Detailed response to the referee # 1

We would like to thank referee 1 for the constructive comments, which have allowed a considerable improvement of the manuscript. The most substantial point the referee stated concerned the analyses of the advective fluxes of nutrients. The respective analysis has been added to the revised version of the manuscript and it further supports our conclusions.

General Comments

This paper shows results from a coupled physical and biogeochemical ocean numerical simulation. The authors identified two anticyclonic eddies off Peru in the simulation and showed that the local biogeochemical processes in the model can not explain the temporal variations in nitrate concentration within eddies. Although the authors found that local biogeochemical processes are less important than advective processes, the analyses presented by the authors were mostly focused on the role of biogeochemical processes, with some hydrographic investigations to track the origin of the advected water. Because the authors found that advective processes are important, then the advective fluxes should be analyzed directly, as they are available from the numerical results. Another effective tools to track the origin of the water mass would be particle tracking. Without these analyses, the paper seems to lack the supporting evidences to derive the conclusions that nutrient injected into and out of the eddies by advection are playing important roles in time variations of nutrients within the eddies.

We agree with Referee #1 that models offer the opportunity to perform in-depth analysis of advective processes and that this will bring more insight on the processes playing a role on nutrient variation within the eddies. Following Referee #1's advice we have computed the advective fluxes within the selected eddies. We focus on the vertical and horizontal advection because in the high-resolution configuration used here, they are of leading order (Fig.1 and Fig. 2).

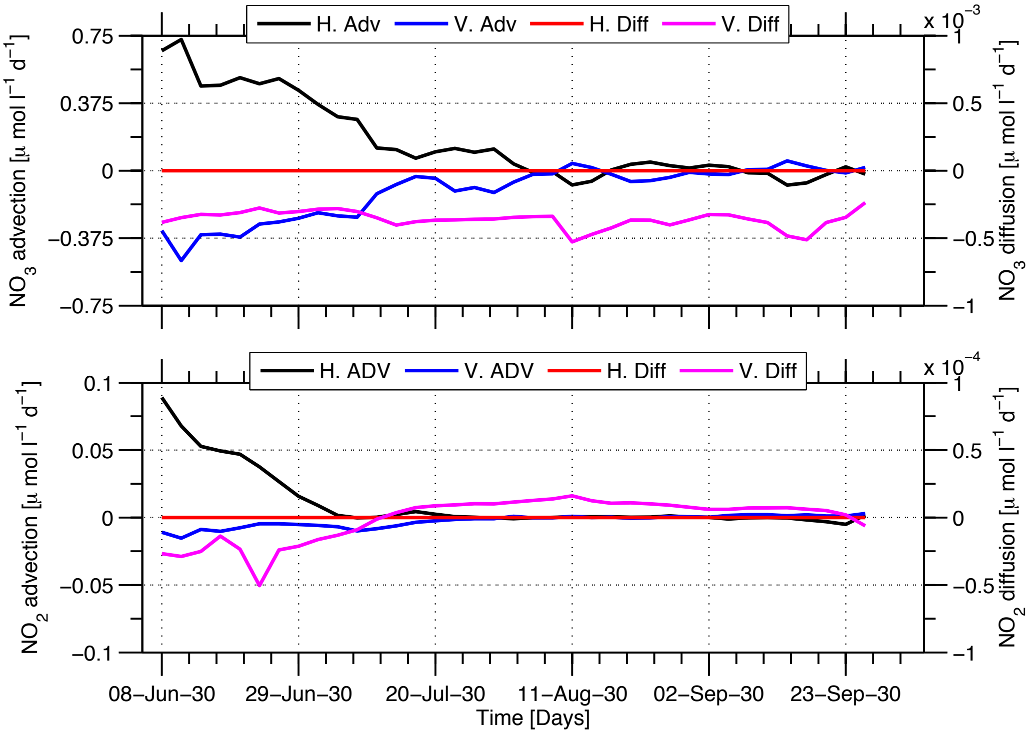

Figure 1. Nitrate (upper panel) and nitrite (lower panel) advective and diffusive fluxes within the eddy A_{sim}. Lines indicate horizontal (black) and vertical (blue) advection [μmol $l^{-1}d^{-1}$], horizontal (red) and vertical diffusion [μmol $l^{-1}d^{-1}$]. Note the different scales on the left (advective transport) and right (diffusive transport) axis.

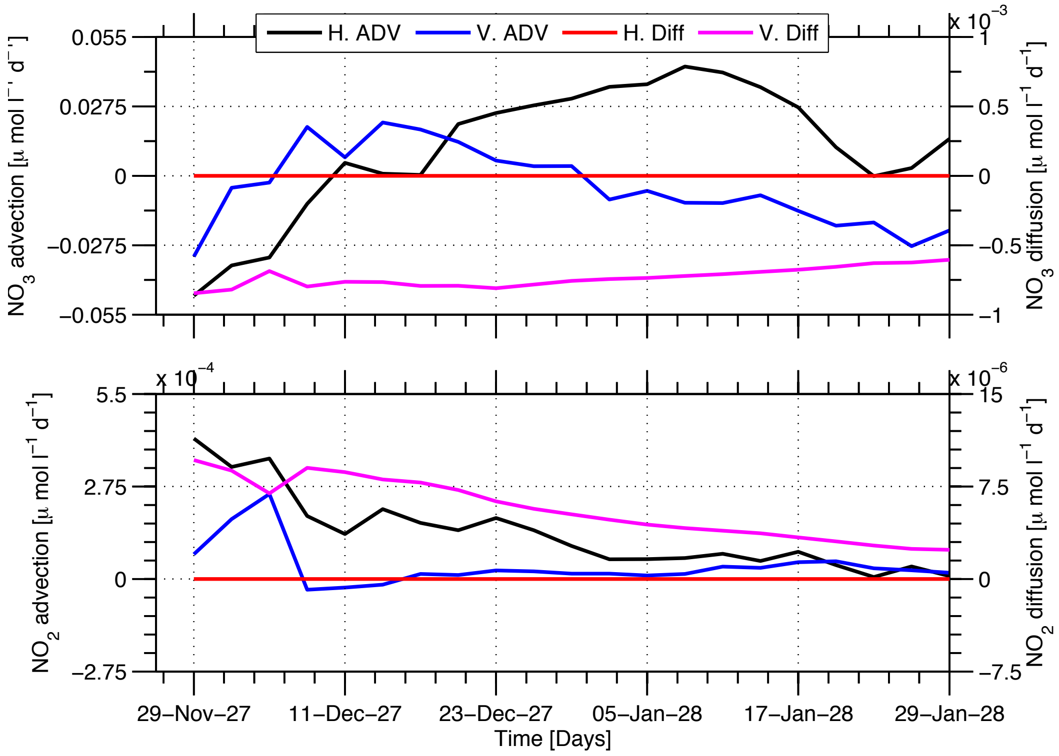

Figure 2. Nitrate (upper panel) and nitrite (lower panel) advective and diffusive fluxes within the eddy B_{sim}. Lines indicate horizontal (black) and vertical (blue) advection [μmol $l^{-1}d^{-1}$], horizontal (red) and vertical diffusion

[μmol $l^{-1}d^{-1}$]. Note the different scales on the left (advective transport) and right (diffusive transport) axis.

Addition to the text, section 3.2, page 7 and page 8:

…. To investigate the origin of water masses present in the selected eddies, we analyse the advective transports of both nitrate and nitrite into the eddy during the eddy's lifetime (Fig. 10 and Fig. 12). The water mass properties within the structure are also analysed and compared with the surrounding environment during different instants of the eddy's lifetime (Fig. 11 and Fig. 13). Figure 10 illustrates the nitrate and nitrite fluxes into the eddy $A_{sim.}$ It shows a strong injection of nutrients from the lateral margins of the eddy. This nutrient injection is elevated in the first months following the eddy formation. The cumulative fluxes of both nitrate and nitrite significantly increase in this period and follow the evolution of both nitrate and nitrite within the eddy. These dynamics suggest a strong exchange with the surrounding environment during this period. This is also visible in the water mass properties within the eddy structure (Fig. 11). At the surface, waters present within the eddy A_{sim} are relatively cool and fresh compared to the water masses present following the eddy formation (Fig. 11-a-b)…..

The nutrient fluxes across the edge of the eddy B_{sim} are presented in Figure 12. It shows a contribution of both horizontal and vertical transport to the nutrient variation within the eddy, during the eddy's lifetime. After the eddy B_{sim} formation, the nitrate fluxes through the edge of the eddy B_{sim} are dominantly out-going, showing a loss of nitrate to the surrounding environment (Fig. 12-a). These out-going fluxes reduce the nitrate availability within the eddy. About half a month later, the nitrate concentration within the eddy increases. This increase is to a large extent due to the nitrate supply into the eddy structure from both vertical and horizontal boundaries. On the contrary, the nitrite supply into the eddy is largest and positive in the month following the eddy formation and decreases afterwards (Fig. 12-b).

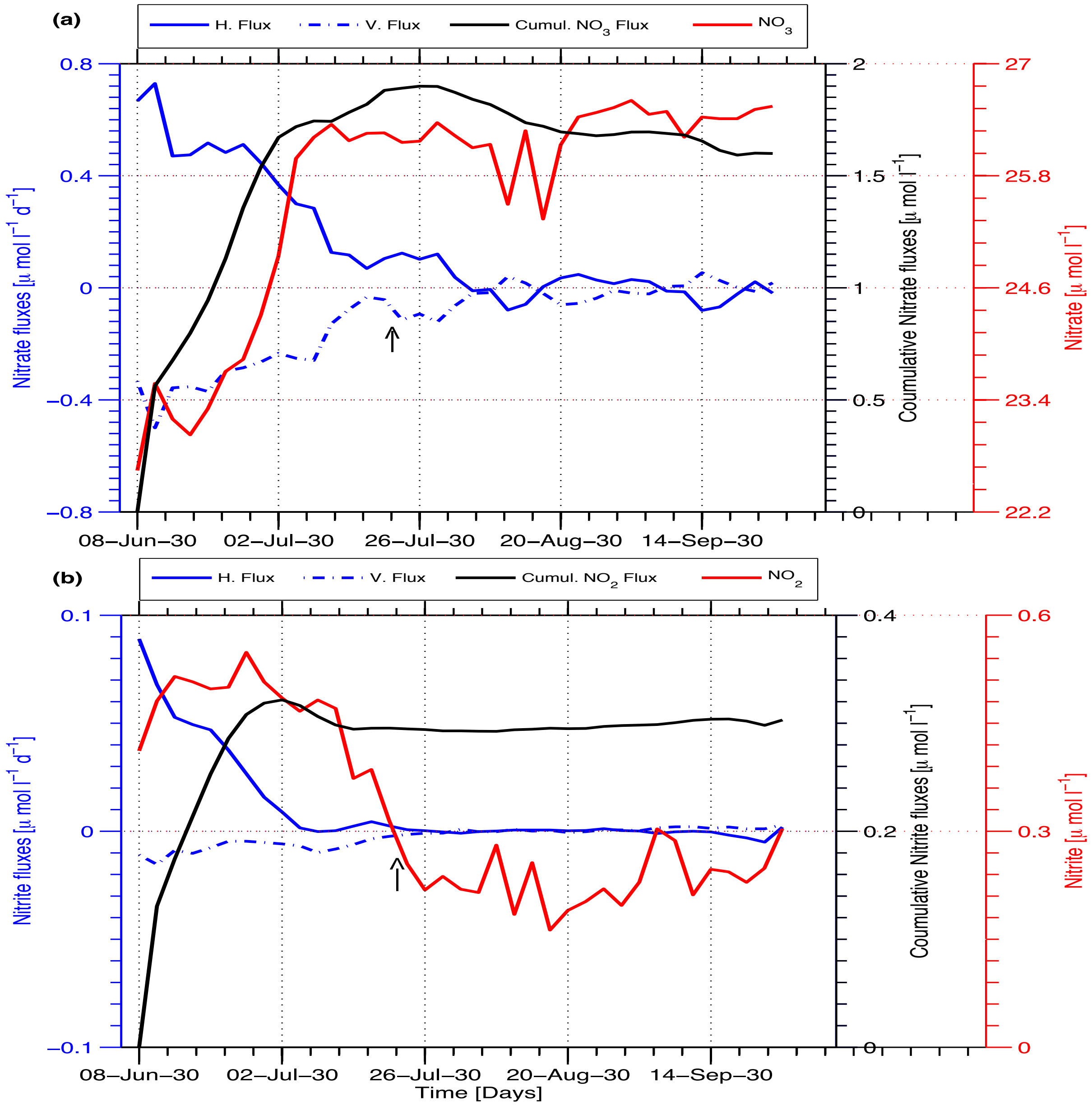

Figure 10. Nitrate (a) and nitrite (b) advective fluxes into the eddy A_{sim}. Lines indicate horizontal (solid blue, μmol $l^{-1}d^{-1}$), vertical (dashed blue, μmol $l^{-1}d^{-1}$) and cumulative (black, μmol l^{-1}) advective fluxes. Red line represents the available nitrate within the eddy [μmol l^{-1}]. Arrows indicate the time where the sections in Figure 4 were taken

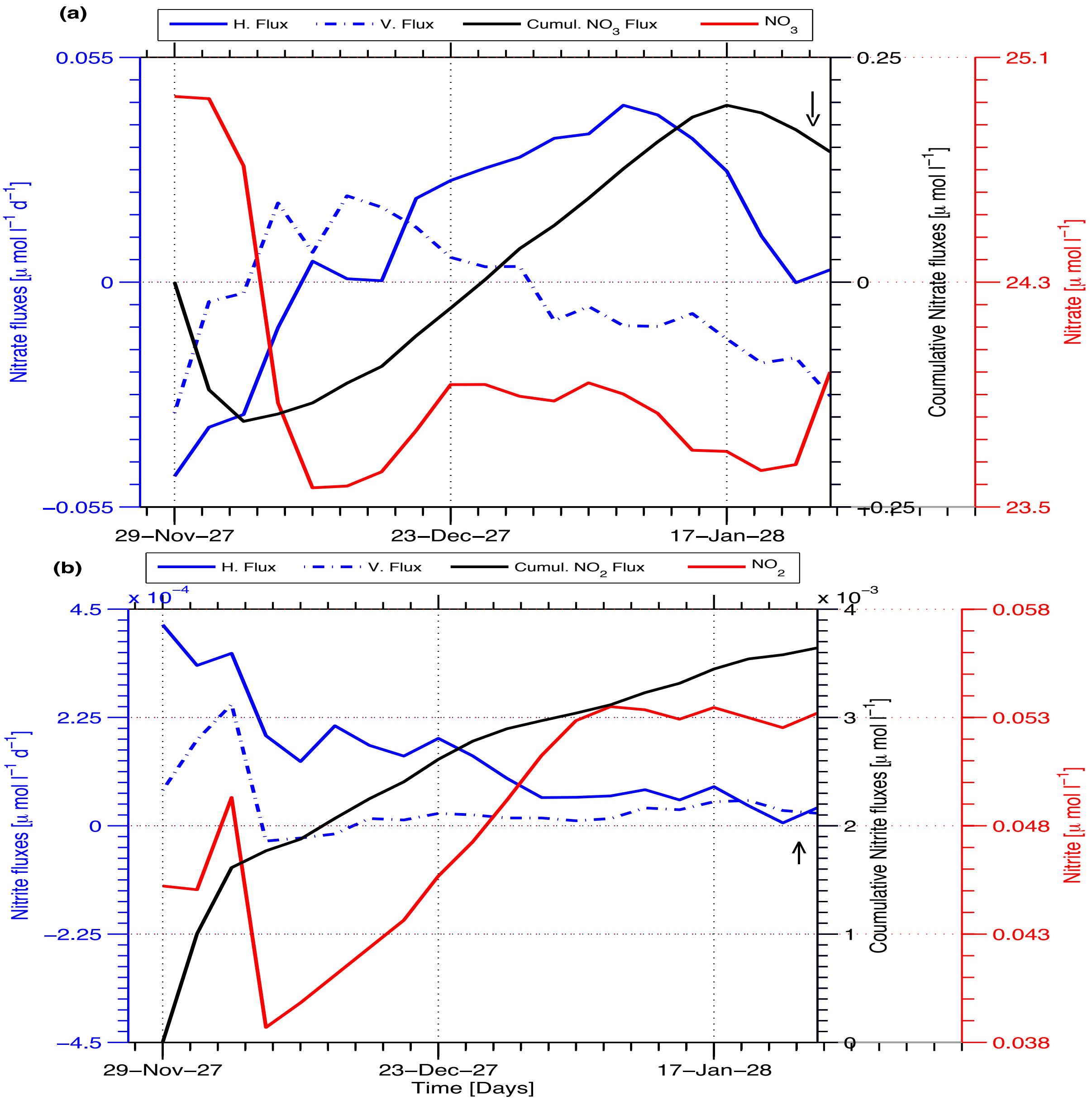

Figure 12. Nitrate (a) and nitrite (b) advective fluxes into the eddy B$_{sim}$. Lines indicate horizontal (solid blue, μmol l^{-1}d^{-1}), vertical (dashed blue, μmol l^{-1}d^{-1}) and cumulative (black, μmol l^{-1}) advective fluxes. Red line represents the available nitrate within the eddy [μmol l^{-1}]. Arrows indicate the time where the sections in Figure 5 were taken

Specific Comments P1 L16 “. . . to enhance near-surface vertical transport and thus increase the . . .” For this sentence, references should include submesoscale papers e.g. Levy et al, Mahadevan and Archer 2000.

The Levy et al, 2001 and Mahadevan and Archer, 2000 have been added.

P1 L24 “Eastern Tropical Pacific (ETSP)” Should be “Eastern Tropical South Pacific”
Changed accordingly.

P3 L28 “Fig. 2-c” Should be “Fig. 3C”.
Changed accordingly.

P3 L29 “Fig. 3-f” Should be “Fig. 3-c”.
Changed accordingly.

P4 L17 “. . . apparently indicative of on-going denitrification within the structure, . . .” As the authors have numerical results for denitrification shown in Fig. 6, these numerical indications should be mentioned here as well.

The goal of the respective subsection is to describe the eddy dynamics as generally viewed in snapshots obtained during oceanographic measurement campaigns. Our point is that snapshots-based interpretation of the processes involved can be misleading in regions governed by mesoscale processes. The comprehensive description of the biogeochemical processes controlling the dynamics within the eddy is presented with more detail in the results and discussion section.

P4 L21 “:. . . with weaker strength of the westward component . . .” Why westward components are weaker?
The asymmetry in the eddy velocity is linked to the flow dynamics during the eddy generation (Chaigneau et al. 2011, Colas et al. 2012, Holte et al 2013). Anticyclonic eddies in the ETSP are generated by the instability of the subsurface poleward Peru-Chile Undercurrent (PCUC, Chaigneau et al. 2011, Colas et al. 2012). A more detailed analysis will be presented in the revised paper.

Note that, following the referee 3, the analysis of the eddy velocity asymmetry have been removed from the new version of the manuscript.

Is this result consistent with the observations?

The observed anticyclonic eddy in the ETSP shows also asymmetric velocities, both in the meridional and zonal velocity components (Chaigneau et al. 2011, Stramma et al. 2013, Thomsen et al. 2016).

Addition to the text, section 2.2.1, page 4:

Else, the eddy A_{sim} presents a subsurface velocity maximum, similar to the observed patterns within anticyclonic eddy in the ETSP (Chaigneau et al. 2011, Holte et al 2013, Stramma et al. 2013, Thomsen et al. 2016). This characteristic is related to the poleward flowing PCUC (Chaigneau et al. 2011, Colas et al. 2012, Holte et al 2013).

P4 L30 "show" should be "shows"

Changed accordingly.

P5 L1 "Minimum velocities" Isn't it "Maximum velocity magnitudes"?

It should be minimum velocity. The eastward component (positive velocity) is minimum at the surface and the westward component (negative velocity) is minimum at the subsurface. However, it is indeed preferable to describe the most prominent feature, which is the maximum velocity magnitude. This will be revised in the new version of the manuscript.

Addition to the text, section 2.2.2, page 5:

... Figure 5 -e and Figure 5 -f show the vertical section of the eddy B_{sim} velocities. Maximum velocities are found at the surface layers in the westward flow and at the subsurface layers in the eastward flow, respectively.

Why westward components are subsurface? Is this result consistent with the observations?

The subsurface velocity maxima in the eddy in the ETSP region are linked the subsurface poleward PCUC (Colas et al. 2012, Holte et al 2013). Eddies and meander type structures are shed by the Peru-Chile Undercurrent (Chaigneau et al. 2011, Colas et al. 2012, Holte et al 2013). Observations in the ETSP have found mode water anticyclonic eddies with subsurface velocity maxima, in both zonal and meridional components (Chaigneau et al. 2011, Stramma et al. 2013, Thomsen et al. 2016).

Addition to the text, section 2.2.2, page 5:

This circulation pattern is similar to the observed velocity within anticyclonic eddies in this region (Chaigneau et al. 2011, Stramma et al. 2013, Thomsen et al. 2016) and likely linked to the dynamics of the PCUC (Chaigneau et al. 2011, Colas et al. 2012, Holte et al. 2013).

P5 L9 "Asim,," Remove one of ",".

Changed accordingly

P5 L13 "Figure 7 shows the time . . ." The authors should explain how the each biogeochemical term, and nutrient concentration within the eddies are computed here.

In order to answer this comment, a subsection explaining how the biogeochemical terms as well as the advective transport are calculated is now added in the new version of the manuscript.

Addition to the text, section 2.3, page 5:

2.3 Analysis of physical and biogeochemical dynamics within the eddy

In order to have insights into the processes controlling the nutrient distribution within the eddies, the advective transport (vertical and horizontal), sources and sinks of nutrients are analysed during the eddy evolution. The time evolution of nutrient concentrations is also presented. The eddy volume is defined here as the volume between 100m and 200m within the eddy shape. The horizontal advective transport of nutrients is calculated at the edge of the eddy structure, while the vertical transport is calculated at upper (100 m) and lower (200 m) extremes of the eddy volume. The nutrient concentration, as well as the nutrient sources and sinks correspond to the averaged quantities within the eddy volume. The sources and sinks of nitrate consist of nitrification and denitrification, respectively. For nitrite, multiple sources and sinks are accounted. The sources are denitrification and nitrification, while the sinks consist of nitrification, denitrification and anammox.

P6 L25 "These water match those from . . ." The authors should show if eddies often propagate northward in this region, and how PV distribute on average.

No, eddies in the ETSP do not propagates always northward. According to Chaigneau et al. (2008) and Johnson et al. (2010), the eddies in the ETSP propagate westward and present a meridional deflection.

The eddy trajectory is now added in the new version of the manuscript and compared with the altimetry-derived eddy genesis and propagation in the region off Peru.

Addition to the text, section 2.2.1, page 4:
Generated in the southern part of the Peruvian shelf (around 14.5° S) about 42 days before the instant presented in Figure 4, the eddy A_{sim} propagates north-westward. This eddy genesis and propagation is in agreement with altimetry observations (Chaigneau et al. 2008).

Addition to the text, section 2.2.2, page 5:
The age of eddy B_{sim} is about two months (54 days) and it was generated offshore near to 85°W and 12°S. The place of generation of model eddy B_{sim} is in agreement with the eddy genesis inferred from the altimetry observations (Chaigneau et al. 2008). Possibly detached from a meander type structure, the eddy B_{sim} propagates westward and is deflected poleward.

In 3.2 The authors compared the source and sink of nitrate and nitrite with the concentrations of these tracers within the eddies in Fig. 7 and 9. But cumulative production and reduction

are straight lines, which means that only one rate for production and reduction at some point is used to evaluate the source and sink contributions. Is the result same if time evolutions of sink and source are taken into account? Also when the authors compute each terms within the eddies, does the averaging domain vary as the eddy evolves?

The cumulative production and reduction consist of the spatial averaged quantities within the eddy (now from 100-200 m depth). The full time history of the fluxes is taken into account, and the cumulative integral is smoother than the actual fluxes, but it is not a straight line. The eddy domain varies with time as the shape of the eddy is not constant. At each instant, fluxes within the eddy and the actual eddy volume are considered to compute the cumulative flux per liter eddy volume.

The authors should conduct more comprehensive investigations to track the origin of the water inside the eddies, by computing advective transport both along vertical and horizontal directions, and diffusive transport by parameterized turbulent diffusion. The Lagrangian particle tracking is also another effective method for this.

We thank the reviewer for this suggestion. The advective transports are now included in the new version of the manuscript (section 3.2, page 7 and page 8).

Also, in this paper, only two eddies are analyzed. Are these presented biogeochemical features within the eddies are representative for most of the eddies? Are cyclonic eddies not important?

Indeed, in the paper only two anticyclonic eddies (mode water eddies) are analysed. According to Colas et al. (2012), the mode water anticyclonic eddies (also known as subsurface anticyclonic vortices) are the predominant anticyclonic eddy feature in this region. The main goal of this paper is to understand the diverse nutrient patterns observed at the subsurface layer of two mode-water anticyclonic eddies off Peru.

The cyclonic eddies also play an important role on the nutrient dynamics in this region. The uplifted isolines within the cyclonic eddies (McGillicuddy et al. 1998) may bring upward the deep nutrient-rich waters, contributing to the nutrient cycle in the upper layers. Note, however, that this is beyond the scope of the manuscript.

Nonetheless, in order to gain more insight into the processes governing the nutrient dynamics within anticyclonic eddies, we conducted a particle-release experiments. Anticyclonic eddies tracked at the vicinity of the particle-release locations have trapped particles within their centre. The number of particles within these eddies varied in time, suggesting an exchange with surrounding environment during their propagation. This result supports the hypothesis that nutrient patterns within anticyclonic eddies can be strongly affected by physical exchange processes with surrounding waters.

Addition to the text, section 2.4, page 6:

2.4 Particle release experiment

In order to have a more general overview of the processes controlling the dynamics of the eddies in the ETSP, we conduct a particle-release experiments and analyse the anticyclonic eddies that are in the vicinity of the particle-release locations at the time of the release. In these experiments, particles are released in three different locations in ETSP: (1) along the shelf between 13°S - 15°S, (2) along the shelf between 9°S 11°S, and (3) offshore between 13°S-15°S in latitude and 85°W-86°W (cf. Fig. SI-2 in supplementary information). The particles are released in the entire water column on the shelf and in the upper 300 m at the offshore site, in early austral summer (January) and early winter (June) of the last three climatological years of the model simulation.

Addition to the text, section 3, page 8 and page 9:

3.3 Eddy stirring and nutrient entrainment

The eddies A_{sim} and B_{sim} showcase that the nutrient supply by physical dynamics is the dominant mechanism that controls simulated (diverse) nutrient pattern within the eddies. The nutrient exchange with surrounding waters occurs throughout the entire lifetime of the eddies.. This indicates that the nutrient availability in the vicinity of the eddy plays a role for the nutrient distribution within the eddy's structure. To elucidate this suggestion, we carried out particle-release experiments (subsection 2.4) and analysed the eddies that passed and/or were generated close to the particle-released areas. Figure 14 illustrates the particle distribution in the subsurface layer (between 100 - 200m depth) of anticyclonic eddies interior during their propagation. From the early stages on, particles are entrained and trapped within the eddy structures.

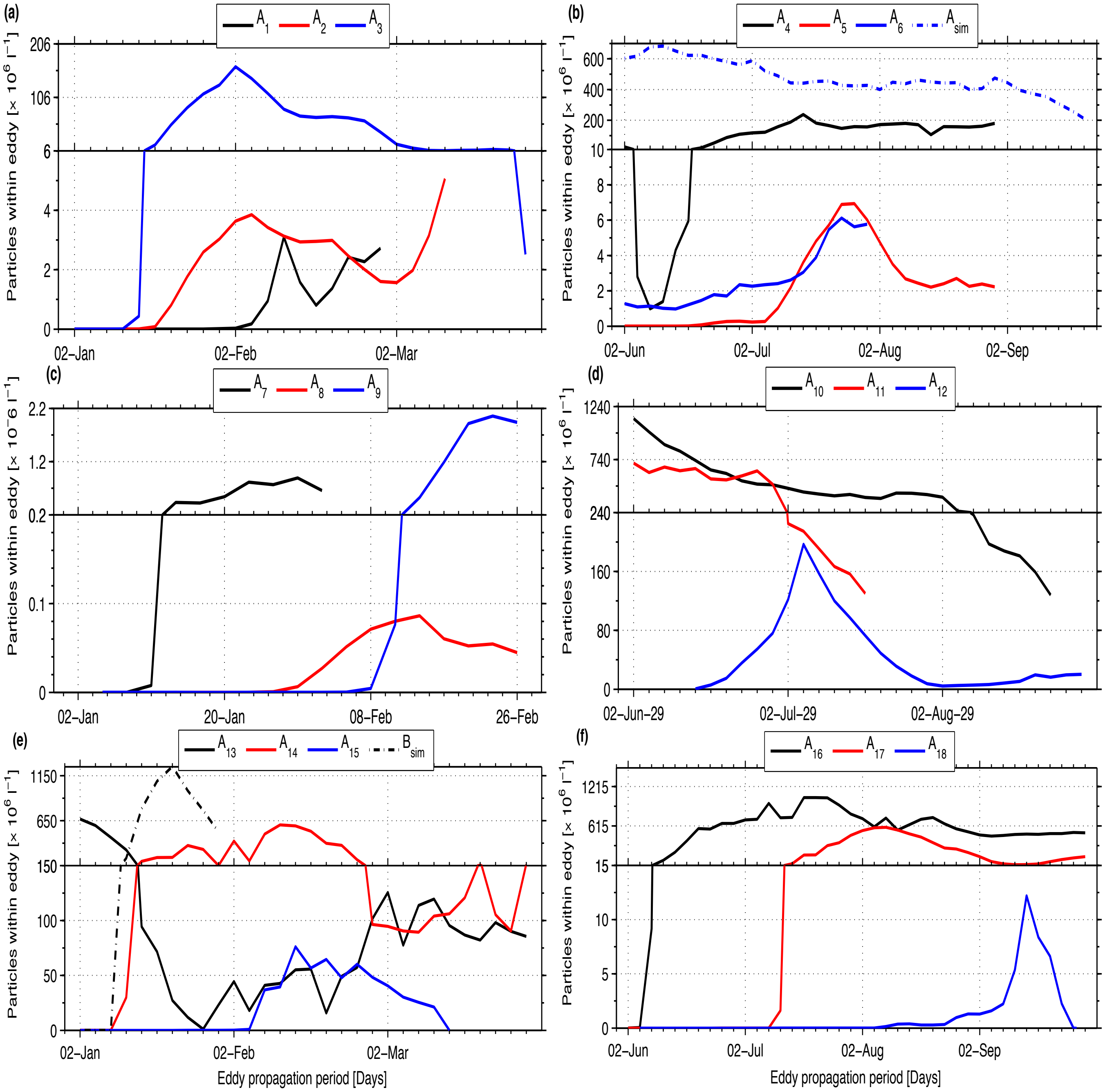

Figure 14. Particle distribution at the subsurface layer of anticyclonic eddies during their propagation, during summer (left) and winter (right) seasons. Anticyclonic eddies tracked at the vicinity of southern (a,b), northern (c,d) and offshore (e,f) particle-release locations. Detailed description of particle-release experiments can be found in the supplementary information.

These particles are transported offshore during propagation of the eddies. Every tracked eddy shows a pronounced temporal variation of the amount of particles within the structure, an indicative of exchange of properties with surrounding waters. This behavior occurs in eddies tracked during both austral summer (Fig. 14-a,c,e) and austral winter (Fig. 14-b,d,f).

Addition to the text, section 4, page 10:

Anticyclonic eddies tracked during the particle-release experiments corroborate this suggestion and show the occurrence of water mass exchange between the eddy and the surrounding environment. Particle numbers within these eddies are repeatedly increased and decreased, showing a loss and gain of quantities to/from the surrounding environment.

Addition to the text, section 5, page 10:

In a more general context the particle-release experiments realized in this study also emphasize the role of water mass exchange between eddies and the surrounding environment for the temporal evolution of properties within the eddy structure.

Addition to the supplementary information, section 3, page 2:

3. Particle-release experiments

In Figure SI-2 are illustrated the locations of particle release (light blue) as well as the tracked anticyclonic eddies (filled circles and triangles) during the model particle-release experiments. The particle-release experiments, which consisted of releasing inactive Lagrangian particles along the shelf and off Peru, are conducted to investigate the capability of anticyclonic eddies to exchange water masses with the surrounding environment. In order to cover possible seasonality effects, the particles were released in both summer and winter seasons of the southern hemisphere.

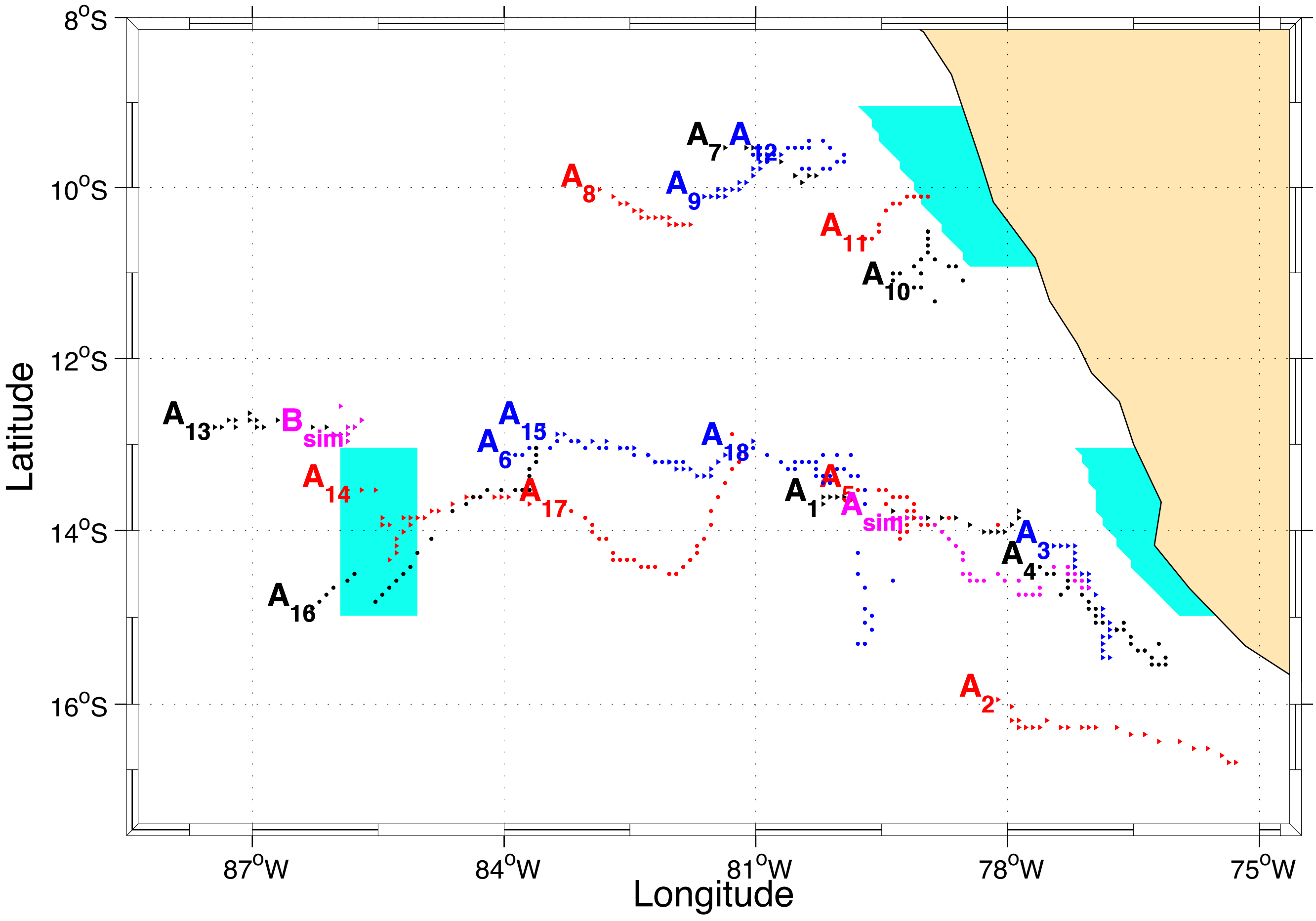

Figure SI-2. Particle release sites (light blue) and the trajectory of tracked anticyclonic eddies (filled circles and triangles) during the particle release experiment. Colour in tracked eddies correspond to model years, with black for year 28, red for year 29 and blue for year 30. Eddies tracked during summer and winter are represented in filled circles and triangles respectively.

Addition to the text, section 5, page 10 and page 11:

This physical exchange of water mass properties with the ambient environment is likely to contribute to shaping the nutrient patterns within cyclonic eddies.

References

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Thomsen et al. (2016). *The formation of a subsurface anticyclonic eddy in the Peru-Chile Undercurrent and its impact on the near-coastal salinity, oxygen, and nutrient distributions*, Journal of Geophysical Research Oceans, 120, doi: 10.1002/2015JC010878, 2015.