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Key Points:

- Satellite SST and wind stress show the phenology and extent of the recent record-breaking marine heat wave along the U.S. West Coast
- Warm SSTs occurred from January 2014 to August 2016 but abated along the coast during the upwelling season
- The largest SST anomalies occurred off central and Southern California in late 2015 during decreased upwelling-favorable winds

Correspondence to:
C. L. Gentemann,
cgentemann@esr.org

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Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave

Chelle L. Gentemann[1], Melanie R. Fewings[2], and Marisol García-Reyes[3]

[1]Earth and Space Research, Seattle, Washington, USA, [2]Department of Marine Sciences, University of Connecticut, Groton, Connecticut, USA, [3]Farallon Institute, Petaluma, California, USA

Abstract From January 2014 to August 2016, sea surface temperatures (SSTs) along the Washington, Oregon, and California coasts were significantly warmer than usual, reaching a maximum SST anomaly of 6.2°C off Southern California. This marine heat wave occurred alongside the Gulf of Alaska marine heat wave and resulted in major disturbances in the California Current ecosystem and massive economic impacts. Here we use satellite and blended reanalysis products to report the magnitude, extent, duration, and evolution of SSTs and wind stress anomalies along the West Coast of the continental United States during this event. Nearshore SST anomalies along the entire coast were persistent during the marine heat wave, and only abated seasonally, during spring upwelling-favorable wind stress. The coastal marine heat wave weakened in July 2016 and disappeared by September 2016.

1. Introduction

A large warm anomaly in sea surface temperature (SST), or marine heat wave, nicknamed "the Blob," appeared in the Gulf of Alaska in November 2013 [*Bond et al.*, 2015; *Alaska Ocean Observing System*, 2016], lasting through June 2016. This SST anomaly developed as a result of decreased surface cooling and decreased equatorward Ekman transport in the Gulf of Alaska due to a persistent atmospheric high-pressure ridge [*Bond et al.*, 2015; *Hartmann*, 2015]. The ridge also prevented normal winter storms from reaching the West Coast of the United States (U.S.) and contributed to drought conditions across the entire West Coast during 2014 through mid-2016 [*NOAA*, 2016b; *Seager et al.*, 2015]. Atmospheric teleconnections spanning the entire North Pacific led to the persistence of the marine heat wave during 2013–2015 [*Di Lorenzo and Mantua*, 2016].

Along the U.S. West Coast (within ~200 km from the coast), warm SST anomalies began to appear in 2014. Regional studies suggest the initial appearance of the warming varied along the coast. On 16 September 2014, 32 km offshore of Newport, OR, at National Data Buoy Center buoy 46050, SSTs increased 7°C in 1 h; the water then remained warmer than normal until June 2015 [*Peterson et al.*, 2015]. In a model including the San Francisco region, the SST warm anomaly first appeared along the coast in early 2014, abated, and then reappeared late in 2014 [*Chao et al.*, 2016]. Using Argo profiling float temperature data, the same study showed that the warm layer extended from the surface to 80 m depth early in 2014, deepened to 140 m later in March/April/May, and then thinned at the coast during the upwelling season (June/July/August). In Southern California in fall 2014, SST anomalies reached 5°C and were confined to the upper 50 m [*Zaba and Rudnick*, 2016]. Off Baja California, there were two separate periods of warming: May 2014–April 2015 and September–December 2015 [*Robinson*, 2016]. The first period was related to weakened upwelling-favorable winds, while the second was suggested to be related to an El Niño event.

El Niño conditions were present in the tropics in 2014–2015. While El Niño events can have large impacts on the California Current Upwelling System (CCUS), a combination of observational, reanalysis, and model studies indicates that the SST anomalies in the central CCUS during 2015–2016 were primarily related to the large-scale marine heat wave and only weakly influenced by the concurrent El Niño [*Jacox et al.*, 2016; *NOAA*, 2015b]. Similarly, the Southern California SST anomaly appeared to be caused by a combination of increased surface heat flux and changes in winds rather than the northward advection typically associated with El Niño [*Zaba and Rudnick*, 2016]. Somewhat in contrast with those observations, warm-water species of copepods were recorded off Newport, OR, which are commonly associated with El Niño, suggesting poleward and/or onshore advection off Oregon [*Welch*, 2015].

Associated with the anomalous high water temperatures during this period, observed changes in zooplankton community composition resulted in important disturbances in the entire marine ecosystem [*NOAA*, 2016a]. In California a major Cassin's auklet mortality event occurred October 2014 through January 2015 alongside lower productivity at almost every trophic level [*NOAA*, 2015a]. In 2015 there were unusual mortality events for California sea lions, Guadalupe fur seals, and common murres. Poor foraging conditions resulted in the marine mammal mortality event, but the cause of the seabird mortality is not yet clear [*NOAA*, 2016a]. A combination of warm water and high nutrient concentrations resulted in a toxic algal bloom of *Pseudo-nitzschia* along the entire U.S. West Coast during April–October 2015, unprecedented in duration and extent [*Di Liberto*, 2015; *Kudela et al*., 2015]. The domoic acid produced by this bloom forced the closing of the Oregon and Washington recreational razor clam harvest season, significantly delayed the opening of the commercial and recreational crab fishing season along the entire West Coast, and led to a partial closure of sardine and anchovy commercial and recreational harvest in California [*Washington Department of Fish and Wildlife* (*DFW*), 2015a; *Washington DFW*, 2015b; *California Department of Public Health*, 2015; *Oregon DFW*, 2015; *California DFW*, 2015].

Ecosystem health along the U.S. West Coast, and primary productivity in particular, are strongly related to Ekman transport. In the summer, the prevailing equatorward winds result in offshore Ekman transport, upwelling deep, cold, nitrate-rich waters into the coastal euphotic zone [*Huyer*, 1983; *Sverdrup*, 1942]. North of Cape Mendocino in Northern California, these equatorward winds are strongly seasonal and drive seasonal upwelling, peaking in July. From Cape Mendocino to Point Conception, persistent equatorward winds drive almost year-round upwelling, with a seasonal change in strength, peaking in May [*Dorman and Winant*, 1995]. The Bakun upwelling index (UI) is one estimate of the volume of water upwelled along the coast and transported offshore, based on the alongshore component of geostrophic winds derived from synoptic atmospheric pressure fields [*Bakun*, 1973]. Using the Bakun UI, *Leising et al*. [2015] reported strong upwelling along the U.S. West Coast for all of 2013; normal upwelling in 2014, except in June when strong upwelling occurred from 36–42°N; and stronger (weaker) than average upwelling-favorable conditions north (south) of 33°N during 2015. Although upwelling was still occurring during the time period of the large-scale marine heat wave, the ecological disturbances that occurred suggest that where the upwelling was not weaker than usual, the upwelled source water characteristics and their nutrient content may have been atypical, impacting primary productivity.

Two scientific workshops on the recent Pacific SST anomalies were held in 2015 and 2016 (http://sccoos.org/projects/anomalies_workshop/ and http://www.nanoos.org/resources/anomalies_workshop/workshop2.php). A main goal that emerged is to understand the relative importance of changes in atmosphere-ocean heat flux, local wind stress, cross- and along-coast advection, and subsurface temperature structure in creating the SST anomalies throughout the various regions of the CCUS. Although some regional studies have been published and reviewed above, a detailed description of the SST and wind anomalies along the entire coast of the continental U.S. is needed. Here we use satellite-blended reanalysis products for SST and wind and the Bakun UI to (1) describe the magnitude and timing of the SST and wind anomalies along the continental U.S. West Coast during 2014–2016 and (2) determine whether the SST anomaly pattern along the coast can be explained by the anomalies in upwelling-favorable wind stress.

2. Data and Methods

2.1. Multiscale Ultra-high Resolution SST

NASA Jet Propulsion Laboratory produces the global, daily, 1 km, multiscale ultra-high resolution, motion-compensated analysis of SST (MUR SST) version 4.0 [*Chin et al*., 2013]. This high temporal and spatial resolution analysis incorporates SSTs from eight satellites, using both infrared and passive microwave retrievals, and in situ data. It has been used previously for research on coastal upwelling [*Vazquez-Cuervo et al*., 2013] and is available from 2002 to present. The 5 day and 30 day running averaged SSTs for June 2002 through July 2016 were calculated from daily data. These averaged data were used to calculate climatologies at each spatial grid point using the 2002 to 2012 data; then anomalies were determined by subtracting the climatology. Anomalies were calculated from 2002 to 2012 period to provide an average as long as possible from the same data set but purposefully excluding the unprecedented warm anomaly that began in 2013.

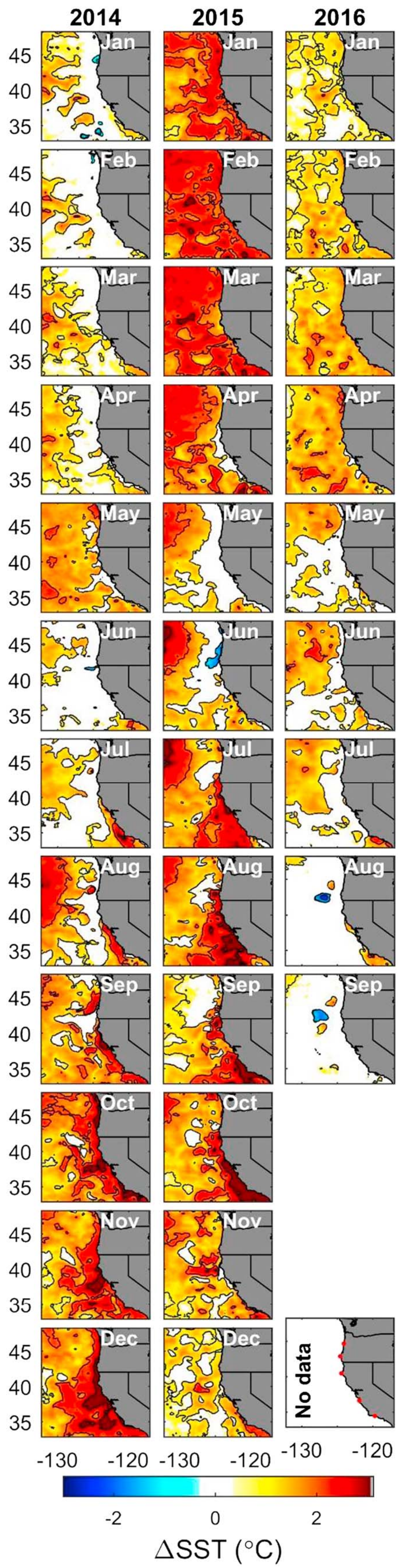

Figure 1. Monthly SST anomalies, relative to the 2002–2012 climatology. White indicates the anomalies <1 SD for that location and month. The SD varies from 0.34 to 1.97°C over the study area. In the plot with "no data," the red dots indicate, from top to bottom, Newport, Cape Blanco, Cape Mendocino, Monterey, and Santa Barbara.

2.2. Bakun Upwelling Index

The Bakun UI is produced by the Pacific Fisheries Environmental Laboratory using global, gridded, 6-hourly sea level atmospheric pressure fields from the Fleet Numerical Meteorological Oceanographic Center [*Bakun*, 1973]. The Bakun UI is produced for 15 locations, every 3° latitude from 21°N to 60°N, and follows the U.S. West Coast [*Schwing and Bakun*, 2016]. Sea level pressure is used to estimate the geostrophic winds, which are converted to wind stress and then Ekman transport as described in *Schwing et al*. [1996].

2.3. European Centre for Medium-Range Weather Forecasts Re-Analysis-Interim Winds

We used the 6-hourly, 0.75° gridded European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)-Interim 10 m wind velocity [*Dee et al*., 2011]. Wind stress was calculated using the Coupled Ocean-Atmosphere Response Experiment version 3.5 neutral stability algorithm [*Edson et al*., 2013], and then daily averages were determined from the 6-hourly data. Data were averaged into daily and monthly maps, then interpolated onto the MUR SST 1 km grid for this study. The alongshore wind stress was calculated from ERA-Interim wind vectors rotated into an along-coast coordinate system at each location, using the coastline smoothed with a 150 km low-pass filter. Ekman transport was calculated from the alongshore wind stress, following *Schwing et al*. [1996], for comparison with the Bakun UI.

3. Results

3.1. Magnitude and Timing of SST Anomalies

In the first months of 2014, the warm anomalies were present approximately 200 km offshore of the continental U.S. West Coast (Figure 1), but later in 2014, warm SST anomalies larger than 1 standard deviation (SD) extended to the coast. Warm anomalies appeared first in the Southern CCUS (south of Cape Mendocino), in March–May. They then disappeared in June 2014 everywhere north of Point Conception, reappearing in July in the Southern CCUS, with anomalies greater than 2°C (Figure 1).

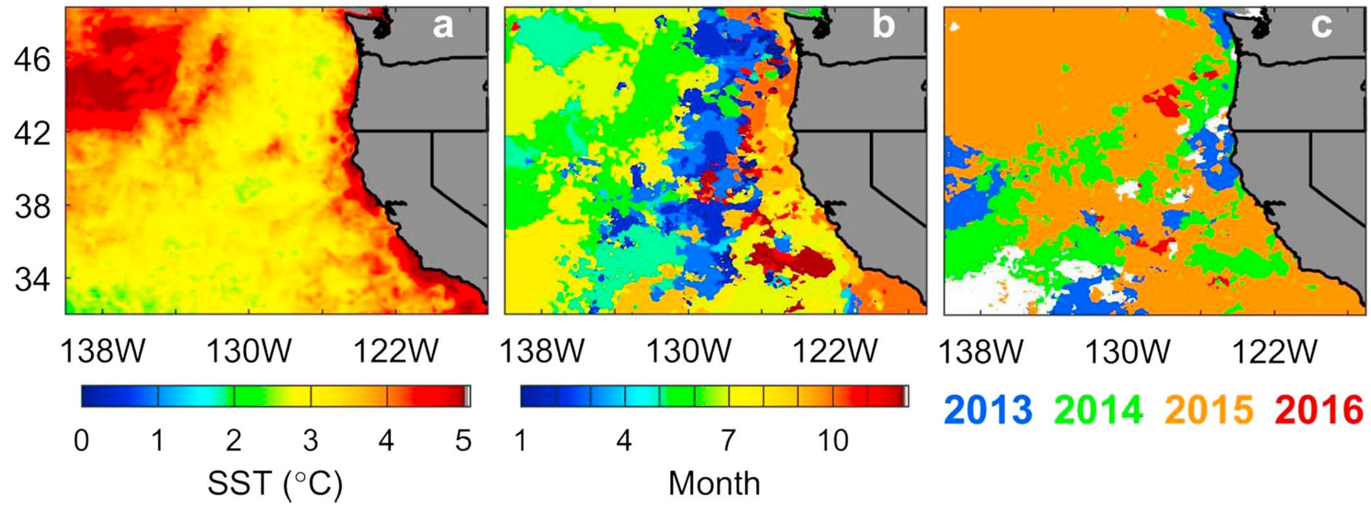

Figure 2. (a) The maximum 5 day average SST anomaly at each location during 2002 to July 2016, relative to the 2002–2012 climatology; (b) maximum anomaly month; and (c) maximum anomaly year. White indicates the years before 2013.

In the Northern CCUS (north of Cape Mendocino), the SST remained near climatological values through July and August (Figure 1, left column).

By September, warm anomalies extended along the entire coast except at the known upwelling region near Cape Blanco in Oregon. These strong warm anomalies then persisted along the entire coastline from October 2014 to March 2015, with the anomalies stronger at the coast than offshore.

In March 2015, the nearshore positive anomalies began to lessen in magnitude south of Cape Blanco. By May, normal SST occurred along the entire CCUS (Figure 1, middle column). Offshore SST, however, remained anomalously high. The temperatures at the coast in the northern part of the upwelling system continued to decrease until June 2015, when a cold anomaly briefly developed along the Oregon coast north of Cape Blanco. This was the only substantial cold SST anomaly in the entire CCUS between February 2014 and July 2016. From July 2015 to October 2015, the coastal SSTs were again >1 SD warmer than climatology. From November 2015 to April 2016 the entire mapped region was fairly uniformly warm, though not as warm as the previous year. During May–July 2016, the core of the climatological upwelling season, the warm anomalies decreased in most of the CCUS but lingered south of Cape Mendocino. In August 2016, the anomalies were absent from the northern region and then absent from the entire region in September 2016.

The location and timing of the maximum SST anomalies between June 2002 and July 2016 are shown in Figure 2. The maximum 5 day anomaly in the entire domain was 6.2°C, on 14 September 2015 between Point Conception and San Miguel Island at 120.54°W, 34.24°N (Figure 2a). In the region analyzed, all the large warm anomalies (above 3°C) occurred after 2013, and 77% were greater than 3°C, 25% were greater than 4°C, and 3% of the anomalies were greater than 5°C.

The maximum SST anomalies in the offshore and coastal regions had different timing. In the northwest part of the study area, at approximately 138°W and 44°N near the location of the Blob, the maximum SST anomaly of ~5°C occurred in May to July 2015 (Figure 2, top left of each plot). The maximum SST anomaly was smallest through a meridional corridor at ~130°W, between the offshore maximum and the coast; in this region, the maximum anomaly was 2–3°C and occurred in February and March 2015 (yellow in Figure 2a and dark blue in Figure 2b). However, in the CCUS, the maximum anomalies reached >5°C and precede the offshore anomalies, occurring in 2013 and 2014 along Washington, 2014 along Oregon, and 2013 and 2015 along most of California. In the CCUS, regardless of year (Figure 2c), the maximum anomalies occurred at the end of the upwelling season (between August and September) when the upwelling-favorable wind stress is typically weak.

3.2. Timing of SST Anomalies Versus Wind Anomalies

The interruption of the anomalously warm SSTs along the coast occurred in April to July or August each year, during the climatological upwelling season (Figures 1 and 2), and was more consistent in the Northern than the Southern CCUS. To compare the SST anomalies between these regions, and compare to upwelling-favorable winds in more detail, Figure 3 shows the time series of SST 1000 km offshore and 1 km offshore of the coast for two latitudes: one in the Northern CCUS (Newport, OR) and one in the Southern CCUS (Monterey, CA), along with alongshore wind stress and the Bakun UI for both coastal sites.

Offshore temperatures already exceeded the average at the start of 2014, and were almost continuously elevated above normal through mid-2016, only returning to normal variability in June 2016 (Monterey; Figure 3e) and August 2016 (Newport; Figure 3a). The offshore SST anomalies are larger in the northern (Newport; Figure 3a) region than the southern (Monterey; Figure 3e) region. Both regions show changes in the timing of the seasonal cycle.

The nearshore SST phenology is more complex (Figures 3b and 3f). In the Newport area, nearshore SST started slightly cool in 2014 and was normal until May, despite an anomalously strong downwelling-favorable wind period (February to mid-March). Another strong downwelling period occurred in April–June, associated with the first significant coastal warm SST, in May. Winds switched to stronger than usual upwelling-favorable in mid-May, associated with abatement of the SST anomalies. During the summer of 2014 (July–September), winds were normal (upwelling-favorable); however, large SST anomalies appeared in September and remained high until April 2015. In October–November 2014, there was another strong downwelling episode, but SST anomalies were already large and positive; afterward, winds were more favorable to upwelling than normal at some periods until the end of June, but the SST was in normal in May 2015 and only became colder during June. In July, SST was anomalously warm again, although upwelling-favorable winds remained mostly normal until a period of strong downwelling-favorable winds in November–December and in winter 2016. SST remained high until May 2016 about a month after winds became upwelling-favorable and stronger than normal in April 2016. While upwelling-favorable winds (and the Bakun UI) remained either normal or stronger than normal, SST warmed again in July 2016, decreasing to normal values in August.

In Monterey, nearshore SSTs were slightly warm during some periods, but mostly normal in winter-spring 2014, while alongshore winds were normal (weak). By the end of May (peak of upwelling season), winds became weaker than normal; however, SST remained normal until the end of June, when winds weakened further and SST anomalies increased rapidly. SST remained anomalously high until mid-April 2015 despite the mostly normal upwelling conditions. From mid-April to July (in the core of the upwelling season), winds were weaker than normal; however, SST returned to normal values in mid-April to mid-June and developed warm anomalies afterward. Winds remained weak but within normal values afterward and even stronger than normal in the fall, but SST anomalies reached their highest values in October. SST decreased in December, but remained above normal until September 2016, despite the normal upwelling winds in that period.

In both the northern and southern regions, coastal SSTs returned to within normal range each year during the spring (Figures 1, 3a, and 3e), coinciding with strong upwelling-favorable conditions (Figures 3c and 3g).

In the Northern CCUS (Newport; Figure 3d), the Bakun UI anomalies are qualitatively similar to the high-resolution wind stress anomalies (Figure 3c), although the size of the Bakun UI anomalies, relative to the SD, is smaller than for the high-resolution wind stress product. However, in the Southern CCUS, the Bakun UI is within normal range for all of spring and summer 2014–2016 (Figure 3h), whereas the high-resolution wind stress indicates substantially weakened wind stress during summer 2014 and 2015 (Figure 3g). The variability in the strength of upwelling-favorable winds for 2014 and 2015 seen in the alongshore wind stress (Figures 3c and 3i) is reflected in nearshore SST variability (Figures 3b and 3f) but is not seen in the Bakun UI (Figure 3h).

4. Summary and Discussion

Coastal SST anomalies appearance differed, in timing and latitude, and then those offshore associated with the Blob. The offshore warming originated from the Gulf of Alaska marine heat wave, from January 2014 to August 2016 [*Bond et al*., 2015] (Figures 1 and 2). The nearshore anomalies first appeared along the Southern California in March 2014. The coastal SST anomalies extended north to cover the entire CCUS by May 2014 and continued through August 2016 (Northern CCUS) or September 2016 (Southern CCUS; Figure 1). Through 2014–2016, warm offshore SST expanded eastward, but the magnitude of the anomalies

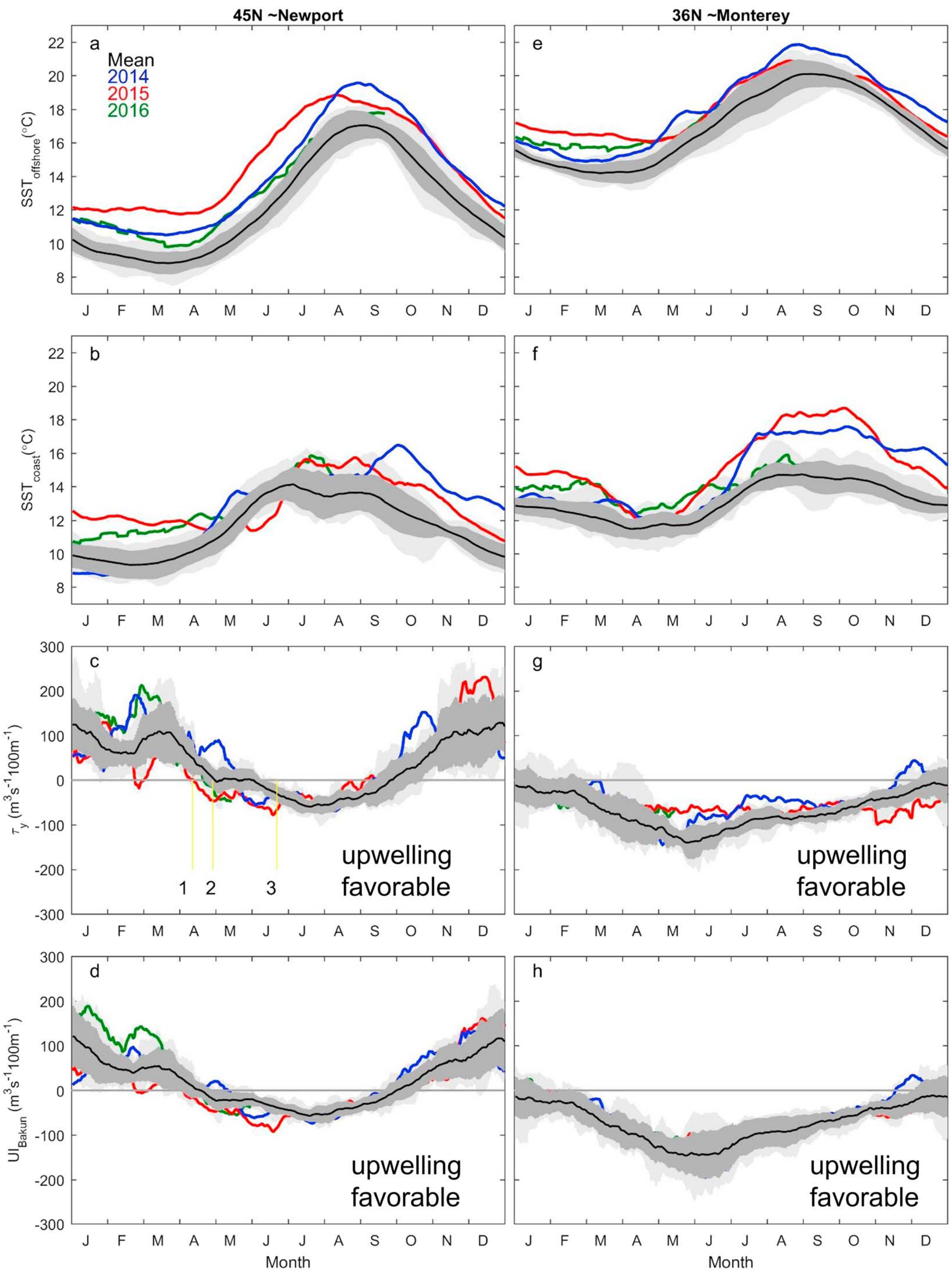

Figure 3. Time series of daily SSTs and winds, smoothed with a 30 day running mean, in the (a–d) northern and (e–h) southern parts of the CCUS. (Figures 3a and 3e) SST 1000 km offshore. (Figures 3b and 3f) SST 1 km offshore. (Figures 3c and 3g) Alongshore wind stress, in units of Ekman transport (wind stress divided by water density and Coriolis parameter) per 100 m coastline length. (Figures 3d and 3h) Bakun upwelling index. In Figure 3c, the onset of upwelling-favorable wind stress in 2015 is indicated by the yellow line labeled "1," the minimum date of onset 2002–2013 by the line labeled "2," and the maximum date of onset 2002–2013 by the line labeled "3." In Figures 3c, 3g, 3d, and 3h, the negative values indicate the upwelling-favorable conditions. In each plot, light grey indicates the envelope of maximum and minimum values during 2002–2013; dark grey indicates the envelope of ±1 SD around the mean during 2002–2013; and the black, blue, red, and green lines indicate the mean during 2002–2013 and the values during 2014, 2015, and 2016, respectively. To emphasize anomalies >1 SD from the mean, the data are plotted so that the yearly lines are obscured when within 1 SD of the mean.

shows three distinct regions: offshore, coastal, and a meridional corridor at approximately 130°W. The maximum warm anomalies were larger in both the offshore northerly region and along the U.S. West Coast (5–6°C peak warming) than in the corridor (approximately 3°C peak warming; Figure 2). The timing of the peak coastal warm anomalies varied by region, occurring in 2013 (Washington and Northern California), 2014 (Oregon), or 2015 (central and Southern California).

The onshore warm anomalies only abated for short periods in May–June of each year, at the start of the climatological upwelling season (Figures 1 and 3). Each year, warm anomalies began increasing again after the peak upwelling season, as winds started to relax in July. By October 2014, the warm anomalies were fairly uniform throughout the coastal region as well as the offshore areas, suggesting that they were related to the same large-scale atmospheric patterns that resulted in the Blob.

Onshore SST anomalies were generally stronger and more persistently high in California than further north, with a peak of 6.2°C on 14 September 2015, just south of Point Conception (Figure 2). Since the offshore warming was strongest in the north, it is interesting that the reverse is true along the coast. In the Northern CCUS, the largest coastal SST anomaly occurred in October 2014 during an unusually strong downwelling-favorable wind event that apparently brought the offshore warm water onshore (Figures 1 and 3). In the Southern CCUS, the largest coastal anomalies at Monterey occurred in September 2015, during weaker than normal upwelling-favorable winds.

Peterson et al. [2015] suggested that the rapid change in temperature and the presence of warm-water, non-local, copepods off Oregon made advection the likely driver of the rapid warming that occurred in Newport in September 2014 [*Welch*, 2015]. Figure 3b shows that the rapid warming (Figure 3b) is coincident with anomalously strong downwelling-favorable winds (Figure 3c), which likely advected the offshore warm surface water (Figure 3a) onshore. This may also explain the appearance at the coast of the unusual copepod species, if they were present in an offshore water mass.

Changes to upwelling phenology, specifically the timing of the spring transition, have a strong impact on the health of the marine ecosystems in the subsequent season [*Kosro et al*., 2006; *Holt and Mantua*, 2009]. However, as in Figure 3, the presence of upwelling-favorable winds does not always result in the upwelling of cold water that is typically nutrient rich. These observations emphasize the need to examine winds and temperatures simultaneously, as examining one or the other might be misleading regarding the oceanographic conditions relevant for the ecosystem. The nutrients in upwelled water are important for primary productivity at the base of the marine food web. A delay in the spring transition to upwelling-favorable winds, a short upwelling season, or high water temperatures (which can indicate low nutrients) can significantly impact the type, size, and diversity of phytoplankton and lead to a disruption in the energy cascade to higher trophic levels [*Barth et al*., 2007; *Bertram et al*., 2001; *Wiafe et al*., 2008]. Here we showed a combination of persistent warm SSTs and weaker and shifted upwelling season, particularly in 2015, were associated with the substantial ecosystem disturbances in the CCUS during 2014–2016.

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