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Dear Dr Herndl,

We highly appreciated all the comments and suggestions from both reviewers about our manuscript entitled "THE OMZ AND NUTRIENT FEATURES AS A SIGNATURE OF INTER-ANNUAL AND LOW-FREQUENCY VARIABILITY OFF THE PERUVIAN UPWELLING SYSTEM" by M. Graco and co-authors. We have revised the manuscript following all the reviewers' suggestions and recommendations. In particular, we now focus on the inter-annual variability and have left behind the results on the intra-seasonal variability considering that the data have limitations that are now discussed more thoroughly. New diagnostics are provided to expand the section on the role on ENSO and the identification of the two regimes.

Some sections have thus been completely rewritten and new figures were included. We have thoroughly checked over the grammar and syntax, and improved the English so that the paper should be now friendlier to read.

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

We are grateful to the editorial office for his understanding in the review process and the works of the reviewers.

Best regards

Michelle I. Graco

<u>Reply to reviewer 1 (Report 2)</u>

General comments:

The revised manuscript by Graco et al. has improved compared to the first version. However, there are still some shortcomings, which need to be solved before the manuscript can be published. The connection of the measurements to El Nino and La Nina periods is weak and should be strengthened (see below). Very disappointing is the fact that none of the 7 !!! co-authors seemed to have looked carefully at the revised manuscript (see below) and left the work for the reviewers as was the case already at the first version. The English is still bad (I know all authors are no native English speakers, but some help should be searched to make the manuscript better readable). I recommend revision of the manuscript.

We thank the reviewer for his constructive comments. We have improved the manuscript following the recommendations. In particular we have strengthened the section on the link between O_2 and ENSO/Kelvin wave activity (see also the specific comments). Note that we have also expanded the section presenting the data by now showing anomalies relative to the mean seasonal cycle and the mean seasonal cycle for T and O_2 (new figure 3), which serves as material for introducing the analysis on the relationship between OMZ variability and the equatorial Kelvin wave and ENSO.

The text has also been modified in many parts and proofread in order to improve the spelling and make it easier to read.

Specific comments:

So far, the authors missed the opportunity to well relate the measurements to the El Nino and La Nina periods. In line 242 a 1997-1998 El Nino event and a 1999-2001 La Nina event are mentioned but these events are not clearly defined and other weaker events are not really referenced. According to the ONI index El Nino's during the time period presented are: 5/97-5/98 (defined as strong), 6/2002-2/2003 (moderate), 7/04-4/05 (weak), 9/06-1/07 (weak), 7/09-4/10 (moderate) and La Ninas 7/98-3/01 (moderate), 8/07-6/08 (moderate), 7/10-4/11 (moderate) and 8/11-3/12 (weak). These events are well visible in the parameter distribution, especially in the N deficit and the 15°C time series. Hence the El Nino and La Nina time periods should be mentioned in the text and related to the figures instead of listing some years with deepening of the thermocline and mention a coincidence with El Nino conditions (lines 233 to 237). In line 302 the end of 2011 was described as strong La Nina condition, but according to the ONI index it was only a weak La Nina.

Following the reviewer's recommendation, we have clarified our methodology. In particular we provide a table (new table 1) summarizing the characteristics of the inter-annual events over the period of interest (moderate versus strong, Central Pacific El Niño versus Eastern Pacific El Niño). The selection of the El Niño years and El Niño types follows Yu and Kim (2013).

Table 1: El Niño and La Niña years and types of the event

El Niño (red) and La Niña (blue) years	**Magnitude (Yu and Kim, 2013)**	**Type (Eastern Pacific versus Central Pacific)**
1997/1998	Strong (extraordinary)	EP
1998/1999	moderate	
1999/2000	moderate	
2000/2001	weak	
2002/2003	moderate	CP
2004/2005	moderate	CP
2006/2007	moderate	Mixed
2007/2008	moderate	
2009/2010	moderate	CP
2010/2011	moderate	

References:

Yu J.-Y. and S. T. Kim, 2013: Identifying the types of major El Niño events since 1870. Int. J. Climatol., 33:2105–2112. doi:10.1002/joc.3575.

Here is a list of errors that a co-author should have noticed in case of reading the manuscript:

We thank the reviewer for his thorough review. We have proofread the manuscript and we hope it is now friendlier to read.

-line 250 Figure 3a. This is still a reference from the first version of the manuscript, now it is Fig. 2c. Similar on line 297 it has to be figure 2 not figure 3.

It was corrected

- Line 316: ‘see horizontal lines in figure 6a,b’. In the revised version there are no horizontal lines marked for the standard deviation as had been in the first version of the manuscript.

It was corrected.

-Line 345: ‘Z_ZMO (Fig. 6 d)’. Figure 6d is Z_OMZ.

It was corrected.

- Line 359: ‘Figure 7b’. In Figure 7 no a,b,c, are marked.

It was corrected.

- Line 438: In the reply-letter it is stated that the units will be used always the same, but in line 438 and 796 the unit for oxygen are different compared to the text.

It was corrected.

- Figure 6 legend is not correct, (b) is now (c); (c) is now (d), (d) is now (e). Figure legend should be adjusted when the figures modified.

It was corrected.

- Figure 7 legend: As mentioned above, no a, b, c is marked in the figure but mentioned in the legend.

It was corrected.

- The author wrote in the reply-letter that repetition of definitions were removed. However, ESSW (line 220) was already defined in line 63, SSW (line 254 and line 426) already in line 227, IEKW_1 and IEKW_2 (line 311) already in lines 189/190, while CTW (line 521) is not defined.

It was corrected.

- References were not checked: Line 464, there is no Naqvi 1991 in the reference list (only Naqvi and Noronha 1991) line 465 no Codispoti et al 1985 (only Codispoti and Christensen 1985), line 468 no Morales et al 1996. Kalvelage et al. 2013 in the reference list is not cited in the text.

It was corrected.

-In the abstract (line 30) acidic oxygen minimum Zone is mentioned. In the entire text acidic is not mentioned again. Even if not investigated in this manuscript it should be briefly mentioned in the longish general review.

The world acidic was removed.

-May be define SST in line 89.

It was corrected.

-Line 123 ‘20 nm’ is strange; better write ‘20 nm off the coast’.

It was corrected.

-Line 140: I don’t understand the meaning of ‘of the Oxygen Minimum Zone- OMZ and changes…’

The paragraph was removed.

-Line 221 ‘during summer and spring periods’, mention austral summer and austral spring as you do later in the text.

It was corrected.

-Line 227-228: SSW can’t ‘penetrate into the coast’, may be write ‘penetrates into the near-coastal area’ or whatever you like to describe.

It was corrected.

-Line 258: Better include ‘depth’ after ‘thermocline’.

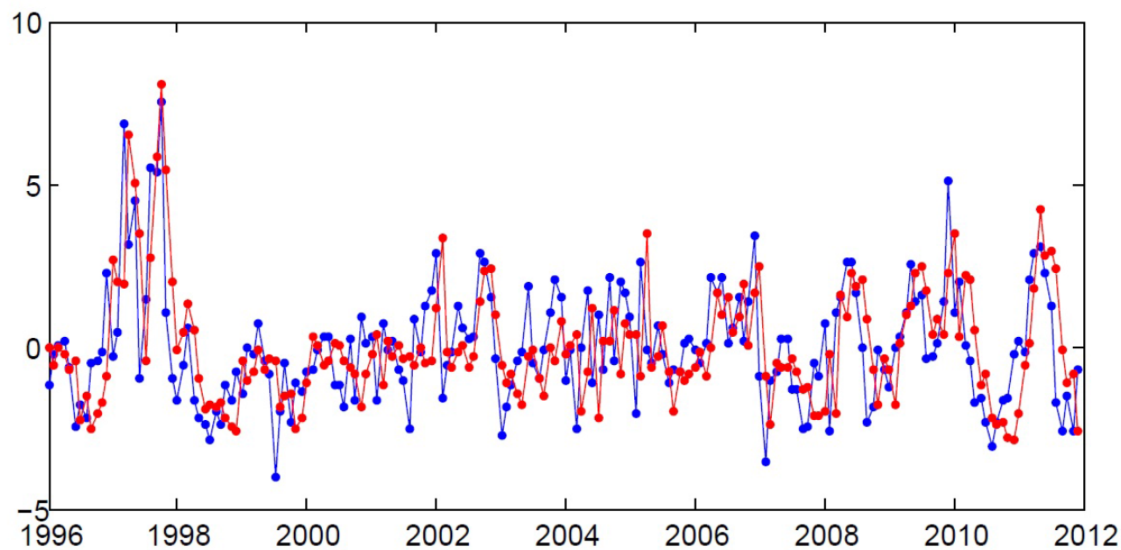
It was corrected.

-Define ’N.S’ in line 262 and in the header of table 2.

It was corrected.

-Line 320: ‘delayed by 1 month’, Where can I see this?

This statement is based on the consideration that the Kelvin waves of the first and second baroclinic modes are both forced in the central-western Pacific but propagate at different speeds (~2.8 m/s for mode 1 and ~1.7 for mode 2). Assuming that they propagate freely from the central-western Pacific, the difference in phase speed yields a ~1 month delay between mode 1 and mode 2 when they reach 95°W. We provide the figure that shows the mode 1 and mode 2 Kelvin Waves at 95°W. The maximum correlation is for lag -1 month (mode 1 ahead mode 2).



-Line 692: As I am not able to access all the grey literature listed in this manuscript, is '3°N' correct, as the title states costa peruana, and the Peruvian coast starts south of

The reviewer is right. The northern border of Peru is at ~3°S. However, in the title of this publication, the authors refers to 3°N because the cruise was done at 3°N.

-Line 775: Define E and C in the table header and not only in the text.

Following the reviewer recommendation, we now also define the E and C indices in the caption of the Table.

-Figure 1 legend: Mention station 4 as 12°02'S; 77°29'W as in the text, not only by one geographical coordinate.

It was corrected.

-Figure 2 legend: Mention 15°C marked in Figure 2a to indicate the lower thermocline limit. In the figure the numbers are difficult to read.

The figure 2 was improved.

-Figure 3a: The numbers are difficult to read. May be describe in the figure legend the curves, e.g. 15°C (solid black line), etc.

It was corrected.

-In Figure 4 legend it is stated that that the oxylines 22.5 and 45 are included in the figure; I can't find them in the figure.

The caption of Figure 4 was corrected.

-Why is there a black line in Figure 5 at 60 m depth?

The black line was removed. It was an error.

Reply to reviewer 2 (Report 1)

The paper improved significantly from its first version. Objectives, structure, figure layout, and narrative are much clearer now. Still, English grammar/usage and several confusing paragraphs need revision. Overall, I think that the paper is valuable for publication after some clarifications. I strongly suggest an extra analysis exploring the link between local wind and the biogeochemical time series variability. Besides, I am not convinced that a monthly time series can resolve the whole intra-seasonal band (30-90 days). I have attached a list of issues that need clarification or a better justification.

We thank the reviewer for his constructive comments. We have proofread the manuscript so as to make it easier to read. We have also clarified and expanded some sections. In particular the presentation of the data for T, S and O_2 has been expanded so as to better introduce the subsequent analyses and ease the interpretation of the inter-annual variability. In particular, we now provide the new figure 3 that shows the evolution of the anomalies of T and O_2 relative to the mean seasonal cycle, and of the seasonal cycle as a function of depth, along with statistics.

Regarding the issue of the intra-seasonal band, we have also considerably revised the manuscript and acknowledged the fact that it is indeed difficult to quantitatively address variability at the intra-seasonal time scales with our oceanographic data. The paper thus now focuses on the inter-annual timescales. Still, we believe that intra-seasonal variability not accounted by our data can have a residual effect on the lower frequency signal (i.e. inter-annual) through rectification processes, which we now briefly discuss in the discussion section.

Since the focus is now on inter-annual timescales, we do not investigate the relationship with local winds owned to the fact that the oceanic teleconnection is notoriously dominant at inter-annual timescales and limitations associated to wind products over the period of interest (see Goubanova et al. (2011) for a discussion).

References:

Goubanova K., V. Echevin, B. Dewitte, F. Codron, K. Takahashi, P. Terray, M. Vrac, 2011: Statistical downscaling of sea-surface wind over the Peru-Chile upwelling region: diagnosing the impact of climate change from the IPSL-CM4 model. *Clim. Dyn.*, DOI 10.1007/s00382-010-0824-0.

Specific comments

-Multiples times the authors used “owned” to indicate “due” or “as a consequence” (or any proper synonym related to the last two verbs). Need correction.

This has been corrected accordingly.

-Introduction

-70-72: Could you explain why oxygen determines low N:P ratios?

Under the low oxygen conditions of the coastal upwelling waters, other redox processes can be dominant such as denitrification and anammox. Both processes makes use of nitrate as an electron acceptor that determines the high rates of nitrogen transformation in N_2 that is exchanged with the atmosphere. This results in alow N/P ratio, below the classical Redfield ratio of 16.

-83-84: What type of reduction are you talking about?

Sanchez et al. (1999) reported that during the 1997– 1998 El Niño event large scale oxygenation off the Peru margin was caused by circulation changes. The latter led to the depression of the OMZ below 100 m. Under these circumstances, the OMZ off Peru and northern Chile could be reduced by 61% (Helly and Levin, 2004). We have re-written this sentence in the new version.

References:

Sánchez, G., Calienes, R., and Zuta, S.: The 1997-1998 El Niño and its effect on the marine coastal system off Perú. CALCOFI reports, 41, 62-86, 1999.

Helly, J.J., and Levin, L.A.: Global distribution of naturally occurring marine hypoxia on continental margins. Deep-Sea Research Part I, 51, 1159-1168, 2004.

-91-92: The statement is confusing since ENSO variability off Peru is also triggered by Equatorial Kelvin waves. Need better integration with previous paragraph.

Following reviewer´s recommendations, we have clarified this part. Our point was to state that depending on the timescale of variability of the equatorial Kelvin wave (i.e. intra-seasonal versus inter-annual), the consequences for the Peruviang upwelling are different. Inter-annual Equatorial Kelvin Waves are not trapped along the coast but radiate as Extra-tropical Rossby waves, whereas intra-seasonal Kelvin waves are trapped along the coast. The text has been modified.

-94: thermocline depth instead of thermocline

It was corrected.

-102-103: I cannot understand the paragraph’s conclusion, considering that Modoki peaks are in Oct-Dec, i.e. mid-spring to early summer, and the canonical El Nino peaks are in Jan-April, i.e. early summer to early fall.

This statement was confusing and was removed.

-Methods

-129-130: How oxygen deficient water can trigger high productivity? I would think that high productivity leads to low oxygen conditions.

Upwelled waters are characterized by high nutrient and low oxygen but the high productivity is only associated with nutrients. In order to avoid misunderstanding the sentence was changed to: “The presence of nitrate-rich ESSW (Zuta and Guillén, 1970; Strub et al., 1998; Graco et al., 2007; Silva et al., 2009) triggers the high primary production of the region, with maximum values in spring-summer, out of phase of winter upwelling maximum (Echevin et al., 2008; Chavez and Messié, 2009; Gutiérrez et al., 2011a, Vergara et al., 2016).”

-131-132: “out of phase of winter upwelling maximum” does not make sense. What do you mean?

This is a peculiar characteristic of the Peruvian upwelling system: the peak season for productivity is not in phase with the period of peak upwelling, which takes place in Austral winter when the along-shore winds are maximum and variable (see figure 1 of Dewitte et al. (2011). Several hypotheses have been put forward to explain such a feature. Modelling approaches show that lower irradiance, maximum mixing (Vergara et al., 2016) decrease the levels of primary productivity (Sverdrup model). Alternatively, other authors point to iron deficiency as main cause of this low winter productivity (Echevin et al., 2008).

References

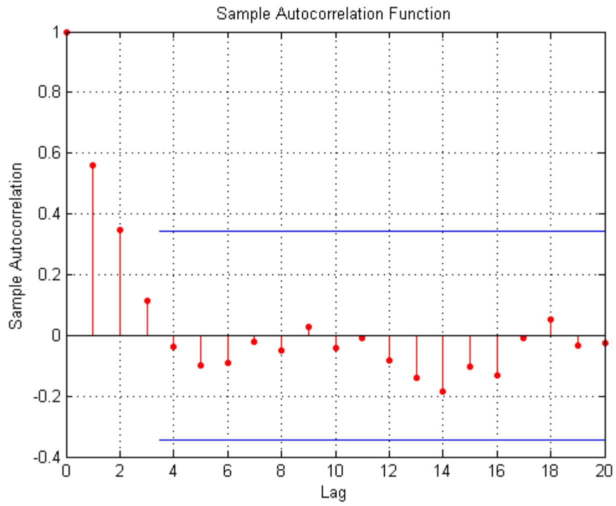
Dewitte, B., S. Illig, L. Renault, K. Goubanova, K. Takahashi, D. Gushchina, K. Mosquera-Vásquez, and Purca, S.: Modes of covariability between sea surface temperature and wind stress intra-seasonal anomalies along the coast of Peru from satellite observations (2000-2008). J. Geophys. Research, 116, C04028, doi:10.1029/2010JC006495, 2011.

Vergara, O., B. Dewitte, I. Montes, V. Garçon, M. Ramos, A. Paulmier, and O. Pizarro: Seasonal Variability of the Oxygen Minimum Zone off Peru in a high-resolution regional coupled model. Biogeosciences. 13, 4389-4410, 2016.

Echevin, V., Aumont, O., Ledesma, J., and Flores, G.: The seasonal cycle of surface chlorophyll in the Peruvian upwelling system: A modeling study. Progr. Oceanogr. 72, 167-168, 2008.

-178: How did you estimate correlation significance? Are you correcting for the time series autocorrelation in the test? That has to be considered.

The significance of the correlation is based on the estimate of the degree of freedom of the time series. The latter is derived from the auto-correlation of the time series taking the lag when it reach zero the first time. Below is an example for the oxycline time series:



Autocorrelation function for oxycline over the period 1996-2011 (not show in the manuscript).

-Results

-Figure 3:

a) The three series together are hard to compare. I suggest either using more contrasting color for the time series, or showing only the thermocline and oxycline depths (or thermocline and OMZ depths, opt to you).

Figure 3 has been changed so as to clarify this point and also to ease the interpretation of the variability. We now present the anomalies of (T,O_2) as a function of depth (with the thermocline and oxycline depths overlapped) along with the mean seasonal cycle as a function of depth. Mean seasonal cycles have been calculated over the period 1999-2011 so as to exclude any residual effect of the strong 1997-1998 El Niño. A new figure 3 is shown.

b-d) I suggest adding the 1st and 3th quartiles, so we can have an idea of the data dispersion for each month.

We have modified figure 3 and the seasonal cycle is now presented as a function of depth. The seasonal cycle is computed over the period 1999-2011 to avoid the strong signature of the 1997-1998 El Niño and there is little dispersion associated to its estimate. For instance, if we select randomly 10 years out of the 13 years and recalculate the seasonal cycle, we find little differences.

-246: Why I should expect a shallow oxycline condition for summer-fall. Need to explain.

In summer-fall, the shallow oxycline is due to the high remineralization of organic matter, higher stratification and oxygen consumption**.** Note that oxygen poor waters can intercept the euphotic layer and the continental shelf, promoting suboxic and even anoxic conditions in the underlying surface sediments (O_2 < 8.9 µmol kg^{-1}, Fig. 2c). See also Vergara et al. (2016) for a description of the seasonal variability off Callao from a model simulation (their figure 13).

-250: “deficient water deepens” suggests vertical advection, but that is not necessarily the case. Subsurface oxygen can increase due to vertical mixing. Also, decreased phytoplankton production in winter leads to decreased subsurface respiration, so lower oxygen consumption.

During austral winter (July-August) due to higher variable winds (See Fig 1b of Dewitte et al. (2011)), there is an increase in mixing that is associated to a lower phytoplankton production, which yields to the oxygen deficient waters (up to 70 m depth, figure 2c and 3).

-256-257: Defining intra-seasonal as fluctuations shorter than a year is not correct. That would include the seasonal cycle, which is evidently not intra-seasonal.

The text has been clarified. Intra-seasonal timescales refer to timescales in the frequency band [30-120] days.

-263: “Decoupling in the linear sense” Need to explain.

“Linear sense” refers to the correlation analysis that provide the estimate of the linear relationship between two variables. The fact that the correlation is low means that there is no linear relationship. However since we are dealing with a highly non-linear system, this does not mean that there is not a causal relationship between the oxycline and the 15°C isotherm.

-264: Are those trends statistically significant? Two cm per decade is really small, especially considering potential measurement errors. It may be interesting to calculate the linear trend independently for each month or season.

Following the reviewer suggestions, we have estimated the significance of the trend and its seasonal variability (see results). The new table 3 was introduced in the revised manuscript:

Table 2: slope of the linear fit for oxygen, temperature,salinity, nitrate and nitrite as a function of depth over the period 1999-2011. The slope for thermocline and oxycline depths are also provided as a function of season. The confidence level estimated based on a Student’s T-test is indicated in parenthesis when larger than 80%.

Depth (meter)	**O_2** (μmol kg^{-1} decade^{-1})	**T** (°C decade^{-1})	**S** (PSU decade^{-1})	**Nitrate** (μmol L^{-1} decade^{-1})	**Nitrite** (μmol L^{-1} decade^{-1})
0	24.03 (90%)	-0.04	0.026	0.93	0.11
10	47.55 (95%)	0.53 (80%)	0.013	-0.17	-0.22 (80%)
25	40.35 (95%)	0.65 (90%)	0.025 (80%)	-1.67	-0.01
50	14.40 (85%)	0.50 (90%)	0.003	0.01	-0.15
75	6.04 (90%)	0.34 (90%)	-0.002	1.85	-0.57
90	6.76 (95%)	0.42 (95%)	-0.001	2.51 (80%)	-0.75
100	7.53 (95%)	0.46 (95%)	0.003	2.95 (80%)	-0.88

	OMZ (m decade^{-1})		**Thermocline** (m decade^{-1})	
Annual	-0.64 (95%)		-0.30 (95%)	
Seasonal	**Summer**	**Winter**	**Summer**	**Winter**
	-0.74 (95%)	-0.77 (95%)	-0.63 (95%)	0.03
	Fall	**Spring**	**Fall**	**Spring**
	-0.76 (95%)	-0.69 (95%)	-0.49 (95%)	-0.48 (95%)

-272-274: Could you indicate which depth intervals correspond to surface, subsurface, and bottom waters? That could help to better understand the time series description.

Following reviewer´s recommendation, the caption of Figure 2 was expanded so as to provide more details on the data.

-276: I would mention strongest vertical mixing instead of stronger upwelling. That is finally the most likely mechanism explaining the pattern.

We are referring here to the distribution of Nitrate into the water column, so that the most likely mechanism is upwelling. During winter, high nitrate concentrations are found over the entire water column (> 15 µmol L^{-1}). Although the Peruvian upwelling benefit from upwelling favorable winds during all the year, it is during the winter season when winds are the strongest leading to maximum upwelling and high variability which implies the mixing. Both processes are likely to be at work to bring nitrate to the surface.

-285: Explain why phosphate is not a limiting nutrient.

Nitrogen appear more limiting than phosphate because an active N loss is observed in large parts of the water column promoted under low/depleted oxygen conditions and coincident with a pronounced secondary nitrite maximum and a strong nitrogen deficit (Codispoti et al., 1986).

-286-287: "whereas nitrate is depleted at surface and in the water column" Confusing statement, describe better. Why do you cite Kock et al. (2016) to describe the nitrate depletion in your dataset?

Following reviewer´s recommendation we have clarified this statement and write a new paragraph.

-288: "registered the highest nitrate values" delete nitrate

It was corrected.

-289-290: First you talk about nitrate concentration, and then nitrite variability. You cannot indicate 'also' to connect the two sentences. Besides, I do not see an increase in nitrite variability after 2000.

The text has been clarified. “After 2000, nitrate concentrations registered the highest values (> 20 µmol L^{-1}) for the entire time series coincident with lower nitrite and silicate concentrations (Figure 4).”

-292-299: Ndef was estimated using a constant of 12.6. Is that constant derived for the Peruvian coastal region only? Does it change in the oceanic region? If that is the case, could you conclude that there was low nitrate consumption during El Nino 1997-98, when oceanic Subtropical Surface Waters penetrated into the coastal region?

The constant of 12.6 was defined for the Peruvian waters, particularly in the coastal areas. This value is lower than in oceanic waters (Codispoti and Packard, 1980). There are a lot of grey literature that propose this non-Redfield relationship in the Peruvian waters. This condition is the consequence of the low oxygen (OMZ) and the high nitrogen loss under denitrification-anammox activity.

During El Niño there are Subtropical Surface Waters (SSW) coming to the coast. Low nutrient conditions are characteristics of these waters compared with the Cold Coastal Waters (CCW), and high-oxygen prevents the nitrogen loss and high nitrogen deficit.

-299: “Nitrate reduction” is confusing. Do you mean that nitrate concentration decrease, or are you talking about a redox reaction?

The depleted oxygen conditions lead to an increase of the redox. Nitrate is one of the electron acceptor available in these waters.

-303: isotherm depth instead of isotherm

It was corrected.

-312: “These waves differ from their vertical...” sentence does not make sense

The sentence was rewritten: “These waves have a different vertical structure and phase speed”

-319: Could you explain why a downwelling coastal-trapped wave decreases wind-driven upwelling? A CTW can modify the source of water being upwelled, but the wind driven transport remains the same if wind does not change.

What is meant here is that a downwelling coastal-trapped Kelvin wave will depress the thermocline depth along the coast, which opposes to the effect of the upwelling favorable winds. The text has been clarified.

-333: What do you define by low frequency variability?

This statement was removed since we no longer discuss intra-seasonal timescales. Note however that the EKW_2 tends to have more energy in the low periods (~4-8 years) than EKW_1 (see figure 7)

-338: I do not understand when you say “skewed from 2000”. Why is noteworthy?

The skewness refers to the asymmetry of the timeseries. A negative skewness means that the amplitude of the negative anomalies is larger in absolute value than the amplitude of the positive anomalies, or that there are more occurrence of negative anomalies than positive anomalies. This is now quantified and we provide the value of the skewness:

"It is noteworthy that EKW_2 is negatively skewed from 2000 (normalized skewness = -0.8910 cm) and there is a negative trend of upwelling events from 2000 (trend = -0.0177 cm/decade)"

-344-345: Confusing. I could figure out what do you mean after examining Figure 6, but the text is not clear at all.

The text has been clarified.

-351: It is not possible to resolve fluctuations shorter than 60 days with your monthly observations (1/60 day-1 is the Nyquist frequency), so why do you talk about the 50-180 days band. I do not even think that you could properly resolve fluctuations shorter than 90 days.

The text has been corrected accordingly. Intra-seasonal variability refers to timescales between 60 days and 180 days. We no longer discuss intra-seasonal variations in the data considering their limitations (gaps and aliasing). This is now explicitly mentioned in the text of the revised manuscript.

-Figure 6.

What are the y-axis units in panels f-j. I cannot understand the result if I do not know what the y-axis represents. Delete c) in the titles from panels 6f-j.

The figure was improved.

-362: Why is this interesting? What does it imply?

This section has been completely rewritten and the text has been clarified.

-365: I would rather indicate that the EOF2 has weaker low-frequency variability compared to EOF1, instead of stronger high frequency variability

the text was modified accordingly.

-369: Where that 'also' comes from? It does not make sense, since you indicated a different feature for the EOF1 in previous paragraph

We apologize for the misuse of "also" here. We meant "in addition".

-371: Why is this interesting? Explain.

This section has been completely rewritten and the text has been clarified.

-380: How do you visualize that the mode tends to capture higher frequencies?

This section was rewritten and we no longer discuss intra-seasonal variability

-384-385: “over the period after 2000” do you mean “after 2000”?

Yes. This has been changed accordingly.

-388: The main conclusion is not clear. What are those different regimes? How do you connect your results with the “two regimes” statement?

This part was presented in the discussion and clarified.

-Discussion

395: “with in particular a marked semi-annual cycle” does not make sense. Do you mean “particularly, with a marked semi-annual cycle”. I disagree that the OMZ has a strong semi-annual cycle. The semiannual fluctuation exists but is weak. Please show the interquartile range or the standard deviation in Fig. 3b-d.

We now provide a new figure 3 that shows the evolution of the anomalies of T and O_2 relative to the mean seasonal cycle, and of the seasonal cycle as a function of depth, along with statistics.

-399: delete “Firstly,”

done

-400: You did not explore the connection between the equatorial variability and the OMZ in the seasonal time scale. This is kind of surprising considering that your biogeochemical time series can resolve properly the seasonal band (which is not the case for the intra-seasonal). That the 15°C isotherm depth in the equator has similar semiannual cycle that the OMZ off Peru does not mean that a connection exists.

The paper focuses on the ENSO timescales and we have left behind a thorough discussion of the seasonal cycle because the latter is not dominated by the oceanic teleconnection and would require additional analyses that are beyond the scope of the current study.

-406-408: Could nitrification contribute to the subsurface peak in nitrite?

Yes this is possible. Molina and Farías (2009) indicate that aerobic NH4+ oxidation could contribute between 8% and 76% of NO2− production and support the important role of aerobic NH4+ oxidizers in the nitrogen cycling in the OMZ and at its upper boundary.

References

Molina V. and L. Farías, 2009. Aerobic ammonium oxidation in the oxycline and oxygen minimum zone of the eastern tropical South Pacific off northern Chile (~20°S). Deep Sea Research Part II: Topical Studies in Oceanography. The Oceanography of the Eastern South Pacific II: The Oxygen Minimum Zone. Volume 56, Issue 16. Pages 1032–1041, doi.org/10.1016/j.dsr2.2008.09.006

-444-451: Could you explain why denitrification/anammox decreased during El Nino 1997-98? What are the underlying-processes explaining the pattern?

During El Niño events, the chemical of the upwelling change. Physical characteristics change, water masses distribution change and in consequence the depth of the mixed layer, surface temperatures, salinities. A deepening of the oxygen minimum zone (OMZ) under strong El Niño events determine a higher availability of oxygen in the water column and changes in the biogeochemistry. The main electron acceptor is oxygen and not nitrogen and as a consequence denitrification and anammox tend to decrease during El Niño, as we observe particularly during the strong 1997-98 El Niño.

-455: What does the "overshoot" concept mean? Why did you mention that?

This concept was introduced by Codispoti et al. (1986). It refers to the drastic change in thermocline depth associated to the Extraordinary El Niño events, like in 82-83. For clarity the sentence was removed and we no longer refer to this concept.

-456: Is there a reason for the 3 years anomalies? Is that based in observations? Why is relevant the study by Guillen and Calienes (1981)?

This statement was removed.

-463: What about nitrification? Does nitrification increase or decrease during La Nina? How does nitrification impact the nitrogen cycling?

According to our analysis (Figure 6e), nitrite concentration decreases below ~50m during both CP and EP El Niño events. During La Niña events, it would increase since the C index also accounts for La Niña events (C is negative). Under EP condition, oxygenated waters are dominant in the water column and as our results show under CP the OMZ is less intense. Both conditions could be associated with lower accumulation of nitrite and suggest lower nitrate consumption processes. The opposite is observed under cold or La Niña period (like 1999-2001 years).

-470-473: I am not convinced that the weaker coupling after 2000 is due to a non-linear relationship between equatorial dynamics and the OMZ. I would expect that i) the biogeochemical processes in the OMZ are influenced by local and remotely driven dynamics; ii) the equatorial dynamics clearly prevail during the strongest El Nino events (like 1997-98); and iii) both local and equatorial dynamics are relevant during neutral or weak El Nino conditions.

We have clarified the text and explain better this concept. It is based on the observation that the percentage of explained variance of the dominant EOF mode decreases when we carry out the EOF analysis only for the period after 1999 and by comparison with the EOF analysis over the entire years 1996-2011. The first EOF mode is the one that relates the most to ENSO so if its variance decreases; it means that the share of the "coupled" variability that relates linearly to ENSO decreases. High-order EOF modes tends to grasp the share of the coupled variability that is "natural" that is independent of the external forcing (e.g. Kelvin wave or wind) and has to results from non-linearity of the system.

-503-523: I disagree with the justification for not exploring the local wind impact on the biogeochemical processes off Peru. One of the main results by Illig et al. (2014) was that the local forcing (wind, heat fluxes) has much important contribution than the equatorial Kelvin wave disturbances to explain the SST signal off Peru. Besides, Echevin et al. (2014) found that local winds dominate the chlorophyll variability in the submonthly band, and that both local and remote forcing have similar contribution in the intra-seasonal band (see their spectral analysis Fig. 11). Therefore, could you report the correlation between alongshore wind near Callao and the biogeochemical time series?

Since the paper now focuses on inter-annual timescales, we have left behind the discussion on the role of local forcing, which, we agree, could be relevant for the intra-seasonal timescales. At ENSO timescales, wind forcing could also play a role. However due to limitations in the data sets (see Goubanova et al (2011) for a discussion), it is difficult to address this issue quantitatively. We have clarified that the paper is focused on the oceanic teleconnection. In the discussion, we mention the limitations associated to the wind data sets to address the inter-annual timescales.

-526-527: The trend are small, tone done this idea.

We have revised the analysis of the trends and have corrected some mistakes. We have also performed additional analysis and provide the confidence level of the slopes.

THE OMZ AND NUTRIENTS FEATURES AS A SIGNATURE OF INTERANNUAL AND LOW FREQUENCY VARIABILITY OFF THE PERUVIAN UPWELLING SYSTEM

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Abstract

Over the last decades, the Humboldt Current Upwelling Ecosystem and particularly the Northern component off Peru, has drawn the interest of the scientific community because of its unique characteristics: 1) it is the upwelling system with the biggest catch productivity, 2) although with the shallowest, intense and acidic Oxygen Minimum Zone (OMZ), 3) it is also an area of intense nitrogen loss and anammox activity, and 4) experiences one of the most intense interannual variability associated with the equatorial remote forcing compared to other tropical oceans. In this context, we examined the oceanographic and biogeochemical variability associated with the OMZ off central Peru, from a monthly time-series (1996–2011) recorded off Callao (12º02'S, 20 nm). The data reveals a rich spectrum of variability of the OMZ that includes frequencies ranging from intraseasonal (~40-180 days) to interannual. Owned to the efficient oceanic teleconnection off Peru, the observed variability is interpreted in the light of an estimate of the equatorial Kelvin wave considering peculiarities of its vertical structure (i.e. first two baroclinic modes). The span of the data set allows contrasting and suggesting two OMZ regimes, one associated to the strong 1997/98 El Niño event during which the OMZ adjusted to downwelling conditions and deepened by more than 100 m and, and the other one characteristics of the post-2000 period and associated to enhanced variability at intraseasonal timescales. The latter regime is shown not to be related in a straightforward manner to the intraseasonal equatorial Kelvin wave activity. The data also reveals suggest a long-term deepening of the oxygen deficient waters from 2000.

Keywords: Oxygen minimum zone, nutrients, Kelvin waves, El Niño, Upwelling Ecosystem, Peru.

1. Introduction

The upwelling region off Peru hosts a complex biogeochemical system that is unique for at least two reasons. First it is embedded into the permanent, very shallow and intense Oxygen Minimum Zone (OMZ) of the Eastern Tropical South Pacific (Gutiérrez et al., 2008), and second it exhibits a significant variability at different time scales, particularly at inter-annual scale associated to the impact of Equatorial Kelvin waves and the El Niño-Southern Oscillation, ENSO (Chavez et al., 2008).

The OMZ is generated by the combination of high oxygen demand during organic matter remineralization and the sluggish ventilation in the region (Wyrtki, 1962; Helly and Levin, 2004). It is wide in the vertical extension (~ 500 m), intense (< 22.5 µmol kg^{-1}), and at some latitudes the upper boundary could be very shallow (25-50 m) intersecting the euphotic zone and impinging the continental shelf (Morales et al., 1999; Schneider et al., 2006; Fuenzalida et al., 2009; Paulmier and Ruiz, 2009; Ulloa and Pantoja, 2009). The OMZ off Peru is associated with the presence of nutrient-rich Equatorial Subsurface Water (ESSW) transported poleward by the Peru-Chile Undercurrent (PCU) (Strub et al., 1998; Fuenzalida et al., 2009; Silva et al., 2009).

The OMZ variability in terms of distribution and intensity has a direct impact on the biogeochemical processes of the northern component of the Humboldt upwelling system, because oxygen is: 1) a key factor in biogeochemical cycles, particularly the carbon (Friederich et al., 2008) and nitrogen processes (e.g. Kock et al., 2016; Hammersley et al., 2007; Lam and Kuypers, 2011), 2) This activity determines low N:P ratio, below the classical Redfield ratio of 16 with strong impacts in the primary and secondary production and in general in all the biogeochemistry of the system (Franz et al., 2012) and 3) a control factor in the distribution of organisms (e.g. Bertrand et al., 2010; Criales-Hernández et al., 2006; Ekau et al., 2010; Gutiérrez et al., 2008, Levin et al, 2002).

The position, strength and thickness of the Eastern South Pacific OMZ can be greatly modified by local and/or remote forcing (e.g. interannual time scales, Morales et al., 1999; Gutiérrez et al., 2008). During ENSO episodes, changes in the equatorial dynamics extend to the Peruvian coast, which behaves as an extension of the equatorial waves guide (Clarke and van Gorder, 1994). Strong El Niño (EN) events, like the 1997-1998 EN, affect the circulation and water masses distribution that determine the deepening of the OMZ, below 100 m depth, and the occurrence of large oxygenation events in the water column and over the sediments along the Chilean and Peruvian coast (Morales et al., 1999; Sánchez et al., 1999; Gutiérrez et al., 2008). Helly and Levin (2004) reported about 60% reduction in the sea floor area influenced by the Eastern South Pacific OMZ off Peru and northern Chile during EN years.

Recent studies indicate that the characteristics of the interannual variability have changed in recent decades with an increasing occurrence of the so-called Central Pacific (or Modoki) El Niño events in the 90s (Yeh et al., 2009; Lee and McPhaden, 2010; Takahashi et al., 2011). This type of El Niño event is rather peculiar for the coast of Peru since it is associated to an overall cooling of SST (shallowing of the thermocline) along the coast (Ashok et al., 2007; Dewitte et al, 2012), conversely to the more documented extreme Eastern Pacific El Niño event (like 1997/98 El Niño). Additionally, perturbations of equatorial origin are also characterized by the propagation of Intraseasonal Equatorial Kelvin Waves (IEKW) that reach the coast of Peru and generate poleward-propagating coastal trapped Kelvin waves (cTKW) (Clarke, 1983; Dewitte et al., 2011; Illig et al., 2014). These cTKWs can modulate the thermohaline and biogeochemical conditions of the water column (Blanco et al., 2002; Hormazábal et al.,2001; Gutiérrez et al., 2008, Echevin et al., 2014).

IEKWs are also modulated at interannual timescale (Dewitte et al., 2008) with in particular a distinct seasonality of the IEKW activity between the two types of El Niño event. Mosquera-Vásquez et al (2014) showed that IEKW activity is larger for the peak phase (i.e. Oct – Dec) of Central Pacific El Niño events while during extreme El Niño events it tends mostly to act as a trigger of ENSO and thus peaks in Jan-Apr. Taking into account that only Central Pacific El Niño events have occurred since 2000, the last decade is characterized by an overall IEKW larger activity in Austral summer compared to the previous decade.

Owned to the impact of IEKW on the coastal chlorophyll surface concentration (Echevin et al., 2014) and on dissolved oxygen (Vergara et al., 2016), the study of the relationship between ENSO and the OMZ would require taking into account timescales of variability ranging from intraseasonal to interannual. Only a few time series of chemical data, oxygen and nutrients, along the Peruvian coast have been published exploring the behavior of interannual changes and remote forcing (Calienes and Guillén, 1981; Guillén and Izaguirre de Rondán, 1973; Guillén et al., 1989; Ledesma et al., 2011). Here, we analyze a unique long term time series of oxygen and inorganic nutrient data off central Peru in order to document timescales of variability of O_2 and nutrient, as well as get insights on the impact of the equatorial variability on the biogeochemical conditions of this coastal upwelling region. The period (1996-2011) encompasses the extreme Eastern Pacific 1997 - 98 El Niño, followed by moderate Central Pacific El Niño events and a strong La Niña episode in 2010.

2. Methods

2.1. Time series

A monthly time series (1996-2011) of vertical profiles of temperature, salinity, oxygen and nutrients (nitrate, nitrite, phosphate and silicate) collected by the Instituto del Mar del Peru (IMARPE) during the period 1996-2011, at station 4 (20 nm, 145 m), located off central Callao (12°02' S, 77°29´ W, Figure 1) was used. Filtering of the data was performed by eliminating statistical outliers. The time series were standardized with their annual cycle in order to explore several temporal scales of variability in the study area.

The region of Callao have been identified as one of the major upwelling cells off central Peru (Rojas de Mendiola, 1981) with a subsurface well developed OMZ (Wooster and Gilmartin, 1961; Zuta and Guillén, 1970). The presence of nitrate-rich and oxygen deficient ESSW (Zuta and Guillén, 1970; Strub et al., 1998; Graco et al., 2007; Silva et al., 2009) triggers the high primary production of the region, with maximum values in spring-summer, out of phase of winter upwelling maximum (Echevin et al., 2008; Chavez and Messié, 2009; Gutiérrez et al., 2011a, Vergara et al., 2016). The OMZs are associated with areas of intense microbial activity associated with organic matter remineralization, oxygen consumption and nitrogen loss (Helly and Levin, 2004). Recent studies in the Peruvian oxygen minimum zone show not only denitrification but also the anammox process as the prevalent pathway for nitrite and nitrate reduction and a loss of nutrient available for phytoplankton. Others studies have documented the impact in the oxygen regime on the continental shelf off Callao of the remotely-driven effects of El Niño and coastal trapped waves that show effects at monthly to interannual time-scales on the boundaries of the Oxygen Minimum Zone- OMZ and changes in the benthic fauna (Gutiérrez et al., 2008).

2.2. Water column profiles

Water samples were collected monthly with Niskin bottles during cruises of R/V IMARPE VIII, R/V SNP-1 and R/V SNP-2 for the period 1996 to 2011. Temperature was measured by inversion thermometer through 2001 and by CTD (Seabird SBE 19+) from 2002. Salinity was measured by salinometer through 2001 and by CTD plus salinometer from 2002. IMARPE performs comparative analysis between CTD, thermometer and salinometer during all the monthly cruises in order to present consistent information.

Dissolved oxygen and nutrients were measured at standard depths (0, 10, 30, 50, 75, 100 m). Dissolved oxygen was determined by a modified Winkler method (Grasshoff et al., 1999), with a precision of 0.5 μmol kg^{-1} (large errors for values lower than 10 μmol kg^{-1}). Nutrient samples (nitrate, nitrite, phosphate and silicate) were stored frozen until analyses using standard colorimetric techniques, the precision for nitrate analysis was $\pm$0.5 μmol L^{-1}, for nitrite $\pm$0.08 μmol L^{-1}, for phosphate $\pm$ 0.03 μmol L^{-1} and $\pm$0.25 μmol L^{-1} for silicate (Parsons et al., 1984).

The fixed nitrogen deficit (Ndef) was determined by the formula:

$$Ndef = 12.6 \times [\ HPO_4^{2-}] - ([NO_3^-]+[NO_2^-])$$

The constant 12.6 is the empirically-determined N:P ratio of organic matter produced in these waters (Codispoti and Packard, 1980). Positive values indicate nitrate deficit.

The OMZ was defined as the area with oxygen concentrations lower than 22.5 μmol kg^{-1}. This concentration was considered as the OMZ upper boundary (Schneider et al., 2006; Fuenzalida et al., 2009; Ulloa and Pantoja, 2009).

2.3. Statistical analysis of Time series

Linear interpolation was applied to complete minor gaps into the 1996-2011 time series. Monthly anomalies were calculated as the difference between the original data and the mean seasonal cycle over the full period, normalized by the standard deviation. To compare variances, the time-series were analyzed with discrete wavelets (Torrence and Compo, 1998) to represent temporal changes in spectra. The principal component of the first two dominant Empirical Orthogonal Function (EOF) analysis (Emery and Thomson, 1998) was applied to the combined normalized (by standard deviation) monthly time series of physical (temperature and salinity) and chemical (oxygen, inorganic nutrients) data sets. It was performed at all depths in order to summarize the main signal of physical chemical co-variability in the water column. The first and second EOF analysis was applied for two periods (1996-2011 and 2000-2011) of time in order to evaluate the impact of the 1997-1998 El Niño on the statistics and grasp changes in the relationship between variables. The Pearson correlation coefficient (r) was calculated between series.

2.4 Intraseasonal Equatorial Kelvin Waves (IEKW) and El Niño indices

The amplitude of IEKW is derived from an Ocean General Circulation Simulation named Mercator. This simulation has been validated from observations in Mosquera-Vásquez et al. (2014), which indicates that it has comparable skill than the SODA oceanic reanalysis in the near equatorial region (Carton and Giese, 2008).

The method for deriving the wave coefficient consists in projecting the pressure and current anomalies from the model between 15°S and 15°N onto the theoretical vertical mode functions obtained from the vertical mode decomposition of the mean stratification. Kelvin wave amplitude is then obtained by projecting the results onto the horizontal modes at each grid point in longitude. The method has been shown to be successful in separating first and second baroclinic waves (Dewitte et al., 1999, 2008) that propagate at different phase speeds and impact the Peru coast in a very specific way (Illig et al., 2014). In particular, due to the sloping thermocline from west to east along the equator, the second baroclinic mode Kelvin wave is more energetic and influential on the upwelling variability off the Peruvian coast (Dewitte et al., 2011, 2012). For the correlation analysis with the dissolved oxygen data, we select the IEKW amplitude (in cm) at 90°W for the first and second baroclinic modes (hereafter IEKW_1 and IEKW_2)

In order to diagnose the large scale interannual variability in the tropical Pacific, we also use the Oceanic El Niño Index (ONI) provided by the national Weather Service NOAA (NOAA, CPC. 2015); and two other indices recently proposed by Takahashi et al. (2011) that characterise the variability associated to extreme EL Niño variability (E index) and the variability associated to Central Pacific and La Niña events (C index). Conveniently, these two indices are independent (uncorrelated) and derived from the EOF analysis of the SST anomaly in the tropical Pacific (see Takahashi et al. (2011) for details). The HadISST data set is used (Rayner et al., 2003) to derive them over the period 1950-2015, but only the values of the period 1996-2011 are used here.

3. Results

3.1. Oceanographic dynamics off central Peru (Callao, 1996-2011)

Vertical distributions of temperature (a) and salinity (b) off Callao (St 4) during 1996-2011 years are shown in Figure 2. The data set collected in this coastal and shallow station shows a water column with strong interannual signal, with significant changes in the 15º C isotherm depth. Here, the 15º C isotherm depth is considered as a proxy of the lower limit of the thermocline position, from 20 m to more than 100 m like during the 1997-1998 El Niño.

Under "normal" conditions, cold (< 15º C) and relatively salty (34.8-35.1) subsurface waters, characteristics of the Equatorial Subsurface Waters (ESSW), were dominant. Maximum temperatures at surface (up to 22º C, Figure 2a) occurred during summer and spring periods, when a shallow mixed layer occurs (up to 20 m water depth 15°C, Figure 3a). The climatology of the 15° C isotherm depth (Z_15°C) indicates a semi-annual component (Figure 3b), shallower in early fall and spring and deeper in winter during more intense upwelling events.

The time series of temperature (Figure 2a) shows a strong deepening in the 15º C isotherm (see also Figure 3a) from the end of 1997 until the beginning of 1998. This was a consequence of warm and salty (>35.2) Subtropical Surface Waters (SSW) penetration into the coast through transport and the crossing of the downwelling Kelvin wave and associated extra-tropical Rossby wave. This situation corresponds to the impact of the intense 1997-1998 El Niño, that switched off the coastal upwelling characteristics during almost one year. Note that the disappearance of the 15°C isotherm in the first 100 m took place in early 1997 (around April), well ahead the El Niño peak phase (around November).

Between 1999 and 2001 the 15° C isotherm depth presented lower interannual variability and in general a shallow position. A slight deepening of the thermocline takes place at the beginning of 2002, 2005, during winter of 2006, 2008 and 2009. This thermocline deepening was coincident with high salinity values and the occurrence of weak or moderate El Niño conditions.

3.2 The dissolved oxygen and the Oxygen Minimum Zone (OMZ) variability

The dissolved oxygen distribution shows a similar pattern to the thermohaline variables with strong anomalies during the 1997-1998 El Niño and the subsequent 1999-2001 La Niña event, (Figure 2c and 3). Shallow positions (20-40 m) of the oxycline (iso-oxygen of 45 µmol kg^{-1}) and OMZ upper boundary (22.5 µmol kg^{-1} iso-oxygen) were registered under active upwelling of ESSW and during the 1999-2001 La Niña event. On average, this condition is characteristic not only during summer-fall periods (see the climatological annual pattern, Figure 3b and c) but also in springtime suggesting a semi-annual component. During these seasons oxygen poor waters can intercept the euphotic layer and also the continental shelf, promoting suboxic and even anoxic conditions in the underlying surface sediments (O_2 < 8.9 µmol kg^{-1}, Fig. 3a). During austral winter (July-August) the oxygen deficient waters deepen (up to 70 m depth, figure 2c and 3).

At interannual scale, during the strong 1997-98 El Niño, a significant deepening of the oxycline and OMZ upper boundary is observed, when well-oxygenated Surface Subtropical Waters (SSW) occupied the water column down to at least 100 m depth. Besides the strong amplitude of the oxygen fluctuation associated to the 1997-98 El Niño, an interesting feature from the OMZ temporal distribution is the relatively large intraseasonal (i.e. periods lower than 1 year) variability since 2000 (see 2006, 2008, 2009, 2011 Figure 2 and 3). The relationship between O_2 anomalies and thermocline during the 1997 - 98 El Niño (i.e. positive O_2 anomalies associated to a deepening of the thermocline) breaks down afterwards for some events. Before 2000, the oxycline and the OMZ's upper boundary present a significant correlation with the 15ºC isotherm ($r = 0.43$, v-p < 0.01 and $r = 0.67$, v-p < 0.01 respectively), after the 2000, the correlation drops down ($r = 0.12$, v-p > 0.01(N.S) and $r = 0.44$, v-p < 0.01, respectively) suggesting a decoupling (in the linear sense) between O_2 and thermocline. The position of the OMZ upper limit show a negative trend estimated by a linear fit in -0.02 m/decade between

1996 and 2011, and in -0.12 m/decade after 2000 that suggest a long-term deepening of the oxygen deficient waters.

3.3 Nutrients and biogeochemical activity

The time series of inorganic nutrients vertical distribution off Callao are shown in Figure 4. Nitrate and nitrite concentrations ranged from ca. 0.0 to 27.0 µmol L^{-1} and ca. 0.2 to 9.0 µmol L^{-1} values respectively. Lower nitrate values are present at surface and bottom waters, particularly during summer and fall periods, while maximum nitrite values appear at subsurface waters in opposite relationship with nitrate levels. During winter periods maximum nitrate concentrations characterize the entire water column (> 15 µmol L^{-1}), coincident with the period of maximum upwelling intensities. The vertical distributions of silicate and phosphate exhibit a similar pattern than nitrate.

Nutrient time series also present a strong interannual signal mostly prominent during the 1997 – 98 El Niño event with low nitrate concentrations (< 10 µmol L^{-1}) coincident with minimum and even zero nitrite values and low silicate and phosphate levels (<10 µmol L^{-1} and 1 µmol L^{-1} respectively; Figure 4a, b). Between 1999 and 2001 nitrate concentrations were also lower than 10 µmol L^{-1} on average, but in contrast with the previous El Niño episode, subsurface nitrite reached maximum values (up to 9 µmol L^{-1}) coincident with an intense OMZ development and shallow thermocline. Silicate depletion is observed near the surface, while phosphate appears as a non-limiting nutrient in the surface waters. Elevated phosphate concentration in the surface waters is typical near the coast, whereas nitrate is depleted at surface and in the water column (Kock et al., 2016). At subsurface, high silicate (> 25 µmol L^{-1}) and phosphate (3 µmol L^{-1}) concentrations were observed. After 2000, nitrate concentrations registered the highest nitrate values (> 20 µmol L^{-1}) for the entire time series. The variability of nitrite concentrations also increased after 2000; high nitrate levels were coincident with lower nitrite and silicate concentrations (Figure 4).

In order to explore some biogeochemical activity related with the nitrogen cycle and the OMZ variability off Callao, the Ndef in the water column is estimated (Figure 5). Ndef values range from negative (-5 µmol L^{-1}), indicative of low nitrate consumption, up to 40 µmol L^{-1} corresponding to conditions of high deficiency in nitrate. The Ndef, particularly at subsurface, exhibits a clear interannual signal with minimum values (zero-negative) during the 1997-1998 El Niño coincident with well-oxygenated waters (Figure 3). In contrast, between 1999 and 2001 years, maximum Ndef (30-40 µmol L^{-1}) occurred under a shallow and well-developed OMZ. Nitrate reduction during this period was associated to high nitrite at subsurface (Figure 4).

After 2000, the Ndef water column conditions were highly variable coincident with the variability in the OMZ distribution. Strong deficient conditions were registered in 2005, 2007 and at the end of 2011 coincident with the strong La Niña conditions. Ndef at subsurface (50 and 90 m depth) was significantly correlated with the 15ºC isotherm (r= 0.43, v-p < 0.01) and with the OMZ though the correlation is relatively low (r 0.28, v-p < 0.01).

3.4 Equatorial forcing of the OMZ

In this section, we first document the evolution of the IEKW activity during 1996-2011 and then interpret the variability of the biogeochemical parameters off Peru documented above in the light of the characteristics of the remote equatorial forcing. The evolution of the amplitude of the first and second baroclinic modes Kelvin waves (IEKW_1 and IEKW_2) at 90°W in terms of sea level anomalies is shown in Figures 6 a,b. These waves differ from their vertical structure and phase speed, and are the most energetic along the equator. They transmit their energy along the coast in the form of coastal trapped Kelvin wave and can trigger extra-tropical Rossby waves (Clarke and Shi, 1991). It is assumed that waves with amplitude larger than one standard deviation over the study period (see horizontal lines in figure 6a,b) are downwelling Kelvin waves, whereas amplitudes more negative than -1 standard deviation correspond to upwelling Kelvin waves. Therefore, coastal-trapped downwelling (upwelling) waves will tend to reduce (increase) wind-driven coastal upwelling near Callao.

Our data reveal that the IEKW_2 is delayed by 1 month compared to the IEKW_1, consistent with the difference in phase speed of the waves and their propagation from the central equatorial Pacific up to 90°W. Maximum correlation between both time series was before 2000 (r 0.67, v-p< 0.01), being significantly lower (r 0.42, v-p< 0.01) for the period after 2000. The lower coherency between both Kelvin wave modes can be interpreted as resulting from non-linear interactions of the waves with the mean thermocline near 120°W (see Mosquera-Vásquez et al., (2014)). While the variability of both modes at 90°W looks similar, owned to their different vertical structure, their impact of the regional oceanic circulation off Peru is distinct, with in particular the second baroclinic mode Kelvin wave being trapped at a latitude closer to the equator than the first baroclinic mode Kelvin waves (Clarke and Shi, 1991). The second baroclinic mode Kelvin wave is also associated to lower frequency variability than the first baroclinic Kelvin wave as revealed by the global wavelet spectra analyses of the IEKW_1 and IEKW_2 timeseries at 90°W (Figure 6 a,b) consistently with Dewitte et al. (2008). The equatorial Kelvin wave experiences modal dispersion near 120°W (see Mosquera-Vásquez et al 2014) so that the amplitude and coherence of IEKW_2 and IEKW_1 can change along their propagation to the east of 120°W. This explains the different spectrum of variability of IEKW_2 and IEKW_1 although both waves exhibit an energetic peak around 50 days that corresponds to the forcing by intraseasonal atmospheric fluctuations in the western- central Pacific (e.g. Westerly Wind Bursts). It is noteworthy that the IEKW_2 is negatively skewed from 2000 (normalized skewness = -0.8910 cm) and there is a negative trend of the upwelling events from 2000 (trend = -0.0177 cm/decade), features that are also encountered for the Z_15°C (Fig. 6c) (normalized skewness = -1.330 m and trend = 0.0250 m/decade). Positive anomalies of IEKW (Figure 6 a, b) are associated to a deepening of Z_15°C (<0), as was observed during the 1997-1998 El Niño, the weak 2002-03 El Niño and during 2006, 2008 and 2010 warm seasons. During these periods IEKW_1 and IEKW_2 are in phase with comparable amplitude and the Z_15°C and the Z_ZMO (Fig. 6 d) are out of phase. The IEKW_1 and IEKW_2 are highly correlated with Z_15°C and Z_OMZ variables, but we find that IEKW_2 has a stronger relationship with the Z_15°C and Z_OMZ (r -0.54, -0.40 respectively, v-p<0.01) than IEKW_1 (r -0.34, -0.23 respectively, v-p<0.01).

The global wavelet spectrum analysis of Z_15°C and Z_OMZ (Fig. 6 h, i) reveals a rich spectrum of variability that encompasses low frequency and intraseasonal frequencies. The intraseasonal frequencies (~50-180 days) are consistent with the forcing by IEKW_2 while the low-frequency timescales result from the combined effect of both waves. Consistently the nitrogen deficit at 50 m (N_def; Fig. 6d) exhibits a comparable spectrum than Z_15°C and Z_OMZ though with a significant dominant peak at ~4 years.

In order to further document the variability in physical and biogeochemical variables and synthesize their relationship, an EOF analysis is performed combining all normalized time series. The results are presented in Figure 7 and table 1. The first EOF (EOF_1) mode of the combined temperature, salinity, oxygen, nitrate and nitrite explains 48 % of the total variability and covers the large fluctuations associated to the 1997- 1998 El Niño event (Figure 7 b). Fluctuations after 2000 are more in phase with the C index, with a relatively low correlation (r

-0.49; Table 2) suggesting the influence of Central Pacific and La Niña events on the OMZ dynamics. Interestingly the amplitude of the mode gives a similar weight (in absolute value) to temperature (-0.58), salinity (-0.46), oxygen (-0.48) and nitrite (0.46) (see first column of Table 1).

The second EOF mode (EOF_2) accounts for 24% of the explained variance and exhibits higher-frequency timescales than EOF_1 with no clear relationship with the 1997-1998 El Niño event since its correlation with the E index (that accounts for extreme El Niño events) is not significant (Figure 7b, Table 2). The relative amplitude of the variables for this mode also indicates a larger contribution of biogeochemical variables. The amplitude of nitrate (-0.86) and oxygen (0.27) were larger than the physical variable amplitudes (temperature, 0.17 and salinity 0.09). Interestingly EOF_2 is not linearly related to the Kelvin wave modes and the El Niño indices (Table 2) over the entire period. Only the correlation with the C index is significant but remains relatively low (-0.35).

The large signature of the strong 1997 - 98 El Niño event onto the EOF modes questions to which extent the statistics is impacted by the consideration of this event. In order to test the sensitivity of the results to the period under consideration and attempt to isolate features independent of the strong 1997/98 El Niño event, the similar combined EOF analysis was performed over the period 2000-2011 (Figure 7c). The results indicate that the EOF modes capture significantly distinct characteristics than the EOF modes obtained for the full period. The most visible change is that the modes tend to capture higher frequencies, which is also revealed through spectral analysis (not shown). The amplitude of the mode for each variable is also drastically changed compared to the analysis over the full period with in particular, for EOF_2,the amplitude for temperature (0.43) being increased along with the one of oxygen (0.61) (see Table 1). It suggests a distinct statistical relationship between variables over the period after 2000. Another noticeable change is in the relationship of the P and C time series El Niño indices and Kelvin wave coefficients. In particular, the EOF_2 is also correlated to IEKW_2, which was not the case for the analysis over the full period. Overall, the results of the EOF analysis suggest two different regimes of OMZ dynamics related to distinct physical equatorial forcing.

4. Discussion

The time series of oxygen and nutrients between 1996 and 2011 in the central area of Peru reveal a rich spectrum of variability in the position and intensity of the OMZ with timescales spanning the intraseasonal, seasonal (with in particular a marked semi-annual cycle) to interannual frequencies. Consistently with a previous study (Gutiérrez et al., 2008), such variability can be largely interpreted as resulting from the remote equatorial forcing owned to the efficient oceanic teleconnection off Peru.

Firstly, on a **seasonal** scale, the oxygen data exhibit a marked semi-annual pattern, similar to the seasonality of the 15C isotherm depth. The signature in the isotherm is consistent with the equatorial oceanic teleconnection considering that thermocline variability along the equator has a semi-annual cycle (Yu and McPhaden, 1999, Ramos et al., 2006). A shoaling of the oxycline and OMZ was observed during summer/fall (January-April) and early spring (October), up to < 50m, usually overlapped with the periods of the highest levels of chlorophyll-*a* and primary productivity rates in the area (Pennington et al., 2006, Echevin et al., 2008). Low nutrient values at sea surface are consistent with phytoplankton uptake, while low nitrate can dominate at subsurface because of the high nitrate reduction activity and nitrogen loss under more intense OMZ conditions (Graco et al., 2007, Echevin et al., 2008; 2014). During austral winter (July-August), under strong upwelling favorable winds, the opposite was observed with a deepening of the oxycline and the OMZ (> 40-50 m) and the increase of nutrients. This result is consistent with models that show a dual role of winds in winter: stronger winds favor upwelling and nutrient availability while increased high-frequency wind activity produced mixing and oxygenation in the water column (see Vergara et al., 2016). In addition, a decrease in primary productivity in this season determine a lower nutrient uptake and lower availability of organic matter and in consequence less oxygen consumption (Graco et al., 2007; Echevin et al., 2008).

Superimposed to the seasonal/semiannual variability stronger changes in the OMZ conditions and nutrients occur at interannual scales. The study period appears to cover two contrasting biogeochemical regimes. (1) one associated to the strong 1997 – 1998 El Niño and the subsequent La Niña events representing a marked ENSO cycle and (2) the period after 2000 characterized by episodic weak Warm and strong Cold Events with strong intraseasonal variability in the environmental forcing (i.e. equatorial Kelvin wave).

Under ***the strong El Niño*** **1997-1998 period**, the chemical time series (oxygen and nutrients) evidence the modulation of the biogeochemistry activity by remote forcing from the Equatorial Pacific. The water column is dominated by warm, oxygenated and nutrient- poor water masses, which resulted from the onshore intrusion of Subtropical Surface Waters (SSW) in the central area off Peru during El Niño events (Morón, 2000, Morón and Escudero, 1991); and it is associated to the geostrophic adjustment of the circulation in the form of downwelling coastal Kelvin and extra-tropical Rossby waves (Dewitte et al., 2012). It is shown that the Kelvin waves of both modes are in phase and correspond to marked downwelling conditions of comparable magnitude. The disappearance of the 15°C isotherm in the first 100 m took place in the early 1997 (around April) well ahead the El Niño peak phase (around November) associated to the impact of the downwelling Kelvin waves that were triggered in December and March 1997 in the western Pacific (Dewitte et al., 2003). These waves deepened the coastal thermocline, initiating the anomalous conditions prior to the development of El Niño (Ramos et al., 2008). The biogeochemical activity was clearly coupled to the physical forcing during this strong event. There was a significant deepening of the nutricline (> 80 m depth) associated to a thermocline deepening and the disappearance of oxygen deficient waters (< 45 μM). Our EOF analysis and the high correlation with the El Niño indices (ONI and E, Table 1) point to this interannual modulation. Similar conditions were reported for the 1982-1983 strong El Niño when a significant deepening of the thermocline, oxycline and nutricline, and a general increase in oxygen concentration in the subsurface layers were observed off Peru (Guillén et al 1989). These conditions appear unfavorable for the development of an important primary productivity, due to a lower nutrient availability in the surface layer. Low values of Ndef associated to low nitrate and almost zero nitrite concentrations suggest lower denitrification and/or anammox activity. The significant effect on denitrification in the eastern South Pacific Ocean due to changes in the equatorial winds during El Niño was previously described by Codispoti et al. (1988) as a large-scale response to EN. On the continental shelf off Callao, Graco et al (2008), showed the occurrence of interannual variability in denitrification and anammox rates, with a significant decrease in nitrogen loss processes under El Niño coupled also with a decrease in primary productivity and an increase in oxygen levels. Conversely, during the **cold phase of the ENSO cycle, 1999-2001 La Niña event**, there is a shoaling of the OMZ upper boundary and the nutricline (silicates and phosphate) coupled with a shallow thermocline and associated with IEKW_1 and 2 activities, in phase but dominated by negative anomalies. Codispoti et al., (1988) proposed a thermocline “overshoot” in the years following an El Niño event, and Guillén and Calienes (1981) suggest that cold anomalies can occur up to three years after an El Niño, as observed in this study. In fact, during 1999-2001 our results show a dominance of cold, oxygen deficient and nutrients rich upwelling waters off the central Peru. The co-occurrence of a shallow and intense OMZ (< 20 m depth) with low nitrate values (< 10 μmol L^{-1}), subsurface nitrite maximum (up to 9 μmol L^{-1}) and high Ndef point to an important biogeochemical activity during the cold periods or la Niña event not previously reported. These conditions suggest a high organic matter remineralization coupled to an intense oxygen demand and denitrification/anammox processes in the area. High nitrite pools in the water column were described as a typical feature under oxygen deficient waters (Deuser et al., 1978; Naqvi, 1991) and a tracer of denitrification (Codispoti and Packard, 1980; Codispoti et al., 1985; 1986; 2001) and anammox activity (Hammersley et al., 2007; Lam et al., 2009; Lam and Kuypers, 2011) off Peru. Similar results were observed in other upwelling ecosystems (Calvert and Price, 1971, Morales et al., 1996; Naqvi et al., 1994) and in the Eastern tropical South Pacific (Codispoti and Christensen, 1985; Tyrrell and Lucas, 2002).

After 2000, the oceanographic conditions responded to ***"episodic weak Warm and strong Cold Events"*** and were characterized by an apparent decoupling between the physics (thermocline) and the OMZ, suggesting a non-linear relationship between the OMZ dynamics and the remote equatorial forcing over this period. Our results suggest that the biogeochemical variables appear modulated by an intense seasonal variability to which is superimposed higher frequency variability associated to upwelling (downwelling) IEKW activity coincident with a the higher frequency of occurrence of Central Pacific El Niño events for the last decade (2002-2004, 2006, 2008/2009; Yu and Kim, 2013). A less intense OMZ (oxygen > 10 μmol L^{-1}), higher nitrate levels (> 20 μmol L^{-1}), almost zero nitrite values and low Ndef at the subsurface waters appear under these intermittent "warm periods" characterized by downwelling IEKW activity, like in 2002, 2006, and 2008. The low Ndef and high nitrate concentrations suggest a low nitrogen loss in the area under these conditions. On the contrary, episodic “cold events”, as in 2005, 2007 and 2010-2011, are associated with negative anomalies of the IEKW (upwelling), a well-developed OMZ and an intense nitrogen recycling as suggested by the high Ndef values. While the length of the data set is a limitation (only 12 years of data after 2000), the analysis suggests a long-term trend in oxygen concentration near the oxycline (decreasing trend) that is consistent with an increasing trend in the amplitude of the upwelling events associated to the second baroclinic mode Kelvin wave (IEKW_2). In particular, after 2000, the IEKW_2 is negatively skewed (-0.8910 cm) and upwelling events show a negative tendency (-0.0177 cm/decade). Note that the IEKW_2 is more likely to be influential on the coastal circulation than the first baroclinic mode Kelvin wave due to its vertical structure having two nodes on the vertical, which is similar to the dominant empirical modes along the coast in this region (see Echevin et al. (2014)). Similar desoxigenation trends in the last decades have been recently reported for other coastal upwelling systems (California Current, *Bograd et al.,* 2008; Benguela Current, Monteiro pers. com.) and they could trigger changes in phytoplankton size and/or community structure, as was observed in California Current (Chavez pers.com.).

We now discuss limitations of our analysis. While our results suggest that the OMZ variability off Callao can be understood in terms of the oceanic equatorial teleconnection, our interpretation of the OMZ variability does not consider aspects of the wind forcing, although the latter is highly variable in the central Peru region and is influential on the upwelling dynamics. While during El Niño events, there is in general a weakening of the upwelling favorable winds at regional scale owned to the relaxation of the South Eastern branch of the trade winds, near the coast winds can intensified locally owned to the effect of the underlying warm waters (Dewitte and Takahashi, 2016, submitted). To which extent such anomalous winds influence the local oceanic circulation and associated biogeochemical response remains to be investigated. Considering the limited knowledge on this aspect, we have not introduced the analysis of the local wind forcing at interannual timescale here. Regarding intraseasonal wind variability, Dewitte et al. (2011) reports two regimes of along-shore wind variability off Callao. One regime associated to extra-tropical storms activity modulating the South Pacific Anticyclone and corresponding to frequencies ranging to 1 to 25 days, and a second regime with frequencies ranging from 30 to 90 days that is associated to atmospheric teleconnections from the western tropical Pacific. Illig et al. (2014) evaluate the influence of these two wind regimes on the oceanic teleconnection at intraseasonal timescales based on the experimentation with a regional oceanic model and found that they are weakly influential on the propagation of the Kelvin wave of equatorial origin. Therefore, the limitation of not including the winds in our analysis may not be detrimental to our results. Note also that Gutiérrez et al. (2008), estimated that 43% of the temporal variability in the oxygen regime over the continental shelf off Callao is explain by the remote forcing. Echevin et al. (2014) also show evidence that subsurface nutrient and chlorophyll intraseasonal variability are mainly forced by the coastally trapped waves triggered by intraseasonal equatorial Kelvin waves reaching the South-American coast. In the central and southern part of Peru, that include our study area (Callao 12° 02´S), IEKW-forced CTW signature on the circulation and aspects of the biogeochemistry thus emerges as dominant process over the local wind impact at the timescales of interest in this paper (i.e. periods > 1 month).

In addition, while the global trend in the open ocean appear to be an expansion of the oxygen, deficient waters, particularly in the tropical oceans during the past 50 years (Stramma et al., 2008; 2010), our results suggest a long-term deepening of the oxygen deficient waters from 2000 (-0.12 m/decades). In fact, in the coastal areas many questions remain open related with short-term temporal variability and the onshore-offshore physical and biogeochemical coupling dynamics that regulate in a complex interplay the intensity and distribution of the OMZ and can determine different biogeochemical scenarios with a potential impact for the coastal human communities (Gutiérrez et al., 2011b). The data presented in this paper could therefore serve as a useful benchmark for testing paradigms for explaining OMZ variability under different mean state conditions, changes in nutrients condition that can modulate the phytoplankton response and productivity, as well as for the validation of regional coupled modeling platforms intended to address low-frequency variability of the OMZ in the Eastern Pacific.

To conclude, the study period appears to illustrate distinct regimes of 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 and a higher frequency variability of upwelling (downwelling) IEKW activity.

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Table 1:
Percentage of explained variance of the EOF modes (first line) and eigenvectors of the EOF modes (i.e. amplitude of the EOF mode in terms of the different variables).

	EOF1	EOF2	EOF1_2000-2011	EOF2_2000-2011
Percentage of explained variance	48 %	24%	45%	28%
Temperature	-0.58	0.17	-0.33	0.43
Salinity	-0.46	0.09	-0.36	0.11
Oxygen	-0.48	0.27	-0.37	0.61
Nitrate	-0.01	-0.86	-0.59	-0.64
Nitrite	0.46	0.39	0.51	0.06

Table 2 : Coefficient correlation Pearson at 95% confidence interval between the first two PC timeseries and the Kelvin wave and El Niño indices.

	EOF1	EOF2	EOF1_2000/2011	EOF2_2000-2011
IEKW_1	-0.34	N.S.	N.S .	N.S.
IEKW_2	-0.60	N.S.	-0.37	0.40
ONI	-0.65	N.S.	-0.57	N.S.
E	-0.73	N.S.	N.S.	0.37
C	-0.28	-0.35	-0.49	N.S .

Figure Legends

Figure 1. Location of the sampling station (St 4; 20 nm, 145 m depth) in the coastal upwelling ecosystem off central Peru, Callao (12º 02´ S).

Figure 2. Time series of temperature (°C) (a), salinity (b) and dissolved oxygen (µmol kg^{-1}) (c) during the 1996-2011 study years.

Figure 3. Time series of the depth of the 15º C isotherm, oxycline (45.0 µmol kg^{-1}) and the OMZ upper boundary (22.5 µmol kg^{-1}) (a) and the seasonal pattern of the 15° C isotherm depth (b), the oxycline depth (45.0 µmol kg^{-1}) (c) and the upper boundary of the OMZ depth (22.5 µmol kg^{-1}) (d) during 1996-2011 time series.

Figure 4. Time series of nitrate (a), nitrite (b), silicate (c) and phosphate (d) during 1996-2011. Contours in solid and dashed lines indicate the 22.5 µmol kg^{-1} and 45 µmol kg^{-1} oxy-lines, respectively. Units are µM L^{-1}.

Figure 5. Time series of N deficit (µmol L^{-1}) at St. 4 off Callao during 1996-2011.

Figure 6. Evolution of the (a) Intraseasonal Equatorial Kelvin Waves (IEKW) anomalies at 90°W for the first (IEKW_1) and second (IEKW_2) baroclinic modes. Units are cm (equivalent sea level). The standard deviation is indicated by the horizontal dashed lines. Time resolution of the data is every 5 days, (b) depth of the thermocline; (c) OMZ's upper boundary depth and

(d) Fixed Nitrogen deficit (Ndef) at 50 m (e) at St. 4 off Callao during 1996-2011. On the right hand side of each timeseries, the global spectrum wavelet analysis are shown (f-j).

Figure 7. Temporal series of (a) the C and E indices (b) the principal component of the first two dominant EOF modes of the temperature, salinity, oxygen, nutrient and nitrite combined timeseries over the period 1996-2011(c) same as (b) but for the period 2000-2011. Timeseries were normalized by their standard deviation prior to analysis.

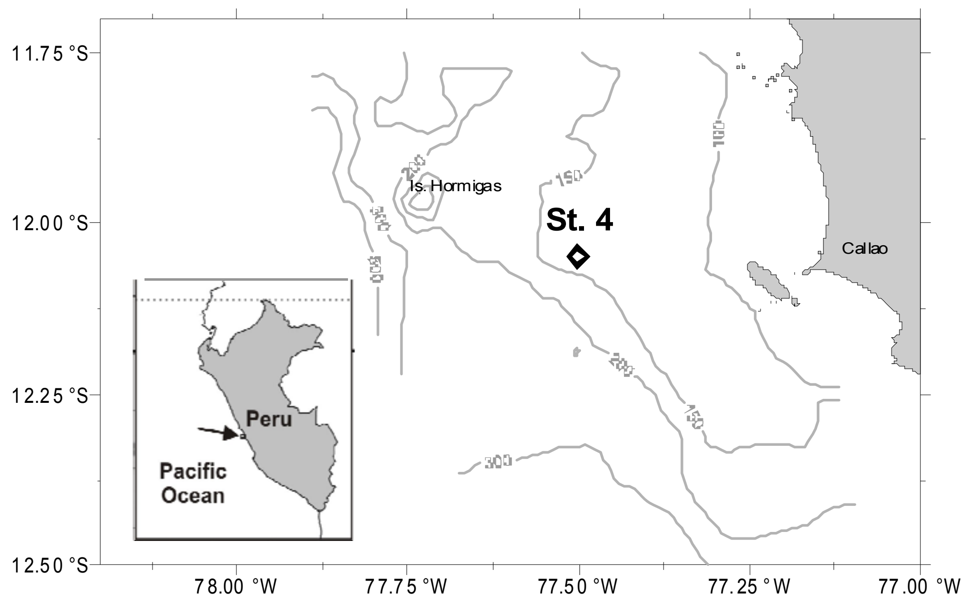

11.75 °S
12.00 °S
12.25 °S
12.50 °S
78.00 °W
77.75 °W
77.50 °W
77.25 °W
77.00 °W
Is. Hormigas
St. 4
Callao
150
100
200
300
Peru
Pacific
Ocean

Figure 1.

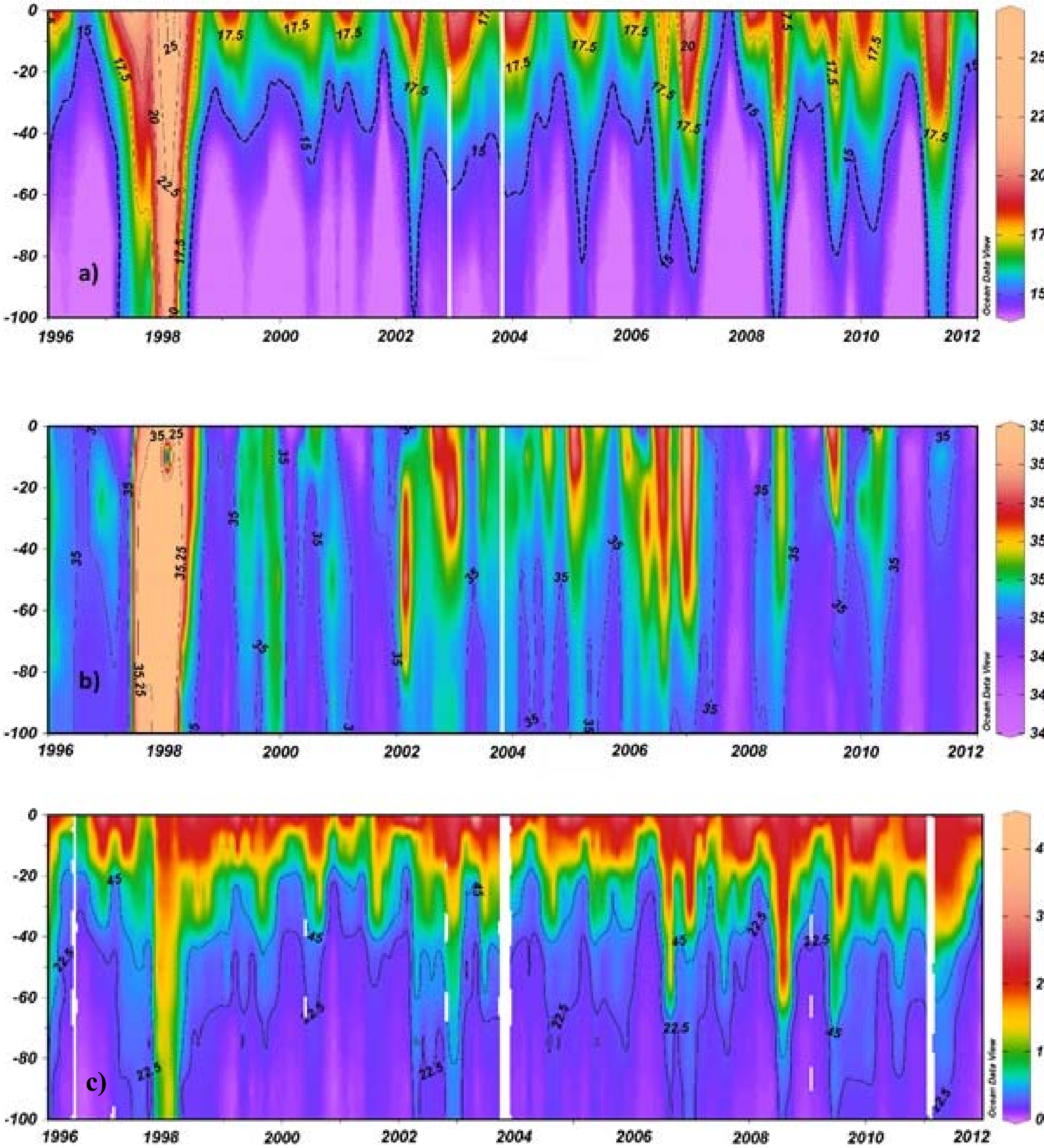
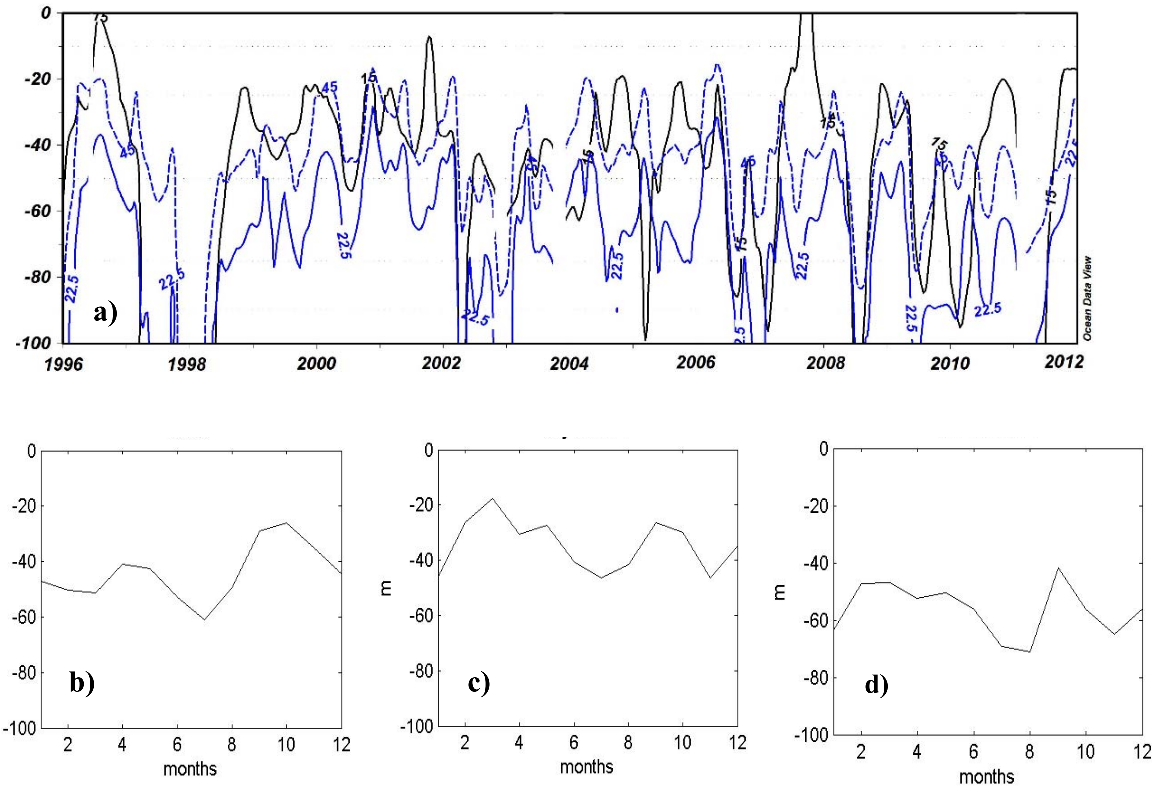

a)
b)
c)
0
-20
-40
-60
-80
-100
1996
1998
2000
2002
2004
2006
2008
2010
2012
25
22.5
20
17.5
15
35.25
35.2
35.15
35.1
35.05
35
34.95
34.9
34.85
400
300
200
100
0
Ocean Data View

Figure 2.



a)
b)
c)
d)
1996
1998
2000
2002
2004
2006
2008
2010
2012
months
m
Ocean Data View

Figure 3.

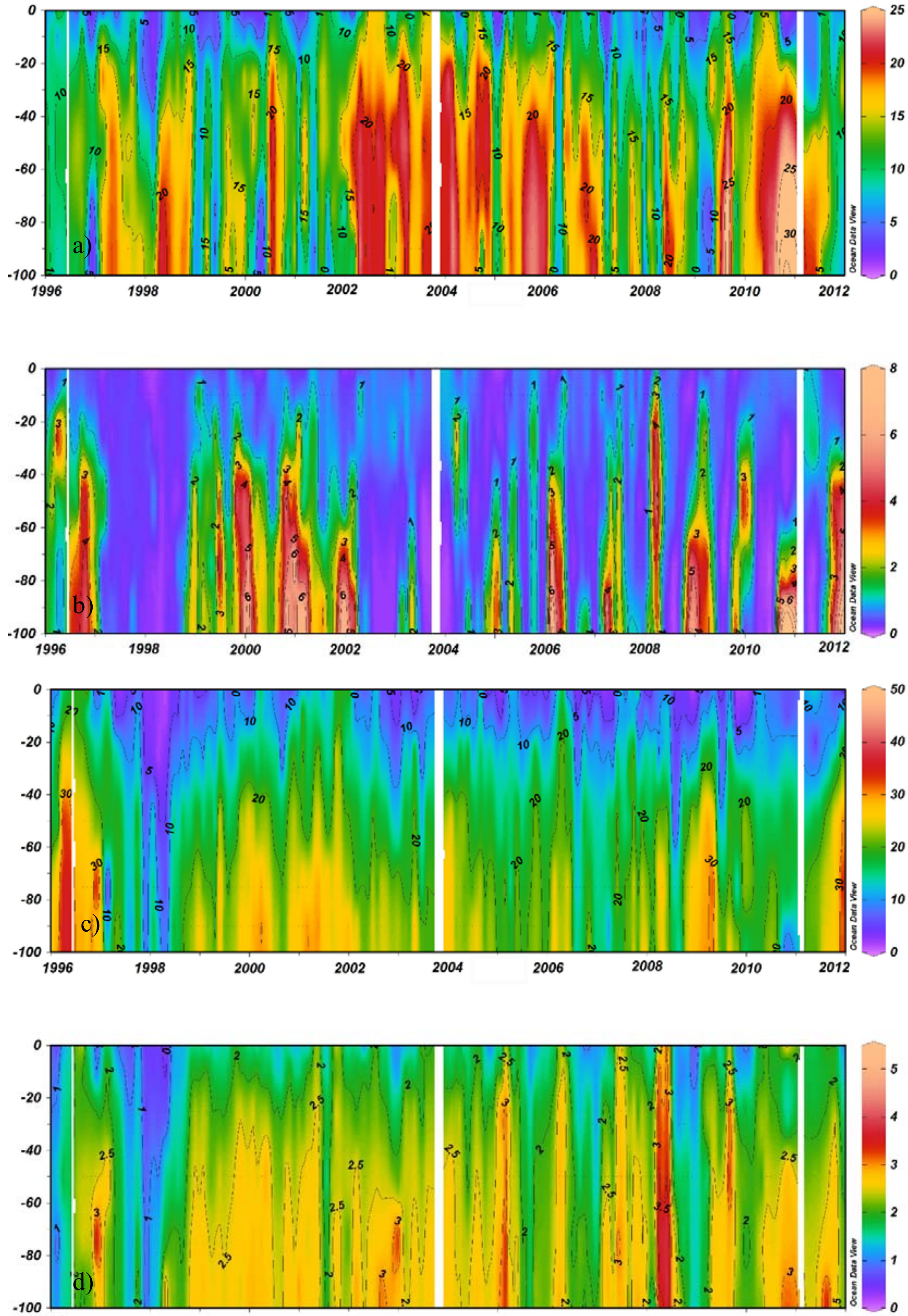

a)
b)
c)
d)
0
-20
-40
-60
-80
-100
1996
1998
2000
2002
2004
2006
2008
2010
2012
25
20
15
10
5
0
8
6
4
2
50
40
30
3
1
Ocean Data View

Figure 4.

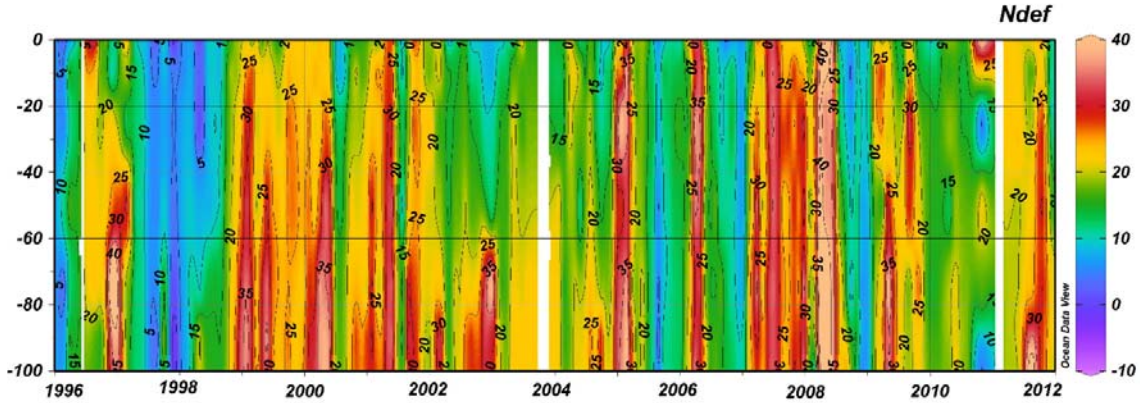


Figure 5.

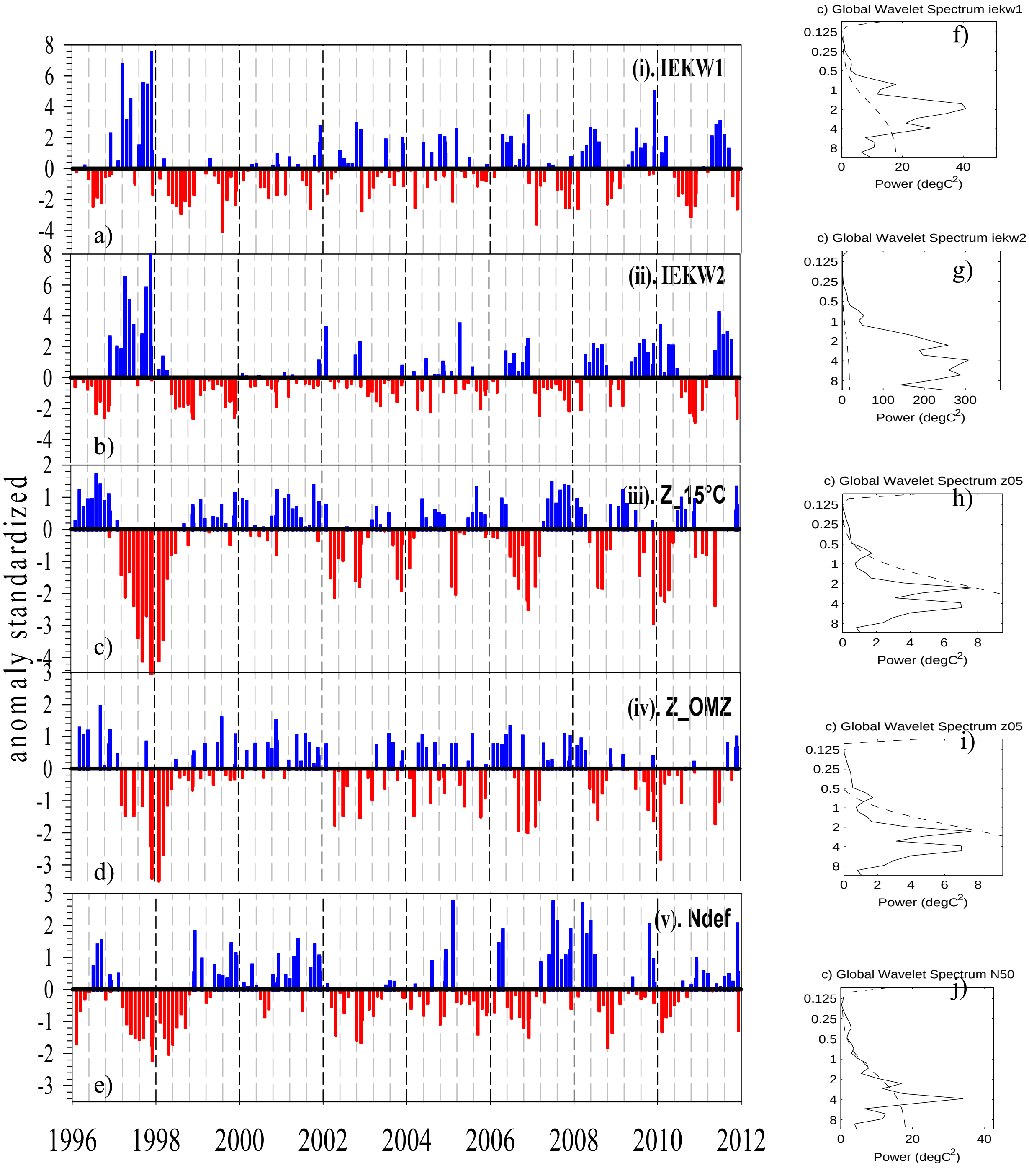

anomaly standardized
(i). IEKW1
a)
(ii). IEKW2
b)
(iii). Z_15°C
c)
(iv). Z_OMZ
d)
(v). Ndef
e)
1996
1998
2000
2002
2004
2006
2008
2010
2012
c) Global Wavelet Spectrum iekw1
f)
c) Global Wavelet Spectrum iekw2
g)
c) Global Wavelet Spectrum z05
h)
c) Global Wavelet Spectrum z05
i)
c) Global Wavelet Spectrum N50
j)
Power (degC2)

Figure 6.

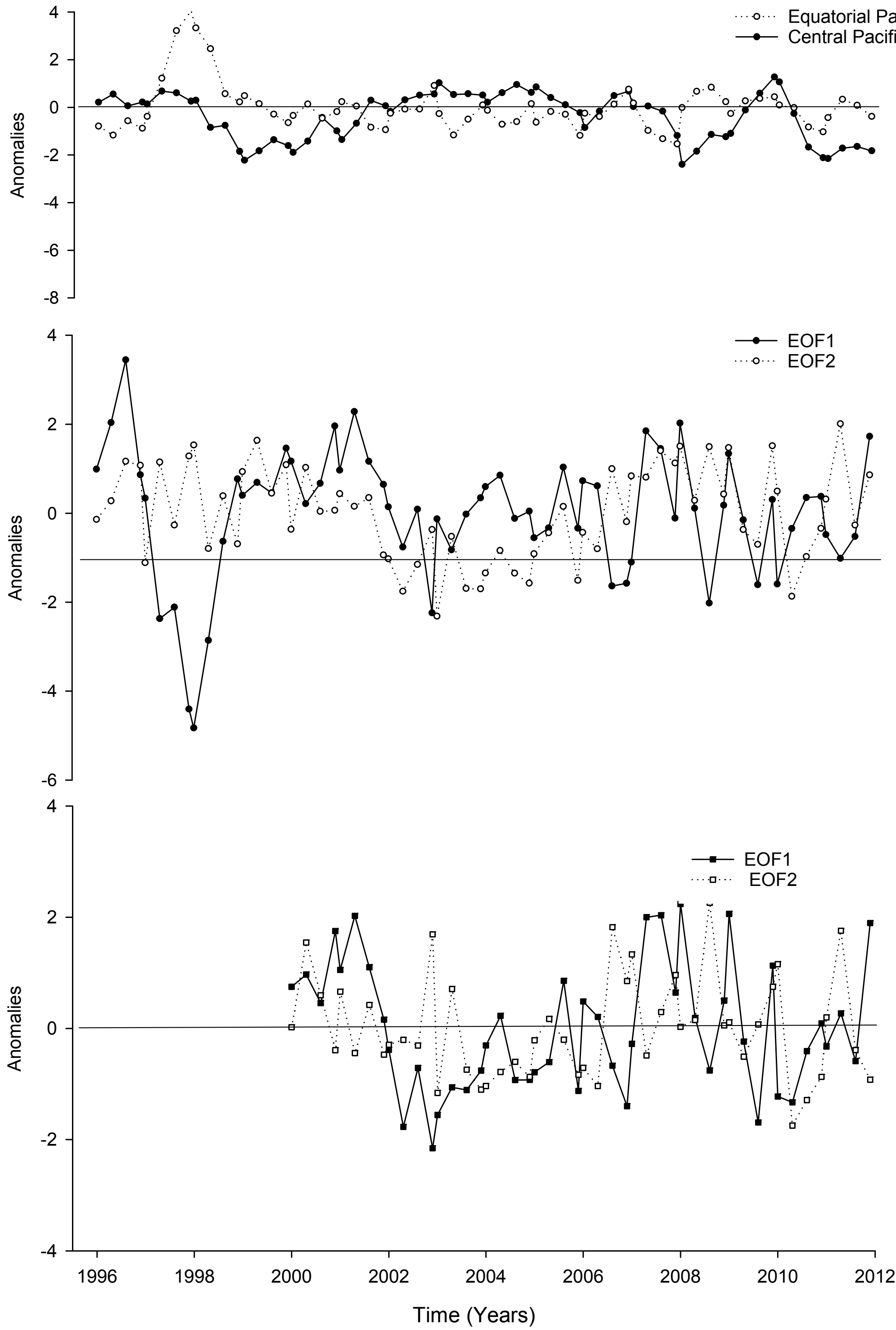

Equatorial Pacific (E)
Central Pacific (C)
Anomalies
EOF1
EOF2
Anomalies
EOF1
EOF2
Anomalies
4
2
0
-2
-4
-6
-8
4
2
0
-2
-4
-6
4
2
0
-2
-4
1996
1998
2000
2002
2004
2006
2008
2010
2012
Time (Years)

Figure 7.