The signature of NAO and EA climate patterns on the vertical structure of the Canary Current Upwelling System

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Response to Referee #1 (RC1):

Referee: The manuscript describes analyses of ocean and other model output in the vicinity of the Canary Current Upwelling System. Specifically, it examines three different metrics of upwelling system indices, the vertical temperature structure of nearshore and offshore water columns, and the patterns of temperature that are correlated with wintertime indices of the North Atlantic Oscillation and East Atlantic atmospheric patterns. Oceanic temperature is obtained from the Global Ocean Ensemble Physics Reanalysis dataset obtained from CMEMS.

The authors find that (1) different upwelling indices have different values and seasonal cycles, (2) the isothermal depth of nearshore profiles during upwelling is less than that for offshore profiles, and (3) upwelling is most intense during the positive phase of the NAO and (4) especially that in combination with the negative phase of the EA.

In my opinion, the main advance of this paper is item (4) and this result is interesting and useful. Analysis of the upwelling indices appear and vertical structure are to me less novel, though it might be argued that they raise interesting questions (e.g., about what is the best upwelling index to use) and provide useful context (e.g., typical and anomalous isothermal layer depths) for the remainder of the paper.
Response: We are very grateful for your detailed review and suggestions for improvement and thank you for your effort. Please find below the reply to your comments.

Main Recommendation:

Referee: I think the manuscript would benefit from the authors choosing the best upwelling index to characterize the upwelling, presenting only that, and then expand on the NAO/EA parts of the paper. Is the comparison of UI important? Is the 5 month time-lag between UI_ERA and UI_SST important beyond showing that indices based on different data and approaches are different?
Response: Although the usage and comparison of different upwelling indices is not new, we used different data sets to detect upwelling as precisely as possible. Additionally, since we compare the vertical structure of upwelling to the climate patterns, our aim was to include a wind- and a temperature-based UI. For that reason, in the new version of the manuscript we include UI_PFEL and UI_SST, covering both the surface wind that changes with the phases of NAO/EA and the temperature which is important for the assessment of the vertical structure of the ocean. We agree that the usage of two different wind-based indices does not add any new insights to the current study, so we decided to remove the UI_ERA5 and keep the UI_PFEL as also suggested by other reviewers.

Referee: It would be helpful if the authors would include a local map of winds associated with the NAO and EA patterns (to understand their impact on local upwelling), along with their time-series, showing highlighted periods of upwelling that were used for averaging the model. At the moment, the method by which averaging is done is not clear. How many days contributed to the NOA+, NAO-, NAO+EA, and NAO-EA+ fields shown in Figure 6 and 7. How much uncertainty is there in the averages calculated? Perhaps time-series or pdfs of upwelling events associated with different climate conditions could further support the argument that statistics change in different climate conditions. How much uncertainty is there in the averages calculated?

Response: We agree with the reviewer and added the following figures and table to the manuscript:

i) A map with the wind fields (ERA5 data) during NAO+/- and EA+/- phases (Fig. 2)

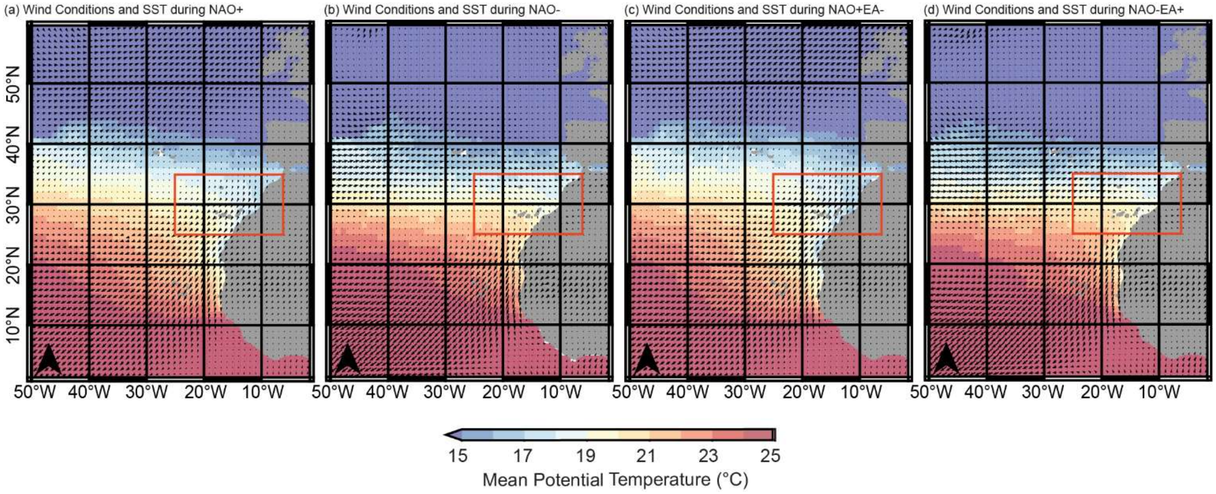

Figure 2: Wind conditions and SST during positive and negative NAO, and during combined opposite phases of NAO and EA. Wind data obtained from ERA5, SST data from Copernicus (for detailed information on NAO+, NAO-, NAO+EA-, and NAO-EA+ see tab. 1 and fig. 4)

ii) A table with years of NAO and EA positive and negative phases (Table 1).

NAO	1993	1994	1995	1996	1999	2000	2007	2008	2010	2012	2014	2015	2016	2017
EA	1993	1994	1995	1996	1999	2000	2007	2008	2010	2012	2014	2015	2016	2017

Table 1: Phases of NAO+ (red) and NAO- (blue) with the corresponding phases of the EA. Combined opposite phases are marked in yellow.

iii) A figure of the climatology of NAO and EA along with the used threshold (0.5) and the combined opposite phases (Fig. 4).

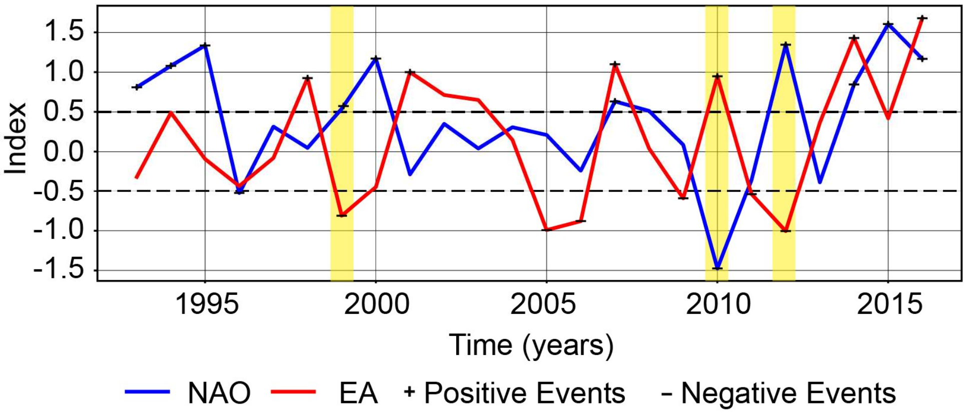

Figure 4: Winter means of NAO and EA. Positive and negative phases are marked with + and -, respectively, combined opposite phases are marked in yellow.

iv) Plot of the upwelling indices for different climate conditions

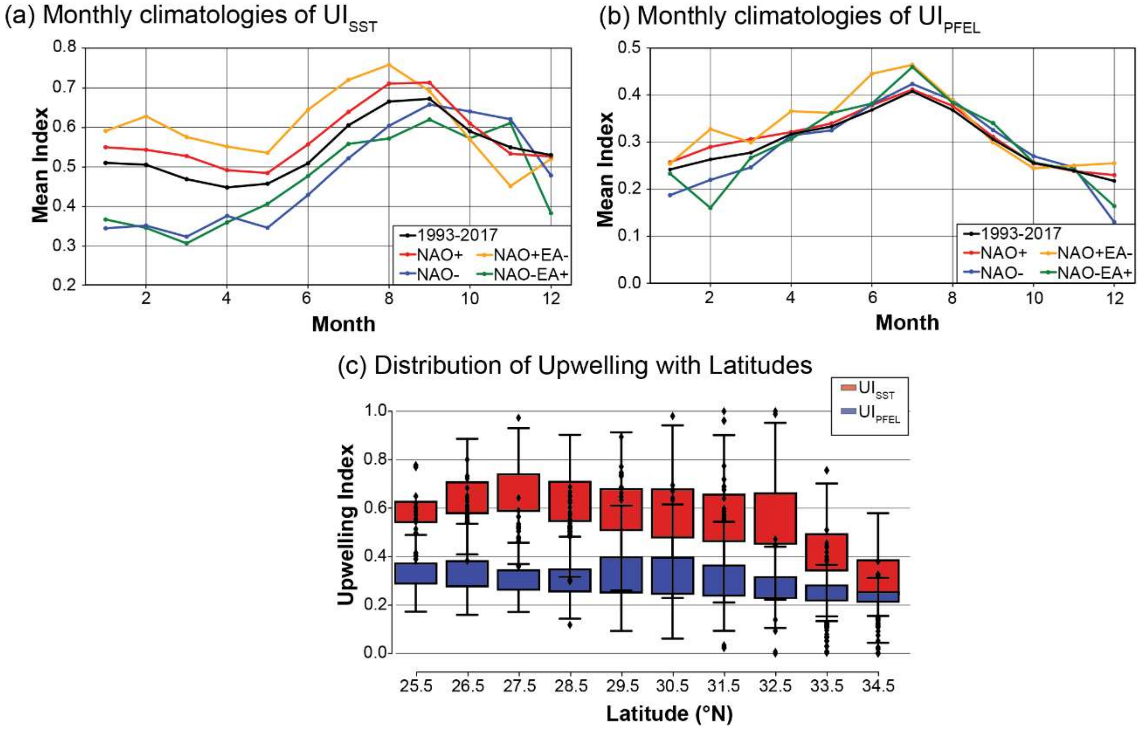

Figure 5: Box-plot of normalized upwelling indices as a function of latitude (a), monthly climatologies of normalized upwelling indices from 1993-2017 (b), during years of NAO+ (c), and during years of NAO- (d)

We also agree that the method of averaging was not clear enough. We added the following sentence to the manuscript which hopefully answers the question (Section 2, from line 169):

The composite plots of upwelling are obtained by summing and averaging the temperature of each grid cell for all months with a positive and negative NAO as well as months with combined opposite phases of NAO and EA (average computed for the winter months (DJFM) of the years listed in Table 1).

The new plots of the upwelling indices for different climatic conditions (NAO+, NAO-, NAO+EA- and NAO-EA+) shown in Fig. 5 provide further support to our arguments.

The following was added to the text (section 3.1, from line 198):

The impact of the climate patterns on the upwelling indices is well illustrated in Fig. 5 which displays UI_{SST} (5a) and UI_{PFEL} (5b) averaged over years of positive and negative phases (e.g. UI_{SST} for NAO+ correspond to monthly values averaged over NAO+ years). Averages over all the years (1993-2007) as well as averages over years of coupled phases (marked in yellow in Table 1) are also shown for comparison. More differentiated and consistent relationships can be inferred for UI_{SST} than for UI_{PFEL}, particularly from December to July (Fig. 5a). Larger values of UI_{SST} are associated with positive phases of the winter NAO, as expected due to the strengthening of the alongshore winds during NAO+ (Fig. 2). However, Fig. 5 also shows that maximum upwelling indices occur in years of NAO+EA- combinations, while minimum values occur during either NAO- years or NAO-EA+ combinations. Additionally, the time lag between the UI_{SST} and UI_{PFEL} differs with the phases of the climate pattern. Previous studies identified a lag of 2 month which is only visible during years of NAO+EA-. During the other phases and throughout the whole period of the study, a greater time lag of 3 months becomes visible. This suggests that besides the influence of the bottom topography (Nykjær and Van Camp, 1994, *J. Geophys. Res.*, **99**, 14197-14207), differences in the inertia of atmosphere and ocean and advection processes (Benazzouz et al., 2014, *Cont. Shelf Res.*, **81**, 38-54), the climate patterns and especially the combined phase of NAO+EA- play a role. Due to the limited number of years (only two) in which coupled NAO+EA- conditions occur (Table 1) caution is required in generalizing this result. Nonetheless, these results are qualitatively similar to a recent analysis of the impact of opposing NAO and EA phases during winter on precipitation, groundwater levels, and wind power generation in Portugal (Neves et al., 2019, *J. Hydrol.*, **568,** 1105-1117, and 2021, *J. Clean. Prod.*, **320**, 128828).

Other comments

Referee: Lines 115-124: The calculation of UI_ERA5 I think should rotate the winds to the alongshore direction and then calculate the wind stress, rather than the reverse as is done presently.
Response: Thank you for the comment. Since we decided to remove the UI_ERA5, this is not applicable in the current manuscript.

Referee: The results section (around lines 210), the authors claim that a change in the ILD of 1-2 m during upwelling events. There is no error analysis to show significance of this, but even if there was, is a 10% deepening important? And (as they point out), this is not a new result (Line 213). This section might be dropped.
Response: Indeed 10% is not much. Since we use the ILD during NAO/EA years as an indicator of changes in the upwelling activity and ocean stratification, we think it is important to mention the changes detected in the ILD in years where NAO/EA play a role. We did, however, reduce the section and re-write the paragraph at the end of section 3.2 as:

The ILD represents the limit of the sea-air-interaction at these scales and thus the maximum depth until which mixing influenced by kinetic and energy in the ocean occurs (Chu and Fan, 2011, *Oceans and Land Surface*, 1001-1008; Sprintall and Tomczak, 1992, *J. Geophys. Res.*, **97**, 7305-7316). In the study region the ILD shows a strong annual cycle with shallower mean depths in summer (~20 m) than in winter (100-120 m). In general, deeper ILDs during winter are explained by increased storm activity, stronger winds and greater heat losses at the surface as well as by negative buoyancy forces leading to more efficient mixing (Troupin et al., 2010, *J. Mar. Syst.*, **80**, 172-183; Yamaguchi and Suga, 2019, *J. Geophys. Res*, **124**, 8933-8948). During summer, in contrast, high stratification is favoured due to greater surface warming through solar radiation and the ILD deepens during years (Barton et al., 2013, *Prog. Oceanogr.,* **116**, 167-178). Still, when compared to normal summers we observe a deepening (of 1 to 2.5 m) of the ILD during upwelling events, especially nearshore. Nevertheless, the ILD alone is not a sole indicator of upwelling as along-shore wind and Ekman transport play the major role (Benazzouz et al., 2014, *Cont. Shelf Res.*, **81**, 38-54; Polonsky and Serebrennikov, 2018, *Izv. - Atmos. Ocean. Phys.*, **54**, 1062-1067).

Referee: Similarly, What's to be interpreted as important in Figures 4 and 5. They do show differences in coastal and offshore profiles, but the figures seems routine. Why characterize the vertical profiles or representative sections? As the authors point out, the description that they give are in agreement with other works (Line 243).
Response: We agree that the figure does not add any new finding to the study. We will remove it from the manuscript and would like to make it available as supplementary material. Although it is in agreement with other works, to our knowledge, the representation with those data and methodologies were never presented. Therefore, we would like to keep figure 5 (now fig. 6) in the manuscript to show the vertical structure of the ocean during upwelling and to make it easier to understand figure 6 (composite SST for the climate patterns, now fig. 7).

Referee: Line 178: The result that the trends in UI are small over 25 years is interesting and useful.
Response: Thank you for the comment.

Referee: Line 271: Minor comment: I think the authors mean "observed down to ~50 m depth"? Also Fig 6 has an error in listing 97.04 m twice. I think the authors mean ~200 m in the bottom row?

Response: There are still minor differences at a depth of ~100 m, however, we agree that the extreme signatures can be observed to a depth of ~50 m so we changed the depth in the manuscript. The bottom row represents the depth of 199.79 m, we will correct the error in the figure. Thank you for noticing.

Referee: Figure 7 is very interesting and compelling.
Response: Thank you very much for the comment.