Reply to reviewer # 1

The authors are thankful to the reviewer for their continued valuable comments and suggestions to improve the quality of this paper. We have incorporated all comments to the maximum extent in the revised manuscript. A point by point reply is given below:

Comments

1. The overall framing as a study of QBO impacts on the global monsoon is somewhat confusing. The title and Introduction strongly suggest that the main focus will be on QBO modulation of the global monsoon systems themselves, yet several of the key results concern boreal winter teleconnections involving the NAO and PNA. These patterns are important in their own right, but they do not directly affect the North American or East Asian monsoons at the time when those monsoons are active, so the link to "global monsoon" is not always clear. I think the manuscript would benefit from either (i) making a more explicit and physically motivated connection between the diagnosed NAO/PNA anomalies in DJF and monsoon-related diabatic heating (or including more direct analysis of austral summer monsoon regions), or (ii) adjusting the title and Introduction to emphasize that this is a study of QBO modulation of tropical convection and NH winter teleconnections under ENSO-neutral conditions, rather than of global monsoon rainfall per se. Clarifying this framing would make the main claims easier to identify and follow.

Reply: We agree with you regarding the primary emphases in our paper and have changed the title to "QBO Modulation of Global Monsoon Systems with Application to Northern Winter and Summer for Neutral to Moderate ENSO Conditions". We have tried to clarify and strengthen our interpretation of causes for circulation changes in the Northwest Pacific during JJA, as well as those in the Northeast Pacific and North Atlantic during DJF.

2. Even in the revised version, I still find it hard to extract 2–3 clear, headline conclusions that are not confirmations of previous studies. The Introduction, Results and Conclusions mention several themes (QBO impacts on the global monsoon, UTLS pathways distinct from Holton–Tan, neutral- ENSO conditions, NAO/PNA responses), but these are not distilled into a small set of explicit take-home messages. As a reader, I remain unsure what I am meant to remember as the key new findings beyond the general statement that "the QBO influences regional monsoon behaviour and some NH teleconnections." some of which is well described in papers that are cited in the introduction. If possible, I would encourage the authors to clearly articulate 2–3 central claims and to structure the presentation of the results around those specific claims a little bit more bluntly.

Reply: The four themes of this paper are: 1) It provides a unified seasonal perspective on how the QBO modulates regional circulations and monsoon throughout the globe, 2) It suggests that QBO modulation of the Northwest Pacific during JJA is due to local modulation of deep convection and the Tibetan High by QBO MMC temperature anomalies in the subtropics during QBO W. We also provide a new interpretation of the index level on the pattern of local circulation in the Western tropical Pacific during JJA and DJF. 3) During neutral ENSO and DJF, the QBO exhibits modulation of the PNA pattern, with enhanced flow into Alaska during QBO W. 4) During neutral ENSO and DJF, the QBO exhibits clear modulation of the NAO pattern, with a westward shift during QBO W. In the revised manuscript, we have emphasized these themes.

3. I think there should be a citation on line 45 to back up the claim that the QBO affects monsoons this way, since I don't think it's a given for most people.

Reply: As per your suggestion in the next comment, the introduction has been further revised, and the above statement no longer exists.

4. I find the revised introduction to be somewhat difficult to follow. The text tends to wander between themes: it begins by stating that both ENSO and the QBO can influence the global monsoon, then later steps back to define the QBO, describe its pathways and impacts, and then returns again to QBO–monsoon and QBO–ENSO relationships. In addition, the manuscript repeatedly refers to a "UTLS teleconnection pathway" proposed by Kumar et al. (2024), independent of the Holton–Tan mechanism, without ever clearly describing what this mechanism entails. I suggest reorganizing the Introduction so that the concepts (global monsoon, ENSO, QBO, and the UTLS pathway of Kumar et al. 2024) are each introduced once, in a logical sequence, with a concise explanation of the mechanisms that are central to the present study.

Reply: Thanks for nice suggestion, the introduction has been revised after incorporating the above comment to improve the logical sequence with concise mechanism.

Reply to reviewer # 2

The authors are thankful to the reviewer for their continued valuable comments and suggestions to improve the quality of this paper. We have incorporated all comments to the maximum extent in the revised manuscript. A point by point reply is given below:

Specific comments

L104-105: 'However, this study does not provide an in-depth view of the QBO association with the GM system from both a phenomenological and mechanical perspective.'

As the authors have noted, a key strength of this study is its ability to provide an in-depth view of the underlying mechanical processes. I encourage the authors to further enhance the manuscript by addressing aspects related to this strength that are currently underexplained.

Reply: Following your suggestions, we have clarified our view that the JJA QBO influence is via MMC temperature anomalies modulating deep convection in the subtropical Northwest Pacific, but that during DJF the QBO anomalies in static stability are regarded as consistent with the anomalous long-wave pattern, rather than a primary thermodynamic causal agent.

1 The role of Instability: The authors argue that the key mechanism through which the QBO modulates regional GM circulations lies in UTLS temperature anomalies and the resulting changes in atmospheric instability. They suggest that because these instability changes vary regionally, the associated convection and large-scale circulation responses also differ across specific latitude–longitude sectors, with particularly pronounced signals over the Northwest Pacific, Northeast Pacific, and North Atlantic.

However, instability changes alone do not appear sufficient to explain the modulation of GM circulations. For instance, instability (N''^2) does not show a one-to-one correspondence with upward motion (W''), as illustrated in the right panels of Fig. 10. More specifically, while the instability anomaly over the Northwest Pacific seems consistent with the sign of the upward motion (Fig. 10d), this relationship is not evident over the Northeast Pacific and North Atlantic. In some longitudes, significant instability anomalies do not coincide with any meaningful upward or downward motion, whereas substantial motion anomalies appear in regions where instability itself is not statistically significant (cf. arrows and shadings in the 4th column of Fig.10).

Furthermore, the same UTLS cold anomaly induces a surface cyclonic circulation anomaly over the Northwest Pacific but an anticyclonic circulation anomaly over the other two regions. This raises the question of whether UTLS temperature and instability anomalies genuinely lead the modulation of GM circulations, as claimed, or whether the documented relationships may instead reflect concurrent, but not necessarily causal, features of the system.

Given these issues, additional clarification is needed regarding the physical role of instability in the proposed mechanism and how it can adequately explain the contrasting circulation responses among the three regions.

Reply: We agree with you that static stability does not explain the modulation over the Northeast Pacific and the North Atlantic. Owing to changes in the dynamical background and geographical location, the role of static stability can vary seasonally. The Northwest Pacific patterns are described for boreal summer (JJA), whereas the other two regions for boreal winter (DJF), when planetary wave radiation from tropical convective centers into the NH is active. It is noteworthy that the vertical pattern of anomalies differs between the Northwest Pacific (cool anomaly below 70 hPa and warm above) and the other two regions (cool anomaly below 200 hPa and warm above). We have rewritten parts of the text to explain the contrasting circulation responses (L577-583). The possible observed mechanism is that QBO modulation of tropical deep convection alters the planetary wave train pattern emanating from the tropics to extratropic along the UTLS, rather than invoking a primary feedback role for static instability, such as during JJA over East Asia (L656-658).

2 Subtropical route in Northwest Pacific in JJA: As described in the Introduction, the subtropical route is fundamentally governed by the interaction between the subtropical jets (STJs) and synoptic-and planetary-scale waves. However, this pathway becomes notably weaker during boreal summer. The STJs shift poleward (Contours in Figs. 3&4), making it difficult for UTLS temperature and zonal wind anomalies to influence the jet, and both synoptic and planetary waves are relatively weak during this season.

Given these seasonal characteristics, it is unclear whether the GM circulation changes over the Northwest Pacific in summer can be legitimately interpreted as a manifestation of the subtropical route. Additional justification is needed to clarify whether the mechanism proposed by the authors indeed corresponds to the subtropical route in summer, or whether a different physical pathway is at play in this season.

'In the subtropical route, when a QBO MMC pattern arrives at the tropopause, it alters the meridional temperature gradient, and consequently the distribution of zonal wind by the thermal wind law. The resulting changes in static stability and wind shear in the UTLS can affect deep convection (Giorgetta et al. 1999a, Collimore et al. 2003, Nie and Sobel, 2015). The resulting QBO zonal wind anomalies can influence the STJs, which can, in turn, interact with synoptic and planetary-scale waves which originate in the extratropics and dissipate in the subtropics (Garfinkel and Hartmann, 2011; Inoue and Takahashi, 2013; Haynes et al., 2021).'

Reply: It is much less confusing to use the phrase "UTLS route", which necessarily goes through the subtropics. We have rewritten the introduction to clarify what we mean by the UTLS route. The salient role of the MMC UTLS temperature anomaly during JJA is emphasized, at a time when the STJ is well poleward of the region of interest. We agree that during boreal summer the STJs shift poleward and planetary waves are relatively weak, and we highlight this point in the revised text (L82-83, L530-532, L551- L554). Accordingly, we are providing additional justification in the section focusing on the Northwest Pacific during JJA, supported by relevant references, to clarify the mechanism for UTLS pathway during boreal summer. The possible observed mechanism is that QBO MMC temperature anomalies around the tropopause in the subtropical region affect UTLS static stability and modulate deep convection, rather than modulating synoptic wave interaction with the STJs (L 644-647).

3 PNA: The authors claim that the QBO excites a PNA pattern. While the spatial pattern in SLP indeed resembles the canonical PNA structure, it is important to recognize that the classical PNA pattern is typically generated through a sequence of processes whereby deep convection–induced diabatic heating in the mid–upper troposphere (500–200 hPa) initiates Rossby wave trains that propagate into the midlatitudes. It remains unclear whether the QBO triggers the Northeast Pacific SLP anomalies through this same physical pathway.

To justify the use of the term "PNA pattern," I recommend that the authors examine whether there is corresponding wave propagation in the 500-hPa geopotential height field, or alternatively, assess whether the anomalous pattern exhibits strong correlations with a conventional PNA index.

If the anomalies are confined primarily to SLP without clear evidence of the characteristic mid–upper tropospheric wave train, it would be more appropriate to refer to the feature as a "PNA-like pattern" rather than a true PNA pattern.

Reply: Thank you for the valuable suggestion. The 500 hPa geopotential height (GPH) anomaly patterns resemble the MSLP which support the claim that the QBO excites PNA pattern. These patterns have been added as supporting information (Fig. S3), with a revised text to describe them.

4 Completeness of the manuscript

4-1) References

L49-50: 'ENSO is a major driver of global teleconnections (Mooley and Parthasarathy, 1984; Shen and Lau, 1995; Krishnamurthy and Goswamy, 2000; Yuet al., 2021).'

Mooley and Parthasarathy (1984) do not discuss ENSO, and the references cited in this section focus exclusively on the Indian monsoon. To support the use of the term "global teleconnections," additional references that address broader large-scale or inter basin teleconnection pathways are needed.

Reply: The citation Mooley and Parthasarathy (1984) has been replaced with appropriate references focuses on ENSO teleconnections (e.g. Horel and Wallace, 1981; Park et al. 2023) (L43-44).

L50-51: 'Over the Northwest Pacific, ENSO significantly modulates regional atmospheric circulation and associated precipitation patterns (Wang et al., 2024).'

The study in question does not examine atmospheric circulation, rather, it focuses on "oceanic circulation". I recommend that the authors replace or supplement the current citation with the following three references, which are more appropriate for the context.

Refs:

1. Wang, B., Wu, R., & Fu, X. (2000). Pacific-East Asia teleconnection: How does ENSO affect East Asian climate? Journal of Climate, 13(9), 1517–1536. https://doi.org/10.1175/1520-0442(2000)0132.0.CO;2
2. Wu, R., Hu, Z. Z., & Kirtman, B. P. (2003). Evolution of ENSO-related rainfall anomalies in East Asia. Journal of Climate, 16(22), 3742-3758. https://doi.org/10.1175/1520-0442(2003)016<3742:EOERAI>2.0.CO;2
3. Park, C. H., & Son, S. W. (2024). Subseasonal variability of ENSO–East Asia teleconnections driven by tropical convection over the Indian ocean and Maritime Continent. Geophysical Research Letters, 51(13), e2023GL108062. https://doi.org/10.1029/2023GL108062

Reply: Thanks for suggesting more relevant references and current citation has been replaced with these citations.

L94-95: 'The effects of the QBO on rainfall in different parts of the globe, particularly within the tropical and subtropical regions, have been examined in some previous observational studies (Seo et al., 2013; Gray et al., 2018; Ma et al., 2021).'
While the other two studies are appropriate, Ma et al. (2021) does not examine the effects of the QBO on "rainfall". Instead, it focuses on "surface air temperature". The authors may wish to reconsider the relevance of this reference in the current context.
Reply: The citation has been removed from the above context.

L91-93: 'For example, when QBO E occurs at 70 hPa, the East Asian STJs weakens and shifts poleward, weakening the East Asian winter monsoon (Ma et al., 2021).'
I recommend adding an appropriate reference to support this statement. "For example, when the QBO easterly phase occurs at 70 hPa, the East Asian subtropical jet weakens and shifts poleward (Park et al., 2022),"
Refs:
1. Park, C. H., Son, S. W., Lim, Y., & Choi, J. (2022). Quasi-biennial oscillation-related surface air temperature change over the western North Pacific in late winter. International Journal of Climatology, 42(8), 4351-4359. https://doi.org/10.1002/joc.7470

Reply: The citation has been replaced as suggested and can now be found at line L85 due to shifts in the text.

L47-48: 'both the QBO and ENSO can modulate the Rossby source term (Chapter 8, James 1994), and therefore modify climatological structures associated with stationary Rossby wave trains, including the Pacific-North America pattern (PNA) and North Atlantic Oscillation (NAO)'.
L83-86: 'QBO modulation of deep convective centers can modulate the planetary wave trains which emanate from them, with poleward energy dispersion along the UTLS. This can, in turn, modulate regional circulation features in the extratropics, including the NAO and PNA patterns.'
Additional relevant references are also needed here to adequately support the authors' statement.
Reply: Additional relevant references have been added to support the above statements (L46, L90-91).

The authors are requested to conduct a careful and comprehensive proofreading to address these remaining issues, and improving the readability of the manuscript.
Reply: Thank you for the thorough evaluation of the manuscript and suggesting the appropriate references at relevant places, which improved its completeness. We also carried out careful proofreading to enhance readability.