

Dear Reviewer #3, we would like to sincerely thank you for your time reviewing our manuscript and for your constructive comments. In this response letter, referee comments are listed, followed by our corresponding responses in bold.

This article aims to improve our understanding of the temporal variability of Fe fluxes in the Humboldt Current System off the Peruvian coast, using a valuable dataset collected around 12°S and 14°S during 2017. The study addresses an important topic and provides potentially valuable insights into the physical and biogeochemical processes controlling Fe distribution and offshore export in the Peruvian oxygen minimum zone. However, I have several concerns that should be addressed to strengthen the interpretation of the results and the main conclusions.

Major revisions:

1. The proposed link between PCUC intensification and reduced benthic Fe(II) efflux is plausible; however, the role of advection needs to be more explicitly considered and distinguished from changes in sedimentary Fe release. Because the PCUC is a poleward-flowing current whose velocity increased substantially between the April and May occupations, sampling at the same repeat stations does not necessarily imply that the same water masses, or water masses with the same biogeochemical history, were sampled during both periods. Enhanced PCUC transport may alter Fe concentrations through changes in water-mass provenance, alongshore transport, and residence time, independently of, or in addition to, changes in sedimentary Fe release. Therefore, the observed decreases in dFe and pFe cannot be attributed solely to reduced reductive dissolution in the sediments based on the present evidence. This issue is particularly relevant because Lüdke et al. (2020) interpreted the contemporaneous decrease in phosphate partly as a consequence of enhanced advection and reduced time for the accumulation of sediment-derived phosphate. Therefore, the decrease in PO₄ may not constitute independent evidence for reduced sedimentary Fe efflux, as suggested here. I recommend that the authors explicitly evaluate the potential contribution of PCUC advection and changes in water-mass properties to the observed Fe variability. In particular, the physical evidence supporting the proposed mechanism (e.g., changes in PCUC velocity, isopycnal displacement, water-mass properties, and near-bottom oxygen conditions between occupations) should be presented or quantitatively related to the Fe observations. If the available data do not allow the advective and benthic contributions to be separated, this limitation should be acknowledged and the conclusion that the PCUC regulates sedimentary Fe(II) efflux should be stated more cautiously.

Response: The reviewer has raised a few good points which are testable with available data. To address the reviewer's concerns, we've examined (1) whether intensified PCUC brought in different water masses influencing the anoxic shelf; (2) whether pre-formed dFe concentrations have changed in the source water; (3) how faster flowing PCUC may dilute benthic dFe concentrations; and (4) the variability of benthic dFe supply from reducing sediments.

In a figure below, we show conservative temperature-absolute salinity cross plots

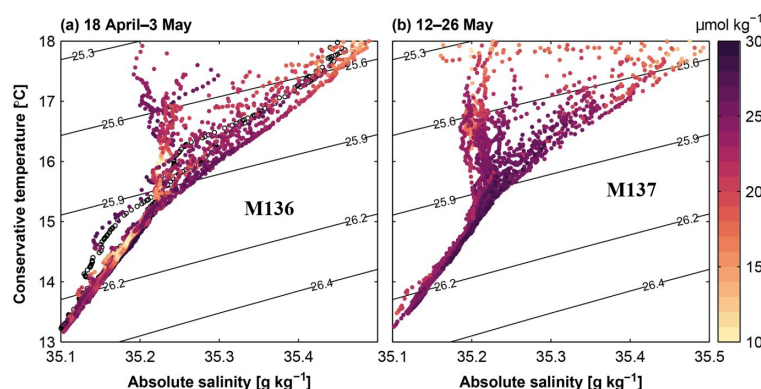
along the 12°S at depths of 50-300 m for M136 (left) and M137 (right) from Lüdke et al. (2020). In these plots, waters with potential density anomalies larger than 25.9 kg m⁻³ were predominantly ESSW, displaying a clear linear relationship between temperature and salinity. These plots further show that, despite an apparent increase in nitrate concentrations, the water mass bathing the Peruvian anoxic shelf at 12°S remains predominantly ESSW during both cruises M136 and M137. Multiyear temporal variations in dFe from equatorial subsurface currents (50 – 600 m) based on historic GEOTRACES cruises have been documented, with maximum dFe and $\delta^{56}\text{dFe}$ differences of 0.3 nmol/kg and 0.5‰ along the equator in central Pacific at 140°W (Camin et al., 2026). Such small dFe variations could account for only 5% dFe decrease over the Peruvian shelf, so that pre-formed dFe variations in source water could not be the main driver for the temporal dFe decrease observed.

The intensification of PCUC was caused by a downward displacement of the Coastal Trapped Waves (CTW; Lüdke et al., 2020), which in turn displaced thermocline and nutricline downward, pushed low-oxygen waters deeper in the water column and thus induced increased dissolved oxygen (DO) concentration in the near-bottom waters above the continental slope. Correspondingly, DO concentrations observed at 200 m depth in bottom waters during M137, a depth range that is usually occupied by anoxic water masses, were larger than 5 $\mu\text{mol/kg}$ (Lüdke et al., 2020). These temporal increases in bottom water DO allow DO diffusion from bottom water to sediment porewater, and could reduce benthic dFe flux from reducing sediments. Bottom water DO and H₂S levels have been shown to impact benthic dFe fluxes (e.g., Schlosser et al., 2018; Rapp et al., 2020). Please also refer to our responses to reviewer #1's first major comment.

We agreed with the reviewer that faster flowing PCUC may reduce the accumulation time for sediment-derived dFe and phosphate. As the reviewer has pointed out, declined benthic phosphate concentration has been partly attributed to PCUC intensification (Lüdke et al., 2020), a process that could also dilute benthic dFe concentrations. In section 4.2 in the revised manuscript, we stated in lines 266-272 that “A key finding from our study is the drastic decline in dFe and pFe concentrations on the Peruvian shelf at 12°S within a month (Fig. 3a, b). Concentrations of dFe and pFe within the core Fe(II) plume in May 2017 were 3.5 and 10 times, respectively, lower than those one month earlier in April 2017., the declines in dFe and pFe observed here at repeat stations in April and May 2017 correspond to the strengthening of the poleward flowing PCUC, with maximum velocities increasing respectively from 0.25 m s⁻¹ to 0.5 m s⁻¹ (Lüdke et al., 2020). Elevated alongshore currents due to intensified PCUC would reducing accumulation of both dFe and pFe over the shelf. Given the similar across-shelf velocities discussed above, the dilution effect from PCUC intensification would reduce benthic dFe and pFe by half if benthic diffusive Fe(II) fluxes from sediment remain the same. This estimated reduction in benthic Fe concentration cannot

fully account for the 4 - 10 fold decrease observed, implying along-shore current velocity alone cannot fully explain the variations in offshore Fe fluxes.”

We have included the above discussion in section 4.2 in the revised manuscript, and have added the transect distributions of DO for the two sampling campaigns in Supplementary Information (Figures S2 and S3), showing downward displacements of isopycnals over the Peruvian shelf.



This cross plot between conservative temperature – absolute salinity diagram was modified from Lüdke et al. (2020), where data from CTD profiles between the 100 and 400 m isobaths were shown for (a) 18 April–3 May 2017 (M136) and (b) 12–26 May 2017 (M137). Color coding showed nitrate concentrations.

References:

- Camin, C., Labatut, M., Pradoux, C., Murray, J. W., and Lacan, F.(2026) Iron isotope insights into equatorial Pacific biogeochemistry, *Ocean Sci.*, 22, 791–820.
- Rapp, I., Schlosser, C., Browning, T. J., Wolf, F., Le Moigne, F. A., Gledhill, M., Achterberg, E. P., and Engel, A.: El Niño-Driven Oxygenation Impacts Peruvian Shelf Iron Supply to the South Pacific Ocean. *Geophys. Res. Lett.*, 47, e2019GL086631
- Schlosser, C., Streu, P., Frank, M., Lavik, G., Croot, P. L., Dengler, M., and Achterberg, E. P.: H₂S events in the Peruvian oxygen minimum zone facilitate enhanced dissolved Fe concentrations. *Sci. Rep.*, 8, 12642

2. Figure 5 presents the conceptual mechanism proposed to explain temporal changes in the efficiency of the open-marine Fe shuttle. However, the schematic appears to attribute most of the variability to changes in PCUC intensity and associated bottom-water oxygenation, while upwelling and offshore transport are represented as essentially unchanged between the two scenarios. This simplification is difficult to reconcile with other results presented in the manuscript. The authors explicitly identify offshore eddy stations and discuss distinct Fe concentrations and Fe-isotope signatures associated with these mesoscale structures, including possible lateral supply of sediment-derived Fe. Thus, mesoscale circulation does not appear to be merely a hypothetical process in this region, but rather a component of the circulation sampled

during the cruises and potentially relevant to the observed Fe distributions. If the manuscript aims to explain changes in the efficiency of the open-marine Fe shuttle, the processes controlling cross-shelf and offshore transport should be considered together with changes in sedimentary Fe release. Mesoscale eddies, filaments, and frontal circulation may influence the trapping, redistribution, and offshore export of sediment-derived Fe, as well as water-mass residence times and oxygen distributions. Therefore, it is unclear whether the substantially larger Fe plume observed in April relative to May reflects only enhanced sedimentary Fe release under more reducing conditions, or also differences in lateral transport and mesoscale circulation between the two occupations. I recommend that the authors clarify the role of the observed eddies and, where possible, evaluate whether mesoscale/cross-shelf circulation differed between April and May. Figure 5 should either incorporate these transport pathways or clearly state that it represents only the hypothesized PCUC–oxygen–sedimentary Fe mechanism rather than the complete physical framework controlling the open-marine Fe shuttle. Similarly, the representation of unchanged upwelling and offshore transport between the two PCUC states should be justified or identified explicitly as a schematic assumption.

Response: These are very good points. We agree that variations in upwelling intensity and offshore current velocities would influence offshore Fe flux transport efficiency, as also pointed out by reviewer #1. In the upwelling zones, upwelling intensity is primarily governed by alongshore wind stress near sea surface (Steinfeldt et al., 2015; Siedlecki et al., 2012). During the sampling periods of M136 (20 April to 1 May) and M137 (15-16 May), alongshore wind stress from ASCAT scatterometer (see Figure R1 below; Lüdke et al., 2020) was relatively invariant and persistently low ($0\text{--}0.1\text{ N m}^{-2}$), and the estimated upwelling rates only show marginal variations ranging from 1.3×10^{-7} to $9.7 \times 10^{-6}\text{ m s}^{-1}$ (Xie et al., 2020). Collectively, these pieces of evidence suggest that wind-driven upwelling intensity remains relatively unchanged during both cruises M136 and M137. Conversely, a modeling study by Siedlecki et al. (2012) has indicated that downwelling (similar to the downward displacement of isopycnals during PCUC intensification) would strengthen benthic transport of water masses toward offshore (Figure R2 shown below). We've incorporated the above discussion in section 4.2.

Mesoscale eddies, filaments, and frontal circulation in theory all contribute to the transport of chemical constituents from the Peruvian shelf to offshore waters. Looking at the identical DO, dFe, pFe profiles and heavy $\delta^{56}\text{dFe}$ values within the core of low-oxygen waters at the crossover stations at the eddy site, we are confident to infer that these stations receive little Fe from the reducing shelf sediments, which in contrast has light $\delta^{56}\text{dFe}$ signatures, and are not the end receiver of the open-marine Fe shuttle. In the revised manuscript, we specify that the schematics in Figure 5 did not consider the full complex physical circulation involving mesoscale processes. We've also modified Figure 5 to include the representation of PCUC intensification.

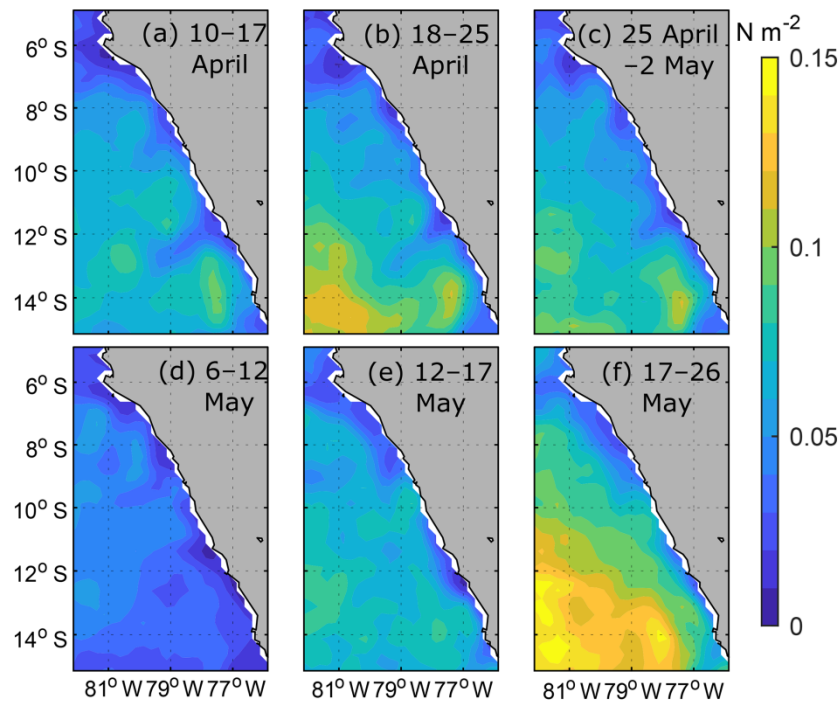


Figure R1. Alongshore wind stress from ASCAT scatterometer (Lüdke et al., 2020)

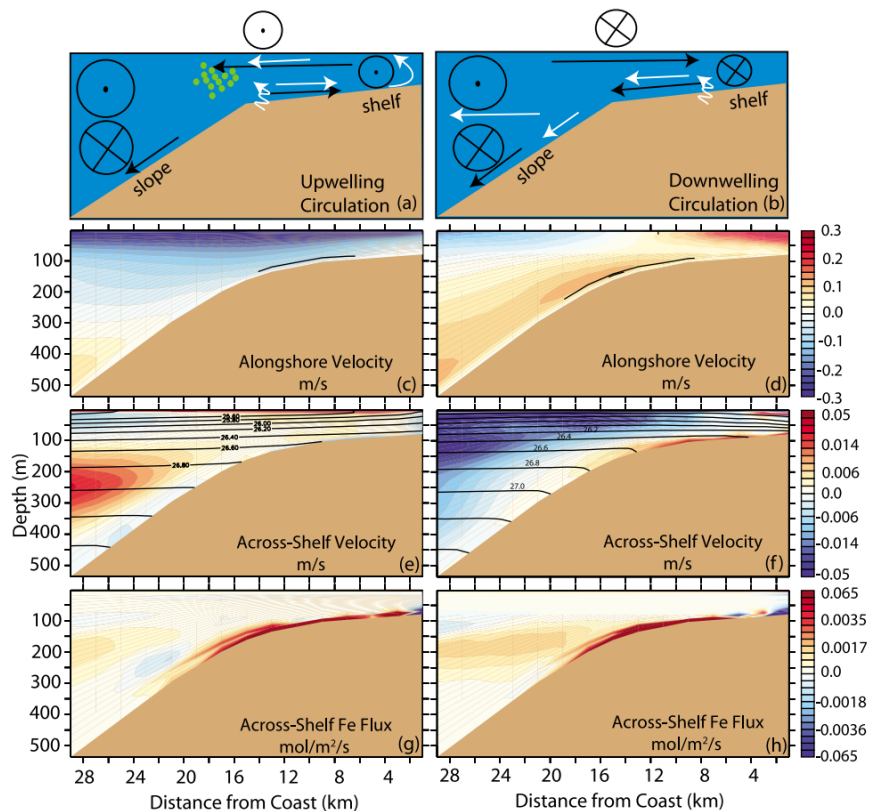


Figure R2. Model outputs from Siedlecki et al. (2012)

Reference:

Steinfeldt, R., Sültenfuß, J., Dengler, M., Fischer, T., and Rhein, M.: Coastal

upwelling off Peru and Mauritania inferred from helium isotope disequilibrium, Biogeosciences, 12, 7519–7533

Xie, R. C., Le Moigne, F. A. C., Rapp, I., Lüdke, J., Gasser, B., Dengler, M., Liebetrau, V., and Achterberg, E. P.: Effects of ^{238}U variability and physical transport on water column ^{234}Th downward fluxes in the coastal upwelling system off Peru, Biogeosciences, 17, 4919–4936, <https://doi.org/10.5194/bg-17-4919-2020>, 2020.

Minor revisions:

Line 34: Change “aera” to “area”.

Response: Fixed.

Lines 85–86: Please include the sampling dates of the stations either on the map or in the figure legend. Also indicate the date corresponding to the chlorophyll data shown in the figure.

Response: We added a table in the revised manuscript listing the sampling dates of all stations and their respectively Coastal El Niño Index, given the limited space in Figure 1b. We specified in the revised manuscript that chlorophyll data shown in Figure 1b are an average over the duration from 21 March to 20 June 2017.

Lines 93–96: Please rewrite this section to clearly describe the stations sampled during each cruise and provide the corresponding cruise dates. Please also indicate the El Niño conditions prevailing during each sampling period according to the Coastal El Niño Index (ICEN).

Response: In the revised manuscript, we’ve included in Table 1 the latitudes, longitudes, sampling dates, and corresponding cruise number for each station. The corresponding Coastal El Niño Index for each sampling date is also indicated in Table 1.

Figure 2: Please use the same colors and symbols as in Figure 1b for the profiles shown in Figure 2.

Figures: Please use consistent colors and symbols throughout all figures to facilitate comparison among stations, cruises, and sampling periods.

Response: In the revised manuscript, we used consistent colors and symbols throughout all figures.

Figure 3: Why is the inset map in Figure 3a different from the map shown in Figure 1? Please make the maps consistent or clarify the reason for the difference.

Response: We now specified in the figure caption that “The Inset map in a) shows

all stations during cruise M136 (grey dots) along the 12°S transect, and the color symbols denote the Fe isotope stations.”

Figures 3 and 4: Please indicate when the background oxygen data shown in these figures were collected and whether they correspond to the same sampling periods as the Fe observations.

Response: In both the original and revised manuscript, we have specified “Dissolved oxygen concentrations are derived from the oxygen sensor mounted on the TM-rosette frame during the M136 cruise” for Figure 3 and “DO concentrations are derived from the oxygen sensor attached to the TM-rosette during M138 cruise” for Figure 4.