



The influence of the quasi-biennial oscillation on the Madden–Julian oscillation

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Abstract | The stratospheric quasi-biennial oscillation (QBO) and the tropospheric Madden–Julian oscillation (MJO) are strongly linked in boreal winter. In this Review, we synthesize observational and modelling evidence for this QBO–MJO connection and discuss its effects on MJO teleconnections and subseasonal-to-seasonal predictions. After 1980, observations indicate that, during winters when lower-stratospheric QBO winds are easterly, the MJO is ~40% stronger and persists roughly 10 days longer compared with when QBO winds are westerly. Global subseasonal forecast models, in turn, show a 1-week improvement (or 25% enhancement) in MJO prediction skill in QBO easterly versus QBO westerly phases. Despite the robustness of the observed QBO–MJO link and its global impacts via atmospheric teleconnections, the mechanisms that drive the connection are uncertain. Theories largely centre on QBO-related temperature stratification effects and subsequent impacts on deep convection, although other hypotheses propose that cloud radiative effects or QBO impacts on wave propagation might be important. Most numerical models, however, are unable to reproduce the observed QBO–MJO relationship, suggesting biases, deficiencies or omission of key physical processes in the models. While future work must strive to better understand all aspects of the QBO–MJO link, focus is needed on establishing a working mechanism and capturing the connection in models.

During the 1960s and 1970s, expanding observational data sets drove the discovery of several climatic patterns and oscillations^{1–6}. One such pattern was the quasi-biennial oscillation (QBO)^{7–10}, a descending reversal of the zonal-mean zonal wind in the tropical stratosphere, which alternates between an easterly (QBOE) and westerly (QBOW) phase over a period of ~20–30 months^{3,9} (FIG. 1a). Through thermal wind balance, these downward-propagating wind signals — descending at a rate of ~1 km per month — are accompanied by equatorial temperature anomalies of ~1–2 K that are negative during QBOE phases and positive during QBOW phases⁹. While disruptions to the QBO cycle have occurred^{11,12}, the reliability of the oscillation makes the QBO one of the most predictable features of the tropical atmosphere¹³. The QBO is also theoretically well understood; tropospheric atmospheric waves propagate upward into the stratosphere, interacting with and depositing momentum into the stratospheric mean flow and driving the oscillation^{9,14–16}.

In addition to the QBO, the expansion of observations in the 1960s and 1970s also aided the discovery of the Madden–Julian oscillation (MJO)^{17–19}. The MJO

describes a complex of wind and convection, primarily in the troposphere, that slowly propagates eastward at ~5 m s⁻¹ from the tropical Indian Ocean into the western Pacific¹⁹ (FIG. 1b). An MJO event consists of large-scale regions of both enhanced and suppressed convection over 1,000-km spatial scales (termed the active phase and suppressed phase, respectively). The active phase is associated with convergent zonal winds in the lower troposphere and divergent winds aloft, and the suppressed phase is associated with opposing wind conditions (FIG. 1b) that, together, can be on the scale of 5,000–10,000 km in the tropics. The MJO fluctuates on subseasonal timescales with a variable period of 30–90 days, and exhibits seasonal and interannual variability in its strength and structure^{20–22}. Its well-organized tropical convection and circulation patterns further lead to a host of climate impacts around the world via atmospheric teleconnections²³, making the MJO one of the most important sources of subseasonal-to-seasonal (S2S; about 2 weeks to 2 months) predictability in the tropics and mid-latitudes^{24,25}.

While the QBO and MJO have been studied independently for decades, in 2016, it was proposed that these

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two modes of variability might be linked²⁶. It appears, for example, that up to 40% of the year-to-year variability in boreal winter (herein December to February) MJO activity is related to the QBO²⁷, with a stronger and slower MJO during QBOE winters compared with QBOW winters (defining the QBO based on the tropical wind at 50 hPa)^{26,27}. The QBO also modulates S2S predictability of the MJO²⁸, as well as related phenomena in both the tropics and mid-latitudes, in ways that could have societal implications for water resource management, energy, infrastructure or agriculture^{24,25}.

While the QBO–MJO link appears quite strong, the contrasting characteristics between the QBO and the MJO (namely, that the QBO is primarily stratospheric and the MJO is mainly tropospheric), the absence of theory linking the MJO to stratospheric processes²⁹ and the small effect of the QBO on other modes of tropical convection^{30–36} make the mechanisms driving this apparent coupling unclear. Moreover, climate models are generally unable to simulate a robust QBO–MJO relationship, challenging conceptions of the observed link and reducing confidence that models correctly capture key physical processes in the tropics^{37–40}. Thus, a wealth of literature has emerged to better understand the QBO–MJO connection, its mechanisms and its impacts.

In this Review, we synthesize understanding of the QBO–MJO connection. We begin by examining observational and modelling evidence for QBO–MJO coupling. We then discuss the potential mechanisms driving such a link, before following with the implications for S2S forecasts and MJO teleconnections. We end with discussions of future research priorities.

The QBO–MJO relationship

While observational evidence for a QBO–MJO link was first presented in the early 1990s⁴¹, the topic received renewed observational and modelling interest in 2016 (REF.²⁶).

Observational features. The coupling between the QBO and the MJO exhibits pronounced seasonality. Significant relationships are apparent only during boreal winter, spanning December to February, although connections also hold through to March (FIG. 2a). The linear correlation between QBO phases (defined at 50 hPa) and MJO strength, as measured by the seasonal mean amplitude of daily MJO indices, is ~ -0.5 during this season,

which is statistically significant above the 95% confidence level (FIG. 2a). Although a possible connection has been suggested during boreal summer⁴², this relationship is substantially weaker than that observed during winter, and exhibits pronounced decadal variability⁴³. Thus, unless otherwise stated, all following discussion of the QBO, QBOE and QBOW will refer explicitly to boreal winter, when robust QBO–MJO coupling is evident.

While the wintertime QBO–MJO connection is seemingly a stable feature in the present climate, the coupling exhibits temporal variability over the twentieth century. In particular, as revealed by various analysis methods and data sets, their strong and significant relationship is only evident since the mid-to-late 1980s^{36,44} (FIG. 2b). It is thought that anthropogenic climate change — in particular, sensitizing MJO activity to the QBO via cooling of the tropical lower stratosphere and warming of the upper troposphere⁴⁴ — or a change in the vertical structure of the MJO³⁶ might have permitted the emergence of the QBO–MJO connection at this time; both hypotheses are yet to be confirmed. Moreover, owing to sparse data records, it is difficult to reliably measure any QBO–MJO connection prior to the 1970s, and, thus, determine, with confidence, whether the link does disappear further back in time.

Nevertheless, a robust coupling between the QBO and the MJO exists in the present climate, as evident in their significant negative correlation (FIG. 2a). This connection manifests as a more active^{26,27} and slower²⁷ MJO during QBOE compared with QBOW (FIG. 3). For example, MJO amplitude, as measured by an outgoing longwave radiation (OLR)-based MJO index, is 1.96 for QBOE, 1.35 for QBOW and 1.58 for all winters²⁶. Accordingly, MJO-related precipitation anomalies (a function of convective activity), tend to be ~ 20 – 40% larger for both active and suppressed phases during QBOE²⁶ (FIG. 3). These changes are partly thought to be related to more organized and consistent MJO behaviour, and an interrelated 10-day increase in the MJO period during easterly QBO phases²⁷. However, there is subtle disagreement on whether it is best to characterize the MJO change on the basis of its amplitude, MJO activity level, duration of events⁴⁵ or as a combination of these factors⁴⁶. Regardless, several observational analyses, which differ in their definitions of the QBO and the MJO, as well as their analysis methods, lend support to strong wintertime changes in the MJO associated with the QBO^{42,45–47}.

The QBO connection to tropical convection is also unique to the MJO. For instance, the QBO has only a small impact on seasonal-mean tropical convection: during QBOE, boreal winter mean convection is slightly stronger in the western Pacific and weaker in the eastern Pacific^{27,33,34}, but changes do not appear to be statistically significant²⁷. Furthermore, the QBO shows no statistically significant link to El Niño–Southern Oscillation (ENSO)³⁰ nor to other modes of tropical variability^{35,36}, such as convectively coupled equatorial waves⁴⁸. Moreover, while a QBO impact on tropical cyclones was noted in the 1980s⁴⁹ (Atlantic tropical cyclone activity was higher when the QBO at 30 hPa was westerly), that

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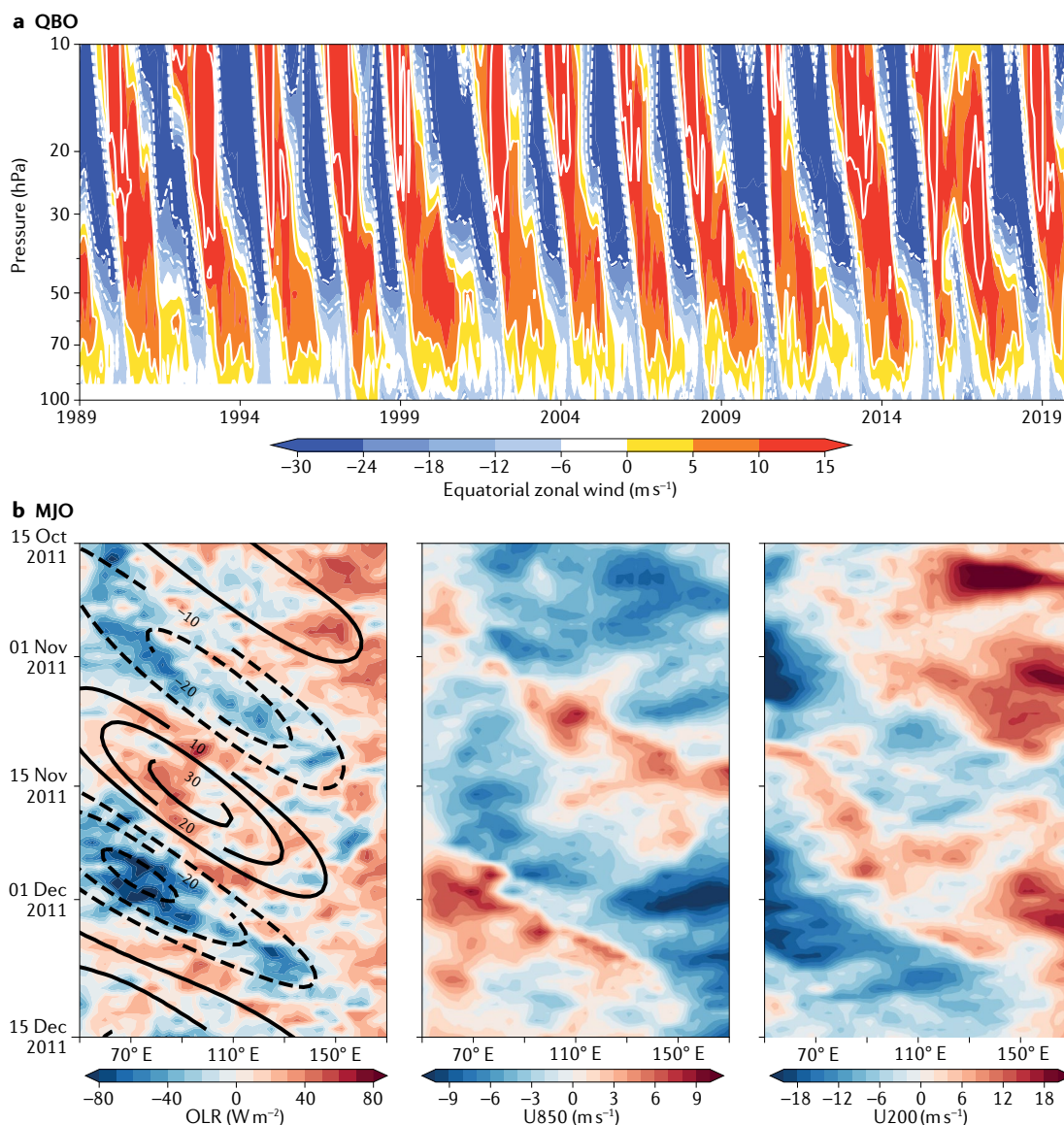


Fig. 1 | **The QBO and the MJO.** **a** | Monthly-mean zonal winds from radiosonde observations at the Singapore sounding site as an indication of stratospheric quasi-biennial oscillation (QBO) winds. The wind direction (phase of the QBO) changes every 10–15 months, with signals propagating downward from the upper stratosphere to the tropopause at 100 hPa (~17 km). White contours show 10 m s^{-1} intervals, with negative contours dashed. **b** | Outgoing longwave radiation (OLR; bandpass filtered at 20–100 days as contours)¹¹³ and zonal wind anomalies¹¹⁴ at 850 hPa (~1.5 km) and 200 hPa (~12 km), averaged over 5° S – 5° N . Active phases of the Madden–Julian oscillation (MJO) (blue shading with dashed contours in the left panel), propagating eastward in time, are evident around 70° – 90° E in late October–early November and late November–early December.

relationship has since disappeared over approximately the same time the QBO–MJO link has emerged³¹.

Modelling the QBO–MJO connection. Climate models, were they able to capture a QBO–MJO connection, might prove useful in helping understand the three key observational features of the QBO–MJO connection: the seasonality, the emergence after the late 1980s and the uniquely strong connection to the MJO but not to other modes of convective variability. Moreover, modelling the relationship could allow more in-depth quantification of the QBO–MJO link, as well as guide understanding of any projected future changes and

of the physical drivers. Yet, despite contemporary improvements^{50,51}, models are historically deficient in simulating the QBO and MJO individually^{9,19,52–55}, presenting challenges in investigating their interrelationship. Indeed, no numerical model to date has been able to capture the statistics of the QBO–MJO link as robustly as observed.

The most promising simulations of the QBO–MJO connection have come from global forecast models, particularly those optimized for S2S timescales^{28,43,56–59}. The majority of these models are able to qualitatively reproduce the QBO–MJO relationship, but the amplitude of their simulated changes in the MJO are less than

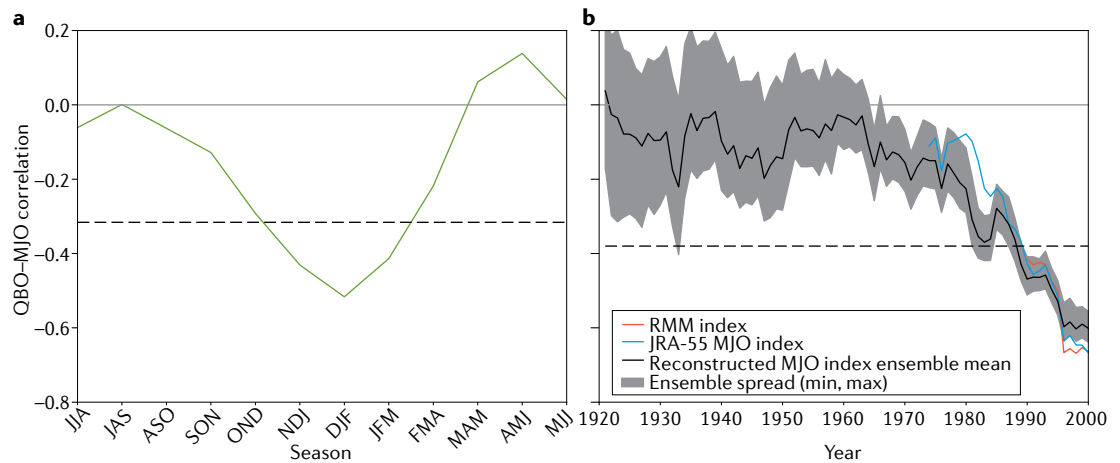


Fig. 2 | Seasonality and emergence of the QBO–MJO connection. a | Correlations between 3-month mean quasi-biennial oscillation (QBO) index¹¹⁵ and Madden–Julian oscillation (MJO) amplitude¹¹⁶. The dashed black line represents the 95% confidence level, revealing significant correlations during boreal winter only. **b** | The 30-year running correlation between winter QBO index and MJO amplitude using different MJO indices^{117–119}; the ordinate on the x axis is given by the central year of the 30-year running window. Grey shading signifies the maximum and minimum 30-year running correlations for the reconstructed MJO index, derived from the 56 members of the long-term MJO index ensemble. The dashed black line represents the 95% confidence level, illustrating a statistically significant relationship between the QBO and the MJO only after the 1980s. Panel **a** adapted from REF.²⁸, Springer Nature Limited. Panel **b** adapted from REF.⁴⁴, CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

half of the observed change^{56,57}. However, interpreting a QBO–MJO link in S2S models is complicated by their initialization from the observed state; any resulting QBO–MJO connection could arise from the model realistically representing the physical mechanism behind the connection⁵⁸ or from the model simply maintaining the observed state containing the observed QBO–MJO connection^{43,56,59}. Debate persists in this regard.

Global climate models (GCMs) are also limited in their ability to simulate the QBO–MJO connection^{37–40}. For example, of the four CMIP5 and 13 CMIP6 models that possess a reasonable representation of the QBO and the MJO, none show a statistically significant difference in MJO activity between QBOE and QBOW phases^{38,39}. Across all runs of 13 CMIP6 models, no single ensemble member captures a relationship as strong as that observed over a comparable ~40-year period to observations (FIG. 4), and sampling MJO activity changes in QBO neutral winters (where QBO winds are weak) confirms that any apparent QBO modulation is simply due to noise³⁹. In individual ensemble member simulations, increased MJO activity in GCMs is as likely during QBOW winters as it is during QBOE winters^{39,40}. Moreover, even when a model shows a change in MJO activity of the same sign as that observed, its magnitude is never more than half of the observed QBO modulation^{39,40}.

The source of deficiencies in GCMs is still unclear, but might partly relate to low model resolution and parameterized convection. Indeed, simulations performed with cloud-permitting models (that can more realistically represent convective processes compared with GCMs) have shown promise in better capturing the QBO–MJO connection. A cloud-permitting model without a cumulus parameterization, for example, can simulate a systematically weakened MJO during a stronger-than-observed

imposed QBOW phase compared with a QBOE phase, a modulation consistent with observations, albeit weaker⁶⁰. Furthermore, idealized experiments have identified a QBO impact on a cloud-permitting model's MJO-related convection, although the model QBO signals were larger in magnitude and lower in the atmosphere than observed⁶¹.

Model biases in the QBO and/or the MJO^{50,51} could further contribute to models' inability to simulate QBO–MJO coupling^{39,40}. For example, models might have poor depiction of the MJO around the tropopause, inadequately capture the MJO influence on optically thin cirrus clouds^{62,63} or contain biases in the vertical structure of the MJO^{35,64}. Similarly, models might exhibit biases in the strength or structure of the QBO in the lowest part of the stratosphere^{37,39,50} or omit other unknown processes around the tropopause, all of which could contribute to deficiencies in model simulations of the QBO–MJO link.

These general issues regarding model representation of QBO–MJO coupling, in addition to the seasonality and temporal variability of the QBO–MJO relationship, might spur scepticism that the entire relationship is a statistical fluke and/or lacks robustness. However, the QBO–MJO link has passed strict statistical tests that make it difficult to dismiss out of hand: the QBO–MJO correlation shows significance at a posteriori confidence levels, coinciding with a 99.85% a priori confidence²⁶. The main aspects of the QBO–MJO connection have been confirmed in many instances and appear robust to the definition of the QBO or the MJO, the data set considered or the analysis method. Furthermore, a hint of a QBO–MJO relationship exists in cloud-permitting models and in S2S forecast models, even if the reasons why remain unclear. While GCMs have difficulty directly emulating the QBO–MJO relationship, they also

demonstrate that a link as strong as that observed seems unlikely to have occurred by chance³⁹. The compilation of this evidence suggests that the QBO–MJO connection

is real and that models are unable to simulate the relationship, owing to an absence of important physical processes.

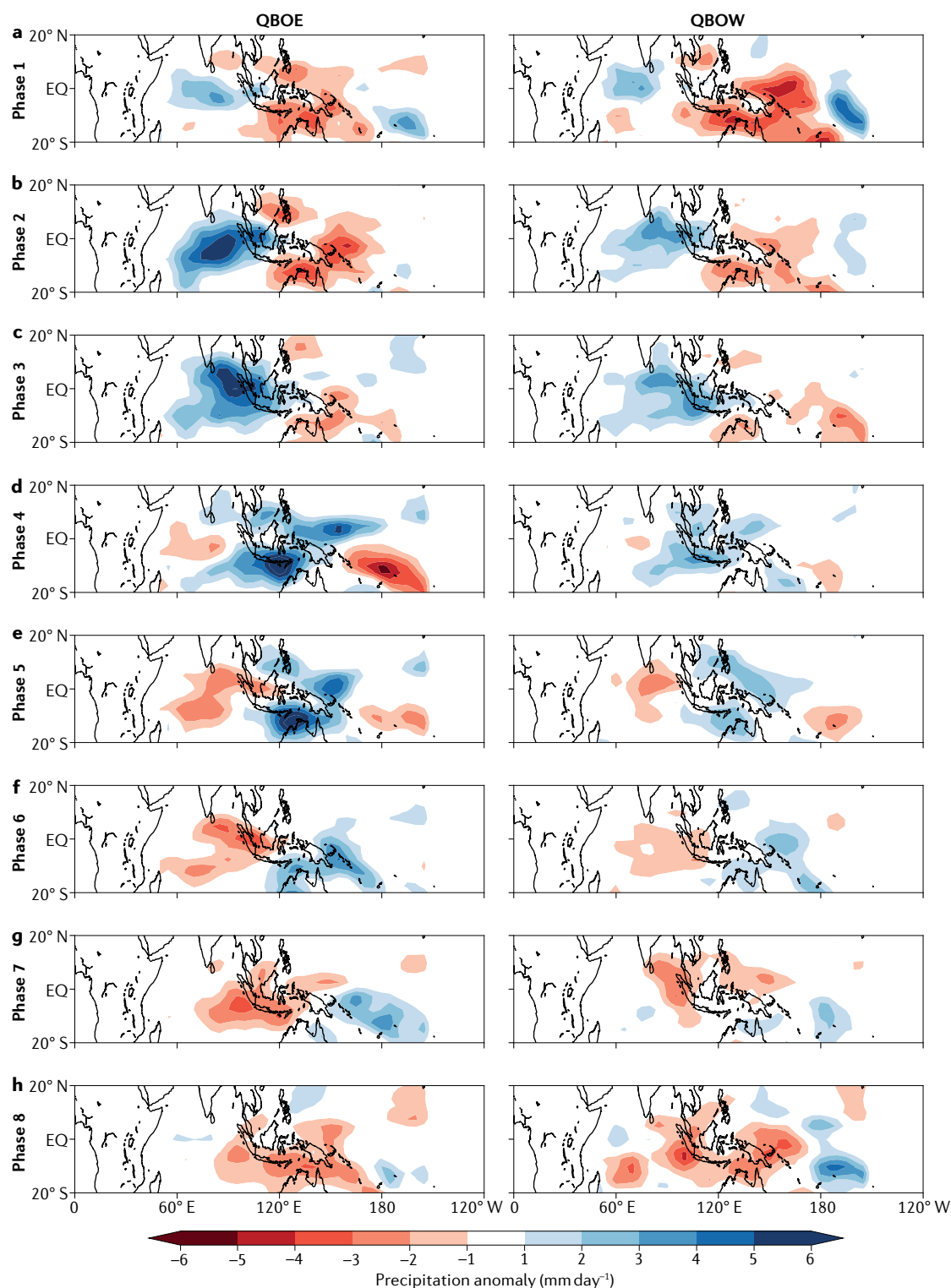


Fig. 3 | **MJO precipitation in QBOE and QBOW winters.** Composites of bandpass-filtered (20–100 days) precipitation anomalies¹²⁰ for Madden–Julian oscillation (MJO) phase 1 (panel **a**), phase 2 (panel **b**), phase 3 (panel **c**), phase 4 (panel **d**), phase 5 (panel **e**), phase 6 (panel **f**), phase 7 (panel **g**) and phase 8 (panel **h**) during quasi-biennial oscillation (QBO) easterly (QBOE; left) and QBO westerly (QBOW; right) winters from 1998 to 2019. Only days when the MJO amplitude, based on the outgoing-longwave-radiation-based MJO index¹¹⁶, is greater than one standard deviation are used. During all phases, MJO precipitation is significantly enhanced in QBOE winters compared with QBOW winters. EQ, equator.

Possible mechanisms

The mechanism linking the QBO and the MJO must be able to explain its many features, including why the connection appears only in boreal winter, why the QBO effect on tropical convection seems unique to the MJO and why the connection emerged around the 1980s. To date, there is no consensus on a mechanism that can account for all such features. However, several hypotheses have been proposed, including: QBO temperature stratification effects, cloud-radiative feedbacks, QBO wind shear effects and QBO changes to vertical wave propagation, each of which is now discussed (FIG. 5). Implicit to all these hypotheses is the assumption that the QBO exerts a downward impact on the MJO, and not the MJO impacting the QBO. This direction of causality is suggested by lead-lag relationships, which illustrate that QBO changes lead the MJO by ~2 months²⁷. Further, there is no clear hypothesis for why MJO activity might vary approximately every 2 years independently of the QBO, which further favours the notion that the QBO–MJO relationship is driven by QBO signals subsequently affecting the MJO.

QBO temperature anomalies. The QBO temperature stratification mechanism has been the most frequently studied pathway linking the QBO and the MJO^{27,35,36,40,61,64}, building on the context of how the QBO might change seasonal-mean convection^{32–34,65,66}. The mechanism contends that, during easterly QBO phases, cold temperature anomalies driven by adiabatic cooling destabilize the upper troposphere and lower stratosphere, promoting more vigorous deep convection, and, thus, stronger MJO events. The opposite conditions occur during westerly QBO periods: adiabatic heating leads to stabilization of the upper troposphere, reduced convection and, in turn, weaker MJO activity (FIG. 5).

This mechanism might explain several key aspects of the observed QBO–MJO relationship. The observed seasonality, for example, could be linked to the strongest MJO signals (in winter at the equator)^{19,67} co-occurring in space and time with the strongest QBO temperature anomalies (in winter at the equator)^{9,68,69}. When also factoring in that the tropopause tends to be highest and coldest during boreal winter^{70,71}, it seems possible that MJO convection could reach higher altitudes, increasing the likelihood of interaction between QBO-related and MJO-related anomalies, and, thus, explaining wintertime coupling. Furthermore, the emergence of the connection in the late 1980s could be linked to anthropogenic forcing (namely, increasing greenhouse gases and ozone depletion)^{44,72} warming the troposphere and cooling the stratosphere since the mid-twentieth century, decreasing stabilization to allow for QBO–MJO coupling⁴⁴. Finally, the uniqueness of the QBO connection to the MJO could be explained by the MJO's vertical structure, which tends to be deeper, less tilted and has stronger local temperature anomalies than other modes of organized convection^{36,64}. Deeper convection is more likely to feel the effects of QBO temperature signals at upper levels, while the reduced tilt and stronger local temperature anomalies might further allow more local feedback between QBO temperature signals and MJO convection.

In addition to these observational characteristics, the inability of models to simulate the QBO–MJO link can also be justified by the temperature stratification mechanism. Specifically, GCMs typically show weaker-than-observed QBO-related temperature anomalies around the tropopause^{37–40,50}, which could inhibit the subsequent effects on stabilization and the MJO. Indeed, a small-domain cloud-permitting model experiment illustrates that the magnitude of QBO-like temperature anomalies can impact MJO convection⁶¹.

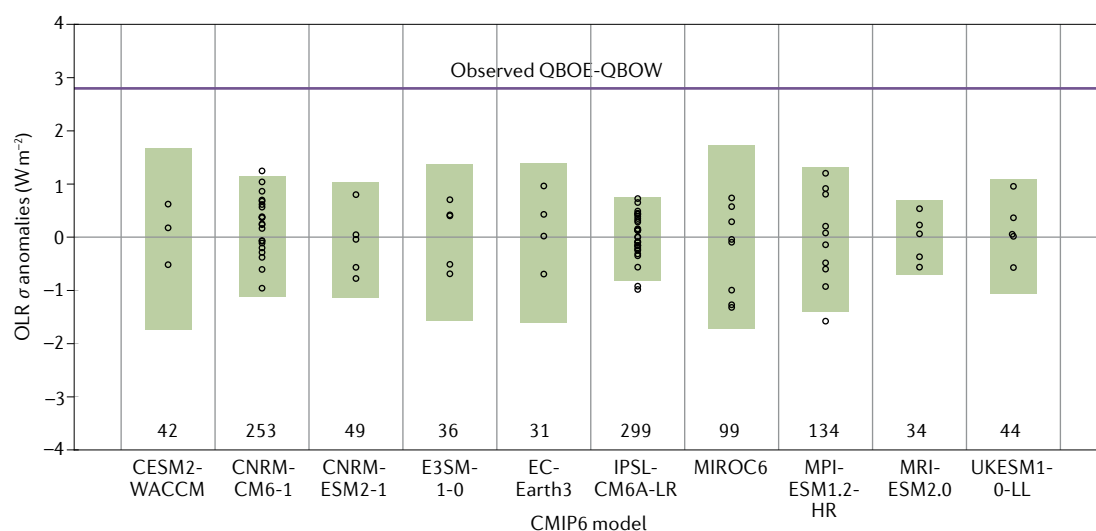


Fig. 4 | MJO activity in CMIP6 models. The difference in Madden–Julian oscillation (MJO) activity — as represented by the standard deviation of MJO-filtered outgoing longwave radiation (OLR) anomalies over the Maritime Continent from 1979 to 2014 — between quasi-biennial oscillation (QBO) easterly (QBOE) and QBO westerly (QBOW) winters in ten CMIP6 models. Small black circles illustrate the difference for each ensemble member and the bars denote the 2.5th to 97.5th range obtained by resampling with replacement from the QBO neutral years (number of years denoted at the bottom) with an equivalent sample size to observations. The purple line illustrates the observed QBOE–QBOW difference, which all models fail to reproduce. Adapted from REF.³⁹, CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

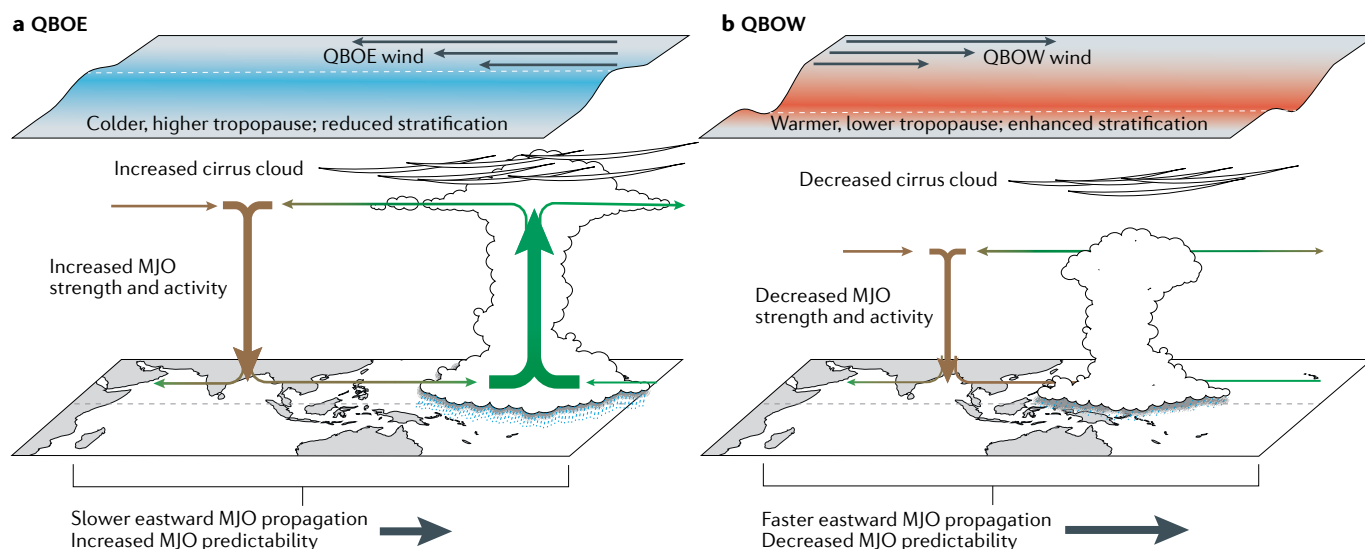


Fig. 5 | **Schematic illustration of the QBO–MJO connection.** Mechanisms and impacts of quasi-biennial oscillation (QBO)–Madden–Julian oscillation (MJO) coupling during QBO easterly (QBOE; panel **a**) and QBO westerly (QBOW; panel **b**) winds.

However, several aspects of the temperature stratification hypothesis are still tenuous or disputed. QBO temperature anomalies are typically small at the tropopause, with an average amplitude of less than 0.5 K at 100 hPa in winter. It is also not clear whether MJO convection reaches deep enough into the tropopause region frequently enough to be strongly affected by QBO temperature changes⁷³. Furthermore, there is also disagreement as to whether the temperature mechanism explanations for seasonality and emergence of the QBO–MJO connection posited previously are correct and supported by observed evidence³⁶. For example, QBO temperature anomalies were strong during the period from 1958 to 1978 when the QBO–MJO link was weak, but weaker during 1978–1998 when the QBO–MJO link emerged^{36,68}. Thus, it is difficult to attribute the emergence of the QBO–MJO link solely to QBO temperature changes. In addition, a climate model with a reasonably simulated MJO and a stratosphere forced towards observations indicated that, even when QBO temperature signals are well represented, the model still lacks any QBO–MJO connection⁴⁰. Errors in model simulation of QBO temperature anomalies are, therefore, not the only reason for models failing to capture the QBO–MJO relationship⁴⁰.

QBO effects on high clouds. Since QBO temperature effects alone might not explain the QBO–MJO link, a related hypothesis emerged highlighting the potential importance of cloud–radiative feedbacks, in particular, owing to QBO changes in high cirrus clouds^{27,36,74}. During QBOE winters, cold temperatures around the tropopause favour a ~20–30% increase in cirrus cloud fraction over the Indo-Pacific warm pool compared with QBOW²⁷. These clouds radiatively cool the lower stratosphere and warm the troposphere^{75–77}, which might further destabilize the upper troposphere to facilitate deep convection in QBOE. QBOW phases have the opposite

effects: reduced upper-level cirrus clouds anomalously warming the lower stratosphere and cooling the troposphere could stabilize the atmosphere and reduce MJO-related deep convection. Cirrus cloud changes could also affect the MJO through other pathways, for example, changing the diurnal cycle of convection⁷⁴ and influencing MJO organization^{74,78}. Alternatively, they might cause other changes in cloud–radiative feedbacks³⁶, potentially altering large-scale ascent and precipitation associated with the MJO⁶⁵, increasing its amplitude.

Cloud–radiative feedbacks are thought to be an important driving mechanism for the MJO itself^{79–86}, and the MJO influences cirrus clouds during its life cycle^{36,62,63}. Thus, any QBO-related changes in high clouds and cloud–radiative feedbacks — which strengthen 6% from QBOW to QBOE, although not statistically significant³⁶ — might qualitatively support and partly explain the uniquely strong link between the QBO and MJO-related convection. The sensitivity of cirrus clouds to the base state in the tropopause region^{87,88} could contribute to the wintertime seasonality. Moreover, the unique vertical structure of the MJO makes it more sensitive to cloud–radiative feedbacks compared with other modes of organized convection³⁶, and well-documented deficiencies in simulating clouds with parameterized convection⁸⁹ could explain the absence of a QBO–MJO connection in models. However, many of these hypotheses regarding the role of clouds remain relatively untested in models and observations, and clear, quantitative conclusions regarding the viability of a cloud-related mechanism are still lacking.

QBO wind anomalies and other mechanisms. QBO wind anomalies have also been proposed as a potential influence on the MJO and its connection to the QBO. An early hypothesis, for example, contended that QBO-related changes in vertical wind shear near the tropopause might shear off cloud tops, impacting

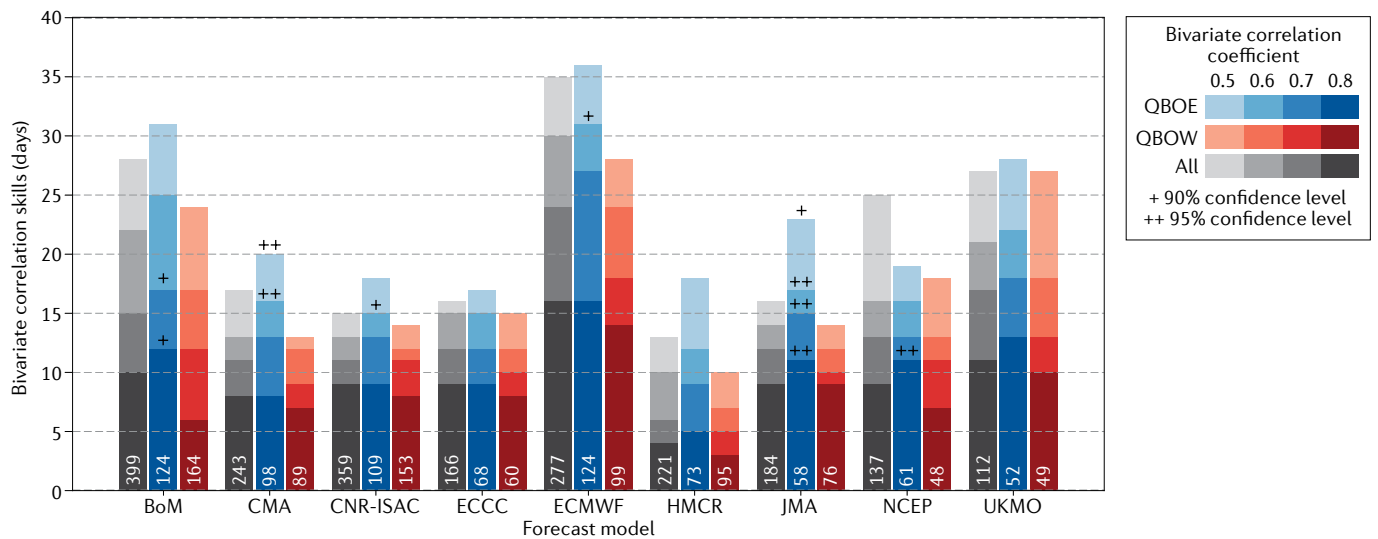


Fig. 6 | MJO prediction skill during different phases of the QBO. Deterministic prediction skill of winter Madden–Julian oscillation (MJO) forecasts, as represented by the bivariate correlation coefficient⁹⁷, for all initialization dates (black shades), those during quasi-biennial oscillation (QBO) easterly (QBOE; blue shades) and those during QBO westerly (QBOW; red shades). Only models with more than 100 initialization dates were used. Single and double plus signs indicate 90% and 95% confidence levels, respectively, as determined using a bootstrap method. All models show higher MJO prediction skill in QBOE winters than in QBOW winters, although the skill differences are statistically insignificant in some models. Adapted from REF.⁵⁷, Springer Nature Limited.

convective systems by limiting their ability to grow deep or organize coherently^{32,33}. However, observational and modelling evidence provides little support for this theory as a mechanism explaining the QBO–MJO connection^{33,61}: no observational evidence has shown that QBO winds shear off MJO convection, and a modelling experiment imposing various QBO-like wind shear signals found no changes in the strength of MJO-related convection⁶¹.

A further hypothesis discussed in the literature is that QBO wind anomalies affect the MJO by altering the behaviour of atmospheric waves excited by convection⁹⁰. Modulation of vertically propagating waves by vertical shear in the equatorial stratosphere is central to the physical mechanism of the QBO^{14–16}. It is possible that changes to wave breaking, propagation, reflection and/or attenuation in the tropics might affect the MJO. For example, QBO-like wind shear in the lower stratosphere has been shown to alter small-scale gravity wave reflection back into the troposphere in a high-resolution model⁹⁰. These gravity waves influence organized convection in the model and favoured organized systems moving in the same direction as the stratospheric wind shear⁹⁰. Other idealized, cloud-permitting model experiments in which QBO-like oscillations are generated internally have also illustrated impacts on organized convection owing to wind shear, though not always shear in the stratosphere^{91,92}. However, there have been few investigations of these mechanisms specifically in relation to the QBO–MJO link or which explain why the MJO is affected more than other organized convective modes.

Other mechanisms might also explain the QBO–MJO link and additional hypotheses are still being formulated. These include, for example, the influence of ozone feedbacks^{38,93} or modulation of the MJO via

QBO-related changes in the extratropics^{94–96}. To date, however, no proposed mechanism explains all aspects of the observed QBO–MJO coupling or accounts for why numerical models struggle to show a relationship.

Global impacts

The QBO–MJO connection has far-reaching global impacts and is highly relevant to society through the ways in which it modulates prediction skill on S2S timescales.

Impacts on S2S prediction. A QBO modulation of MJO prediction skill was recognized shortly after the rediscovery of the QBO–MJO link²⁸. Specifically, S2S global forecast models exhibit improved MJO prediction skill during QBOE relative to QBOW^{43,57}. Across models, the change in skill ranges from 5 to 10 days, with an average of 1 week (FIG. 6). Considering the maximum lead time of skilful MJO prediction is, at most, on the order of 4–5 weeks⁹⁷, this 1-week modulation by the QBO represents an ~25% improvement in MJO prediction skill. However, it is unclear how statistically significant these changes are. In at least one database of subseasonal forecast model experiments⁹⁸, the QBO-dependent MJO prediction skill change is not significant, especially in forecasts of more than 2 weeks⁵⁹.

The ability of a forecast model to correctly simulate the QBO does not have a strong impact on the change in MJO prediction skill^{43,59}, indicating that the model stratosphere might not be the main driver of changes in skill. Instead, part of the improved MJO prediction skill in QBOE versus QBOW arises from an increase in the number of strong MJO events during QBOE^{28,43,57}, as strong MJO events are generally more predictable than weak ones⁹⁷. Still, changes in MJO strength alone do

not entirely explain the QBO effect on MJO prediction skill^{28,43,57}; subtle differences in the models' tropospheric initial conditions between QBOE and QBOW (which are not well understood), as well as the increased consistency of observed MJO propagation during QBOE winters, also contribute to prediction skill changes⁴³.

The ramifications of the QBO–MJO connection have further importance for S2S predictions outside the tropics, specifically in the mid-latitudes through atmospheric teleconnections^{99–102}. These include predictions of mid-latitude geopotential height anomalies¹⁰¹, local precipitation¹⁰² and high-impact weather features such as atmospheric rivers¹⁰⁰. In the latter case, depending on the MJO phase and lead time, the inclusion of the QBO as a predictor in a statistical model sometimes doubled the skill in predicting atmospheric river activity in British Columbia and California compared with forecasts only using the MJO¹⁰⁰. Similarly, including the QBO as a predictor of anomalous S2S rainfall in the USA increased the frequency with which skilful wintertime forecasts could be made over more than 80% of the USA and, in certain seasons and regions, increased the average success rate per forecast by more than 2% per opportunity¹⁰².

However, including the QBO as a predictor does not always improve mid-latitude prediction skill, nor does it always change skill in the manner expected. In the above-mentioned empirical S2S prediction model of US rainfall, for example, while including the QBO as a predictor improved model skill where it was high, it decreased performance in some cases where the model skill was modest or poor¹⁰². Furthermore, dynamical forecast models have shown that, depending on the region of interest, both QBOE and QBOW winters can lead to stronger MJO impacts on prediction skill of geopotential height in the mid-latitudes than when QBO winds are weak¹⁰¹. The sensitivity of these results to particular regions, QBO phase, MJO phase and forecast lead times makes straightforward interpretation of how the QBO modulates S2S prediction skill difficult. Care should also be taken when interpreting dynamical models' behaviour in different QBO phases: the uncertainty regarding why these models often fail to capture a strong QBO–MJO link suggests that the models might miss relevant processes. Still, in certain cases and applications, there is strong evidence suggesting that S2S prediction can be improved by considering the QBO state.

Impacts on teleconnections. In addition to changing MJO and S2S predictability, the QBO–MJO link also exerts a global influence through QBO-related mediation of MJO teleconnections. For example, during QBOE winters, the MJO-induced atmospheric Rossby wave train — a large-scale pattern of alternating positive and negative pressure anomalies that impacts weather and climate globally — becomes more pronounced and better organized than during QBOW winters^{27,103}. Perhaps, in part through changes to this wave train, MJO-related changes to the North Pacific storm track also show sensitivity to the QBO, becoming more longitudinally elongated and intense in QBOE than in QBOW¹⁰⁴. Throughout the Northern Hemisphere extratropics more generally, upper-tropospheric geopotential height

variability is twice as strongly linked to the MJO during QBOE compared with QBOW¹⁰⁵. QBO modulation of MJO teleconnections also has strong impacts around East Asia: circulation anomalies associated with the MJO in this region are stronger in QBOE²⁷, and, depending on MJO phase, MJO-related precipitation anomalies show a 35–70% difference between QBOE and QBOW¹⁰⁶.

Yet, like the QBO's impact on S2S prediction skill, it is not always the case that MJO teleconnections are stronger in QBOE than in QBOW. For example, the MJO connection to upper-tropospheric geopotential height variability in certain regions, like north-western North America, is stronger during QBOW winters¹⁰⁵. Furthermore, the amplitude of the North Atlantic Oscillation's response to strong MJO activity in the Indian Ocean is ~50% stronger in QBOW than in QBOE¹⁰⁷. While there is also some indication that the QBO might modulate the MJO's connection to the Arctic Oscillation, the nature of that link varies depending on the phase of the MJO and the QBO¹⁰⁸.

Overall, the varied nature of QBO impacts on different MJO teleconnections, and how that link depends on the MJO phase, makes it difficult to disentangle the mechanism explaining how the QBO modulates MJO teleconnections. It is likely that a combination of multiple factors is at play, depending on the particular teleconnection being considered: the QBO impact could stem from QBO-induced changes to the MJO itself (such as changes in the strength of the MJO²⁷ or how regularly it propagates¹⁰⁵), QBO changes to background state (such as the subtropical jet)¹⁰⁵ or a combination of both.

Summary and future perspectives

The QBO–MJO link is a feature of the present climate system that is observationally nuanced and theoretically stimulating, pushing the limits of current modelling capabilities and possessing relevance to society. The key aspect of the QBO–MJO link, observed in many data sets and via many analysis methods, is that, when QBO winds in the lower stratosphere are easterly, the boreal winter MJO is much stronger and more active^{26,27,36,42,45–47} (FIGS 2,3). Accordingly, the MJO is more predictable by ~1 week during QBOE phases^{28,43,57} (FIG. 6). In seasons aside from boreal winter, no strong QBO–MJO connection is apparent, nor does it appear that these two phenomena were linked prior to approximately the 1980s^{36,44} (FIG. 2b). Despite the strength of the observed QBO–MJO relationship, numerical models show a weak or absent connection^{37–40} (FIG. 4). Mechanistic explanations for the coupling have largely centred on QBO temperature-mediated stability changes in the upper troposphere, but other mechanisms involving cloud-radiative feedbacks, QBO wind anomalies and changes to wave propagation have also been proposed, and, at present, it is not clear what is driving the relationship. Further research is unquestionably vital in continuing to advance understanding on this topic.

Future observational work. A central focus of future observational research should be more detailed examination of the physical processes driving the QBO–MJO connection. Such work would have clear utility in ruling

certain hypotheses out, supporting others and setting clear benchmarks against which numerical models could be assessed. In particular, a coherent physical mechanism for the QBO–MJO link should explain its mysterious aspects, especially its seasonality and why only the MJO is strongly affected.

Of the various physical mechanisms, more research on clouds and cloud-radiative effects, especially associated with high cirrus clouds, would be particularly useful. Examining the radiative properties of high clouds in relation to the MJO, and how they vary as the MJO and the QBO evolve, would provide more evidence of how much these clouds can impact the MJO. The causality of changes in clouds should be kept in mind, as it is possible that the increase in high clouds during QBOE winters could arise from stronger MJO events rather than cause changes to the MJO, though determining causality from observations is challenging and might require modelling experiments.

Regarding more dynamically driven mechanisms, more work should also be done to identify if and how the QBO controls wave propagation across the tropical tropopause, and how this affects the tropospheric circulation, tropical convection and the MJO in particular. For example, spectral analyses of wave momentum fluxes^{109,110} in QBOE versus QBOW winters could illuminate wave-mean flow interactions or wave modulations associated with the QBO–MJO link. QBO wind anomalies might affect the vertical propagation of waves into the stratosphere, which might subsequently reflect, refract or feed back on the MJO. Work that convincingly connects idealized modelling results on these types of dynamical impacts on organized convection^{90–92} to the observed MJO would be highly insightful. Yet, a potential challenge in this regard is the lack of long-term, high-vertical-resolution observations needed to study vertically propagating small-scale waves, which might not be captured in reanalyses.

Observational analyses could further address why the QBO affects the MJO but not other modes of organized convection and continue to explore whether the QBO–MJO link truly did not exist prior to the 1980s. Given the sparsity of observations over the pre-1980 period, examining QBO and MJO signals in other data sets aside from twentieth century reanalyses might impact the results; for example, research could use sounding data to track the behaviour of the QBO and the MJO and investigate whether any QBO–MJO link is observed.

The role of other tropical phenomena in driving or modulating the QBO–MJO link, in particular, ENSO, should also be explored more. While the QBO–MJO link is apparent even when strong ENSO seasons are excluded^{26,27,36,45,46}, the role of ENSO in influencing or modulating the QBO–MJO connection should be studied further. A limited observational data span could make such analysis difficult, necessitating either novel analysis techniques or the use of numerical model experiments.

Future modelling work. As models struggle to capture the QBO–MJO link, an emphasis should be placed on modelling efforts. First and foremost, finding any model

configuration that convincingly reproduces a strong QBO–MJO connection would represent a major step forward on this problem.

Analysis of why models fail to show a QBO–MJO link has largely highlighted deficiencies in simulating the QBO, especially QBO temperature anomalies in the lower stratosphere. This focus is logical, given the attention on the temperature mechanism, but it appears that even correcting QBO wind and temperature biases by nudging a model's stratosphere towards observations does not improve the QBO–MJO link in the model⁴⁰. Attention might be focused, therefore, on biases in simulating the MJO, in particular, deficiencies in models' representations of the MJO's vertical structure and its strength and propagation⁵¹. The absence of a QBO–MJO connection in models should provide further motivation to improve MJO simulation, perhaps with more focus on convective and dynamical processes in the upper troposphere. Other upper-tropospheric or lower-stratospheric biases in models could further be examined, including chemical, cloud and small-scale wave processes that could be relevant directly to the QBO–MJO link, or contribute to model biases in other fields around the tropopause, such as temperature.

Another technical modelling issue that might be important in capturing the QBO–MJO link is the resolution of climate models and their need to resort to parameterizations. Cloud-permitting models have shown somewhat promising results compared with models with parameterized convection^{60,61}. A cloud-permitting model with a weaker-than-observed QBO–MJO connection had no QBO–MJO link when experiments were repeated at a coarser resolution with a cumulus parameterization⁶⁰. Such work suggests that high resolution might be necessary to faithfully represent convective processes and their interaction with the QBO. It is also possible that low model resolution might impact the ability of models to properly capture small-scale gravity waves and any subsequent influence they have on organized convection^{90–92} or the MJO.

A challenge in such high-resolution modelling is the need for multi-year simulations required to capture several QBO cycles. However, this computational issue might be avoided either through modelling case studies of particular MJO events⁶⁰ or through utilizing cloud-permitting models in more idealized configurations, like with imposed QBO states^{60,61,65}, or with self-sustaining QBO-like oscillations^{91,92}. A third approach could utilize super-parameterized climate models, which embed cloud-permitting models within traditional climate model grid cells⁸⁹. If, ultimately, model resolution is central to the QBO–MJO connection, it is likely that the lessons learned from this research will guide improvements to existing convective, gravity-wave or other parameterization schemes. It also might illuminate processes important to simulating the MJO more generally.

If a model can be found that convincingly demonstrates a QBO–MJO connection like that observed, modelling work should next focus on understanding the mechanisms of the QBO–MJO link. Depending on the modelling framework, mechanism denial

experiments could isolate certain aspects of the QBO while disabling others or holding them fixed⁶¹. Work could also look at how changes to the background climate affect the QBO–MJO link, for example, examining how the QBO–MJO link changes under global warming. Another advantage of models is the ability to run many experiments over long time periods, so that the statistics of the QBO–MJO link, like any ENSO influence or decadal variability, could be examined more.

Future S2S prediction work. Given the apparent utility in using both the QBO and the MJO to make skillful S2S predictions, leveraging the QBO–MJO link to improve S2S forecasts should continue to be explored. To the extent possible, untangling whether QBO-related changes in S2S predictability are due to modulations of the MJO or to the background state should be a priority. Such research could also aid in understanding the physics behind if and how the QBO alters the wide array of MJO teleconnections.

Understanding the sources of improved MJO prediction in QBOE versus QBOW winters could also improve operational centres’ ability to make reliable forecasts. For those forecast models that do show prediction skill differences in QBOE and QBOW winters, work should be carried out to better understand how forecast uncertainty differs depending on the QBO phase, and to determine how best to leverage changes in prediction skill or predictability. Building on existing experiments⁵⁶, a coordinated multi-model experiment

could be carried out to better understand the respective impact of the model initial conditions versus the direct downward impact of the QBO on the model MJO during a forecast. For example, coordinated experiments could set tropospheric initial conditions fixed and alter the stratosphere in various ways, perhaps including nudging to observations, climatology or idealized profiles to ensure that stratospheric signals are robustly represented.

If representation of stratospheric processes is key for improved MJO prediction, modelling centres should put more effort into improving the stratosphere in forecast models. For example, while many forecast models are initialized with observed QBO winds, the amplitude of the QBO winds currently cannot be intrinsically maintained beyond 2 weeks, and tends to degrade towards weak tropical stratospheric easterlies^{111,112}. However, if, instead, the initial conditions matter more than the QBO’s direct impact, effort could be put into improving MJO simulation itself: state-of-the-art S2S forecast models still struggle to keep the MJO signal strong for longer than 10 days, especially when the MJO propagates through the Maritime Continent⁹⁷. These coordinated efforts might also help resolve the inconsistency in the literature regarding whether MJO prediction skill changes due to the QBO are significant or not, via more unified diagnostics and focused experiments with a large sample size.

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- Sobel, A. H. *Storm Surge: Hurricane Sandy, Our Changing Climate, and Extreme Weather of the Past and Future* (Harper Wave, 2014).
- Hand, E. The storm king. *Science* **350**, 22–25 (2015).
- Hitchman, M. H., Yoden, S., Haynes, P. H., Kumar, V. & Tegtmeier, S. An observational history of the direct influence of the stratospheric quasi-biennial oscillation on the tropical and subtropical upper troposphere and lower stratosphere. *J. Meteorol. Soc. Jpn* **99**, 239–267 (2021).
- Yanai, M. & Maruyama, T. Stratospheric wave disturbances propagating over the equatorial Pacific. *J. Meteorol. Soc. Jpn* **44**, 291–294 (1966).
- Wallace, J. M. & Gousky, V. E. Observational evidence of Kelvin waves in the tropical stratosphere. *J. Atmos. Sci.* **25**, 900–907 (1968).
- Maruyama, Taketo The quasi-biennial oscillation (QBO) and equatorial waves. *Pap. Meteorol. Geophys.* **48**, 1–17 (1997).
- Ebdon, R. & Veryard, R. Fluctuations in equatorial stratospheric winds. *Nature* **189**, 791–793 (1961).
- Reed, R. J., Campbell, W. J., Rasmussen, L. A. & Rogers, D. G. Evidence of a downward-propagating, annual wind reversal in the equatorial stratosphere. *J. Geophys. Res.* **66**, 813–818 (1961).
- Baldwin, M. P. et al. The quasi-biennial oscillation. *Rev. Geophys.* **39**, 179–229 (2001).
- Gray, L. J. et al. Surface impacts of the quasi-biennial oscillation. *Atmos. Chem. Phys.* **18**, 8227–8247 (2018).
- Osprey, S. M. et al. An unexpected disruption of the atmospheric quasi-biennial oscillation. *Science* **353**, 1424–1427 (2016).
- Newman, P. A., Coy, L., Pawson, S. & Lait, L. R. The anomalous change in the QBO in 2015–2016. *Geophys. Res. Lett.* **43**, 8791–8797 (2016).
- Hamilton, K., Osprey, S. & Butchart, N. Modeling the stratosphere’s “heartbeat”. *Eos* <https://doi.org/10.1029/2015EO032301> (2015).
- Lindzen, R. S. & Holton, J. R. A theory of the quasi-biennial oscillation. *J. Atmos. Sci.* **25**, 1095–1107 (1968).
- Holton, J. R. & Lindzen, R. S. An updated theory for the quasi-biennial cycle of the tropical stratosphere. *J. Atmos. Sci.* **29**, 1076–1080 (1972).
- Plumb, R. A. & Bell, R. C. A model of the quasi-biennial oscillation on an equatorial beta-plane. *Q. J. R. Meteorol. Soc.* **108**, 335–352 (1982).
- Madden, R. A. & Julian, P. R. Detection of a 40–50-day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.* **28**, 702–708 (1971).
- Madden, R. A. & Julian, P. R. Description of global-scale circulation cells in the tropics with a 40–50-day period. *J. Atmos. Sci.* **29**, 1109–1123 (1972).
- Zhang, C. Madden-Julian oscillation. *Rev. Geophys.* **43**, RG2003 (2005).
- Zhang, C. & Dong, M. Seasonality of the Madden-Julian oscillation. *J. Clim.* **17**, 3169–3180 (2004).
- Hendon, H. H., Zhang, C. & Glick, J. Interannual variation of the Madden-Julian oscillation during austral summer. *J. Clim.* **12**, 2538–2550 (1999).
- Hendon, H. H. & Salby, M. L. The life cycle of the Madden-Julian oscillation. *J. Atmos. Sci.* **51**, 2225–2237 (1994).
- Zhang, C. Madden-Julian oscillation: Bridging weather and climate. *Bull. Am. Meteorol. Soc.* **94**, 1849–1870 (2013).
- Vitart, F. et al. The subseasonal to seasonal (S2S) prediction project database. *Bull. Am. Meteorol. Soc.* **98**, 163–173 (2017).
- Meeth, G. A. et al. Initialized Earth System prediction from subseasonal to decadal timescales. *Nat. Rev. Earth Environ.* **2**, 340–357 (2021).
- Yoo, C. & Son, S.-W. Modulation of the boreal wintertime Madden-Julian oscillation by the stratospheric quasi-biennial oscillation. *Geophys. Res. Lett.* **43**, 1392–1398 (2016).
- Son, S.-W., Lim, Y., Yoo, C., Hendon, H. H. & Kim, J. Stratospheric control of the Madden-Julian oscillation. *J. Clim.* **30**, 1909–1922 (2017).
- Marshall, A. G., Hendon, H. H., Son, S.-W. & Lim, Y. Impact of the quasi-biennial oscillation on predictability of the Madden-Julian oscillation. *Clim. Dyn.* **49**, 1365–1377 (2017).
- Zhang, C., Adames, Á. F., Khouider, B., Wang, B. & Yang, D. Four theories of the Madden-Julian oscillation. *Rev. Geophys.* **58**, e2019RG000685 (2020).
- Christiansen, B., Yang, S. & Madsen, M. S. Do strong warm ENSO events control the phase of the stratospheric QBO? *Geophys. Res. Lett.* **43**, 10489–10495 (2016).
- Camargo, S. J. & Sobel, A. H. Revisiting the influence of the quasi-biennial oscillation on tropical cyclone activity. *J. Clim.* **23**, 5810–5825 (2010).
- Gray, W. M., Sheaffer, J. D. & Knaff, J. A. Influence of the stratospheric QBO on ENSO variability. *J. Meteorol. Soc. Jpn* **70**, 975–995 (1992).
- Collimore, C. C., Martin, D. W., Hitchman, M. H., Huesmann, A. & Waliser, D. E. On the relationship between the QBO and tropical deep convection. *J. Clim.* **16**, 2552–2568 (2003).
- Liess, S. & Geller, M. A. On the relationship between QBO and distribution of tropical deep convection. *J. Geophys. Res. Atmos.* **117**, D03108 (2012).
- Abhik, S., Hendon, H. H. & Wheeler, M. C. On the sensitivity of convectively coupled equatorial waves to the quasi-biennial oscillation. *J. Clim.* **32**, 5833–5847 (2019).
- Sakaeda, N., Dias, J. & Kiladis, G. N. The unique characteristics and potential mechanisms of the MJO-QBO relationship. *J. Geophys. Res. Atmos.* **125**, e2020JD033196 (2020).
- Lee, J. C. & Klingaman, N. P. The effect of the quasi-biennial oscillation on the Madden-Julian oscillation in the Met Office Unified Model Global Ocean Mixed Layer configuration. *Atmos. Sci. Lett.* **19**, e816 (2018).
- Lim, Y. & Son, S.-W. QBO-MJO connection in CMIP5 models. *J. Geophys. Res. Atmos.* **125**, e2019JD032157 (2020).
- Kim, H., Caron, J. M., Richter, J. H. & Simpson, I. R. The lack of QBO-MJO connection in CMIP6 models. *Geophys. Res. Lett.* **47**, e2020GL087295 (2020).
- Martin, Z., Orbe, C., Wang, S. & Sobel, A. H. The MJO-QBO relationship in a GCM with stratospheric nudging. *J. Clim.* **34**, 4603–4624 (2021).
- Kuma, K.-I. A quasi-biennial oscillation in the intensity of the intra-seasonal oscillation. *Int. J. Climatol.* **10**, 263–278 (1990).
- Densmore, C. R., Sanabia, E. R. & Barrett, B. S. QBO influence on MJO amplitude over the Maritime Continent: Physical mechanisms and seasonality. *Mon. Weather Rev.* **147**, 389–406 (2019).

43. Wang, S., Tippett, M. K., Sobel, A. H., Martin, Z. K. & Vitart, F. Impact of the QBO on prediction and predictability of the MJO convection. *J. Geophys. Res. Atmos.* **124**, 11766–11782 (2019).
44. Klotzbach, P. et al. On the emerging relationship between the stratospheric Quasi-Biennial oscillation and the Madden-Julian oscillation. *Sci. Rep.* **9**, 2981 (2019).
45. Zhang, C. & Zhang, B. QBO-MJO connection. *J. Geophys. Res. Atmos.* **123**, 2957–2967 (2018).
46. Nishimoto, E. & Yoden, S. Influence of the stratospheric quasi-biennial oscillation on the Madden-Julian oscillation during austral summer. *J. Atmos. Sci.* **74**, 1105–1125 (2017).
47. Hood, L. L. QBO/solar modulation of the boreal winter Madden-Julian oscillation: A prediction for the coming solar minimum. *Geophys. Res. Lett.* **44**, 3849–3857 (2017).
48. Kiladis, G. N., Wheeler, M. C., Haertel, P. T., Straub, K. H. & Roundy, P. E. Convectively coupled equatorial waves. *Rev. Geophys.* **47**, RG2003 (2009).
49. Gray, W. M. Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Weather Rev.* **112**, 1649–1668 (1984).
50. Richter, J. et al. Progress in simulating the quasi-biennial oscillation in CMIP models. *J. Geophys. Res. Atmos.* **125**, e2019JD032362 (2020).
51. Ahn, M.-S. et al. MJO propagation across the Maritime Continent: Are CMIP6 models better than CMIP5 models? *Geophys. Res. Lett.* **47**, e2020GL087250 (2020).
52. Giorgetta, M., Manzini, E., Roeckner, E., Esch, M. & Bengtsson, L. Climatology and forcing of the quasi-biennial oscillation in the MAECHAM5 model. *J. Clim.* **19**, 3882–3901 (2006).
53. Charlton-Perez, A. J. et al. On the lack of stratospheric dynamical variability in low-top versions of the CMIP5 models. *J. Geophys. Res. Atmos.* **118**, 2494–2505 (2013).
54. Slingo, J. et al. Intraseasonal oscillations in 15 atmospheric general circulation models: Results from an AMIP diagnostic subproject. *Clim. Dyn.* **12**, 325–357 (1996).
55. Kim, D., Sobel, A. H., Maloney, E. D., Frierson, D. M. W. & Kang, I.-S. A systematic relationship between intraseasonal variability and mean state bias in AGCM simulations. *J. Clim.* **24**, 5506–5520 (2011).
56. Martin, Z., Vitart, F., Wang, S. & Sobel, A. The impact of the stratosphere on the MJO in a forecast model. *J. Geophys. Res. Atmos.* **125**, e2019JD032106 (2020).
57. Lim, Y., Son, S.-W., Marshall, A. G., Hendon, H. H. & Seo, K.-H. Influence of the QBO on MJO prediction skill in the subseasonal-to-seasonal prediction models. *Clim. Dyn.* **53**, 1681–1695 (2019).
58. Abhik, S. & Hendon, H. H. Influence of the QBO on the MJO during coupled model multiweek forecasts. *Geophys. Res. Lett.* **46**, 9213–9221 (2019).
59. Kim, H., Richter, J. H. & Martin, Z. Insignificant QBO-MJO prediction skill relationship in the SubX and S2S subseasonal reforecasts. *J. Geophys. Res. Atmos.* **124**, 12655–12666 (2019).
60. Back, S.-Y., Han, J.-Y. & Son, S.-W. Modeling evidence of QBO-MJO connection: A case study. *Geophys. Res. Lett.* **47**, e2020GL089480 (2020).
61. Martin, Z., Wang, S., Nie, J. & Sobel, A. The impact of the QBO on MJO convection in cloud-resolving simulations. *J. Atmos. Sci.* **76**, 669–688 (2019).
62. Virts, K. S. & Wallace, J. M. Observations of temperature, wind, cirrus, and trace gases in the tropical tropopause transition layer during the MJO. *J. Atmos. Sci.* **71**, 1143–1157 (2014).
63. Del Genio, A. D., Chen, Y., Kim, D. & Yao, M. The MJO transition from shallow to deep convection in CloudSat/CALIPSO data and GISS GCM simulations. *J. Clim.* **25**, 3755–3770 (2012).
64. Hendon, H. H. & Abhik, S. Differences in vertical structure of the Madden-Julian Oscillation associated with the quasi-biennial oscillation. *Geophys. Res. Lett.* **45**, 4419–4428 (2018).
65. Nie, J. & Sobel, A. H. Responses of tropical deep convection to the QBO: Cloud-resolving simulations. *J. Atmos. Sci.* **72**, 3625–3638 (2015).
66. Giorgetta, M. A., Bengtsson, L. & Arpe, K. An investigation of QBO signals in the east Asian and Indian monsoon in GCM experiments. *Clim. Dyn.* **15**, 435–450 (1999).
67. Madden, R. A. Seasonal variations of the 40–50 day oscillation in the tropics. *J. Atmos. Sci.* **43**, 24, 3138–3158 (1986).
68. Martin, Z., Sobel, A., Butler, A. & Wang, S. Variability in QBO temperature anomalies on annual and decadal timescales. *J. Clim.* **34**, 589–605 (2021).
69. Tegtmeier, S. et al. Zonal asymmetry of the QBO temperature signal in the tropical tropopause region. *Geophys. Res. Lett.* **47**, e2020GL089533 (2020).
70. Reid, G. C. & Gage, K. S. On the annual variation of height of the tropical tropopause. *J. Atmos. Sci.* **38**, 1928–1937 (1981).
71. Yulaeva, E., Holton, J. R. & Wallace, J. M. On the cause of the annual cycle in tropical lower-stratospheric temperatures. *J. Atmos. Sci.* **51**, 169–174 (1994).
72. Aquila, V. et al. Isolating the roles of different forcing agents in global stratospheric temperature changes using model integrations with incrementally added single forcings. *J. Geophys. Res. Atmos.* **121**, 8067–8082 (2016).
73. Gettleman, A. & Forester, P. M. F. A climatology of the tropical tropopause layer. *J. Meteorol. Soc. Jpn* **80**, 911–924 (2002).
74. Sun, L., Wang, H. & Liu, F. Combined effect of the QBO and ENSO on the MJO. *Atmos. Ocean. Sci. Lett.* **12**, 170–176 (2019).
75. Hartmann, D. L., Holton, J. R. & Fu, Q. The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration. *Geophys. Res. Lett.* **28**, 1969–1972 (2001).
76. Yang, Q., Fu, Q. & Hu, Y. Radiative impacts of clouds in the tropical tropopause layer. *J. Geophys. Res. Atmos.* **115**, D00H12 (2010).
77. Hong, Y., Liu, G. & Li, J.-L. Assessing the radiative effects of global ice clouds based on CloudSat and CALIPSO measurements. *J. Clim.* **29**, 7651–7674 (2016).
78. Zhang, C. & Ling, J. Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. *J. Clim.* **30**, 3439–3459 (2017).
79. Raymond, D. J. A new model of the Madden-Julian oscillation. *J. Atmos. Sci.* **58**, 2807–2819 (2001).
80. Sobel, A. & Maloney, E. An idealized semi-empirical framework for modeling the Madden-Julian oscillation. *J. Atmos. Sci.* **69**, 1691–1705 (2012).
81. Sobel, A. & Maloney, E. Moisture modes and the eastward propagation of the MJO. *J. Atmos. Sci.* **70**, 187–192 (2013).
82. Crueger, T. & Stevens, B. The effect of atmospheric radiative heating by clouds on the Madden-Julian Oscillation. *J. Adv. Model. Earth Syst.* **7**, 854–864 (2015).
83. Del Genio, A. D. & Chen, Y. Cloud-radiative driving of the Madden-Julian oscillation as seen by the A-Train. *J. Geophys. Res. Atmos.* **120**, 5344–5356 (2015).
84. Zhang, B., Kramer, R. J. & Soden, B. J. Radiative feedbacks associated with the Madden-Julian oscillation. *J. Clim.* **32**, 7055–7065 (2019).
85. Adames, Á. F. & Kim, D. The MJO as a dispersive, convectively coupled moisture wave: Theory and observations. *J. Atmos. Sci.* **73**, 913–941 (2016).
86. Kim, D., Ahn, M., Kang, I. & Del Genio, A. D. Role of longwave cloud–radiation feedback in the simulation of the Madden-Julian oscillation. *J. Clim.* **28**, 6979–6994 (2015).
87. Davis, S. M., Liang, C. K. & Rosenlof, K. H. Interannual variability of tropical tropopause layer clouds. *Geophys. Res. Lett.* **40**, 2862–2866 (2013).
88. Tseng, H.-H. & Fu, Q. Temperature control of the variability of tropical tropopause layer cirrus clouds. *J. Geophys. Res. Atmos.* **122**, 11062–11075 (2017).
89. Randall, D., Khairoutdinov, M., Arakawa, A. & Grabowski, W. Breaking the cloud parameterization deadlock. *Bull. Am. Meteorol. Soc.* **84**, 1547–1564 (2003).
90. Lane, T. P. Does lower-stratospheric shear influence the mesoscale organization of convection? *Geophys. Res. Lett.* **48**, e2020GL091025 (2021).
91. Bui, H., Nishimoto, E. & Yoden, S. Downward influence of QBO-like oscillation on moist convection in a two-dimensional minimal model framework. *J. Atmos. Sci.* **74**, 3635–3655 (2017).
92. Nishimoto, E., Yoden, S. & Bui, H. Vertical momentum transports associated with moist convection and gravity waves in a minimal model of QBO-like oscillation. *J. Atmos. Sci.* **73**, 2935–2957 (2016).
93. Raphaelidini, B., Teruya, A. S. W., Leite da Silva Dias, P., Massaro, L. & Takahashi, D. Y. Stratospheric ozone and quasi-biennial oscillation (QBO) interaction with the tropical troposphere on intraseasonal and interannual timescales: a normal-mode perspective. *Earth Syst. Dyn.* **12**, 83–101 (2021).
94. Wang, J., Kim, H.-M. & Chang, E. K. M. Interannual modulation of Northern Hemisphere winter storm tracks by the QBO. *Geophys. Res. Lett.* **45**, 2786–2794 (2018).
95. White, I. P., Lu, H., Mitchell, N. J. & Phillips, T. Dynamical response to the QBO in the northern winter stratosphere: Signatures in wave forcing and eddy fluxes of potential vorticity. *J. Atmos. Sci.* **72**, 4487–4507 (2015).
96. Garfinkel, C. I. & Hartmann, D. L. Influence of the quasi-biennial oscillation on the North Pacific and El Niño teleconnections. *J. Geophys. Res.* **115**, D20116 (2010).
97. Kim, H., Vitart, F. & Waliser, D. E. Prediction of the Madden-Julian oscillation: A review. *J. Clim.* **31**, 9425–9443 (2018).
98. Pegion, K. et al. The Subseasonal Experiment (SubX): A multimodel subseasonal prediction experiment. *Bull. Am. Meteorol. Soc.* **100**, 2043–2060 (2019).
99. Baggett, C. F., Barnes, E. A., Maloney, E. D. & Mundhenk, B. D. Advancing atmospheric river forecasts into subseasonal-to-seasonal time scales. *Geophys. Res. Lett.* **44**, 7528–7536 (2017).
100. Mundhenk, B. D., Barnes, E. A., Maloney, E. D. & Baggett, C. F. Skillful empirical subseasonal prediction of landfalling atmospheric river activity using the Madden-Julian oscillation and quasi-biennial oscillation. *NPJ Clim. Atmos. Sci.* **1**, 20177 (2018).
101. Mayer, K. J. & Barnes, E. A. Subseasonal midlatitude prediction skill following quasi-biennial oscillation and Madden-Julian oscillation activity. *Weather Clim. Dyn.* **1**, 247–259 (2020).
102. Nardi, K. M. et al. Skillful all-season S2S prediction of US precipitation using the MJO and QBO. *Weather Forecast.* **35**, 2179–2198 (2020).
103. Hood, L. L., Redman, M. A., Johnson, W. L. & Galarneau, T. J. Jr Stratospheric influences on the MJO-induced Rossby wave train: Effects on intraseasonal climate. *J. Clim.* **33**, 365–389 (2020).
104. Wang, J., Kim, H.-M., Chang, E. K. M. & Son, S.-W. Modulation of the MJO and North Pacific storm track relationship by the QBO. *J. Geophys. Res. Atmos.* **123**, 3976–3992 (2018).
105. Toms, B. A., Barnes, E. A., Maloney, E. D. & van den Heever, S. C. The global teleconnection signature of the Madden-Julian oscillation and its modulation by the quasi-biennial oscillation. *J. Geophys. Res. Atmos.* **125**, e2020JD032653 (2020).
106. Kim, H., Son, S.-W. & Yoo, C. QBO modulation of the MJO-related precipitation in East Asia. *J. Geophys. Res. Atmos.* **125**, e2019JD031929 (2020).
107. Feng, P.-N. & Lin, H. Modulation of the MJO-related teleconnections by the QBO. *J. Geophys. Res. Atmos.* **124**, 12022–12033 (2019).
108. Song, L. & Wu, R. Modulation of the westerly and easterly quasi-biennial oscillation phases on the connection between the Madden-Julian oscillation and the Arctic Oscillation. *Atmosphere* **11**, 175 (2020).
109. Kim, Y.-H. & Chun, H.-Y. Contributions of equatorial wave modes and parameterized gravity waves to the tropical QBO in HadGEM2. *J. Geophys. Res. Atmos.* **120**, 1065–1090 (2015).
110. Pahlavan, H. A., Wallace, J. M., Fu, Q. & Kiladis, G. N. Revisiting the quasi-biennial oscillation as seen in ERA5. Part II: evaluation of waves and wave forcing. *J. Atmos. Sci.* **78**, 693–707 (2021).
111. Butler, A. H. et al. The Climate-system Historical Forecast Project: do stratosphere-resolving models make better seasonal climate predictions in boreal winter? *Q. J. R. Meteorol. Soc.* **142**, 1413–1427 (2016).
112. Garfinkel, C. I. et al. Extratropical atmospheric predictability from the quasi-biennial oscillation in subseasonal forecast models. *J. Geophys. Res. Atmos.* **123**, 7855–7866 (2018).
113. Liebmann, B. & Smith, C. Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Am. Meteorol. Soc.* **77**, 1275–1277 (1996).
114. Hersbach, H. et al. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* **146**, 1999–2049 (2020).
115. Naujokat, B. An update of the observed quasi-biennial oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci.* **43**, 1873–1877 (1986).
116. Kiladis, G. N. et al. A comparison of OLR and circulation-based indices for tracking the MJO. *Mon. Weather Rev.* **142**, 1697–1715 (2014).
117. Wheeler, M. C. & Hendon, H. H. An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Weather Rev.* **132**, 1917–1932 (2004).
118. Kobayashi, S. et al. The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteorol. Soc. Jpn* **93**, 5–48 (2015).

119. Oliver, E. C. J. & Thompson, K. A reconstruction of Madden–Julian oscillation variability from 1905 to 2008. *J. Clim.* **25**, 1996–2019 (2012).
120. Liu, Z., Ostrenga, D., Teng, W. & Kempler, S. Tropical Rainfall Measuring Mission (TRMM) precipitation data and services for research and applications. *Bull. Am. Meteorol. Soc.* **93**, 1317–1325 (2012).

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Author contributions

S.-W. S. conceived the work, created the general outline and coordinated creation of figures. Z.M. wrote the initial draft and coordinated subsequent editing. All authors contributed to writing and editing the manuscript, including especially selection of figures, formulation of schematics and discussion of key points and of future work.

Competing interests

The authors declare no competing interests.

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