



## **A carbon budget for the California upwelling system**

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f ratio**

### **ABSTRACT**

We have constructed a carbon budget for the California upwelling system using Monterey Bay as a case study. By estimating new production within the region, we provide the relative magnitudes for components of carbon flow within the upwelling system. The pathways addressed include vertical particulate organic carbon flux, dissolved organic carbon production, lateral diffusion, carbon transfer to higher trophic levels, and carbon injection into the deep ocean. Through this budget analysis, we are able to account for 60.2-86.3% of the carbon produced by wind-driven upwelling.

### **INTRODUCTION**

With carbon dioxide concentrations increasing in the atmosphere, questions concerning the ocean's ability to sequester and store carbon have been addressed and debated over past decades. Battle et al. (2000) provided an annual estimate of oceanic carbon sequestration of  $\sim 2.0 \pm 0.6$  gigatons of carbon per year ( $\text{Gt C y}^{-1}$ ,  $\text{Gt} = 10^{15}\text{g}$ ) for the period 1991 to 1997. It remains to be completely understood how this carbon is partitioned throughout the ocean system, and specifically, how much carbon, in organic form, is injected into the deep ocean from coastal upwelling environments. Observations

off the Oregon coast suggest that a significant fraction (up to 20%) of the material produced within the coastal waters may be transported into the deep ocean (Barth et al., 2002). Other researchers have also witnessed the removal of carbon by water mass subduction, emphasizing the relative importance of this mechanism (Kadko et al., 1991; Collins et al., 2003). This potentially large sink of organic carbon needs to be quantified in order to better model the flow of material within coastal upwelling environments, and better understand global carbon budgets. In this contribution, we attempt to construct a carbon budget for the California upwelling system. By addressing individual pathways we can provide an estimates of the coastal upwelling contribution of organic carbon to both the deep and open ocean off the coast of California.

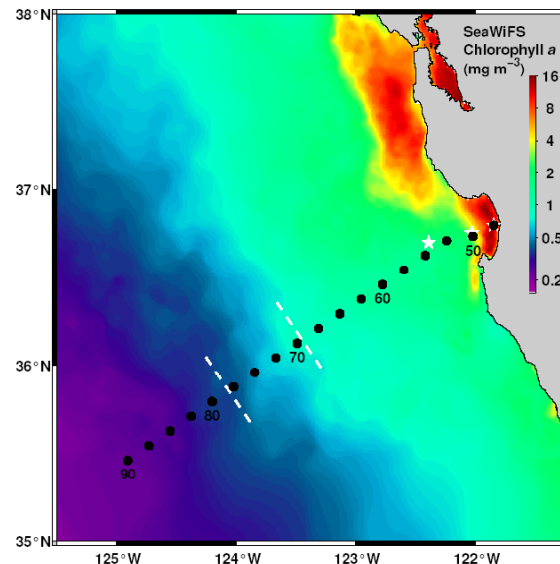
Coastal upwelling systems are significant contributors to the global new production of the World's oceans. While encompassing only about 1% of the area of the ocean, they may provide 11% of the estimated 7.2 Gt C y<sup>-1</sup> of annual new production (Chavez and Toggweiler, 1995). The coast of California represents one such region where upwelled nutrients support an abundance of plant and animal species. During the spring and summer, winds predominantly blow from the northwest along the coast, pushing surface waters offshore through Ekman transport, and causing cool deep nutrient rich waters to rise into the surface sunlit zone thereby fertilizing the phytoplankton (Pennington and Chavez, 2000). Due to this resultant enhanced primary production, the region centered around Monterey Bay has historically been an important fishing ground for anchovies and sardines, as well as a valuable habitat for marine mammals and sea birds.

Upwelling off the coast of California can occur year-round south of Point Conception, but is observed only during the spring and summer from Point Conception to as far north as the Canadian border. For our investigation we narrow this range to include regions of consistent spring and summer upwelling that tend to terminate at the California-Oregon border, a distance of approximately 760 kilometers from Point Conception, as regions north of this boundary have characteristically sporadic upwelling events. Monterey Bay is centered within this region and so will be used as an analogue of the California upwelling system, due to the long time series of measurements available. These data include cruise measurements from the California Cooperative

Oceanic Fisheries Investigations (CalCOFI) and the Monterey Bay Aquarium Research Institute's Studies of Ecological and Chemical Responses to Environmental Trends (SECRET) programs, both started in 1949 and 1997 respectively.

Figure 1 displays the station locations for the CalCOFI and SECRET sampling line 67, extending offshore from Monterey Bay. The hydrography of this sampling line encapsulates well the dynamic transition from the near-coastal upwelling environment to the offshore oceanic nutrient poor regions. This is evident in the surface chlorophyll concentrations with high values present near shore and low concentrations existing in the offshore waters.

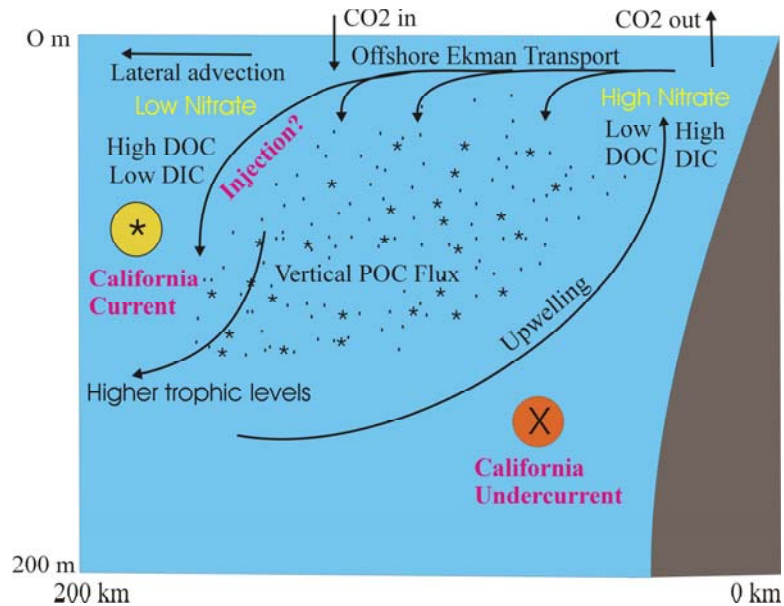
Figure 1: April-May mean chlorophyll image for the period of 1999-2002 estimated by SeaWiFS. The black dots are the CalCOFI line 67 extending offshore from Monterey Bay. The white stars illustrate the locations of the SECRET sampling positions C1, M1 and M2 (mooring stations 1 and 2). The white dashed lines represent the average position of the California Current jet, which marks the transition from productive near coastal waters to oligotrophic offshore oceanic waters (figure from Collins et al. 2003).



Organic carbon flow occurs within this environment in numerous ways (Figure 2). As stated above, the coastal winds predominantly blow from the northwest during the upwelling season, March to July. This drives the surface water offshore and causes deeper nutrient rich waters to rise into the euphotic zone. Phytoplankton growth is initiated by this input of new nutrients, namely nitrate, which are subsequently consumed by diatom-dominated phytoplankton blooms (Pennington and Chavez, 2000). This production based on upwelled nitrate is termed new production, while the ratio of new production to total primary productivity (new plus regenerated production) is called the *f* ratio (Dugdale and Goering, 1967). The *f* ratio is a measure of the amount of carbon that is available for export or supply to higher trophic levels. In this budget analysis of organic carbon, the various pathways that are addressed include estimates of new

production, particulate organic carbon (POC) flux, dissolved organic carbon (DOC) production, carbon and nitrate lost by lateral advection in the surface waters, carbon transfer to higher trophic levels, and finally an estimate of the amount of carbon which may be lost to the deep ocean through injection.

Figure 2: A diagram of the California upwelling system extending 200 kilometers offshore and to a depth of 200 meters. The diagram describes the various components of carbon flow through the coastal upwelling system.



## MATERIALS AND METHODS

### Primary Production and Upwelling Rate Estimates:

All data used for calculating integrated primary production and new production were acquired from the Biological Oceanography Group's (BOG) database of all CalCOFI and SECRET quarterly cruise sections of the line 67 extending offshore from Monterey Bay. The stations used for our analysis from this cruise line include inshore station C1, M1 mooring, M2 mooring, 67-50, 67-65, and 67-70 (figure 1). Details of sample collection, incubation, and analysis are described in Pennington and Chavez (2000).

Average spring and summer primary production values from 1997-2004 for the above listed stations were used in computing an integrated primary productivity for line 67, extending from 8-170 kilometers offshore. As these stations begin 8 kilometers

offshore and extend out 170 kilometers, an effective box with a 160 kilometer offshore range in used for calculating new production on a  $m^2$  basis.

In order to estimate new production by the quantity of nitrate injected into the surface waters through the upwelling season, upwelling volume per day was calculated from the mean daily cycle of upwelling velocity computed by Olivieri and Chavez (2000) based on a 12 year record of upwelling indices. The volume upwelled was computed for the Monterey Bay region by using a Rossby radius of deformation equal to 32 kilometers for the latitude  $36^\circ N$  (Chavez, 1996). This volume was then summed to produce the total volume upwelled during the average year. Spreading this total volume over our defined range of coastline from the California-Oregon border to Point Conception (760 km) then produced an upwelling rate in  $m^3$  per unit time for the California upwelling system.

#### New Production Estimates:

Estimations of new production were acquired using four methods. The first of these calculations involved plotting sections of all available CalCOFI and SECRET salinity data by month for the upwelling season (March to July) using Ocean Data View (ODV). These sections were then extracted and average values were computed for 25 kilometer by 25 meter bins. The surface and midwater bins (0-25 meter and 25-50 meters bins respectively) were both subtracted from the following months average bin values in order to determine the change in salinity between months. This change in salinity is due to the upwelling of deep water of a higher salt content. By developing a relationship, using a first order regression, between salinity and nitrate concentrations for all Line 67 data extending from 60-200 meters we were able to equate the change in salinity between months to an addition of nitrate. This calculation assumes that the source waters of freshly upwelled nitrate are located at a depth of approximately 60 meters (Chavez et al., 1989). The change in salinity between each month of the upwelling season was then summed to represent the total change in salt. Using the regression relationship described above, this change in salt was converted to an addition of nitrate, and then at an estimate of new production using a C:N ratio of 6.8 (Chavez and Barber, 1985).

This time series of daily upwelling volume was then coupled with nitrate concentrations at 60 meters from the M1 mooring, which provided the daily amount of

nitrate injected into the euphotic zone from wind-driven upwelling. The nitrate concentrations at the mooring location were derived from a temperature-nitrate relationship (Olivieri and Chavez, 2000). The daily new nitrate addition was then summed to produce a value of total nitrate upwelled through the average year. As most upwelling only occurs in the spring and summer, this total new nitrate value coupled with a C:N = 6.8, assuming complete consumption of the upwelled nitrate, produced an estimate of new production for the upwelling season.

A third estimate of new production was calculated assuming a source water nitrate concentration of 20  $\mu\text{M}$  (Chavez and Toggweiler, 1995). The total volume of water upwelled through the average year, as described above, was combined with this assumption of nitrate concentration to produce an estimate of the total nitrate upwelled through the year. Using the same C:N ratio, this quantity was then converted to an estimate of new production.

Global estimates of coastal upwelling volume assume a rate of 1 Sverdrup per 1000 kilometers of coastline (Chavez and Toggweiler, 1995). Using this assumption and calculating the length of the coastline from the California-Oregon border to Point Conception (760 km), we produced an estimation of the volume upwelled annually within our defined range of the California upwelling system. This was coupled with the previous assumption of source water nitrate concentration described above to produce a total nitrate addition for the region. Our fourth estimate of new production was then derived from this estimate of nitrate addition and our previously described C:N ratio.

#### POC Flux Estimate:

Our estimate of POC flux at a depth of 100 meters was derived from three separate sediment trap programs in the vicinity of Monterey Bay (PilskaIn et al. 1996; Smith and Druffel, 1998; and unpublished data from MBARI sediment trap S2). Using the relationship described by Martin et al. (1987), we first determined whether any spatial variability existed between the programs' 100 meter flux estimate. Little variability was evident, so these estimates were combined and plotted against a logarithmic scale of depth. A power function was then applied to this relationship in order to then calculate the flux of POC at 100 meters.

#### DOC Production Estimate:

The production of DOC was estimated using profiles from a 2003 Baja California transit which sampled stations in proximity to the nearshore SECRET cruise stations. It was assumed that the difference between surface water DOC concentrations and the concentrations at 60 meters represented the amount of DOC produced within the water column. This was then coupled with the calculation of upwelling volume to provide an estimate of annual DOC production.

#### Estimating Lateral Diffusion Loss Terms:

To calculate the amount of carbon and nitrate lost by lateral diffusion, offshore and alongshore gradients of these parameters were analyzed. Surface Nitrate was extracted from ODV using all available data from the BOG database, which included line 67 CalCOFI and SECRET cruise data. The chlorophyll surface data were derived from a series of cruises between 1988-1991, referred to as the PP cruises (BOG database). This was done because of limited chlorophyll sampling from the CalCOFI cruises, and a future analysis of the offshore chlorophyll gradient should also include the SECRET cruises.

Two assumptions were made to derive these terms. First, that the alongshore gradient was minimal and what material was exported from the southern end of our defined range of coastal upwelling was balanced by new material coming in from the north. Second, that there is minimal advection across the frontal boundary of the California Current. This requires us to only calculate a loss term based on diffusion at the boundary.

The gradients were determined through a first order regression analysis between surface nitrate and chlorophyll concentrations and distance. The slopes produced by the regression analysis represent the gradients in these parameters with distance. Chlorophyll was then converted to particulate nitrogen by assuming  $1 \mu\text{M N per } \mu\text{g chlorophyll}$  (Chavez, 1996), then to its carbon equivalent using the  $\text{C:N} = 6.8$ . The gradient of these parameters was then coupled with the summertime eddy diffusivity calculated for the region by Brink et al. (1991) to quantify the amount of material lost by diffusion. The new production estimates were then adjusted to the amount of nitrate lost, while the

carbon loss term represents the portion of material transported into the North Pacific Gyre.

**Transfer Efficiency Estimation:**

An estimate of transfer efficiency was employed from the Chavez et al. (1989) model of the Peruvian upwelling system. These researchers determined 2-3% of the primary production was incorporated into anchoveta biomass during peak years of anchoveta abundance. Using this estimate, we were able to partition an amount of carbon which may be removed from the system in the form of higher organisms.

**RESULTS**

Table 1 describes the results of calculations for integrated primary production, new production, POC flux at 100 meters, DOC production, lateral advection loss terms, carbon transfer to higher trophic levels, and the percent of new production left unaccounted.

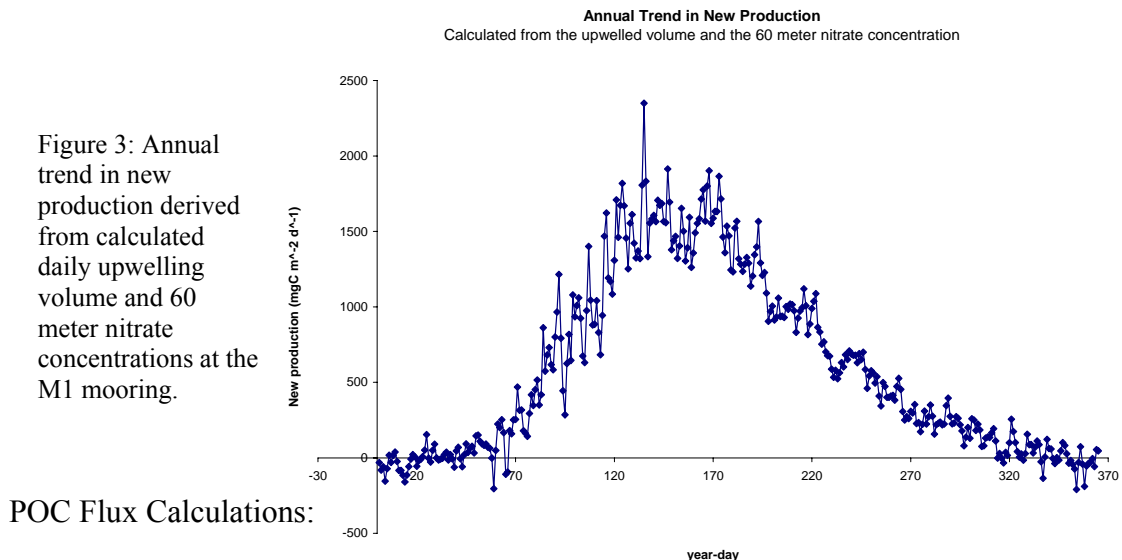
Table 1: Results for calculations of integrated primary production, new production, POC flux at 100 meters, DOC production, lateral advection loss terms, and higher trophic level transfer all in units of grams carbon per square meter per year. F ratios are computed for each estimate of new production based on the calculated integrated primary productivity. The percent of each described pathway is calculated based on the new production estimate using the 60 meter nitrate concentration from the M1 mooring. The estimate of carbon injection comes from Barth et al. (2002).

<b>RESULTS</b>	<b>gC m<sup>-2</sup> y<sup>-1</sup></b>	<b>Percent</b>	<b>f ratio</b>
<b>Integrated Primary Production</b>	346.6		
<b>New Production (adjusted to nitrate loss)</b>			
Salinity change	66.2		0.19
M1 60 meter nitrate*	211.9	100	0.61
20 uM nitrate	218.7		0.63
Global upwelling volume	321.7		0.93
<b>POC FLUX at 100 Meters</b>			
Derived Power Function	51.8	21.1-40.7	
Pilskaln et al. 1996	86.2		
Berelson et al. 2003	44.7		
Martin et al. 1987	77.9		
<b>DOC Production</b>			
Baja Transit Estimate	32.2	15.2-20	
Wetz and Wheeler, 2003	~42.4		
<b>Lateral Advection Loss Terms</b>			
Nitrate	4.7		
Carbon	1.5	0.7	
<b>Higher Trophic Levels</b>			
Chavez, Barber and Sanderson, 1989	6.9-10.4	3.2-4.9	
<b>Carbon Injection</b>			
Barth et al. 2002	~42.4	20	
<b>Unaccounted New Production</b>		13.7-39.8	
* estimate used for calculating percents			

The calculation of integrated primary production based on spring and summer averages of SECRET line 67 data from 1997-2004 produced a value of  $346.6 \text{ gC m}^{-2} \text{ y}^{-1}$ . The total volume upwelled through the year, spread out over our range for the California upwelling system (760 km), produced an upwelling rate of approximately 0.5 Sverdrups.

Calculations of new production produced estimates ranging from  $66.2\text{-}321.7 \text{ gC m}^{-2} \text{ y}^{-1}$ . The low and high estimates of new production are based both on the change in salinity through the upwelling season and from the global estimate of upwelling volume (Chavez and Toggweiler, 1995), respectively. The new production estimate based on a calculated upwelling volume of 0.5 Sverdrups for the California upwelling system and the assumption of  $20 \text{ }\mu\text{M}$  nitrate source water concentration (Chavez and Toggweiler, 1995) produced a value of  $218.7 \text{ gC m}^{-2} \text{ y}^{-1}$ . The estimate of new production from the sum of daily upwelled nitrate, using the daily upwelled volume and the 60 meter nitrate concentration from the M1 mooring, was  $211.9 \text{ gC m}^{-2} \text{ y}^{-1}$ . F ratios based with the integrated primary productivity calculation produced values of 0.19, 0.93, 0.63, 0.61; for the order of new production estimates just described.

As the estimate of new production based on the daily upwelled volume and the M1 60 meter nitrate concentration more accurately describes the seasonal trend in coastal upwelling, this estimate is used in calculating the percentages of organic carbon accounted for during our investigation into the pathways of carbon flow. Figure 3 displays the calculated annual cycle in new production for the average year derived from the upwelling volume and 60 meter nitrate concentrations.



The power function derived from plotting the measured carbon fluxes from the three sediment trap programs within the region of Monterey Bay (Pilskaln et al. 1996; Smith and Druffel, 1998; MBARI S2 sediment trap, unpublished) produced the following equation

$$\text{POC Flux} = (\text{Depth}/111448)^{-0.7063},$$

which when solved for a depth of 100 meters calculates a particulate carbon flux of 51.8 gC m<sup>-2</sup> y<sup>-1</sup>. Other estimates of POC flux at 100 meters were also computed using the relationships described by Berelson et al. (2003) and Martin et al. (1987), which both produced results of 44.7 and 77.9 gC m<sup>-2</sup> y<sup>-1</sup>, respectively. Incorporating Pilskaln et al.'s (1996) estimate based on an opaline silica:organic carbon ratio, which assumed silica to be a conservative tracer between 100 and 450 meters, produced a range of POC flux estimates from 44.7-86.2 gC m<sup>-2</sup> y<sup>-1</sup>. Using this range we account for between 21.1-40.7 % of the new production estimate based on daily upwelling volume and 60 meter nitrate concentrations at the M1 mooring.

#### DOC Production:

Production of DOC based on profiles from the Baja California 2003 transit (Carmen Castro, unpublished) and the calculation of upwelling volume estimated a rate of 32.2 gC m<sup>-2</sup> y<sup>-1</sup>. This estimate seems to be in good agreement with deck incubation experiments conducted off the Oregon coast during the upwelling season by Wetz and Wheeler (2003), which concluded that approximately 20% of the organic carbon produced was partitioned into the dissolved fraction. Using their estimate of 20% we provide of range of DOC production from 32.2-42.4 gC m<sup>-2</sup> y<sup>-1</sup>, representing between 15.2-20% of our new production estimate.

#### Lateral Diffusion:

Brink et al. (1991) reports measurements of eddy diffusivity in the offshore direction for the summer of both 1987 and 1988 to be 8.62e7 cm<sup>2</sup> s<sup>-1</sup>. Using the calculated gradients of nitrate and chlorophyll (-0.034 and -0.011, respectively) we were able to compute loss terms of both parameters by lateral diffusion. Figure 4 displays

plots of both the surface nitrate and chlorophyll versus distance with their respective regressions.

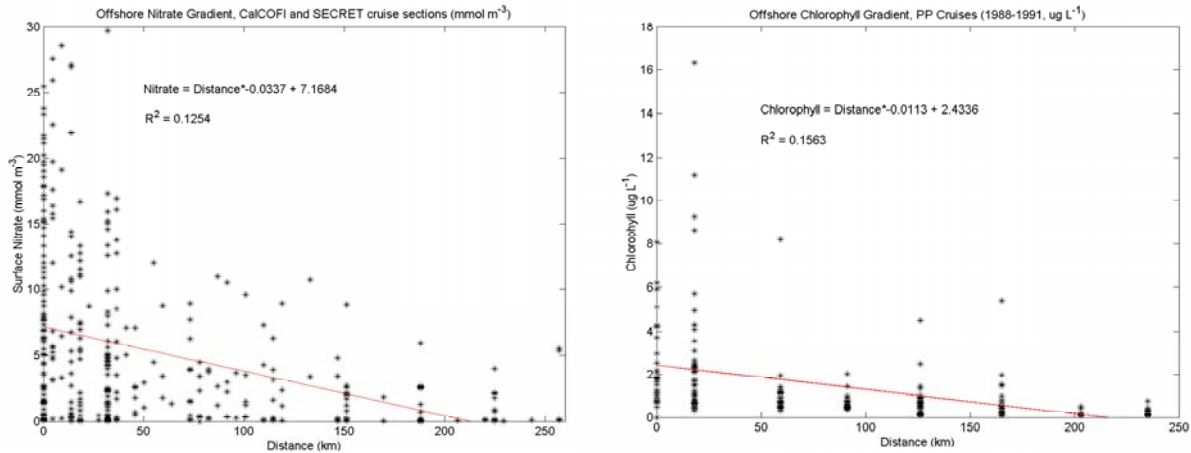


Figure 4: Regression plots of surface nitrate and surface chlorophyll versus distance offshore. The slopes of the regressions represent the gradient extending offshore from each parameter, and are used in calculating advective loss terms.

The nitrate loss term reported in table 1 is in units of  $\text{gC m}^{-2} \text{y}^{-1}$ . This is strictly for comparison, as the resultant loss of  $57.7 \text{ mmol nitrate m}^{-2} \text{y}^{-1}$  was deducted from the calculation of total nitrate addition, thereby adjusting the new production calculations.

The carbon loss term of  $1.5 \text{ gC m}^{-2} \text{y}^{-1}$  represents 0.7% of the new production estimate and is material that is laterally diffused out of the coastal system and into the North Pacific Gyre.

#### Higher Trophic Levels:

Using the estimate of carbon transfer efficiency from Chavez et al. (1989) for the Peruvian upwelling system and the calculated integrated primary productivity for line 67, we compute a carbon transfer to high trophic levels ranging between  $6.9\text{-}10.4 \text{ gC m}^{-2} \text{y}^{-1}$ . This range represents between 3.2-4.9% of our estimate of new production.

#### Carbon Injection/Unaccounted New Production:

Adopting the estimate provided by Barth et al. (2002) that approximately 20% of the carbon produced over the continental shelf may be available for injection into the

deep ocean, we compute a carbon injection rate of  $42.4 \text{ gC m}^{-2} \text{ y}^{-1}$ . Summing the percentages accounted for by these various carbon pathways, leaves between 13.7 and 39.8% of new production unaccounted for.

## **DISCUSSION**

### **Integrated/New Production;**

During the upwelling season primary production within Monterey Bay is enhanced dramatically compared to the remainder of the year. The estimate of net primary production provided by Pilskaln et al. (1996) is  $456.3 \text{ gC m}^{-2} \text{ y}^{-1}$ , significantly higher than our calculated value of  $346.6 \text{ gC m}^{-2} \text{ y}^{-1}$ . Our estimate spans a range of years that includes a dramatic El Niño event that significantly reduced levels of primary production within Monterey Bay (Chavez, 1996). This results in an estimate which is slightly conservative, and may not be representative of primary productivity levels during years of strong upwelling.

The various calculations of new production produced a wide range of estimates for the Monterey Bay region. The lowest of these estimates was based on the salinity change through the upwelling season, and likely dramatically underestimates the levels of new production within the system. This may be due to the design of the calculation, as the salinity will increase rapidly at the beginning of the upwelling season, but assuming the upwelling is fairly constant, will not change significantly between months within the season. The resultant calculated addition of nitrate will then be considerably underestimated as new nitrate is continually pumped into the system but not being accounted for due to no change in salinity.

New production calculated from the global estimate of upwelling volume (Chavez and Toggweiler, 1995) produced the highest value in our range of estimates. This assumes a global coastal upwelling rate of 1 Sverdrup per 1000 kilometers, which is significantly higher than the calculated annual upwelling volume based on the time series of daily upwelling velocities (Olivieri and Chavez, 2000). We calculate an annual upwelling rate for the coastline extending from the California-Oregon border to Point Conception (760 km) of approximately 0.5 Sverdrups, which is significantly less than the

global estimate of upwelling volume provided by Chavez and Toggweiler (1995). This more robust calculation of upwelling volume coupled with daily nitrate observations at 60 meters from the M1 mooring produced what we believe to be the most realistic estimate of our calculations for new production within Monterey Bay. The annual calculated trend in new production produced from this estimate (figure 3) agrees well with other estimates of its annual cycle within Monterey Bay (Berelson et al., 2003, figure 9).

Other researchers using the assumption of source water nitrate concentrations equal to 20  $\mu\text{M}$  (Chavez et al, 1989; Jahncke et al., 2004) have predicted new production values for the Peruvian upwelling system. Using this assumption for our case study we were able to closely match the estimate from 60 meter nitrate concentrations at the M1 mooring, which provided confidence that this more robust calculation using daily nitrate could be used in assessing the quantities of organic carbon flow through the various previously described pathways.

The f ratio produced from the estimate of new production based on 60 meter nitrate concentrations produced a value of 0.61, which is significantly lower than the observed mean f ratio of 0.89 for the 1991 spring upwelling season (Chavez and Smith, 1995). The new production estimate during this time period was also substantially higher ( $638.8 \text{ gC m}^{-2} \text{ y}^{-1}$ ). These inconsistencies are most likely reflective of our mean calculations including El Niño years, as both the estimates of integrated primary production and daily mean nitrate included years of drastically reduced production and nitrate concentrations in response to El Niño conditions (Chavez, 1996).

#### POC Flux/ DOC Production:

By coupling various sediment trap programs for the Monterey Bay vicinity (Pilskaln et al., 1996; Smith and Druffel, 1998; MBARI S2 sediment trap, unpublished), we were hoping to average any spatial variation that could be present within the system. Using the Martin et al. (1987) relationship for particle flux with the various program estimates, we were able to estimate minimal spatial variability in POC flux. This provided confidence in development of a power function by plotting these various estimates together on a logarithmic depth axis. The value produced from our equation

sits well within the range of 100 meter carbon flux estimates for the Monterey Bay region. The combined range of these fluxes accounts for between 21.1 and 40.7 % of the estimated new production. It is highly possible that these fluxes are underestimated as they may miss larger sinking aggregates such as giant appendicularian houses, which have been commonly observed within Monterey Bay during the upwelling season (Hamner and Robison, 1992). These large aggregates can be as great as 2 meters in diameter and one estimate from manned submersible and remotely operated vehicle dives suggested a distance between aggregates along the bottom of Monterey Canyon at 1600 meters to be 1-2 m<sup>-1</sup> (Hamner and Robison, 1992). These animals may play a significant role in removing carbon produced in the surface waters, which the sediment traps may not be sampling. Future research needs to address this issue for more accurate carbon budget analyses.

The estimate of DOC production is perhaps the most uncertain estimate in this analysis. The limited profiles from the 2003 Baja California transit used to produce our estimate of DOC production are from February, when Monterey Bay is in a more characteristically oceanic phase (Pennington and Chavez, 2000). A study off the Oregon coast using deck incubation experiments determined that approximately 20 percent of the organic material produced was in the dissolved fraction (Wetz and Wheeler, 2003). This number increased once nitrate had been exhausted and the bloom collapsed. The cycle of increased DOC production towards the end of a bloom is not accounted for in our analysis, which may mean we have underestimated this term.

#### Lateral Diffusion/Trophic Transfer/Carbon Injection:

Calculating the amount of material lost to the North Pacific Gyre through lateral mixing processes involved determining the gradients in surface water concentrations of chlorophyll and nitrate. The nitrate gradient is derived from a regression of CalCOFI and SECRET spring and summer Line 67 section data and so contain many years of El Niño events. This likely causes an underestimate in the calculation of its offshore gradient. The chlorophyll gradient calculation is based on three years of cruises and may differ perhaps if SECRET line 67 cruises had be added. Aside from any possible underestimation, drifter analyses indicate that flow within the coastal transition zone is

highly variable and so particles have the potential to be mixed at varying rates due to inhomogeneous flow (Davis, 1985; Brink et al., 1991). Calculating the loss due to diffusion then is a more conservative approach due to the difficulties in addressing offshore advection.

We calculate that approximately 0.7 % of the material produced within the California upwelling system is transported to the open ocean. If we extrapolate this amount over our entire defined range of the California upwelling system, this would imply that the North Pacific Gyre receives approximately 0.2 teragrams of carbon per year ( $\text{Tg y}^{-1}$ ,  $\text{Tg} = 10^{12}\text{g}$ ). The implications of this contribution to the open ocean ecosystem in terms of eventual fate of this carbon are interesting to consider, and future research needs to address this component of carbon transfer.

By calculating the transfer of material between phytoplankton and anchovies based on an estimate from the Peruvian upwelling system, we determine that between 3.2 and 4.9 % of the new production is converted into higher trophic level biomass and removed from the system. This concept of material leaving the region as some form of nektonic or avian organism seems to be a difficult one to put a number on. Jahncke et al. (2004) used the difference between the material produced in the surface waters and the material accounted for in sediment traps for the Peruvian upwelling system to determine that approximately 85 % of the new production is used to support secondary production. They failed to address other pathways of carbon flow, such as addressed here. As such, we adopt the significantly lower estimate by Chavez et al (1989) to determine the amount of material transferred to secondary production, and admit that this number may be highly variable.

Carbon produced within the coastal zone has been observed being injected into the deep ocean off the coast of Oregon and California during the upwelling season (Kadko et al., 1991; Barth et al., 2002; Collins et al., 2003). This injection into the deep ocean may represent a substantial removal process, and has been estimated to account for 20 % of the production of carbon within the upwelling zone (Barth et al., 2002). Based on this estimate we calculate an injection rate for the California upwelling system of approximately  $42.4 \text{ gC m}^{-2} \text{ y}^{-1}$ .

## California Upwelling System Carbon Budget

Based on the calculations of integrated primary production and new production, and the various pathways of organic carbon flow addressed, a remainder of between 13.7 and 39.8 % of the new production estimate is unaccounted for. Various possibilities can be credited for preventing closure of this budget, all of which include underestimating the magnitude of the addressed pathways of carbon flow. Another possibility may also include neglecting the offshore advective flux of carbon, as the inhomogeneity of flow makes this parameter difficult to measure. By making the assumption that southern export was balanced by northern import, may also be invalid as acceleration or deceleration of the southern flow will create an imbalance of fluxes in this direction.

Of global importance concerning rising atmospheric carbon dioxide levels is the magnitude of carbon injection within upwelling systems. Based on our calculation of carbon injection from Barth et al.'s (2002) estimate, the California upwelling system could provide approximately 5.13 teragrams of carbon per year ( $\text{Tg y}^{-1}$ ) to the deep ocean, representing 0.2 % percent of the ocean's ability of sequester carbon on an annual basis (Battle et al., 2000). Also the transport of giant appendicularian houses to the deep ocean may be of equal, or perhaps greater magnitude. This could represent a large transport mechanism which sediment traps may or may not be accounting for and future research needs to be conducted on this topic. Both of these pathways represent the removal of carbon from interaction with the atmosphere on decadal time scales and are of critical importance in global carbon budgets.

## CONCLUSIONS/RECOMMENDATIONS

Through this budget analysis of the California upwelling system, we have accounted for 60.2-86.3 % of the carbon produced in the euphotic zone through wind-driven upwelling. Based on our estimate of new production, 21.1-40.7% is transferred out of the system in the form of sinking particles, 15.2-20 % is partitioned into dissolved form, 0.7 % of the particulate carbon may be lost to the North Pacific Gyre through diffusion, and 3.2-4.9 % is transmitted up the food chain to higher organisms. Including an estimated carbon injection rate of approximately 20% (Barth et al., 2002), this may

only leave a small fraction unaccounted for (between 13.7 and 39.8%). Each pathway considered in this budget needs to be further addressed, as models of carbon flow will not be accurate until a better understanding of the various components is accomplished. Areas for future research include addressing carbon contributions to the open ocean ecosystems by coastal upwelling environments through advective as well as diffusive flux, more thorough analyses of DOC production within Monterey Bay, and investigations into the relative importance of sinking giant appendicularian houses on carbon flux to the deep ocean. The simplicity of this analysis has provided a foundation of critical thinking for addressing the way in which material may be transported through the upwelling system along the coast of California, as well as their magnitudes relative to new production.

## **ACKNOWLEDGEMENTS**

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## **References:**

Barth J.A., T.J. Cowles, P.M. Kosro, R.K. Shearman, A. Huyer, and R.L. Smith (2002). Injection of carbon from the shelf to offshore beneath the euphotic zone in the California Current. *Journal of Geophysical Research* 107(C6): 10-1:10-8.

Battle M., M.L. Bender, P.P Tans, J.W.C. White, J.T. Ellis, T. Conway, R.J. Francey (2000). Global Carbon Sinks and Their Variability Inferred from Atmospheric O<sub>2</sub> and  $\delta^{13}\text{C}$ . *Science*, 287: 2467-2470.

Berelson W., J. McManus, K.Coale, K. Johnson, D. Burdige, T. Kilgore, D. Colodner, F. Chavez, R. Kudela, J. Boucher (2003). A time series of benthic flux measurements from Monterey Bay, CA. *Continental Shelf Research* 23: 457-481.

Brink K.H., R.C. Beardsley, P.P. Niiler, M. Abbott, A. Huyer, S. Ramp, T. Stanton, and D. Stuart (1991). Statistical properties of near-surface flow in the California coastal transition zone. *Journal of Geophysical Research* 96(C8): 14,693-14,706.

Chavez F.P. (1996). Forcing and biological impact of onset of the 1992 El Niño in central California. *Geophysical Research Letters* 23(3): 265-268.

Chavez F.P. and R.T. Barber (1985) Plankton production during El Niño. *International Conference on the TOGA Scientific Programme. World Climate Research Publication Series No. 4*. Geneva: World Meteorological Organization, pp. 23-32.

Chavez F.P., R.T. Barber and M.P. Sanderson (1989). The potential primary production of the Peruvian upwelling ecosystem: 1953-1984. In: *The Peruvian upwelling ecosystem: dynamics and interactions*, edited by D.P. Pauly, P. Muck, J. Mendo, and L. Tsukayama. ICLARM Conference Proceedings 18, 438 pp.

Chavez F.P. and S.L. Smith (1995). Biological and chemical consequences of open ocean upwelling. In: *Upwelling in the Ocean: Modern Processes and Ancient Records*, edited by C.P. Summerhayes, K.C. Emeis, M.V. Angel, R.L. Smith and B. Zeitzschel. J. Wiley & Sons, NY, 422 pp.

Chavez F.P. and J.R. Toggweiler (1995). Physical estimates of global new production: the upwelling contribution. In: *Upwelling in the Ocean: Modern Processes and Ancient Records*, edited by C.P. Summerhayes, K.C. Emeis, M.V. Angel, R.L. Smith and B. Zeitzschel. J. Wiley & Sons, NY, 422 pp.

Collins, C.A., J.T. Pennington, C.G. Castro, T.A. Rago, F.P. Chavez (2003). The California Current system off Monterey, California: physical and biological coupling. *Deep-Sea Research II* 50: 2389-2404.

Davis, R.E. Drifter observations of coastal surface currents during CODE: the method and descriptive view. *Journal of Geophysical Research* 90(C3): 4741-4755.

Dugdale R.C. and J.J. Goering (1967). Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnology and Oceanography* 12(2): 196-206.

Hamner W.M. and B.H. Robison (1992). *In situ* observations of giant appendicularians in Monterey Bay. *Deep-Sea Research* 39(7/8): 1299-1313.

Jahncke J., D.M. Checkley Jr., and G.L. Hunt Jr. (2004). Trends in carbon flux to seabirds in the Peruvian upwelling system: effects of wind and fisheries on population regulation. *Fisheries Oceanography* 13(3): 208-223.

Kadko D.C., L Washburn, and B. Jones (1991). Evidence of subduction within cold filaments of the northern California coastal transition zone. *Journal of Geophysical Research* 96(C8): 14,909-14,926.

Martin J.H., G.A. Knauer, D.M. Karl, and W.W. Broenkow (1987). Carbon cycling in the northeast Pacific. *Deep-Sea Research, Part A* 34: 267-285.

Olivieri R.A. and F.P. Chavez (2000). A model of plankton dynamics for the coastal upwelling system of Monterey Bay, California. *Deep-Sea Research II* 47: 1077-1106.

Pennington J.T. and F.P. Chavez (2000). Seasonal fluctuations of temperature, salinity, nitrate, chlorophyll and primary production at station H3/M1 over 1989-1996 in Monterey Bay, California. *Deep-Sea Research II* 47: 947-973.

Pilskaln C.H., J.B. Paduan, F.P. Chavez, R.Y. Anderson, and W.M. Berelson (1996), Carbon export and regeneration in the coastal upwelling system of Monterey Bay, central California. *Journal of Marine Research*, 54: 1149-1178.

Smith K.L. Jr. and E.R.M. Druffel (1998). Long time-series monitoring of an abyssal site in the NE Pacific: an introduction. *Deep-Sea Research II*, 45:573-586.

Wetz M.S. and P.A. Wheeler (2003). Production and partitioning of organic matter during simulated phytoplankton blooms. *Limnology and Oceanography* 48(5): 1808-1817.