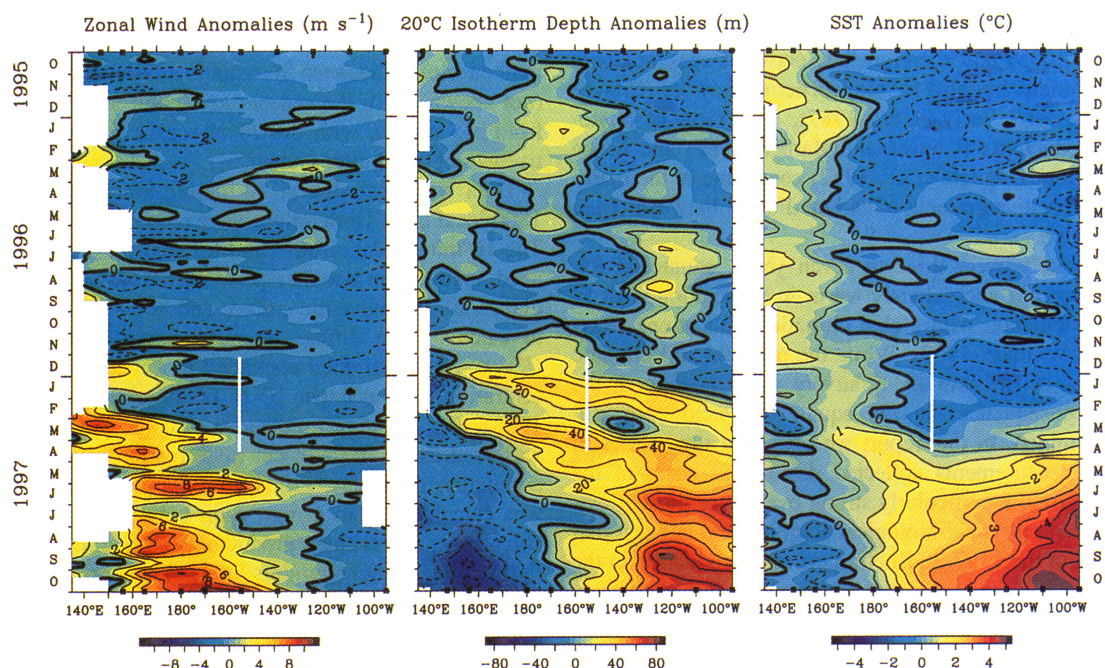
*al.*, 1995; Landry *et al.*, 1997; Verity *et al.*, 1996). The intrinsic growth rate is then the sum of net growth and grazing rate. A second estimate of growth or physiological status is the quantum yield of fluorescence ( $\Phi_f$ ). It was calculated using the mean chlorophyll concentration in the upper 20 m and the upwelling radiance at 683 nm ( $Lu_{683}$ ) measured at 20 m (Chamberlin *et al.*, 1990).  $\Phi_f$  is related in an approximately inverse fashion to the quantum yield of photosynthesis and is used here as an inverse measure of photosynthetic efficiency.

## Results and Discussion

The time/longitude sections of anomalies in surface zonal winds, SST and 20°C isotherm depth (20°C depth, a proxy for the thermocline) are used to describe the onset and development of the 1997-98 El Niño (Figure 1). Anomalous westerly winds were first observed in the western Pacific in December 1996/January 1997. These westerly wind bursts, associated with the 30 to 60 day Madden-Julian Oscillation (Madden and Julian, 1971), generated Kelvin waves that propagated across the Pacific at over 200 km day<sup>-1</sup>, raising sea level and deepening the thermocline (Figure 1B). The anomalies in SST did not appear until after the second set of wind anomalies in March and April 1997 (Figure 1C). A positive gradient between SST and air temperature was maintained during our observation period so the anomalies in SST were not driven by surface heat fluxes but were generated by either vertical or lateral advection. The relative importance of these mechanisms is dictated in part by longitude; near 170°W, advection of water from the warm pool is dominant (McPhaden and Picaut, 1990), while in the eastern Pacific, downwelling accounts for

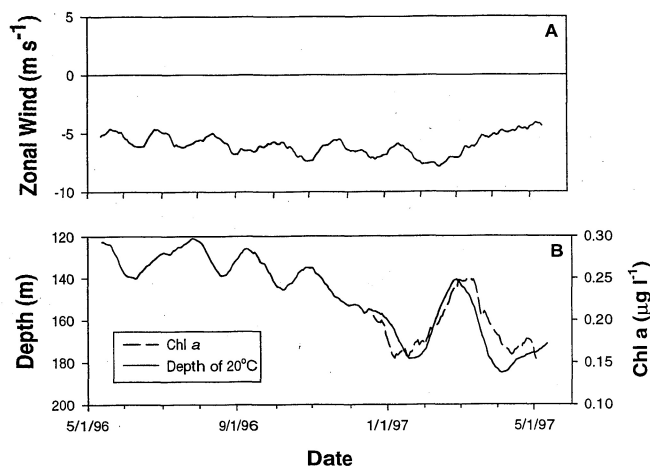
much of the observed anomaly (Kessler and McPhaden, 1995). The increase in the SST anomaly of 2°C from March to May 1997 at the mooring site (Fig. 1C) was likely a combination of these two processes. The first signature of subsurface anomalies was observed at the mooring site in January 1997 (Figure 1B). A recovery of the thermocline was observed in February 1997 prior to arrival of the second Kelvin wave in March 1997. During the observation period the local winds at the mooring site remained easterly and favorable for upwelling (Figures 1A and 2A). Clearly, the subsurface anomalies at 0°, 155°W were not associated with variations in the local winds but were forced remotely from the western Pacific.

The time series of bio-optical properties began in early December 1996, prior to the first set of wind anomalies (Figure 1A). The low frequency variations in chlorophyll and primary production were well-correlated with 20°C depth, but not with the local wind field (Figures 2B and 3). Comparison of the 5-day and 21-day moving averages of chlorophyll and primary production (Figure 3A) shows that single occupations can be severely aliased by higher frequency variations. Time series at 0, 140°W during cool conditions have shown correlation between pigment concentrations and meridional (north-south) current variation associated with the passing of tropical instability waves (TIW; Bidigare and Ondrusek, 1996; Foley *et al.*, 1997). These TIWs may be responsible for the higher frequency variations in the present time series. The strong correlation between 20°C depth and chlorophyll concentration is in contrast with the only other bio-optical time series from the equatorial Pacific (Foley *et al.*, 1997) which exhibited only a weak correlation. The reason for the difference may be related to the lack of competing physical processes in our data, the



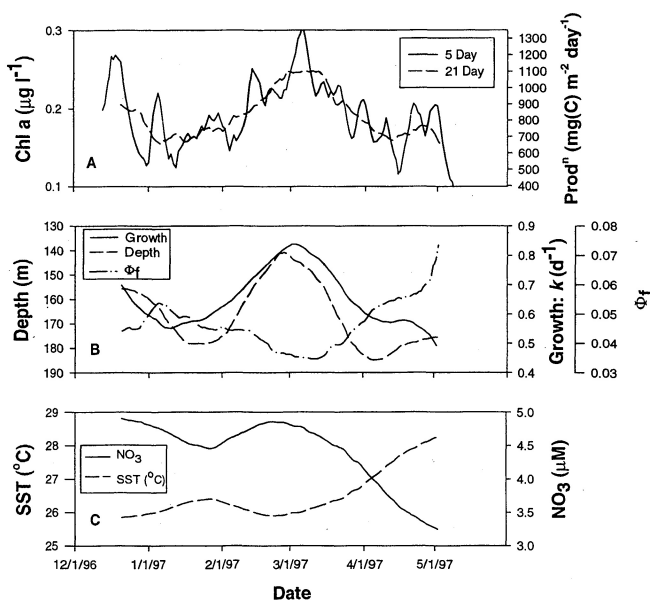
**Figure 1.** Time/longitude sections of anomalies in (A) surface zonal winds (m s<sup>-1</sup>), (B) 20°C isotherm depth (m) and (C) SST (°C) for 24 months ending in October of 1997. Analysis is based on 5-day averages between 2°N and 2°S of moored time series data from the TAO array. Anomalies are relative to monthly climatologies cubic spline fitted to 5-day intervals. Squares on the abscissas indicate longitudes where data were available. Major anomalies in the western Pacific wind field occur on a 30-60 day cycle (Madden and Julian, 1971) beginning in December 1996. Each “burst” of westerlies generates a Kelvin wave that is evident in the depth of the 20°C isotherm as it propagates across the Pacific at over 200 km day<sup>-1</sup>. The SST anomalies lag the subsurface perturbations and are notable after April 1997. The time series of bio-optics was collected at 0°, 155°W from December 1996 to May 1997 (denoted by a cleared strip in the time/longitude sections).





**Figure 2.** (A) Time series of the zonal (east-west) wind vector at 0°, 155°W for the period May 12<sup>th</sup>, 1996 to May 12<sup>th</sup>, 1997. Negative values represent winds originating from the east and are upwelling favorable. 21 day moving averages of the original data are plotted for ease of interpretation. In all figures, the abscissa labels represent the first day of the relevant month. (B) 21-day moving average of the depth of the 20°C isotherm (—) and chlorophyll (— —). The  $r^2$  between wind and chlorophyll is 0.04 and for isotherm and chlorophyll 0.69 ( $n=133$ ).

strength of the 1997-98 El Niño and the associated Kelvin wave signal, or to the confounding effects of biological fouling in the 0, 140°W data. In the present case the physical forcing resulted in an unambiguous response of the phytoplankton community (Figures 2 and 3).

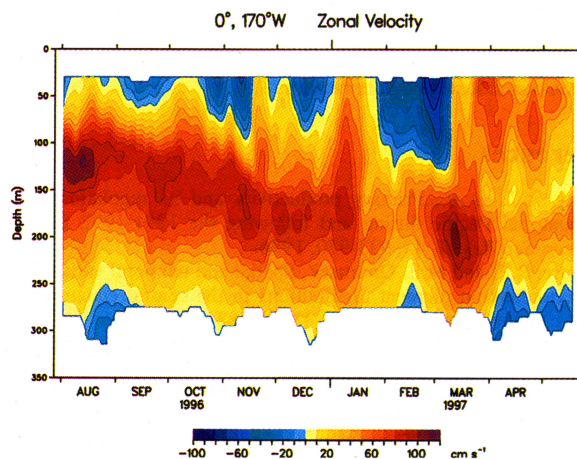


**Figure 3.** (A) Time series of mean chlorophyll *a* concentration for the upper 20 m of the water column, calculated from  $K_{490}$  (Morel, 1988) and integrated primary production, for the period Dec 11<sup>th</sup>, 1996 to May 12<sup>th</sup>, 1997. Five day (—) and 21 day (— —) moving averages of daily data are plotted. (B) 21 day moving average of the depth of the 20°C isotherm (—), phytoplankton growth (— —) and quantum yield of fluorescence,  $\Phi_f$  (— · —). The  $r^2$  between growth and  $\Phi_f$  = 0.80 ( $n=133$ ). (C) 21 day moving average of the surface nitrate concentration (—) calculated from sea surface temperature (— —) (Chavez *et al.*, 1996b).

The calculated NO<sub>3</sub> concentration of ~3.0 μM (Chavez *et al.*, 1996b) at the mooring site (Figure 3C) agrees well with the values of 2.9 to 3.1 μM measured during the mooring recovery cruise in May 1997. Nitrate showed little variation prior to April, was well above levels found in oligotrophic waters (<0.1 μM) and was not as coherent with the chlorophyll and primary productivity time series as was the time series of 20°C depth. During normal conditions, waters from the Equatorial Undercurrent (EUC) are upwelled along the equatorial Pacific (Toggweiler and Carson, 1995) and are the most important source of iron for equatorial Pacific surface waters (Coale *et al.*, 1996). The upwelled iron leads to a very narrow region of enhanced biological productivity at the equator (Chavez *et al.*, 1996a; Barber *et al.*, 1996). However, the iron source is small relative to the macronutrients (nitrate, phosphate) upwelled and a large pool of these remains at the surface once the iron is consumed.

A time series of currents at 170°W (Figure 4) provides clues regarding the processes responsible for the strong biophysical coupling observed at 155°W (Figures 2 and 3). El Niño deepens the EUC but local upwelling-favorable winds continue and the depth from which upwelled water is recruited (~60-100 m) probably remains unchanged, hence reducing upwelled iron. Furthermore, there is a reversal of the surface currents with the passage of the Kelvin waves, which implies downwelling and a greatly reduced shear between upper layers and the EUC. Under these circumstances, iron supply to the surface would cease and the surrounding waters with unused macronutrients and low levels of iron would converge on the equator. The combined effect of these scenarios would be a decrease in the supply of iron to the euphotic zone and hence a decrease in biological productivity (Chavez *et al.*, 1996a; Barber *et al.*, 1996; Bidigare and Ondrusek, 1996; Foley *et al.*, 1997).

Growth rate ( $k$ ) co-varied with 20°C depth and fluctuated between 0.5 and 0.8 day<sup>-1</sup> (Figure 3B), consistent with empirical data from the equatorial Pacific at 140°W (Chavez *et al.*, 1996a; Vault *et al.*, 1995). The quantum yield of fluores-



**Figure 4.** Time series of zonal velocity from an Acoustic Doppler Current Profiler moored at 0°, 170°W for the period August 1996 to May 1997. Eastward velocity is positive. The core of the eastwards flowing Equatorial Undercurrent steadily deepens from 100 m to 200 m by March 1997. We surmise similar changes at 0°, 155°W based on coherence scales of at least 15° longitude for intraseasonal and interannual zonal velocity variations along the equator (Kessler *et al.*, 1995).

cence also co-varied with 20°C depth (Figure 3B); thus, two estimates show the effects of Kelvin wave propagation, presumably through iron supply, on phytoplankton growth. There are several caveats associated with our derived time series of primary production and  $\Phi_p$ . Firstly, the relationship between chlorophyll concentration and productivity, although statistically significant, is purely empirical. Secondly, the biological fluctuations observed at the mooring site are the result of advective processes as well as local changes in phytoplankton growth and productivity. Nonetheless, mean primary productivity in the equatorial Pacific is approximately 900 mg C m<sup>-2</sup> day<sup>-1</sup> (Chavez, *et al.*, 1996a), which is well within the range of our derived values in Fig. 3A. The drop in production in late April 1997, also seen in figure 3B, suggests that primary production was reduced by as much as 50% from that observed between the passage of the two Kelvin waves. At 140°W, a similar 50% decrease in primary productivity was observed (Barber *et al.*, 1996; Foley *et al.*, 1997) associated with the mature phase of the relatively weak 1991-1992 El Niño. Had observations extended further in time we would predict even stronger chlorophyll and productivity anomalies at 0°, 155°W as the 1997-98 El Niño matured and macronutrients approached zero.

With high frequency time series of physical and bio-optical properties we have described the tight bio-physical coupling that exists during the evolution of a strong El Niño, as well as provide insight into the nature of the coupling. These data illustrate the potential for bio-optical time series of this type, combined with atmospheric and oceanographic data, to enhance our understanding of the biogeochemical processes associated with basin scale oceanographic fluctuations. With the launch of SeaWiFS, documenting the biological effects of El Niño in the equatorial Pacific will now be possible from moorings and satellites.

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F. Chavez and P. Strutton, Monterey Bay Aquarium Research Institute, P.O. Box 628, Moss Landing, CA 95039; chfr@mbari.org; stpe@mbari.org.

M. McPhaden, NOAA/PMEL, 7600 Sand Point Way NE, Seattle, WA 98115; mcphaden@pmel.noaa.gov

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