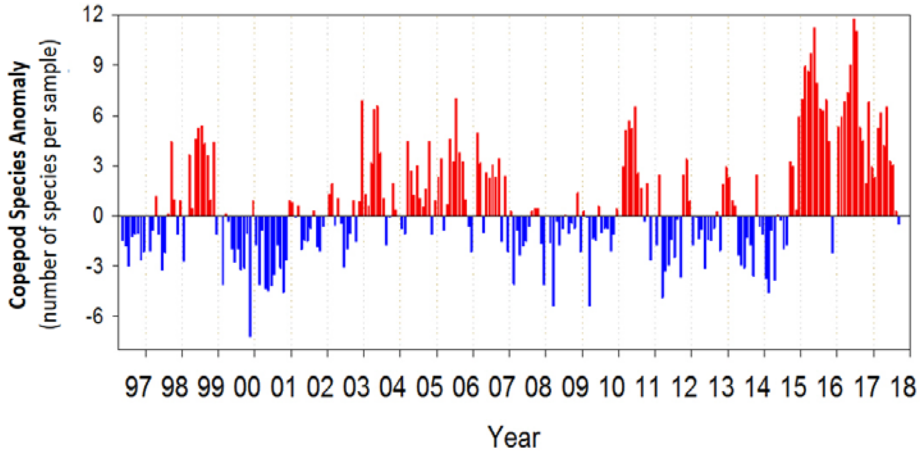
COPEPOD POPULATIONS

Variations in copepod populations in the Northern California Current Ecosystem reflect large-scale and regional changes in ocean circulation patterns.

Copepods are small marine crustaceans that comprise a large and diverse group of species that are a major food source for fish, whales, and seabirds. Copepods are planktonic, that is, they drift with the ocean currents.

Calanus marshallae

Figure 1. Monthly anomalies of copepod species richness*



Source: NOAA/NWFSC, 2017a,b

****Copepod species richness** is the **number of copepod species** in a plankton sample. The anomaly is the difference between the monthly average and the long-term monthly average copepod species richness values.*

Note: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

What does the indicator show?

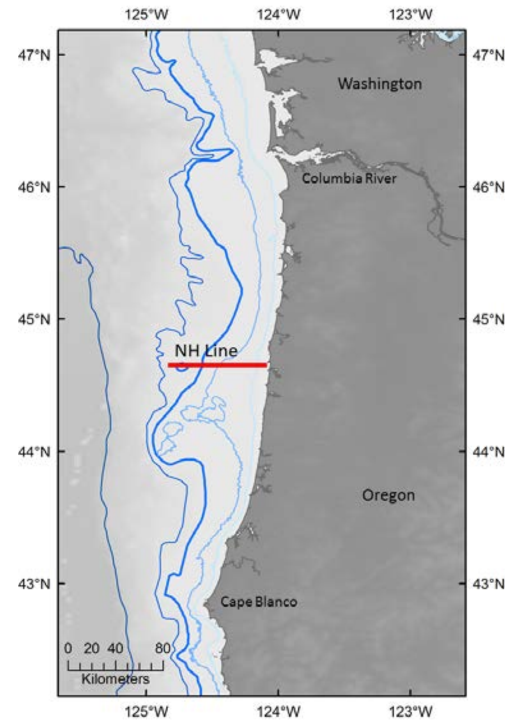
As shown in Figure 1, copepod species richness has fluctuated throughout the last two decades with low anomalies from 1999 until 2002, generally high anomalies from 2003 until 2007, followed by a mixed pattern until a very high jump in species richness in much of 2015 through the summer of 2017. The data in Figure 1 are from a monitoring site off the coast of Newport, Oregon, which is about 300 kilometers north of Crescent City, California, in the northern portion of the California Current System (Figure 2).

Because copepods drift with ocean currents, they are good indicators of the type and sources of waters transported into the northern California Current. Thus, changes in copepod populations at this site are indicative of changes occurring off the California coast.

The copepod *species richness* index represents the average number of copepod species in monthly plankton samples (see *Data Characteristics* for more details). Figure 1 presents monthly anomalies — or departure from the long-term monthly average — in copepod species richness values. These data are derived by subtracting the long term average (using the base period of 1996-2014) of species richness from the observed monthly average. Values are negative when the observed number of copepod species is less than the long-term monthly average, and positive when the observed number is greater.

Negative values in species richness anomalies generally indicate that the copepods are being transported to the monitoring location chiefly from the north, out of the coastal subarctic Pacific which is a region of low species diversity. Copepods from this cold-water region are referred to as northern species. Two of the northern species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich, containing wax esters and fatty acids that appear to be essential for many pelagic fishes to grow and survive through the winter (Miller et al., 2017). Positive values in species richness anomalies generally indicate that the waters originate either from the south or from offshore, which are warmer, subtropical low-salinity waters containing a more species-rich planktonic fauna, referred to as southern species. These southern copepod species are generally smaller than northern species, and have low lipid reserves and nutritional quality.

Figure 2. Location of monitoring site ("NH Line")

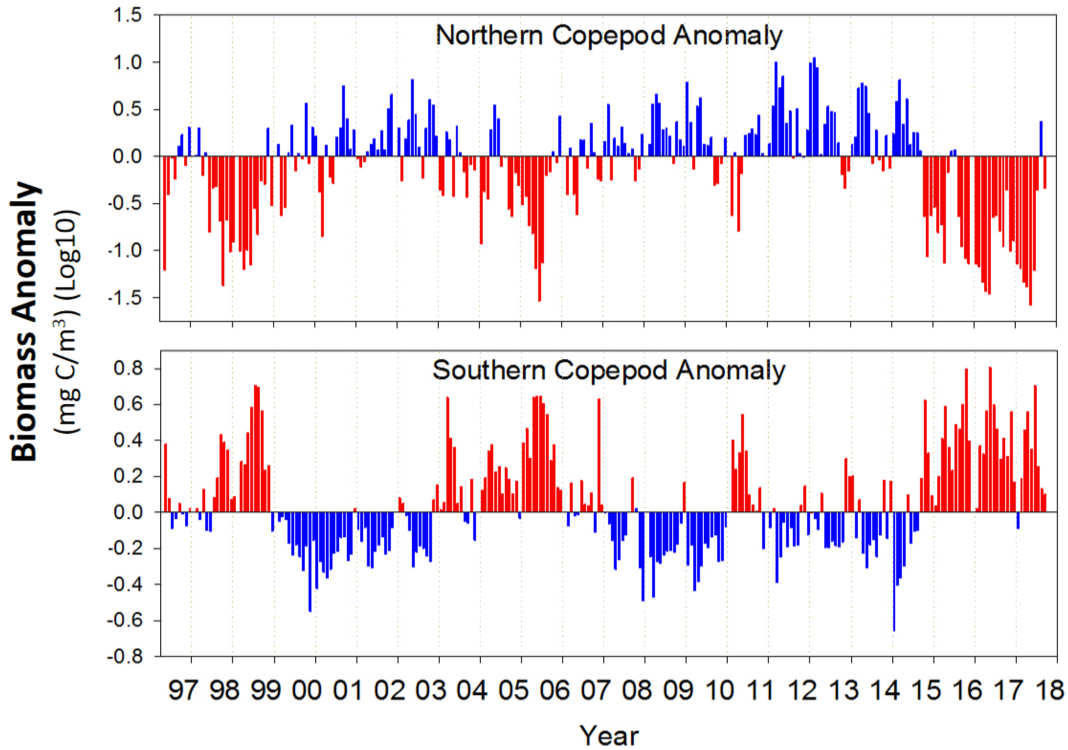


Source: NOAA, 2017

Figure 3 shows the abundance (in milligrams of organic carbon biomass per cubic meter of water) of two copepod groups (see also *Data Characteristics*) based on the affinities of copepods for different water types (i.e., temperature and salinity; Hooff and Peterson, 2006). The main species occurring at the monitoring site are classified into two groups: those with cold-water affinities (northern copepods) and those with warm-water affinities (southern copepods). The cold-water species usually dominate the coastal zooplankton community during the summer, while the warm-water species are usually dominant during the winter. Zooplankton anomalies are on a log10 scale and represent a multiplicative (not additive) scaling relative to the average seasonal cycle: for example, an anomaly of +1 means that observations average 10 times the 1996–2014 monthly average.

Figures 1 and 3 show how the cycle of copepod richness and copepod biomass are related. Over the 22-year time series, during periods when the copepods are dominated by cold water northern species (positive biomass anomalies of northern copepods; Figure 3, top graph), there were usually negative anomalies of southern copepod species (Figure 3, bottom graph) and lower than average species richness (Figure 1). These low frequency changes are independent of the seasonal pattern of low species richness in the summer and high richness in the winter. Throughout much of 2015 and into the summer of 2017, large populations of southern copepod species dominated the coastal waters, and species richness was the highest observed in the 22-year time series as a result of warming ocean temperatures (described below).

Figure 3. Monthly anomalies of copepod biomass*



Source: NOAA/NWFSC, 2017a and b

****Copepod biomass*** *is abundance in* ***milligrams of organic carbon biomass per cubic meter of water****. The anomaly is the difference between the monthly average and the long-term monthly average copepod biomass values.*

Note: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

While copepod population metrics predominantly describe interannual to decadal climate variability, it is likely to indicate long-term climate change, since changes in ocean transport and water mass source are responsive to variations in global climate. Over time, these indices may reveal a clear trend toward one dominant group of copepod species due to climate change.

Why is this indicator important?

Copepods are the base of the food chain, eaten by many fish (especially anchovies, sardines, herring, smelt and sand lance), which in turn are consumed by larger fish, sea mammals and seabirds. Because they are planktonic, copepods drift with the ocean currents and therefore are good indicators of the type of water being transported into the northern California Current. Tracking copepods provides information about changes occurring in the food chain that fuels upper trophic-level marine fishes, birds, and mammals. Knowledge of year-to-year variations in their abundance and species composition predict the abundance of small fishes, as well as species that feed on these fish (Peterson et al., 2014). As noted above, “northern species” are larger and bioenergetically richer than the “southern species.” When copepods largely consist of northern species, the pelagic (water column) ecosystem is far more productive than when southern species dominate.

It is noteworthy that the four years of positive anomalies of northern copepod species from 1999-2002 are correlated with extraordinarily high returns of Coho and Chinook salmon to the rivers of California and Oregon. Conversely, during the years 2003-2007 and 2014-2016, when salmon returns began to decline dramatically, positive anomalies of southern copepod species were occurring. These observations reflect a rich food chain from 1999-2002 and an impoverished food chain from 2003-2007 and 2014-2017.

Like other zooplankton, copepods are useful in the study of ecosystem response to climate variability. Due to their short life cycles (on the order of weeks), their populations respond to and reflect short-term and seasonal changes in environmental conditions and are sensitive to the magnitude of environmental change (Fisher et al., 2015). Moreover, many zooplankton taxa are indicator species whose presence or absence may represent the relative influence of different water types on ecosystem structure.

Copepod species reflect ocean transport processes in the northern California Current. For instance, in both 2015 and 2016, the seasonal springtime shift from a warm southern copepod community to a cold summer northern community did not occur. The copepod community remained with the lowest biomass of lipid-rich northern copepods and the highest biomass of small tropical and sub-tropical southern copepods in the 22-year time series. Anomalously low numbers of copepod species (i.e., a "negative species enrichment anomaly”) indicate the transport of coastal subarctic water into the coastal waters of the northern California Current (1999-2002; 2011 to 2014). Anomalously high species numbers are associated with either a greater amount of onshore transport of warm, offshore, subtropical water, or northward transport of subtropical coastal water along the coastal corridor (as happened in late 2002 to early 2006, and during 2014-15). The species richness remained high throughout 2016, peaking during the summer months when species richness is generally the lowest (Figure 1; Peterson et al., 2017).

Finally, copepod populations may give an advance warning of major changes in ocean conditions. Copepod indices have proven useful for the prediction of the returns of Chinook and Coho salmon (Peterson and Schwing, 2003; Peterson et al., 2014), and forecasts of salmon survival have been developed for the Coho and Chinook salmon runs along the Washington/Oregon coasts based on copepod indices (NOAA, 2018) (see *Sacramento fall-run Chinook salmon abundance* indicator). These same copepod indices have been correlated with the recruitment, that is the addition of young to a population, of the invasive green crab along the west coast of the US (Yamada et al., 2015); anchovy (Emmett, personal communication); and sablefish, rockfish, and sardine

(Peterson et al., 2014). They have also correlated with seabird nesting success in Central California (Jahncke et al., 2008; Wolf et al., 2009; Manugian et al., 2015; also see *Cassin's Auklet breeding success* indicator) and seabird mortality off northern Washington (Parrish, personal communication).

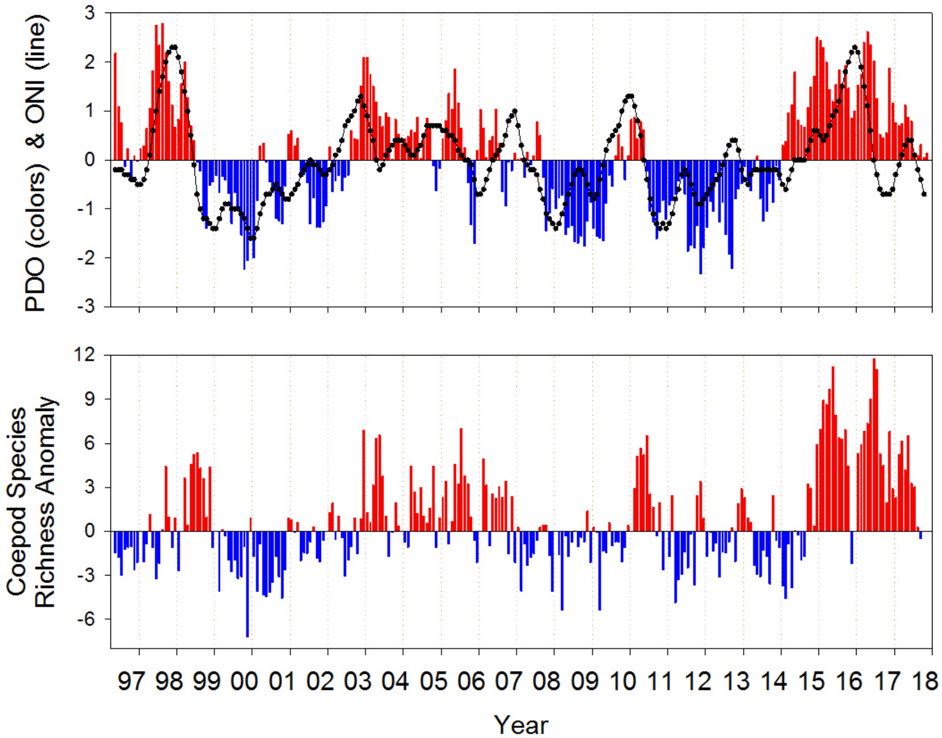
What factors influence this indicator?

Copepod dynamics in this region of the California Current display strong seasonal patterns, influenced by circulation patterns of local winds and coastal currents. The copepod community tends to be dominated by cold-water species during the upwelling season, typically from May through September, as winds blow toward the equator and subarctic waters are transported southward from the Gulf of Alaska. As noted above, the cold-water copepod species are characterized by low species diversity. During winter, offshore warmer waters from the south carry more zooplankton species-rich water to the Oregon continental shelf. During the spring, there is a shift back to the upwelling season with increased northern copepod species and decreased species richness.

The interannual patterns of species richness and biomass anomalies of copepods with different water-type affinities are found to track measures of ocean climate variability (Fisher et al., 2015). The Pacific Decadal Oscillation (PDO) is a climate index based on sea surface temperatures across the entire North Pacific Ocean. When the ocean is cold in the eastern Pacific, the PDO has a negative value; when the ocean is warm in the California Current, the PDO has a positive value. In addition to atmospheric conditions in the North Pacific Ocean (as indexed by the PDO), coastal waters off the Pacific Northwest are also influenced by equatorial Pacific conditions, especially during El Niño events. The presence or absence of conditions resulting from the El Niño Southern Oscillation is gauged using the Oceanic Niño Index (ONI). Positive ONI values indicate warming (El Niño) conditions at the equator, while negative values indicate cooling in the eastern equatorial Pacific.

In Figure 4, the upper panel shows two time series: monthly values of the PDO (red and blue bars) and the ONI (black dotted line). The lower panel is the same graph as Figure 1 (monthly anomalies in copepod species richness). There are clear relationships between interannual variability in the physical climate indicators (PDO and ONI) and copepod species richness anomalies. The switch to a positive PDO in 2014 corresponded with high species richness in 2014 through the summer of 2017. The biomass anomalies of the southern and northern copepod species also ocean climate variability. When the PDO is negative, the biomass of northern copepods is high (positive) and the biomass of southern copepods is low (negative), and vice versa (not shown).

Figure 4. PDO and ONI ocean indices (upper) and copepod species richness (lower) anomalies



Source: NOAA/NWFSC, 2017b

Top graph: Blue bars indicate colder waters; red bars warmer waters.
Lower graph: Blue bars indicate that copepods are being transported chiefly from northern, colder waters; red bars, from southern, warmer waters or offshore.

The shift to high richness anomalies observed in 2014 and persisting through summer 2017 originated from an intrusion of warm water (dubbed the “warm blob”) into the Oregon shelf due to the North Pacific marine heat wave originated in late 2013. Subsequently, the North Pacific heat wave interacted with an El Niño developing in the equatorial Pacific in 2015 resulting in an unusually long period of strong warm anomalies (Peterson et al., 2017). Because of the anomalously warm ocean conditions throughout much of 2015 and 2016, the copepod community was dominated by warm-water species while the biomass of northern species was lower than usual. These conditions lead to poor feeding conditions for small fish, that in turn are prey for juvenile salmon, affecting the local hydrography and pelagic communities. As previously stated, the seasonal shift from a winter warm copepod community to a cold summer community did not occur in 2015 or 2016. However, in July 2017, the copepod community did shift to a community dominated by cold water species and the species richness also dropped to average levels. This is the first indication that the pelagic ecosystem might be returning to normal following 3 years of anomalous conditions that far exceeded previous perturbations the past 22 years (Wells et al., 2017).

Technical Considerations

Data Characteristics

The copepod data are based on biweekly sampling off Newport, Oregon, and are usually available by the end of each month. The sampling station is a coastal shelf station located 9 kilometers offshore, at a water depth of 62 meters. Samples are generally collected during daylight hours, using nets hauled from 5 meters off the bottom to the surface. One milliliter subsamples containing 300-500 copepods were used to enumerate copepods by species, developmental stage, and taxa-specific biomass estimated from literature values or the investigators' unpublished data of carbon weights. Samples collected from 1996 through May 2017 were counted by the same person, thereby limiting taxonomic inconsistencies or bias among plankton counters.

Northern and southern biomass anomalies are derived by converting counts to biomass using length-to-mass regressions and standardized to units of mg Carbon m^{-3}. The copepod biomass data (mg C m^{-3}) are averaged monthly and transformed by taking the base 10 logarithm, specifically log10 (x + 0.01). Monthly biomass anomalies are calculated for each species using 1996–2014 as the base period. Species are grouped based on their water mass affinities (southern or northern), and the individual biomass anomalies are averaged within each group (southern and northern) (Fisher et al., 2015).

Values are posted on two websites (https://www.nwfsc.noaa.gov/oceanconditions and https://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/indicators/climate-and-ocean-drivers.html) and updated annually. Monthly values are available to anyone who requests them. Details of the sampling program and data analysis can be found in Peterson and Schwing, 2003; Peterson and Keister, 2003; and Fisher et al., 2015.

Strengths and Limitations of the Data

This 22-year time series represents the longest biological monitoring of lower trophic levels in the northern California Current. While longer time series of physical variables (e.g., PDO) provide important context for understanding variability over decadal scales, these monitoring efforts provide the foundation for examining relationships between copepod populations and fish, birds, and mammals.

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