Ocean Science Discussions

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Reply on RC1

Gandy Maria Rosales Quintana et al.

Author comment on "Interannual variability in contributions of the Equatorial Undercurrent (EUC) to Peruvian upwelling source water" by Gandy Maria Rosales Quintana et al., Ocean Sci. Discuss., https://doi.org/10.5194/os-2021-13-AC1, 2021

Referee #1 : David Webb

Overall this is a well presented and nicely written paper on the sources of upwelled water off Peru and Ecuador. It does this by following particles tracks from the upwelling regions and shows that much of the upwelled water comes from the Equatorial Undercurrent.

The authors show that the fluxes change from year to year and relate this one to the changing El Nino/La Nina was weak and needs to be improved.

Response: We thank the referee for some positive remarks.

Main points:

Comment 1:The paper only considers upwelling that occurs in the December of each year studied but do not give a reason for this. Figure 3 and Figure 4 indicate that December is a period of weak upwelling off Peru and Ecuador. Was December chosen because it includes the height of the fishing season, is the time when large El Ninos have the most impact, or for some other reason?

Response: According to previous studies (Espinoza-Morriberon et al, 2017, and our results) releasing particles in the Peruvian upwelling system, the seasonal cycle of the vertical mass flux (referred to as the upwelling) peaks from August to October and weakest from December to February, in accordance with the wind stress and nitrate flux.

We considered December by association with El Niño. On reflection, and in response also to Reviewer 2, we will extend our trajectory analysis to include particles released throughout the seasonal cycle.

Comment 2: The paper needs more details on the criteria used for the seeding. Was it for example one particle per cubic meter upwelled during each December?

Response: Thank you for your comment. On line 79, we specify 'Allocating particles in proportion to the upwelling rate', although we can provide more information. Specifically, in each grid cell, we allocate 1 particle per 10 m month^{-1} of upwelling in excess of 50 m month^{-1}, per grid cell. For example, in the

simple case that upwelling is 90 m month^{-1}, the excess upwelling rate is 40 m month^{-1}, so we allocate four particles to this grid cell, distributed spatially in a 2x2 array.

Comment 3: I find it difficult to reconcile figure 5 and 6, in which few particles travel 5 degrees eastward during December, with figure 10 b and d, which show 20% of particles travelling 70 degrees during the year, or figure 7 which implies that some particles come from beyond the dateline.

Response: Thank you for your comment. The EUC has been in-situ measured and modeled along the Pacific from 143E to 95W (Bryden, 1985; Johnson et al., 2002; Tsuchiya et al., 1989) and its termination off Peru and Ecuador (feeding other major currents (Karnauskas et al., 2010; Lukas, 1986; Montes et al., 2010)), since it was discovered in 1952 (Cromwell et al., 1954; Knauss, 1959). Year by year, strong changes in the EUC (velocity, core depth and transport, also including Kelvin waves) have been observed, however when El Niño happens, these changes are characterized by a significant eastward transport of water masses (warm pool). It is then possible for the EUC to extend all the way from the western most Pacific to the Eastern most region, when its velocity exceeds a threshold (e.g., 1996-97 daily velocities in NOAA moored buoys, also shown in Figure 9 with transport values >+20 Sv). Under these circumstances, a considerable fraction of virtual particles is derived from the EUC, as is evident in this study.

Comment 4: Figure 7 needs more explanation, especially 7 a and b (where the caption should refer to the log scale and the base). I presume that "particle concentration" is not "the average of the particle concentrations at the start of each year" but is more "the average of the number of particles passing through each averaging box during the course of the year".

Response: Thank you for your comment. Your interpretation is correct, and we will provide more details. We can alternatively now refer to this diagnostic as 'fractional particle presence'.

RC: I would also like to see a figure showing where particles started. Many obviously started in the regions where, on average, the age is greatest, but as the paper is really about where the upwelled water comes from, age by itself is not enough. Such figures might also help to clarify point 3 above.

Response: We provided this information already in Figure 5 and 6, where the initial positions are shown as black dots for each year. We will clarify the caption to emphasize this point.

Comment 5: My main problems with this paper occur once it starts discussing year to year variations. Around line 35 the paper discusses how the easterly trade winds generates a pressure head in the western Pacific and how below the surface the pressure gradient (high in the west, low in the east) drives the undercurrent. Then around line 195 it discusses the flattening of the thermocline during the onset of an El Nino and that this "allowed more of these waters to progress all the way to the eastern boundary, where upwelling continued along the Peruvian coast. Conversely …"

To me this does not make sense because if the thermocline is flat, there is no east-west pressure gradient and no Undercurrent.

Response: Flattening of the thermocline during El Niño of 1997-98, due to the weakening (or reverse) of the trade winds in the western and central Pacific

region (McPhaden, 1999) is typical of the ENSO variability seen in historical model simulations (Terada et al., 2020) and observations (NOAA buoy array data) (Kessler & Mcphaden, 1995). We do not claim that the thermocline is completely flattened. Rather, it quasi-flattens, shallowing in the western basin and deepening in the eastern region – warming up the cold tongue as observed in previous El Niños (Kessler & Mcphaden, 1995; McPhaden, 1999) for 1 to 3 months (observed in NOAA in situ data). Furthermore, we find that associated with flattening of the thermocline is eastward extension of the EUC, providing relatively more of the upwelling 'source waters' at the eastern boundary. We will clarify this point in the revised manuscript.

RC: There are related problems with figure 10. Upwelling is largest in December 1997, at the height of one of the strongest El Ninos when the fraction of particles coming from the central pacific is also very large. The year 2000 has similar properties at the time of a weak La Nina, but almost nothing happened in 1998 and 1998 when there were strong La Nina. In 1992 there was also a reasonable El Nino, but with hardly any upwelling.

To me this means that simple arguments in the paper are not working – maybe scatter plots of upwelling volume against El Nino index or mean distance travelled in the Undercurrent against El Nino index would show something – but I suspect that more is needed.

Response: We will consider presenting the results obtained from releasing particles in other months throughout the years (see earlier response). Our findings will be accordingly updated.

RC: One of the problems appears to be the length of time integrated. Although the index indicated a large El Nino in December 1997, this was after a full year in which the El Nino was developing. Particles starting in the west or central Pacific early in the year would have travelled eastwards on a strong undercurrent. As the year developed the particles may have stayed ahead of the change in surface winds and so reached the western Pacific. If this is the case, then it was the strong undercurrent early in the year which carried the water eastwards to be upwelled, not the fact that El Nino index was large in December. In addition – why, in the middle of a strong El Nino, when the trades had failed, why was there so much upwelling in the east?

Response: Upwelling associated with the EUC is larger (considering those particles sourced from the eastward-extended EUC), but not the absolute upwelling. So, the upwelling is weaker in 1997, just proportionally more from the EUC. As already mentioned, in revising the manuscript we will expand the Lagrangian analysis to back track particles released in other months of the year, which should account for progressive changes in both the EUC and the coastal upwelling system during evolving ENSO events.

RC: There is also a problem with the year 2000 when there was a weak La Nina. Then both the undercurrent and the winds would have been strong – so by the normal theory all the undercurrent water would be expected to be upwelled before arriving off South America. So why was upwelling so strong this year and why was so much of it from the undercurrent?

Response: We will complement this point with our year-round particle releases. Although, we think that in the 'absence' of supply from the EUC, that coastal upwelling is sourced more locally. Also, EUC intensification not only occurs during El Nino events, but also during other warmer events such as in 2000.

RC: Also why also was upwelling less in other weak La Nina years and why, when there were strong La Nina of 1998-1999, was there little upwelling and so little water coming from the central pacific?

Response: As explained previously, EUC waters are typically upwelling well to the west of the coastal upwelling zone in La Niña years, when the more strongly tilted thermocline brings EUC waters into the surface Ekman layer by the longitude of Galapagos. During a strong La Nina 1998-1999, the EUC next to Galapagos is almost absent (or in the eastern region), so Peruvian upwelled waters sourced from the EUC are consequently less than during weak La Nina. Only local water masses are feeding the Peruvian upwelling region (study area). As also mentioned, we will revisit this finding with more complete Lagrangian analyses (year-round releases). We will further develop and provide a metric of the Peruvian upwelling, 5-daily for the ORCA12 hindcast (1988-2007), alongside diagnostics of predicted coastal upwelling, based on Ekman theory, to which some of the variability in upwelling may be attributed.

Comment 6: Another area in which I am unclear is the relation of El Ninos to fisheries. As I understand it the fisheries in the region are successful because the upwelled water is full of nutrients. This normally implies that it comes from deep in the ocean and that it has not recently been within the surface photic zone where it would lose nutrients. So Undercurrent water is just perfect. I also understand that the reason research on the El Nino started was that with the relaxation of the trades during an El Nino, the surface mixed/nutrient poor layer became thicker and any upwelled water was nutrient poor. So how does this match with so much December 1997 water coming from the undercurrent? At the height of a strong El Nino the water in the photic zone above 100 m should have all spent some time near the ocean surface.

Response: El Niño can have positive and negative effects in the fisheries regarding the species we are analyzing (Ramiro Castillo et al., 1997; Raul Castillo, 1996; Contreras Paya, 2017; Icochea et al., 1989; Tam et al., 2008; Taylor et al., 2008). In this case, we discuss the results obtained from particles travelling within the EUC reaching the Peruvian coast, regarding one of the most abundant demersal species in Peru, Peruvian Hake, that has been widely studied as a bioindicator for the EUC strengthening off the Peruvian coast (Icochea et al., 1989; Tam et al., 2008; Taylor et al., 2008). Also, we have mentioned other benthic and pelagic species that were affected by the presence of the EUC before/during El Niño (Martina, 2004). Of course, the EUC is not the only variable influence on fisheries off Peru. Further analysis of variable coastal upwelling (see earlier comment) will put the EUC influence in a wider context. (We will add these extra references in our work).

***Previous studies have established that the EUC brings important nutrient-rich waters to the southeastern part of our study region (Qin et al., 2016; Slemons et al., 2009; Vichi et al., 2008). Espinoza-Morriberon et al. (2017) explore the relation between vertical fluxes (upwelling) and nitrate with the ROMS-PISCES coupled model, finding that nutrients decrease dramatically during extreme El Niños and other warm events. We will cite and discuss this corroborative evidence in the revised manuscript*.**

Conclusions:

Given these problems I do not really want to spend time on other details. I think a full solution needs a lot more work, a better knowledge of the winds causing upwelling, the effect of stratification on the amount of upwelling, the changing strength of the undercurrent and upwelling at different longitudes and different times of year. I do not think that I can ask for this to be done before publication but I see two ways forward: The first is to accept the difficulties. The paper successfully shows that, on average, a large fraction of the upwelled water can come from the Undercurrent as opposed to currents running along the coastline. The variations with time can also be presented but with the difficulties pointed out and possible explanations noted. Papers that highlight problems with current ideas often get many citations. Another possibility is to concentrate on just the last three months or so of each year, during which the El Nino index will not have changed so much. You should already have the data and it may be simpler to relate the amount of upwelling and contribution from the undercurrent (near the Galapagos) to the El Nino index and the winds near the coast.

Response: Thank you for your valuable comments, we will extend our trajectory analysis to include particles released throughout the seasonal cycle, and separately examine the variations in coastal upwelling (attributed to variations in equatorward winds).