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Abstract

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CMIP6 models underestimate the Holton-Tan effect

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Key Points:

- The CMIP6 models underestimate the weakening of the polar vortex expected when QBO easterlies exist in the tropical lower stratosphere
- Potential vorticity (PV) maps reveal that pooling of PV over mid-latitude Asia is important for coupling the QBO with the polar vortex
- The models underestimate the teleconnection because the 10 hPa QBO westerlies are too weak and too narrow

Abstract

The teleconnection between the Quasi-Biennial Oscillation (QBO) and the Arctic polar vortex is investigated using Coupled Model Intercomparison Project phase 6 (CMIP6) models. We use 14 CMIP6 models, reanalysis, three experiments with prescribed QBOs, one of which has no free polar stratospheric variability, and branched runs in which a QBO is imposed in runs previously devoid of a QBO. Each CMIP6 model underestimates the Holton-Tan effect (HTE), the weakening of the polar vortex with QBO easterlies in the lower stratosphere. To establish why, 850 Kelvin potential vorticity (PV) maps are used to study zonal asymmetries in the teleconnection. The QBO initiates the HTE by promoting equatorward (poleward) intrusion of high (low) PV over mid-latitude Asia (60°E-120°E). The presence of the PV intrusion in a model response is highly correlated with polar cap warming and the HTE. Models with stronger 10 hPa QBO amplitudes generally include the PV intrusion.

Plain Language Summary

In the tropics at altitudes between two and three times as high as commercial airplanes cruise, the winds alternate between blowing to the east for about a year before switching direction and blowing to the west for the next year. This pattern of winds is called the Quasi-Biennial Oscillation (QBO). Despite being high up in the tropical atmosphere, the QBO affects the global circulation in ways that ultimatey influence regional weather. One example of this occurs during winter, when the QBO changes the strength of the jet-stream. Althouch scientists have known about this phenomenon for

over 40 years, this long-distance relationship is complicated. Models of the coupled land, ocean, atmosphere system have steadily improved at representing the QBO. These models also represent the QBO's relationship with the jet-stream, but each model does it differently. We evaluate how the models perform in this study. The difference between models that represent the QBO-jet-stream relationship well and models that do not teaches us more about the relationship. We learn here that the QBO begins communicating with the jet by changing the atmospheric circulation 30 kilometers above Asia, nearly over the Tibetan Plateau. This phenomenon is best represented by models that have stronger QBOs.

1 Introduction

The Quasi-Biennial Oscillation (QBO) influences the global circulation through a suite of teleconnections (Gray et al. 2018). It modulates tropical convection (Son et al. 2017), upper tropospheric mid-latitude flow (Wang et al. 2018; Hitchman et al. 2021), and polar stratospheric flow in the southern (Yamashita et al. 2018) and northern hemispheres (Holton and Tan 1980; Lu et al. 2020). Each teleconnection is sensitive to the QBO's structure, its meridional extent (Hansen et al. 2013), the configuration of its easterly and westerly jets (Garfinkel et al. 2012; Gray et al. 2018), its vertical extent (Andrews et al. 2019), and how deep it reaches into the lower stratosphere (Collimore et al. 2003). Now with the Coupled Model Intercomparison Project 6 (CMIP6) models spontaneously generating the QBO, there is variability in how the models represent its structure (Richter et al. 2020). This suggests that there is variability in how the models represent the QBO teleconnections (Rao et al. 2020a,b). This study focuses on one of these teleconnections, the boreal winter polar stratospheric response to the QBO, the Holton-Tan effect (HTE, Holton and Tan 1980). We have two goals: (1) better understand why the CMIP6 models underestimate the HTE (Fig. 1) while (2) also learning how the middle stratospheric, 850 Kelvin, branch of the teleconnection varies over longitude.

When QBO westerlies are in the middle stratosphere (10 hPa) and QBO easterlies in the lower stratosphere (50 hPa), the polar vortex is weaker than in climatology. This configuration of the QBO, denoted QBO_{E50}, influences where planetary wave breaking occurs in the stratosphere (Hitchman and Husesmann 2009; Lu et al. 2020). QBO easterlies concentrate planetary waves and their breaking into the northern hemisphere (Holton and Tan 1980; Lu et al. 2020). The QBO induced mean meridional circulation (QBO-MMC) is also important for this teleconnection.

The QBO-MMC acts as a residual mean meridional circulation that maintains the dynamically forced temperature response to the QBO against radiative relaxation (Plumb and Bell 1982; Pahlavan et al. 2021; Hitchman et al. 2021). Westerly (easterly) QBO shear coincides with tropical warming (cooling), which is generated by adiabatic descent (ascent). At subtropical to mid-latitudes, the QBO-MMC induces vertical motion in the opposite direction of that in the tropics, yielding opposite temperature responses (Fig. 1q). The QBO-MMC changes the mid-latitude middle stratospheric mean flow geometry, forcing more poleward refraction of planetary waves (Garfinkel et al. 2012; Lu et al. 2014), which would otherwise propagate equatorward. This weakens the polar vortex.

It is not clear how this process varies over longitude. We hypothesize that it does as the QBO demonstrates zonally asymmetric teleconnections elsewhere. It has unique impacts on the North Pacific and North Atlantic jets (Wang et al. 2018). Further, we find that the QBO preferentially communicates with the mid-latitude North Pacific lower stratosphere by inducing more planetary wave absorption there relative to other longitudes (Elsbury et al. 2021). A more speculative hypothesis is that the QBO's zonally asymmetric structure (Hamilton et al. 2004; Hitchman and Huesmann 2009; Tegtmeier et al. 2020) predisposes it to have zonally asymmetric impacts on the extratropical circulation.

2 Methods

The HTE is analyzed over the 1850-2014 period using the same historical CMIP6 models used by Richter et al. (2020) to facilitate comparison between the extratropical responses (this study) and the QBO qualities in each model (their study). The CMIP6 responses to the QBO are compared to 1979-2019 ERA5 reanalysis (Hersbach et al. 2020).

Four experiments with the specified chemistry version of the Whole Atmosphere Community Climate Model (SC-WACCM4, Smith et al. 2014) use a prescribed QBO and are therefore useful for comparing with the CMIP6 models. The model domain is the surface up to 145 kilometers over 66 vertical levels with horizontal resolution of 1.9° latitude, 2.5° longitude. To simulate the QBO, the tropical stratospheric winds from 86 hPa-4 hPa and 22°S-22°N are relaxed toward a climatological 28-month QBO cycle derived from radiosondes (Hansen et al. 2013). The first of the experiments, referred to as PAMIP-WCSC, is a 1500-year simulation with a repeating annual cycle of sea surface temperature (SST) corresponding to present-day climate and a suite of different Arctic sea ice forcings (we neglect a potential influence of Arctic sea ice conditions on the QBO teleconnections). The second experiment, AMIP-WCSC, is a 370-year dataset made up of 10 ensemble members, run from 1978 to 2016, forced by the observed chronology of SST and sea ice variability. The third experiment, CPS-WCSC, is a 300-year simulation forced in the same way as PAMIP-WCSC except the polar stratospheric variability poleward of 60°N is relaxed toward a climatological polar stratospheric state allowing us to diagnose the influence of the QBO on the atmosphere in the absence of a polar stratospheric response to the QBO. The fourth experiment allows us to diagnose the transient atmospheric response to imposing the QBO. A 100-year control simulation devoid of the prescribed QBO is run and restarts are saved for each November 1st. We branch from November 1st and then impose the QBO_{E50} profile. The QBO propagates downward and the runs last until January 31st. More details on PAMIP-WCSC, CPS-WCSC, and the transient runs are given in Elsbury et al. (2021).

Throughout the manuscript, anomalies are calculated as deviations from the seasonal cycle. These anomalies are then subsampled by QBO phase. The QBO_{E50} index can be defined using westerlies at 10 hPa or easterlies at 50 hPa. Both yield similar results. However, the latter captures non-QBO variability for some models. Therefore, the QBO_{E50} index is defined as the December-January (DJ) time averaged, longitudinally averaged, and latitudinally averaged winds between 5°S and 5°N at 10 hPa that exceed 2.5 m/s. Further, similar results are obtained using the phase angle 30 hPa QBO index of Huang et al. (2012). This index allows for more control in picking the vertical structure of the QBO we are interested in, e.g., easterlies at 50 hPa (Fig. S1). Results are consistent for all three QBO indices. Here we present results using the QBO_{E50} index and have phase angle duplicates of Fig. 1 and 4 in supplementary (Fig.S2, Fig. S3).

3 Results

3.1 Zonal mean zonal wind

Figure 1 shows zonal mean zonal wind anomalies for all 18 datasets. The models both overestimate (1b, g, j, o, p) and underestimate (all others) the peak 10 hPa QBO westerlies relative to ERA5 (shown by Richter et al. 2020). The QBO westerlies extend upward and poleward between 20°N-40°N in ERA5, but they are confined equatorward in CMIP6 models. Each CMIP6 QBO is narrow relative to ERA5 (10 hPa QBO widths printed above plots).

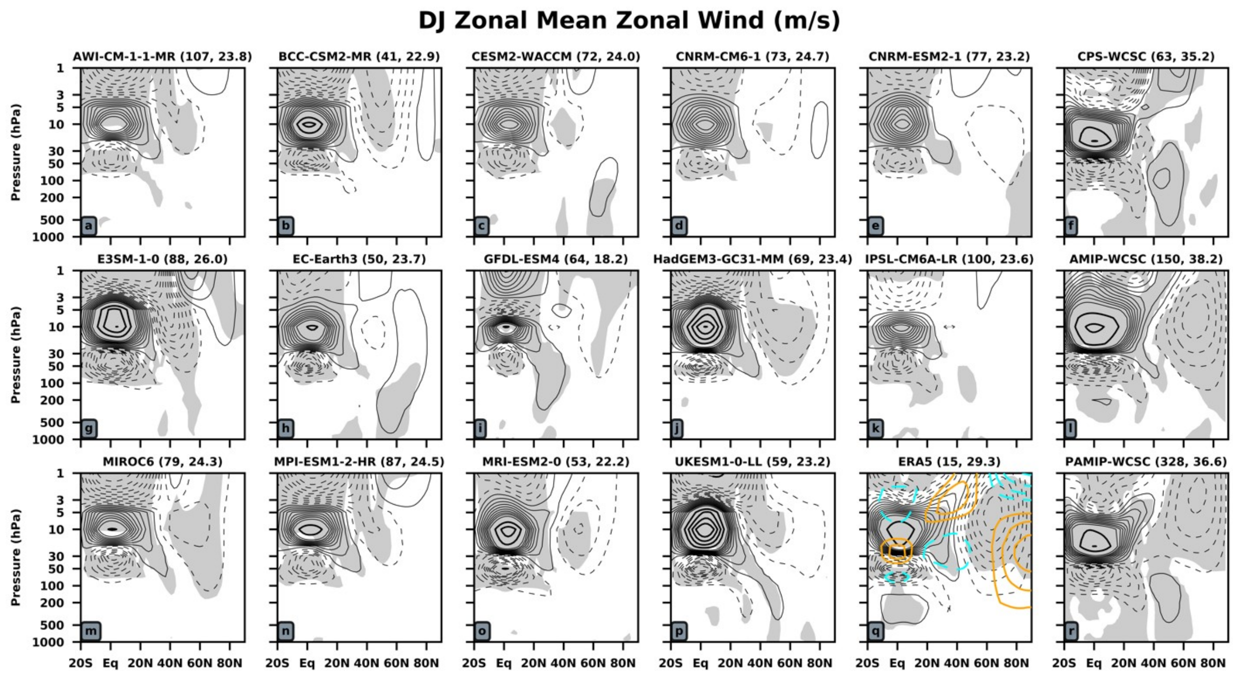

Figure 1: DJ zonal mean zonal wind anomalies. Thin contours show anomalies between +/- 8.5 m/s with intervals of +/- 1m/s. Thick contours correspond to +10, 15, 20 … m/s. Gray shading denotes statistical significance, p-values < 0.05 via a student's t-test, when comparing QBO_{E50} anomalies to all other anomalies. To the right of model titles is the number of DJ periods averaged together to make each composite and the 10 hPa latitudinal width of the QBO. Widths are calculated by applying the "half-maximum" method of Richter et al. (2020) and Bushell et al. (2020) to the anomalous 10 hPa response from each plot. Warm (cool) temperature anomalies are shown on FIg. 1q with +/- 1 K contours.

The 50 hPa peak QBO easterlies match ERA5 in four cases (1g, j, o, p) and are underestimated otherwise. Each unique QBO coincides with unique tropical stratospheric temperature perturbations (not shown), which the QBO-MMC must maintain against radiative relaxation. Therefore, the QBO-MMC differs in each model. Prescribing the QBO ensures that it has sufficient lower stratospheric amplitude. The QBO, in the absence of a HTE, pushes the tropospheric jet poleward (CPS, Fig. 1f). This is moderated by an equatorward jet shift in AMIP and PAMIP (Fig. 1l,r) due to a warm polar stratosphere caused by the HTE (Elsbury et al. 2021, Fig. 6). These experiments with prescribed QBOs show that when a realistic QBO exists in the model, teleconnections more closely resemble observations, notably the HTE.

While some models simulate a weakening of the polar stratospheric winds (BCC-CSM2-MR, HadGEM3-GC31-MM, MIROC6, UKESM1-0-LL), each model underestimates the HTE relative to ERA5 (Fig. 1q) and the prescribed QBO runs (Fig 1l, r). AWI-CM-1-1-MR, E3SM-1-0, MPI-ESM1-2-HR, and MRI-ESM2-0 each have extratropical easterly anomalies, but they are not at polar latitudes. Underestimation of the HTE occurs with all three QBO indices (Fig. S2). This should hinder stratospheric interaction with the tropospheric jet.

3.2 Zonally asymmetric middle stratospheric teleconnection

Before assessing the representation of the middle stratospheric HTE, we need to establish what this teleconnection looks like in a zonally asymmetric sense. Figure 2 shows potential vorticity (PV) on the 850 Kelvin isentropic surface (approximately 10hPa) associated with QBO_{E50} in ERA5. The standard deviation of the field shows that PV varies between 20 and 50 PVU from 30°N to 30°S with larger variability in the North Atlantic mid-latitudes than in the North Pacific (Fig. 2b). The largest variations occur at polar latitudes, especially over the North Pacific.

Relative to the standard deviation, the QBO_{E50} dominates the tropical and subtropical 850 K PV variability (Fig. 2a). At polar latitudes, the polar vortex is most disturbed over the North Atlantic where low PV anomalies peak at -60 PVU, about 50% of the |

standard deviation| there. Fig. 2a mirrors the DJ 850 K first empirical orthogonal function, which accounts for 36% of the variance (Fig. S4).

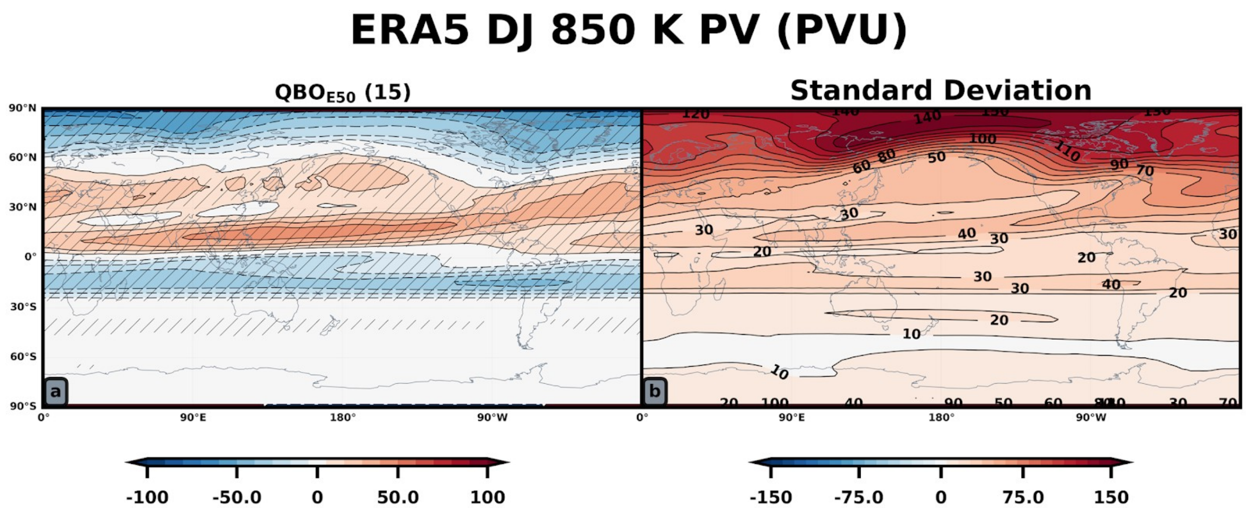

Figure 2: ERA5 DJ 850 Kelvin PV anomalies. Anomalies are deviations from the seasonal cycle for QBO_{E50} indices. Hatching denotes statistical significance, p-values < 0.05 via a student' t-test, when comparing QBO_{E50} anomalies to all other anomalies. The contour interval in line and shading for all panels is +/- 10 PVU. Fifteen DJ seasons are used to make the composite (a). Panel (b) shows the standard deviation of the field with contour intervals 10, 20, 30… PVU.

Two bands of anomalous PV span the tropics, negative in the southern hemisphere, positive in the northern hemisphere (Fig. 2a). This is the signature of the QBO-MMC. Shown by Hitchman and Huesmann (2009), the QBO-MMC converges toward the base of the QBO westerlies, "pinching" together the PV contours: high PV from the northern hemisphere and low PV from the southern hemisphere are concentrated nearer the tropics. The negative PV anomaly in the southern hemisphere shows some zonal asymmetry while the northern hemisphere positive PV band shows strong variation over longitude.

Since internal variability may convolute these PV results, we look for these signatures in dedicated perturbation experiments. Figure 3 shows the evolution of the PV field once a downward propagating QBO_{E50} profile is imposed in the control simulation devoid of a QBO. Anomalies are calculated as the difference between the transient runs and control runs from which the transient simulations are branched.

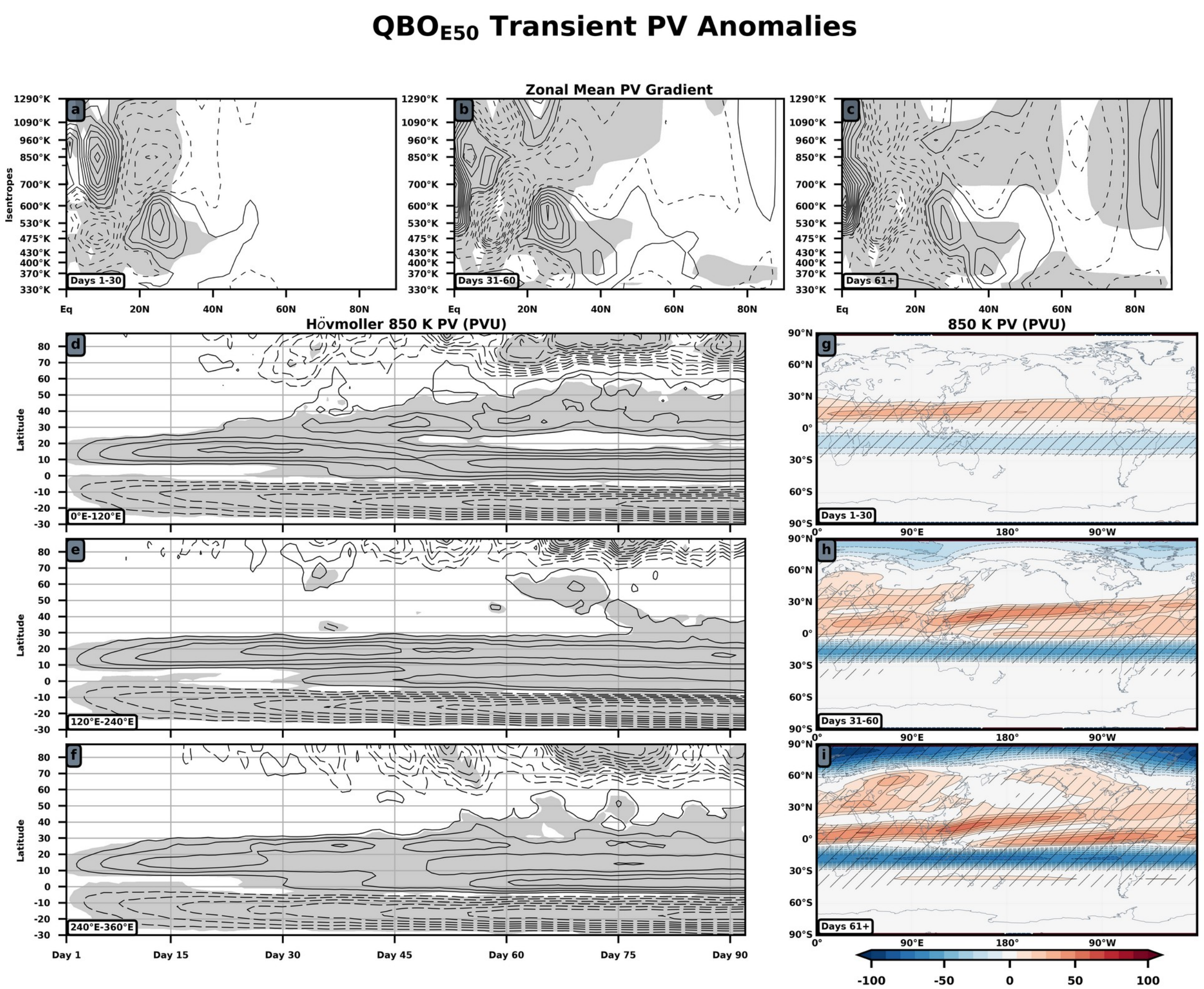

Figure 3: Anomalies after imposing a QBO_{E50} profile in the transient runs. (a-c): Zonal mean meridional PV gradient for successive 30-day periods after branching: dashed-negative (solid-positive) contours begin at negative (positive) $1\text{x}10^{-7}$ $K\cdot m\cdot kg^{-1}\cdot s^{-1}$ and decrease (increase) by negative (positive) $5\text{x}10^{-7}$ $K\cdot m\cdot kg^{-1}\cdot s^{-1}$ intervals. The responses at each isentrope are multiplied by $(\theta/350)^{-9/2}$ to account for logarithmic change in PV with height. (d-f): Latitude-time Hövmollers of 850 Kelvin PV (+/- 10 PVU) averaged over 0°E-120°E (d), 120°E-240°E (e), and (f) 240°E-360°E. Gray shading denotes statistical significance in (a-f), p-values < 0.05 via a

student's t-test, when comparing QBO_{E50} and control responses. (g-h) Maps of 850 K PV (+/- 10 PVU) anomalies with hatching denoting statistical significance.

Figs. 3a-c shows change in the meridional gradient of the zonal mean PV, P_{φ}, once the QBO_{E50} is imposed. Negative anomalies mean that the PV gradient is decreased and linear wave propagation into the region is less likely while the opposite holds true for regions with positive anomalies. During days 1-30, QBOW is located around 850 K and QBOE around 530 K. Planetary waves may propagate through the 850 K westerlies, but not the 530 K easterlies (Fig. 3a). P_{φ} weakens in the middle stratosphere between 30°N-50°N during days 31-60 indicating reduced likelihood for equatorward propagation (Fig. 3b). Beyond day 61, the polar stratospheric gradient weakens and this signal propagates downward (Fig. 3c). How does the spatiotemporal evolution of PV look on a horizontal surface, if we do not take a zonal average?

During the first 30 days at 850 K, the QBO-MMC spins up (Figs. 3g-i). The two anomalous PV bands indicate equatorward motion of the QBO-MMC from both hemispheres and the signal is almost zonally symmetric with more pooling of high PV near Asia (Fig. 3g). During the next 30 days, the positive PV anomalies become more zonally asymmetric, tilting out of the tropics toward the east (Fig. 3h). The evolution of the anomalous negative PV gradient poleward seen in the zonal mean occurs over Eurasia between 30°N and 50°N (Fig. 3h). Pooling of high PV over these continents is consistent with dilution of high PV over the pole during the last 32 days of the simulations (Fig. 3i).

Latitude-time Hövmollers make clear the importance of the Eurasia sector for coupling the QBO with the polar vortex (Figs. 3d-f). Equatorward (poleward) intrusion of high (low) PV occurs between 0°E-120°E during days 30-45 (Fig. 3d). Importantly, this anomalous flattening of the PV gradient (Fig. 3d) leads the other sectors (Fig. 3e-f). Fig. 3 suggests that the HTE begins in the middle stratosphere (Fig. 3a-c), particularly over Eurasia (Fig. 3d,h).

While the PV intrusion is broadly located over Africa, Europe, and Asia, subsequent results will show that the PV response over mid-latitude Asia is most important for the HTE. Therefore, we hereafter refer to this regional PV response as the “PV intrusion” or “Asia P_{φ}.”

3.3 Middle stratosphere in the CMIP6 models

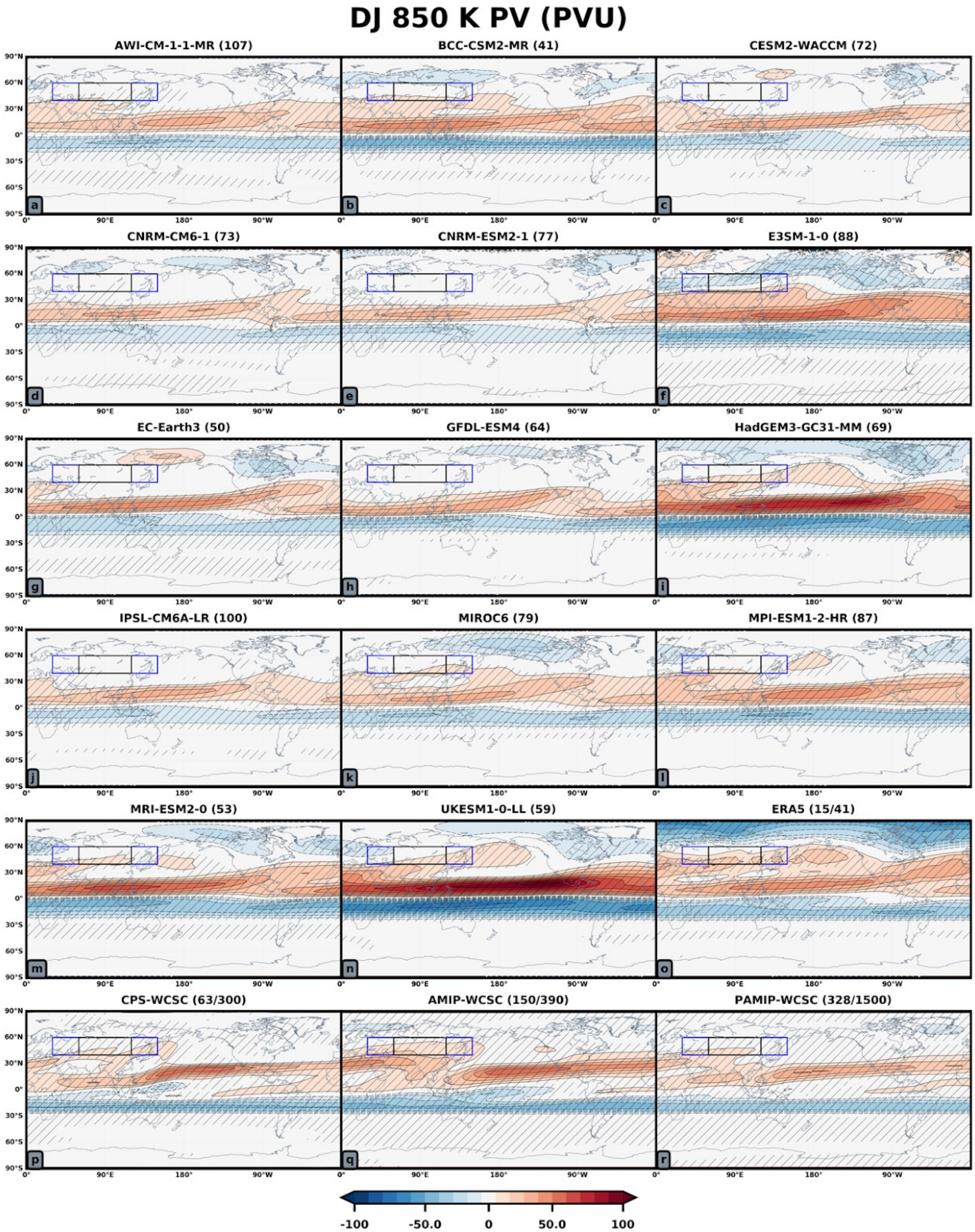

Figure 4: DJ 850 K PV anomalies for the 18 datasets. Contour intervals are +/- 10 m/s. Hatching denotes statistical significance, p-values < 0.05 via a student's t-test, when comparing QBO_{E50} anomalies to all other anomalies. Black and blue rectangles denote where the anomalous $_{P}$ is highly correlated with polar cap warming (Table S1).

Figure 4 shows 850 K PV anomalies for each model. From Fig. 1, the models that exhibit extratropical easterlies at polar latitudes (BCC-CSM2-MR, HadGEM3-GC31-MM, MIROC6, UKESM1-0-LL) or mid-latitudes (AWI-CM-1-1-MR, E3SM-1-0, MPI-ESM1-2-HR, MRI-ESM2-0) exhibit intrusion of high PV over mid-latitude Asia. Models with weaker HTEs (CESM2-WACCM, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, IPSL-CM6A-LR) exhibit no pooling of PV over Asia. The CMIP6 PV intrusions are equatorward of the intrusions in ERA5 or SC-WACCM4, suggesting why the CMIP6 extratropical easterly anomalies are ubiquitously equatorward of the polar stratosphere in Fig. 1. Note that every dataset's QBO is zonally asymmetric with stronger flow around Indonesia or the Indian Ocean, which may explain the location of the PV intrusion (Fig. S5).

Enhanced PV over Asia indicates anomalous cyclonic flow there. Stronger westerlies on its equatorward flank should strengthen P_φ and reduce wave breaking. Stronger easterlies on its poleward flank should weaken P_φ and reduce wave propagation. Indeed, studies using reanalysis (Fig. 3b of Lu et al. 2014) and model experiments (Garfinkel et al. 2012) show that QBO_{E50} suppresses climatological equatorward planetary wave propagation at 850 K between 30°N and 50°N in favor of anomalous poleward propagation. These PV results corroborate those studies and we add and emphasize that this process occurs over Asia.

Fig. 5 suggests that the PV intrusion is associated with the HTE. It establishes the relation between the anomalous polar cap temperatures at 10 hPa and P_φ averaged between 40°N and 60°N over various 60° longitude windows (Table S1). Various 60° longitude windows are used to see over what longitudes P_φ is most strongly associated with the polar cap temperature anomalies. Correlations exceed 0.7 from 30°E-150°E and peak at 0.82 from 60°E-120°E (Table S1). This is where the PV intrusion is located (enclosed by rectangles in Fig. 4). Fig. 5a depicts the relationship between Asia P_φ and polar cap temperatures. The more negative Asia P_φ is, the warmer the polar cap is (Fig. 5a).

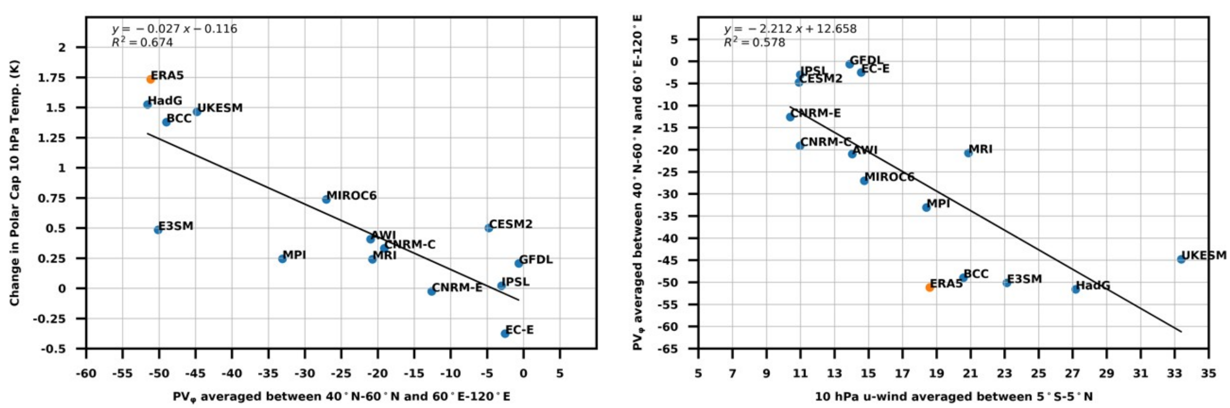

Figure 5: Left: The anomalous meridional PV gradient ($_P$) over Asia is compared to the anomalous 10 hPa polar cap (60°N+) temperature. $_P$ is not divided by the radius of Earth when calculating it. Right: The anomalous 10 hPa QBO, longitudinally averaged and cosine weighted latitudinally averaged zonal winds between 5°S-5°N, of Figure 1 are compared to $_P$ over Asia.

Asia P_φ is a direct response to the QBO – it does not result from the HTE. Indeed, the PV intrusion exists in the CPS 850 K response, which reveals the impact of the QBO in the absence of a polar stratospheric response (Fig. 4r). Furthermore, imposing the QBO in the transient simulations promoted the PV intrusion (Fig. 3). Regression between the 10 hPa QBO westerly velocity and Asia P_φ shows that stronger QBO winds equate to more negative Asia P_φ (Fig. 5b). Citing the strong relationship between Asia P_φ and polar cap temperatures, underestimation of the 10 hPa QBO amplitudes is *partly* suppressing the HTE.

4 Discussion

4.1 Importance of the QBO-MMC

Stronger QBOs have larger effects on the extratropical circulation. Of the 14 CMIP6 models, the eight with strongest 10 hPa QBO westerlies are BCC-CSM2-MR, HadGEM3-GC31-MM, MIROC6, UKESM1-0-LL, AWI-CM-1-1-MR, E3SM-1-0, MPI-ESM1-2-HR, and MRI-ESM2-0 (Fig. 5b, compare with Fig. 2b of Richter et al. 2020). The first four models feature some weakening of the polar vortex while the latter four exhibit anomalous easterlies equatorward of the polar vortex. The models with the weakest 10 hPa QBO westerlies exhibit much weaker easterlies everywhere in the stratosphere (Fig. 1c, d, e, h, i, k).

Our Figs. 4 and 5b show that models with stronger 10 hPa QBO amplitudes feature stronger PV intrusions over Asia. Garfinkel and Hartmann (2011, Fig. 6) show that stronger QBOs have stronger QBO-MMCs, which have larger effects on the extratropical circulation. A speculation then is that the PV intrusion may be the extratropical signature of the QBO-MMC. By underestimating this feature, which confines planetary waves to higher latitudes (Lu et al. 2014), the models underestimate the HTE.

4.2 Limitations of our argument

Underestimating the 10 hPa QBO amplitudes is not the only factor hindering the HTEs. For instance, HadGEM3-GC31-MM and UKESM1-0-LL both overestimate the 10 hPa QBO winds and still underestimate the weakening of the polar vortex relative to ERA5 (Fig. 1j,p).

Figure 1 shows that the QBOs are too narrow. We calculate the latitudinal extents of the QBOs at 10 hPa using the "half-maximum" method of Richter et al. (2020) and Bushell et al. (2020); see the model titles in Fig. 1. Regression between these extents and Asia P_{φ} shows little correlation (Fig. S6). Regardless, Hansen et al. (2013) have already shown that narrow QBOs coincide with a reduced HTE.

5 Conclusions

The HTE is analyzed in the CMIP6 historical simulations studied by Richter et al. 2020. The CMIP6 models consistently underestimate the amplitude of the HTE during December and January relative to ERA5. This conclusion is robust to three different QBO indices.

The underestimation of the HTE coincides with underestimation of the 10 hPa QBO amplitudes. The desired impact that the models are not representing is the intrusion of high PV anomalies over Asia. This signal is highly anticorrelated with polar stratospheric warming taking place during QBO_{E50}. The transient simulations in which the QBO is imposed in a live running atmosphere devoid of a QBO, and CPS, which includes no polar stratospheric variability, both suggest that the QBO promotes the intrusion of high PV air over Asia *by itself*. Further, the presence of this signal in the CMIP6 models that simulate HTE, the 1500-year SC-WACCM4 simulation set, and ERA5 suggest this is an important feature for the teleconnection in nature.

Why does the PV intrusion occur over Asia? The QBO has a stronger amplitude over that sector (Fig. S5), but other factors may play a role too. For instance, orographic gravity wave drag over the Tibetan Plateau has a nonnegligible influence on the stratospheric mean flow (Xu et al. 2017). This will have to be investigated in future work.

Acknowledgments, Samples, and Data

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process. You can only submit data there once as submitting your data coincides with receiving a unique doi, which is meant to go in the acknowledgements.

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Figure 1. Figure 1: DJ zonal mean zonal wind anomalies. Thin contours show anomalies between +/- 8.5 m/s with intervals of +/- 1m/s. Thick contours correspond to +10, 15, 20 … m/s. Gray shading denotes statistical significance, p-values < 0.05 via a student's t-test, when comparing QBO_{E50} anomalies to all other anomalies. To the right of model titles is the number of DJ periods averaged together to make each composite and the 10 hPa latitudinal width of the QBO. Widths are calculated by applying the "half-maximum" method of Richter et al. (2020) and Bushell et al. (2020) to the anomalous 10 hPa response from each plot. Warm (cool) temperature anomalies are shown on FIg. 1q with +/- 1 K contours.

Figure 2: ERA5 DJ 850 Kelvin PV anomalies. Anomalies are deviations from the seasonal cycle for QBO_{E50} indices. Hatching denotes statistical significance, p-values < 0.05 via a student' t-test, when comparing QBO_{E50} anomalies to all other anomalies. The contour interval in line and shading for all panels is +/- 10 PVU. Fifteen DJ seasons are used to make the composite (a). Panel (b) shows the standard deviation of the field with contour intervals 10, 20, 30… PVU.

Figure 3: Anomalies after imposing a QBO_{E50} profile in the transient runs. (a-c): Zonal mean meridional PV gradient for successive 30-day periods after branching: dashed-negative (solid-positive) contours begin at negative (positive) $1x10^{-7}$ $K \cdot m \cdot kg^{-1} \cdot s^{-1}$ and decrease (increase) by negative (positive) $5x10^{-7}$ $K \cdot m \cdot kg^{-1} \cdot s^{-1}$ intervals. The responses at each isentrope are multiplied by $(/350)^{-9/2}$ to account for logarithmic change in PV with

height. (d-f): Latitude-time Hövmollers of 850 Kelvin PV (+/- 10 PVU) averaged over 0°E-120°E (d), 120°E-240°E (e), and (f) 240°E-360°E. Gray shading denotes statistical significance in (a-f), p-values < 0.05 via a student's t-test, when comparing QBO_{E50} and control responses. (g-h) Maps of 850 K PV (+/- 10 PVU) anomalies with hatching denoting statistical significance.

Figure 4: DJ 850 K PV anomalies for the 18 datasets. Contour intervals are +/- 10 m/s. Hatching denotes statistical significance, p-values < 0.05 via a student's t-test, when comparing QBO_{E50} anomalies to all other anomalies. Black and blue rectangles denote where the anomalous $_P$ is highly correlated with polar cap warming (Table S1).

Figure 5: Left: The anomalous meridional PV gradient ($_P$) over Asia is compared to the anomalous 10 hPa polar cap (60°N+) temperature. $_P$ is not divided by the radius of Earth when calculating it. Right: The anomalous 10 hPa QBO, longitudinally averaged and cosine weighted latitudinally averaged zonal winds between 5°S-5°N, of Figure 1 are compared to $_P$ over Asia.