Response to Reviewer #2

Dear reviewer 2,

We would like to acknowledge the manuscript's careful reading and the constructive comments that substantially helped to improve and clarify the paper. Detailed answers to each of your comments can be found hereafter. All authors agree with the modifications made to the manuscript. The comments by the referee are reported in italic font followed by our response. The line numbers reported in the answers referred to the location in the revised manuscript. The new supplementary figures are also provided at the end of this document.

> *General Comments:*
>
> *The results and methods presented in this paper are interesting and valuable for understanding the evolution of EBUS under climate change. However, the manuscript should be accepted only after major revisions are addressed. Below are specific comments and suggestions for improvement:*

Thank you very much for your comment. We hope to address all your concerns and suggestions properly.

> *1. You have used only two points for each EBUS. While you have justified this decision, I recommend including a map of angles for each grid point along the EBUS coast versus one open ocean point (or versus an averaged time series in the open ocean). This could potentially prove your hypothesis in other regions as well, demonstrating the validity over the entire coastal area and possibly providing insight into the spatial distribution.*

We appreciate your thorough review and insightful recommendation. We agree that incorporating this suggestion would enhance our discussion, particularly regarding the hypothesis of the poleward migration of the atmospheric highs from Rykaczewski et al. (2015). Attending to this suggestion, we have calculated the latitudinal distribution of the α_{UI} (see figure below). As expected, the latitudinal distribution is not homogeneous, and the locations of the upwelling intensification (for example 35-45ºN on CalUS) match with our chosen locations based on historical publications on the area (E.g. UP1 and UP2 on the CalUS are at 38ºN and 36ºN, respectively). Our results assess the latitudinal distribution of the upwelling intensity proxy, based on historical records. As the figure and findings from this suggestion are quite interesting, we have decided to add to the manuscript with a new dedicated section in line 365:

"4.5. Latitudinal distribution of α_{UI}

Many authors have previously tested the Bakun hypothesis, providing little consensus on both historical and projected records (Barton et al., 2013; Belkin, 2009; McGregor et al., 2007; Sambe et al., 2016; Sydeman et al., 2014). Such controversy has yielded alternative hypotheses to explain changes observed in the magnitude and timing of upwelling processes. Rykaczewski et al. (2015), suggests an alternative mechanism to the intensification of the upwelling process. They suggest a poleward shift of the oceanic high-pressure system which would stimulate latitude-dependent changes in the upwelling winds. To address this, we have calculated the latitudinal distribution of the α_{UI} (see Fig 6) in each EBUS. The spatial variability of the upwelling intensity proxy, $\alpha_{UI,}$ reveals distinct patterns and regional differences. In the CalUS, upwelling intensification demonstrates consistent upwelling activity between 35°N to 45°N with α_{UI} values reaching up to approximately 10° (Fig 6a). Conversely, in the CanUS, significant upwelling intensification is observed between 20°N and 30°N, with α_{UI} values peaking at 20º and in locations consistent with our dynamical analysis based on literature review (Fig 2b, UP1 and UP2). Similarly, in the HuUS upwelling intensification is confined to low latitudes (10-20 ºS, Fig 6c), and the values are close to those of the CalUS, (index values around 10º), as seen in the previous section. In contrast with the other regions, the BeUS shows intensification at high latitudes with maximum values of α_{UI} (20º) in the upwelling center of this region – Lüderitz upwelling center at 25ºS and Cape Columbine (around 32ºS)-. While results of BenUS and CalUS appear consistent with the findings by Rykaczewski et al, (2015), there is no supportive evidence in the other regions. To elucidate the possible mechanism responsible for such differences we will attend to the driver of the favorable-upwelling wind, the sea level pressure gradient"

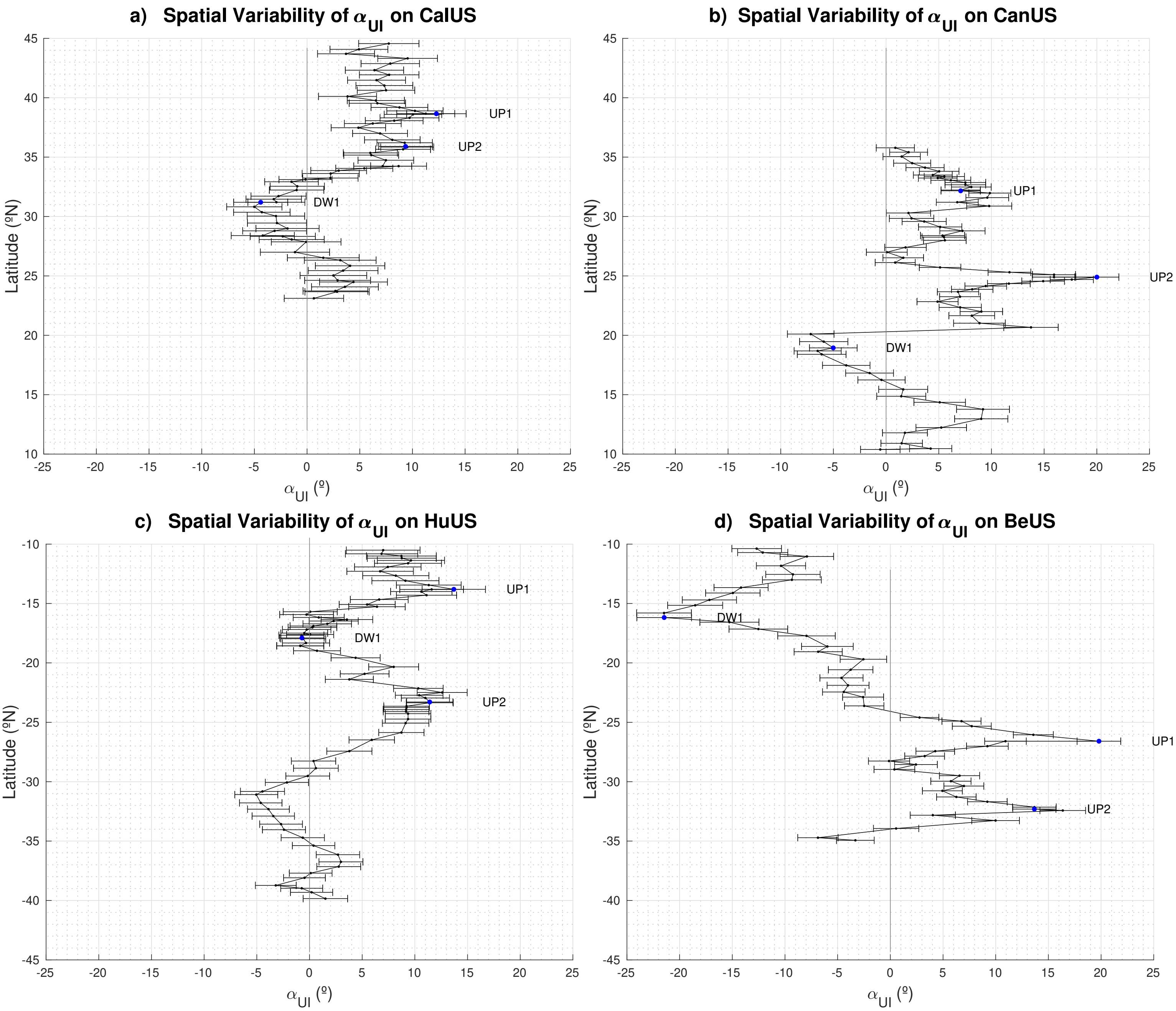

Fig 6: Spatial distribution of the α_{UI} (over the period of 1982-2021) along the coast for CalUS (a), CanUS (b), HuUS(c) and BeUS(c). The α_{UI} is calculated between grid points along the coast and OC1, with error bars representing the Monte Carlo error for each grid point. Key locations UP1, UP2, and DW1 are highlighted with blue markers.

2. As review 1 pointed out, provide an estimation of this new index using averaged time series for both the upwelling areas and the open ocean areas.

We kindly refer reviewer 2 to the answer given to reviewer 1 about the index recalculation using an average time series. Here we provide the response to reviewer 1:

'Thank you for your suggestions. We agree with the reviewer on the importance of providing additional information regarding the effects of averaged regions on our results. While spatial averaging can reduce errors, it is crucial to focus on upwelling regions to fully capture the dynamic processes at play. To address this, we used four different averaging zones in our study. Zone A, encompassed a large average of the whole coastal region. Zone B, covered an area just large enough to include the three main coastal upwelling areas (UP1, UP2 and DW1). Zone C, focused around the two main upwelling centers of each region, and Zone D, targeted only the strongest upwelling center.

When we averaged over larger regions, ignoring the specific dynamics of the upwelling zones, our results remained consistent regardless of the area size. This suggests that larger spatial averaging does indeed reduce random errors. However, this approach tends to obscure the finer-scale dynamics and local variations that are critical for understanding upwelling processes.

In contrast, when we focused on specific upwelling zones, selecting the areas around upwelling centers (Zones C and D), our results were very similar to those obtained without averaging areas. This indicates that focusing on precise upwelling locations captures the essential features of the upwelling dynamics, providing results that are both accurate and representative of the localized processes.'

Zone	CalUS	CanUS	HuUS	BeUS
A	2º±2º	2º±2º	3º±2º	1º±2º
B	2º±2º	3º±2º	4º±2º	2º±2º
C	8º±3º	7º±2º	9º±2º	9º±2º
D	11º±3º	16º±2º	10º±3º	17º±2º
This Study	11º±3º	20º±2º	14º±3º	21º±2º

Table S1: α_{UI} estimation for different portions of the coastal region: Zona A, for the whole coastal area; Zone B just covered an area just large enough to include the three main coastal upwelling areas (UP1, UP2 and DW1); Zone C, include an area around the two main upwelling centers of each region; and Zone D, only include the strongest upwelling center.

3. The figures in the manuscript are blurry. Ensure that all figures are of high resolution and clearly labeled for better readability.

We apologized for the inconvenience. We will provide with high resolution figures in the next update of the manuscript.

4. Explain the methodology used to assess the significance of your results. This is crucial for validating the findings and understanding their robustness.

We apologize for the misunderstanding and appreciate the opportunity to further clarify our methodology. We used two methodologies for uncertainty assessment. For the SST trend error estimation, we applied the 90% confidence interval. For the index, as explained at the end of section 3.3, we used a Monte Carlo simulation to estimate the error given that it is a function of two trends. The text will be modified to clarify the method used as follows in line 197:

'…We also conducted a probabilistic assessment of uncertainties for α_{UI}, taking into account the uncertainties associated with upwelling and open ocean SST series. We performed an error estimation using the Monte Carlo method: individual data points were separately and randomly sampled 10,000 times within their respective $\overline{Up}$- and $\overline{Oc}$-uncertainty ranges. These new sampled series were then used to calculate α_{UI}. The standard deviation of the 10,000 simulations represents the uncertainty of α_{UI}…'

Following reviewer 1 recommendation, we included a new section to the manuscript analyzing the SLP gradient to complement the proposed index and assess the possible drivers of the upwelling intensification. Since we also want to test the hypothesis of a poleward migration of the atmospheric centers (Rykaczewski et al., 2015), we tested the error of the SLP gradients trends computing the gradients within a 3° radius from the core of both continental and oceanic pressure systems, as a migration of the pressure systems should increase the standard deviation of the trends in the surroundings on its core. The following paragraph is added to clarify the methodology of SLP analysis in line 170:
'Additionally, to assess the drivers of change in upwelling intensity, we calculated the sea level pressure (SLP) gradients for each EBUS. The gradients were calculated between the cores of the high- and low-pressure systems (exact positions provided in supplementary material, Fig. S1). To corroborate the Rykaczewski hypothesis, we used the spatial

standard deviation. A displacement of the pressure systems would increase the standard deviation of the trends around their cores.'

5. Expand the discussion on the implications of upwelling intensification. This will help in understanding the broader ecological and economic impacts.

Thank you for your comments, many authors have addressed the implications of upwelling intensification since it holds a huge ecological and economic impacts, however, is difficult to obtain conclusive results since there is not yet an adequate amount of biogeochemical data to effectively investigate the effects of changes in climatic conditions on biogeochemistry in the EBUS. We highlighted the complexity of the ecological impacts and summarize the main possible impacts in line 425 as follow:
'…Their novel methodology holds significant importance in unraveling the connection between the physical upwelling phenomenon and its ecological impacts. However, predicting ecological impacts remains challenging. While intensified upwelling could mitigate habitat warming, it may also increase ocean acidification, hypoxic events and reduce suitable food for fish larvae (Abrahams et al., 2021; Bakun et al., 2015). Nonetheless, they successfully establish a link between decreased SST and changes in upwelling intensity…'

6. Expand the discussion on the differences between your results and the hypothesis of the poleward displacement of upwelling-favorable winds. This comparison is important for contextualizing your findings within existing literature.

We extended the discussion taking into account both reviewers' comments. You will find the expanded discussion in line 543:
'The SST changes in the EBUS respond mainly to changes in the upwelling processes which are ultimately driven by the pressure gradients. We analyzed the pressure gradients trends in all four EBUS. Our findings further support the intensification of the pressure gradients driven by climate change, as stated by Bakun, (1990). However, there are probably other contributors to the intensification of the upwellings. Some researchers question whether the impacts of differential heating on the pressure gradient force drives intensification of coastal upwelling. Rather, a complementary hypothesis proposes that evidence of an intensifying pressure gradient force is limited to poleward migration of the Hadley Cell (Arellano & Rivas, 2019; Rykaczewski et al., 2015; Wang et al., 2015). Nevertheless, these projections are only supported by observational records in the

Humboldt and Benguela Systems, (Sydeman et al., 2014). In contrast, we have tested this hypothesis on the historical record by computing the latitudinal distribution of α_{UI}. The results shown in Fig 6 partially agree with Rykaczewski et al, (2015), as only CalUS and BeUS presented a poleward intensification of α_{UI}. To further understand the drivers of these changes, we examined the spatial stability of the trends in the SLP continental-oceanic gradient was also tested using Monte Carlo simulation. The discrepancy between the latitudinal distribution of α_{UI} and the small standard deviation of trends around the cores of the pressure systems suggests that the hypothesis of poleward displacement of the high-pressure systems remains inconclusive.'

7. The manuscript would benefit from more discussion or possibly a dedicated section on the relationship between climate modes and upwelling. Consider computing correlations between them to provide deeper insights (e.g., Bonino et al. 2019).

Thank you for your suggestions. Indeed, the results of Bonino et al., (2019) are relevant for our paper since their results highlighted the difference of each EBUS driver and variability. We try to tackle this challenge with our index, α_{UI}. The α_{UI} is based on the SST trends and it normalized by the oceanic background that way we aim to reduce large scale variability. Nonetheless, the discussion about climate indices is still valuable and will be expanded as follow in lines 516:

'…On the other hand, Bonino et al. (2019) found that local drivers and trends favoring upwelling (e.g., equatorward wind stress, cyclonic wind stress curl, and thermocline depth variation) explain the low-frequency modulation of upwelling. Bonino et al. (2019) also explored the link between wind-based upwelling indices and climate modes. They found that Atlantic and Pacific upwelling variabilities are mainly independent, while intra-basin domain variabilities present some coherency, which is consistent with our results. This intra-basin covariability is especially marked in the Pacific Ocean, where the shared variability is majorly due to the El Niño Southern Oscillation (ENSO) mode. In contrast, in the Atlantic Ocean, coherent variability is associated with upwelling trends, whereas only in the CanUS is it linked to the AMO. These results suggest that long-term climate indices may influence coastal upwelling dynamics, which is especially important in the Pacific. However, our index, $\alpha_{UI,}$ by normalizing the trend for its oceanic background, our results should account for the effects of local climate indices.'

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