

Here replies to reviewer 1 and 2, the modified manuscript and the supplement with the changes marked

Reply to reviewer 1

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Observed El Niño conditions in the eastern tropical Pacific in October 2015

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Michael McPhaden (NOAA) had a look at the original OSD manuscript and mentioned that the title is confusing. Therefore we modified the title as written above. He also proposed to give a brief opening paragraph about why it is important to study El Niño and as both reviewers especially reviewer 2 proposed to modify the introduction we introduced now an opening paragraph.

Reviewer #1:

Review of the paper "Transition to El Niño conditions in the eastern tropical Pacific in October 2015" by Stramma et al.

This paper documents the changes in water masses and circulation patterns in the equatorial and eastern south pacific from an oceanographic cruise which took place in october 2015 during El Niño (EN). Profiles and sections for temperature, salinity, oxygen, nutrients and ADCP current measurements are compared with those from previous cruises under different neutral, EN-like and La Niña-like conditions. The results

show that the eastern flow associated to the EUC along the equator has greatly diminished in October 2015, and that temperature and oxygen have increased, while salinity has decreased. Near the Peru shore, cross-shore sections along the northern coast (9_ and 12_S) display typical EN conditions with the upwelling of warmer, more oxygenated waters, while the EN patterns are not evidenced at lower latitudes (14_ and 16_S).

General comment: Documenting EN conditions in this region of the Pacific is important particularly as there are not many measurements published in the literature during previous events. I found the paper well written and interesting to read. Most of my comments are minor.

Answer to reviewer 1:

We thank both reviewers for the helpful comments, which helped to improve the manuscript during the revision. We modified the manuscript as explained below in the detailed comments.

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Reviewer #1:

Minor comments: Abstract: L23: transition to EN conditions west of the coastal sections is not well documented in the paper. Figures are not shown and it should be discussed how EN can be present offshore and not nearshore. What is the local process that could compensate the nearshore warming? Wind-driven upwelling? This should be investigated and discussed in more detail.

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Answer to reviewer 1:

From our data we can't decode the processes responsible for the transition to EN west of the coastal stations. A possible explanation is the upwelling of left-over water from the pre El Niño period at the coastal station and the influence of the Peru Coastal Undercurrent which intensifies and shoals during El Niño at the stations west of the shelf station. Another explanation is that the observed transitional

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feature of normal conditions near-shore and El Niño conditions offshore is probably a consequence of the cross-shore pattern in vertical velocity during upwelling. The near-shore vertical velocity is to be expected substantially larger than the offshore vertical velocity (Fennel, 1999). A downwelling Kelvin wave could then neutralize the weak offshore upwelling and bring down the thermocline, while near-shore the strong upwelling would hardly weaken and for some time still bring up remnants of cold oxygen-poor water, until supplies feed from the offshore warmer and oxygen replete waters. The wind field would not need to change in order to produce this transition pattern in hydrography. These explanations are now described in the revised manuscript and the former Figure S7 is now included in the main text as Figure 11.

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Reviewer #1:

Introduction: P2L7: The denomination of Central EN or Modoki has been found in the literature previously to the publication of Dewitte et al., which is mainly a model study focused on the Peru region. I also think that other references (L10) should be cited to document the impact of EN off Chile (Ulloa et al., 2001 is an example but there must others more recent)

Answer to reviewer 1:

Reviewer 2 questioned to discuss the Modoki EN, as it is not investigated in our data set, nevertheless we like to mention its existence, but did not expand it to a longer discussion, we just added a reference to a Nature overview paper (Ashok and Yamagata, 2009). We added the proposed Ulloa et al. paper 2001 as an example for the influence of El Niño also on the Chilean region, however as the introduction should be shortened and we don't investigate the region off Chile and we did not expand this discussion further.

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Reviewer #1:

P2L19: "climate modelling evidence": I would rather ponder this statement and

write that climate models suggest that a doubling in the occurrence..

Answer to reviewer 1:

Text was rewritten as proposed using 'suggest' instead of 'evidence'.

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Reviewer #1:

P3L20: 'nas a result of circulation changes' This is really vague. Could you be more specific?

10 Answer to reviewer 1:

This text on circulation changes was a first information on El Nino related changes for the reference to Helly and Levin 2004. As the processes involved are described in more detail in the manuscript, 'as a result of circulation changes' was removed here.

15 Reviewer #1:

P6L19: 'The equatorial spreading of the thermocline' This spreading of the thermocline is unclear to me. Is it zonal, meridional? Could you rephrase?

Answer to reviewer 1:

20 This is meridional spreading and now 'meridional' is included and the reference to Johnson et al. 2002 was included.

Reviewer #1:

25 P6L25: 'n..intensifies from 16 to 15..' is such a decrease of the mean oxygen concentration robust? This 1 micromole difference seems very small.

Answer to reviewer 1:

Right, this change in oxygen of the ODZ core listed by Paulmier and Ruiz.Pino is removed from the text.

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Reviewer #1:

P7L10: The sentence is clumsy. I also do not understand the concluding sentence of the paragraph. Why should higher salinities be expected in the pycnocline during EN?

10 Answer to reviewer 1:

This part was rewritten, removing the information on the late El Nino phase, which is not investigated in our manuscript. Instead the reason for the higher salinity in the pycnocline due to northward progression of the salinity maximum of the South Pacific Tropical Water under the modified current bands during El Nino is explained.

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Reviewer #1:

P8L6: What about local increase of precipitation and/or poleward displacement of the equatorial front (associated with the ITCZ) which separates fresh waters off Ecuador from more saline waters off Peru?

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Answer to reviewer 1:

Right, the higher precipitation will be the major contribution and is now mentioned before the equatorial upwelling. Some literature shows a very minor shift of the ITCZ in this region (e.g. Chen and Lin 2005, Monthly Weather Review), hence we did not mention it here.

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Reviewer #1:

P8L21: higher PNM during EN. I understand the deepening of the peak due to the deeper pycnocline but not the more intense PNM. How can it be explained? could this be due to an increase in denitrification?

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Answer to reviewer 1:

The higher nitrite concentrations in the PNM during EN are most probably resulting from (i) high nitrite conc. in the PNM of the SPTW which have been transported towards the equator and (ii) higher ammonium oxidation rates due to a reduced photo inhibition at deeper water depths during EN.

10 Denitrification only occurs at suboxic/anoxic conditions. Therefore, the occurrence of denitrification is very unlikely because of the relatively high ambient O₂ concentrations. We modified the text accordingly.

Reviewer #1:

15 P9L6: A citation of EN years considered in Czeschel et al. 2012 would be useful here.

Answer to reviewer 1:

The measurements are from the El Nino years 1982/83 and this information is now mentioned in the text.

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Reviewer #1:

P9L16: I would rather say an 'nocean model' than a climate model which refers more often to ocean-atmosphere coupled models.

25 Answer to reviewer 1:

In the title of the Cravatte et al. paper it is called 'climate model' and in the abstract it is named 'climate-type OGCM', but nevertheless we changed it to 'ocean model' to avoid misunderstanding.

Reviewer #1:

5 P10L2: 'nin Nov 1982' is repeated twice in the sentences

Answer to reviewer 1:

The first reference to November 1982 in this sentence was removed.

10 Reviewer #1:

P10L11: in Fig 6, could you add 'positive eastward' for zonal velocities?

Answer to reviewer 1:

15 We added the velocity flow direction of both components as well as the date of measurements to the figure caption.

Reviewer #1:

20 P11L18: 'November minimum at 95_W'. A reference is missing here and I do not see how this statement on the EUC at 95_W backs up the fact that it should be a reasonable estimate of the EUC in neutral EN conditions.

Answer to reviewer 1:

This transport refers to a reference by Johnson et al. 2002, which was listed earlier in the manuscript. This reference is now included also here.

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Reviewer #1:

P12L5: the reference to Gutierrez et al. is misplaced. This sentence should be moved to L1 where SST are described. I am not sure Sydemann et al is really relevant here.

5 Answer to reviewer 1:

The sentence was moved to the beginning of the paragraph where the SST is described as proposed. The reference to Sydemann was removed.

Reviewer #1:

10 P12L16: I do not have a problem with citing Strub et al which is a review, but other papers should be cited as well (Halpern et al. 2001 , Enfield, 1981; Huyer et al., 1987)

Answer to reviewer 1:

For this text part Halpern 2002, Enfield 1981 and Huyer et al., 1987 were included.

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Reviewer #1:

P12L20: Here same remark as before, I think that Strub et al 1998 can be cited but other papers as well (which are cited by Strub in his review).

20 Answer to reviewer 1:

Again, for this text part Halpern 2002, Enfield 1981 and Huyer et al., 1987 were included.

Reviewer #1:

P12L26: 'nReduction of the ODZ area'z: I do not understand how this area is computed.

25 It seems more a vertical displacement of the OMZ than a reduction of its area.

Could you clarify?

Answer to reviewer 1:

5 The ODZ was defined for dissolved oxygen < 0.5 ml/l and the area considered 6° - 20° S. According to the paper by Helly and Levin (2004) there could be a vertical displacement with a depression by 100 m and the area could be reduced from 77,000 to 30,000 km². This information is now added.

Reviewer #1:

10 P13-16: I think there are too many figures in the supplementary here. Please reduce them and add some of them to the paper section, as it is very difficult to follow without looking at the figures in the supplementary.

Answer to reviewer 1:

15 We moved the supplementary figures S1 and S7 to the main text as they are important to understand the observations. The other supplementary figures are of interest for readers with specific detailed interest and we left them in the supplement.

Reviewer #1:

20 P14L3: could the lower nutrient concentrations in october 2015 be due to the seasonal variations of the nutricline?

Answer to reviewer 1:

25 We do not see any evidence to attribute this decrease in nutrient concentrations to normal seasonal variations. For example, the recent discussion paper by Graco et al. (<http://www.biogeosciences-discuss.net/bg-2015-567/bg-2015-567.pdf>) shows a nutrient concentration time series from 1996 to

2010. The differences between October and December are small for most of the years presented and for all nutrients measurements. Unfortunately, the time series presented does not include either year presented in our manuscript, but we conclude that there is no distinct pattern between October and December since 1996.

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Reviewer #1:

P14L14: I would conclude this sentence by saying explicitly that this process may produce more nitrate. I think that is important as one may think that all nutrient pools (phosphate, silicate AND nitrate) decrease during EN, which is not always the case

10 from your observations.

Answer to reviewer 1:

We have now wrapped up the sentence by clearly pointing out that complete nitrification will result in more nitrate.

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Reviewer #1:

P14L24: You suggest that diatom biomass may increase during EN due to the N:P increase. However both nitrate and phosphate concentration reduce strongly during EN, which should impact negatively phytoplankton growth more than the N:P increase.

20 Previous studies have shown that the surface chlorophyll observed from satellite decreases during EN (Carr et al. 2002) and the ecosystem suffers dramatic changes during extreme EN (Barber and Chavez, 1983, Chavez et al. 2003).

Answer to reviewer 1:

25 In this section we were comparing data from 2012 with data from 2015 (now Fig. 11). While the reviewer is correct that a reduction in both nitrate and phosphate could negatively impact phytoplankton growth even if the N:P ratio was higher, we did not see a decrease in nitrate during our October 2015

cruise. Instead, we found that both nitrate and N:P was higher, which, as we suggest, could increase phytoplankton biomass.

Reviewer #1:

- 5 P15L7: At 12_S, higher nitrate... how can higher nitrate indicate a developing EN?
This sounds contradictory.

Answer to reviewer 1:

- As previously outlined, higher oxygen concentrations during El Nino would result in less denitrification
10 and more complete nitrification, which in turn would result in more nitrate. We have now added text to
the end of this section to make this more clear.

Reviewer #1:

- P16L14: I think you should also mention the strong intraseasonal signals in the equatorial
15 pacific in neutral periods, with the passage of upwelling and downwelling waves
at intraseasonal time scales (Cravatte et al., 2003; Echevin et al. 2013). during a
cruise, if sampling is performed during the passage of a downwelling wave in a neutral
EN period, this might have some similarity with EN conditions.

- 20 Answer to reviewer 1:

The influence of intraseasonal signals is now mentioned and the references Cravatte et al. 2003 and
Echevin et al. 2014 are included.

Reviewer #1:

- 25 P17L15: I do not understand the sentence. Please rephrase.

Answer to reviewer 1:

This sentence was rewritten separating the equatorial observations and the observations off the South American continent.

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Reviewer #1:

P17L18: Measurements are carried out by CNRS, IRD and IMARPE . IFREMER is the owner of the glider, which is part of the french national glider pool.

Here is a link with more precise information (in french): [https://www.ird.fr/toutel-](https://www.ird.fr/toutel-actualite/actualites/communiqués-et-dossiers-de-presse/cp-2015/lancement-de-cienperu-projet-cienperu-projet-d-etude-des-impacts-d-el-nino-2015-2016-sur-l-ecosysteme-marindu-perou)

10 [actualite/actualites/communiqués-et-dossiers-de-presse/cp-2015/lancement-de-](https://www.ird.fr/toutel-actualite/actualites/communiqués-et-dossiers-de-presse/cp-2015/lancement-de-cienperu-projet-cienperu-projet-d-etude-des-impacts-d-el-nino-2015-2016-sur-l-ecosysteme-marindu-perou)

[cienperu-projet cienperu-projet-d-etude-des-impacts-d-el-nino-2015-2016-sur-l-ecosysteme-marindu-perou](https://www.ird.fr/toutel-actualite/actualites/communiqués-et-dossiers-de-presse/cp-2015/lancement-de-cienperu-projet-cienperu-projet-d-etude-des-impacts-d-el-nino-2015-2016-sur-l-ecosysteme-marindu-perou)

Answer to reviewer 1:

15 The text was modified according to your information on the groups carrying out the measurements and the web-link was replaced.

Reply to reviewer 2:

Observed El Niño conditions in the eastern tropical Pacific in October 2015

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Michael McPhaden (NOAA) had a look at the original OSD manuscript and mentioned that the title is confusing. Therefore we modified the title as written above. He also proposed to give a brief opening paragraph about why it is important to study El Nino and as both reviewers especially reviewer 2
5 proposed to modify the introduction we introduced now an opening paragraph.

Reviewer #2:

The authors report on changes observed during the strong Eastern Pacific 'El Niño' event developed in early 2015, and compare this event to previous similar events, neutral,
10 and one 'La Niña-like' event. As expected from models and previous observations, the SSTs increase in the eastern equatorial Pacific, the surface salinity drops, the EUC and other equatorial currents weaken, and the thermocline deepens. As a consequence, the concentration of nutrients decreases, the concentration of oxygen increases, and the OMZ shifts deeper. The effects of 'el Niño' do not spread all the
15 way to the southern station by October 2015, off the coast in Peru. I think that the paper is interesting and worth publishing, but I think that it would vastly improve if the writing is improved in some sections. There are several awkward sentences, and it is difficult to follow the flow of the paper if not an expert on the topic (especially the Introduction). I have minor comments mostly referred to organization and flow.

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Answer to reviewer 2:

We thank both reviewers for the helpful comments, which helped to improve the manuscript during the revision. We modified the manuscript as explained below in the detailed comments.

25 Reviewer #2:

The abstract and the Conclusions contain almost exactly the same information. I would suggest reducing the abstract substantially (it is too long), and keeping the Conclusions section as it is.

30 Answer to reviewer 2:

The abstract was shortened and the conclusion extended by shifting the end of page 15 to the conclusions as you proposed.

Reviewer #2:

5 The Introduction is disorganized and difficult to follow. For example, changes due to climate change are discussed in Page2L5 and again in Page2L19. These should be discussed together. And before, the two types of el Nino should be explained. It makes it difficult to follow for non-experts. The description of indices in Page2L11 could go into Section 2 that could be called Datasets and Methods (or similar). If indices are discussed in the Intro, maybe not in the first paragraph.

10 Answer to reviewer 2:

The order of the presented background information in the introduction was rearranged and the paragraph on the indices moved to the methods and called now as proposed ‘Data sets and methods’.

Reviewer #2:

15 I think that it is a good idea to move some of the Intro material into the mini-introductions in Section 4 and 5 (as it is), but the authors should avoid repetition with elements already described in the more general Introduction (Section 1). I suggest reducing the general Intro to avoid repetition, or put it all in the general Introduction (in which case you could include all the Seasonality changes together), or : : : (but avoiding the repetition of material).
20

Answer to reviewer 2:

We shortened the detailed information in the introduction and presented the detailed information in the later paragraphs.

25

Reviewer #2:

30 Supplementary Fig. 1 should be a main Figure as it is crucial to understand the whole picture (maybe together with current Fig. 1?).

Answer to reviewer 2:

We moved the Supplementary Fig. S1 to the main text as Figure 2 and renamed the other figures accordingly. The region of this new figure 2 for the eastern Pacific is too small to integrate Figure 1 in a Pacific-wide figure to see the details of the different data sets used.

5 Reviewer #2:

Could you somehow combine Fig. 3 and 4? (perhaps with irregular axis, with larger resolution from 0 to 100m).

Answer to reviewer 2:

10 As there are large differences of the scales of oxygen, temperature, salinity and density in the upper 100 m and 100 to 400 m, a combination of both figures would lead to strongly reduced visibility of the changes related to the different El Nino phases. Hence we prefer to keep the two figures separated.

Reviewer #2:

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Fig. 6 (add to the caption the date: : October 2015, so that it's easier to follow without going back to text or Fig. 1)

Answer to reviewer 2:

20 We added the date of measurements as well as the velocity flow direction to the figure caption.

Reviewer #2:

Specific Comments:

Page1L11 "At the equator: : October 2015" awkward phrasing

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Answer to reviewer 2:

This sentence was reorganized for better readability.

Reviewer #2:

Page1L21 to L26 rephrase

Answer to reviewer 2:

- 5 The shortening of the abstract as you proposed also led to a rephrasing of the former lines 21 to 26 on page 1.

Reviewer #2:

- 10 Page2L4-5 rephrase Page2L5 “In contrast : : .” rephrase as for example ‘There has been evidence..., different from the common cold tongue, Eastern Pacific El Nino events: : : ‘ This sentence should come after describing the two types of El Nino. Why is it relevant to talk about the Modoki type if none of the described events fall into this category? (or maybe I missed something). If it is significant, comment on it in the Conclusions?

15

Answer to reviewer 2:

- The sentence was rephrased and shifted behind the general description of the ‘regular’ El Niño as proposed. As the Modoki El Niño is now often mentioned we like to introduce it briefly for readers not familiar with this difference although we do not investigate it in our manuscript. As reviewer 1
20 proposed to describe the Modoki El Niño with more references, we added a reference to an overview paper in Nature, but we did not expand the discussion further.

Reviewer #2:

- 25 Page3L5 avoid repetition of EUC description with text later on the draft.

Answer to reviewer 2:

The information on the EUC was shortened in the introduction and the detailed information was shifted to the later paragraphs.

Reviewer #2:

5 Page3L18-25 “Oxygen increases as a result of circulation changes + explanation” This paragraph talking about oxygen needs more coherence and flow. The explanation about local winds is confusing and needs to be better linked with the following sentence (deeper thermocline) as it is counterintuitive. More upwelling but deeper thermocline? Etc: : :

Answer to reviewer 2:

10 The information is added that the upwelling favorable winds could not produce the observed warming, but that warming is related to the downwelling Kelvin waves.

Reviewer #2:

15 Are all the changes in oxygen due to circulation or are any of these due to reduced primary production (L26)?

Answer to reviewer 2:

The additional influence of reduced primary production is now mentioned and a reference to Gutierrez et al. 2008 was added.

20 Reviewer #2:

Page5L26 rephrase the sentence starting with ‘ Different: : : ‘ (suggestion: The SST distribution in fall 2015 shows a strong and prominent SST increase along Central America and in : : : that differs from the typical EP el Nino distribution.)

25 Answer to reviewer 2:

The sentence was rephrased as proposed.

Reviewer #2:

30 Page6L18 “The equatorial spreading of the thermocline: : : “ rephrase and also explain what spreading of thermocline means.

Answer to reviewer 2:

The sentence was from the original Johnson et al. 2002 paper. Now we included the information that the meridional spreading of the thermocline is related to the zonal EUC velocity strength.

5 Reviewer #2:

Page 7L8-11 rephrase paragraph? Not clear why salinity higher during EN events.

Answer to reviewer 2:

10 This part was rewritten, removing the information on the late El Niño phase, which is not investigated in our manuscript and instead the reason for the higher salinity in the pycnocline due to northward progression of the salinity maximum of the South Pacific Tropical Water under the modified current bands during El Niño is explained.

Reviewer #2:

15 Page 8L4 "In October 2015: : : salinity lower because reduced equatorial upwelling: : :"
and because increased precipitation?

Answer to reviewer 2:

20 Right, the higher precipitation will be the major contribution and is now mentioned before the equatorial upwelling.

Reviewer #2:

Page 8L8 "In the profiles: : : " rephrase

25 Answer to reviewer 2:

The part 'In the profiles to 400 m depth' was moved and the sentence rearranged.

Reviewer #2:

Page9L3-8 What about March 1993? Oxygen is also high only in the high 60m: : : I would suggest to rephrase it so that it is easier to follow the author's logics, and more clear. For example: The oxygen concentration was slightly higher only in the upper
5 60 m for both El Nino events in March 1993 and in October 2015 compared to : : : . However, earlier selected measurements: : : showed a clear oxygen increase to a depth of 350m, hence we conclude that el Nino influence on the water mass distribution: : : .

Answer to reviewer 2:

10 We rewrote this text part as proposed.

Reviewer #2:

Page9L20 "The modeled EUC transports: : :" are you giving some examples from OGCMs in the sentence before, or these are all the OGCMs used? Make it clear: : :

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Answer to reviewer 2:

Yes, these are OGCM examples from the ROMS model mentioned in the sentence before. This information is now included also in the sentence where the examples are given.

20 Reviewer #2:

Page9L23 somewhat repeated information from the General Intro?

Answer to reviewer 2:

The information on the EUC was shortened in the introduction and the sentence on p9 was removed as
25 the major discussion is now in the conclusion paragraph.

Reviewer #2:

Page10L6-9 this segment belongs to intro.

30 Answer to reviewer 2:

This text was shifted to the introduction.

Reviewer #2:

From Page13 onwards the writing flows much better: : :

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Answer to reviewer 2:

Ok.

Reviewer #2:

10 Page14L5-14 I don't understand why nitrate was lower (contrary to El Nino expectations).
Clarify in the text?

Answer to reviewer 2:

Nitrate was actually higher in October 2015 compared to December 2012, as opposed to being lower.

15 Under El Nino conditions upwelling is reduced, and this prevents nutrients such as phosphate and silicate from building up in the mixed layer, however, nitrate and nitrite are different because their distributions are driven more by oxygen availability which regulates nitrification and denitrification. The higher oxygen concentrations during El Nino events reduces fixed N losses and results in higher nitrate concentrations. We have now added this explanation in the text.

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Reviewer #2:

End of page 15 You could move the summary of this sub-section (L18 onwards) into the conclusions.

25 Answer to reviewer 2:

This paragraph was moved to the conclusions as proposed.

Text and supplement with changes marked:

~~Transition to~~ Observed El Niño conditions in the eastern tropical Pacific in 5 **October 2015**

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Abstract. A strong El Niño developed in early 2015. Measurements from a research cruise on the RV *Sonne* in October 2015 near the equator east of the Galapagos Islands and off the shelf of Peru, are used to investigate changes related to El Niño in the upper ocean in comparison with earlier cruises in this region. At the equator at 85°30'W, a clear temperature increase leading to lower densities in the upper
15 350 m had developed in October 2015, despite a concurrent salinity increase from 40 to 350 m; ~~developed in October 2015~~. Lower nutrient concentrations were also present in the upper 200 m, and higher oxygen concentrations were observed between 40 and 130 m. ~~Except for the upper 60 m at 2°30'S, however, there was no obvious increase in oxygen concentrations at sampling stations just north (1°N) and south (2°30'S) of the equator at 85°30'W.~~ In the equatorial current field, the Equatorial
20 Undercurrent (EUC) east of the Galapagos Islands almost disappeared in October 2015, with a transport of only 0.02 Sv in the equatorial channel between 1°S and 1°N, and a weak current band of 0.78 Sv located between 1°S and 2°30'S. Such near-disappearances of the EUC in the eastern Pacific seem to occur only during strong El Niño events. Off the Peruvian shelf at ~9°S, ~~where the sea surface temperature (SST) was elevated~~, upwelling was modified, and warm, saline and oxygen rich water was
25 upwelled. ~~Despite some weak El Niño related SST increase a~~At ~12°S, ~14°S ~~to~~and ~16°S, the

upwelling of cold, low salinity and oxygen-poor water was still active at the easternmost stations of these three sections ~~at 12°S, 14°S and 16°S~~, while further west on these sections a transition to El Niño conditions appeared. Although ~~in~~ since early 2015 the El Niño was strong ~~and in October 2015 showed a clear El Niño influence on the EUC~~, the October measurements in the eastern tropical Pacific ~~the measurements~~ only showed developing El Niño water mass distributions. In particular the oxygen distribution indicated the ongoing transition from ‘typical’ to El Niño conditions progressing southward along the Peruvian shelf.

1 Introduction

The El Niño-Southern Oscillation (ENSO) cycle of alternating warm El Niño and cold La Niña events is the dominant year-to year climate signal on earth. ENSO originates in the tropical Pacific through interaction between the ocean and the atmosphere, but its environmental and socioeconomic impacts are felt worldwide (McPhaden et al., 2006). In the eastern tropical South Pacific El Niño events strongly influence the commercial fishery and weather and impact on the economics and living conditions.

~~Past El Niño events have been observed to have different local occurrences and parameter distributions in recent years. In contrast to the cold tongue, or Eastern Pacific (EP), El Niño events which develop in the eastern Pacific, there has been evidence of an increased occurrence of El Niño events in the central Pacific called Central Pacific (CP) El Niño or ‘El Niño Modoki’ (Dewitte et al., 2012). For a typical CP El Niño, the largest SST increase occurs at the equator between 130°W and 160°E while cooling appears off the shelf of Peru, while for the EP El Niño the SST increases at the equator east of 180°W to South America and southward along the South American coast to Chile (e.g. Dewitte et al., 2012). Different indices exist to describe the El Niño status. The NINO 1+2 index is the temperature difference compared to the 1982-2005 climatological cycle in the eastern tropical Pacific (0-10°S, 80-90°W), and is close to the region of the measurements used here. The Oceanic Niño Index (ONI) has become a standard for identifying El Niño and La Niña events. It is a running 3-month mean sea surface temperature (SST) anomaly for the Niño 3.4 region (i.e., 5°N-5°S, 120-170°W) related to the 1971-2000 base period. Events are defined as 5 consecutive overlapping 3-month periods at or above the 0.5°C anomaly for warm El Niño events, and at or below -0.5°C anomaly for cold La Niña events. The~~

strongest El Niño events since 1950 were observed in the years 1982/83 and 1997/98, the latter also referred to as ‘the climate event of the twentieth century’ (Changnon, 2000). ~~There is e~~Climate modeling evidence for suggest a doubling in the occurrences of extreme El Niño events in the future in response to greenhouse warming (Cai et al., 2015). In early 2015, an El Niño with strength similar to the 1997/98 El Niño developed. Sea surface temperature anomalies were strongest along the equator and the tropical North Pacific, while the development of a temperature anomaly in the eastern tropical Pacific off Peru was, according to NOAA’s ‘ENSO diagnostic discussion archive’, strong in April and May, then weakened and intensified again August to October 2015.

El Niño dynamics modulate near-surface temperature, salinity and density, as well as the mixed layer depth, oxycline depth, and the vertical extent of the low oxygen layer (e.g. Fuenzalida et al., 2009). ~~In the Pacific Ocean, El Niño events are a prominent feature of climate variability with global climate impacts.~~ In the eastern Pacific, ~~El Niño Southern Oscillation (ENSO)~~ variability is most pronounced along the equator and the coasts of Ecuador and Peru (Wang and Fiedler, 2006) but also off Chile (e.g. Ulloa et al., 2001). Weaker trade winds during El Niño conditions result in a weaker equatorial circulation with a generally observed weakening or disappearance of the Equatorial Undercurrent (EUC) (Kessler and McPhaden, 1995; Johnson et al., 2002). During the height of an El Niño event, the EUC episodically disappears in the western and central Pacific and partially reverse (Firing et al., 1983; McPhaden et al., 1990; Johnson et al., 2000; Izumo, 2005), while in the eastern Pacific, episodic disappearance of the EUC seems more rare ~~and was only observed during strong El Niño events~~ (Halpern, 1987; McPhaden and Hayes, 1990; Seidel and Giese, 1999; Johnson et al., 2000; Izumo, 2005). El Niño events lead to a pronounced eastward extension of the west Pacific warm pool, and to a development of atmospheric convection, and hence a rainfall increase, in the usually cold and dry eastern Pacific (Cai et al., 2015).

Past El Niño events have been observed to have different local occurrences and parameter distributions in recent years. There has been evidence of an increased occurrence of El Niño events in the central Pacific called Central Pacific (CP) El Niño or ‘El Niño Modoki’ (e.g. Ashok and Yamagata, 2009; Dewitte et al., 2012), different from the cold tongue, or Eastern Pacific (EP), El Niño events which develop in the eastern Pacific. For a typical CP El Niño, the largest SST increase occurs at the equator

between 130°W and 160°E while cooling appears off the shelf of Peru, while for the EP El Niño the SST increases at the equator east of 180°W to South America and southward along the South American coast to Chile (e.g. Dewitte et al., 2012).

In the Eastern Tropical South Pacific (ETSP), a subsurface low-oxygen zone exists with a pronounced minimum in oxygen at ~100 to 500 m depth and is referred to as an oxygen minimum zone (OMZ) or oxygen deficient zone (ODZ). This ODZ is suboxic (oxygen concentrations below ~4.5-10.0 $\mu\text{mol kg}^{-1}$; e.g. Karstensen et al., 2008; Stramma et al., 2008). In suboxic regions nitrate and nitrite become involved in respiration processes such as denitrification or anammox (e.g. Kalvelage et al., 2013). In the eastern equatorial Pacific the oxygen content has been shown to increase during El Niño events in the upper 300 to 350 m in the equatorial channel (e. g. Fuenzalida et al., 2009; Czeschel et al., 2012), as well as off the Peruvian coast ~~as a result of circulation changes~~ (e.g. Helly and Levin, 2004). Coastal winds during El Niño events are usually upwelling-favourable, ~~and thus could not produce the observed warming (Kessler, 2006)~~. Coastal warming during El Niño is caused by downwelling Kelvin waves generated by mid-Pacific westerly wind anomalies that deepen the eastern thermocline, ~~nutricline and oxycline~~ and allow warming to occur, independent of the local winds (Kessler, 2006). Consequently, during El Niño events the upwelled water off Peru is warmer, more oxygen replete and less nutrient rich. El Niño, in general, results in a depressed thermocline and thus reduced rates of macronutrient supply and primary production (Pennington et al., 2006) off Peru ~~which also contributes to an oxygen increase on the shelf (Gutierrez et al., 2008)~~. In case of strong El Niño events when the oxygen concentration above the shelf bottom increases from about zero to $>40 \mu\text{mol kg}^{-1}$ the sediments respond with tremendous changes of ecological state (Gutiérrez et al., 2008). At a time-series station at ~12°S, 77°30'W off Lima from 1996 to 2010 for temperature, salinity, density, oxygen and nutrients, the influence of El Niño - especially the strong 1997/1998 El Niño - is clearly visible with higher temperature, salinity and oxygen, and lower density, nitrite, silicate and phosphate (Graco et al., 2016).

Here we use measurements from an *RV Sonne* research cruise in October 2015 (Fig. 1) ~~from a section across the equator east of the Galapagos Islands from an ADCP section from the Ecuadorian shelf to 1°N, 85°30'W, from a section across the equator~~ and from 4 sections off the Peruvian shelf, to investigate changes in the upper ocean related to the strong 2015 El Niño in comparison with earlier

cruises in this region. The aim is to unravel the progress of the transition to El Niño conditions in the eastern Pacific several months after the start of the El Niño.

2 Data sets and methods

5 In October 2015 an *RV Sonne* transit cruise (So243; 5 to 22 October 2015) from Guayaquil, Ecuador to Antofagasta, Chile was carried out (Fig. 1) (short cruise report available at: <https://www.lfd.uni-hamburg.de/sonne/wochenberichte/wochenberichte-sonne/so242-243/so243-scr.pdf>), which allowed us to investigate possible El Niño signals at the equator near 85°30'W and off the shelf of Peru at sections perpendicular to the shelf at ~9°S, ~12°S, ~14°S and ~16°S.

10 A Seabird CTD system with a GO rosette with 24 x 10 L water bottles was used for water profiling and discrete water sampling. The CTD system was used with double sensors for temperature, conductivity (salinity) and oxygen. The dual CTD temperature sensors calibrated by the manufacturer are compared during the cruise that the deviation is less than 0.002°C and the accuracy of the temperature measurements is estimated to be 0.002°C or better. The CTD salinity calibration with salinometer
15 salinity samples resulted in a r.m.s. uncertainty of 0.0011. The CTD oxygen sensors were calibrated with oxygen measurements obtained from discrete samples from the rosette applying the classical Winkler titration method, using a non-electronic titration stand (Winkler, 1888; Hansen, 1999). The r.m.s. uncertainty of the CTD oxygen sensor calibration of cruise So243 was determined as ±0.8 μmol kg⁻¹. Oxygen concentrations of less than 3 μmol kg⁻¹ are not resolved by Winkler titration and values
20 below 3 μmol kg⁻¹ were used as 0 μmol kg⁻¹ for the sensor calibration as the H₂S smell of the water of related rosette bottles indicated 0 μmol kg⁻¹.

Nutrients were measured on-board with a QuAAtro auto-analyzer (Seal Analytical). Nitrite (NO₂⁻), nitrate (NO₃⁻), phosphate (PO₄³⁻) and silicid acid (Si(OH)₄ referred to silicate hereinafter) were measured with an analytical precision of 5.5%, 1.3%, 0.4% and 0.5% respectively. The N:P ratio used
25 here was computed as N:P = (NO₃⁻ + NO₂⁻): PO₄³⁻.

Two vessel mounted Acoustic Doppler Current Profilers (ADCP) were used to record ocean velocities in October 2015: an RDI OceanSurveyor 75 kHz ADCP with 8 m bin spacing provided the velocity

distribution to ~650 m depth, while a 38 kHz ADCP with 32 m bin spacing provided velocity profiles down to ~1300 m depth. During the entire cruise the navigation data was of high quality. Due to the interest in the upper ocean the higher resolution 75 kHz ADCP is used here.

Earlier crossings of the equator (Table 1 and Fig. 1) were accomplished in March/April 1993 on RV *Knorr* (Tsuchiya and Talley, 1998), in February 2009 on RV *Meteor* (Czeschel et al., 2011) and in November 2012 on RV *Meteor* (Stramma et al., 2013) at 85°50'W. Sections across the Peruvian shelf between 9°S and 16°S were made during RV *Meteor* cruise M91 in December 2012 (Czeschel et al., 2015; Bange, 2013). Measurement accuracies during these cruises were similar as in October 2015 and the details are described in the related literature. In contrast to October 2015, the CTD stations in 1993, 2009 and 2012 were not carried out at 2°30'S, 85°30'W but at 2°20'S and 2°40'S at 85°50'W and these two stations were combined for a mean profile at 2°30'S. The sections across the equator and off the Peruvian shelf were not at identical geographical coordinates, but we expect that the offset is small compared to the differences measured.

Different indices exist to describe the El Niño status and will be used here to determine the El Niño status at the time of the measurements. The NINO 1+2 index is the temperature difference compared to the 1982-2005 climatological cycle in the eastern tropical Pacific (0-10°S, 80-90°W), and is close to the region of the measurements used here. The Oceanic Niño Index (ONI) has become a standard for identifying El Niño and La Niña events. It is a running 3-month mean sea surface temperature (SST) anomaly for the Niño 3.4 region (i.e., 5°N-5°S, 120-170°W) related to the 1981-2010 base period. Events are defined as 5 consecutive overlapping 3-month periods at or above the 0.5°C anomaly for warm El Niño events, and at or below -0.5°C anomaly for cold La Niña events.

3 The El Niño in 2015

The SST anomaly for 27 September 2015 to 24 October 2015 was strong along the equator to the South American continent and southward off the Peruvian coast (~~Supplement Fig. 2S1~~). The NINO 1+2 index was high at +2.52 in October 2015 (Table 1), hence the 2015 El Niño is a clear EP El Niño. ~~Different to the typical EP El Niño~~ The SST distribution in fall 2015 ~~shows~~ a strong and prominent SST increase

~~was also present~~ along Central America and in the eastern North Pacific at 20-25°N that differs from the typical EP El Niño distribution. This feature, also known as ‘The Blob’, is an unrelated positive temperature anomaly which developed in 2013 in the Gulf of Alaska and progressed along the North American continent to the 20-25°N region in mid-2015 (Kintisch, 2015).

- 5 The only El Niño events since 1950 with an October maximum ONI of more than 1.7, or an overall maximum of 2.0 or larger, are the 1972/73, 1982/83 and the 1997/98 El Niños. In early 2015 the ONI index was even larger than the ONI index of these 3 large El Niño events, while in October 2015 it was at a similar strength as the three earlier strong El Niños (Fig. [32](#)). Accordingly, the 2015 El Niño has to be listed as one of the 4 strongest El Niños since 1950.

10

4 The equatorial region east of the Galapagos Islands

4.1 The hydrographic variability

4.1.1 Background information

- 15 The hydrographic distribution in the eastern equatorial Pacific is influenced by a seasonal cycle as well as El Niño related cycles. At 110°W in the eastern Pacific west of the Galapagos Islands, relationships between zonal velocity, temperature, and salinity in the EUC are all evident in the seasonal cycle. The EUC peaks in strength around April/May, when it also surfaces (Johnson et al., 2002). The thermocline is extremely sharp and shallow. The meridional equatorial spreading of the thermocline associated with the EUC zonal velocity strength is noticeably stronger during April than in October, when in April equatorial SST is lowest and the South Equatorial Current (SEC) is strongest ([Johnson et al., 2002](#)). The laterally isolated salinity maximum within the thermocline just south of the equator is strongest when the EUC velocity is at its greatest (Johnson et al., 2002), and this is also visible in the sea surface salinity (Supplement Fig. [S12](#)) from the MIMOC climatology (Schmidtko et al., 2013). Between austral
- 20 the EUC zonal velocity strength is noticeably stronger during April than in October, when in April equatorial SST is lowest and the South Equatorial Current (SEC) is strongest ([Johnson et al., 2002](#)). The laterally isolated salinity maximum within the thermocline just south of the equator is strongest when the EUC velocity is at its greatest (Johnson et al., 2002), and this is also visible in the sea surface salinity (Supplement Fig. [S12](#)) from the MIMOC climatology (Schmidtko et al., 2013). Between austral
- 25 fall and winter the minimal oxygen concentration of the ODZ core in the eastern South Pacific at the equator ~~changes intensifies from 16 to 15 $\mu\text{mol O}_2\text{L}^{-1}$ for the mean oxygen concentration and~~ from 8 to 5 $\mu\text{mol O}_2\text{L}^{-1}$ ~~for the minimal oxygen concentration~~ (Paulmier and Ruiz-Pino, 2009).

Weaker trade winds during El Niño conditions result in a weaker equatorial circulation while stronger trade winds during La Niña conditions lead to a stronger equatorial circulation (Johnson et al., 2002). During La Niña, the current system at 110°W is spun upwards when compared to El Niño. The cold tongue located in the eastern tropical Pacific is quite weak during El Niño. Surface salinities are generally fresher during El Niño than during La Niña, a feature which is at least partially a product of increased local precipitation associated with the eastward migration of warm sea surface temperatures and convection, and partly a result of the reduced trade winds (Johnson et al., 2002). For the 1996-1998 El Niño-La Niña cycle, a ~~very~~ fresh mixed layer in the eastern equatorial Pacific ~~late in the El Niño~~, and ~~higher a reduction of the strength of the meridional equatorial salinity gradient~~ within the pycnocline (defined by the 20°C isotherm) ~~to one third of the usual value~~ during the El Niño was observed. ~~The higher salinity was caused by the larger equatorward spreading of the subsurface salinity maximum of the South Pacific Tropical Water (SPTW) due to anomalous eastward flow south of the equator with the relaxation of the South Equatorial Current and the weaker EUC at the equator~~ (Johnson et al., 2000). Hence, during El Niño events higher salinity should be expected near the pycnocline.

15

4.1.2 Observations for the 2015 El Niño

SST anomalies for the period 27 September to 24 October 2015 showed an SST anomaly of 2.0-2.5°C at 85°30'W at and south of the equator, and of 1.5-2.0°C just north of the equator (~~Supplement~~ Fig. ~~2S1~~). In the upper 100 m of the water column, oxygen, temperature, salinity and density profiles at the equator on the ~85°30'W meridian (Fig. ~~43~~) reveal differences between March 1993, February 2009, November 2012 and the El Niño of October 2015. It is important to note that 1993 was not defined as an official El Niño year as only 4, instead of 5, consecutive overlapping 3-month periods were at or above the 0.5°C anomaly. However, in March and April 1993 the NINO 1+2 index reached +0.65 and +0.97 (Table 1) and had El Niño like SST anomalies. To this end, we will refer to March 1993 as 'El Niño-like' hereinafter.

In February 2009 the ONI index was for the fourth and last month -0.5 or less, therefore conditions were similar to a weak La Niña event and we will refer to it as 'La Niña-like' hereinafter. In February 2009, in the upper 100 m at the equator at ~85°30'W the oxygen and temperature were lowest and the

density highest compared to the other 3 periods (Fig. 43), representing an expected La Niña parameter distribution. The hydrographic profiles in the neutral ONI period in November 2012 mainly lay between the El Niño profiles for March 1993 and October 2015, and the La Niña-like profiles in February 2009. The November 2012 were somewhat closer to the February 2009 profiles. The El Niño profiles in 5 October 2015 and the El Niño-like profiles in March 1993 showed slightly higher oxygen concentrations and temperature, and lower density in the upper 100 m in comparison to November 2012 and February 2009 (Fig. 43). In October 2015 the salinity compared to the 3 other years was lowest in a deep thermocline in the upper 40 m as expected for the surface layer during an El Niño event because of the increased precipitation and reduced equatorial upwelling. In contrast, a weak salinity maximum was 10 located below 40 m as expected near the pycnocline as saline warm water progresses from the western Pacific eastward during El Niño. In October 2015 the profiles to 400 m depth, the higher temperature, higher and salinity, and lower density reached down to ~350 m ~~in October 2015~~, while the oxygen profile below 130 m merges with the profiles from the other measurement periods (Fig. 54).

The strong thermocline/pycnocline of the eastern tropical Pacific is also a strong nutricline. A consistent 15 general pattern is that nitrate and phosphate increase with depth to ~500 m with a slight maximum at intermediate depths, while silicate continues to increase with depth (Fiedler and Talley, 2006). The vertical distribution of nutrients at the equator at ~85°30'W shows lower nitrate, phosphate and silicate concentrations in the upper 200 m in October 2015 as well as in the El Niño-like year 1993 in comparison to the 2009 and 2012 concentrations (Fig. 65). A primary nitrite maximum (PNM) usually 20 occurs in the lower euphotic zone, and which results from nitrite excretion by phytoplankton and/or a decoupling of ammonia and nitrite oxidation (i.e. higher rates of ammonia vs. nitrite oxidation; Fiedler and Talley, 2006; Lomas and Lipschultz 2006). At the equator in the eastern Pacific nNitrite is close to undetectable below 100 m depth (Fig. 65). In 1993 and 2015, however, the PNM was located ~25 m deeper and maximum nitrite concentrations were considerably higher. This reflects the deeper 25 pycnocline in El Niño years. The enhanced nitrite concentrations seem to be caused by the northward transport of high nitrite concentration found in the PNM of the SPTW (e.g. Tsuchiya and Talley 1998 and as observed during cruise M90) in combination with a reduced photo inhibition of ammonia oxidation at deeper water depths (see e.g. Ward, 2008 ; Grundle et al., 2013). Furthermore, the deep

thermocline and pycnocline in October 2015 indicate that equatorial upwelling was reduced. According to the upper ocean hydrographic and nutrient distribution in October 2015, a clear El Niño situation had adjusted at the equator at $\sim 85^{\circ}30'W$.

At $1^{\circ}N$, $\sim 85^{\circ}30'W$ in the 50-300 m layer, salinity and temperature were higher and the density lower in October 2015 than at the 3 other times, however, the oxygen was not significantly higher during this time (Supplement Fig. S23). At $2^{\circ}30'S$, $\sim 85^{\circ}30'W$ in the 50 to 250 m layer, the salinity, temperature and oxygen were lower and the density higher in the La Niña-like month of February 2009 than at the other three years. The temperature at $2^{\circ}30'S$ in the El Niño of October 2015 was higher in the 50 to 250 m depth range than in the other 3 years and salinity showed slightly higher values at ~ 50 to 100 m and 150 to 250 m depth. The oxygen concentration was slightly higher only in the upper ~ 60 m for both El Niño events profiles in March 1993 and in October 2015 in the upper ~ 60 m compared to 2009 and 2012 (Supplement Fig. S34). However, eEarlier selected measurements at $4^{\circ}S$, $85^{\circ}W$ showed a clear oxygen increase from the near surface to a depth of ~ 350 m depth for the El Niño years 1982/83 in comparison to non El Niño measurements (Czeschel et al., 2012). hHence we conclude that, the El Niño influence on the water mass distribution was still weak at $2^{\circ}30'S$ in October 2015 and only developing in the upper ocean.

4.2 Circulation observations

4.2.1 Background information

20 The EUC, which carries oxygen rich water towards the ODZs of the eastern Pacific, has a seasonal cycle, with a transport peak in the eastern Pacific at $95^{\circ}W$ in April/May of ~ 30 Sv and a minimum in October/November of little less than 15 Sv (Johnson et al., 2002; their Figure 17). The Galapagos Islands form a barrier to the EUC which causes it to bifurcate into a shallow/southern core centered at ~ 50 m depth (EUCs) and a deeper/northern core centered at ~ 150 m depth (EUCd) (Karnauskas et al., 25 | 2010). We are not aware of any El Niño related EUC variability observations east of the Galapagos Islands. Results from an oceanclimate model for $110^{\circ}W$ show an increase in the surface eastward EUC current during austral fall, while during other seasons the EUC is at deeper depth (Cravatte et al., 2007). ROMS (Regional Ocean Model System) model results uns (Montes et al., 2011) for El Niño periods east

of the Galapagos Islands show the EUC flowing at shallower depth associated with lighter water. The model runs display a weakening and southward shift of the EUC branches east of the Galapagos Islands with weaker transports which are variable, depending on the boundary conditions provided by different ocean general circulation models (OGCMs). The modelled ROMS EUC transports at 86°W between 2°N and 2°S at 200 m depth for February/March and October/November depending on the OGCMs are ~10-12 Sv and ~7-8 Sv for OCCAM, ~6-8 Sv and 4-5Sv for SODA, and ~5.5 Sv and 7-8 SV for ORCA (Echevin et al., 2011).

~~During El Niño events the equatorial circulation system of the Pacific weakens, and the eastward flowing EUC has been found to decay (Kessler and McPhaden, 1995, Johnson et al., 2002) and partially reverse, e.g. during the 1982-1983 El Niño at 159°W in September 1982 (Firing et al., 1983).~~ During the 1997/98 El Niño shipboard current measurements showed that the EUC virtually disappeared across much of the Pacific basin, associated with the weakening or even the reversal of the equatorial pressure gradient within the pycnocline (Johnson et al., 2000). For the 1982-1983 El Niño there seems to be a strong time delay for the EUC weakening. In September 1982 at 159°W, the EUC reversed (Firing et al., 1983), however, ~~in November 1982~~ at 95°W, the EUC was strong in November 1982 before being replaced by a westward jet in May 1983 (Hayes et al., 1986).

4.2.2 Observations for the 2015 El Niño

~~We are not aware of any El Niño related EUC variability observations east of the Galapagos Islands. Model results (Montes et al., 2011) for El Niño periods show a weakening and southward shift of the EUC branches east of the Galapagos Islands where the EUC flows at shallower depths and is associated with lighter water.~~ The direct velocity observations in October 2015 on the diagonal section from the Ecuadorian shelf to 1°N, 85°30'W, show only a weak signature of the zonal EUC in the upper 100 m located mainly at, and south, of the equator (Fig. 76a). The weak transport of the EUC is 0.01 Sv between 1°S and 1°N, and 0.29 Sv between 2°30'S and 1°S. The westward flow in the upper 200 m is mainly connected to a northward flow direction (Fig. 76b) north of 1°S. This north-westerly flow indicates the flow of oxygen-poor water from the ODZ off the South American continent to the west near the equator.

The direct velocity observations on the meridional section at $85^{\circ}30'W$ between $1^{\circ}N$ and $2^{\circ}30'S$ and the diagonal continuation to $5^{\circ}S$, $84^{\circ}16'W$, again show the weak signature of the EUC in the upper 100 m located mainly at, and south, of the equator north of $2^{\circ}30'S$ in October 2015 (Fig. 87d). The EUC transport in the upper 300 m is 0.02 Sv between $1^{\circ}S$ and $1^{\circ}N$ and 0.78 Sv between $2^{\circ}30'S$ and $1^{\circ}S$ (Table 2). The stronger eastward flow component in the upper 200 m between $3^{\circ}S$ and $4^{\circ}S$ might be a combination of the EUC and the Southern Subsurface Countercurrent (SSCC; also called Tsuchiya Jet), as described for El Niño periods east of the Galapagos Islands in model results (Montes et al., 2011). The eastward flow near $2^{\circ}S$ below 200 m is the South Intermediate Countercurrent (SICC).

The strongest EUC in our four measurement periods occurred at the end of March 1993, with 12.77 Sv between $1^{\circ}S$ and $1^{\circ}N$ in the upper 300 m (Table 2; Figure 87a). This measurement at the end of March was close to the time of eastern Pacific EUC peak transport in April/May. In addition, it was at the beginning of an El Niño-like phase, where warmer, oxygen-rich water is transported from the western to the eastern tropical Pacific and could enhance the eastward flow component.

In February 2009 the EUC transport between $1^{\circ}S$ and $1^{\circ}N$ was weak (3.55 Sv), although it occurred only two months before the time of the seasonal EUC peak transport. As previously described, February 2009 was at the end of a short La Niña-like period with an ONI index of -0.7, and the low EUC transport might be related to a generally weak eastward transport of warm western equatorial Pacific water during La Niña. On a cruise approximately 1.5 months later in March to April 2009 between the Galapagos Islands and Ecuador, a region of possible strong cross-hemispheric exchange was observed immediately to the east of the Galapagos, where a shallow (200 m) 300 km wide north-eastward surface flow transported 7 to 11 Sv (Collins et al., 2013). This north-eastward flow might have weakened the EUC transport at and south of the equator. The two diagonal sections in March/April 2009 crossed the $85^{\circ}50'W$ section at $\sim 1^{\circ}50'S$ and $2^{\circ}30'S$ and, similar to the February 2009 measurements, showed a 50 m depth eastward and westward flow at $1^{\circ}50'S$ and $2^{\circ}30'S$, respectively, and a westward flow at both of these latitudes at 200 m depth. In contrast to the velocity distribution in March 1993, November 2012 and October 2015 (Fig. 87), the eastward flow component in the upper 200 m south of $2^{\circ}30'S$ almost disappeared in February 2009.

The EUC transport in November 2012 at 85°50'W between 1°S and 1°N was 10.78 Sv in the upper 300 m (Table 2). The months before these measurements had no large ONI index values and should represent the non-El Niño EUC transport in this region for November. The transport of 10.78 Sv in November at 85°50'W is less than the November minimum at 95°W of ~15 Sv ([Johnson et al., 2002; their Figure 17](#)), and seems to be a reasonable estimate east of the Galapagos Islands, as the EUC transport decreases in the eastern Pacific. The core of the EUC below 200 m is quite deep and agrees with the seasonal cycle where the EUC should be located at deeper depth in austral spring.

5 The upwelling region off Peru

5.1 Background information

Off Peru a highly productive year-round upwelling system is located between 4 and 16°S (Chavez and Messié, 2009). [Since the 1950s, an SST decline corresponding to an increase of upwelling was observed off Peru \(Gutiérrez et al., 2011; Sydemann et al., 2014\)](#). The SST off of Peru measured at six locations between 5°S and 12°S over a period of six years shows a seasonal cycle of 2 to 3°C amplitude with the largest SST near March and the minimum near October (Montes et al., 2011; their Fig. 4). This seasonal cycle is also visible in the MIMOC climatology for 9°S and 12°30'S (Supplement Fig. S12). The time series station at ~12°S, 77°30'W shows a seasonal cycle of about 20 m displacement for the 15°C isotherm, the oxycline depth and the upper boundary of the ODZ (Graco et al., 2016). Seasonal eddy fluxes are described along the coast of Peru with the largest signal at approximately 15°S with a peak during the Austral winter (Vergara et al., 2016). ~~[Since the 1950s, an SST decline corresponding to an increase of upwelling was observed off Peru \(Gutiérrez et al., 2011; Sydemann et al., 2014\)](#)~~. The typical nutrient distribution along a cross-shelf section at 12°S ([as seen in December 2012](#)) shows elevated phosphate concentrations in the surface waters near the coast whereas nitrate ~~was~~ [is](#) depleted in the water column and the near surface waters close to the coast (Kock et al., 2016; their Fig. 3).

Conditions which develop along the coast of Ecuador, Peru and northern Chile during El Niño events include a strengthening of the poleward flow along the coast of Peru, persistent deepening of the thermocline, reducing or even reversing the prevailing upwelling induced land-sea temperature gradient, and a southward shift in the position of the ITCZ which brings heavy precipitation to normally arid

regions (Strub et al., 1998). A reduction in coastal cloud cover due to warmer water next to the coast may enhance insolation and reduce atmospheric pressure over land, maintaining the pressure difference and winds over the coast. As a result, upwelling-favourable winds are not greatly reduced when El Niño conditions are observed in the ocean ([Enfield 1981](#); [Huyer et al., 1987](#); Strub et al., 1998; [Halpern et al., 2002](#)). In general, upwelling-favourable winds and upwelling continue during El Niño events, and water continues to be drawn from 50-100 m depth to the surface layer, but the thermocline and nutricline are displaced downward and thickened, so that upwelling during El Niño brings only warm and nutrient-poor water to the surface ([Enfield 1981](#); [Huyer et al., 1987](#); Strub et al., 1998; [Halpern et al., 2002](#)). The intensity of the upwelling appears to be determined by an interplay between alongshore, poleward advection, and wind intensity, but also by the cross-shore geostrophic flow and distribution of the water masses on a scale of 1000 km or more (Colas et al., 2008). In relation to the downward displacement of the thermocline and nutricline, the oxycline is also displaced downward. For the 1997/98 El Niño event, Helly and Levin (2004) described a possible depression of the upper layer of the ODZ (defined by oxygen concentrations < 0.5 ml l⁻¹) by 100 m reducing the ODZ area off Peru and northern Chile (6°-20°S) by 61% (from 77,000 to 30,000 km²).

5.2 Observations for the 2015 El Niño

The SST anomalies for the period 27 September to 24 October 2015 (~~Supplement~~ Fig. [2S1](#)), showed a strong SST anomaly of 1.5-2.0°C between 8°S and 14°S and a weaker anomaly of 0.5-1.5°C between 14°S and 20°S. Differing hydrographic distributions were measured off Peru at ~9°S in December 2012 with a neutral ONI status, and in October 2015 with the strong El Niño. In the entire upper 300 m at ~9°S, temperature, salinity (Supplement Fig. [S45](#) and [S56](#)) and oxygen (Fig. [98](#)) were higher in October 2015 than in December 2012. In contrast to the typical seasonal cycle which is characterized by lower SST in October than in December, the SST at 9°S was higher in October 2015 than in December 2012 as a result of the El Niño related SST increase. Higher upper water column temperatures in October 2015 also correlated to lower densities in the upper 300 m (as can be seen from the selected isopycnals in Fig. [98](#)) despite the concurrent influence on density from the salinity increase. Accordingly the

density changes are temperature dominated. In December 2012 there was strong upwelling at $\sim 9^{\circ}\text{S}$ with the $<5 \mu\text{mol kg}^{-1} \text{O}_2$ layer located below ~ 30 m depth, while in October 2015 this low oxygen layer was only found below 240 m depth. The October 2015 nutrient profiles obtained from shelf stations at $\sim 9^{\circ}\text{S}$ with water depths of little more than 100 m (not shown), highlight that nitrate, phosphate and silicate concentrations were lower, and nitrite concentrations were higher in comparison to profiles from the same location in December 2012, as would be expected for El Niño periods. Although the isopycnals and parameter distribution shows that upwelling at 9°S was occurring in October 2015, it is clear that warmer, saline and oxygen replete water was being upwelled, and that the contribution of oxygen deplete and nutrient rich water was strongly reduced.

At $\sim 12^{\circ}\text{S}$ the measured oxygen distributions for December 2012 and October 2015 are quite similar in the upwelling region at the easternmost station pair with oxygen concentrations of less than $5 \mu\text{mol kg}^{-1}$ (Fig. 109). The oxygen concentration between the isopycnals $\sigma_{\theta} = 25.6$ and 25.8 kg m^{-3} was even lower in October 2015 than in December 2012 in the upwelling region east of $\sim 77^{\circ}30'\text{W}$ (Fig. 109). However, below the oxycline below 50 m depth, temperature, salinity and oxygen concentrations (Supplement Fig. 117f) were higher in October 2015 than in December 2012 and indicate the transition to El Niño conditions. The seasonal signal in the time-series station at $\sim 12^{\circ}\text{S}$, $77^{\circ}30'\text{W}$ shows a shallower 15°C isotherm and oxycline depth of about 20 m in October than in December (Graco et al., 2016), hence the deeper oxycline in October 2015 compared to December 2012 is not a seasonal signal but an El Niño influence. The nutrient distribution at the shelf at $\sim 12^{\circ}\text{S}$ (Supplement-Fig. 11S7) also shows El Niño influence with lower phosphate and silicate in October 2015 than in December 2012. This is in agreement with the observed increase in temperature and salinity, and the lower phosphate and silicate at the time series station at $\sim 12^{\circ}\text{S}$ during the strong 1997/1998 El Niño (Graco et al., 2016). Under El Niño conditions upwelling is reduced and this prevents nutrients such as phosphate and silicate from becoming enriched in the mixed layer. Nitrate and nitrite are different, however, because their distributios are driven more by oxygen availability, which regulates nitrification and denitrification. Indeed However, nitrate was lower and nitrite was higher in December 2012 than in October 2015, with nitrite reaching $5.4 \mu\text{mol L}^{-1}$ at 75 m in December 2012 (Supplement-Fig. 11S7) consistent with the observations of Kock et al. (2016). At the depths of the high nitrite concentrations in December 2012,

very low oxygen concentrations of less than $2 \mu\text{mol kg}^{-1}$ were measured. Under low oxygen conditions incomplete nitrification, incomplete denitrification, or a combination of both, can result in accumulations of nitrite (e.g. Codispoti and Christensen 1985; Gruber 2008; Brockmann and Morgenroth 2010), as was likely the case during 2012. The higher oxygen concentrations in the ODZ at
5 $\sim 12^\circ\text{S}$ during October 2015 would have prevented the build-up of nitrite, as under these conditions denitrification shuts off and nitrification goes to completion, [producing more nitrate](#).

Another notable difference between December 2012 and October 2015 at $\sim 12^\circ\text{S}$ is the lower N:P ratios in the upper 150 m during 2012 vs. 2015 (Fig. [S67e](#)). Again, higher oxygen concentrations in the upper 150 m during 2015 El Niño probably reduced the impact of fixed N loss processes on the N:P signatures
10 of near-surface waters. These results imply that El Niño conditions could, at least, partially alleviate phytoplankton N limitation due to the reduction in the magnitude of denitrification. While it is beyond the scope of the focus of this study, it would be interesting to examine whether this increase in N:P ratios during the 2015 El Niño impacted the phytoplankton communities within this region. The expectation that they may have impacted the phytoplankton communities is certainly reasonable
15 (Rousseaux and Gregg, 2012), as Hauss et al. (2012) observed an increase in diatom biomass when the $\text{NO}_3^-:\text{PO}_4^{3-}$ ratios of water collected from the Peruvian upwelling region were increased.

The results from $\sim 12^\circ\text{S}$ shelf water indicate that upwelling of oxygen-poor water was still continuing in October 2015 at 12°S in the near surface layer, despite the enhanced SST anomaly related to El Niño. Below the oxycline, however, El Niño conditions were developing. The observations west of $77^\circ 48' \text{W}$
20 in the upper 75 m [show](#) that oxygen as well as temperature (not shown) were lower in October 2015, may-be related to a stronger poleward flow [of the Peru Chile Undercurrent \(PCUC\)](#) which has been shown to be a characteristic of El Niño events (Strub et al., 1998). [The PCUC advects seawater property anomalies from equatorial to extratropical regions and shoals during El Niño despite the velocity and transport intensification \(Montes et al. 2011; Chaigneau et al., 2013\)](#).

25 At $\sim 14^\circ\text{S}$ at the easternmost station near the shelf, the oxygen distribution is quite similar for December 2012 and October 2015 (Supplement Fig. [S68](#)), indicating non-El Niño oxygen-poor upwelling near the shelf. West of 77°W , the isopycnals are deeper in October 2015 related to a deeper thermocline with warmer water in the upper 100 m (not shown) and higher oxygen in October 2015 compared to

December 2012. Similar to $\sim 12^{\circ}\text{S}$ the nutrient distribution shows higher nitrate and lower phosphate and silicate in October 2015 compared to December 2012 at $\sim 14^{\circ}\text{S}$. As outlined above, the higher nitrate concentrations in October 2015 likely result from less denitrification and more complete nitrification, as a result of the increased oxygen concentrations, and t
5 forshows a developing El Niño situation.

At $\sim 16^{\circ}\text{S}$ the oxygen concentrations at the shelf were lower in October 2015 than in December 2012 (Supplement Fig. S79), indicating similar as at $\sim 14^{\circ}\text{S}$ non-El Niño upwelling close to the shelf. The higher oxygen near the shelf in December 2012 was probably related to an unusual distribution related to an eddy located near the $\sim 16^{\circ}\text{S}$ section (e.g. Stramma et al., 2013; Czeschel et al., 2015). The SST at
10 $\sim 14^{\circ}\text{S}$ and $\sim 16^{\circ}\text{S}$ was lower in October 2015 than in December 2012, hence the slight increase of SST by El Niño did not compensate the typical seasonal SST signal. Different to the sections at $\sim 9^{\circ}\text{S}$, $\sim 12^{\circ}\text{S}$ and $\sim 14^{\circ}\text{S}$, at $\sim 16^{\circ}\text{S}$ the density distribution below the thermocline did not shift to higher densities in October 2015 which shows that the El Niño influence at 16°S was the weakest of the 4 shelf sections.

The observed transitional feature of normal conditions near-shore and El Niño conditions offshore is probably a consequence of the cross-shore pattern in vertical velocity during upwelling. The near-shore vertical velocity is to be expected substantially larger than the offshore vertical velocity (Fennel, 1999). A downwelling Kelvin wave could then neutralize the weak offshore upwelling and bring down the thermocline, while near-shore the strong upwelling would hardly weaken and for some time still bring up remnants of cold oxygen-poor water, until supplies feed from the offshore warmer and oxygen
15 replete waters. The wind field would not need to change in order to produce this transition pattern in hydrography.

~~In summary, the temperature, salinity and oxygen measurements all indicate that during October 2015 the El Niño was strongest along our northern transects and weakest along our southern transects. This was also apparent in the nutrient properties between the northern and southern portions of our study
20 region. As outlined above, at 12°S the N:P ratio was higher and nitrite concentrations were lower during October 2015 when compared to the non-El Niño period of December 2012, both of which point to a reduction in the magnitude of denitrification. When comparing the differences between coastal nutrient N:P ratios and nitrite concentrations along the coast, we found that the differences between~~

~~October 2015 and December 2012 decreased between 12°S and 14°S, and again between 14°S and 16°S (data not shown). This again highlights the potential for El Niño events to impact N loss processes and upper water column biogeochemistry.~~

5 6 Conclusion

In this study, hydrographic measurements from a cruise to the eastern tropical Pacific in October 2015 were used to investigate the signal of the strong 2015 El Niño in the water mass distribution and in the EUC in comparison to measurements from the years 1993, 2009 and 2012. An increase of temperature from the surface to 350 m depth, and salinity in the 40 to 350 m depth layer appeared at the equator east of the Galapagos Islands at 85°30'W in October 2015. The warmer temperature led to lower densities despite the concurrent influence of the salinity increase on density. In October 2015, nitrate, phosphate and silicate concentrations were all lower in the upper 200 m when compared with previous non-El Niño periods, however, higher oxygen concentrations, which are characteristic of El Niño events, were only located between 40 and 130 m at the equator. Except for an oxygen increase in the upper ~60 m at 2°30'S, no obvious large vertical oxygen increase appeared at 1°N and 2°30'S at 85°30'W. This weak oxygen increase at and near the equator might be related to the weak EUC, which would else be expected to bring oxygen richer water eastwards.

Due to the influence of seasonal and El Niño signals, the velocity and transport observations of the EUC east of the Galapagos Islands were quite variable in the direct velocity measurements in different years. In addition intraseasonal signals with the passage of upwelling and downwelling waves at intraseasonal time scales (Cravatte et al., 2003; Echevin et al., 2013) might modify the measurements. As previously observed in the central and western Pacific, and as predicted from model simulations, the EUC at the equator almost disappeared with a transport of only 0.02 Sv between 1°S and 1°N in October 2015 related to the El Niño conditions. Although weak, the EUC had shifted southward with a transport of 0.78 Sv between 2°30'S and 1°S in October 2015. These observations are in agreement with the predicted weakening and southward shift of the EUC in model results for El Niño periods (Montes et al., 2011). According to earlier observations, the disappearance of the EUC in the eastern Pacific seems

to be related mainly to strong El Niño events. For the very strong 1982/83 El Niño, a disappearance of the EUC was described for the eastern Pacific (Halpern, 1997), whereas for the strong 1997/98 El Niño the EUC disappeared over all longitudes (Izumo, 2005). In contrast, during the moderate El Niños of 1986/87 and 1991/92 a disappearance was described in the western and central Pacific, but only a
5 weakening in the eastern Pacific (McPhaden et al., 1990; McPhaden and Hayes, 1990; Izumo, 2005; Kessler and McPhaden, 1995; Seidel and Giese, 1999).

Four hydrographic sections near the Peruvian shelf between $\sim 9^{\circ}\text{S}$ and $\sim 16^{\circ}\text{S}$ had different El Niño related signals in October 2015. At $\sim 9^{\circ}\text{S}$ there was a large SST increase, and we observed upwelling of lighter water which was both warmer and more oxygenated, all of which are characteristic upwelling
10 features of El Niño events. Between 12°S and 16°S the SST increase in October 2015 was weaker than at 9°S , and at the easternmost stations near the Peruvian shelf at $\sim 12^{\circ}\text{S}$, $\sim 14^{\circ}\text{S}$ and $\sim 16^{\circ}\text{S}$ cold and oxygen-poor water was upwelled as during regular upwelling conditions, probably some left-over water from the pre El Niño period. However, west of the easternmost stations, El Niño type changes were observed also below the thermocline and oxycline, a feature which weakened southward and which may
15 be related to the shoaling and intensification of the PCUC and the influence of a downwelling Kelvin wave.

The 2015 El Niño started strong early in the year, and by October 2015 had an ONI index similar to earlier major El Niño events. The water characteristics at $85^{\circ}30'\text{W}$ at the equator and EUC variability and upwelling at $\sim 9^{\circ}\text{S}$ also indicated that a strong EP El Niño had developed. However, at 1°N and
20 $2^{\circ}30'\text{S}$ at $85^{\circ}30'\text{W}$ and at the sections near the shelf between 12°S and 16°S , the El Niño influence was still weak. To this end, the weak EUC clearly indicated a strong EP El Niño at the equator, while off the South American continent the distribution of hydrographic parameters, oxygen and nutrients indicated a transition period from regular to El Niño conditions progressing southward along the Peruvian shelf. Despite the strong 2015 El Niño, the shift to El Niño distribution in the eastern Pacific was surprisingly
25 slow. As the ONI index increased to the end of 2015, we expect that the El Niño conditions were strengthening in the eastern Pacific after the cruise in October 2015. Measurements carried out by CNRS, IRD and IMARPE-IFREMER with a Glider from IFREMER at about 8°S off Peru between 7 November and 17 December 2015 showed an increase in temperature and oxygen and a decrease in

density at ~100 m when compared to October 2015, thus confirming the expected strengthening of the El Niño conditions. (<https://www.ird.fr/toutel-actualite/actualites/communiqués-et-dossiers-de-presse/cp-2015/lancement-de-cienperu-projet-cienperu-projet-d-etude-des-impacts-d-el-nino-2015-2016-sur-l-ecosysteme-marindu-perou>)

(http://www.ego-network.org/dokuwiki/doku.php?glider=tenuse%2CEL_Nino&posti=0&postj=position_zoom0&pposti=0&ppostj=scaptemperature&chchk=&defset=default_scatter)

In summary, the temperature, salinity and oxygen measurements all indicate that during October 2015 the El Niño was strongest along our northern transects and weakest along our southern transects. This was also apparent in the nutrient properties between the northern and southern portions of our study region. As outlined above, at 12°S the N:P ratio was higher and nitrite concentrations were lower during October 2015 when compared to the non-El Niño period of December 2012, both of which point to a reduction in the magnitude of denitrification. When comparing the differences between coastal nutricline N:P ratios and nitrite concentrations along the coast, we found that the differences between October 2015 and December 2012 decreased between 12°S and 14°S, and again between 14°S and 16°S (data not shown). This again highlights the potential for El Niño events to impact N loss processes and upper water column biogeochemistry.

A Supplement is related to this article.

Author contributions. L. Stramma and T. Fischer conceived the study, wrote the manuscript and carried out the ADCP and hydrographic measurements on the RV Sonne cruise in 2015 as well as on some of

the RV Meteor cruises. D.S. Grundle was co-chief scientist of the RV Sonne cruise in October 2015, organized the nutrient sampling and interpreted the nutrient data. G. Krahnmann calibrated the RV Meteor and RV Sonne CTD data and interpreted the hydrographic data. H.W. Bange was chief scientist on RV Meteor in December 2012, he was responsible for the nutrient measurements on this cruise and
5 interpreted the nutrient data. C.A. Marandino was chief scientist on the RV Sonne cruise in October 2015 and interpreted the nutrient data. All authors discussed and modified the manuscript.

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Table 1. Time and geographical location of CTD data used in this study and the NINO 1+2 and ONI indices for the months of observation or for 2 months for measurements carried out at the end or beginning of a month listed in the tables (<http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices>) and (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml).

Time	location	NINO 1+2	ONI
10 29.03.-31.03.1993	1°N-2°40'S	+0.65 March +0.97 April	+0.5 March +0.7 April
12.02.-13.02.2009	1°N-2°40'S	-0.11	-0.7
01.11.-03.11.2012	1°N-2°40'S	-0.11 Oct. -0.38 Nov.	+0.4 Oct. +0.2 Nov.
07.10.-08.10.2015	1°N-2°30'S	+2.52	+2.0
06.12.-23.12.2012	~9°S-~16°S	-0.68	-0.2
15 10.10.-19.10.2015	~9°S --~16°S	+2.52	+2.1

Table 2. Summed zonal positive (eastward) and negative (westward) ADCP transports in Sv ($10^6 \text{ m}^3 \text{ s}^{-1}$) in the equatorial channel at 85°50'W in March 1993, February 2009 and November 2012 and at 85°30'W in October 2015 as well as the related El Niño status. The velocity data were slightly smoothed and extrapolated to the surface.

Time	1°S – 1°N, 0 – 300 m		2°30'S – 1°S, 0 – 300 m		El Niño status
29.03.-31.03.1993	12.77	-0.38	6.28	-0.07	early El Niño-like
12.02.-13.02.2009	3.55	-1.58	0.55	-1.57	late La Niña-like
25 01.11.-03.11.2012	10.78	-0.94	4.22	-0.36	neutral
07.10.-08.10.2015	0.02	-13.86	0.78	-4.08	El Niño

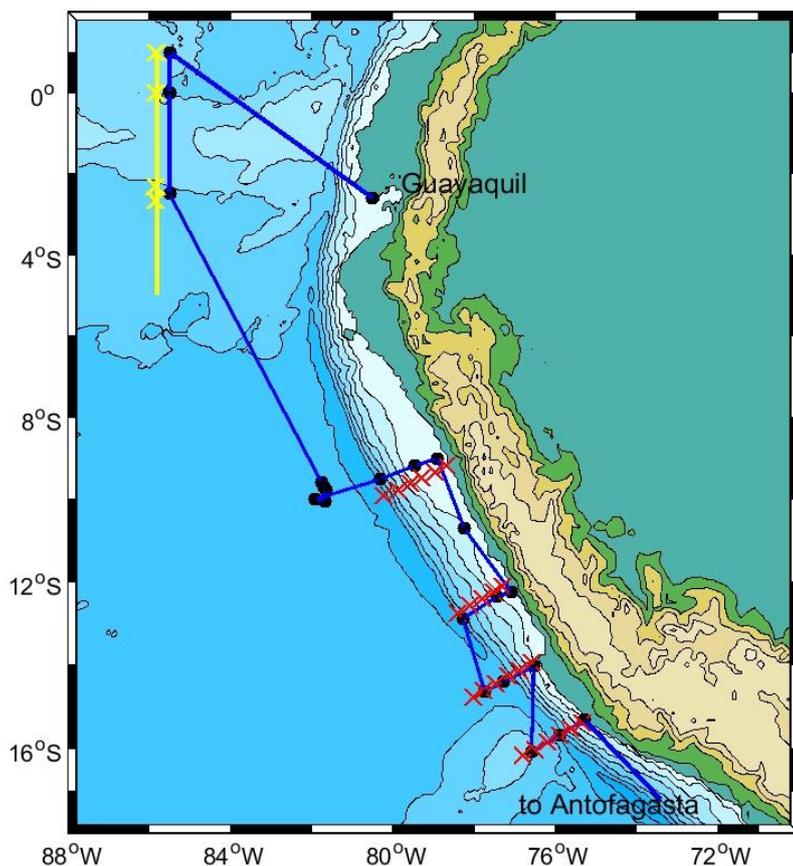
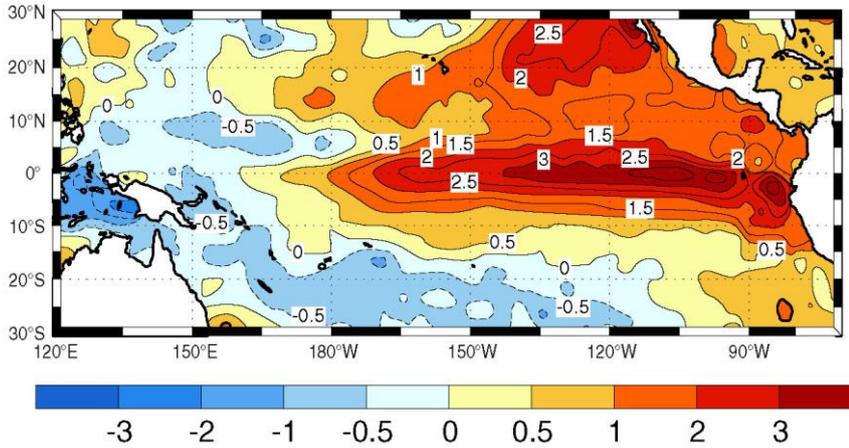


Figure 1. Cruise track (blue line) and CTD stations (black circles) of cruise RV *Sonne* from Guayaquil 5 October to Antofagasta 22 October 2015, as well as equatorial stations March 1993, February 2009 and November 2012 (yellow x), CTD sections off Peru December 2012 (red x) and ADCP sections across the equator (yellow line). Topography (color) with depth/height contours in 1000 m intervals enhanced by the 200 m depth contour.

Average SST Anomalies
27 SEP 2015 - 24 OCT 2015



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Figure 2. Average sea surface temperature anomalies in °C for the period 27 September 2015 to 24 October 2015. Image with permission from NOAA extracted from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/enso_evolution-status-fcsts-web.pdf file version from 26 October 2015, redrawn with very minor modifications to improve the figure quality.

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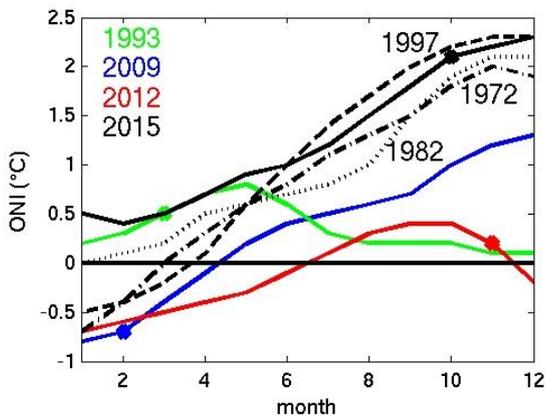
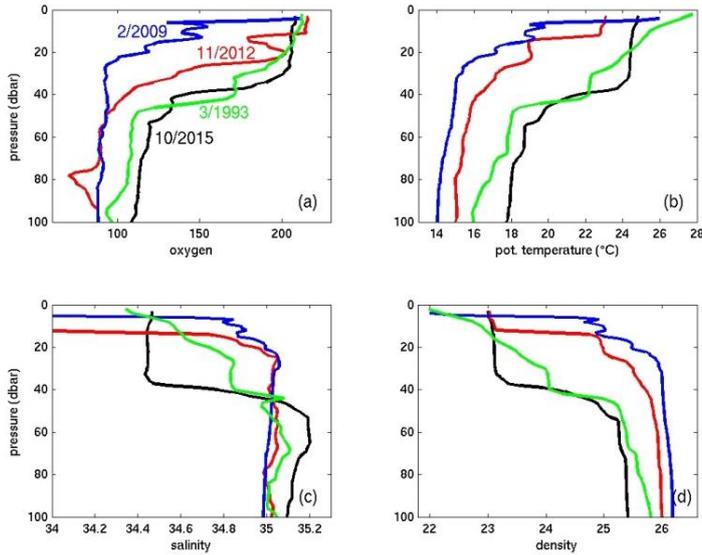


Figure 32. ONI index for the strong El Niño years 1972 (dash-dotted), 1982 (dotted), 1997 (dashed), and the years used here 1993 (green), 2009 (blue), 2012 (red) and 2015 (black line). The months of measurements used here are marked by coloured dots.



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Figure 43. Upper 100 m profiles at the equator at 85°50'W for 30 March 1993 (green), 12 February 2009 (blue), 2 November 2012 (red) and at the equator at 85°30'W for 7 October 2015 (black) for (a) oxygen in $\mu\text{mol kg}^{-1}$, (b) potential temperature in $^{\circ}\text{C}$, (c) salinity and (d) potential density in kg m^{-3} .

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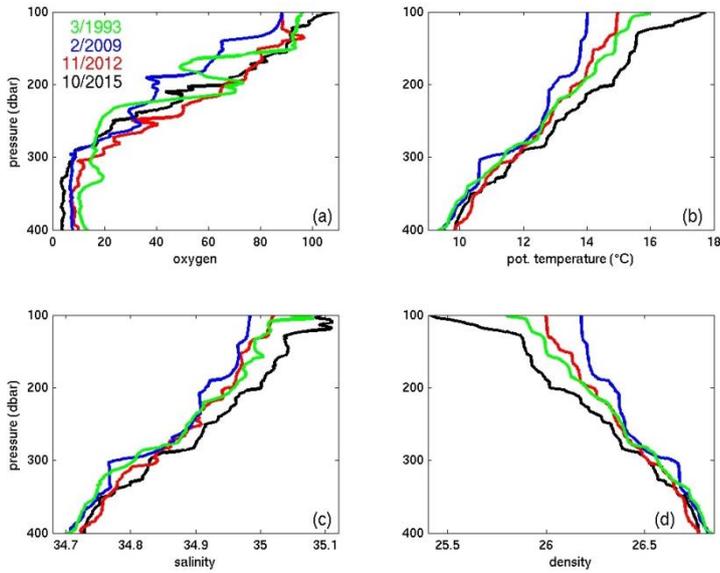


Figure 54. Same as Figure 43, but for 100 to 400 m depth.

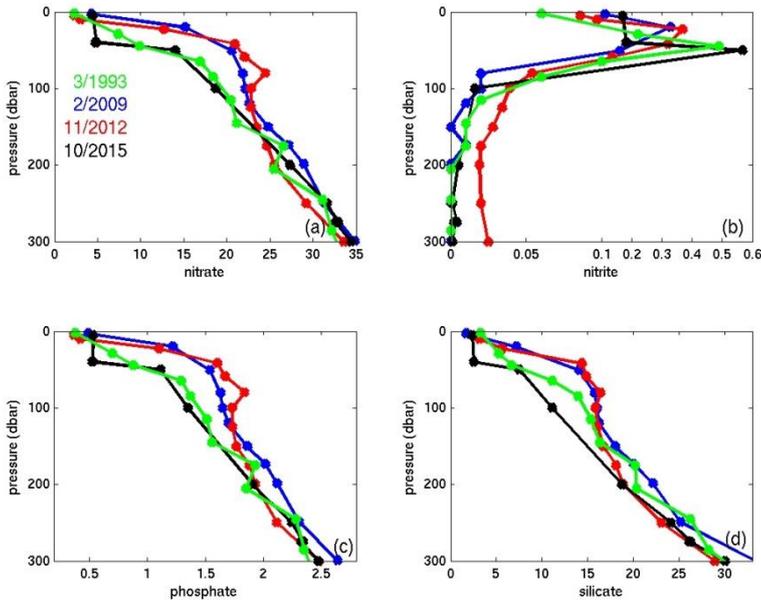
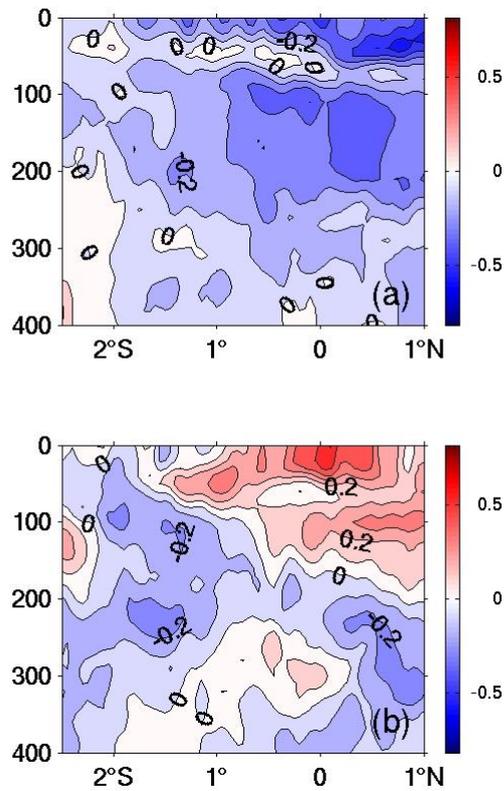


Figure 65. Upper 300 m profiles at the equator at 85°50'W for 30 March 1993 (green), 12 February 2009 (blue), 2 November 2012 (red) and at the equator At 85°30'W for 7 October 2015 (black) for (a) nitrate in $\mu\text{mol L}^{-1}$, (b) nitrite in $\mu\text{mol L}^{-1}$ (scale change at $0.1\mu\text{mol L}^{-1}$), (c) phosphate in $\mu\text{mol L}^{-1}$ and (d) silicate in $\mu\text{mol L}^{-1}$.



5 **Figure 76.** ADCP zonal (positive eastward) (a) and meridional (positive northward) (b) velocity section (in m s^{-1}) on the diagonal section from the Ecuadorian shelf at $\sim 2^{\circ}30'S$ to $1^{\circ}N$, $85^{\circ}30'W$ on 5 and 6 October 2015 (see Figure 1). Contour interval is 0.1 m s^{-1} .

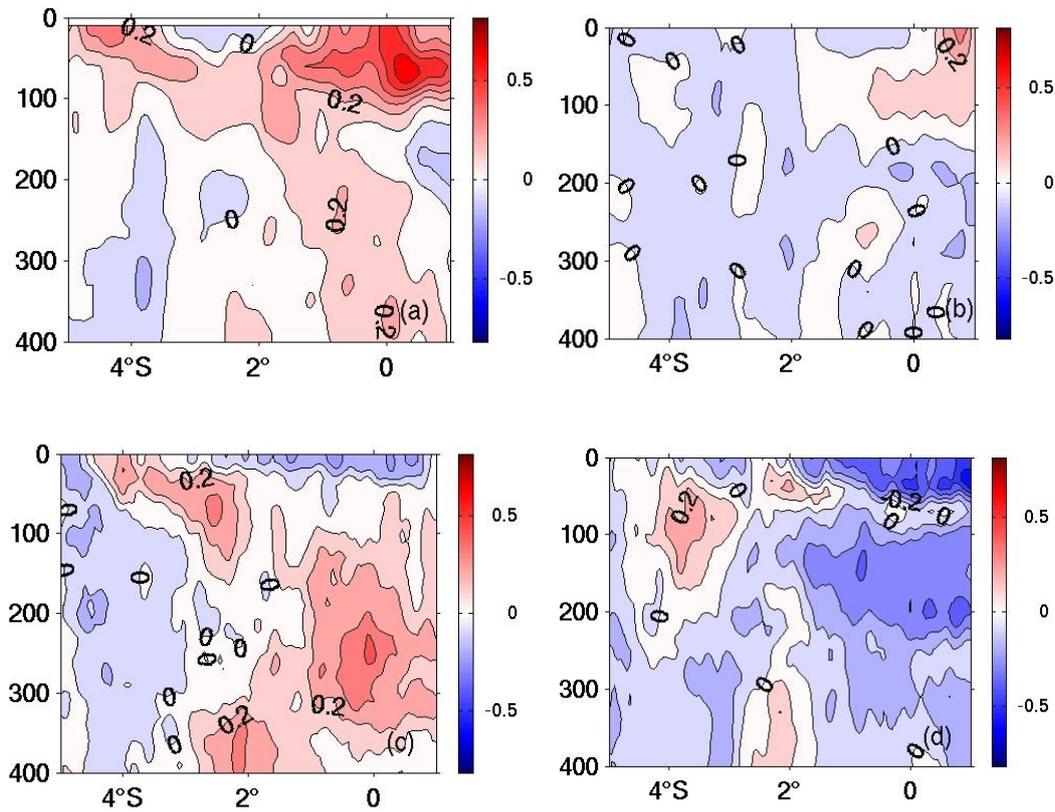


Figure 87. Zonal ADCP velocity sections (in m s^{-1} ; positive eastward; contour interval 0.1 m s^{-1}) on the
 5 meridional path from 1°N to 5°S at $85^\circ50'\text{W}$ **(a)** in March 1993, **(b)** in February 2009 **(c)** in November
 2012 and **(d)** from 1°N to $2^\circ30'\text{S}$ at $85^\circ30'\text{W}$ and diagonal to $5^\circ\text{S } 84^\circ12'\text{W}$ in October 2015 (see Figure
 1).

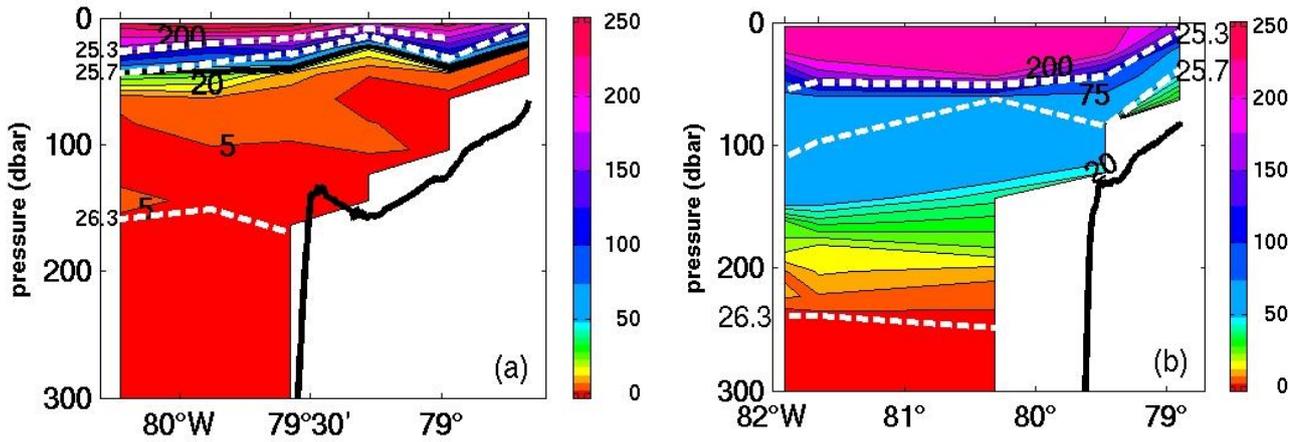


Figure 98. Oxygen section (color; in $\mu\text{mol kg}^{-1}$; same color-scale on both frames) at $\sim 9^\circ\text{S}$ off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines. Please note that the section in October 2015 reaches further west than in December 2012.

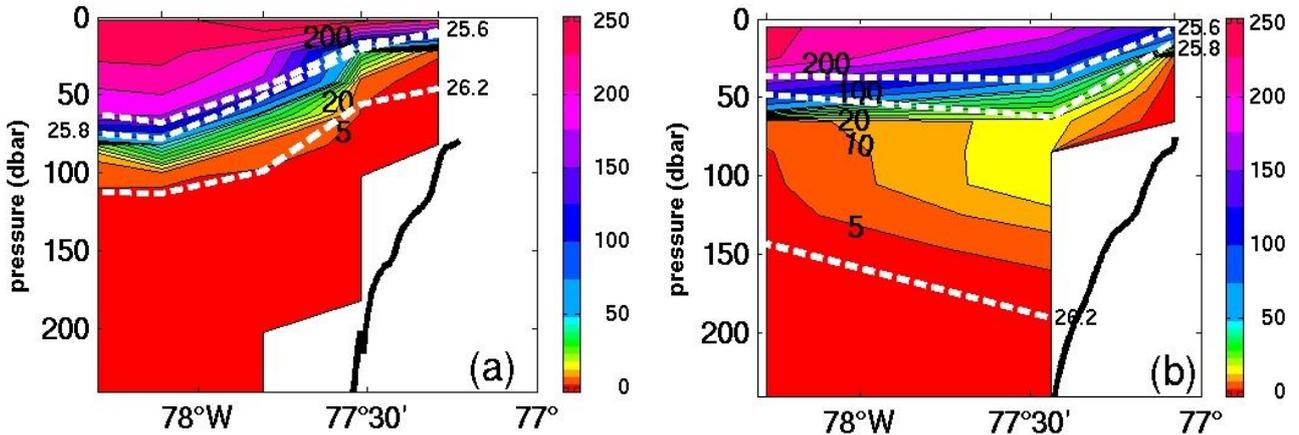


Figure 109. Oxygen section (color; in $\mu\text{mol kg}^{-1}$; same color-scale on both frames) at $\sim 12^\circ\text{S}$ off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines.

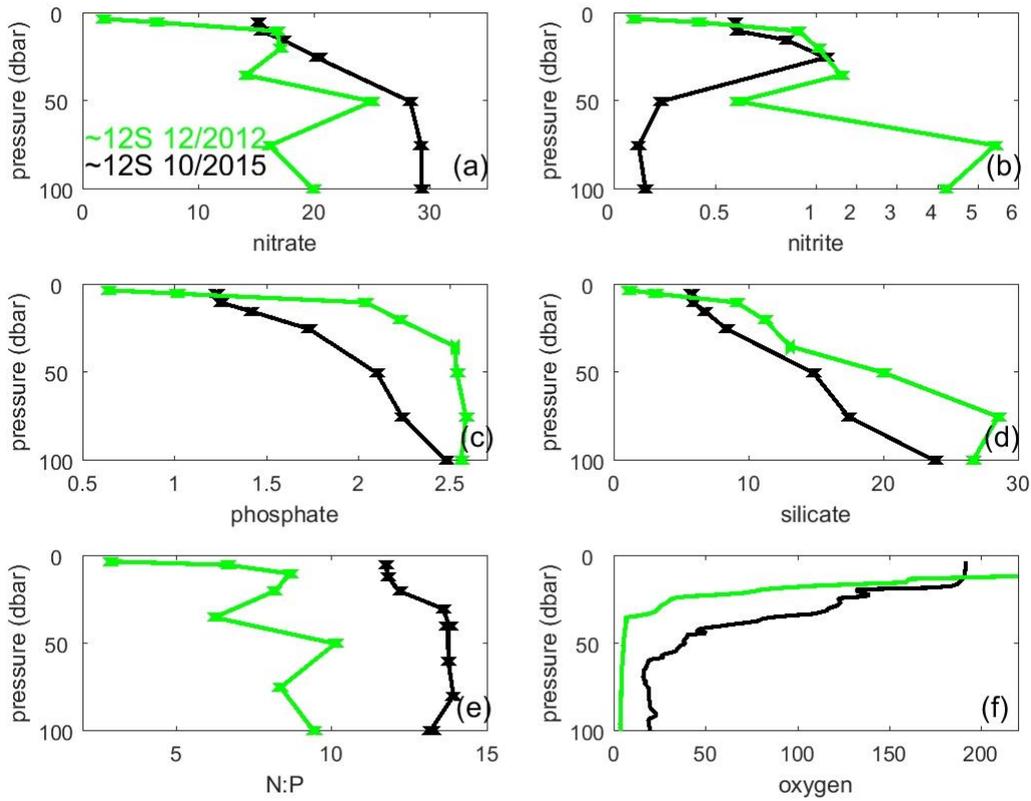
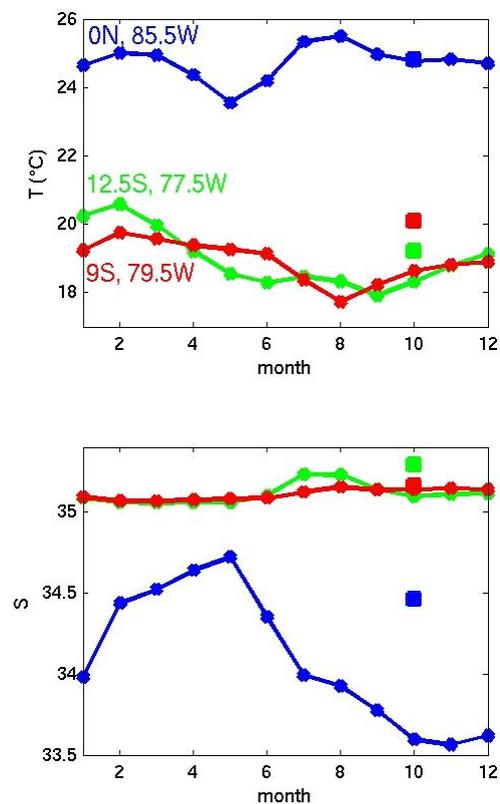


Figure 11. Nutrient profiles at shelf stations with water depth of slightly more than 100 m in December 2012 at 12°15'S, 77°31'W (green) and in October 2015 at 12°21'S, 77°25'W (black) for (a) nitrate in $\mu\text{mol L}^{-1}$, (b) nitrite in $\mu\text{mol L}^{-1}$, (scale change at $1 \mu\text{mol L}^{-1}$), (c) phosphate in $\mu\text{mol L}^{-1}$, (d) silicate in $\mu\text{mol L}^{-1}$, (e) N:P ratio and (f) CTD-oxygen in $\mu\text{mol kg}^{-1}$.

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Supplementary figures



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Fig. S12. Sea surface temperature in °C (top) and sea surface salinity (bottom) from the MIMOC climatology (Schmidtko et al., 2013) for 0°N, 85°30'W (blue line), 9°S, 79°30'W (red line) and 12°30'S, 77°30'W (green line) and surface values from CTD profiles in October 2015 at 0°N 85°30'W (blue square), 9°10'S, 79°28'W (red square) and 12°21'S, 77°25'W (green square).

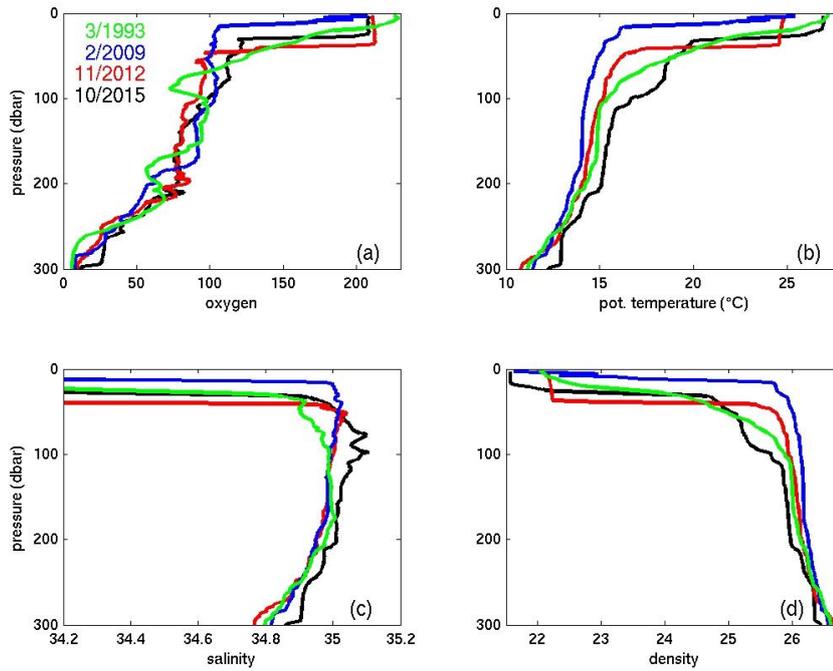


Fig. S23. Upper 300 m profiles at 1°N , $85^{\circ}50'\text{W}$ for 31 March 1993 (green), 13 February 2009 (blue), 2 November 2012 (red) and at $85^{\circ}30'\text{W}$ for 7 October 2015 (black) for **(a)** oxygen in $\mu\text{mol kg}^{-1}$, **(b)** potential temperature in $^{\circ}\text{C}$, **(c)** salinity and **(d)** potential density in kg m^{-3} .

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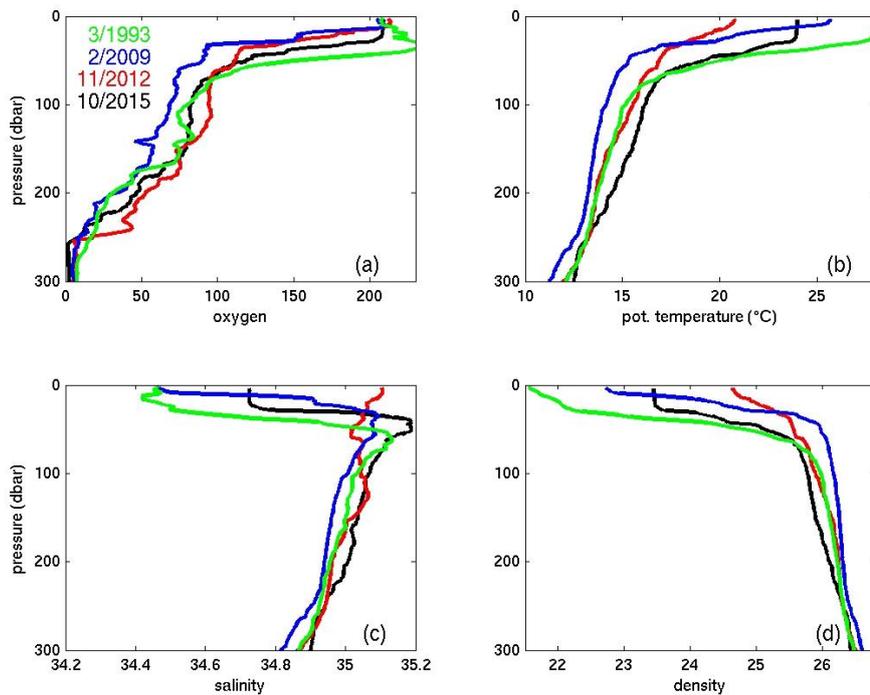


Fig. S34. Upper 300 m profiles at $2^{\circ}30'S$, $85^{\circ}50'W$ for 29 March 1993 (green), 11 February 2009 (blue), 3 November 2012 (red) and at $85^{\circ}30'W$ for 8 October 2015 (black) for **(a)** oxygen in $\mu\text{mol kg}^{-1}$, **(b)** potential temperature in $^{\circ}\text{C}$, **(c)** salinity and **(d)** potential density in kg m^{-3} .

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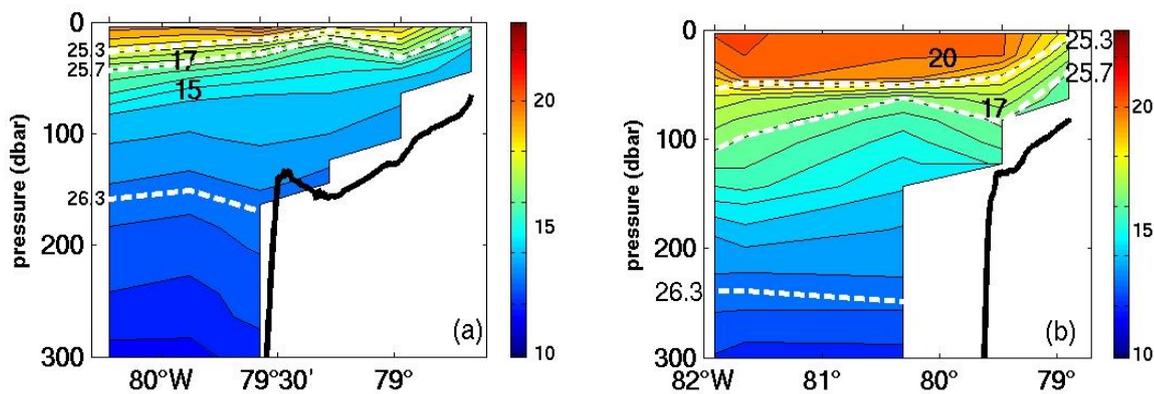


Fig. S45. Temperature section (color; in °C; same color-scale on both frames) at ~9°S off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines.

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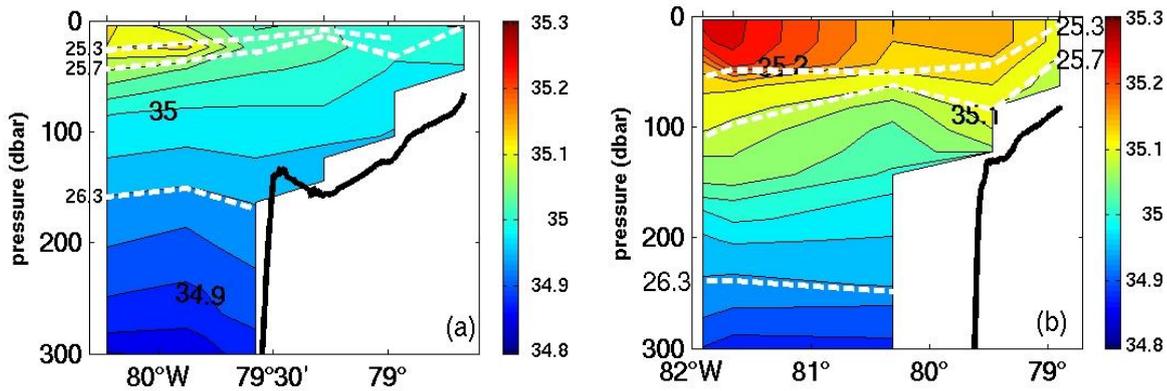
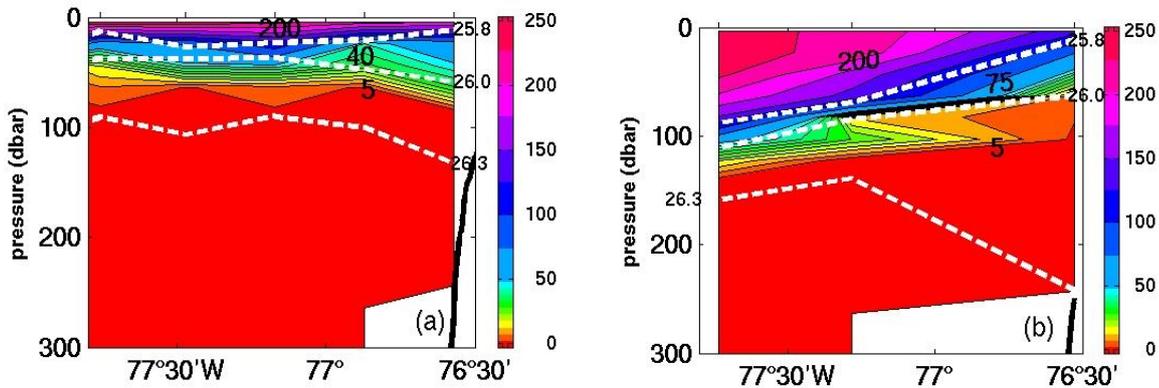
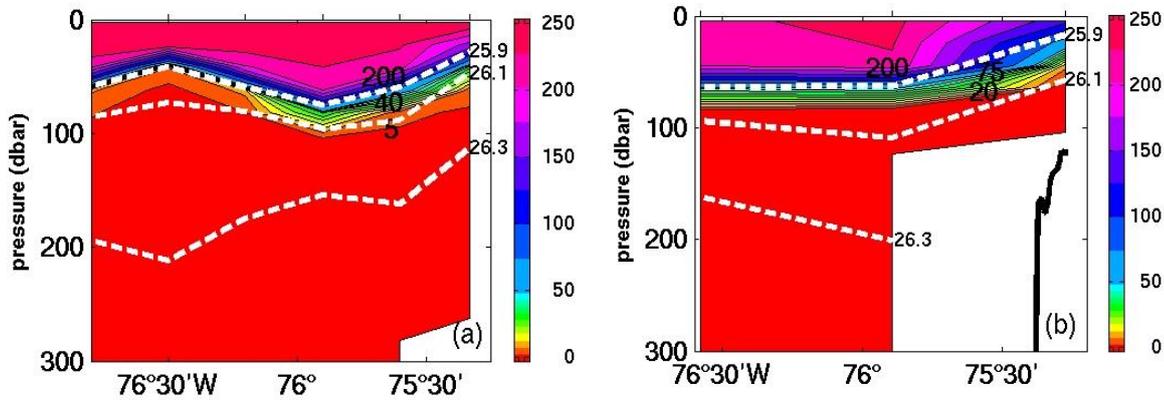


Fig. S56. Salinity section (color; same color-scale on both frames) at ~9°S off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines.



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Fig. S68. Oxygen section (color; in $\mu\text{mol kg}^{-1}$; same color-scale on both frames) at $\sim 14^\circ\text{S}$ off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines.



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Fig. S79. Oxygen section (color; in $\mu\text{mol kg}^{-1}$; same color-scale on both frames) at $\sim 16^\circ\text{S}$ off the Peruvian shelf for December 2012 (a) and October 2015 (b). Three selected isopycnals are included as white dashed lines.

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