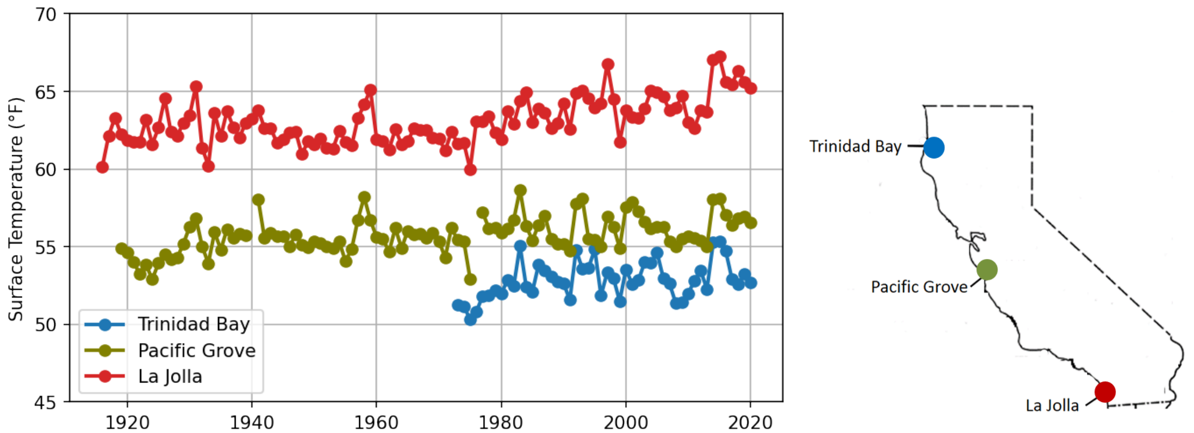
COASTAL OCEAN TEMPERATURE

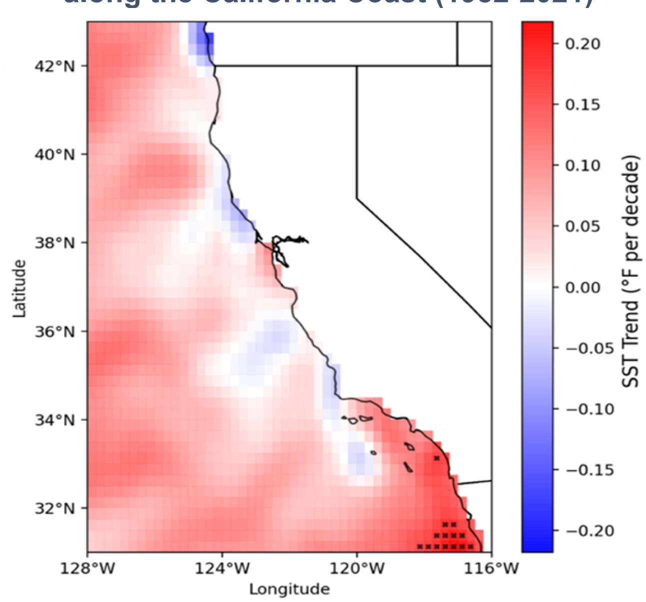
Measurements at California's shore stations show that nearshore coastal waters have warmed over the past century, particularly in Southern California. Similarly, satellite-based records over the past four decades show warming ocean waters off Southern California. An unprecedented marine heatwave affected the West Coast of the United States from 2014 to 2016.

Figure 1. Annual average sea surface temperatures (SST) at selected shore stations (1916-2020)



Source: SIO. 2021

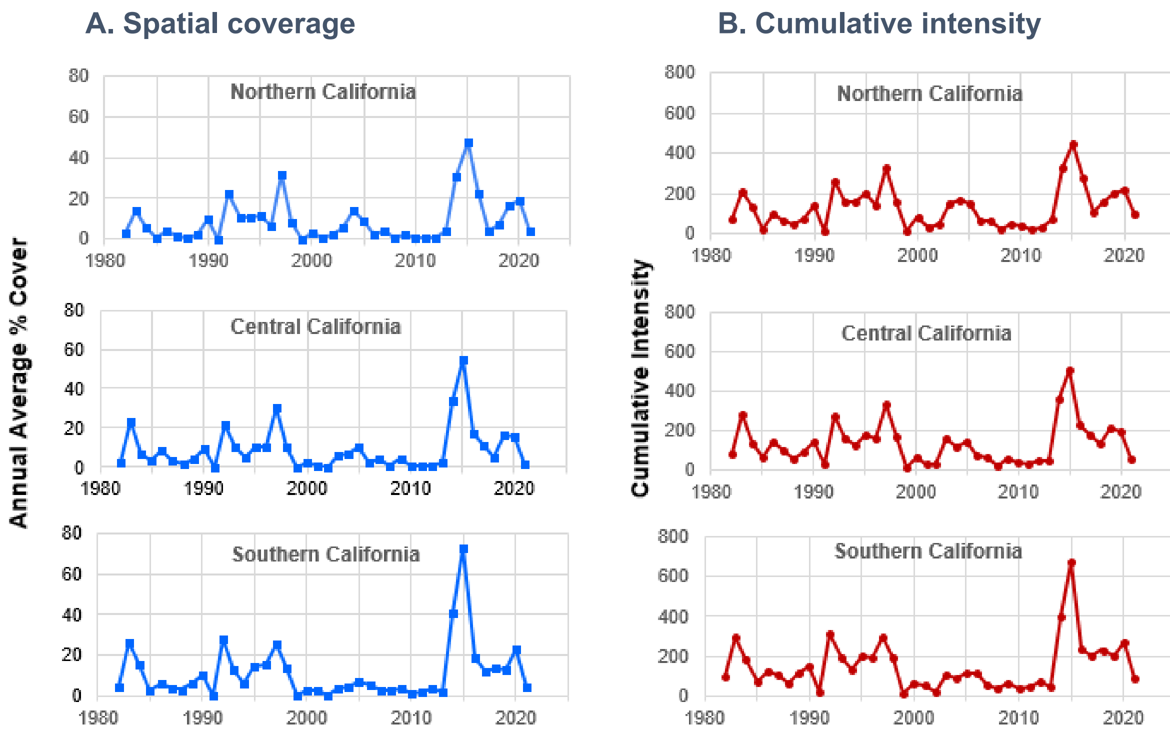
Figure 2. Satellite-based sea surface temperature (SST) trends along the California Coast (1982-2021)



Source: NOAA, 2021a

The map shows SST trends off the California coast, in °F per decade, for the 40-year period (1982 to 2021). Black dots (one off San Diego County; the rest off Mexico) denote locations with statistically significant trends (p<0.05).

Figure 3. Marine heat waves off California (1982-2021)



Source: Data provided by Leising, 2022; also available at NOAA, 2022

*A **marine heat wave** occurs over a region when the difference between the sea surface temperature (SST) and the long-term mean (1971-2000) is above the 90th percentile of all values for a given location on a given day of the year. **[A]**: **Spatial coverage** is the annual average percentage of the region in heat wave status; **[B]**: **Cumulative intensity** is the annual sum of daily average SST measurements above the long-term mean. See Figure 4 for a map of the regions.*

What does the indicator show?

California coastal ocean temperatures have warmed over the past century. Although sea surface temperature (SST) fluctuates naturally each year, warming SST trends of are clearly detected. The longest time series for SSTs are based on measurements at shore stations along the California coast. Figure 1 presents data for three of these stations. SST has increased at the rate of 0.2 degree Fahrenheit (°F) per decade at Pacific Grove between 1919 and 2020, and at a faster rate of 0.3°F per decade at La Jolla between 1916 and 2020. At Trinidad Bay, SSTs increased at the rate of 0.3°F per decade over a shorter time period (1973-2016). All three stations show statistically significant trends ($p<0.05$). SSTs have also increased at other shore stations along the coast (Table 1). Stations farthest south, La Jolla and San Clemente, are experiencing the most warming.

Table 1. Trends in sea surface temperature (°F per decade) at shore stations (p-values less than 0.05 indicate statistical significance.)

Station	Years	Decadal Trend	*p*-value
Trinidad	1973 - 2020	0.34	0.007
Farallon Island	1925 - 2020	0.09	0.061
Pacific Grove	1919 - 2020	0.18	< 0.001
Granite Canyon	1971 - 2020	0.33	0.001
Santa Barbara	1955 - 2020	0.23	0.009
Point Dume *	1956 - 2020	0.21	0.067
Newport Beach	1924 - 2020	0.08	0.194
San Clemente	1965 - 2020	0.39	< 0.001
La Jolla	1916 - 2020	0.27	< 0.001

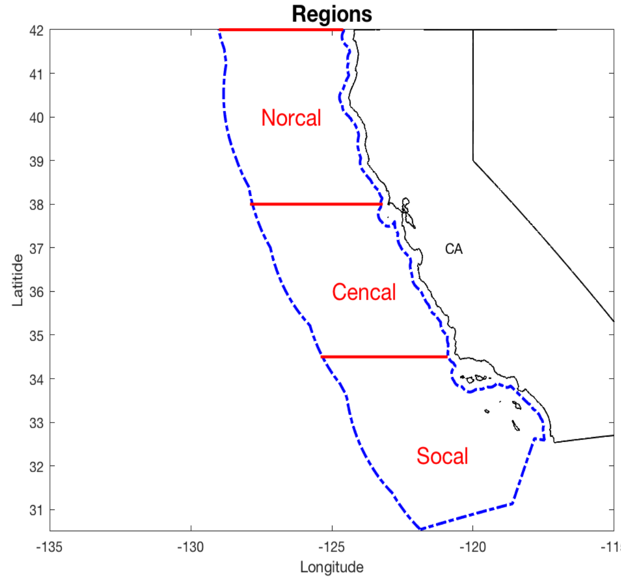
**Uncertain values for Point Dume between 1995 and 2006 were not included in the analysis.*

Globally, average SSTs have increased by 0.88°C (~1.58°F) since the beginning of the 20th century (IPCC, 2021). The global surface temperature — over both land and oceans — has warmed at a rate of about 0.14°F per decade since 1880; the rate of warming from 1981 to 2020 was over twice that rate, at 0.32°F per decade, reflecting sharper increases in sea surface temperatures over the recent period (NOAA, 2021). The Southern California coastal trend over the last four decades is consistent with that sharp global increase.

Four decades of satellite-based data from the National Oceanic and Atmospheric Administration Optimal Interpolation SST reanalysis (NOAA OISST) allow the tracking of SST trends along the entire coast of California and offshore; this would not have been possible with shore station data alone (Huang et al., 2021; Reynolds et al., 2002). As shown in Figure 2, for the period 1982-2021, the waters over the state's continental shelf (within approximately 30 nautical miles offshore) have both warmed and cooled, although the trends are generally not statistically significant ($p>0.05$). However, offshore waters are largely warming. Both near-shore and offshore, Southern California is exhibiting a distinct warming trend compared to the rest of the state, with warming being more prominent near shore.

In recent years, prolonged periods of extremely high ocean temperatures, known as marine heatwaves (MHW), have occurred across the globe, focusing attention on their devastating effects on the marine ecosystem. Two metrics for tracking the size and intensity of MHWs are presented in Figure 3 for Northern, Central and Southern California; see Figure 4 for a map of the regions. A MHW is an extreme climate event in which anomalously warm sea surface temperatures are observed in a region (Oliver et al., 2021). Specifically, a MHW over a region occurs when the difference between the SST and the long-term or "climatological" mean for the period 1971-2000 (the difference is also known as the "anomaly") for a given time and place is above the 90th percentile of the values for a baseline period (Hobday et al., 2016). See discussion in *Technical Considerations* for more information about the metrics. As shown in Figure 3, the largest and most intense MHW recorded in the three regions of California – known as "the Blob" – occurred in 2014 to 2016. While MHWs have occurred in the past, the magnitude and duration of the warming during this event was unprecedented for the west coast of North America (Di Lorenzo and Mantua, 2016; Gentemann et al., 2017). Other notable MHWs occurred in 1983, 1992, 1997 (all associated with El Niños), and more recently in 2019 and 2020 (which, unlike MWHs associated with El Niños, originated in the south, rather than from the Central North Pacific) (Leising et al., 2015).

Figure 4. Marine heatwave monitoring off the California coast



Source: NOAA, 2022

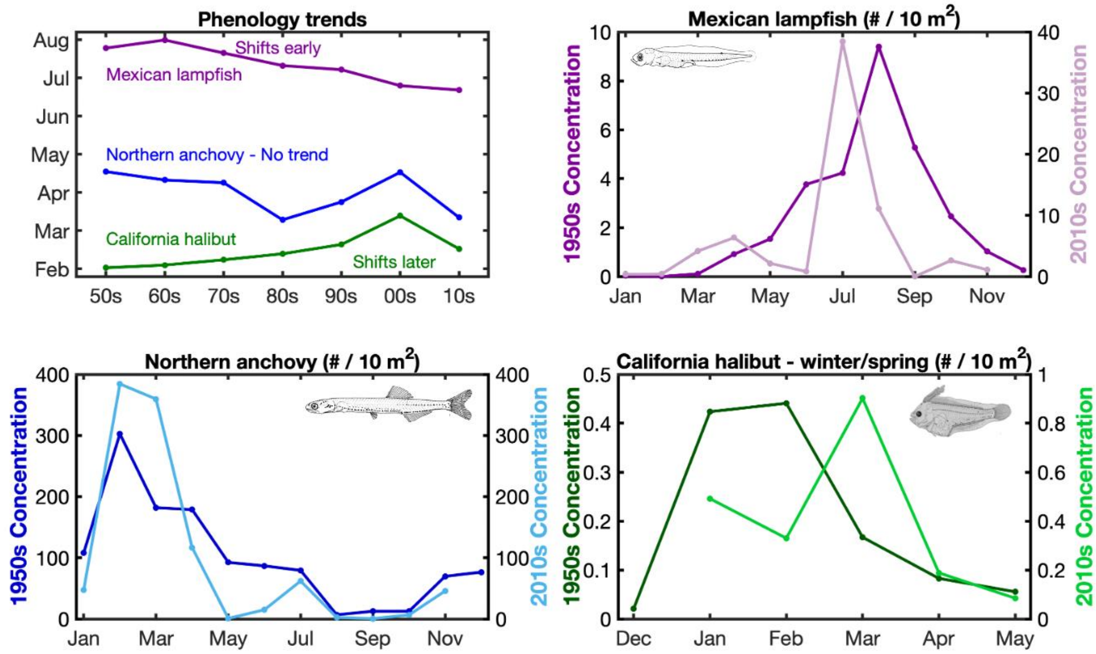
Marine heat waves are monitored along the California Current, including in three regions off the California coast designated as Northern, Central and Southern California regions.

In its latest assessment, the Intergovernmental Panel on Climate Change (IPCC) reports that MHWs have become more frequent over the 20th century, approximately doubling from 1982 to 2016; they have also become more intense and longer in duration since the 1980s (IPCC, 2021). Over the last two decades, MHWs have occurred in all of the world's ocean basins.

Why is this indicator important?

Temperature is one of the best-measured signals of climate change. As atmospheric concentrations of greenhouse gases increase, excess heat is absorbed and stored by the oceans and atmosphere. The ocean's large mass and high heat capacity allow it to store large amounts of heat. It is estimated that over 90 percent of the observed heat energy increase on the Earth over the past 50 years has occurred in the ocean (Jewett and Romanou, 2017; NOAA, 2021b; Rhein et al., 2013). In addition to absorbing excess heat, the ocean also absorbs about 30 percent of carbon emissions. As a result, the ocean acts as a buffer against global warming (IPCC, 2019).

Figure 5. Decadal changes in peak fish larvae abundance



Source: Asch, 2015; updated 2021 using data from California Cooperative Oceanic Fisheries Investigations pers comm.

Graph, top left, shows shifts in the timing of peak larvae abundance (number of fish per 10 m²) for the northern anchovy, California halibut and Mexican lampfish in Southern California waters. Separate graphs compare peak larvae abundance in the 1950s with the 2010s for three fish species. Peak timing shifts earlier in the year for Mexican lampfish and later for California halibut; northern anchovy showed no trend.

Changes in SST along the coast of California have been shown to alter the distribution, abundance, and recruitment of many marine organisms, including commercially important species. Fluctuations in the distribution and abundance of many California coastal marine populations have been related to temperature variability (e.g., Goericke et al., 2007; IPCC, 2019; Sagarin et al., 1999). The direct effects of temperature on the physiological performance of marine organisms and the timing of their key developmental stages (such as from egg to larva) are the likely mechanisms underlying these patterns. Several fish species have shifted their spawning phenology between the 1950's to the 2010's due to increased ocean temperature (Asch, 2015). Commercial species such as California Halibut shifted to reproduce earlier while prey fish Mexican Lampfish and Northern Anchovy shifted to later reproduction or had no change in spawning phenology, respectively (Figure 5). Water temperature can also influence species indirectly, by altering interactions between species and their competitors, predators, parasites, facilitators, and prey.

The California Current, which extends from British Columbia, Canada to Baja California, Mexico, is one of four major "Eastern Boundary Upwelling Systems" – biologically productive marine regions that cover less than one percent of the ocean area, but provide about 20 percent of the world's ocean fish catch (Mann, 2000). In these systems, coastal upwelling creates a band of cool waters along the coast, supplying the food chain with nutrients, and providing habitat that supports high biological productivity. During the Blob, anomalously warm offshore waters in the California Current Ecosystem restricted the cool upwelling habitat to a narrow band along the coast, resulting in reduced upwelling habitat, or "habitat compression" (Santora et al., 2020). This compression was associated with changes in the composition and distribution of marine species, including whale prey. Alterations in prey abundance and distribution, in combination with a delayed Dungeness crab season and other factors, contributed to record increases in whale entanglements in fishing gear during this MHW. To support efforts to understand and mitigate the causes of whale entanglements, a recently developed "habitat compression index" (HCI) tracks patterns in the surface area of cool water over time. A low HCI value indicates that cool habitat is compressed onshore. The HCI is used to assess the likelihood of ecosystem shifts and shoreward distribution patterns of whales and other top predators. The HCI and other indicators of conditions associated with whale entanglements are presented in an online "Whale Entanglement Data Dashboard."

The extremely high temperatures during MHWs have had dramatic effects on the marine ecosystem. MHWs in the 1980's and 1990's, associated with El Niño events, led to negative consequences for the marine ecosystem through local processes (such as changes in physical and chemical properties, and food web changes) and advection, or poleward and/or onshore transport of organisms (Ohman et al., 2017). The 2014-2016 MHW was associated with mass strandings of some marine mammals and sea birds (Cavole et al., 2016; Piatt et al., 2020). High temperatures initiated toxic algal blooms that affected the commercial and recreational crab fishing season and poisoned marine mammals (Gentemann et al., 2017). The closure of the Dungeness crab fishery alone led to a loss of an estimated $48 million in revenue for crab fishermen statewide (Brown, 2016).

The MHW also contributed to the rapid and extensive loss of kelp forests in Northern and Southern California (Gleason et al. 2021, Cavanaugh et al., 2019). In Northern California this led to the closure of the recreational red abalone fishery and the commercial red sea urchin fishery (Gleason et al. 2021). Both kelp and abalone are culturally significant species to Native American Tribes, such as the Chumash and the Scotts Valley Band of Pomo Indians (Santa Ynez Band of Chumash Indians, 2022; Amah Mutsun Tribal Band, 2022; Big Valley Band of Pomo Indians and Middletown Rancheria of Pomo Indians, 2021). Since kelp provide a wide range of ecosystem services as primary producers and as essential habitat for marine organisms, among other things, the loss of kelp forests has larger scale consequences (Bell et al., 2020; Gleason et al, 2020; Teagle et al., 2017). For example, without kelp forests to act as buffers, the coast has become more vulnerable to coastal erosion from high energy storms and swell events; along with sea level rise, coastal erosion is threatening cultural sites along the shoreline in the Amah Mutsun's ancestral territory (Amah Mutsun Tribal Band, 2022).

The 2014-2016 MHW was accompanied by northward shifts in the geographic distributions of a variety of marine animals including fish, sea turtles, pelagic red crabs, southern copepods and many other marine invertebrates (Leising et al., 2015; Cavole et al., 2016; Sanford et al., 2019). During the 2014-2016 and 2019-2020 MHWs, the increased abundance of lipid-poor southern copepods and the decreased abundance of lipid-rich, higher nutritional value northern copepod impacted the entire food web (Cavole et al., 2016, Weber et al., 2021).

Temporary shifts in other species distributions have also occurred during past warm-water anomalies, including major El Niño-Southern Oscillation (ENSO) events (Pearcy and Schoener, 1987), however, these recent North Pacific-originating MHWs differ from El Niños in that they tend to bring a somewhat different assemblage of organisms into the California Current (Leising et al., 2015; Cavole et al., 2016). While the impacts of coastal temperature change are increasingly being documented, offshore temperature variability is complex and may influence a suite of other biological processes, including migration patterns.

Changes in temperature can affect the chemical and physical properties of the ocean. Since warmer water is less dense than colder water, changes in SST can alter currents and transport patterns. Warming SSTs can cause more stable layers of seawater to form near the surface, thus increasing "stratification"; when this happens, upwelling and vertical mixing that transports nutrients, oxygen, carbon, plankton and other material across ocean layers is reduced (Roemmich and McGowan, 1995; Jacox and Edwards, 2011). Temperature also affects the solubility of gases in ocean waters. For example, warmer waters hold less oxygen, while also accelerating the rate of oxygen consumption by marine organisms (e.g., Somero et al., 2015; Breitburg et al, 2018).

Surface ocean water temperature affects weather, specifically the occurrence of coastal fog and the strength of winds, as well as the thickness of the marine atmospheric boundary layer. The latter is a primary factor controlling the inland intrusion of cool coastal air and therefore inland weather patterns. Warmer waters play a role in extreme weather events by increasing the energy and moisture of the atmosphere. Warmer ocean temperatures also contribute to global sea level rise because warming water not only expands but also accelerates the melting of land-based ice sheets (IPCC, 2021).

Global oceans are projected to continue to warm in the 21st century. MHWs are expected to further increase in frequency, duration, spatial extent, and intensity, although changes will not be globally uniform (IPCC, 2021). Given the severe impacts of MHW on the marine ecosystem and the coastal communities and economies it supports, oceanographers have developed the California Current MHW Tracker as a tool for forecasting future MHWs (NOAA, 2022).

What factors influence this indicator?

Global SSTs have increased due to a net heat flux from the atmosphere stemming from the greenhouse effect. Deeper regions of the oceans have also warmed, to depths of 3000 meters during the past several decades (first documented by Levitus et al., 2001; also Levitus et al., 2012). A combination of oceanic and atmospheric processes, including ocean currents, winds, and climate modes like El Niño can lead to the periods of extremely high ocean temperature, and their classification as MHWs depends on the magnitude of 'normal' warming events in a given location (Hobday et al., 2016).

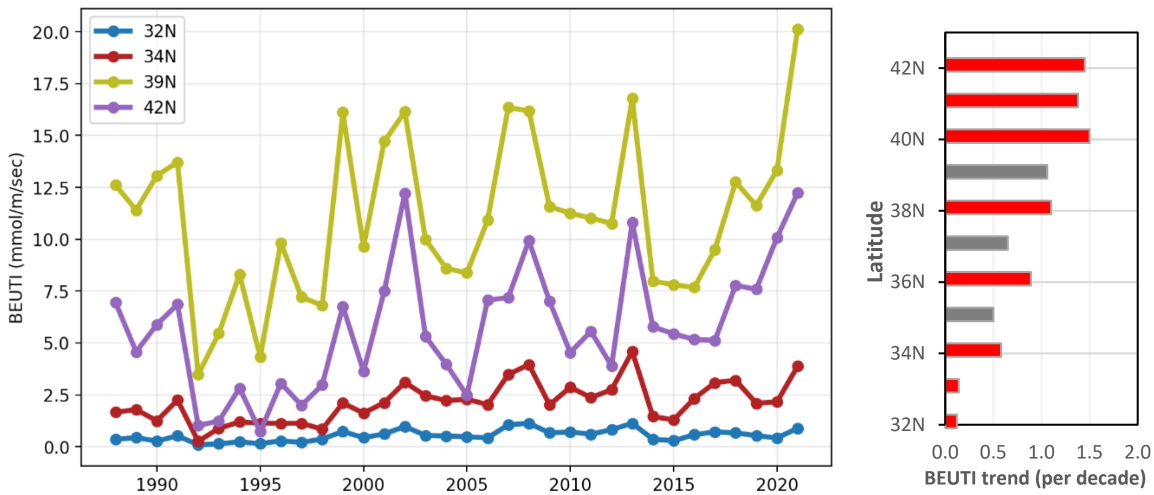
Near-surface ocean water temperatures along the California coast are influenced by seasonal upwelling, already discussed above. Historically, upwelling was measured using only estimates of the amount of water transported. A new index called the Biologically Effective Upwelling Transport Index, or BEUTI (pronounced "beauty") incorporates estimates of the amount of nutrients (nitrate) in vertically transported waters, thus providing information relevant to biological responses (Jacox et al., 2018).

As shown in Figure 6A, annual mean values for BEUTI (in millimoles of nitrate per meter per second) are highest – indicating more effective upwelling – along Northern California, especially at 39°N (due to the enhancing effect of the promontories at Point Arena and Cape Mendocino on the winds). Considerably less effective upwelling occurs along the Southern California coast at 32°N (south of San Diego) and 34°N (off Los Angeles). This difference is due to a combination of strong upwelling-favorable winds in Northern California and cooler waters flowing from the north Pacific within the California Current; the small temperature difference between surface and deeper waters means weaker stratification, which facilitates upwelling. In contrast, Southern California experiences weak upwelling-favorable winds and greater stratification, as warmer waters from the equatorial Pacific dominate (Bograd et al., 2019). Figure 6B shows that over the past 33 years, upwelling trends have generally increased along a latitudinal gradient, with larger increases in Northern California.

Figure 6. Biologically Effective Upwelling Transport Index (BEUTI) along the California Coast

A. **Annual mean values at selected latitudes**

B. **Decadal trends, 1988-2021**



Source: NOAA, 2021

[A] Annual mean values of BEUTI at selected latitudes along the California Coast: 32°N, south of San Diego; 34°N, Los Angeles; 39°N near Point Arena, and 42°N near the California-Oregon border. [B] Linear trends in the magnitude of BEUTI per decade at different latitudes along the California Coast; red bars indicate statistically significant trends (p<0.05)

Trends in coastal temperatures are complex owing to the simultaneous interaction of surface warming and the cooling effect of upwelling. In general, it is expected that surface temperatures will increase offshore and in sheltered coastal waters, where upwelling does not occur or is weak, as observed in the warming trends of La Jolla. In contrast, cooler or non-changing SSTs are expected during the upwelling season in open shelf waters (Seabra et al., 2019), especially off Central and Northern California (García-Reyes and Largier, 2010; Largier et al., 2010). The lack of statistically significant warming trends in the Central and Northern California coast in the last four decades may be an indication of the cooling effect of upwelling in coastal waters. In certain upwelling regions, including the California Current, studies suggest that upwelling favorable winds may intensify with climate change (Bakun, 1990; García-Reyes et al., 2015; García-Reyes and Largier, 2010; Rykaczewski et al., 2015; Sydeman et al., 2014). In the last three decades, the influx of nutrients to the coastal area has increased (Figure 5), likely as a result of the concurrent increase in upwelling favorable winds.

Natural fluctuations in temperature, wind, and circulation patterns that occur in coastal waters can introduce significant interannual and interdecadal fluctuations in the long-term trend. The El Niño (or La Niña) events, positive (negative) phases of the El Niño-Southern Oscillation (ENSO), are responsible for anomalously warm (or cool) ocean temperatures along the California coast. El Niño is the warm or positive phase, with major El Niño events occurring every 5-10 years (UCAR, 1994). La Niña is the cool or negative phase. Additionally, the West Coast is affected by multi-decadal variability in temperature, characterized by patterns such as the Pacific Decadal Oscillation, or PDO (Mantua et al., 1997), and the North Pacific Gyre Oscillation, or NPGO (Di Lorenzo et al., 2008). MHW occurrence involves two interwoven processes: a long-term increase in temperatures driven by anthropogenic climate change and large amplitude fluctuations that are enhanced because of that increase (Fumo et al., 2020). Recent work projects that future SSTs will continue to increase; globally, SSTs for the years 2070 to 2099 are projected in many regions to be warmer than the warmest year in the period from 1976 to 2005 (Alexander et al., 2018).

Technical considerations

Data characteristics

Coastal California is home to the longest continuous record of SST on the US West Coast and the Pacific Rim. Long-term time series from three sites — Trinidad Bay in Humboldt County, Pacific Grove in Monterey County, and La Jolla in San Diego — are presented in this report; these sites were chosen based upon their long operational duration (~40 to 100 years), public data availability, and regional/geographic coverage. Data for the three sites and other California coastal sites have been collected by the Shore Stations Program (SIO, 2021). The time series at Scripps Pier, La Jolla Shores, which extends back to 1916, is the longest running SST data set in the state.

Trinidad Bay temperature measurements are taken daily by staff from the Humboldt State University Marine Laboratory, located on the rocky headland between the ocean and Trinidad Bay. Bay temperature is measured from the fishing pier on the southeast side of the headland. Pacific Grove measurements are taken daily by staff from Stanford University's Hopkins Marine Station from a beach on the north side of Point Cabrillo. This location is representative of coastal conditions on the south side of Monterey Bay. La Jolla temperature measurements are taken daily at Scripps Pier by representatives from Scripps Birch Aquarium. The proximity of the pier to the deep waters at the head of La Jolla submarine canyon results in data representative of oceanic conditions.

The NOAA OISST reanalysis data (v2, Huang et al., 2021) merges satellite and in situ measurements from different platforms into a single gridded SST product, allowing a spatial resolution of roughly 13nm along California (here averaged longitudinally to ~30nmi), and daily temporal resolution, starting in September 1981.The dataset is interpolated to fill gaps on the grid and create a spatially complete map of sea surface temperature. Satellite and ship observations are referenced to buoys to compensate for platform differences and sensor biases (NOAA, 2021a). Data are provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA.

MHW cover and cumulative intensity are products reported in the California Current Marine Heatwave Tracker, an experimental tool for tracking marine heatwaves from

British Columbia to Baja, along the path of the California Current. The tool was designed to investigate the 2014-2016 MHW (NOAA, 2022). Indices are developed to help forecast or predict future MHWs expected to impact the coast. A MHW is based on the definition in Hobday, et al. (2016); however, no time constraint was used since values were summed over relatively large regions. The analysis presented here is based on a long-term baseline mean for the period 1971 to 2000, and the threshold was set at the 90th percentile of all values for the period 1982-2021. Further information about the tracker, including access to the data, is available at the Integrated Ecosystem Assessment webpage.

Five regions along the California Current are monitored, including three in California as shown in Figure 5. For each region, the “spatial coverage,” is calculated as the annual mean of the daily percentage of the area in “heatwave status”. This describes the size of the MHW each year. “Intensity” describes how hot the ocean waters are compared to a historical baseline. This index does not depend on whether it is in “heatwave status.” The “cumulative intensity” presented in Figure 3B is the sum of daily intensity values in a year for a given region, specifically the sum of average daily SST measurements above the baseline temperature. These temperature measurements are standardized for the location and time of day to ensure that the data is comparable over time. The cumulative intensity is the sum of the daily intensity values.

Strengths and limitations of the data

A growing network of ocean monitoring along California is an important resource for separating natural and anthropogenic influences on increasing temperatures. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) and National Oceanic and Atmospheric Administration (NOAA) National Data Buoy programs represent the largest coordinated efforts to collect SST data across broad spatial scales. In addition, the Central and Northern California Ocean Observing System and the Southern California Coastal Observing System provide coordinated long-term monitoring of environmental conditions to support ocean management decisions as part of an eleven-region US Integrated Ocean Observing System (IOOS, 2018).

The NOAA satellite-based product provides a shorter SST record than those of the shore stations, however its record has no spatial gaps and a larger cover offshore, allowing a better understanding of the different trends observed in this indicator along the California coast and over the continental shelf (NOAA, 2021a). It is important to note that the data points closest to shore cover waters over the continental shelf, and do not represent temperatures near shore (beaches and intertidal) values due to its coarser resolution. For nearshore values, the coastal values are more representative, although sparse in space.

Temperature and BEUTI were averaged annually before trends were calculated. This reduces the number of data points and therefore statistical significance.

OEHHA acknowledges the expert contribution of the following to this report:

Marisol García-Reyes, Ph.D.
Farallon Institute
marisolgr@faralloninstitute.org

Andrew Leising, Ph.D.
National Oceanic and Atmospheric Administration
Southwest Fisheries Science Center
Environmental Research Division
andrew.leising@noaa.gov

Fish larvae analysis provided by:
Rebecca Asch, Ph.D., East Carolina University

Additional input from:
Steven Bograd, Ph.D., NOAA
Tessa M. Hill, Ph.D., UC Davis Bodega Marine Laboratory

References:

Alexander AA, Scott JD, Friedland KD, Mills KE, Nye JA, et al. (2018). Projected sea surface temperatures over the 21st century: Changes in the mean, variability and extremes for large marine ecosystem regions of Northern Oceans. *Science of the Anthropocene* **6**(9).

Amah Mutsun Tribal Band (2022). Impacts of Climate Change on the Amah Mutsun Tribal Band. Prepared by Mike Grone, PhD, Amah Mutsun Land Trust. In: OEHHA 2022 Indicators of Climate Change in California.

Asch, R. G. (2015). Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proceedings of the National Academy of Sciences of the United States of America* **112**(30): E4065–E4074.

Bakun A (1990). Global climate change and intensification of coastal ocean upwelling. *Science* **247**: 198-201.

Big Valley Band of Pomo Indians & Middletown Rancheria of Pomo Indians (2021). Summary of the Lake, Sonoma, and Mendocino County Tribal Listening Session (May 18-19, 2021), hosted by the Big Valley Band of Pomo Indians, the Middletown Rancheria of Pomo Indians, and the Office of Environmental Health Hazard Assessment.

Bindoff NL, Cheung WWL, Kairo JG, Arístegui J, Guinder VA et al. (2019): Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, et al. (Eds.)].

Bograd SJ, Schroeder ID and Jacox, MG (2019). A water mass history of the southern California Current System. *Geophysical Research Letters* **46**: 6690-6698.

Breitburg D, Levin LA, Oschlies A, Gregoire M, Chavez FP, et al. (2018). Declining oxygen in the global ocean and coastal waters. *Science* **359** (6371).

Brown EG (2016). Governor Edmund G. Brown, Jr. Letter to Honorable Penny Pritzker, Secretary, U.S. Department of Commerce, dated February 9, 2016.

Cavanaugh KC, Reed DC, Bell TW, Castorani MCN and Beas-Luna R. (2019). Spatial variability in the resistance and resilience of giant kelp in southern and Baja California to a multiyear heatwave. *Frontiers in Marine Science* **6**: 413.

Cavole LM, Demko AM, Diner RE, Giddings A, Koester I, et al. (2016). Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. *Oceanography* **29**: 273–285.

CSIRO. 2021. Forecasting Marine Heatwaves, The Project: Marine heatwaves in the Indo-Pacific region, their predictability and social-economic impacts.

Di Lorenzo E and Mantua N (2016) Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change* **6**(11): 1042–1048.

Di Lorenzo E, Schneider N, Cobb KM, Franks PJS, Chhak K, Miller AJ, et al. (2008). North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters* **35**(8).

Fumo JT, Carter ML, Flick RE, Rasmussen LL, Rudnick DL and Iacobellis SF (2020). Contextualizing marine heatwaves in the Southern California bight under anthropogenic climate change. *Journal of Geophysical Research: Oceans* **125**: e2019JC015674.

García-Reyes M and Largier J (2010). Observations of increased wind-driven coastal upwelling off Central California. *Journal of Geophysical Research* **115**(C4).

García-Reyes M, Sydeman WJ., Schoeman DS, Rykaczewski RR, Black BA, et al. (2015). Under pressure: Climate change, upwelling, and eastern boundary upwelling ecosystems. *Frontiers in Marine Science* **2**: 109.

Gentemann C, Fewings M and García-Reyes M (2017). Satellite sea surface temperature along the West Coast of the United States during the 2014-2016 Northeast Pacific marine heat wave. *Geophysical Research Letters* **44**: 312-310.

Gleason MG., Caselle JE, Heady WN, Saccomanno VR, Zimmerman J, et al. (2021). *A Structured Approach for Kelp Restoration and Management Decisions in California*. The Nature Conservancy, Arlington, Virginia.

Goericke R, Venrick EL, Koslow TL, Sydeman WJ, Schwing FB, et al. (2007). The State of the California Current, 2006-2007: Regional and local processes dominate. *CalCOFI Reports* **48**: 33-66.

Henson SH, Beaulieu C and Lampitt R (2016). Observing climate change trends in ocean biogeochemistry: When and where. *Global Change Biology* **22**: 1561-1571.

Hobday, AJ, Alexander LV, Perkins SE, Smale DA, Straub SC, et al. (2016). A hierarchical approach to defining marine heatwaves. *Progress in Oceanography* **141**: 227–238.

Huang, B, Liu , Banzon V, Freeman E, Graham G, et al. (2021). Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1. *Journal of Climate* **34**: 2923-2939.

IPCC (2019). Summary for policy makers. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor, M, et al. (Eds.)].

IPCC (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte VP, Zhai A, Pirani SL, Connors C, Péan S, et al. (Eds.)].

Jacox, MG and Edwards CA (2011). Effects of stratification and shelf slope on nutrient supply in coastal upwelling regions. *Journal of Geophysical Research: Oceans 116*(C3).

Jewett L and Romanou A (2017). Ocean acidification and other ocean changes. In: Climate Science Special Report: Fourth Natoinal Climate Assessment, Volume I [Wuebbles DJ, Fahey DF, Hibbard KA, Dokken DJ, Stewart BC et al. (Eds)]. U.S. Global Change Research Program, Washington, DC, pp. 364-392

Largier, JL, Cheng BS and Higgason KD (2010). Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries. Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils (Marine Sanctuaries Conservation Series ONMS-11-04). National Oceanic and Atmospheric Administration.

Leising AW, Schroeder ID, Bograd SJ, Abell J, Durazo R, et al. (2015). State of the California Current 2014-15: Impacts of the warm water “blob”. CalCOFI Report **56**: 31-68.

Levitus S, Antonov JI, Boyer O, Baranova HE, Garcia RA, et al. (2012), World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010, *Geophysical Research Lett*ers **39**: L10603.

Levitus S, Antonov JI, Wang J, Delworth TL Dixon KW and Broccoli AJ (2001). Anthropogenic warming of Earth's climate system. *Science* **292**(5515): 267-270.

Mann KH. 2000. Ecology of coastal waters, with implications for management. 2nd edn. Malden: Blackwell Science.

Mantua N, Hare S, Zhang Y, Wallace J and Francis R (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* **78**: 1069-1079.

NOAA (2021a). National Oceanic and Atmospheric Administration, National Centers for Environmental Information, Optimum Interpolation Sea Surface Temperature (OISST) v2.1. Retrieved June 13, 2021.

NOAA (2021b). National Centers for Environmental Information, State of the Climate: Global Climate Report for Annual 2020, published online January 2021. Retrieved May 20, 2021.

NOAA (2022). National Oceanic and Atmospheric Administration, Environmental Research Division, NOAA Fisheries—Southwest Fisheries Science Center. The California Current Marine Heatwave Tracker – An experimental tool for tracking marine heatwaves. California Current Project.

Ohman MD, Mantua N, Keister J, Garcia-Reyes M. and McClatchie S. (2017). ENSO impacts on ecosystem indicators in the California Current System. Variations. CLIVAR & OCB Newsletter **15**(1): 8-15.

Oliver EC, Benthuysen JA, Darmaraki S, Donat MG, Hobday AJ, et al. (2021). Marine heatwaves. *Annual Review of Marine Science* **13**: 313–342

Pearcy WG and Schoener A (1987). Changes in marine biota coincident with the 1982-83 El Niño in the northeastern subarctic Pacific Ocean. *Journal of Geophysical Research* 92: 14417–14428.

Piatt, JF, Parrish JK, Renner HM, Schoen SK, Jones TT, et al. (2020). Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014-2016. *PloS one*, **15(1)**: e0226087.

Rhein M, Rintoul SR, Aoki S, Campos E, Chambers D, et al. (2013). Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, et al. (Eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Roemmich D and McGowan J (1995). Climatic warming and the decline of zooplankton in the California Current. *Science* **267**(5202): 1324-1326.

Rykaczewski, R. R., Dunne, J. P., Sydeman, W. J., García-Reyes, M., Black, B. A., & Bograd, S. J. (2015). Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern boundary currents through the 21st century. *Geophysical Research Letters* ***42***(15): 6424-6431.

Sagarin RD, Barry JP, Gilman SE and Baxter CH (1999). Climate-related change in an intertidal community over short and long time scales. *Ecological Monographs* **69**(4): 465-490.

Sanford, E., Sones, J. L., García-Reyes, M., Goddard, J. H., & Largier, J. L. (2019). Widespread shifts in the coastal biota of northern California during the 2014–2016 marine heatwaves. *Scientific reports* **9**(1): 1-14.

Santa Ynez Band of Chumash Indians (2022). *Impacts of Climate Change on the Santa Ynez Band of Chumash Indians.* In: OEHHA 2022 Indicators of Climate Change in California.

Santora JA, Mantua NJ, Schroeder ID, Field JC, Hazen EL, et al. (2020) Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements. *Nature Communications* **11**: 536.

Seabra R, Varela R, Santos AM, Gomez-Gesteira M., Meneghesso C, et al. (2019). Reduced nearshore warming associated with eastern boundary upwelling systems. *Frontiers in Marine Science* **6**: 104.

SIO (2021). Shore Stations Program. Trinidad temperature measurements and salinity samples collected by staff at Humboldt State University Marine Laboratory; Pacific Grove measurements collected by the Stanford University Hopkins Marine Station; Scripps Pier measurements collected by the Birch Aquarium at Scripps staff and volunteers. Data provided by the Shore Stations Program, sponsored at Scripps Institution of Oceanography by California State Parks and Recreation, Division of Boating and Waterways, Award C1670003. Retrieved June 13, 2021.

Somero GN, Beers JM, Chan F, Hill TM, Klinger T and Litvin SY (2015). What changes in the carbonate system, oxygen, and temperature portend for the northeastern Pacific Ocean: A physiological perspective. *BioScience* **66**(1): 14-26.

Sydeman WJ, García-Reyes M, Schoeman DS, Rykaczewski RR, Thompson SA, et al. (2014). Climate change and wind intensification in coastal upwelling ecosystems. *Science* **345**: 77-80.

Teagle H, Hawkins SJ, Moore PJ, Smale DA (2017). The role of kelp species as biogenic habitat formers in coastal marine ecosystems, *Journal of Experimental Marine Biology and Ecology* **492**: 81-98

UCAR (1994). El Niño and Climate Prediction, Reports to the Nation on our Changing Planet. University Corporation for Atmospheric Research, pursuant to National Oceanic and Atmospheric Administration (NOAA) Award No. NA27GP0232-01.

Weber ED, Auth TD, Baumann-Pickering S, Baumgartner TR, Bjorkstedt EP, et al. (2021). State of the California Current 2019–2020: Back to the Future with Marine Heatwaves? *Frontiers in Marine Science* **8**.