Response to Anonymous Referee # 1

Major Comments:

1. Comment: While I appreciate the power of the STRIPES analysis, I must point out that the first time I read the paper I did not understand at all what the authors were doing. Only after skimming Jenney et al 2019 and looking at supplemental figure 1 did I fully understand what was happening. I worry that a casual reader may be less patient. To be constructive, I suggest that supplemental figure 1 be included in the main text, and I would also suggest adding a figure of lat vs. lon Z500 with a few panels corresponding to different periods explicitly showing how the wave train leads to Z500 alternating anomalies. I realize this is already in Jenney et al but a new, at first not intuitive, index needs a certain amount of repetition. As as aside, I was surprised that the STRIPES was just as strong in the European sector as in North Pacific/ NorthAmerica. I would have expected a stronger response closer to the Pacific. The ACC results also indicate that the additional predictability from the MJO is mainly in the Atlantic sector too rather than the North Pacific (Figures 4 and 5). To me this is counter-intuitive, as the MJO should immediately and directly affect the North Pacific, especially in the first few weeks, and then affect the Atlantic more weakly later on. Additional discussion would be helpful. (I can try to reason why my intuition is incorrect, but really the authors should help with this)

    (a) Response:

    We agree that the STRIPES index is new and may not be familiar to the reader. Therefore, as suggested, we have added supplemental Figure 1 to the main paper in Section 2.3: Methods. We have additionally added two panels of spatial z500 anomalies at lead 12 days following phase 6 and phase 2 of the MJO to additionally aid the reader in understanding STRIPES.

    We have also included additional text: *"... Specifically, a composite of average z500 anomalies for each MJO phase and lead (phase-lead diagram) is created for each grid point in the Northern Hemisphere (example shown in Figure 1a). For further intuition of the phase-lead diagram, Figure 1a and 1b show composite z500 anomalies for the domain around 45°N and 5°W (marked by the white X) 12 days following phase 6 and phase 2, respectively. The value of the box in the phase-lead diagram is the same as the value plotted at the X in Figure 1b,c. In a phase-lead diagram, MJO induced quasi-stationary rossby waves are apparent as slowly alternating-sign z500 anomalies with lead following a specific phase of the MJO (e.g. Figure 1a). In addition, the MJO is a propagating phenomenon with a phase speed of approximately 5-8 days/phase. Therefore, if there is a teleconnection signal 10 days following phase 2, this signal is likely also present 5 days following phase 3 in the same region, in a composite sense. On a phase-lead diagram, this is seen as a diagonal line or 'stripe' slanted at the phase speed of the MJO (Figure 1a). Therefore, if a region is sensitive to the MJO, we expect alternating z500 anomaly stripes approximately sloped at the average phase speed of the MJO, as in Figure 1a, which we refer to as the 'stripey-ness'.*

    To calculate STRIPES, averages along the slopes in the phase-lead diagram corresponding to the MJO phase speed are calculated, and if there are alternating stripes (i.e. sensitivity to the MJO), the resulting averages concatenated together will oscillate between positive and negative z500 anomalies as a sine wave, for which the amplitude can be calculated. The amplitude of this oscillatory vector is the STRIPES index (Jenney et al. 2019)."

    In regards to the STRIPES result of the North Pacific, the reviewer mentions that the Pacific and European sectors have similar STRIPES values. We hypothesize that the Atlantic and European sectors may have similar STRIPES values to the Pacific from enhanced blocking over the Atlantic and Europe following the MJO (Henderson et al. 2016) leading to more persistent stripes.

    This explanation has been added to Section 3.1: Extratropical Sensitivity: *"Interestingly, the Pacific and Atlantic sectors have similar STRIPES values. One may expect higher STRIPES values over the Pacific compared to the Atlantic since the Pacific is generally known to have a strong response to the MJO. We hypothesize that the Atlantic and European sectors also have similar STRIPES values to that of the Pacific due to enhanced blocking over the Atlantic and Europe at later leads following the MJO (Henderson et al. 2016). Since the STRIPES index accounts* *for all leads as well as the strength and consistency of the z500 anomalies, we therefore may expect STRIPES values over the Atlantic and European sectors to be large as well."*

In terms of the ACC result showing additional prediction skill from the MJO in Atlantic/European sector rather than over the Pacific, this is likely because prediction skill on Week 1 timescales is already generally good over all locations, and it is on this weekly timescale that the Pacific is most strongly impacted by MJO teleconnections. Therefore, we may not expect the prediction skill to be significantly different over the Pacific for these early leads. Where we would expect the MJO to provide additional prediction skill is on longer than one week timescales.

This additional explanation has been added to Section 3.2.1: *"Note that prediction skill at one week lead times is not likely to be significantly different following active MJOs compared to inactive MJOs since forecast models already have relatively good prediction skill for these early leads. Where we would expect the MJO to provide additional prediction skill is on timescales longer than one week."*

2. Comment: Between lines 192 and 203 the authors form an argument that I don't find convincing. As this argument underlies the reset of the paper, this is a major issue. To this reviewer, the clearest evidence that the QBO can enhance MJO related prediction skill would be if the difference in ACC between EQBO/MJO and EQBO/noMJO or between WQBO/MJO and WQBO/noMJO is larger than the difference between noQBO/MJO and noQBO/noMJO. Based on supplemental table 1 it seems that this kind of comparison isn't possible due to possible contamination by the ENSO signal, though perhaps the authors could compute the mean Nino3.4 index for each composite included on supplemental table 1. If the mean Nino3.4 value for each composite is small, then La Nina and El Nino events balance out and the net prediction skill added by ENSO is small. Instead the authors evaluate a pair of differences that only partially reflect on whether the QBO is enhancing MJO related prediction skill, but rather reflect alternately on whether there is prediction skill associated with the MJO, and separately whether is prediction skill associated with the QBO (in Figures 4-6). Unless the authors perform the test in the previous paragraph, there is no basis for this statement of the authors "When these two significances appear together, we can say that a particular strong QBO increases the impact of the MJO on midlatitude prediction skill". Stated another way, the difference EQBO/MJO minus noQBO/MJO does not reflect anything about the MJO per se. Rather it reflects skill associated with EQBO. Hence I don't find figure 6 useful, other than the fact that it shows that the QBO enhances skillful forecasts in the Atlantic sector (which is a nice result, and consistent with Garfinkel et al 2018 already cited and Boer and Hamilton 2008, but the authors interpretation is completely different). In order for Figure 6 to have any bearing on the MJO, the authors need to include an additional figure showing EQBO/noMJO minus noQBO/noMJO to which we can compare the difference shown in figure 6. If there is a significant difference between EQBO/MJO minus noQBO/MJO as compared to EQBO/noMJO minus noQBO/noMJO, then there is evidence that there is some mutual interaction between the MJO and the EQBO. The authors could then rinse and repeat for WQBO. In its present form, the authors analysis only convinces me that both the QBO or the MJO separately enhance predictability on S2S timescales in these models as compared to noQBO or noMJO.

   (a) Response:

   This reviewer mentions that the two types of significance the authors use are insufficient as evidence for whether the QBO can enhance MJO related prediction skill. We appreciate this comment as the authors now realize how the results, as originally posed, were confusing. In fact, we completely agree with the reviewer on what must be done to make this convincing, but realize now that some of the important steps were too quickly glossed over since they ultimately had little impact on the result. With this in mind, we have now rewritten the results section on prediction skill, and in the process, added some additional analysis to make the argument even stronger in a statistical sense. Given the statistical tests added, the resulting figures have changed - however, the overall story remains the same as requirements 1-3 were already considered/included in the earlier version of the paper. We want to thank this reviewer for their insightful comments to help us improve the heart of this paper. Specifically, we now have added 3 "requirements" that can hopefully now be more clearly stated and followed throughout the results discussion and figures. The first requirement is the presence of an MJO impact on midlatitude prediction skill during specific phases of the QBO, where an 'MJO impact' on midlatitude prediction skill is defined as a significant difference in midlatitude ACC between active MJO and inactive MJO events. The second requirement is that the magnitude of the significant MJO impact under strong QBOs is significantly larger than the significant MJO impact under NQBO. As also highlighted by the reviewer, the second requirement is calculated through a comparison of the MJO impact during strong QBOs to the MJO impact during NQBO. These two requirements together ensure that (1) there is an MJO impact and (2) that this impact is enhanced during strong QBOs compared to neutral QBOs. The third requirement is the presence of regions/leads where E/WQBO-MJO events significantly lead to higher prediction skill than NQBO-MJO given requirement 1 and 2 are satisfied. We applied this requirement to see if regions with enhanced MJO impacts during strong QBOs also have overall greater prediction skill following active MJO events compared to NQBO-MJO events, as regions of enhanced prediction skill is the focus of this paper. The reviewer also points out the small sample size of NQBO-noMJO. We agree the sample size is small and while there is not much that can be done about it, our new results include significance tests at every step that take into account the small sample sizes. We include the following discussion in the paper: *"It should be noted that inactive MJOs during NQBO events with ENSO removed only occur 12 times in ECMWF and 3 times in NCEP. When this is the case, there is shading across all longitudes (Figure S5). If ENSO events are not removed, the sample sizes increase to 47 and 52, for ECMWF and NCEP respectively (see Table S1). When we calculate the MJO impact during NQBO when ENSO is included (Figure S6), we see that much of the shading east of 0° is not apparent. The presence of skill east of 0° when ENSO is not included may be due to small sample sizes of the NQBO events. Thus, when comparing MJO impacts between strong and neutral QBOs, it is important to keep sample size in mind. That being said, the statistical analysis we have applied here for requirements 1-3 account for the small sample sizes in the analysis."*

3. Comment: I found section 3.2.5 extraneous and hard to understand without first skimming Tseng et al 2018. Consider deleting.

    (a) Response: Thank you for this comment. The other reviewer had similar concerns and so we have decided to remove Section 3.2.5: Northern Hemisphere Prediction Skill and Sensitivity.

Minor comments:

4. Comment: Line 13 "7-14 days", actually there is enhanced predictability up to day 28 in figures 4-6. Why limit to 14 days?

    (a) Response: Thank you for pointing this out. It was an oversight, and we have updated it to say "Week 1-4".

5. Comment: Line 77 There is earlier work that argues that the QBO may modulate ENSO teleconnections. See Garfinkel and Hartmann 2010, Richter et al 2015, and Hansen et al 2016

    (a) Response: We have added QBO effects on ENSO teleconnections to the ENSO discussion in the methods. *"Some earlier research indicates that ENSO has a limited impact on the QBO-MJO interaction (e.g. Yoo and Son 2016; Nishimoto and Yoden 2017); however, recent work on QBO-MJO teleconnections has shown a possible dependency of results on ENSO (Son et al., 2017; Wang et al., 2018; Sun et al., 2019). In addition, other research suggests that the QBO affects ENSO teleconnections (Garfinkel and Hartmann, 2010; Richter et al., 2015; Hansen et al., 2016), which may consequently impact the MJO and its teleconnections."*

Technical comments:

6. Comment: Line 2 stationary Rossby wave **and** tropical-extratropical teleconnections

    (a) Response: Thank you for this comment. We have changed this sentence to say: *"The Madden-Julian Oscillation (MJO) is known to force extratropical weather days-to-weeks following an MJO event through excitation of stationary Rossby waves, also referred to as tropical-extratropical teleconnections."*

7. Comment: Line 19 excitation of **quasi**stationary Rossby waves (the MJO can't force stationary waves on monthly mean or seasonal mean timescales)

(a) Response: Fixed. Thank you.

8. Comment: Line 126 the reference to figure 3 seems incorrect. Figure 3 shows something else entirely.

   (a) Response: This should say Supplemental Figure 3. This has been corrected. Thank you.

9. Comment: Figure 1, title of bottom-right panel is incorrect (It probably should be WQBO-MJO)

   (a) Response: Fixed. Thank you.

Response to Anonymous Referee # 2

1. Section 2.3: I suggest the authors revise the method section to make it more accessible to a broader audience. The authors also jump into explaining the details of each analysis technique (i.e., STRIPES and ACC). Before jumping into the details, it would be helpful to the readers if the authors could first outline what they attempt to quantify and how it relates to the objective of this study. More specifically, I suggest the following points.

   1.1) Comment: For readers who are unfamiliar with Jenney et al. 2019, it would be difficult to understand the STRIPES index. I suggest to move the Supplemental Figure S1 to the main manuscript and include further visual illustrations on how the STRIPES index is calculated.

   (a) Response:
   We agree that the STRIPES index is new and may not be familiar to the reader. Therefore, as suggested, we have added supplemental Figure 1 to the main paper in Section 2.3: Methods. We have additionally added two panels of spatial z500 anomalies at lead 12 days following phase 6 and phase 2 of the MJO to additionally aid the reader in understanding STRIPES. We have also included additional text: "... Specifically, a composite of average z500 anomalies for each MJO phase and lead (phase-lead diagram) is created for each grid point in the Northern Hemisphere (example shown in Figure 1a). For further intuition of the phase-lead diagram, Figure 1a and 1b show composite z500 anomalies for the domain around 45°N and 5°W (marked by the white X) 12 days following phase 6 and phase 2, respectively. The value of the box in the phase-lead diagram is the same as the value plotted at the X in Figure 1b,c. In a phase-lead diagram, MJO induced quasi-stationary rossby waves are apparent as slowly alternating-sign z500 anomalies with lead following a specific phase of the MJO (e.g. Figure 1a). In addition, the MJO is a propagating phenomenon with a phase speed of approximately 5-8 days/phase. Therefore, if there is a teleconnection signal 10 days following phase 2, this signal is likely also present 5 days following phase 3 in the same region, in a composite sense. On a phase-lead diagram, this is seen as a diagonal line or 'stripe' slanted at the phase speed of the MJO (Figure 1a). Therefore, if a region is sensitive to the MJO, we expect alternating z500 anomaly stripes approximately sloped at the average phase speed of the MJO, as in Figure 1a, which we refer to as the 'stripey-ness'.

   To calculate STRIPES, averages along the slopes in the phase-lead diagram corresponding to the MJO phase speed are calculated, and if there are alternating stripes (i.e. sensitivity to the MJO), the resulting averages concatenated together will oscillate between positive and negative z500 anomalies as a sine wave, for which the amplitude can be calculated. The amplitude of this oscillatory vector is the STRIPES index (Jenney et al. 2019)."

   1.2) Comment: I suggest the authors add more discussion on the novelty and benefits of STRIPES analysis. Why do the authors choose to use the STRIPES index to quantify the model's ability to represent MJO teleconnection instead of using some other simpler techniques (e.g., averaging absolute values of z500 anomaly composites based on RMM phases)?

(a) Response:

The STRIPES index was used over more common techniques because it allows us to regionally quantify the strength, consistency and propagation of the MJO impact on the extratropics using only one metric. This has been added to the text: "Therefore, the STRIPES index allows us to regionally quantify the strength, consistency and propagation of the MJO impact on the extratropics and thus, allows us to quantify the ability of hindcast models to capture tropical-extratropical teleconnections on one to four week timescales in a single metric."

1.3) Comment: Discussion on potential caveats of STRIPES analysis should also be included. For example, as discussed by the authors, the propagation speed of the MJO can change with the QBO. In such a case, using the same phase speed to calculate the STRIPES index could be problematic. Is the sensitivity to choosing different phase speeds tested?

(a) Response:

As the reviewer suggests, the changes in phase speed of MJO under different phases of the QBO may impact the STRIPES values. This is also discussed in Jenney et al. (2019) if the reviewer is interested in further discussion. Specific to this work, we conducted a sensitivity analysis and found that our STRIPES analysis and conclusions are not sensitive to the exact value of the phase speed over the range of observed phase speeds of 5-8 days/phase. This analysis of the sensitivity of the STRIPES index to the phase speed of the MJO is now included in the text: "It should be noted that the westerly phase of the QBO has been documented to reduce the propagation speed of the MJO (Nishimoto and Yoden 2017), however, we find that our STRIPES results are robust to changes in phase speed of +/- 2 days/phase."

1.4) Comment: Line 108: Please clarify what "the resultant vector" means.

(a) Response:

We have removed the term 'resultant vector', and replaced the sentence with a more detailed description. "To calculate STRIPES, averages along the slopes in the phase-lead diagram corresponding to the MJO phase speed are calculated, and if there are alternating stripes (i.e. sensitivity to the MJO), the resulting averages concatenated together will oscillate between positive and negative z500 anomalies as a sine wave, for which the amplitude can be calculated. The amplitude of this oscillatory vector is the STRIPES index (Jenney et al. 2019)."

2. Section 3.1: I was a bit confused about how to interpret the results in this section. The authors explain that Figures 1 and 2 represent the sensitivity of z500 anomaly to the MJO and QBO states. However, when the authors apply the normalization, the maps appeared noisier and no regions stood out to be "sensitive" to the MJO and QBO states (in Fig. 3). Does this mean that the regions of high values in Figs. 1-2 are just regions of greater variance in z500 and do not necessarily represent the high sensitivity to the MJO and QBO? I suggest the authors recreate Figs. 1 and 2 using normalized z500 anomalies (e.g., by the standard deviation of z500), which I think would be a more proper way to show the sensitivity of z500 to the MJO and QBO states.

   (a) Response:

   We do not standardize the z500 anomalies in Figure 1, 2 and 3 because the variance of z500 has greater variability in the midlatitudes compared to the tropics and therefore, may mute the extratropical signal. Furthermore, differences in composite anomaly amplitude between EQBO and WQBO are also of interest for this work. If we normalize the EQBO and WQBO by their respective maximum anomaly amplitudes in the original Figure 1 and 2 (results shown in the original Figure 3), we ignore this potential difference between the two QBO phases (i.e. one phase could lead to stronger anomalies, in a mean or event-by-event sense, than the other). In section 2.3, we state: "Also note that since our application focuses on extratropical sensitivity in z500, we use z500 anomalies in terms of meters instead of standard deviation for STRIPES, different from Jenney et al. (2019). Standardization may mute the extratropical signal due to the greater variability of z500 in the midlatitudes, which is of main interest here. In addition, we wish to retain any differences in z500 anomaly amplitudes between the QBO phases." The fact that the normalized plots look different compared to the non-normalized plots suggests that this anomaly amplitude difference may be appreciable between the two QBO phases, and thus, we choose not to normalize here. In regards to the standardization technique used for Figure 3 (now Figure S2), the reviewer mentions the noisiness of the figure and lack of specific regions 'sensitive' to the MJO. Since we divided by the absolute max of the z500 anomalies to normalize, the noisiness suggests the importance of the combined influence of the magnitude of the z500 anomaly as well as the stripy-ness to determine regions of sensitivity. Furthermore, the maximum is itself a noisy value. Due to the extensive confusion from this figure, and the fact that it is not a main part of this paper's focus, we have moved it to supplemental material.

2.1) Comment: And please clarify what "distinct stripes" on line 176 and "stripey-ness" on line 181 mean.

(a) Response:

We have added a more detailed description of distinct stripes and stripey-ness: "In addition, the MJO is a propagating phenomenon with a phase speed of approximately 5-8 days/phase. Therefore, if there is a teleconnection signal 10 days following phase 2, this signal is likely also present 5 days following phase 3 in the same region, in a composite sense. On a phase-lead diagram, this is seen as a diagonal line or 'stripe' slanted at the phase speed of the MJO (Figure 1a). Therefore, if a region is sensitive to the MJO, we expect alternating z500 anomaly stripes approximately sloped at the average phase speed of the MJO, as in Figure 1a, which we refer to as the 'stripey-ness'."

3. Section 3.2: There were many interesting results presented in this section, but some interpretations of the results must be done more carefully. One of the conclusions that the authors make is that the prediction skills increase during MJO active states when combined with WQBO more than with EQBO states (section 3.2.4). This could be because there is a greater difference in the MJO amplitude between its active and inactive periods during WQBO then EQBO. I suggest the authors check the average amplitude of the RMM index during the different combination states of the QBO and MJO. Another point to check is if the similar samples of different RMM phases are included in each combination of QBO and MJO states. If there are any skewness in the samples of RMM phases, that should be considered for the interpretation of the Results.

(a) Response:

The reviewer suggests that the more prevalent enhanced prediction skill following active MJOs during WQBO over EQBO may be due to the differences in MJO amplitude, and suggest that the authors look at the RMM index. This is a great suggestion, and a few recent studies have found that the amplitude of the MJO is enhanced during EQBO compared to WQBO (e.g. Son et al. 2017, Nishimoto and Yoden 2017, Densmoore et al. 2019) while another says that EQBO has a greater number of strong MJOs than WQBO (Zhang and Zhang 2018). Neither findings explain why WQBO-MJO appears to impact the midlatitude prediction skill more than EQBO-MJO. The reviewer also suggests that we check the skewness of samples of MJO phases within the analysis. This has also been calculated in Zhang and Zhang (2018), where they found that the MJO tends to propagate further into the Pacific Ocean during EQBO. However, this also does not explain why WQBO-MJO appears to impact the midlatitude prediction skill more than EQBO-MJO. With all of this said, this paper is specifically about the resulting changes in prediction skill under different QBO-MJO states, rather than a dynamical explanation behind the changes in prediction skill. This is an important next step for this work.

4. Section 3.2.5: The authors could consider eliminating this section. I am not sure how much value is added by including this section. The general finding that is summarized in this section (i.e., no relationship between z500 sensitivity and prediction skill) could be summarized in a few sentences in the summary or conclusion section.

(a) Response:

Thank you for this comment. The other reviewer had similar concerns and so we have decided to remove Section 3.2.5: Northern Hemisphere Prediction Skill and Sensitivity.

5. Lines 336-338: I think it would be nice to add more information/discussion on the dynamics behind the importance of WQBO state to the NAO and AR associated with the MJO

   (a) Response:

   The dynamics behind the importance of WQBO-MJO connection on the NAO and ARs is on going research. We agree this would be an interesting discussion, and an important next step. In the introduction, we hypothesize that the QBO may impact ARs through “its modulation of MJO-induced Rossby waves, and consequently, changes in the steering and frequency of atmospheric rivers.” However, the paper specifically focuses on the resulting changes in prediction skill rather than the dynamical explanation behind these changes in prediction skill, and therefore, is beyond the scope of the paper.

Subseasonal Midlatitude Prediction Skill Following QBO-MJO Activity

Kirsten J. Mayer [1] and Elizabeth A. Barnes [1]

[1]Department of Atmospheric Science, Colorado State University, Fort Collins, CO, USA.

Correspondence: Kirsten J. Mayer (kjmayer@rams.colostate.edu)

Abstract. The Madden-Julian Oscillation (MJO) is known to force extratropical weather days-to-weeks following an MJO event through excitation of stationary Rossby waves, also referred to as tropical-extratropical teleconnections. Prior research has demonstrated that this tropically forced midlatitude response leads to increased prediction skill on subseasonal to seasonal (S2S) timescales. Furthermore, the Quasi-Biennial Oscillation (QBO) has been shown to possibly alter these teleconnections through modulation of the MJO itself and the atmospheric basic state upon which the Rossby waves propagate. This implies that the MJO-QBO relationship may affect midlatitude circulation prediction skill on S2S timescales. In this study, we quantify midlatitude circulation sensitivity and prediction skill following active MJOs and QBOs across the Northern Hemisphere on S2S timescales through an examination of the 500 hPa geopotential height field. First, a comparison of the spatial distribution of Northern Hemisphere sensitivity to the MJO during different QBO phases is performed for ERA-Interim reanalysis and ECMWF and NCEP hindcasts. Secondly, differences in prediction skill in ECMWF and NCEP hindcasts are quantified following MJO-QBO activity. ~~We~~ In both hindcast systems, we find that regions across the Pacific, North America and the Atlantic ~~exhibit increased prediction skill following MJO-QBO activity, but these regions are not always collocated with the locations most sensitive to the MJO under a particular QBO state. Both hindcast systems demonstrate enhanced prediction skill 7-14 days following active MJO events~~ demonstrate an enhanced MJO impact on prediction skill during strong QBO periods on Week 1-4 lead times compared to MJO events during neutral QBO periods.

1 Introduction

Previous research has focused on the impact of the Madden-Julian Oscillation (MJO) on the extratropical circulation in order to extend midlatitude prediction skill (e.g. Henderson et al., 2016; Baggett et al., 2017; Tseng et al., 2018; Zheng et al., 2018). The MJO is a 20-90 day tropical intraseasonal convective oscillation (Madden and Julian, 1971, 1972, 1994), and through its convective heating, initiates an extratropical response through the excitation of ~~stationary~~ quasi-stationary Rossby waves. These waves modulate the mid-latitude circulation days to weeks following MJO activity and have been shown to provide coherent and consistent modulation of midlatitude circulation into subseasonal-to-seasonal (2-5 Weeks; S2S hereafter) timescales (e.g. Hoskins and Karoly 1981; Sardeshmukh and Hoskins 1988; Henderson et al. 2016; Tseng et al. 2018).

More recent research has demonstrated a dependence of the MJO on a stratospheric phenomenon known as the Quasi-biennial Oscillation (QBO). The QBO is an approximately 28 month, downward propagating zonal mean, zonal wind oscillation in the tropical stratosphere and has many subsequent impacts such as modulation of the upper tropical troposphere (e.g. Collimore et al. 2003; Garfinkel and Hartmann 2011b; Son et al. 2017), the subtropical jet (e.g. Simpson et al. 2009; Garfinkel and Hartmann 2011a) and the stratospheric polar vortex (e.g. Holton and Tan 1980; Garfinkel et al. 2018). The QBO is typically divided into two phases, easterly and westerly (EQBO and WQBO, respectively), determined by the direction of the anomalous zonal wind in the lower tropical stratosphere (Baldwin and Dunkerton, 2001). Recent work has shown that the MJO convective envelope tends to be stronger and have slower eastward propagation and longer path lengths during EQBO compared to WQBO (Son et al., 2017; Nishimoto and Yoden, 2017; Densmore et al., 2019; Zhang and Zhang, 2018). Son et al. (2017) hypothesize that this slower MJO propagation during EQBO is a consequence of strengthened MJO convection, as stronger MJO events tend to propagate more slowly across the Maritime Continent. However, Zhang and Zhang (2018) argue that stronger MJO wintertime events during EQBO are a consequence of a greater number of MJO days instead of larger amplitudes of individual MJO events. While there are still uncertainties regarding the exact impacts of the QBO on the MJO, these studies demonstrate the importance of considering the QBO in MJO research.

Much of the recent MJO-QBO research has focused on the direct impacts of the QBO on the tropical tropopause, and thus, MJO activity, while only a handful of studies have examined how the QBO subsequently impacts MJO teleconnections ~~(Baggett et al., 2017; Mundhenk et al., 2018; Wang et al., 2018)~~(e.g. Baggett et al., 2017; Mundhenk et al., 2018; Wang et al., 2018). Baggett et al. (2017) and Mundhenk et al. (2018) emphasize the impact of the QBO on MJO teleconnections through its modulation of MJO-induced Rossby waves, and consequently, changes in the steering and frequency of atmospheric rivers. Wang et al. (2018) found that when accounting for the phase of the QBO, the amplitude of the North Pacific storm track shift in response to MJO activity is greater during EQBO compared to WQBO, which they hypothesize to be from increased MJO strength during EQBO.

An MJO-QBO relationship has also been found in dynamical models. For example, Abhik and Hendon (2019) recently demonstrated that hindcast simulations, initialized with observations during active MJOs, capture the increase in MJO amplitude and maintenance during EQBO events after about 5 days. In addition, this strengthened MJO amplitude during EQBO has been shown to translate to increased MJO prediction skill (Marshall et al., 2017; Lim et al., 2019), suggesting that the prediction skill of the subsequent midlatitude teleconnections may also increase following the MJO under EQBO conditions. Baggett et al. (2017) further ~~show that S2S~~ shows that prediction skill of atmospheric rivers ~~is increased~~ on Week 1-2 timescales varies with QBO phase within ECMWF hindcasts over North America ~~out to 3 weeks~~ following MJO activity. This highlights the potential for an MJO-QBO relationship to modulate midlatitude prediction skill on S2S timescales.

Since hindcast models capture the increase in MJO amplitude during EQBO as well as exhibit enhanced prediction skill of the MJO in Weeks 1-3 under strong QBOs, this raises the question as to whether the MJO-QBO relationship also translates to enhanced prediction skill of MJO teleconnections under specific QBO phases. This paper explores this question through an analysis of the influence of the QBO on midlatitude prediction skill following active MJOs on S2S timescales within the ECMWF and NCEP hindcasts.

2 Data and Methodology

2.1 Data

We utilize daily mean 500-hPa geopotential height (z500; years 1979-2017) from the European Centre for Medium-Range Weather Forecasts Interim reanalysis (ERA-I; Dee et al. 2011) as well as the ECMWF and NCEP hindcasts obtained from the S2S database ~~(Vitart, 2017)~~ established by the World Weather Research Program/World Climate Research Program (WWRP/WCRP; Vitart 2017). The ECMWF hindcasts are composed of 11 ensemble members with hindcasts initialized 4 times a week (years 1995-2016). The NCEP hindcasts are composed of 4 ensemble members with hindcasts initialized daily (years 1999-2010). ~~The~~ In the following analysis, the ensemble mean for both models was used, and so, the different number of members between ECMWF and NCEP may contribute to differences in results between models. ~~In the following analysis, the ensemble mean for both models was used.~~

We focus on December, January and February (DJF) since MJO teleconnections are strongest during boreal winter (e.g. Madden 1986), and the relationship between the MJO and QBO is strongest during these months as well (e.g. Yoo and Son 2016; Son et al. 2017). The annual cycle is removed from the ERA-I reanalysis by subtracting the daily climatology of z500 across 1979-2017 from the z500 field. For the hindcast models, a daily, lead-dependent climatology is subtracted from each models' z500 field. To do this, we calculate the daily climatology for each lead time independently. Since the ECMWF model is not initialized daily, two (forward and backward moving) 31-day running means are applied to the climatology at all lead times to reduce noise, following Sun et al. (2018). These smoothed lead-dependent daily climatologies are then subtracted from the z500 field of the corresponding model to remove the annual cycle.

There is presently no definitive understanding of the impact of the El Nino Southern Oscillation (ENSO) on the QBO-MJO relationship. Some earlier research indicates that ENSO has a limited impact on the QBO-MJO interaction (e.g. Yoo and Son 2016; Nishimoto and Yoden 2017); however, recent work on QBO-MJO teleconnections has shown a possible dependency of results on ENSO (Son et al., 2017; Wang et al., 2018; Sun et al., 2019). In addition, other research suggests that the QBO affects ENSO teleconnections (Garfinkel and Hartmann, 2010; Richter et al., 2015; Hansen et al., 2016), which may consequently impact the MJO and its teleconnections. Thus, in an attempt to ensure our results are not somehow biased by ENSO, we use the Nino3.4 Index (climatedataguide.ucar.edu/climate-data) to remove strong ENSO winter seasons from our analysis. Specifically, when the amplitude of the NINO3.4 index for a month within DJF is greater than 1°C (signifying El Nino) or less than -1°C (signifying La Nina), that DJF season is excluded from the analysis. With that said, we have repeated our analysis with ENSO seasons included and find ~~our~~ that our STRIPES conclusions remain the same. The prediction skill conclusions also remain the same during EQBO, but the WQBO results appear more sensitive to ENSO (see Supplemental Figures ~~S7-S10).~~ S6-S9). The impact of ENSO on the MJO-QBO relationship and their teleconnections still remains an active area of research.

2.2 MJO and QBO Indices

The real-time multivariate MJO (RMM) index is used to define the amplitude and phase of the MJO in the ERA-I reanalysis (Wheeler and Hendon, 2004). This index uses empirical orthogonal function (EOF) analysis applied to anomalous outgoing longwave radiation (OLR) and 200- and 850-hPa zonal wind, near-equatorially averaged (15°S to 15°N), to determine the first two principal components (RMM1 and RMM2). A day is considered to have an active MJO when the RMM amplitude for that day (defined as $\sqrt{(RMM1^2 + RMM2^2)}$) is greater than 1.0. The MJO phase is then defined as $tan^{-1}(RMM2/RMM1)$ and largely corresponds to the longitudinal location of the convective envelope. Active MJO dates within ERA-I that correspond to initialization dates in ECMWF and NCEP are determined from this index. The RMM index is not separately calculated for each hindcast model because we do not aim to quantify the ability of the models to forecast the MJO directly (e.g. Vitart 2017). Rather, we use the index calculated from reanalysis to see how the hindcast models initialized on observed active MJO days ultimately forecast MJO teleconnections.

Identical to the definition of ~~(Yoo and Son, 2016)~~Yoo and Son (2016), the QBO index is calculated within ERA-I using monthly standardized zonal wind at 50-hPa, area-averaged between 10°S to 10°N. Westerly QBO (WQBO) and Easterly QBO (EQBO) events are defined as when the standardized value is greater than 0.5σ or less than -0.5σ, respectively. Absolute values less than 0.5σ are considered neutral QBO (NQBO) events.

2.3 Methods

Quantification of each models' ability to represent MJO teleconnections under different QBO phases is conducted using the Sensitivity to the Remote Influence of Periodic Events (STRIPES) index (Jenney et al., 2019). STRIPES is an index recently developed to determine regions of extratropical sensitivity to remote periodic events such as the MJO. As used here, the STRIPES index quantifies the strength and consistency of MJO teleconnections in z500 through average phase and 0-28 day lead information at individual grid points for a variety of observed phase speeds (5-8 days/phase; Wheeler and Hendon 2004). Specifically, a composite of average z500 anomalies for each MJO phase and lead (phase-lead diagram) is created for each grid point in the Northern Hemisphere ~~. If a region is~~ (example shown in Figure 1a). For further intuition of the phase-lead diagram, Figure 1a and 1b show composite z500 anomalies for the domain around 45°N and 5°W (marked by the white X) 12 days following phase 6 and phase 2, respectively. The value of the box in the phase-lead diagram is the same as the value plotted at the X in Figure 1b,c. In a phase-lead diagram, MJO induced quasi-stationary rossby waves are apparent as slowly alternating-sign z500 anomalies with lead following a specific phase of the MJO (e.g. Figure 1a). In addition, the MJO is a propagating phenomenon with a phase speed of approximately 5-8 days/phase. Therefore, if there is a teleconnection signal 10 days following phase 2, this signal is likely also present 5 days following phase 3 in the same region, in a composite sense. On a phase-lead diagram, this is seen as a diagonal line or 'stripe' slanted at the phase speed of the MJO (Figure 1a). Therefore, if a region is sensitive to the MJO, we expect alternating z500 anomaly stripes approximately sloped at the average phase speed of the MJO~~in the phase versus lead diagram (as seen in Supplemental Figure S1 for example). Regions not sensitive to the~~

~~MJO will appear noisy with smaller amplitudes and less coherent stripes. Averages~~ , as in Figure 1a, which we refer to as the 'stripey-ness'.

To calculate STRIPES, averages along the slopes in the phase-lead diagram corresponding to the MJO phase speed are calculated, and if there are alternating stripes (i.e. sensitivity to the MJO), the ~~resultant vector will look like~~ resulting averages concatenated together will oscillate between positive and negative z500 anomalies as a sine wave, for which the amplitude can be calculated. The amplitude of this oscillatory vector is the STRIPES index (~~Jenney et al. 2019). Therefore, the~~ Jenney et al. 2019). The more sensitive the region is to MJO teleconnections, the larger the STRIPES index. ~~Since our application focuses on extratropical sensitivity in z500, we do not standardize our data for STRIPES as in Jenney et al. (2019). Standardization may mute the extratropical signal due to~~ Therefore, the ~~greater variability of z500 in the midlatitudes, which is of main interest here.~~ STRIPES index allows us to regionally quantify the strength, consistency and propagation of the MJO impact on the extratropics and thus, allows us to quantify the ability of hindcast models to capture tropical-extratropical teleconnections on one to four week timescales in a single metric.

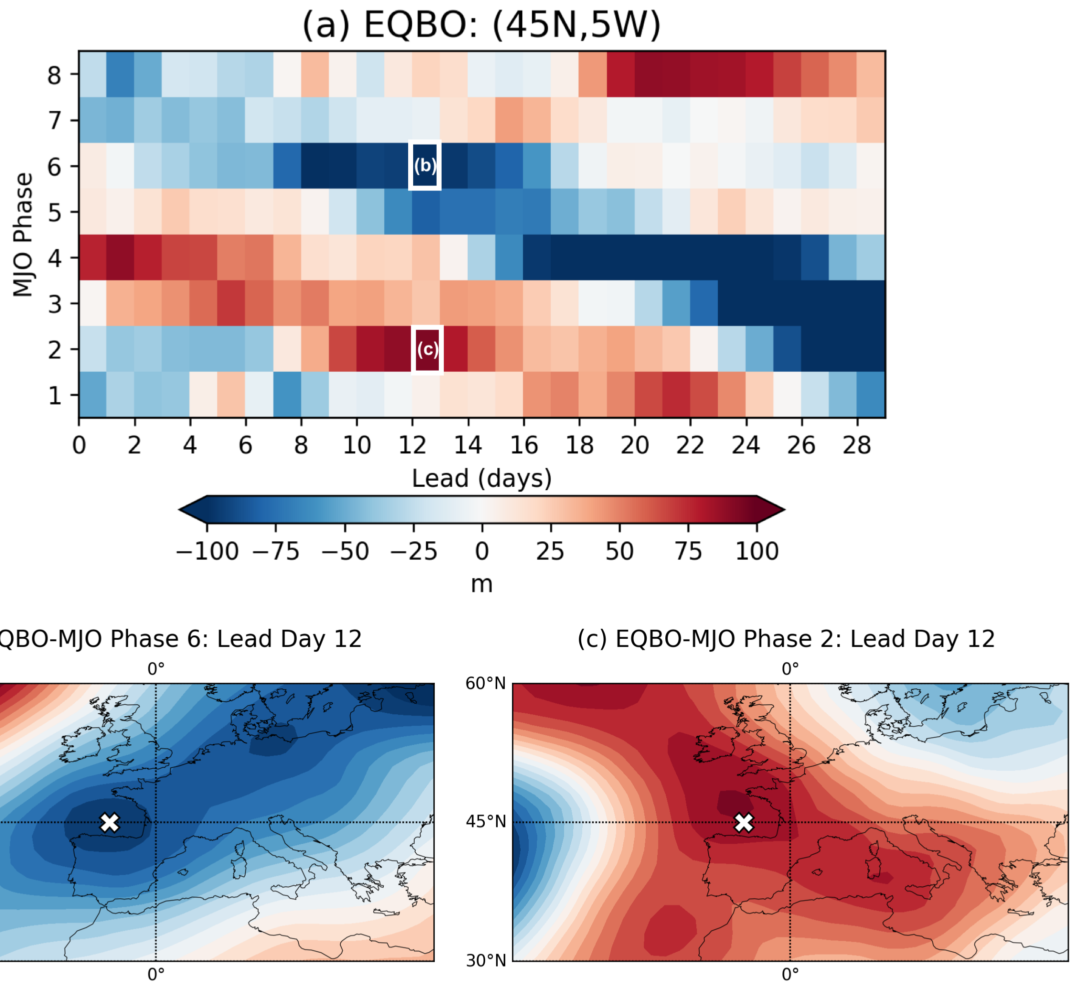

Figure 1. Boreal winter (DJF) composite ERA-I z500 anomalies subsampled to ECMWF initialization dates (1995-2016) for (a) each MJO phase during EQBO vs lead at 45N and 5W. White boxes and text denote the corresponding panels below. The bottom panels include composite ERA-I z500 anomalies subsampled to ECMWF initialization dates (DJF, 1995-2016) over Europe for (b) Phase 6 and (c) Phase 2 at lead day 12. The white X denotes 45°N and 5°W.

For equal comparison of STRIPES between the models and reanalysis, we calculate STRIPES for ERA-I only with dates that overlap with the hindcasts~~. Thus,~~ , thus, the ERA-I STRIPES figures differ for ECMWF versus NCEP dates. It should be noted that the westerly phase of the QBO has been documented to reduce the propagation speed of the MJO (Nishimoto and Yoden 2017), however, we find that our STRIPES results are robust to changes in phase speed of +/- 2 days/phase. Also note that since our application focuses on extratropical sensitivity in z500, we use z500 anomalies in terms of meters instead of standard deviation for STRIPES, different from Jenney et al. (2019). Standardization may mute the extratropical signal due to the greater variability of z500 in the midlatitudes, which is of main interest here. In addition, we wish to retain any differences in z500 anomaly amplitudes between the QBO phases.

STRIPES values that are statistically larger than expected by chance are determined using ~~the~~ a bootstrapping method. The number of random days grabbed corresponds to the observed number of days for the QBO-MJO event of interest. In order to retain autocorrelation within MJO events, we keep the day-of-year (DOY) and phase distribution information for each MJO event and randomly sample years (with replacement). Since the ECMWF hindcast data is not initialized on the same day each year, if the DOY needed is not available for a particular year, we instead use the date of initialization closest to this DOY. From this sample, we calculate STRIPES. This is repeated 250 times for each latitude and longitude. ~~We repeat this calculation 250 times due to computational limits.~~ Any STRIPES value greater than the 90^{th} percentile of these bootstrapped values are deemed significant. ~~Since autocorrelation is retained, this statistical analysis is more difficult to pass, and thus, the 90^{th} percentile was used instead of the 95^{th} percentile.~~ When the data is subdivided by QBO phase, we begin to see the effects of sample size on the uncertainty, leading to fewer points of significance. However, when ~~all MJO days~~ the QBO phase is not considered or in other words, when all MJO events are included (see Figure ~~3~~S1), the statistical analysis shows significance in regions of large STRIPES values. This bootstrapping analysis is only conducted on ERA-I, as these are the ‘observed’ sensitivities and thus, the regions of interest.

To quantify midlatitude prediction skill, a daily area-weighted Pearson correlation is conducted between hindcast and ERA-I anomalous z500 (anomaly correlation coefficient; ACC). The data is separated into NQBO-, EQBO- and WQBO-MJO events in each hindcast dataset and the corresponding reanalysis data is obtained from ERA-I. The ACC between a given model day and the same day in ERA-I is calculated within a centered 60° longitude wide box extending from 30-60° N. Our conclusions are not affected by the latitudinal extent of the box when it is varied by +/- 10-30 °N. This calculation is repeated for every initialization and subsequent lead time as well as every 5° longitude beginning at 0°E. ACCs are grouped and averaged by QBO phase to obtain average ACCs across the Northern Hemisphere at every lead for each QBO phase (see Supplemental Figure ~~S2~~ S3 for an example). ~~Differences between EQBO- or WQBO-MJO ACCs and NQBO-MJO ACCs capture the additional midlatitude prediction skill following active MJOs during E/WQBO compared to neutral QBO. Differences between EQBO-MJO or WQBO-MJO ACCs and EQBO-inactive MJO or WQBO-inactive MJO ACCs capture the additional midlatitude prediction skill following active MJOs during a particular strong phase of the QBO (see Supplemental Table S1 for sample sizes).~~

Statistically significant differences in ACCs across lead and longitude are also computed with ~~the~~ a bootstrapping method. Specifically, all model data within DJF is shuffled and random dates are grabbed. The number of random dates corresponds to the number of observed dates for the particular QBO phase and MJO activity being tested. ~~The corresponding random~~ These dates are then found in ERA-I. The spatial correlations between the model and the observations are calculated and then averaged to get an average ACC. This is repeated for each QBO-MJO combination, and the differences between their ACCs is calculated. The above analysis is repeated 10,000 times for each longitude and lead time. Differences greater than the ~~97.5~~90^{th} percentile of the 10,000 bootstrapped differences are considered significantly greater from that expected by chance. In this bootstrapping analysis, we were able to repeat the calculations 10,000 times (instead of 250) because the calculation was less computationally expensive.

3 Results

3.1 Extratropical Sensitivity

The left column of Figure ~~1~~ 2 shows the STRIPES analysis of ERA-I for days within the ECMWF hindcasts, split by QBO phase. Darker shading indicates regions of greater sensitivity to the MJO for each QBO state. Regions along the North Pacific and Atlantic storm tracks as well as over North America are highlighted by STRIPES following the MJO for all phases of the QBO (Figure ~~1a~~2a,c,e). This is consistent with previous research as these regions have been shown to be sensitive to MJO excited Rossby waves through, for example, their modulation of the North Atlantic Oscillation (Cassou, 2008), the Pacific North American Oscillation (Mori and Watanabe, 2008) and Northern Hemisphere wintertime blocking (Henderson et al., 2016). Interestingly, the Pacific and Atlantic sectors have similar STRIPES values. One may expect higher STRIPES values over the Pacific compared to the Atlantic since the Pacific is generally known to have a strong response to the MJO. We hypothesize that the Atlantic and European sectors also have similar STRIPES values to that of the Pacific due to enhanced blocking over the Atlantic and Europe at later leads following the MJO (Henderson et al. 2016). Since the STRIPES index accounts for all leads as well as the strength and consistency of the z500 anomalies, we therefore may expect STRIPES values over the Atlantic and European sectors to be large as well.

The right column of Figure ~~1~~ 2 shows the STRIPES analysis of the ECMWF hindcasts for the same dates. ECMWF largely captures the spatial patterns and locations sensitive to the MJO under different QBO phases (spatial correlation with ERA-I: $r_{NQBO-MJO}$ = 0.92, $r_{EQBO-MJO}$ = 0.93, and $r_{WQBO-MJO}$ = 0.95), but overall the model has smaller STRIPES values than ERA-I. This is likely a result of model forecast degradation at later lead times since the calculation of STRIPES utilizes z500 forecasts out to 28 days lead time.

An examination of the NCEP hindcasts shows that it also generally captures regions sensitive to the MJO under varying phases of the QBO (Figure ~~2b~~3b,d,f; spatial correlation with ERA-I: $r_{NQBO-MJO}$ = 0.96, $r_{EQBO-MJO}$ = 0.95, and $r_{WQBO-MJO}$ = 0.93) and is also weaker than the corresponding ERA-I analysis (Figure ~~2a~~3a,c,e). The ERA-I STRIPES analysis for NCEP hindcasts largely has the same features as the ERA-I analysis for ECMWF hindcasts, but with larger values due to differences in sample size and dates of initialization between NCEP and ECMWF. From this STRIPES comparison (Figures ~~1 and~~ 2 and 3), we conclude that the ECMWF and NCEP hindcast models generally capture Northern Hemisphere regions sensitive to the MJO as highlighted by large spatial correlations between each model and ERA-I.

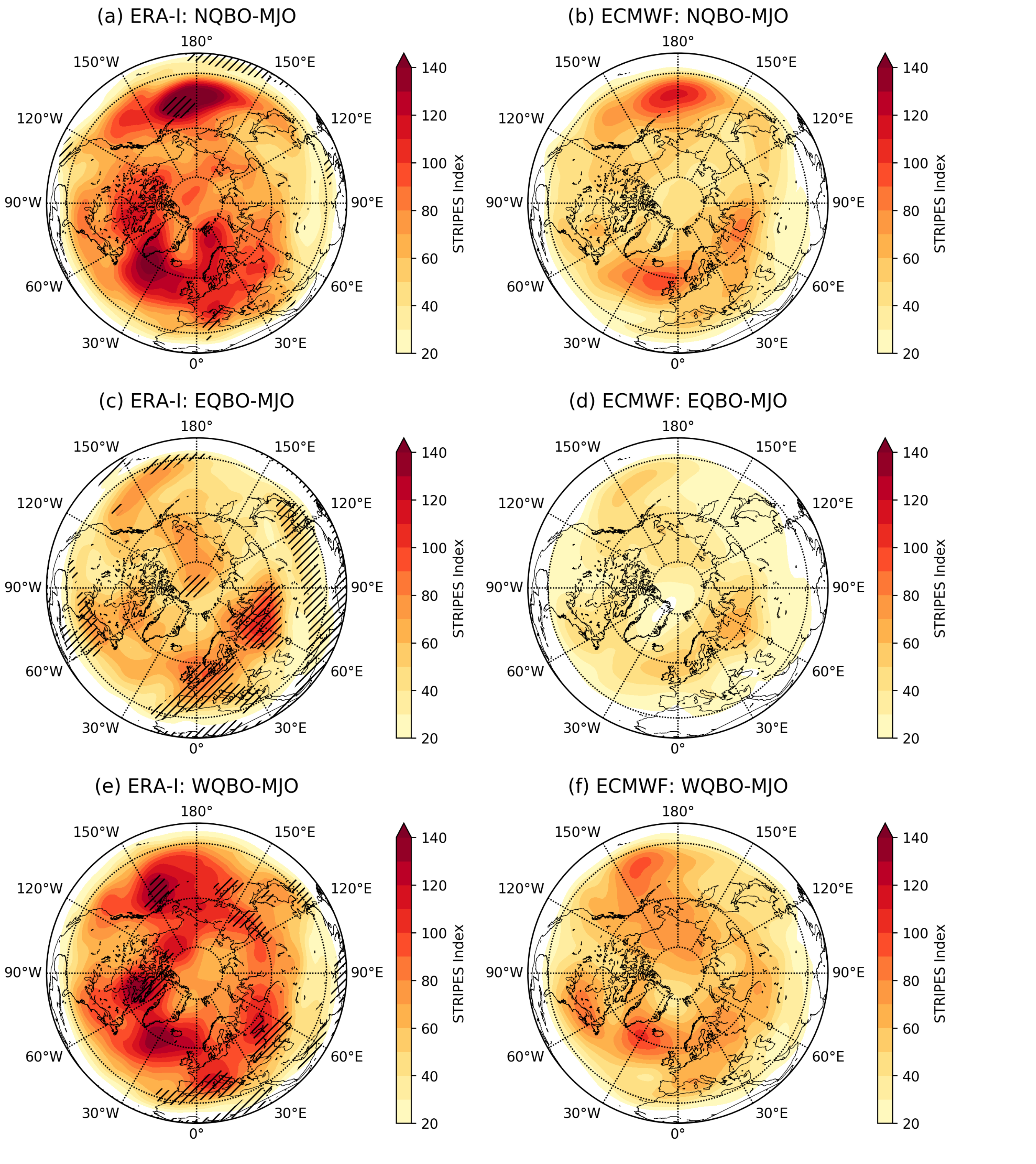

Figure 2. STRIPES values for (left) ERA-Interim and (right) ECMWF for all (top) NQBO-MJO, (middle) EQBO-MJO and (bottom) WQBO-MJO events. (a,c,e) Black hatches denote STRIPES values that are statistically larger than expected by chance at 90% confidence in ERA-I.

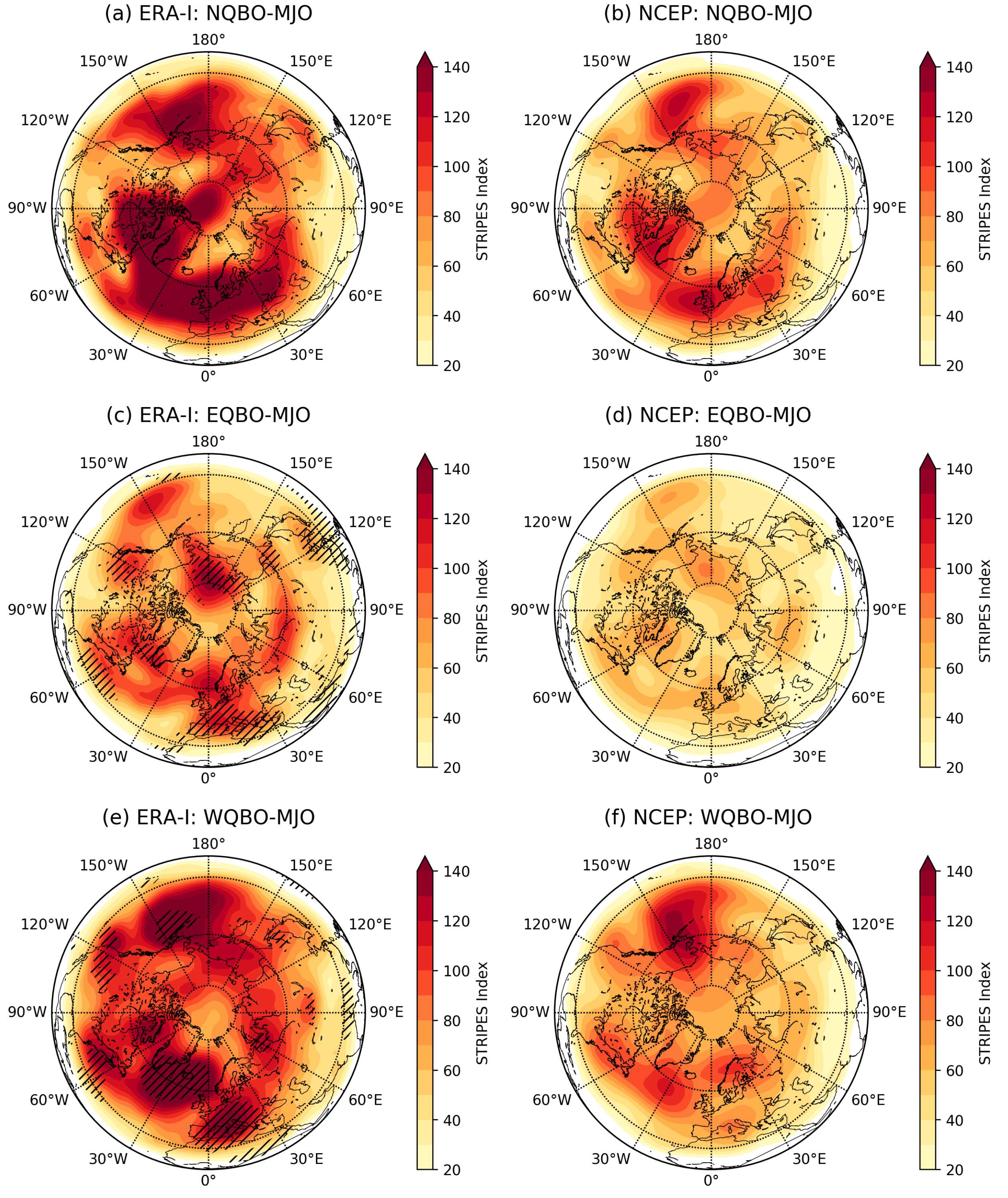

Figure 3. STRIPES values for (left) ERA-Interim and (right) NCEP for all (top) NQBO-MJO, (middle) EQBO-MJO and (bottom) WQBO-MJO events. (a,c,e) Black hatches denote STRIPES values that are statistically larger than expected by chance at 90% confidence in ERA-I.

Recent research has shown that during EQBO, the MJO amplitude is larger and the convective envelope propagates slower compared to MJO activity during WQBO (Son et al., 2017; Nishimoto and Yoden, 2017; Zhang and Zhang, 2018). If direct impacts to the MJO (e.g. through changes in upper tropospheric tropical static stability) lead to changes in MJO teleconnection sensitivity across the Northern Hemisphere, we might expect EQBO-MJO events to have larger midlatitude sensitivity to the MJO compared to WQBO-MJO. ~~Based on our STRIPES analysis~~Instead, we find that Northern Hemisphere sensitivity to the MJO is significantly reduced during EQBO-MJO events compared to WQBO-MJO events (compare Figure ~~1c~~2c,e and Figure ~~2c~~3c,e; significance of difference not shown). We explored this further and found that this difference can largely be explained by the tendency for WQBO to have larger magnitude z500 anomalies compared to EQBO, not more distinct stripes~~, which~~. This is likely due to ~~differences in sample size . In other words~~the larger sample size during EQBO (Table S1) leading to reduced noise in the average. Therefore, when the amplitude differences between the z500 anomalies are accounted for through normalization, the difference in Northern Hemispheric sensitivity to the MJO between QBO phases is greatly reduced (Figure ~~3). The data is normalized by dividing by the average absolute value of the Phase vs Lead diagram for each latitude-longitude point prior to computing the STRIPES index. By doing so, we are able to reduce the impact of the anomaly magnitude on the STRIPES index, and thus, the index mainly provides information on the “stripey-ness”.~~ S3).

~~STRIPES values for (left) ERA-Interim and (right) ECMWF for all (top) NQBO-MJO, (middle) EQBO-MJO and (bottom) WQBO-MJO events. Black hatches denote STRIPES values that are statistically larger than expected by chance at 90% confidence in ERA-I.~~

~~STRIPES values for (left) ERA-Interim and (right) NCEP for all (top) NQBO-MJO, (middle) EQBO-MJO and (bottom) WQBO-MJO events. Black hatches denote STRIPES values that are statistically larger than expected by chance at 90% confidence in ERA-I.~~

~~Normalized STRIPES values for (left) ECMWF hindcasts' dates in ERA-I and (right) NCEP hindcasts' dates in ERA-I for (top) EQBO-MJO and (bottom) WQBO-MJO events. Data is normalized by dividing by the average absolute value of the Phase vs Lead diagram for each latitude-longitude point and then calculating STRIPES on these normalized values.~~

3.2 Prediction Skill

3.2.1 Regional Prediction Skill

Knowing that the ECMWF and NCEP hindcasts generally capture regional sensitivity to the MJO, we next address whether ~~the QBO impacts midlatitude skill during MJO events and whether regions of increased sensitivity to MJO-QBO activity translate to increased prediction skill. Here, skill is calculated as an anomaly spatial correlation between z500 from the hindcasts and ERA-I (see Section 2.3), and we compare this skill over active QBO-MJO combinations to skill during NQBO-MJO and inactive MJO.~~ strong QBOs enhance MJO impacts on midlatitude skill. As mentioned in the introduction, EQBO has been found to impact the MJO in ways that may enhance MJO teleconnections (e.g. Son et al. 2017; Nishimoto and Yoden 2017). Since enhanced activity may provide a prominent signal above model noise and uncertainty, and thus, hypothetically lead to enhanced prediction skill, we focus here on only improved prediction skill (see Supplemental ~~Figures S4-S5~~ Figure S4 for regions of decreased prediction skill). Note that prediction skill at one week lead times is not likely to be significantly different following active MJOs compared to inactive MJOs since forecast models already have relatively good prediction skill for these early leads. Where we would expect the MJO to provide additional prediction skill is on timescales longer than one week. Here, skill is calculated as an anomaly spatial correlation coefficient (ACC) between z500 from the hindcasts and ERA-I (see Section 2.3), and we compare this skill over QBO-MJO combinations to skill during inactive MJOs. Figure 4 shows z500 ~~anomaly prediction skill~~ ACC as a function of lead time for the North Pacific (165°W, 30-60°N), North Atlantic (30°W, 30-60°N), and Europe regions (0°E, 30-60°N). ~~There are multiple ways to think about skill following MJO-QBO activity and therefore we include two types of statistical information. The first type of significance (hollow circles) represents the impact of the phase of strong QBOs on~~

We invoke two requirements to address the question of whether a particular strong QBO (EQBO or WQBO) enhances the MJO impact on midlatitude prediction skill compared to ~~neutral QBO during active MJO. In other words, where the orange/teal line (EQBO-/WQBO-MJO)is significantly above the black line (NQBO-MJO). The second type of significance (colored dots) represents changes in prediction skill following active MJOs compared to inactive MJOs during a particular QBO phase, or said another way, where solid lines~~ an inactive QBO (NQBO), and a third requirement to answer whether the MJO leads to enhanced midlatitude prediction skill under a strong QBO compared to an NQBO. Each requirement builds on the previous requirement. For example, we can only examine requirement two if requirement one has been passed. These requirements are summarized below:

1. A significant MJO impact
2. A significant MJO impact during a strong QBO that is *significantly greater than* an MJO impact during NQBO
3. Enhanced prediction skill following an MJO during a strong QBO that is *significantly greater than* that during NQBO

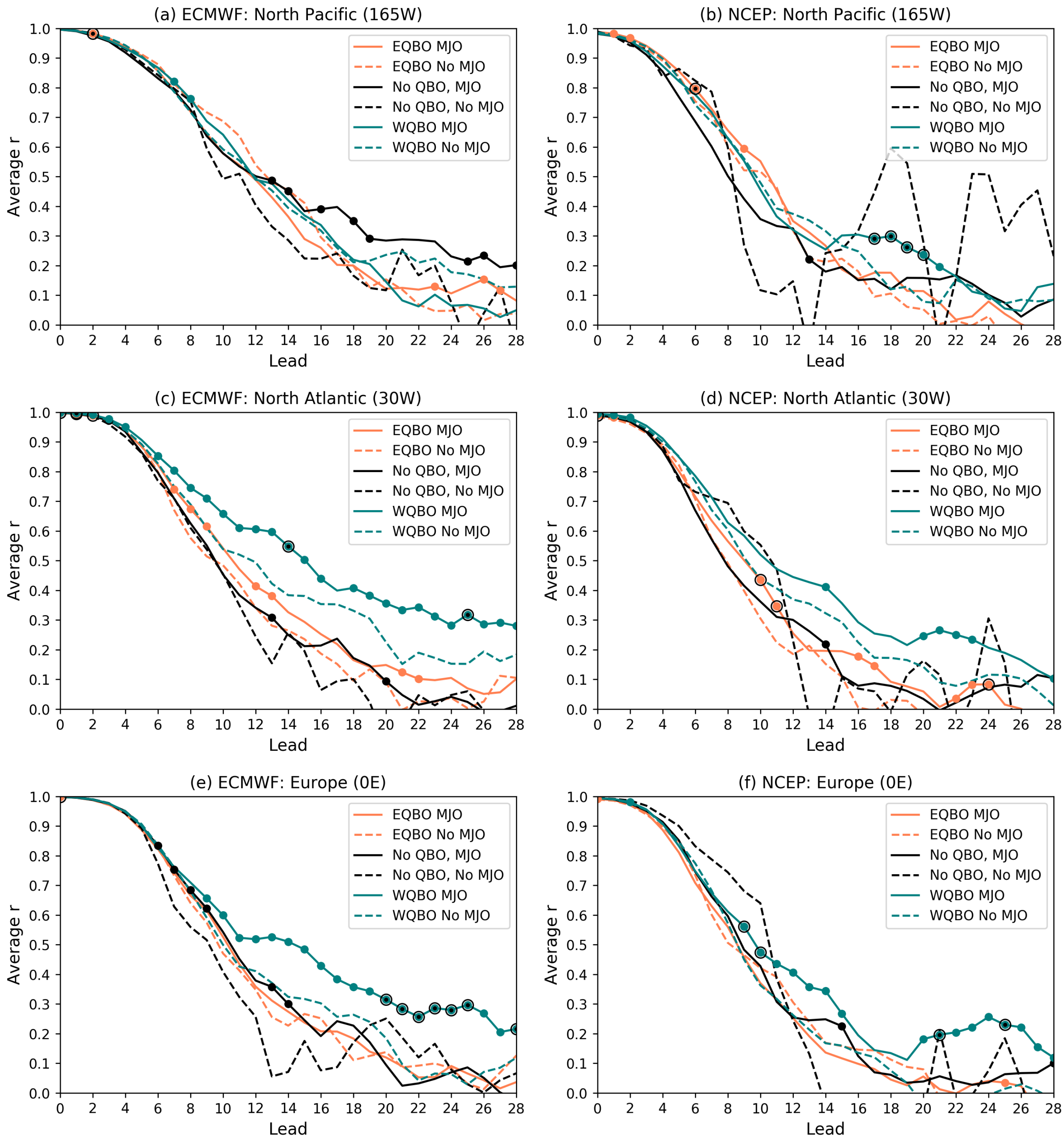

Figure 4. Anomalous spatial correlation coefficient at (top) 165°W, (middle) 30°W and (bottom) 0°E for (left) ECMWF and (right) NCEP. Solid lines correspond to active MJOs while dashed lines correspond to inactive MJOs. Colors refer to the phase of the QBO. Colored dots denote regions/leads where requirement 1 is passed at 90% confidence for the corresponding QBO. Black circles indicate regions/leads where requirement 2 is passed at 90% confidence and small black dots on orange/teal lines indicate regions/leads where requirement 3 is passed at 90% confidence. See text for details.

The first requirement is the presence of an MJO impact on midlatitude prediction skill during specific phases of the QBO. An 'MJO impact' on midlatitude prediction skill is defined as a significant difference in midlatitude ACC between active MJO and inactive MJO events and is denoted by colored dots in Figure 4. In other words, where the solid line (EQBO-/WQBO-/NQBO-MJO) ~~are~~ is significantly above the ~~dashed lines~~ corresponding colored dashed line (EQBO-/WQBO-/NQBO-noMJO). ~~The presence of both of these forms of significance (colored dots within the hollow circles) represents where there is greater prediction skill following active MJOs compared to inactive MJOs during a particular QBO phase (colored dots) *and* active MJOs during a strong QBO phases compared to active MJOs during NQBO (hollow circles). When these two significances appear together, we can say that a particular strong QBO increases the impact of the MJO on midlatitude prediction skill.~~

~~First we focus on the differences in skill between strong QBO phases and NQBO following active MJOs (hollow circles) . For ECMWF, the North Atlantic and Europe (~~

Where there is an MJO impact we continue to the second requirement. The second requirement is that the magnitude of the significant MJO impact under strong QBOs is larger than the significant MJO impact under NQBOs. This second requirement is denoted by black circles around the colored dots in Figure ~~4c,e) have significantly increased prediction skill out to Week 4 following WQBO-MJO (hollow circles on solid teal line) compared to NQBO-MJO. For NCEP, there is significantly increased prediction skill Week 2~~ 4. These two requirements together ensure that (1) there is an MJO impact and (2) that this impact is enhanced during strong QBOs compared to neutral QBOs.

Requirement three specifies significantly enhanced prediction skill following ~~EQBO-MJO in the North Pacific and Weeks 23 in the North Atlantic and Week 4 over Europe following WQBO-MJO (Figure 4b,d,f) .~~ an MJO during strong QBOs compared to NQBO. In Figure 4, this is when a colored line (EQBO-/WQBO-MJO) is significantly above the black line (NQBO-MJO) and is denoted as a small black dot on a teal/orange dot. We applied this requirement to ensure that regions with enhanced MJO impacts during strong QBOs also have overall greater prediction skill following active MJO events compared to NQBO-MJO events.

~~Focusing next on differences in skill between active and inactive MJOs during strong QBO phases (colored dots), the MJO leads to enhanced prediction skill compared to inactive MJO~~ For requirement one, we see that there is an MJO impact in the North Atlantic and Europe during WQBO out to Week 4 in ECMWF (Figure 4c,e; teal dots)~~, and in~~ . In NCEP during WQBO, we see an MJO impact on Weeks 2 and 4 over Europe and Weeks 3-4 in the North ~~Atlantic and Europe during WQBO in NCEP. For all of these cases, this increase in prediction skill following the MJO is not present during NQBO (absence of black dots), and suggests that the changes to the basic state and/or to the MJO itself during WQBO is associated with enhanced midlatitude MJO impact over the North Atlantic and Europe for ECMWF and NCEP.The presence of both of these forms of significance (colored dots within the hollow circles) represents where a particular strong QBO increases the impact of the MJO~~ Pacific and North Atlantic (Figure 4b,d,f; teal dots). For requirement 2, there is an enhanced MJO impact during WQBO in ECMWF over Europe during Weeks 3-4 and in NCEP over the North Pacific in Week 3. For all of the regions requirement 2 is passed, requirement 3 is also satisfied. Therefore, where WQBO enhances the MJO impact on midlatitude prediction skill. ~~In the three regions depicted in Figure 4, the two forms of significance overlap in ECMWF and NCEP over the North Atlantic and Europe through Week 3 and 4 (Figure 4c,e; teal dots inside hollow circles).~~

~~Anomalous spatial correlation coefficient at (top) 165W, (middle) 30W and (bottom) 0E for (left) ECMWF and (right) NCEP. Solid lines correspond to active MJOs while dashed lines correspond to inactive MJOs. Colors refer to the phase of the QBO. Colored dots denote significantly increased skill between active and inactive MJO under a specific QBO state at 95% confidence. Hollow black circles indicate a significantly increased skill between E/WQBO-MJO events and NQBO-MJO events at 95% confidence.~~

3.2.2 ~~Northern Hemisphere Prediction Skill: Dependence on active MJO~~

, WQBO also leads to increased prediction skill following MJO events compared to NQBO.

While Figure 4 shows results for three specific regions, we extend these results to all longitudes in ~~Figures 5 and 6. To determine how the impact of the MJO on midlatitude prediction skill changes following a particular phase of the QBO (colored dots in Figure 4), we examine the difference between prediction skill following active MJOs compared to inactive MJOs during both EQBO and WQBO (Figure 5).~~ Figure 5. Specifically, the four panels show the difference in ACC between EQBO-MJO and EQBO-noMJO (Figure 5a,b; orange solid and dashed lines in Figure 4) and WQBO-MJO and WQBO-noMJO (Figure 5c,d; teal solid and dashed lines in Figure 4). The left column of Figure 5 shows the differences within ECMWF and the right column shows differences within NCEP. Shading specifies increased prediction skill following the MJO compared to inactive MJOs during the specific phase of the QBO ~~. Regions of significantly increased prediction skill following the MJO compared to inactive MJOs during the specific phase of the QBO are denoted with~~ and grey dots denote a significant MJO impact (Requirement 1), as denoted in Figure 4 by the colored dots. Regions where the MJO impact is significantly enhanced during a strong QBO compared to NQBO is denoted with a black circle around the grey dots (~~orange and teal dots in Figure 4).~~Requirement 2), and when the MJO leads to enhanced prediction skill during strong QBOs compared to NQBO (Requirement 3), a small black dot is plotted, as in Figure 4.

~~During EQBO in both models~~ Focusing on the first requirement (grey dots), during EQBO (Figure 5a,b), there is ~~enhanced prediction skill following active MJOs starting~~ an MJO impact on midlatitude prediction skill in North America ~~and~~ at Week 2 leads for NCEP and ECMWF and extending into Asia ~~(90W - 90E)~~ at Week 2-3 leads for ECMWF and at Week 4 leads for NCEP. During WQBO in ECMWF and NCEP (Figure 5c,d), there is ~~increased prediction skill following the MJO~~ an MJO impact in the East Pacific into North America through Week 1. ~~In ECMWF, this increased skill~~ This impact continues through Week 2 into the North Atlantic and ~~continues over the Atlantic and Europe from Week~~ Europe and continues over Europe for Weeks 3-4 (Figure 5c,d). In NCEP, ~~additional prediction skill~~ the MJO impact also occurs in the Pacific during Week 3 ~~and over the North Atlantic by Week 4~~ (Figure 5d).

From Figure 5, we see that in both models, ~~active MJOs during EQBO generally lead to enhanced skill~~ there is an MJO impact on midlatitude prediction skill during EQBO from North America to East Asia ~~while active MJOs during WQBO generally lead to enhanced skill~~ and during WQBO from the North Pacific through Europe on subseasonal timescales. ~~The regions of enhanced prediction skill following active MJOs during EQBO and WQBO are not associated with enhanced prediction skill following active MJOs during NQBO (see Supplemental Figure S6). This suggests that following MJO activity,~~

~~subseasonal prediction skill is enhanced in the Pacific to Europe by the MJO during strong QBOs while MJO activity during NQBO does not significantly enhance prediction skill (although sample size for NQBO-noMJO is small, Table S1).~~

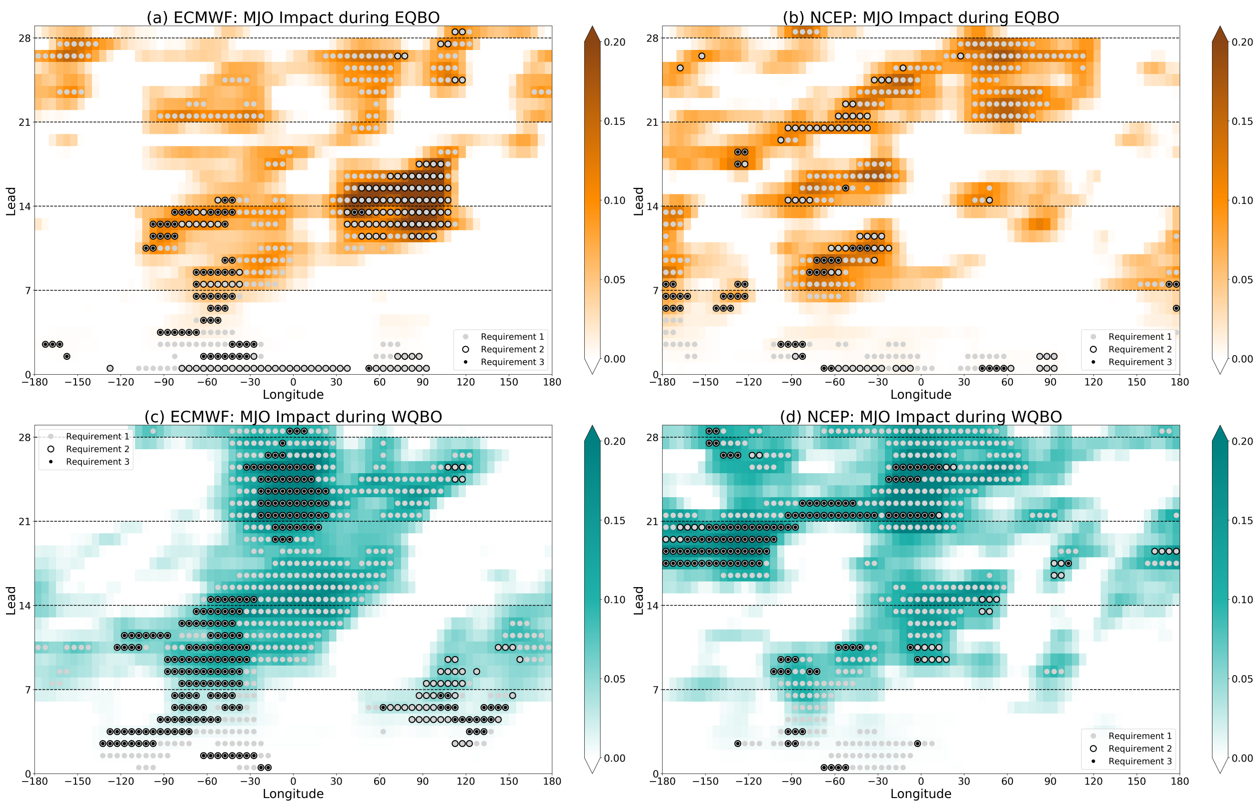

Figure 5. Anomalous correlation coefficient between (top) EQBO-MJO and EQBO-noMJO and (bottom) WQBO-MJO and WQBO-noMJO for (left) ECMWF and (right) NCEP at each longitude and lead from model initialization. Correlations are calculated within a 60°wide box, centered on each longitude, extending from 30-60°N. Shading denotes the phase of the QBO. Grey dots denote regions/leads where requirement 1 is passed at 90% confidence. Black circles indicate regions/leads where requirement 2 is passed at 90% confidence and small black dots indicate regions/leads where requirement 3 is passed at 90% confidence. See text for details.

3.2.2 ~~Northern Hemisphere Prediction Skill: Dependence on active QBO~~

~~To further explore the importance of QBO-MJO activity on subseasonal prediction, we examine the difference between prediction skill following active MJOs during strong QBO compared to active MJOs during NQBO . Similar to Figure 5,~~ For the second requirement (black circles), we see that during EQBO in ECMWF (Figure 5a) the MJO impact is greater than during NQBO over North America and the North Atlantic on Week 1-2 and over Asia on Week 2-3. For NCEP (Figure 5b), this occurs over the North Pacific to the Atlantic on Week 1-2 timescales, and again over the Atlantic on Week 3-4. During WQBO in ECMWF (Figure 5c), there is an enhanced MJO impact in the ~~left column of Figure 6 shows the differences for ECMWF and the right column for NCEP. Specifically, the four panels show the difference in ACC between EQBO-MJO and~~

~~NQBO-MJO (Figure 6a,b; orange and black solid lines in Figure 4)and WQBO-MJO and NQBO-MJO (Figure 6c, d; teal and black solid lines in Figure 4). As in Figure 4, black hollow circles indicate significant increases in prediction skill between the specified QBO and NQBO during active MJO . During EQBO in both models (Figure 6a,b~~East Pacific into the North Atlantic through Week 2. This enhanced MJO impact reemerges over the North Atlantic by Week 4. In NCEP (Figure 5d), there is ~~mainly enhanced prediction skill following active MJOs~~ an enhanced MJO impact over the Pacific ~~in Week 1~~ on Week 3 and over North America ~~in Week 2 compared to NQBO. For WQBO in both models (Figure 6c,d), there is also enhanced prediction skill following active MJOs compared to NQBO from Week 1 to 4 over the Pacific and into Europe. Specifically, this enhanced prediction skill in ECMWF(Figure 6c) is located in the Pacific and extends into the Atlantic for Weeks~~ and the Atlantic on Week 4. Thus, Figure 5 suggests that strong QBOs enhance the MJO impact on midlatitude subseasonal prediction skill from the Pacific to Europe, although we remind the reader once again of the small NQBO sample sizes.

For the third requirement (small black dots), during EQBO this requirement is satisfied over North America and the North Atlantic on Week 1-2 ~~, and continues through the Atlantic and into Europe during Weeks 3 and~~ timescales in ECMWF and NCEP. For WQBO in ECMWF, this requirement is satisfied over the East Pacific through the Atlantic on Week 1-2 leads and reemerges over the North Atlantic and Europe during Week 4. ~~In NCEP(Figure 6d), this enhanced prediction skill spans from the Pacific to Europe during Weeks 1-4. Note that in all panels, much of the enhanced skill is confined to a specific longitudinal region. Since the QBO oscillates with a period of about 28 months, we may expect enhanced prediction skill to remain around the same region through Week 4 when examining skill differences between QBO phases. However, this confined skill could also be due to a stationary rossby wave signal following strong QBO-MJOs that is not present following NQBO-MJOs. Therefore, since the prediction skill is enhanced and confined to a specific longitudinal region out to Week 3, we speculate that this enhanced non-propagating skill is likely from either a stationary rossby wave signal or enhanced skill from the strong QBOs effect on the midlatitudes compared to NQBO~~For NCEP, during WQBO the third requirement is satisfied on Week 3-4 timescales over the North Pacific to the Atlantic. Interestingly, for WQBO in both models, the third requirement is almost always satisfied over the regions/leads where requirement two is satisfied. This suggests that WQBOs enhance the MJO impact on midlatitude prediction skill as well as enhance overall prediction skill compared to NQBOs following active MJOs from the Pacific to Europe on Week 1-4 timescales in ECMWF and on Week 3-4 timescales in NCEP.

Since EQBO is thought to increase the amplitude of the MJO as well as help to propagate the MJO further into the Pacific Ocean compared to WQBO (Son et al., 2017; Nishimoto and Yoden, 2017; Zhang and Zhang, 2018), ~~it may be~~ one may have expected that active MJOs during EQBO conditions ~~will~~ would lead to stronger MJO teleconnections and thus, act to enhance subseasonal prediction skill in the midlatitudes. However, from Figure ~~6~~ 5 we see that ~~both EQBO *and* WQBO tend to have greater~~ while EQBO has an enhanced MJO impact on Week 1-4 leads from North America to East Asia, WQBO has an enhanced MJO impact as well as enhanced overall prediction skill compared to NQBO ~~during active MJO across a range of longitudes and lead times. Specifically over the Pacific during EQBO-MJO and the Pacific through Europeduring WQBO-MJO. While unexpected, this result is partially supported by previous research, where enhanced prediction skill of Atmospheric Rivers over Alaska is found following active MJOs during WQBO (Baggett et al., 2017), and~~ on subseasonal timescales, specifically from the North Pacific through Europe. Perhaps most striking is the enhanced MJO impact and increased prediction skill following active MJO events during WQBO over the North Atlantic in Weeks 3-4 in both ECMWF and NCEP. This result is supported by recent research showing that the North Atlantic Oscillation and MJO connection is stronger during WQBO ~~(Feng and Lin, 2019).~~

~~Anomalous correlation coefficient between (top) EQBO-MJO and NQBO-MJO and (bottom) WQBO-MJO and NQBO-MJO for (left) ECMWF and (right) NCEP at each longitude and lead from model initialization. Correlations are calculated within a 60wide box, centered on each longitude, extending from 30-60N. Hollow black circles indicate significant increases in prediction skill at 95% confidence from E/WQBO-MJO activity compared to NQBO-MJO activity.~~

3.2.3 ~~Summary of Northern Hemisphere Prediction skill~~

~~The presence of both of these forms of significancerepresents where strong QBOs increase the impact of the MJO on midlatitude prediction skill. As a reminder, hollow circles indicate where there is significantly greater skill following EQBO or WQBO-MJO than NQBO-MJO, while grey dots indicates where EQBO-, WQBO-, or NQBO-MJO leads to significantly greater skill than EQBO-, WQBO-, or NQBO-noMJO. To better visualize this overlap, Figure 7 combines both forms of significance from Figures 5 and 6 for ease of visualization, where the previously grey dots are now orange (teal)for EQBO (WQBO). In EQBO in both models (Figure 7a, b), there is very little overlap of the two forms of significance (orange dots in hollow circles). On the other hand, for WQBO in both models (Figure 7c,d), most of the East Pacific and Atlantic that exhibit significantly increased prediction skill following active MJOs compared to inactive MJOs (teal dots) are collocated~~ (Feng and Lin 2019; Song and Wu 2020). Furthermore, enhanced prediction skill of Atmospheric Rivers over Alaska is also found following ~~WQBO-MJO compared to NQBO-MJO (hollow circles). This indicates that there is significantly greater prediction skill following~~ active MJOs ~~compared to inactive MJOs during WQBO as well as active MJOs during NQBO. In other words, WQBOs increase the impact of the MJO on~~ during WQBO (Baggett et al., 2017). Previous research has shown that WQBO alone leads to enhanced midlatitude prediction skill ~~between the East Pacific and Atlantic compared to NQBO.~~

~~Lead vs longitude plots with combined significance from Figure 5 and 6. Colored dots denote significant increases in prediction skill at 95% confidence from active MJO compared to inactive MJO under the specific QBO phase for the plot, where the color refers to the phase of the QBO. Orange is EQBO and teal is WQBO. Hollow black circles indicate significant increases in prediction skill at 95% confidence from E/WQBO-MJO activity compared to NQBO-MJO activity.~~

3.2.3 ~~Northern Hemisphere Prediction Skill and Sensitivity~~

~~In section 3.1, we saw that ECMWF and NCEP hindcasts generally capture regional sensitivity to the MJO under different phases of the QBO. From previous research, we also know that robust midlatitude circulation following certain phases of the MJO tends to have additional forecast skill (Tseng et al., 2018),~~ over the North Atlantic (Boer and Hamilton, 2008); however, we specifically look at the difference between active and inactive MJOs under WQBO and therefore, ~~we may expect a link between regional sensitivities and increased prediction~~ have removed any possible WQBO background skill.

~~In an attempt to systematically examine the relationship between MJO sensitivity and prediction skill~~ It should be noted that inactive MJOs during NQBO events with ENSO removed only occur 12 times in ECMWF and 3 times in NCEP. When this is the case, there is shading across all longitudes ~~, STRIPES values are averaged from 30-60~~(Figure S5). If ENSO events are not removed, the sample sizes increase to 47 and 52, for ECMWF and NCEP respectively (see Table S1). When we calculate the MJO impact during NQBO when ENSO is included (Figure S6), we see that much of the shading east of 0° is not apparent. The presence of skill east of 0° ~~N and compared to prediction skill averaged along leads 8-18 days (Figure 8). Days 8-18 are chosen based on previous research on MJO teleconnection timescales (e.g. Cassou 2008; Henderson et al. 2016; Tseng et al. 2019), however, these results are insensitive to variations of +/- 5 days. Figure 8 shows the average prediction skill across leads 8-18 days for EQBO in orange (Figure 8a,b) and WQBO in teal (Figure 8c, d) along with average STRIPES values in black for all longitudes. While one can certainly find locations where they appear to oscillate together, their correlations are low (see panel titles). The exception being NCEP during EQBO (Figure 8b)and ECMWF during WQBO (Figure 8c), where the correlation is around 0.4. For the other two panels, it appears that increased regional z500 sensitivity to the MJO in the Northern Hemisphere does not clearly translate to increased prediction skill. It is possible that these correlations are low due to differences in the signal-to-noise ratio between composites and daily spatial correlations~~when ENSO is not included may be due to small sample sizes of the NQBO events. Thus, when comparing MJO impacts between strong and neutral QBOs, it is important to keep sample size in mind. That being said, the statistical analysis we have applied here for requirements 1-3 account for the small sample sizes in the analysis.

4 Conclusions

The MJO is the dominant mode of intraseasonal variability in the tropics (Madden and Julian, 1971; Adames and Kim, 2016), and through its convective heating, modulates midlatitude weather, days to weeks after an MJO event (e.g. Vecchi 2004; Zhou et al. 2012; Henderson et al. 2016; Tseng et al. 2019). Recent research has shown that the QBO impacts MJO amplitude, propagation, and prediction skill (Son et al., 2017; Nishimoto and Yoden, 2017; Zhang and Zhang, 2018; Marshall et al., 2017; Lim et al., 2019) as well as modulates MJO teleconnections (e.g. Baggett et al. 2017; Mundhenk et al. 2018; Wang et al. 2018). This raises the question as to whether the QBO also affects the prediction skill of MJO teleconnections. The goal of this study is to address this question through an examination of differences in Week 1-4 prediction skill between different combinations of QBO-MJO activity.

Through a STRIPES analysis (Jenney et al., 2019), we show that ECMWF and NCEP hindcasts are capable of simulating midlatitude MJO sensitivity, in a composite sense, out to Week 4 under different phases of the QBO. ~~Thus, we~~ We then use these hindcasts to study enhanced S2S prediction skill following QBO-MJO activity. Increased prediction skill is determined from significant increases in spatial correlations of z500 for various QBO-MJO combinations. First, comparing ~~strong QBOs to NQBOs, we find that there is enhanced prediction skill following MJOs during EQBO over the Pacific, and enhanced prediction skill from the Pacific to Europe following MJOs during WQBO. Second, comparing~~ active MJOs to inactive MJOs during different QBO phases (Requirement 1), we find that ~~when active MJOs occur during EQBOs, there is enhanced prediction skill~~ there is an MJO impact on midlatitude prediction skill during EQBO from North America ~~into Asia over Weeks 2-3 in ECMWF and Weeks 2-4 in NCEP. During WQBO , this enhanced prediction skill is located in the Pacific through North America in Week 1 and continues through Week~~ to East Asia and during WQBO from the North Pacific through Europe. Second, when comparing the MJO impact between strong QBOs and NQBO (Requirement 2~~over the North Atlantic and through Week 3-4 over the Atlantic and Europein ECMWF. Additional prediction skill in NCEP appears in the Pacific during Week 3 and the North Atlantic by Week 4. In contrast, there is no enhanced prediction skill following MJO activity compared to inactive MJOs during NQBO in these regions and suggests that~~), we see that strong QBOs enhance the MJO impact on midlatitude subseasonal prediction skill from the ~~impact of the MJO on prediction skill over the~~ Pacific to ~~the Atlantic is only apparent during strong QBOs. Together, these two forms of significance inform us on when and where strong QBOs increase the impact of the MJO on midlatitude prediction skill . Over North America, the Atlantic and Europe (ECMWF and NCEP) following active MJOs during WQBO, the two forms of significance overlap and thus, implies that WQBO (compared to NQBO)increases the impact of the MJO~~ Europe. Lastly, to ensure that regions with enhanced MJO impacts during strong QBOs also have overall greater prediction skill following active MJO events compared to NQBO-MJO events (Requirement 3), and find that WQBOs enhance the MJO impact on midlatitude prediction skill ~~. On the other hand, regions with both forms of significance during EQBO are scarce. When comparing all regions of enhanced prediction skill to regional sensitivity (STRIPES), we found no clear relationship, except possibly in ECMWF during WQBO and NCEP during EQBO~~as well as enhance overall prediction skill compared to NQBOs from the Pacific to Europe on Week 1-4 timescales in ECMWF and on Week 3-4 timescales in NCEP.

This study provides insight on improved prediction skill following different MJO-QBO combinations; however, more research is needed to determine the causal link between the MJO-QBO, midlatitude teleconnections and prediction skill. It is unclear whether enhanced midlatitude prediction skill is a consequence of the QBO's direct effects on the tropical environment in which the MJO forms and/or through the modulation of the atmospheric basic state through which Rossby waves propagate.

We ~~motivate~~ motivated this study by suggesting that enhanced MJO prediction following EQBO (Marshall et al., 2017; Lim et al., 2019; Abhik and Hendon, 2019) may also lead to enhanced midlatitude prediction skill following MJOs during EQBO. However, we find that *both* EQBO and WQBO lead to ~~enhanced midlatitude prediction skill~~ an enhanced MJO impact in these hindcasts rather than only EQBO. Enhanced skill following MJOs during both EQBO and WQBO may partially be explained by Kim et al. (2019) who find no significant impact of the QBO on MJO prediction skill within the ~~SubX database~~ Subseasonal Experiment database (SubX; Pegion et al. 2019), which suggests these models do not differentiate between the two phases of the QBO. In addition, ~~there is~~ we find that there is an enhanced MJO impact as well as increased prediction skill following MJO events during WQBO compared to NQBO on S2S timescales, specifically over the North Atlantic out to Week 4 lead times. This result is supported by a growing body of work suggesting the importance of WQBO on MJO teleconnections. For example, recent work has shown that the North Atlantic Oscillation and MJO relationship is stronger during WQBO ~~(Feng and Lin, 2019)~~ (Feng and Lin, 2019; Song and Wu, 2020) and prediction skill of Atmospheric Rivers over Alaska is enhanced following WQBO-MJO (Baggett et al., 2017). Finally, while strong ENSO events were removed from our analysis in an attempt to separate the effects of the QBO from those of ENSO, an ENSO influence may still remain. In addition, the sample sizes for MJO-QBO activity are not large (Table S1), although we attempt to account for this through statistical analysis. Even so, this work suggests that both phases of the QBO may impact prediction skill of MJO teleconnections and should be considered in future studies.

Data availability. ERA-I Reanalysis data are provided by the European Centre for Medium Range Forecasts (https://www.ecmwf.int/en/forecasts/-datasets/reanalysis-datasets/era-interim/). The ECMWF and NCEP hindcasts are provided by the World Weather Research Program/World Climate Research Program (ECMWF: https://apps.ecmwf.int/datasets/data/s2s/ and NCEP: http://iridl.ldeo.columbia.edu/SOURCES/.Models/.SubX/). RMM Index data are provided by the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt). The Nino3.4 Index data was provided by NOAA/OAR/ESRL Boulder, CO (climatedataguide.ucar.edu/climate-data/).

Author contributions. Kirsten Mayer led the collection of the data, the data analysis and writing of the manuscript. Elizabeth Barnes aided with the experimental design, analysis techniques and writing of the manuscript.

Competing interests. The authors declare that they have no competing interests.

Acknowledgements. This research was partially funded by NOAA Research through supporting K. J. M. and partially funded by the NOAA MAPP S2S Prediction Task Force through supporting E. A. B. on NOAA grant NA16OAR4310064.

References

Abhik, S. and Hendon, H. H.: Influence of the QBO on the MJO during coupled model multiweek forecasts, Geophys. Res. Lett., 2019.

Adames, Á. F. and Kim, D.: The MJO as a Dispersive, Convectively Coupled Moisture Wave: Theory and Observations, J. Atmos. Sci., 73, 913–941, 2016.

Baggett, C. F., Barnes, E. A., Maloney, E. D., and Mundhenk, B. D.: Advancing atmospheric river forecasts into subseasonal-to-seasonal time scales, Geophys. Res. Lett., 44, 2017GL074 434, 2017.

Baldwin, M. P. and Dunkerton, T. J.: Stratospheric harbingers of anomalous weather regimes, Science, 294, 581–584, 2001.

Boer, G. J. and Hamilton, K.: QBO influence on extratropical predictive skill, Clim. Dyn., 31, 987–1000, 2008.

Cassou, C.: Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation, Nature, 455, 523–527, 2008.

Collimore, C. C., Martin, D. W., Hitchman, M. H., Huesmann, A., and Waliser, D. E.: On The Relationship between the QBO and Tropical Deep Convection, J. Clim., 16, 2552–2568, 2003.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, d. P., and Others: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quart. J. Roy. Meteor. Soc., 137, 553–597, 2011.

Densmore, C. R., Sanabia, E. R., and Barrett, B. S.: QBO Influence on MJO Amplitude over the Maritime Continent: Physical Mechanisms and Seasonality, Mon. Weather Rev., 147, 389–406, 2019.

Feng, P. and Lin, H.: Modulation of the MJO?Related Teleconnections by the QBO, J. Geophys. Res. D: Atmos., 2019.

Garfinkel, C. I. and Hartmann, D. L.: The Influence of the Quasi-Biennial Oscillation on the North Pacific and El-Nino teleconnections, J. Geophys. Res. D: Atmos., 2010.

Garfinkel, C. I. and Hartmann, D. L.: The Influence of the Quasi-Biennial Oscillation on the Troposphere in Winter in a Hierarchy of Models. Part I: Simplified Dry GCMs, J. Atmos. Sci., 68, 1273–1289, 2011a.

Garfinkel, C. I. and Hartmann, D. L.: The Influence of the Quasi-Biennial Oscillation on the Troposphere in Winter in a Hierarchy of Models. Part II: Perpetual Winter WACCM Runs, J. Atmos. Sci., 68, 2026–2041, 2011b.

Garfinkel, C. I., Schwartz, C., Domeisen, D. I. V., Son, S.-W., Butler, A. H., and White, I. P.: Extratropical Atmospheric Predictability From the Quasi-Biennial Oscillation in Subseasonal Forecast Models, J. Geophys. Res. D: Atmos., 140, 1, 2018.

Hansen, F., Matthes, K., and Wahl, S.: Tropospheric QBO–ENSO Interactions and Differences between the Atlantic and Pacific, J. Clim., 29, 1353–1368, 2016.

Henderson, S. A., Maloney, E. D., and Barnes, E. A.: The Influence of the Madden–Julian Oscillation on Northern Hemisphere Winter Blocking, J. Clim., 29, 4597–4616, 2016.

Holton, J. R. and Tan, H.-C.: The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb, J. Atmos. Sci., 37, 2200–2208, 1980.

Hoskins, B. J. and Karoly, D. J.: The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing, J. Atmos. Sci., 38, 1179–1196, 1981.

Jenney, A. M., Randall, D. A., and Barnes, E. A.: Quantifying Regional Sensitivities to Periodic Events: Application to the MJO, J. Geophys. Res. D: Atmos., 124, 3671–3683, 2019.

Kim, H., Richter, J. H., and Martin, Z.: Insignificant QBO-MJO prediction skill relationship in the subseasonal reforecasts, Under review in Journal of Geophys. Res.: Atmos, 2019.

Lim, Y., Son, S.-W., Marshall, A. G., Hendon, H. H., and Seo, K.-H.: Influence of the QBO on MJO prediction skill in the subseasonal-to-seasonal prediction models, Clim. Dyn., 53, 1681–1695, 2019.

Madden, R. A.: Seasonal variations of the 40-50 day oscillation in the tropics, J. Atmos. Sci., 43, 3138–3158, 1986.

Madden, R. A. and 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. and 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.

Madden, R. A. and Julian, P. R.: Observations of the 40–50-Day Tropical Oscillation—A Review, Mon. Weather Rev., 122, 814–837, 1994.

Marshall, A. G., Hendon, H. H., Son, S.-W., and Lim, Y.: Impact of the quasi-biennial oscillation on predictability of the Madden–Julian oscillation, Clim. Dyn., 49, 1365–1377, 2017.

Mori, M. and Watanabe, M.: The Growth and Triggering Mechanisms of the PNA: A MJO-PNA Coherence, Journal of the Meteorological Society of Japan, 86, 213–236, 2008.

Mundhenk, B. D., Barnes, E. A., Maloney, E. D., and Baggett, C. F.: Skillful empirical subseasonal prediction of landfalling atmospheric river activity using the Madden–Julian oscillation and quasi-biennial oscillation, npj Climate and Atmospheric Science, 1, 20 177, 2018.

Nishimoto, E. and Yoden, S.: Influence of the Stratospheric Quasi-Biennial Oscillation on the Madden–Julian Oscillation during Austral Summer, J. Atmos. Sci., 74, 1105–1125, 2017.

Pegion, K., Kirtman, B. P., Becker, E., Collins, D. C., LaJoie, E., Burgman, R., Bell, R., DelSole, T., Min, D., Zhu, Y., Li, W., Sinsky, E., Guan, H., Gottschalck, J., Metzger, E. J., Barton, N. P., Achuthavarier, D., Marshak, J., Koster, R. D., Lin, H., Gagnon, N., Bell, M., Tippett, M. K., Robertson, A. W., Sun, S., Benjamin, S. G., Green, B. W., Bleck, R., and Kim, H.: The Subseasonal Experiment (SubX): A Multimodel Subseasonal Prediction Experiment, Bull. Am. Meteorol. Soc., 100, 2043–2060, 2019.

Richter, J. H., Deser, C., and Sun, L.: Effects of stratospheric variability on El Nino teleconnections, Env. Res. Lett., 10, 2015.

Sardeshmukh, P. D. and Hoskins, B. J.: The Generation of Global Rotational Flow by Steady Idealized Tropical Divergence, J. Atmos. Sci., 45, 1228–1251, 1988.

Simpson, I. R., Blackburn, M., and Haigh, J. D.: The Role of Eddies in Driving the Tropospheric Response to Stratospheric Heating Perturbations, J. Atmos. Sci., 66, 1347–1365, 2009.

Son, S.-W., Lim, Y., Yoo, C., Hendon, H. H., and Kim, J.: Stratospheric Control of the Madden–Julian Oscillation, J. Clim., 30, 1909–1922, 2017.

Song, L. and 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.

Sun, L., Wang, H., and Liu, F.: Combined effect of the QBO and ENSO on the MJO, Atmospheric and Oceanic Science Letters, 12, 170–176, 2019.

Sun, S., Bleck, R., Benjamin, S. G., Green, B. W., and Grell, G. A.: Subseasonal Forecasting with an Icosahedral, Vertically Quasi-Lagrangian Coupled Model. Part I: Model Overview and Evaluation of Systematic Errors, Mon. Weather Rev., 146, 1601–1617, 2018.

Tseng, K.-C., Barnes, E. A., and Maloney, E. D.: Prediction of the Midlatitude Response to Strong Madden-Julian Oscillation Events on S2S Time Scales: PREDICTION OF Z500 AT S2S TIME SCALES, Geophys. Res. Lett., 45, 463–470, 2018.

Tseng, K.-C., Maloney, E., and Barnes, E.: The Consistency of MJO Teleconnection Patterns: An Explanation Using Linear Rossby Wave Theory, J. Clim., 32, 531–548, 2019.

Vecchi, G. A.: The Madden-Julian Oscillation (MJO) and northern high latitude wintertime surface air temperatures, Geophys. Res. Lett., 31, 3500, 2004.

Vitart, F.: Madden-Julian Oscillation prediction and teleconnections in the S2S database: MJO Prediction and Teleconnections in the S2S Database, Q.J.R. Meteorol. Soc., 143, 2210–2220, 2017.

Wang, J., Kim, H.-M., Chang, E. K. M., and Son, S.-W.: Modulation of the MJO and North Pacific Storm Track Relationship by the QBO, J. Geophys. Res. D: Atmos., 123, 3976–3992, 2018.

Wheeler, M. C. and 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.

Yoo, C. and Son, S.-W.: Modulation of the boreal wintertime Madden-Julian oscillation by the stratospheric quasi-biennial oscillation, Geophys. Res. Lett., 43, 2016GL067 762, 2016.

Zhang, C. and Zhang, B.: QBO-MJO Connection, J. Geophys. Res. D: Atmos., 123, 2957–2967, 2018.

Zheng, C., Kar-Man Chang, E., Kim, H.-M., Zhang, M., and Wang, W.: Impacts of the Madden–Julian Oscillation on Storm-Track Activity, Surface Air Temperature, and Precipitation over North America, 2018.

Zhou, S., L'Heureux, M., Weaver, S., and Kumar, A.: A composite study of the MJO influence on the surface air temperature and precipitation over the Continental United States, Clim. Dyn., 38, 1459–1471, 2012.