Response to Editor

Title: QBOi El Niño Southern Oscillation experiments: Teleconnections of the QBO

Authors: Hiroaki Naoe, et al.

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The authors would like to thank the Editor for his time and effort in reviewing our manuscript entitled "QBOi El Niño Southern Oscillation experiments: Teleconnections of the QBO". Above all, the authors are deeply grateful for insights to reconsider us further to improve the paper. We incorporate your valuable comments and suggestions on our proposed revised manuscript. Our Editor's responses and revision are shown in "blue text", whereas Editor's comments are shown "in black". Individual responses to the Editor are as follows.

Black: Editor's comments

Blue: Authors response to the Editor, and all line numbers refer to the revised R1 text, not current revised R2 text.

To Editor:

Co-editor decision: Reconsider after major revisions by David Battisti, 17 July 2025

Dear Prof. Naoe and co-authors:

Thank you for your revised manuscript (WCD 2025-1148). I am recommending major revisions before the manuscript is accepted for publication, although they are better described as "minor but mandatory" revisions since they don't require much in the way of analysis. Rather, they are required because the discussion of the response of the Walker circulation should be revisited (see next paragraph), and the abstract and Short Summary still do not reflect the degree to which the models do not simulate the observed telelconnections between the QBO phase and the frequency of SWW in the polar vortex. Finally, I appreciate the additional discussion that others reasons for why the models have such poor teleconnections to the polar vortex and the subtropical Pacific Jet. Your explanation for both is that the amplitude of the QBO in the lower stratosphere is too weak, and this is a very reasonable and important insight from the QBOi experiments. You should emphasize this in the discussion section and mention it in the abstract.

Please feel free to contact me if you have questions.

Regards, David

Thank you very much for your suggestions to note that the text is not sufficiently described about discussion of the Walker circulation and about the abstract and Short Summary which still do not reflect the degree to which the models do not simulate the observed teleconnections. We revised the text to add these points and reflect our model results that are struggling with the observed response in the abstract and Short Summary. Also, we emphasize important insight from the QBOi experiments that the most models are to struggle with observed responses in the polar vortex and subtropical jet due to weakened QBO amplitudes in the equatorial lower stratosphere.

- the abstract and Short Summary still do not reflect the degree to which the models do not simulate the observed telelconnections between the QBO phase and the frequency of SWW in the polar vortex.

→ We reflect this point to add sentences in the Abstract:

L36-37: "… to idealized El Niño or La Niña conditions (QBOi EN and LN experiments, respectively). In LN, four out of nine models are to reproduce the observed Holton-Tan relationship within a half of the observed amplitude. In the Arctic winter climate, …",

→ in the Short summary:

L51-52: "The polar vortex–QBO links ~~While QBO teleconnections~~ are ~~qualitatively~~ reproduced by ~~the~~ multi-model ensemble within a half of observed amplitude."

→ and in the discussion section:

L780: ", but much weaker than the observed response within at most a half of the observed amplitude (Fig. 2)."

- Finally, I appreciate the additional discussion that others reasons for why the models have such poor teleconnections to the polar vortex and the subtropical Pacific Jet. Your explanation for both is that the amplitude of the QBO in the lower stratosphere is too weak, and this is a very reasonable and important insight from the QBOi experiments. You should emphasize this in the discussion section and mention it in the abstract.

Thank you very much for your suggestions. We emphasize important insight from the QBOi experiments in the discussion section that the most models are to struggle with QBO teleconnection in these regions and mention about that.

Abstract, L43-44: "… modulated by the prevailing phases of ENSO. Overall, the QBOi models show unrealistically weak QBO wind amplitudes in the lower stratosphere, which could explain the weak polar vortex and APJ responses and the weak precipitation signals in the tropics. The QBO teleconnection to the Walker circulation … "

Short summary, L51-53: "~~While QBO teleconnections~~ are ~~qualitatively~~ reproduced by ~~the~~ multi-model ensemble within a half of observed amplitude.~~,~~ Poor performance of QBO signals in the tropics, subtropics, and polar regions is likely~~they are not consistent~~ due to unrealistically weak ~~modelled~~ QBO amplitudes in the lower stratosphere ~~bias and other systematic model biases~~."

Discussion section, L783-784: "The observed strength … the opposite direction (Fig. 3).

One may ask if a model-specific equatorial wind level such as 30 hPa can be more efficient for models to reproduce QBO's impact on the polar vortex (the Holton-Tan effect) than the standard 50-hPa equatorial wind that are optimal for observed teleconnections. However, for both 30-hPa and 50-hPa QBO indices most models underestimate equatorial QBOs and they are struggling to reproduce observed polar vortex responses to the QBO. We have examined whether model performance of QBO amplitude and/or climatological polar night jet strength is related to the ability of model to capture the QBO-induced polar vortex responses. QBO amplitudes at 50 hPa for most models are poor performance, while climatological polar vortices in NH winter can be reproduced with observed strength. This means that unrealistically weak low-level QBO amplitudes can weaken the QBO teleconnections to the polar vortex, as indicated by the previous QBOi multi-model ensemble studies (Richter et al., 2022; Anstey et al., 2022c).

Major SSWs occur … "

Discussion section, L798: "The APJ changes … capture a stronger APJ in EN than in LN. We have also examined whether the subtropical jet route of the QBO teleconnection can be influenced by the QBO amplitude and/or the climatological position of the subtropical jet. Although most QBOi models underestimate the QBO amplitude, models with larger QBO amplitudes do not necessarily exhibit stronger jet responses, nor do models with smaller amplitudes consistently show weaker responses. This means that neither the QBO amplitude nor the APJ position explains the inter-model spread in the QBO-APJ connection. Other factors, such as transient and stationary eddies, may determine the QBO-APJ connection in the model.

The positive equatorial Pacific signal … "

Major comments:

Concerning the Walker circulation, the original analysis used a season (JJA) and definition of the QBO that was based on observations and was applied to all models. The results showed little impact of the QBO phase on the Walker circulation (now

in Figs. S9-S11). The revised manuscript uses time periods and QBO definitions that maximize the correlation between the QBO phase and the Walker circulation response in each model, and the results show that most models reproduce the observed circulation anomalies over the Indian Ocean and Maritime Continent. What is missing in this discussion is that, the difference in circulation over this region due to QBO-W minus QBO-E for the La Nina conditions is (given the weak statistical significance) basically the same for the El Nino conditions (c.f., Figs. 11 and 12) and (not surprisingly) for the control simulation (c.f., Fis S12 with Figs. 11 and 12). Hence, it should be noted in the text (and in the abstract) that the impact of QBO phase on the Walker circulation is insensitive to the phase of ENSO. Below, I also suggest a sentence to reflect this result be included in the abstract.

I agree on the missing discussion about the Walker circulation. According to your suggestion, we add a sentence in the abstract:

L45-46: "… and most models, with the QBO-W phase featuring upper-level westerly and lower-level easterly anomalies over the Indian Ocean–Maritime Continent relative to the QBO-E phase, although its amplitude and timing are model-dependent. ~~In models, t~~This~~e~~ impact of the QBO phase on the Walker circulation appears not to be~~is~~ ~~in~~sensitive to the phase of ENSO."

And, we modify the sentence in the discussion section:

L825-827: "A distinct QBO signal, characterized by upper-level westerly and lower-level easterly anomalies, is observed in the equatorial troposphere in ERA5, which is not very sensitive to the ENSO phase~~ during both El Niño and La Niña years~~."

Abstract suggestions (note: all line numbers refer to the revised text, not the Author tracked changes).

- Lines 37-40: change to read "… are found in LN than in LN, although the differences in frequency are much smaller than that observed. Unlike in the observations, there is no discernible difference in the QBO westerly (QBO-W) and QBO easterly (QBOE) phases. The Asia-Pacific subtropical …."

According to your suggestion, this part is modified to:

L37-39: "… are found in EN than LN~~.~~, and unlike the observations ~~The frequency~~there is no discernible differences of~~in~~ SSW frequencies between QBO westerly (QBO-W) and QBO easterly (QBO-E) phases~~are indistinguishable, suggesting that the polar vortex responses to the QBO are much weaker than those to the ENSO in these models~~."

- Sentence starting on line 41 ("The sign and … phases of ENSO"): delete this line because it is redundant with the sentence starting in the previous line ("IN the tropics …").

We agree on redundance with these sentences, and we merge them together into as follows:

L41-43: "In the tropics, ~~these experiments do not show a robust or coherent QBO influence on precipitation. T~~he sign and spatial pattern of the QBO precipitation response vary widely across models and experiments, indicating that any potential QBO signal is strongly modulated by the prevailing phases of ENSO."

- Lines 45-46, modify to read "…and most models, with the QBO-W phase featuring upper-level westerly and lower-level easterly anomalies over the Indian Ocean-Maritime Continent relative to the QBO-E phase, although its amplitude and timing are model-dependent. In models, the impact of the QBO phase on the Walker circulation is insensitive to the phase of ENSO.

According to your suggestion, this part is modified to:

L45-46: "… and most models, with the QBO-W phase featuring upper-level westerly and lower-level easterly anomalies over the Indian Ocean–Maritime Continent relative to the QBO-E phase, although its amplitude and timing are model-dependent. ~~In models, t~~This~~e~~ impact of the QBO phase on the Walker circulation appears not to be~~is~~ ~~in~~sensitive to the phase of ENSO."

Minor Comments

The colorbar keys in Figure 2 are unreadable, and there are too many contours in the plots. Reduce the number of contours, or consider uneven contour intervals.

→ The colorbar keys in Figure 2 are revised to be readable.

→ We consider uneven contour intervals in the tropics and extratropics:

L333: "Contour interval~~s~~ are~~is~~ 3 (10) m s^{-1} north (south) of 20° N."

Figure caption 3: Delete the line "While for … multi-model mean" and append this to the figure caption. "The dashed line in panel (a) shows the difference in observations when all years (1959-2022) are included in the analysis."

→ This part of Figure caption 3 is revised as follows:

L356-357: "… in each QBO phase. The dashed line in panel (a) shows the QBO composite difference in ERA5~~While for the experiments, ENSO is neutral,~~ when all years (1959–2022)~~in ERA5~~ are included in the analysis~~ (1959–2022)~~. MMM …"

There is unnecessary and tedious detail in describing the deficiencies in nearly all the models to reproduce the observed relationship between the QBO phase on the phase of ENSO. Please delete lines 391-397 and replace them with the simple conclusion "Only one model (ECHAMsh) shows the observed relationship between the frequency of minor warmings and the phase of ENSO."

→ We agree with you and delete these unnecessary and tedious details. We modify these sentences as follows:

L390-397: "… not capture the LN response (e.g., EC-EARTH, MIROC-AGCM, MRI-ESM2.0). Only one model (ECHAMsh) shows the observed relationship between the frequency of minor warmings and the phase of ENSO, and it~~ECHAM5sh~~ has similar frequencies in CTL and LN and more events in EN. ~~GISS shows large spreads in CTL and EN, suggesting that the response is not statistically robust. In Fig. 4b, frequencies of minor SSWs are similar in both ENSO-neutral and El Niño years and there are fewer events in La Niña years in ERA5. There is a large spread in minor SSW frequencies between the models. EC-EARTH and ECHAM5sh show high frequencies of minor SSWs in EN whereas LMDz and MRI-ESM2.0 show low frequencies of minor SSWs. MIROC-AGCM produces fewer SSWs in the CTL, EN, and LN experiments, and MIROC-ESM shows relatively higher frequencies for both major and minor SSWs in EN and LN compared to the other MIROC model. The GISS ensemble shows large spread in all three experiments, suggesting an important role for internal variability.~~"

In Figure 4, please elaborate in the text why there are two (sometimes three) symbols for the same experiment in the GISS models and for the CNT experiment using the MIROCESM?

→ These are ensemble members. Some models in CTL, EN, and LN experiments have two-to-three ensemble simulations and other models have only one member. No daily zonal wind data were archived for WACCM, for the rest the plot follows the availability reported in Table 1. We update an explanation in the figure caption 4 as follows:

L403: "⋯, occurring across full seasons. It is noted that ~~D~~different ~~-~~multiple marker signs in the same experiment ~~of a triplet~~ for a model~~are used to~~ indicate ensemble members (depending on data availability).~~,~~ ~~and u~~Uncertainties are estimated ⋯"

On Lines 540-541, "… and models show a distinct QBO signal between EN and LN experiments." I don't see this in Fig. 8. Figure 8 shows none of the models produce a robust precipitation response predicated on the phase of ENSO – anomalies are only a small fraction of those observed, and only (at best) a few percent of climatology.

→ We agree, the meaning of the sentence was to convey to the reader that in some models, the precipitation or OLR signals are different between experiments. For example, EC-EARTH shows a significant positive signal in the equatorial western Pacific in the LN experiment, which is the opposite sign in the EN experiment. Similarly, in LMDz this same region, including Australia, shows opposing signs of the signal. These anomalies are higher than 1.4 mm day in magnitude, so we couldn't really say that they are only a few percent of the climatology, we think they're large enough to be worth mentioning.

→ This sentence is modified as follows:

L540-541: "None of the models show an OLR signal comparable to observations, and some models (EC-EARTH, ECHAM5sh, LMDz and GISS) show OLR (and precipitation; Fig. 8) responses that appear distinct ~~QBO signal~~ between EN and LN experiments in regions such as the equatorial Pacific. In other words, there is no consistent or robust precipitation response across models or experiments. "

Lines 612-614: That the observed precipitation response may depend on the sign of ENSO should be the first sentence in Section 5.1. The second line ("Overall, all … experiments and models) is redundant with the discussion that immediately precedes it, and it should be deleted.

→ We agree. These 2 sentences are deleted. Instead, they are placed to the beginning of Section 5.1 with some wordings.

→ L522: "5.1 Tropical precipitation

Several studies have proposed that the observed signal from the QBO on tropical precipitation depends on the underlying ENSO phase (e.g., Taguchi et al., 2010, García Franco et al., 2022, 2023). This section investigates this hypothesis using these QBOi models and experiments through the analysis of tropical precipitation and OLR. Figure 8 …"

→ L611-615: "~~These results emphasize that the QBO signal on tropical precipitation may strongly depend on the state of ENSO as suggested by the observations (García-Franco et al., 2023). Overall, some models show a robust and significant precipitation response to the QBO but this response is distinct from observations and varies in sign and magnitude amongst experiments and models.~~"

Figures 11 and 12. Again, the color of the contour lines does NOT match the shading scale in the colorbar; rather, the contour lines are all the same color. Please delete this phrase in both figure captions and indicate in the figure caption the contour interval of the plotted anomalies.

→ We agree. The figure 11 caption is modified as follows:

L701: "Black contours are drawn at 4 m s^{-1} intervals. Colored contours use the same intervals as the shading, with red contours indicating positive and blue indicating negative differences. ~~and the colored contour intervals match the shading scale in the color bar.~~ The target season …"

Line 717: ESM2.0 or MRI?

→ MRI-ESM2.0 is right.

Lines 825-829: It should be noted that the impact of QBO phase on the Walker circulation is insensitive to the phase of ENSO.

We modify it as follows:

L825-827: "A distinct QBO signal, characterized by upper-level westerly and lower-level easterly anomalies, is observed in the equatorial troposphere in ERA5, which is not very sensitive to the ENSO phase ~~during both El Niño and La Niña years~~."