CMIP6 Models Underestimate the Holton-Tan Effect

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Abstract The teleconnection between the Quasi-Biennial Oscillation (QBO) and the Arctic polar vortex is investigated using Coupled Model Intercomparison Project 6 (CMIP6) models. Output from 14 CMIP6 models is compared with reanalysis, three experiments with prescribed QBOs, one of which has no free polar stratospheric variability, and transient experiments in which a QBO is prescribed in runs previously devoid of a QBO. Each CMIP6 model underestimates the Holton-Tan effect (HTE), the weakening of the polar vortex expected with QBO easterlies in the tropical lower stratosphere. To establish why, potential vorticity maps are used to investigate longitudinal variations in the teleconnection. Prescribing easterly QBO in the transient experiments promotes more high-latitude planetary wave breaking by influencing the mid-latitude stratospheric circulation, particularly over Asia. CMIP6 models that better simulate this response over Asia better simulate the HTE. These models also have stronger 10 hPa QBO westerlies.

Plain Language Summary In the tropics at altitudes between two and three times as high as commercial airplanes fly (10–30 kilometers), successive sets of easterly and westerly winds propagate downward approximately every 28 months. This pattern of winds is called the Quasi-Biennial Oscillation (QBO). Despite being in the middle to lower tropical stratosphere, the QBO affects the global circulation in ways that ultimately influence regional weather. One example of this occurs during winter, when the QBO changes the strength of the westerly flow that forms in the Arctic polar stratosphere in the absence of solar radiation, the polar vortex. Although scientists have known about this phenomenon for 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 polar vortex, but each model does it differently. The difference between models that represent the QBO-polar vortex relationship well and models that do not, teaches us more about the relationship. We learn here that the QBO communicates with the polar stratosphere partly by changing the atmospheric circulation 30 kilometers above Asia. This phenomenon is best represented by models that have stronger QBOs.

1. Introduction

The Quasi-Biennial Oscillation (QBO) is a pattern of descending and alternating easterly and westerly winds in the tropical stratosphere that influences the atmospheric circulation globally (Gray et al., 2018). The QBO can enhance or suppress tropical convection (Son et al., 2017), change the strength and location of the jet-stream (Wang et al., 2018), and change the velocity of the polar stratospheric wind in the southern (Yamashita et al., 2018) and northern hemispheres (Lu et al., 2020). These large-scale remote atmospheric responses to the QBO are sensitive to its structure, its meridional extent (Hansen et al., 2013), its vertical extent (Andrews et al., 2019), how deep the QBO extends into the lower stratosphere (Collimore et al., 2003), and the phase of its easterly and westerly jets (Gray et al., 2018). 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), suggesting that there is variability in how the models represent the QBO teleconnections. This presents an opportunity to use multiple models to study one of the most extensively researched, yet still enigmatic, teleconnections associated with the QBO, the Holton-Tan effect (HTE, Holton & Tan, 1980).

During early winter, if QBO westerlies are located in the middle stratosphere (10 hPa) and QBO easterlies in the lower stratosphere (50 hPa), hereafter referred to as QBOE, the polar stratospheric westerlies (polar vortex) are weaker than average (Holton & Tan, 1980). One explanation of how this happens emphasizes the QBO mean meridional circulation (QBO-MMC). The QBO-MMC acts as a residual mean meridional circulation that maintains the dynamically forced temperature response to the QBO against radiative relaxation (Hitchman et al., 2021; Pahlavan et al., 2021; Plumb & Bell, 1982). During QBOE, the westerly vertical wind shear below the 10 hPa QBO westerlies coincides with tropical warming, generated by descending motion. This subsidence in the tropics
is part of a broader circulation cell, with compensating upward motion and cooling in the subtropics. The QBO-MMC changes the mid-latitude middle stratospheric mean flow geometry, which is associated with more poleward propagation of planetary waves during QBOE (Garfinkel et al., 2012; Lu et al., 2014). While checking the fidelity of the HTE in CMIP6 models, Rao et al. (2020) showed the result of this mechanism, models with more poleward propagation of planetary waves in the middle stratosphere during QBOE, promote more descending motion throughout the polar stratosphere, and presumably more warming.

Something unclear about this teleconnection is how it varies over longitude. Seeing the HTE in the zonal-mean partly arises out of necessity, since it is helpful to see the residual mean meridional circulation response to QBOE (e.g., Figure 4 of Rao et al., 2020). Still, considering zonal asymmetry in the teleconnection opens up the interesting question of whether or not the teleconnection develops along a preferred regional pathway.

Fewer studies consider the zonally asymmetric response to the QBO during winter. We have done this for the lower stratosphere (Elsbury et al., 2021). Hamilton et al. (2004) and Hitchman and Huesmann (2009) have done this for the middle stratosphere. Both studies showed that the QBO itself is zonally asymmetric, with stronger QBO westerlies near Indonesia than near South America. Hamilton et al. (2004) attributed this zonal asymmetry in the tropics to influence by the equatorward propagating extratropical stationary wave, which had a marked wave-1 component. Hitchman and Huesmann (2009) showed that the signature of the QBO-MMC shows up in the potential vorticity (PV) field. With this in mind, we analyze PV along the 850 Kelvin (∼10 hPa) isentropic surface throughout this study. PV is well-suited for this analysis because its meridional gradient is proportional to the refractive index (Andrews et al., 1987, equation 5.3.7), which is the field allowing for visualization of the mean flow geometry (Lu et al., 2014).

### 2. Methods

The HTE is analyzed over the 1850–2014 period using the same historical CMIP6 models used by Richter et al. (2020). The CMIP6 responses to QBOE are compared to that in 1979–2019 ERA5 reanalysis (Hersbach et al., 2020).

In addition, the QBO is prescribed in four experiments with the specified chemistry version of the Whole Atmosphere Community Climate Model (SC-WACCM4, Smith et al., 2014) to see how imposing a more realistic QBO affects the HTE. 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 prescribe the QBO, the tropical zonal-mean zonal wind from 86 hPa to 4 hPa is continuously relaxed towards a 28-month QBO cycle derived from radiosondes using a relaxation constant of 10 days that decays away from the equator so that the model atmosphere freely evolves poleward of 22°S–22°N (Matthes et al., 2010). The first experiment, PAMIP-WCSC, is a concatenation of 1,500 one-year simulations forced with an annual cycle of sea surface temperature (SST) corresponding to present-day climate and a few different Arctic sea-ice forcings (we neglect a potential influence of Arctic sea-ice conditions on the QBO teleconnections). Each of the 1,500 ensemble members is initialized with one of the 28 months in the QBO cycle, which yields a large sample size of atmospheric responses to the QBO. The second experiment, AMIP-WCSC, consists of 10 ensemble members of Atmospheric Model Intercomparison Project (AMIP) experiments, that is, forced by the 1979–2016 observed chronology of SST and sea-ice variability. The third experiment, CPS-WCSC, is identical to the 300-year chunk of the PAMIP-WCSC experiment (the control) forced with present-day SST and sea-ice, but with horizontal wind and temperature poleward of 60°N and above 200 hPa relaxed to the climatological polar stratospheric state of the control using a relaxation timescale of 2.5 hr. This allows us to diagnose the influence of the QBO on the atmosphere in the absence of a polar stratospheric response to the QBO. For the fourth experiment, we run a 100-year control simulation without prescribing a QBO. We then run 100 perturbation experiments by branching from the 100 November 1st's of this control and prescribing QBOE, which begins propagating downward as soon as each experiment begins. These experiments run through January 31st and allow us to diagnose the transient atmospheric response to QBOE.

These results focus on December and January (DJ), when QBOE forces the most Rossby wave breaking near the polar stratosphere and prior to the sign reversal of the HTE in February (Lu et al., 2020). Anomalies for all data sets, except the transient experiments, are calculated as deviations from the seasonal cycle. These anomalies are subsampled by QBO phase to highlight the role of the QBO. Since, the CMIP6 QBOs have weak 50 hPa amplitudes, which is where we would ideally index the QBO using its easterlies, the QBO is indexed using the
latitudinally and longitudinally averaged 5°S–5°N time averaged DJ 10 hPa zonal wind >2.5 m/s. This works because the 10 and 50 hPa QBO winds are anticorrelated with the mid-winter polar vortex velocity (Anstey et al., 2021). Several QBO indexing schemes were tested. To show that the results are robust to different QBO indexing, duplicates of Figures 1 and 4 created using the phase angle index of Huang et al. (2012) (Figure S1 in Supporting Information S1) are shown in supplementary (Figures S2–S3 in Supporting Information S1).

3. Results

3.1. Zonal-Mean Zonal Wind

Figure 1 shows the effect of QBOE on the zonal-mean zonal wind in all 18 data sets. The ERA5 QBO easterlies are positioned near 50 hPa and they show a peak velocity of −12.5 m/s (Figure 1a). The CMIP6 models systematically underestimate the amplitude of the lower stratospheric QBO easterlies, as shown by Richter et al. (2020). The ERA5 QBO westerlies are positioned near 10 hPa and they show a peak velocity of 19.5 m/s (Figure 1a). PAMIP-WCSC, AMIP-WCSC, and CPS-WCSC closely reproduce this signal, each showing peak QBO westerly velocities just exceeding 20 m/s (Figures 1b–1d). The CMIP6 models exhibit no systematic bias in the QBO westerlies like they do for the QBO easterlies. Of the CMIP6 models, BCC-CSM2-MR and MRI-ESM2-0 most closely match the peak westerly velocity of ERA5 (Figures 1f and 1q), E3SM-1-0, HadGEM3-GC31-MM, and UKESM1-0-LL all overestimate it (Figures 1j, 1m and 1r), and all other CMIP6 models underestimate it.

Compared to ERA5, every model underestimates the weakening of the polar vortex expected during QBOE. The polar vortex weakens by over 6.5 m/s at 5 hPa and 60°N in ERA5 (Figure 1a). This response is half as strong in the multi-century PAMIP-WCSC and AMIP-WCSC experiments (Figures 1b and 1c) and it is absent from CPS-WCSC by construction (Figure 1d). Of the CMIP6 models, only HadGEM3-GC31-MM and MIROC6 show weakening of the polar stratospheric westerlies poleward of 60°N (Figures 1m and 1o). BCC-CSM2-MR, MRI-ESM2-0, and UKESM1-0-LL all show the next-most realistic responses with weakening of the stratospheric westerlies between 40°N and 60°N (Figures 1f, 1q and 1r). The other CMIP6 models show little polar stratospheric
response to QBOE. This underestimation of the HTE also occurs with different QBO indexing (Figure S2 in Supporting Information S1).

3.2. Zonally Asymmetric Middle Stratospheric Teleconnection

As a way to learn more about the HTE so that we may understand why the models underestimate it, we now switch our focus to results from idealized experiments with SC-WACCM4. Figures 2 and 3 show the transient atmospheric response to prescribing QBOE, calculated as the difference between the 100 November and January (NDJ) QBOE perturbation experiments and the 100 NDJ periods from the control experiment without a QBO. Figures 2a–2c shows the change in the meridional gradient of the zonal-mean PV, PVϕ, and corresponding zonal-mean zonal wind anomalies. Negative PVϕ anomalies mean that linear planetary wave propagation into a region is less likely while the opposite holds true for regions with positive anomalies. During November, QBO westerlies are located around 850 K and easterlies around 530 K. The tropical positive PVϕ response near 850 K suggests that planetary waves propagating through the extratropical winter hemisphere westerlies may enter the QBO westerlies, as shown by Hamilton et al. (2004). Conversely, planetary waves will not enter the 530 K QBO easterlies, consistent with the classic Holton-Tan mechanism (Figure 2a).

**Figure 2.** (a–c) Anomalous zonal-mean meridional potential vorticity (PV) gradients for each month after branching: dashed-negative (solid-positive) contours begin at negative (positive) $1 \times 10^{-7}$ K-m-kg$^{-1}$-s$^{-1}$ and decrease (increase) by negative (positive) $5 \times 10^{-7}$ K-m-kg$^{-1}$-s$^{-1}$ intervals. The responses at each isentrope are multiplied by $(\theta/350)^{-9/2}$ to account for logarithmic change in PV with height (Lait, 1994). Gray shading denotes statistical significance, p-values <0.05 via a student's t-test, when comparing the perturbation experiments and control. Westerly (red) and easterly (blue) zonal-mean zonal wind is underlaid with ±1 m/s intervals between −10 and 10 m/s (d–f) Maps of 850 K PV (lined contour intervals ±10 PVU) anomalies and (g–i) 850 K PVϕ reversal frequency (PWBs/month) as in Hitchman and Huesmann (2009). Hatching denotes statistical significance for (d–i).
During December, PVϕ weakens in the middle stratosphere between 30°N and 50°N, suggesting that the upward and equatorward propagating planetary waves that ordinarily enter this region from the extratropics during winter are inhibited - the waves are confined to higher latitudes (Figure 2b). PVϕ steepens lower in the mid-latitude stratosphere (∼530 K), supporting more upward planetary wave propagation, particularly over the North Pacific (Elsbury et al., 2021). During January, the polar stratospheric PVϕ weakens and this signal moves downward in time (Figure 2c). What does the spatiotemporal evolution of PV look like on an isentropic surface?

The QBO westerlies form during November near 850 K, shown by positive and negative PV bands in the equatorial region of the hemispheres, each indicating enhanced cyclonic vorticity, consistent with increased westerly flow throughout the tropics (Figure 2d). The PV anomalies are larger by Indonesia and weaker near South America, which appears to result from the anomalous wave-1 response to the QBO (Figure S4 in Supporting Information S1).

During December, the positive PV band tilts north out of the tropics towards the east (Figure 2e). The positive maximum of what is mostly a wave-1 PV streamer is positioned over Asia (black dot, Figure 2e) and the negative maximum is over the North Pacific (Figure S4 in Supporting Information S1). Less planetary wave breaking (PWB) occurs equatorward of the Asia PV response, but more occurs poleward of it (Figure 2h), illustrating how prescribing QBOE increases high-latitude PWB.

During January, PWB occurs at all longitudes near 70°N, with the largest increase near 90°E (Figure 2i). The zonal-mean change in January PWB is two days/month at 70°N (not shown), which is consistent with reanalysis (Lu et al., 2020, Figure 4).

To further reveal the spatiotemporal evolution of the mid-to-high-latitude PV response, three latitude-time plots of the PV response are shown longitudinally averaged over three different domains, 0°E–120°E (Figure 3a), 120°E–240°E (Figure 3b), 240°E–360°E (Figure 3c). Three weeks into November, the northern hemisphere high PV band begins to extend to higher latitudes between 0°E and 120°E (Figure 3a). Around December 1st between 0°E and 120°E, the first sign of extratropical PWB becomes visible (Figure 3a). The high-latitude 120°E–240°E response is relatively docile (Figure 3b), and low PV anomalies form at high-latitudes over 240°E–360°E (Figure 3c), but well after low PV anomalies first appeared at high-latitudes between 0°E and 120°E. Further, the
Figure 4. DJ 850 K PV anomalies, deviations from the seasonal cycle, during QBOE DJs. Lined contour intervals are ±10 PVU. Hatching denotes statistical significance, p-values <0.05 via a student’s t-test, when comparing QBOE anomalies to all other anomalies. The black rectangle is the key region identified in Figure 5a. As in Figure 2e, black dots approximate where the positive part of the wave-1 PV streamer should be.
polar stratosphere warms most between 0°E and 120°E (Figures 3d–3f). The results of Figures 2 and 3 lead us to believe that the PV response over Asia is important for the HTE.

3.3. Middle Stratosphere in the CMIP6 Models

Figure 4 shows 850 K PV responses to QBOE in each data set. The ERA5 response is similar to that in the transient experiments as are the PAMIP-WCSC and AMIP-WCSC responses, albeit the high-latitude low PV anomalies are much weaker for these experiments compared to ERA5 (Figures 4a–4c). The CPS-WCSC response is similar to that from PAMIP-WCSC, however there is no low PV response at high-latitudes by construction (Figure 4d).

It is worth noting that all CMIP6 models have similar tropical PV responses. The PV anomalies and the QBO westerlies are generally stronger near Indonesia than near South America (Figures S5 and S6 in Supporting Information S1). Hamilton et al. (2004) and Hitchman and Huesmann (2009) found similar responses with in situ wind observations, model experiments, and reanalysis.

Recalling the zonal-mean zonal wind responses from Figure 1, the CMIP6 models that are better at simulating the HTE are BCC-CSM2-MR, HadGEM3-GC31-MM, MIROC6, MRI-ESM2-0, and UKESM1-0-LL. Now looking at Figure 4, the PV responses for these models generally agree that there should be an increase in PV over mid-latitude Asia (black dots, Figures 4f, 4m, 4o, 4q and 4r). Conversely, in models with weaker HTEs like CESM2-WACCM, CNRM-CM6-1, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, and IPSL-CM6A-LR, the PV changes very little over mid-latitude Asia (Figures 4g–4l and 4n). Without the positive maximum of the wave-1 PV streamer over Asia, likely more PWB is allowed to happen at lower latitudes, inhibiting the HTE.

To investigate this hypothesized relationship between the mid-latitude 850 K PV responses and the HTE, for each model and ERA5 we calculated the change in latitude weighted polar cap (north of 60°N) temperature as a function of change in PVϕ latitudinally averaged between 40°N and 60°N and longitudinally averaged over various 60° longitude windows (Table S1 in Supporting Information S1). We used various 60° longitude windows (e.g., 0°E–60°E, 30°E–90°E) to see if any one region was more correlated with the change in polar cap temperature during QBOE. Correlations are highest for PVϕ between 30°E and 150°E, exceeding 0.7, and peaking at 0.82 (p < 0.05) between 60°E and 120°E (Table S1 in Supporting Information S1). The more negative the 60°E–120°E PVϕ is, the warmer the polar cap (Figure 5a).

The polar cap temperature also may be associated with the strength of the QBO. Of the 14 CMIP6 models, the eight with strongest 10 hPa QBO westerlies are AWI-CM-1-1-MR, BCC-CSM2-MR, E3SM-1-0, HadGEM3-GC31-MM, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The first four models feature some weakening of the polar vortex while the last four exhibit anomalous easterlies equatorward of the polar vortex. The models with the weakest 10 hPa QBO westerlies exhibit much weaker anomalous easterlies everywhere in the stratosphere. However, it turns out that the QBO westerlies are only moderately correlated with the polar cap temperature (Figure 5b). Rather, PVϕ over Asia explains more spread in the polar cap temperature change than the QBO westerlies.

Figure 5. (a) Anomalous 10 hPa polar cap (60°N+) temperatures as a function of anomalous PVϕ over Asia. PVϕ is not divided by the radius of Earth when calculating it. (b) Change in polar cap temperature as a function of 10 hPa Quasi-Biennial Oscillation (QBO) westerly velocity (c): Change in PVϕ over Asia as a function of 10 hPa QBO westerlies.
Since the QBOs vary amongst the CMIP6 models, it seems that the presence/absence of the Asia PV$_\phi$ response in a model depends on the representation of the model's QBO. We first compare the latitudinal widths of the Figure 1 QBO westerlies against the Asia PV$_\phi$ response and no relationship is obvious (Figure S7 in Supporting Information S1), which is surprising as Hansen et al. (2013) show that reducing the latitudinal width of the QBO in a model weakens the HTE. We next compare the 10 hPa QBO westerly velocities of Figure 1 against Asia PV$_\phi$ and find that the stronger the QBO westerlies are, the more negative the PV$_\phi$ is over Asia (Figure 5c), suggesting some close relationship between the QBO and the mid-latitude circulation.

4. Discussion and 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 different methods of QBO indexing.

Underestimation of the HTE coincides with the absence of the positive component of a wave-1 PV streamer over mid-latitude Asia. The absence of this response is apparent in models with weaker 10 hPa QBO westerlies, suggesting the amplitude of the QBO is relevant for reproducing the HTE. However, factors aside from the strength of the QBO must be considered in subsequent research as the QBO strength is only moderately correlated with polar cap warming during QBOE.

Our transient experiments reveal how the QBO affects PV$_\phi$ and planetary wave breaking in high-latitudes. These changes are consistent with the changes to planetary wave breaking promoted by the QBO-MMC (Garfinkel et al., 2012; Lu et al., 2014). Hitchman and Huessmann (2009) showed that the convergent equatorward flow of the QBO-MMC below the QBO westerlies is consistent with an increase (decrease) in PV north (south) of the equator, which we find in every data set. These changes in PV are zonally asymmetric though, particularly over Asia, and more work is needed to understand why. The 1500-year data set, the transient experiments, and CPS, which includes no polar stratospheric variability, all suggest that the QBO by itself promotes the development of the PV streamer over Asia. The PV streamer over Asia varies as a function of the 10 hPa QBO westerly strength. The strength of the QBO-MMC is also proportional to the strength of the QBO (Garfinkel & Hartmann, 2011), hence models with weak QBOs may have weak QBO-MMCs and limitations for producing the HTE.

Data Availability Statement

CMIP6 data is archived and provided by the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/cmip6/). The authors thank to various modeling centers that have run the simulations, processed the data, and made it publicly available. ERA5 reanalysis may be accessed with Copernicus (https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.bd0915c6?tab=overview). Doi:10.24381/cds.bd0915c6. Output from the AGCM experiments is available from https://doi.org/10.5281/zenodo.5153962.

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