Reply letter to EGUSPHERE-2023-1009 | HESS
Mangrove as nature-based mitigation for ENSO-driven compound flood risks in a river delta

Dear Dr. Jasper Dijkstra,
Dear editor,

Thank you for the valuable feedback.

Please find below a point-by-point response to all referee comments.

We hope you appreciate our response to their constructive remarks.

Kind regards,
Ignace Pelckmans

Referee comments

1. The MS completely relies on numerical modelling. It would be nice to see a comparison to, or a discussion of analytical solutions of this problem (or a reasoning why numerics are better than analytics in this case). This would also function as a theoretical framework for hypothesis and system behaviour, and could help identify other deltas (regimes) where mangroves may have a similar protective role, without the need for expensive numerical modelling. Will this be covered in Pelckmans et al in prep (l372)?

   Thank you for this suggestion. While we have not included an analytical solution, we do agree that be briefly addressed. Observations of long-period waves (tidal waves, surges, etc.) have pointed out the importance of network of channels and wetlands (Montgomery et al. 2018, Stark et al. 2015, Krauss et al. 2009, Horstman et al. 2021). This has been supported by numerical experiments (e.g. Deb et al. 2022; Horstman et al. 2015), including our initial modelling efforts in the Guayas delta (Pelckmans et al. 2023, *accepted*). Analytical solutions, such as described by Van Rijn (2011) or Montgomery et al. (2019), typically do not include this spatial complex network of wetlands intertwined by channels but instead assume continuous wetlands. While we believe that such approach is very valuable to investigate wave attenuation on a small scale or illustrate general concepts, we believe it is not sufficient to capture the complex interaction of discharge, extreme sea level, wetlands, and delta geometry on the delta scale.

   We suggest extending lines 68-73 to:

   “The presence of coastal wetlands, such as mangroves in the tropics and tidal marshes in temperate regions, can contribute to reducing the peak water level of upstream propagating ESLs along estuarine or deltaic tidal channels (Temmerman et al., 2023). When the rising water levels exceed the elevation of channel banks, water can flow into the intertidal wetlands where it is temporarily stored, consequently contributing to lower upstream ESLs (Stark et al., 2015; Horstman et al., 2015). The landscape setting and network of channels and intertwining wetlands strongly affects estuarine hydrodynamics (Deb et al. 2022). Numerical hydrodynamic models explicitly consider the geometry of wetlands and channels (Smolders et al. 2015, Dominicis et al. 2023, Temmerman et al. 2023) in contrast to analytical approaches which typically describe wetlands as uniform un-channelized zones with increased friction (Montgomery et al. 2019) or a single channel (Van Rijn 2011).”

2. Spatial scale seems to be very important; this could be stressed more in abstract and title (.e.g [...] flood risks in a large river delta.), and in the discussion. It is nice that you demonstrate the principle here, but how relevant is this to other deltas in the world, which are smaller, narrower, have an other tidal range, lower discharge?

We fully agree. We propose to change the title to “Mangrove as nature-based mitigation for ENSO-driven compound flood risks in a large river delta” and adapt the last sentence of the abstract: “Our numerical experiments in a large tropical delta show that mangrove conservation and restoration programs can contribute to nature-based flood mitigation, especially the oceanic component of compound flood risks.” In section 4.3 we suggest adding:

“The capacity of mangroves to reduce upstream HWLs is also affected by the geometry and size of the delta. In shorter deltas, the HWLs travel less long through channels fringed by mangroves and as such, less water can be temporarily stored in the surrounding mangroves. Hence, we expect lower attenuation rates in shorter mangroves. For wider deltas where the relative part of the tidal prism which is temporarily stored in the mangroves is lower, we also expect lower attenuation rates than described in this paper. Vice versa, in longer deltas where HWL travel longer through channels fringed by mangroves and in narrow deltas, where the relative part of the tidal prism, which is temporarily stored in the mangroves, we expect higher attenuation rates. Moreover, in wide estuaries or open bays, where coastal wetlands only occupy a narrow strip relative to the width of the bay, the ESL attenuation provided by the wetlands is limited (Haddad et al. 2016; Cassalho et al. 2021; Temmerman et al. 2023).”

3. I believe this is a useful study that illustrates the importance of conserving/restoring mangroves in deltas to mitigate (compound) flooding. But I am also wary of overstating the effect of nature-based solutions, and I think the authors need to be a bit more careful there, either by providing stronger proof for their assumptions/parameterisations (e.g. a small sensitivity study, which could even be done in the form of an extra scenario (e.g. 'what if we thin the forest?')), or by addressing the limits to their conclusions more clearly. To put it bluntly, and to challenge you to prove the opposite: I think the effect of mangroves is overestimated, and that they hardly play a role in shorter deltas.

In Pelckmans et al. (2023) we include several sensitivity analyses such as the sensitivity to channelisation and the drag exerted by mangrove trees on the flow. Our results revealed a low sensitivity to drag coefficients on the delta scale. Instead, the role of channelization was found to be much more important, which further justifies why an analytical 1D approach is not sufficient (see comment 1). We will add this statement to Section 4.3 to emphasize this to the reader:

“*Moreover, a developed channel network is essential to distribute the HWL from the main estuarine channel into the wetlands and, as such, upstream HWL reduction is more sensitive to wetland topography and degree of channelization than to vegetation-induced drag (Pelckmans et al. 2023).*”

We agree we must be more careful to not overstate the role of mangroves for extreme high water level reduction. To avoid overgeneralizing our results, we will extend section 4.3 as suggested in the previous comment. Regarding cases with varying extreme sea level magnitudes and discharges, we have included scenarios with increasing sea and river forcing to illustrate that the role of mangroves increases with increased sea levels and discharge. To further nuance our results, we will add in section 4.4:

“*However, mangrove conservation and restoration is not a one-size-fits-all solution to mitigate flood risks in tropical river deltas. For instance, attenuation rates attributed to mangroves can be expected to be lower in shorter and wider deltas (Section 4.3). Nevertheless, we should note that in smaller estuaries, wetlands can still provide protection against wind waves and local surges (Temmerman et al. 2023; Gijsman et al. 2021). We suggest future studies to include* *observations and numerical modelling of a wider variety of estuary and delta morphologies and scales.*"

To further support our message, we propose to also add high water profiles under varying El Niño strength scenarios in the appendix. Whilst the incoming extreme water levels are similar, the morphology, freshwater discharge and mangrove distribution is different from the eastern branch. Nevertheless, also here the effect of mangroves increase with El Niño strength.

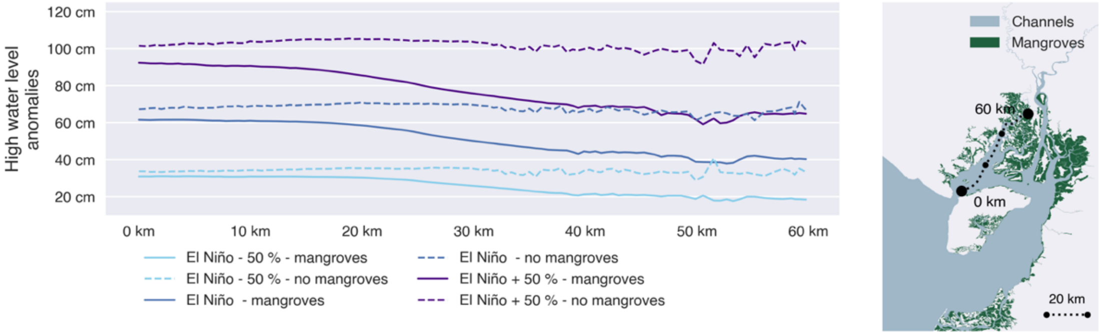

***Figure S3** | High water level anomalies (a) during the simulated spring tide over a transect (b) running from the northern entrance of the delta through the western main branch of the Guayas delta, receiving no river discharge, for three scenarios, 255 each one simulated with and without mangroves: a scenario with 50 % of the El Niño ocean and riverine forcing ("El Niño ocean & river – 50 %), 100 % of the El Niño ocean and riverine forcing ("El Niño ocean & river") and with 150 % of the El Niño ocean and riverine forcing ("El Niño ocean & river + 50 %). High water level anomalies are defined as the difference between each model scenario and the corresponding Neutral model scenario (without El Niño forcing).*

4. l130: Good to see that authors explicitly address the vegetation drag. But maybe too much? A diameter of 3.5 cm combined with 85 (~9x9)roots per m2 gives a blocked frontal area of 32%, which seems high. Is there any sensitivity or calibration study to warrant this? And why didn't they use local observations - the environments and consequently the vegetation properties are quite different in Australia and Japan. Besides, h in Eq 4 is not defined.

   As stated above, in the initial paper on this numerical model, we have conducted such a sensitivity analysis which showed a low sensitivity of the high water level attenuation to variations in vegetation-induced drag. Recent reporting on measured drag coefficients in Japanese Rhizophora mangroves show a mangrove drag coefficient of approximately 1 (Yoshikai et al. 2022), which indeed implies that we might overestimate the drag in our model. However, the sensitivity analysis in Pelckmans et al. (2023) indicates a difference of approximately 2.5 cm in upstream high water levels in the eastern branch. No local observations are available. In the text below equation 1, h is defined as water depth (m).

5. Mangrove elevation calibrated to measured elevation levels. Nice method, but are these supported by any actual measures? Alike to mangrove dimensions, did you do some sensitivity checks?

   Mangrove elevation is not directly validated because there are no measurements. We have analyzed the sensitivity; high water levels with 50 cm higher mangroves resulted in 15 cm higher upstream high water levels in the eastern branch. Vice versa, 50 cm lower mangroves resulted in 12 cm lower upstream high water levels.

6. l140: what is the source of the mangrove cover data?

The data are derived from Sentinel 2. We will edit line 140 to:

"Intertidal areas, which consist of vegetated mangroves and bare mudflats, are included in the computational domain and are delineated using remote sensing dataset (Sentinel 2 imagery)."

7. l146: NSE should not have a unit?

   Correct, thank you for the note. We will remove the 'm' unit in line 146.

8. l150: the part on generating conditions is a bit confusing despite the actual procedure being quite straightforward.

   We agree and propose to change the section to:

   "*2.3.1 Seaward boundary*

   The El Niño seaward boundary condition, referred to as the El Niño oceanic forcing, corresponds to spring tides during the period 1-3 March 1998, which include the highest water levels for the 1997-1998 El Niño event. We generate this El Nino oceanic forcing following a stepwise procedure. In the first step, we obtained astronomical tidal water levels from global tidal models TPXO9 (Egbert and Erofeeva, 2002). In a second step, because TPXO9 data do not include the local El Niño driven sea level anomalies, we increased water levels by a constant value, calibrated against observed water levels at Isla Puna near the delta mouth (Fig. 1 and Fig. 2a). For scenarios not affected by El Niño conditions i.e., referred to as neutral conditions, we estimated neutral water levels which do not necessarily coincide with the TPXO9 data. Therefore, in a third step, we calculated neutral ocean water levels by subtracting El Niño sea level anomalies from the water level data obtained in step 2. These anomalies were calculated by Belliard et al. (2021) who calculated anomalies as how much sea levels were higher due to the El Niño conditions as compared to neutral astronomical tidal conditions, based on tidal harmonic analysis."

9. 2.3.2 should be landward boundary, not seaward

   Thank you.

10. 2.3 Model scenarios should be 2.4

    Thank you.

11. l195: by making the mangrove areas 10m higher they cannot flood at all. I don't think it is a realistic parameterisation of the actual land use change (conversion into shrimp ponds or urbanisation with unprotected slums). This parameterisation effectively is a channelization that exaggerates the difference between yes-no mangrove presence. Likewise, converting all mangrove area into +10m land is very extreme.

    While the reviewer's comment is surely true for the slums, the majority of mangrove loss is driven by aquaculture expansion. These are industrial-scale ponds surrounded by high consolidated levees, which are assumed to be high enough to avoid overtopping during high water level events, as this would disrupt aquaculture practices. With increasing frequency of extreme sea level events and associated flooding, the aquaculture industry will very likely heighten their levees to prevent flooding. Therefore we have chosen to fully exclude the aquaculture ponds.

12. l245: formatting is different

    Thank you

13. l243: significantly > substantially (the first is a statistical term). (also line 364; please check the entire ms yourself)

    Thank you

14. l370: most optimal > optimal

    Thank you

15. What about the long-term effect of mangrove removal on tidal prism, channel depth and resulting water levels?

    Modeling long-term morphodynamics falls outside of the scope of our paper. We do not intend to ask the question 'what if all mangroves are removed' but rather illustrate that intertidal wetlands should be incorporated in compound flood studies as they can be essential in protecting deltas against increasing and intensifying flood risks. Nevertheless, we will indeed point out to the reader that large-scale wetland loss has a larger impact than loss of flood protection by adding to section 4.3:

    "Moreover, the complete removal of mangroves will result in tidal prism reduction and likely to long-term morphodynamic changes, such as infilling and narrowing of tidal channels, which will potentially further affect the tidal hydrodynamics and propagation/attenuation of extreme high water levels through the delta. However, modelling such long-term morphodynamic responses was beyond the scope of our study. Instead we aimed to illustrate that intertidal wetlands should be incorporated in compound flood risk assessments as they can be essential in protecting deltas against flood risks."

16. To inform on the potential for nature based solutions: What if potentially suitable habitat would be converted into mangroves again?

    This is addressed in our future paper on spatial patterns. We will change line 369 to:

    "Our results call for further research on what are the optimal spatial configurations for mangrove conservation and restoration programs, and also on the effects of restoring aquaculture ponds back to mangroves."

17. Model error is 0.18 m (does this differ among the 11 gauges?). Whilst this does not inform on how well HWL alone are simulated, this value is quite close to the differences between some model scenarios.

    This is a justified comment. Calibration and validation is described in detail in Pelckmans et al. (2023), where it is illustrated that especially the tidal amplification (and increase in HWL) is accurately captured. In the manuscript, we will put attention to model performance in the eastern branch by adding to line 146:

    "Model performance is evaluated with a Nash and Sutcliffe model efficiency (Allen et al., 2007; Nash and Sutcliffe, 1970) of 0.85 ± 0.10 (mean ± standard deviation), a root mean square error of 0.18 ± 0.09 m over the entire delta, and a root mean square error of 0.10 ± 0.01 m for four

tide gauge stations in the eastern branch."

18. The results are discussed per set of scenarios, it would be nice to have a table (though a bit repetitive) that easily, visually compares the effects of all scenarios in a single figure.

    We will add a table with water level increases over the transect and the difference between these increases with or without mangroves:

Table 2. Overview of the simulated increase in water level in the eastern branch. Differences between each mangrove and no mangrove scenario is shown in the bottom row.

	Neutral	*El Niño 50%*	*El Niño*			*El Niño 150%*
			ocean	river	ocean & river	
mangroves	1.40 m	1.47 m	1.32 m	1.58 m	1.48 m	1.49 m
no mangroves	1.60 m	1.75 m	1.69 m	1.79 m	1.87 m	1.97 m
effect of mangroves	0.20 cm	0.28 m	0.37 m	0.21 m	0.39 m	0.48 m

19. You addressed flood levels along the thalweg of the estuary (where the difference w/wo mangroves is the smallest), but what about flood levels further into the mangrove areas, i.e. closer to some urban areas (this eems especially relevant for the western branch).

This would be an interesting comparison indeed. However, the model is calibrated and validated against tide gauges along the main channels. The focus of our paper is to answer the broader scientific question on the role of mangroves in reducing extreme high water levels on the delta scale. Flood reduction in the mangroves area itself would be a rather applied research aim and be strongly dependent on the location of urban areas relative to mangrove areas and as such. As such, it would inevitably be site-specific.

Dear Referee,
Dear editor,

Thank you for the valuable feedback.

Please find below a point-by-point response to all referee comments.

We hope you appreciate our response to their constructive remarks.

Kind regards,
Ignace Pelckmans

Referee comments

1. My biggest concern is the limited information provided about the model in this publication. I appreciate that another paper already discussed the model but considering that the paper is all about modeling outcomes I believe that more information on model design (e.g. mesh size and approach, calibration, validation, sensitivity testing, roughness, etc) would ensure that the reader can understand the context of the results better. This would also help to put the discussion in context.

We do agree that more info can be provided on the mesh and calibration and the governing equations can be removed (third referee comment). However, we believe including the sensitivity analysis in this paper would increase the length of this paper substantially. An extensive sensitivity analysis is described in the published article on the model setup (Pelckmans et al. 2023). We will edit section 2.2 to:

”

2.2 Model description

The present modeling study builds further on the work by Pelckmans et al. (2023), which presents the hydrodynamic model setup, calibration and validation against observed tidal water levels for 11 tide gauge stations throughout the delta. The present paper focuses on the modeling of extreme high water levels under El Niño conditions, whereas Pelckmans et al. (2023) only accounted for ENSO neutral conditions (i.e., without additional El Niño-driven forcing). Below we briefly summarize the model setup by Pelckmans et al. (2023), to which we refer the reader to for more details.

The model domain includes the entire Gulf of Guayaquil (Fig. 1), stretching from the edge of the continental shelf in the open ocean up to the landward boundaries, which approximately correspond to the upstream tidal limits along the Daule and Babahoyo rivers. Intertidal areas, consisting of vegetated mangroves and bare mudflats, are delineated through remote sensing (Sentinel 2 imagery) and are included in the domain. The mesh becomes finer (1) along the bathymetric gradient from the open sea towards the delta mouth area, (2) with decreasing channel width in the channels dissecting the delta and (3) with decreasing distance to channels in the mangroves. Resulting mesh sizes range from 250 m at the open sea to 3 m in the narrowest channels. Mesh resolution in the main channel in the eastern branch of the delta does not exceed 75 m and has a minimum of 25 nodes per channel cross-section. The resulting mesh consists of 3 212 408 nodes and 6 425 420 elements.

The bathymetry is obtained from the General Bathymetric Chart of the Ocean (GEBCO, 2020) in the open ocean and from the Oceanographic Institute of the Navy in Ecuador (INOCAR) inside the delta. The surface elevation of the mangrove forest is calibrated to match measured inundation levels (Belliard et al., 2021) and intertidal mudflat topographies were obtained through remote sensing. The mangroves are characterized by a complex network of aerial roots, exerting a vegetation-induced drag in addition to the drag exerted by the bed. This vegetation-induced drag force is modeled as the drag force on random or staggered arrays of rigid vertical cylinders with uniform properties (Baptist et al., 2007; Horstman et al., 2021):

(same as equation 4 in manuscript)

where C_D is the dimensionless bulk drag coefficient and equals 1 (Baptist et al., 2007), D is assumed to equal 3.5 cm and is the representative diameter of the mangrove prop roots and M is set equal to 85 m-2 as the representative density of prop roots. Values for the latter two are obtained from literature on observations of Rhizophora trees in Australia and Japan (Mazda et al., 2005, 1997).

Bed friction in the channels is described by the Manning formulation where the Manning coefficient is calibrated to fit observed water levels at 11 tide gauge stations spread in the delta. To isolate uncertainties in the intertidal mangrove topography and vegetation-induced drag from the effects of the Manning coefficient in the subtidal channels, we calibrated the subtidal channel Manning coefficient during five consecutive high and low waters around a neap tide (22-24 September 2019) as mangroves in the Guayas do not flood during neap tides (Belliard et al. 2021). The tested manning values ranged between 0.0075 and 0.02 (with an incremental step of 0.0025). The best model performance was obtained with a value of 0.0175 in the western branch and outer delta and a value of 0.0125 in the eastern branch. For the calibrated neap tides, simulated water levels resulted in a root mean square error of 0.11 ± 0.06 m (average and standard deviation over the 11 tide gauge stations) on an observed tidal range between 1.49 m and 2.88 m, and Nash and Sutcliffe model efficiency (Nash and Sutcliffe, 1970) of 0.98 ± 0.02.

The model is validated against water levels at 11 tide gauge stations for four consecutive high and low waters during a spring tide on October 28-30, 2019. Model performance is considered excellent with Nash and Sutcliffe model efficiency (Allen et al., 2007) of 0.85 ± 0.10 m, and root mean square error of 0.18 ± 0.09 m over the entire delta with tidal range between 2.74 m and 4.72 m and root mean square error of 0.10 ± 0.01 m for four tide gauge stations in the eastern branch with tidal range between 4.17 m and 4.37 m."

2. For instance, in it's current form I cannot understand how the 'without mangrove' scenario was tested. Was the model simply curtailed at the intertidal boundary to simulate vertical walls or was there another approach applied? If the model runs without mangroves simply cut-off the mangroves then this manuscript is much more about tidal hydraulics then mangroves per se. As such, it would be helpful to understand the study approach. This also has implications for tidal nodes (is the amplification at 100 km due to nodal dynamics?) and the size of the model mesh elements.

For the no mangrove scenarios, the mangroves are raised with 10 m in order to ensure that they are no longer intertidal (line 195). We believe this is the most realistic representation of mangrove replacement by aquaculture ponds, which are industrial-scale ponds surrounded by high consolidated levees. These are assumed to be high enough to avoid overtopping during high water level events, as this would disrupt aquaculture practices. We will extend line 195 to:

"*These four scenarios are run either (1) including the mangrove areas in the domain (i.e., allowing them to flood) or (2) excluding the mangrove areas from the domain (i.e., preventing them from flooding by setting the mangrove platform elevation 10 m higher than the high water levels (HWLs)). The latter scenarios, excluding mangroves, can be considered representative for mangrove conversion to aquaculture ponds. These aquaculture ponds are surrounded by high consolidated levees, which are assumed to be high enough to avoid overtopping during high water level events, and as such are completely excluded from the intertidal zone.*"

We agree that by completely removing the mangroves, we are affecting the tidal hydrodynamics by removing temporal storage. However, this is a well-known and well-described process in how intertidal wetlands such as mangroves reduce upstream peak water levels (Temmerman 2023), as described in the introduction of the present manuscript (lines 70 - 72). As such, we believe that our simulations are an accurate representation of mangroves versus aquaculture.

3. Note that you may wish to remove the section on governing equations as this isn't new information and is common amongst many models. In contrast I would rather see details for the set-up, calibration and verification of the model runs. This is important as I cannot tell from the existing model if the results reported are within or outside the calibration accuracy. I think the authors may also wish to discuss implications of variable roughness on the results, especially as this pertains to mangroves (noting that not all mangroves have pneumatophores).

As suggested by the reviewer, we removed the paragraphs describing the governing equations and expanded on the model set-up and calibration. A sensitivity analysis on mangrove roughness is presented in Pelckmans et al. (2023) which shows a low sensitivity of mangrove roughness to deltaic high water levels; upstream water levels in the eastern branch only increase or decrease with roughly 2.5 cm if the vegetation-induced drag is multiplied by a factor 3 or ⅓ respectively. We agree to put the reader's attention to this by expanding section 4.3:

"*While the Guayas delta is predominantly covered by Rhizophora mangle, other tropical deltas might be covered by a wider variety of mangrove species with different morphologies and consequently, different mangrove-induced drag. Nevertheless, previous studies have pointed out a low sensitivity of mangrove-induced drag on water levels in the channels (Chen 2021,Pelckmans 2023,Horstman 2015)*."

4. As it appears that the model results are focused on tidal hydraulics, it would be helpful to get an indication of the changes to the velocity field (and/or flows) when the model domain is changed (to exclude mangroves). Did the velocities go up appreciably? Further, I'd assume that the roughness of the mangroves is only relevant to the flows when the flow velocities are fast and the water is shallow. Does it make a difference during high tide?

There are no observed data available on flow velocities in the area within our model domain and therefore, the model is solely calibrated and validated against observed water levels. We believe this is sufficient as the aim of our scenarios is to elucidate on the propagation of deltaic extreme water levels, not velocities. Since velocities are neither calibrated, nor validated, we prefer not to report on them.

5. Finally, I think it's important to provide some indication of the likelihood of the co-incidence of the oceanic surge and inflows at this site. How many times has it happen in the known data record?

El Niño events are characterized by prolonged increase in mean sea level and discharge which typically last multiple months and therefore, the coincidence of an extremely high spring tide and extremely high discharges is common during strong (Eastern Pacific) El Niño events (Belliard et al. 2021). In the current manuscript, we emphasize that there is a lack of knowledge on compound floods due to this prolonged combined effect in line 63: "So far there are no studies on estuarine or deltaic ESL dynamics due to long-term (weeks to months) combined increases in both river discharge and sea level, such as during strong El Niño events."

To further stress this to the reader, we will edit lines 45 - 49 to:
"*Likewise, the unusual warm surface waters cause sea levels to increase through thermal expansion for multiple months (Nerem et al., 1999), with sea level anomalies (SLAs) which can reach up to +40 cm in front of the Ecuadorian and Peruvian coasts, here further referred to as the oceanic forcing on El Niño-driven ESLs (Belliard et al., 2021; Colas et al., 2008). Simultaneously, the increased atmospheric convection leads to increased precipitation, and hence increased river discharge for multiple months in coastal Ecuador and Northern-Peru (Takahashi, 2004; Tobar and Wyseure, 2018; Rollenbeck et al., 2022). Here, this is further referred to as the riverine forcing on El Niño-driven ESLs. Over the coverage of available data records (for both river discharge and tide gauges), eight El Niño events occurred for which four substantial discharge and sea level anomalies were recorded (Belliard et al. 2021).*"

And in section 4.2 we will edit lines 294 - 295 to:

“*When the intensification of precipitation is driven by long-term climatic fluctuations, such as El Niño (continuing for several weeks to a few months), there is a higher likelihood that the resulting peak discharges are coinciding with ocean-driven ESLs (also continuing for several weeks to a few months) (Dykstra and Dzwonkowski, 2021; Wu et al., 2021).*”