Response of O_2 and pH to ENSO in the California Current System in a high resolution global climate model

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Abstract. Coastal upwelling systems, such as the California Current System (CalCS), naturally experience a wide range of O_2 concentrations and pH due to the seasonality of upwelling. Nonetheless, changes in the El Niño/Southern Oscillation (ENSO) have been shown to measurably affect the biogeochemical and physical properties of coastal upwelling regions. In this study, we use a novel, high-resolution global climate model (GFDL-ESM2.6) to investigate the influence of warm and cold ENSO events on variations in the O_2 concentration and the pH of the CalCS' coastal waters. An assessment of the CalCS response to six El Niño and seven La Niña events in ESM2.6 reveals significant variations in the response between events. However, these variations overlay a consistent physical and biogeochemical (O_2 and pH) response in the composite mean. Focusing on the mean response, our results demonstrate that O_2 and pH are affected rather differently in the euphotic zone above $\sim$100 m. The strongest O_2 response reaches up to several 100km offshore, whereas the pH signal occurs only within a $\sim$100 km-wide band along the coast. By splitting the changes in O_2 and pH into individual physical and biogeochemical components that are affected by ENSO variability, we found that O_2 variability in the surface ocean is primarily driven by changes in surface temperature that affect the O_2 solubility. In contrast, surface pH changes are predominantly driven by changes in dissolved inorganic carbon (DIC), which in turn is affected by upwelling, explaining the confined nature of the pH signal close to the coast. Below $\sim$100 m, we find conditions with anomalously low O_2 and pH, and by extension also anomalously low aragonite saturation, during La Niña. This result is consistent with findings from previous studies and highlights the stress that the CalCS ecosystem could periodically undergo in addition to impacts due to climate change.

1 Introduction

Ocean deoxygenation (decreasing O_2 concentration) and ocean acidification (decreasing pH) are considered to be major oceanic ecosystem stressors that can severely reduce habitat suitability in benthic and pelagic ecosystems (e.g., Doney et al., 2009a; Doney, 2010; Gruber, 2011; Bopp et al., 2013; Breitburg et al., 2015). Coastal upwelling ecosystems, such as the

California Current System (CalCS), support some of the world's most productive fisheries due to the seasonal, wind-driven upwelling of nutrient-rich waters (e.g., Chavez and Messié, 2009; Messié et al., 2009). The upwelled waters fuel biological production in the CalCS but are also characterized by lower O_2 and lower pH than the surrounding surface waters (e.g., Bograd et al., 2008; Nam et al., 2011). Although the CalCS is accustomed to seasonal fluctuations in O_2 and pH, several observational studies suggest that both have decreased in the last decades, particularly within 100 km of the coast (e.g., Bograd et al., 2008; Feely et al., 2008; Nam et al., 2011; Bednaršek et al., 2014; Bednaršek and Ohman, 2015). Specifically, Bograd et al. (2008) found a shoaling of the hypoxic threshold, which is typically considered to be ~60 μmol kg^{-1} (Gray et al., 2002; Diaz and Rosenberg, 2008; Vaquer-Sunyer and Duarte, 2008), of up to 90 m in the southern CalCS between 1984 and 2006. Furthermore, Feely et al. (2008) report an incidence of nearshore surface waters becoming corrosive during the early upwelling season (May/June) of 2007, with the saturation state of aragonite (Ω_{arag}) dropping below one, corresponding to pH < 7.75 (aragonite is a mineral form of calcium carbonate, $CaCO_3$, found in the shells of certain calcifying marine organisms). Turi et al. (2016) used a regional ocean model to demonstrate that a recent intensification of upwelling-favorable winds is linked to a drop in coastal pH and Ω_{arag}. It currently remains unclear whether these observed and modeled changes in the CalCS' ocean biogeochemistry are ongoing signals of anthropogenic climate change, and thus could continue into the future, or whether they are driven by natural fluctuations in the climate system (e.g., Bakun, 1990; Narayan et al., 2010; Bakun et al., 2015; Rykaczewski et al., 2015; Wang et al., 2015).

The eastern North Pacific region is affected by several teleconnective climate patterns, including the El Niño Southern Oscillation (ENSO; e.g., Alexander et al., 2002; Mantua and Hare, 2002; Di Lorenzo et al., 2008; Alexander, 2010; Di Lorenzo et al., 2010; Macias et al., 2012; Franks et al., 2013; Capotondi et al., 2015; Newman et al., 2016). ENSO is a major driver of interannual physical variability and affects a range of variables on a local scale in the CalCS, such as sea-surface temperature, thermocline depth, and the intensity and depth of upwelling (e.g., Chavez et al., 2002; Schwing et al., 2005; Checkley Jr. and Barth, 2009; Jacox et al., 2015b), and operates remotely through two distinct pathways: (i) through the atmosphere by affecting the intensity and location of the Aleutian Low pressure system and the fluxes of momentum, heat, and freshwater through the surface ocean and (ii) through the ocean by generating thermocline anomalies in the tropical Pacific that propagate eastward along the equator and northward as coastally trapped waves. During a typical ENSO warm event (El Niño), the atmospheric influence is twofold: surface heat fluxes into the ocean are anomalously high and the Aleutian Low intensifies and is displaced southeastward, causing a decrease in equatorward, upwelling-favorable winds in the CalCS. From the oceanic side, the coastally trapped waves cause a depression of the thermo- and nutricline in the nearshore region, leading to reduced upwelling of nutrient-rich, cool waters and thus limiting biological production in the surface waters (Bograd and Lynn, 2001). Source waters for upwelling in the CalCS also tend to be anomalously warm, shallow, and fresh during El Niño (Jacox et al., 2015b), resulting in similarly warm and fresh anomalies at the surface. During an ENSO cold event (La Niña), these processes are typically reversed, with nearshore surface waters being anomalously low in O_2 and pH due to a shoaling of the isopycnal surfaces (Nam et al., 2011).

A number of studies have looked at the influence of ENSO on the physics, biogeochemistry, and biology of the CalCS over the past several decades. For instance, the influence of the strong 1997/1998 El Niño and subsequent La Niña on the coastal

upwelling ecosystem of the US West Coast has been well documented by a variety of observational studies that focus on the physics and hydrography (e.g., Collins et al., 2002; Kosro, 2002; Lynn and Bograd, 2002; Ryan and Noble, 2002; Schwing et al., 2002b), on nutrients and primary production (e.g., Castro et al., 2002; Kahru and Mitchell, 2000, 2002; Kudela and Chavez, 2002), and on zooplankton and higher trophic levels (e.g., Benson et al., 2002; Hopcroft et al., 2002; Pearcy, 2002; Peterson et al., 2002). A handful of observational studies have investigated the impact of the 1982/1983 El Niño on the physical regime of the CalCS (e.g., Simpson, 1983; Huyer and Smith, 1985), and the effect of the 2002/2003 El Niño on the physics and biology (e.g., Murphree et al., 2003; Schwing et al., 2002a). Several regional modeling studies have shown the connection between ENSO and the vertical transport, water column density, origins and properties of upwelled water (Jacox et al., 2014, 2015b), and demonstrated the relative importance of remote versus local forcing on both the physics and the biogeochemistry of the CalCS (Frischknecht et al., 2015; Jacox et al., 2015a; Frischknecht et al., 2017). During the 2010/2011 La Niña, Nam et al. (2011) observed decreases in O_2 and pH in the upwelling region along the coast that were 2-3 times larger than expected solely due to the cross-shore shoaling of the isopycnal surfaces. They found that the additional reduction of O_2 was related to decreased subsurface primary production and a short-term strengthened poleward flow of the California Undercurrent. In addition, pH dropped below the critical value of 7.75 both during the upwelling season (typically April-September) and the two following La Niña months. These results suggest that severe low-O_2 and low-pH conditions may occur if La Niña conditions overlap with seasonal upwelling.

To our knowledge, the study by Nam et al. (2011) is the only one to investigate the influence of ENSO on both O_2 and pH in the CalCS. It is only recently that CalCS ENSO responses have begun to be monitored by modern oceanographic and biogeochemical measurements. Moreover, we have yet to come across any studies investigating responses across multiple ENSO events. Earth System Models (ESMs), such as those participating in the Climate Model Intercomparison Project Phase 5 (CMIP5), provide an opportunity to address these limitations. Global ESMs used for multi-centennial climate change simulations, however, simulate the ocean at a fairly coarse horizontal resolution ($\sim 1°$ Stock et al., 2011). Models with such resolutions are challenged to reproduce the responses of coastal ecosystems to basin-scale ocean variability (Saba et al., 2016). It is commonly acknowledged that at least $0.1°$ horizontal ocean resolution is necessary to resolve the Rossby radius of deformation (e.g., Fiechter et al., 2014; Dunne et al., 2015), which is around 20-60 km in the CalCS (Chelton et al., 1998). In this study, we use a high-resolution ($0.1°$), fully-coupled climate model developed at the Geophysical Fluid Dynamics Laboratory (GFDL-ESM2.6) to investigate the effect of ENSO on O_2 and pH in the CalCS and to address the following questions:

1. How consistent is the physical and biogeochemical response of the CalCS across ENSO events? How do these responses differ between different model resolutions?

2. What are the primary drivers and mechanisms affecting O_2 and pH in the CalCS?

3. Is there a difference in ENSO's influence on O_2 and pH between the nearshore as opposed to the offshore and between the surface as opposed to at depth?

4. How can these results help inform the observational community about the location and frequency necessary to capture ENSO signals in their time series?

This novel model setup allows us to investigate both oceanic and atmospheric components of the ENSO forcing on the CalCS, as the horizontal oceanic resolution is high enough to simulate coastally trapped waves propagating north along the coast and the atmospheric component allows for a representation of basin-scale teleconnection processes.

2 Model details and methods

2.1 Model setup and simulation

We use a prototype, fully coupled global Earth System Model (ESM2.6) developed by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). In contrast to GFDL's publicly released models that undergo years of iterative development and analysis to assure fidelity to a suite of observational metrics, ESM2.6 was implemented as a single test simulation as proof of concept. ESM2.6 was built upon the high-resolution CM2.6 physical climate model (Delworth et al., 2012; Griffies et al., 2015; Saba et al., 2016). The model's ocean component is GFDL's Modular Ocean Model Version 5 (MOM5; Griffies, 2012) with a horizontal resolution of $0.1°$ and 50 vertical layers. The ocean biogeochemistry model is the Carbon, Ocean Biogeochemistry and Lower Trophics (COBALT) model as used in Stock et al. (2014a, b) with modifications as described in Stock et al. (2017). COBALT includes 33 prognostic tracers, as well as three phytoplankton groups and three zooplankton groups to represent the coupled elemental cycles of carbon, nitrogen, phosphorus, silicate, iron, alkalinity (ALK), and lithogenic material. Its carbonate chemistry calculation is based on the ORNL/CDIAC CO2SYS carbonate chemistry routines (Lewis and Wallace, 1998). Disk space limited the amount of output that could be saved. Therefore, we analyze all available full-depth profiles of temperature, salinity, O_2, and the hydrogen ion concentration ($[H^+]$), from which we compute pH, as well as surface dissolved inorganic carbon (DIC) and surface ALK on monthly timescales.

We analyze a 52-year control simulation with constant 1990 atmospheric CO_2 forcing. As this simulation was not forced by a transient atmospheric CO_2 signal, it lends itself particularly well to the analysis of interannual variability. The physical climate of the 52-year control simulation was initialized from 01 January of year 141 of a CM2.6 1990 control simulation. The ocean biogeochemistry was initialized from 01 January of year 105 of a previous development version of ESM2.6 1990. Observed climatologies of O_2, nitrate, phosphate, and silicate were taken from the World Ocean Atlas 2005 (WOA05; Garcia et al., 2006a, b), and modeled DIC and ALK were initialized from the Global Data Analysis Project (GLODAP; Key et al., 2004). The ocean biogeochemistry in the previous ESM2.6 development version was started from a spun-up ESM2M-COBALT 1860 control simulation (Stock et al., 2014a).

2.2 Methods

We identified model ENSO events through the ± 1 standard deviation of the wintertime (November-December-January; NDJ) Niño3.4 index, i.e., using area-averaged sea surface temperatures (SSTs) over $5°$S-$5°$N, $170°$W-$120°$W. We chose to focus

on NDJ rather than the more common DJF (December-January-February), as the maximum ENSO signal observed in nature occurs on average during this time period. In addition, there is a lag in the climate system of several months between the maximum ENSO signal and when this signal is experienced by the mid-latitudes (Alexander et al., 2002).

Due to drift issues in the carbonate chemistry at the beginning of the simulation, we used a Lanczos high-pass filter with a cutoff frequency of 10 years (121 weights; Duchon, 1979). The drift affects roughly the first 10 to 20 years of the simulation (see Fig. S1 in the Supplement). We opted not to remove these affected years, but rather to filter the data, in order to retain as many years as possible, given the relative brevity of the simulation. This procedure removed any long-term trends and decadal variability, and retained variability on an interannual timescale (i.e., the timescale of ENSO frequency). Using this approach, we were left with six El Niño and seven La Niña events in the time-filtered data.

For the majority of the analyses, unless otherwise noted, we employed standardized anomalies (σ, where a value of 2 corresponds roughly to a 95% significance as indicated by a Student's t-test) instead of showing absolute values. In order to allow for a more pattern-driven interpretation of ENSO-related signals in the figures, the modeled time series was normalized at each grid point by the interannual standard deviation derived from each time series. Specifically, a monthly mean climatology is subtracted for each month creating a monthly mean time series of anomalies. The Lanczos time filtering is then applied, which removes variability on time scales longer than 10 years. From this, seasonal averages of time-filtered anomalies are created for each year. Thus, the interannual standard deviation of the seasonal anomalies is computed and used to standardize (i.e., normalize) the seasonal time-filtered anomalies.

Figures 6 through 10 show El Niño minus La Niña composites. This approach assumes linearity in the signal, i.e., that the influence of El Niño is -1 times the influence of La Niña. While there are non-linearities both in the ENSO region (i.e., SSTs in the tropical Pacific) and in the response to the SST anomalies in the extratropics (e.g., Dommenget et al., 2013; Hoerling et al., 1997), the signal is roughly linear, i.e., a significant portion of the response to El Niño events is roughly equal and opposite to La Niña events over the North Pacific (DeWeaver and Nigam, 2002). In addition, given the large amount of variability in both El Niño and La Niña events, and the limited number of ENSO events in observations and in ESM2.6, taking the difference between the two greatly enhances the signal-to-noise ratio.

The notation of 0, 0/1, and 1, as used in Fig. 5, indicates the years during which an ENSO event starts and ends. Typically, events start around June of one year (year 0) and end in spring to summer of the following year (year 1), with a peak during NDJ (0/1). We employ this terminology as used by Rasmusson and Carpenter (1982).

2.3   Comparison of modeled and observed ENSO in the North Pacific

To assess the model's performance in representing the physical regime of the North Pacific, we compare the physical manifestation of ENSO in ESM2.6 to a suite of observational data sets. In addition, we expand on this evaluation by comparing ESM2.6 to its GFDL precursor model, ESM2M, which has a horizontal oceanic resolution of $1°$. We use a 500-year preindustrial ESM2M control run without transient atmospheric CO_2 forcing. Since we analyze normalized values, differences in the magnitude of ENSO and its impact on the CalCS ecosystem would be taken into account between the two runs, including the possible influence of different atmospheric CO_2 concentrations.

A comparison of climatological SST from the Hadley Center (HadISST) and sea level pressure (SLP) from NCEP reanalysis over the North Pacific reveals that both models simulate well the climatological mean SST signal and range as well as the position and magnitude of the North Pacific High pressure system off the southern US West Coast and the Aleutian Low in the Gulf of Alaska (Fig. 1a, d, and g). During El Niño (La Niña), both models represent the composite average SST signals over the

5   whole North Pacific with positive (negative) SST anomalies along the equator and in the Gulf of Alaska and negative (positive) SST anomalies in the subtropical gyre around 30°N (Fig. 1, b, c, e, f, h, and i). Both models also simulate the intensification (weakening) of the Aleutian Low during El Niño (La Niña), though the changes are overestimated and biases in orientation relative to the observed record are apparent. It should be noted that both the orientation and position of the Aleutian Low in the observations and in ESM2.6 are likely affected by the limited number of events present in both time series and could lead to a

10 bias in the results (Deser et al., 2017).

To shed light on the vertical structure of temperature and density, we compare four vertical offshore cross-sections from the ESM2.6 and ESM2M models to output from a Regional Ocean Modeling System (ROMS) reanalysis of the CalCS (Fig. 2). We chose to use the ROMS reanalysis as a comparison as it has a high spatiotemporal resolution and combines the strengths of individual data sources with those of an unconstrained (i.e., no data assimilation) ocean model, to yield a product that is more

15 useful than either of those alone. The offshore cross-sections are located at 44°N, 40°N, 36°N, and 32°N for the 222 km closest to the US West Coast. The 1980-2010 ROMS reanalysis covers the CalCS at 0.1° (∼10 km) resolution, assimilates available satellite (SST, SSH) and in situ (temperature, salinity) data (see Neveu et al. (2016) for details), and has been used extensively to describe CalCS physical dynamics, particularly in response to ENSO variability (Jacox et al., 2015b, a, 2016). ESM2.6 and the ROMS reanalysis show similar results for the composite difference between warm and cold ENSO events, indicating a

20 significantly improved representation of the CalCS ENSO response in ESM2.6 relative to ESM2M. All three models agree on the sign of the temperature anomalies during El Niño (although ESM2M underestimates the magnitude of these anomalies), and ESM2.6 and ROMS highlight the largest temperature anomalies in the nearshore region and above 150 m water depth. All three models agree that density surfaces tend to deepen during El Niño (green lines) and shoal during La Niña (blue lines), with a difference in depth of up to 30 m between mean El Niño and La Niña conditions.

25 Additionally, we compare springtime (February-March-April; FMA) variability of modeled versus observed NASA-SeaWIFS surface chlorophyll (CHL) concentrations along the US West Coast (Fig. 3). Due to its brevity, the CHL record does not lend itself well to an ENSO composite analysis, so we analyze CHL interannual variations via the standard deviation. We find that ESM2.6 represents well the strong cross-shore gradient in CHL variability all along the coast, with high variability of up to 2.5 standard deviations nearshore and lower variability offshore. ESM2M on the other hand only manages to reconstruct the

30 same nearshore values in the region between 40-45°N, but underestimates the cross-shore gradient significantly to the north and south of this. Both models overestimate the CHL variability offshore at around 36-40°N in comparison to the observed variability.

Finally, we compare modeled versus observed Niño3.4 indices and find that the SST variability in the tropical Pacific is overestimated in both models, with the maximum SST variance in ESM2.6 being roughly twice as high as in ESM2M and up to five

35 times higher than in the observations (see Fig. S2 in the Supplement). Both models simulate the large-scale atmospheric and

oceanic responses associated with ENSO. However, ENSO events that are similar in magnitude to the strongest on record are far more common and regular in the model than the recent historical record suggests. This offers an opportunity to isolate large ENSO signals, though even with normalization the biogeochemical imprint of ENSO events is likely accentuated relative to other sources of variation. Furthermore, due to its high horizontal oceanic resolution, ESM2.6 does a particularly good job of

5 reproducing the cross-shore gradients in SST and CHL along the US West Coast, with warm temperatures and increased CHL variability close to the coast. ESM2M's coarse horizontal resolution on the other hand does not allow for a representation of finer-scale processes related to coastal upwelling and it thus fails to correctly model the cross-shore SST and CHL gradients. We thus focus on ESM2.6 to gain insight into the regional biogeochemical response of the CalCS to strong ENSO events.

3 Results

10 ### 3.1 Individual representations of ENSO in ESM2.6 in the CalCS

Figure 4 highlights the variability in SST (with overlaid SLP), O_2, and pH between two of the six El Niño events (Event 2 and Event 6; see Figs. S3 to S5 in the Supplement for the other four El Niño events, and Fig. S5 for the individual SST/SLP La Niña events). The responses of all three variables to the different events are highly variable. While some of the SST/SLP responses are similar to the signals typical during an Eastern Pacific-type El Niño in the observational record (see Supplement),

15 the responses to Event 2 and Event 6 are drastically different from each other and from observed signals. For SST, O_2, and pH, Fig. 4a-c show widespread areas of alternating negative and positive anomalies with no clear gradients between the coast and offshore. For Event 6 on the other hand, all three variables exhibit stronger anomalies, covering broader areas offshore (Fig. 4d-f).

Figure 5a-f shows the temporal evolution of surface and subsurface (100 m) temperature, O_2, and pH for the six individual

20 El Niño and seven individual La Niña events, as well as the composite mean, for a region within 100 km of the coast and averaged over 34–44°N (see Fig. 5h for the specified region). We analyze the surface as well as 100 m since the surface is where heat transfer and chemical interactions with the atmosphere take place, and thus the atmospheric impact of ENSO is the greatest, and 100 m is roughly the depth of the heart of the thermocline. In addition to the modeled results, we show SST from the Hadley Center (HadISST; Fig. 5g). At the surface, temperature anomalies are on average positive (negative) during

25 El Niño (La Niña) with values of -1σ to 3σ (-2σ to 1σ) for the individual events (Fig. 5a and d). On average, the variability of modeled SST (Fig. 5a) compares well with the observed SST (Fig. 5g), both for El Niño and La Niña, and especially for the composite mean. In the case of O_2, the coastal surface waters experience lower-than-usual O_2 conditions during El Niño (σ on average around -1), whereas O_2 concentrations tend to be elevated with σ of up to 1 during La Niña (Fig. 5b). At 100 m, the strongest temperature signal occurs during the spring (FMA) following the typical El Niño season (NDJ). Furthermore,

30 the CalCS experiences higher-than-usual O_2 conditions during El Niño and lower O_2 concentrations during La Niña at 100 m. As was the case with temperature, the largest O_2 signal occurs with σ between 1 and 2 during FMA. This contrasting behavior exhibited by O_2 at the surface and at 100 m is not exhibited by pH, which like temperature displays a consistent signal throughout the water column (Fig. 5c and f).

As the results in Figs. 4 and 5 show, the variability between individual events is extremely high. Due to this fact, we focus our analyses on the composite mean over all El Niño and La Niña events for the remainder of the study.

3.2 Response of temperature, O_2, and pH to mean ENSO signal

We illustrate the mean response of surface temperature, O_2, and pH to ENSO in Fig. 6a-c. SST anomalies here are positive between the coast and ∼300-500 km offshore, as well as offshore north of 40°N and south of 28°N, with anomalies of up to 2σ (Fig. 6a). Offshore between ∼28°N and 40°N, in the region of the subtropical gyre, SST anomalies are negative around $1-2\sigma$, and reflect a typical observed El Niño signal. The surface O_2 anomalies largely reflect the SST signal, albeit with a reversed sign, as would be expected from a solubility-driven response. Close to the US West Coast, O_2 anomalies are lower than -2σ and become less negative further offshore. Positive O_2 anomalies of around $0.8-2\sigma$ are found offshore in the region of the subtropical gyre (Fig. 6b). The surface pH signal differs from the SST and O_2 signals, in that positive pH anomalies, with a maximum around 2σ, are limited to a very narrow band of ∼100 km along the coast (Fig. 6c). Between 100 km and around 500 km offshore, El Niño minus La Niña pH anomalies are negative around -0.8σ, while further offshore in the region of the subtropical gyre, pH anomalies are predominantly positive again.

We investigate ENSO-driven changes in temperature, O_2, and pH in the subsurface (100 m) in Fig. 6d-f. A similar cross-shore gradient in temperature occurs at 100 m compared to the surface, with anomalies larger than 2σ in some regions along the coast (Fig. 6d). However, the 100 m signal is more limited to within a ∼100 km wide band along the coast. The mean response of 100 m O_2 to ENSO is drastically different than the O_2 response at the surface, with positive anomalies within a 100 km band along the coast, indicating that two different processes govern the O_2 response to ENSO at the surface and at depth (Fig. 6e). The 100 m pH signal looks largely the same as the surface pH signal, with a slightly broader cross-shore region with positive pH anomalies of up to 2σ (Fig. 6f). These positive pH anomalies are also more widespread northward and southward along the coast at 100 m compared to the surface. Furthermore, the 100 m pH signal is very similar to the 100 m O_2 signal (compare Fig. 6e and 6f), suggesting a common subsurface process influencing both variables.

In Fig. 7 we examine the same offshore cross-sections as in Fig. 2 and focus on the response of temperature, O_2, and pH to ENSO in the vertical plane. Again, we show El Niño minus La Niña composite anomalies. The differing response of O_2 to ENSO at the surface and at 100 m that we observed in Fig. 6 is also clearly visible in all four offshore cross-sections in Fig. 7 (b, e, h, and k). The pH (Fig. 7(c, f, i, l)) and O_2 responses are very similar between 32°N and 36°N, suggesting that here, they are both affected by the same processes. Between 40°N and 45°N on the other hand, El Niño minus La Niña pH anomalies are mostly positive throughout the water column, indicating that in this region there is a different process at play affecting pH in the top ∼100 m as opposed to O_2 at the same latitude.

3.3 Drivers and processes behind changes in O_2 and pH in the CalCS

In the surface ocean, O_2 is affected by four main processes: (i) changes in SST, which affect the O_2 solubility, (ii) wind-driven variability, which drives the O_2 gas exchange across the air-sea interface, (iii) primary production, which reduces CO_2 and increases O_2 in the surface ocean, and (iv) ocean circulation, which affects horizontal advection and upwelling. We assume

that the total change in O_2 during El Niño is the sum of two components that include temperature-related and temperature-unrelated processes (after Fay and McKinley, 2013), thus:

$$\Delta O_2 \approx \underbrace{\frac{\partial O_2}{\partial T} \cdot \Delta T}_{\text{temperature-related}} + \underbrace{\text{Residual}}_{\text{temperature-unrelated}} \tag{1}$$

For the analysis in Fig. 8, we derive the temperature-related component from the solubility of O_2, using the solubility coefficients of Weiss (1970) as demonstrated in (Sarmiento and Gruber, 2006, page 329). Since the total change in O_2 is just the composite mean (ΔO_2 in Equation 1), we calculate the temperature-unrelated component, or residual term, from the difference between ΔO_2 and the temperature-related component. The negative correlation between temperature and O_2 in the surface ocean (as seen in Fig. 6a and b) can largely be explained by a rise in temperature causing a decrease in the amount of O_2 that can be dissolved in the surface waters and thus leading to a drop in surface O_2 (Fig. 8b). We argue that while increased storm activity during El Niño could enhance the O_2 gas exchange through the air-sea interface, the decrease in wind stress over the CalCS, which is typically associated with El Niño, is expected to have an overall reducing effect on the O_2 gas exchange. As the CalCS is on average a source of O_2 to the atmosphere (Sarmiento and Gruber, 2006), this effect contributes to an increase in O_2, and thus opposes the solubility effect. The residual effect (Fig. 8c), which is a combination of upwelling of waters with a certain O_2 signal and the biological imprint on O_2 concentrations, acts on average to decrease O_2 in the surface ocean. This is likely due to primary production being limited during El Niño (e.g., Bograd and Lynn, 2001).

At 100 m, where El Niño leads to an increase in O_2 along the coast and up to ~200 km offshore, the main driver of the O_2 change is the residual term, i.e., the contribution that is not directly linked to changes in temperature (Fig. 8f). This term could include local biological effects and/or circulation-driven changes between water masses with different histories of O_2 supply and consumption. In this case, the simulated O_2 increase is consistent with the deepening of isopycnal surfaces during El Niño (Fig. 2), replacing older, O_2-poor waters associated with dense subsurface waters in the CalCS, with less dense, elevated O_2 waters. Figure 9 demonstrates that during El Niño, the depth at which oxygen falls below the hypoxic threshold (where O_2 is $\leq 60\ \mu\text{mol}\,\text{kg}^{-1}$) deepens on average by 20 m in the first 100 km along the coast from a mean climatological depth of around 300 m, representing a 6-7% change. This deepening of O_2-depleted waters, where remineralization rates are high, can help explain the modeled increase in O_2 seen along the coast in Fig. 7 (b, e, h, and k) and Fig. 8d.

We consider the contributions of surface DIC, ALK, temperature (T) and salinity (S) to ENSO-driven changes in surface pH in Fig. 10. For this analysis we focus on surface values, as DIC and ALK were saved only in the surface layer in the simulation. To decompose pH into these four drivers, we use a Taylor expansion according to the following equation (after Lovenduski et al., 2007; Doney et al., 2009b; Turi et al., 2014, 2016):

$$\Delta \text{pH} \approx \frac{\partial \text{pH}}{\partial \text{DIC}} \cdot \Delta \text{DIC} + \frac{\partial \text{pH}}{\partial \text{ALK}} \cdot \Delta \text{ALK} + \frac{\partial \text{pH}}{\partial T} \cdot \Delta T + \frac{\partial \text{pH}}{\partial S} \cdot \Delta S \tag{2}$$

where the partial derivatives denote the sensitivities of pH to small changes in the four drivers. We determined these sensitivities by adding a small perturbation to each driver and recalculating pH with these new values using the online tool "CO2calc"

(Robbins et al., 2010). We did this procedure for each driver and then multiplied each sensitivity by the change in each variable as calculated in the ENSO composites shown in Fig. 8 (corresponding to the Δ-terms in Equation 2).

Changes in DIC are primarily what drive the increase in pH in the nearshore 100 km of the central CalCS ($34°N–40°N$; Fig. 10c), whereas the contributions from SST and ALK counteract the effect of DIC by reducing pH in the same region (Fig. 10b and d). During El Niño, upwelling is weakened and the thermocline is depressed, thus limiting the supply of low-pH and high-DIC waters to the surface. Likewise, the supply of cold, high-ALK waters is inhibited, leading to a decrease in pH due to a positive correlation with ALK and a negative correlation with temperature. North of $\sim$40°N, changes in DIC and SST contribute to an overall slight decrease in pH, whereas changes in ALK lead to an increase in pH. Thus, the SST contribution to pH mainly acts through the mechanism of surface heat fluxes, rather than through changes to the upwelling of cooler waters, as the contribution of changes in SST to the overall changes in pH (Fig. 10b) are of the same sign all along the coast and extend further offshore than the contributions of both DIC and ALK. The contributions of salinity and of the residual term are negligible throughout the whole CalCS (Fig. 10e and f).

4 Discussion and conclusions

The influence of ENSO on the physics and ultimately the biogeochemistry of the CalCS is very complex, due to the multiple processes that are affected by ENSO-driven climate variability. In this study, we delved into the processes through which ENSO can influence O_2 and pH in the CalCS, and explained how physical variability can influence the carbon and oxygen systems of the CalCS. Our results demonstrate that in the surface ocean above the thermocline (above $\sim$100 m), interannual variability associated with ENSO modulates O_2 and pH through two different mechanisms. In the case of surface O_2, the strongest signal extends hundreds of km offshore, mirroring the SST signal where elevated temperatures during El Niño lower the O_2 solubility and thus cause a decrease in O_2. The decomposition of O_2 into temperature-related and temperature-unrelated components further confirmed that changes in the O_2 solubility are the main driver for the surface O_2 anomalies. Furthermore, our results show a decoupling between the response of O_2 to ENSO in the surface ocean above the thermocline and the waters below that. Below 100 m, O_2 is mainly modulated through changes in the vertical structure which affect the depth and location of the hypoxic threshold. During El Niño for example, while the surface ocean above the thermocline experiences a decrease in O_2, the concentration of O_2 in the waters below that increases and the hypoxic threshold deepens due to a depression of the thermocline. During La Niña, the mechanism is reversed and we model an increase in O_2 at the surface and a decrease below 100 m (not shown). In the case of pH on the other hand, the strongest changes occur in and are limited to a narrow band of $\sim$100 km along the central US West Coast ($\sim$34–40°N), both at the surface and below the thermocline. We inferred from the decomposition of pH into its individual components that changes in DIC, driven by modifications to the depth of the thermocline during an ENSO event, are the main driver of pH variability in the nearshore 100 km, whereas temperature and ALK counteract the DIC effect. Further offshore on the other hand, SST changes become more important in determining pH variability and the contributions of DIC and ALK tend to cancel each other. These results also suggest that during La Niña, the first 50-100 km along the coast are more readily supplied with cool, nutrient-rich water, thus enhancing the coastal upwelling

effect, and potentially fueling biological production. At the same time, this process also brings more [H^+], DIC, and ALK to the surface, thus overall lowering surface pH more toward a state of acidity. During El Niño on the other hand, this process is suppressed, thus limiting the supply of nutrients and inhibiting biological production. At the same time however, the supply of [H^+] is also limited, therefore having an overall increasing effect on surface pH.

5   The findings for pH are in line with Nam et al. (2011), who noted an increase in nearshore surface pH during El Niño and a decrease during La Niña due to an uplifting of isopycnal surfaces and thus a higher supply of low-pH waters to the surface. In the case of O_2 on the other hand, our results differ from what Nam et al. (2011) concluded. While we found a significant increase (decrease) in O_2 in the nearshore surface waters above 100 m during La Niña (El Niño), their study suggests that during the 2010/2011 La Niña, O_2 anomalies were lower than average. Their explanation for this observation is that due to

10   an increased poleward flow of the California Undercurrent during La Niña, subsurface primary production was limited and thus caused a reduction in O_2 concentrations. Our results however suggest that the modeled increase (decrease) in surface O_2 during La Niña (El Niño) is mainly driven by changes to the O_2 solubility due to anomalous surface cooling (warming). Furthermore, the analysis suggests that below 100 m, the opposing decrease (increase) in nearshore O_2 during La Niña (El Niño) is attributable to a shoaling (deepening) of isopycnal surfaces, affecting the location of low-O_2 waters. One potential

15   between our study and the one by Nam et al. (2011) is that our study focuses on a composite mean ENSO signal over several events and the focus of theirs is on a specific event.

    As Nam et al. (2011) pointed out, the large variability in O_2 and pH during ENSO events seen in their study, which can be seen also in ours, suggests that the carbonate ion concentration ([CO_3^{2-}]) and thus the saturation state of aragonite (Ω_{arag}) experience similar fluctuations in their amplitude (Turi et al., 2016). If the pH drops below 7.75, which corresponds to $\Omega_{arag} <$

20   1, waters become unfavorable for calcifying organisms to build and maintain their shell structure (e.g. Feely et al., 2008; Bednaršek et al., 2014; Bednaršek and Ohman, 2015). Our results suggest that during La Niña, the surface waters are more corrosive but also more oxygenated than during El Niño, while the waters below 100 m are both more corrosive and more deoxygenated. While primary production in the CalCS is greater during La Niña, the ecosystem is also more stressed by O_2, low-pH, and low-Ω_{arag} conditions which could add to or enhance the impact of these stressors due to climate change, as also

25   noted by Nam et al. (2011). A more in-depth, quantitative analysis of the biological and physical mechanisms driving O_2 and pH in the CalCS is anticipated to be the focus of future publications on ESM2.6.

    This modeling study can help inform future observational studies on the frequency as well as horizontal and vertical resolution of O_2 and pH measurements necessary to capture the surface and subsurface biogeochemical expressions of ENSO in the CalCS. We show that it is critical to have a strong observational network particularly in the nearshore 100 km along the US

30   West Coast, as this is where the ENSO signal is largest, both in O_2 and in pH. Furthermore, the modeled contrasting response of O_2 to ENSO at the surface and at 100 m highlights the necessity of having vertical sections that go deep enough and have a sufficient vertical resolution to capture signals both in the euphotic zone above the thermocline as well as in the waters below it. This study additionally demonstrates that the diversity of ENSO events might contribute to the variability of the physics and biogeochemistry in the CalCS, and thus emphasizes the importance of analyzing long enough time series to include a variety

35   of different events. In addition to the variability between different types of ENSO events, other sources of internal climate

variability unrelated to ENSO contribute to noisiness in the physical and biogeochemical signals in the CalCS (e.g., Deser et al., 2017).

While there is a clear link between ENSO events in the equatorial Pacific and ocean conditions in the CalCS, the evolution of any single event can be influenced by a number of processes. Each ENSO event evolves differently (e.g., Capotondi et al., 2015) and the variability between events, including the timing, strength and location of temperature anomalies, can influence atmospheric teleconnections over the North Pacific (e.g., Calvo et al., 2017) and the propagation of coastally trapped waves (e.g., Frischknecht et al., 2015, 2017). Atmospheric teleconnections, and the associated winds and air temperatures over the CalCS, are influenced by SSTs in other basins, including the Indian Ocean (e.g., Annamalai et al., 2007; Han et al., 2013) and the Kuroshio-Oyashio extension in the western North Pacific (e.g., Smirnov et al., 2015) and potentially by Arctic sea ice concentrations (e.g., Alexander et al., 2004; Screen et al., 2014). Differences in the state of the atmosphere and ocean at the time of an ENSO event also influence the magnitude of the anomalies and their evolution. Base state differences, such as changes in the position of the jet stream or decadal variability in the Pacific, can arise from variability on interannual to centennial time scales (e.g., Li et al., 2011; Zhou et al., 2014). The climate system is highly nonlinear and generates variability unrelated to ENSO events, contributing noisiness in the physical and biogeochemical ENSO-related signals in the CalCS. The noise is quite large, as has been demonstrated by the spread in ensembles of model simulations with the same ENSO conditions in the tropical Pacific but slightly different initial conditions (e.g., Hoerling and Kumar, 1997; Sardeshmukh et al., 2000; Alexander et al., 2002; Deser et al., 2017). Thus, the evolution of anomalies in the CalCS is expected to differ between ENSO events in both nature and models, which may partly explain the difference between the study by Nam et al. (2011), which analyzed a single La Niña event, and the present study. The uncertainty in the extratropical response to ENSO emphasizes the importance of analyzing long enough time series to include a variety of different events.

Data availability. The ROMS reanalysis output is available from http://oceanmodeling.ucsc.edu. The GFDL model output is available upon request. The SLP observational data are from the NCEP Reanalysis and were downloaded at https://www.esrl.noaa.gov/psd/data/gridded/. The SST observational data are from the Hadley Center at http://www.metoffice.gov.uk/hadobs/hadisst/. Finally, the CHL data are from SeaWIFS 1998-2010 and were obtained from NASA at https://oceandata.sci.gsfc.nasa.gov/SeaWiFS/.

Author contributions. GT wrote the manuscript. GT, MA, CS, and JD outlined the initial stages of the project. GT, MA, NSL, AC, and JS were responsible for streamlining the direction and scope of the project. JS created all the figures. MJ supplied the ROMS simulation output. CS, JD, and JJ set up and ran the ESM2.6 and ESM2M models. JJ managed the model output and storage. All authors contributed to the discussion and revision of the manuscript contents.

Competing interests. The authors declare that they have no conflict of interest.

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FMA SST (°C, shaded), DJF SLP (mb, contour)
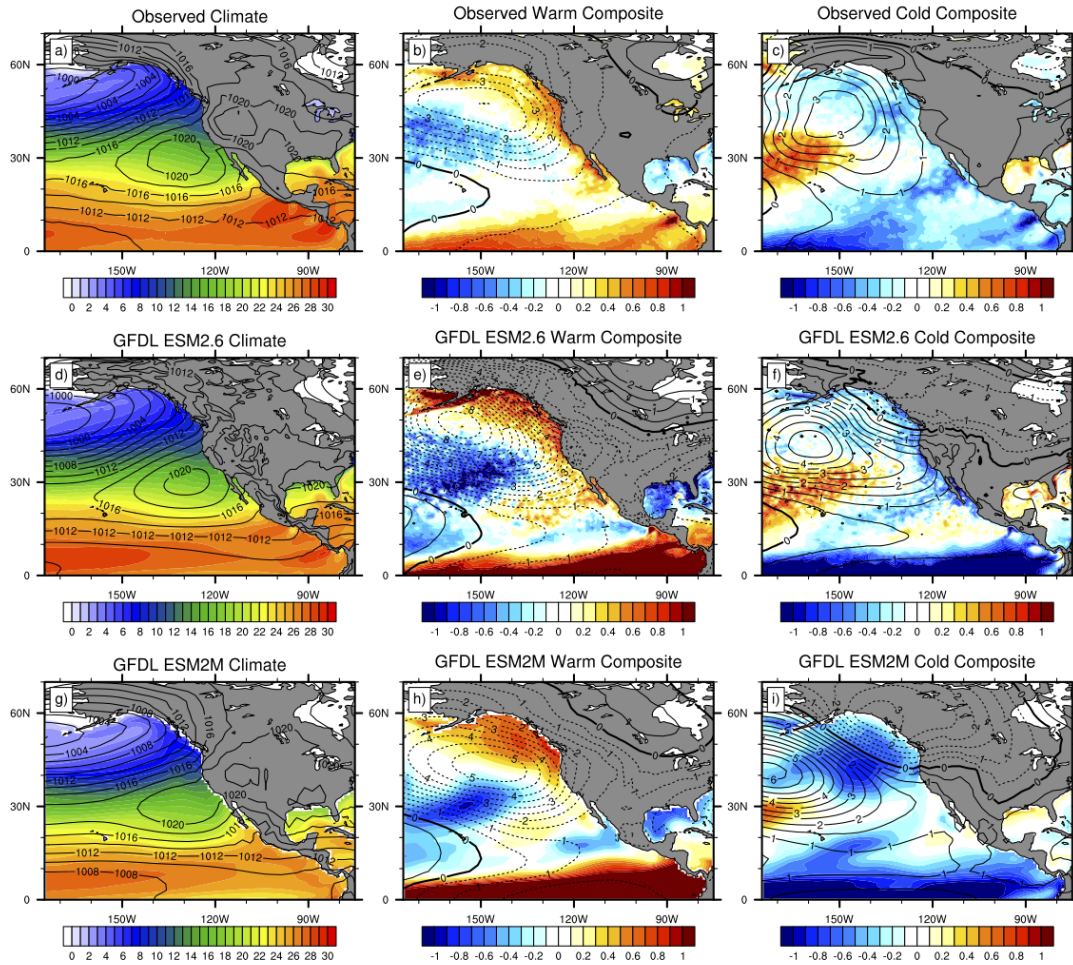
Figure 1. FMA sea surface temperature (°C, shaded) and DJF sea level pressure (mb, contour) in the eastern North Pacific: (a, d, and g) climatology (4 mb contour interval), (b, e, and h) El Niño/warm high-pass composite (0.5 mb contour interval), and (c, f, i) La Niña/cold high-pass composite (0.5 mb contour interval) for (a-c) observations (sea surface temperature: HadISST; sea level pressure: NCEP Reanalysis), (d-f) ESM2.6, and (g-i) ESM2M.
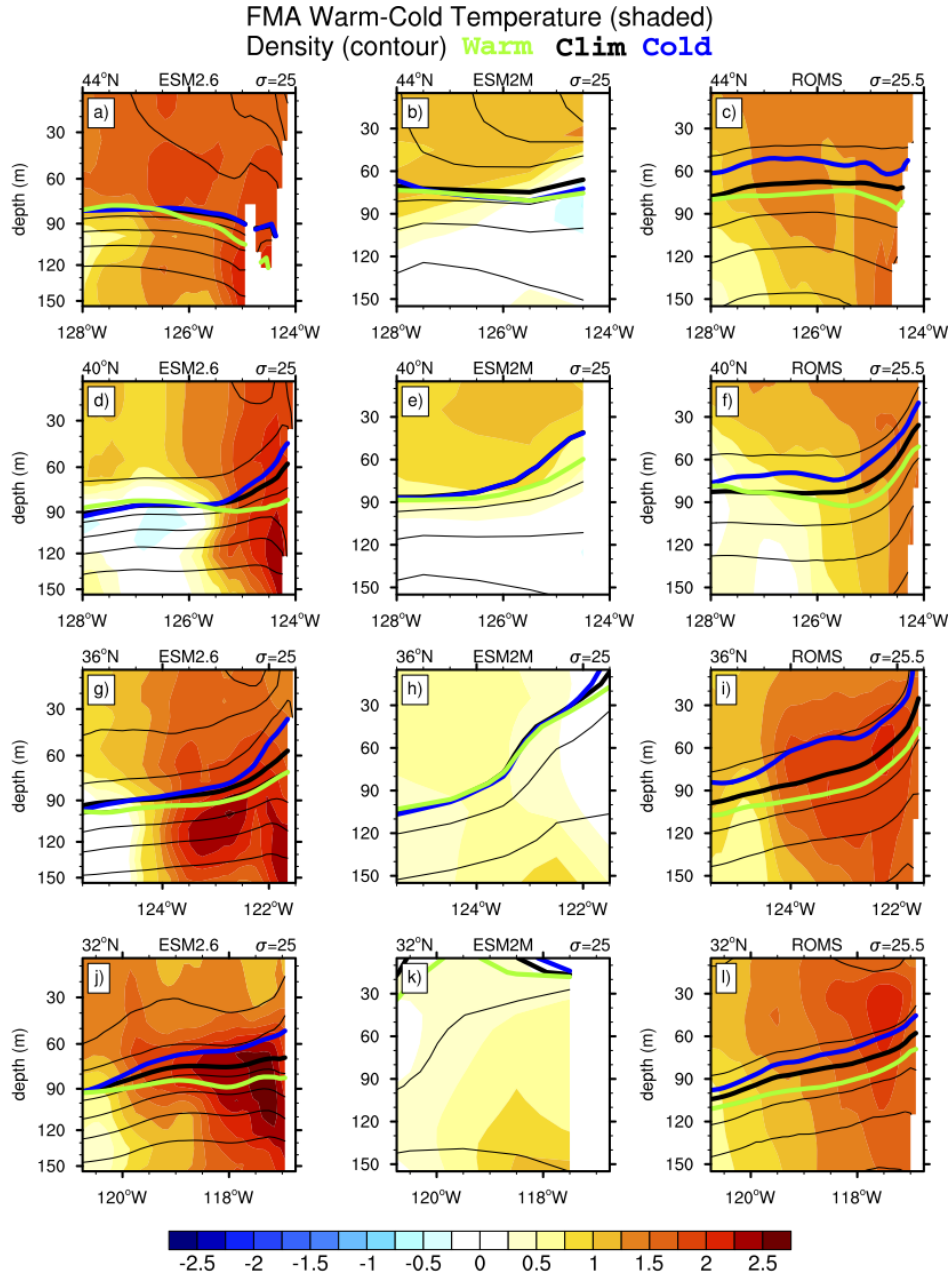
Figure 2. ESM2.6 depth-longitude cross-sections of FMA warm-cold high-pass filtered standardized anomalies of temperature (unitless) for (first column) ESM2.6, (second column) ESM2M, and (third column) ROMS. The contours show the mean climatological density lines (first row) 44°N, (second row) 40°N, (third row) 36°N, and (fourth row) 32°N for the 222 km nearest the US West Coast. The bold lines show the positions for the σ=25 level (ESM2.6 and ESM2M) and the σ=25.5 level (ROMS) for the climatology (black), El Niño conditions (green) and La Niña conditions (blue) and the thin lines indicate density increments of 0.25.
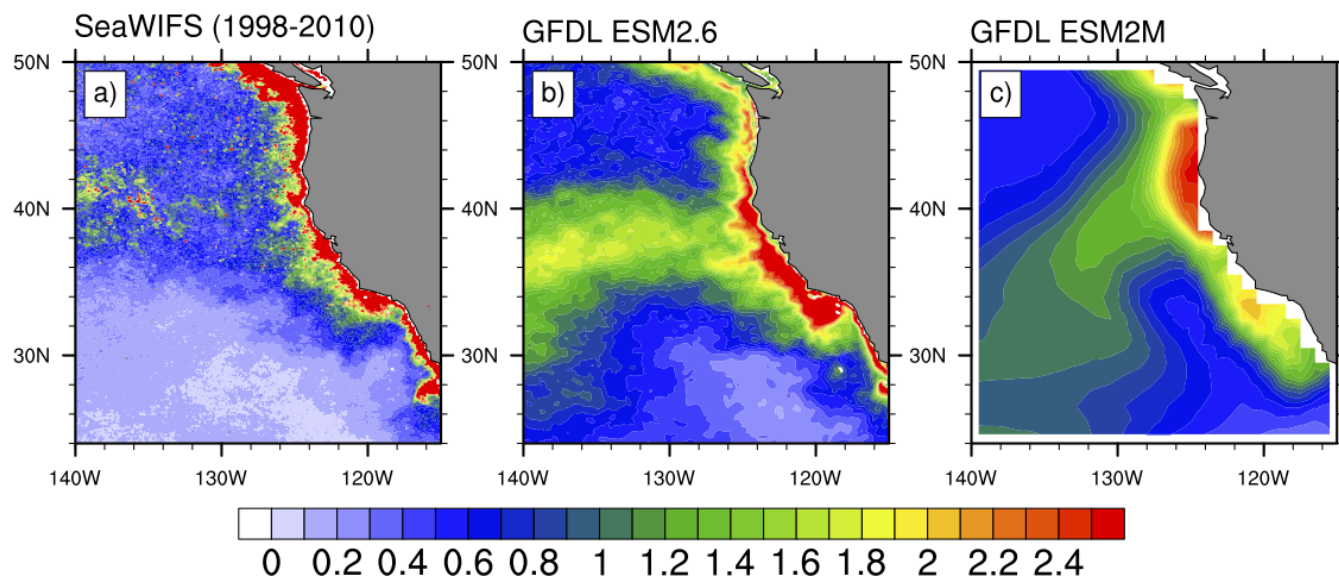
Figure 3. FMA interannual standard deviation of surface chlorophyll concentrations (standardized by area average to produce comparable scales; unitless) for a) 1998-2010 NASA-SeaWIFS observations, b) ESM2.6, and c) ESM2M.
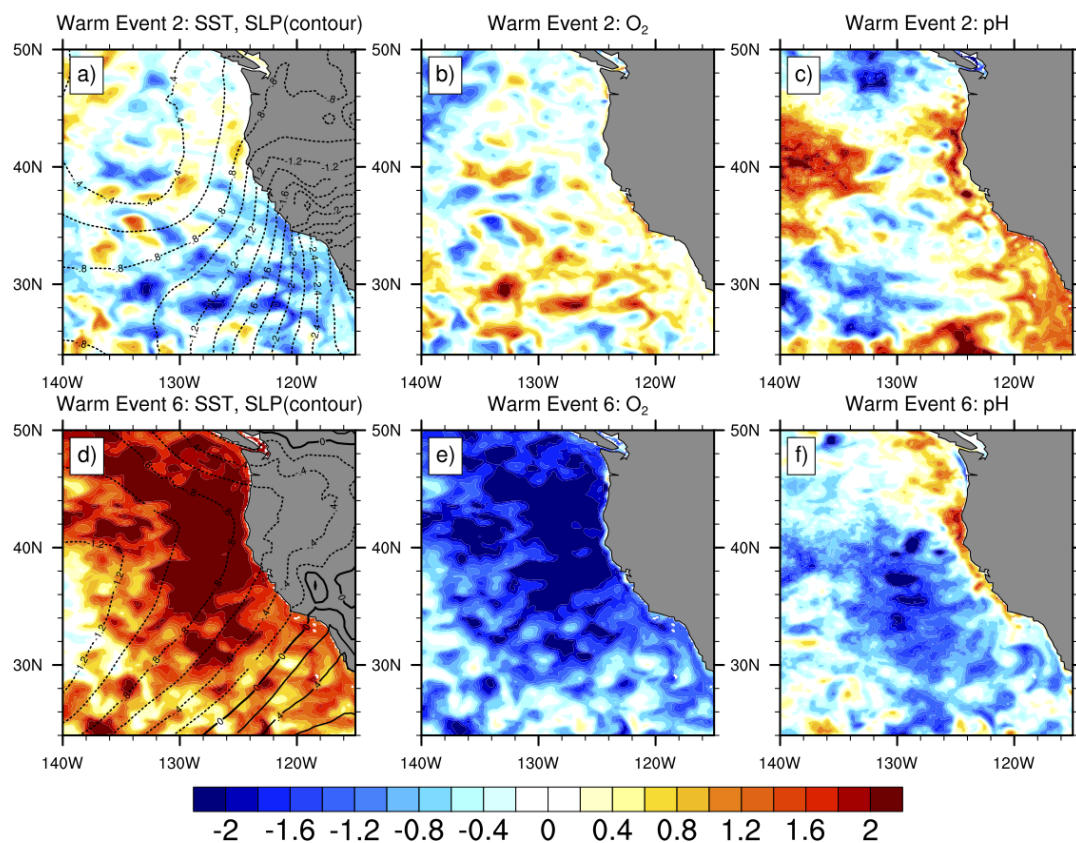
Figure 4. ESM2.6 FMA high-pass filtered standardized anomalies (unitless) for two warm El Niño events based on NDJ Niño3.4 anomalies: (a-c) Event 2 and (d-f) Event 6, with a) and d) sea surface temperature with sea level pressure (0.2 σ interval contours), b) and e) surface O_2, and c) and f) surface pH.
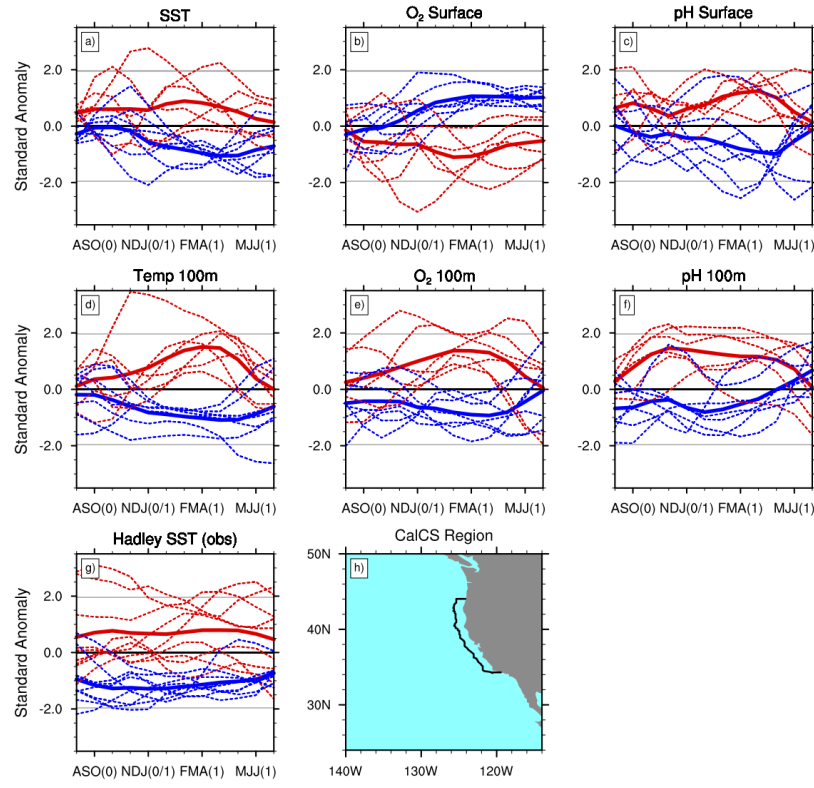
Figure 5. Temporal evolution of individual warm (red) and cold (blue) events (dashed) and composite of all events (solid) for area averages between 34°N and 44°N and 100 km offshore of the US West Coast for a) ESM2.6 sea surface temperature, b) ESM2.6 surface O_2, c) ESM2.6 surface pH, d) ESM2.6 100 m temperature, e) ESM2.6 100 m O_2, f) ESM2.6 100 m pH, and g) HadISST sea surface temperature. The time series are high-pass filtered and seasonally averaged and show the evolution of standardized anomalies (unitless) during the peak ENSO years from JAS before the peak to JJA after the peak. The black outline in h) highlights the area within the CalCS used for this analysis. The notation of 0/1 is as used in Rasmusson and Carpenter (1982).
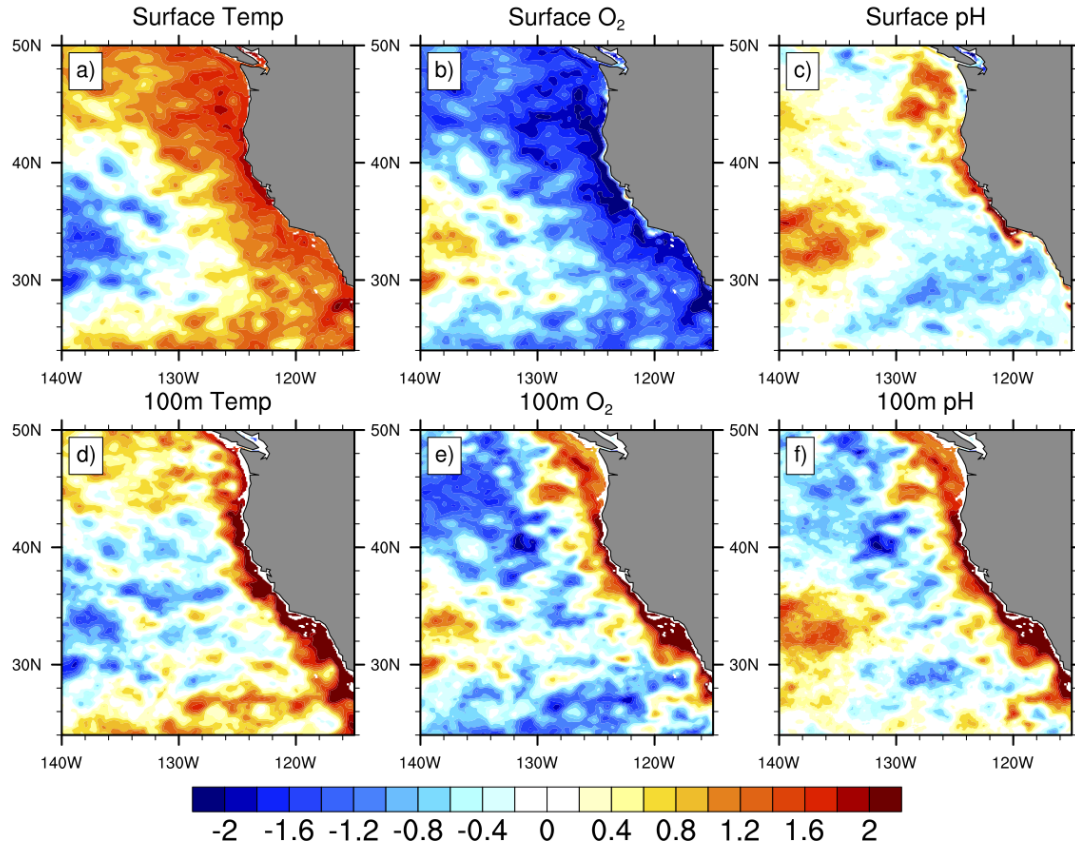
Figure 6. ESM2.6 FMA warm-cold high-pass filtered standardized anomalies (unitless) for a) sea surface temperature, b) surface O_2, c) surface pH, d) 100 m temperature, e) 100 m O_2, and f) 100 m pH.
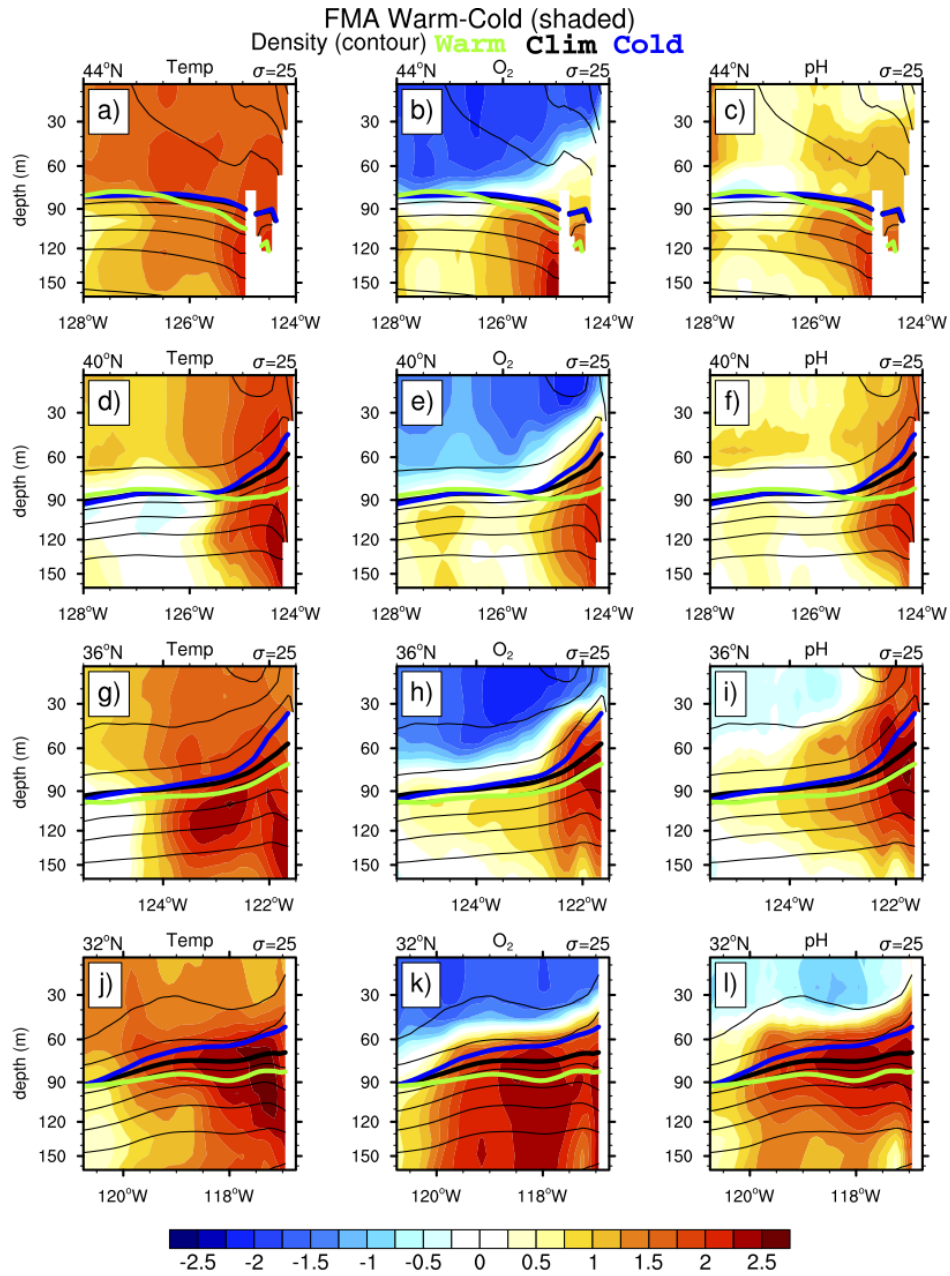
Figure 7. ESM2.6 depth-longitude cross-sections of FMA warm-cold high-pass filtered standardized anomalies (unitless) of (first column) temperature, (second column) O_2, and (third column) pH (shaded) with mean climatological density lines (contour) along (first row) 44°N, (second row) 40°N, (third row) 36°N, and (fourth row) 32°N for the 222 km nearest the US West Coast. The bold lines show the positions for the $\sigma=25$ level for the climatology (black), El Niño conditions (green) and La Niña conditions (blue) and the thin lines indicate density increments of 0.25.
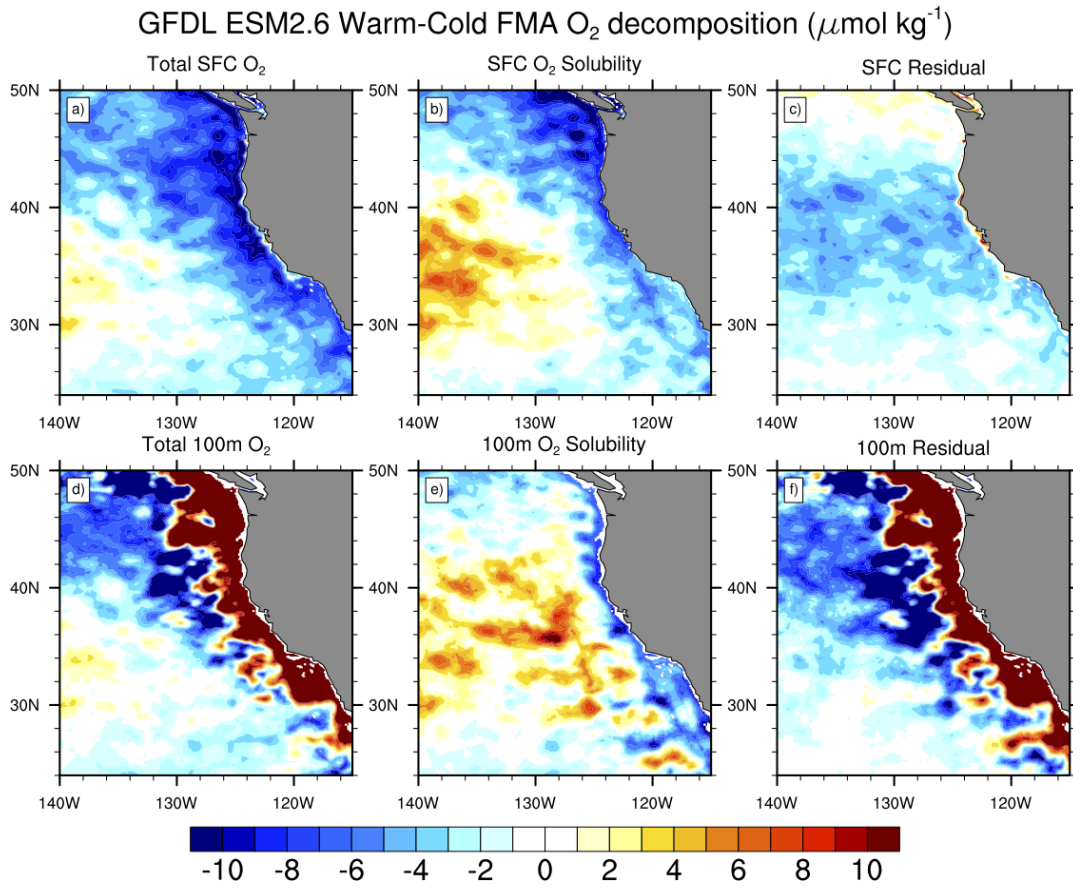
Figure 8. ESM2.6 FMA warm-cold high-pass filtered anomalies (μmol kg^{-1}) for O_2 and its components a) surface total O_2, b) O_2 due to Δ surface temperature (solubility), c) residual surface processes, and d) 100 m total O_2, b) O_2 due to Δ 100 m temperature (solubility), c) residual 100 m processes.
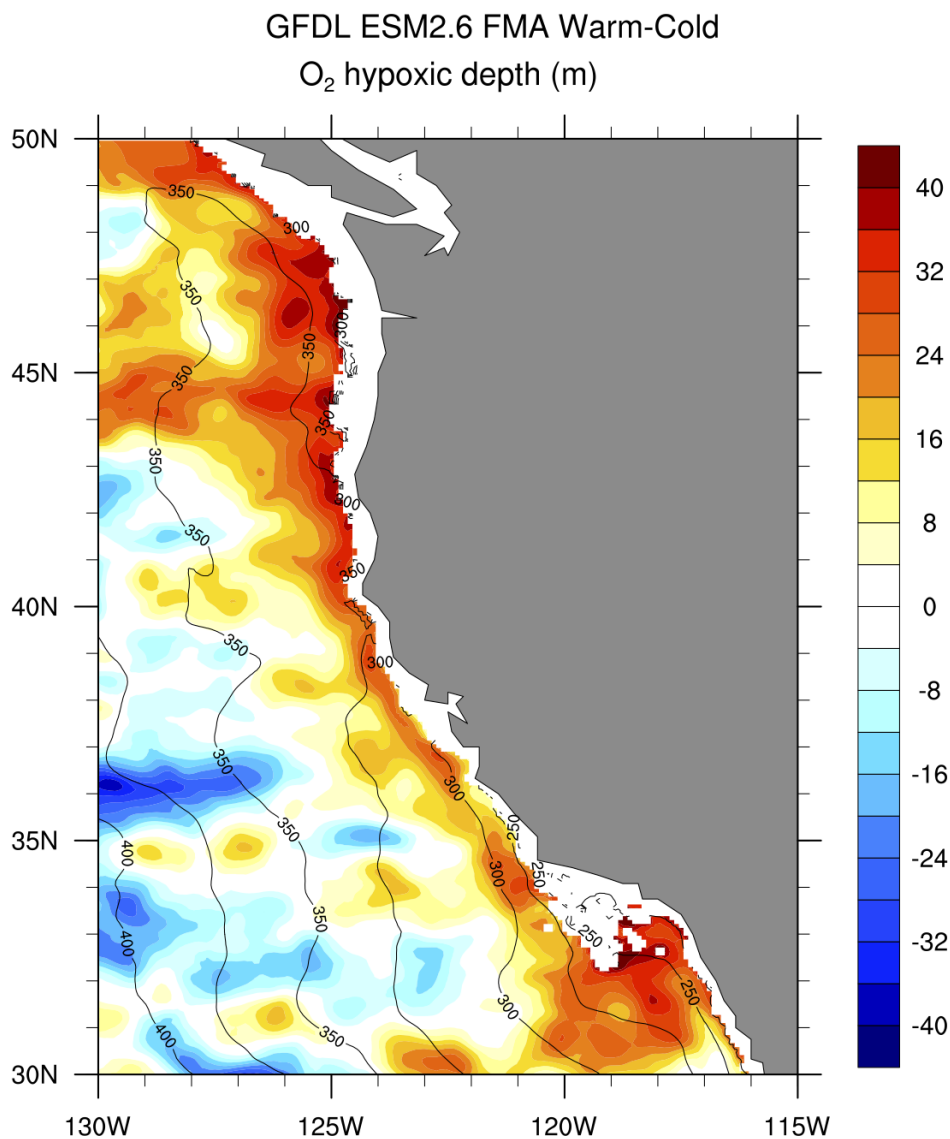
Figure 9. ESM2.6 FMA warm-cold high-pass filtered anomalies (m) for depth of the hypoxic threshold ($O_2 \leq 60\ \mu mol\ kg^{-1}$) and FMA mean climatological depth of the hypoxic threshold (25 m interval contours). White areas near the coast indicate an absence of the hypoxic level in the vertical layer. Positive numbers indicate a deepening of the hypoxic threshold.
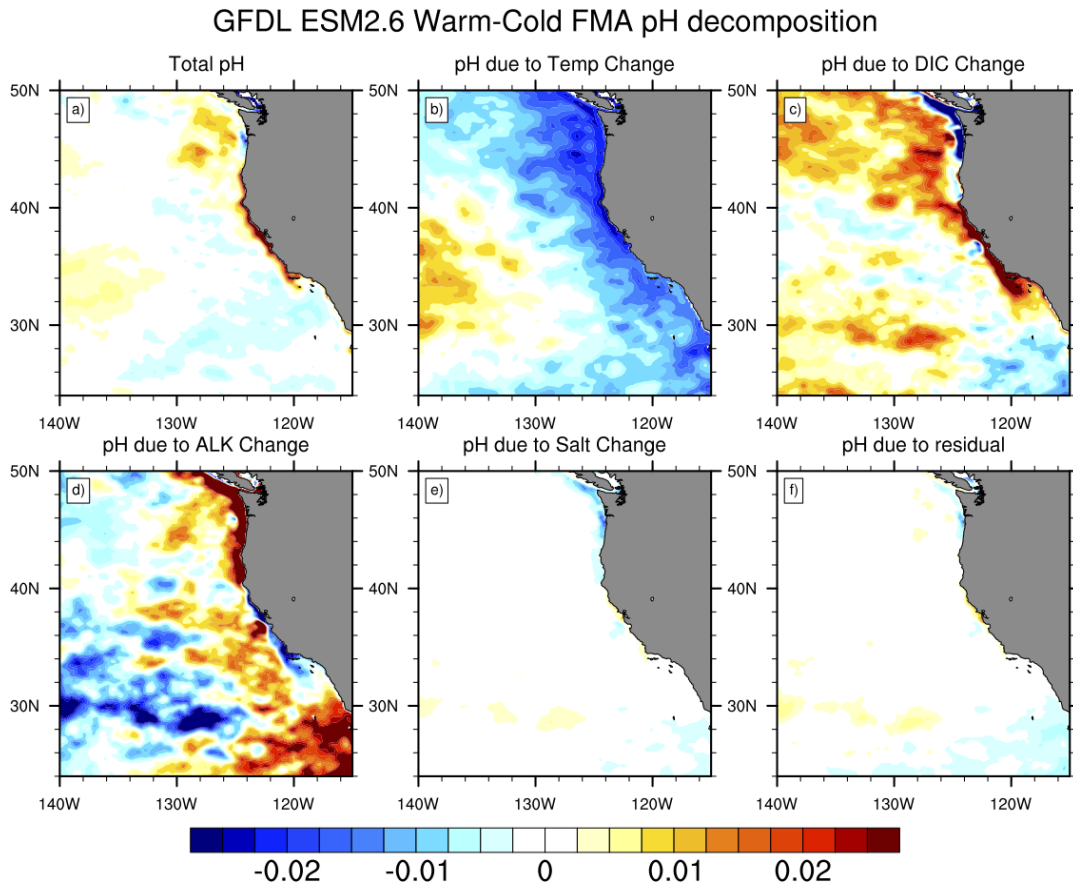
Figure 10. ESM2.6 FMA warm-cold high-pass filtered standardized anomalies for surface pH (unitless) and its components a) total pH, b) pH due to Δ temperature, c) pH due to Δ dissolved inorganic carbon, d) pH due to Δ total alkalinity, e) ph due to Δ salinity, and f) residual processes.

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