PERSPECTIVE
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Madden–Julian oscillation changes under anthropogenic warming

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The Madden–Julian oscillation (MJO) produces a region of enhanced precipitation that travels eastwards along the Equator in a 40–50 day cycle, perturbing tropical and high-latitude winds, and thereby modulating extreme weather events such as flooding, hurricanes and heat waves. Here, we synthesize current understanding on projected changes in the MJO under anthropogenic warming, demonstrating that MJO-related precipitation variations are likely to increase in intensity, whereas wind variations are likely to increase at a slower rate or even decrease. Nevertheless, future work should address uncertainties in the amplitude of precipitation and wind changes and the impacts of projected SST patterns, with the aim of improving predictions of the MJO and its associated extreme weather.

The MJO is a phenomenon that causes tropical precipitation to alternate between amplified and suppressed periods within a season[1]. Enhanced precipitation and wind anomalies associated with the MJO begin in the equatorial Indian Ocean, and then move slowly eastwards into the west Pacific at a speed of 5 m s^{-1}. Wind perturbations converge in regions of enhanced MJO precipitation in the lower troposphere, and diverge in the upper troposphere, a 'first baroclinic' structure to the MJO circulation that is assumed throughout our Perspective. Areas of suppressed precipitation follow enhanced precipitation by about 20–25 days. The whole cycle takes on average about 40–50 days to repeat.

In addition to creating significant variability in tropical precipitation in the Indian and west Pacific oceans, corresponding pressure fluctuations, vertical motion and diverging winds drive tropical and extratropical wind anomalies. The tropical MJO circulations modulate hurricanes in the east Pacific and Atlantic[2,3], play a role in initiating El Niño/Southern Oscillation (ENSO) events[4,5,6] and further cause a modulation of droughts, heat waves and flooding, among other impacts[7]. For example, atmospheric rivers — plumes of high atmospheric water vapour that can impinge on the coastal terrain of the US West Coast and cause severe flooding events — are modulated by the MJO[8,9]. Statistical modelling that uses the state of the MJO as a predictor produces significant forecast skill for North American West Coast atmospheric river activity at leads of 5 weeks, demonstrably longer than that associated with state-of-the-art weather prediction models[10,11].

Given the acute impacts of the MJO on extreme weather events in our current climate, a substantial body of work over the last decade has been devoted to understanding how the MJO might change with anthropogenic warming. This work has exploited modelling tools that represent the MJO and general climate system with increasing fidelity[12]. Conventional wisdom posits that a warming climate will produce a more intense MJO that will increase the MJO's effect on extreme weather, and possibly lead to improved prediction capability for extreme events on subseasonal timescales[13]. However, the ability of the MJO to produce remote impacts (including modulation of extreme events) depends on the ability of the MJO to drive strong circulations. Recent studies suggest that a warming climate may produce a different degree or even different sign of changes in MJO precipitation intensity versus MJO wind intensity[14]. The growing literature on MJO change in a warmer climate, the mixed signals regarding changes in precipitation and wind variability, and the advent of improved modelling tools for the MJO provide an excellent opportunity to assess the state of the field and highlight critical gaps in our knowledge.

This Perspective reviews progress on MJO change in the future climate from early observational approaches through to recent sophisticated modelling techniques. We highlight the emerging likelihood that MJO precipitation variations will strengthen in a future warmer climate whereas wind variations will only change modestly or even decrease in intensity. Changes to MJO precipitation and wind strength in a warming climate are interpreted through the theoretical lens of 'moisture mode theory', where the tropics are assumed to have weak temperature gradients and processes regulating moisture control the maintenance and propagation of MJO precipitation[15]. In particular, the preferential warming of the upper troposphere in a future warmer climate is expected to reduce the strength of MJO circulation fluctuations per unit precipitation. Findings that contradict the emerging consensus on MJO change in a warmer climate are also highlighted, as well as gaps in our understanding that suggest areas for future research focus.

Initial clues from observations

To date, observational studies suggest that MJO amplitude has increased as the climate has warmed, although a substantial amount of uncertainty remains. Assessments of changes in subseasonal wind variability over the second half of the twentieth century indicate increases in wind variance that coincided with a period of rises in sea surface temperatures (SSTs)[16–18]. Reconstructions of MJO activity over the entirety of the twentieth century using dynamical variables show weak trends in MJO amplitude (13% increase per century)[19]. Other studies indicate an upward trend in MJO activity over the last few decades of the twentieth century, but with a strong seasonal dependence such that amplitude increases preferentially occur in Northern Hemisphere summer[20]. It has further been suggested that increases in the frequency of certain MJO phases (geographical locations of MJO precipitation centres) are responsible for some of the high-latitude warming observed over

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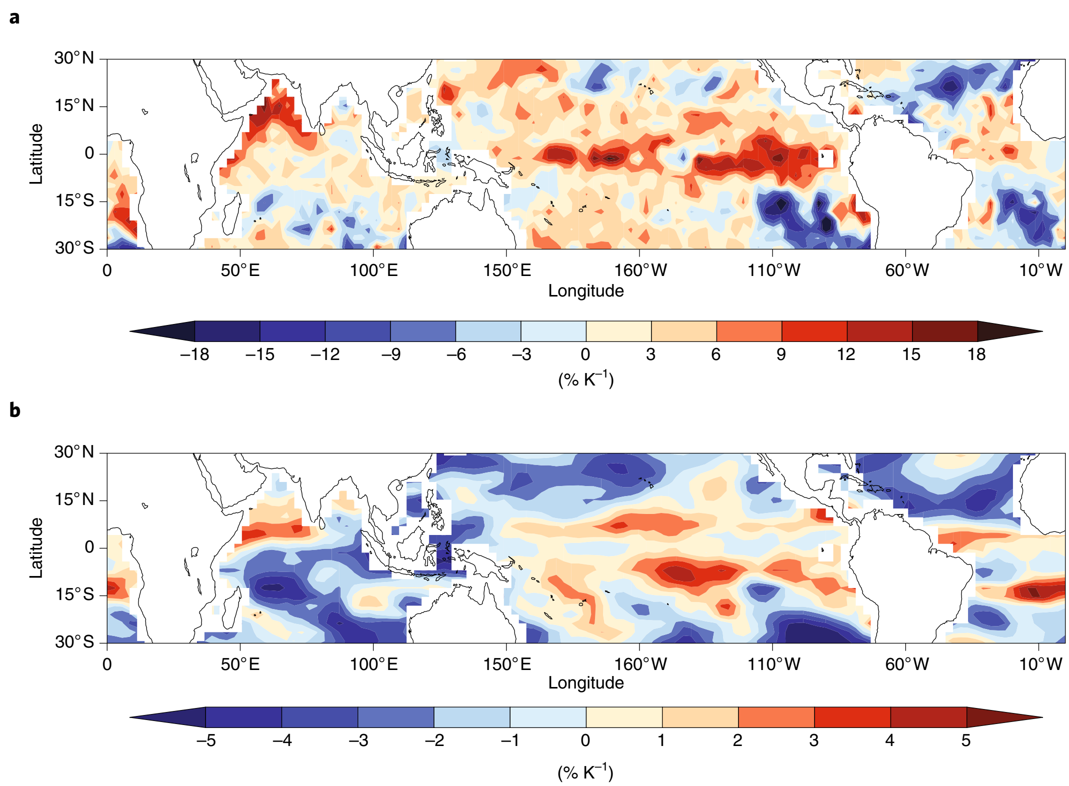

Fig. 1 | Model average intraseasonal precipitation and wind amplitude changes with warming. a,**b**, Multimodel mean difference between the November–April RCP8.5 and historical standard deviation of the 30–90 day filtered precipitation (**a**) and 850 hPa zonal wind (u_{850}; **b**). Differences are computed for 2081–2100 relative to 1986–2005. The six CMIP5 models used to construct the multimodel mean are indicated in Fig. 2.

the past few decades[21]. A criticism of previous observational studies is that discontinuous satellite data records in the second half of the twentieth century could complicate interpretation of trends in MJO activity[22]; one modelling study suggested that results for the MJO change from the observational record should be used with caution as natural variability may account for a large fraction of the MJO change observed[23].

The Indo-Pacific warm pool approximately spans equatorial ocean regions from 70° E to 180°. Observational relationships showing that higher Indo-Pacific warm pool SSTs correspond to stronger MJO activity have been used in conjunction with climate model projections of twenty-first century warm pool SSTs to extrapolate MJO activity into the future[24]. However, such an approach does not account for changes in warm pool SST relative to the tropical mean, which has been demonstrated to be an important regulator of local tropical convective behaviour[25]. In particular, evidence exists that a quantity called normalized gross moist stability (NGMS) is important for regulating MJO strength[26]. The NGMS provides a measure of how efficiently tropical convection (associated with precipitation) removes moisture, sensible heat and potential energy added to the atmosphere[27,28]. Lower NGMS generally indicates that more vigorous convection is needed to produce the same energy export, which also supports stronger convection in the MJO. NGMS tends to be locally decreased where local SSTs are high relative to the tropical mean SST[29], essentially due to a strengthened vertical moisture gradient in the lower troposphere[30]. Hence, failing to account for the pattern of SST change across the entire tropics makes extrapolation of MJO activity based only on Indo-Pacific warm pool SST changes imperfect.

A substantial amount of recent research has also analysed the modulation of the MJO by modes of climate variability such as ENSO, the tropical quasi-biennial oscillation, decadal variability and the Indian Ocean Dipole[31–37]. As the modulation of the MJO by these phenomena is not a perfect analogue to the effect of anthropogenic climate change on the MJO, these studies will not be discussed further here.

Changes in MJO characteristics in models

Given the limitations of observations for providing insight into how the MJO may change in a future warmer climate, the scientific community has increasingly turned to models. Although imperfect representations of the climate system, models have provided useful clues as to how MJO precipitation and wind variability may change in a warmer future. Modelling studies show that projected MJO precipitation and wind changes are often intriguingly different from each other.

MJO amplitude. Global climate models and more idealized models have been used to assess changes in MJO characteristics in a warming climate since at least the late 1990s. Most, but not all, models indicate that precipitation variations and other measures of convection associated with the MJO will increase in intensity in a warmer climate. A study using twelve Coupled Model Intercomparison Project Phase 3 (CMIP3)[38] models assessed to have good MJO representations analysed the projected changes in MJO convective activity at the end of the twenty-first century in a business-as-usual GHG emission scenario[31]. MJO convective activity was defined using tropical outgoing long-wave radiation (OLR) filtered to spatial and temporal scales characteristic of the MJO, however, this convective activity measure should be used with some caution as different inferences on MJO change may be derived from OLR versus precipitation[39]. Seven models exhibited an increase in MJO convective activity, and five models a decrease. MJO amplitude changes ranged from −13% to +31% relative to pre-industrial

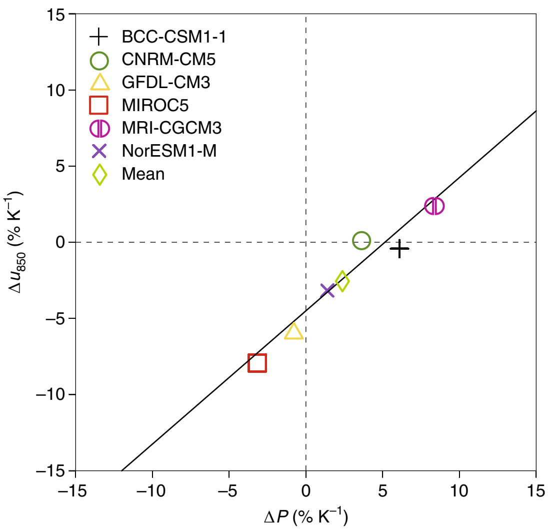

Fig. 2 | Indo-Pacific warm pool intraseasonal precipitation and wind amplitude changes with warming. Differences in the November–April 30–90 day standard deviation of precipitation and u_{850} under RCP8.5 relative to the historical simulation for 10° S–0°, 90° E–180°. Differences are computed for 2081–2100 relative to 1986–2005. The six CMIP5 models shown are labelled, with more information provided in ref. [46]. The least-squares fit regression line is shown ($\Delta u_{850} = 0.9\Delta P - 5$, where P is precipitation), with a squared correlation coefficient of 0.94.

control simulations. Since that CMIP3 study, a larger proportion of studies have projected that MJO convection will strengthen in a warmer climate. Values of the increase in MJO precipitation amplitude on the order of 8–10% K^{-1} have been reported in several of these studies[30,39,40]. This is greater than the rate at which tropical column water vapour increases under the Clausius–Clapeyron relationship under the assumption of fixed relative humidity[39,41]. However, other evidence demonstrates substantial differences in the magnitude[42,43] or even sign of intraseasonal (30–90 day timescale) precipitation changes[44] in an anthropogenically warmed climate. A recent study[44] examined changes in warm pool precipitation variance at the end of the twenty-first century (2081–2100) in Coupled Model Intercomparison Project Phase 5 (CMIP5)[45] models in a pathway reaching 8.5 W m^{-2} by 2100. Of the six models assessed to have good MJO simulations[46], four showed increases in Indo-Pacific warm pool intraseasonal precipitation amplitude and two showed decreases. Per cent changes in intraseasonal precipitation amplitude ranged from about −10% to +20% for total warming, despite the mean change across all models being positive. Conclusions were also similar when isolating signals with 13,000–40,000 km wavelengths around the Equator that are characteristic of the size of the MJO. This same set of six models is further examined here to extend the analysis shown in the previous study[44]. Figure 1a shows the multimodel mean change in the standard deviation of November–April precipitation between the end of the twenty-first century and historical period, expressed as a per cent change per K of global mean temperature warming. The multimodel mean amplitude of Indo-Pacific warm pool intraseasonal precipitation variability is shown to increase, consistent with the consensus view in the scientific literature. However, Fig. 2 shows a substantial spread in the change across models of –4% to +8% K^{-1} in the Indo-Pacific warm pool, consistent with the previous CMIP5 analysis[44].

One potential reason for different MJO precipitation amplitude changes among models is different patterns of SST change. An analysis with CMIP3 models indicates that the amplitude of Indian Ocean MJO precipitation increases tend to occur in models with an SST warming pattern that is El Niño-like, whereas models that show a decrease in MJO amplitude do not exhibit such a warming pattern[31]. This point was further reinforced by a study that used an atmospheric general circulation model (AGCM) in which the same global mean SST change but different patterns of warming were imposed. Either increases or decreases in MJO precipitation amplitude could be obtained for the same global mean temperature change, but different warming patterns[29].

Changes to the strength of MJO circulations with warming are even more uncertain, and generally do not scale with MJO precipitation changes. An early modelling study in which SST was increased uniformly by 3 K in an AGCM demonstrated an increase of approximately 30% in upper tropospheric equatorward momentum transport associated with the MJO, suggesting stronger MJO circulations[47]. This increased transport contributed to upper tropospheric westerly winds at the Equator when averaged around a latitude belt, a state called superrotation[48]. The onset of superrotation associated with stronger MJO circulations in a warmer climate has also been documented in other models[12,49–52]. However, many other modelling studies have shown changes in MJO wind variability that are either ambiguous[43,53], or have opposite-signed or fractionally smaller MJO wind amplitude changes relative to precipitation amplitude changes[12,14,29,39,40,44]. Boreal winter intraseasonal precipitation and 850 hPa (lower troposphere) wind variance maximizes in the Indo-Pacific warm pool to the west of 165° W in the current climate[44]. Under the warming scenario with the six CMIP5 models described above[44], the multimodel mean u_{850} standard deviation change in the Indo-Pacific warm pool decreases in amplitude despite MJO precipitation amplitude increasing (Fig. 1b). Intraseasonal wind variability does increase in the central and east Pacific, associated with an eastward extension of MJO activity that is also seen in the precipitation field. Figure 2 shows that the majority of models and the multimodel mean indicate either little change or decreased intraseasonal wind amplitude in the Indo-Pacific warm pool at the end of the twenty-first century under the warming scenario. Changes in intraseasonal wind amplitude range from −8% to +2% K^{-1}. Even models with a precipitation amplitude increase can produce a decrease in wind anomaly amplitude. It is perhaps not a coincidence that the relative changes in intraseasonal precipitation and lower-tropospheric wind amplitude fall approximately along a line of slope one offset from the origin, for reasons that will be discussed in more detail below (see MJO wind amplitude)[44]. These changes are also manifest in a physically consistent weakening in the intraseasonal vertical velocity field relative to precipitation (not shown here)[40,44], and extend through the depth of the troposphere[14].

As noted above, weakening of MJO wind anomalies in a warmer climate would be particularly impactful, as MJO wind anomalies can initiate ENSO events, produce remote circulation responses (teleconnections) in mid-latitudes and modulate the stratosphere[54]. It was recently shown in a sophisticated climate model that employed a concept called 'superparameterization'[55] to simulate clouds that quadrupling atmospheric CO_2 concentrations relative to pre-industrial times results in weaker mid-latitude circulations generated by the MJO. The rate of decrease in the strength of mid-latitude teleconnections is proportional to the reduction in tropical MJO circulation amplitude[14], which is not surprising as such teleconnections are forced by divergent winds associated with MJO convection. If such weakening of teleconnections were to occur, it would make the MJO less important for regulating mid-latitude features such as heat waves, flooding and drought, and possibly weaken an important source of mid-latitude prediction.

Changes in other characteristics. Other characteristics of the MJO are also projected to change in a warmer climate. Many models project that MJO convection will travel further eastwards into the

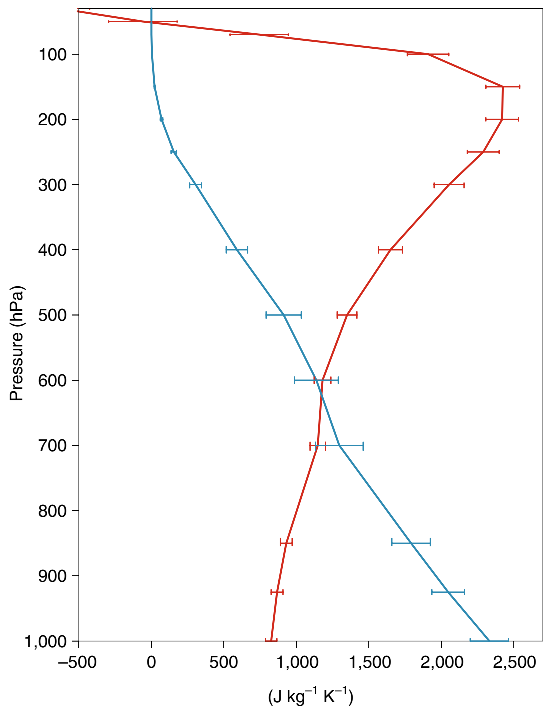

Fig. 3 | Indo-Pacific warm pool dry static energy and latent heat profile changes with warming. Changes in the multimodel CMIP5 mean vertical structures of dry static energy and latent heat in RCP8.5 relative to the historical simulation over the region 10° S–0°, 90° E–180°. Dry static energy (red line) is given by $cpT + gz$, where T is temperature, g is gravity, z is the height and cp is specific heat of dry air at constant pressure. Latent heat (blue line) is given by Lq, where L is the latent heat of vaporization and q is the specific humidity. The bars at each level represent ±1 s.d.calculated across all models relative to the multimodel mean.

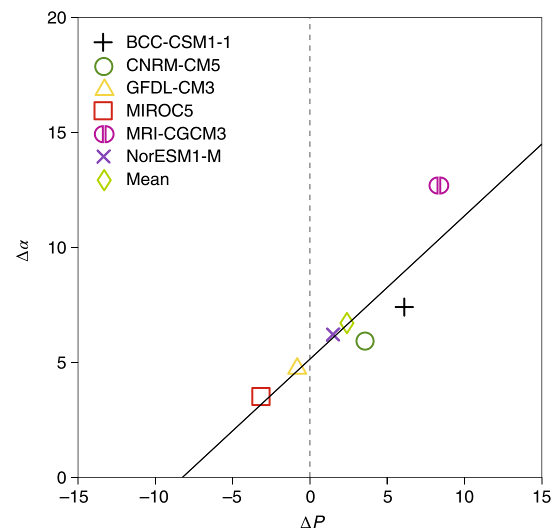

Fig. 4 | Indo-Pacific warm pool α and intraseasonal precipitation amplitude changes with warming. The value of α describes the efficiency with which a diabatic heating anomalies moistens the atmosphere through vertical advection. Differences in the November–April 30–90 day standard deviation of precipitation and α vertically averaged from 100–900 hPa under RCP8.5 relative to the historical simulation over the region 10° S–0°, 90° E–180°. Differences are computed for 2081–2100 relative to 1986–2005. The least-squares fit regression line is shown ($\Delta\alpha = 0.7\Delta P + 5$), with a squared correlation coefficient of 0.8.

central and eastern Pacific with warming[39,40,44,53]. This is consistent with the tendency for models to produce an El Niño-like warming pattern in the tropical Pacific with preferentially enhanced central and east Pacific equatorial SSTs[25]. Evidence of this eastward extension is seen in Fig. 1. MJO convection is projected to increase in depth in a warmer climate[14,40], consistent with the general tendency for convective clouds in the tropics to become deeper[56]. Most studies also project that MJO propagation speed will increase, resulting in a shift in the MJO towards shorter timescales[30,39,40,42,49,57], although not every model produces a speed-up in propagation speed with warming[53]. Many[12,39,57], but not all[53], models also show that MJO events become more frequent with warming, possibly consistent with the reduction in timescale.

Why does the MJO change with warming?

In addition to basic documentation of MJO changes in a future warmer climate, modelling studies have started to answer why these changes may occur. New diagnostic tools that exploit the weak horizontal temperature gradients of the tropical atmosphere have been developed to explain why MJO wind and precipitation anomalies change in amplitude, and provide insight into why they do not scale with each other. Changes in other characteristics such as MJO propagation speed cannot yet be explained confidently from physical principles.

MJO precipitation strength. Compelling mechanisms have been proposed to explain possible increases in MJO precipitation amplitude, lack of strong increases in MJO wind variability and increases in MJO propagation speed in a warmer climate. Figure 3 shows the multimodel mean change with temperature in the latent heat profile of the Indo-Pacific warm pool (blue line, proportional to the moisture content of the atmosphere) between the end of the twenty-first century and the present day in the six CMIP5 models analysed above[44]. The vertical moisture gradient increases in the lower half of the troposphere in response to the surface warming. This result is expected, given that the relative humidity of the tropical atmosphere remains fairly constant in these models, and the temperature profile approximately follows a moist adiabat[30]. In the tropics, vertical velocity is approximately equal to the apparent heating rate (that associated with MJO convection) multiplied by the inverse of the tropical dry static stability (related to the rate of vertical temperature change with height)[58]. This vertical velocity moistens by moving air vertically across the low-level vertical moisture gradient. All else held constant, an increased moisture gradient makes a given MJO heating anomaly more effective at moistening the atmosphere and maintaining moisture anomalies that foster tropical precipitation[59]. This fact has been used to explain why MJO precipitation is stronger in a warmer climate through use of the moist static energy budget[12,30,39,51,60], but also through explicit use of the moisture budget[14]. From the former perspective, and consistent with the discussion in the previous section, a stronger vertical moisture gradient under global warming produces lower NGMS and hence a stronger MJO[30].

From the moisture budget perspective, a quantity called α has been defined that gives the efficiency with which a heating anomaly, associated with MJO precipitation (for example), can drive moistening through upward motion[61]. The value of α is proportional to the vertical moisture gradient, but also inversely proportional to static stability, with the latter dependence coming from the relationship between vertical velocity and heating described above. An increase in α with warming implies that heating becomes more efficient at moistening the atmosphere, which can then foster longer-lasting and stronger convection. Figure 4 shows that the CMIP5 models in which α increases the most under global warming are associated with

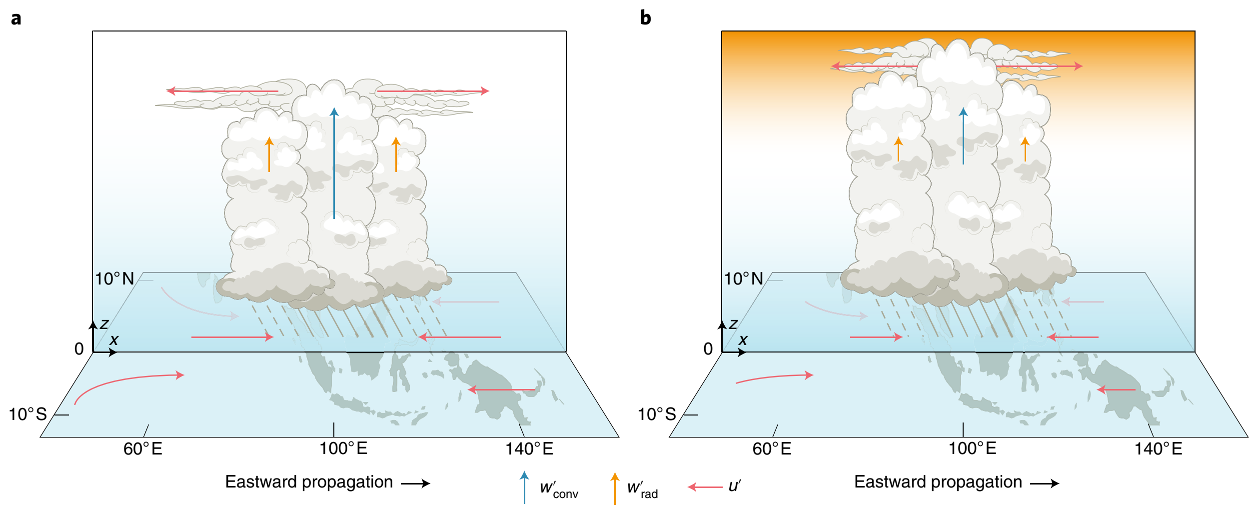

Fig. 5 | Schematic summarizing our best understanding of changes in MJO convective anomalies and the anomalous large-scale circulation. a, Current climate. **b**, A warmer climate. As the climate warms, the mean vertical gradient in water vapour (blue shading) increases. Tropospheric temperature (orange shading) will also increase, with the largest increments occurring in the upper troposphere, resulting in increased static stability. The increased static stability will result in weaker anomalous horizontal (u') and vertical (w') motions and less extensive upper-level clouds[73]. conv, convective; rad, radiative. The stronger moisture gradient will probably outstrip the stronger static stability to result in more efficient moistening of the troposphere by heating in a warmer climate, fostering stronger MJO convection. A warmer climate will also result in a deeper troposphere, deeper convection, weaker anomalies in long-wave radiative heating and faster propagation.

the largest increases in intraseasonal precipitation amplitude, consistent with findings from a recent modelling study[14]. Interestingly, tropical temperatures increase proportionally by a greater amount in the upper troposphere in these models, indicating an increase in static stability; this is reflected in a greater change in the dry static energy (the sum of sensible heat and potential energy) aloft in Fig. 3. Despite this preferential warming aloft, vertical moisture gradient changes dominate[14] to make α larger in the models with increased precipitation amplitude. The increase in static stability does have substantial consequences for intraseasonal variability in a warmer climate, as it mediates the strength of the wind response associated with precipitation anomalies (discussed in more detail below, see MJO wind amplitude). Another mitigating factor that decreases the impact of the increased moisture gradient on MJO precipitation anomalies is that convective heating becomes more elevated in many models in a warmer climate[14,40]. This shifts MJO convective heating and associated vertical motion towards higher elevations relative to the strongest lower-troposphere moisture gradient, results in less moistening and slightly moderates increases in MJO precipitation amplitude[14].

Other factors may also affect MJO amplitude in a warmer climate. In the current climate, long-wave cloud radiation feedbacks are thought to support the MJO. Widespread high cloudiness in MJO precipitation regions reduces long-wave radiation emission to space[15,62], producing anomalous heating of the troposphere. This anomalous heating is thermodynamically balanced by upward motion, which moistens the atmosphere. Climate models show that these long-wave cloud feedbacks become less supportive of MJO convection in a warmer climate[12,14,30,51,60], probably because increased low-level water vapour decreases the upwelling long-wave flux that interacts with high clouds, diminishing the effect of clouds on outgoing long-wave radiation to space[30]. On the other hand, surface latent heat fluxes may become slightly more supportive of MJO convection in a warmer climate[12,14]. Advection of dry air from the higher latitudes into the tropics is a stabilizing mechanism for the MJO, as this process curbs the moisture anomalies that support MJO convection[63] One study in which increased MJO activity and superrotation was produced with warming argued that reduced damping by horizontal moisture advection supported stronger MJO convective variability in their model[51]. In this study, the generation of upper-tropospheric mean westerly winds with warming allowed increased penetration of extratropical weather disturbances into the equatorial region that mixed out and weakened the climatological Equator-to-pole moisture gradient. This weaker moisture gradient diminished the ability of dry air to be transported into the deep tropics during MJO events, thus supporting stronger MJO convection.

MJO wind amplitude. As indicated above, tropical vertical velocity scales approximately as the heating rate divided by tropical static stability[58]. The heating rate anomaly is approximately proportional to precipitation in MJO convective regions. These relationships suggest that if the static stability of the tropics increases in a warming climate (which indeed is robustly predicted by climate models; see Fig. 3), then MJO wind anomaly amplitude should increase more slowly than the precipitation anomaly amplitude, or may even decrease[14,29,40,60]. Figure 2 shows that Indo-Pacific warm pool intraseasonal wind anomaly changes have a linear relationship with precipitation anomaly changes, characterized by a one-to-one line offset from the origin, with wind anomaly changes consistently lower. This relationship between wind and precipitation anomalies is what is expected for models with a similar static stability change per unit surface temperature warming and first baroclinic structure to the MJO, ignoring any changes to the vertical structure or horizontal scale of the MJO[29,44]. This relationship also helps explain why MJO teleconnections to the mid-latitudes would be expected to weaken in a warmer climate. Upper-tropospheric divergence and divergent wind anomalies associated with tropical convection in the presence of a suitable background flow initiate circulations that propagate to higher latitudes[64,65]. If the strength of MJO wind anomalies decreases, comparable decreases in divergence and divergent wind anomalies should occur that weaken MJO teleconnections to higher latitudes. This weakening of MJO teleconnections was indeed shown to occur with warming in a recent modelling study[14], although the relationship needs to be verified in a broader set of models.

MJO propagation speed. To explain the faster propagation associated with the MJO in a warmer climate, several studies have invoked the stronger low-level vertical moisture gradient. Anomalous low-level converging winds and shallow vertical motion to the east of MJO precipitation causes moistening that would be enhanced in the presence of stronger vertical moisture gradients, accelerating eastward propagation[12,14,40,60]. Horizontal moisture gradient changes may also influence MJO propagation, although the impact is still unclear. A recent modelling study attributed faster MJO propagation to increased north-south humidity gradients in a warmer climate[60], although another in which superrotation is induced with climate warming and a strengthened MJO shows a reduction in mean north–south humidity gradients[51]. Still other work has questioned the overall importance of horizontal moisture advection for regulating changes in MJO propagation speed across different climate states[52]. Propagation of the MJO in a warmer climate may also be influenced by a variety of other factors, including the aforementioned static stability changes[60]. In general, the processes responsible for changes in MJO propagation speed remain less studied than other aspects, and require further focus.

Future directions

The schematic in Fig. 5 provides a summary of the likely changes to MJO strength in a warmer climate, and the most salient processes regulating these changes. Although a consensus seems to be emerging that MJO convective variability is likely to increase in a future warmer climate (while wind amplitude changes are likely to increase to a lesser extent or even decrease), key issues remain unresolved. Better constraining the amplitude of MJO precipitation change per degree of warming seems necessary, including the dependence on the pattern of SST change that has been shown to have a strong impact on both the degree and sign of MJO precipitation amplitude changes in a warmer climate[29,31]. Recent observational and modelling analysis calls into question the ability of the current generation of climate models to represent the pattern of SST change in the tropical Pacific with fidelity, which may affect the quality of their future projections[66]. Assessment of how MJO amplitude changes depend on the SST pattern change in the upcoming ensemble of CMIP6[67] models provides an excellent opportunity to revisit this issue, including the fidelity of SST trends in historical simulations relative to observations. Although substantial evidence exists that the relationship between MJO wind amplitude changes and precipitation amplitude changes is modulated by the increase in tropical static stability with warming, more work is needed to understand how changes in both vertical and horizontal MJO structure mediate this relationship, including in the context of teleconnections where the strength of upper-tropospheric divergent flow is critical. Changes to MJO amplitude and structure aside, how basic state changes such as meridional shifts or extensions of the North Pacific jet stream[68] affect MJO teleconnections in a future warmer climate has practical implications for MJO impacts and forecasts. The likelihood that increased MJO activity will produce more fundamental changes in tropical climate by inducing superrotation also needs to be examined. The weakening of circulation anomalies relative to precipitation anomalies should also apply to phenomena other than the MJO, including ENSO[14]. Hence, future work with CMIP6 and other models should also assess how a future warmer climate may modulate teleconnections associated with a broader range of phenomena.

The processes that may lead to stronger MJO precipitation variations in a warmer climate need to be more closely scrutinized in a broader set of models, including those with the improved models of CMIP6. Particular factors that require examination are the impact of vertical moisture and temperature profile changes, changes to horizontal moisture gradients, vertical heating profile changes, changes in the strength of wind–evaporation feedbacks and cloud–radiation interactions, among other factors. Figure 4 suggests that factors other than changes to vertical moisture and temperature profiles alone are responsible for changes in MJO activity, otherwise the regression line would go through the origin. This same set of factors also needs to be scrutinized in the context of why the MJO may speed up and exhibit shorter timescales in a warmer climate. Theoretical constructs for MJO dynamics other than the 'moisture mode' framework[69,70] should also be considered to test their applicability to predict MJO changes in a warmer climate[52]. Finally, not only the increases in SST, but also direct impacts of GHG changes on the atmosphere have been documented to impact the tropical hydrologic cycle[71,72], and so it is logical to expect similar impacts on the MJO. The atmospheric components of climate models can be forced alternately with only SST changes or GHG changes to assess the implications for the MJO.

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The authors declare no competing interests.

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