Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model

Ryan R. Rykaczewski[1] and John P. Dunne[2]

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[1] A leading hypothesis relating productivity with climate variability in the California Current Ecosystem (CCE) describes an alternation between warmer, well-stratified periods of low productivity and cooler periods of high productivity. This empirical relationship suggests that productivity will decline with global warming. Here, we explore the response of productivity to future climate change in the CCE using an earth system model. This model projects increases in nitrate supply and productivity in the CCE during the 21st century despite increases in stratification and limited change in wind-driven upwelling. We attribute the increased nitrate supply to enrichment of deep source waters entering the CCE resulting from decreased ventilation of the North Pacific. Decreases in dissolved-oxygen concentration and increasing acidification accompany projected increases in nitrate. This analysis illustrates that anthropogenic climate change may be unlike past variability; empirical relationships based on historical observations may be inappropriate for projecting ecosystem responses to future climate change. **Citation:** Rykaczewski, R. R., and J. P. Dunne (2010), Enhanced nutrient supply to the California Current Ecosystem with global warming and increased stratification in an earth system model, *Geophys. Res. Lett.*, *37*, L21606, doi:10.1029/2010GL045019.

1. Introduction

[2] Eastern boundary upwelling ecosystems such as the California Current Ecosystem (CCE) are productive regions of the ocean that support massive populations of small pelagic fish. High productivity in the CCE is sustained by the supply of cool, nutrient-rich waters forced to the sunlit surface layer by alongshore, equatorward winds [*Huyer*, 1983]. An inverse relationship between sea-surface temperature and biological production has been observed in the CCE during the past several decades [*McGowan et al.*, 2003; *Palacios et al.*, 2004]. Increased water-column stratification associated with warmer surface temperatures inhibits the exchange of waters across the pycnocline and decreases primary production. This dynamical understanding has encouraged the hypothesis that increased surface temperatures (and associated increased water-column stratification) resulting from increased greenhouse gases (GHGs) will decrease nutrient supply to the euphotic zone in the CCE and other stratified, mid-latitude ocean ecosystems [*Behrenfeld et al.*, 2006; *McGowan et al.*, 2003; *Palacios et al.*, 2004; *Roemmich and McGowan*, 1995] with deleterious consequences for fisheries. Alternatively, *Bakun* [1990] proposed that increasing land-sea atmospheric pressure gradients with increased GHGs would result in intensified alongshore, upwelling-favorable wind stress, forcing a greater volume of deep, nutrient-rich waters to the surface and increasing primary production. While these hypotheses are both based on sound conceptual understanding of ecosystem processes in the CCE, they project opposite temporal trends in productivity and demonstrate the challenges associated with predicting ecosystem responses to increased GHGs in the absence of a comprehensive and quantitative modeling framework.

2. Methods

[3] We examined changes in nutrient supply and production of the CCE under projected conditions of future global climate using an earth system model (ESM 2.1) developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). ESM 2.1 is a dynamic atmosphere-ocean general circulation model [*Delworth et al.*, 2006] coupled to a marine biogeochemistry model which includes major nutrients (N, P, Si, and Fe) and three phytoplankton functional groups with variable stoichiometry [*Dunne et al.*, 2007]. Utilization of a global model allows comprehensive assessment of the atmospheric, hydrographic, and biogeochemical processes affecting productivity in the context of global change. As nitrate is the main nutrient limiting primary production in the CCE [*Eppley et al.*, 1979], we assess potential changes in production by quantitatively examining the physical and biological factors affecting nitrate concentration under IPCC future concentrations scenario SRES A2 [*Nakicenovic and Swart*, 2000]. In the model configuration used here, atmospheric deposition of nutrients was not varied over the interannual to centennial time scale.

3. Model Results and Analysis

[4] ESM 2.1 projects a basin-wide increase in upper 200-m ocean temperature in the North Pacific of about 2 °C from 1860 to 2100 (Figure 1a) in response to increased GHGs. Temperature in the CCE increases to a lesser extent (about 0.5 °C). The Aleutian Low and Pacific High pressure systems are projected to intensify and shift poleward in the future (Figure S1a of the auxiliary material), a result consistent with other IPCC-style models [*Yin*, 2005].[1] The low-latitude

[1]Visiting Scientist Programs, University Corporation for Atmospheric Research, Princeton, New Jersey, USA.
[2]Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, New Jersey, USA.

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[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL045019.

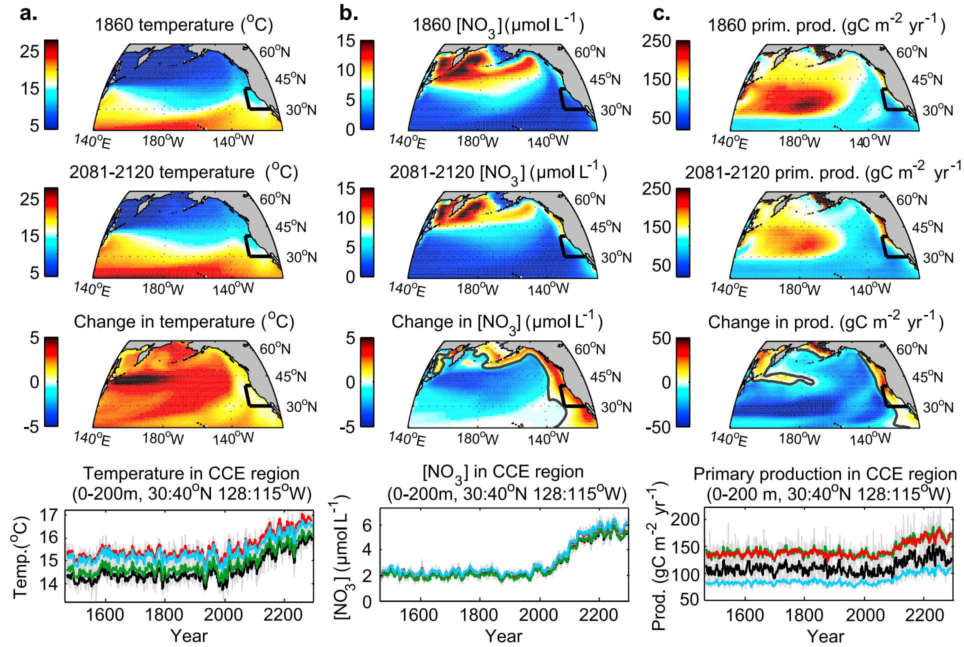

Figure 1. Modeled biogeochemical properties in the North Pacific during pre-industrial and 2081–2120 periods. Upper maps display mean conditions during a 40-year period representative of pre-industrial (year 1860) climate conditions. Middle maps display mean conditions during the 2081–2120 period given GHGs specified by IPCC scenario A2. Lower maps display the difference in each property (2081–2120 values minus pre-industrial values). The bottom plot displays seasonal values (gray) of each property in the CCE region outlined by the coastal box in each map. Colored, bold lines display the seven-year mean for each season; January through March average in black, April through June in green, July through September in red, and October through December in blue. (a) Temperature (°C) averaged in the upper 200 m. (b) Mean nitrate concentration (μmol/L) averaged in the upper 200 m. (c) Integrated primary production (gC/m/yr).

easterlies weaken [*Vecchi et al.*, 2006], and the westerlies and high-latitude easterlies weaken and shift poleward, resulting in reduced meridional gradients in zonal winds and a lower magnitude of wind-stress curl throughout the North Pacific (Figures S1b and S1c). These projected changes in wind-stress curl (Figure S2a) induce basin-scale decreases in the magnitude of vertical velocities in areas of both downwelling (i.e., Ekman pumping in the subtropical gyre) and upwelling (i.e., Ekman suction in the subpolar gyre). In the CCE, changes in offshore wind-stress curl induce a modest increase in upwelling (by about 10% above pre-industrial values) while alongshore winds show no temporal trend in strength. This result is consistent with other global general circulation models [*Wang et al.*, 2010] and does not support the earlier hypothesis of increased coastal upwelling with increased GHGs [*Bakun*, 1990]. Note, however, that representation of upwelling is sensitive to changes in model resolution [*Bakun et al.*, 2010; *Capet et al.*, 2004], and the response of coastal winds to GHGs may be underrepresented in global general circulation models.

[5] Despite increased surface temperatures, associated increased stratification (Figure S2b), and relatively modest changes in upwelling, nitrate concentration in the upper 200 m of the CCE is projected to increase 80% by year 2100 (Figure 1b). This significant increase in nitrate concentration is in opposition to the decreased concentration in the subtropical North Pacific that is expected given the increased stratification. Consistent with these changes in nutrient concentration, production and chlorophyll concentration over most of the North Pacific are projected to decline with future warming (Figure 1c). The projected decline in production is greatest in the subtropical region (20% median decline by 2100 relative to pre-industrial levels between 20° and 45° N) where primary production is limited by the supply of macronutrients. In the subarctic Pacific, where production is colimited by iron, light, and macronutrients, the relative decline in production is less (5% decline between 45° and 65° N); increased stratification acts to reduce light limitation and thus iron demand in the subarctic, enhancing the efficiency of nitrate uptake. Primary production is projected to increase in the CCE with future warming (10% by 2100) in response to increased nitrate supply tempered by increased iron and light colimitation.

[6] Interannual to decadal climate variability in ocean and atmospheric conditions is projected to persist in the coming century [*Wittenberg et al.*, 2006], and variability in ocean stratification induces an inverse relationship between surface temperature and nutrient supply on these time scales during both pre-industrial and future periods. However, this variability is superimposed on a projected long-term increase in both temperature and nutrient supply to the CCE during the 21st century. Natural climate variability acts to obscure the multi-decadal to centennial scale response of nitrate concentrations to increased GHGs in ESM 2.1. In the model output examined here, the 20-year period ending in 2058 is the first such period during which the nitrate concentrations (mean ±1 standard deviation) in the CCE are distinctly greater than the pre-2000 concentrations.

[7] While the multi-decadal scale decline in primary productivity in the larger subtropical North Pacific is expected

Table 1. Nitrate Flux Into the CCE[a]

Time Period	Origin of Advective NO_3 Flux				Biological (Remin. - Uptake)	Mixing and Diffusion
	Below	North	South	West		
1860 control	6.30 (±1.0)	0.87 (±0.4)	0.53 (±0.2)	3.07 (±0.3)	−1.20 (±0.39)	0.19 (±0.19)
1981–2000	8.06 (±1.3)	1.34 (±0.6)	0.84 (±0.3)	3.56 (±0.5)	−1.29 (±0.45)	−0.16 (±0.20)
2081–2100	10.31 (±1.1)	1.02 (±0.3)	1.09 (±0.5)	5.81 (±0.6)	−1.48 (±0.37)	0.15 (±0.14)
Change (1860 to 2090)	+4.01	+0.14	+0.56	+2.74	−0.28	−0.03
Percent change	+64%	+16%	+107%	+89%	−24%	−18%

[a]Modeled nitrate flux into the CCE (represented by a control volume 30° to 40° N; 128° W to the coast; 0 to 200 m) during different 20-year periods. Units of nitrate flux are kmol/s. We report advective fluxes directed into the CCE (i.e., poleward flow at the southern boundary, equatorward flow at the northern boundary, eastward flow at the western boundary, and positive upwelling at 200 m). Net biological and diffusive fluxes are reported. Standard deviations are noted in parentheses and were calculated from annual means during each 20-year period.

given enhanced ocean stratification [*Sarmiento et al.*, 2004; *Steinacher et al.*, 2010], the mechanism behind the surprising increase in nitrate concentration of the CCE is more subtle. We assess the processes influencing nitrate flux into the CCE, including water transport from various sources, nitrate concentration in these source waters, mixing and stratification, and biological uptake and remineralization. The relative importance of changes in water transport versus changes in nitrate concentration of source waters is apparent by comparing differences between nitrate flux (Table 1) and water transport (Table 2). The largest contribution to the projected increase in nitrate supply is increased vertical nitrate flux from below; the projected supply of nitrate by vertical transport is 64% greater during 2081–2100 than during the pre-industrial period. In comparison, the vertical transport of water into the CCE from below increases only 10%, indicating that the majority of the increased vertical nitrate flux is due to changes in nitrate concentration of the region's deep source waters rather than in the volume of vertical transport.

[8] Three factors influence the nitrate concentration of these deep source waters: the initial nitrate concentration of the water mass when subducted below the ocean surface layer (i.e., "preformed" nitrate concentration), the rate of nitrate remineralization/utilization over its history, and the length of time the water mass accrues nitrate below the euphotic zone. We investigated modeled changes in concentrations of nitrate in source waters by recording time-varying nitrate concentrations and trajectories of waters later delivered to the 100-to-200-m depth layer in the CCE (Figures 2a–2d). Under pre-industrial conditions with relatively high downwelling rates in the central North Pacific, nutrient-depleted waters from the sunlit, surface mixed layer are pumped to depth and subsequently upwelled in the CCE after a period of about five years. With decreased downwelling over the central North Pacific under conditions of increased GHG concentrations, surface waters are less rapidly pumped to the depths that supply the CCE upwelling region. Instead, waters upwelling under projected future conditions follow a deeper trajectory en route to the CCE and have been isolated from the euphotic zone for a longer period (about 15 years (Figure 2b)). These source waters have greater preformed nitrate concentration and accrue a greater amount of nitrate during their prolonged transport below the euphotic zone (Figure 2c). The projected nitrate concentration in waters entering the 100-to-200-m depth layer of the CCE is 2.7 μg/L greater under 2081–2120 conditions than under pre-industrial conditions. About 20% of this increase is attributable to an increase in preformed nitrate concentration. The remaining 80% of this increase (2.2 μg/L) is a consequence of the prolonged transit of source waters below the euphotic zone en route to the CCE. This increase in transit time more than compensates for the projected 22% decrease in the rate of nitrate remineralization during transit.

[9] This result is further demonstrated by comparing the 'ideal age' of water parcels during the pre-industrial and future periods. Ideal age is a modeled water property that is synchronized with the model's time step, increasing one year in value per modeled year and reset to zero in the surface mixed layer. In the future, 'ideal age' in the CCE increases significantly (Figure 3a), confirming the result implied by the trajectory analysis; projected increases in nitrate concentration over the 21st century are attributable to reduced ventilation of the CCE's source waters and are not attributable to changes in upwelling (Figure 3b) or surface mixing (Figure 3c).

4. Discussion

[10] The conclusion that increased nutrient supply to the CCE will result from long-term warming and stratification of the North Pacific is counterintuitive given the inverse relationship between ocean temperatures and ecosystem productivity in recent observations. Survey data of appropriate multi-decadal duration corroborate this proposed mechanism of long-term change. *Aksnes and Ohman* [2009] report

Table 2. Water Transport Into the CCE[a]

Time Period	Origin of Water Transport			
	Below	North	South	West
1860 control	0.68 (±0.09)	0.26 (±0.09)	0.49 (±0.19)	2.38 (±0.24)
1981–2000	0.74 (±0.14)	0.33 (±0.12)	0.49 (±0.12)	2.61 (±0.34)
2081–2100	0.75 (±0.08)	0.23±(0.26)	0.43 (±0.07)	3.10 (±0.26)
change (1860 to 2090)	+0.07	−0.03	−0.06	+0.72
percent change	+10%	−13%	−13%	+30%

[a]The region examined and sign convention are as in Table 1. Units of water transport are Sv (i.e., 10^6 m^3/s).

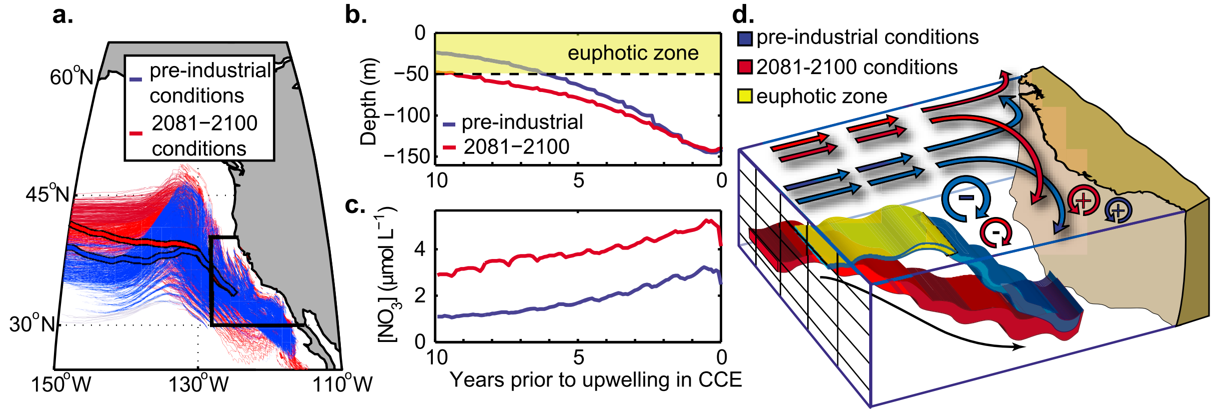

Figure 2. Modeled trajectories of water parcels prior to arrival in the CCE under pre-industrial (1860) and future (2081–2120) conditions. The thick lines indicate the mean horizontal trajectories of water parcels which later compose the 100-to-200-m layer of the CCE. Thin lines denote individual tracer trajectories. Under projected climate conditions (red), water parcels arriving in the CCE are expected to originate from (a) more northerly and (b) deeper sources in comparison to the pre-industrial period (blue). (c) These future source waters accrue greater nitrate concentrations, as they follow trajectories with a greater time period below the euphotic zone. (d) A poleward shift and weakening of westerly winds and a corresponding decrease in the level of negative wind-stress curl over the eastern subtropical North Pacific is projected. This decreases downward pumping of nutrient-depleted surface waters to depths which are subsequently advected to the CCE upwelling system.

shoaling of the nutricline depth since 1949 in the southern CCE despite an increase in stratification. At Ocean Station Papa in the eastern subarctic Pacific, *Whitney et al.* [2007] report a decrease in oxygen concentrations in waters below the mixed layer since 1956 coincident with an increase in surface temperature. Similarly, *Nakanowatari et al.* [2007] report decreasing oxygen concentrations since 1955 in the northwest Pacific attributed to increased warming and stratification in the Sea of Okhotsk.

[11] The projected increase in nitrate and production in the CCE is matched by other responses with potentially deleterious consequences. Decreases in oxygen concentration (18% by 2100) and pH (0.5 pH units) in CCE waters are projected (Figures S3a and S3b). Recent decreases in oxygen concentration of waters have been observed in both the Southern California Bight [*Bograd et al.*, 2008] and along the Oregon continental shelf with severe effects on the benthic ecosystem [*Chan et al.*, 2008]. Our results indicate that such hypoxic events will become more frequent during the coming century with increased stratification and reduced ventilation of the central North Pacific and continued uptake of anthropogenic CO_2.

[12] The implications of future increases in primary production for living marine resources remain uncertain. Populations of pelagic fish and zooplankton feeding near the surface may benefit from increased primary production, but mid-water and benthic organisms unable to tolerate more frequent hypoxic events may perish or be forced to migrate. Ocean acidification may also influence the taxonomic composition of phytoplankton and zooplankton at the base of the food web [*Feely et al.*, 2009].

[13] Our conclusion concerning the projected increased nitrate concentrations and productivity of the CCE is based on one model of the earth's atmosphere, ocean, and ecosystems; namely GFDL's ESM 2.1. Biases in the atmosphere and ocean model used here [*Gnanadesikan et al.*, 2006] influence the modeled biogeochemical properties.

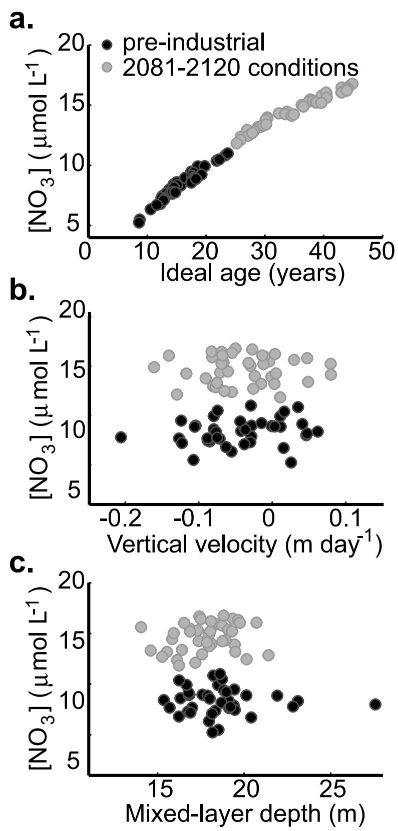

Figure 3. Relationships between mean annual nitrate concentration at 200-m depth and (a) ideal age, (b) mixed-layer depth, and (c) vertical velocity. Properties are representative of a location offshore of Pt. Conception, CA (34.5° N, 121.5° W) and plotted during two 40-year periods under pre-industrial and projected (2081–2120) conditions.

Although the ultimate robustness of our conclusion is sensitive to uncertainties associated with modeling global climate [*Giorgi and Francisco*, 2000], our conclusions are nonetheless relevant to the broad discipline of projecting ecosystem responses in demonstrating the potential for unanticipated results when qualitative theories are examined using quantitative methods. While many previous studies have suggested that primary production will decrease with the increased stratification associated with future warming, especially in stratified, subtropical regions [*Behrenfeld et al.*, 2006; *Sarmiento et al.*, 2004; *Steinacher et al.*, 2010], we demonstrate that local responses to changing climate can differ significantly from this global response. Additionally, we demonstrate that the dominant modes of biological and physical variability may change as the earth system is perturbed under GHG forcing. The deterioration and projected reversal of the historical temperature:nitrate relationship in the CCE at multi-decadal to centennial time scales demonstrates the limitations associated with reliance on empirical, historical relationships to predict future changes. Projections based on idealized conceptual approaches, past behavior of the system, and local response alone may not be robust, and use of regional models may be limited in their ability to project future ecosystem conditions when changes in source-water properties are not considered. Prudent and comprehensive consideration of both local and remote factors is required to estimate the response of regional ecosystems to climate change.

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J. P. Dunne, Geophysical Fluid Dynamics Laboratory, NOAA, 201 Forrestal Rd., Princeton, NJ 08540-6649, USA.

R. R. Rykaczewski, Visiting Scientist Programs, University Corporation for Atmospheric Research, 201 Forrestal Rd., Princeton, NJ 08540-6649, USA. (rrykacze@ucar.edu)