

Does positioning of the North Pacific Current affect downstream ecosystem productivity?

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[1] Fluctuations in the positioning of major ocean currents can influence ecosystem dynamics, but previously the technology has been lacking to make direct observational assessments. Here, we test the hypothesis that positioning of the North Pacific Current (NPC) is related to biological attributes of the central-northern California Current Ecosystem (CCE). To test this hypothesis we use newly available data from the Argo array and compare it with a suite of well-known ecosystem indicators over 6 years, 2002 through 2007. We found increased biomass and productivity when the NPC was shifted poleward, and suggest that positioning influences advective transport of nutrients and perhaps key planktonic organisms from the sub-arctic domain thereby enhancing mid to upper trophic level species. This study is significant because climate change is predicted to cause poleward shifts in the westerlies that drive ocean currents and positioning of large marine gyre systems. Rather than reducing ecosystem productivity, poleward shifts in positioning of the NPC may be beneficial for many species of the central-northern CCE. **Citation:** Sydeman, W. J., S. A. Thompson, J. C. Field, W. T. Peterson, R. W. Tanasichuk, H. J. Freeland, S. J. Bograd, and R. R. Rykaczewski (2011), Does positioning of the North Pacific Current affect downstream ecosystem productivity?, *Geophys. Res. Lett.*, 38, L12606, doi:10.1029/2011GL047212.

1. Introduction

[2] Biological productivity of eastern ocean basins is understood to be coupled to regional upwelling and remotely forced large-scale currents and advection [Mann and Lazier, 1996]. It is hypothesized that when the bulk of flow (volume

transport) from the North Pacific Current (NPC) is more southerly, cold, northern source waters entering the California Current Ecosystem (CCE) can result in greater biological productivity there [Chelton and Davis, 1982; Chelton *et al.*, 1982; Di Lorenzo *et al.*, 2008]. This hypothesis has gained favor with new observations of greater salmon survival in the northern CCE in years of greater “sub-arctic” zooplankton biomass [Peterson and Schwing, 2003; Mackas *et al.*, 2007; Keister *et al.*, 2011]. The “sub-arctic” copepods are large with high lipid concentrations [Lee *et al.*, 2006], thus are thought to support more efficient energy transfer to upper trophic level (TL) consumers.

[3] While it is clear that wind-forcing drives NE Pacific circulation and hence the southward transport of source waters and materials (e.g., plankton) into the CCE [Parrish *et al.*, 2000], positioning of currents may also play a role in downstream ecosystem productivity. Until very recently, quantitative information on current positioning has been lacking. The Argo array provides a new technology for assessing ocean currents globally and has contributed substantially to understanding circulation in the North Pacific [Freeland and Cummins, 2005; Freeland, 2006; Cummins and Freeland, 2007]. Based on recent analyses, the NPC traverses the sub-arctic region of the North Pacific and bifurcates into the Alaska Current and California Current in a transition zone ranging from about 42° N–52° N [Freeland, 2006; Cummins and Freeland, 2007]. What is the effect of this variability in NPC positioning on downstream ecosystem dynamics?

[4] Monthly resolved data on the latitude of the dividing streamline (i.e., latitude at longitude from ~135° W to ~180° W) are now available to be correlated with biological information. For a period of substantial ecosystem variability (2002–2007), we test the hypothesis that positioning of the NPC and related flow rates in the NPC and California Current (CC) influence biomass and estimates of biological productivity in the central-northern CCE. To test this hypothesis, we correlated information on NPC positioning with mid to upper TL ecosystem indicators (Table 1). The biological data represent well-known predators and their prey from mesozooplankton (calanoid copepods and euphausiid crustaceans) to forage fish (juvenile rockfish of the genus *Sebastes*), and salmon (coho and Chinook) and marine birds (auklets and murre). This research is motivated by recent unprecedented ecosystem variability [Brodeur *et al.*, 2006; Sydeman *et al.*, 2006, 2009; Field *et al.*, 2010] and corresponding historic fisheries closures in California and Oregon from 2008 to 2010 [Lindley *et al.*, 2009; Pacific

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Table 1. Biological Data Sets, Showing Sampling Location, Interval, and Length of Each Time Series

Biological Data Set	Location	Sampling Interval	Time Series Length
Northern Copepod Abundance	Central Oregon	Biweekly	1996–2009
Copepod Species Richness	Central Oregon	Biweekly	1996–2009
<i>T. spinifera</i> Abundance	Northern California	Annual	2002–2007
<i>T. spinifera</i> Biomass	British Columbia	Annual	1991–2007
<i>E. pacifica</i> Abundance	Northern California	Annual	2002–2007
<i>E. pacifica</i> Biomass	British Columbia	Annual	1991–2007
Juvenile Rockfish Abundance	Northern California	Annual	1983–2007
Auklet Productivity	Northern California	Annual	1971–2007
Auklet Phenology	Northern California	Annual	1972–2006
Murre Productivity	Northern California	Annual	1972–2007
Murre Phenology	Northern California	Annual	1972–2006
Coho Marine Survival	Oregon	Annual	1970–2007
Chinook – Sacramento River	California	Annual	1983–2009
Chinook – Russian River	California	Annual	2000–2009

Fishery Management Council (PFMC), 2009] (<http://www.pfcouncil.org>).

2. Materials and Methods

2.1. Current Data

[5] Details of the Argo array are given by *Freeland and Cummins* [2005]; the spatial resolution of the array is estimated at 420km nearest neighbor distance (auxiliary material).¹ The latitudinal position of the NPC at longitudinal points across the North Pacific was determined from differences between the dynamic heights at locations representing the sub-arctic and sub-tropical gyres. Flow in the currents was calculated from the gradient of dynamic heights [*Freeland, 2006; Cummins and Freeland, 2007*]. We used January through September monthly resolved values in analyses (see below). We selected the January–September period because winter, spring and summer ocean conditions are important to CCE productivity [*Wells et al., 2008; Black et al., 2011*].

2.2. Biological Data

[6] Biweekly sampling of copepods using oblique tows of a 0.202mm net on the Newport Hydrographic Line, Oregon (44.65° N) are used to estimate a monthly May–September “northern copepod index,” representing biomass anomalies for three species with sub-arctic zoogeographic affinities [*Hooff and Peterson, 2006*] and overall diversity (no. species recorded per month). Biomass of adult euphausiids *Thysanoessa spinifera* and *Euphausia pacifica* are estimated from net samples from a transition region, Barkley Sound (Vancouver Island, British Columbia; 48.85°N, 125.38°W) (details provided by *Tanasichuk* [1998a, 1998b]). The median annual biomass for March to February was used in analyses. *T. spinifera* and *E. pacifica* catch per unit effort (CPUE) are provided by NMFS net sampling at eight stations in the Gulf of the Farallones, California [*Sakuma et al., 2006*]. An index of juvenile rockfish abundance for 10 species was calculated from mid-water trawl net (9mm cod-end) samples after the raw catch was adjusted to a common age of 100 days to account for interannual differences in age structure [*Field et al., 2010*]. Data on breeding success (chicks fledged per breeding pair) and phenology (mean timing of egg laying)

of seabirds (Common Murre *Uria aalge* and Cassin’s Auklet *Ptychoramphus aleuticus*) were collected by biologists from PRBO Conservation Science under contract with U.S. Fish and Wildlife Service on Southeast Farallon Island, California [*Sydeyman et al., 2009*]. Salmon data come from Oregon and California. The Oregon Production Index, reflecting the percent smolt–adult returns for coho salmon in Oregon, was calculated by the formula $SAR = a*1000/(b)*100$, where SAR is the percent smolt-to-adult return, *a* is hatchery and fishery adults (thousands), and *b* is the total hatchery smolts (millions [*Peterson and Schwing, 2003*]). Chinook salmon data sets from California include the Sacramento Index (total fish/year including ocean harvest and river harvest, fishery harvest, and escapement [*PFMC, 2009*]). Chinook returns to the Russian River were monitored by video camera as fish passed over an inflatable dam by the Sonoma County Water Agency (SCWA, unpublished data). Abundance values for both Chinook and coho salmon were lagged (two years and one year, respectively) to align them with ocean conditions during the year of ocean entry. These biological variables were selected as they constitute a community of interacting species and parameters from the epipelagic food web of central-northern California. No variables were deleted after selection. In combining these variables using multivariate statistics (see below), we developed a biological index that combines measurements of abundance, biomass, diversity, recruitment success, and phenology. For convenience and because these variables are interrelated, we refer to these measurements collectively as “productivity” in the manuscript.

2.3. Statistics

[7] Correlations between biological variables are included in the auxiliary material (Table S1). To simplify the analyses, we subjected data on the NPC position and biological variables to empirical orthogonal function analysis and used the resulting EOF1 (EOF_{position} and EOF_{biology}, respectively) in correlations. We conducted EOF analysis on the monthly NPC position data from 135° W to 160° W, 2002–2007, as these data reflect the area in the NE Pacific where the NPC positioning can vary substantially [*Cummins and Freeland, 2007*]. As most physical and biological time series show non-stationarity, we also correlated de-trended values of EOF_{biology} and EOF_{position}. We employed Spearman rank correlation and regression analyses to test for relationships

¹Auxiliary materials are available in the HTML. doi:10.1029/2011GL047212.

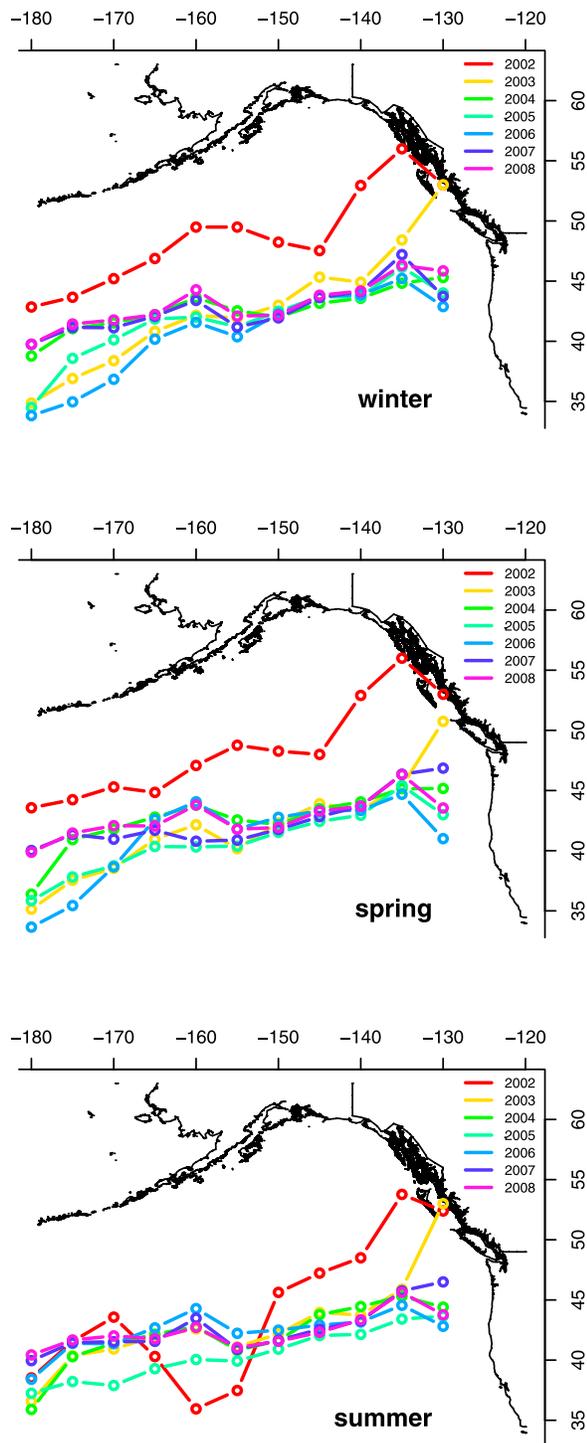


Figure 1. The latitude of the dividing streamline between waters going north (into the Gulf and Alaska) and waters flowing south (into the California Current) for every 5° of longitude for the NPC across the North Pacific from the North American continent (130°W) to 180°W. Note the substantially higher latitude and position of the NPC in early 2002.

between positioning of the NPC and flow in the NPC and California Currents with biological variables.

3. Results

[8] The NPC was most northerly in 2002, shifted southwards from 2003 to 2006, and then moved to an intermediate latitude in 2007 (Figure 1). EOF1_{position}, representing the dividing streamline of the NPC, explained 86% of the variance with consistent loadings on longitudes ≤ 160° W (Table S2). EOF1_{biology}, representing productivity at multiple trophic levels in the central and northern portions of the CCE, explained 65% of the variance and showed consistent loading (~0.3) for all variables except for *E. pacifica* in California and coho salmon survival off Oregon, both of which loaded strongly on EOF2_{biology}. We interpret EOF1_{biology} as an indicator of productivity (Figure 2). Correlation of EOF1_{position} and EOF1_{biology} showed a significant positive relationship accounting for 81% of the variation in biological productivity (Figure 3, top; Spearman rho = 0.943, linear regression: $\beta = 1.213, r^2 = 0.809$). Analysis of the residuals after de-trending corroborated the previous finding of a positive relationship (Spearman rho = 0.829, linear regression: $\beta = 0.932, r^2 = 0.636$). The biological variables which showed the strongest relationship with EOF1_{position} included the relative abundance of the coastal euphausiid *T. spinifera* off California, juvenile *Sebastes*, Cassin’s auklet productivity, and Sacramento and Russian river fall run Chinook salmon abundances (Table 2). Despite previous reports of the importance of volume transport [e.g., Keister *et al.*, 2011], we found little evidence of relationships between flow in the NPC (Spearman rho = 0.486) or

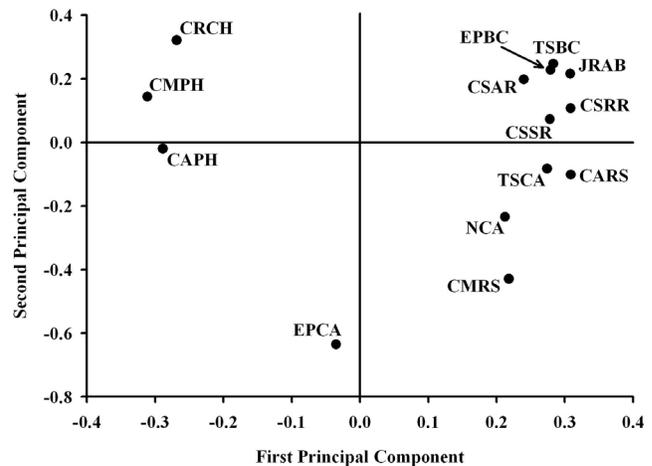


Figure 2. First and second principal components for 14 biological variables. EPCA, *E. pacifica* abundance, California; CSAR, Coho salmon marine survival; CMRS, Common murre productivity; NCA, Northern copepod abundance; TSCA, *T. spinifera* abundance, California; CARS, Cassin’s auklet productivity; CSSR, Chinook salmon Sacramento River abundance; CSRR, Chinook salmon Russian River abundance; JRAB, Juvenile rockfish abundance; EPBC, *E. pacifica* biomass, British Columbia; TSBC, *T. spinifera* biomass, British Columbia; CAPH, Cassin’s auklet phenology; CMRH, Common murre phenology; CRCH, Copepod species richness.

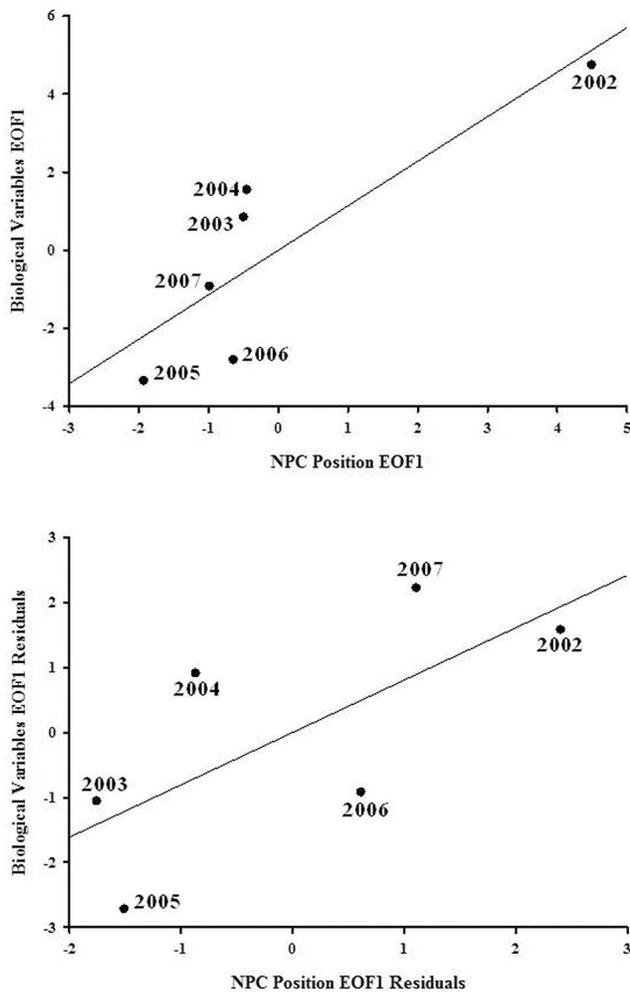


Figure 3. The relationship between position of the NPC for the months of January–September for longitudes 135°W to 160°W (at 5-degree intervals) and the multivariate biological productivity index for (top) raw ($r^2 = 0.809$) and (bottom) detrended values ($r^2 = 0.636$).

CC (Spearman rho = 0.429) and biological productivity as indexed by EOF1_{biology}.

4. Discussion

[9] This exploratory study showed substantial variability in latitudinal positioning of the North Pacific Current in the NE Pacific. As noted by others [Cummins and Freeland, 2007; Batten and Freeland, 2007] despite changes in the density of Argo floats, 2002 was strikingly different than the latter years, with the NPC shifted approximately 8° of latitude (~880 km) to the north. In turn, we and others [Grantham et al., 2004] have found substantial changes in the biology of the CCE, some positive and some negative. Negative perturbations have received considerable attention as they included hypoxic conditions in the benthic zone off Oregon and substantial “die-offs” of demersal fish and crustaceans affecting fisheries. In contrast, our results show enhanced biomass and biological productivity of zooplankton (copepods and euphausiids), forage fish (juvenile *Sebastes*), seabirds, and salmonids with greater poleward

positioning of the NPC. These taxa comprise a community of interacting species of the epipelagic food web, therefore integrating these variables by means of multivariate statistics (EOF1_{biology}) is appropriate. Importantly, the change in positioning of the NPC from 2002 through 2007 was non-stationary from poleward to equatorward. Through simple de-trending of both data sets, thereby isolating the interannual variability from a monotonic trend, we revealed that ~64% of the variation in biological productivity could be related to positioning of the NPC. Moreover, detrending revealed that this relationship was not just due to the unusual positioning of the NPC in 2002; all years were important to this linear relationship. Therefore, while our time series are short, the indicators we developed of NPC positioning (EOF1_{position}) and biological productivity (EOF1_{biology}) are novel, and may offer predictive understanding of how current structure and ecosystem dynamics in the NE Pacific are related.

[10] To date, few have attempted to relate biogeochemical and productivity changes in the CCE to positioning of the NPC (but see Batten and Freeland [2007]). In 2003, a special volume of GRL was devoted to describing a subarctic water mass intrusion in the CCE in 2002 [e.g., Freeland et al., 2003; Kosro, 2003]. This intrusion, related to NE Pacific atmospheric conditions [Murphree et al., 2003], resulted in anomalously high chl-a concentrations in the northern CCE [Thomas et al., 2003]. In 2006, another special volume of GRL was devoted to describing anomalous upwelling and poor biological productivity in the CCE in 2005 [e.g., Schwing et al., 2006; Sydeman et al., 2006]. Here, we contribute the hypothesis that the 2002 subarctic water mass intrusion and 2005 unusual upwelling–ecosystem dynamics appear to be related to positioning of the NPC.

[11] Shifts in the NPC may relate to changes in CCE biology either by advection of different plankton into the CCE [Keister et al., 2011], or by changes in the supply of inorganic nutrients and other water properties which are then acted upon by local upwelling. Shifts in the NPC probably would not cause direct changes in upwelling as was observed in 2005, but could influence the chemical composition of waters being upwelled. When the NPC is shifted equatorward there may be greater distinction

Table 2. Results of Spearman Rank Correlation of Biological Variables Against Position of the North Pacific Current Based on EOF1_{position}^a

	Spearman Rho	p < t
Northern Copepod Abundance, OR	0.6000	0.2080
Copepod Species Richness, OR	−0.6571	0.1562
<i>T. spinifera</i> Abundance, CA	0.7714	0.0724
<i>T. spinifera</i> Biomass, BC	0.4857	0.3287
<i>E. pacifica</i> Abundance, CA	−0.2571	0.6228
<i>E. pacifica</i> Biomass, BC	0.6571	0.1562
Juvenile Rockfish Abundance, CA	0.9429	0.0048
Cassin’s Auklet Productivity, CA	0.8407	0.0361
Cassin’s Auklet Phenology, CA	−0.7537	0.0835
Common Murre Productivity, CA	0.4286	0.3965
Common Murre Phenology, CA	−0.9429	0.0048
Coho Marine Survival, OR	0.3714	0.4685
Chinook Abundance, Sacramento R., CA	0.7714	0.0724
Chinook Returns, Russian R., CA	0.7714	0.0724

^aN = 6 years. Bold indicates significance of p < 0.1 without adjustment for serial autocorrelation.

between the subarctic and subtropical ecosystems of the NE Pacific, and, mechanistically, a clear biogeographic boundary separating the GoA and CCE (i.e., the dividing streamline of the NPC). Under these conditions, plankton communities vary considerably between the two domains. Conversely, when the NPC is shifted poleward, the CCE may be more similar to the GoA, influenced by the subarctic water mass with its larger planktonic organisms and more efficient food web structure. Batten and Freeland [2007] provide some evidence in support of this hypothesis. In considering 2 of the 3 species that comprise the “northern copepod index,” *Acartia longiremis* and *Calanus marshallae* both were found north and south of the dividing streamline in 2002 when the NPC was far to the north, but were mostly limited to north of the streamline in 2003 when the NPC was more southerly. While we have not studied this potential biogeographic boundary mechanism in detail, we surmise that when the NPC is shifted to a southerly position, surface waters are warmer and the water column is more stratified and subjected to less storm mixing. In contrast, when the current is more northerly, it experiences less solar radiation (and less surface heating, stratification, and more storms), making for a more “porous” boundary, and creating a more GoA-like CCE.

[12] In summary and conclusion we have shown that positioning of the NPC is associated with downstream ecosystem productivity in the CCE. This is important because one of the clearest results from Global Climate Models (GCM) are poleward shifts in westerly winds [Yin, 2005; Bengtsson *et al.*, 2006; Archer and Caldeira, 2008]. In the Southern Ocean a concomitant shift in positioning of the Antarctic Circumpolar Current is predicted with poleward shifts in the westerlies [Saenko *et al.*, 2005]. If westerly winds in the NE Pacific move poleward, it is likely that the NPC current will also shift to a more northerly position, perhaps on a more frequent basis, making for fewer differences in plankton community structure between the GoA and northern CCE. Results of this study indicate that the CCE could then become more productive, at least for the epipelagic seabird-salmon-rockfish community evaluated in this study and perhaps for other communities in the CCE as well [e.g., Cloern *et al.*, 2010].

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