Reviewer 1

Review of “QBOi El Niño Southern Oscillation experiments: Assessing relationships between ENSO, MJO, and QBO” by Elsbury et al., submitted to EGUsphere

This study investigates the extended winter MJO in an ensemble of QBOi climate models forced separately by perpetual El Niño and La Niña SST conditions. The results indicate that the simulated MJOs are largely insensitive to the stratospheric QBO, as the models fail to capture the observed lower stratospheric QBO-related changes that are critical for MJO modulation. However, the authors find that the simulated MJO and other convectively coupled equatorial wave activities differ markedly between the positive and negative phases of ENSO, with some deviations from previous studies.

Overall, the manuscript is well-written, and the methodologies are clearly presented. However, I have major concerns regarding the SST forcing used in the models. Given that the study’s conclusions heavily rely on these model experiments, I recommend that the authors reassess their experimental design and verify whether their results remain robust in light of previous literature before considering the manuscript for publication.

Thank you for your detailed and thoughtful review. We now articulate our objective, rationale for the experimental setup, have incorporated a sensitivity test of MJO sensitivity to regular (not extreme ENSO) SSTs, and have expanded the conclusion section consistent with your comments and those from the other reviewer. The biggest change is the addition of a new Figure 4, which follows from your Major comment (1) and minor comment (4).

Major comment:

1. To enhance the atmospheric response to ENSO in their simulations, the authors scale the annual cycle of SST by two factors. Notably, the multiplicative factor of 1.8 for the positive ENSO phase is quite large, producing conditions similar to those observed during extreme El Niño events. This scaling also amplifies ENSO asymmetry by a factor of two, as illustrated in Fig. 1. Therefore, the conclusion that MJO activity is stronger during El Niño compared to La Niña is likely driven by these amplified SST perturbations in the models. Previous studies (e.g., Hendon et al. 1999) have reported that exceptionally warm Pacific SSTs can influence MJO activity by allowing the eastward propagation farther to the east. Similarly, the record-breaking strong MJO event in March 2015 (Marshall et al. 2016) was linked to warm equatorial central Pacific SSTs. Given the strong SST forcing in these experiments, enhanced MJO events are not unexpected but rather could be a reflection of selective amplification. Therefore, I recommend using composite SST anomalies without artificial amplification. This approach would provide a more representative assessment of ENSO’s overall impact on MJO activity rather than capturing only extreme conditions. Such a revision would ensure that the study’s conclusions are more robust and broadly applicable.

We appreciate this thoughtful comment and have added a new analysis (Fig. 4) to assess sensitivity of the simulated MJOs to normal amplitude SSTs and comment along these lines in the conclusion section: L613-622.

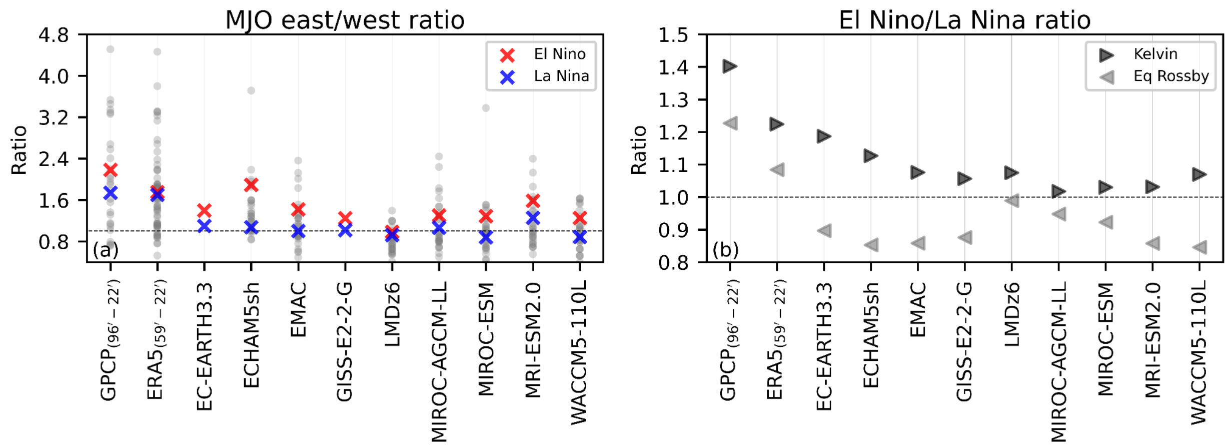

Figure 4: (a) Ratio of eastward to westward MJO precipitation spectral power (from Figure 2) filtered for wavenumbers +/- 1 to 3 and 30 to 96 day frequencies. Red and blue X's denote El Niño and La Niña, respectively, using the same notation for both the GPCP and ERA5 composite averages and the climatological values from the perpetual El Niño and La Niña simulations. Gray dots indicate interannual east/west ratios from GPCP, ERA5, and the QBOi Experiment 1 simulations (1979-2009 AMIP) by these same models; EC-EARTH3.3 and GISS-E2-2G did not run Experiment 1. (b) Ratio of Kelvin wave and equatorial Rossby wave power in El Niño to that in La Niña. Each wave is filtered using equivalent depths of 8 to 90 meters, with wavenumbers of 1 to 14 for the Kelvin wave and -1 to -10 for the equatorial Rossby wave.

Following this comment, we compared a broad measure of MJO quality and propagation, the MJO E/W ratio, between the perpetual ENSO simulations and each model's 1979–2009 AMIP simulations (QBOi Experiment 1), which are more representative of typical ENSO amplitudes. Across models, El Niño forcing increases the E/W ratio, often pushing it toward the upper tail of the AMIP-based internal variability distribution, indicating more robust eastward MJO propagation, whereas many La Niña simulations produce ratios near unity. Notably, all perpetual ENSO E/W ratios remain within the spectrum of their AMIP-based values, underscoring that the modeled responses, while produced by extreme forcings, do not exceed the range of variability seen under more normal SSTs.

2. L167: Since the models are forced with artificially amplified SSTs, comparing their results directly with observed/reanalysis El Niño/La Niña composites is not entirely justified, as the simulations represent exaggerated ENSO conditions rather than typical observed events.

Yes, this is true. We now acknowledge this limitation multiple times in the manuscript: in the Methods section (L182-186) and in the Results section (L396-398). This point is certainly true, but we feel that it is necessary to have a verification benchmark (based on GPCP/ERA5) to compare the perpetual ENSO model responses against.

3. The objective of this study is not clearly discussed. While I recognize that ongoing research involves perpetual ENSO experiments in QBOi models, the specific aim of this work should be explicitly stated at the end of the introduction to provide clarity and context for the reader.

Thank you for this comment. We have revised our background Section so that it includes L110-123:

In this study, we document the influence of ENSO on the MJO using a multi-model ensemble of idealized experiments with perpetual El Niño and La Niña forcings. These simulations were coordinated by the Atmospheric Processes And their Role in Climate (APARC, previously "SPARC") Quasi-Biennial Oscillation initiative (QBOi, Butchart et al. 2018). In addition to prescribing ENSO, the models internally generate QBOs, meaning both types of interannual internal variability may modulate the MJO in these experiments. Our aim is to assess the extent to which model behavior is consistent with previously reported ENSO-MJO relationships, recognizing that past studies have found different ENSO-MJO links and that the simulated QBOs may also project onto the MJOs. The coordinated QBOi protocol allows us to revisit these relationship in a controlled framework that isolates atmospheric responses to fixed, high-amplitude ENSO SSTs across many models. These perpetual ENSO conditions represent the strongest observed El Niños and La Niñas and offer an upper bound on ENSO's effect on MJO characteristics, providing a high signal-to-noise database for studying this connection. We also selectively incorporate Phase 1 QBOi experiments, performed as 1979-2009 Atmospheric Model Intercomparison Project experiments, and hence, more representative of typical ENSO amplitudes (Butchart et al. 2018, Experiment 1). Unlike Coupled or Atmospheric Model Intercomparison Project experiments, or historical reanalysis datasets, these simulations avoid complications associated with time-evolving forcings, event-to-event ENSO variability, and background SST biases.

Minor comments:

1. Please include the horizontal resolution and the number of vertical levels for each model in Table 1 to provide a clearer representation of their configurations.

We updated Table 1 to include horizontal resolution and number of vertical levels.

2. L146: The figure references for El Niño and La Niña SSTs appear to be reversed.

Thanks, we fixed this.

3. L240: How does ENSO influence the periodicity of the QBO? A brief explanation would be helpful.

Add a brief explanation to L258-260: "In short, the periodicity of the QBO decreases in all El Niño simulations and increases in all La Niña simulations, which is attributed to ENSO modulating convection and the low-frequency circulation, thereby influencing generation of tropical waves and their filtering by the large-scale circulation and the QBO."

4. Instead of showing wavenumber-frequency spectra for three different parameters in Figs.2-4, I suggest considering any usual variable like OLR/precipitation. However, a more detailed analysis of eastward and westward propagating modes could provide

valuable insights. For example, comparing the ratio of eastward to westward modes in the low-frequency range between ERA5 and simulations might offer an interesting perspective.

Thank you for this helpful suggestion. We removed our previous Figure 3 (the OLR CLIVAR wavenumber-frequency spectra), made our previous Figure 4 our new Figure 3 (the U850 CLIVAR wavenumber-frequency spectra), and added the E/W ratio figure above as the new Figure 4. This coincides with new text in the manuscript: L389-415.

5. 6: The ERA5 tropospheric temperature anomalies appear slightly stronger during El Niño compared to La Niña, potentially leading to stronger cold caps in the UTLS and modulating MJO convection. Are the differences shown in the right column statistically significant?

Yes, they are statistically significant. See Figure R3 in our Author Comment: https://editor.copernicus.org/index.php?_mdl=msover_md&_jrl=778&_lcm=oc108lcm109w&_acm=get_comm_sup_file&_ms=125830&c=287405&salt=16908123551425922323

6. L467: How does the precipitation-based WF spectra capture the UTLS K-wave signal, which is most likely the dry K-wave?

It does not :) - thanks for pointing this out. We now specify when we are referring to the dry K-wave vs. the convectively coupled wave; see L485-492.

7. Abhik et al. (2019) and Sakaeda et al. (2020) highlighted that many DJF EQBO events tend to coincide with La Niña conditions, whereas Niño 3.4 values are more uniformly distributed during WQBO. Did the authors find a similar nonlinear relationship between ENSO and QBO in their model simulations? A brief discussion on how well the models capture this observed relationship would be valuable.

Following from the major changes elsewhere in the manuscript, we omitted more targeted analysis along these lines. Judging by Figures 2 and 4 of Kawatani et al., this relationship between ENSO phase and lower stratospheric QBO sign appears to be represented poorly: https://egusphere.copernicus.org/preprints/2024/egusphere-2024-3270/egusphere-2024-3270.pdf

8. Is the QBO Fourier amplitude calculation based on the zonal wind? Given that QBO-related temperature changes typically occur above and below zonal wind anomalies, cooler (warmer) temperature anomalies are expected to be located below the lowest level of QBO descent in EQBO (WQBO). Including the zonal-mean temperature profile from both the simulations and ERA5 would provide better clarity. The authors may consider following the approach of Son et al. (2017).

Yes, the Fourier amplitude calculation is based on zonal wind and we have opted to keep it defined this way. We have opted to not use the zonal-mean temperature profile in this way as we already include analysis on tropical lower stratospheric stability.

9. L562: In WACCM, the QBO descends to the lower stratosphere (~90 hPa), which could contribute to the weak sensitivity of MJO activity to the QBO. In MIROC, the weak positive MJO variability difference appears to be off-equatorial. Discuss these differences.

We discuss the WACCM La Niña QBO descent at L535-537 and now point out these off-equatorial MIROC differences at L591-594.

Reviewer 2

Overview: The study evaluates the simulated MJO in an ensemble of climate model experiments with perpetual El Niño or La Niña state. The study thoroughly examines the characteristics of the MJO, such as its lifetime, structure, and propagation. Given the lack of QBO-MJO coupling in the climate models, the authors can also attribute the difference in MJO activities between perpetual El Niño or La Niña simulations from the ENSO states. Overall, the manuscript contains some interesting information, but it can be improved by clarifying the goals and motivation for the study setup.

Thank you for your thoughtful review. We now articulate our objective, rationale for the experimental setup, have incorporated a sensitivity test of MJO changes to regular (not extreme ENSO) SSTs, and have expanded the conclusion section consistent with your comments related to MJO inter-model differences and the missing QBO-MJO interaction in models.

Major Comments:

1. I struggled to understand the main objectives of the study and how the presented analyses met the objectives. The authors need to clarify the goals of the study and present analyses that align with the goals. Lines 106-107 on page 3 state that "more process level understanding of how the ENSO and the QBO influence the MJO is needed, which we pursue here using unique coordinated model experiments". Despite this statement, I found no "process-level" diagnoses of the models. The results mainly presented statistics on MJO properties such as lifetime, structure, and propagation. The lack of consistency in the stated goal of the work and presented results makes readers lost in what they should be getting out of this work.

Thank you for this comment. We have revised our background Section to articulate our simple motivation. After some background on previous ENSO-MJO and QBO-MJO studies, we include L110-123:

In this study, we document the influence of ENSO on the MJO using a multi-model ensemble of idealized experiments with perpetual El Niño and La Niña forcings. These simulations were coordinated by the Atmospheric Processes And their Role in Climate (APARC, previously "SPARC") Quasi-Biennial Oscillation initiative (QBOi, Butchart et al. 2018). In addition to prescribing ENSO, the models internally generate QBOs, meaning both types of interannual internal variability may modulate the MJO in these experiments. Our aim is to assess the extent to which model behavior is consistent with previously reported ENSO-MJO relationships, recognizing that past studies have found different ENSO-MJO links and that the simulated QBOs may also project onto the MJOs. The coordinated QBOi protocol allows us to revisit these relationship in a controlled framework that isolates atmospheric responses to fixed, high-amplitude ENSO SSTs across many models. These perpetual ENSO conditions represent the strongest observed El Niños and La Niñas and offer an upper bound on ENSO's effect on MJO characteristics, providing a high signal-to-noise database for studying this connection. We also selectively incorporate Phase 1 QBOi experiments, performed as 1979-2009 Atmospheric Model Intercomparison Project experiments, and hence, more representative of typical ENSO amplitudes (Butchart et al. 2018, Experiment 1). Unlike Coupled or Atmospheric Model Intercomparison Project experiments, or historical reanalysis datasets, these simulations avoid complications associated with time-evolving forcings, event-to-event ENSO variability, and background SST biases.

2. Because I did not clearly understand the goals of the work, I also struggled to understand why a particular experimental setup was chosen. In particular, the authors should clarify the motivation for perpetual El Niño or La Niña simulations. To understand processes of MJO, QBO, and ENSO interactions, why were the perpetual El Niño or La Niña simulations needed? Why was it insufficient to instead examine how MJO varies with the simulated internal variability of ENSO? Why was it also necessary to amplify ENSO forcing in the simulations? These choices of experimental setup need to align with the clarified goals of the study.

The motivation for using perpetual El Niño or La Niña conditions is to obtain many realizations of the MJO and QBO, per model, while reducing influence from internal variability or scenario uncertainty (i.e., changes from non-fixed historical conditions, GHGs).

It is not necessarily insufficient to examine how MJO varies with simulated internal variability of ENSO. However, there are drawbacks to this approach. In theory, you can analyze MJO-ENSO interaction by using CMIP6 or AMIP6 simulations and reanalysis (e.g., ERA5). However, those data sets include time-evolving historical forcings (e.g., GHGs), event-to-event variations in ENSO amplitude/spatial structure, remote impacts from other parts of the Earth System, and basic-state SST biases that influence ENSO's form (e.g., cold tropical Pacific in CMIP6). Perpetual El Niño and La Niña simulations are desirable because they circumvent these issues.

The high amplitude El Niño and La Niña forcings are used to maximize signal versus noise in the atmospheric response (both MJO & QBO) to ENSO. The SST amplitudes are representative of the strongest observed ENSO events and so constitute an "upper bound" on the atmospheric response to ENSO.

We have summarized our motivation plus the rationale for these experiments at L110-123.

3. Using ERA5 precipitation as an "observational" reference is inappropriate. ERA5 precipitation is not considered observations but rather considered a forecast since precipitation is not assimilated. The quality of reanalysis precipitation is particularly

uncertain in the tropics (Gehne et al. 2016). The authors should use satellite-based precipitations to validate the simulations. The same applies to OLR in Fig. 3. The authors should use satellite OLR, not ERA5 OLR.

Gehne, M., T. M. Hamill, G. N. Kiladis, and K. E. Trenberth, 2016: Comparison of Global Precipitation Estimates across a Range of Temporal and Spatial Scales. *Climate*, 29, 7773–7795, https://doi.org/10.1175/JCLI-D-15-0618.1.

Thank you for this comment. We have incorporated daily GPCP v1.3 (1996-2022) as our "observational" reference. To your point, ERA5 and GPCP produce results that are more different than expected. The description of GPCP and NOAA satellite-based OLR are described at L187-193. PERSIANN data was not used, as previously stated in an Author Comment, because missing data at some longitudes through 1995 precluded the wavenumber-frequency analysis.

4. In section 4 (discussion and conclusion), it would be helpful to expand the discussion on the causes of inter-model differences in the results and why the models still cannot simulate the MJO-QBO link. The authors seem to conclude that, on average, the simulations indicate that the MJO is sensitive to ENSO states. However, there were differences in how each model simulated such sensitivity. What causes the inter-model differences in MJO sensitivity to ENSO? While the models can simulate MJO sensitivity to ENSO, why can't they simulate MJO sensitivity to the QBO?

We have expanded the discussion and conclusion to highlight inter-model differences in MJO sensitivity to ENSO forcing: we now discuss the impact of convective scheme and horizontal resolution at L622-630.

We also expand the discussion and conclusion with speculations on why models cannot simulate QBO-MJO relationships. This is more speculative, but we propose that the dry Kelvin wave representation near the UTLS is involved (e.g., Hendon and Abhik 2018) and hypothesize some key model factors (resolution, basic state wind biases) that may affect this wave's representation; see L632-645.

Minor Comments:

1. Throughout the manuscript, the authors refer to a few manuscripts in preparation (Kawatani et al. in preparation and Naoe et al. in preparation). I am unsure if it is a good practice to keep referring to manuscripts in preparation. Readers cannot access those and cannot obtain information that the authors refer to in those manuscripts. I suggest avoiding references to manuscripts in preparation.

We have removed the "in preparation" comments as the Kawatani et al. manuscript is accepted and Discussion on the Naoe manuscript has wrapped up.

2. In section 2.4 (page 7, lines 191-202), it is helpful first to clarify why two separate techniques are needed to obtain the power spectra. From my guess, the authors did so to separate the spectral signal in a particular season (Nov-April) vs the entire year. Please clarify.

We have added this clarification between L212-224.

3. Some tables were too big, and it was hard to find information referenced in the text. Instead, the authors can consider converting them into figures (e.g., Tables 2 and 3).

We converted Table 3 (the QBO metrics) into a figure, Figure 7.

4. Page 17, Lines 411-413 ("Composites of the background SSTs associated with…). Which figure or table supports this statement? Please clarify.

We now clarify that we are referring to Back et al. 2024 (their Figure 5) at L437-438: https://journals.ametsoc.org/view/journals/clim/37/18/JCLI-D-23-0656.1.xml

5. Page 18, Lines 441-443: "the diversity analysis affirms that the fast and standing MJO archetypes are closely associated with El Niño and La Niña, respectively". I struggled to find evidence for this statement. To support this statement, the authors should probably show how many standing, jumping, slow, and fast MJO events were found in each perpetual El Niño and La Niña simulations. Figure 5 does not support this statement. To my understanding, Fig. 5 only shows the pattern correlation of simulated and reanalysis OLR hovmollers, given that each propagation type occurs. So, Fig. 5 only shows the simulation skills of the MJO with a particular propagation pattern and how the skills differ between the El Niño and La Niña simulations.

Nice catch - we revised this language to reflect what the figure shows, that the pattern correlation of certain archetype hovmollers (e.g., fast MJO) with the reanalysis hovmollers, is higher. We have also printed the number of each type of events on Figure 5, which is described at L440-444.