Meridional asymmetry of source nutrients to the equatorial Pacific upwelling ecosystem and its potential impact on ocean–atmosphere CO$_2$ flux; a data and modeling approach

R.C. Dugdale$^{a,*}$, A.G. Wischmeyer$^{a}$, F.P. Wilkerson$^{a}$, R.T. Barber$^{b}$, F. Chai$^{c}$, M.-S. Jiang$^{c}$, T.-H. Peng$^{d}$

$^{a}$ Romberg Tiburon Center, San Francisco State University, 3152 Paradise Drive, Tiburon, CA 94920, USA
$^{b}$ NSOE Marine Laboratory, Duke University, 135 Duke Marine Lab Road, Beaufort, NC 28516, USA
$^{c}$ School of Marine Science, University of Maine, 5471 Libby Hall, Orono, ME 04469-5741, USA
$^{d}$ NOAA Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry Division, 4301 Rickenbacker Causeway, Miami, FL 33149-1026, USA

Received 15 August 2000; received in revised form 26 March 2001; accepted 17 July 2001

Abstract

Si(OH)$_4$, NO$_3$, and TCO$_2$ are shown to be distributed asymmetrically in a north/south direction about the equatorial Pacific using data from WEPOCS III and JGOFS EqPac cruises. Equatorial SiOH$_4$ concentrations are shown to be the product of both geochemical and physical interactions with chemical processes, occurring in at least three regions remote from the equatorial Pacific, and physical delivery processes from the equatorial undercurrent (EUC) to the surface layer varying over a range of time scales. The EUC was partitioned into upper and lower portions, the upper providing source water to the central upwelling area and the lower crossing the Pacific without upwelling and thought to reenter the surface along the coast of Peru and to the eastern equatorial upwelling area. The source waters from the North Pacific, the north equatorial countercurrent (NECC) and from the South Pacific, the New Guinea coastal undercurrent (NGCUC) also were partitioned according to source for the upper and lower EUC. Mean concentrations and ranges of nutrients for each source partition were obtained from field data. Current flow and advective data output from a 3-D physical model were used with the field nutrient data to calculate nutrient fluxes into the EUC. Although the inflow of water from the north and south were approximately equal, the stronger asymmetric distribution of Si(OH)$_4$ compared to NO$_3$ resulted in identifying the South Pacific source as only 30% of the total supply of Si(OH)$_4$ to the EUC and the cause of a low Si(OH)$_4$:NO$_3$ condition. These results suggest a coupling between Southern Ocean productivity, equatorial productivity, and the efflux of CO$_2$ to the atmosphere from the equatorial upwelling system.

1. Introduction

The role of the tropical Pacific Ocean and the low latitudes as a center for initiation of climate variation has received growing attention. The equatorial Pacific during normal upwelling has surface $p$CO$_2$ values above atmospheric levels and
because of its vast area, is a significant net source of CO₂ to the atmosphere. This elevated pCO₂ is a result of air–sea gas exchange which is too slow to expel excess CO₂ advected vertically with upwelled water (Broecker and Peng, 1982). The reduced upwelling and deepening of the thermocline during El Niño events eliminates or diminishes this source of atmospheric CO₂ to the atmosphere and is a major factor in slowing or eliminating the increase of atmospheric CO₂ during El Niño events (Chavez et al., 1999; Feeley et al., 1997). The normally elevated pCO₂ of the equatorial Pacific upwelling has also been attributed to the inability of the phytoplankton to use sufficient upwelled CO₂ to reduce the surface pCO₂ to atmospheric levels or lower (Barber and Chavez, 1991). Both limitation by macro- and micro-nutrients (e.g., iron, Coale et al., 1996; Gordon et al., 1997; Landry et al., 1997), combined with grazing control (Cullen et al., 1992; Frost and Franzen, 1992), have been invoked to explain the apparent underutilization of upwelled nutrients. However, low silica input to the equatorial upwelling system has been implicated as the primary cause of this low new production of organic carbon (Dugdale and Wilkerson, 1998), since the major phytoplankton generating CO₂ sequestration are the diatoms (Smetacek, 1998) that have an obligate requirement for silicic acid (silicate; Si(OH)₄). They are unique in the phytoplankton in being subject to Si(OH)₄ limitation of their growth. Although diatoms do not dominate the equatorial community in cell number, their contribution to the biomass and fluxes may be significant (Bidigare and Ondrusek, 1996).

Reduced regeneration of detrital silica compared to nitrogen or phosphorus leads to a greater downward vertical flux of Si relative to the non-siliceous nutrients. This silicate pump process (Dugdale et al., 1995) leads to reduced Si(OH)₄:-NO₃ or Si(OH)₄:PO₄ ratios in surface waters of the ocean, and increases the likelihood of Si(OH)₄ limitation of diatom production and so of new production and vertical flux. Ku et al. (1995), using ²²⁸Ra-derived nutrient budgets, suggested “new Si(OH)₄” to limit new production in the equatorial Pacific, which has been recently confirmed using ³²Si by Leynaert et al. (2001). Recently, the biological functioning of the equatorial Pacific upwelling system has been well described by a Si(OH)₄ limited 1-D model (Chai et al., 2002; Dugdale et al., 2002).

An understanding of the role of Si(OH)₄ in the equatorial Pacific upwelling productivity ecosystem and CO₂ fluxes requires a knowledge of the sources and variability of nutrients in this system. In this study, the relative distributions of nutrients and TCO₂ and their sources from the north and south sides of the equator and contributions of the two source regions to the equatorial undercurrent (EUC) at its origin in the western Pacific are described. The distributions of these nutrients are asymmetric about the equator and the nutrient distributions to achieve a fuller understanding of the potential implications of this asymmetry.

2. Data and modeling methods

The following data sets (Table 1) were used to evaluate distributions of nutrients including TCO₂ in the equatorial Pacific: WEC88 (Barber, 1992; Carr et al., 1992), US JGOFS EqPac TT011 (Murray et al., 1995) and WEPOCS III (Lukas et al., 1991).

<table>
<thead>
<tr>
<th>Study/cruise</th>
<th>Location</th>
<th>Date</th>
<th>Source of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>JGOFS EqPac/T011</td>
<td>140°W, 12.5°N–12.5°S</td>
<td>Fall 1992</td>
<td>Murray et al. (1995)</td>
</tr>
</tbody>
</table>
Output of two models, a 1-D equatorial upwelling productivity model and a 3-D physical model were used in conjunction with data, to evaluate nutrient and $\text{TCO}_2$ fluxes. The 1-D model of the equatorial upwelling ecosystem includes the nutrients $\text{Si(OH)}_4$, $\text{NO}_3$, and $\text{NH}_4$, two phytoplankton fractions (picoplankton and diatoms), microzooplankton, and mesozooplankton grazers (Chai et al., 2002). Iron is included implicitly as a modification of the photosynthetic characteristics. The model structure (Chai et al., 2002), sensitivity analyses in which source $\text{Si(OH)}_4$ is varied, and results of model experiments (Dugdale et al., 2002) are described elsewhere in this volume. The 3-D physical model is the NCAR Climate System Model (CSM) ocean component (Gent et al., 1998), which is a modified version of the GFDL Modular Ocean Model (MOM 1.1, Pacanowski et al., 1991). The model configuration for the Pacific Ocean and model performance have been reported in Li et al. (2001). The Pacific Ocean model domain is between $45^\circ$S and $65^\circ$N, $100^\circ$E and $70^\circ$W, with realistic geometry and topography. The longitudinal resolution of the equatorial Pacific is $2^\circ$ everywhere, while the latitudinal is $0.5^\circ$ within $10^\circ$S and $10^\circ$N, tapering off to $2^\circ$ at higher latitudes. There are 40 vertical layers, with 23 levels located in the upper 400 m. The surface forcing can be separated into momentum, heat, fresh-water fluxes, and irradiance for photosynthesis. The momentum fluxes are calculated with the zonal and meridional wind speeds from the comprehensive ocean atmosphere data set (COADS) (da Silva et al., 1994). The annual mean zonal and meridional velocities were obtained from the 3-D model for 1988. Box diagrams also were developed using this output to evaluate annual mean transport for 1988 in a similar way to that described by Toggweiler and Carson (1995).

3. Results

3.1. Meridional distribution of nutrients and $\text{TCO}_2$ at source depths

A careful examination of the available data for the equatorial current system reveals a meridional asymmetry in both nutrient and CO$_2$ concentrations below the euphotic zone. During the WEC88 study at $150^\circ$W made in February 1988, $\text{Si(OH)}_4$ and $\text{NO}_3$ concentrations from 0 to 400 m were greater on the north side of the equator compared to the south (Fig. 1). The distribution of equatorward currents from $15^\circ$S to $15^\circ$N at $150^\circ$W shows meridional flow into the EUC from both north and south at about 50 to 100 m depth (Carr et al., 1992). Asymmetry in the distribution of nutrients also is seen in the JGOFS EqPac fall, 1992 survey cruise, TT011 (Figs. 2a and b) at $140^\circ$W, with higher nutrients to the north. In both the WEC88 and TT011 data, the isopleths slope deeply to the

![Fig. 1. Meridional contours of nutrients at 150°W on the WEC88 cruise. From Carr et al. (1992, their Fig. 5).](image-url)
south compared to the north and upwelling is evident in the near vicinity of the equator at depths above 150 m and downwelling below that depth. Source water concentrations in the range 100–200 m depth are greater to the north of the equator. No $\text{TCO}_2$ data were available for WEC88; however, during TT011 the $\text{TCO}_2$ distribution shows a downward slope of the isopleths to the south (Fig. 2c), with lowest concentrations to the north at depths above 150 m. Below that depth the greatest concentrations are to the north. Asymmetry in nutrients is also apparent in the

![Graphs](image-url)  

Fig. 2. Meridional contours at 140°W on the US JGOFS TT011, fall 1992 survey cruise of (a) $\text{Si(OH)}_4$, (b) $\text{NO}_3$, and (c) $\text{TCO}_2$ (mmol m$^{-3}$).
annual mean distribution of Si(OH)$_4$ at 200 m in the western Pacific (Conkright et al., 1998; Levitus et al., 1993), where a band of high Si(OH)$_4$ can be seen north of the equator (Fig. 3) at the known location of the north equatorial countercurrent (NECC). Asymmetry is also evident in the WEPOCS III section at 143°E for Si(OH)$_4$ (Fig. 4c), with low values of Si(OH)$_4$ to the south and high to the north at depths below 150 m. No upwelling signal is evident, consistent with the known east-west patterns of equatorial upwelling (Wyrtki, 1981; Philander et al., 1987).

These asymmetric distributions with greater nutrient concentrations to the north also are seen in meridional sections of temperature from 0 to 400 m along 155°W (Reverdin, 1995, Fig. 6.4). The meridional isotherms show steep slopes to the south similar to the nutrients and are correlated at the thermocline with the equatorial currents. These asymmetries result from the south equatorial current (SEC) that overrides the equator in the shallow depths and is compensated by flow at depth from the north (Fine et al., 1994), which is one of the sources of the EUC (Tsuchiya et al., 1990).

3.2. Identification of the EUC

The system of currents in the western Pacific, a “watermass crossroads” (Fine et al., 1994), is complex. The major currents are shown in Fig. 5. The equatorial region forms a boundary between the tropical gyres to the north and to the south. The gyre boundaries are not symmetric about the equator. The northern gyre boundary is entirely north of the equator. However, the southern gyre overrides the equator in the surface regions as the SEC, and a compensating southward flow occurs at depth from the northern gyre. The NECC is the boundary between the gyres at the surface. In the thermocline the boundary is north of the equator in the EUC. This sloping boundary gives rise to the asymmetric meridional distribution of properties, including nutrients and the physical processes that result in cross-equatorial transport of southern waters. Since the EUC is the source of upwelled water to the equatorial ecosystem, nutrient conditions in the EUC are important. These nutrient concentrations are the result of initial inputs at its origin, entrainment from the

![Fig. 3. Annual mean Si(OH)$_4$ concentrations at 200 m in the Pacific (mmol m$^{-3}$), higher Si(OH)$_4$ values in green. Taken from http://ingrid.ldgo.columbia.edu/SOURCES/.LEVITUS98/.](http://ingrid.ldgo.columbia.edu/SOURCES/.LEVITUS98/)
north and south by the NECC, and by recirculation in cells to the north and south (Toggweiler and Carson, 1995).

To identify the EUC and its sources, the water mass analyses of the WEPOCS III data by Fine et al. (1994) and Lukas et al. (1991), and an analysis of sources of NO₃ for the equatorial Pacific system by Toggweiler and Carson (1995), are further analyzed to provide insight into the cause and consequences of the meridional asymmetry in nutrient concentrations. Combined with the output of a 3-D physical model, a coherent and general picture of the nutrient environment embedded in the current structure of the equatorial Pacific can be described.

Fig. 4. Meridional section at 143°E, WEPOCS III cruise (a) temperature (°C), (b) salinity, (psu = pss) and (c) Si(OH)₄ (mmol m⁻³).
The temperature, salinity and Si(OH)₄ data from the WEPOCS III cruise are contoured at 143°E, from 3°S to 7°N (Fig. 4). The slope of the isotherms (Fig. 4a) indicates a westward flowing current, the New Guinea coastal undercurrent (NGCUC) from 3°S to 0°N at depths of 200–400 m, and an eastward flowing current from 0°N to 5°N with the steepest isotherms from 0°N to 2°N (the EUC). The salinity section (Fig. 4b) for 0–400 m shows high salinity water, >35 pss to the south and lower salinity, <35 pss to the north, with vertical isohalines in the 0°N to 2°N area coinciding with the strong eastward flow, the EUC. The apparent displacement of the eastward flow slightly north of the equator in the WEPOCS III data is likely due to the path of the NGCUC flowing northward along the New Guinea coast before turning back to feed the EUC. The core of the EUC observed by ADCP data at 143°E along the WOCE WHP-P9 section in July–August 1994 is centered at 1.7°N (Kaneko et al., 1998) rather than on the equator.

When the temperature and salinity are plotted for the WEPOCS III stations from 3°S to 7°N (Fig. 6, annotated with station latitudes), different water masses can be identified. These are: (a) NGCUC, as defined by Fine et al. (1994; their Fig. 2), with maximum salinity of 35.5 pss at a temperature of 20°C that occurs at 3–1°S; (b) the NECC water with reduced salinity, 34.8 pss at 20°C, found at 4–7°N; and (c) water from 0°N to 2.5°N with characteristics between the two end members, NGCUC and NECC that makes up the EUC.

3.3. Characterization of lower and upper EUC

Toggweiler and Carson (1995) separated the EUC into two vertical components, the “lower EUC water, as water with temperatures of 11–14°C, salinities of 34.8–35.0 pss, the documented 13°C water of the EUC (Fig. 6) transporting 10 Sv to the east across 155°E. The temperature versus salinity line end-points for this water fall exactly along the left boundary of the NGCUC (Fig. 6) at latitudes 0–1°N and slightly mixed with NECC water. The source of this water occurs at about 300–350 m in the NGCUC and at about 250–325 m in the 0–2°N region of the eastward flowing EUC (Fig. 4a and b). The upper EUC water, i.e. above the lower EUC (100–250 m depth), has temperatures from 14°C to 25°C and salinities of 34.85–35.35 pss (Figs. 4a, b and 6), in the 0–2°N band. Stations within the 0–2°N band and at these depths are mixtures of NGCUC and NECC (Fig. 6).

3.4. Nutrient sources for the lower and upper EUC

In order to separate out different contributions of nutrient sources to the EUC, the WEPOCS III data set was used to determine the mean and ranges of certain water properties (including nutrients) for the component currents; the lower and upper NGCUC (Table 2), the lower and upper NECC (Table 3) and the resultant mixture, the lower and upper EUC (Table 4). Data for the NGCUC (Table 3) from 3.25°S, station 18 were separated into (a) the lower NGCUC based on a temperature range of 11–14°C; these isotherms rise to the 0° latitude boundary of the EUC (Fig. 4a) and the depth range of the lower EUC; and (b) the upper NGCUC with temperatures of 14–28°C. NECC data (Table 2) from 6°N to 7°N were separated into the lower NECC with a temperature range of 11–13°C; these isotherms fall to the
2°N boundary of the EUC and the depth range of the lower EUC (Fig. 4a), and the upper NECC with a temperature range of 13–28°C. The selection of data for the EUC (Table 4) was based upon latitudinal boundaries of the EUC seen in the WEPOCS III data at 143°E, 0–2°N, with temperature boundaries for the lower EUC of 11–14°C as specified by Toggweiler and Carson (1995) and of 14–28°C for the upper EUC (Tables 2–4).

The lower NGCUC source (Table 2) for the lower EUC occurs in the depth range 294–343 m. The salinity range 34.83–35.01 psu fits the Toggweiler and Carson (1995) description of the source water for the lower EUC “13°C water” (see above). This water (lower NGCUC, Table 2) is low in silicate compared to nitrate, 8.8–14.4 and 15.9–20.7 mmol m⁻³, respectively. Toggweiler and Carson (1995) recognized that the “deepest part of the NGCUC at 300 m coincides with 11–12°C water (in the EUC) that does not upwell and feeds the Peru–Chile undercurrent” (Toggweiler et al., 1991). At 3.25°S, WEPOCS III station 18 (lower NGCUC), 300 m depth, the following properties; 12.28°C temperature, 34.95 psu salinity, NO₃⁻ = 18.6 mmol m⁻³, Si(OH)₄ = 7.8 mmol m⁻³, confirm the low-silicate, high-nitrate nature of this source water for the EUC. The upper NGCUC water (100–287 m depth) has salinity of 35.01–35.45 psu and also Si(OH)₄ concentrations less
than NO₃, 1.8–7.8 and 2.8–14.9 mmol m⁻³, respectively, and is a poor source of silicate to the upper EUC.

The lower NECC (Table 3), as defined by the extracted data to occur in the depth range 217–272 m, has a narrow range of salinities, 34.56–34.57 pss, and is rich in nutrients with about equal concentrations of Si(OH)₄ and NO₃, 24.5–34.3 and 23.1–30.6 mmol m⁻³. The upper NECC, 107–175 m depth, also has a narrow range of salinities, 34.64–34.75 pss. The nutrient concentrations are low, silicate ranges from 4.4 to 11.4 mmol m⁻³, and NO₃ from 3.0 to 11.6 mmol m⁻³, but are present in about equal concentrations as in the lower NECC.

The lower salinity, high Si(OH)₄ water of the NECC north of the equator has T-S properties of the Mindanao current (MC)/Celebes Sea water according to Fine et al. (1994) and is supplied primarily from this North Pacific source. Water properties for stations in the MC located against the Mindanao coast, e.g., WEPOCS III at 7.9°N, 126.6°E, show low salinity, 34.65 pss, temperature of 15.26°C at 200 m, and low silicate, 10.3 mmol m⁻³, raising the question of how high silicate values arise at 200 m in the NECC?

Contouring the WEPOCS III stations from 126°E to 134°E and from 7°N to 12°N for nutrients, temperature and salinity has been useful in understanding this condition (Fig. 7a–c). Two features appear in the 200 m contours, a high-silicate eddy-like structure centered at about 8°N, 130°E and low-silicate structure at about 8°N, 126.5°E (Fig. 7c). This feature is also present in

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Water properties of the lower and upper NGCUC mean (min–max) values from WEPOCS III data (italics represent temperature definition boundaries)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower NGCUC</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>294–343</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>11.00–14.00</td>
</tr>
<tr>
<td>(11.00–14.00)</td>
<td>(14.00–28.00)</td>
</tr>
<tr>
<td>Salinity (pss)</td>
<td>34.838–35.014</td>
</tr>
<tr>
<td>Silicate (mmol m⁻³)</td>
<td>11.45</td>
</tr>
<tr>
<td>Nitrates</td>
<td>8.8–14.4</td>
</tr>
<tr>
<td>Phosphate (mmol m⁻³)</td>
<td>18.3</td>
</tr>
<tr>
<td>(15.9–20.7)</td>
<td>(2.8–14.9)</td>
</tr>
<tr>
<td>O₂</td>
<td>(1.23–1.53)</td>
</tr>
<tr>
<td>(3.60)</td>
<td>(3.55)</td>
</tr>
<tr>
<td>(3.54–3.66)</td>
<td>(3.32–4.03)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Water properties of the lower and upper (NECC), mean (min–max) values from WEPOCS III data (italics represent temperature definition boundaries)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower NECC</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>217–272</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>11.72–12.97</td>
</tr>
<tr>
<td>(11.00–13.00)</td>
<td>(13.00–28.00)</td>
</tr>
<tr>
<td>Salinity (pss)</td>
<td>34.561–34.579</td>
</tr>
<tr>
<td>Silicate (mmol m⁻³)</td>
<td>29.8</td>
</tr>
<tr>
<td>(24.5–34.3)</td>
<td>(4.4–11.4)</td>
</tr>
<tr>
<td>Nitrates</td>
<td>27.1</td>
</tr>
<tr>
<td>(23.1–30.6)</td>
<td>(3.0–11.6)</td>
</tr>
<tr>
<td>Phosphate (mmol m⁻³)</td>
<td>1.83</td>
</tr>
<tr>
<td>(1.59–2.04)</td>
<td>(0.38–0.90)</td>
</tr>
<tr>
<td>O₂</td>
<td>1.94</td>
</tr>
<tr>
<td>(1.6–2.31)</td>
<td>(3.17–3.89)</td>
</tr>
</tbody>
</table>
contours of silicate at 0, 50, 100, and 150 m (not shown). Temperature and salinity contours (Fig. 7a and b) show essentially the same features. Water properties are those of the MC/Celebes Sea water; from Fine et al. (1994, their Fig. 2), temperature of 12–12.5°C, salinity of 34.5 psu, and Si(OH)₄ of 24 mmol m⁻³ at 300 m. The location of the high-silicate, low-temperature feature is consistent with the location of the Mindanao eddy (Fig. 5), first recognized by Takahashi (1959) and named by Wyrtki (1961). This cyclonic eddy produces a dome-like structure (the Mindanao Dome, Lukas et al., 1991) in the elevated nutrient distributions. This doming of temperature and

Fig. 7. Contours at 200 m from the WEPOCS III data of (a) temperature (°C), (b) salinity (psu = ps) and (c) Si(OH)₄ (mmol m⁻³).
nutrients at the western boundary also was observed on the 143°E section of the WHP-89 (Kaneko et al., 1998) between 5°N and 9°N and may be a significant feature in the biological production processes of the equatorial Pacific.

The lower EUC (Table 4), defined by temperature boundaries in the WEPOCS III data set, occurs between 218 and 293 m depth. Salinities, nutrients and oxygen all show some mixing from NECC with the major NGCUC, lowering the salinities and oxygen values and raising nutrient concentrations above the lower NGCUC levels. Silicate especially is increased, and means of silicate and nitrate are nearly equal, 17.8 and 19.9, with ranges from 14.0 to 25.5 and 17.6 to 25.3 mmol m⁻³, respectively. The upper EUC water, 108–266 m depth in the 0°N to 2°N band, is a mixture of NGCUC and NECC (Table 4). Salinities and oxygen are lower and nutrients are higher than in the NGCUC. Silicate concentrations in the 0–1°N band range from 2 to 15 mmol m⁻³ and 2 to 20 mmol m⁻³ for the 1–2°N region. The silicate concentrations in the 2–3°N band are enriched by the NECC and range from 2 to 30 mmol m⁻³. The mean concentrations of Si(OH)₄ and NO₃ in the 0–2°N, 108–266 m depth range are 5.7 (range of 2.0–13.6 mmol m⁻³) and 9.2 mmol m⁻³ (range of 4.0–16.4 mmol m⁻³).

3.5. Model data

The mean velocity field for 1988 derived from the 3-D physical model was combined with mean silicate and nitrate concentrations measured for the source waters (Tables 2 and 3) to generate nutrient fluxes. Fig. 8 shows the pattern of horizontal currents in the western Pacific between 10°N and 10°S at 326 m depth as given by the 3-D physical model. The NGCUC flows northwards along the New Guinea coast at 140°E and starts to turn around between 2°S and the equator to contribute to the lower EUC. Together, the MC (126°E) and the flow of water out of the Celebes Sea at 115°E provide the second source water mass of the lower EUC. Fig. 9 displays a modeled zonal velocity section at 143°E. At 2.5°S at a depth of 150–250 m strong gradients indicate mixing of NGCUC water into the EUC. From the temperature, salinity and silicate contours at 143°E (Fig. 4a–c) we chose the position of the EUC at

![Fig. 8. Horizontal currents (relative vectors) at 326 m depth, modeled annual mean for 1988 from 3-D model. The black rectangle displays the area chosen for the box calculation (compare Fig. 11).](image-url)
$143^\circ$E to be 0–2$^\circ$N, consistent with the tendency of
the early origin EUC to be north of the equator
(Fig. 8). If we had chosen the EUC boundary to be
symmetrical about the equator in the data set for
$143^\circ$E, the effect would not have been large. At
200 m depth, temperature would increase about
1$^\circ$C from 18$^\circ$C to 19$^\circ$C, and salinity would
increase 0.2 pss from about 35.0 to 35.2 pss (see
Table 4). The annual mean zonal flow at 150 m
depth (Fig. 10a) shows maximum zonal velocities,
up to 90 cm s$^{-1}$, between 160$^\circ$W and 140$^\circ$W. This
is also the area of strongest upwelling (Philander
et al., 1987). The core of the undercurrent at these
longitudes is symmetrical about the equator.
North and south of the EUC two westward-
flowing currents indicate vertical extensions of the
SEC. The $-20$ cm s$^{-1}$ isoline from 130$^\circ$E to 150$^\circ$E
indicates the upper NGCUC. The NECC (5–
7.5$^\circ$N) has comparatively small eastward velocities
up to 10 cm s$^{-1}$. Along the equator, water masses
from both the north and the south feed into the
EUC (Fig. 5). At 2.5$^\circ$S and 2.5$^\circ$N, the southern
and northern boundaries of the EUC, modeled
meridional velocities are of the same magnitude,
approximately 2 cm s$^{-1}$. Therefore, meridional
asymmetries in nutrient concentrations would lead
to an asymmetric inflow of nutrients into the EUC
and, hence, into the surface layer.

3.6. Nutrient budget for the EUC

To understand the impact of differential nu-
trient supply to the EUC, the 3-D physical model

---

Fig. 9. Zonal velocity (cm s$^{-1}$) at $143^\circ$E, modeled annual mean for 1988. Negative numbers—westward flow, positive numbers—eastward flow.

Fig. 10. Modeled annual mean, for 1988 of zonal velocity (cm s$^{-1}$) at 150 m depth, Negative numbers—westward flow, positive numbers—eastward flow.
and data from WEPOCS III were used to construct a nutrient budget of biogeochemical flux for the equatorial upwelling ecosystem. Partitioning of 3-D modeled flow between upper EUC and lower EUC for the region near the origin of the EUC, 130–160°E and 3°S to 3°N is shown in Fig. 11 as percent of the total flow out of the eastward face, 35 Sv. The flux of silicate and nitrate from the north and south were calculated from the modeled flow data and the mean nutrient concentrations for the north and south sources, the NECC and the NGCUC (Tables 2 and 3). The flows entering the western faces at 130°E were attributed to the northern sources according to the 3-D model results. The calculated fluxes of silicate and nitrate are given in Table 5. The total flow from north and south into the EUC are nearly equal for the lower EUC, 6.4 and 7.4 Sv, respectively. The same approximate proportions are calculated for the upper EUC, 11.2 Sv from the north and 10.5 Sv from the south. The total inflow to the upper EUC is about twice that of the lower EUC.

The fluxes of nitrate into the lower EUC show a different story from nitrate (Table 5), with about twice the amount from the north compared to the south, 191.9 and $84.6 \times 10^3$ mol Si s$^{-1}$, respectively. The proportions of silicate flux to the upper EUC from north and south are approximately the same as for the lower EUC, about twice as high from the north as from the south, 84.9 and $39.8 \times 10^3$ mol Si s$^{-1}$.

The calculated mean concentrations of NO$_3$ and Si(OH)$_4$ for the upper and lower EUC from the combined model and data approach (Table 5) are close to the mean concentrations obtained from data analysis (Table 4). For the lower EUC mean modeled NO$_3$ concentration is $22.4$ mmol m$^{-3}$ versus data $19.9$ mmol m$^{-3}$; modeled Si(OH)$_4$ concentration is $20.0$ mmol m$^{-3}$ versus data $17.8$ mmol m$^{-3}$. For the upper EUC, mean modeled NO$_3$ concentration is $7.5$ mmol m$^{-3}$ versus $9.2$ mmol m$^{-3}$ data; Si(OH)$_4$ modeled mean is $5.8$ mmol m$^{-3}$ versus data mean $5.7$ mmol m$^{-3}$.

The flux of nitrate out of the 160°E face was calculated from model and data to be

![Fig. 11. Box calculation for the EUC source water region (compare Fig. 8). 100% is equivalent to 35 Sv.](image-url)
310 × 10^3 mol N s⁻¹ for the lower EUC for a total of 489 mol N s⁻¹ and 178 × 10^3 mol N s⁻¹ for the upper EUC. This value is about 30% lower than the Toggweiler and Carson (1995) modeled estimate of 660 × 10^3 mol N sec⁻¹ entering from the west at 180°W. In summary, about 50% of nitrate is supplied by north and south sources to both lower and upper EUC near its origin, but silicate is supplied more from the north, about 70% and 30%, respectively. The consequences of this analysis is that changes in the EUC silicate relative to nitrate would be induced by changes in the NGCUC source waters far to the south in the Southern Ocean according to Toggweiler and Carson (1995).

### 3.7. Local sources of silicate for the EUC

There are also local sources of silicate in the western equatorial Pacific of potential importance, a result of the very high and variable precipitation, up to 1.5 m yr⁻¹ (Lukas and Lindstrom, 1991). Low-salinity water in the vicinity of the Indonesian islands has been commented on (Lukas and Lindstrom, 1991) and the rivers of the region are good candidates for the injection of fresh water high in silicate. Milliman et al. (1999) estimated that 25% of the annual sediment flux to the ocean is provided from these rivers, which can be expected to exhibit very high silicate concentrations, 250 mmol m⁻³ or greater. The silicate eventually embedded into the current system is likely to be regenerated from an initial near shore diatom bloom as observed in the Amazon and Orinoco river plumes (Milliman et al., 1999). The WEPOCS III 143°E section (Fig. 4b and c) has been replotted with a depth scale 0–100 m in Figs. 12a and b, and shows a pool of low salinity, elevated silicate water against the north coast of New Guinea and likely to be entrained into the NGCC and or the NGCUC. Several WEPOCS III stations (Lukas et al., 1991) taken close to the Mindanao coast, e.g., Stations 41 and 42 show salinities of 33.64 and 33.76 psu, at the surface, lower than any of the water masses in the area and have elevated silicate concentrations, 7.2 and 5.5 mmol m⁻³. The lower salinity, higher silicate characteristics occur only in the upper 5–10 m. Silicate must be mixed into the underlying waters quickly, or be used in new production (Mackey et al., 1995) within the surface region low-salinity barrier layer. Although the elevated silicate values

### Table 5

<table>
<thead>
<tr>
<th>Flow (Sv)</th>
<th>Mean Si(OH)₄ (mmol m⁻³)</th>
<th>Flux of Si(OH)₄ (10^3 mol s⁻¹)</th>
<th>% Si flux</th>
<th>Mean NO₃ (mmol m⁻³)</th>
<th>Flux of NO₃ (10^3 mol s⁻¹)</th>
<th>% NO₃ flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower EUC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West inflow</td>
<td>5.28</td>
<td>29.8</td>
<td>157.5</td>
<td>27.1</td>
<td>143.2</td>
<td></td>
</tr>
<tr>
<td>North inflow</td>
<td>1.16</td>
<td>29.8</td>
<td>34.4</td>
<td>27.1</td>
<td>31.3</td>
<td></td>
</tr>
<tr>
<td>South inflow</td>
<td>7.39</td>
<td>11.5</td>
<td>84.6</td>
<td>18.3</td>
<td>135.1</td>
<td></td>
</tr>
<tr>
<td>Total inflow</td>
<td>13.82</td>
<td>20.0</td>
<td>276.5</td>
<td>22.4</td>
<td>309.7</td>
<td></td>
</tr>
<tr>
<td>Total N inflow</td>
<td>6.44</td>
<td>191.9</td>
<td>69</td>
<td></td>
<td>174.5</td>
<td>56</td>
</tr>
<tr>
<td>Total S inflow</td>
<td>7.39</td>
<td>84.6</td>
<td>31</td>
<td></td>
<td>135.1</td>
<td>44</td>
</tr>
<tr>
<td>EUC (Table 4)</td>
<td>17.8</td>
<td></td>
<td></td>
<td></td>
<td>19.9</td>
<td></td>
</tr>
<tr>
<td>Upper EUC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West inflow</td>
<td>8.26</td>
<td>7.6</td>
<td>62.8</td>
<td>6.9</td>
<td>57.0</td>
<td></td>
</tr>
<tr>
<td>North inflow</td>
<td>2.91</td>
<td>7.6</td>
<td>22.1</td>
<td>6.9</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>South inflow</td>
<td>10.47</td>
<td>3.8</td>
<td>39.8</td>
<td>8.2</td>
<td>85.8</td>
<td></td>
</tr>
<tr>
<td>Total inflow</td>
<td>21.63</td>
<td>5.8</td>
<td>124.6</td>
<td>7.5</td>
<td>162.9</td>
<td></td>
</tr>
<tr>
<td>Total N inflow</td>
<td>11.17</td>
<td>84.9</td>
<td>68</td>
<td></td>
<td>77.0</td>
<td>47</td>
</tr>
<tr>
<td>Total S inflow</td>
<td>10.47</td>
<td>39.8</td>
<td>32</td>
<td></td>
<td>85.8</td>
<td>53</td>
</tr>
<tr>
<td>EUC (Table 4)</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td>9.2</td>
<td></td>
</tr>
</tbody>
</table>
are not particularly high, the WEPOCS III cruise was not designed to track down fresh-water inputs of silicate and it seems likely that much higher values could be observed at the appropriate locations and seasons.

4. Discussion

4.1. Sources of Si(OH)₄ for the EUC

The above analysis of the sources of nutrients to the origin of the EUC in the western Pacific shows the southern source, the NGCUC to be low in silicate compared to nitrate and the northern source, the NECC to have both nutrients in about equal proportions. Both the upper and lower EUC are enriched in silicate and nitrate from mixing of NECC water along the northern boundary of the EUC. The result is that at its origin, the lower EUC contains approximately equal and high amounts of silicate and nitrate; the upper EUC is relatively low in these two nutrients and silicate is present at lower concentrations than nitrate.

The lower EUC of NGCUC origin is fed by SubArctic Mode Water (SAMW) that never upwells along the equator and enters the Peru–Chile undercurrent and turns back into the upper equatorial waters (Toggweiler and Carson, 1995). SAMW identified by Toggweiler et al. (1991) at GEOSECS station 2.6 (45°S, 166.7°W) at 152 m depth had a temperature of 10.19°C, salinity of 34.8 pss, Si(OH)₄ of 4.1 mmol m⁻³, and NO₃ of 12.3 mmol m⁻³. GEOSECS stations 303 and 306 exhibited similar lower silicate versus nitrate conditions with Si(OH)₄ of 5.9 and 5.7 mmol m⁻³ and NO₃ of 12.4 and 14.2 mmol m⁻³, respectively. The surface waters north of the Southern Ocean polar front at the northern edge of the Antarctic circumpolar current (ACC) and the source to the SAMW (Toggweiler et al., 1991) have long been known to have low silicate and high nitrate (Broecker and Peng, 1982) and were identified as a low-silicate HNLC area by Dugdale et al. (1995). Recent investigations reveal the origin of this low-Si(OH)₄, high-NO₃ condition to be the result of immense diatom blooms (Pondaven et al., 2000) advancing seasonally from north to south, stripping Si(OH)₄ from the euphotic zone in a ratio of about 4:1, Si(OH)₄ to NO₃ (Brzezinski, pers. commun.). This long-path, lower NGCUC, low-Si(OH)₄, high-NO₃ water has potential impacts on
the equatorial Pacific productivity primarily in the far eastern portion of the equatorial Pacific upwelling system (Toggweiler and Carson, 1995).

The waters of the upper EUC provide the source of upwelling waters to the west, from the date line east to about 110°W with Si(OH)₄ concentrations from 2.0 to 13.6 mmol m⁻³ that are limiting to diatoms. This is the range of Si(OH)₄ considered in the 1-D model of equatorial upwelling productivity (Chai et al., 2002; Dugdale et al., 2002), and the range of Si(OH)₄ concentrations observed at 120 m source depth in the JGOFS EqPac cruises, 3.33–13.08 mmol m⁻³ (Table 2 in Dugdale et al., 2002).

4.2. Impact of Si(OH)₄ distribution on productivity and TCO₂ in the equatorial Pacific

Changes in Si(OH)₄ source concentrations are predicted to result in changes in the equatorial air–sea exchange of CO₂ as a consequence of changes in diatom productivity. Our 1-D ecosystem model (Chai et al., 2002; Dugdale et al., 2002) shows sensitivity of sea-surface TCO₂ to silicate source concentrations with a maximum in TCO₂ at intermediate source silicate concentrations of about 8 mmol m⁻³, about the middle of the range of source concentrations observed in recent equatorial cruises (Dugdale et al., 2002, Fig. 3e, Table 2). Whether the curve of TCO₂ vs. source [Si(OH)₄] is actually dome-shaped as the 1-D model suggests, a decrease in surface TCO₂ with elevated source silicate (up to 15 mmol m⁻³) and TCO₂ was observed during the US JGOFS TT011 cruise on a section from 2°N to 2°S at 140°W (Dugdale et al., 2002, Fig. 14). These conditions were also observed in the JGOFS EqPac cruise TT012, when an instability wave passed through 140°W (Foley et al., 1997). Diatoms increased markedly during this event (Iriarte and Fryxell, 1995).

The range in silicate concentration in the Upper EUC, 2.0–13.6 mmol m⁻³ (Table 4) corresponds closely to the observed range of source silicate concentrations for US JGOFS cruises, 3.33–13.08 mmol m⁻³ (Dugdale et al., 2002, Table 2). From data and modeling, this range of silicate concentrations at source depths can be expected to be a factor influencing changes in surface TCO₂ concentrations on the equator. The extent to which these changes in TCO₂ are translated into surface pCO₂ and air–sea exchange of CO₂ depends on other factors as well, e.g., alkalinity, pH changes, and species composition. Diatom uptake of carbon does not affect alkalinity, only TCO₂. A species shift to coccolithophores would affect pCO₂ strongly through reduction in alkalinity during calcite formation. Changes in aeolian input of Fe to the surface of the equatorial Pacific upwelling system also could affect the impact of diatom productivity, i.e. through changes in the Si:C composition ratio of the diatoms (Takeda, 1998). However, here we deal only with the interaction of diatoms, silicate source concentrations and changes in TCO₂.

4.3. Time scales of impact of local and remote Si(OH)₄ supply

These observational and model results suggest the possibility of feedback between the climate/land sea interface and the equatorial ecosystem and surface TCO₂. The Indonesian area river input of silicate has been shown in the present communication to appear in at least the surface waters at the western boundary. Very likely most silicate export to the sea will occur at the sediment interface, i.e. on the continental shelf at about 200 m. The depth range is appropriate for incorporation into the NECC. The export of Si(OH)₄ from the rivers to sea is certain to be seasonal in this area of extremely high precipitation, up to 1.5 m yr⁻¹, and to show El Niño La Niña variation also. El Niño-induced drought conditions in the western Pacific might show up quickly as changes in source Si(OH)₄ concentrations in the 140°W upwelling. Consequently, a seasonal and interannual signal in silica may appear in the equatorial upwelling system. Although they were unable to determine the cause, Archer et al. (1997) found an annual cycle in the concentration of silicate as a function of density in both the JGOFS EqPac and Hawaii Time Series data.

The potential seasonal and interannual El Niño, La Niña effects discussed above may be analogs for longer time scales changes as suggested by Cane (1998). For example, there could conceivably
exist feedback between silicate supply from the Southern Ocean and the equatorial Pacific diatom productivity. During glaciation the advance of the ice may have reduced annual Si production (Pondaven et al., 2000) in the Southern Ocean, trapping less Si and increasing the supply of Si to equatorial Pacific through the SAMW (Toggweiler and Carson, 1995; Tsuchiya, 1991). The equatorial Pacific could be expected to respond to increased silica with increased new and export production due to diatoms, which would reduce surface TCO$_2$ and $p$CO$_2$, resulting in additional cooling, i.e. a positive feedback. Evidence for such a positive feedback might be found if Si deposition events in the Southern Ocean and the Equatorial Pacific were found to be out of phase.

In conclusion, the sources of silicate for equatorial upwelling are meridionally asymmetric. They are spread widely geographically, from the Southern Ocean to the North Pacific and the Indonesian Islands, with potential sources of variability that include changes in ocean circulation, in El Niño/La Niña phenomena, and stages of glaciation. Changes in silicate supply may cause variability in surface TCO$_2$ directly through diatom utilization of inorganic carbon and indirectly through effects on ecosystem composition, e.g., by switching productivity away from picoplankton CO$_2$ utilization (Dugdale et al., 2002) or from coccolithophore CO$_2$ production (Harrison, 2000; Treguer and Pondaven, 2000). Studies of both short-term and long-time scale nutrient conditions, especially of silicate, may yield new insights into climate change and climate variability originating in this key area of the ocean for the exchange of CO$_2$ with the atmosphere.

Acknowledgements

We wish to thank the National Science Foundation JGOFS-Synthesis and Modeling Program (SMP) for financial support (grant OCE-9802060 to RCD and FPW), and the other SMP investigators for thoughtful discussions at SMP workshops. We also thank two anonymous reviewers for helpful suggestions and thank Dr. Aude Leynaert for her especially helpful review. This is US JGOFS contribution number 697.

References


Toggweiler, J.R., Carson, S., 1995. What are upwelling ecosystems contributing to the ocean’s carbon and nutrient budgets? In: Summerhayes, C.P., Emeis, K.-C., Angel, M.V., Smith, R.L., Zeitschel, B. (Eds.), Upwelling in the