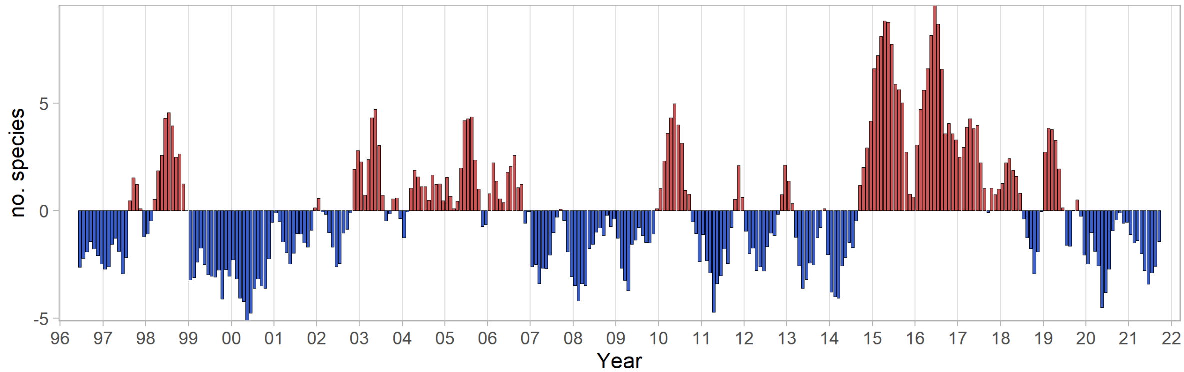
COPEPOD POPULATIONS

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

Figure 1. Monthly anomalies of copepod species richness in the northern California Current System*



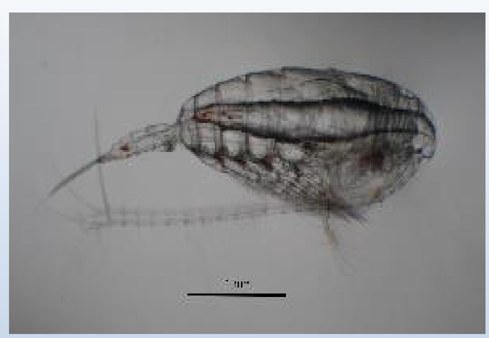
Source: NOAA/NWFSC, 2021

**Copepod species richness is the number of copepod species in a plankton sample. The monthly anomaly is the difference between the monthly average and the long-term monthly average of copepod species richness values. Samples are collected from the northern California Current, which flows along the west coast of North America, from southern British Columbia to Baja California*.

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 since the late 1990s with no clear trend. The data 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 (see Figure 2). Low anomalies occurred 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 mid-2018, before returning to negative anomalies in 2020 and 2021. The copepod *species richness* index represents the average number of copepod species collected in monthly plankton samples (see *Data Characteristics* for more details). Figure 1 presents monthly anomalies — that is, the departure from the long-term monthly

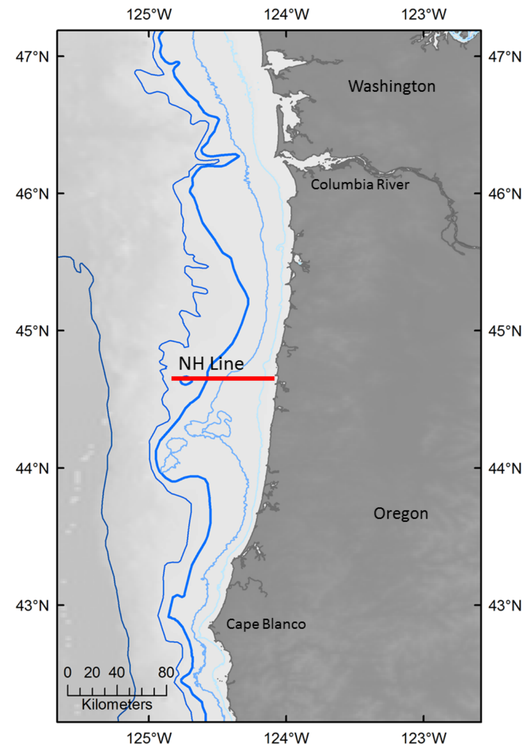


Calanus marshallae

Copepods are a large and diverse group of small marine crustaceans and a key component of the food chain. They link primary producers (such as algae and other phytoplankton) and higher trophic levels such as fish, whales, and seabirds.

average — in copepod species richness values. 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. While copepod population metrics such as species richness (Figure 1) and biomass (Figure 3) predominantly describe interannual to decadal climate variability, they likely indicate long-term climate change, since changes in ocean transport and water mass source are responsive to variations in global climate.

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



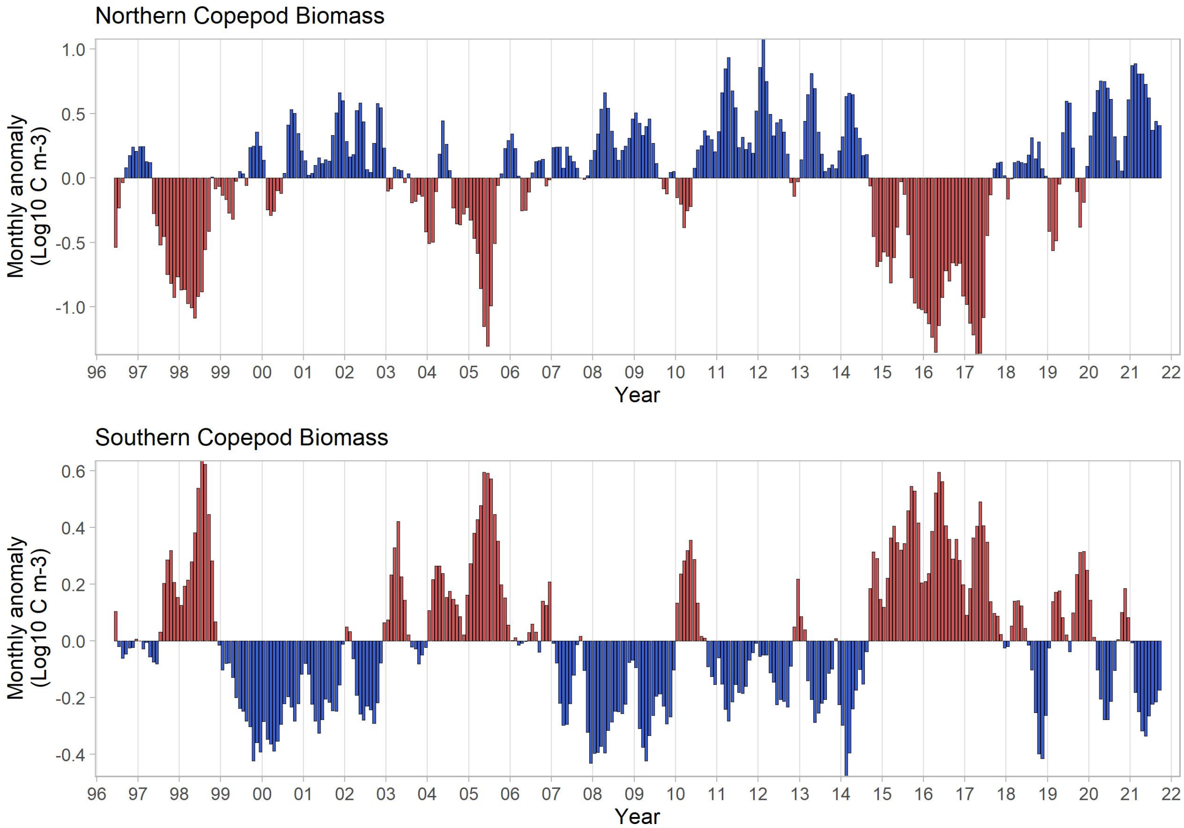
Source: NOAA/NWFSC, 2021

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 off Oregon are also indicative of changes occurring off the California coast. These changes impact all levels of the food chain in California's marine ecosystems.

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. While 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.

Figure 3 shows the abundance, in milligrams of organic carbon biomass per cubic meter of water, of two copepod groups based on the affinities of copepods for different water masses (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). 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). Therefore, positive biomass anomalies of northern copepods generally translate to the base of the food web composed of lipid rich copepods. On the contrary, the southern copepod species are generally smaller than the northern species, and have low lipid reserves and nutritional quality. Therefore, positive biomass anomalies of southern copepods generally translate to the base of the food web composed of lipid poor 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 1996–2021 monthly average.

Figure 3. Monthly anomalies of copepod biomass in the northern California Current System *



Source: NOAA/NWFSC, 2021

**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 of 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.

Figures 1 and 3 show how the cycle of copepod richness and copepod biomass are related. Over the 25-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 25-year time series as a result of anomalously warm ocean temperatures (described below).

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, marine 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. 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.

Year-to-year variations in the species composition and abundance of copepods has been correlated to the abundance of small fishes, as well as species that feed on these fish (Peterson et al., 2014). For example, following four years of positive anomalies of northern copepod species from 1999-2002, extraordinarily high returns of Coho and Chinook salmon occurred in 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 2014-2016.

Like other zooplankton, copepods are useful indicators of the 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 ocean transport processes and perturbations in the northern California Current on ecosystem structure. For example, during the marine heat wave in 2015 and 2016 (see *Coastal ocean temperature* indicator), the seasonal springtime shift from a warm southern copepod community to a cold summer northern community did not occur. The lowest biomass of lipid-rich northern copepods and the highest biomass of small tropical and sub-tropical southern copepods in the 25-year time series occurred during this time period. This time period was also marked by novel ecosystem states and unprecedented changes in the distribution, timing and abundance of species ranging from phytoplankton, zooplankton, and fish to whales (Cavole et al. 2016, Peterson et al., 2017, Morgan et al. 2019).

Finally, copepod populations may give an advance warning of major changes in the ocean ecosystem. 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/NWFSC, 2021 and also see *Chinook salmon abundance* indicator). These same copepod indices have been correlated with the recruitment of the invasive green crab along the west coast of the US (Yamada et al., 2015, 2021); and the recruitment of sablefish, rockfish, and sardine in the northern, central and southern California Current respectively (Peterson et al., 2014). They have also been 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), seabird mortality off northern Washington (Parrish, personal communication), and nest occupancy rates of the iconic and threatened seabird the marbled murrelet (Betts et al., 2020).

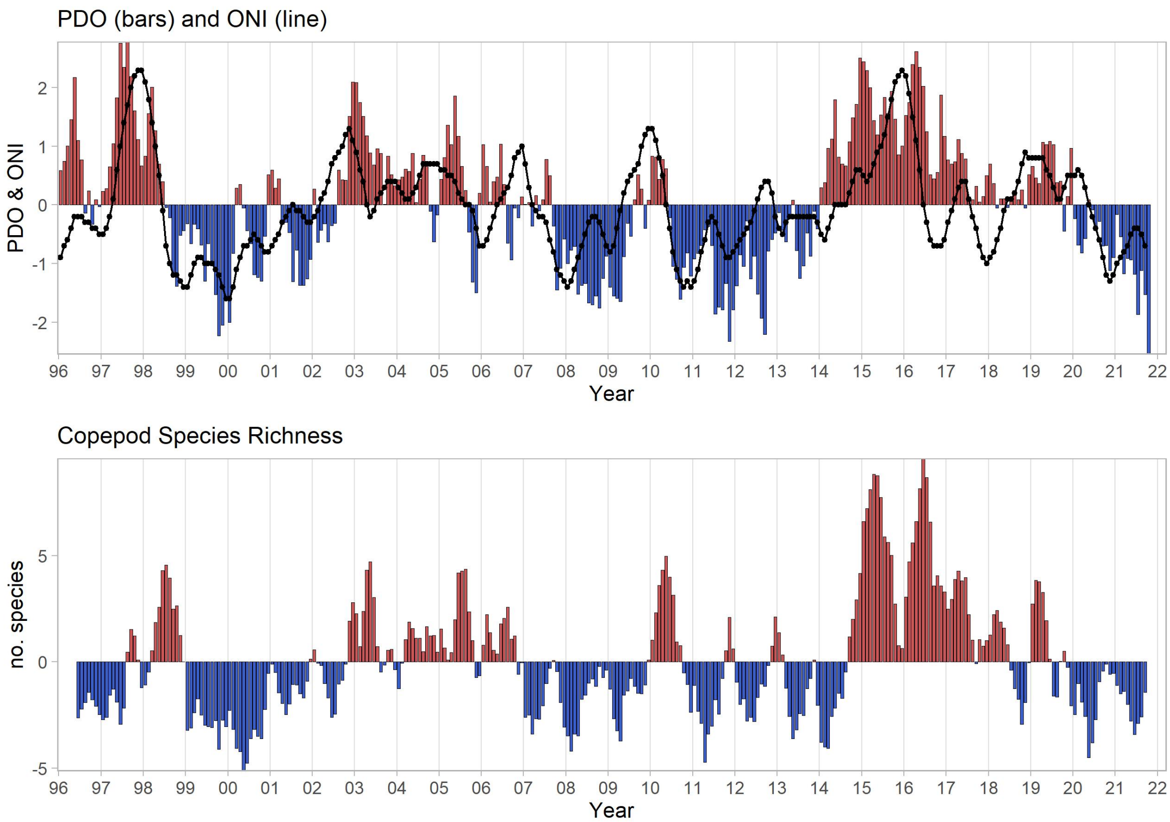
What factors influence this indicator?

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 (Hooff and Peterson, 2006).

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 (Keister et al. 2011, 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 California Current, the PDO has a negative value; when the ocean is warm in the California Current, the PDO has a positive value. Coastal waters off the Pacific Northwest are also influenced by equatorial Pacific conditions, especially during El Niño events. The Oceanic Niño Index (ONI) tracks sea surface temperature anomalies at the equator, where positive ONI values indicate warming (El Niño) conditions, while negative values indicate cooling conditions.

Figure 4 shows the relationship between the PDO and ONI ocean indices and copepod species richness. 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 the 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. When the PDO turned negative again in 2020, species richness also declined. The biomass anomalies of the southern and northern copepod species also track 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. Relationship between the Pacific Decadal Oscillation and Oceanic Niño Indices (upper) and copepod species richness (lower) anomalies



Source: NOAA/NWFSC, 2021

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 that originated in late 2013 (Bond et al., 2015). 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, which 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.

Technical considerations

Data characteristics

The copepod data are based on biweekly to monthly 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.

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–present 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 updated annually and posted on two websites (https://www.fisheries.noaa.gov/west-coast/science-data/local-biological-indicators and https://www.integratedecosystemassessment.noaa.gov/regions/california-current-region/indicators/climate-and-ocean-drivers.html). Monthly values are available here https://www.fisheries.noaa.gov/content/newportal-blog-northwest-fisheries-science-center. 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 25-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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