nature portfolio

# Peer Review File

# Shifts in MJO Behavior Enhance Predictability of Subseasonal Precipitation Whiplashes

Corresponding Author: Professor Bin Wang

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

**Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.**

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

[Editorial Note: The reviewer's attachment is displayed on the final three pages of this file]

Reviewer #2

(Remarks to the Author)
The authors investigate the future projection of MJO diversity under two different scenarios. This study found that fast and jumping MJO becomes more frequent in the warmer scenario. This study also suggests that such changes can possibly lead to rapid changes in precipitation at sub-seasonal timescales (precipitation whiplash). I believe this study will help improve the understanding of MJO impacts through MJO diversity. I think this paper is acceptable after a few major revisions. I recommend a major revision with the following comments.

Major comments
1. In this study, good models are selected based on the RMSE at a certain threshold (0.3). They concatenate the composites of four MJO types in a particular model and calculate the RMSE. Is there any possibility of leading to good models by one or two certain MJO types, which are relatively well simulated in particular models? I want to check the spread of the performance among the four MJO types in MME12. It is because one or two certain MJO types with a great simulation possibly mislead to the GOOD performance of simulating all MJO types. Furthermore, the sensitivity test for the different thresholds is needed.

Recommend reference) Back et al. 2024; MJO diversity in CMIP6 models. https://doi.org/10.1175/JCLI-D-23-0656.1.

2. It is understandable that the frequency of the precipitation whiplash increases with the increase in frequency of fast/jump MJO in warmer climates. However, for that to be correct, the frequency of the precipitation whiplash associated with the fast/jump MJO should be larger than that associated with the stand/slow MJO in historical experiments. According to Fig. 4a, most regions except the equatorial Pacific (especially the equatorial western Pacific) show a lower or comparable frequency of the precipitation whiplash between fast/jumping and standing/slow MJO types. This result seems to suggest that precipitation whiplash for fast/jumping, which is not present today, may suddenly arise in future climates. I want to ask about the similarity of the difference in frequency of precipitation whiplash between fast/jump and stand/slow MJO by calculating the pattern correlation between Fig. 4a and Fig. 4b. Furthermore, how can we interpret the different responses between two different periods?

3. The authors suggest that moist GW might be important for MJO propagation speed under stratified fluid conditions. They further investigate the changes in moist GW and decompose them into impacts of changes in dry static energy and moisture destabilization. Before decomposing into two terms, the authors should show the relationship between moist GW speed and MJO propagation speed. A scatter plot between the speed of moist GW and that of MJO in the historical experiment for individual models would be helpful in supporting the authors' claim.

4. The authors show that the behaviors of jumping MJO become fast-propagating MJO in a warmer climate. I think it is quite unusual to say "jumping MJO" for this Hovmöller diagram (Fig. 3e). I wonder how we can interpret the physical mechanisms of the jumping MJO. Is it induced by a strong barrier effect on the maritime continent? Or is it induced by the re-emergence of enhanced convection over the western Pacific? How can we understand such changes in jumping MJO with the changes in background conditions in a warmer climate? It would be better to discuss the mechanisms of jumping MJO.

Minor comments
1. I wonder if the definition of climatology and anomaly is quite sensitive to these results in a warmer climate. How did you calculate the climatology and anomaly in two different SSP scenarios? The authors have to clarify how to calculate the climatology and anomaly.

2. If you do not compare the GOOD and POOR models, I think you don't need to mention the POOR models and should focus only on the underlying mechanism of MJO diversity in warmer climates. If you want to include this comparison, the authors should mention what determines the GOOD and POOR models.

3. The jet position over the Pacific can influence the response of the MJO teleconnection. If the precipitation whiplash in the subtropics is induced by the MJO teleconnection, is there any difference in the subtropical jet among the four MJO types in historical experiments? Furthermore, I wonder whether the changes in jets in warmer climates are negligible for the changes in MJO teleconnection.

4. L187-191: The authors should better describe how moist GW is related to the MJO propagation speed and Kelvin-Rossby couplet in more detail. I think this relationship can be described more thoroughly. Furthermore, the authors should discuss a comparison between these results and the literature.

5. Please provide the reference for L190-191 “The MJO propagation speed depends on moist gravity wave speed.”

6. There is no Supplementary Fig. 3i.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The authors have addressed my previous comments and the article is worthy of publication as is.

Reviewer #2

(Remarks to the Author)
Review of NCOMMS-24-61149A-Z

Thank you for addressing most of my previous comments. The manuscript has improved substantially. While the proposed mechanism explaining the rapid propagation of MJOs in future climate makes logical sense, the supporting analysis requires further development. I do not expect additional analyses to be performed for this study, but I recommend that the authors tone down their assertions regarding this mechanism and present it more as a hypothesis worthy of future investigation rather than a definitive conclusion. Except this, I do not have any further critical concerns, but I do have some minor suggestions.
Minor Comments
1. Line 233: Please add a sentence explaining the physical meaning of the R-K ratio to improve clarity for readers.
2. Regarding the mechanisms related to the Gravity wave: There remains a conceptual gap between the R-K ratio and its connection to moist gravity wave speed. The authors should explicitly explain how the R-K ratio relates to moist gravity wave speed to strengthen this important theoretical link.
3. The study primarily examines MJO propagation through the Rossby-Kelvin wave couplet framework. Since this represents only one of several mechanisms explaining MJO dynamics, the manuscript would benefit from acknowledging other theoretical perspectives, particularly moisture mode theories. I suggest expanding the discussion to address how different theoretical frameworks might identify or interpret changes in MJO diversity under future climate scenarios.
4. Figure 6: Please add a complementary schematic diagram depicting the mechanism in the current climate to facilitate direct comparison with the future climate scenario.

Reviewer #1 (Remarks to the Author):

Although the topic of Madden-Julian Oscillation (MJO) shifts under climate change is scientifically relevant, this paper may fall short of the novelty required to meet the standards of Nature Communications. There is considerable overlap with existing literature, particularly from researchers such as Tim Li's group at the University of Hawaii, Bin Wang (a co-author of this work), and others who have published extensively on this subject. Moreover, the methodology employed and the limited discussion on the mechanisms behind MJO propagation modes raise concerns about the robustness and originality of the findings. To clarify, this is a solid piece of research and certainly appropriate for other high-impact journals, such as AGU Geophysical Research Letters or the Journal of Climate. Given these considerations, I leave it to the editor's discretion to make the final decision after evaluating feedback from the other reviewers.

**AUTHOR RESPONSE:**

We genuinely appreciate your time and effort in reviewing and providing valuable comments on the manuscript. Our point-by-point responses to your comments are as follows. Line numbers are highlighted in green. References are at the end of this document.

Major Comments

1. This paper largely re-examines MJO propagation patterns under climate change, a topic that has been extensively studied. Previous works, including those mentioned above, have covered similar themes in depth. To justify publication in a high-impact journal, this manuscript would need to provide a significantly new perspective or a groundbreaking finding that advances the field beyond current knowledge. At present, it falls short of this standard.

   **AUTHOR RESPONSE:**

   We concur with the reviewer that novelty is paramount in contemporary research. We wish to clarify that no existing studies have examined the future changes in the MJO's diverse propagation modes and their impacts on future global compound hazards. The novelty of our work is summarized as follows:

   - We extend the concept of diversity to climate change study and demonstrate an anticipated increase in fast and jumping MJO events under warming.
   - We present a new mechanism to quantitatively elucidate competition between atmospheric stabilization and moisture effect in causing the future eastward acceleration of the MJO in a heuristic framework, which is a breakthrough.
   - We reveal the impact of MJO behavioral changes on severe subseasonal precipitation whiplash globally for the first time.

   We have also included a schematic diagram summarizing the key physical processes involved in the MJO's eastward acceleration under future warming (**Fig. R1**), now designated as Fig. 6 in the main text. Furthermore, by employing improved methods and conducting more comprehensive analyses and sensitivity tests in this revision, we show that the main arguments of this study remain unchanged (see our subsequent responses), certifying the robustness and credibility of our findings.

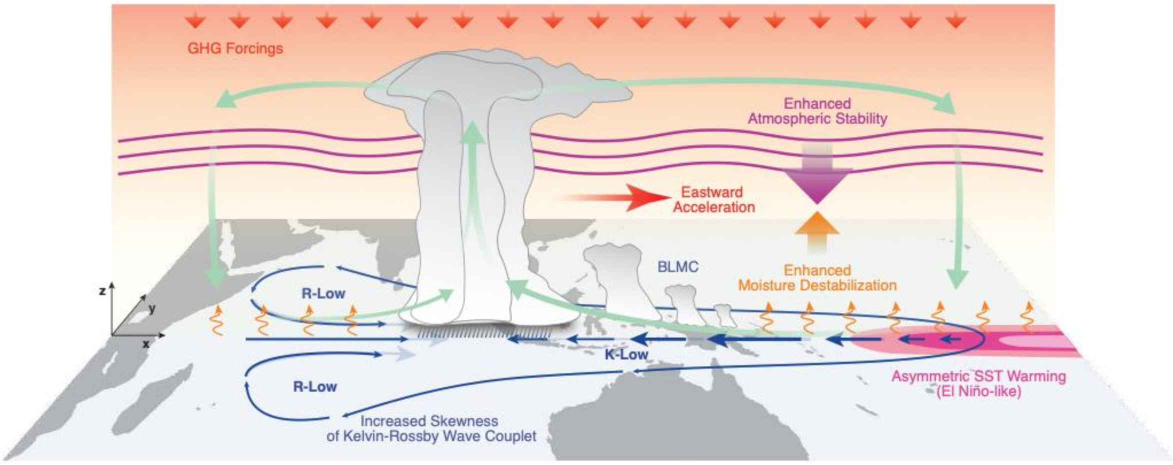


**Fig. R1. Key physical processes associated with the MJO's eastward acceleration.** Schematic diagram summarizing the key processes that explain the eastward acceleration of MJO in future warmer climates. See text for explanation.

2. While the authors' approach to calculating MJO propagation based on minimum OLR anomaly at each longitude appears innovative at first glance, it is quite restrictive and may limit the reliability of the results. This difficulty is largely due to the zonal asymmetries of the Indo-Pacific warm pool (60ºE-180º). The method proposed by the authors could lead to biases or an incomplete representation of the MJO's propagation dynamics, as it may overlook broader patterns that are essential to understanding MJO diversity. Numerous alternative methodologies have been proposed in the literature, such as those discussed by Yang (2007) in Convectively Coupled Equatorial Waves. Part II: Propagation Characteristics. Yang's approach provides a more comprehensive framework for assessing convectively coupled equatorial waves and MJO propagation characteristics. The authors should carefully consider such alternatives or provide a clear justification as to why their chosen method offers an advantage. As it stands, the methodology section appears restrictive and may affect the generalizability of the findings.

**AUTHOR RESPONSE:**

Thank you for your suggestion. We have tried the Radon method that you suggested following the literature (Challenor et al. 2001; Yang et al. 2007) and compared it with ours. We found that when the MJO phase speed tends to be constant over time, the two methods yield similar estimates (**Fig. R2a, b**). However, when the MJO phase speed changes over time, the two estimates differ greatly (**Fig. R2d, e**). The reason for such a discrepancy is that the Radon method is a signal-processing method that transforms the coordinate by rotation and finds the angle (which corresponds to phase speed in the time-longitude plot) at which a maximum summed squares of signals along the rotated x-axis is obtained (Challenor et al. 2001). Therefore, it is biased to the signal intensity and thus would mistakenly capture the slow phase speed near Day 0, when the convective intensity of the MJO is the strongest, thus missing out on capturing the overall propagation speed (**Fig. R2c**). In contrast, the linear regression-based method is insensitive to local extremity and can reasonably estimate the overall phase speed of the MJO (**Fig. R2d**), which justifies our use of the linear regression-based method in this study.

Furthermore, we have improved our regression-based approach by estimating the phase speed using Sen's slope, which is resistant to outliners and more robust than the ordinary least-square fit (Sen 1968). In most cases, this improved method yields almost the same phase speed as the original one (**Fig. R2b, c**), but it shows a more robust estimate of the phase speed in some cases (**Fig. R2e, f**). We have updated the Methods and the results accordingly using the improved approach (L435–443).

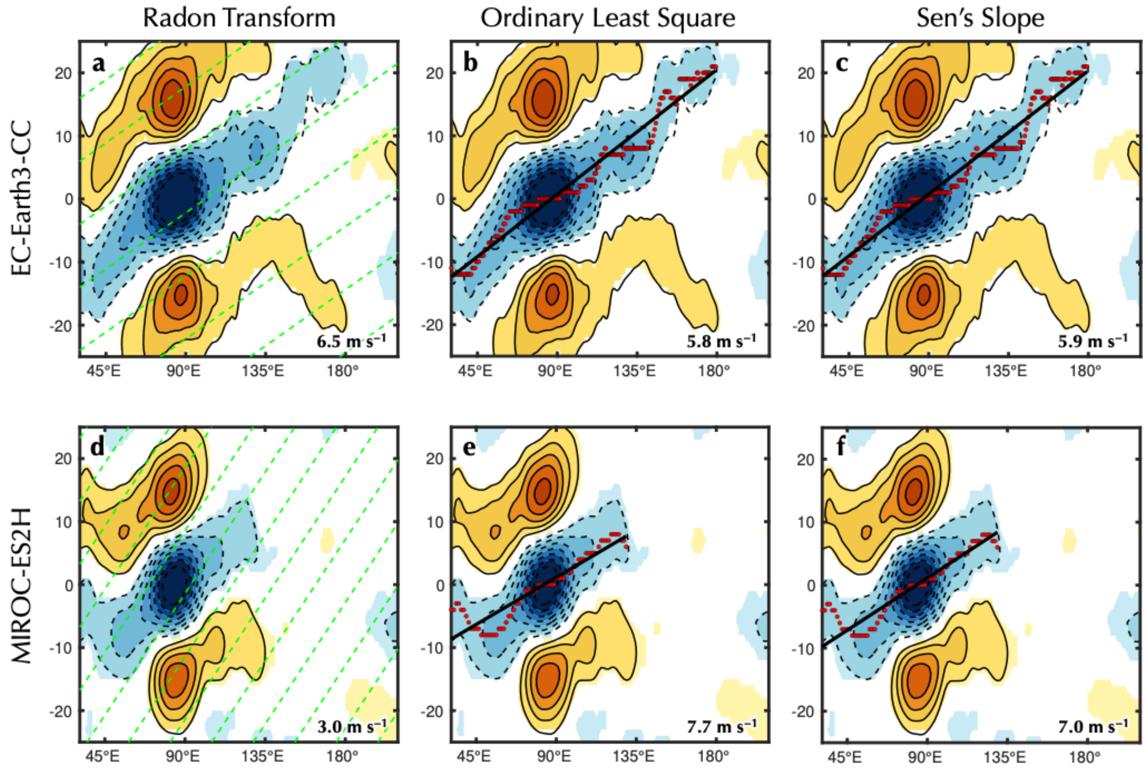


**Fig. R2. Comparison of phase speed estimates using the Radon transform, ordinary least square, and Sen's slope methods**. The comparison is based on the composited MJO events in the historical period (1979–2014) from **a–c,** EC-Earth3-CC, and **d–f,** MIROC-ES2H models, which serve as examples for illustration. The green dashed lines in panels a and d are tracks with the same phase speed estimated from the Radon transform method but at different intercepts. For the rest of the panels, the solid black lines and red points denote the linear regression line and the minimum OLR points (at most $-3$ W $m^{-2}$) at each longitude, respectively.

3. One of the main weaknesses of this manuscript is the limited exploration of mechanisms underlying the different MJO behaviors, particularly fast-propagating and jumping events. While the paper identifies these categories, there is minimal discussion of the physical drivers or atmospheric conditions that might explain why these distinct modes of propagation occur. For a more comprehensive understanding, the authors could have elaborated on the role of atmospheric stability, moisture distribution, and other relevant factors influencing MJO behavior.
   **AUTHOR RESPONSE:**
   We appreciate the reviewer's comment. We have significantly enriched the introduction by explaining the physical mechanisms behind different MJO behaviors (i.e., standing, jumping, slow, and fast modes) and the contrasting roles of the dry static stability and specific humidity in affecting the equatorial wave speed and, thereby, the phase speed of the MJO. Beyond these, our work qualitatively clarifies the roles of atmospheric stabilization and moisture destabilization in the future MJO phase for the first time, contributing to a deeper understanding of the MJO's future eastward acceleration. We hope these address the reviewer's concern here.

4. Given the substantial focus on MJO propagation diversity, I would expect a deeper examination of the specific mechanisms that lead to variations in propagation speed and type for instance throughout the use budget analysis. In addition, Exploring and explaining the

mechanisms of Madden-Julian Oscillation (MJO) propagation patterns under climate change using the Clausius-Clapeyron (C-C) relation is a valuable approach, as it connects moisture availability to temperature, which directly impacts convection and atmospheric instability; key drivers of MJO dynamics. A warmer atmosphere, per the C-C relation, can hold significantly more moisture, especially in tropical regions where the MJO originates. This increased moisture availability influences MJO propagation by potentially intensifying convection within the MJO. Without this, the findings appear descriptive rather than explanatory, which may limit the study's impact and contribution to advancing our understanding of MJO dynamics.

**AUTHOR RESPONSE:**

Thank you for your comment. We agree with the reviewer that the moisture effect is an important component of the MJO propagation mechanism. However, an MJO event with a stronger convective intensity would not necessarily mean its propagation must change accordingly, nor would the moisture effect be the only dominant factor in the propagation mechanism. Previous diagnostic and numerical studies (Wang et al. 2016; Wang and Chen 2017; Wang and Lee 2017; Chen and Wang 2019, 2020) have shown that what fundamentally determines the MJO propagation speed is the asymmetry in the coupled Kelvin-Rossby wave packet. Increased moisture availability, as a result of warming and the C-C relation, decelerates the moist GW speed by wave dynamics (Wang 1988; Holton 2004; Frierson 2007). The effect of warming on moisture through the C-C relation has already been considered in our moist GW wave diagnostics. This heuristic diagnostic enables us to show that, in a quantitative sense, the effect of dry static stability overtakes the moisture effect in accelerating the moist GW speed under global warming (**Fig. R3c**). This explains the MJO's skewed wave couplet and, hence, the MJO's future eastward acceleration. We have also added scatter plots proving the robust relationship between the MJO propagation speed, the Rossby-Kelvin ratio, and the moist GW speed (**Fig. R3a, b**). We have substantially revised the "The physical origin of the MJO acceleration under anthropogenic warming" section based on the new analyses (L209–308). The figure now refers to Fig. 5 in the main text.

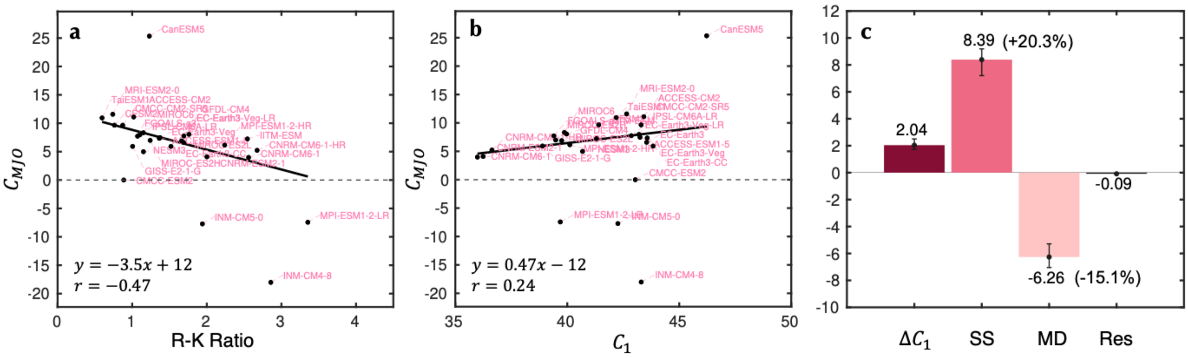


**Fig. R3. Future MJO acceleration driven by the stronger effect of warming-induced atmospheric stabilization than moisture destabilization.** Scatter plots showing the relationship of the mean MJO propagation speed against **a,** the coupled Rossby-Kelvin (R-K) ratio and **b,** the regional mean-state moist gravity wave (GW) speed averaged over 10°S–10°N, 50°–150°E based on 28 CMIP6 models. The regression is estimated using Sen's slope. The equation and the Kendall rank correlation coefficient are shown on the bottom left. **c,** A bar plot showing the effects of static stability (SS) and moisture destabilization (MD) on the future change of moist GW speed ($\Delta C_1$) (units: m s$^{-1}$) averaged in 50°–150°E, 10°S–10°N during the SSP5-8.5 (2064–2099) scenario, compared to the historical run. The quantities are computed based on the background 3-month running mean fields (see "Methods"), with the central month being the month of day 0 of each MJO event. The MME12 mean value and the percentage change with respect to the historical regional mean $C_1$ (41.35 m s$^{-1}$) are shown, with the uncertainties representing the inter-model spread from the 25th to 75th percentile of the values output by the 12 good models.

Minor Comments

1. The paper would benefit from a more thorough review of existing studies on MJO propagation. Integrating more insights from similar studies would situate this research within the broader context of current MJO research.
   **AUTHOR RESPONSE:**
   We have significantly enriched the introduction by including a more thorough review of the MJO theories on the propagation mechanisms and the physical origin of the MJO's diversified propagation modes.

Reviewer #2 (Remarks to the Author):

The authors investigate the future projection of MJO diversity under two different scenarios. This study found that fast and jumping MJO becomes more frequent in the warmer scenario. This study also suggests that such changes can possibly lead to rapid changes in precipitation at sub-seasonal timescales (precipitation whiplash). I believe this study will help improve the understanding of MJO impacts through MJO diversity. I think this paper is acceptable after a few major revisions. I recommend a major revision with the following comments.

**AUTHOR RESPONSE:**

We genuinely appreciate your time and effort in reviewing and providing valuable comments on the manuscript. We have substantially improved the manuscript as per the reviewers' advice. Our point-by-point responses to your comments are as follows. Line numbers are highlighted in green. References are at the end of this document.

Major comments

1. In this study, good models are selected based on the RMSE at a certain threshold (0.3). They concatenate the composites of four MJO types in a particular model and calculate the RMSE. Is there any possibility of leading to good models by one or two certain MJO types, which are relatively well simulated in particular models? I want to check the spread of the performance among the four MJO types in MME12. It is because one or two certain MJO types with a great simulation possibly mislead to the GOOD performance of simulating all MJO types. Furthermore, the sensitivity test for the different thresholds is needed.

Recommend reference) Back et al. 2024; MJO diversity in CMIP6 models. https://doi.org/10.1175/JCLI-D-23-0656.1.

**AUTHOR RESPONSE:**

Thank you for your suggestions and the reference. We have performed sensitivity tests on the threshold for selecting good models, which will affect the multi-model ensemble mean (MME). We show that the future rise in the fast MJO events is consistently projected by the MME based on different thresholds (**Fig. R4**). Note that using a threshold of 0.35 gives the same set of good models based on the original threshold of 0.3, and its results are thus omitted here. Furthermore, we have followed the reviewer's suggestion to evaluate the model performance based on individual MJO types. Furthermore, we confirm that the top-performing models based on individual MJO types are among the 12 good CMIP6 models using the original evaluation scheme (which is based on all four MJO types combined), and likewise for the poor models (**Fig. R5**). These show the robustness and aptness of the model evaluation scheme adopted herein. The above sensitivity tests demonstrate the aptness of our original evaluation scheme and the robustness of the main arguments of this study. The above are now mentioned in L115–121.

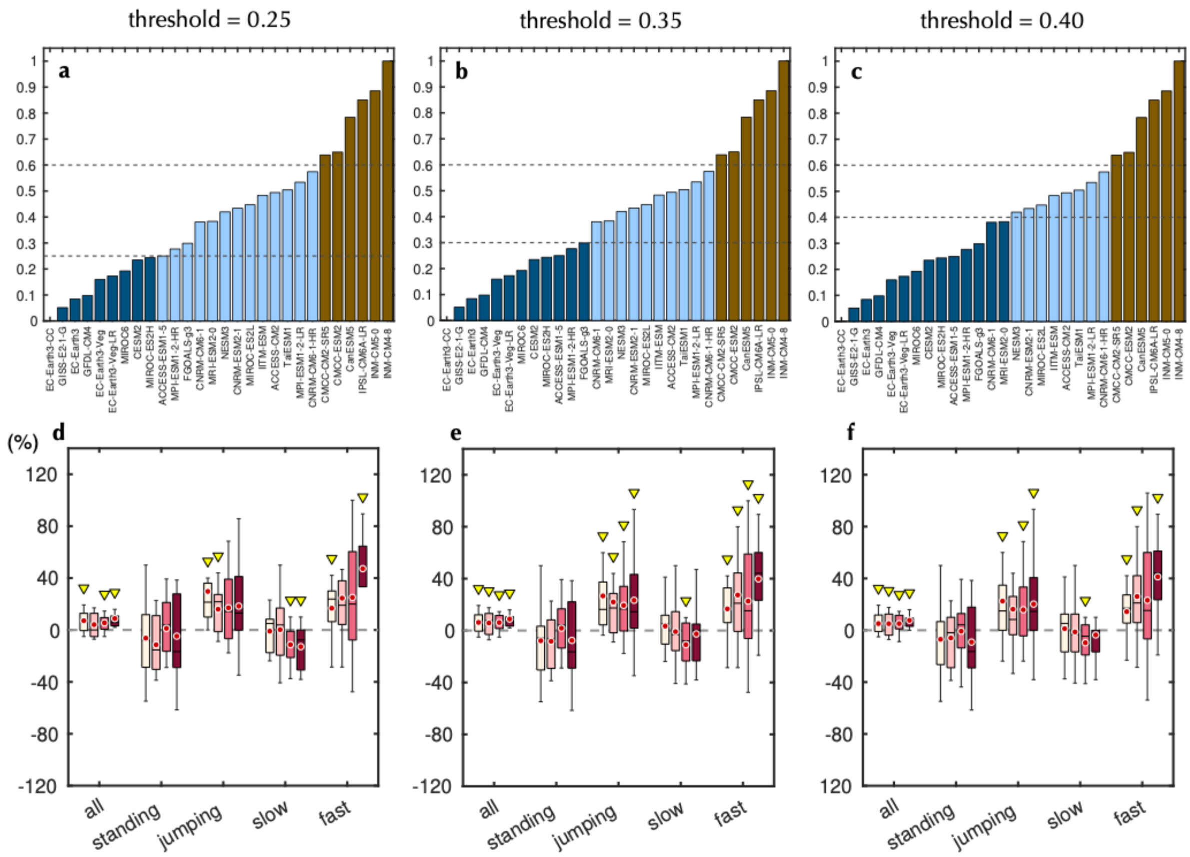

**Fig. R4. Sensitivity tests on the selection of good models.** Similar to Supplementary Fig. 1b, but for the good models (denoted by navy blue bars) based on a threshold of **a,** 0.2, **b,** 0.25, and **c,** 0.4. Note that using a threshold of 0.35 gives the same set of good models as the original threshold (0.3). **d–f,** Similar to Fig. 1b, but based on the three different thresholds.

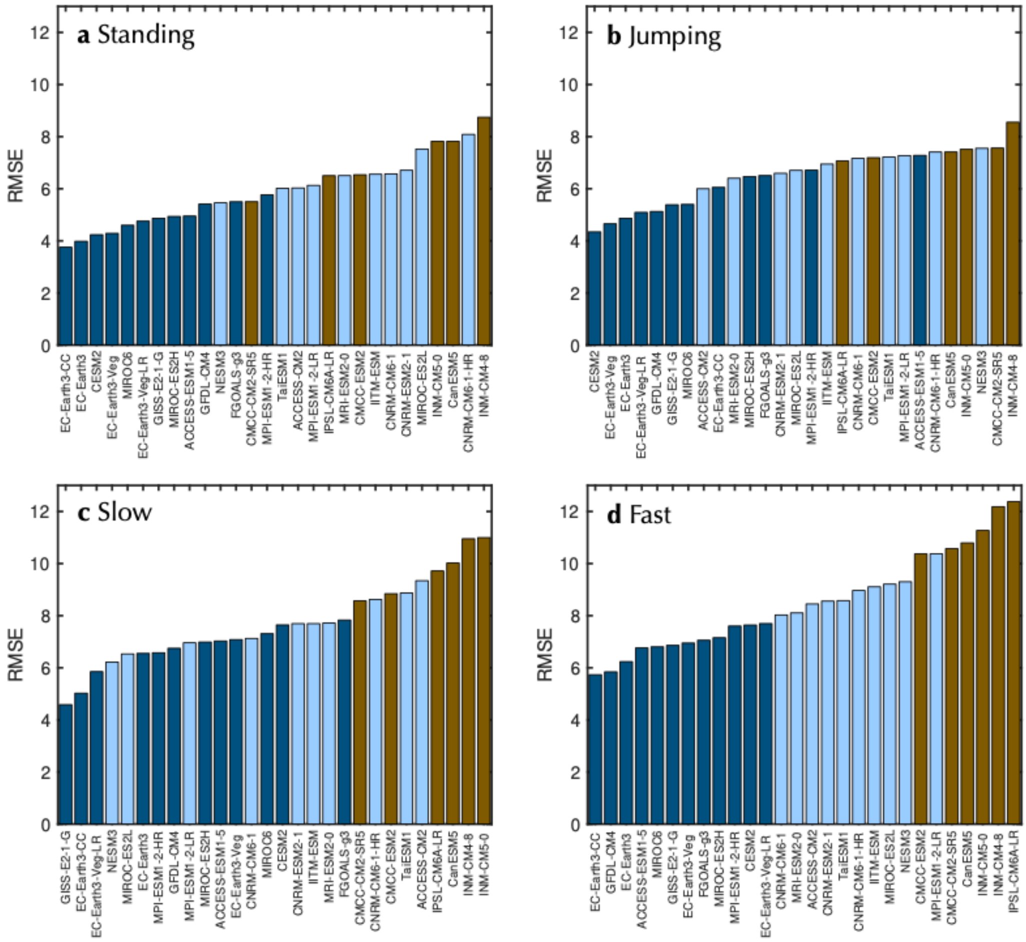


**Fig. R5. CMIP6 model performance based on individual MJO types.** The performance of CMIP6 model in reproducing **a,** standing, **b,** jumping, **c,** slow, and **d,** fast MJO based on RMSE. Bars in navy blue indicate the 12 good models selected based on the original evaluation scheme on the overall performance of all four MJO types, while bars in brown denote the six poor models.

2. It is understandable that the frequency of the precipitation whiplash increases with the increase in frequency of fast/jump MJO in warmer climates. However, for that to be correct, the frequency of the precipitation whiplash associated with the fast/jump MJO should be larger than that associated with the stand/slow MJO in historical experiments. According to Fig. 4a, most regions except the equatorial Pacific (especially the equatorial western Pacific) show a lower or comparable frequency of the precipitation whiplash between fast/jumping and standing/slow MJO types. This result seems to suggest that precipitation whiplash for fast/jumping, which is not present today, may suddenly arise in future climates. I want to ask about the similarity of the difference in frequency of precipitation whiplash between fast/jump and stand/slow MJO by calculating the pattern correlation between Fig. 4a and Fig. 4b. Furthermore, how can we interpret the different responses between two different periods?

**AUTHOR RESPONSE:**

Thank you for your insightful comments. Because the number of standing and slow events is higher than the other two in the historical period, we have revised the figure by normalizing it by the number of MJO events of each type before taking the difference (**Fig. R6**). The result now shows a more consistent response of the occurrence of precipitation whiplash between two periods than before. Note that the pattern correlation coefficient of the difference in precipitation whiplash between panels a and b is 0.68, implying that some of the occurrences of precipitation whiplash will be unprecedented due to increased intraseasonal variability under global warming.

Hotspots of significant changes in precipitation whiplash occurrence that may impact human activities are outlined in black. The discussion of the revised figure can be found in the section "Role of the altering MJO diversity in global subseasonal precipitation whiplashes" (L174–208).

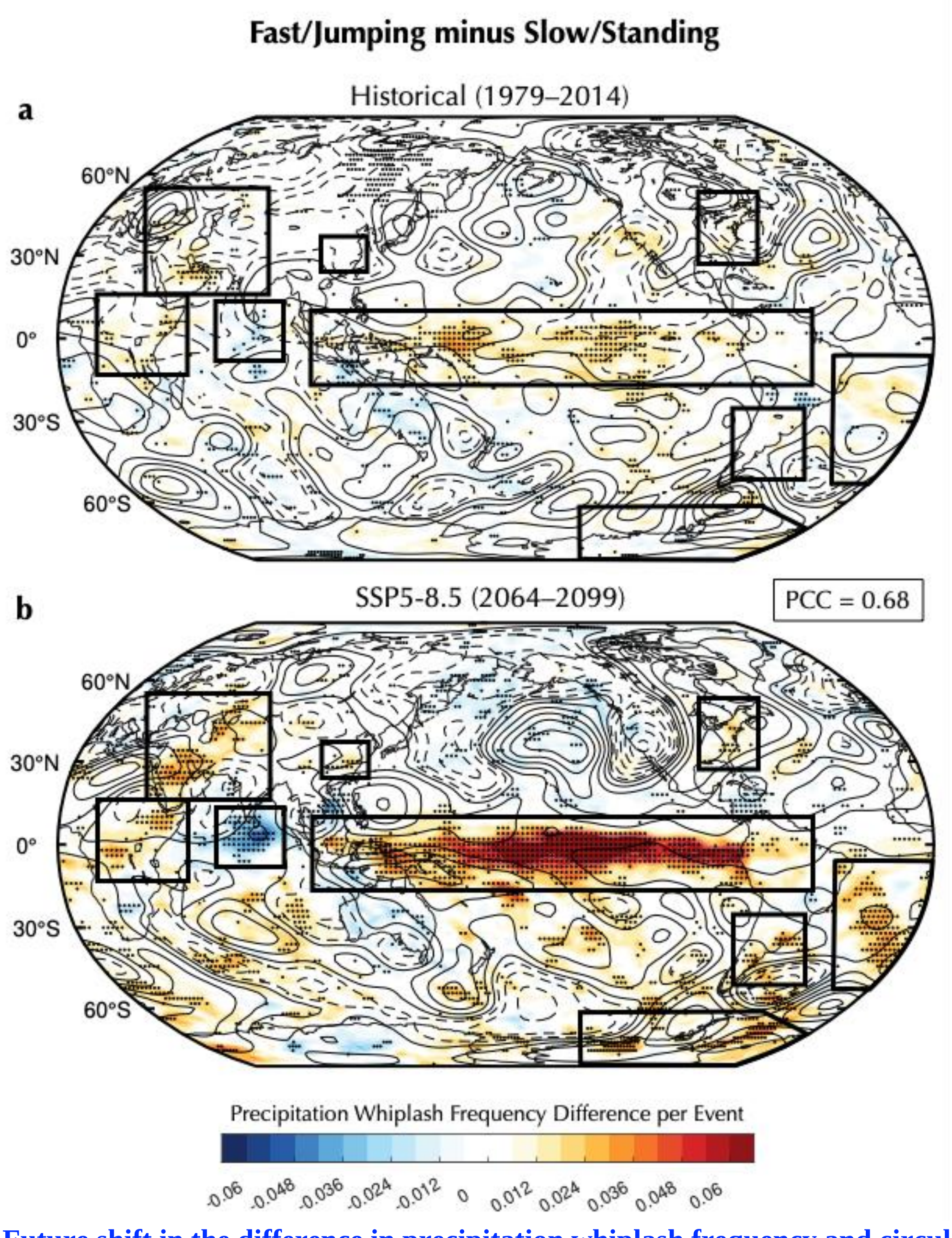


**Fig. R6. Future shift in the difference in precipitation whiplash frequency and circulation variability between fast/jumping and slow/standing MJOs. a,** Global map showing the difference in precipitation whiplash frequency (shading; see "Methods" for definitions) and the 500-hPa streamfunction variability (i.e., standard deviation) (contour, units: $10^5$ $m^2$ $s^{-1}$) per fast/jumping event compared to that per standing/slow event in the historical simulation (1979–2014) based on the MME12. Stippling denotes the difference in precipitation whiplash frequency is statistically significant at the 0.05 level across the models (Student's *t*-test). Solid (dashed) contours indicate positive (negative) values, with levels from −12 to −2 in an interval of 2, −0.5, 0.5, and from 2 to 12 in an interval of 2 (units: $10^5$ $m^2$ $s^{-1}$). **b,** Similar to panel a, but for the SSP5-8.5 simulation (2064–2099). Global hotspots of the heightened risk of precipitation whiplash are outlined in black. The pattern correlation coefficient of the significant difference in precipitation whiplashes between the historical and future periods is shown in the middle right.

3. The authors suggest that moist GW might be important for MJO propagation speed under stratified fluid conditions. They further investigate the changes in moist GW and decompose them into impacts of changes in dry static energy and moisture destabilization. Before decomposing into two terms, the authors should show the relationship between moist GW speed and MJO propagation speed. A scatter plot between the speed of moist GW and that of MJO in the historical experiment for individual models would be helpful in supporting the authors' claim.

**AUTHOR RESPONSE:**

Thank you for your very constructive suggestion. We have constructed scatter plots confirming a robust linear relationship between the MJO propagation speed, the Rossby-Kelvin (R-K) ratio, and the moist GW speed based on 28 CMIP6 models **(Fig. R3a, b)**. The results demonstrate that the R-K ratio and the moist GW speed are closely related to the MJO propagation speed, proving the use of the moist GW diagnostic to understand the MJO acceleration **(Fig. R3c)**. The new figure now refers to Fig. 5 in the main text, and the relevant discussion can be found in L239–248.

4. The authors show that the behaviors of jumping MJO become fast-propagating MJO in a warmer climate. I think it is quite unusual to say "jumping MJO" for this Hovmöller diagram (Fig. 3e). I wonder how we can interpret the physical mechanisms of the jumping MJO. Is it induced by a strong barrier effect on the maritime continent? Or is it induced by the re-emergence of enhanced convection over the western Pacific? How can we understand such changes in jumping MJO with the changes in background conditions in a warmer climate? It would be better to discuss the mechanisms of jumping MJO.

**AUTHOR RESPONSE:**

Thank you for your good questions. The jumping mode is shaped by a strong, westward-propagating equatorial Rossby wave that hinders the MJO's eastward propagation but initiates subsequent convection over the western Pacific Ocean (Gonzalez and Jiang 2019; Wei et al., 2023). The physical mechanisms behind the four different modes of MJO propagation are now explained in the Introduction (L71–91).

Minor comments

1. I wonder if the definition of climatology and anomaly is quite sensitive to these results in a warmer climate. How did you calculate the climatology and anomaly in two different SSP scenarios? The authors have to clarify how to calculate the climatology and anomaly.

**AUTHOR RESPONSE:**

We extracted intraseasonal anomalies from the daily OLR data using a 20–70-day bandpass Butterworth filter for MJO event detection and analysis. We compute the climatology based on the period of interest in different scenarios. The extraction of intraseasonal anomalies is independent of the mean state. These are now clarified in the Methods section (L388–393).

2. If you do not compare the GOOD and POOR models, I think you don't need to mention the POOR models and should focus only on the underlying mechanism of MJO diversity in warmer climates. If you want to include this comparison, the authors should mention what determines the GOOD and POOR models.

**AUTHOR RESPONSE:**

Thank you for your comment. In our opinion, mentioning the poor models is still necessary because it justifies why we do not simply use all CMIP6 models for analysis—not every model can realistically simulate the propagation behavior of MJO. That is why we need to determine good models. The possible model deficiencies that determine the good models from the poor models are discussed in L133–137.

3. The jet position over the Pacific can influence the response of the MJO teleconnection. If the precipitation whiplash in the subtropics is induced by the MJO teleconnection, is there any difference in the subtropical jet among the four MJO types in historical experiments? Furthermore, I wonder whether the changes in jets in warmer climates are negligible for the changes in MJO teleconnection.

**AUTHOR RESPONSE:**

We think it deserves another study to carefully attribute the change of the MJO teleconnection in response to the jet stream position change. Due to the length of this study, it will be studied in our future work. Thank you for your inspiring comment.

4. L187-191: The authors should better describe how moist GW is related to the MJO propagation speed and Kelvin-Rossby couplet in more detail. I think this relationship can be described more thoroughly. Furthermore, the authors should discuss a comparison between these results and the literature.

**AUTHOR RESPONSE:**

This statement is now supported by our new analysis (**Fig. R3**). Please see also our response to your major comment #3. Thank you.

5. Please provide the reference for L190-191 “The MJO propagation speed depends on moist gravity wave speed.”

**AUTHOR RESPONSE:**

Citations added. This statement is now supported by our new analysis (**Fig. R3**). Please see also our response to your major comment #3. Thank you.

6. There is no Supplementary Fig. 3i.

**AUTHOR RESPONSE:**

Corrected with thanks.

**References:**


Challenor, P. G., P. Cipollini, and D. Cromwell, 2001: Use of the 3D Radon Transform to Examine the Properties of Oceanic Rossby Waves. *J Atmos Ocean Technol*, **18**, 1558–1566, https://doi.org/10.1175/1520-0426(2001)018<1558:UOTRTT>2.0.CO;2.

Chen, G., and B. Wang, 2019: Dynamic moisture mode versus moisture mode in MJO dynamics: importance of the wave feedback and boundary layer convergence feedback. *Clim Dyn*, **52**, 5127–5143, https://doi.org/10.1007/s00382-018-4433-7.

——, and ——, 2020: Circulation Factors Determining the Propagation Speed of the Madden–Julian Oscillation. *J Clim*, **33**, 3367–3380, https://doi.org/10.1175/JCLI-D-19-0661.1.

Frierson, D. M. W., 2007: Convectively Coupled Kelvin Waves in an Idealized Moist General Circulation Model. *J Atmos Sci*, **64**, 2076–2090, https://doi.org/10.1175/JAS3945.1.

Gonzalez, A. O., and X. Jiang, 2019: Distinct Propagation Characteristics of Intraseasonal Variability Over the Tropical West Pacific. *Journal of Geophysical Research: Atmospheres*, **124**, 5332–5351, https://doi.org/10.1029/2018JD029884.

Holton, J. R., 2004: *An Introduction to Dynamic Meteorology*. 4th ed. Elsevier Academic Press, 1–535 pp.

Sen, P. K., 1968: Estimates of the Regression Coefficient Based on Kendall's Tau. *J Am Stat Assoc*, **63**, 1379–1389, https://doi.org/10.1080/01621459.1968.10480934.

Wang, B., 1988: Dynamics of Tropical Low-Frequency Waves: An Analysis of the Moist Kelvin Wave. *Journal of the Atmospheric Sciences*, **45**, 2051–2065.

——, and G. Chen, 2017: A general theoretical framework for understanding essential dynamics of Madden–Julian oscillation. *Clim Dyn*, **49**, 2309–2328, https://doi.org/10.1007/s00382-016-3448-1.

——, and S.-S. Lee, 2017: MJO Propagation Shaped by Zonal Asymmetric Structures: Results from 24 GCM Simulations. *J Clim*, **30**, 7933–7952, https://doi.org/10.1175/JCLI-D-16-0873.1.

——, F. Liu, and G. Chen, 2016: A trio-interaction theory for Madden–Julian oscillation. *Geosci Lett*, **3**, 1–16, https://doi.org/10.1186/s40562-016-0066-z.

Wei, Y., H. Ren, W. Duan, and G. Sun, 2023: Westward-Propagating Disturbances Shape Diverse MJO Propagation. *Geophys Res Lett*, **50**, https://doi.org/10.1029/2023GL104778.

Yang, G.-Y., B. Hoskins, and J. Slingo, 2007: Convectively Coupled Equatorial Waves. Part II: Propagation Characteristics. *J Atmos Sci*, **64**, 3424–3437, https://doi.org/10.1175/JAS4018.1.

Reviewer #2 (Remarks to the Author):

Review of NCOMMS-24-61149A-Z

Thank you for addressing most of my previous comments. The manuscript has improved substantially. While the proposed mechanism explaining the rapid propagation of MJOs in future climate makes logical sense, the supporting analysis requires further development. I do not expect additional analyses to be performed for this study, but I recommend that the authors tone down their assertions regarding this mechanism and present it more as a hypothesis worthy of future investigation rather than a definitive conclusion. Except this, I do not have any further critical concerns, but I do have some minor suggestions.

**AUTHOR RESPONSE:**

Thank you very much for your time and efforts in reviewing our manuscript. We agree with the reviewer's suggestion and have toned down our descriptions of the physical mechanism regarding the MJO acceleration in the final paragraphs of the Discussion section. We acknowledge that the trio-interaction theory is just one of the four distinct MJO theories and further work needs to be done to support the theory proposed in this study. Our point-to-point responses to your comments are as follows. The line numbers for the revised text are highlighted in yellow.

Minor Comments

1. Line 233: Please add a sentence explaining the physical meaning of the R-K ratio to improve clarity for readers.

**AUTHOR RESPONSE:**

Thank you for the advice. We have now explained the physical meaning of the R-K ratio in L229–238, as quoted below for your quick reference.

*The R-K ratio describes the relative strength of the Rossby and Kelvin wave components in the structure of the MJO. A higher R-K ratio suggests the Rossby wave is more dominant, while a lower ratio indicates a greater contribution from the Kelvin wave. This ratio affects how the MJO moves: the Rossby wave, excited by MJO heating, tends to push the MJO complex westward, whereas the Kelvin wave component drives it eastward. The Kelvin wave component is a low-pressure system located to the east of MJO convection (Wang et al. 2016). A stronger Kelvin wave component enhances boundary layer moisture convergence, which boosts moist static energy, atmospheric convective instability, and shallow convection east of the MJO convection, thereby promoting its eastward movement.*

2. Regarding the mechanisms related to the Gravity wave: There remains a conceptual gap between the R-K ratio and its connection to moist gravity wave speed. The authors should explicitly explain how the R-K ratio relates to moist gravity wave speed to strengthen this important theoretical link.

**AUTHOR RESPONSE:**

Thank you for your comment. We reckon that the change in the R-K ratio has little to do with (or at least not directly associated with) the changes in gravity wave speed. Rather, the changes in gravity wave speed and the horizontal structure (R-K ratio) affect MJO propagation speed independently and jointly. The gravity wave speed or moist gravity wave speed is an intrinsic geophysical parameter determining the propagation speed of large-scale equatorial waves and MJOs. The Kelvin wave propagates with the gravity wave speed, while the long Rossby wave speed is about one-third of the gravity wave speed (Matsuno 1966). Both are related to the gravity wave speed or the atmospheric static stability. We have clarified this point in the revision (L253–258). Thank you.

3. The study primarily examines MJO propagation through the Rossby-Kelvin wave couplet framework. Since this represents only one of several mechanisms explaining MJO dynamics, the manuscript would benefit from acknowledging other theoretical perspectives, particularly moisture mode theories. I suggest expanding the discussion to address how different theoretical frameworks might identify or interpret changes in MJO diversity under future climate scenarios.

**AUTHOR RESPONSE:**

Thank you for your comment. We have expanded the Discussion section (L389–420) to tone down our results by mentioning the other existing MJO theories and how they might interpret the changes in MJO diversity, as quoted below for your quick reference.

*In this study, the explanation of the physical processes changing MJO propagation was underpinned by the trio-interaction theory. However, several other theories have also been proposed in the literature(Lau and Peng 1987; Chang and Lim 1988; Wang 1988; Hendon 1988; Wang and Rui 1990; Hu and Randall 1994; Majda and Stechmann 2009; Adames and Kim 2016; Wang et al. 2016). Among them, four theories specifically address the MJO's propagation and selection mechanisms for the spatial and temporal scales(Zhang et al. 2020): the skeleton theory(Majda and Stechmann 2009), the 'moisture-mode' theory(Adames and Kim 2016), the gravity-wave theory(Yang and Ingersoll 2013), and the trio-interaction theory(Wang et al. 2016).*

*One fundamental feature discovered by Madden and Julian (1972)(Madden and Julian 1972)—which was not used to verify the theories—is the sea-level low pressure is ahead of eastward propagating MJO convection. Numerous observational studies have shown that the boundary layer convergence associated with the low-pressure anomaly leads the MJO, which shows a salient vertical tilted structure against its propagation in the fields of moist static energy, specific humidity, and vertical velocity(Hendon and Salby 1994; Sperber 2003; Tian et al. 2006; Jiang et al. 2015; Wang and Chen 2017; Wang et al. 2018). This vertical structure and the characteristic coupled Rossby-Kelvin wave structure are essential for verifying the theories.*

*Among the four theories, only the trio-interaction theory effectively captures the characteristic vertical and horizontal structure by incorporating the boundary layer dynamics and convective interaction with the Kelvin and Rossby waves. The trio-interaction theory unravels an inherent linkage between the MJO circulation structure and its eastward propagation. It suggests that different cumulus parameterization schemes can lead to different R-K ratios and, thus, different propagation speeds. The skeleton theory and moisture-mode theory can be viewed as a special form of the trio-interaction under a generalized theoretical framework that uses different cumulus parameterization schemes(Wang and Chen 2017).*

*Various theories may interpret MJO eastward propagation speed differently. For instance, in the "moisture-mode" theory, the eastward propagation of the MJO is mainly maintained by large-scale horizontal and vertical moisture advection(Sobel and Maloney 2012, 2013; Adames and Kim 2016). This theory would interpret the future rise in fast-moving MJO events as the result of an increased horizontal advection of moisture that causes a positive column- or lower troposphere-integrated moisture (or MSE) tendency to the east(Maloney 2009; Kim et al. 2014; Cui and Li 2019; Wang et al. 2025). However, the positive moisture tendency ahead of MJO can arise from both the intensification of the MJO convection and its eastward movement, making it a less clear indicator of propagation speed. It may also overlook the impact of dry static stability in accelerating moist GW waves and the MJO. Future research on aspects such as the extent to which the BL frictional coupled Kelvin-Rossby feedback is important compared to other processes, such as moisture and cloud-radiative feedback, in both the present and future climates, will facilitate the reconciliation of existing theories and further advance our understanding of future changes in MJO diversity and dynamics.*

4. Figure 6: Please add a complementary schematic diagram depicting the mechanism in the current climate to facilitate direct comparison with the future climate scenario.

**AUTHOR RESPONSE:**

We have updated Figure 6 accordingly and improved its visualization as well. Thank you very much for the advice.

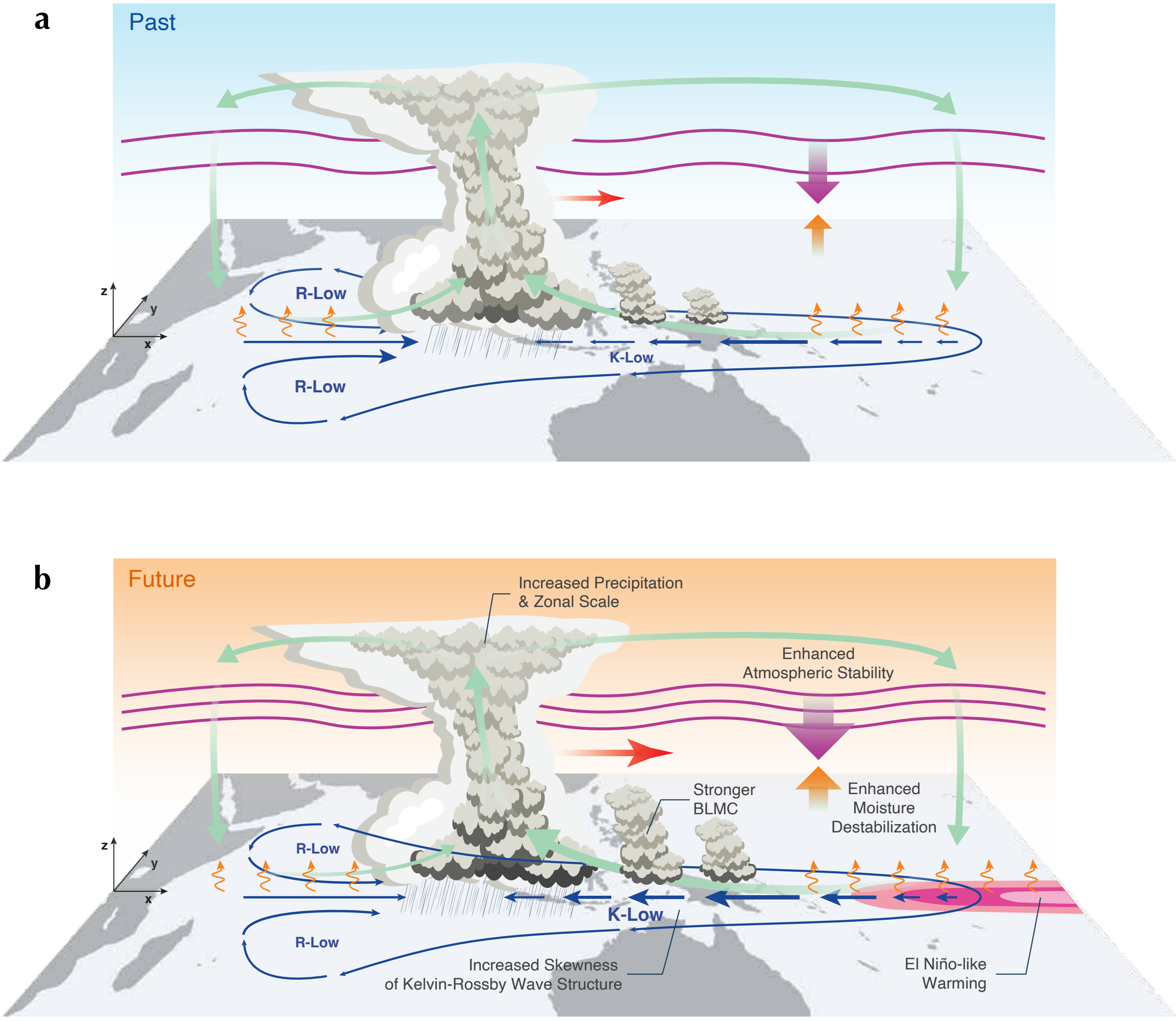


**Fig. 6. Key physical processes associated with the Madden-Julian Oscillation (MJO)'s eastward acceleration.** Schematic diagrams depicting the three-dimensional structure of the MJO and its dynamics **a,** in the past and **b,** in future warmer climates. Panel b details the key changes in the physical processes that contribute to the MJO's eastward acceleration. BLMC stands for boundary-layer moisture convergence.


**References:**

Adames, Á. F., and D. Kim, 2016: The MJO as a Dispersive, Convectively Coupled Moisture Wave: Theory and Observations. *J Atmos Sci*, **73**, 913–941, https://doi.org/10.1175/JAS-D-15-0170.1.

Chang, C.-P., and H. Lim, 1988: Kelvin Wave-CISK: A Possible Mechanism for the 30–50 Day Oscillations. *J Atmos Sci*, **45**, 1709–1720, https://doi.org/10.1175/1520-0469(1988)045<1709:KWCAPM>2.0.CO;2.

Cui, J., and T. Li, 2019: Changes of MJO propagation characteristics under global warming. *Clim Dyn*, **53**, 5311–5327, https://doi.org/10.1007/s00382-019-04864-4.
Hendon, H. H., 1988: A Simple Model of the 40-50 Day Oscillation. *J Atmos Sci*, **45**, 569–584, https://doi.org/10.1175/1520-0469(1988)045<0569:ASMOTD>2.0.CO;2.
Hendon, H. H., and M. L. Salby, 1994: The Life Cycle of the Madden–Julian Oscillation. *J Atmos Sci*, **51**, 2225–2237, https://doi.org/10.1175/1520-0469(1994)051<2225:TLCOTM>2.0.CO;2.
Hu, Q., and D. A. Randall, 1994: Low-Frequency Oscillations in Radiative-Convective Systems. *J Atmos Sci*, **51**, 1089–1099, https://doi.org/10.1175/1520-0469(1994)051<1089:LFOIRC>2.0.CO;2.
Jiang, X., and Coauthors, 2015: Vertical structure and physical processes of the Madden-Julian oscillation: Exploring key model physics in climate simulations. *Journal of Geophysical Research: Atmospheres*, **120**, 4718–4748, https://doi.org/10.1002/2014JD022375.
Kim, D., J.-S. Kug, and A. H. Sobel, 2014: Propagating versus Nonpropagating Madden–Julian Oscillation Events. *J Clim*, **27**, 111–125, https://doi.org/10.1175/JCLI-D-13-00084.1.
Lau, K.-M., and L. Peng, 1987: Origin of Low-Frequency (Intraseasonal) Oscillations in the Tropical Atmosphere. Part I: Basic Theory. *J Atmos Sci*, **44**, 950–972.
Madden, R. A., and P. R. Julian, 1972: Description of Global-Scale Circulation Cells in the Tropics with a 40–50 Day Period. *Journal of Atmospheric Sciences*, **29**, 1109–1123.
Majda, A. J., and S. N. Stechmann, 2009: The skeleton of tropical intraseasonal oscillations. *Proceedings of the National Academy of Sciences*, **106**, 8417–8422, https://doi.org/10.1073/pnas.0903367106.
Maloney, E. D., 2009: The moist static energy budget of a composite tropical intraseasonal oscillation in a climate model. *J Clim*, **22**, 711–729, https://doi.org/10.1175/2008JCLI2542.1.
Matsuno, T., 1966: Quasi-Geostrophic Motions in the Equatorial Area. *Journal of the Meteorological Society of Japan. Ser. II*, **44**, 25–43, https://doi.org/10.2151/jmsj1965.44.1_25.
Sobel, A., and E. Maloney, 2012: An Idealized Semi-Empirical Framework for Modeling the Madden–Julian Oscillation. *J Atmos Sci*, **69**, 1691–1705, https://doi.org/10.1175/JAS-D-11-0118.1.
——, and ——, 2013: Moisture Modes and the Eastward Propagation of the MJO. *J Atmos Sci*, **70**, 187–192, https://doi.org/10.1175/JAS-D-12-0189.1.
Sperber, K. R., 2003: Propagation and the Vertical Structure of the Madden–Julian Oscillation. *Mon Weather Rev*, **131**, 3018–3037, https://doi.org/10.1175/1520-0493(2003)131<3018:PATVSO>2.0.CO;2.
Tian, B., D. E. Waliser, E. J. Fetzer, B. H. Lambrigtsen, Y. L. Yung, and B. Wang, 2006: Vertical Moist Thermodynamic Structure and Spatial–Temporal Evolution of the MJO in AIRS Observations. *J Atmos Sci*, **63**, 2462–2485, https://doi.org/10.1175/JAS3782.1.
Wang, B., 1988: Dynamics of Tropical Low-Frequency Waves: An Analysis of the Moist Kelvin Wave. *Journal of the Atmospheric Sciences*, **45**, 2051–2065.
——, and H. Rui, 1990: Dynamics of the Coupled Moist Kelvin–Rossby Wave on an Equatorial $\beta$ -Plane. *J Atmos Sci*, **47**, 397–413, https://doi.org/10.1175/1520-0469(1990)047<0397:DOTCMK>2.0.CO;2.
——, and G. Chen, 2017: A general theoretical framework for understanding essential dynamics of Madden–Julian oscillation. *Clim Dyn*, **49**, 2309–2328, https://doi.org/10.1007/s00382-016-3448-1.

——, F. Liu, and G. Chen, 2016: A trio-interaction theory for Madden–Julian oscillation. *Geosci Lett*, **3**, 1–16, https://doi.org/10.1186/s40562-016-0066-z.
——, and Coauthors, 2018: Dynamics-oriented diagnostics for the Madden-Julian Oscillation. *J Clim*, JCLI-0332.1, https://doi.org/10.1175/JCLI-D-17-0332.1.
Wang, J., M. J. DeFlorio, H. Kim, K. Guirguis, and A. Gershunov, 2025: Future MJO Change and Its Impact on Extreme Precipitation and Temperature Over the Western US in CMIP6. *Journal of Geophysical Research: Atmospheres*, **130**, https://doi.org/10.1029/2024JD042123.
Yang, D., and A. P. Ingersoll, 2013: Triggered Convection, Gravity Waves, and the MJO: A Shallow-Water Model. *J Atmos Sci*, **70**, 2476–2486, https://doi.org/10.1175/JAS-D-12-0255.1.
Zhang, C., Á. F. Adames, B. Khouider, B. Wang, and D. Yang, 2020: Four Theories of the Madden-Julian Oscillation. *Reviews of Geophysics*, **58**, https://doi.org/10.1029/2019RG000685.

**Review for Nature Communications.**

**Title:** Shifts in Madden-Julian Oscillation Behavior Enhance Predictability of Subseasonal Weather Whiplashes

**Authors:** Tat Fan Cheng; Bin Wang; Fei Liu; Guosen Chen; and Mengqian Lu

Although the topic of Madden-Julian Oscillation (MJO) shifts under climate change is scientifically relevant, this paper may fall short of the novelty required to meet the standards of *Nature Communications*. There is considerable overlap with existing literature, particularly from researchers such as Tim Li's group at the University of Hawaii, Bin Wang (a co-author of this work), and others who have published extensively on this subject. Moreover, the methodology employed and the limited discussion on the mechanisms behind MJO propagation modes raise concerns about the robustness and originality of the findings. To clarify, this is a solid piece of research and certainly appropriate for other high-impact journals, such as *AGU-Geophysical Research Letters* or the *Journal of Climate*. Given these considerations, I leave it to the editor's discretion to make the final decision after evaluating feedback from the other reviewers.

**Major Comments**

- This paper largely re-examines MJO propagation patterns under climate change, a topic that has been extensively studied. Previous works, including those mentioned above, have covered similar themes in depth. To justify publication in a high-impact journal, this manuscript would need to provide a significantly new perspective or a groundbreaking finding that advances the field beyond current knowledge. At present, it falls short of this standard.

- While the authors' approach to calculating MJO propagation based on minimum OLR anomaly at each longitude appears innovative at first glance, it is quite restrictive and may limit the reliability of the results. This difficulty is largely due to the zonal asymmetries of the Indo-Pacific warm pool (60ºE-180º). The method proposed by the authors could lead to biases or an incomplete representation of the MJO's propagation dynamics, as it may overlook broader patterns that are essential to understanding MJO diversity. Numerous alternative methodologies have been proposed in the literature, such as those discussed by Yang (2007) in *Convectively Coupled Equatorial Waves. Part II: Propagation Characteristics*. Yang's approach provides a more comprehensive framework for assessing convectively coupled equatorial waves and MJO propagation characteristics. The authors should carefully consider such alternatives or provide a clear justification as to why their chosen method offers an advantage. As it stands, the methodology section appears restrictive and may affect the generalizability of the findings.
- One of the main weaknesses of this manuscript is the limited exploration of mechanisms underlying the different MJO behaviors, particularly fast-propagating and jumping events. While the paper identifies these categories, there is minimal discussion of the physical drivers or atmospheric conditions that might explain why these distinct modes of propagation occur. For a more comprehensive understanding, the authors could have elaborated on the role of atmospheric stability, moisture distribution, and other relevant factors influencing MJO behavior.

Given the substantial focus on MJO propagation diversity, I would expect a deeper examination of the specific mechanisms that lead to variations in propagation speed and type for instance throughout the use budget analysis. In addition, Exploring and explaining the mechanisms of Madden-Julian Oscillation (MJO) propagation patterns under climate change using the Clausius-Clapeyron (C-C) relation is a valuable approach, as it connects moisture availability to temperature, which directly impacts convection and atmospheric instability; key drivers of MJO dynamics. A warmer atmosphere, per the C-C relation, can hold significantly more moisture, especially in tropical regions where the MJO originates. This increased moisture availability influences MJO propagation by potentially intensifying convection within the MJO. Without this, the findings appear descriptive rather than explanatory, which may limit the study's impact and contribution to advancing our understanding of MJO dynamics.

**Minor Comments**

- The paper would benefit from a more thorough review of existing studies on MJO propagation. Integrating more insights from similar studies would situate this research within the broader context of current MJO research.