Anonymous Reviewer #1
Received and published: 30 August 2017

The reviewer's comments are in *italics* and the Authors' replies are in plain text.

The authors would like to thank anonymous reviewer #1 for her/his thorough review of the manuscript and for the insightful comments that have greatly helped improve the publication.

1. Summary
Turi et al. use a high-resolution fully-coupled global earth system model (GFDLESM2.6) to uncover the O2 and pH response of the California Current System (CalCS) to El Niño/Southern Oscillation (ENSO). Despite significant variations of the response to individual events due to ENSO diversity, composite means for warm/cold events reveal consistent physical and biogeochemical changes along the US West Coast. While the O2 response to ENSO is wide-spread and differs between the surface (driven by changes in the solubility) and at 100m (driven by changes in the thermocline structure), the pH response is mainly confined to the coastal environment, highlighting the dominant role of changes in dissolved inorganic carbon (DIC) and upwelling associated with ENSO.

2. General comments
The influence of ENSO on the physical and biogeochemical environment of the CalCS is evidenced both in observational and model-based data. Investigating the associated changes in the current system improves our understanding of the ecosystem functioning, its sensitivity to change and is relevant for ocean management. Even though the imprint of ENSO on the CalCS has been thoroughly studied, the diversity among ENSO events and the lack of high-frequency 3-dimensional observational records render modeling studies (such as the one presented) extremely valuable in providing opportunities to study ecosystem changes on interannual time scales. The paper presents results on O2 and pH changes in the CalCS based on a global high-resolution fully coupled earth system model, which is, to my knowledge, unprecedented. In my opinion, it thus addresses relevant scientific questions within the scope of Ocean Science. The work is generally well presented and structured. I recommend this manuscript for publication with Ocean Science after addressing the few minor comments on the manuscript listed below.

3. Specific and purely technical comments

Methods

Page 5, Line 1: What do you mean by "interannual standard deviations"? I assume you apply the Lanczos filter as described, deseasonalize the data which yields time series that retain only anomalies on interannual time scales, right? From these time series, you compute standard deviations and use them to normalize the response? I *guess the term "interannual standard deviations" got me confused and you might want to clarify this passage, as the normalization of all the data is key to interpreting your results.*

The standardized anomalies during February-March-April (FMA) are computed starting with monthly data. A monthly mean climatology is subtracted for each month creating a monthly mean time series of anomalies. The Lanczos time filtering is now applied, which removes variability on time scales longer than 10 years. FMA averages of time filtered anomalies are created for each year. The inter-annual standard deviation of the FMA anomalies is computed and used to standardize (normalize) the FMA time-filtered anomalies.

We also removed the clause "as they were on the lower end of the frequency spectrum" from this paragraph, which could have made the description less clear.

Model Evaluation
The authors demonstrate that ESM2.6 shows an improved coastal ENSO response compared to ESM2M. They also compare their model results to a data-assimilative ROMS hindcast. Can the authors elaborate on the reason of using the data assimilative regional model for means of comparison? Would e.g. the long (though not as high-frequent) CalCOFI records provide an additional opportunity for a model independent evaluation of the presented response?

Our main reason for using the ROMS reanalysis was that it is the best available spatio-temporally resolved estimate of the physical ocean state off the US West Coast. Individual data sources provide reasonably well resolved information on portions of the water column (e.g., satellite data for the surface), or poorly resolved information on the full water column (e.g., CalCOFI, Argo, etc.). The ROMS reanalysis assimilates these data (including CalCOFI), so it combines the strengths of the observations with the strengths of an unconstrained (no data assimilation) ocean model, to give a product that is more useful than either of those alone.

Page 6, Lines 5-10: Nino 3.4 variance seems substantially overestimated in the global models. Moreover, ENSO seems to be more periodic with a maximum in the frequency spectrum at 3 years return time (Figure A1). I would like to encourage the authors to elaborate on this fact and the potential implications of this particular issue in the model for their interpretation of the presented results in more detail.

Yes, the ENSO variance is overestimated and events are more periodic in both versions of the models, especially GFDL ESM2.6, compared to observations. These aspects of the model are discussed in the text and shown in the supplemental material. First, based on long model runs it is not clear that one can fully describe ENSO's spectra with ~50 years of data (Wittenberg 2009, also see the spread in the spectra from 52-year segments of the 500-year ESM2M in Fig. S1). While it is still likely that the SST variance in Nino 3.4 is too large, the atmospheric response in the sea level pressure over the North Pacific is not as large relative to observations. In addition, we are not able to compare the extratropical coastally trapped ocean wave response to observations. So, the we are not able to fully evaluate the influence of the amplitude of ENSO events on the CCS. However, to address this issue we have normalized the fields examined here by the local standard deviation, which should partly compensate for differences in magnitudes of events between the model simulations and observations.

A more quantitative model comparison between GFDL-ESM2.6, GFDL-ESM2M, and the ROMS reanalysis goes beyond the scope and focus of this manuscript, and is anticipated to be the focus of future publications on ESM2.6.

Figure 5: Plot a) showing SSTs could basically be backed up by satellite observations, not? I was surprised to see such a large spread among different events, in particular in the phasing of the peak anomalies (is this ESM specific, or does it really reflect the ENSO diversity?). It would be interesting to see whether observations show similar differences, or whether the phasing is more synchronous.

The spread is indeed large, and is also seen in observations, as can be seen in the following Figure showing standardized anomalies of Hadley SST anomalies (a combination of satellite and in situ data) for the top nine El Niño events. The difference in circulation can result from a number of factors including ENSO diversity, differences in SST anomalies in the tropical Pacific and random fluctuations in the extratropical atmosphere and ocean ("climate noise"). This aspect of the differences between events is now discussed in greater detail in the last paragraph in the paper.

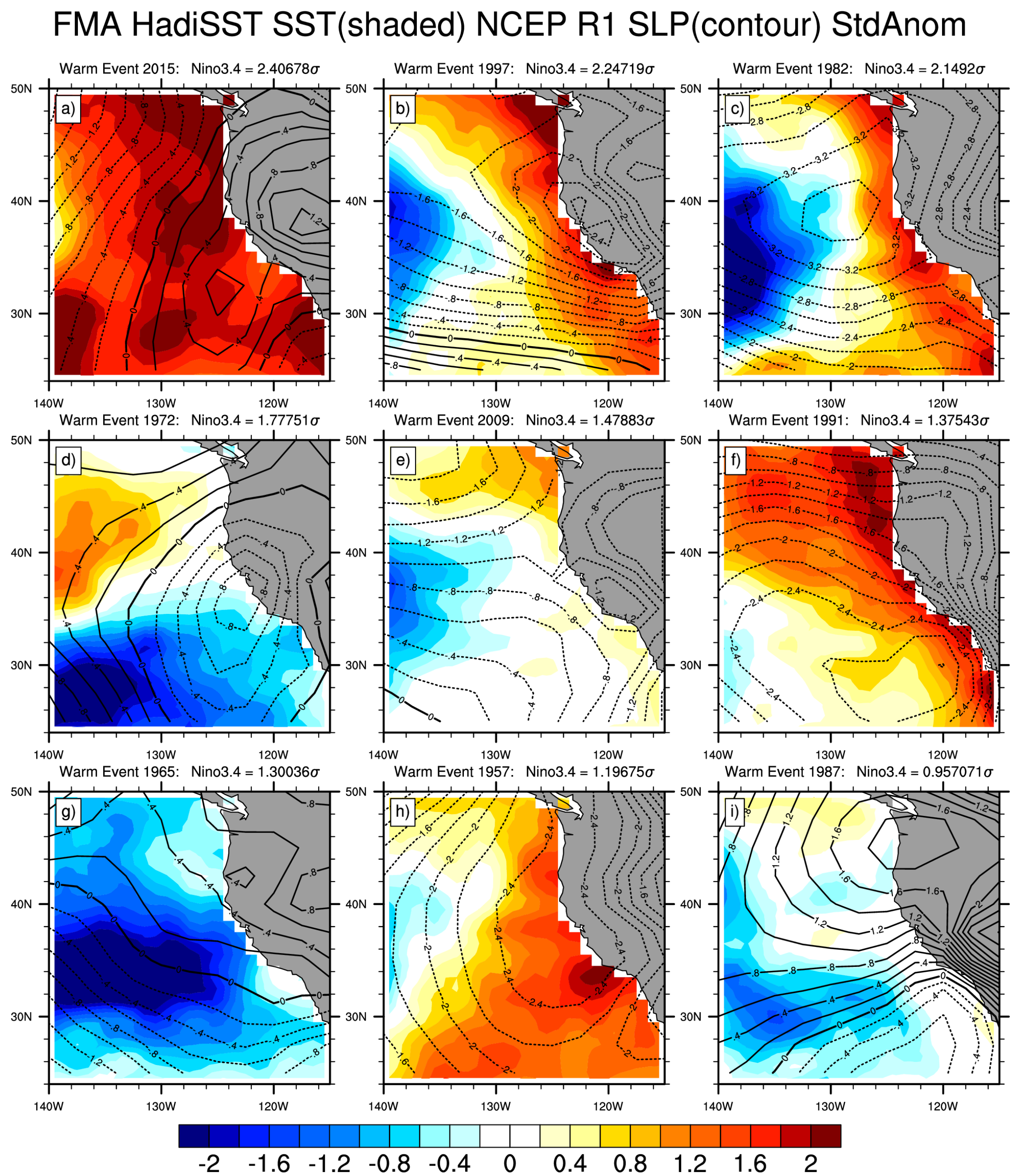
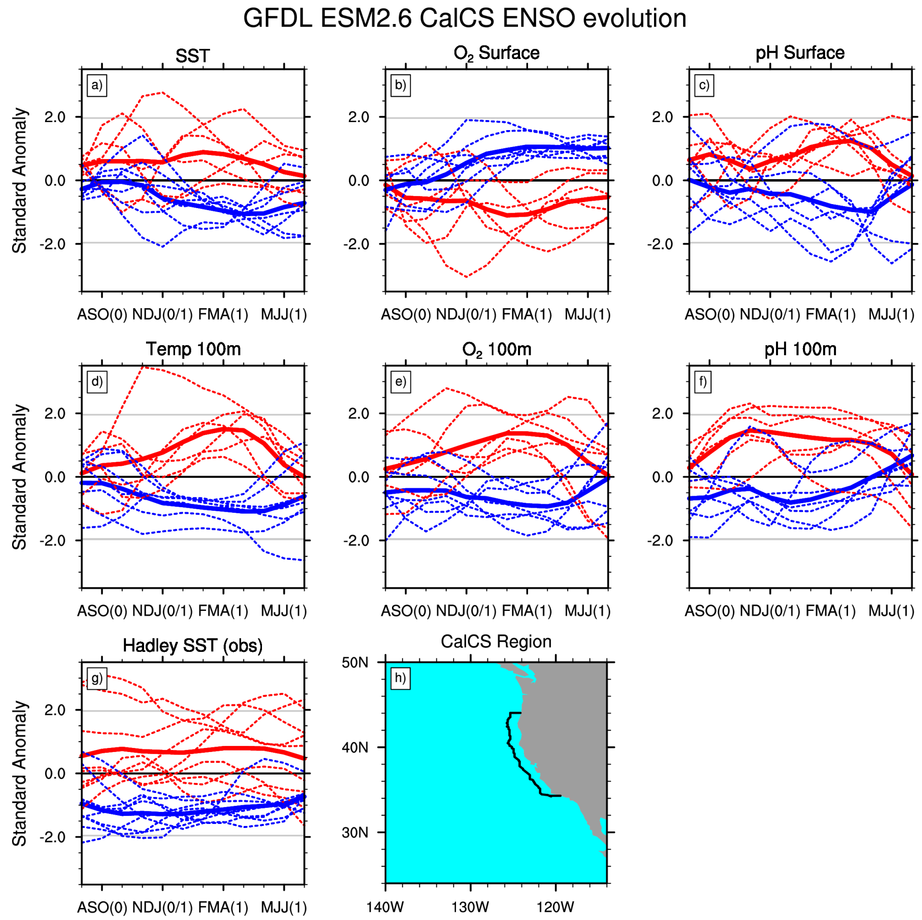


Figure. The sea level pressure (SLP, contours in hPa) and sea surface temperature (SST, shading in °C) for nine observed El Nino events.

We replaced the original Figure 5 of the document with the following figure. The bottom left panel was added, showing the observed Hadley SST for the top 9 warm and cold events. Both the model and observations indicate that the SST composite signal is most robust (smallest event-to-event differences) in mid-to-late winter, especially for La Niña events. This also supports our argument for using FMA as our winter months as opposed to the more common DJF.



Bottom left panel, which shows the observed SST anomalies for individual El Niño (red) and La Niña (blue) events (dashed lines) and the composite average (thick solid line) has been added to Figure 5 in the manuscript.

Page 7, Line 19: Just out of curiosity, why is it that the ESMs do not reproduce the asymmetry in Nino3.4 indices we find in observational records?

We are not fully sure we know what the reviewer is referring to by the statement "ESMs don't reproduce the asymmetry in Nino3.4". We interpret it to mean that the amplitude of El Niño events is bigger than La Niña events in nature compared to the model. To address this point, the probability density function (PDF, smoothed histogram) is shown below for standardized SST anomalies in the Nino3.4 region. The observed SST PDF is slightly skewed with slightly larger anomalies for El Niño (compared to La Niña events with a slightly negative median value). The ESM2M is nearly Gaussian (although it is based on a much longer period of record). ESM2.6 is somewhat bimodal but has slightly larger El Niño as opposed to La Niña values. Note that the shapes of the curves are probably sensitive to the number of years and thus would vary for different 50-year periods.

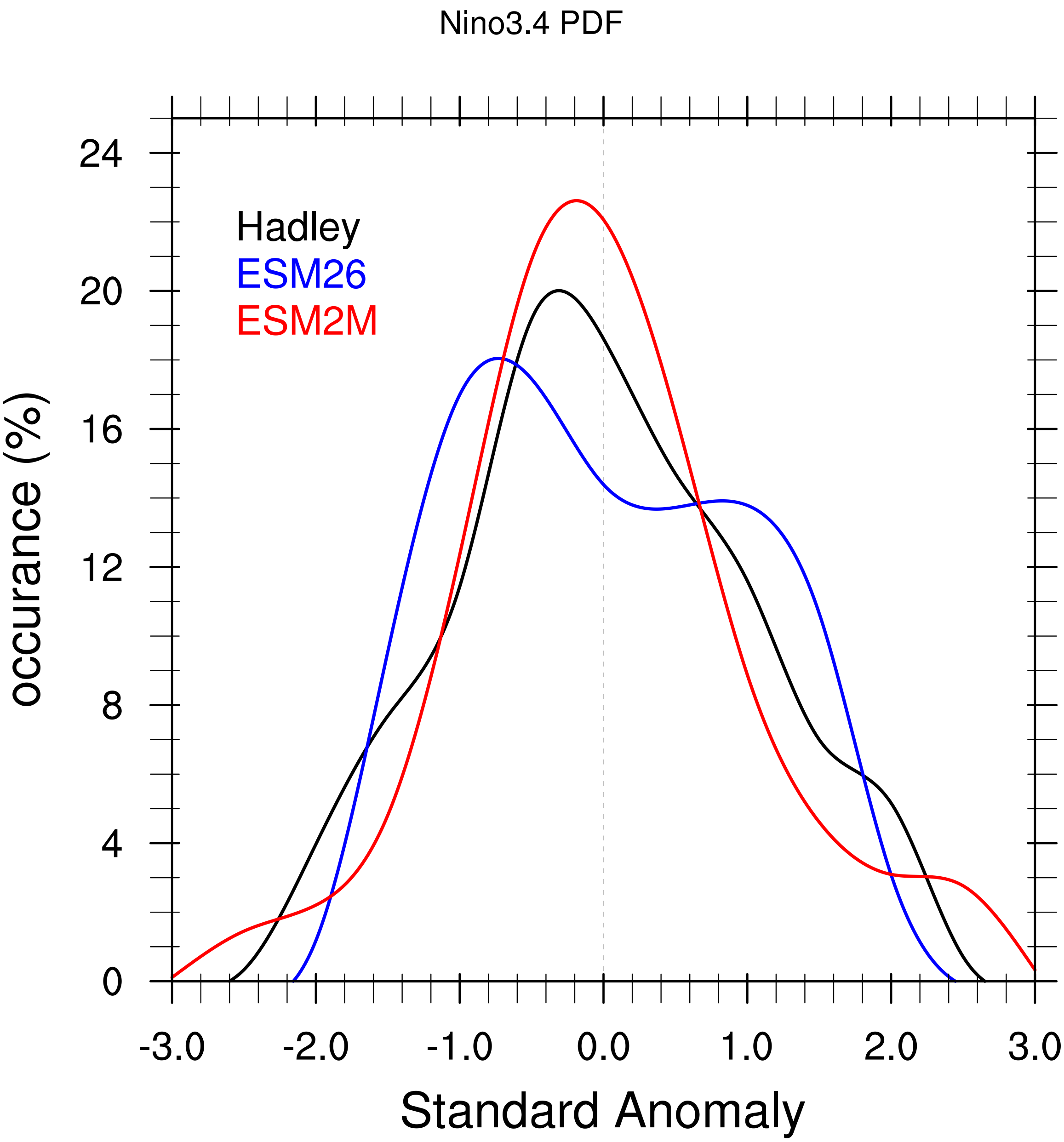


Figure. Probability Density function (PDF), as estimated by a smoothed histogram, of the SST anomalies in Nino 3.4 standardized by the Nino3.4 regional average standard deviation for observations (black), ESM2M (red) and ESM2.6 (blue).

Results

Page 7, Line 32 and Page 8, Line 6: I think it is important to be more specific about the "subsurface process" that is likely dominating the response you observe at 100m. Using a hindcast simulation on a regional model setup covering the period from 1979- 2016, Frischknecht et al. 2017 discussed forcing mechanisms that are also relevant for the findings you present (see their Figure 4). They showed that the bulk part of the coastal response to ENSO is due to changes in the density structure of the water column. While these changes are mainly driven by oceanic forcing (i.e. through coastally trapped *waves), changes in the wind forcing do not explain the deepening of isopycnals during El Nino, but cause changes in upwelling velocities.*

Actually, Frischknecht et al., 2017 (Fig. 4) show that both the remote oceanic and local atmospheric forcing drive nitrate anomalies in the CalCS, although it looks like they attribute the nitrate changes to different mechanisms for the oceanic vs. atmospheric forcing. The wind alters the density structure of the water column and is the reason why isopycnals slope upwards close to the coast. The reviewer's comment is clearly addressed by the following two publications:

1. Jacox et al. (GRL, 2015) showed the contributions of the local and remote forcing to vertical transport and subsurface nitrate concentrations. The wind drives variability in both, as does the remote forcing (Fig. 2). Overall, they contribute approximately equally to ENSO-related nitrate flux anomalies in the central CalCS (Fig. 3).

2. Frischknecht et al. (JGR, 2015) show the contributions of remote and local forcing to physical and biogeochemical anomalies along the US west coast (Fig. 9). Nitrate anomalies are driven more by remote forcing in the southern CalCS, by local wind forcing in the northern CalCS, and by wind and remote forcing approximately equally in the central CalCS (consistent with Jacox et al., 2015). In the case of chlorophyll, they find similar contributions from the remote and local forcing, though the overall variance explained by either is pretty low.

Page 8, Line 11: Maybe worth remembering the reader that you are discussing EN-LN differences. I got confused here when I first read through it and wasn't sure what this "largely positive" refers to.

Thank you for pointing this out. The text was changed in the following way to make this clearer to the reader:

"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..."

Page 9, Line 25: This "potential upwelling increase in the northern CalCS during El Nino" seems puzzling to me. What forcing mechanisms would actually be the cause? I am not aware of other studies that would support this finding, and if there are, please refer to them. I think backing up this finding, if possible, would be great.

Indeed, studies that have looked into this have found that at least up to ~43°N the canonical response to El Niño is reduced upwelling and not an increase in upwelling (e.g., Jacox et al., JGR 2015, Fig. 3).

As this sentence was speculative at best, and a more quantitative assessment of the driving forcing mechanisms is beyond the scope of this study, we have decided to remove it.

Discussion and Conclusions: The end of this section could benefit from a more accentuated take home message that goes beyond the presentation of the scientific findings. What did we learn from using this high-resolution earth system model compared to the low-resolution ESM2M or regional setups (e.g. Jacox et al. 2015,2016, Frischknecht et al. 2015, 2017). I think the paper discussion could benefit from adding a comment to the implications the authors already state.

We have added the following paragraph to the end of the discussion section to discuss this topic in more depth:

"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 initial different 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."

Figures

Generally, the figures all have very cryptic titles and headings (e.g. GFDL ESM2.6 FMA SST (shaded) SLP (contour) Hipass Seas StdAnom, Figure 4). I think cleaning up the figure titles/headings and including the necessary information in the figure caption (while explaining used acronyms and abbreviations) would ease the reader's understanding and greatly help to focus on the relevant things.

We have cleaned up the cryptic figure titles without deleting too much information about the figures, and have made sure that any abbreviations in the titles are explained in the main text or in the captions.

Figure 5: In the caption, it says "(see gray boxes in Fig. 6)". These boxes are however not visible in Fig. 6, right? I assume this comment needs to be removed.

Thank you for pointing this out. This was a relic from an older version and has been removed.

Figure 5: The notation of (0/1) reflecting the evolution of an event before and after its peak is hard to grasp in the beginning. Make sure to better introduce this notation or change the x labels in the figures.

The following description of the 0/1 ENSO notation has been added to the text:

"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)."

Figure A1: What do the dashed lines in the plots to the right represent?

The dashed lines in the plots on the right-hand side of Fig. A1 represent the +/- 1 standard deviation boundaries. A sentence was added to the figure caption to clarify this and this figure has been moved to the Supplementary.

<u>References:</u>

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Jacox, M. G., Fiechter, J., Moore, A. M., and Edwards, C. A.: ENSO and the California Current coastal upwelling response, Journal of Geophysical Research: Oceans, 120, 1691–1702, 2015.

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Anonymous Reviewer #2
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The reviewer's comments are in *italics* and the Authors' replies are in plain text.

The authors would like to thank anonymous reviewer #2 for her/his thorough review of the manuscript and for the insightful comments that have greatly helped improve the publication.

General comments

Turi et al. use a state-of-the-art Earth System Model to address the effects of ENSO in O2 and pH in coastal waters of the California Current System. They find that the mean drivers at surface differ for both O2 and pH: the O2 response extends for several hundreds of km due to temperature-related changes in solubility, while coastal upwelling affects DIC and drives pH changes within 100 km from the coast. Below 100m depth, the responses of O2 and pH seemed coupled; both responded to changes in isopycnal surfaces (e.g., by coastally trapped waves). I found the approach and results very interesting and sound; I also appreciate the focus on two very important variables (O2 and pH) and their connections (rather than looking at them in an isolated way). I'd recommend this manuscript for publication after my moderate comments are addressed; in particular, I think that including discussion/conclusions on the large variability between events would strengthen the manuscript.

Specific comments

**The abstract would benefit from introducing early on why we care about the effect of ENSO on coastal O2 and pH (I'd suggest one or two lines at the very start).*

We have rewritten the abstract and added the following sentences to it:

"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."

**Section 2.1:*

-Page 4 Line 6: What is meant by "prototype"? It gives the impression of a model in the early stages of development – but I don't think it is the case. Please consider explaining better or re-wording.

Indeed, we use the word "prototype" in the way the reviewer suggests, i.e., as a model in the early stages of development. We added the following statement to the section "Model details and methods" to make this clearer:

"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."

-Line 18-19: I am wondering why WOA05 was used instead one of the more recent versions (2009, 2013). Also, I suggest referring to WOA data as "climatologies" rather than as "modeled" data.

Thank you for pointing this out. In the section "Model details and methods", the word "modeled" was substituted with "observed climatologies".

WOA05 was used for expediency as this was the most readily available data set. It was used as a proof of concept.

**Section 2.2:*
-Pag4 Line 23: Why is wintertime NDJ instead of the more common (and likely more winter-appropriate) DJF? (or even JFM).

The following paragraph in the Methods subsection was modified to better describe our choice:

"We identified model ENSO events through the +/-1 standard deviation of the wintertime (November-December-January; NDJ) Niño3.4 index (area-averaged SST 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)."

-Line 24: This sentence makes one wonder: What are the drift issues in the carbonate chemistry? It would be useful to read a line or two about this, to keep the reader from wondering if there is anything wrong with the model and better justify the need of a filter. If the drift happens only at the beginning of the simulation as stated, why not consider those years as "spinup time" and remove them from the analysis? Please explain more or re-word the sentence.

As global carbonate chemistry equilibrium timescales are on the order of thousands of years with respect to water masses and on the order of tens of millennia with respect to river inputs and sediment burial, running the model to equilibrium was not an option in this case.

Figure 1 below shows the temporal evolution of dissolved inorganic carbon (DIC) for the 52 simulation years. The unfiltered DIC is shown in red, and the Lanczos-filtered DIC is shown in blue. The drift affects the first 10 to 20 years of the simulation. The authors 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.

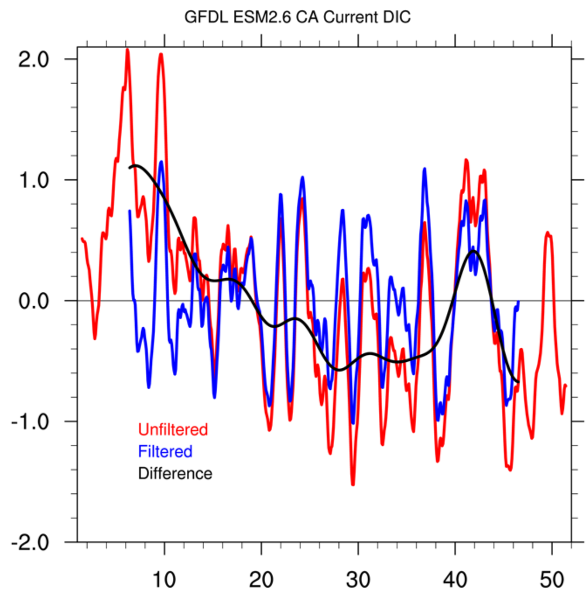

Figure 1: *Temporal evolution of unfiltered (red) and filtered (blue) DIC and the difference between the two (black) for the 52 model years.*

**Section 2.3:*
-P5 Line 10: Please cite source of the climatological SST and SLP

The sentence was expanded to read:

"A comparison of climatological SST from the Hadley Center (HadISST) and sea level pressure (SLP) from NCEP reanalysis..."

References to HadISST and NCEP are also mentioned in the caption of Figure 1 and in the "Data Availability" section.

-Line 19-21: The location of the sections needs to be described.

The first two sentences of that paragraph were rewritten to read:

"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). 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."

-Lines 24-29: In line 24, please remove "very" – one could argue that EMS2.6 and ROMS are not "very" similar. Also, while the qualitative description is useful, it would be great to also see a more quantitative comparison (e.g., compare mean and ranges of warm-cold ENSO signal for the 3 models)

The word "very" was removed.

A more quantitative model comparison between GFDL-ESM2.6, GFDL-ESM2M, and the ROMS reanalysis goes beyond the scope and focus of this manuscript, and is anticipated to be the focus of future publications on ESM2.6. The reviewer and reader is referred to Dunne et al. (2015) for further information on comparisons of GFDL's Earth System Models.

-Line 30: as asked for wintertime: why is springtime defined as FMA?

The following paragraph in the Methods subsection was modified to better describe our choice:

"We identified model ENSO events through the +/-1 standard deviation of the wintertime (November-December-January; NDJ) Niño3.4 index (area-averaged SST 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)."

The same answer applies to FMA.

-Same line: mention source of CHL observations (SeaWiFS)

A reference to NASA-SeaWIFS was added. The sentence now reads:

"Additionally, we compare springtime (FMA) variability of modeled versus observed NASA-SeaWIFS surface chlorophyll (CHL) concentrations along the US West Coast (Fig. 3)."

References to NASA-SeaWIFS are also made in the caption of Figure 3 and in the "Data Availability" section.

-P6 L3-5: I think the lag between ESM2.6 and observations should be mentioned.

The authors would like to clarify that the values in the models do not correspond to an actual year in nature and thus there is no way to say that there is a temporal lag by comparing the three time-series on the right side of Figure A1. The left side of Figure 1a, shows the spectra of the models and observations and does not contain information about lag (even if the model years corresponded to those in nature).

Furthermore, it would be useful to see the ROMS reanalysis in fig A1 (ideally, it would be closer to the observations and strengthen the justification of its use to evaluate both GFDL's models). The latter is just a suggestion.

Unfortunately, it isn't possible to add a corresponding analysis for the ROMS reanalysis, as it's a regional ocean model that only covers the area offshore of the US West Coast. The analyses presented in Fig. A1 are based on the Niño3.4 region (5°S-5°N and 170°W-120°W).

**Section 3, Results:*
-P7 L19: Please add a sentence or two to justify the assumption of linearity

We have added the following text to page 5, lines 12-18, to discuss why we use El Niño minus La Niña and the assumption of linearity.

"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."

-L31-34, From "This difference… ": This belongs to the discussion and should be removed from the Results section. It is actually proved later.

These two sentences were removed completely from the document.

-P8 L9: I recommend to rewrite "The pH (Fig 7c, f, i, l) and O2 responses are…"

Done.

-L 14: "we next split … El Niño composite means into their individual components". At first, I thought this meant that you were going to divide again in the individual ENSO events. Please consider re-wording (e.g., "into their different drivers")

This whole sentence was removed from the document.

-L23: I recommend citing page or table from Sarmiento and Gruber (2006), to enable the reader to find the equations easily. Otherwise, add the equations here or in an appendix. Also, while T has a dominant role in solubility, salinity also affects solubility and I suggest to mention it (it would be great if the S role could be quantified as well!).

Thank you for pointing this out. We added a page number to this reference.

As a matter of fact, we do mention the role of salinity in the text and show them in Figure 10 e and f:

"Thus, the SST contribution to pH seems to mainly act 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 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 (Figs. 10e and f)."

-L32-32: The residual effect: does it also consider the effect of winds?

The residual effect includes any effect that is not temperature-, DIC-, ALK-, or salinity-driven, for instance the effect of nutrients, which in our case is negligible. The mechanical effect of wind would affect any or all of these variables through the process of upwelling, and cannot be disentangled with our approach.

-P9 L12: Comment only – it's unfortunate that DIC and Alk couldn't be saved beyond

the surface. If these simulations are run again in the future, maybe those two variables could be saved instead of [H+] (if disk space allows for one extra output).

Indeed. The authors would have preferred this situation as well.

-L15-16: The partial derivatives of pH are key and deserve a more explicit description of how they were calculated. The cited CO2calc is just a calculator of the carbonate system. How did you alter DIC/Alk/T/S in order to calculate the changes on pH?

The following text was added to enhance the description of the partial derivatives:

"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..."

-L27-29: does this call for a reference to Fig 6a?

It does call for referencing a figure but it is probably best to reference to Figure 10b, as we are talking about the contribution of changes in SST to pH, not the actual SST anomalies. The reference was added.

**Section 4, Discussion and Conclusions:*

-Most of the analysis was performed for the mean ENSO signal (ie, composite of all ENSO events), so the conclusions are mostly based on this mean. However, the manuscript also describes early on large differences between events (Section 3.1). It would be beneficial for the manuscript to expand the conclusions in terms of this large variability between events (e.g., are the processes identified as responsible for the mean signal be still dominant in all the individual events? Any suggestions on the causes of the variability?)

We have added the following paragraph to the end of the discussion section to discuss this topic in more depth:

"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 initial different 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."

The references here have been added to the response to reviewer #1 and have been added to the reference list in the manuscript.

-Note that in the Results section there is a lot of discussion. You could either remove the discussion parts in the Results (as suggested above for a particular case, but there are more instances), or you could also move all discussions to Section 3 and rename it "Results and Discussion". In the latter case, Section 4 would be a shorter Conclusions section.

The authors opted to move all of the discussion text into the section "Discussion and Conclusions".

-P10 L29-30: Could your differences with respect to Nam et al (2011) be based on the fact that you work with a mean ENSO signal and they focus on a specific event?

Yes, this is the case. The following sentence was added to the document to clarify this:

"One potential difference 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."

Technical comments

**I'd suggest to rewrite "100 km" as "hundreds of kilometers" where "100" intends to mean "hundreds" rather than "one hundred" (e.g., in the abstract "reaches up to several 100 km offshore"; also in section 4)*

Done.

**Pag4 Line 18: I think it'd be better to refer to "the beginning of year 141 of *a* CM2.6 1900 control simulation", rather than *the*, because "*the* control simulation" makes me think of the control run being described (ESM2.6 control simulation)*

Done.

**Pag4 Lines 30-32: I suggest re-ordering this sentence: first state the need to interpret patterns of ENSO-related signals, and then explain that to this end, you use standardized anomalies.*

Done.

**P5 Lines 5-6: By now, the models have been introduced and are referred to as EMS2.6 and ESM2M. Please remove the "GFDL-"; same for figure captions.*

Done.

**P5 L31: "does not" instead of "doesn't"*

Done.

**P8 L10: should it be 32 and 36 degrees N?*

Done.

**P9 L26: replace "seems to mainly act" by "mainly acts"*

Done.

**Figures*

-Remove titles in the figures; make sure captions capture all the information in the current titles. In Fig 2, make a legend for the density contours (if the latter is not possible, then keep only the "Density (contours)…" text in the title).

We have cleaned up the cryptic figure titles without deleting too much information about the figures, and have made sure that any abbreviations in the titles are explained in the main text or in the captions.

-Fig 5: Explain in the caption the zeros and ones found in the x labels. The caption says "gray" outline in g, but it looks like black. Also, note that the solid line is hard to distinguish from the dashed ones on the screen (it's ok in the printed version) – I suggest to make solid lines thicker if possible.

Thank you for pointing out the reference to the gray box. This was a relic from an older version and has been removed.

We also added the following text to page 5, lines 19-21:

"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)."

-*Why there are two figures labeled A1 and A2, if there is no Appendix section? Shouldn't these figures be labeled consecutively, following the order in which they were mentioned?*

Thank you for pointing this out. The authors have decided to use the Supplementary Material instead of an Appendix for the final published version.

**References: I did not check the references thoroughly, but spotted a mistake in Robbins et al (2010): it says "Max" instead of "Mac"*

Thank you for pointing this out. The reference was corrected and the other references have been double-checked for typos and errors.

References:

Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N. C., and Scott, J. D.: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans, Journal of Climate, 15, 2205–2231, 2002.

DeWeaver, E. and S. Nigam: Linearity in ENSO's Atmospheric Response. J. Climate.15:17, 2446-2461, 2002.

Dommenget, D, T Bayr, and C. Frauen: Analysis of the non-linearity in the pattern and time evolution of El Niño southern oscillation. Climate Dyn., 40: 2825, 2013.

Dunne, J. P., Stock, C. A., and John, J. G.: Representation of Eastern Boundary Currents in GFDL's Earth System Models, California Cooperative Oceanic Fisheries Investigations Reports, 56, 72-75, 2015.

Frischknecht, M., Münnich, M., and Gruber, N.: Remote versus Local Influence of ENSO on the California Current System, Journal of Geophysical Research: Oceans, 120, 1353–1374, 2015.

Frischknecht, M., Münnich, M., and Gruber, N.: Local atmospheric forcing driving an unexpected California Current System response during the 2015–2016 El Niño, Geophysical Research Letters, 44, 2017.

Hoerling, M. P., A. Kumar, and M. Zhong: El Niño, La Niña, and the nonlinearity of their teleconnections. J. Climate, 10, 1769–1786, 1997.

Anonymous Reviewer #3
Received and published: 30 August 2017

The reviewer's comments are in italic and the Authors' replies are in regular text.

The authors would like to thank anonymous reviewer #3 for her/his thorough review of the manuscript and for the insightful comments that have greatly helped improve the publication.

1. General Comments: Turi and colleagues conduct here a well-detailed and interesting analysis of how ENSO impacts the temperature, O2, and pH field structures of the California Current System (CCS). The paper's focus on temperature, O2 and pH and driving mechanisms is highly relevant to attribution and descriptive studies of the CCS, given ecosystems' vulnerability to changes in these variables, and thus should generate a broad and interested audience. Specifically, Turi et al. reveal significant model improvement in representing ENSO physical variability of the CCS in a coupled high resolution model (vs. CMIP5-type resolution), which they use to evaluate the diversity and mechanisms driving ENSO impacts off the California coast. The authors uncover large variations in the CCS response, a point that is somewhat under-developed in the paper and should be further elaborated on given its high relevance to CCS-ENSO studies. Using a composite analysis of the 3-D spatial structure and component decomposition of O2 and pH anomalies from their simulated ENSO events, they suggest different mechanisms driving O2 and pH anomalies at different depths, with changes in temperature as a major driver of surface O2 anomalies, while changes in isopycnals depth and upwelling accounting for most of the variability in pH and O2 at depth. Overall, the paper by Turi and colleagues is well written, the approach is novel, and results are thought provoking, though I felt the discussion section could be further developed given their interesting results and their relevance to other CCS studies. This paper is suitable for publication in the Journal of Ocean Science and I recommend strengthening it with the following comments, revision, and suggestions below.

2. Specific Comments:

1) The paper is appropriately and well titled, but since temperature is so prevalently used in figures and discussed throughout the paper, and since temperature is also an important ecosystem stressor, perhaps it ought to be in the title as well?

Thank you for this suggestion. The authors discussed this and came to the conclusion that the title should remain as it is, since the main focus is on the biogeochemistry (pH and O_2), and temperature is predominantly used to support or explain findings related to pH and O_2.

2) The introduction provides a thorough review of previous work, and could perhaps be improved by adding a few lines on processes driving O2 and pH variability in the *upper 150 m of the CCS (i.e. upwelling, solubility, and productivity and respiration, etc.). This would help putting the processes section in context.*

As the analysis and discussion of the mechanisms driving O_2 and pH variability is the main focus of our paper (see our question 2 at the end of the introduction) and is shown and proven in detail in the results and discussion sections, we have opted not to expand on it in the introduction which is more focused on putting this study in the context of other publications.

3) The method section could use more detailed description of the model and its configuration, e.g. : what is the model's vertical resolution? How long as the model been spun up for? What is the general structure of the BGC model?

The text was expanded to include more information and now reads as:

"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)."

4) It would also be helpful to explain the choice of using a coupled configuration vs. a hindcast simulation (CORE2/NCEP-forced run) of the high resolution model. Wouldn't a hindcast run provide a more realistic representation of ENSO impacts on ocean biogeochemistry and physics? This would also allow for more appropriate comparison to observations.

Indeed, a hindcast simulation would also be very worthwhile to do, however past studies have already focused on analyzing ROMS hindcasts for the CalCS and North Pacific regions in terms of biogeochemical and physical properties (e.g., Turi et al., 2016, Frischknecht et al., 2015, Jacox et al., 2015). The reviewer and the readers are referred to these publications for more in-depth analyses and discussions of model-observation differences, as an additional hindcast simulation is beyond the scope of this study. However, it is important to also evaluate how these processes are simulated in coupled models, which can be used to make short term forecasts and long-term climate projections.

5) The authors extensively uses FMA anomalies without justifying the choice of this season/ period. Is this associated with the time scales (2-3 months) of coastal wave propagation from the equatorial region post the maximum equatorial SST anomaly typically observed in DJF? Or is this simply based on the timing of the maximum CCS impact as shown in the mean response in Fig 5? This is especially confusing as some variables are plotted in FMA (SST, O2, pH) while others are shown for DJF (e.g. SLP). FMA is also described as spring, but spring is typically MAM, and winter is DJF. Please explicitly state the choice for FMA, and describe acronyms somewhere in paper/figures (FMA=February-March-April, etc.).

The following paragraph in the "Methods" subsection was modified to better describe our choice:

"We identified model ENSO events through the +/-1 standard deviation of the wintertime (November-December-January; NDJ) Niño3.4 index (area-averaged SST 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)."

Regarding coastal propagation: this is very difficult to detect, given the monthly resolution of our model output. The following three Hovmöller diagrams (Figs. 1-3) show the temporal evolution of SST, O_2, and pH from 0°N to 50°N and underline our choice of NDJ for SST as opposed to DJF.

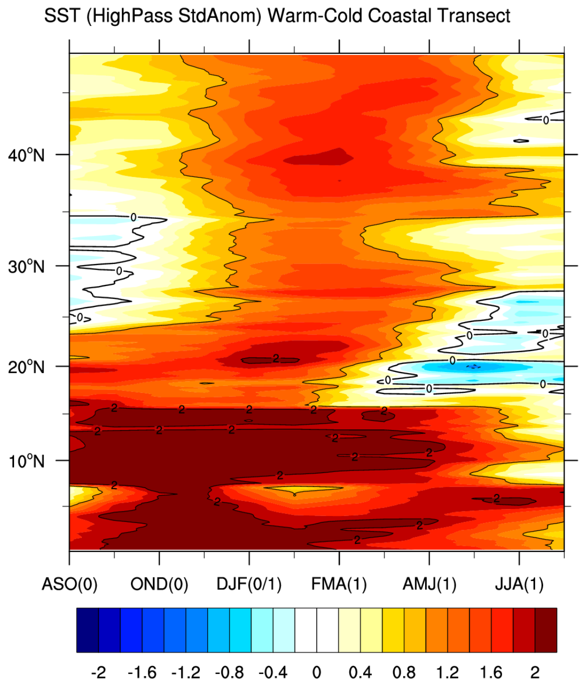

***Figure 1**: SST Hovmöller diagram.*

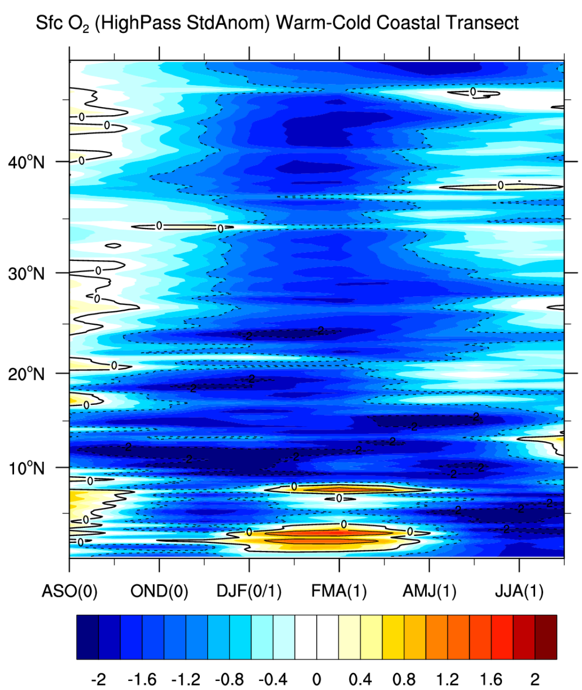

***Figure 2**: O_2 Hovmöller diagram.*

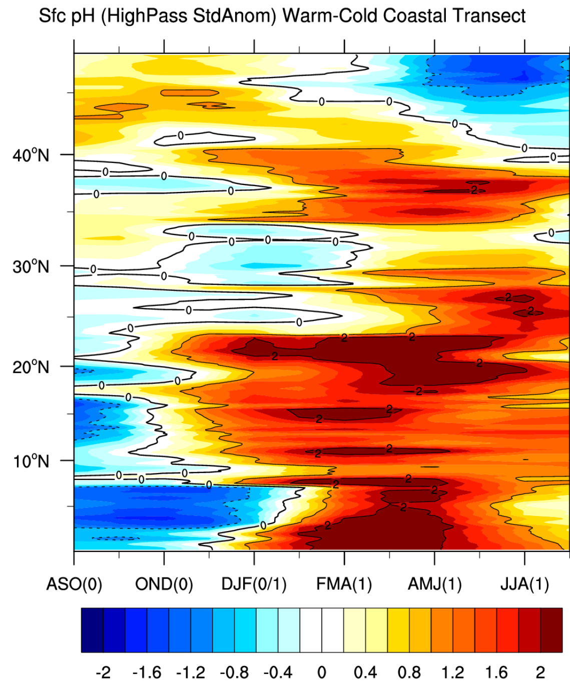

Figure 3*: pH Hovmöller diagram.*

6) Fig A1 ought to be within the paper rather than a supplementary or appendix since this seems to be a major deficiency in the model and should be made more visible and relevant. Additionally, the method section could also benefit from a comparison of simulated BGC fields to the WOA climatologies, i.e. how large are the BGC biases, and how do they differ in the high resolution vs. low resolution version of the GFDL model, at least for the CCS. A discussion of the implications of model biases on the paper's results could help provide a more thorough overview of the potential and limitations of the authors' approach, especially when relating their results to observations.

We note that the ESM2.6 is a prototype simulation, where the parameters at this resolution have not been changed from the coarser resolution, i.e. the model has not been "tuned", as is the case with formal model releases. Thus, the results should be viewed in the context of what processes can be simulated with such a model, rather than a detailed documentation of model performance. However, we did think it was important to document some aspects of the model performance in terms of factors that influence the ENSO signal in the California current region. A more quantitative model comparison between GFDL-ESM2.6, GFDL-ESM2M, and the ROMS reanalysis goes beyond the scope and focus of this manuscript, and is anticipated to be the focus of future publications on ESM2.6. The reviewer and reader is referred to Dunne et al. (2015) for further information on comparisons of GFDL's Earth System Models.

7) The diversity of the ENSO SST and SLP anomalies shown in Figure 4 is very interesting, and so is the diversity of the averaged O2 and pH changes shown in Fig 5. It would be useful and highly relevant to see similar maps as shown for SST and SLP (as Fig 4) for O2 and pH for different events (perhaps in Appendix, but preferably in the paper). This is perhaps most useful to inform observations-based studies which are often limited to few or single ENSO events. Generally, the diverse response in BGC should be detailed further and reasons for this diversity could also be explored, especially since this is one of the paper's main stated and novel research questions. e.g. What were the initial conditions prior to each event? Do similar patterns emerge in the CCS from different ENSO events (eastern vs. central El Niño)? Do both O2 and pH show the same degree of variability as SST and SLP? The diversity of SST and SLP to ENSO events could also be shown for the observations, and would be interesting to assess whether such high variations across ENSO events differs in obs. vs model.

The authors have created a new figure (substituting old Figure 4 in the main part of the manuscript), showing the most notable two events for SST, O_2, and pH each, highlighting the wide range of variability in all these variables in a more condensed form. The following two figures (Figs. 4 and 5) show the top 6 warm events for O_2 and pH, from which we chose two panels each to create new Figure 4.

We have also added a paragraph at the end of the Discussion section detailing the possible sources for the differences during ENSO events.

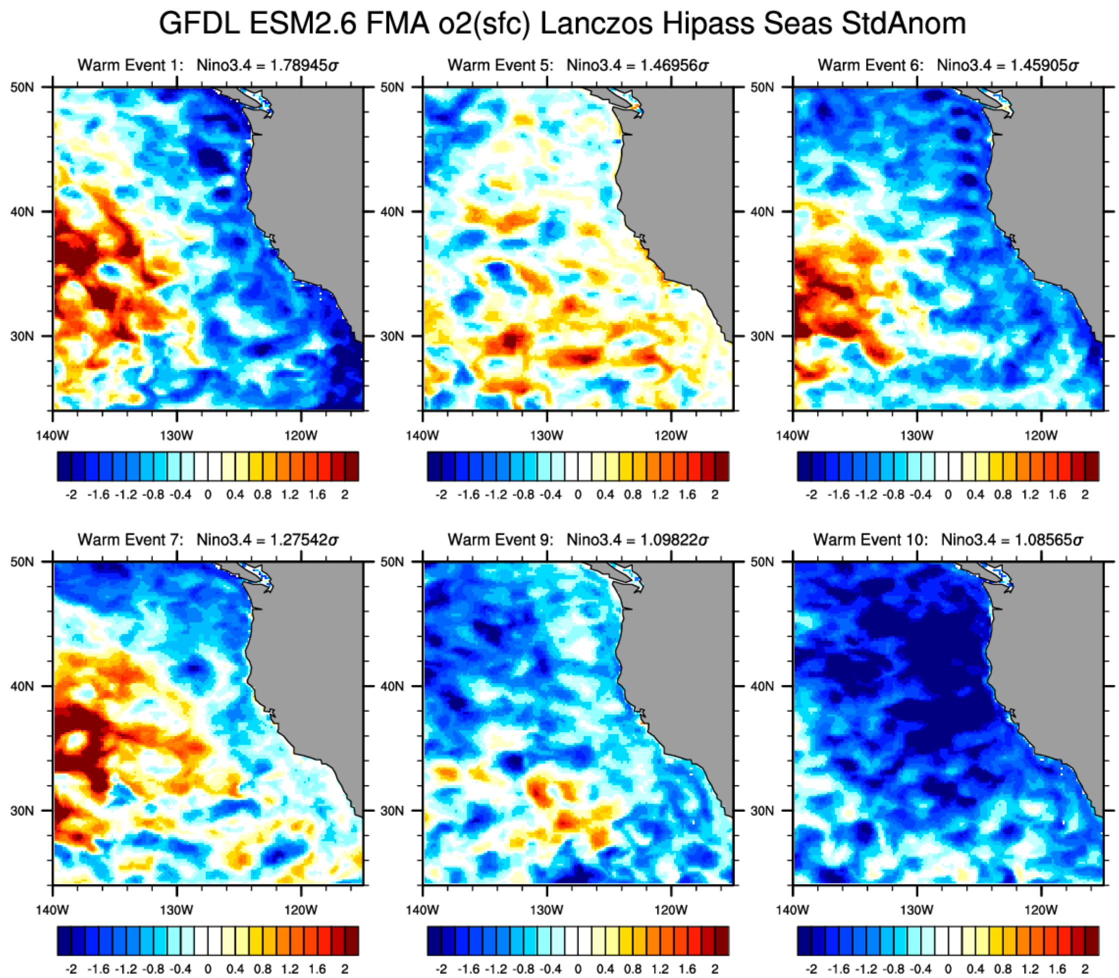

Figure 4: *Top 6 warm ENSO events for O_2.*

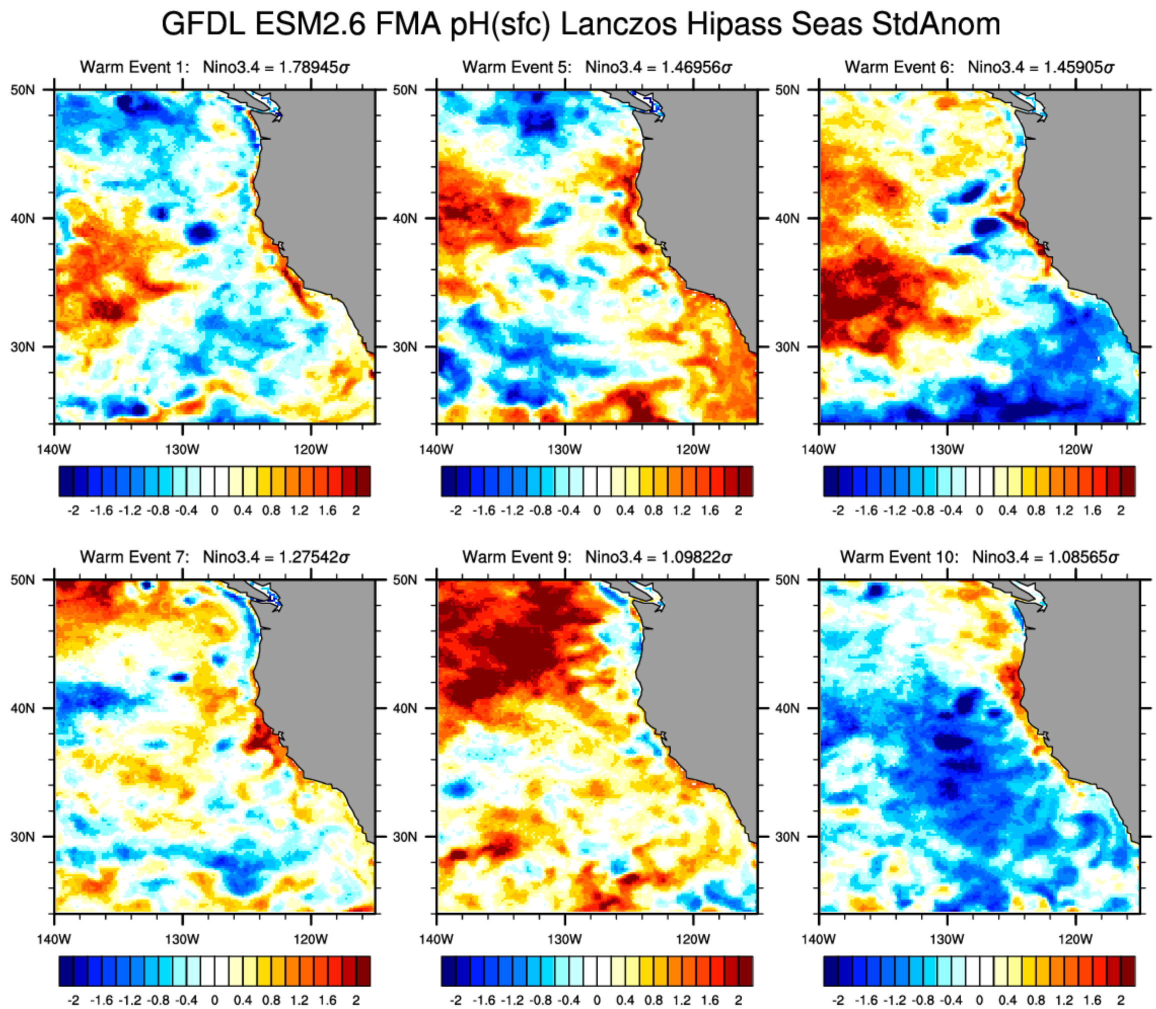

***Figure 5**: Top 6 warm ENSO events for pH.*

8) At the same time, the diversity of the CCS response to ENSO questions the use of the composite mean difference to evaluate "typical" ENSO impacts; i.e. how representative is the composite mean of the ENSO anomalies used in Fig 6-10. Perhaps adding a statistical test/stipplings to show which of these patterns are significant could help address this?

In the paragraph in the Methods subsection we note the following sentence:

"For the majority of the analyses, unless otherwise noted, we employed standardized anomalies (sigma, where a value of 2 corresponds roughly to a 95% significance as indicated by a Student's t-test) instead of showing absolute values."

Thus, the reader can see where the local response is significant based on where the standardized values exceed 2.

9) In page 9 line 5-6, the authors propose deepening of the thermocline during El Niño to explain the increase in O2 at 100m all along the coast, but for pH changes, they invoke a dipole in upwelling north vs. south 40oN (Pg9 L 25). This is confusing since changes in intensity or source of upwelling and isopycnal depths should impact pH and O2 similarly. How do the authors reconcile this discrepancy?

We agree that this was confusing. As this sentence was speculative at best, and a more quantitative assessment of the driving forcing mechanisms is beyond the scope of this study, we have decided to remove it (see response to reviewer #1 as well).

10) The process analysis conducted here is valuable in understanding the CCS biogeochemical response to ENSO physical changes. Important questions on which of these physical processes drive these biogeochemical anomalies however remain unclear, and perhaps could be discussed further. e.g., what is the role of "remote" wave propagation vs "local" atmospheric forcing of upwelling on the biogeochemical anomalies presented here? This could be addressed using existing figures or editing figures, e.g. superimposing SLP anomalies on BGC anomalies to assess role of atmospheric forcing effects on spatial anomalies in pH and O2. The analysis of Frischknecht et al (2015) regarding the roles of remote vs local forcing in driving physical and biogeochemical anomalies could also be discussed in relation to Turi et al's regionally distinct imprints of ENSO on CA CCS.

Ideally, the authors would have wanted to add an in-depth analysis of local versus remote forcing to this study, especially since the horizontal resolution of ESM2.6 of 10km allows for the resolution of Rossby radius of deformation in the CalCS (20-60km in that region, i.e. it is "wave permitting"). However, unfortunately, given the fact that our model output frequency is only monthly, it was not realistically possible for us to adequately resolve and thus track coastally propagating waves (which move on time scales of days to weeks). The authors hope and anticipate that such an analysis will be possible in a future study with ESM2.6 in the CalCS and along the west coast of the American continents.

The reviewer is referred to the following publications for more in-depth analyses of local vs. remote forcing: Frischknecht et al. (JGR, 2015) and Jacox et al. (GRL, 2015).

11) Another important question that belong to the mechanisms section and discussion but is unclear is what is the role of changes in transport vs. changes in biological production and respiration rates on O2 anomalies? In an MITgcm hindcast simulation, Ito and Deutsch (2013) decompose O2 changes due to ENSO to changes in respiration rates, transport, and solubility in the northern tropical Pacific OMZ and show that a warmer thermocline is also more oxygenated, in agreement with Turi et al's model results. They argue however that during El Niño, declines in O2 respiration rate in the thermocline associated with reduced carbon export that result from a deeper *thermocline, reduced nutrients export to surface and reduced productivity, is the main driver of O2 changes. The heaving of isopycnal shown and suggested by Turi goes in the same direction but doesn't preclude reinforcing biological effects from being a contributing or dominant component.*

Thank you for bringing up the Ito and Deutsch (2013) publication. The "control volume" in the Ito and Deutsch analysis (see the white region in their Fig 1b) excludes the CalCS, thus we have decided not to include discussion of these results in our manuscript.

12) Generally, the discussion section could benefit from expanding on how these results fit in the context of other studies' findings. The diversity of ENSO events is especially relevant to past and future studies of ENSO and the CCS, mainly that a generic CCS response to ENSO shouldn't be expected given effects of initial local conditions, different teleconnections, etc.

We have added the following paragraph to the end of the discussion section to discuss this topic in more depth:

"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 initial different 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."

The references here have been added to the citation list in the paper and are also provided in response to reviewer 1.

13) The figure titles and captions are hard to read for quick readers, and could really use more attention to explaining acronyms, reducing repetitions, and clarifying what the figure is trying to convey. e.g. the terms "high-pass filtered standardized" is already stated in methods and needs not be repeated in each figure.

We have cleaned up the cryptic figure titles without deleting too much information about the figures, and have made sure that any abbreviations in the titles are explained in the main text or in the captions.

3. Technical Corrections:

1) Pg 4 Line 9, what is vertical resolution?

The model consists of 50 vertical layers. This was added to the text.

2) Pg 4 Line 18: Do authors mean "observed climatologies of O2, nitrate, etc."? To my knowledge, WOA doesn't include modeled fields.

Yes. This was changed in the text.

3) Fig 2. Caption Line 2: "ROMS Climatology"? Shouldn't it be an anomaly rather than a climatology?

The word "climatology" was removed.

4) Fig 5, "gray box", do authors mean Fig 5g?

The reference to the gray box was removed.

5) Pg 6. L20." magnitude of +/- sigma". Sigma from area average?

Our use of sigma is explained at the end of the Methods section by the following paragraph:

"For the majority of the analyses, unless otherwise noted, we employed standardized anomalies (sigma, 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."

6) Page 7 "Fig 5b and e" or "5b" only?

Yes, it should be 5b only. This has been changed.

7) Figure 3 and chlorophyll seems less relevant to the paper's theme and could be delegated to Appendix/supplementary.

Thank you for this suggestion. We have decided to leave it in the main part of the text, as it supports our model evaluation section. Moreover, comments from the other reviewers were in favor of broadening the discussion on model evaluation, thus we were not willing to cut back on this topic.

<u>References:</u>

Alexander, M. A., Bladé, I., Newman, M., Lanzante, J. R., Lau, N. C., and Scott, J. D.: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans, Journal of Climate, 15, 2205–2231, 2002.

Frischknecht, M., Münnich, M., and Gruber, N.: Remote versus Local Influence of ENSO on the California Current System, Journal of Geophysical Research: Oceans, 120, 1353–1374, 2015.

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

Giuliana Turi[1], Michael Alexander[2], Nicole S. Lovenduski[3], Antonietta Capotondi[2], James Scott[4], Charles Stock[5], John Dunne[5], Jasmin John[5], and Michael Jacox[6]

[1]National Snow and Ice Data Center, Boulder, CO, USA
[2]NOAA/ESRL, Boulder, Colorado, USA
[3]Department of Atmospheric and Oceanic Sciences and Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA
[4]CIRES, University of Colorado at Boulder, and NOAA/ESRL, Boulder, Colorado, USA
[5]NOAA/GFDL, Princeton, New Jersey, USA
[6]University of California, Santa Cruz, CA and NOAA/SWFSC, Monterey, CA, USA

Correspondence to: Dr. Michael Alexander (michael.alexander@noaa.gov)

Abstract. ~~We~~ 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 ~~El Niño/Southern Oscillation (ENSO) events on the physics and biogeochemistry of the California Current System (CalCS). We focus on the effect of ENSO on~~ ENSO events on variations in the O_2 concentration and the pH of the ~~coastal waters of the CalCS~~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 ∼100 ~~m~~m. The strongest O_2 response reaches up to several 100~~km~~ km offshore, whereas the pH signal occurs only within a ∼100 ~~km-wide~~ 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 ∼100 ~~m~~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., **?????**). 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., **??**). 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., **??**). 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~~ km of the coast (e.g., **?????**). Specifically, **?** found a shoaling of the hypoxic threshold, which is typically considered to be $\sim$60 ~~μmol kg^{-1}~~ µmol kg^{-1} (**???**), of up to 90 ~~m~~ m in the southern CalCS between 1984 and 2006. Furthermore, **?** 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). **?** 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., **?????**).

The eastern North Pacific region is affected by several teleconnective climate patterns, including the El Niño Southern Oscillation (ENSO; e.g., **?????????**). 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., **????**), 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 (**?**). Source waters for upwelling in the CalCS also tend to be anomalously warm, shallow, and fresh during El Niño (**?**), 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 (**?**).

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., **?????**), on nutrients and primary production (e.g., **????**), and on zooplankton and higher trophic levels (e.g., **????**). A handful of observational studies have investigated the impact of the 1982/1983 El Niño on the physical regime of the CalCS (e.g., **??**), and the effect of the 2002/2003 El Niño on the physics and biology (e.g., **??**). Several regional modeling studies have shown the connection between ENSO and the vertical transport, water column density, origins and properties of upwelled water (**??**), and demonstrated the relative importance of remote versus local forcing on both the physics and the biogeochemistry of the CalCS ~~(**??**)~~(**???**). During the 2010/2011 La Niña, **?** 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 **?** 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 ($\sim 1°$ **?**). Models with such resolutions are challenged to reproduce the responses of coastal ecosystems to basin-scale ocean variability (**?**). It is commonly acknowledged that at least 0.1° horizontal ocean resolution is necessary to resolve the Rossby radius of deformation (e.g., **??**), which is around 20-60 ~~km~~ km in the CalCS (**?**). 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 (**???**). The model's ocean component is GFDL's Modular Ocean Model Version 5 (MOM5; **?**) 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 **??** with modifications as described in **?**. COBALT includes 33 prognostic tracers~~and its~~, 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 (**?**). 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 ~~alkalinity (ALK)~~ 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 ~~the beginning~~ 01 January of year 141 of ~~the~~ a CM2.6 1990 control simulation. The ocean biogeochemistry was initialized ~~with modeled~~ 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; **??**), and modeled DIC and ALK were initialized from the Global Data Analysis Project (GLODAP; **?**). The ocean biogeochemistry in the previous ESM2.6 development version was started from a spun-up ESM2M-COBALT 1860 control simulation (**?**).

2.2 Methods

We identified model ENSO events through the ±1 standard deviation of the wintertime (November-December-January; NDJ) Niño3.4 index (area-averaged SST 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 (**?**).

Due to drift issues in the carbonate chemistry at the beginning of ~~our~~ the simulation, we used a Lanczos ~~high pass~~ high-pass filter with a cutoff frequency of 10 years (121 weights; **?**). This procedure removed any long-term trends and decadal variability, ~~as they were on the lower end of the frequency spectrum,~~ 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 ~~our~~ 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. ~~To this end, we normalized~~ 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.

Figures **??** through **??** 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., **??**), 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 (**?**). 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, ~~thus allowing for a more pattern-driven interpretation of ENSO-related signals in our figures.~~ 0/1, and 1, as used in Fig. **??**, 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 **?**.

2.3 Comparison of modeled and observed ENSO in the North Pacific

To assess ~~our~~ the model's performance in representing the physical regime of the North Pacific, we compare the physical manifestation of ENSO in ~~GFDL-ESM2~~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, ~~GFDL-ESM2M~~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. **??**a, d, and g). During El Niño (La Niña), both models represent the composite average SST signals over the 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. **??**, 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 bias in ~~our~~ the results (**?**).

To shed light on the vertical structure of temperature and density~~along the US West Coast~~, 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. **??**). 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~~km) resolution, assimilates available satellite (SST, SSH) and in situ (temperature, salinity) data (see **?** for details), and has been used extensively to describe CalCS physical dynamics, particularly in response to ENSO variability (**???**). ESM2.6 and the ROMS reanalysis show ~~very~~ similar results for the composite difference between warm and cold ENSO events, indicating a 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~~ 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~~ m between mean El Niño and La Niña conditions.

Additionally, we compare springtime (February-March-April; FMA) variability of ~~observed versus modeled~~ modeled versus observed NASA-SeaWIFS surface chlorophyll (CHL) concentrations along the US West Coast (Fig. **??**). Due to its brevity, the CHL record ~~doesn't~~ 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 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 times higher than in the observations (~~Fig. **??**). In summary, both~~ see Fig. S1 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 ~~our~~ 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 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

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

~~The SST and SLPresponses of the CalCS to six different modeled~~ Figure **??** highlights the variability in SST (with overlaid SLP), O_2, and pH between two of the six El Niño events ~~are highly variable (Fig. **??**~~(Event 2 and Event 6; see Figs. S2 to S4 in the Supplement for the other four El Niño events, and Fig. S5 for the individual SST/SLP La Niña events). The ~~SST~~

~~and SLP signals in Fig. **??**a are the most~~ 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 ~~(e.g., **??**). In this case, the CalCS experiences positive SST anomalies within ~200-300 km of the coast and negative SST anomalies further offshore in the region of the subtropical gyre, both with a magnitude of $\pm 2\sigma$. This reflects the typical SSTsignal in the eastern North Pacific prevalent during El Niño with a strong cross-shore SST gradient. In addition, the SLP signal reflects the typical atmospheric pattern over this region associated with El Niño, with negative SLP anomalies of up to -2σ to the north of ~38°N, indicating an intensification of the Aleutian Low over the Gulf of Alaska, and positive SLP anomalies of around 1σ to the south. Although the SST anomalies in~~ (see Supplement), 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. **??**~~c are similar to Fig. **??**a, the SLP anomalies are substantially different with negative SLP anomalies over the whole CalCS region and the adjacent landmass. The other cases show more widespread negative SST anomalies closer to the coast of 1-2σ (Fig. **??**b and d), a more intense warming in the Gulf of Alaska (Fig. **??**e), and stronger, more domain-wide positive SST anomalies with a maximum greater than 2σ offshore of the Oregon coast (Fig. **??**f). During La Niña, the SST and SLP anomalies tend to be of opposite sign, with cold anomaliesclose to the coast and warmer waters further~~ a-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. ~~**??**~~**??**d-f).

Figure **??**a-f shows the temporal evolution of surface and subsurface (100 ~~m~~m) temperature, O_2, and pH for the six individual El Niño and seven individual La Niña events, as well as the composite mean, for a region within 100 ~~km~~ km of the coast and averaged over 34–44°N (see Fig. **??**~~g~~ h for the specified region). We analyze the surface as well as 100 ~~m~~ 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~~ 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. **??**g). At the surface, temperature anomalies are on average positive (negative) during El Niño (La Niña) with values of -1σ to 3σ (-2σ to 1σ) for the individual events (Fig. **??**a and d). On average, the variability of modeled SST (Fig. **??**a) compares well with the observed SST (Fig. **??**g), 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. **??**b~~and e~~). At 100 ~~m~~m, the strongest temperature signal occurs during the spring (FMA) following the typical El Niño season (NDJ). Furthermore, the CalCS experiences higher-than-usual O_2 conditions during El Niño and lower O_2 concentrations during La Niña at 100 ~~m~~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~~ m is not exhibited by pH, which like temperature displays a consistent signal throughout the water column (Fig. **??**c and f).

~~For all three variables, the magnitude of the standardized anomalies is very comparable both during El Niño and La Niña. Overall, the variability between the individual warm and cold events~~ As the results in Figs. **??** and **??** ~~is quite large, indicating on the one hand the variability in the atmospheric and oceanic responses to tropical Pacific conditions and on the other hand the importance of internal climate variability in driving anomalies unrelated to ENSO (e.g., **?**). Furthermore, the initial conditions~~

~~differ substantially from event to event and thus the temperature, O_2, and pH responses could be in part controlled by the mean background state of the ocean immediately preceding an event~~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. **??**a-c~~, where we show standardized anomalies of these quantities, representing El Niño minus La Niña composites. Showing warm minus cold anomalies amplifies the ENSO signal, thus increasing its significance. This approach assumes linearity in the signal, i.e., that the influence of El Niño is -1 times the influence of La Niña~~. SST anomalies here are positive between the coast and ~300-500 ~~km~~ km offshore, as well as offshore north of 40°N and south of 28°N, with anomalies of up to 2σ (Fig. **??**a). Offshore between ~28°N and 40°N, in the region of the subtropical gyre, SST anomalies are negative around 1-2σ, 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 0.8-2σ are found offshore in the region of the subtropical gyre (Fig. **??**b). 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~~ km along the coast (Fig. **??**c). Between 100 ~~km~~ km and around 500 ~~km offshore,~~ 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 ~~largely~~ predominantly positive again.

We investigate ENSO-driven changes in temperature, O_2, and pH in the subsurface (100 ~~m~~m) in Fig. **??**d-f. A similar cross-shore gradient in temperature occurs at 100 ~~m~~ m compared to the surface, with anomalies larger than 2σ in some regions along the coast (Fig. **??**d). However, the 100 ~~m~~ m signal is more limited to within a ~100 ~~km~~ km wide band along the coast. ~~This difference can be explained by coastally trapped waves depressing the thermocline on their path poleward along the coast, by weakened upwelling along the CalCS coast, likewise affecting the depth of the thermocline, or by a combination of both processes. At the surface on the other hand, warming through the atmosphere likely contributes to a broader area of positive anomalies.~~ The mean response of 100 ~~m~~ m O_2 to ENSO is drastically different than the O_2 response at the surface, with positive anomalies within a 100 ~~km~~ km band along the coast, indicating that two different processes govern the O_2 response to ENSO at the surface and at depth (Fig. **??**e). The 100 ~~m~~ 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. **??**f). These positive pH anomalies are also more widespread northward and southward along the coast at 100 ~~m~~ m compared to the surface. Furthermore, the 100 ~~m~~ m pH signal is very similar to the 100 ~~m~~ m O_2 signal (compare Fig. **??**e and **??**f), suggesting a common subsurface process influencing both variables.

In Fig. **??** we examine the same offshore cross-sections as in Fig. **??** 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~~ m that we observed in Fig. **??** is also clearly visible in all four offshore cross-sections in

Fig. **??** (b, e, h, and k). The ~~O_2 and pH responses in~~ pH (Fig. **??**(c, f, i, l)) and O_2 responses are very similar between ~~30~~32°N and ~~35~~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 ~~largely~~ 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~~ m as opposed to O_2 at the same latitude. ~~To disentangle the processes and drivers behind these changes in O_2 and pH and ultimately understand how ENSO affects these quantities in the CalCS, we next split the O_2 and pH El Niño composite means into their individual components.~~

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 **?**), thus:

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

For ~~our~~ the analysis in Fig. **??**, we derive the temperature-related component from the solubility of O_2, using the solubility coefficients of **?** as demonstrated in ~~**?**~~(**?**, 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. **??**a 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. **??**b). 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 (**?**), this effect contributes to an increase in O_2, and thus opposes the solubility effect. The residual effect (Fig. **??**c), 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., **?**).

At 100 ~~m~~m, where El Niño leads to an increase in O_2 along the coast and up to ~200 ~~km~~ 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. **??**f). 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. **??**), replacing older, O_2-poor waters associated with dense subsurface waters in the CalCS, with less dense, elevated O_2 waters. Figure **??** demonstrates that during El Niño, the depth at which oxygen falls below the hypoxic threshold (where O_2 is $\leq$60 ~~$\mathrm{mol\,kg^{-1}}$~~ $\mu\mathrm{mol\,kg^{-1}}$) deepens on average by 20 ~~m~~ m in the first 100 ~~km~~ km along the coast from a mean climatological depth of around 300 ~~m~~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. **??** (b, e, h, and k) and Fig. **??**d.

We consider the contributions of surface DIC, ALK, temperature (T) and salinity (S) to ENSO-driven changes in surface pH in Fig. **??**. For this analysis we focus on surface values, as DIC and ALK were saved only in the surface layer in ~~our~~ the simulation. To decompose pH into these four drivers, we use a Taylor expansion according to the following equation (after **????**):

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

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" (**?**). We did this procedure for each driver and then multiplied each ~~of them~~ sensitivity by the change in each variable as calculated in the ENSO composites shown in Fig. **??** (corresponding to the Δ-terms in Equation 2).

Changes in DIC are primarily what drive the increase in pH in the nearshore 100 ~~km~~ km of the central CalCS (34°N–40°N; Fig. **??**c), whereas the contributions from SST and ALK counteract the effect of DIC by reducing pH in the same region (Fig. **??**b 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 ∼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. ~~This result suggests that there is a dipole pattern in the upwelling along the coast, with a decrease in upwelling in the central CalCS and a potential increase in the northern CalCS during El Niño.~~ Thus, the SST contribution to pH ~~seems to mainly act~~ 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. **??**b) 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 (~~Figs~~Fig. **??**e 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 ∼100 ~~m~~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 ~~several 100 km~~ 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. ~~Our~~ 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~~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~~ 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 ∼100 ~~km~~ km along the central US West Coast (∼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~~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. ~~Our~~ These results also suggest that during La Niña, the first 50-100 ~~km~~ 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. ~~These~~ The findings for pH are in line with **?**, 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 **?** concluded. While we found a significant increase (decrease) in O_2 in the nearshore surface waters above 100 ~~m~~ 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 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, ~~our~~ the analysis suggests that below 100 ~~m~~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. ~~In addition to this analysis, the role of horizontal advection in our model needs to be investigated in more detail, but is beyond the scope of this study~~ The differing results between this study and the one by **?** is attributable to the fact that our study focuses on a composite mean ENSO signal over several events and the focus of theirs is on a specific event.

As **?** 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 (**?**). If the pH drops below 7.75, which corresponds to $\Omega_{arag} < 1$, waters become unfavorable for calcifying organisms to build and maintain their shell structure (e.g. **???**). Our results suggest that during La Niña, the surface waters are more corrosive but but also more oxygenated than during El Niño, while the waters below 100 ~~m~~ 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 noted by **?**. 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~~ km along the US West Coast, as this is where the ENSO signal is largest, both in O_2 and in pH. Furthermore, ~~our~~ the modeled contrasting response of O_2 to ENSO at the surface and at 100 ~~m~~ 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. ~~Our~~ 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 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., **?**).

5 ~~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/~~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., **?**) and the variability between events, including the timing, strength and location of temperature anomalies, can influence atmospheric teleconnections over the North Pacific (e.g., **?**) and the propagation of coastally trapped waves (e.g., **??**). 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., **??**) and the Kuroshio-Oyashio extension in the western North Pacific (e.g., **?**) and potentially by Arctic sea ice concentrations (e.g., **??**). 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., **??**). 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 ensemble of model simulations with the same ENSO conditions in the tropical Pacific but slightly initial different conditions (e.g., **????**). 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 **?**, 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.

5 ~~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 figures except for Fig. **??** (created by GT). 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.~~

5 ~~Competing interests~~

~~The authors declare that they have no conflict of interest.~~

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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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