

# Upper Ocean Circulation Modulation by Phytoplankton Concentration in the Equatorial Pacific and the Indian Ocean

S. NAKAMOTO

*Earth Science and Technology Organization, 1-15, Nisishinbashi, Minatoku, Tokyo, 105 Japan,*

S. PRASANA-KUMAR

*POD, National Institute of Oceanography, Dona Paula, 403 004 India*

J.M. OBERHUBER,

*DKRZ, Hamburg, Germany*

P. SAMMARCO,

*LUMICON, Chauvin, LA, USA*

K. MUNEYAMA,

*JAMSTEC, 2-15, Natsushima, Yokosuka, 237-0061, Japan*

T. SATO

*The DEEPSTAR Group, JAMSTEC, 2-15 Natsushima, Yokosuka, 237-0061, Japan*

AJOY KUMAR

*RSALAS, University of Miami, 4600 Rickenbacker Causeway, Miami, FL, 33149 USA*

R. BROUIN

*Scripps Institution of Oceanography, UCSD, La Jolla, CA 92093-0021 USA*

## ABSTRACT

Wind patterns in the equatorial Pacific and Indian oceans are the factors that regulate the chlorophyll pigment distributions in the equatorial region of these oceans. Trade winds and coastline of the Pacific basin supports wave-guide dynamics in the equatorial Pacific, while the spatial asymmetry of wind pattern along with the north-south coastline of the Indian ocean makes upper ocean circulation more complex than that in the Pacific.

We propose a feedback mechanisms between phytoplankton and currents in the equatorial Pacific and Indian ocean, based on numerical experiment using mixed layer-isopycnal ocean general circulation model which includes photosynthesis process parameterizations.

In the equatorial Pacific, the quasi-permanent upwelling brings nutrient-rich subsurface waters to the euphotic zone, thus the ocean currents supports perennial phytoplankton bloom. The phytoplankton inhibits downward solar radiation penetration in the equatorial Pacific, resulting in cross equatorial density gradient in the upper ocean. This strengthens the geostrophically balanced westward currents in both side of the equatorial wave guide ( within 5degree bands). Once these currents reach the western Pacific coast, they feed the Equatorial undercurrent(EUC). In contrast, in the Indian ocean upwelling is not well developed due to the asymmetric wind pattern about the equator and relatively short duration of the equatorial undercurrent in the Indian ocean. These along with wind reversal and north-south coastal asymmetry, does not support a chlorophyll pigments distribution in the equatorial wave-guide to bring about a meridional density gradient by altering the penetration of solar radiation. Relevant upper ocean circulations modulated by phytoplanktons in the equatorial regions of the Pacific as well as the Indian ocean are discussed.

## INTRODUCTION

In the ocean there are algae and some bacteria which can synthesize high-energy organic compounds from low-energy inorganic compounds such as water and carbon dioxide. The source of energy for these organisms is either solar radiation ( photosynthesis ), or chemical energy derived from the oxidation of inorganic compounds ( chemosynthesis ). The

photosynthetic algae require water as the H-donor in the photosynthesis process by liberating oxygen from water and transfers electrons to plastoquinone (1,2,3,4). This is the essence of living organisms that produces extra entropies than dead phytoplankton debris.

During photosynthesis in green plants, light energy is used to convert carbon dioxide and water into oxygen and organic compounds (4). In the visible domain the absorbed radiation is essentially converted into heat, even if energy storage occurs within the organic compounds created through photosynthesis (5). Penetrated solar radiation into deep ocean is converted to internal energy to distributed at depth and thus contributes slowly to the heating of the ocean.

The amount of solar radiation energy within the approximate spectral range, 350 to 700 nm, is coined as the photosynthetic available radiation (PAR). This definition does not prejudice the possible usefulness of this energy for phytoplankton because all photons within the defined spectral range must be counted. To be efficient in the photosynthetic process, the photons must be absorbed by the algal pigments. Thus, one can define photosynthetically usable radiation (PUR), as the fraction of radiant energy of such wave length that it can be absorbed by the algae (6). The solar energy stored in the body of biota converted to chemical energy to sustain biological activities, and ejected into the atmosphere and the ocean via soil and sea water. The amount of solar radiation converted into and stored as chemical energy, in the form of organic matter created through photosynthesis is coined as the photosynthetically stored radiation (PSR). When converted into its energetic equivalent, the daily primary production within the entire euphotic zone allows the PSR to be computed (7). The amount of such stored energy (recovered into heat elsewhere and with delay) may hardly exceed 2% of the visible incident radiation (6,7). This small fraction may be important in geochemical application in a long time scale, while it can be negligible when geophysical phenomenon of solar heating is under scrutiny. In the application of carbon circulation in the ocean, the PUR that was absorbed by phytoplankton but immediately ejected into auxiliary system (turbulent mixed layer) may alter the physical and chemical environment through thermodynamics in the turbulent mixed layer.

In this paper, we study the effect of phytoplankton concentration on under-water radiation transfer process through their thermodynamical effect due to photosynthesis by living phytoplankton. In section 2, ocean radiation transfer and optical processes parameterization will be introduced. In section 3, the numerical model experiments and the results will be discussed with observations. The section 4 will be discussion on remotely sensed phytoplankton biomass and bio-physical interaction process in the ocean.

#### **RADIATION TRANSFER PROCESS IN THE UPPER OCEAN.**

In the upper ocean, the sea water is stirred primarily by frictional effects from the wind, although

buoyancy disturbances ( e.g., night time surface cooling, enhanced buoyancy flux) due to solar heating and precipitation can contribute to the water mixing. Such a layer is coined as "turbulent mixed layer", in which water is unstable and well mixed vertically. It is the mixed layer that exchange heat, water vapor, materials as well as entropy that drive the entire bio-physical oceanic mixed layer system.

Since water buoyancy in the mixed layer is determined by temperature and salinity, the dynamics of the turbulent mixed layer is governed by the processes involving heat flux and salt flux such as turbulent kinetic energy of wind, solar radiation, sensible heat, latent heat, long wave radiation from sea surface, precipitation minus evaporation, and turbidity of sea water (8,9).

Suppose the ocean is calm and turbulence in the ocean is negligible, the isopycnal interface (interface between two different density layers) shifts upward and downward depending only upon the atmospheric wind pattern. This is the "Ekman pumping", which raises nutrient-rich deep layer water toward surface where enough solar radiation energy and carbon dioxide leads to photosynthesis.

With the existence of turbulence, there exists cross-isopycnal flow coined as "convective entrainment" and "convective detrainment" at the bottom of the mixed layer. The convective entrainment velocity indicates the rate of mixed layer thickening caused by the turbulent entrainment of fluid across the bottom of the mixed layer and by its incorporation into the mixed layer. The convective entrainment velocity is determined from the conservation of turbulent kinetic energy in the mixed layer, and responds to the surface momentum and buoyancy fluxes as well as the penetration of the solar radiation through the bottom of the mixed layer. Thus, the interaction of solar radiation with biochemical reaction in the process of photosynthesis plays a role in determining the entrainment velocity in the turbulent mixed layer. (In the ocean interior, cross-isopycnal flow is excited due to turbulence as well as small-scale motion such as internal waves and internal tides.) The modern isopycnal ocean models have successfully treated such cross-isopycnal mixing process with improved numerical schemes (10,11). The processes that govern the evolution of the ocean turbulent mixed layer are illustrated in the context of a bulk mixed layer model. The term "bulk" implies that the temperature and salinity are explicitly specified to be constant over the depth of the mixed layer. Extinction of solar radiation in the ocean can be approximated by a flux form of Beer's law, which includes shortwave radiations incident upon the ocean surface, wavelength dependent albedo decay with wavelength dependent volume shortwave extinction coefficient of the ocean.

The value of extinction coefficient is increased relative to clear water if the water is turbid. In turbid water, selective absorption occurs by chlorophyll and other biotic pigments, suspended sediments, and dissolved matter. Away from the coast, it is principally the chlorophyll content that affects water clarity (12). Absorption at the near infrared wavelength is insensitive to water turbidity, while absorption in visible wavelengths depends crucially on the chlorophyll content.

#### NUMERICAL EXPERIMENTS FOR TESTING UPPER OCEAN MODULATION BY PHYTOPLANKTON BIOMASS.

Solar radiation absorption and local heating within the upper ocean are strongly influenced by the abundance of phytoplankton as depicted by the chlorophyll content. According to whether this concentration is high or low, the heat deposition occurs within a layer that may vary thickness from less than 10m to more than 100m. Morel and Antoine (13) proposed a simple parameterization (hereafter denoted as MA94), accounting for this dependence, that allows the vertical profile of heating rate to be prescribed from the phytoplankton pigment concentration, as it can be remotely detected from space, by using ocean color sensors.

Their parameterization, MA94, is developed for oceanic case I water, allowing the vertical profile of the solar radiation absorption and heating rate. The heating rate associated with solar infra-red radiation is rapidly absorbed within a few tens of centimeters, without influenced by chlorophyll pigments. The amount of absorbed energy at any depth can be computed for any oceanic water provided that chlorophyll pigment content in the upper layer is known. It is anticipated that the chlorophyll pigments in the phytoplankton body catch visible photon energy in their chloroplast and involve photosynthesis at that depth. This leads to biophysical interaction through biological heating of upper ocean. Since most of ocean GCM without biological heating employ solar radiation penetration down to 17m ( or 23m ) globally, the biological heating near the depth of around 5m may change upper ocean mixed layer dynamics significantly.

Nakamoto et al.,(14) and Nakamoto et al.,(15) conducted numerical experiments to examine the effect of MA94 parameterization in a three-dimensional ocean general circulation model. They incorporated remotely sensed Coastal Zone Color Scanner (CZCS) chlorophyll pigment concentration data and atmospheric data from the European Center for Medium-range Weather Forecast (ECMWF) into an updated version of the OPYC primitive equation ocean general circulation model (designated hereafter as OPYC). (10). The model

domain was set in global ocean geometry. The model resolution is approximately 1 degree horizontally with thirteen layers vertically, based on NOAA 5 minutes resolution data. The top layer of the model represents the turbulent mixed layer through which atmospheric processes directly force the model. Solar radiation is allowed to penetrate downwards through the ocean surface and is absorbed below the surface in the ultra-violet and visible wave lengths with a constant penetration depth of 23m (16), hereafter referred to as clear-water parameterization PS77. This parameterization depth corresponds to the clearest ocean waters (17).

In order to examine the effect of varying chlorophyll content in the ocean mixed layer, they replaced the above clear-water parameterization PS77 with the alternative parameterization, MA94, accounting for a heating rate within the upper ocean influenced by chlorophyll pigments. The control run with clear water parameterization, PS77, of OPYC was carried out for 50 years, which is sufficient to obtain a cyclo-stationary state for the upper ocean, the thermocline. Using the last snapshot of the 50<sup>th</sup> year control-run as initial condition, chlorophyll forcing parameterization MA94 experiment was conducted for additional 10 years until another cyclo-stationary state for global ocean SST was obtained. The difference between the experiments using parameterization PS77 and MA94 delineates the bulk nature of the effect of varying chlorophyll pigments on downward radiation transfer processes in the upper ocean, because atmospheric forcing in both model runs were the same.

They analyze their model data in the Arabian Sea and compared with available ocean observations to examine the effect of photosynthesis by living phytoplankton. The Arabian Sea represents typical one-dimensional mixed layer dynamics because of the homogeneity of horizontal sea temperature in the area (18,19). They also analyzed the model data in the Equatorial Pacific, where horizontal advection plays an important role in determining the ocean thermal fields.

In the Arabian Sea, ocean model results showed reduction of penetrating solar radiation across the mixed layer base due to consumption of solar radiation by phytoplanktons in the mixed layer. The mixed layer thickness decreased by 20 m in the model experiment because of the increased mixed layer temperature due to the existence of chlorophyll in the layer during the fall inter-monsoon period. Field experiments during the Indian Joint Global Ocean Flux Study (JGOFS) in the Arabian Sea revealed a similar behavior: that is, increasing SST (in excess of 28C) and decreasing mixed layer depth (about 30m) from April to May (18). When chlorophyll pigments

subsurface cooled through the effect of vertical shift of solar heating toward the surface. Figure 1 displays the difference of vertical section of the temperature (which is the depth-latitude plot of temperature from Chlorophyll driven ocean model MA94 minus that from non-chlorophyll ocean model PS77) along the latitude of 20N in October. It is noted that the mixed layer temperature rises more than 0.3 K at about 50m near 69E, while subsurface temperature becomes lower by 0.5 K.

The equatorial Pacific, where permanent existence of phytoplankton along the equatorial upwelling region, is an excellent example of the bio-physical interaction of ocean biosphere with auxiliary system (i.e., ocean mixed layer bounded by the equatorial wave-guide). Because of smaller seasonal excursion of relatively shallower mixed layer in the equatorial ocean, the effect of biological heating is more dynamically pronounced in the equatorial region. As was the case in the Arabian Sea, the mixed layer base along the equator was raised and the north-south slope of the mixed layer base shoaled towards the equator. This generates anomalous westward geostrophic currents north and south of the equator. In the western equatorial, these anomalous geostrophic currents merge into and strengthen the equatorial undercurrents (EUC), supplying water mass from the 200m depth in the west to the eastern surface equatorial Pacific (Figure 2). This phytoplankton-induced response of the undercurrent enhances upwelling around 110W, resulting in a lower SST anomalies due to the strengthened EUC transport than without phytoplankton in the upper ocean layer in ocean model (15).

## DISCUSSION

Noting that carbon dioxide flux between the ocean and the atmosphere to be a function of wind as well as sea water properties, and that ability of sea water to exchange carbon dioxide is influenced by the change of ions regulated by processes both involving acid-base equilibrium and biological process, we explored a possible feedback mechanism between ocean biology and ocean physics in the turbulent mixed layer in the upper ocean, using remotely sensed chlorophyll content, ocean general circulation model.

We considered the ocean system to be steady and spontaneous in terms of chemical constituents with living organisms in geological time scale. First, we assumed that the ocean fluid is regulated by geophysical fluid dynamics without living organisms as a first approximation. Next, we included the effect of photosynthesis process in the upper ocean turbulent mixed layer by using simple parameterization of solar radiation penetration process under the existence of phytoplankton. This

parameterization is based on field measurement in the ocean with bio-optical consideration. We interpreted the parameterization to be useful for application of photosynthesis process in the ocean turbulent mixed layer physics, which enable us to study the interaction between ocean biology and ocean physics.

Based on the above idea, we summarized two numerical experiments conducted recently using Ocean Mixed Layer-Isopycnal General Circulation Model (OPYC) and CZCS satellite derived chlorophyll pigment concentration data.

Ocean model experiments indicated that by absorbing solar radiation chlorophyll pigments influence the upper ocean mixed layer heat budget significantly: Sea Surface Temperature (SST) in the Arabian sea increases by up to 0.3K and mixed layer thickness decreases due to biological heating in one dimensional radiation transfer process in the ocean. It is interesting to note that the Indian Ocean has its uniqueness by its land-sea coastline and seasonal atmospheric forcing that hinders permanent chlorophyll pigment distributions along the equatorial ocean as is the case in the Pacific ocean.

In the open ocean, where horizontal advection is essential, there may be a possible interaction between the biological heating and rotating fluid in the earth system: our model experiment indicates that chlorophyll pigments in the equatorial Pacific lifts the base of the mixed layer because of the shift of the biological heating toward the ocean surface due to the existence of phytoplankton in the equatorial upwelling region. This results in shoaling of the mixed layer base towards the equator, inducing the westward geostrophic currents that merge into the equatorial undercurrent in the western equatorial Pacific. This implies further implication of carbon circulation in the equatorial Pacific ocean. The induced westward geostrophic currents in both side of the equator merged into EUC in the western equatorial Pacific region. From the recent deep water (3000m) sediment trapping experiments conducted in the western equatorial Pacific indicated the sinking zooplankton debris whose living communities are known to be located at mid depth (around 200m) in the south eastern tropical Pacific around 10S, 100W (Personal communication from Professor Motoyoshi Oda of Tohoku University, 2000). Such sediment trapping experiment data may be useful for further comparison with numerical model results as verification of biologically induced geostrophic currents in the equatorial Pacific ocean. Due to the possible transport of iron-rich deep water originated in the Asian and west-Pacific islands, it is anticipated that the strengthened EUC by photosynthesis activity of phytoplankton may play an role of positive feedback for the east equatorial Pacific phytoplankton

of phytoplankton may play a role of positive feedback for the east equatorial Pacific phytoplankton biomasses.

From numerical model experiments, it is proposed that chlorophyll pigment content in the upper ocean modifies the upper ocean heat energy accumulation by changing the ocean radiation transfer processes vertically. It is also shown that the space-time variation of phytoplankton activity in the upper ocean leads to inhomogeneity of downward heat penetration length in the presence of phytoplankton in the turbulent mixed layer: in the equatorial Pacific, where relatively shallow thickness and small seasonal excursion of the turbulent mixed layer is vulnerable to the heating through photosynthesis of phytoplankton. Thus, we believe the photosynthesis effect in the upper ocean may be incorporated in climate modeling of global thermohaline circulation as a bio-geochemical-physical feedback mechanism.

**ACKNOWLEDGEMENT**

This work is partly supported by parallel ocean numerical modeling project between the Earth Science and Technology Organization (ESTO) and Japan Marine Science and Technology Center (JAMSTEC) under supervision of Dr. T. Tsuchiya. S.N is partly supported from the "Carbon Flux Mapping Study and Related Technology Development" under the Science and Technology Agency of Japanese government. Regarding with multi-disciplinary modeling experiments, authors have been stimulated through discussion with Professor Motoyoshi Oda of Tohoku University.

**REFERENCES,**

1. Moore, W.J.,1972, , Prentis Hall, (Japanese edition) ,1972.
2. Niiler, P.P., 1975, J. Marine Res. 33, 405-422.
3. Parsons, T.R.,M.Takahashi, and B.Hargrave, 1990, 3<sup>rd</sup> edition, Pargamon Press, 330pp.
4. Atkins, P.W., Physical Chemistry, 1993.
5. Voet, D., J.G. Voet, and C.W. Pratt, 1999, John Wiley & Sons.
6. Morel, A., 1976, Deep Sea Res., 25, 673-688,.
7. Morel, A., 1988, J. Gephys. Res., 93, 10749-10768,.
8. Turner, J.S., and E.B.Kraus, 1967, Tellus, XIX, 88-97.
9. Deardorff, J.W., 1983, , J. Phys. Oceanogr. 13, 988-1002, 1983.
10. Oberhuber, J.M , 1993,J. Phys. Oceanogr., 23, 808-829.
11. Bleck, R., and L.T.Smith 1990,J. Geophys. Res. 95, 3273-3285.
12. Ohlmann, J.C., D. A. Siegel, and L. Washburn, 1996, J. Geophys. Res., 103, 5379-5395.
13. Morel, A., and D. Antoine, 1994, J. Phys. Oceanogr., 24, 1652-1665.
14. Nakamoto, S., S. Prasanna Kumar, J.M. Oberhuber, K. Muneyama, R. Frouin, 2000,
15. Geophys. Res. Letetrs. 27, 747-756.
16. Nakamoto, S., S. Prasanna Kumar, J.M. Oberhuber, J.Ishizaka, K. Muneyama,

- a. R.Frouin, 2001, Geophys. Res. Letters. In press, .
17. Paulson, C.A., and J.J.Shimpson 1977, J. Phys. Oceanogr., 7, 952-956, 1977.
18. Baker, K.S. and R. Frouin, 1987, Limnol. Oceanogr. 32, 1370-1377.
19. Prasanna-Kumar, S., and T.G. Prasad, , Curr. Sci., 71, 834-841, 1996.
20. Fischer, A.S., 2000, PhD. Thesis, MIT/Woods Hole.

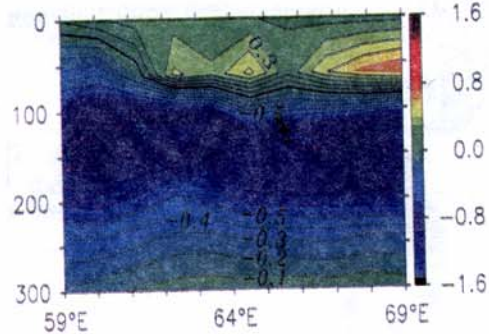


Figure 1. The difference of vertical section of the temperature ( which is the depth-latitude plot of temperature from Chlorophyll driven ocean model MA94 minus that from non-chlorophyll ocean model PS77) along the latitude of 30N in October. It is noted that the mixed layer temperature rises more than 0.3 K at about 50m near 69E, while subsurface temperature becomes lower by 0.5 K.

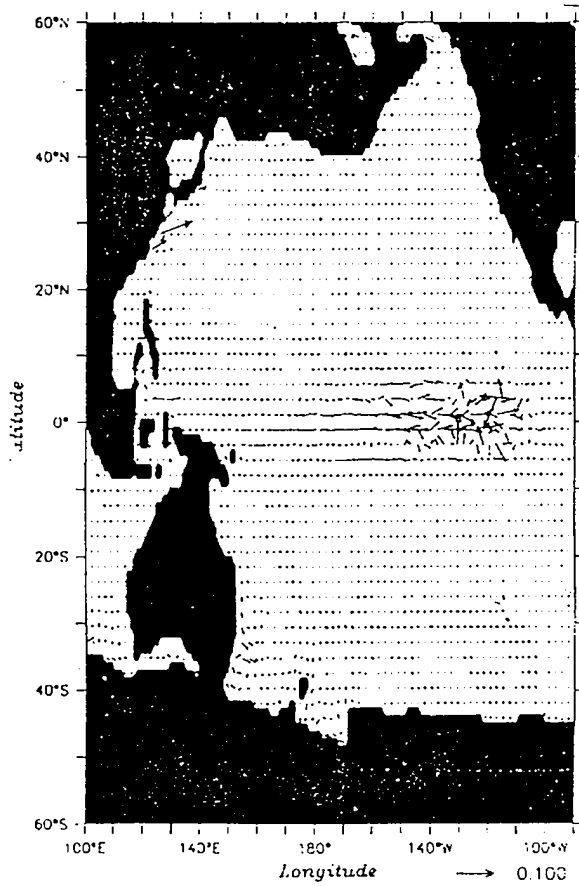


Figure 2. The anomalous westward geostrophic currents north and south of the equator. In the western equatorial, these anomalous geostrophic currents merge into and strengthen the equatorial undercurrents (EUC), supplying water mass from the 200m depth in the west to the eastern surface equatorial Pacific ocean.