Review of "Dakar Niño variability under global warming investigated by a high-resolution regionally coupled model"

by Koseki, S., Vázquez, R., Cabos, W., Gutiérrez, C., Sein, D. V., and Bachèlery, M.-L.

General comments

The aim of this work is to characterize the future of the coastal upwelling regions off the Senegalese coast, under the IPCC' RCP8.5 pathway (i.e., highest emission scenario), using a high-resolution regionally-coupled model. This is an important topic, because the future of the upwelling regions around the world is still under investigation and subject to debates. In Benguela and California systems, a consensus for a positive trend in upwelling-favorable winds seems to exist (Sydeman et al., 2014), the signal is less clear for the Canary region. Particularly the response of marine ecosystems to climate change/global warming is still uncertain (e.g., Xiu et al., 2018). Also, the upwelling regions in eastern tropical oceans are known to be not well represented in climate models (Richter, 2015). So a better knowledge of their variability and underlying mechanisms is still needed.

However, the current study presents several issues, some major, some minor, that need to be addressed before publication. The detail of these issues is given below. I therefore recommend major revisions.

REPLY: We greatfully appreciate the reviewer for the constructive comments. Following the suggestions, we have corrected our manuscriprt by adding more analysis and reply point-by-point as follows. Please note that the tracked changes in the revised maniscript are shown in blue color and the number of lines and figures are for the revised manuscript.

Major comments

In this section, the major issues are detailed.

Dakar Niño

This coastal Niño phenomenon is, like the ENSO or other coastal Niños, is a recurring climate pattern, characterized by sea-surface temperatures (SST) warmer by a few degrees than normal, with only a few occurrences in a decade. This is different from the definition given at L.37-38.

REPLY: Thank you very much for this comment. We rephrased it for clarity as: "and some extreme events of SST warm anomalies are called Dakar Niño". Please see lines 38-39.

This is also different from the Dakar Niño Index (DNI) which depicts the temporal variability of the SST, averaged over the 21°–17°W, 9°–14°N region. In this perspective, the title could be changed to reflect either the exploration of the variability of the DNI under RCP8.5 or the future of Dakar Niño under RCP8.5. This is particularly true regarding Figs. 5 and 6. The former is using the DNI, while the latter is focusing on Dakar Niño and Dakar Niña.

REPLY: Thank you very much for this comment. This study first started analyzing Dakar Niño Index between present and future climate and our main discussions are based on Dakar Niño and Niña events. Therefore, we would prefer to keep "Dakar Niño" in the title. However, "variabiltiy" has been omited from the title.

In response to the comment below, we have added a new figure (Fig.4) showing DNI and frequency of Dakar Niño/Niña events in ERA5 and ROM simulations. This new figure might help to avoid confusion. Please see line 171-175.

The existence of a Dakar Niño (or Niña) is the result of complex land-sea-atmosphere interaction system. According to Oettli et al. (2016), the coastal, alongshore, wind variability, the mixed-layer depth anomaly, and the modulation of the mixed-layer temperature (mostly due to the shortwave radiation variations), are the necessary components to develop a Dakar Niño. The current work is mainly focusing on the coastal winds and some atmospheric variables (sea-level pressure, 2m temperature,...), forgetting about the other components of the dynamical system. It would be preferable, in this work, to also discuss about the evolution of the costal ocean mixed-layer, and its heat budget, under the RCP8.5. At L.257, there is a mention of the land-sea thermal contrast anomalies. It would be interesting to discuss how the contrast helps to maintain, or not, the favorable alongshore winds.

REPLY: Thank you very much for the helpful comment. Indeed, the process of the changes in Dakar Niño/Niña events should be discussed. Here, we estimated the more important components of the ocean mixing layer heat budget (according to Oettli et al., 2016) and Figure R2 shows the composite differences between Dakar Niño and Dakar Niña in current (1980-2010) and future climate (2069-2099). Please note that we examine surface net heat flux (proposed by Oettli et al., 2016) and vertical advection. Our analyses indicate that the vertical motion variability intensifies and is deepened due to reinforced meridional wind-stress variability under global warming (Figs. 6 and 8, please note that the numbering of figures have been changed) and therefore, here, as a first order, we compare surface heat flux and vertical thermal advection roles. The vertical thermal advection (Vadv) is defined as in Vijith et al. (2020)

$$-w_{oml}\frac{\Delta T}{D}$$

here, w_{oml} is the vertical velocity (m/s) at the bottom of ocean mixing layer (m), D is the ocean mixing layer depth (model's output), and $\boldsymbol{\Delta T}$ is the difference between the ocean mixing layer temperature and the temperature at the layer just below the ocean mixing layer.

Please note that the vertical thermal advection is estimated by monthly-mean data because of the data availability. Therefore, the transient-compoent of vertical advection is not included here and there could be some under/overestimation.

As Fig.R2, our analysis shows that in the current climate, surface heat flux is relatively more responsible for warming SST, but vertical advection also explains the warming SST in the Dakar box. On the other hand, in the future climate, the role of vertical advection is extensively increased. This result supports our frist argument: stronger meridional wind variability can excite the vertical motion variability and consequently, Dakar Niño/Niña events can be reinforced. In addition, Fig. 6e shows that the upper ocean layer becomes much warmer than subsurface ocean layer between 40m depth. As the reviewer mention as below, the ocean is more stratified in the future climate. This indicates that the contribution of vertical thermal advection could increase since $\partial T/\partial z$ increased in the upper layer. We added this discussion and Figure as Fig.11 in the Section 4. Please see lines 294-320. Moreover, we rephrased the last part of Abstract referring to this result. Please see line 21-23.

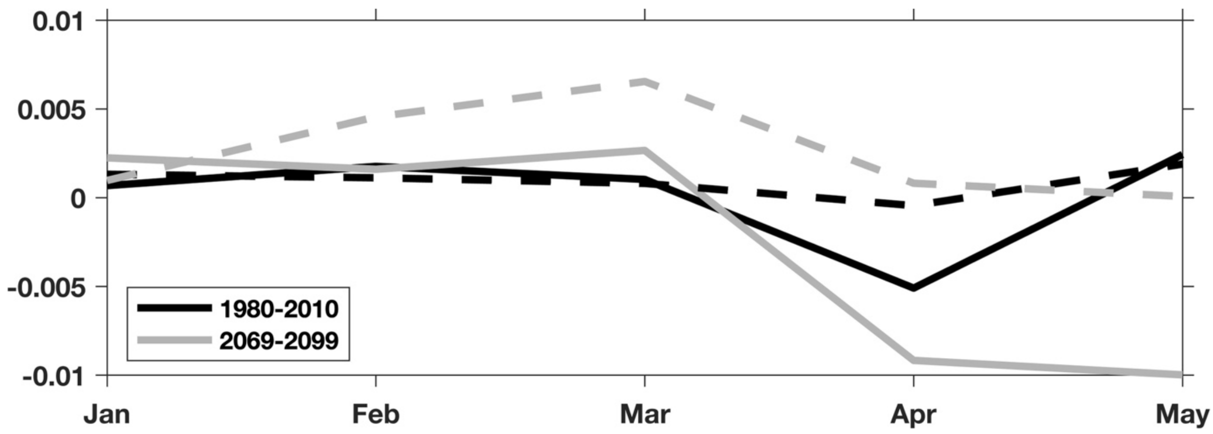

Fig.R1 Monthly time series of lag-composite difference of (solid) surface net heat flux and (dashed) vertical thermal advection between Dakar Niño and Dakar Niña events (Niño minus Niña) in (black) 1980-2010 and (grey) 2069-2099. March is lag=0. The unit is K day^{-1}.

Also, we analyzed the composite difference of ocean mixing layer in the Dakar Index box between Dakar Niño and Dakar Niña as shown in Fig.R3.

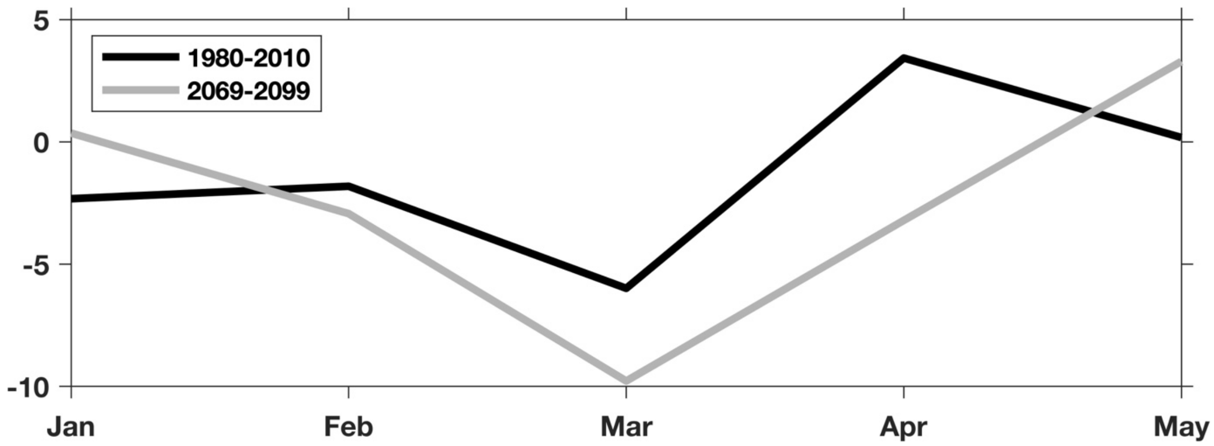

Fig.R2 Monthly time series of lag-composite difference of ocean mixing layer depth between Dakar Niño and Dakar Niña events (Niño minus Niña) in (black) 1980-2010 and (grey) 2069-2099. March is lag=0. The unit is m.

As Oettil et al. (2016) shows, the mixing layer depth tends to be shollower during the Dakar Niño in our simulation. Interestingly, the composite difference in the ocean mixing layer is larger in the future climate, especially from February to April. One of the possible reasons for this is because the meridional wind variability increased and the mechanical contribution to deepening the mixing layer can increase the difference in ocean mixing layer. However, the ocean mixing layer is also a function of temperature and salinity, so it could be difficult to make an attribution. We added this figure in Supplementary Information as Fig.S4 and some descriptions. Please see lines 294-320.

Regarding the thermal contrast between land and sea, our argument is based on Bakun's hypothesis combining sea-level pressure (SLP) anomalies in Fig 10. In both cases of Dakar Niño and Niña, continental SLP anomalies show steeper zonal gradient running along the coastal region. This gradient can be favorable for meridional wind anomalies for Dakar Niño (reducing equatorward anomaly) and Niña (increasing equatorward wind anomaly), which is consistent with Bakun's hypothesis. We added this discussion in the revised manuscript. Please see lines 287-288.

A time series of the DNI is also needed for the periods 1980-2010 and 2069-2099, to provide the reader with the number and intensity of the events. This is also particularly important to understand Fig. 4.

REPLY: Thank you very much for the helpful comment. We plotted the time series of the Dakar Index and events of Dakar Niño and Niña (Fig.R3 as follows). From this plot, the frequency of Dakar Niño and Niña is 7/9 and 8/6 in the present and future climate, respectively. It seems that there would be not a large change of the event frequency with more events being over 1 K. We added this description in the revised manuscript. Please see lines 171-175.

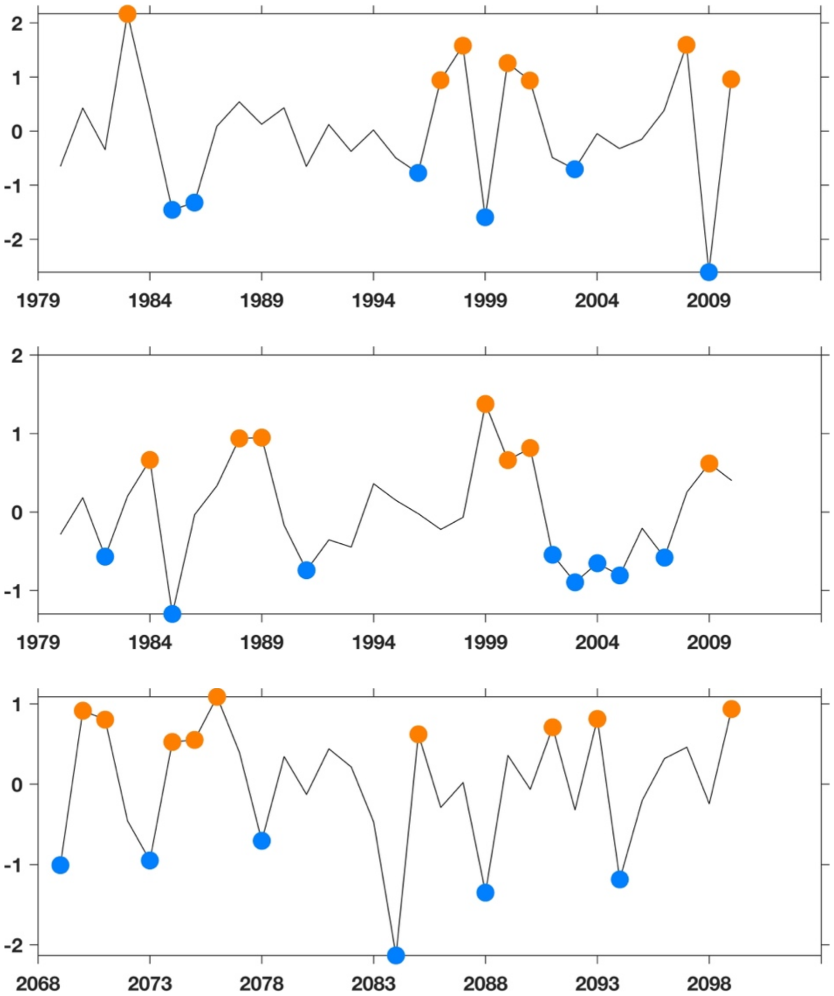

Fig.R3. Time series of Dakar Index (detrended SST averaged 9°N-14°N and 20°W-17°W) for (top) ERA5, (middle ROM_P, and (bottom) ROM_F The orange and blue dots indicate Dakar Niño and Niña events defined in this study, respectively.

Target of the study

There is some confusions throughout the main text. The title indicates that this work is focusing on the Dakar Niño, which is a coastal, phenomenon with specific characteristics (see previous sub-section), but the Senegalese–Mauritania Frontal Zone (SMFZ) is also often referred, introducing some sort equivalence in the reader's mind, between two different phenomena.

REPLY: Thank you very much for pointing this out. As Fig. 2 shows, the high interannual variability of SST is found around the SMFZ and some extreme events are referred to Dakar Niño/Niña. Therefore, while the SMFZ is the name of an area with certain climatic features, Dakar Niño/Niña are the phenomena. To make this point clearer, we modified a sentence in the introduction. Please see lines 38-39.

Also, this study discusses the intensity and the location changes of the Dakar Niño between present and future periods, but doesn't tackle the frequency change. It would be informative to also present if, under RCP8.5, the number of Dakar Niño events is likely to increase/decrease.

REPLY: As we replied above, we added the new plot of Dakar Niño Index and the number of events in Fig. 4. Accoridng to this plot, there are no large change in the frequency of Dakar Niño and Niña events between the present and futuree climate

The Bakun hypothesis (or Upwelling intensification hypothesis, Cropper et al., 2014) is introduced at L.235. This is an important topic to discuss when it comes to the future of tropical upwelling regions, because several studies have been dedicated to corroborate or contradict the Bakun hypothesis. See for example Oettli et al. (2021, p.255–256) for a discussion on this. I would recommend to better highlight how this study seems to corroborate the upwelling intensification hypothesis.

REPLY: As we replied to the comment above, our result is supporting the Bakun's hypothesis during Dakar Niño and Niña events: In particular, SLP anomalies over the land are favorable conditions for generating meridional wind anomalies. We added more discussion on this point. Please see lines 287-288.

On the other hand, it is still an open question why the SLP anomalies over the land surface are like that while the connection with the Mediterranean seems stronger in the future than in the present. It will be interesting to investigate this pattern as a future work.

Clarity

The global structure of the text is not clear and needs to be rethought, because it is often difficult to understand what the authors are describing and putting emphasis on.

Throughout the text sometimes appears some vague statements which need to be clarified:

REPLY: Thank you very much for helpful suggestions. We solved this vagueness of our description.

L.64-68: The apparent opposite conclusion on model resolution between Sylla et al. (2022) and Vázquez et al. (2022) should be better emphasized and explained, because of its implication for the current work.

REPLY: This might be caused by eddy-permitting model or not. Vázquez et al. (2022) utilized the eddy-permitting models around the Northeastern tropical Atlantic. This study also uses the model. We already added this point. Please see line 69.

L.158: What is the meaning of this anomaly pattern for the Dakar Niño?

REPLY: This pattern is the anomaly of climatological fields, therefore, it might be difficult to discuss the indication for Dakar Niño from this plot. For the climatological aspects, we already described some indications. Please see lines 171-174.

L.188-189: "This deeper connection of ocean temperature in ROMF can be indicative of the stronger SST variability". This is unclear what the authors are saying here. This needs to be clarified.

REPLY: This was too speculative and therefore, we changed this part as another reviewer also pointed out. Please see lines 207-208.

L. 228: "[...] indicating that the wind variability might be more relevant due to local effects". This also is unclear. What are those local effects?

REPLY: This statement is based on Fig.8: the wind variability over the subtropical Atlantic is not changed, but the coastal wind variability increases in the future. Therefore, the anticyclone variability is not responsible for the wind variability along the western African coast. To clarify which local effects are responsible for the higher wind variability, we analyzed the surface temperature and SLP anomalies. We modified the sentence. Please see lines 246-247.

L.278-280: How? What would be the mechanism?

REPLY: To clarify this speculation, we performed the heat budget between surface heat flux and vertical thermal advection. Please lines 294-320.

L.283-285: Again, how? What would be the mechanism?

REPLY: To clarify this speculation, we performed the heat budget between surface heat flux and vertical thermal advection. Please lines 294-320.

Figs. 5 and 6: The mix between DNI and Niño/Niña events makes things difficult to follow.

REPLY: To make it clearer, we added the new Fig.4 and corresponding descriptions. Please see lines 171-177.

L.292-293: This statement is not clear. What are the other climate modes? Please clarify.

REPLY: The other climate modes we argue here are NAO and ENSO. We added these modes. Please line 346.

Specific comments

L.25: The region of the Senegalese–Mauritania Frontal Zone (SMFZ) looks similar to the Senegalo-Mauritanian Upwelling System (SMUS) used in Sylla et al. (2019) or the Mauritania-Senegalese Upwelling Region (MSUR) used in Vázquez et al. (2023). Please clarify what is the SMFZ compared to SMUS and MSUR.

REPLY: The SMFZ is a "front" and more confined area than SMUS and MSUR and the upwelling should be one of factor to frontogenesis of the SMFZ (this has not been done yet, but Koseki et al., 2019 has done for Angola-Benguela Frontal Zone. A similar work will be possible in the future). Then, we modified the sentence. Please see line 27.

L.26: "[...] one of the most pronounced oceanic frontal zones generated along the eastern boundary current system". Source?

REPLY: Added Oettil et al. (2021).

L.28: Please remove the second left bracket.

REPLY: Done.

L.36: Please remove the second left bracket.

REPLY: Done.

L.43: "[...] stronger Benguela Niño events compared to Dakar Niño events". Source? (Probably L.116-117).

REPLY: Because there is no paper (as far as we know) for direct comparison between Beneguela and Dakar Niños, we omitted that part.

L.47: Local or multi-fleet fishery? The former is certainly more sustainable, but also more sensitive than the latter. The latter has probably more impact on worldwide economy than the former. Please clarify.

REPLY: In this study we do not specifiy which types of fleet and ships. Rather, our statement would be more general.

L.64: "Sylla et al. (2022)" is missing in the references.

REPLY: Added.

L.65: "Resolution" instead of "Resoliution".

REPLY: Corrected.

L.86: Please explain what RCP8.5 is by adding what is said at L.138 (Which then can be shorten as "Under RCP8.5").

REPLY: Added. Please see line 88.

L.119-120: What is the source of the poor representation of coastal upwelling in ERA5?

REPLY: This might be due to the relatively coarser resolution than ESA. Please see 123.

L.120: "[...] and ERA5 has a warm bias (Vázquez et al., 2022)."

REPLY: Corrected.

L.134: "The meridional SST gradient greater than 0.5K/100km is shown in blue".

REPLY: Corrected.

L.134: Why between 21° and 16°W when the DNI is defined between 21° and 17°W? Is it a typo?

REPLY: Corrected.

L.135: "[...] respectively (bottom).".

REPLY: "(bottom)" is for the SST standard deviation.

L.135: "deviation" instead of "devitation".

REPLY: Corrected.

L.136: "kelvin" instead of "Kelvin".

REPLY: Corrected.

L.143: March is the peak phase of the Dakar Niño.

REPLY: Corrected and modified following another reviewer. Please see lines 144-148.

L.148: “isotherm” instead of “of temperature”.

REPLY: Corrected.

L.165: “21°–17°W, 9°–14°N”

REPLY: Corrected.

L.167: “SST over 21°–17°W, 9°–14°N”.

REPLY: Corrected.

L.168: How is the significance of the correlations evaluated. And for the wind stress, because there are two components (zonal and meridional), both can be significant, as well as only one over two. Does the figure only shows correlations when significant in both directions? Please clarify.

REPLY: The significance of correlation is based on *p*-value ($p< 0.05$) as captioned. The vector with *u* “or” *v* is significant. We added this in the caption. Please see line 186-188.

L.193: “section” instead of “seciton”.

REPLY: Corrected.

L.196: “Niñas” instead of “Niña”.

REPLY: Corrected.

L.210: “section” instead of “seciton”.

REPLY: Corrected.

L.212: Is 16°W also a typo?

REPLY: Corrected.

L.253-254: “Composite anomalies of the 2m temperature during Dakar Niño (left) and Niña (right) events in ERA5 (top), ROM_P(middle), and ROM_F (bottom) in March.”

REPLY: Corrected.

L.277: Unclear what is the variability is referring to. Is it among warm (cold) events?. Is it in terms of number of warm (cold) events. Please rewrite and clarify.

REPLY: Here, the variability is referred to SST inter-annual variability defined as Dakar Index. As the composite analysis suggests, Dakar Niña (cold SST anomalies) tend to intensify more. We repharsed the sentence. Please see lines 332.

L.324-524: The references doesn't follow the Copernicus Publications guidelines. Please revise according to them.

REPLY: Actually, we followed https://publications.copernicus.org/for_authors/manuscript_preparation.html and download the format file for Endnote for Copenicus Publication. After we submitted our manuscript was processed through technical check and then, it was sent to the editor and reviewers. Therefore, we assume that the style of reference is acceptable.

Figure 3: In order to understand Fig.4, we need to know the mean state from January to May for the SST and the wind stress.

REPLY: Thank you for the comment. We added this as new Fig.S3.

Figure 5: The land mask should be in a different color than 0 (gray for example, similar to the mask in Fig. 7)

REPLY: Corrected.

Figure 6: Same as Fig. 5

REPLY: Corrected.

Figure 7: Is the standard deviation calculated for all the months of March in "Present" (ERA5 and ROM_P) and "Future" (ROM_F) periods? If it's the case, why not doing a composite with/without Dakar Niño/Niña?

REPLY: Yes, the standard deviation in the plot includes all the months of March. In this study, we focus on how the Dakar Niño/Niña (extreme events of SST anomalies) will be changed under global warming. Therefore, we made a composite for Dakar Niño and Niña in the present and future climate to investigate which process can explain the changes in the events.

References used in this review

Cropper, T. E., Hanna, E., and Bigg, G. R.: Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012, Deep Sea Res. Part I Oceanogr. Res. Pap., 86, 94–111, https://doi.org/10.1016/j.dsr.2014.01.007, 2014.

Oettli, P., Morioka, Y., and Yamagata, T.: A regional climate mode discovered in the North Atlantic: Dakar Niño/Niña, Sci. Rep., 6, 18782, https://doi.org/10.1038/srep18782, 2016.

Oettli, P., Yuan, C., and Richter, I.: The other coastal Niño/Niña—the Benguela, California, and Dakar Niños/Niñas, in: Tropical and Extratropical Air-Sea Interactions, edited by: Behera, S. K., Elsevier, 237–266, https://doi.org/10.1016/B978-0-12-818156-0.00010-1, 2021.

Richter, I.: Climate model biases in the eastern tropical oceans: Causes, impacts and ways forward, WIREs Clim. Change, 6, 345–358, https://doi.org/10.1002/wcc.338, 2015.

Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Rykaczewski, R. R., Thompson, S. A., Black, B. A., and Bograd, S. J.: Climate change and wind intensification in coastal upwelling ecosystems, Science, 345, 77–80, https://doi.org/10.1126/science.1251635, 2014.

Sylla, A., Mignot, J., Capet, X., and Gaye, A. T.: Weakening of the Senegalo–Mauritanian upwelling system under climate change, Clim Dyn, 53, 4447–4473, https://doi.org/10.1007/s00382-019-04797-y, 2019.

Vázquez, R., Parras-Berrocal, I. M., Koseki, S., Cabos, W., Sein, D. V., and Izquierdo, A.: Seasonality of coastal upwelling trends in the Mauritania-Senegalese region under RCP8.5 climate change scenario, Sci. Total Environ., 898, 166391, https://doi.org/10.1016/j.scitotenv.2023.166391, 2023.

Xiu, P., Chai, F., Curchitser, E. N., and Castruccio, F. S.: Future changes in coastal upwelling ecosystems with global warming: The case of the California Current System, Sci Rep, 8, 1–9, https://doi.org/10.1038/s41598-018-21247-7, 2018.