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**Key Points:**
- The Madden-Julian Oscillation (MJO) convective activities have no significant impact on Quasi-Biennial Oscillation (QBO) downward propagation speed
- There is also no evidence that monthly MJO activities impact stratospheric wave activity that could potentially influence QBO dynamics
- The documented relationship between the QBO and the MJO is not driven by MJO modifications to the stratospheric wave spectrum

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

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# The Lack of Evidence on the Madden-Julian Oscillation to Drive Its Relationship With the Quasi-Biennial Oscillation Through Modulation of Stratospheric Wave Activity

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**Abstract** Previous studies have found that Madden-Julian Oscillation (MJO) amplitude depends on the Quasi-Biennial Oscillation (QBO) during boreal winter. This MJO-QBO relationship is important to realizing subseasonal-to-seasonal prediction skills, but the underlying mechanism remains unclear. It is often thought that this relationship arises through the modulation of the upper-troposphere and lower-stratosphere lapse rate by the QBO, but this mechanism assumes the one-way impact of the QBO onto the MJO. Alternatively, the MJO can be hypothesized to influence the QBO by modulating stratospheric wave activity that is known to be critical to QBO dynamics. Therefore, using satellite and reanalysis data, this study examines whether MJO monthly activity can impact stratospheric wave activity and QBO downward propagation speed. The results depicted a lack of such impacts, suggesting this observed MJO-QBO relationship cannot be driven by the MJO modulation of stratospheric wave forcing.

**Plain Language Summary** The intraseasonal fluctuation in cloudiness and rainfall in the troposphere around Indonesia and nearby oceans is higher when the lower-stratospheric winds become easterly during December, January, and February. It is important to understand why this troposphere-stratosphere coupling occurs to extend the range of prediction skills. The changes in the lower-stratospheric winds are associated with changes in the upper-tropospheric temperature, which is often claimed responsible for enhancing or suppressing the development of cumulonimbus clouds and driving the documented troposphere-stratosphere coupling. However, this previously hypothesized mechanism assumes a one-way impact where the stratosphere impacts the troposphere. Instead, this study analyzes the potential influence of tropospheric cloudiness on the stratospheric winds. Cumulonimbus clouds can generate stratospheric waves, which are known to regulate the direction of stratospheric winds. However, our results show that the intraseasonal fluctuation of cloudiness cannot affect the stratospheric waves. It displays a lack of evidence that the intraseasonal fluctuation in cloudiness can drive its observed connection with the stratosphere.

## 1. Introduction

The Madden-Julian Oscillation (MJO) and Quasi-Biennial Oscillation (QBO) are both known to be the sources of subseasonal-to-seasonal (S2S) prediction skills through their influences on global weather and climate (Kim et al., 2019; Mundhenk et al., 2017). The MJO is the dominant mode of tropical intraseasonal convective variability on timescales of about 40–50 days (Madden & Julian, 1971, 1972). The QBO, on the other hand, is the dominant mode of interannual variability in the tropical stratosphere, characterized by alternating zonal easterlies and westerlies that propagate downward completing a cycle with mean period of about 28 months (Baldwin et al., 2001). Recent studies found that MJO activities are enhanced when the QBO at 50 hPa is easterly and are suppressed when the QBO is westerly during boreal winter (Nishimoto & Yoden, 2017; Son et al., 2017). Despite the importance of the MJO-QBO relationship in S2S forecasting, we currently do not understand the mechanism of their relationship fully, and numerical models struggle to capture the observed MJO-QBO relationship (Kim et al., 2020; Lee & Klingaman, 2018). Among the number of hypothesized mechanisms of the MJO-QBO relationship, one that has not been examined is the potential modulation of the QBO by the MJO by affecting stratospheric wave activities. The objective of this study is to test this hypothesis by assessing if the MJO has a significant impact on stratospheric waves that can influence QBO dynamics.

Previous studies hypothesized that QBO-related changes in static stability around the tropopause layer cause changes in MJO activity (Son et al., 2017; Yoo & Son, 2016). According to this mechanism, the presence of cold temperature anomalies during QBO easterlies reduces static stability near the tropopause, which then destabilizes deep convection, promoting stronger MJO convection (Martin et al., 2019; Nishimoto & Yoden, 2017). It is also suggested MJO-induced temperature anomalies near the tropopause act together with the QBO to further reduce static stability, which leads to stronger MJO convection during QBO easterlies (Hendon & Abhik, 2018). However, a general circulation model cannot replicate the observed MJO-QBO relationship simply by adding the QBO-induced temperature anomalies in the upper troposphere and lower stratosphere (Martin, Orbe, et al., 2021), questioning the applicability of this static-stability mechanism to explain the MJO-QBO relationship. This mechanism also assumes that the MJO-QBO relationship occurs through one-way impact: the QBO impacts MJO activities while neglecting the possible impacts of the MJO on QBO dynamics.

Given that the MJO significantly modulates the activity of deep convection, which can generate stratospheric equatorial waves that play fundamental roles in QBO dynamics (Baldwin et al., 2001), it is plausible that the observed MJO-QBO relationship partly arises from the modulation of stratospheric wave activities associated with MJO activities. For example, active MJO during QBO easterlies may increase stratospheric Kelvin wave activity due to greater convective activity and enhanced vertical group velocity of Kelvin wave within the easterly background. If that happens, the increased Kelvin wave activity can induce greater westerly forcing in the stratosphere by momentum damping, causing the QBO to descend faster and switch from easterly to westerly as MJO activity also weakens. Therefore, the described modulation of stratospheric waves by the MJO can potentially contribute to the preferred occurrence of enhanced MJO activity during QBO easterlies. Such modulation of QBO wave forcing by tropical convection has also been shown with ENSO (Schirber, 2015; Taguchi, 2010). Although Martin, Son, et al. (2021) discuss this MJO impact on the stratosphere as a possible but unlikely mechanism, no studies so far have examined this hypothesis. Therefore, to deepen our understanding of the MJO-QBO relationship, this study tests if the MJO can alter stratospheric wave spectrum that could modify the QBO descent rate using reanalyses data.

## 2. Data and Methods

All presented analyses of this study are done using December-January-February months when the MJO-QBO connection appears (Yoo & Son, 2016).

### 2.1. Identification of Monthly MJO Activity

To assess the potential impact of the MJO on stratospheric wave activity or the QBO, we identify monthly MJO activity using the Outgoing longwave radiation (OLR)-based MJO Index (OMI, Kiladis et al., 2014). The amplitude of this index represents MJO amplitude, which is derived from the leading pair of empirical orthogonal functions (EOF) of intraseasonal bandpass-filtered OLR over 20°S–20°N. Given the period of the QBO, a persistent effect on stratospheric wave forcing must exist on a monthly timescale to affect the QBO. Therefore, for the MJO to affect the QBO, the MJO must have some cumulative monthly effects on the stratosphere. For this reason, we identify MJO active and inactive months that may have distinct effects on the stratosphere.

To identify MJO active and inactive months, we generate a monthly standardized anomalous amplitude of the OMI. OMI amplitude is first averaged monthly, then the seasonal cycle is removed. The monthly OMI amplitude anomaly is then normalized using its standard deviation of each month of the year. The sensitivity of results is scrutinized by repeating the analysis using Real-time Multivariate MJO (RMM) Index (Wheeler & Hendon, 2004). We present results using the OMI only, but we discuss any sensitivity of the results to the choice of MJO indices.

### 2.2. Reanalyses Data

The European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 (Hersbach et al., 2020) reanalysis is used to examine stratospheric wave activity and the state of the QBO. The hourly ERA5 data has $0.25° \times 0.25°$ horizontal grids on isobaric levels from surface to 1 Pa with 37 levels. The results using ERA5 data from 1979 to 2019 are presented, but the same analyses are repeated with ERA-Interim (Dee et al., 2011) and the results are insensitive to the choice of reanalyses unless stated otherwise. We use the zonal wind from the reanalyses to diagnose stratospheric wave activities associated with the QBO and MJO.

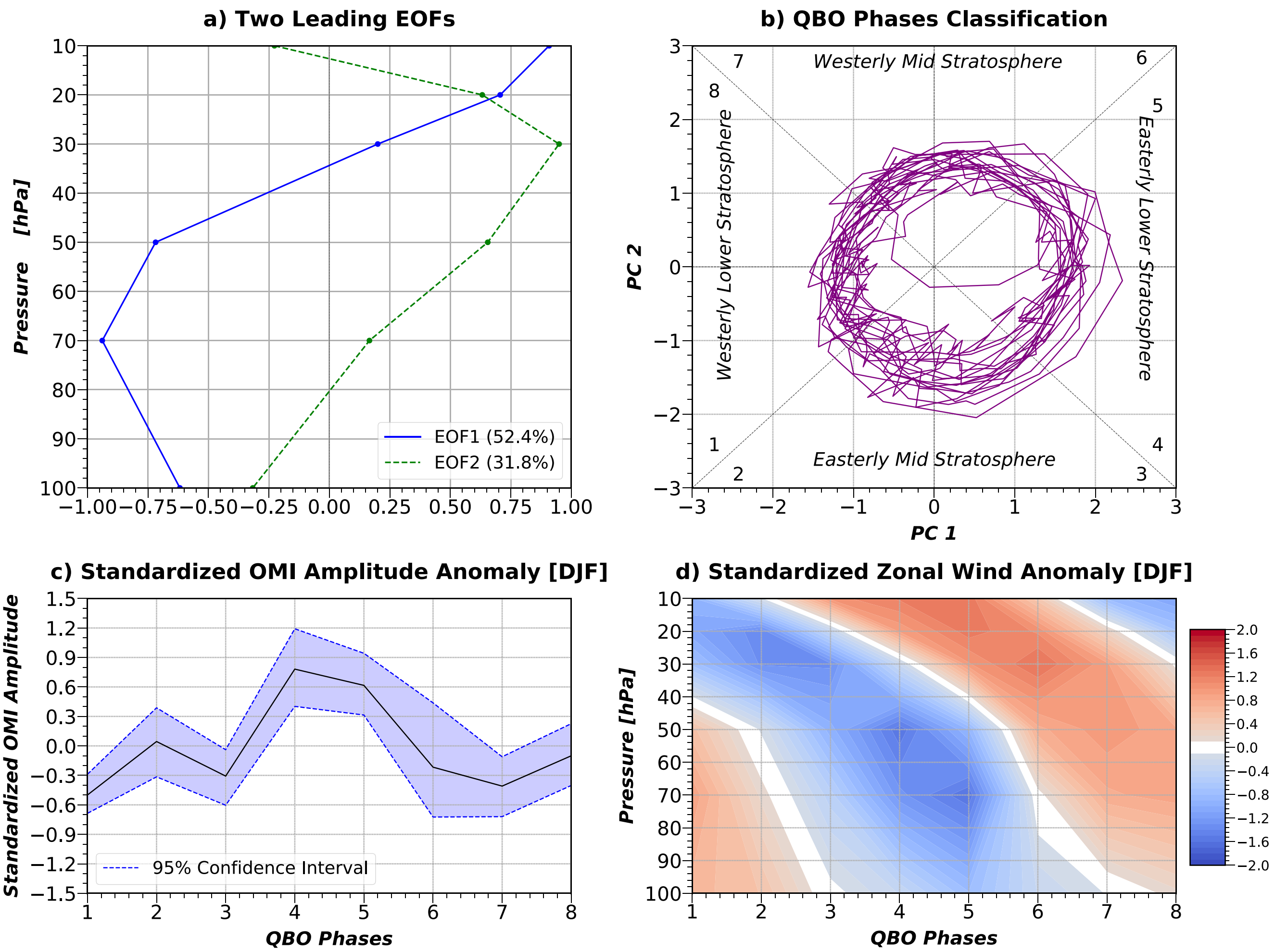


**Figure 1.** (a) The vertical structure of the two leading empirical orthogonal functions of normalized monthly mean zonal wind anomalies averaged over 10°S–10°N. The legend shows the percentage of variance explained by each. (b) Quasi-Biennial Oscillation (QBO) phase diagram defined by the two leading PCs corresponding to EOF1 and EOF2. Eight QBO phases are defined as shown. (c) Average monthly anomalies of OMI amplitude during different phases of the QBO. Shading shows the 95% confidence interval. (d) Vertical profile of the normalized monthly zonal mean zonal wind anomalies composited based on QBO phases.

## 2.3. QBO Indices

Two distinct QBO indices are used to identify QBO states and re-examine the relationship between the MJO and QBO.

### 2.3.1. Single-Level QBO Index

A single-level QBO Index is defined by the normalized monthly zonal mean zonal wind at 50 hPa averaged over 10°S–10°N using ERA5, which is similar to the index used in prior studies (Son et al., 2017; Yoo & Son, 2016). The seasonal cycle from monthly zonal wind is eliminated, and the anomaly is normalized by using its standard deviation of each month of the year. QBO phase is defined as easterly when this single-level QBO index is smaller than −0.5, westerly when it is greater than 0.5, and neutral otherwise. While this single-level index is commonly used, it does not capture the vertical structure of the QBO. Therefore, the EOF-based QBO index (Densmore et al., 2019) is also used to capture the vertical structure and evolution of the QBO.

### 2.3.2. Empirical Orthogonal Function (EOF)-Based QBO Index

The EOF analysis of normalized monthly zonal-mean zonal wind anomalies averaged from 10°S to 10°N within 100–10 hPa layer is used to identify QBO phases, following Densmore et al. (2019). Figure 1a shows the resultant first and second leading EOFs of such normalized monthly zonal-mean zonal wind anomalies. The corresponding monthly principal components, normalized by their standard deviations, are then used to define the phase of the QBO using Equation 1.

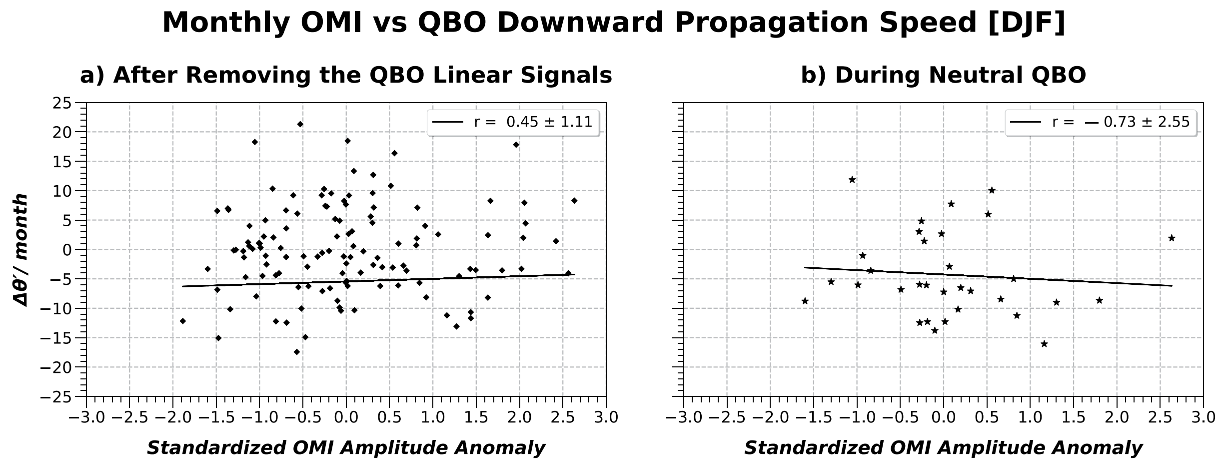


**Figure 2.** (a) Scatter plots of the standardized monthly Outgoing longwave radiation-based Madden-Julian Oscillation Index amplitude anomalies and the monthly Quasi-Biennial Oscillation (QBO) downward propagation speed after removing its linear dependency of QBO phase (see text for more description). (b) Same as panel (a), except showing the relationship during the neutral QBO phase without the removal of linear QBO signal. The *r* values in the legend show regression slopes and their range obtained by the bootstrap resampling.

$$\theta = \arctan\left(\frac{PC2}{PC1}\right) \tag{1}$$

The QBO moves counterclockwise around the phase space with time as the oscillation propagates downward through the stratosphere (Figure 1d). The time rate of change in this QBO phase ($\theta$) then represents its downward propagation speed. The evolution of the QBO is divided into eight phases (Figure 1b), which capture the downward propagation of zonal wind anomalies (Figure 1d). The magnitude of the QBO is defined by $\sqrt{PC1^2 + PC2^2}$.

### 2.4. Statistical Significance Test

To test the significance of the presented results, we apply a bootstrapping re-sampling method using 1,000 iterations with repetitions at the 95% confidence level throughout the study. To consider auto-correlations when testing the significance of correlations, we generate a distribution of the null value by reversing the temporal sequence of one of the timeseries following the method described in Kiladis et al. (2016). Given that the same data is used to generate the null distribution, the same auto-correlation characteristic is retained. A correlation is considered statistically significant when the distribution obtained by bootstrapping does not overlap with its null distribution at the given confidence level.

## 3. Reassessment of the MJO-QBO Relationship

Using the EOF-based QBO index, Figure 1c shows the average standardized monthly OMI anomalies during the eight phases of QBO. When the QBO is easterly in the lower stratosphere (i.e., QBO Phases 4–5), there are higher activities of the MJO, which is consistent with previous findings (e.g., Nishimoto & Yoden, 2017; Son et al., 2017). As discussed in Section 1, we hypothesize that the months of active MJO convection may generate more stratospheric waves compared to inactive months, leading to a faster downward propagation speed of the QBO. To examine this potential impact of the MJO on QBO propagation speed, we estimate the downward propagation speed of the QBO using the time rate of change in QBO phase angle (Equation 1).

The downward propagation speed of the QBO is known to depend on QBO phases, where westerlies tend to descend faster than easterlies (Baldwin et al., 2001). MJO activity also depends on QBO phases, therefore, an apparent relationship between QBO downward propagation speed and the MJO may not be a direct relationship. Therefore, we must first eliminate the dependence of QBO propagation speed on QBO phases, before assessing its relationship to monthly MJO activity. To do so, we remove the time-mean and the first three harmonics of the seasonal cycle from the time series of QBO downward propagation speed. To eliminate the dependence of QBO downward propagation speed on the QBO, a linear relationship between the QBO and monthly anomalous downward propagation speed is reconstructed using a regression model. It is then removed from the time series of monthly anomalous QBO downward propagation speed. Figure 2a shows the scatter plot of this monthly anomalous downward propagation speeds of the QBO without its linear dependence on QBO phases against monthly OMI amplitudes. Figure 2a shows that the regression slope is slightly positive, but it is not statistically significant. This result suggests that there is no significant relationship between the monthly activity of the MJO and QBO downward propagation speed.

Given that our approach does not completely eliminate the state-dependent propagation speed of the QBO, we repeat the analysis during QBO neutral phases exclusively, without the removal of linear QBO signal (Figure 2b). In contrast to Figure 2a, the regression slope is negative but it is again not statistically significant. Repeated analyses using QBO easterly or westerly months only also did not show any significant dependence of QBO downward propagation speed on MJO monthly activity (Figure S1 in Supporting Information S1). Furthermore, using ERA-Interim, during QBO neutral phases, the same analysis shows a small positive slope when OMI is used and a small negative slope when the RMM index is used (not shown). This contrasting result using different choices of reanalyses and the MJO index, in addition to the lack of statistical significance, further supports that the QBO monthly downward propagation speed is not dependent on MJO monthly activity.

## 4. The MJO Impacts on Stratospheric Waves Activity in Reanalysis

Our results in the previous section suggest that MJO monthly convective activity has no significant impact on the monthly downward propagation speed of the QBO. To further support this result, this section demonstrates that monthly MJO activities have no robust impact on stratospheric wave activities to modulate the QBO. To evaluate stratospheric wave activity, the wavenumber-frequency Fast Fourier Technique is applied to hourly zonal wind anomalies from ERA5, at 50 hPa between 15°N and 15°S. Following the methods of Wheeler and Kiladis (1999), power spectra are calculated with a 96-day window, but we center them on the 15th of each month, generating a monthly timeseries of power spectra. As shown by Pahlavan, Fu, et al. (2021), ERA5 captures the expected signals of equatorial waves from 50 hPa zonal wind (see their Figure 3). We also confirmed that our method captures similar climatological power spectra.

We also check if the reanalysis and our method capture the expected variability in the power spectra associated with the QBO. To do so, we first remove the time-mean and the first three harmonics of the seasonal cycle of monthly power spectra at each resolved wavenumber and frequency. The anomalous monthly power spectra are then normalized by their standard deviation at each resolved wavenumber and frequency, and they are regressed onto the single-level QBO index. The resultant wavenumber-frequency regression coefficients are presented in Figure 3. The positive shading indicates that stratospheric waves are more active during QBO westerlies, and the negative shading indicates they are more active during QBO easterly. Kelvin wave activity becomes higher during QBO easterlies and shifts toward a slower propagation speed perhaps due to the changes in the background zonal wind by the QBO (Dias & Kiladis, 2014). In contrast, ER and MRG become more active during QBO westerlies. These results demonstrate that ERA5 captures the expected variability of stratospheric waves associated with the QBO (Yang et al., 2011, 2012). The same analysis is applied to the average power of frequencies above 1 cycle/day (Figures 3a and 3b). The westward-propagating components of these high-frequency waves are found to be more active during QBO easterlies while eastward-propagating components are less weakly dependent on QBO phases. Pahlavan, Wallace, et al. (2021) also showed that forcing from small-scale gravity (SSG) waves with a wavenumber higher than 20 are a dominant contributor to the QBO. Our analysis also showed that both eastward and westward SSG waves become more active during QBO westerlies (not shown).

To examine stratospheric wave variability associated with MJO activities, the influence of the QBO on monthly activities of stratospheric waves must be first eliminated as its strong dependence on the QBO is demonstrated in Figure 3. To remove the QBO dependence from monthly power spectra, we remove a linear QBO signal using a regression model, as done in Section 3. The remaining normalized monthly power spectrum anomalies are then regressed onto monthly OMI amplitude. The shading in Figures 4c and 4d is the resultant regression coefficient, where positive values represent higher activities of stratospheric waves during MJO active and negatives represent higher activities during MJO inactive months. Figure 4 shows the lack of any significant modulation of any stratospheric waves by monthly MJO activities. This result remains the same even if we depict the monthly amplitude of particular OMI phases. Additionally, we did not find any dependence of SSG wave activities on the MJO (not shown).

Given some limitations in our linear approach to remove the QBO signal, we examine how the activity of selected waves varies non-linearly with both the monthly QBO and OMI indices. We define the monthly activity of

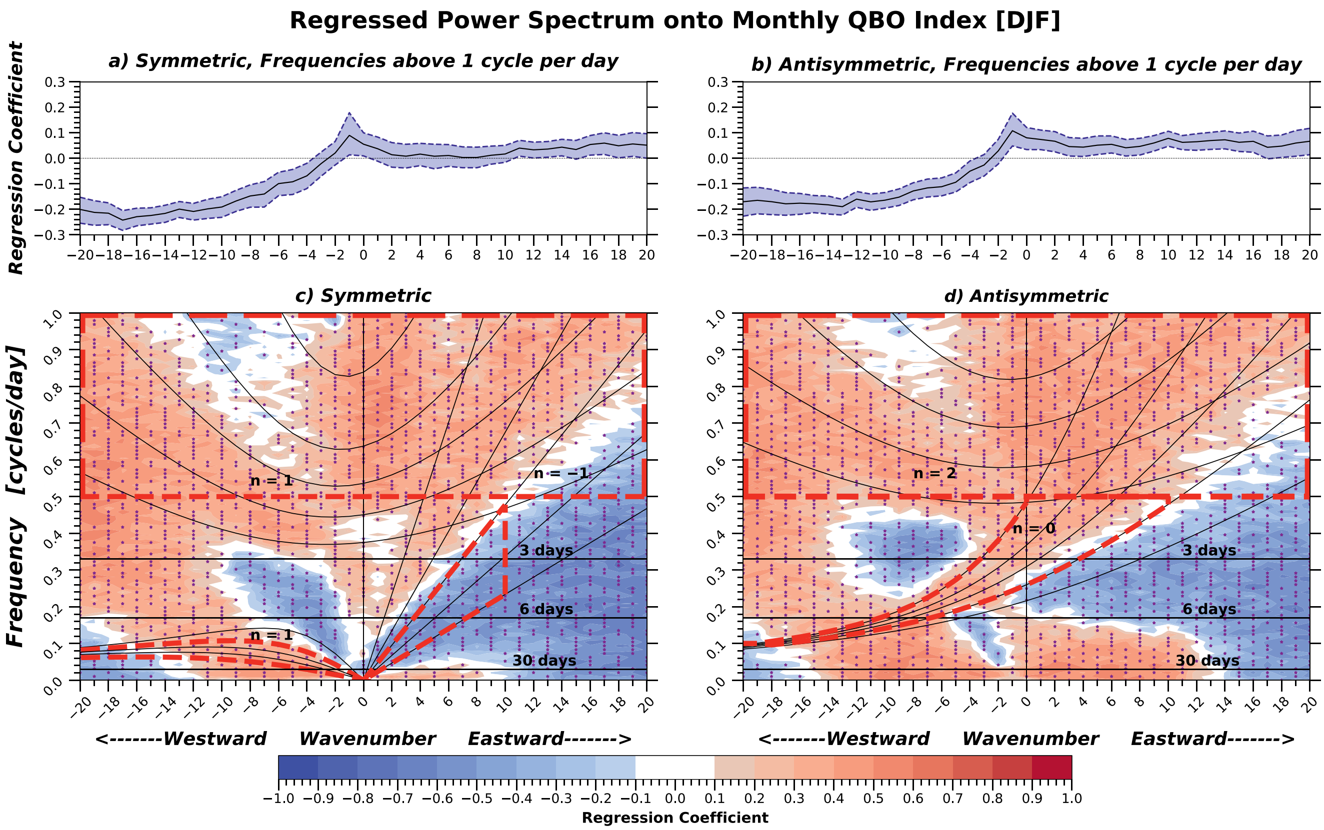


**Figure 3.** (a, b) Regression coefficients of the monthly power spectra of 50 hPa ERA5 zonal wind averaged above 1 cycle/day onto the single-level Quasi-Biennial Oscillation index for symmetric and antisymmetric components. (c, d) The same regression coefficients of the wavenumber-frequency spectra with overlaid theoretical dispersion curves with equivalent depths of 12, 25, 50, 100, and 300 m. These dispersion curves show the intrinsic frequency and wavenumber without including the effects of background winds (Dias & Kiladis, 2014). The blue shading (a, b) and black dots (c, d) show the 95% confidence interval or statistical significance.

Kelvin, ER, MRG, and Inertia-Gravity (IG) waves by averaging the monthly power spectra within corresponding wavenumber-frequency domains defined by the dashed-red lines in Figures 3 and 4. Following Pahlavan, Wallace, et al. (2021), IG wave is defined as the combined power of both symmetric and antisymmetric components with frequency above 0.5 cycle/day. Shading in Figure 5 shows the average values of the anomalous and standardized monthly activity of each wave. Figure 5 shows that the QBO strongly modulates the activities of all waves, but there is no clear variability with the MJO. Similar analyses are performed for different pressure levels in the tropopause and stratosphere (between 100 and 10 hPa), and a lack of MJO influence on stratospheric waves is noticed at all levels. These analyses support our conclusion that the monthly MJO activities have no significant effect on the tropopause to stratospheric wave activities (Figures S2 and S3 in Supporting Information S1).

## 5. Conclusion

This study examines if MJO monthly activities can influence stratospheric waves, leading to the modulation of QBO dynamics, which was speculated to partly drive the documented relationship between the MJO and QBO (Son et al., 2017; Yoo & Son, 2016). This hypothesis is tested using reanalyses data that have been demonstrated to capture stratospheric waves and their forcing of the QBO (Pahlavan, Wallace, et al., 2021). To test the effect of the MJO on the stratosphere, we examine if the downward propagation of the QBO or power spectra of stratospheric waves vary with monthly activity of the MJO.

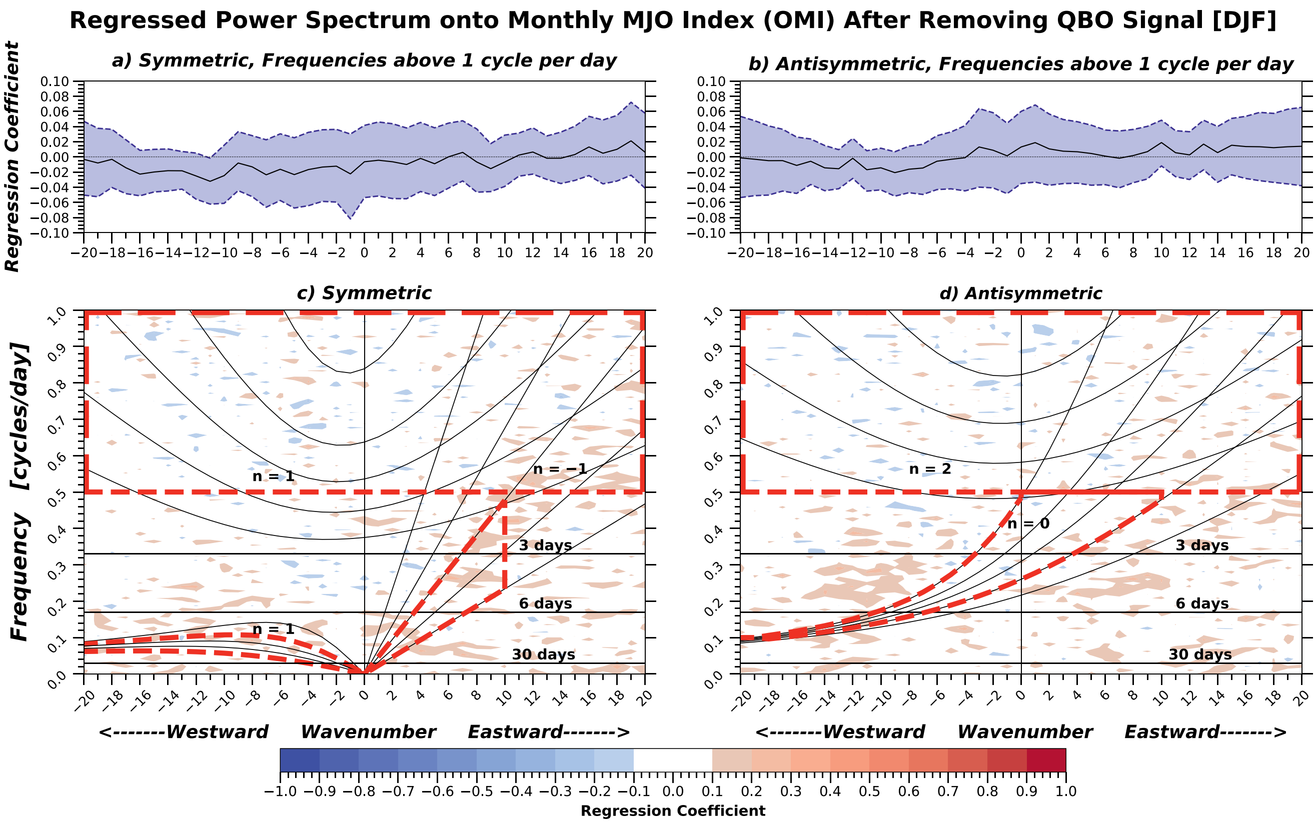


**Figure 4.** Same as Figure 3 but regressed onto monthly Outgoing longwave radiation-based Madden-Julian Oscillation Index index after removing the linear signal associated with the Quasi-Biennial Oscillation from the power spectrum timeseries.

We find no significant linear or non-linear association between monthly MJO activities and QBO downward propagation speeds or stratospheric wave activity between 100 and 10 hPa that could substantially contribute to the MJO-QBO relationship. Our results support that the MJO-QBO relationship likely arises from the one-way impact of the QBO onto the MJO (Martin, Son, et al., 2021). Any effects of the MJO on the stratosphere are likely canceled out on the monthly timescale due to the propagation of MJO enhanced and suppressed convective envelopes, resulting in no substantial impact on the stratospheric waves or the QBO. However, our results do not eliminate possible effects of the MJO on the QBO through other pathways, such as the modulation of extratropical circulation (Garfinkel et al., 2012).

Concluding, our results suggest discarding the hypothesis we put forth, which helps us narrow down possible mechanisms of the MJO-QBO relationship. Future studies should continue to explore new and previously hypothesized mechanisms, such as the ones that attribute the MJO-QBO relationship to the changes in the static stability and cloud-radiative forcing by the QBO.

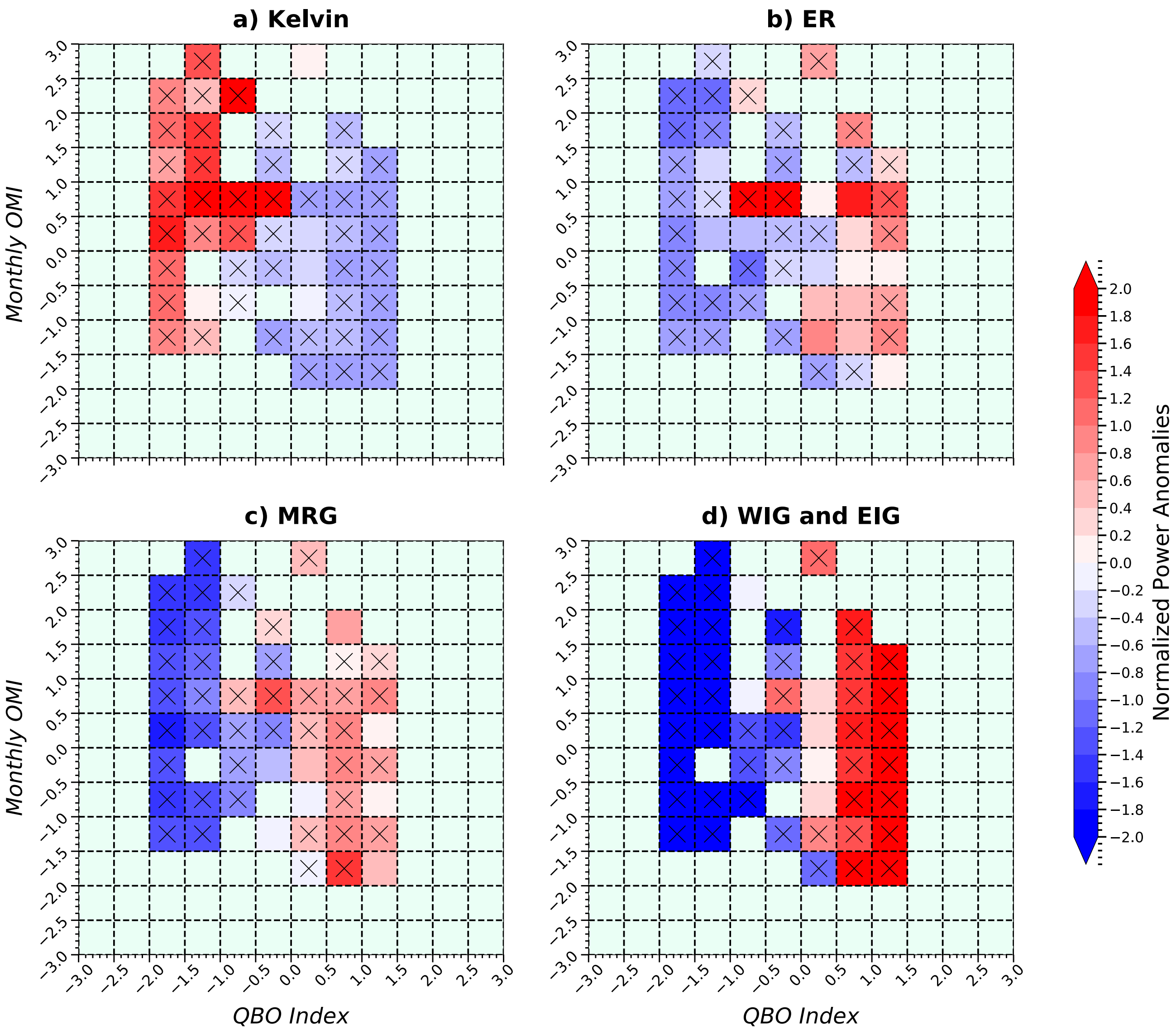


**Figure 5.** Mean monthly normalized power anomalies of (a) Kelvin, (b) ER, (c) MRG, and (d) Inertia-Gravity (WIG and EIG) waves conditioned by the monthly Outgoing longwave radiation-based Madden-Julian Oscillation Index and single-level Quasi-Biennial Oscillation indices. The *X* represents the statistical significance at the 95% confidence level. See Figure 3 and text for the wavenumber-frequency domain that defines each wave.

## Data Availability Statement

The ERA5 monthly mean and hourly zonal wind data (Hersbach et al., 2020) used for this study can be downloaded from the ECMWF website: https://doi.org/10.24381/cds.bd0915c6. The OMI daily data (Kiladis et al., 2014) is downloaded from the NOAA Physical Science Laboratory website: https://psl.noaa.gov/mjo/mjoindex/omi.1x.txt.

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