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Projected Sea Surface Temperature Pattern Change and Madden-Julian Oscillation Activity in a Warmer Climate

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Key Points:

- Variability in projected 21st century warming patterns modulate the strength of Madden-Julian Oscillation (MJO) amplitude increases
- Ensemble members with the largest MJO precipitation amplitude increases show a more El Niño-like warming pattern
- An El Niño-like warming pattern supports strengthened MJO activity through increased Pacific meridional and vertical moisture gradients

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The Madden Julian Oscillation (MJO) consists of a tropical convective region that propagates eastward through the Indo-Pacific warm pool. Decadal climate variability alters sea surface temperature patterns, affecting the MJO's basic state. This investigation examines the impact of projected SST and moisture pattern changes over the 21st Century on MJO precipitation and zonal wind amplitude changes in 80 members of the Community Earth System Model 2 Large Ensemble in the SSP370 radiative forcing scenario, each with its unique representation of decadal variability. Ensemble members with strongest MJO precipitation change in a given 20-year period have a more El Niño-like east Pacific warming pattern. MJO amplitude increases for east Pacific warming because of a strengthened meridional moisture gradient that supports MJO eastward propagation. A stronger vertical moisture gradient also exists for ensemble members with preferential east Pacific warming, which supports a stronger MJO under moisture mode theory.

Plain Language Summary The Madden Julian Oscillation (MJO) is a region of convective storms that moves eastward in the tropics from the Indian Ocean toward the central Pacific, and repeats every 30–90 days. The MJO can influence extreme weather events across the globe, and affect their prediction. Changes to the MJO in a future warmer climate are strongly dependent on the details of the ocean warming and moisture patterns, which is the primary motivation for this study. A climate model forced with a high greenhouse gas emission scenario is examined, and an ensemble of 80 members is generated from different initial states. The projected ocean warming and moistening pattern changes in individual ensemble members can be weighted more toward the western, central or eastern Pacific in individual ensemble members, especially in earlier decades of the record. MJO strength increases most for simulations with stronger east Pacific ocean warming, which is accompanied by greater increases in moisture along the equator and in the lower atmosphere. Understanding these pattern changes in a warming climate is critical for fresh-water resources and societal planning for oceanic regions and Pacific islands.

1. Introduction

The MJO is the dominant mode of intraseasonal tropical climate variability (Hayashi & Itoh, 2017; Jiang et al., 2020; Madden & Julian, 1971, 1972). Although a comprehensive explanation for the MJO remains elusive, substantial evidence exist that free tropospheric moisture perturbations and the processes that help maintain them support MJO related precipitation anomalies and eastward propagation (Madden & Julian, 1972; Sobel & Maloney, 2012, 2013). Moisture mode (MM) theory has been used to show that processes that increase moisture anomalies near MJO convection support disturbance growth, and processes that support moistening to the east of convection such as horizontal moisture advection support eastward propagation (Gonzalez & Jiang, 2017; Kim et al., 2017; Maloney, 2009; Sobel & Maloney, 2013).

MJO precipitation variability is highly sensitive to tropical sea surface temperatures (SST) change (Maloney & Xie, 2013; Takahashi et al., 2011), although it is expected to increase in intensity in a future warmer climate to first order due to stronger basic state vertical moisture gradients with warming (Arnold et al., 2013; Bui & Maloney, 2018; Kang et al., 2021; Maloney & Xie, 2013; Maloney et al., 2019). The response of MJO winds to warming is more complicated, with some models projecting weakening of MJO zonal wind amplitude, even with increased MJO precipitation variance (Adames & Maloney, 2021; Bui & Maloney, 2018; Jiang et al., 2020). These results are consistent with tropical weak temperature gradient thermodynamic balance, which mandates that increases in the tropical static stability with warming are associated with a weaker circulation per unit diabatic heating (Hsiao et al., 2020). The MJO becoming stronger in a warmer environment could result in stronger enhanced and suppressed phases, which may cause its modulation of Atmospheric Rivers (ARs) and Tropical Cyclones (TCs) to become stronger (Bui & Maloney, 2018; Maloney & Hartmann, 2000; Zhou et al., 2021). However, the weakening of MJO circulations per unit precipitation may complicate this effect (Bui & Maloney, 2022).

Climate models show differences in future warming patterns across models, and on decadal timescales within individual models (Bui et al., 2023; Rugenstein et al., 2020). The pattern of SST change provides uncertainty in how the MJO will respond to a warmer climate. Maloney and Xie (2013) show that future MJO precipitation amplitude changes are strongly modulated by the SST warming pattern, and those precipitation variance changes are related to MJO wind variance changes through WTG thermodynamic balance. Due to increases in tropical static stability with warming, MJO wind amplitude can decrease for some warming patterns even with MJO precipitation amplitude increases. In the current climate, years with El Niño SST anomalies increase the mean meridional moisture gradient in the Maritime Continent (MC) region and support MJO propagation through increased horizontal moisture advection (Kang et al., 2021). Takahashi et al. (2011) showed that climate model projections with more El Niño-like warming patterns tend to produce stronger MJO amplitude, with the opposite for those with more La Niña-like warming patterns. Thus, while warmer SSTs generally increase the vertical moisture gradient that supports a stronger MJO (Maloney, 2009), there is also a pattern effect to warming on MJO amplitude. This is what will be addressed in this study.

This investigation addresses the impact of SST and moisture pattern change on the amplitude of the MJO in a future warmer climate (e.g., Maloney & Xie, 2013). This investigation is motivated by two main hypotheses: (a) MJO behavior in a warmer climate is strongly sensitive to changes the pattern of basic state SST and moisture changes. An eastern Pacific warming pattern in an ensemble member, whether a transient decadal pattern or a long-term trend, is expected to most strongly intensify the MJO. (b) Changes to the mean vertical moisture gradient and horizontal surface temperature and moisture gradients can be used to understand how MJO activity is influenced by SST pattern changes, including variability among ensemble members. The study analyzes how projected SST pattern changes in future decades influence MJO activity, including changes to the spatial distribution of MJO variance. The investigation evaluates how differing changes to the mean vertical and horizontal moisture gradients in the tropics among ensemble members, as they relate to differing patterns of SST change, regulate MJO amplitude change.

Other recent studies have also begun to examine this issue. Bui et al. (2024) grouped SST pattern changes in the CESM2 large ensemble using k-means clustering and looked at the change in MJO activity for strong, weak, and moderate El Niño-like patterns. They found that MJO amplitude increases are greatest for stronger El Nino-like warming. Our investigation uses a different approach to this problem by first separating CESM2 ensemble members into those showing strong and weak MJO amplitude changes, and then examining the SST and moisture pattern changes associated with these. Hence, our analysis approaches the problem from a different direction, although will ultimately produce similar conclusions.

2. Data and Methodology

2.1. Community Earth System Model 2

The Community Earth System Model 2 (CESM; Hurrell et al., 2013; Kay et al., 2015; Danabasoglu et al., 2020) is a numerical model that can be used to simulate past climate or can be used for climate projections on various timescales (e.g., weeks to centuries). The standard CESM2 has a grid resolution of 1.25° × 0.94°, and incorporates hypothetical climate emission scenarios through the shared socioeconomic pathways (SSP; Rodgers et al., 2021). Prior studies have documented that CESM2 has a better representation of the MJO compared to previous versions (Danabasoglu et al., 2020; Riahi et al., 2017). Climate model ensembles with each member having different initial conditions allow a different future evolution of decadal climate variability and provide insight into uncertainty in future climate projections (Diffenbaugh & Barnes, 2023).

2.2. Methods

Eighty CESM2 ensemble members with the radiative forcing scenario SSP370, which is one of the highest forcing scenarios for CMIP6, are used for the investigation (Riahi et al., 2017; Rodgers et al., 2021). This pathway corresponds to a climate forcing of 3.7 $\frac{W}{m^2}$ at 2100. MJO activity and its changes are defined using precipitation and 850 mb zonal wind variability. MJO variability is isolated by detrending the data in individual variables by removing the least squared regression fit, removing the seasonal cycle, and applying a frequency-wavenumber bandpass filter to isolate 30–90 days frequencies and zonal wavenumbers (k) 1–5 (Bingham et al., 1967; Madden & Julian, 1994; Maloney & Xie, 2013; Raymond & Fuchs, 2009; Wheeler & Kiladis, 1999). The standard deviation of this filtered precipitation and zonal wind data set defines MJO amplitude, or activity, for the rest of the investigation. Only boreal winter (November–March) is examined in this investigation since MJO variance is strongest then (Madden & Julian, 1994; Wheeler & Kiladis, 1999). How MJO activity change relates to SST and moisture pattern changes across different ensemble members and in the ensemble mean for 20-year decadal periods (2041–2060 and 2081–2100) relative to a historical period defined as 1985–2005 is examined.

Figures S1–S4 in Supporting Information S1 provide some context for the diversity of SST pattern changes that can exist between different ensemble members. Figure S1 in Supporting Information S1 shows the east Pacific warming and the change in the East-West temperature difference with time, including both the ensemble mean and ensemble spread. While the Niño3.4 SST change and the mean tropical Pacific East-West SST gradient change generally go up relative to 1985–2005, some ensemble members indicate that the west Pacific can warm more than the east before 2055. Further, examples of SST patterns that are subjectively determined to be more weighted toward the east or west Pacific are included in Figures S2–S4 in Supporting Information S1 to show the diversity of patterns (Figures S2–S4 in Supporting Information S1). Figure S2 in Supporting Information S1 shows that in 2021–2040, preferential SST warming can be either shifted toward the west, central, or east Pacific in individual ensemble members. After the midpoint of the century, preferential warming and precipitation patterns changes become more uniform with all ensemble members eventually showing an El Niño-like warming pattern at the end of the 21st century (Figures S3 and S4 in Supporting Information S1).

In part of the analysis, the 33% of ensemble members with biggest MJO amplitude increases (MJO plus) and the bottom 33% (MJO minus) are compared to assess how basic state changes differ, including mean SST, precipitable water (PW), meridional PW gradient change. MJO amplitude is defined by taking the temporal standard deviation of a space-time filtered variable at each grid cell, and then averaging across the tropics from 15°S to 15°N for each ensemble member separately. A two-tailed t-test is also applied to assess the significance of differences between the MJO plus and MJO minus maps for each 20-year decadal period. A different top and bottom 33% of members is defined separately based on MJO precipitation and zonal wind amplitude. An analysis of differences in mean vertical humidity profile change for these subsets is also conducted. The meridional PW gradient change for the western and central Pacific is isolated (140°E–150°W and 10°S–10°N). This region sees the most prominent PW gradient change for the ensemble members with the strongest increase in MJO activity, and the meridional PW gradient in this region is important for regulating MJO propagation in observations (Kang et al., 2021). Changes to PW in this region are also likely important for influencing MJO propagation across the Pacific in a warmer climate. Scatterplots of meridional moisture gradient change, lower tropospheric humidity change (850 to 1,000 hPa), and tropospheric humidity gradient change (lower troposphere minus middle troposphere [450 to 600 hPa]) versus MJO amplitude change across ensemble members are also assessed.

3. Results and Discussion

3.1. SST and Horizontal Moisture Pattern Changes Influence on MJO Amplitude Changes

The difference in the SST and moisture pattern change between MJO plus and minus members indicates that greater MJO precipitation amplitude increases are associated with a more El Niño-like warming and moistening pattern, respectively, as seen in Figure 1, including more warming in the MC region through which the MJO transits (Kim et al., 2017). The pattern is generally consistent with that found by Takahashi et al. (2011) for CMIP3 models and (Bui et al., 2024) in the CESM2 large ensemble. While our results support Bui et al. (2024), we arrive at them using a different approach as they used k-mean clustering to first identify SST pattern changes in a warmer climate, and then relate changes in MJO characteristics relative to them.

The warming pattern change is also associated with changes in the mean moisture field that affects MJO dynamics. The PW change for the members with biggest MJO amplitude increases minus the smallest increases are plotted in Figure 1b. The members with strongest MJO precipitation amplitude increase have a moisture pattern change that is more El Niño-like and mimics the SST pattern change seen in Figure 1a, with greater moistening in the east Pacific and MC region, and suggestions of a stronger meridional moisture gradient in the western and central Pacific. A two-tailed t-test between MJO plus and MJO minus members indicates the central and eastern

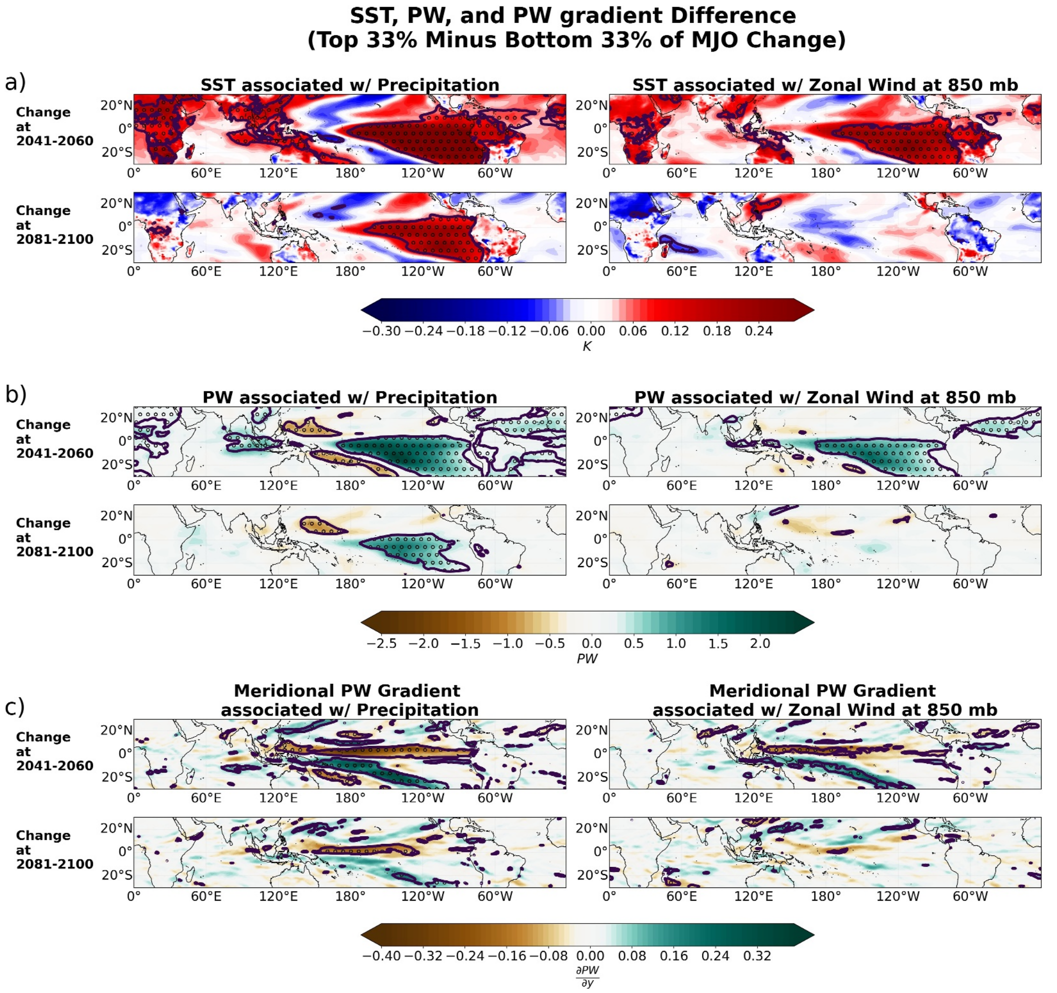

Figure 1. Difference in (top) sea surface temperatures, (middle) precipitable water (PW), and (bottom) meridional PW Gradient change for the ensemble members with top 33% of Madden-Julian Oscillation (MJO) amplitude change (MJO Plus) minus the bottom 33% of MJO amplitude change (MJO Minus). Precipitation and zonal wind amplitude changes are analyzed for two 20-year periods in the future (2041–2060 and 2081–2100). A two-tailed test is used to determine statistically significant differences are outlined by purple contours and filled by purple circle hatching at the 95% confidence level.

equatorial Pacific relative moistening and off-equatorial drying is statistically significant at the 95% confidence level across all future periods. Moisture field changes associated with the greatest MJO wind amplitude changes are less robust, although tend to have an El Niño-like moistening pattern for the 2041–2060 period. The most robust PW change differences between MJO plus and minus members and largest regions of statistical significance occur during 2041–2060 for both MJO precipitation and zonal wind amplitude change. Results for MJO wind amplitude change are likely less robust than for precipitation because increases in tropical static stability with warming cause MJO circulation variability to decrease per unit precipitation (Maloney & Xie, 2013). We hypothesize the most robust signals in SST and PW patterns occur during 2041–2060 because the pattern of SST change shows more variability across ensemble members during this period than later in the century, when the pattern of SST change is El Niño-like for all ensemble members.

A warmer east Pacific may not only directly support stronger MJO convection as it propagates into that region (e.g., Bui & Maloney, 2018), but it might also support stronger meridional moisture gradients that support eastward MJO propagation into that region (e.g., Kang et al., 2021). In particular, a stronger meridional humidity gradient would support stronger horizontal advection to the east of MJO convection through advection associated with the MJO meridional wind perturbations acting on the mean humidity gradient, which helps supports eastward MJO propagation (Adames & Kim, 2016; Maloney, 2009). Differences in the meridional humidity gradient

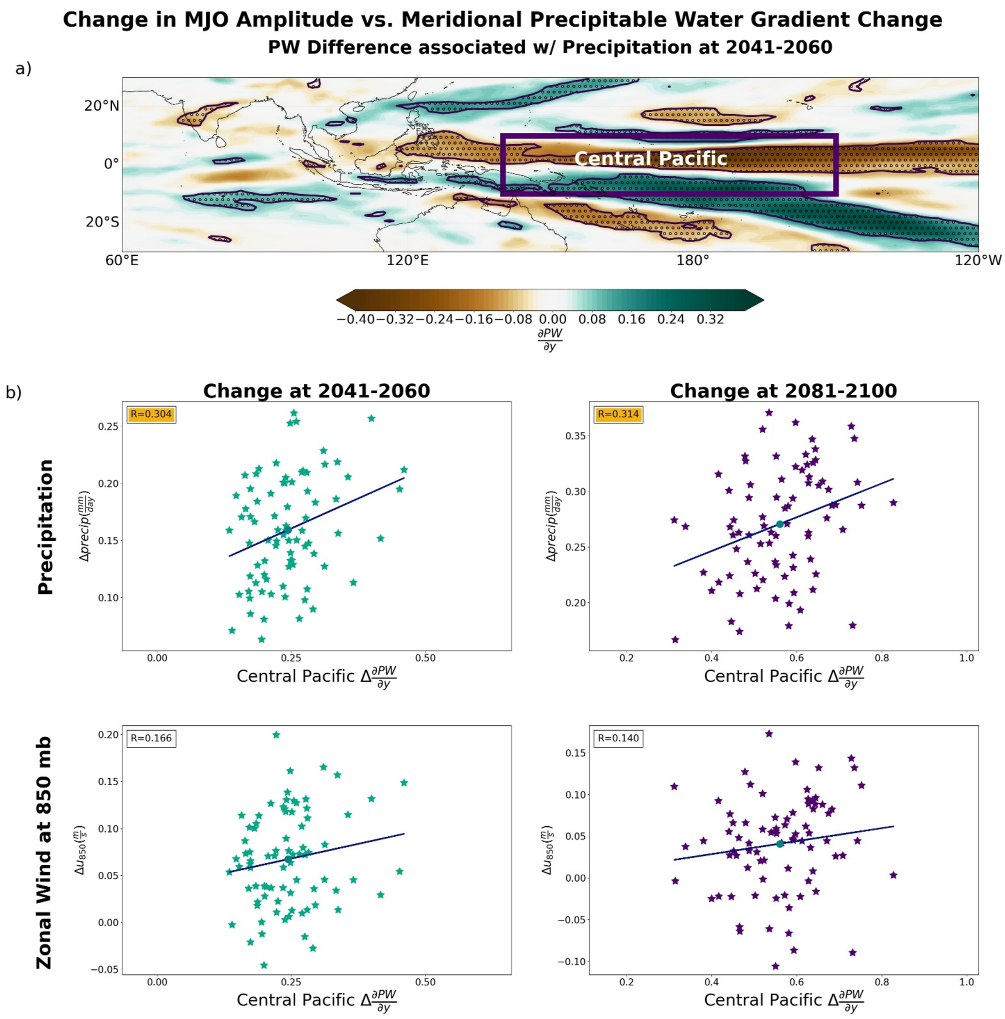

Figure 2. (a) Same as upper left of Figure 1c, except a dark purple box is added to define an averaging region, and (b). Relationship between Madden-Julian Oscillation amplitude change averaged over the entire tropics (15°S–15°N) and central Pacific meridional PW gradient change (panel a box) for precipitation and 850 mb zonal wind relative to 1985 to 2005 for 2041–2060 and 2081–2100. Statistically significant correlations are indicated in yellow and each point is an ensemble member.

change between members with the strongest and smallest MJO amplitude changes are examined in Figure 1c. The meridional PW gradient difference between MJO plus and minus members for precipitation amplitude change indicates a significantly stronger meridional humidity gradient across the equatorial Pacific, especially during the 2041–2060 period, which would support eastward propagation. Results for members with the strongest and weakest zonal wind amplitude show an increased meridional humidity gradient during the 2041–2060 period, although results are much less robust later in the century. The zonal PW gradient difference between MJO plus and minus members was also assessed (not shown). While the zonal moisture gradient change in the west and central Pacific was generally positive in the west and central Pacific for MJO plus members relative to MJO minus (e.g., see also Kim et al., 2017; Ren et al., 2021; Rushley et al., 2022), with some regions of statistical significance, the pattern of change was much less robust than for meridional gradient changes.

One question is whether a stronger meridional moisture gradient for individual members consistently produces an increased MJO amplitude. A scatterplot of the amplitude of central Pacific meridional PW gradient change (relative to 1985–2005) versus tropical MJO precipitation amplitude change shows that there is a modest positive, statistically significant correlation between these two quantities (Figure 2b). Note that the absolute value of the PW gradient was taken before averaging in the central Pacific box shown in Figure 2a, such that the Northern and Southern Hemisphere gradients are treated equivalently. The relationship between precipitable moisture gradient

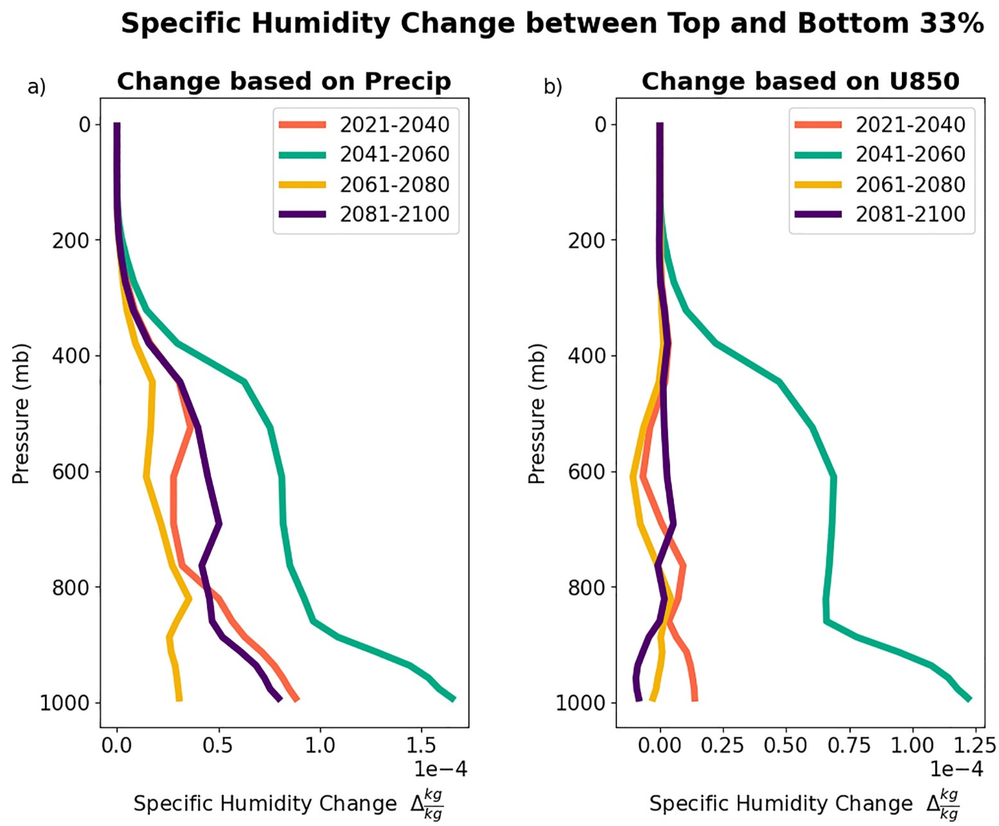

Figure 3. Change of tropical Pacific vertical specific humidity profile in the Equatorial Pacific (140°E–150°W and 10°S–10°N) between the members having the top 33% minus bottom 33% of Madden-Julian Oscillation amplitude changes for (a) precipitation and (b) 850 mb zonal wind. Changes are defined relative to 1985 to 2005.

change with 850 mb zonal wind amplitude change is not statistically significant (Figure 2b). The substantial spread that exists in the relationships in Figure 2b is likely contributed by internal MJO variability, although other factors may also help to explain increases in MJO amplitude for some ensemble members, such as changes to the vertical moisture gradient and its effect on vertical advective moistening (e.g., Bui et al., 2024). While outside the scope of this paper, the role of internal variability could potentially be assessed by examining a long atmosphere-only simulation with fixed SST pattern change, although active air-sea coupling is removed in such a situation. The following subsection examines whether changes to the vertical profile of moisture helps to explain preferential increases in MJO activity for some members.

3.2. Vertical Moisture Gradient and MJO Activity

Previous modeling studies have suggested that MJO amplitude may increase in a warmer climate due to increases in the tropospheric vertical humidity gradient (Arnold et al., 2013). We now examine the difference in mean tropical equatorial Pacific specific humidity profiles (140°E–81°W and 10°S–10°N) between MJO plus and minus members. Members with stronger MJO precipitation amplitude change have moister equatorial Pacific profiles, especially in the lower troposphere (Figure 3), with this signal most notable for 2041–2060. The left panel (Figure 3a) suggests stronger vertical moisture gradients for model simulations with increased MJO precipitation amplitude, consistent with that expected from prior studies (Arnold et al., 2015). The difference in moisture profiles between ensemble members with large and small MJO wind amplitude change is not as pronounced as for precipitation amplitude change (Figure 3b). A notable moistening signal only exists for 2041–2060 in wind amplitude changes. Maloney et al. (2019) showed that the increasing disconnect between MJO precipitation and wind amplitude grows most strongly after 2060 due to increasing dry static stability changes in the tropics with warming. In general, ensemble members with greater MJO precipitation amplitude change are associated with a moister equatorial troposphere and increased vertical humidity gradient, which would support

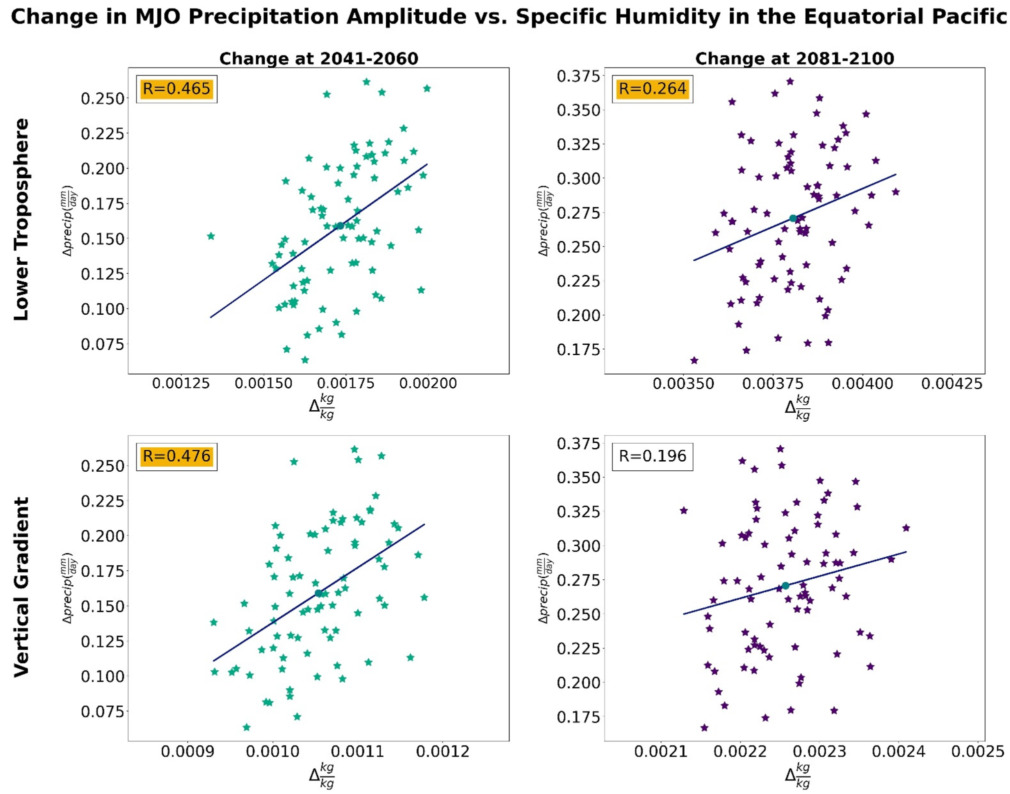

Figure 4. Relationship between Madden-Julian Oscillation precipitation and wind amplitude change averaged over the entire tropics (15°S–15°N) and equatorial Pacific (140°E–150°W and 10°S–10°N) lower tropospheric specific humidity change (top row) and vertical specific humidity gradient change (bottom row) relative to 1985 to 2005 for 2041–2060 and 2081–2100. Statistically significant correlations are indicated in yellow and each point is an ensemble member.

stronger MJO precipitation amplitude through more efficient moistening by vertical advection through MJO circulations (Maloney et al., 2019).

The relationship between basic state lower troposphere specific humidity and vertical specific humidity gradient changes in the tropical Pacific and MJO amplitude change in individual ensemble members is now examined (Figure 4). The vertical gradient is defined by the change between lower tropospheric (850–1,000 hPa) and middle tropospheric (450–600 hPa) layers. A statistically significant correlation exists between MJO precipitation amplitude change and lower tropospheric humidity and vertical humidity gradients, especially for 2041–2060, although a large degree of scatter still exists. Correlations later in the century are more modest when a more general El Niño-like warming pattern commences for all ensemble members. The correlations associated with MJO wind amplitude change are generally weaker and not significant during 2081–2100 (not shown here). Vertical specific humidity gradient change over a deeper atmospheric layer (lower tropospheric specific humidity change minus upper troposphere [200 to 450 hPa]), were also assessed, but produced similar results to only using the lower half of the troposphere (not shown). These results generally support the hypothesis that ensemble members with stronger vertical humidity gradient change have bigger MJO amplitude increases. However, other factors such as internal MJO variability are also important given that a substantial amount of scatter exists in the relationship and vertical humidity gradient changes only explain about a quarter of the MJO precipitation amplitude changes. It is worth noting that correlations between the zonal SST gradient change and MJO activity also showed significant positive correlations, although correlations were not as high as for vertical or horizontal moisture gradients.

4. Conclusions

The CESM2 large ensemble under the SSP370 forcing scenario is used to assess how the pattern of SST and moisture changes in a warmer climate and their differences among ensemble members impacts MJO amplitude and propagation change in the tropics (Maloney & Xie, 2013). Under moisture mode theory, eastward propagation and MJO precipitation amplitude is more strongly supported when meridional SST and moisture gradients are increased and higher equatorial SST increases the vertical moisture gradient (Sobel & Maloney, 2012, 2013). CESM2 ensemble members with the highest tropics-wide MJO precipitation amplitude increase exhibit a more El Niño-like warming and moistening pattern. The basic state meridional PW gradient change is especially notable in the central Pacific and preferentially increases for ensemble members with the highest MJO amplitude change, which would produce more moistening to the east of MJO convection in the central to eastern Pacific through meridional moisture advection by the horizontal MJO flow acting on a strengthened meridional moisture gradient. Greater vertical moisture gradient increases in the members having more El Niño-like warming also supports stronger MJO precipitation amplitude increases. MJO wind amplitude increases are generally more muted and have a less robust relationship with the warming pattern, consistent with increases in tropical static stability in a warmer climate (Maloney & Xie, 2013). Overall, increased mean vertical and meridional moisture gradients support stronger eastward MJO amplitude as interpreted through MM theory, with ensemble members having more El Niño-like warming supporting stronger MJO precipitation amplitude. However, we note that substantial scatter exists in the relationship between individual ensemble members' MJO amplitude changes and characteristics of basic state moisture changes. This likely reflects the influence of internal variability in MJO activity on the results. Future work will characterize the role of internal MJO variability on future projections of MJO amplitude by examining time slice experiments with fixed SST for both historical and future warming scenarios.

We arrive at a similar conclusion to Bui et al. (2024) on a more El Niño-like warming pattern change in a future climate supporting stronger MJO amplitude change, although with a different approach. Other similar conclusions include the MJO wind amplitude change not being as strong as the MJO precipitation amplitude change, and large internal variability being present in the ensemble members. However, while Bui et al. (2024) start by clustering tropical SST into ensemble members with weak, moderate, and strong El Niño warming pattern changes before examining how MJO amplitude changes in those clusters, we start from ensemble members with strong and weak MJO amplitude changes and analyze the resulting changes in SST warming patterns. Our differing approach produces consistent results to prior findings in Takahashi et al. (2011) and Bui et al. (2024).

This study concludes that projected SST pattern change does influence MJO precipitation amplitude. Moreover, the investigation supports the hypothesis that MM theory can be used to help interpret how the MJO's maintenance and propagation changes in a warmer climate. However, simulations with the greatest changes in MJO wind amplitude are not explained as easily by changes in the background SST state. Ultimately, this investigation is useful not only because it provides more insight into how the MJO may change in a future warmer climate, but also adds insight on how the magnitude of MJO impacts might change in the future and their uncertainties. Future work based on this investigation will relate future temperature and moisture pattern changes and their uncertainty to societal impacts in specific oceanic regions, which contain vulnerable communities. An analysis of how ARs and TCs are influenced by MJO activity changes will also be conducted.

Acronyms

ARs	Atmospheric Rivers
CESM2	Community Earth System Model 2
CMIP	Coupled Model Intercomparison Project
MJO	Madden Julian Oscillation
MC	Maritime continent
MM	Moisture mode
SST	Sea surface temperature
SSP	Shared socioeconomic pathways
TCs	Tropical cyclones
PW	Precipitable water

Data Availability Statement

The dataset used is the Community Earth System Model 2 (CESM2) and is downloaded from the National Center for Atmospheric Research (NCAR) website at https://www.cesm.ucar.edu/community-projects/lens2/data-sets were used in the creation of this study (Danabasoglu et al., 2020; Hurrell et al., 2013; Kay et al., 2015; Riahi et al., 2017; Rodgers et al., 2021). The facilities to complete data analysis is the Walter Scott Jr, College of Engineering Cluster known as the ASHA Supercomputer at Colorado State University (CSU). The usage of cropping, detrending, and filtering the data was used in ASHA. Figures and Maps were made with Matplotlib version 3.8.2 (Caswell et al., 2023; Hunter, 2007), available under the Matplotlib license at https://matplotlib.org/. The kf (zonal wavenumber-frequency) filter from ncl to python version by Carl Schreck and Jared Rennie on GitLab https://k3.cicsnc.org/carl/monitor/-/blob/master/python/realtime_filter.py (Rennie & Schreck, 2020). The code associated with this investigation for the calculation and storage of Precipitation, Zonal Wind at 850 mb, SST, PW, and SHQ is licensed under CSU and published on GitHub https://doi.org/10.5281/zenodo.10819124 (Bowden, 2024).

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