An exploration of the connection between quasi-biennial oscillation and Madden-Julian oscillation

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Abstract

Recent studies have shown arguments about the connection between stratospheric quasi-biennial oscillation (QBO) and activities of Madden-Julian oscillation (MJO) during boreal winter on interannual timescale, especially for the question of which aspects of MJO, amplitude or occurrence frequency, can really be modulated by QBO. This study re-examines the interannual variability of the seasonally averaged amplitude and the occurrence of both ‘active’ (amplitude > 1.0) and ‘inactive’ (amplitude < 1.0) MJO days in boreal winter December–January–February (DJF), and their relation to QBO variation. Significant correlations between the QBO index and the indicators of MJO activity reveal that wintertime amplitude of ‘active’ and ‘inactive’ MJO days are typically larger in QBO easterly phase (EQBO) than in QBO westerly phase (WQBO). More importantly, we can also expect more ‘active’ MJO days and simultaneously less ‘inactive’ MJO days in EQBO winter as a consequence of more days in winter shifting from ‘inactive’ to ‘active’ due to larger MJO amplitudes. The significantly positive (negative) correlation between the time series of averaged amplitude and occurrence of ‘active’ (‘inactive’) MJO days can as well be interpreted as evidence that QBO is closely connected to the occurrence of MJO days via modulating MJO amplitudes. These results update our current understanding of the QBO-MJO connection, which is helpful to advance the MJO prediction.

1. Introduction

Madden-Julian oscillation (MJO) dominates the intraseasonal variability of equatorially organized convective systems in the tropical atmosphere and is characterized by the eastward propagation of convective disturbance along the equator from the Indian Ocean to the central Pacific with a life cycle of about 30 ~ 60 days (Madden and Julian 1971, 1972, 1994, Li et al 2018). Given the fact that remarkable changes in weather or climate over tropics, subtropics, mid-latitudes and even polar regions have been detected as being driven or modulated by the MJO (e.g. Cassou 2008, Lavender and Matthews 2009, Yoo et al 2012, Seo et al 2016, Seo and Lee 2017), it is recently considered as a major source of global predictability on the subseasonal timescale (e.g. Waliser 2011, Vitart 2017). Although the prediction skill of MJO in state-of-the-art operational models has been evaluated over the past decade (e.g. Kim et al 2014, Vitart 2017), MJO prediction is still the challenge in tropical meteorology and there is plenty of room for improvements. Better understanding of the evolution of MJO events and its contributing factors will benefit the forecast skill of MJO, which may further narrow the gap between medium range weather forecasts and seasonal forecasts.

Quasi-biennial oscillation (QBO) dominates the interannual variability of the tropical stratosphere and manifests itself as the downward propagation of periodic reversals of the easterly and westerly zonal
wind with a period of about two years (Ebdon and Veryard 1961, Lindzen and Holton 1968, Baldwin et al. 2001, Huesmann and Hitchman 2001). QBO-varying zonal winds accompany the anomalies of temperature, static stability, and a secondary circulation according to the thermal wind relation (Baldwin et al. 2001). Thus, dynamic and thermodynamic circumstances in the upper troposphere and lower stratosphere (UTLS) especially near the tropopause layer (~100 hPa) are also varied with the QBO phases. In this regard, tropical convective systems over certain regions are thought to be modulated by the factors around tropopause (e.g. Reid and Gage 1985, Gray et al. 1992, Collimore et al. 2003, Emanuel et al. 2013).

Although MJO features the intraseasonal variability, it undergoes pronounced year-to-year variation as well. Very recently, interannual variability in the averaged amplitude of MJO in boreal winter has been reported to connect with QBO variation (Yoo and Son 2016, Nishimoto and Yoden 2017, Son et al. 2017). The primary finding is that there is a significantly negative correlation between the seasonally averaged amplitude of MJO and QBO index in winter, suggesting that MJO amplitudes are typically larger in the QBO easterly phase (EQBO) than in the QBO westerly phase (WQBO). The contrasts between these two QBO phases in the vertical wind shear in the UTLS, tropopause temperature, cirrus cloud formation near tropopause, and more commonly, static stabilities at 100 hPa, can be used separately or together to explain the effect of QBO on MJO amplitudes (Yoo and Son 2016, Son et al. 2017, Martin et al. 2019). However, a more recent study of Zhang and Zhang (2018) (hereafter ZZ18) argued that the correlation between QBO index and MJO amplitude found in previous studies is driven by more MJO days, not really by stronger MJO amplitudes. Mechanism proposed in their study is the weaker barrier effect of the Maritime Continent on MJO propagation in EQBO winter, leading to more MJO events and longer durations.

The recent findings on the influence of QBO on MJO have important implications for the subseasonal-to-seasonal (S2S) prediction (Marshall et al. 2017, Lim et al. 2019, Wang et al. 2019). To further unravel the underlying relationship between QBO and MJO, this study re-examined the interannual variability of MJO in boreal winter, including the seasonally averaged amplitude and the occurrence of both ‘active’ (amplitude > 1.0) and ‘inactive’ (amplitude < 1.0) MJO days, and their relation to QBO variation. A focal point in our analysis is to check the correlation between the two series of averaged amplitude and occurrence of MJO days. Due to the dependency of the definition of an ‘active’ MJO day on the criterion of the amplitude, we speculated that a strong association may exist between the amplitude and occurrence of MJO days in winter, that is, larger MJO amplitudes are likely to increase the occurrence of ‘active’ MJO days.

### Table 1. Correlation coefficients of the time series of occurrence and averaged amplitude of ‘active’ and ‘inactive’ MJO days against various QBO indices from 1979 to 2019.

| QBO Index | Occr. (>1) | Amp. (>1) | Occr. (<1) | Amp. (<1) |
|-----------|-----------|-----------|-----------|-----------|
| U30       | −0.18     | 0.03      | 0.17      | −0.004    |
| U50       | −0.43     | −0.5      | 0.43      | −0.54     |
| U70       | −0.39     | −0.57     | 0.39      | −0.5      |
| U100      | 0.3       | 0.01      | −0.3      | 0.08      |

This paper is organized as follows. Data and methods are described in section 2. Results are presented in section 3. A summary is given in section 4.

### 2. Data and methods

The fifth-generation reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ERA5; Hersbach et al. 2020), at 1° × 1° spatial grids, from January 1979 to December 2019, was used to define the QBO phases and examine the circulation changes related to QBO. The reanalysis dataset from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) was also used to verify the results and the conclusions are not sensitive to the reanalysis choice. As a proxy for tropical convection, the daily outgoing longwave radiation (OLR) data from 1979 to 2019 was derived from the National Oceanic and Atmospheric Administration (NOAA) web site (https://psl.noaa.gov/data/gridded/data.interp_OLR.html) with a 2.5° × 2.5° grid spatial resolution. For OLR data, the daily anomalies were calculated by removing long-term daily climatology. The intraseasonal variability, i.e. MJO-related daily anomalies, in tropical convection was then extracted by applying a 20–100 day band-pass filter to OLR time series. Anomalously negative OLR values represent the anomalous deep convection within the tropics.

In line with previous studies (Yoo and Son 2016, Son et al. 2017, Zhang and Zhang 2018), the monthly 50 hPa zonal-mean zonal wind from ERA5 averaged over 10° S–10° N (U50) was used as an indicator of QBO here. The interannual variability of QBO was calculated by the seasonal-mean (DJF) U50. Then, the easterly (westerly) phase of QBO was defined when the seasonal mean U50 is easterly and more negative than −0.5 standard deviations (westerly and more positive than 0.5 standard deviations) from the mean. Based on this criterion, a total of 13 and 17 years were selected as EQBO and WQBO during the 40 winters of 1979–2019, respectively. In particular, the remaining ten winters were classified as neutral phase of QBO (NQBO) in this study (figures 2 and 3).
Likewise, other QBO indices, such as U30, U70, and U100 were also used (Table 1).

The eight MJO phases and their amplitudes during 1979–2019 were determined by the OLR-based MJO index (OMI), which was obtained from the NOAA Earth System Research Laboratory website (www.esrl.noaa.gov/psd/mjo/mjoindex/). Kiladis et al. (2014) has reported that OMI is a better proxy for the convective signature of MJO than Real-time Multivariate MJO index (RMM) (Wheeler and Hendon 2004). An MJO day is referred to as ‘active’ when its amplitude (\(\sqrt{PC_1^2 + PC_2^2}\)) is greater than 1.0. The principal component time series (PC1 and PC2) of the OMI are constructed by projecting the 20–96 day filtered OLR onto the two leading empirical orthogonal functions of the 30–96 day eastward filtered OLR (Kiladis et al. 2014). The amplitude of OMI is non-dimensional. Note that the ‘inactive’ MJO (amplitude < 1.0) days were also considered in this study and marked as phase 0. The results are not sensitive to a reasonable change of the amplitude threshold. Although not shown, another index, RMM, which was available from the Australian Bureau of Meteorology website (www.bom.gov.au/climate/mjo/), was used to verify the results and the general conclusions were not sensitive to the choice of MJO index.

A Monte Carlo test has been adopted to determine the statistical significance of the MJO-induced OLR anomalies in figures 4 and 5. OLR anomalies are selected at random from \(N\) wintertime days in which the MJO is ‘active’ or ‘inactive’, where \(N\) matches the number of ‘active’ or ‘inactive’ MJO days in which a chosen phase occurs. The composite mean of the random sample of \(N\) days is recorded. Then we repeat this random selection process 5000 times to obtain a probability density function of composite mean values and associated percentiles. Composite mean OLR anomalies for a specific MJO phase are considered significant at the 90% level if they lie outside of the upper or lower 5th percentiles computed from the random sampling procedure.

### 3. Results

The interannual variability of MJO activities, which are denoted as the time series of occurrence and averaged amplitude of ‘active’ and ‘inactive’ MJO days during the winters from 1979 to 2019, are shown in figure 1. Note that the ‘occurrence’ in this study refers to the number of MJO days. Interestingly, a significantly positive correlation is found between the occurrence and averaged amplitude of ‘active’ MJO days, with a large correlation coefficient of 0.77 that is significant at the 99% confidence level. Conversely, the time series of the occurrence of ‘inactive’ MJO days is negatively correlated with their averaged amplitude.

![Figure 1. Time series of occurrence (red lines) and averaged amplitude (blue lines) of (a) ‘active’ and (b) ‘inactive’ MJO days in winters (DJF).](image-url)
Figure 2. Box plots of the distribution of MJO amplitudes in the winters under westerly, neutral, and easterly phase of QBO (WQBO, NQBO, and EQBO) respectively. Central line of box shows median, outer lines of box shows upper and lower quartile. Whiskers are plotted at 1.5 times the inter-quartile range. Solid squares denote mean values.

in winters (coefficient = −0.61, significant at 99% confidence level). The strong in-phase (anti-phase) behavior in the time series of the occurrence and averaged amplitude of ‘active’ (‘inactive’) MJO days provides a clue as to our speculation that change in amplitude due to certain factors (e.g. QBO) may alter the occurrence frequency of MJO. More importantly, these close linkages illuminate that the two components of MJO activities in winter, the amplitude and occurrence frequency, cannot be discussed separately. Furthermore, since there is a nearly perfect negative relationship between the occurrence of ‘active’ and ‘inactive’ MJO days in winters (r ≈ −1), significant correlation between the time series of the averaged amplitude of ‘active’ and ‘inactive’ MJO days can also be found (r = 0.38, significant at 95% confidence level).

Given the significant correlations between the averaged amplitude and occurrence of MJO days, we speculate that a tight connection may exist between those indicators of MJO activities and QBO index. Thus, the correlation coefficients between various QBO indices (U30, U50, U70, U100) and the time series of averaged amplitude and occurrence of ‘active’ and ‘inactive’ MJO days in winters are displayed in table 1. As expected, U50 and U70 are found to be significantly and negatively correlated with the time series of averaged amplitude of both ‘active’ and ‘inactive’ MJO days, similar to the studies of Yoo and Son (2016) and Son et al (2017), implying larger amplitudes of MJO in EQBO winter. More importantly, significantly negative (positive) correlation between QBO indices at 50/70 hPa and the occurrence of ‘active’ (‘inactive’) MJO days can also be found, suggesting that stratospheric EQBO tend to increase (reduce) the occurrence of ‘active’ (‘inactive’) MJO days. Moreover, there is no significant correlation between QBO index at 100 hPa and the MJO activities, which may be partly due to that the zonal wind near the tropopause layer can be affected by multiple factors, such as tropical convection or Brewer-Dobson circulation (e.g. Randel and Jensen 2013), in addition to the QBO. Considering the downward propagation of the zonal wind, a time lag of a few months may exist for the connection between U30 and the response of MJO activities.

To further demonstrate the connection between QBO and MJO, the distributions of daily amplitude of MJO during WQBO, NQBO and EQBO winters are shown in box plots in figure 2. It is clear that the first, third quartile, median and mean values of MJO amplitudes show an increase when the QBO phase shifts from westerly to easterly, suggesting that EQBO winter is associated with intensified tropical convection leading to larger MJO amplitudes. Moreover, comparing the quartiles across these three QBO phases, one thing to notice is that more MJO days are binned into ‘inactive’ (Amplitude < 1.0) category in WQBO, whereas higher occurrence of ‘active’ (Amplitude > 1.0) MJO days in EQBO can be observed. This suggests that ‘inactive’ MJO days would shift to ‘active’ state with the enhancement of
MJO amplitude during EQBO winter, which can also be inferred from the results shown in figure 6 in Lim et al (2019) using S2S models. Combining figures 1, 2 and table 1, especially for the significant correlations between the averaged amplitude and occurrence of MJO days, these results provide important insights into the relationship between MJO and QBO, that is, stronger MJO activities in EQBO are a consequence of larger amplitudes as well as more ‘active’ MJO days.

Our conclusion abovementioned is different from the study of ZZ18, which found that greater number of ‘active’ MJO days, not greater amplitudes of MJO during EQBO than WQBO, was used to explain the connection between the QBO index and the MJO. Their conclusion was based on fact that the correlation between QBO index and seasonally averaged amplitude of ‘active’ MJO days during extended boreal winter November–March (NDJFM) is not significant at 95% confidence level (figure 2 in their study). However, given the fact that the correlation coefficient shown in the figure 2(b) of ZZ18 was still at 90% confidence level, the potential modulation of MJO amplitude by QBO need to be treated with more caution. On the other hand, the different notions about the QBO-MJO connection may be shaped by the different definitions used for winter (DJF for this study, NDJFM for ZZ18) and time spans (1979–2019 in our analysis, 1979–2016 in ZZ18) focused in these two studies. Nevertheless, it should be pointed out that our analysis does not invalidate all the results of ZZ18 on the QBO-MJO connection. Based on Lagrangian MJO tracking, the weaker barrier effect of the Maritime Continent on MJO propagation during EQBO demonstrated by ZZ18 can also be adopted to explain our findings of the QBO-MJO connection.

Figure 3 makes a comparison of the occurrence and averaged amplitude of each MJO phase during
different QBO winters. It is interesting to find that stratospheric QBO exert broad influences on all MJO phases, including the ‘active’ MJO phases 1–8 and ‘inactive’ MJO phase 0. The increment in the amplitude of individual MJO phase can be seen during the transition from westerly to easterly phase of QBO (figure 3(b)). Note that MJO phase 0 (‘inactive’ MJO days) also features a larger amplitude in EQBO winter, which is likely to diminish the occurrence of ‘inactive’ days and meanwhile increase the occurrence of ‘active’ days in winter, as shown in figure 3(a). Larger amplitude and higher occurrence of eight MJO phases in EQBO winter are evidence that preferable circumstance for the convective activity in EQBO winter likely influences whole evolution process of MJO including its initiation, development and extinction. In addition to the weaker barrier effect of the Maritime Continent, possible mechanisms with respect to static stability or wind shear around the tropical tropopause can also be applied to explain the modulation of MJO by QBO (Yoo and Son 2016, Son et al 2017).

The impact of QBO on MJO amplitude can be directly illustrated from the composite mean values of bandpass-filtered (20–100 days) OLR anomalies for each MJO phase in WQBO and EQBO winters (figures 4 and 5). When only ‘active’ MJO days (amplitude exceeds 1.0 and noticeable eastward propagation) are included as in figure 4, a distinct enhancement of convective activity during EQBO winter can be seen when compared to WQBO winter. Although the ‘inactive’ MJO days are rarely divided into eight phases in previous literature due to the unorganized and unrecognized convection related to ‘inactive’ MJO phases, it is evident from figure 5 that OLR anomalies for ‘inactive’ MJO phases during EQBO winters are also generally stronger than during WQBO winters.

The integrated effect of QBO on amplitude and occurrence of MJO can be simply represented by the sum of squared deviations from the climatological mean (simply, sum of squares (SS)) of the bandpass-filtered (20–100 days) OLR anomalies. Note that all winter days, including ‘active’ and ‘inactive’ MJO
days, are considered to calculate the SS field. Given the dipole pattern of the bandpass-filtered OLR anomalies for each MJO phase (figures 4 and 5), the DJF-mean of the filtered OLR anomalies in the tropics can be ignored roughly owing to the counteraction of those opposite patterns for first and second half of the MJO event (figure not shown). Thus, the SS is larger when the sample contain higher occurrence of larger values. Figure 6 shows the spatial distribution of the differences in the ‘averaged’ SS field between EQBO and WQBO winter. SS for EQBO and WQBO are divided by the number of winters (13 for EQBO, and 17 for WQBO) respectively. As expected, larger SS of filtered OLR in EQBO than in WQBO can be found all over Indo-Pacific warm pool region, which feature the MJO events.
4. Conclusions

Recently, literature has emerged that offers different understanding about the connection between QBO and MJO. ZZ18 argued that the significant correlation between QBO index and MJO amplitude proposed in previous studies (Yoo and Son 2016, Marshall et al. 2017, Son et al. 2017) are caused by more ‘active’ MJO days, not really by the larger amplitudes of MJO days in EQBO than in WQBO. Motivated by this argument, in this work, we re-examined the interannual variability of averaged amplitude and occurrence of MJO days during boreal winters (DJF), and also the connection between QBO and the amplitude as well as the occurrence of MJO. Both ‘active’ and ‘inactive’ MJO days were considered in this study for the possible transition between these two types of MJO days.

The central finding of this study is that there is a significantly positive (negative) correlation between the averaged amplitude and occurrence of ‘active’ (‘inactive’) MJO days in winters, suggesting that larger MJO amplitudes are accompanied by higher occurrence of ‘active’ and meanwhile lower occurrence of ‘inactive’ MJO days. This finding implies that variability in amplitude and occurrence of MJO should not be discussed separately. Then the correlations between MJO activities, including amplitude and occurrence of ‘active’ and ‘inactive’ days, and QBO index reveal that amplitudes of ‘active’ and ‘inactive’ MJO days during EQBO winters are larger than during WQBO winters, which is consistent with previous studies. More importantly, due to the modulation of MJO amplitude by QBO, we can also expect higher occurrence of ‘active’ MJO days and simultaneously lower occurrence of ‘inactive’ MJO days during EQBO winters than during WQBO winters. In addition, these responses of MJO activities to QBO are supported by the box plots as well, which visualizes the distribution of the daily amplitude under different QBO phases. Uniform change in the amplitude and occurrence of each MJO phase in different QBO phases not only implies the broad impact of QBO on MJO but also provides a clue for the potential mechanisms.

In brief, compared to WQBO, EQBO favors the development of tropical convection, leading to larger amplitude of MJO and then resulting in more MJO days shifting from ‘inactive’ to ‘active’ state. Thus, higher occurrence of ‘active’ MJO days and simultaneously lower occurrence of ‘inactive’ MJO days in EQBO winter can be expected. These results update our general understanding of QBO-MJO connection. A tighter relationship between QBO and MJO is established in this study. In view of the important role of QBO-MJO connection in predictability on S2S timescales, the tighter QBO-MJO connection will be helpful to advance the S2S prediction.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

Baldwin M P et al 2001 The quasi-biennial oscillation Rev. Geophys. 39 179–229
Cassou C 2008 Intraseasonal interaction between the Madden–Julian oscillation and the North Atlantic oscillation Nature 455 523–7
Collimore C C, Martin D W, Hitchman M H, Huesmann A and Waliser D E 2003 On the relationship between the QBO and tropical deep convection J. Clim. 16 2552–68
Ebdon R A and Veryard R G 1961 Fluctuations in equatorial stratospheric winds Nature 189 791–3
Emanuel K, Solomon S, Folini D, Davis S and Cagnazzo C 2013 Influence of tropical tropopause layer cooling on Atlantic hurricane activity J. Clim. 26 2288–301
Gray W M, Sheaffer J D and Knaff J A 1992 Hypothesized mechanism for stratospheric QBO influence on ENSO variability Geophys. Res. Lett. 19 107–10
Hamill T M and Kiladis G N 2014 Skill of the MJO and Northern Hemisphere blocking in GEFS and medium-range reforecasts Mon. Weather Rev. 142 868–85
Henderson S A and Maloney E D 2018 The impact of the Madden–Julian oscillation on high-latitude winter blocking during El Niño–Southern Oscillation events J. Clim. 31 5293–318
Henderson S A, Maloney E D and Barnes E A 2016 The influence of the Madden–Julian oscillation on Northern Hemisphere winter blocking J. Clim. 29 4597–616
Hersbach H et al 2020 The ERA5 global reanalysis Q. J. R. Meteorol. Soc. 146 1999–2049
Huesmann A S and Hitchman M H 2001 The stratospheric quasi-biennial oscillation in the NCEP reanalyses: climatological structures J. Geophys. Res. 106 11859–74
Kiladis G N, Dias J, Straub K H, Wheeler M C, Tulich S N, Kikuchi K, Weickmann K M and Ventrice M J 2014 A comparison of OLR and circulation-based indices for tracking the MJO Mon. Weather Rev. 142 1697–715
Kim H-M, Webster P J, Toma V E and Kim D 2014 Predictability and prediction skill of the MJO in two operational forecasting systems J. Clim. 27 5364–78
Kim H, Vitart F and Waliser D E 2018 Prediction of the Madden–Julian oscillation: a review J. Clim. 31 9425–43
Lau K-M and Waliser D E 2011 Intraseasonal Variability in the Atmosphere-Ocean Climate System 2nd (Heidelberg: Springer) p 613
Lavender S L and Matthews A J 2009 Response of the West African monsoon to the Madden–Julian oscillation J. Clim. 22 4097–116
Lee S 1999 Why are the climatological zonal winds easterly in the equatorial upper troposphere? J. Atmos. Sci. 56 1353–63
Li T, Wang L, Peng M, Wang B, Zhang C, Lau W and Kuo H 2018 A paper on the tropical intraseasonal oscillation published in 1963 in a Chinese journal Bull. Am. Meteorol. Soc. 99 1765–79
Lim Y, Son S-W, Marshall A G, Hendon H H and Seo K-H 2019 Influence of the QBO on MJO prediction skill in the subseasonal-to-seasonal prediction models Clim. Dyn. 53 1681–95
Lindzen R S and Holton J R 1968 A theory of the quasi-biennial oscillation J. Atmos. Sci. 25 1095–107
Madden R A and Julian P R 1971 Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific J. Atmos. Sci. 28 702–8
Madden R A and Julian P R 1972 Description of global-scale circulation cells in the tropics with a 40–50 day period J. Atmos. Sci. 29 1109–23
Madden R A and Julian P R 1994 Observations of the 40–50 day tropical oscillation—a review Mon. Weather Rev. 122 814–37
Marshall A G, Hendon H H, Son S-W and Lim Y 2017 Impact of the quasi-biennial oscillation on predictability of the Madden–Julian oscillation Clim. Dyn. 49 1365–77
Martin Z, Wang S, Nie J and Sobel A 2019 The Impact of the QBO on MJO Convection in Cloud-Resolving Simulations J. Atmos. Sci. 76 669–88
Nishimoto E and Yoden S 2017 Influence of the stratospheric quasi-biennial oscillation on the Madden–Julian oscillation during austral summer J. Atmos. Sci. 74 1105–25
Randel W and Jensen E 2013 Physical processes in the tropical tropopause layer and their roles in a changing climate Nat. Geosci. 6 169–76
Reid G C and Gage K S 1985 Interannual variations in the height of the tropical tropopause J. Geophys. Res. 90 5629–35
Seo K-H and Lee H-J 2017 Mechanisms for a PNA-like teleconnection pattern in response to the MJO J. Atmos. Sci. 74 1767–81
Seo K-H, Lee H-J and Frierson D M W 2016 Unraveling the teleconnection mechanisms that induce wintertime temperature anomalies over the Northern Hemisphere continents in response to the MJO J. Atmos. Sci. 73 3557–71
Son S, Lim Y, Yoo C, Hendon H H and Kim J 2017 Stratospheric control of the Madden–Julian oscillation J. Clim. 30 1909–22
Vitart F 2017 Madden–Julian oscillation prediction and teleconnections in the S2S database Q. J. R. Meteorol. Soc. 143 2216–20
Vitart F and Robertson A W 2018 The sub-seasonal to seasonal prediction project (S2S) and the prediction of extreme events npj Clim. Atmos. Sci. 1 1–7
Waliser D E 2011 Predictability and forecasting Intraseasonal Variability of the Atmosphere-Ocean Climate System 2nd edn (Heidelberg: Springer) p 613
Wang S, Tippett M K, Sobel A H, Martin Z and Vitart F 2019 Impact of the QBO on prediction and predictability of the MJO convection J. Geophys. Res. 124 11766–82
Wheeler M C and Hendon H H 2004 An all-season real-time multivariate MJO index: development of an index for monitoring and prediction Mon. Weather Rev. 132 1917–32
Yoo C, Lee S and Feldstein S B 2012 Mechanisms of extratropical surface air temperature change in response to the Madden–Julian oscillation J. Clim. 25 5777–90
Yoo C and Son S-W 2016 Modulation of the boreal wintertime Madden–Julian oscillation by the stratospheric quasi-biennial oscillation Geophys. Res. Lett. 43 1392–8
Zhang C 2005 Madden–Julian oscillation Rev. Geophys. 43 RG2003
Zhang C 2013 Madden–Julian oscillation: bridging weather and climate Bull. Am. Meteorol. Soc. 94 1849–70
Zhang C and Zhang B 2018 QBO-MJO connection J. Geophys. Res. 123 2957–67