Review for "Dakar Niño variability under global warming investigated by a high resolution regionally coupled model" by Koseki et al.

The study by Koseki et al. investigates how sea surface temperature (SST) variability at the Senegalese-Mauritania coast associated with so called Dakar Niños might change in the future. Utilizing a regionally high-resolution coupled climate model they find that the Dakar Niño variability increases under the RCP8.5 scenario. This is explained by an increase in the wind variability and higher ocean stratification under global warming.

The manuscript is mostly well structured and written and provides interesting results on the future of SST variability in the Northeastern Tropical Atlantic. However, I find that it is sometimes hard to follow the presentation of the results and that the investigation of the processes needs some work. Also, there are some recent studies dealing with similar questions that should be taken into account. I summarize my major comments and list minor points and specific comments below.

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

Major comments:

A) Definition of Dakar Nino

It is not really clear to me what exactly this study regards as Dakar Niño variability. Is it all interannual SST variability in the region considered here (i.e. from 7ºN to 21ºN)? Everything related to the position of the front (line 37/38)? Or just SST anomalies occurring in the Dakar Niño Index box which is much more confined? Is the peak in SSTA variability around 20ºN in boreal summer also related to Dakar Niños? Please provide a definition and make sure to be consistent throughout the manuscript. Also, please indicate the Dakar Niño box in Figure 4.

REPLY: Thank you very much for the helpful comment. Throughout the manuscript, we focus on SST interannual variability as the box-mean (9N-14N and 20W-17W defined by Oettli et al., 2016), which is defined as Dakar Index in Oettli et al. (2016). The events of Dakar Niño/Niña in **March** are defined as the Dakar Index plus/minus ± the standard deviation. According to Oettli et al. (2016) who found this event first, March variability is maximum and we follow their definition. While we described the definition, the location of description was not adequate. Therefore, we moved the definition of Dakar Niño/Niña events in this study to Line 171-173 in the revised manuscript to improve the readability.

In addition, as another reviewer suggests, we added a time series of Dakar Index and events of Dakar Niño and Niña in Fig.R1 as follows, as well as its description in the revised manuscript. Please see lines 171-177. Due to this new figure, we added a box of the Dakar Index in Fig.3.

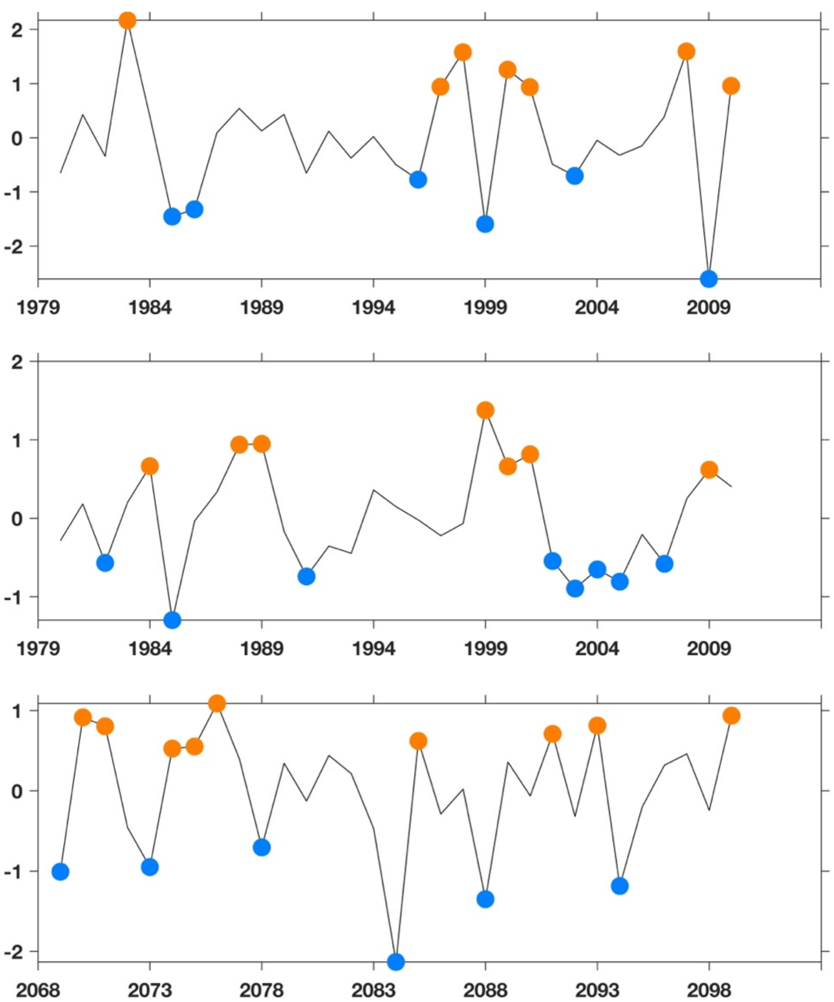

Fig.R1. Time series of Dakar Index (detrended SST averaged 9°N-14°N and 20°W-17°W) for (top) ERA5, (middle ROM_P, and (bottom) ROM_F The orange and blue dots indicate Dakar Niño and Niña events defined in this study, respectively.

B) Processes behind Dakar Niño variability

I believe that more analysis is needed on the processes by which Dakar Niños and Niñas are driven in the simulations and how they change in the future. For example, Oettli et al. (2016) argue that heat fluxes are important for the generation of Dakar Niños but they are not considered here. The same goes for changes in the depth of the mixed layer.

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)

$$\text{Vadv} = -w_{oml}\frac{\Delta T}{D}$$

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 using monthly-mean data because of the data availability. Therefore, the transient component of vertical advection is not included, which could lead to 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 addtion, as Fig. 7e shows, the upper ocean layer become much warmer than sub-surface ocean layer between 40m depth. As the reviewer mentions 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.

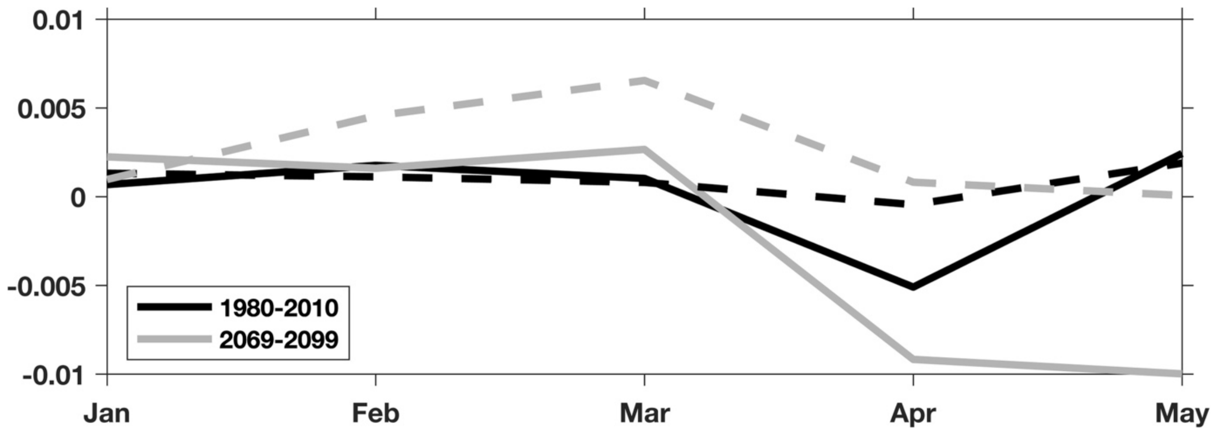

Fig.R2 Monthly time series of lag-composite difference of (solid) surface net heat flux and (dashed) vertical thermal advection between Dakar Niño and Dakar Niña events (Niño minus Niña) in (black) 1980-2010 and (grey) 2069-2099. March is lag=0. The unit is K day^{-1}.

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.

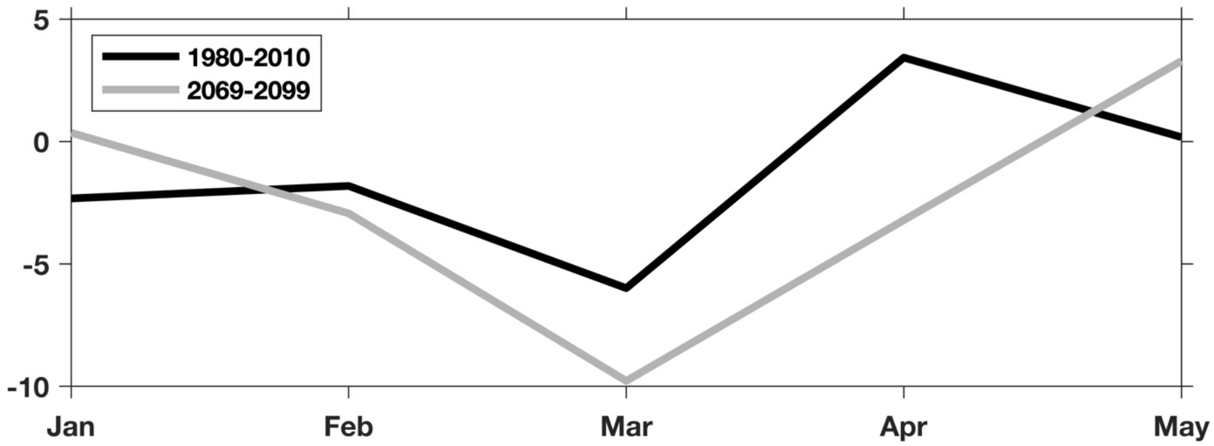

Fig.R3 Monthly time series of lag-composite difference of ocean mixing layer depth between Dakar Niño and Dakar Niña events (Niño minus Niña) in (black) 1980-2010 and (grey) 2069-2099. March is lag=0. The unit is m.

As Oettli 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 could be the meridional wind variability and the, the mechanical contribution to deepening the mixng layer can increase the difference in ocean mixing layer. However, the ocean mixing layer is also function of temperature and salinity, which could be difficult to make an attribution. We added this figure in Supplementary Information as Fig.S5 and some description. Please see lines 294-320.

It is also not clear to me why stronger stratification should lead to higher variability. Stratification is also increasing in the equatorial Atlantic but there, the argument is that this hinders subsurface-surface coupling and thus leads to weaker variability.

REPLY: Thank you very much for giving an oppostunity to discuss our argument more. For this statement, we show the composite of ΔT in the vertical thermal advection in March during Dakar Niña events for ROM_P and ROM_F in Fig.R4.

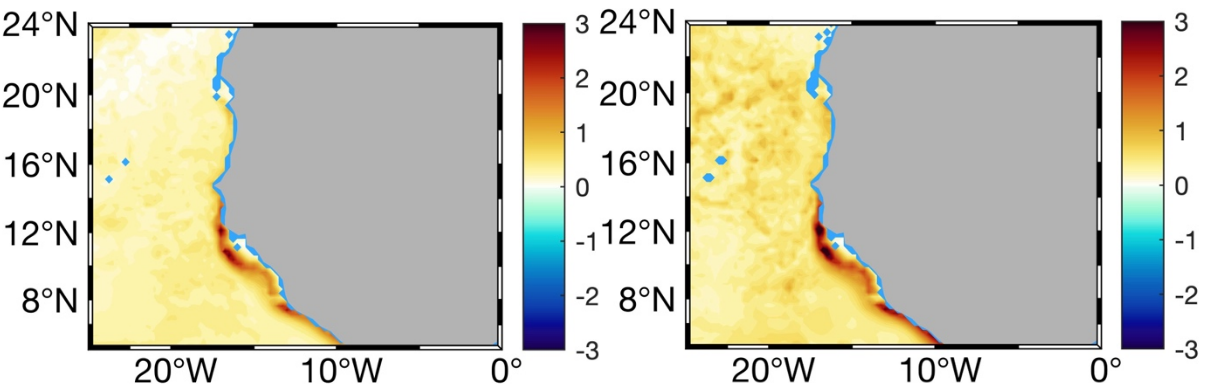

Fig.R4. The composite of ΔT during Dakar Niña in March for (left) ROM_P and (right) ROM_F.

In both cases, there is a strong vertical temperature gradient along the coast, ROM_F shows relatively larger ΔT. In addition, offshore areas also have larger ΔT entirely. Given the same vertical velocity anomaly emerges in present and future climate, the future climate will have more vertical thermal advection during Dakar Niña events.

On the other hand, during Dakar Niño events, there is not difference in the mixing layer depth (already ckecked). Therefore, under global wamring, espeacially, Dakar Niña will be more reinforced as shown by our Fig. 7.

It is further argued that correlation between the DNI and ocean temperatures at greater depth means stronger SST variability (line 189). Why would that be?

REPLY: We agree that this argument might be too speculative. The deeper connection between DNI and ocean temperature just gurantees that the Dakar Niño/Niña events would be deeper in the future, not larger variability. Therefore, we removed this statement and instead, we added "indicating that Dakar Niño and Niña events would influence deeper ocean in the future" . <u>Please see lines 207-208</u>.

In the conclusions "stronger vertical velocity variability" (279) is mentioned. Where is this shown?

REPLY: As in the previous case, this argument might also be too speculative due to less process-wise analysis. As the reviewer suggests and we have done in Fig.R2, which suggest that the role of vertical thermal advection is responsible for enhancing Dakar Niño and Niña events in the future. Therefore, we rephrased here as "inducing a stronger vertical thermal advection". Please see lines at 333.

C) Literature to be taken into account

There are some recent studies dealing with the future of the variability in the Dakar Niño region that should be cited here:

Yang et al. (2021) find increasing variability in the Northeastern Tropical Atlantic under global warming. Chang et al. (2023) look at changes in temperature and wind patterns in eastern boundary upwelling regions in HighResMip simulations. Also, a study on the future of Benguela Niños was recently published (Prigent et al., 2023) and could be mentioned in line 142.

REPLY: Thank you very much for providing information. We added these articles in discussion of the revised manuscript and corresponding descriptions. Please see lines 326-331.

Minor points:

1) Model validation

While I like the comparisons shown in Fig. 2, they could be improved and further complemented with line plots. The axis labels are very small and the color scale of (e) to (h) is hard to interpret (this also applies to Fig. 7). I would also find it more instructive to show SST in °C. In addition, one could show a line plot with SST and its standard deviation averaged over certain latitude bands overlaid for the different data sets and model simulations. This would facilitate an easier comparison in terms of timing and amplitude. I believe that it would probably show that the season of highest variability in the model is shifted towards later in the year (April instead of March) which makes the focus on March later in the analysis a bit questionable.

REPLY: Thank you very much for constructive suggestions. We improved the figure following the comments. Regading the latitude band plot, we added the figure as Supplementary Information new Fig.S1. Regarding the unit of SST, we added a new analysis of surface heat flux and vertical thermal advection as above, and the unit of temperature in this computation is K. Therefore, it could be reasonable to have the unit of K.

Yes, our model has a peak of variability by about one month later. However, to compare with the observation, it could be better to invesigate the same month between models and observations. Our model still shows a strong variability in March. We added this justification in the revised manuscipt. Please see line 146-150.

Further, in line 120, it is stated that the model has a warm bias. Where? What is the general pattern of SST difference to observations?

REPLY: This statement is about ERA5 bias compared to the ESA satellite data, not our model. As we cite, Vázquez et al. (2022) have done more model assessment with the same models and same experiments. Additionally, you can find more details this fact in Vázquez et al. (2023). Therefore, this study has not performed detailed assessment of the model performance.

2) Seasonality of SST in the region

The seasonal cycle in SST shown in Figure 2 is mainly explained in terms of a meridional movement of the front driven by meridional currents. However, I believe that it is largely impacted by the upwelling season in the southern part of the region, i.e. cooler waters are upwelled to the surface in February to April.

REPLY: Thank you very much for this comment. Actually, we had already mentioned the role of upwlling at line 105-107 citing some references.

Regarding the seasonal migration of the Mauritania current (line 105), is there a reference for this? Does it fit with the findings by Klenz et al. (2018)?

REPLY: We cited Klenz et al. (2018) as a reference of Mauritania Current. Plesse see lines 110-111.

3) Role of remote forcing

It is stated (lines 42 to 44, also 116 to 118) that Benguela Niño events are stronger than Dakar Niños because of the additional role of remote forcing from the Equator. Is this something that has actually been shown (in this case, please provide a reference) or just an assumption of the authors?

REPLY: The remote foricng for Benguela Niño has been a well-established mechanism and therefore, we have already cited related papers. At lines 42-44, the references were missed, then we added the literatures. As far as we know, there is no study on direct comparison between Benguela and Dakar Niño. Therefore, the statement at lines 116-118 might be speculative and we deleted the sentence “and the Benguela Niño/Niña has more larger intensity than Dakar Niño/Niña because of the strong remote influence from the equator via equatorial and coastal Kelvin waves”.

4) Correlation with Dakar Niño index (Figure 4)

How do the correlations in Figure 4 change when they are based on April instead (see comment 1 above)? Also, I am not sure the propagating signal described is really propagating (associated with a Rossby wave). Couldn't the SST anomaly just decrease first at the coast due to coastal processes and linger around for longer offshore?

REPLY: As we replied above, we focus on March in order to keep the consistency with the observation. We would expect that there might be some differences, but some of characteristics might be quite similar.

Regarding the Rossby wave, our statement here just indicate a possibility of Rossby wave as Martín-Rey and Lazar (2019) showed. Their arguement is the connection between boreal spring variability, Atlantic Meridional Mode (AMM), and summer Atlantic Zonal Mode (AZM). AMM signal can propagate as Rossby Wave, and it reflects in the western boundary as Kelvin wave propagating eastward and genetating AZM. Our lag correlation map might give an indication of AMM after Dakar Niño, but it is unknown the connection between Dakar Niño and AMM and this will be one of possible futute works, which is out of scope of this study.

Specific comments:

- At several instances, "reinforced" is used when probably "strengthened" or "increased" is meant (e.g. line 23, 206, 217, 226, 269,...)

REPLY: Changed.

- line 17/18 and 186 to 191: Here, it is not clear whether the correlation gets stronger or whether high correlation is extending deeper in the ocean. Please rephrase to make this clear.

REPLY: At the upper ocean, the correlation is relatively stronger and the correlation is much deeper. As we replied above, we rephrase this part. Please see lines 207-208.

- line 33: "feature" instead of "exhibit"

REPLY: Changed.

- line 41: "driven by"

REPLY: Added.

- line 52: In contrast to what?

REPLY: Chnaged to “However”.

- line 53: “even in” instead of “until”

REPLY: Changed.

- line 58: “recently” instead of “timely”

REPLY: Changed

- Figure 1: What is shown by the shading?

REPLY: That is the topography height in NEMO. We added it in the caption.

- line 105: What is “inversely” referring to? When are the trade winds relaxing?

REPLY: Yes.

- line 111: “second maximum” in terms of timing or location?

REPLY: Here, we mean both SST gradient and interannual varability peaks are almost overlapping as shown in Fig.2. We added “at the same timing and location”.

- line 116: “has larger” (without “more”)

REPLY: The sentence was removed replying to the comment above.

- line 128: “focus region”

REPLY: Changed.

- line 138/139 “K” or “°C” instead of “degree”

REPLY: Changed.

- line 149: ORA-S5 is a reanalysis product.

REPLY: Changed.

- line 152: Please rephrase this sentence.

REPLY: Rephrased. Please lines 158-159.

- caption to Fig. 4: “January” (typo)

REPLY: Corrected.

- line 173: "south of" instead of "below"

REPLY: Changed.

- line 177: What does "somewhat simulated well" mean? Please rephrase.

REPLY: Chnaged to "to some extent "and changed well to "realistically".

- line 178: "is correlated", "SST anomalies develop"

REPLY: Corrected.

- line 179: "compared to ERA5"

REPLY: Correcnted.

- line 181: Should be "S2"

REPLY: Changed, but please note that this I snow Fig.S3 because of an addition new Supplementary figure.

- line 199: "1 standard deviation"

REPLY: Changed, but please note that the senence has been moved to lines 171-173 as we replied above.

- line 284: "is" instead of "can be also"

REPLY: Corrected.

References:

Chang, P., G. Xu, J. Kurian et al., 2023: Uncertain future of sustainable fisheries environment in eastern boundary upwelling zones under climate change, Comm. Earth & Environment, https://doi.org/10.1038/s43247-023-00681-0

Klenz, T., Dengler, M., and Brandt, P., 2018: Seasonal variability of the Mauritania Current and hydrography at 18°N. Journal of Geophysical Research: Oceans,123, 8122–8137. https://doi.org/10.1029/2018JC014264

Prigent, A., Imbol Koungue, R., Lübbecke, J.F. et al. Future weakening of southeastern tropical Atlantic Ocean interannual sea surface temperature variability in a global climate model. Clim Dyn (2023). https://doi.org/10.1007/s00382-023-07007-y

Yang, Y., L. Wu, Y. Guo et al., 2021: Greenhouse warming intensifies north tropical Atlantic climate variability, Sci. Adv. 2021;7:eabg9690

REPLY: Thank you very much for the information on further literature. We added these articles and descriptions referrign to them. Please see lines 326-331.