Response to Referee 1

Summary

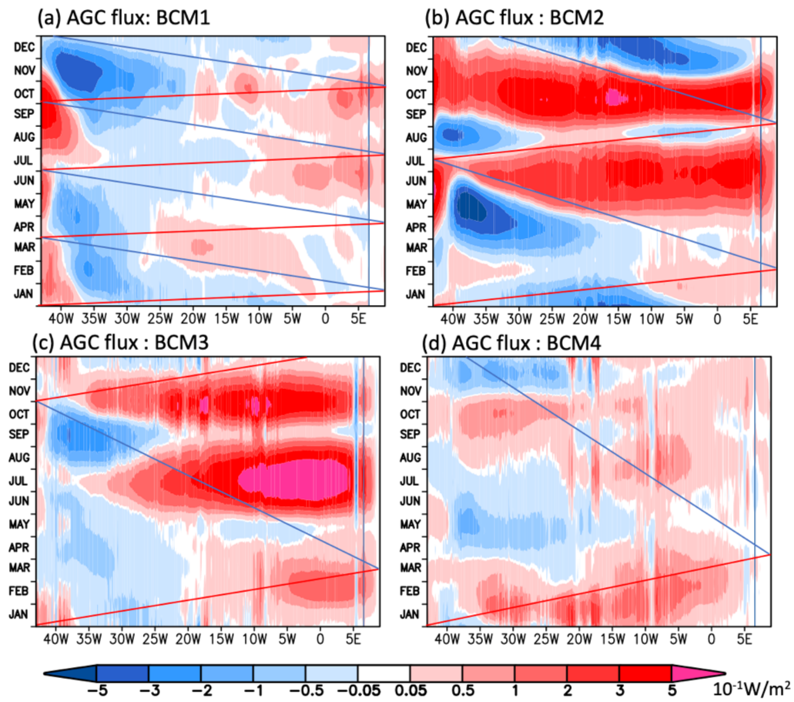
Using a newly developed wave flux diagnostic as a tool, the authors examine the genesis of the eastern equatorial Atlantic warming in 2019. The model allows analyzing the contributions of individual baroclinic modes, and the authors examine the first four of those. They find that the 3rd and 4th modes have substantial contributions to the warming and that these modes are locally forced. Prior those higher modes, there is a 2nd mode Rossby wave that appears to be excited in the off-equatorial region and reflected into a Kelvin wave at the western boundary. The authors suggest that this 2nd mode Kelvin wave helped to precondition the event.

The authors show some interesting results and I believe the diagnostic tool could be useful for obtaining a deeper understanding of equatorial Atlantic variability. It is less clear, however, how useful this diagnostic tool is for prediction purposes and for quantifying individual contributions. Furthermore, the English in the manuscript could use some editing. Detailed comments follow.

Major Comments

1) Figure 8 shows some good evidence for Kelvin wave propagation. For the Rossby waves, however, there is little agreement with the theoretical phase speed and, in fact, the data shows little evidence for any westward propagation. Does this mean that the Kelvin waves are mostly transmitted into coastally trapped waves at the eastern boundary? Do you have a way of quantifying the relative amounts of reflected and transmitted energy?

Thank you for the comment. The local wave energy flux at one grid is essentially determined by averaging the flux from both Kelvin and Rossby waves. Indeed, in climatological scenarios, the waveguide of Rossby wave is clear and agrees well with the theoretical group velocity (see the Figure below). However in Figure 8, when the climatological variability is excluded and high-frequency (subseasonal) Kelvin waves dominate, the low-frequential Rossby waveguide is obscured by subseasonal Kelvin waves. Although high-frequency wave signal is not likely to excite reflected Rossby waves, it can be transmitted to inertia oscillations and dissipates rapidly. From only Figure 8, it is hard to say how much energy is transferred into coastally trapped waves. To give a rough estimation of the energy entering the off-equatorial area, we have calculated the meridional flux in the newly selected transection at 3ºS (see Figure 9 in the revised manuscript). It turns out that in the 2019 event, waves only in the first and third mode will transport significant energy to the coastal region.



XT diagram for AGC flux at the equator. Same as Figure 8 in the revised manuscript but for the climatological wave signal.

2) How well do the Kelvin waves correspond to the surface wind stress forcing in terms of location and timing? Is there a proportionality between the strength of the equatorial wind stress anomalies and the excited wave energy? This could also help to further clarify the relative contributions from off-equatorial and equatorial waves.

Thank you for the comment. To reveal the association between surface wind and the wave energy, we have employed wind stress from the ERA5 dataset and added it in our figures. The updates of the figures regarding the wind information include: 1. In Figure 4, we added the timeseries of the zonal wind anomaly averaged in the western equatorial Atlantic (40^{o}W-20^{o}W, 3^{o}S-3^{o}N, which is traditionally regarded as the wave source region) to show the correlations between the geopotential anomaly and the wind anomaly; 2. In Figure 8, the XT diagram of zonal wind anomaly is drawn as contours to demonstrate its correspondence to the excitement of waves at the equator; 3. In Figure 10, we have drawn the horizontal distribution of mean wave energy flux and mean zonal wind anomaly to compare the source region of wave energy with the pattern of wind anomaly in the event season.

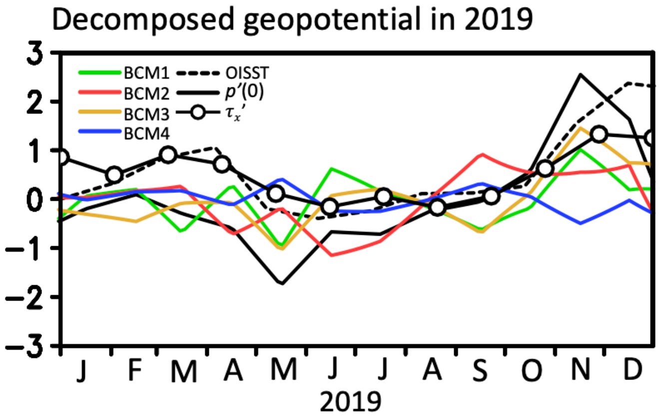


Figure 4 in the revised manuscript. Solid black line is the zonal wind stress averaged in the western equatorial basin.

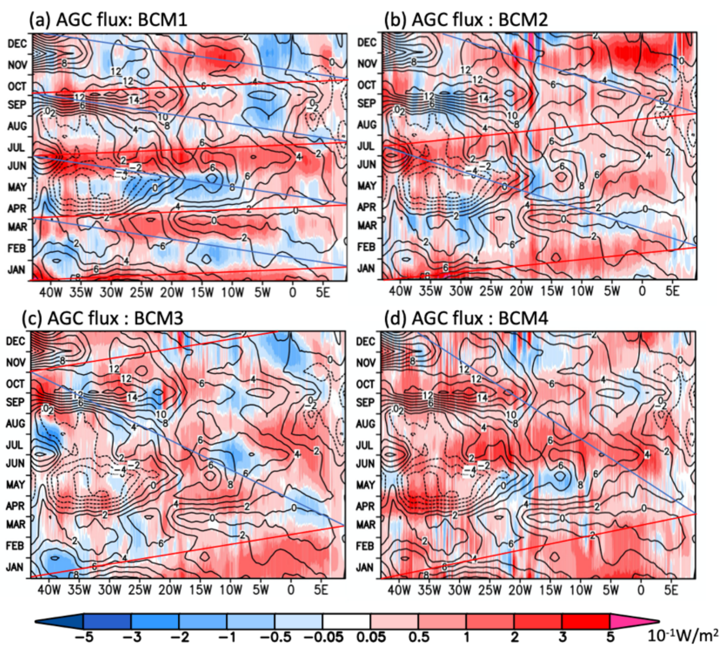


Figure 8 in the revised manuscript. Contours are the zonal wind stress anomaly with the interval of 0.002 N/m2.

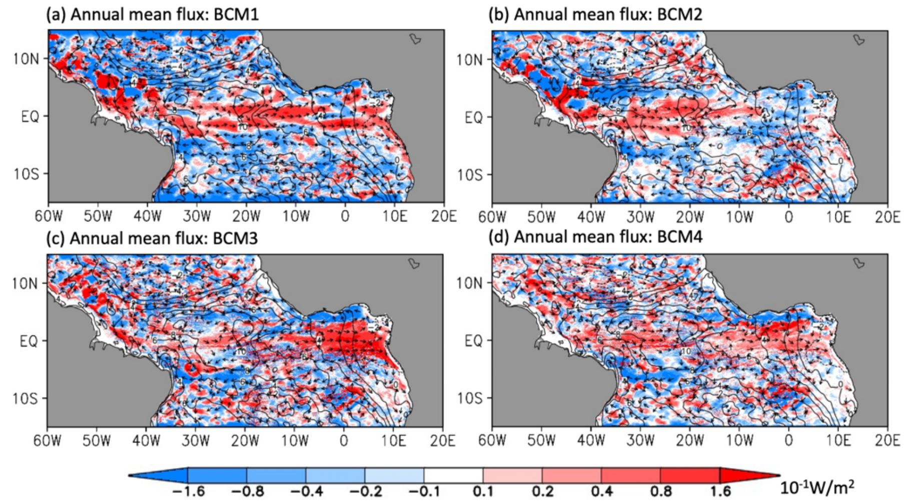


Figure 10 in the revised manuscript. Contours are the zonal wind stress anomaly with the interval of 0.002 N/m2.

Those figures have suggested the strong association between locally equatorial forcing with high-mode waves (in the third and fourth mode shown as Figure 8 and 10). Meanwhile, the mismatch between the wind anomaly peak and the wave energy source in Figure 10b confirms the contribution of off-equatorial waves to the equatorial wave energy in the second mode. The detailed description and analysis for those updated figures have also been given in the revised manuscript (line 172-175 and line 208-217).

3) The 3rd and 4th modes seem to make a strong contribution to the equatorial Atlantic warm event. Since these waves seem to be excited locally, they offer very little predictive potential. Does this diminish the prospect of predicting similar events? Can you estimate the relative contributions from the 2nd (reflected) mode and the 3rd and 4th modes?

Thank you for the comment. There are several metrics that can help to evaluate the contribution of waves in each mode. For example, using wave energy E in Eq. (5) to directly calculate the wave energy. However, Song et. al (2023) has indicated that the square fashion of potential energy applied in either Eq. (5) or other research such as (Imbol Koungue et al., 2017) can not reflect the influence of linear superposition by waves in multiple vertical modes on the thermocline displacement. Showing the geopotential anomaly with the sign should be more proper. Thus, by giving Figure 4, we think the relative contribution of each mode on the event has already been revealed, that the 1st-3rd modes are of similar importance, while the wave in the 4th mode makes the negative contribution on the thermocline deepening. We agree that the origin of the Kelvin waveguide in the 3rd mode is located at around 15oW (as shown in Fig. 8 and Fig. 10c), taking around 1.5 months to pass the ATL3 region based on its wave speed (around 0.9 m/s), which will crucially shorten the leading time for skillful prediction. However it also takes one or two months for the displacement of thermocline to affect SST so that the locally-forced 3rd-mode wave may still have some potential. Also, the high-mode wave can make contributions to the excitement of the associated coastally-trapped Kelvin waves so as to support the prediction for SST events in the down-wave offshore region along the African coastline. On the other hand, the diagnosis of waveguide should be the previous step for the designing of predicting skills, in which sense the revelation of locally-forced waves is also meaningful.

Song, Qingyang, Hidenori Aiki, and Youmin Tang. "The role of equatorially forced waves in triggering Benguela Niño/Niña as investigated by an energy flux diagnosis." *Journal of Geophysical Research: Oceans* (2023): e2022JC019272.

Imbol Koungue, Rodrigue Anicet, Serena Illig, and Mathieu Rouault. "Role of interannual K elvin wave propagations in the equatorial A tlantic on the A ngola B enguela C urrent system." *Journal of Geophysical Research: Oceans* 122.6 (2017): 4685-4703.

4) The potential negative interference of baroclinic modes is an interesting argument. It would be interesting to examine this in more detail and to show how important this effect is and if it is a systematic feature. Previous studies have shown that similar (average) equatorial Atlantic wind forcing can have different outcomes in terms of the ATL3 SST (Richter et al. 2013; Martin-Rey et al. 2019). Could this be explained by wave interference? This also connects to the inconsistent influence of ENSO on the equatorial Atlantic (Chang et al. 2006).

Thank you for the comment. We agree that the wave interference might be possible to cause the diversity of SST events. Song (2023 a,b) designed several numerical experiments with linear ocean models to investigate Atlantic/Benguela Niño events in recent 30 years. They found that linear superposition of out-phase waves among different modes can eliminate the displacement of thermocline so as to prevent the onset of SST events even if both the wind anomaly and wave signal in each mode are prominent. However, the non-linear interaction and energy transfers between modes are still missing in their studies owing to the deficiency of linear models. In this study, although the reanalysis data contain much richer information than the result by linear ocean models, the decomposition process however also discards the possible evidence of non-linear interactions. On the other hand, going deep into this discussion might be beyond the scope of this study to introduce the useful tool for equatorial wave diagnosis.

Song, Qingyang, Hidenori Aiki, and Youmin Tang. "The role of equatorially forced waves in triggering Benguela Niño/Niña as investigated by an energy flux diagnosis." *Journal of Geophysical Research: Oceans* (2023): e2022JC019272.

Song, Qingyang, Youmin Tang, and Hidenori Aiki. "Dual wave energy sources for the Atlantic Niño events identified by wave energy flux in case studies." *Journal of Geophysical Research: Oceans* (2023): e2023JC019972.

5) How do your results compare with those of Richter et al. (2022) who specifically examined the genesis of the 2019 event?

Thank you for the comment. Richter et al. (2022) have shown a possible link of the off-equatorial Rossby wave with the onset of the 2019 event. In their analysis, they diagnosed the sea level anomaly as well as the wind curl in the north tropical Atlantic to reveal the propagation of Rossby waves. This study agrees well with their results. By wave energy flux, this study confirms the off-equatorial Rossby waves and their influence on the Atlantic Niño event in 2019 to some extent. Furthermore, we have found that the second mode is the most prominent mode to exert this off-equatorial influence on the event. In line (226-229), we have put a short discussion in the context of the study by Richter et al. (2022) to give our point.

6) In Fig. 9, modes 3 and 4 seem to be maximum at the 0-meridian in late fall/early winter. This is the eastern edge of the ATL3 region and so it is not clear how important these two modes are for the equatorial warm event. Does the strong amplitude at this longitude indicate that the waves pass through to the eastern boundary? Is there evidence that they are transmitted into coastally trapped waves?

Thank you for the comment. As we have explained in the comment 3, the respective contribution of waves in each vertical mode to the event can be roughly evaluated in Figure 4 of the revised manuscript, where the averaged geopotential is a good metric to represent the displacement of thermocline hence can reflect the influence of waves on SST. From Figure 4, the waves in mode 3 are definitely crucial for the SST event, while the wave in mode 4 is insignificant. This result agrees well with the numerical experiments using linear ocean models by Song et al (2023). Regarding the waves in the eastern basin, to investigate whether they are transmitted into coastally trapped waves, we have selected an extra meridional transection as S5 at 3oS off the coastline with the width of 5o and calculated the meridional flux passing this section (see the revised Figure 7 and Figure 9 below). We found that "*The peaks of meridional fluxes passing S5 occur almost simultaneously with the peaks of zonal fluxes passing S4, suggesting that the possible energy transferring from the equatorial region to the coastal region may mainly originate from the wind forcing in the eastern basin. Hence on the one hand, the wave exciting the coastally-trapped KWs is not remotely forced; on the other hand, the third-mode wave that carries the highest energy to the coastal region (Figure 9 c) will dissipate rapidly when traveling off the equator due to its short Rossby deformation radius. The results therefore provide evidence that the anomalous SST event of the Benguela/Angola area in 2019 is mainly triggered by local forcing*" (line 201-207 in the revised manuscript).

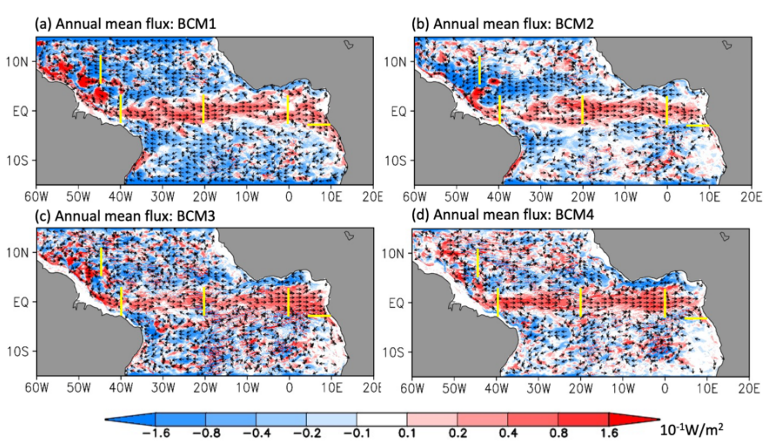


Figure 7 in the revised manuscript.

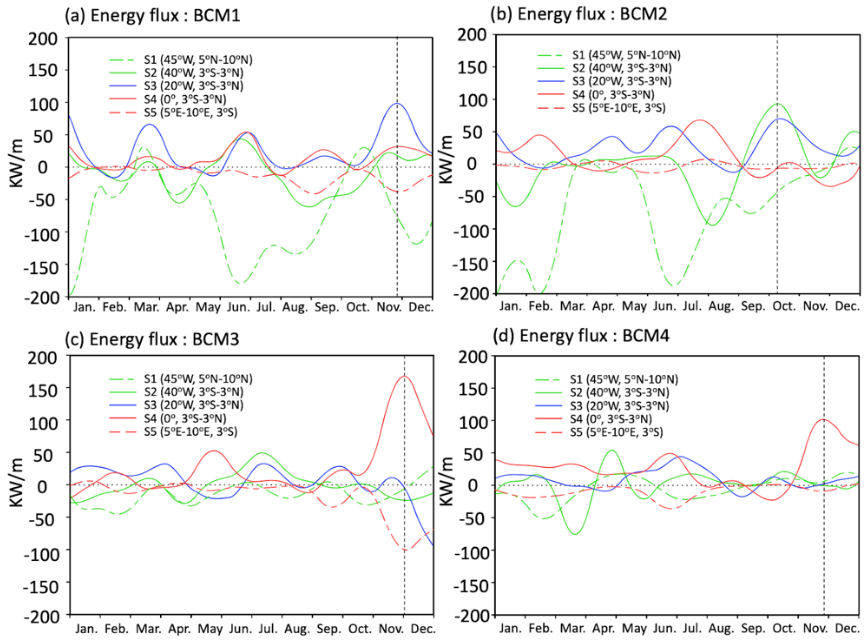


Figure 9 in the revised manuscript. The dashed red line is the newly selected meridional transection at 3^{o}S.

Song, Qingyang, Youmin Tang, and Hidenori Aiki. "Dual wave energy sources for the Atlantic Niño events identified by wave energy flux in case studies." *Journal of Geophysical Research: Oceans* (2023): e2023JC019972.

7) In Fig. 9b, the authors stress the S1 peak in September and how it is followed by an opposite signed peak in S2. This, however, is only a secondary peak. A much stronger peak occurs in late June. How do they authors explain that this peak is not followed by a peak in S2?

Thank you for the comment. The local flux in Figure 9 is determined by both the Kelvin and Rossby waves passing the transaction. Therefore, to explain the flux variation in S2, we should go back to Figure 8 to check the energy transfer route. In Figure 8b, it is found that Kelvin waves are holding from the boreal summer, meanwhile in late June, a strong Rossby wave is just approaching S2 bringing the negative (westward) flux to pass S2 in Figure 9b. In this sense, the reflected Kelvin waves by off-equatorial waves passing S1may indeed cause positive (eastward) flux in S2 from summer, however it is balanced by the negative (westward) flux of equatorial Rossby waves until Sep.. But we agree that the original sentence can cause confusion. Hence we have revised this sentence as "*Moreover, in the second mode, the eastward energy flux peaks in around Oct. on S2 just after strong westward energy flux passing the off-equatorial transection S1 from Jun. to Oct., which may suggest a wave energy transfer route that sequentially passes S1, S2 and S3 to influence the ATL3 region. It hence illustrates the influence of the wave energy from off-equatorial regions on the Atlantic Niño in 2019 to some extent.*" (line 197-200 of the revised manuscript).

Minor Comments

1) l. 14: Please provide some references for the Atlantic Niño phenomenon.

Thank you for the comment. We have put Giannini et al. (2003) as the reference for the Atlantic Niño phenomenon.

Giannini, Alessandra, R. Saravanan, and Ping Chang. "Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales." *Science* 302.5647 (2003): 1027-1030.

2) ll. 16-19: I believe Rodriguez-Fonseca et al. (2009) is an important paper for the influence of the Atlantic Niño on ENSO and should be referenced here.

Thank you for the comment. We have added Rodriguez-Fonseca et al. (2009) as the reference for the remote influence of the Atlantic Niño.

Rodríguez-Fonseca, Belén, et al. "Are Atlantic Niños enhancing Pacific ENSO events in recent decades?." *Geophysical Research Letters* 36.20 (2009).

3) Do you use realistic bottom topography to obtain Hb (depth of ocean bottom)?

Thank you for the comment. Yes, although we did not employ independent topography data, as the reanalysis dataset of 50 vertical levels are fully involved, the realistic bottom topography is literally applied.

4) In the methods section you say that you use long-term climatological temperature and salinity distributions to calculate the modes. Would your results change much if you used the actual temperature and salinity from 2019?

Thank you for the comment. If only the annual mean temperature and salinity in 2019 is applied to calculate the modes, both the obtained eigen vector and eigen value (gravity wave speed) for each mode will be different so as to affect not only the total wave energy but also the contribution of each mode. However, when you apply only the TS data in 2019 to represent the mean state, you indeed improperly estimate the wave-induced anomaly and introduce errors, which is inappropriate in this study.

5) There are many places were editing the English would improve the readability of the manuscript. A few examples are listed below:

1. **a) l. 41: "in addition to involve in-situ and altimetric data"**

The meaning is not clear. Maybe "in addition to including in-situ and altimetric data" was meant?

1. **b) ll. 41-42: "The implementation of ocean linear model in those proposals are necessary"**

Maybe "This will require the use of linear ocean models" was meant?

1. **c) l. 97: "Then though Eq. (5)" -. Then, through Eq. (5),"**
2. **d) ll. 97-98: "pressure flux is redirected to the direction of the group velocity"**

I am not quite sure I follow this. Please rephrase.

1. **e) l. 99: “are hence able to be detected” -> “can therefore be detected”**
2. **f) ll. 126-127: “It may suggest that mixed RWs in the nature of cross equatorial meridional velocity are raised by subseasonal forcing.”**

“in the nature of”: perhaps “in the form of” was meant?

“raised by” -> “excited by”

Thank you for your careful review. All the mentioned errors have been revised and a proofreading has been made through the manuscript to make it better readerable.

References

Chang, P., Fang, Y., Saravanan, R. et al. The cause of the fragile relationship between the Pacific El Niño and the Atlantic Niño. Nature 443, 324–328 (2006). https://doi.org/10.1038/nature05053

Martín-Rey, M., Polo, I., Rodríguez-Fonseca, B., Lazar, A., & Losada, T. (2019). Ocean dynamics shapes the structure and timing of Atlantic Equatorial Modes. *Journal of Geophysical Research: Oceans*, 124, 7529– 7544. https://doi.org/10.1029/2019JC015030

Richter, I., Behera, S. K., Masumoto, Y., Taguchi, B., Sasaki, H., & Yamagata, T. (2013). Multiple causes of interannual sea surface temperature variability in the equatorial Atlantic Ocean. *Nature Geoscience*, 6, 43– 47.

Rodríguez-Fonseca, B., Polo, I., García-Serrano, J., Losada, T., Mohino, E., Mechoso, C. R., and Kucharski, F. (2009), Are Atlantic Niños enhancing Pacific ENSO events in recent decades? Geophys. Res. Lett., 36, L20705, doi:10.1029/2009GL040048.