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Key Points:
- None of the CMIP6 models simulate the observed QBO-MJO connection
- Simulated MJO activity differences between QBO phases are consistent with sampling noise
- Models have a weaker QBO signal near the tropopause than observed

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The Lack of QBO-MJO Connection in CMIP6 Models

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Abstract Observational analysis has indicated a strong connection between the stratospheric quasi-biennial oscillation (QBO) and tropospheric Madden-Julian oscillation (MJO), with MJO activity being stronger during the easterly phase than the westerly phase of the QBO. We assess the representation of this QBO-MJO connection in 30 models participating in the Coupled Model Intercomparison Project 6. While some models reasonably simulate the QBO during boreal winter, none of them capture a difference in MJO activity between easterly and westerly QBO that is larger than that which would be expected from the random sampling of internal variability. The weak signal of the simulated QBO-MJO connection may be due to the weaker amplitude of the QBO than observed, especially between 100 to 50 hPa. This weaker amplitude in the models is seen both in the QBO-related zonal wind and temperature, the latter of which is thought to be critical for destabilizing tropical convection.

Plain Language Summary The QBO, which is a dominant mode of interannual variability in the tropical lower stratosphere, has been found to strongly modulate the MJO, a dominant mode of subseasonal variability in the tropical troposphere. We show that while half of the CMIP6 climate models simulate the QBO, none of them capture the observed QBO-MJO relationship. The weak signal of the simulated QBO-MJO relationship may be due to the models' weaker amplitude of the QBO-related wind and temperature signal in the lower stratosphere, which is thought to be critical for modulating the MJO.

1. Introduction

Very recently, studies have found convincing observational evidence of stratosphere-troposphere coupling in the tropics on subseasonal timescales, especially during the boreal winter. The stratospheric quasi-biennial oscillation (QBO) has been found to strongly modulate the tropospheric Madden-Julian oscillation (MJO) (hereafter, QBO-MJO connection) (Abhik & Hendon, 2019; Hendon & Abhik, 2018; Marshall et al., 2017; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016; Zhang & Zhang, 2018). The QBO is a quasi-periodic oscillation of the equatorial stratospheric zonal winds between easterlies and westerlies (e.g., Baldwin et al., 2001) with an average period of 28 months, which affects the large-scale atmospheric structure in the tropical lower stratosphere and upper troposphere. In observations, during the QBO easterly phase (QBOE), the boreal winter MJO tends to be stronger, more organized, and propagates further eastward (e.g., Son et al., 2017). This MJO response to QBO forcing is stronger than the MJO response to El Nino Southern Oscillation (ENSO) forcing, especially over the MJO active region (e.g., Son et al., 2017). Klotzbach et al. (2019) have argued that this QBO-MJO connection has only become significant in recent decades (after the 1980s) because of anthropogenically forced cooling trends in the lower stratosphere and warming trends in the upper troposphere acting to reduce the static stability at the equatorial tropopause. However, although the observational evidence is clear, the related mechanism is not settled.

If this observed QBO-MJO connection is robust and can be represented in Global Climate Models (GCMs), it offers the potential for enhanced subseasonal to seasonal prediction in both the tropics and extratropics and more accurate representation of MJO variability in climate simulations. In addition, because the observational record only extends back a few decades, GCMs could be invaluable tools for studying the key mechanism for the QBO-MJO connection. However, the majority of the last generation of GCMs have been suffering from deficiencies in simulating the characteristics of both the QBO (Butchart et al., 2018; Richter et al., 2020; Schenzinger et al., 2017) and MJO (Ahn et al., 2017), making a further investigation of their interaction a challenging task. One model that has been shown to capture both the QBO and MJO is the Met Office Unified Model, but even so, this model was found to not capture the QBO-MJO connection (Lee & Klingaman, 2018). Furthermore, in initialized simulations where a realistic QBO and MJO state can be maintained for a few days after the initialization date, the direct impact of the forecasted QBO on the forecasted MJO was found to be marginal (Kim et al., 2019).

The lack of the QBO-MJO connection in models is thought to be partly due to their coarse vertical resolution, which may be insufficient to resolve the QBO and related wave-mean flow interactions (e.g., Geller et al., 2016; Richter et al., 2014). However, to date, only a small number of individual models have been probed for evidence of a QBO-MJO connection (Lee & Klingaman, 2018). Many of the new state-of-the-art models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) are now capable of simulating an internally generated QBO (Richter et al., 2020). The larger number of CMIP6 models with reasonable QBO provides an unprecedented opportunity to test whether the QBO-MJO connection is simulated. In addition, the large sample size (i.e., multiple ensembles) available from many models allows us to place both the modeled and observed QBO-MJO connections within the context of the magnitude of apparent connections that could arise from the chance sampling of internal variability that is unrelated to the QBO. The reanalysis and CMIP6 model data are introduced in section 2. The simulated QBO-MJO connection is assessed in section 3, followed by a summary in section 4.

2. Data and Methods

The ECMWF Interim Reanalysis product (ERAI; Dee et al., 2011) is used to examine the observed QBO and MJO. Here, the terms "ERAI" and "observations" are used interchangeably. Details of the CMIP6 models and experiment can be found on the CMIP website (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6). A total of 30 models from the CMIP6 historical simulation are analyzed based on the availability of data at the time of writing this manuscript, and they are consistent with the models used in Richter et al. (2020). Available ensemble members are listed in Figure 1. Daily mean outgoing longwave radiation (OLR) and monthly mean zonal wind and temperature output are compared with ERAI. The analysis period is 1979–2014 for both observations and models which are interpolated onto a common 2° longitude and 2° latitude grid using bilinear interpolation.

To evaluate model performance in simulating the QBO, time series of monthly mean zonal-mean zonal wind averaged over 10°S to 10°N (hereafter, [U]) at 50 hPa are compared (Figure 2). A model is considered to simulate the QBO if [U] between 10 and 100 hPa exhibits alternating westerlies and easterlies, and the standard deviation (σ) of the deseasonalized time series is at least 20% of observed at all levels between 10 and 70 hPa (similar to Richter et al., 2020, except they used 5°S to 5°N average to define [U]). This is evaluated with all ensembles, but the existence of the QBO in a model does not depend on ensemble members. According to these criteria, 50% (15 out of 30) of the CMIP6 models internally generate the QBO, a huge progress since CMIP5 in which only five (about 10% of the models) were able to simulate a realistic QBO (Butchart et al., 2018; Schenzinger et al., 2017). However, although there are three times as many models with the QBO in CMIP6 compared to CMIP5, the overall quality of the representation of the QBO in CMIP models has not improved, with the largest deficiency being the too low amplitude at all levels below 20 hPa (Richter et al., 2020). This deficiency in QBO amplitude can be seen from Figure 2: observed easterlies (westerlies) peak at approximately ~ -15 (10) m s^{-1}, while modeled QBO anomalies are often smaller than this. The easterly anomalies in HadGEM3-GC31-LL and UKESM1–0-LL come close to observed values; however, the westerly anomalies in these models are smaller than observed.

The QBO-MJO relationship is further investigated in 13 models with all available ensembles. They are the 15 models with QBO found above, but removing two due to lack of daily OLR data needed for MJO analyses. We only focus on boreal winter, from December to February (DJF), when the QBO-MJO connection has been shown to be significant (e.g., Yoo & Son, 2016). QBOW or QBOE phases are defined as when the DJF-mean [U] anomaly at 50 hPa is larger than +0.5 or less than −0.5 times the standard deviation of [U] across all months for all years. In the 35 winters (1979–2014) examined here, there are 10 QBOE and 16 QBOW years in the observations, with a similar number of QBO years in each model ensemble member (at least 9 QBOE and 11 QBOW years).

3. QBO-MJO Connection in CMIP6

To examine whether CMIP6 models simulate reasonable MJO activity during boreal winter, the MJO activity is calculated in the 13 models, as well as in the observations (Figure 1). The daily OLR data for both ERAI

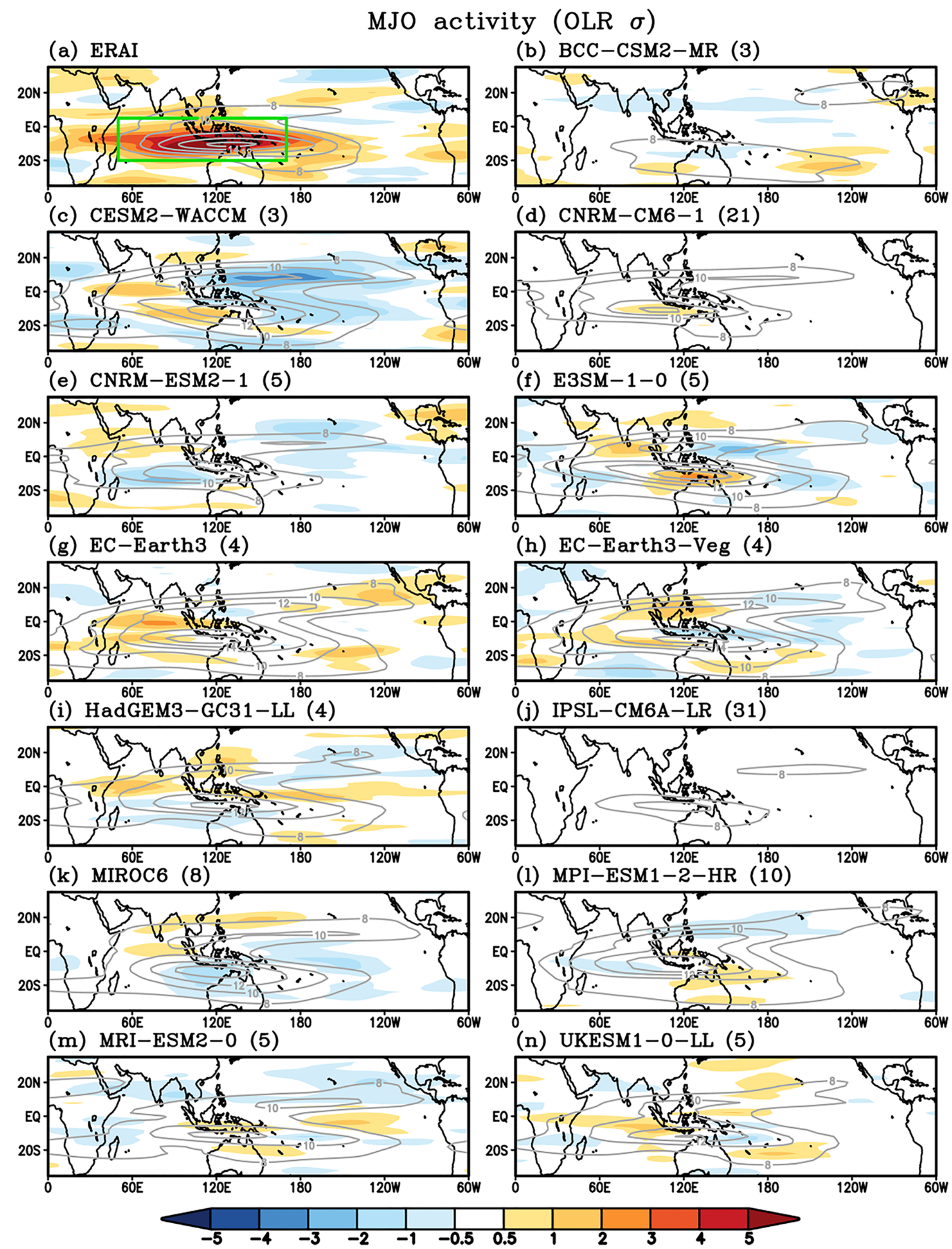

Figure 1. The climatological MJO activity (W m^{-2}, contour) defined as the MJO-filtered OLR standard deviation (OLR σ) during DJF calculated across all years from 1979 to 2014 for (a) ERAI and (b–n) CMIP6 models (ensemble average). The differences in MJO activity between QBOE and QBOW composites are depicted as shading. Number of ensemble members are shown in parenthesis.

and our selected CMIP6 models are filtered following Wheeler and Kiladis (1999). The full time series is detrended (rather than 96-day overlapping segments, as in Wheeler & Kiladis, 1999); 5% of the data are tapered to zero at the ends of the timeseries to minimize spectral leakage. After tapering, a complex fast Fourier transform is performed, and the spectral wavenumber-frequency data are filtered to retain only the eastward propagating coefficients for 20- to 100-day periods and wavenumbers 1–5. This is hereafter referred to as MJO-filtered OLR. Consistent with Yoo and Son (2016), the MJO activity is then defined as the standard deviation of the MJO-filtered OLR across all DJF days that fall into a particular category, for example, all years, QBOE years, or QBOW years. The contours in Figure 1 show the climatological MJO activity, that is, the standard deviation of MJO-filtered OLR calculated using all winter (DJF) from 1979 to 2014. For each model, this measure was calculated for each ensemble member and Figure 1 displays the

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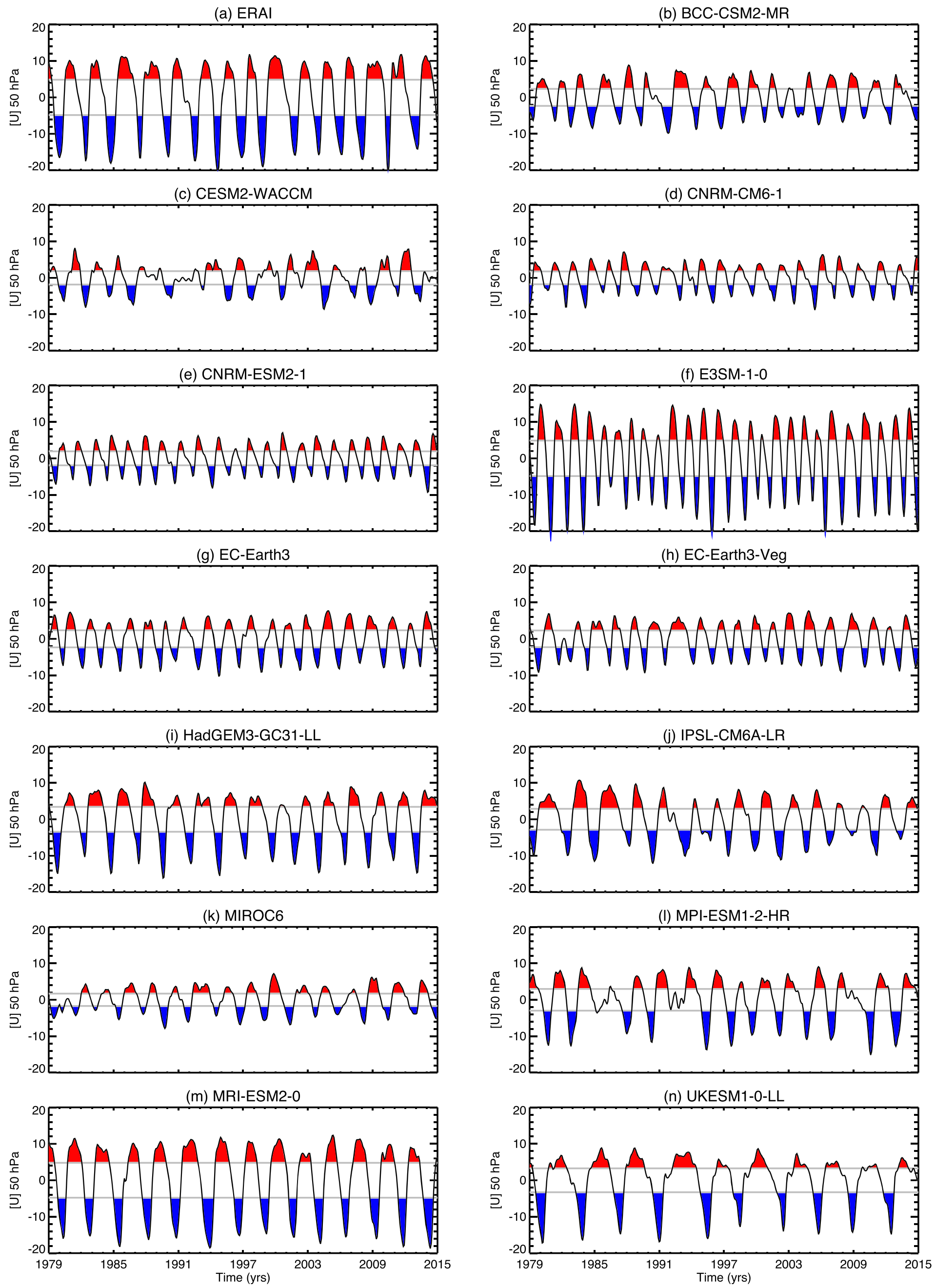

Figure 2. Time series of anomalous monthly mean zonal-mean zonal wind averaged over 10°S to 10°N ([U]) at 50 hPa for (a) ERAI and (b–n) one ensemble member of each CMIP6 model. Gray horizontal lines represent +0.5 (−0.5) standard deviation of [U], that is, the threshold used for the definition of QBO. Periods of QBOW (QBOE) are depicted in red (blue).

ensemble mean. The observations (Figure 1a, contours) exhibit strong MJO activity over the entire Indo-Pacific warm pool with the maximum over the Maritime Continent (50°E to 170°E, 20°S to 5°N, green box in Figure 1a), consistent with previous studies (e.g., Son et al., 2017). The CMIP6 models, overall, reasonably simulate the climatological MJO activity by this measure in the Indo-Pacific region. For better comparison, the climatological MJO activity averaged over the Maritime Continent region in each ensemble is compared (Figure 3a). Although some models simulate too weak (BCC-CSM2-MR and IPSL-CM6A-LR) or too strong (EC-Earth3 and EC-Earth3-Veg) MJO activity, most of them are likely representative of the real world in this measure.

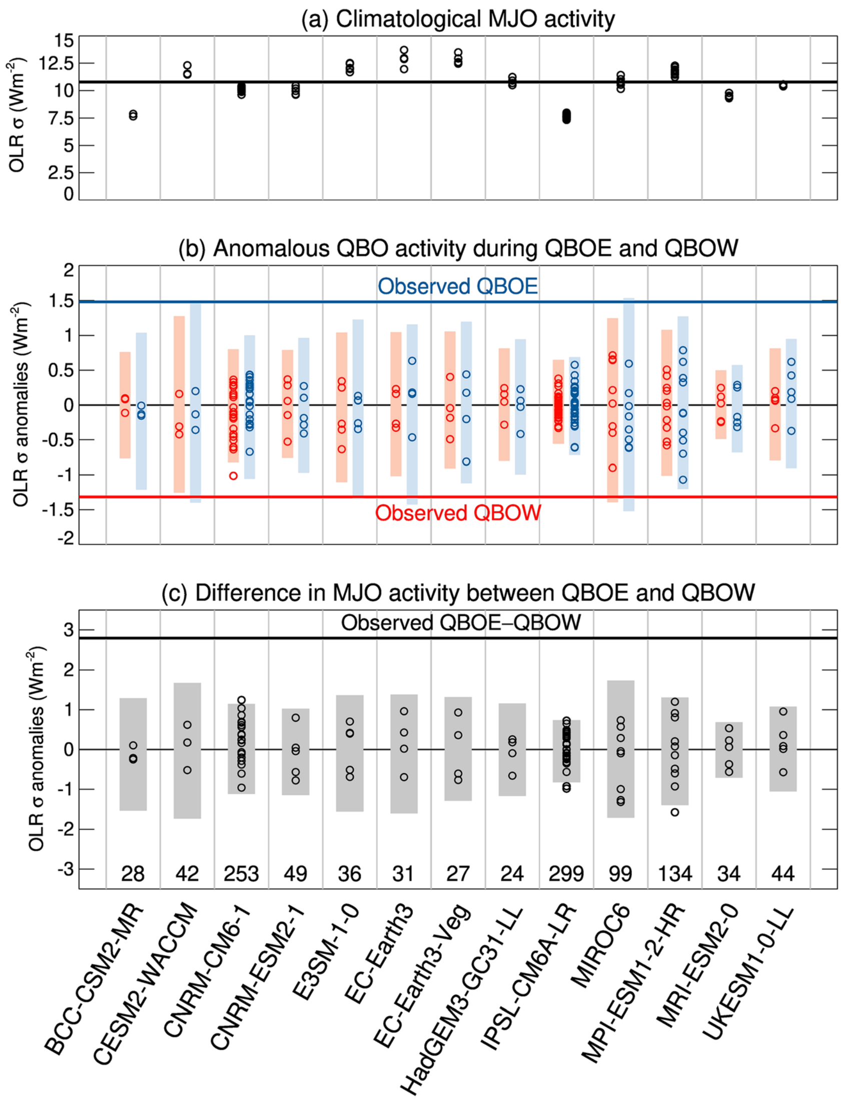

Figure 3. Assessment of QBO influence on the MJO activity averaged over the Maritime continent region (50°E to 170°E, 20°S to 5°N, green box in Figure 1a). (a) MJO activity calculated using all years for each historical ensemble member (circles) and observations (horizontal line). (b) Difference in MJO activity between QBOE years and all years (blue) and QBOW years and all years (red). Bars show the 2.5th–97.5th range of anomalies obtained by resampling with replacement from the QBO neutral years with an equivalent sample size to observations. (c) As (b) except for the difference between QBOE and QBOW and with the numbers quoting the number of QBO neutral years available for each model.

The difference in MJO activity between QBOE and QBOW is shown in Figure 1 (shading). It is the difference between the MJO-filtered OLR standard deviation calculated using QBOE winters and calculated using QBOW winters. For the models (Figures 1b–1n), the difference between QBOE and QBOW is calculated for each individual member and then Figure 1 displays the ensemble mean of this difference. The observed QBO-MJO connection is clearly apparent (Figure 1a): MJO activity is stronger during QBOE than QBOW with the maximum difference in the Maritime Continent area, consistent with previous studies (e.g., Yoo & Son, 2016). However, none of the CMIP6 models simulate an MJO activity difference between QBO phases that is as strong or coherent as that found in observations. Some models (CNRM-ESM 2-1 and MIROC6) simulate the opposite sign compared with observations. The two models (CNRM-CM6-1 and IPSL-CM6A-LR), which have the largest number of ensembles (21 and 31 ensembles, respectively), have almost zero difference in MJO activity between QBOE and QBOW (Figures 1d and 1j), presumably because the samples are large enough that all differences in MJO activity that arise through sampling noise that is unrelated to the QBO have been sufficiently averaged out.

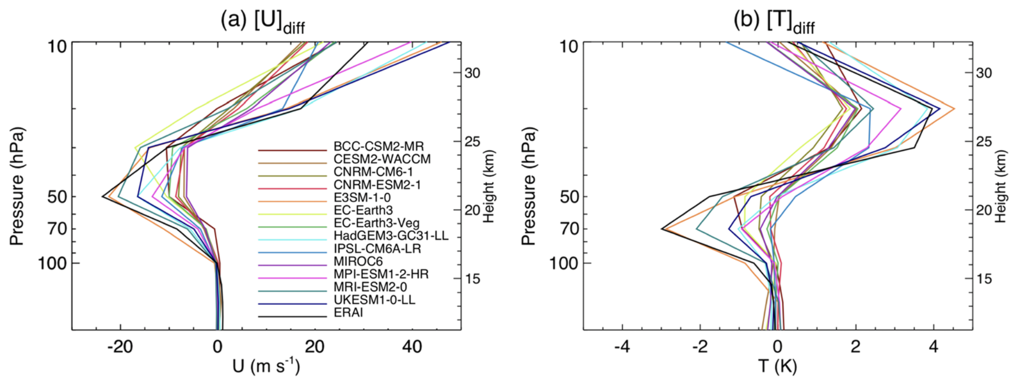

Figure 4. Composites of zonal-mean (a) zonal wind and (b) temperature averaged between 10°S and 10°N for QBOE minus QBOW years ($[U]_{diff}$ and $[T]_{diff}$, respectively) for ERAI (black) and individual models' ensemble mean (colored).

It is clear from the ensemble means (Figure 1) that none of the CMIP6 models seem to capture a reasonable magnitude and spatial distribution of the difference in MJO activity between QBOE and QBOW. The large ensemble size presented in the CMIP6 archive allows us to further investigate whether any individual member (i.e., an equivalent record length to the observations) is capable of capturing the QBO-MJO connection. Furthermore, the large number of QBO-neutral years available in the models allow us to assess the degree to which sampling uncertainty, unrelated to the QBO influence, may contribute to the large signal found in observations (assuming the variability in the models is comparable to that in observations). To perform this assessment, we consider the area average over the Maritime Continent (green box in Figure 1a), where the observed signal is largest. Figure 3b shows the anomalous MJO activity during QBOE and QBOW (i.e., the difference in the standard deviation of MJO-filtered OLR calculated using QBOE or QBOW years and that calculated using all years). Each individual model ensemble member (circles) can be compared with the observed anomalies (horizontal lines). This makes clear that there is no consistent difference in MJO activity during westerly or easterly QBO phases for any model. The discrepancy between models and observations is even more apparent when considering the difference between QBOE and QBOW, where no single ensemble member exhibits anything close to the observed value (Figure 3c).

The number of neutral QBO years (DJF) available from the models ranges from 27 to 299 (numbers quoted in Figure 3c). For many models, we therefore have a large pool of neutral QBO years available from which to test the magnitude of anomalous MJO activity that could be expected to arise from the sampling of internal variability that is unrelated to the QBO, given a record length that is equivalent to observations. In the observed record, 10 years are classed as QBOE, 16 as QBOW and 9 as neutral. We use a bootstrapping with replacement procedure on the neutral years pooled from all ensemble members to assess, for each model, the magnitude of differences in MJO activity that can arise through sampling variability that is unrelated to the QBO, given these sample sizes. The bootstrapping procedure is performed 1,000 times for each test and the bars in Figures 3b and 3c show the 2.5th–97.5th percentile range of anomalies from these 1,000 samples. A difference that lies outside of the range of the bars has less than a 5% chance of occurring through sampling, based on the models variability. This makes clear that the modeled differences found are entirely consistent with the sampling of internal variability that is unrelated to the QBO (almost all circles lie within the bars). The observed difference between QBOE and QBOW is, however, far greater than what the models suggest could arise through sampling of variability that is unrelated to the QBO.

The conclusions to be taken from this analysis are (1) the CMIP6 models do not exhibit a statistically significant dependence of MJO activity on the QBO phase and (2) the observed signal appears to be well outside the range that could be expected to arise due to sampling issues. So, most likely the observed QBO-MJO connection is real and models are deficient in representing this connection. A caveat to conclusion (2) is that this has been made based on the modeled representation of variability across neutral years. Assessing the fidelity of this variability is challenging with only 9 neutral years in the observational record. Note that results are consistent if years with strong ENSO events (defined using the Nino 3.4 index as in Son et al., 2017) are omitted from the analysis. Also, note that considering only strong QBO years (using 1.0 standard deviation of QBO index) or only strong MJO years (defined when the daily OLR-based MJO index [Kiladis et al., 2014] amplitude exceeds 1.0 at any time during the DJF season) do not change these conclusions.

The QBO-induced static stability is thought to be a driver of the observed QBO-MJO connection (Hendon & Abhik, 2018; Martin et al., 2019; Nie & Sobel, 2015; Nishimoto & Yoden, 2017; Son et al., 2017; Yoo & Son, 2016; Zhang & Zhang, 2018): that is, the negative temperature anomalies during QBOE reduce the static stability near the tropopause in the tropical Indo-Pacific and through some mechanism, that is yet to be fully elucidated, this is thought to promote stronger deep convection associated with the MJO. To understand why CMIP6 models fail to capture the QBO-MJO connection, we compare the vertical structure of the 10°S to 10° N averaged zonal-mean zonal wind and zonal-mean temperature and their difference between QBOE and QBOW (hereafter, $[U]_{diff}$ and $[T]_{diff}$, respectively). Observations show a strong QBOE minus QBOW signal with the prevailing easterlies maximizing near 50 hPa (Figure 4a) associated with maximum temperature differences near 70 hPa (Figure 4b) that maintains the thermal wind balance. Only E3SM-1-0 simulates a reasonable magnitude of the QBO signal in both $[U]_{diff}$ and $[T]_{diff}$ while the rest of the models have a weaker magnitude than the observed in the core level (100 to 30 hPa). The observed $[U]_{diff}$ at 50 hPa, for example, is about -25 m s^{-1} while CMIP6 (except E3SM-1-0) ranges from -5 to -20 m s^{-1}. The observed $[T]_{diff}$ at 70 hPa is about -3 K, but CMIP6 (except E3SM-1-0) ranges from 0 to -2 K, substantially weaker than the observed. The QBO signal in the lower stratosphere/upper troposphere and thus the change of static stability may be too weak for the tropical convection to be affected by the QBO forcing. E3SM-1-0 does, however, provide a counterexample to this. It has a relatively reasonable QBO vertical structure compared to others, but the simulated QBO does not translate into the MJO responses expected (Figures 1 and 3). Note that the E3SM-1-0 is biased toward westerly winds especially at lower levels (Richter et al., 2020) which could also influence the QBO-MJO connection.

4. Summary

Recent studies have found convincing observational evidence of a QBO-MJO connection: MJO activity being stronger during the easterly phase than the westerly phase of the QBO during boreal winter (DJF). We assess the representation of the QBO-MJO connection in the historical simulations of 13 GCMs participating in CMIP6 that were identified from a total of 30 models as having a reasonable representation of the QBO and providing daily OLR data for the quantification of the MJO. None of the models show a difference in MJO activity between easterly and westerly QBO that is larger than that which would be expected from the random sampling of internal variability that is unrelated to the QBO. The observed QBO-MJO connection is much stronger and, based on comparison with modeled variability, such a connection is unlikely to have occurred by chance. The weaker representation of the QBO-MJO connection in models relative to the observation may be due to the weaker amplitude of the QBO signal that is seen both in the QBO-related zonal-mean wind and temperature, the latter of which is thought to promote stronger deep convection associated with the MJO, although the mechanism is yet to be fully elucidated and one model does provide a counterexample to this hypothesis (i.e., that the model has a reasonable representation of lower stratosphere QBO temperature anomalies). Another possible reason for the lack of the QBO-MJO connection could arise from biases in simulating the 3D structure of the MJO, a common problem in recent GCMs (Klingaman et al., 2015). In particular, the deep convection needs to reach high enough in order to realize the QBO influence. An examination of the biases in OLR during DJF (not shown) reveals a complex structure, with models generally exhibiting convection that is too deep to the south of the Maritime Continent, too shallow to the north of it, and approximately the correct height over the Maritime Continent region. It is, therefore, unclear the extent to which such biases might impact the QBO-MJO connection but this certainly warrants further investigation. More detailed analysis of MJO simulation is necessary to confirm this. It is also possible that a deficiency in the representation of some other process is responsible for the lack of QBO-MJO connection in CMIP6. Progress could surely be made on this issue if more models can improve their representation of the structure of QBO anomalies in the lower stratosphere and MJO in the troposphere.

Acknowledgments

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