# Transport and coastal zooplankton communities in the northern California Current system

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[1] Alongshore transport was estimated from the gridded AVISO altimeter data and water level data from NOAA tide gauges (1993–2010) for the northern California Current (NCC) system. The biomass of the cold neritic copepods including *Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis* (dominants in the eastern Bering Sea, coastal Gulf of Alaska, and NCC) was estimated from a 15 year time series of zooplankton samples (1996–2010) collected biweekly at a coastal station 9 km off Newport Oregon U.S.A. The alongshore currents and the biomass of the cold neritic copepods exhibit a strong seasonal pattern and fluctuate in opposite phase: positive alongshore current (from south) leads to low biomass in winter and negative alongshore current (from north) leads to high biomass in summer. When the Pacific Decadal Oscillation (PDO) is positive, i.e., warm conditions around the northeast Pacific, there is more movement of water from the south in the NCC during winter. When the PDO is negative, there is more movement of water from the north during summer. The mean biomass of cold neritic copepods was positively correlated with the survival rate of juvenile coho salmon and cumulative transport was negatively correlated with coho salmon survival, i.e., in years when a greater portion of the source waters feeding the NCC enters from the north, the greater the salmon survival. We conclude that alongshore transport manifests PDO signals and serves as a linkage between large scale forcing to local ecosystem dynamics. **Citation:** Bi, H., W. T. Peterson, and P. T. Strub (2011), Transport and coastal zooplankton communities in the northern California Current system, *Geophys. Res. Lett.*, *38*, L12607, doi:10.1029/2011GL047927.

## 1. Introduction

[2] Despite the growing literature documenting that many marine organisms are impacted by large scale climate variability, mechanisms downscaling the large scale forcing to local ecosystems are less well known. In the northern California Current (NCC), one key linkage is that between the Pacific Decadal Oscillation (PDO) and local upwelling. The strength of upwelling appears to be related to basin scale climate variability as the PDO [*Mantua et al.*, 1997; *Peterson and Schwing*, 2003; *Pierce et al.*, 2006]: in general, a negative phase of PDO results in increased upwelling, while the positive PDO, or warm phase, leads to downwelling conditions and a strong poleward flow along the west coast of the United States [*Di Lorenzo et al.*, 2008]. Such changes in physical conditions have widespread effects on different trophic levels including phytoplankton [*Henson and Thomas*, 2007; *Thomas et al.*, 2009], zooplankton [*Hooff and Peterson*, 2006; *Peterson and Keister*, 2003], ichthyoplankton [*Parnel et al.*, 2008], fish [*Logerwell et al.*, 2003; *Miller and Sydeman*, 2004], and seabirds [*Ainley and Hyrenbach*, 2010; *Parrish and Zador*, 2003]. Among all the taxa, Pacific salmon, an iconic species to the west coast of the United States, has perhaps received the most attention [*Francis and Hare*, 1994; *Logerwell et al.*, 2003; *Mantua et al.*, 1997; *Peterson and Schwing*, 2003].

[3] The interannual variation in biomass and productivity of the zooplankton responds predictably to PDO sign changes [*Hooff and Peterson*, 2006] which in turn may have profound effects on upper trophic levels. For example, in the northern California Current system, zooplankton showed distinctive community structures under different physical conditions [*Keister and Peterson*, 2003; *Peterson and Keister*, 2003]. When the PDO is negative, the biomass of cold water lipid-rich copepod species was high; when the PDO is positive, the biomass of warm oceanic and lipid-deplete species was relatively high. Furthermore, the changes in copepod species composition have been related to juvenile salmon survival [*Bi et al.*, 2011; *Peterson and Schwing*, 2003; *Peterson*, 2009] suggesting a tight coupling between copepods and salmon through the food chain.

[4] In the NCC system, the relationship between large scale forcing and local ecosystem dynamics including zooplankton communities and juvenile salmon ocean survival was mostly examined through correlative analysis [e.g., *Mantua et al.*, 1997; *Mackas et al.*, 2001; *Peterson and Schwing*, 2003; *Hooff and Peterson*, 2006; *Bi et al.*, 2011], but the mechanistic linkages remain less known. Basin scale transport was postulated as the linkage between large scale climate variability and the NCC ecosystem at decadal scales [*Di Lorenzo et al.*, 2008]. *Keister et al.* [2011] showed that interannual variations in copepod community structure (based on ordination analysis of all copepod species from the NH 05 time series) could be explained by variations in transport derived from the ROMS model of *Di Lorenzo et al.* [2008]. The NH 05 time series highlight the biweekly zooplankton samples along with other environmental variables including temperature, salinity, nutrients, and chlorophyll *a* concentration since 1996 – present with some historical measurements in 1969–1973. This long term dataset has been widely used to investigate zooplankton in relation to seasonal upwelling and large scale climate forcing [e.g., *Hooff and Peterson*, 2006; *Di Lorenzo et al.*, 2008; *Peterson*, 2009; *Keister et al.*, 2011]. To achieve a clearer understanding of the mechanistic linkage between large-scale forcing to highest trophic levels in the

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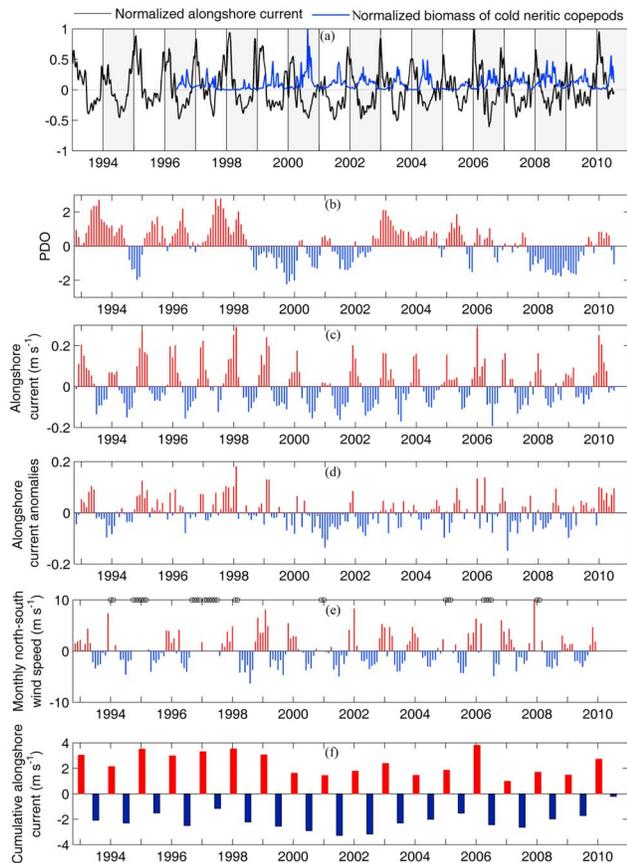
**Figure 1.** (a) Time series of normalized alongshore geostrophic current velocities (blue line) over the 1° next to the coast and the normalized biomass of cold neritic copepods (black line) collected 9 km offshore of the coast along the Newport hydrographic line (44.67 N). Positive values for current velocities indicate northward currents. (b) The Pacific Decadal Oscillation: monthly values from 1993–2010. (c) Monthly average alongshore geostrophic current velocities: red bars represent northward and blue bars represent southward. (d) Monthly anomalies of alongshore current velocities. (e) Monthly average of alongshore wind speed: red bars represent northward, blue bars represent southward and open circles indicate missing data. (f) Cumulative annual alongshore transport: blue bars representing southward and red bars representing northward.

California Current, the present study focuses (a) on copepods at the species level — the "cold water neritic group", (b) on geostrophic transport estimated from observations of sea level, and (c) on mechanistic linkages between the PDO, copepod species composition, bioenergetics of food chain structure, and survival of coho salmon in coastal waters of the northern California Current. We hypothesize that when the PDO is persistently negative, the source waters which feed the northern California Current off Washington and Oregon are from the north (which brings with it more lipid-rich cold water copepods) resulting in higher juvenile salmon survival; conversely when the PDO is positive, a greater proportion of the water feeding the NCC is from the south or offshore, which leads to more lipid-replete warm water copepods, poor feeding conditions for salmon and thus a lower juvenile

salmon ocean survival rate. We explore this hypothesis using the AVISO and tide gauge sea surface height (SSH) data sets to derive geostrophic alongshore currents and compare these currents to copepod community structure. The present study extends the classical study of *Chelton et al.* [1982] who demonstrated that large-scale interannual fluctuations in transport of the California Current (estimated from sea level data) do indeed explain variations in zooplankton displacement volume (their study) and zooplankton species composition and community structure (the present study).

## 2. Data and Analysis

### 2.1. Sea Level Anomaly

[5] Gridded satellite altimeter sea level anomaly (SLA) data from AVISO (http://www.aviso.oceanobs.com/) and verified hourly water level data from tide gauges (http://tidesandcurrents.noaa.gov/) were used in the present study. We downloaded the delayed time, updated version of AVISO SLA, gridded weekly at 1/3° in a rectangular projection from October 7, 1992 – November 4, 2009. To extend this time series to mid-2010, we downloaded the near real time daily SLA data from November 5, 2009 – June 30, 2010 and binned the daily data into weekly data. The hourly tide gauge water level data were processed as described by *Saraceno et al.* [2008] to match the satellite altimeter data. We first discarded sea level data from AVISO within 1° of the coast. These were replaced by sea level anomalies that were calculated by interpolating between the tide gauge observations and the offshore altimeter data. Finally, geostrophic current velocities were calculated from the SLA [*Saraceno et al.*, 2008]. In the present study, we calculated a mean alongshore current velocity within 1° of the coast at the Newport Hydrographic (NH) line (47.67°N). To investigate interannual variability of transport in relation to large scale forcing, the cumulative current velocities as proxies for alongshore transport were calculated in two different approaches. In the first approach, we calculated the cumulative current velocities for the winter and summer respectively to examine alongshore transport in relation to the PDO. The summer season was defined as those dates when the alongshore current flows persistently towards the south (with the decision rule that negative values had to persist for >14 days, done to avoid short term changes in current direction). A similar rule was applied to determination of the date when "summer" ended: until the alongshore northward current occurs (positive values > 14 days). The winter season was defined as those months when the alongshore current flows persistently toward the north from the autumn of the previous year (the so-called Davidson Current) until the southward current re-appears the following spring. In general, the summer season started on May 1 (±36 days) and the winter season started on October 27 (±34 days). In the second approach, we calculated alongshore current velocities from April–December, which is considered as the critical period for juvenile salmon in the ocean [*Pearcy*, 1992].

### 2.2. Zooplankton Data

[6] Zooplankton samples were collected biweekly during daytime hours from 1996–2010 at NH05 (44.65°N, 124.18°W). Samples were collected as vertical tows using 50-cm diameter ring nets with 202-$\mu$m mesh. Nets were hauled from 5 m off the bottom to the surface. Volume filtered was estimated
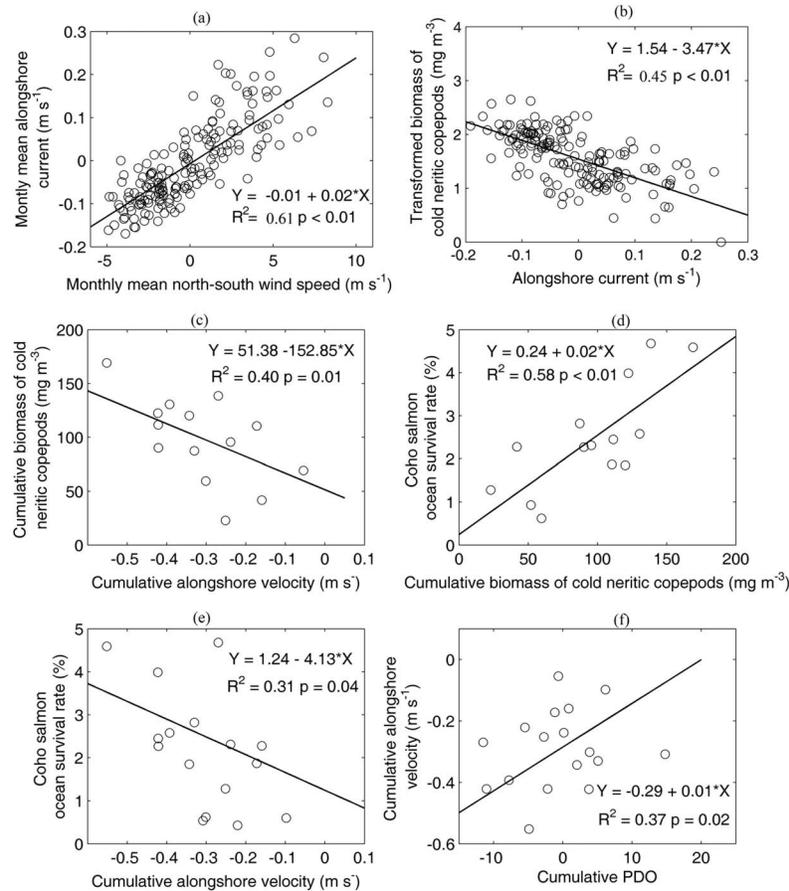
**Figure 2.** (a) Correlation between the monthly average alongshore current speed and alongshore wind speed. (b) Correlation between the monthly average alongshore current velocities and the quad-root transformed biomass of cold water copepods. (c) Correlation between the cumulative biomass of cold neritic copepods and cumulative alongshore transport from April to December. (d) Correlation between the mean biomass of cold water copepods from April to December and the "marine survival" rate of juvenile coho (*Oncorhynchus kisutch*) in the same year. (e) Correlation between the cumulative alongshore transport from April–December and the "marine survival" rate of juvenile coho salmon survival in the same year. (f) Correlation between the cumulative alongshore transport and the cumulative PDO from April–December.

with the aid of a TSK flowmeter mounted off-center in the mouth of the net. In the lab, the plankton net samples were rinsed with freshwater, diluted to 5–10 times the settled volume and two 1-mL subsamples were removed with a Hensen-Stempel pipette and all individuals enumerated by species. Biomass values were calculated from the abundance estimates by multiplying number per cubic meter for each taxa by taxa- and stage-specific weights derived largely from the published literature. Copepod species were classified into four categories depending upon water mass affinities (see *Hooff and Peterson* [2006] for additional details). In the present study, we focused on seven cold neritic species: *Acartia hudsonica*, *A. longiremis*, *Calanus marshallae*, *Centropages abdominalis*, *Epilabidocera longipedata*, *Pseudocalanus mimus*, and *Tortanus discaudatus*. These species are characteristic of shelf waters off Oregon, Washington, Vancouver Island, and the Gulf of Alaska as well as the Bering Sea [*Hooff and Peterson*, 2006; *Mackas et al.*, 2001].

### 2.3. PDO, Wind Data, and Coho Salmon Marine Survival

[7] Values of the PDO were obtained from http://jisao.washington.edu/pdo. The PDO is the leading principle

component of sea surface temperature in the North Pacific and describes a low frequency climate pattern in this region [*Mantua et al.*, 1997]. Wind data were downloaded from NOAA buoy 46050 (44.64°N, 124.50°W). Wind data were decomposed into north-south and east-west components and the monthly averages of the north-south and east-west components were calculated. "Marine survival" of coho salmon (*Oncorhynchus kisutch*) is derived from the Oregon Production Index (OPI) which is calculated by summing the number of coho salmon adult caught in the fishery with the number of adults that return to their hatcheries-of-origin then dividing by the number of smolts (juveniles) released by hatcheries [*Pacific Fishery Management Council*, 2010]. The OPI coho are salmon that entered the ocean in April/May as juveniles and returned as adults in the autumn, ~1.5 years after leaving their hatcheries.

### 3. Results

[8] The alongshore current showed a strong seasonal cycle, flowing southward during the summer time, typically starting from March–April through September, and flowing northward

during the winter season, beginning in October–November (Figure 1a). The seasonal cycle of alongshore current was general consistent with alongshore (north-south) wind speed, i.e., southward wind induced southward alongshore current (Figures 1c and 1e). Correlation analysis showed that the monthly average current speed was positively correlated with wind speed (north-south component, Figure 2a, 61% of the variance explained, $p < 0.01$).

[9] The biomass of the seven cold neritic copepods also exhibited a strong seasonal pattern: high abundance in summer and low abundance in winter (Figure 1a). The biomass of cold neritic copepods fluctuated in opposite phase of the alongshore current: positive alongshore current (northward) corresponding to low biomass and negative alongshore current (southward) corresponding to high biomass. Correlation analysis on monthly alongshore current velocities and the copepod biomass showed a negative relationship (45% of variance explained, $p < 0.01$), i.e., the greater the transport of water from the north, the higher the biomass for cold neritic copepods (Figure 2b).

[10] The variation in monthly average alongshore current was generally consistent with the PDO (Figures 1b and 1d). At the monthly time scale, negative PDO in 1994, 1998–2002, 2007–2009 corresponded to negative anomalies of alongshore current (indicating strong southward flow) and positive PDO in the other years corresponded to positive anomalies of alongshore current (and weaker flow). However, the anomalies of alongshore current were more variable than PDO (Figure 1d). At the annual scale, the annual cumulative alongshore transport was also consistent with the PDO (Figure 1f). The cumulative alongshore current from April–December was significantly correlated with the cumulative PDO values in the same period (Figure 2f, 37% of variance explained, $p = 0.02$).

[11] The cumulative transport, from April to December, was significantly correlated with the mean biomass of cold neritic copepods and coho salmon survival in the same period. The variation in cumulative transport showed negative correlation with the mean biomass of cold neritic copepods suggesting that the greater the transport from north, the higher the biomass of cold neritic copepods (Figure 2c, 40% of variance explained, $p = 0.01$). The mean biomass of cold neritic copepods was also positively correlated with the survival rate of juvenile coho salmon in the region (Figure 2d, 58% of variance explained, $p < 0.01$), while the cumulative transport from the south showed negative impacts on juvenile coho salmon survival rates (Figure 2e, 31% of variance explained, $p = 0.04$). Thus, the arrival of more water from north (negative transport) led to greater abundances of neritic copepods and higher salmon survival (explaining ~58% of the variance in annual coho survival).

## 4. Discussion

[12] The current study provides supporting evidence for a mechanistic understanding for some previous studies of zooplankton in the Northern California Current system, which have hypothesized that transport controls climate-correlated shifts in species composition [*Hooff and Peterson*, 2006; *Mackas et al.*, 2001]. We showed that the cumulative alongshore transport reflected changes in large scale forcing and explained the variation in the biomass of cold neritic copepods at monthly and annual scales. The semi-annual alternation of coastal currents off Oregon has been known for decades [*Sverdrup et al.*, 1942], with the coastal branch of the California Current) flowing south in summer and the coastal "Davidson Current" flowing north in winter. Similarly the presence of a cold-water (northern) copepod community in summer and a warm-water (southern) copepod community in winter was noted by *Peterson and Miller* [1977]. These results should not be surprising, since zooplankton, being planktonic, by definition "go where the water goes". Thus the study described here quantifies these relationships and shows that inter-annual variations in transport and copepods species composition in coastal waters are linked to basin-scale forcing.

[13] The annual cumulative transport also explained a large portion (45%) of the variance in annual juvenile coho salmon survival in this region, suggesting that transport helps explain the correlations between PDO and salmon [*Francis and Hare*, 1994; *Beamish et al.*, 2000; *Logerwell et al.*, 2003; *Mantua et al.*, 1997]. Knowledge of the role of transport in determining copepod community structure in the upwelling zone off Oregon explains the correlations of "northern copepods" with coho salmon that reside off Oregon, as first published by *Peterson and Schwing* [2003]. The link between copepods and salmon was further explored by *Peterson and Hooff* [2005], *Hooff and Peterson* [2006], and *Peterson* [2009] who suggested that when the PDO is in a persistent phase (either cool or warm) there is a chain of events that leads to either good or poor ocean conditions. When the PDO is persistently negative, waters which upwell are cold, salty and have higher nutrient content compared to years when PDO is persistently positive [*Chhak et al.*, 2009]. Waters which upwell during negative PDO are influenced more by a sub-arctic water type whereas when the PDO is positive, a subtropical water type dominates coastal waters in the Pacific Northwest. The result is a food chain that is anchored by large sub-arctic lipid-rich copepods when PDO is negative but smaller sub-tropical lipid-deplete copepods when PDO is positive. Thus, during years when the PDO is negative, the lipid-rich food chain favors coho salmon which need to accumulate vast amounts of body fat both to survive their first winter at sea [*Beamish et al.*, 2004], and to fuel their upstream spawning migration one year later.

[14] Our investigations on alongshore transport highlights the importance of the source waters that feed the northern California Current. Recent papers [e.g., *Schwing et al.*, 2010] point to the need to understand how basin scale physical signals propagate to local scales and how these signals in turn affect ecosystem structure. It should be clear from our work here that basin scale signals, manifested by the PDO, and seasonal changes in local winds, affect alongshore currents which in turn set copepod community structure off the Oregon coast, thus providing a mechanism that links the PDO with salmon. Moreover, this study may perhaps serve to provide a mechanism to understand the synchronies among populations and teleconnection patterns at different spatial scales discussed by *Alheit and Bakun* [2010]. Further research on the source of the water mass entering the region will provide useful information on the current status of the coastal ecosystem of the northern California Current.

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