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New production in the warm waters of the tropical Pacific Ocean

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Abstract. The average depth-integrated rate of new production in the tropical Pacific Ocean was estimated from a calculation of horizontal and vertical nitrate balance over the region enclosed by the climatological 26°C isotherm. The net turbulent flux of nitrate into the region was computed in terms of the climatological net surface heat flux and the nitrate-temperature relationship at the base of the 26°C isotherm. The net advective transport of nitrate into the region was estimated using the mean nitrate distribution obtained from the analysis of historical data and previous results of a general circulation model of the tropical Pacific. The rate of new production resulting from vertical turbulent fluxes of nitrate was found to be similar in magnitude to that due to advective transport. Most (about 75%) of the advective input of nitrate was due to the horizontal transport of nutrient-rich water from the eastern equatorial region rather than from equatorial upwelling. An average rate of new production of 14.5-16 g C m^{-2} yr^{-1} was found for the warm waters of the tropical Pacific region. These values are in good agreement with previous estimates for this region and are almost five times less than is estimated for the eastern equatorial Pacific, where most of the nutrient upwelling occurs.

1. Introduction

The equatorial Pacific region is among the most productive oceanic regimes [*Betzer et al.*, 1984; *Chavez and Barber*, 1987] and, because of the upwelling of deep nutrient-rich water to the euphotic zone throughout the year, may contribute a significant fraction of the global new production. In the eastern and central equatorial Pacific, the effect of upwelling is evident as a tongue of cold nutrient-rich surface water [*Wyrtki*, 1981]. In contrast, the thermocline and nutricline are deeper in the western equatorial Pacific than in the eastern and central regions [*Craig et al.*, 1982], so upwelling brings mostly warm, nutrient-poor water from above the thermocline (nutricline) into the upper surface layer. It has been estimated [*Chavez and Barber*, 1987] that the nitrate upwelled eastward of the dateline in the equatorial Pacific could support a high proportion (18-56%) of the global new production. However, this represents an upper bound estimate for that region, since only a fraction of the nitrate upwelled is used by phytoplankton locally. In fact, a significant amount of the nitrate is transported away from the region [*Carr*, 1991; *Fiedler et al.*, 1991]. In contrast to what is known about the eastern equatorial Pacific, little is known about the contribution to global new production by the warm pools of the western equatorial Pacific. Since in this region nitrate upwelling is less intense, turbulent vertical transport of nitrate should be a relatively more important physical input.

New production is defined as the production of phytoplankton resulting from nitrogen supplied from outside the euphotic zone [*Dugdale and Goering*, 1967], whereas regenerated production is that production associated with nitrogen regenerated within the euphotic zone. In the open ocean, the main external source of nutrients to the euphotic zone is the upwelling and turbulent transport of nutrients from deep water. New production can be measured by a number of methods such as sediment traps at the bottom of the euphotic zone, the uptake of ^{15}N-labeled nitrate, and the net flux of nitrate into the euphotic zone. New production also gives a measure of the primary production which can be removed from the surface layer of the ocean without destroying the long-term integrity of the pelagic ecosystem [*Eppley and Peterson*, 1979; *Platt et al.*, 1989]. As such, rates of new production, when averaged over timescales longer than a year, represent the biologically mediated transport of carbon from the ocean surface layer to the ocean interior. This is not net transport, however. Several studies have shown considerable spatial and temporal variability in the rates of new production even in open ocean regions. Therefore the way measurements are averaged has a profound effect on the results [*Platt and Harrison*, 1985].

The abilities to evaluate the importance of the tropical Pacific region to global new production and to pre-

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dict anomalous conditions have been constrained by a lack of synoptic observations in this large and remote area of the ocean. Attempts have been made to estimate new production in coastal upwelling [*Dugdale et al.*, 1989] and frontal regions [*Sathyendranath et al.*, 1991] from satellite observations of sea surface temperature, the observed correlation between nitrate concentration and temperature, and empirical relationships between nitrate concentration and new production. In the North Atlantic, a lower limit to new production has been estimated from changes in phytoplankton biomass determined from the coastal zone color scanner data and variations in the depth of the nutricline [*Campbell and Aarup*, 1992]. In oceanic regions, as in the western tropical Pacific, where surface nitrate concentrations are generally undetectable by conventional techniques and where seasonal variations in phytoplankton biomass are small [*Dandonneau*, 1992], the aforementioned methods for estimating new production are not applicable.

Here, we combine the new production model presented by *Lewis* [1992] with results from a general circulation model of the tropical Pacific [*Philander et al.*, 1987] and historical temperature and nitrate data to estimate the annual mean rate of new production in the warm waters of the tropical Pacific region. The analysis is constrained by the horizontal and vertical nitrate balance and employs the surface heat flux, a quantity amenable to remote sensing [*Liu*, 1988; *Liu and Gautier*, 1990], to estimate nitrate fluxes. While other estimations of new production based on nitrate balance [*Chavez and Barber*, 1987; *Fiedler et al.*, 1991] in this region consider only the input of nitrate due to upwelling, we evaluate the transport of nitrate due to turbulent fluxes, which are difficult to estimate at large scales as well.

2. Approach

In the tropics, large warm pools of near-surface water are enclosed at the margins by continental land masses and at the surface and depth by constant annual mean temperature isopleths [*Niiler and Stevenson*, 1982]. In a steady state ocean, heat is conserved and new production is balanced by the net input of essential nutrients into the euphotic zone. To estimate the annual mean new production over the warm waters (temperature, >26°C) of the tropical Pacific Ocean, we base our arguments on the close relationship between the fluxes of heat and nutrients in this region.

2.1 Fluxes of Heat

In the upper layer of the ocean, the heat and mass conservation equation may be written as

$$c_p \rho (\nabla \cdot \overline{UT} + \nabla \cdot \overline{U'T'}) = \nabla \cdot E \qquad (1)$$

$$\nabla \cdot \overline{U} = 0 \qquad (2)$$

where T is temperature (Celsius), U is the velocity (meters per second), c_p is the specific heat of seawater (J kg^{-1} °C^{-1}), ρ is the water density (kilograms per cubic meter), and E is the irradiance vector (J m^{-2} s^{-1}). Overbars indicate mean values, and primes indicate departures from mean conditions.

A simple model of the heat flux in the warm-water pool of tropical regions has been obtained by *Niiler and Stevenson* [1982] by integrating (1) and (2) over a fixed volume of water which is bounded by a three-dimensional surface of a constant annual mean temperature (A_T) at depth, the ocean sea surface (A_S), and the insulating continental land masses. By virtue of the constant-temperature boundary condition, the advective term vanishes, because water that enters the volume is on average of the same temperature as water which leaves it, and hence there is no net flux of heat by mean advection. Therefore the steady state solution is a balance between the net surface heat flux into the volume and the turbulent heat transport out of the volume. The turbulent transport that removes heat from the pool can be caused by a variety of processes operating on different time and space scales from seasonal to microstructure. For instance, this includes eddy heat flux due to time-dependent ocean motions on scales of tens to hundreds of kilometers and turbulent diffusion operating on scales of a few meters to a few millimeters. In the tropical Pacific warm-water pool, *Niiler and Stevenson* [1982] found that most of the heat transport is due to vertical turbulent transport, since horizontal turbulent fluxes are relatively very small. Therefore

$$\int\!\!\int_{A_S} Q_0 \, dA = c_p \rho \int\!\!\int_{A_T} \overline{W'T'} \, ds \qquad (3)$$

where Q$_0$ is the net surface heat flux (watts per squared meter), which is integrated over the surface area A_S; $\overline{W'T'}$ is the mean annual vertical turbulent flux of heat, which is integrated over the subsurface isotherm of area A_T, and dA and ds refer to the surface and subsurface elements, respectively. Equation (3) states that the net surface heat flux into a volume of ocean which is bounded by coast and at depth by a constant mean annual temperature surface is transported out of the volume by turbulent vertical mixing only. A term to account for the penetrating irradiance through the subsurface [*Lewis et al.*, 1990] is small, given the depth of the chosen isotherm (26°C).

2.2 Fluxes of Nitrate

Similarly, if the mean concentration of nitrate in the upper layer of the ocean is constant, the net physical input of nitrate into this layer must be equivalent to the nitrate consumption, which basically represents new production. Then, the nitrate conservation equation in the upper layer of the ocean is

$$\nabla \cdot \overline{UN} + \nabla \cdot \overline{U'N'} = P_n \qquad (4)$$

where N is the nitrate concentration (mmol N m^{-3}), and P_n is the local new production rate (mmol N m^{-3} s^{-1}). We can proceed by integrating (4) and (2) over the same surface (A_S) and subsurface (A_T) boundaries as above. In this case, since the nitrate concentration is not constant along the isothermal subsurface boundary A_T, a net advective input of nitrate can occur if water entering the volume has on average a higher concentration of nitrate than water leaving the volume. Therefore new production over the whole volume enclosed by the surface (A_S) and subsurface (A_T) boundaries and the continental landmasses is equivalent to the net advective and turbulent input of nitrate,

$$\int\int_{A_S} P_N\,dA = \int\int_{A_T} \overline{UN}\,ds + \int\int_{A_T} \overline{U'N'}\,ds \quad (5)$$

where P_N $(=\int_0^{z_T} P_n\,dz$, where z_T is the depth of the subsurface isothermal boundary) represents the depth-integrated new production (mmol N m^{-2} s^{-1}), and $\overline{UN}$ and $\overline{U'N'}$ are the annual mean net fluxes of nitrate due to advective and turbulent transports, respectively.

2.3 Nitrate-Temperature Relationship

In the ocean, temperature and nitrate are well correlated [e.g., *Kamykowski and Zentara*, 1986]. We can exploit this empirical observation to combine (3) and (5), neglecting for now-horizontal turbulent fluxes of nitrate, and the spatial covariance between heat flux across the isothermal boundary and the slope of the nitrate-temperature relationship in the region to yield

$$\iint_{A_S} P_N\,dA = \iint_{A_T} \overline{UN}\,ds + \frac{\overline{dN}}{dT}\frac{1}{c_p\,\rho}\iint_{A_S} Q_0\,dA \quad (6)$$

Here, the annual mean rate of new production is due to advection plus the turbulent input of nitrate expressed as the product of the net surface heat flux and the average slope of the nitrate-temperature relationship at the base of the subsurface boundary A_T. Note that as before, the turbulent transport refers to a variety of space and time scales of motions (seasonal to microstructure) and thus is not equivalent to the vertical turbulent diffusion of nitrate alone. The net surface heat flux can be evaluated from climatology or from satellite observations; the nitrate-temperature relationship can be taken from historical data. Similarly, the advective transport of nitrate can be obtained from the mean water transport normal to the subsurface boundary A_T and the annual mean nitrate concentration along this boundary.

3. Data

Approximately 4870 vertical profiles with simultaneous observations of nitrate concentration and temperature from the tropical Pacific between 20°N and 20°S of latitude and 120°E and 80°W of longitude have been used in this analysis (Figure 1). This data set was obtained from three sources: (1) the National Oceanographic Data Center (NODC), (2) the ocean atlas [*Osborne et al.*, 1992], and (3) work by Fiedler and colleagues in the eastern equatorial Pacific between August and December 1986 to 1988 [*Fiedler et al.*, 1991; P.C. Fiedler, personal communication, 1993]. These data were reformatted, checked for gross errors, and merged. Duplicate data, detected by having identical date, location, depth, temperature, and nitrate concentration, were eliminated. Most of the stations (about 80%) were obtained from the NODC data set. The NODC data used here were collected mainly between 1967 and 1972 (Figure 2). We have excluded data collected before 1952 to increase the probability that similar analytical methods were used in the determination of nitrate concentration. Data were available for all months of the year.

On the basis of the distribution of temperature and nitrate concentration, the 26°C isotherm was chosen as the subsurface boundary A_T because it encloses most of the tropical Pacific region and because nitrate is generally detectable along the bottom of it. About 3300 stations were located inside the region enclosed at the surface by the climatological 26°C isotherm. At each of these stations the depth of the 26°C isotherm and the nitrate concentration at that depth were determined. In the region between 5° and 12°S latitude and 125° and 140°E longitude, a few stations had surface temperatures cooler than 26°C, and they were excluded from the analysis. Standard deviation statistics for the observed temperature, isotherm depth, and nitrate data were calculated for 5° by 5° squares of latitude and longitude. Since discrete vertical profiles were used in this analysis, the slope of the nitrate-temperature relationship at the base of the 26°C isotherm was operationally defined as that obtained using temperatures between 20° and 27°C. Given the vertical resolution of the data set, it was not possible to use a narrower range of temperature. To estimate the mean slope of the region, the surface area enclosed by the 26°C isotherm was divided into 178 boxes of 5° of latitude and longitude. In each of them, the slope was obtained from a linear regression of temperature (independent variable) versus nitrate concentration of the pooled data. Only those 5° squares containing three or more observations were used in the analysis. The average slope for the entire region and its 95% confidence intervals were calculated from the slope values of all the boxes for which data were available (164 boxes). Second- and third-order polynomial regressions between nitrate and temperature were tested and rejected on the basis of a small increment in the correlation coefficient over the linear model.

The advective transport of nitrate into and out of the volume of water which is warmer than 26°C was calculated as the product of the mean nitrate concentration at the subsurface boundary and the mean water transport normal to the boundary. To estimate horizontal nitrate transport at the lateral boundaries, we consider that the warm-water region was bounded on the side by an isothermal well-mixed layer of 50-m depth. The concentration of nitrate at the 26°C boundary was obtained from the contoured map of nitrate which was based on the pooled data. The mean water transport across the part of the boundary where nitrate was detectable was calculated by spatial integration of the mean circulation values reported by *Philander et al.* [1987] using the trapezoidal rule. They obtained these values from the

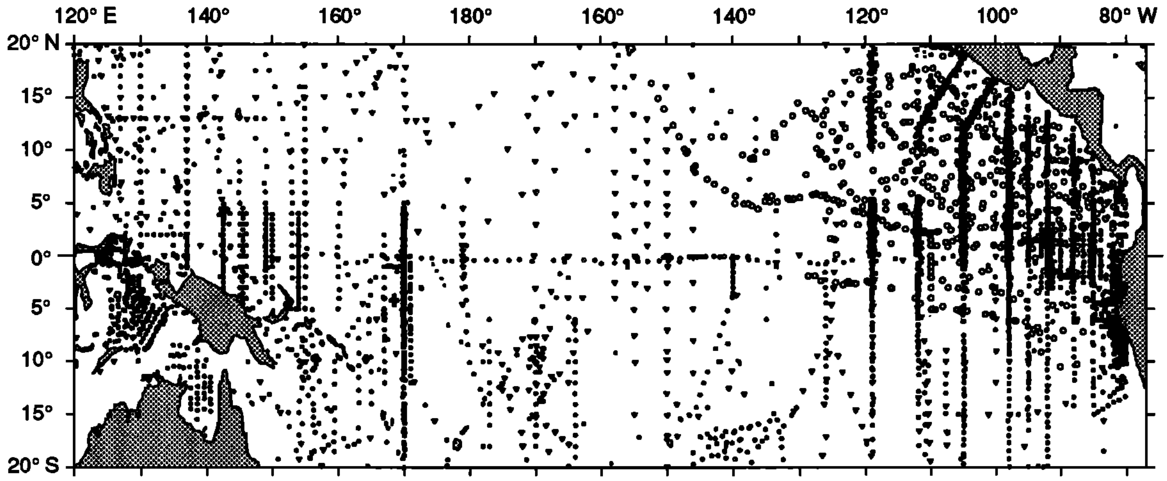

Figure 1. Locations of the stations used in this analysis. Solid circles, National Oceanographic Data Center (NODC; 3845 stations); triangles, ocean atlas (454 stations); open circles, Fiedler and colleagues (574 stations).

third year of simulation of a general circulation model of the tropical Pacific which was forced with monthly averaged climatological winds. The surface area enclosed by the 26°C isotherm and the mean annual net surface heat flux integrated over this area were calculated using three different climatological data sets: Weare climatology, which has a 5° by 5° latitude-longitude grid [*Weare et al.*, 1981]; Esbensen and Kushnir climatology on a 4° latitude by 5° longitude grid [*Esbensen and Kushnir*, 1981]; and Oberhuber climatology on a 2° by 2° latitude-longitude grid [*Oberhuber*, 1988].

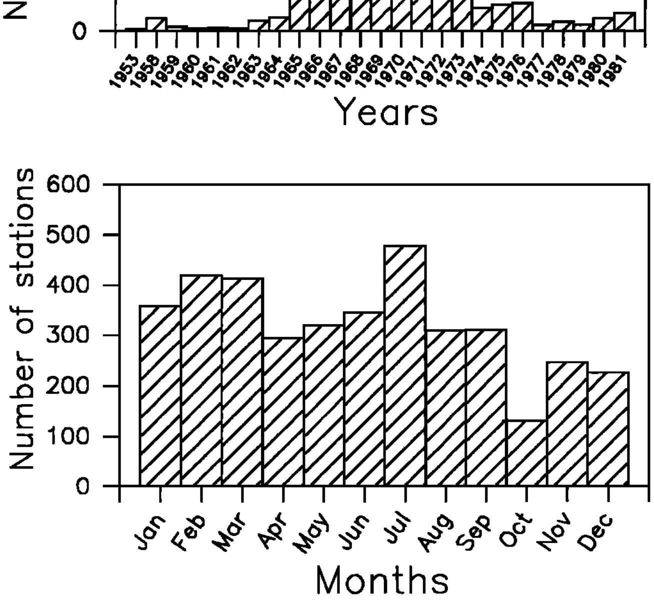

Figure 2. Yearly and monthly distribution of the NODC data.

4. Results

4.1 Temperature and Nitrate Distribution

A contour plot of all the sea surface temperature data in the tropical Pacific (Plate 1a) reproduces the main features present in the annual mean climatologies. In the eastern equatorial Pacific, surface temperatures were relatively cool and the gradients were large, indicating upwelling at the equatorial divergence as well as advection from the Peru upwelling region. Farther west, a large pool of water of more than 28°C was found between 10°N and 15°S. The standard deviations of surface temperature (Plate 1b) showed higher values near the coast. A distribution similar to that of temperature was found for the surface nitrate concentrations (Plate 2a), where the highest nitrate concentrations were associated with the coldest surface waters. However, the nitrate-enriched zone was almost symmetrical about the equator, whereas the cold-water tongue was less sharply defined to the south. Along the equator, surface nitrate concentrations were >4 μM eastward of 160°W. Waters with >1 μM nitrate extended to about 170°E longitudinally and beyond 5°N and 5°S latitudinally. Outside this region, nitrate concentration was generally low (<0.5 μM) or undetectable. The standard deviations of nitrate concentration (Plate 2b) were higher in the eastern side between the equator and 10°S than elsewhere.

In the tropical Pacific, water warmer than 26°C was found beyond 20°N and 20°S westward of 150°W and between 3° and 15°N toward the east, coinciding with the North Equatorial Countercurrent. In this region, nitrate was detectable only in the southeastern boundary. Vertically, the 26°C isotherm subsurface boundary was located mainly at depths of 80 to 120 m (Figure 3a)

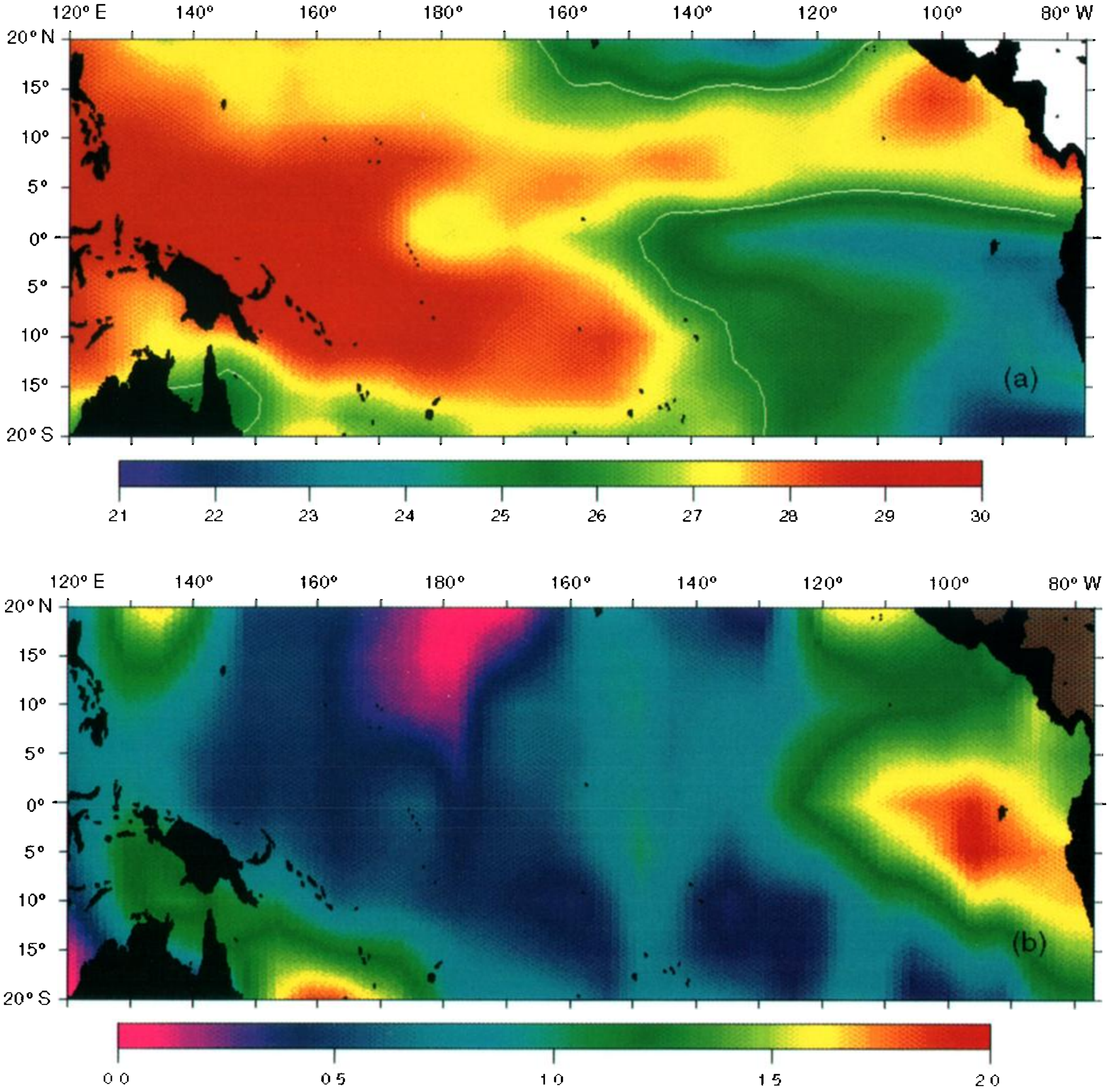

Plate 1. (a) Surface distribution of temperature (degrees Celsius) in the tropical Pacific region and (b) its 5°-square standard deviation. The location of the 26°C isotherm is shown by a white line.

in the western tropical Pacific. Toward the east and away from the equator, the depth of the 26°C isotherm shoaled. The concentration of nitrate at the 26°C isotherm (Figure 4a) was not constant but followed a pattern similar to that of the isotherm depth. Higher nitrate concentrations (>5 μM) were found near the equator, where the isotherm was deeper. Beyond 15°N and 15°S, nitrate concentrations were usually undetectable in waters of 26°C. This distribution agrees with previous observations along the west coast of North and South America [*Zentara and Kamykowski*, 1977], where it has been found that a given nutrient concentration occurs at colder temperatures as latitude increases. North of the equator, between 145° and 150°E, a marked gradient of nitrate concentrations was found that was not reflected in the depth of the isotherm. An examination of the data available for this region showed that the nutricline was sometimes shallower than the 26°C isotherm. The variabilities in the depth (Figure 3b) and in the nitrate concentration (Figure 4b) at the 26°C isotherm were higher on the eastern and western sides than centrally.

4.2 Nitrate-Temperature Relationship

A scatter diagram of temperature versus nitrate concentration in the upper 250 m of the surface area en-

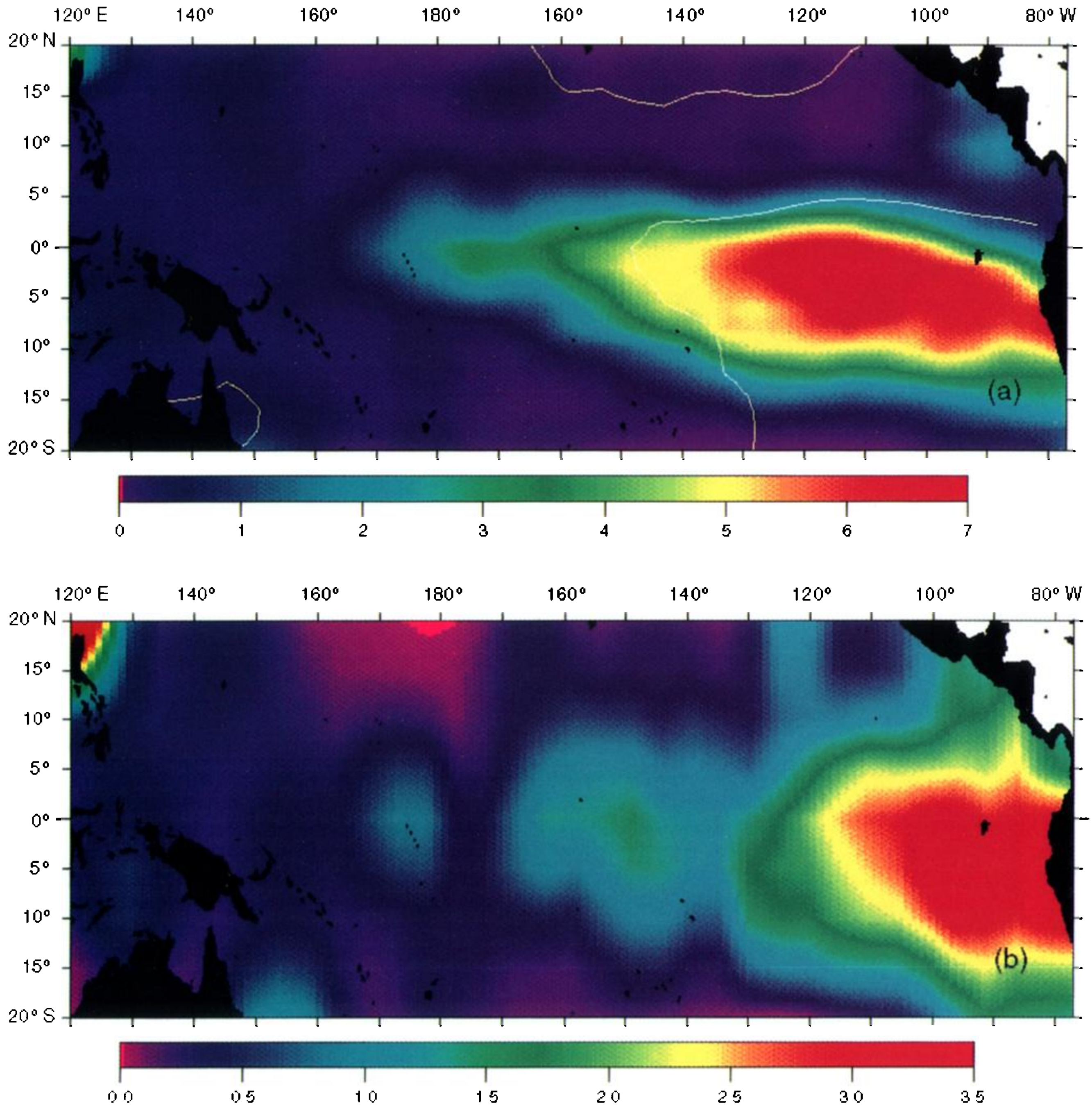

Plate 2. (a) Surface distribution of nitrate concentration (micromolar) in the tropical Pacific region and (b) its 5°-square standard deviation. The location of the 26°C isotherm is shown by a white line.

closed by the 26°C boundary is shown in Figure 5. Three different regions can be distinguished in this plot: (1) a region where temperature is low (generally <15°C) but nitrate concentration has a high range (15-36 μM) of values, (2) an intermediate zone where the gradient of temperature is high (15-26°C) and changes in temperature and nitrate are well correlated, and (3) a warm (>26°C) upper layer where nitrate concentration is undetectable or, when it is present, the slope of the temperature-nitrate relationship is lower than that of the intermediate region. When only surface data were considered (Figure 5 inset), temperature and nitrate were poorly correlated, indicating that surface temperature is not a good predictor of surface nitrate concentration in this region. Studies of the relationship between temperature and nitrate concentration in the upper layer of the ocean [*Kamykowski*, 1987; *Minas and Minas*, 1992] have shown that seasonal and spatial variations in the slope are related to the rate of nitrate uptake by phytoplankton. Below this upper layer, the value depends on the balance between bacterial denitrification and nitrate regeneration from decomposing organic matter as well as on physical transport processes [*Zentara and Kamykowski*, 1977].

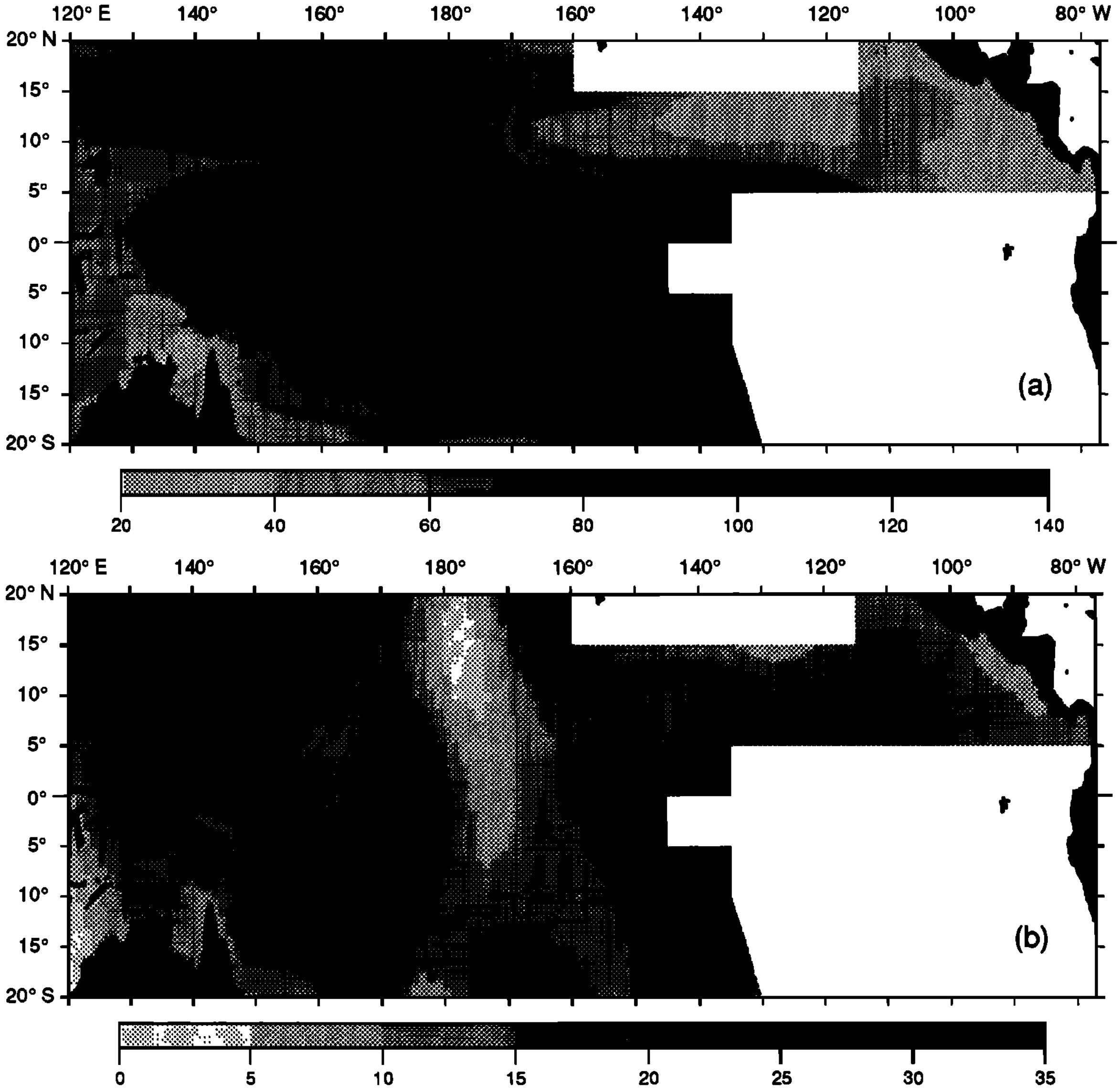

Figure 3. (a) The depth of the 26°C isotherm subsurface boundary (meters) and (b) its 5°-square standard deviation.

The slope of the nitrate-temperature relationship at the base of the 26°C isotherm (Figure 6a) showed longitudinal as well as latitudinal variations. Along the tropical Pacific, the slopes in the eastern sector (<-1.4 μM °C^{-1}) were steeper than those in the western sector (>-0.8 μM °C^{-1}). Latitudinally, the values were less variable, with the least steep slopes occurring in the western side poleward of 10°N and 15°S where the nutricline was deeper than the 26°C boundary. The variability in the slope (Figure 6b) was higher near the equator between 160° and 180°W than elsewhere. These differences in slopes imply that a higher turbulent exchange of nitrate occurs in the eastern side, where the slopes are steeper, than in the western side for an equivalent turbulent flux of heat. Previous studies in this region have found slopes of -1.12 and -2.04 μM °C^{-1} between 180° to 93°W and 1.1°S and 1.1°N [*Halpern and Feldman,* 1993] and eastward of 130°W between 5°S and 20°N [*Fiedler et al.,* 1991], respectively, which are consistent with the values estimated here. The average slope of the nitrate-temperature relationship was -0.89 μM °C^{-1} (95% confidence intervals, -1.00 to -0.78 μM °C^{-1}) in the region enclosed by the 26°C isotherm.

4.3 Nitrate Fluxes

The total surface area enclosed by the climatological 26°C isotherm and continental land masses and the annual mean net surface heat flux into this region are shown in Table 1. Slight variations were obtained in the total surface area between the data sets, mostly because of differences in the northern location of the 26°C isotherm. The net surface heat flux into the region obtained from climatologies ranged between 8.3×10^{14} and 11×10^{14} W. Using the mean slope for the region given above, the new production resulting from turbulent input of nitrate into the Pacific warm water pool ranges from 5.47×10^{12} to 7.26×10^{12} mol N yr^{-1} or an average of 0.25-0.31 mmol N m^{-2} d^{-1} over the entire area.

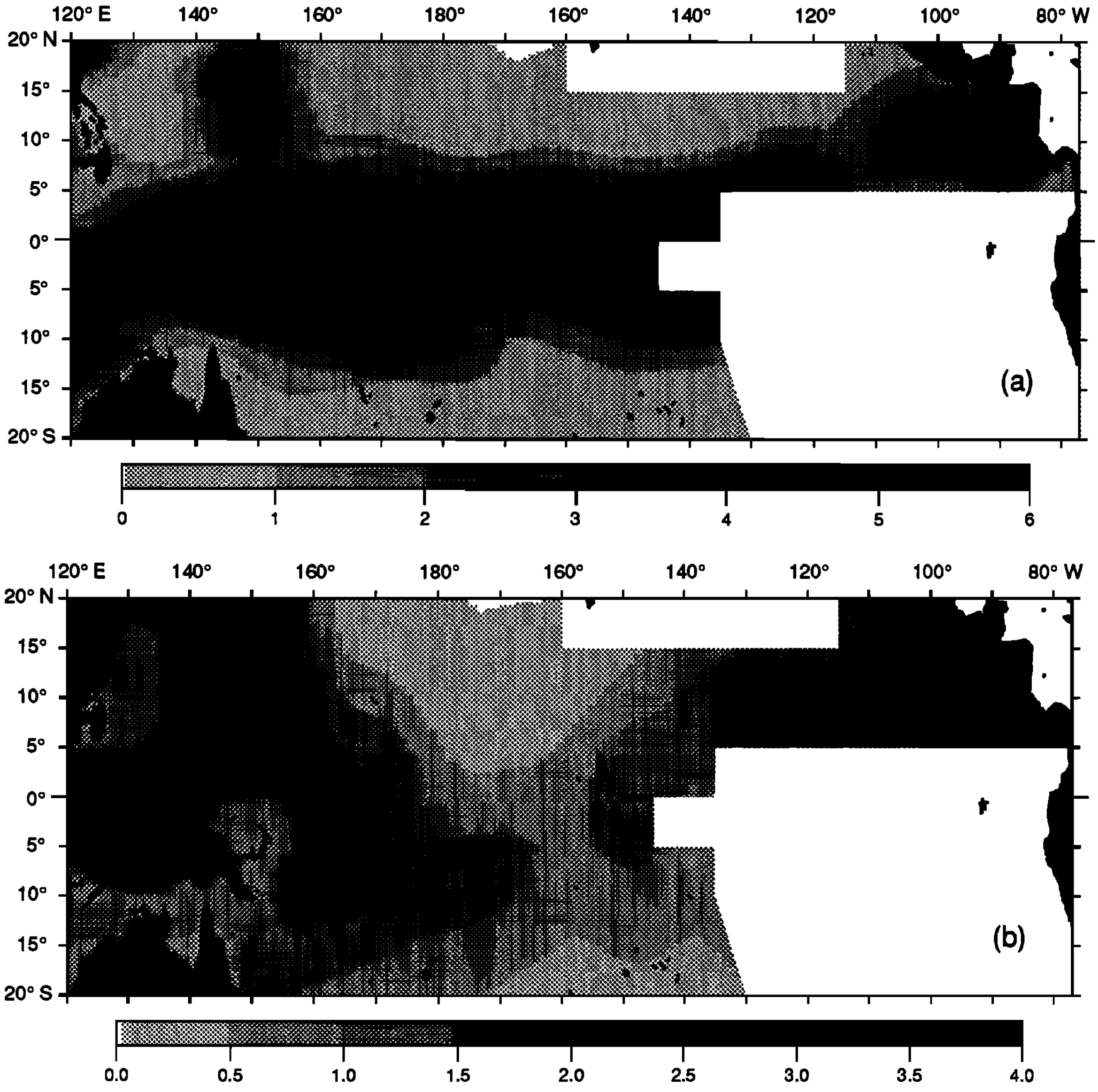

Figure 4. (a) Nitrate concentration (micromolar) at the depth of the 26°C isotherm and (b) its 5°-square standard deviation.

For comparison, this can be expressed in stoichiometrically equivalent carbon units using a Redfield ratio of 6.6; the new production rate is then 4.37 x 10^{14} to 5.74 x 10^{14} g C yr^{-1} or 19.9-24.9 mg C m^{-2} d^{-1}.

The net advective input of nitrate into the region enclosed by the 26°C isotherm (Table 2) is due to upwelling (26%) as well as horizontal transport (74%) of nitrate into the region. At the 26°C surface, most (>60%) of the horizontal advection of nitrate occurs meridionally from the south eastward of 110°W rather than zonally from the east between 2.5°N and 10°S. According to the data available, the variability in the concentration of nitrate at the boundary is small (about ±1 μM). Most of the vertical transport of nitrate is due to upwelling within 1° of the equator, whereas downwelling occurs north of the equator and represents <30% of the nitrate upwelled. Along the equator, the model of *Philander et al.* [1987] indicated maximum upwelling near 150° to 180°W with diminished upwelling eastward and westward of this region. In the vertical, their model shows that upwelling is constrained to the upper 100 m. The longitudinal pattern in upwelling velocities has been supported by other studies in this region [*Halpern et al.*, 1989; *Halpern and Freitag*, 1987]. Also, calculations of upwelling as a function of depth based on direct observations of divergence [*Halpern and Freitag*, 1987] and on a model of equatorial circulation [*Bryden and Brady*, 1985] show that vertical velocities fall sharply above 50 m and below 100 m. Although vertical nitrate input is constrained to within a degree of the equator [*Halpern and Freitag*, 1987], divergence of upwelled water produces a nutrient-rich area larger in meridional and zonal extent than the zone of upwelling.

5. Discussion

We have estimated the mean annual rate of new production in the warm water of the tropical Pacific from a consideration of the large-scale nutrient balance based on the net surface heat flux, mean ocean circu-

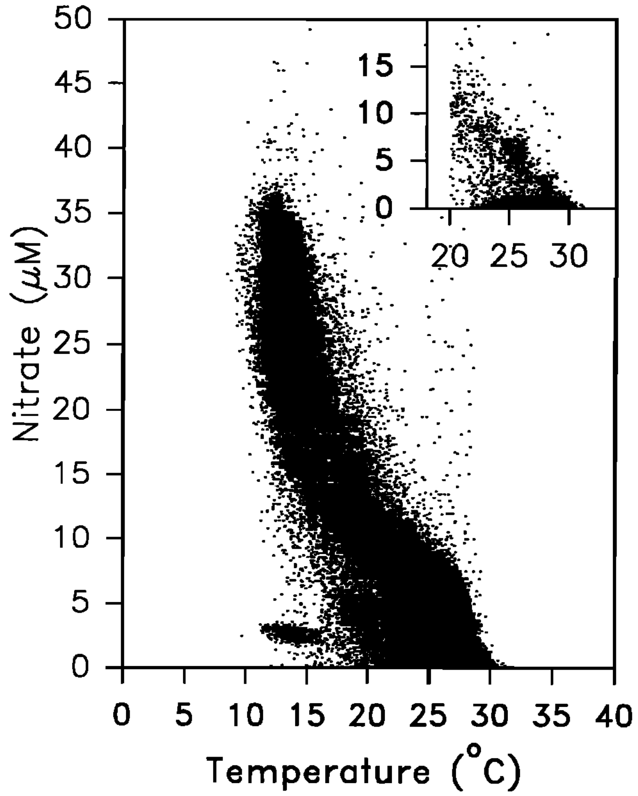

Figure 5. Scatter plot of temperature (degrees Celsius) versus nitrate concentration (micromolar) in the upper 250 m of the region enclosed by the 26°C isotherm (n=48,100). The same relationship is shown for the surface values in the insert (n=4,870).

lation, and nitrate and temperature correlation. Previously, new production has been inferred from nitrate-temperature correlation and experimental relationships between nitrate concentration and the uptake of nitrate [*Dugdale et al.*, 1989] or the f ratio, i.e., the ratio of new production to total production [*Sathyendranath et al.*, 1991]. The approach used in this study is potentially more robust than previous approaches because it does not require estimates of total production and it is independent of the relationship between f ratio and nitrate concentration, which have large uncertainties. However, our parameterization of new production provides only a large-scale average and cannot provide detail on spatial or temporal variability in the rate of new production. Also, it does not allow a direct comparison to estimates of new production based on nitrate uptake (^{15}N experiments) [*Dugdale et al.*, 1992; *Peña et al.*, 1992], which, though more sensitive, are discrete and restricted to short timescales.

5.1 Potential Sources of Error

Model assumptions. In this study, new production has been defined as the production resulting from the net physical transport of nitrate into the volume bordered by the 26°C isotherm. This operational definition neglects other inputs of nitrogen to the region such as inputs from rain and from biological nitrogen fixation. In most of the ocean, fluxes of nitrate from below the nutricline are much more important than those from other sources [e.g., *Eppley and Peterson*, 1979]. In some locations, however, nitrogen fixation [*Capone and Carpenter*, 1982; *Carpenter and Romans*, 1991] can be significant. Although we are not aware of nitrogen fixation measurements in the tropical Pacific, this input is likely to be small, since this process requires iron [*Morel et al.*, 1991], an element scarce in this region [*Martin et al.*, 1991]. Another consideration in the definition is that we assume that depth-integrated new production over the depth of the 26°C isotherm is equal to that of the euphotic zone. In the eastern tropical Pacific, the depth of the euphotic zone is around 60 to 70 m [*Peña et al.*, 1990; *Fiedler et al.*, 1991], which is close to that of the 26°C isotherm (Figure 3a). In the western equatorial Pacific, the euphotic zone depth as estimated from the average surface chlorophyll concentration within 10° latitude of the equator (0.11 mg m^{-3} [*Dandonneau*, 1992]) and from *Morel's* [1988] model is about 95 m which is almost 25 m shallower than the 26°C isotherm depth. However, several studies [*Murray et al.*, 1989; *Barber and Chavez*, 1991] of the tropical Pacific have shown phytoplankton production at the 0.1% light level, which is several meters below the euphotic zone, arbitrarily defined as the depth at which light is reduced to 1% of surface irradiance. Therefore our assumption regarding enclosure of the most significant productive layer is satisfied for the entire area considered.

To estimate turbulent fluxes of nitrate into the region, we have assumed that there is no significant spatial covariance between the net heat flux across the 26°C isotherm and the slope of the nitrate-temperature relationship. Although there are no data available for estimating its value, the general trend in heat flux differs noticeably from the general trends in the slope of the temperature-nitrate relationship. Using the climatological net surface heat flux data of *Weare et al.* [1981] as a rough indicator of what occurs to the subsurface heat flux and our slope of the nitrate temperature relationship, we found no significant covariance (r^2=-0.16) between these variables. On an annual scale, net surface heat fluxes in the tropical Pacific show mostly latitudinal variations, being higher near the equator and decreasing away from it [*Esbensen and Kushnir*, 1981; *Weare et al.*, 1981; *Oberhuber*, 1988]. Similarly, turbulent vertical fluxes are generally three to five times higher within 2° of the equator than they are poleward [*Peters et al.*, 1989]. In comparison, we have found mainly longitudinal variations in the 5°-square slope of the temperature-nitrate relationship, with higher values in the western tropical Pacific, whereas heat fluxes vary latitudinally rather than longitudinally. Also, the slope of the nitrate-temperature relationship within 1° of the equator was not significantly different (p <<0.1) from that poleward.

Finally, we have assumed that horizontal turbulent fluxes of nitrate into the region were small compared to turbulent vertical fluxes. At the 26°C isotherm, the concentration of nitrate in the upper layer was detectable only in the southeastern boundary that surrounded the cold nutrient-rich waters of the eastern

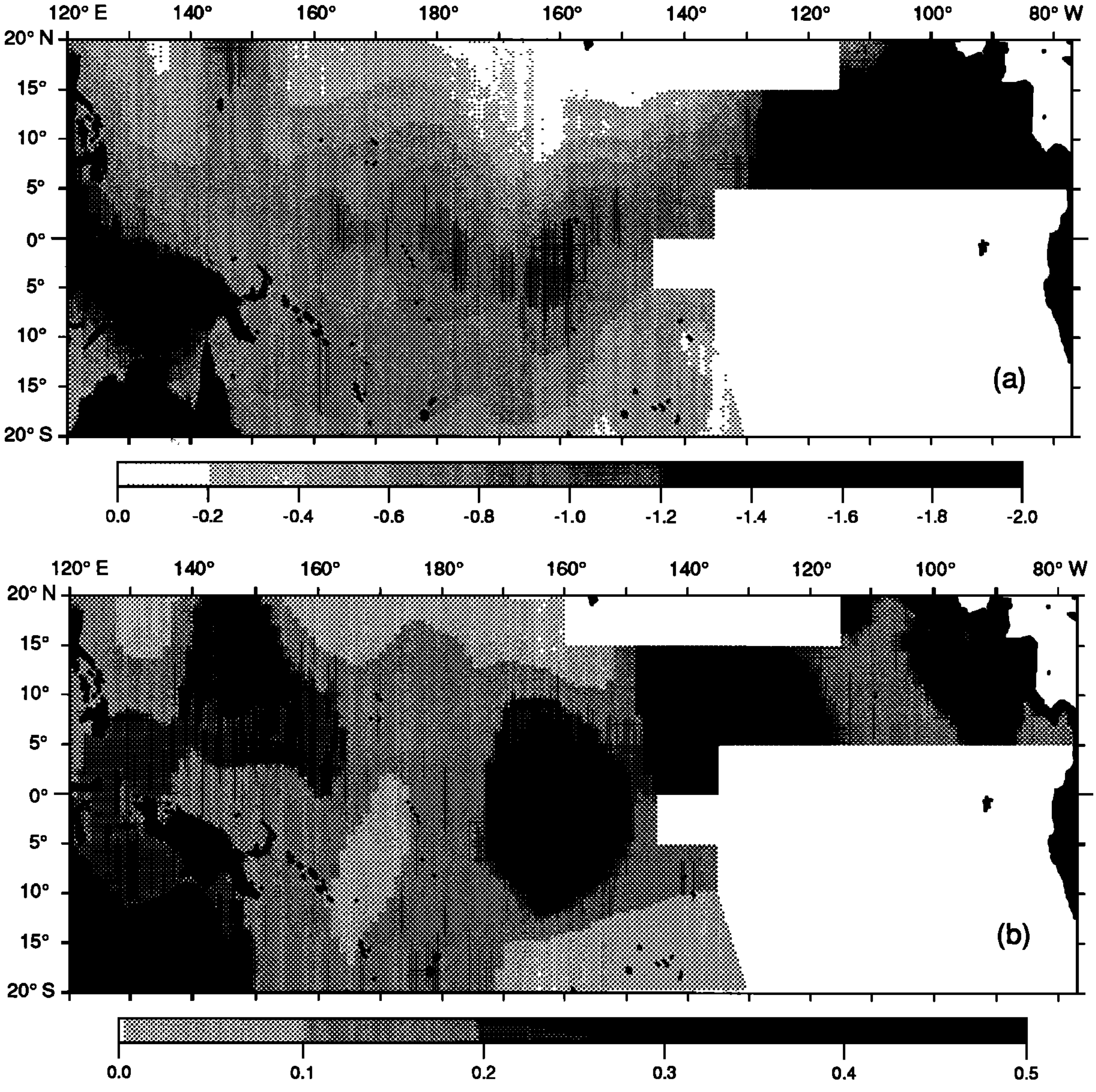

Figure 6. (a) The slope of the temperature-nitrate relationship (micromolar per degree Celsius) at the base of the 26°C isotherm and (b) the standard deviation of the slope at every 5°-square in the region enclosed by the 26°C isotherm.

equatorial Pacific. In this region the maximum horizontal nitrate gradient was 10^{-5} mmol m^{-4}. An upper layer of 50 m and a lateral turbulent exchange coefficient of 10^3 m^2 s^{-1} [*Bryden and Brady*, 1989] will result in the transport of 3.3 x 10^{11} mmol N d^{-1} into the region, which, though it may be significant locally, is 2 orders of magnitude less than the estimated total turbulent vertical transport.

Model parameter estimates. Climatological temperature fields [*Esbensen and Kushnir*, 1981; *Weare et al.*, 1981; *Oberhuber*, 1988] in the tropical Pacific show that water warmer than 26°C reaches near 21°-24°N and 20°-21°S in the western region, whereas our data set coverage is limited to 20° latitude from the equator. This discrepancy can be ignored with little consequence in our analysis, where the horizontal grid boxes are as wide as 5° latitude and longitude. Also, despite the uneven temporal and spatial distributions of the data, they reproduce the main features present in the climatological temperature field.

With the data available, we have obtained a 95% confidence interval of about ±12% in the estimation of the average slope of the nitrate-temperature relationship for the region. In comparison, the individual heat flux components have large uncertainties [*Weare et al.*, 1981], so that the total heat flux has very large error bounds. In the tropical Pacific, the different estimates of net annual heat flux agree within a factor of 2 [*Niiler and Stevenson*, 1982]. Therefore most of the uncertainty in the new production estimate due to turbulent input of nitrate is associated with errors in the magnitude of the net surface heat flux. The error in the estimation of the net advective transport of nitrate associated with changes of 1 *μM* in the nitrate concentration of the source water is about 26% of the net advective transport. Although there are no data available for evaluating the errors in

Table 1. Heat Flux, Nitrate Transport, Surface Area Enclosed by 26°C Isotherm in the Tropical Pacific, and Corresponding New Production

Net Heat Flux, W x 10^{14}	Area, m^2 x 10^{13}	Mean Turbulent Nitrate Transport, mol N yr^{-1} x10^{12}	New Production, mg C m^{-2} d^{-1}*	Source
11.0	6.31	7.26	24.9	*Weare et al.*, 1981
10.7	6.44	7.04	23.7	*Oberhuber*, 1988
8.3	5.98	5.47	19.9	*Esbensen and Kushnir*, 1981

*Determined using Redfield C/N ratio of 6.6 (atom/atom)

the mean water transport, the mean ocean circulation values given by *Philander et al.* [1987] agree well with field observations [*Halpern and Freitag*, 1987] and other model outputs [*Bryden and Brady*, 1985; *Halpern et al.*, 1989]. We conclude that the main quantifiable source of error in our estimation of new production is related to uncertainty in the value of the net surface heat flux used in the calculation.

For the western equatorial Pacific, annual mean surface heat fluxes reported in the literature range from 25 to 100 W m^{-2} [*Esbensen and Kushnir*, 1981; *Reed*, 1985; *Gordon*, 1989]. In this region the ocean circulation is too slow and the temperature gradient is too weak for either advection or mixing to carry any significant heat away from the region [*Niiler and Stevenson*, 1982]. Thus in order to maintain a steady annual mean temperature, the net heat flux through the sea surface must balance the vertical turbulent fluxes of heat. However, because the near-isothermal salt-stratified layer [*Lukas and Lindstrom*, 1991] found in the western equatorial Pacific seems to insulate the deep ocean from the surface layer much of the time [*Godfrey and Lindstrom*, 1989], either the net surface heat fluxes (18-22 W m^{-2}) used by *Niiler and Stevenson* [1982] are too large, or the vertical fluxes of heat occur only episodically, for example, in association with wind bursts. For example, *Godfrey and Lindstrom* [1989] estimate a turbulent vertical heat flux of only 10-16 W m^{-2} in the top 100 m of the western equatorial Pacific from data obtained in calm conditions, which is substantially smaller than that estimated by *Niiler and Stevenson* [1982]. However, Godfrey and Lindstrom suggested that the strong westerly winds that occur intermittently in this region might produce strong mixing events. Field observations in the western Pacific between November 1989 and January 1990 have shown strong vertical shear down to 150 m in response to westerly wind events [*McPhaden et al.*, 1992]. Although the mean wind speeds are weak in the western equatorial Pacific, their variability is large. A climatology of westerly wind bursts in the western Pacific [*Keen*, 1988] shows that this area experiences such wind events more often than regions to the east and that these events are far more frequent in the northern winter season.

Considerable progress has been made in the computation of the most important terms of surface heat fluxes (i.e., surface solar irradiance and latent heat flux) from satellite observations [*Liu and Gautier*, 1990]. Estimations of net surface heat flux in the tropical Pacific derived from metereological reports from merchant ships and fishing vessels have uncertainties related to poor spatial and temporal coverage. Heat flux estimations based on satellite data, which can provide basin-wide coverage for days to years, may considerably improve the estimation of this parameter and thus reduce the error in our new production estimate.

5.2 Comparison With Other New Production Estimates

Measurements to calculate the long-term new production of the tropical Pacific are unavailable and likely to remain so for a considerable time. Thus the only values available for a comparison of new production estimates at these scales is that obtained by *Bacastow and Maier-Reimer* [1990] from a three-dimensional model of the carbon cycle in the ocean. They have estimated a new production rate of 18-20 g C m^{-2} yr^{-1}, which is only slightly higher than the one we have obtained (14.5-16 g C m^{-2} yr^{-1}) for approximately the same region. Given the uncertainties in both our and their estimates and the approximations involved in these parameterizations, the agreement between the two estimates is remarkably good.

In the eastern equatorial Pacific region, a mean integrated annual new production of 1.3 x 10^{15} to 1.9 x 10^{15} g C yr^{-1} (or 320-470 mg C m^{-2} d^{-1}) has been reported within 5° of the equator and between 90° and 180°W [*Chavez and Barber*, 1987]. These values were based on estimation of nitrate upwelling and are approximately 30 to 90% higher than the total integrated new production estimated in this study. The area considered in the present analysis is approximately six times larger than that considered by Chavez and Barber and includes large unproductive areas in the western Pacific not included by them. Several studies [e.g., *Thomas*, 1979] have shown the persistence of unused nitrate in surface waters of the eastern and central equatorial Pacific despite irradiance and stratification conditions favorable to complete nutrient uptake. This persistence results in an important fraction of the nitrate upwelled being transported away from the upwelling zone [*Carr*, 1991; *Fiedler et al.*, 1991]. Because Chavez and Barber did not considered this loss of nitrate, their estimation represents the upper limit of local new production. However, since downwelling of nitrate out of the euphotic zone (which represents a nutrient sink) was small in the

Table 2. Mean Advective Nitrate Balance of Region Enclosed by 26°C Isotherm in the Tropical Pacific and Corresponding Mean New Production

Mechanism	Nitrate Transport, mol N yr^{-1}	New Production, mg C m^{-2} d^{-1}*
Vertical Advection		
Upwelling	2.0×10^{12}	7.0
Downwelling	-5.5×10^{11}	-1.9
Net input	1.5×10^{12}	5.1
Horizontal Advection		
Meridional	2.6×10^{12}	9.1
Zonal	1.6×10^{12}	5.7
Net input	4.2×10^{12}	14.8
Net transport	5.7×10^{12}	19.9

*Determined using Redfield C/N ratio of 6.6 (atom/atom)

region considered in this study, most of the upwelled nitrate is eventually consumed by phytoplankton, but consumption may occur well away from the equator.

A net advective balance of nitrate into the euphotic zone of the eastern tropical Pacific [*Fiedler et al.*, 1991] gave an estimate of new production of 200 mg C m^{-2} d^{-1} eastward of 130°W and within 5° of the equator, which was about 30% of total production. A similar value for new production (196 mg C m^{-2} d^{-1}) was estimated from turbulent and advective fluxes of nitrate within 5° of the equator along a transect at 150°W [*Carr*, 1991]. In this region, turbulent diffusion of nitrate was about 30% of the advective transport of nitrate, and the resulting new production was about 40% of the total production. These values are almost five times higher than our mean new production (44 mg C m^{-2} d^{-1}). Considering a mean total production of 312 mg C m^{-2} d^{-1}, as found between 160°W and 140°E and within 5° of the equator [*Barber and Chavez*, 1991], the new production estimated here is about 14% of the total production. This represents a lower-bound estimate, since we have considered regions away from the equator where total production is likely to be lower.

The productivity of the tropical Pacific region is very strongly affected by interannual events like El Niño–Southern Oscillation (ENSO). Studies of both surface productivity and fluxes to the sediments [*Dymond and Collier*, 1988] suggest that the interannual variability associated with these events far exceeds the seasonal variability. It has been estimated [*Chavez and Barber*, 1985] that the total primary productivity within 5° of the equator and between 82° and 172°W was 2-3 times lower during El Niño than in normal oceanographic conditions. ENSO conditions also suppressed new production at a site close to the equator but enhanced it away from the equator [*Dymond and Collier*, 1988]. An important manifestation of El Niño is the increase in sea surface temperatures above their long-term mean values by as much as 4°C in the central and eastern Pacific. This increase in the heat content of the upper ocean greatly exceeded (about 10 times) the estimated change in the surface heat flux [*Reed*, 1986]. This implies a decrease in the vertical transport of heat through the thermocline and therefore a decrease in the input of nitrate into the surface layer. Model analysis has shown that changes in the tropical Pacific sea surface temperature are associated mostly with anomalous zonal advection of warm water eastward and with variations in the depth of the thermocline [*Wyrtki*, 1975; *Seager*, 1989; *Halpern*, 1987]. As a result of variations in the westerly winds, the thermocline is raised in the west and depressed in the east [*Halpern*, 1987]. Since the thermocline is depressed below the depth of entrainment in the eastern Pacific, the water upwelled toward the surface is warm and depleted of nutrients.

5.3 New Production and the Relationship to Net Air-Sea Exchange of Carbon

Most of the new production in the ocean results from the supply of inorganic nitrogen from below the euphotic zone [e.g., *Eppley and Peterson*, 1979]. If the vertical transport of dissolved inorganic carbon and nitrate is in approximately the Redfield ratio and if the C and nitrate are taken up in the euphotic zone and exported out of it in the same ratio, there would be no net biologically mediated transport of carbon to the deep ocean [*Eppley and Peterson*, 1979]. Unlike nitrate, however, atmospheric CO_2 enters the ocean by sea-air gas exchange and is redistributed through the combined effects of advection, mixing, formation of particulate matter in the surface layer, and subsequent remineralization in deep water. If there were sufficient data available for the tropical Pacific to allow us to determine the inorganic carbon concentration versus temperature relationship at the base of the subsurface boundary, the mean annual vertical flux of inorganic carbon could be estimated using the same computation as that for the turbulent nitrate fluxes. Then the rate of new production could be compared with the rate of carbon fluxes, and the net air-sea exchange of carbon dioxide could be evaluated.

6. Conclusion

Our analysis gives an estimate of new production in the warm waters of the tropical Pacific from a consideration of the large-scale nutrient balance. In this region, the new production resulting from vertical turbulent fluxes of nitrate was of the same magnitude as that due to advective nitrate transport. Most (about 75%) of the advective transport of nitrate was due to horizontal transport (zonal and meridional) from the eastern equatorial Pacific rather than upwelling. Previous estimations of new production from nutrient budgets [*Chavez and Barber*, 1987; *Fiedler et al.*, 1991] in the tropical Pacific region have ignored the input of nitrate due to vertical turbulent transport. The method employed here, which considers the input of nitrate due to turbulent diffusion as well as to advection, yields more representative estimates of the large-scale average new production than those calculated from advection alone. We have estimated the new production resulting from vertical turbulent fluxes of nitrate based on fluxes of heat at the sea surface. This approach can be applied to other regions of the world's oceans. The possibility therefore exists that there is a means to estimate new production from remotely sensed observations which does not require the determination of physiological parameters of nitrate uptake from ship observations that are notoriously variable. Therefore although our estimation of new production is based on several assumptions and is less sensitive than direct estimations, it provides an estimate over oceanographically significant scales of time and space which are inaccessible to ship observations.

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