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Dear Editor,

We highly appreciated all the comments and suggestions from both reviewers about our manuscript entitled "THE OMZ AND NUTRIENT FEATURES AS A SIGNATURE OF INTERANNUAL AND LOW FREQUENCY VARIABILITY OFF THE PERUVIAN UPWELLING SYSTEM" by Michelle Graco, Sara Purca, Boris Dewitte, Carmen G. Castro, Octavio Morón, Georgina Flores, Jesús Ledesma and Dimitri Gutiérrez. We have revised the manuscript following the reviewers' suggestions. All recommendations have been taken into account. In particular, we have expanded the analysis to include the 2010-11 La Niña event so that the data are now covering the period 1996-2011. Some sections have been completely rewritten and we have thoroughly checked over the grammar and syntax, and improved the English so that the paper should be now friendlier to read.

Note that our manuscript is aimed at contributing to the Special Issue: Biogeochemical processes, tropospheric chemistry and interactions across the ocean/atmosphere interface in the coastal upwelling off Peru.

We hope that you will find our revised manuscript now suitable for a publication in Biogeosciences.

Best regards

Michelle Graco

Reply to reviewer 1

As mentioned above, the time series are great. In the text it is stated, that the records are used until the end of 2009. No information is given, that the measurement program stopped. In case the measurements continued until the end of 2011 it would improve the manuscript considerably to extend the time series.

We have expanded the analysis to include the 2010-11 La Niña event so that the data are now covering the period 1996-2011.

To extend the IEKW for 2011, we used the outputs of another general circulation model simulation than SODA. This simulation belongs to the set of MERCATOR global OGCM simulations (http://www.mercator-ocean.fr/) and was used recently in Mosquera et al. (2014) to analyze the equatorial Kelvin wave in the Pacific.

Following the reviewer's recommendation, we have rewritten the description of the method to derive the Kelvin wave, which should be clearer now.

References added to the revised manuscript:

Illig S., B. Dewitte, K. Goubanova, G. Cambon, J. Boucharel, F. Monetti, C. Romero, S. Purca and R. Flores, 2014: Forcing mechanisms of intraseasonal SST variability off Peru in 2000-2008: local versus remote forcings. J. Geophys. Res.-Oceans, Vol. 119, 6, 3548-3573.

Mosquera-Vásquez, B. Dewitte and Serena Illig. The central Pacific El Niño intraseasonal kelvin wave JGR: Oceans (2014). 10.1002/2014JC10044.

It is mentioned that in 2002 the measurements changed from Niskin bottles to CTD measurements, hence a discussion how this change in method influences the measurements is needed.

The reviewer is right; the change in the technique could be influential on the data set. In fact, after 2002 we kept measuring temperature and salinity using both the CTD and the Niskin bottles to verify that there is no off-set from before and after 2002. In general, both measurements are very close.

Normally an abbreviation is defined and then used in the following text. In this manuscript, the repeated definitions of the same abbreviations are strange and make the manuscript difficult to read. E.g., IEKW is defined on page 7 two times in lines 1 and 2, on page 8 line

18, page 11 line 27 and page 17 line 1. ESSW is defined page 3 line 8, page 7 line 25 and page 9 line 10. Similar for other abbreviations.

It was corrected accordingly.

The units used in the figures and text should be the same. Oxygen in the text is presented as micromole/kg (e.g. page 9 line 8), in figure 3 as micromole/L; for nutrients in micromole/L (e.g. page 10, line 14) in Figure 5 as microM.

It was corrected accordingly.

May be use months instead of seasons to better define the period you refer to.

It was corrected accordingly.

Page 10 line 28 to page 11 line 2: The changes mentioned are difficult to see in Figure 5d, may be add the depths range in the text you are considering.

It was corrected accordingly.

Page 10 lines 3 to 5. PC1 And PC2 are mentioned and shown in Figure 6b. In paragraph 2.3 (page 6) where the method is described, only PC1 is mentioned. PC2 should be also explained in paragraph 2.3.

It was corrected accordingly.

All the specific comments and minor changes in the text and figures were taken into consideration in order to improve each section.

Reply to reviewer 2

The paper addresses an interesting topic of physical-chemical coupling in the northern Humboldt System. This region is particular attractive because of its strong connection with equatorial dynamics, high biological productivity, as well as a shallow and intense oxygen minimum zone that influences nitrogen cycling and biological dynamics. The study examines

the temporal and vertical variability of relevant physical and chemical variables during the period 1996-2009, covering the strong El Nino 1997-98 and subsequent La Nina 1998-99, as well as period with relatively neutral or weak ENSO conditions after 2002. The authors conclude that most of the physical-chemical variability off Peru is linked to equatorially originating remote forcing. They also suggest enhanced physical-chemical intraseasonal variability after 2002, associated with a change in the intraseasonal equatorial Kelvin wave (IEKW) activity. None of those statements is well supported in the paper. Three aspects could be argued against the conclusions.

We thank the reviewer for his constructive comments. We have revised the manuscript to clarify these points. In particular, we have quantify this through the EOF combined analysis done over the full period (including the 1997/98 El Nino event) and an additional EOF analysis for a reduced period that exclude the 1997/98 El Nino event) (i.e. 2000-2011). The nature of the coupling (as inferred from the eigenvalues of the EOF model) is also significantly impacted (See new Table 1). We have also included a new Table 2 that presents the correlation between the PC timeseries of the EOF analysis and the indices of El Niño and the equatorial Kelvin wave supporting our interpretation.

First, since the local forcing (e.g. coastal winds, heat fluxes) was not examined; it is not possible to conclude that remote forcing is the dominant forcing.

We agree with the reviewer that a limitation of our study is to disregard the role of local wind forcing. Following the reviewer's suggestion, we have expanded the discussion on the role of wind forcing based on previous studies (Dewitte et al 2011, Echevin et al 2014; Illig et al., 2014) (see discussion section). In our study we are not addressing the higher-frequency variability associated to wind forcing dueto the lack of *in situ* data over this period and limitations of the satellite products (see introduction of Goubanova et al. (2011) for a discussion on this topic). We have toned down some of the statement regarding this mater, but, we maintain that the variability of our data set can be to a large extent understood in terms of the oceanic teleconnection from the equatorial region, which is consistent with recent modeling studies (Dewitte et al., 2012; Illig et al., 2014; Echevin et al., 2014) and former observational works (Gutierrez et al., 2008).

References:

Dewitte B., J. Vazquez-Cuervo, K. Goubanova, S. Illig, K. Takahashi, G. Cambon, S. Purca, D. Correa, D. Gutiérrez, A. Sifeddine, and Ortlieb, L.: Change in El Niño flavours over 1958-2008: Implications for the long-term trend of the upwelling off Peru. Deep Sea Research II, 123-135, 2012.

Echevin, V., Albert, A., Lévy, M., Graco, M., Aumont, O., Piétri, A. and Garric, G.: Intraseasonal variability of near shore productivity in the Northern Humboldt Current System: The role of coastal trapped waves. Continental Shelf Res.,7314–30, 2014.

Gutiérrez, D., Enríquez, E., Purca, S., Quipuzcóa, L., Marquina, R., Flores G., and Graco, M.: Oxygenation episodes on the continental shelf of central Peru: remote forcing and benthic ecosystem response. Prog. Oceanogr. 79, 177–189, 2008.

Illig S., B. Dewitte, K. Goubanova, G. Cambon, J. Boucharel, F. Monetti, C. Romero, S. Purca and R. Flores,: Forcing mechanisms of intraseasonal SST variability off Peru in 2000-2008: local versus remote forcings. J. Geophys. Res.-Oceans, Vol. 119, 6, 3548-3573, 2014.

Second, the coastal time series have monthly resolution that precludes a proper characterization of the dominant 40-60 day intraseasonal variability off Peru, making difficult to connect the physical-chemical changes off Callao to the IEKW variability.

We agree that the monthly resolution will tend to damp the amplitude of the intraseasonal variability. However since we focus on the frequency band [40-90] days, we believe that it is still reasonable to address the intraseasonal variability with the monthly data. The potential limitation associated to aliasing that would require to be investigated further based on mooring data. There is however no biogeochemical data from a long-term mooring available in this region. The establishment of a long-term mooring is one of the future actions planned by IMARPE with the international collaboration.

Third, the characterization is strongly dependent on El Nino 1997-98 and subsequent La Nina disturbances. It is not clear for me if a novel scenario exists after 2002.

We have completely re-written the discussion section. The time series presented here illustrate two different regimes for the OMZ dynamics and biogeochemical activity off Peru. One regime with a strong asymmetry associated to the extreme Eastern Pacific 1997- 1998 El Niño when the OMZ disappeared in the upper layer and the subsequent intensification of the OMZ and nitrogen lost during 1999-2001 La Niña. Other regime since 2000 characterized by a strong intraseasonal variability in the intensity of the OMZ and the availability of nutrients, loss nitrogen processes; and a tendency for a decoupling between the chemistry and the physical forcing associated with weaker but more frequent warm events. We hope that we have stated clearly in this new version of the manuscript.

The introduction is weak. I suggest be more concise and define better the paper goals. The sentence “in order to infer potential biogeochemical scenarios in connection with equatorial variability” appears to me too vague.

Following the reviewer's suggestion, we have presented a more concise introduction and have clarified the objectives.

The instruments to measure temperature and salinity changed in 2002. Could that explain the apparent change in the physical-chemical coupling after 2002? Do you have a period with overlapping observations of thermometer, salinometer, and CTD to check the measurements consistency?

After 2002, we kept measuring temperature and salinity using both the CTD and the Niskin bottles to verify that there is no offset from before and after 2002. In general, both measurements are very close.

Is the EOF analysis really needed? Only the PC time series were shown, what about the spatial pattern?

The EOF analysis is performed in order to summarize the variability for physical and biogeochemical parameters. The results on the EOF analysis have been completely rewritten and should be clearer in this new version. We have also expanded this analysis to support the idea of the two regimes. Following the reviewer's suggestion, we also provide the eigenvalues of the EOF modes (spatial patterns) which are informative on the way the variables relate to each other (See Table 2).

Results. Page 8 Line 17: Year 2008 is not El Nino according to El Nino 3.4 index. Lines 22-24: How do you support the Z_15_C - ENSO connection?

We agree with reviewer's statement that the El Niño 3.4 index in 2008 does not indicate a warm event. However, the costal El Niño index 1+2 indicates a warm period, which is related to the crossing of downwelling Kelvin wave. The Peruvian coast is one of the few regions in the world that requires two indexes for monitoring El Niño. In 2012, the national technical committee for El Niño study (ENFEN; http://www.met.igp.gob.pe/variabclim/enfen/) defined the ICEN (Coastal El Niño index) based on the anomaly of the sea surface temperature of the El Niño region 1+2 (90° W- 80°W, 10°S-0°). The ICEN index is better indicator of the ENSO cycle off the Peruvian coast. It gives an idea not only of the El Niño impact on the physical and chemical fields but also on the El Niño consequences on the biota and consequently on the economic resources. We will include this in the methodology.

We have also extended the discussion indicating that after the 1997 - 98 El Niño, the interannual variability in the equatorial Pacific consists in a different type of El Niño events. Those events are referred to as Central Pacific El Niño events and are characterized by an

increased variability of the intraseasonal Kelvin wave activity during the development and peak phase compared to the strong El Niño events (See Mosquera et al. (2014). Therefore, the period 2000-2011 can be considered as a period with enhanced intraseasonal variability compared to the previous decade.

It possible to include numerical model outputs in the analysis? Several regional model efforts have been done in the region that might be useful to interpret better the observations.

We agree that model experiments could provide additional material for interpreting the observations. For OMZ regional modeling, we are only aware of the study by Montes et al. (2014) and Vergara et al. (2016) that addresses the seasonal cycle, not the interannual variability. It is beyond the scope of the present study to present model simulations over the period of interest, which would deserve a thorough validation. This is actually a work in progress and the results will be reported shortly.

I do not understand why do you use only the global wavelet spectrum. Examining wavelets in the time-frequency domain is more informative, especially to see temporal changes in the IEKW activity.

We perform an analyze in the time frequency wavelet frequency in addition to the global wavelet spectrum and finally we decide to use the GWS because both convey the same information, that is the strong interannual signature associated with El Niño and the intraseasonal signature that appear in the band of 180 days (6 months)-90 days (3 months). In the Figure 8, GWS showed the significance interannual periods for all-time series, over the dotted line.

Overall the discussion needs a better integration of biogeochemical processes influencing the observed vertical profiles of oxygen and nutrients.

Following the reviewer's suggestion, we have improved the discussion on this matter.

All the specific comments and minor changes in the text and figures were taken into consideration in order to improve each section.