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Extratropical teleconnections in a multi-model ensemble nudged towards the observed QBO

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Abstract. The Quasi-Biennial Oscillation (QBO), the dominant mode of interannual variability of monthly-mean zonal winds and temperatures in the equatorial stratosphere, has a significant influence on the circulation in other regions of the stratosphere and troposphere in boreal winter. To better understand these teleconnections, results from twelve models are analysed for three complementary experiments in which the QBO is either internally generated by the models (free-running), nudged towards the observed QBO, or nudged towards the observed climatology. For the multi-model ensemble mean we assess how well the free-running experiment captures the observed teleconnections, and whether the simulated teleconnections improve when the models have a more realistic QBO.

The observed relationship between the QBO phase and the strength of the boreal winter Polar Night Jet is weakly captured by the free-running experiment. This relationship is strengthened when the models are nudged towards the observed QBO, primarily because a larger proportion of the models exhibit this relationship. Both free-running and nudged-QBO experiments capture a robust but small and insignificant increase in Sudden Stratospheric Warning (SSW) frequency during the QBO-easterly phase. Neither experiment captures the observed QBO influence on the timings of SSWs during winter nor the QBO teleconnection to the North Atlantic Oscillation. Nudging the QBO does, however, influence the latitudinal profile of the North Pacific sub-tropical jet and strength of tropical precipitation.

We find that a more realistic representation of the QBO is beneficial for certain teleconnections, but that effective teleconnections are ultimately reliant on how well the models respond to the QBO.

1 Introduction

The Quasi-Biennial Oscillation (QBO) is the dominant mode of interannual variability of zonal mean monthly-mean winds and temperatures in the equatorial stratosphere (Baldwin et al., 2001). Mean zonal winds alternate between westerly and easterly phases which descend from around 1 hPa to below 70 hPa, at approximately 1 km/month, with periods ranging from 20 to 36 months and averaging ~28 months. The zonal-wind QBO has a latitudinal width extending from approximately 15°S to 15°N. First discovered by Reed et al. (1961) and Veryard & Ebdon (1961) this quasi-biennial phenomenon results from vertically propagating waves depositing momentum in the regions where the zonal mean winds change sign in the vertical thereby driving the observed descent (e.g. Andrews et al., 1987; Dunkerton, 1997; Kawatani et al., 2010). What is less well understood, and poorly represented in many global climate models, is how the QBO influences the stratosphere and troposphere away from the equatorial regions via extratropical teleconnections (e.g. Ebdon, 1975; Holton & Tan, 1980, 1982; Baldwin et al., 2001; Gray et al., 2018; Rao et al., 2020; Yamazaki et al., 2020; Anstey et al., 2022b; Kumar et al., 2024).

Studies of how the equatorial QBO influences other parts of the atmosphere tend to focus on the strength of the Northern Hemisphere (NH) stratospheric Polar Night Jet (PNJ) during boreal winter, typically represented by the magnitude of the zonal-mean zonal wind around 60°N, 10 hPa. The teleconnection between the phase of the QBO zonal-mean zonal winds when measured at 50 hPa, either westerly (QBOW) or easterly (QBOE), and the strength of the PNJ was first assessed by Holton & Tan (1980, 1982). They found that the PNJ is weaker during winters with QBOE and stronger during QBOW, suggesting a causal link between the equatorial QBO and the strength of the NH polar vortex. The leading proposed mechanism for this teleconnection relates to the QBO's influence on the latitudinal position of the zonal-mean zonal wind zero-wind line in the stratosphere (Holton and Tan, 1980). This zero-wind line, which has a zonal phase speed of 0 ms^{-1} relative to the surface, can act as a wave-guide, modulating the equatorward propagation and dissipation of planetary waves emanating from the extratropical troposphere through wave-mean flow interaction. Under QBOE conditions the zero-wind line occurs north of the equator at approximately 20°N, whereas under QBOW conditions it lies approximately 6°N. For QBOE the waves are more likely to be constrained within the polar vortex region increasing the probability that easterly momentum will be deposited into the high-latitude stratosphere which results in a weakening of the PNJ. For QBOW the upward wave fluxes are less latitudinally constrained and less concentrated in the region of the PNJ allowing a stronger PNJ to develop. This teleconnection is generally referred to as the stratospheric polar route (Gray et al., 2018) or the Holton-Tan Effect (HTE).

There is gathering evidence that the position of the zero-wind line may not be the only mechanism contributing to the QBO-PNJ teleconnection. The equatorial zonal temperature anomalies and vertical wind shear zones (Baldwin et al., 2001) induced by the alternating phases of the QBO stimulate, through thermal wind balance, a residual tropical meridional circulation (Plumb & Bell, 1982; Garfinkel et al. 2012). This results in the formation of an Eliassen-Palm flux divergence dipole in the extratropical middle stratosphere (Rao et al., 2021; Andrews et al., 1987) which modifies the refractive index (Lu et al., 2014). This modulates the concentration of the upward flux of planetary waves which then influences the strength of the PNJ (Garfinkel et al., 2012; Lu et al., 2014, 2020; Rao et al. 2021; Karami et al., 2023).

Regardless of the mechanism, this boreal winter QBO-PNJ teleconnection remains an important benchmark against which the equator-to-polar stratospheric interaction in General Circulation Models (GCMs) can be tested.

This observed relationship between the QBO and the strength of the boreal winter PNJ has an influence on the likelihood and timing of Sudden Stratospheric Warmings (SSWs; Labitzke 1982; Anstey et al. 2022b; Elsbury et al. 2024). SSWs represent the rapid reversal of the westerly winter PNJ towards easterly when the polar vortex is either displaced from the pole or split into two vortices (Scherhag 1952; Charlton and Polvani, 2007). If the PNJ is in a weakened state during QBOE winters, it is more likely that deposition of upward fluxes of easterly momentum will induce a reversal of the PNJ resulting in an SSW. Over recent decades (1958 – 2019) the frequency of occurrence for SSWs is ~0.9 for QBOE winters compared to ~0.5 for QBOW winters (Baldwin et al., 2021) when measured at 60°N, 10 hPa. SSWs also occur, on average, earlier during QBOE winters than during QBOW winters (Gray et al., 2004). The timing of stratospheric final warmings (SFW) has also been linked to the phase of the QBO (Thiéblemont et al., 2019). Winters without SSWs tend to have earlier SFWs (Hu et al., 2014), hence QBOW winters are more likely to have earlier SFWs (Thiéblemont et al., 2019).

A teleconnection between the QBO and the large-scale lower tropospheric pressure pattern of the North Atlantic Oscillation (NAO; Hurrell et al. 2003) in boreal winter is of interest due to the NAO's influence on winter-time weather patterns across Europe (Thompson & Wallace, 2001). If the teleconnection is robust, the slowly varying QBO might improve NAO predictability (e.g. Boer & Hamilton, 2008; Scaife et al., 2014; O'Reilly et al., 2018; Wan et al., 2025). The most likely route for the QBO-NAO teleconnection is via the modulation of the strength of the PNJ which exerts a downward influence on the underlying tropospheric circulation (Kidston et al. 2015). For example, when an SSW occurs, the zonal-mean wind reversal of the PNJ descends over the course of a few days towards the tropopause and occasionally through the tropopause to influence the background flows in the troposphere (Baldwin & Dunkerton, 2001). This increases the likelihood of blocking weather patterns over the North Atlantic and Northern Eurasia typically resulting in anomalously cold surface conditions (Baldwin & Dunkerton, 2001).

The QBO is also believed to influence the latitudinal position and strength of the North Pacific tropospheric Sub-Tropical Jet (STJ; Garfinkel & Hartmann 2011) in October-November and February-March via the residual mean meridional circulation either side of the equator associated with the QBO. In the lower stratosphere the zonal wind component associated with the meridional circulation arcs down to the subtropical troposphere where it can interact with the STJ. The response of the STJ over the Pacific sector (130° – 240° E) for QBOW minus QBOE (QBOW-E) conditions from October – March is a strengthening around 30°N and a weakening around 50°N, suggesting a slight southward shift of the STJ (Anstey et al. 2022b; Park et al., 2022).

Of course, the teleconnections between the QBO and the strength of the PNJ, frequency and timing of SSWs, phase of the NAO, and strength of the North Pacific circulation coexist with the influence of El-Niño-Southern-Oscillation (ENSO;

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Trenberth 1997; Domeisen et al. 2019) teleconnections on monthly-to-seasonal timescales, and certain phases of the Madden-Julian Oscillation (MJO; Madden & Julian, 1994; Cassou 2008; Garfinkel et al. 2012; Lee et al. 2019) on sub-monthly timescales. This superposition of non-QBO influences together with a relatively small sample size of observed QBOs adds complexity to the analysis of teleconnections in observational studies (e.g. Gray et al., 2018; Kumar et al., 2022; Kumar et al., 2024).

The Atmospheric Processes And their Role in Climate (APARC, formerly SPARC) QBO initiative (QBOi; Anstey et al., 2022a) has previously investigated the fidelity of the QBO in a set of coordinated experiments (Butchart et al. 2018) using a set of Atmospheric General Circulation Models (AGCMs). This is referred to as QBOi phase 1. Various aspects of the modelled QBO and its influence were investigated, including an evaluation of the fidelity of the QBO (Bushell et al., 2022), the waveforcing of the QBO (Holt et al., 2022), the predictability of the QBO in forecast experiments (Stockdale et al., 2022), the impact of the QBO on the tropical tropopause (Serva et al., 2022), the response of the QBO to a warming climate (Richter et al,. 2022), the interaction of the QBO and perpetual ENSO (Kawatani et al., 2025; Naoe et al., 2025), and the influence of perpetual ENSO and the QBO on the MJO (Elsbury et al., 2025). Of relevance to this study Anstey et al. (2022b) investigated the ability of the models to capture various extratropical teleconnections. Two sets of model experiments which differ only in the prescribed Sea-Surface Temperature (SST) and sea ice (SI) conditions were run to assess the response of the extratropical teleconnections to the free-running internally generated model QBOs. The first experiment included historically-varying SSTs and SI surface boundary conditions, whereas the second used climatological SSTs and SI.

Anstey et al. (2022b) found that the correlation between the phase of the QBO at 50 hPa and the sign of the PNJ in the ensemble mean is generally consistent with observations, however, the magnitude of the response is relatively weak. This could be attributable to systematically weak amplitudes of the free-running model QBOs in the lower stratosphere (Bushell et al., 2022). It was suggested that if the strength of the model QBOs could be improved, the strength of teleconnections might also be improved.

Following on from the QBOi phase 1 experiments, a new set of QBOi phase 2 experiments were formulated to address the question of how models respond to a realistic QBO in the lower-to-middle equatorial stratosphere (Anstey et al., *in prep*). There are three phase 2 experiments. Each experiment consists of an atmosphere-only configuration similar to those for the Coupled Model Intercomparison Project 6 (CMIP6) Atmospheric Model Intercomparison Project (AMIP) experiments (Eyring et al. 2016). The first experiment (**Exp1**) is similar to the free-running AGCM experiments of phase 1 where only historically-evolving SSTs and SI are prescribed and where the equatorial stratospheric QBO is spontaneously generated by each model. The second experiment (**Exp1-ObsQBO**) is similar to Exp1 but the zonal-mean zonal winds in the lower-to-middle equatorial stratosphere are relaxed towards observations so that all models have a very similar and realistic equatorial QBO in terms of strength and evolution over time. The teleconnections linked to the QBO can, therefore, be assessed equitably across all models. The third experiment (**Exp1-NoQBO**) is similar but with the lower-to-middle equatorial stratospheric zonal-mean zonal winds relaxed towards the climatology of the observed stratosphere resulting in the absence of a QBO. This neutralisation of the QBO region could provide insights into the combined influence of internal model variability, the SST/SI boundary conditions, and the CMIP6 atmospheric forcings on the QBO teleconnections assessed in Exp1-ObsQBO.

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We address the following key question in this paper: Are extratropical teleconnections improved in model simulations where the observed QBO is prescribed (Exp1-ObsQBO), compared to model runs with an internally-generated spontaneous QBO (Exp1)?

Section 2 provides an overview of the relaxation scheme used to nudge the equatorial stratosphere towards observations in the Exp1-ObsQBO and Exp1-NoQBO experiments and describes the experiment forcings. In subsequent sections each teleconnection is assessed in reanalysis and the multi-model ensembles. Section 3 assesses the QBO-PNJ relationship, Section 4 analyses the QBO-SSW relationship, Section 5 looks at the QBO-NAO relationship, and Section 6 considers the QBO-North Pacific STJ and precipitation relationship. Concluding remarks are given in Section 7.

2 Experiments, Models and Methods

The three experiments, Exp1, Exp1-ObsQBO, and Exp1-NoQBO are described in Anstey et al. (*in prep*). Here we introduce the essential attributes of these experiments. Each experiment consists of an atmosphere-only AMIP-like configuration similar to those for the CMIP6 AMIP historical experiments (Eyring et al. 2016). The three experiments differ in terms of how the equatorial stratosphere evolves (Table 1). For Exp1 the equatorial stratosphere is not subject to nudging. All models used in this study spontaneously generate QBO-like variability in the tropical stratosphere (Anstey et al., *in prep*). For Exp1-ObsQBO and Exp1-NoQBO the zonal-mean component of the zonal wind in the equatorial stratosphere is nudged (Fig. 1) using the same methodology as for the SNAPSI protocol (Stratospheric Nudging And Predictable Surface Impacts; Hitchcock et al., 2022). Nudging is generally limited to the zonal-mean component of the zonal wind in order to allow waves in the tropical stratosphere to evolve freely, but full-field nudging is adopted by some models (see Anstey et al., *in prep*, Table 2).

Table 1: Summary of QBOi phase-2 nudging experiments (see Anstey et al., *in prep*.)

Experiment	*Nudging target state (tropical stratosphere)*
Exp1	None
Exp1-ObsQBO	Realistic (ERA5)
Exp1-NoQBO	Climatological (ERA5)

The observational dataset used to generate the zonal-mean zonal wind nudging data is ERA5 (fifth generation ECMWF atmospheric reanalysis of the global climate ; Hersbach et al., 2020). The climatological nudging dataset for Exp1-NoQBO is an annually-repeating monthly climatology of ERA5 zonal-mean zonal winds over the period 1979 - 2020. The region of the equatorial stratosphere nudged towards ERA5 (Fig. 1a,b) encompasses 80 hPa – 8 hPa, 12°S – 12°N, with a nudging timescale of 5 days. Outside of this core region the nudging timescale tails off to infinity so that no nudging occurs below 100 hPa, above 5 hPa, and polewards of 20°S and 20°N.

The ocean boundary conditions consist of CMIP6 AMIP historically-evolving monthly SSTs and SI concentrations (Eyring et al. 2016). Atmospheric forcings include CMIP6-defined historically-evolving atmospheric aerosols, volcanic aerosols, solar variability, and trace gas concentrations (Eyring et al. 2016). The historically-evolving ozone concentrations defined by CMIP6 are known to have an imprint of the observed QBO (Butchart et al. 2023) which has the potential to influence the structure and evolution of the descending QBO in the free-running experiment (Exp1), hence the QBOi phase-2 protocol

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suggested adopting an annually-repeating monthly climatological CMIP6 ozone for all three experiments (see Anstey et al., *in prep*, Table 5). Each experiment has a duration of 42-years from 1979 to 2020.

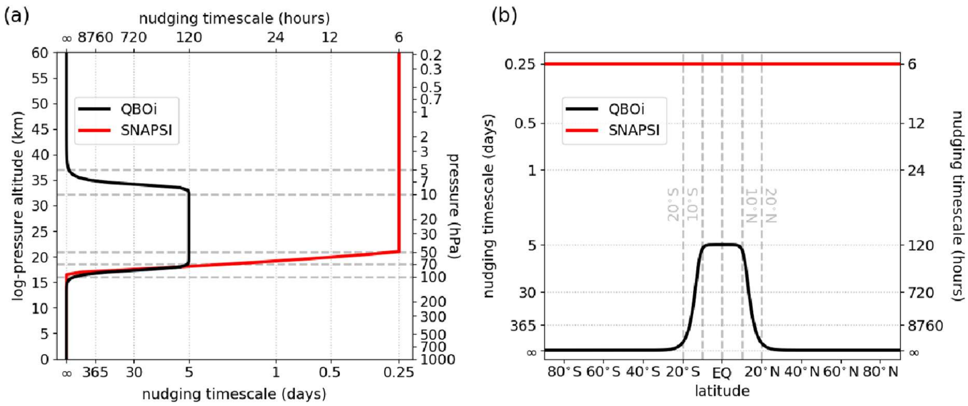

Figure 1: Spatial dependence of nudging timescale in (a) the vertical and (b) meridional directions for the QBOi phase-2 nudging experiments Exp1-ObsQBO and Exp1-NoQBO (black curves). The mathematical expressions corresponding to the QBOi profiles shown in (a) and (b) are detailed in Anstey et al., (*in prep*). Vertical and meridional profiles of nudging timescale from the SNAPSI protocol (Hitchcock et al., 2022) are shown in red for comparison with the QBOi profiles (see Anstey et al., *in prep.*, Appendix A for further details of the QBOi-SNAPSI comparison).

The twelve models from eleven different modelling centres that contributed to the multi-model ensemble (MME) analysis in this paper are: BCC-CSM2-MR, CAS-ESM, CESM2, EC-EARTH3, E3SMv2, ESM4, GRIMs-4.0, LMDz, MIROC6.1p1, MIROC6.1p2, HadGEM3GA7.1, and MRI-ESM2.0. The models are described in Anstey et al. (*in prep*) which confirms that most models are able to reproduce QBO-like variability in the equatorial stratosphere, but with a rather large model spread in the rendition of the simulated QBOs. Anstey et al. also shows that, with nudging, all the models reproduce well the observed QBO in Exp1-ObsQBO, and that mean biases and inter-annual variability are removed from the equatorial winds in Exp1-NoQBO. For the extra-tropical stratosphere, they show that, however imposed, the nudging does not significantly impact the climatology of each model's monthly and zonal-mean zonal winds and temperatures, nor does it significantly change the interannual standard deviation of these quantities in the models.

The strongest correlation between the PNJ and the equatorial zonal-mean zonal winds for ERA5 occurs around 50 hPa during boreal mid-winter (Fig. 2a). This result is mirrored by the Exp1-ObsQBO MME-mean (Fig. 2b). We therefore define the QBO index as the equatorial zonal-mean zonal wind at 50 hPa, averaged from 5°S to 5°N. This is consistent with previous QBO teleconnection studies, from Holton & Tan (1980, 1982) through to the QBOi phase 1 analysis (Anstey et al., 2022b). Thresholds for easterly and westerly QBO phases are defined as ±0.5 standard deviation (σ) of the QBO index, i.e. QBO-easterly occurs when the zonal-mean zonal wind is less than -0.5σ of the climatological zonal-mean zonal wind and for QBO-westerly is greater than +0.5σ. This produces thresholds for observations, and Exp1-ObsQBO, that are broadly similar to the ±5 ms^{-1} thresholds used in previous studies. For Exp1, the ±0.5σ threshold accounts for the varying strengths of the QBOs in each model, so that the proportion of QBOE and QBOW years is approximately the same for each model and is consistent with observations. The winter period over which the QBO index is calculated varies depending on the teleconnection and is defined within each section.

The observation dataset used for the North Pacific precipitation analysis is the Global Precipitation Climatology Project (GPCP; Adler et al., 2018). This dataset provides global estimates of precipitation from 1979 to 2023 at 2.5° resolution. Neutral ENSO winters are defined as when the Oceanic Niño Index (ONI) is below 0.5°C in magnitude, where ONI is the

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area-averaged NINO3.4 (5°N-5°S, 120°-170°W; Trenberth 1997, Gray et al, 2018) sea-surface temperature anomalies with a 5-month rolling average.

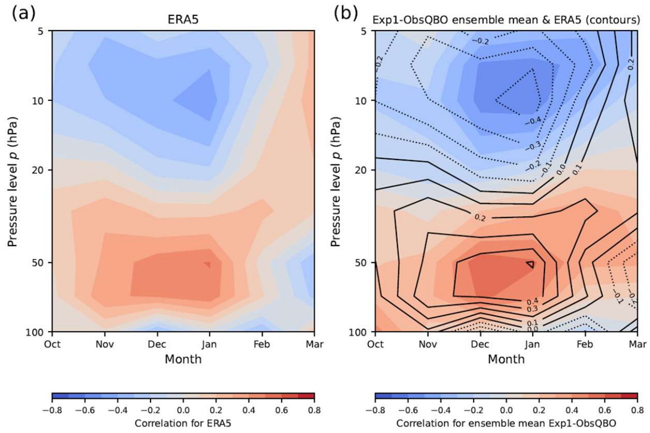

Figure 2: The strongest correlation between the Polar Night Jet (zonal-mean zonal wind at 60°N, 10 hPa) and the equatorial zonal-mean zonal wind in the QBO-region over early-mid boreal winter occurs around 50 hPa in (a) the ERA5 dataset 1979 – 2020, and (b) the Exp1-ObsQBO multi-model ensemble mean.

3 QBO influence on the strength of the boreal winter stratospheric polar vortex

The observed Holton-Tan relationship, measured as the correlation between the QBO index at 50 hPa and the NH stratospheric PNJ, strengthens during early winter, peaks in January, and tails off in February and March (Fig. 2a) over the period 1979 - 2020. This can be seen more clearly by compositing the ERA5 zonal-mean zonal wind (Uzm) for QBOE and QBOW winters separately and calculating the difference (QBOE-W; Fig. 3). There is a significant negative PNJ response in November of -4 ms^{-1}, increasing to -8 ms^{-1} in December, before peaking at -20 ms^{-1} in January. In February the response is weakly negative and is no longer significant, and reverses sign in March to +12 ms^{-1} becoming significant.

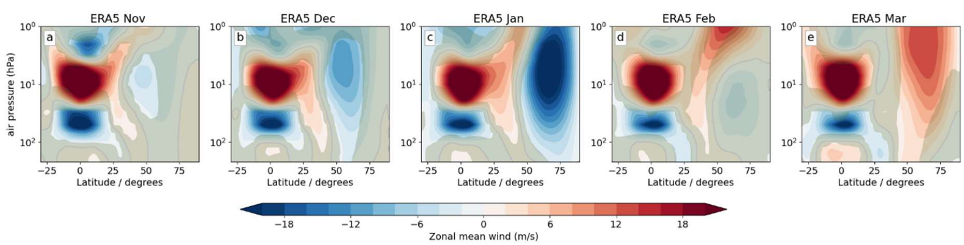

Figure 3: The observed PNJ response to the equatorial QBO at 50 hPa peaks in January. Panels show ERA5 zonal-mean zonal wind QBOE-W monthly evolution, (a-e) November – March, for the period 1979 - 2020. Regions not significant at the 2-sided 90% level (5% - 95%) are shaded in olive-green. Significance is calculated using a Monte-Carlo statistical approach by creating 500 random-composites of QBOE-W with the same QBOE and QBOW sample sizes as observations. Significance is measured against the distribution of values for each grid-point.

We examined whether this observed Holton-Tan effect is captured in the three QBOi experiments (Exp1, Exp1-ObsQBO, and Exp1-NoQBO) by repeating the QBOE-W composite analysis for the MMEs (Fig. 4). The MME response for each experiment is calculated by compositing the QBOE and QBOW for each month across all models and deriving the composite QBOE-W response. The Exp1 MME (Fig. 4a-e) exhibits a weak but significant negative Uzm response in the PNJ region with a peak magnitude of -2 ms^{-1} December-to-March. This demonstrates that the Exp1 MME captures a Holton-Tan-like

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response to the free-running QBOs spontaneously generated by each model. A comparison with the equivalent results of QBOi phase 1 (Anstey et al. 2022b; experiment 2: free-running QBOs and climatological SST/SI boundary conditions) reveals that the Exp1 MME PNJ response is smaller in magnitude (-2 ms^{-1} vs -5 ms^{-1}, January). This weaker response might be attributable to differences in boundary conditions, the experiment periods, the atmospheric forcings, and/or the fact that the underlying models have either evolved or differ between QBOi phase 1 and phase 2 experiments.

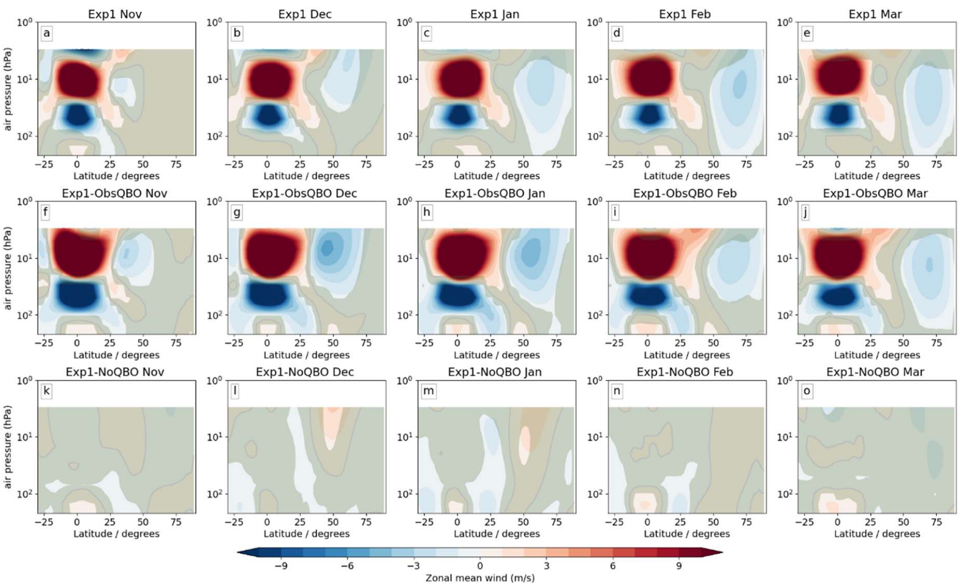

Figure 4: As Fig. 3, but for the three experiments. There is a significant PNJ response to the QBO in Exp1 which increases in magnitude in Exp1-ObsQBO. MME zonal-mean zonal wind monthly evolution, November – March (1st – 5th columns) for each experiment; Exp1 (a – e), Exp1-ObsQBO (f – j), Exp1-NoQBO (k – o). The colour scale is half that of Fig. 3 in order to reveal the detail in the stratospheric polar vortex.

The Exp1-ObsQBO PNJ response (Fig. 4f-j) is also significant but remains weak compared to reanalysis. The absolute November-January values are approximately twice those of Exp1, peaking at -5 ms^{-1} and -4 ms^{-1} in December and January, respectively, suggesting that nudging models towards the observed QBO has most impact in early-mid-winter. In February and March, the values are similar to Exp1. Upon examination, this early-mid-winter improvement in the magnitude of the PNJ response arises from an increased number of models capturing a response of the correct sign. For the winter-mean (December-January-February; DJF) PNJ, five of the eleven models capture a negative response for Exp1, which is improved for Exp1-ObsQBO where ten of the twelve models produce a negative response (Table A1). Seven of these (BCC-CSM2-MR, CAS-ESM, CESM2, ESM4, LMDz, MIROC6.1p1, MIROC6.1p2) have a significant PNJ response.

For the Exp1-NoQBO experiment we selected the same QBOE and QBOW winters as for Exp1-ObsQBO to provide a direct comparison, allowing the impacts of the atmospheric forcings and SST/SI boundary conditions to be assessed independently of the QBO. The PNJ responses (Fig. 4k-o) are weak and insignificant across the winter months, suggesting that CMIP6 atmospheric forcings and SST/SI boundary conditions have little impact on the modelled PNJ when the winters are conditioned by the observed QBOE-W.

These results indicate that the free running MME can capture a Holton-Tan-like response, albeit much weaker than in reanalysis, and that this teleconnection is improved in magnitude if the models are nudged towards a more realistic QBO.

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Despite this improvement the PNJ response remains weak, approximately 20% of that seen in observations. To quantify the likelihood of capturing a PNJ response of the observe magnitude, we randomly sub-sampled the QBOE and QBOW winters from all winters across the models in each MME with a QBOE-W sample size equivalent to reanalysis to produce a distribution of PNJ values. We focus on January when the peak PNJ response occurs in reanalysis. Figure 5 demonstrates that the distributions that arise from sub-sampling the MME's fail to capture the magnitude of the observed PNJ response (black line towards the left of the plot). The $\pm 2\sigma$ range for the Exp1 experiment (blue histogram) is approximately -12 ms^{-1} to +7 ms^{-1}, and for the Exp1-ObsQBO (red histogram) from -14 ms^{-1} to +6 ms^{-1}. The Exp1 and Exp1-ObsQBO distributions are not significantly different (Student t-test $p = 0.17$) which indicates that the doubling of the PNJ response from Exp1 to Exp1-ObsQBO is unlikely to be significant. As might be expected, both the Exp1 and Exp1-ObsQBO distributions are significantly different to the Exp1-NoQBO distribution (not shown; $p < 0.01$), which underlines the role of the QBO in modulating the strength of the PNJ.

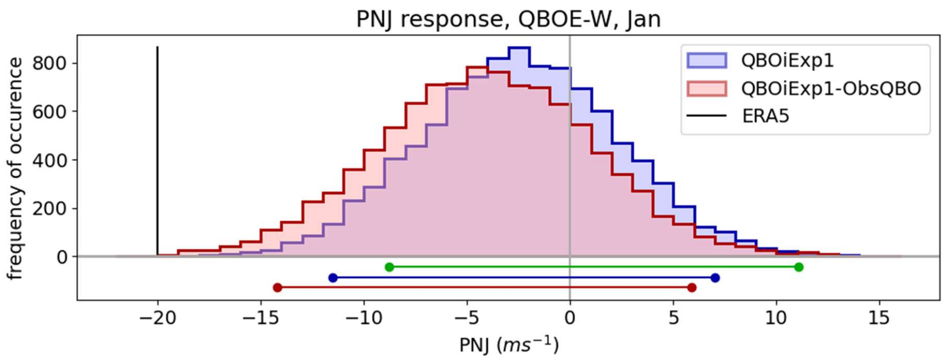

Figure 5: Neither the Exp1 nor Exp1-ObsQBO experiments capture the magnitude of the observed January PNJ response to QBO. Distribution of PNJ values when sub-sampling the multi-model ensembles with a QBOE-W sample size equivalent to observations. The distributions shown use Monte-Carlo random sub-sampling-with-replacement with 10,000 iterations for clarity, whereas the statistics given in the main text uses the more statistically robust sub-sampling-without-replacement. The distributions for Exp1-ObsQBO (red) and Exp1 (blue) are accompanied by horizontal lines of similar colours beneath the graph indicating the $\pm 2\sigma$ range. The $\pm 2\sigma$ range for the Exp1-NoQBO distribution (distribution not shown for clarity) is included as the green line. The vertical black line towards the left represents the observed PNJ response.

It is no surprise that the sub-sampled Exp1-ObsQBO MME distribution does not capture the magnitude of the observed January PNJ response given that no individual model appears capable of consistently producing such a large response. In addition, the timing of the peak PNJ response of individual models varies from December to March. We did, however, find that some models capture the magnitude of the observed December PNJ response. Moreover, if we consider the DJF-mean PNJ response we find that most individual models have a negative response (Table A1) similar in magnitude to ERA5 (-6 ms^{-1}). These results might indicate that the magnitude of the observed January response is an overestimate given the small observational sample size, or alternatively, that the models only produce a weak mid-winter teleconnection despite the fact that some individual models can capture a reasonable winter-mean HTE. Anstey et al. (*in prep*) shows that the interannual PNJ variability is similar across all three experiments which supports the suggestion that the models are failing to fully capture the mechanism by which the QBO modulates the strength of the PNJ.

The design of the QBOi phase 2 experiments provides an opportunity to assess the contribution of the QBO to the interannual variability of the PNJ over the period of the simulations. By comparing the results of Exp1-ObsQBO and Exp1-NoQBO we can assess the predictable component of PNJ variability associated with the observed QBO in the presence of evolving CMIP6-forcings and SST/SI boundary conditions. Figure 6 shows the January PNJ timeseries for ERA5 (black

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line), and the MME-means for Exp1-ObsQBO (red line) and Exp1-NoQBO (green dashed line). The Pearson correlation between the PNJ of ERA5 and Exp1-ObsQBO is significant (r = 0.61; p < 0.001). This suggests that approximately 30% – 40% of the observed interannual PNJ variance in January is accounted for by the influence of variability in the equatorial stratosphere including the QBO. This conclusion is supported by the small and insignificant correlation (r = 0.06; p ~ 0.68) between ERA5 and the Exp1-NoQBO MME-mean where the QBO in the equatorial stratosphere has been neutralised. This also demonstrates that the combination of historically-varying forcings and SST/SI boundary conditions, at least in the models, do not have a measurable contribution to the predictability of the observed January PNJ over the 1979 – 2020 period. For Exp1 the QBO is neither synchronised with observations nor synchronised between contributing members so perhaps it is not surprising that there is an insignificant correlation between the observed PNJ and Exp1 MME PNJ (r = 0.17; p ~0.27; not shown in Fig. 6). The magnitude of PNJ variability in Exp1-ObsQBO MME-mean is weaker than in ERA5, which mirrors the results of QBOi phase 1 forecast experiments (Stockdale et al., 2022). The fact that ERA5 represents one realisation whereas the MME result is an average of an ensemble of model experiments may contribute to this difference. This is likely linked to the well-known signal-to-noise paradox which is known to impact the magnitude of the predictable signals in seasonal forecast systems (Eade et al., 2014). Despite this, these results indicate that models which are constrained to mirror the observed variability of the January QBO are more likely to capture a significant fraction of the observed variability in the PNJ.

Expanding this analysis across the winter months (Table 2) we find that the Exp1-ObsQBO MME-mean PNJ correlation with observations is significant in early winter ramping up to a peak correlation in January. In late winter the correlations are small and insignificant. This result may be influenced by the fact that the observed QBOE-W teleconnection to the PNJ is only significant in early-winter (Fig. 3b-c) and not in late-winter (Fig. 3d-e). However, given that the MME composite QBOE-W PNJ responses in late winter are significant (Fig. 4d-e,i-j) it may indicate that, for observations, a late-winter response is being masked by other influences (e.g. ENSO, forcings, interannual variability, smaller sample sizes).

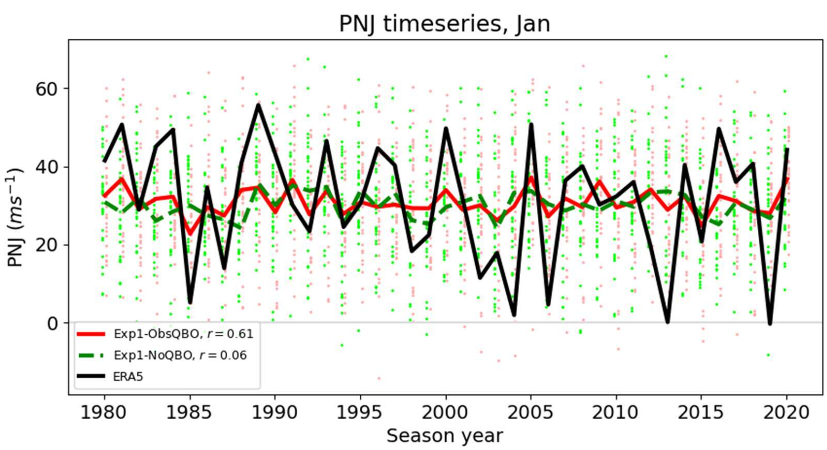

Figure 6: The observed PNJ is better predicted in the multi-model ensemble nudged towards the observed QBO. Time evolution of the January PNJ in ERA5 (black line), and the MME-means of Exp1-ObsQBO (red line) and Exp1-NoQBO (green line). The PNJ value for each member is plotted with pale red (Exp1-ObsQBO) and pale green (Exp1-NoQBO) dots.

If it was only the Exp1-ObsQBO MME-mean that exhibited this significant PNJ timeseries correlation in November, December, and January, this would strengthen the attribution of the PNJ interannual variability to the QBO. However, both Exp1 and Exp1-NoQBO also have early-winter months where the correlation is significant (Table 2). For Exp1, the PNJ

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timeseries correlation peaks in November and becomes less significant in December. For Exp1-NoQBO, the correlation is significant in December. In January, however, it can be stated with some confidence that the Exp1-ObsQBO PNJ correlation (r = 0.61) is likely accounted for by the equatorial stratosphere containing the observed QBO given that the Exp1 and Exp1-NoQBO correlations are small and insignificant.

Table 2: Pearson correlation coefficient values between the timeseries of the observed PNJ and the MME-mean PNJ for each experiment over the period 1979 – 2020. Correlations with a *p*-value < 0.050 are in italics, and < 0.025 in bold.

	November	December	January	February	March
Exp1	**0.35**	*0.31*	0.17	0.02	0.28
Exp1-ObsQBO	**0.35**	**0.49**	**0.61**	0.15	0.02
Exp1-NoQBO	0.22	**0.35**	0.06	0.06	0.07

4 QBO influence on the timing and frequency of SSWs

Before considering the relationship between the phase of the QBO and the timing and frequency of SSWs in observations and models, we examine the influence of the climatological strength of the PNJ on the winter frequency of SSWs. This relationship for the Exp1-NoQBO experiment is shown in Fig. 7: we see a clear, strong, negative correlation such that models with a weaker PNJ have a higher number of SSWs per year (e.g. >1.6 for GRIMs) compared to those with a stronger PNJ (e.g. 0.6 for CAS-ESM). This agrees with Anstey et al., (2022) (their Fig. 8), with a similar slope of the regression line (-0.046 vs ~-0.05 in Anstey et al., 2022). Similar correlations were found for the Exp1 and Exp1-ObsQBO experiments (Table A2, row 1). When the results are filtered by ENSO phase (Table A2, rows 2-4), the slope is larger for El Niño than for La Niña for all experiments, whilst the r values are smaller. Since El Niño tends to correspond to a weakened PNJ and increased wave-1 activity compared to La Niña (Garfinkel & Hartmann 2008), this slight change in linear response is not surprising, as a stronger PNJ against a background of weaker planetary wave activity will likely be more quiescent. When filtered by initial vs subsequent (non-initial, i.e. SSWs that occur after the first SSW in a winter) SSWs (Table A2, rows 5-6), again, similar correlations are found although the r values are slightly improved for the initial vs subsequent SSWs in Exp1 and Exp1-ObsQBO. This may reflect the fact that, after an initial warming, the PNJ is likely already in a weakened state, hence the climatological state is of less consequence to subsequent warmings that may occur, and other factors such as total wintertime wave forcing are likely of more consequence.

We now consider the relationship between the phase of the QBO and the frequency of SSWs. The SSW frequencies for each QBO phase and experiment, calculated for all the models (MME-mean: MMM), for those with strong vortices only (SVMM; see Table A3 for a list), and ERA5 data are shown in Fig. 8 (All ENSO). In ERA5 (ERA5/All ENSO, 1st from left) there is an increase in SSW frequency during QBOE vs QBOW, although we do not have an error estimate for the frequencies. In the multi-model ensembles (MMM/All ENSO, 2nd from left) we see a small and insignificant increase in SSW frequency during QBOE vs QBOW in both the Exp1-ObsQBO and Exp1. The difference in frequency reverses in the Exp1-NoQBO experiment, where the winters are composited according to the QBO phase found in ERA5 and Exp1-ObsQBO. This indicates that the difference in frequency during Exp1-ObsQBO and Exp1, whilst insignificant, is likely attributable to the QBO, and not some other extraneous forcing or nudging effect.

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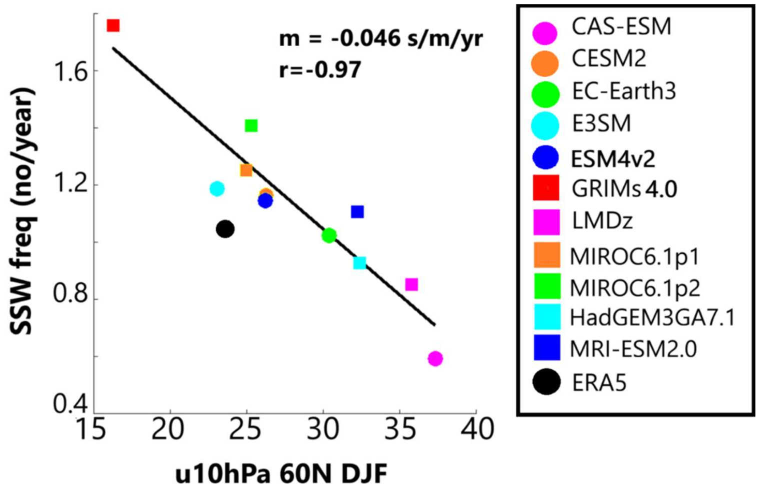

Figure 7: Scatter plot showing the regression between DJF PNJ strength (*x*-axis) and Sudden Stratospheric Warming (SSW) frequency across the different models in the Exp1-NoQBO experiment, and also for the ERA5 reanalysis. Slope (*m*) and correlation coefficient (*r*) are calculated from the model values only and displayed inside the scatter plot.

If we analyse only models with a strong NH polar vortex (i.e. average DJF 60°N zonally averaged zonal winds over 0.5 standard deviations above the experiment multi-model mean; SVMM/All ENSO, 3rd from left) we see a similarly increased SSW frequency during QBOE vs QBOW in both Exp1-ObsQBO and Exp1, with slightly more significance due to the more tightly constrained spread in SSW frequencies (i.e. shorter error bars), particularly in Exp1. We also applied the same analysis to the models with a significant Holton-Tan effect, as found in Sect. 3 (not shown): like the MME-mean, we found an insignificant increase in SSW frequency during QBOE vs QBOE in Exp1 and Exp1-ObsQBO, and the opposite in Exp1-NoQBO.

We also filtered the winters and SSWs according to ENSO phase to produce a similar analysis of QBOE vs. QBOW SSW frequencies. In general, this filtering did not significantly impact the model results, for any of the multi-model means studied (not shown), although a large and significant decrease in SSW frequency during QBOW (~0.3/yr) vs QBOE was found in the strong vortex model mean during Exp1 filtered for La Niña winters only (see Fig. 8, SVMM/ La Niña, 5th from left). We also see this in the ERA5 data: QBOW/La Niña winters exhibit a very low SSW frequency, less than 0.5/year (see Fig. 8, ERA5/ La Niña, 4th from left). Since it has generally been found that both QBOW (Holton & Tan 1980) and La Niña (Garfinkel & Hartmann 2008; Palmeiro et al. 2023) are associated with a strengthened polar vortex, this strong SSW suppression during QBOW/La Niña may be seen as their combined influence causing a very strong polar vortex that is difficult to disturb (see Fig. 7). The analysis was also repeated for initial and non-initial SSWs (not shown) and, again, no significant impact upon the results of any of the multi-model means was found.

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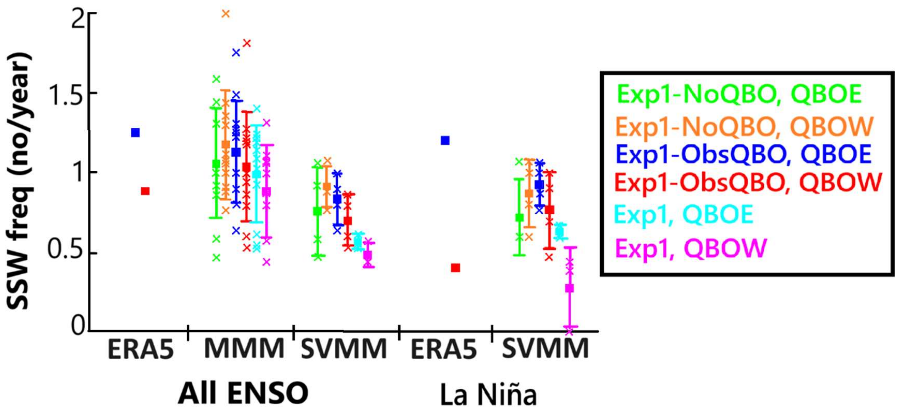

Figure 8: The influence of the QBO phase on the SSW frequency seen in observations is weakly captured by the Exp1 and Exp1-ObsQBO experiments. The plot shows the distribution of average SSW frequencies during each QBO phase in each experiment and ERA5 data. Model results are grouped together to show the results from across all models (MMM = multi-model ensemble mean), and those with a relatively strong NH polar vortex (SVMM=Strong Vortex Model Mean): a list of models used in the SVMM is provided in Table A3. The ERA5 and model results are also filtered to show the results across all boreal winters (All ENSO) and using La Niña winters only. Individual model means, calculated across ensemble members, are indicated by crosses, and the multi-model means and standard deviations are indicated by filled squares and error bars respectively.

Overall, while the differences in SSW frequency are mostly small and insignificant, we do see a modest increase in SSW frequency during QBOE vs QBOW in both Exp1-ObsQBO and Exp1 experiments that is robust across various types of model-means and filtering (Holton-Tan effect, strong vortex, ENSO phase, and SSW relative timing). The large inter-model spread in SSW frequencies means that significance is only achieved when one QBO phase has an exceptionally strong and quiescent polar vortex, as was seen during QBO-W/La Niña in Exp1 for models with a relatively strong vortex only.

The timing of mid-winter initial SSWs is also thought to be influenced by the phase of the QBO. Previous observation-based studies showed that the early winter weakening of the stratospheric polar vortex during QBOE can favour an earlier occurrence of SSWs (e.g. Gray et al., 2004). This is evident in ERA5 (Fig. 9a) where the observed distribution of SSW timings occurs approximately one month earlier during QBOE winters (top blue bar) compared to QBOW winters (top red bar) and are significantly different at the 99% level. During QBO-neutral winters (grey bar) the distribution of SSWs is indistinct from the QBOW winters suggesting that the only phase of the QBO that impacts SSW timings is QBOE. For the Exp1-ObsQBO and Exp1 experiments the MME-mean responses do not capture the observed SSW-timing separation between QBOE and QBOW winters (Fig. 9 MMM-Exp1-ObsQBO and MMM-Exp1). Furthermore, when model results were filtered according to ENSO phase, SSW relative timing (initial vs subsequent), models with a Holton-Tan effect (see MHT, Fig. 9a), and stronger than average polar vortices (SVMM), no significant QBO modulation was found due to the persistently large spread in SSW timings (not shown). However, in terms of individual models, some exceptions such as HadGEM3GA7.1 and especially LMDz6 show the expected behaviour when the observed QBO is imposed but not in the free runs (Fig. A1).

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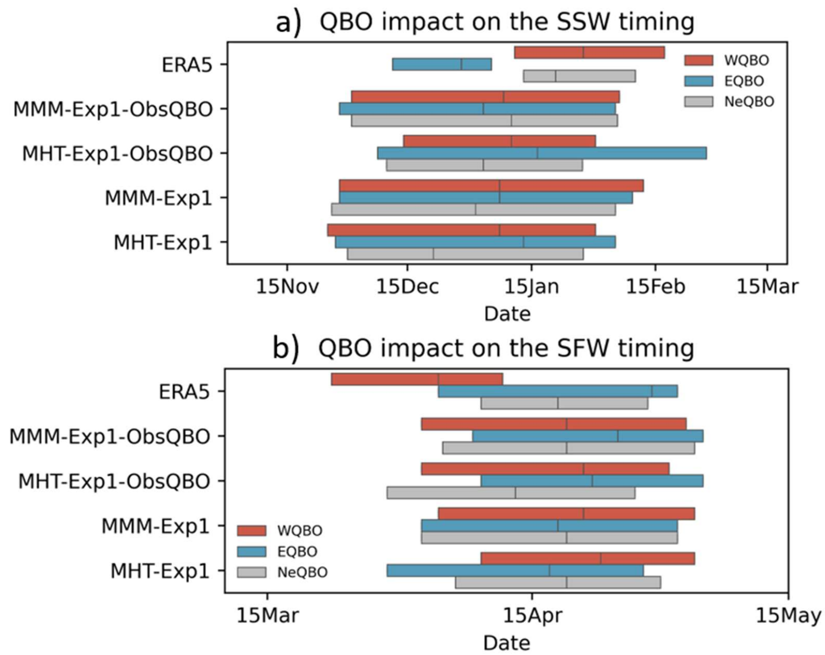

Figure 9: Experiments are unable to capture the significant variations of SSW and SFW timing seen in observations. (a) Timing distribution of mid-winter SSWs and (b) the stratospheric final warming (SFW) dates for easterly (blue), westerly (red), and neutral (grey) QBO years in ERA5, the multi-model mean (MMM) and the Mean Holton-Tan (MHT) subset in Exp1-ObsQBO and Exp1. Colour bars extend from the 25^{th} to 75^{th} percentile with the mean indicated by a vertical line.

A possible impact of the QBO on the timing of stratospheric final warming (SFW) as suggested by Thiéblemont et al. (2019) is also explored. Being more dynamically active than mid - late SFWs, early SFWs are usually followed by downward propagating anomalies and tropospheric impacts similar to SSWs (Palmeiro et al. 2017; Butler et al. 2019). This means that these events could represent a stratospheric channel for extratropical tropospheric teleconnections to the QBO, or at least the QBO phase could improve their predictability and that of their potential impacts.

Figure 9b shows that the mean date of occurrence of SFWs in ERA5 is a month earlier during QBOW compared to QBOE. Again, models struggle to capture such an impact, although results are more similar to reanalysis when the observed QBO is imposed in Exp1-ObsQBO. Hu et al. (2014) showed that early SFWs tend to occur in years without SSWs, so considering the strengthening effect of QBOW on the vortex and the decreased frequency of occurrence of mid-winter-SSWs, the earlier occurrence of the SFW during QBOW in ERA5 is expected. Again, individual models struggle to capture such an impact, but as before, results are more similar to reanalysis when the observed QBO is imposed. This statement is particularly true for EC-Earth3, LMDz, and MIROC6.1p1 which show an improved performance in late winter for Exp1-ObsQBO compared to Exp1 (Fig. A2a).

The QBO impact on the SSW and SFW dates is, in general, consistent with the model's Holton-Tan representation, and is sometimes improved by nudging the observed QBO. Why models do not capture the QBO impact on the timing of these extreme polar stratospheric events could be related to model biases in early winter (i.e. a too weak polar vortex) or a poor representation of the SSW seasonal cycle.

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5 QBO influence on the NAO

One possible route for a teleconnection between the QBO and NAO is via the Holton-Tan modulation of the PNJ. Variability of the PNJ in boreal winter can propagate downwards to the troposphere and affect surface climate variability (Baldwin & Dunkerton, 2001). The DJF correlation between the PNJ and NAO in observations is found to be significant (r ~0.4; Fig. 10 left column). For each of the three experiments the PNJ-NAO correlations in the MME-mean (Fig. 10 right column) are also significant and of similar magnitude to observations. This confirms that the majority of the individual models significantly capture this downward connection. Previously we have demonstrated that the phase of the QBO significantly influences the strength of the PNJ anomalies in observations, Exp1 MME, and Exp1-ObsQBO MME, so we considered whether the QBO could influence the strength of the NAO via the PNJ.

The observed correlation between the QBO and NAO is found to be insignificant throughout most of the winter months but is strongest in January (Fig. 11a; r ~0.2 - 0.3). In an attempt to improve the significance of the observed teleconnection a longer period (1959 – 2021) than covered by the experiments was analysed. The equivalent MME correlations are small ($r < 0.1$; Fig. 11a) and are generally not statistically significant. Acknowledging the weakness of the observed QBO-NAO correlation, the lack of significance in the model QBO-NAO relationship may arise due to several factors. These could include the relatively weak magnitude of the MME QBO-PNJ response of the Exp1 and Exp1-ObsQBO experiments (Sect. 3), the insignificant influence of the QBO on the timings of SSWs compared to observations (Sect. 4), and/or the differences in the timing of the individual models' QBO impacts on the PNJ (not shown). These can lead to a large uncertainty with respect to both magnitude and timing of the QBO-NAO relationship as indicated by the wide range of correlation coefficients diagnosed for the individual models from November-onwards (Fig. A3).

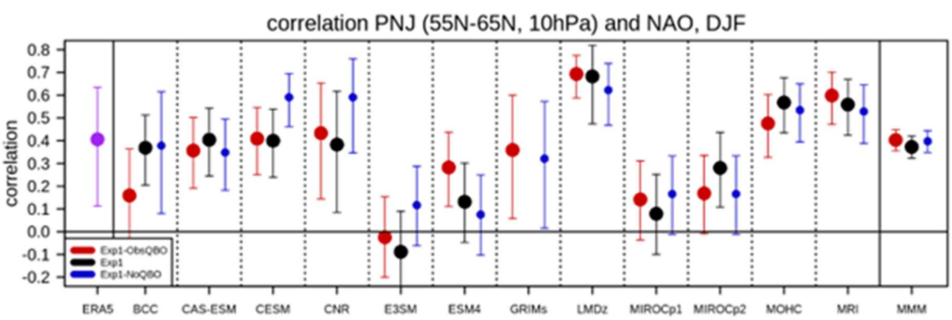

Figure 10: The NAO is significantly correlated with the PNJ in observations (left column, purple), most models, and all MME-means. Correlation between the strength of the polar night jet (55°N-65°N, 10 hPa) and the NAO index (defined here as the sea level pressure difference in the Atlantic sector (290°E-360°E) between the mid-(30°N-60°N) and high- (60°N-90°N) latitudes) in DJF for the models and ERA5. The error bars denote the 95% confidence interval of the correlation.

When the MMEs are subsampled to include only those seven models which display statistically significant winter stratospheric QBO-PNJ teleconnection (MME2, Fig. 11b; see Sect. 3 for list of models) the mean of the Exp1-ObsQBO simulations shows a weak (r ~ 0.1) but statistically significant positive correlation between the QBO and NAO in January (Fig. 11b). This might indicate some limited predictability of the NAO stemming from the QBO teleconnection. If we compare this result with the QBO-NAO correlations for the Exp1 and Exp1-NoQBO experiments there is significant overlap, suggesting that the weak correlation response might not be linked to the QBO. It should be noted that the correlations are very small, effectively accounting for less than 1% of NAO interannual variability in the MMEs. In

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observations, the QBO-NAO correlation is very weak, so perhaps it is not surprising that the NAO response to the QBO is difficult to isolate in model experiments and highlights the challenges of inferring details of such a coupling.

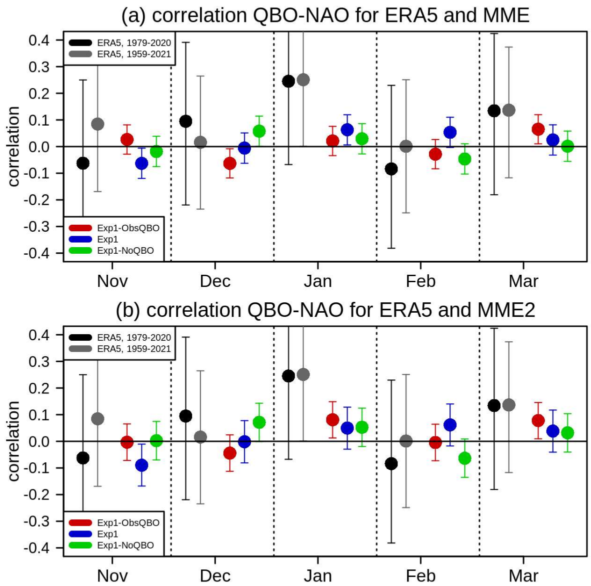

Figure 11: The correlations between QBO at 50 hPa and the NAO index in January for observations and the multi-model means are on the margins of significance. Pearson correlation between the QBO phase (5°S-5°N, 50 hPa) and strength of the NAO index from November to March for (a) the multi-model mean MME simulations and (b) the multi-model mean MME2 of only those simulations which exhibit a statistically significant HT effect on the PNJ in DJF, compared to ERA5. Error bars denote the 95% confidence interval of the correlation calculated across all simulations (i.e. models and ensemble members) contributing to the MME and MME2.

6 QBO influence on the North Pacific STJ and Precipitation

The North Pacific Sub-Tropical Jet (STJ) is known to influence the Asian winter precipitation, summer monsoon (Lee et al., 2013; Choi and Kim 2019; Hunt and Zaz 2023), and the occurrence of western disturbances in tropical regions which typically propagate along the STJ. The influence of the QBO on the strength and position of the STJ may be associated with the downward arch-shaped extension of the QBO zonal wind anomaly (e.g. QBOE-W negative anomaly shown in Fig. 3, equatorial blue region) connecting the equatorial QBO at ~50 hPa and the upper troposphere and lower stratosphere in the subtropical and mid-latitudes (Garfinkel and Hartmann, 2011b; Seo et al., 2013, Garfinkel and Hartmann, 2011a; Park et al., 2022). Following Anstey et al. (2022b) we examined the latitudinal shift of the winter zonal-mean STJ from its climatological position as a function of the QBO phase.

The observed winter (ONDJFM) North Pacific upper tropospheric zonal-mean zonal winds, when composited by QBOW-QBOE at 50 hPa, exhibits a latitudinal profile (Fig. 12, black line) with a maximum around 25°N – 30°N, and a minimum around 42°N – 47°N, either side of the climatological STJ at 35°N which reflects the reanalysis result of Anstey et al. (2022b; see their Fig. 12). The MME-mean for Exp1 (blue line) shows some variation in the mid-latitudes with a peak around 30°N - 35°N and trough around 45°N - 50°N although neither are significant (see blue envelope). Nudging the QBO (Exp1-ObsQBO; red line) and thereby improving the equatorial stratospheric wind profiles improves the representation of the latitudinal wind profile equatorward of 35°N, with a larger and significant peak. However, nudging the QBO degrades the response poleward of 35°N where the jet is expected to be weaker during QBOW. For both Exp1 and Exp1-ObsQBO the

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peak in the latitudinal wind profile appears to be shifted approximately 5° northwards of the observed peak suggesting a systematic bias in the MME responses. This is despite the latitude of the climatological STJ for Exp1 and Exp1-ObsQBO multi-model means coinciding with that of ERA5 (not shown). The reason for this bias remains unclear. Repeating this analysis using the QBO phase at 70 hPa does not substantively change the results.

Previous studies (e.g. Gray et al., 2018; Hitchman et al., 2021) have suggested a link between the tropical teleconnection route of the QBO and the STJ. The argument is that the strength and location of tropical convection may modify the horizontal propagation of waves thereby impacting the position and strength of the STJ. In boreal winter, the QBOW phase is associated with an easterly anomaly in the upper troposphere (weaker westerlies) across the Pacific and an equatorward shift in the STJ (Kumar et al., 2022; Park et al., 2022). For this reason, we investigated potential relationships between the simulated QBO-related responses in tropical precipitation and the STJ zonal wind anomalies in Exp1 and Exp1-ObsQBO.

Comparing these two experiments shows that nudging the QBO modifies the tropical and subtropical precipitation and zonal wind responses to the QBO phases (Fig. 13). In observations (GPCP; Fig. 13a), the zonal wind response is characterised by a positive QBOW-E response in the North Pacific which is maximised in the central region (180°E - 210°E, 30°N), and a negative zonal wind response, aligned with a strong precipitation signal in the equatorial eastern Pacific. This spatial pattern in either mid-latitude zonal winds or equatorial precipitation is not diagnosed in the MME of Exp1 (Fig. 13c). However, the MME of the nudged experiment, Exp1-ObsQBO, shows a zonal wind response of a similar spatial pattern and sign, both in the equatorial and North Pacific sectors (Fig. 13e).

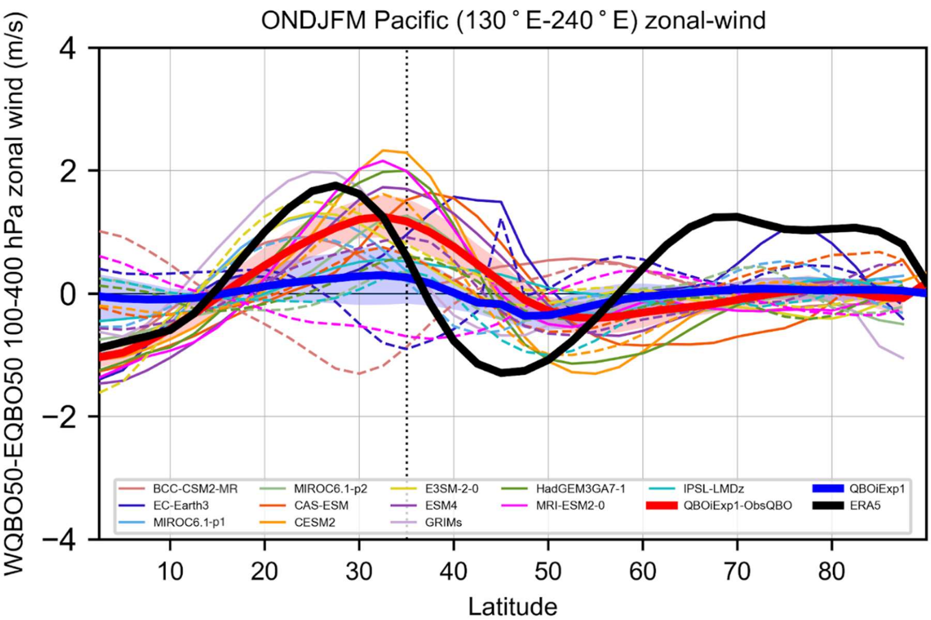

Figure 12: The response of the STJ to QBOW-E is smaller and shifted northwards compared to observations. October-March QBOW minus QBOE 100 – 400 hPa pressure-weighted zonal-mean zonal wind anomalies averaged over the North Pacific (130°E – 240°E) for the time period October 1979 to March 2020. The QBOW and QBOE groups are each deseasonalized before subtraction. Each model's zonal-wind anomalies are shown with a characteristic colour, which is used to denote its Exp1 response (dashed line) and its Exp1-ObsQBO response (solid line). The thick black curve shows the ERA5 anomalies over the experiment period and the thick blue and red curves show multi-model averages of the Exp1 and Exp1-ObsQBO ensembles, respectively; we average across a model's respective ensemble members before computing the multi-model averages so that each model is given equal weight in the multi-model average. 2.5 and 97.5 percentile confidence intervals, denoted by shading, are computed about Exp1 and Exp1-ObsQBO by resampling the model ensemble means 10,000 times with replacement. The vertical dashed line denotes the latitude of the climatological STJ.

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These spatial patterns of westerly wind anomalies in the eastern tropical Pacific (red box in Fig. 13a,b) in both the observations and nudged experiment may help explain the peak zonal mean wind results at 30°N shown in Fig. 12. The negative zonal wind anomalies near the equator are stronger in the nudged experiment coinciding with a stronger subtropical response in the zonal wind. In contrast, for the free-running Exp1, there are weaker tropical and subtropical wind responses, suggesting that the strength of the tropical precipitation and wind are related to the subtropical wind response.

The magnitude and spatial distribution of the zonal wind response, in both the tropics and subtropics, however, appear to be related to the phases of ENSO. When considering only neutral ENSO winters (defined when the ONI is below 0.5°C in magnitude), both the tropical and subtropical precipitation and zonal wind signals weaken in observations and Exp1-ObsQBO (Fig. 13 b,f). Specifically, the North Pacific zonal wind signal in the nudged experiment becomes a dipole, with negative anomalies in the western jet (region indicated by red box in Fig. 13 a,b) and positive anomalies in the eastern jet.

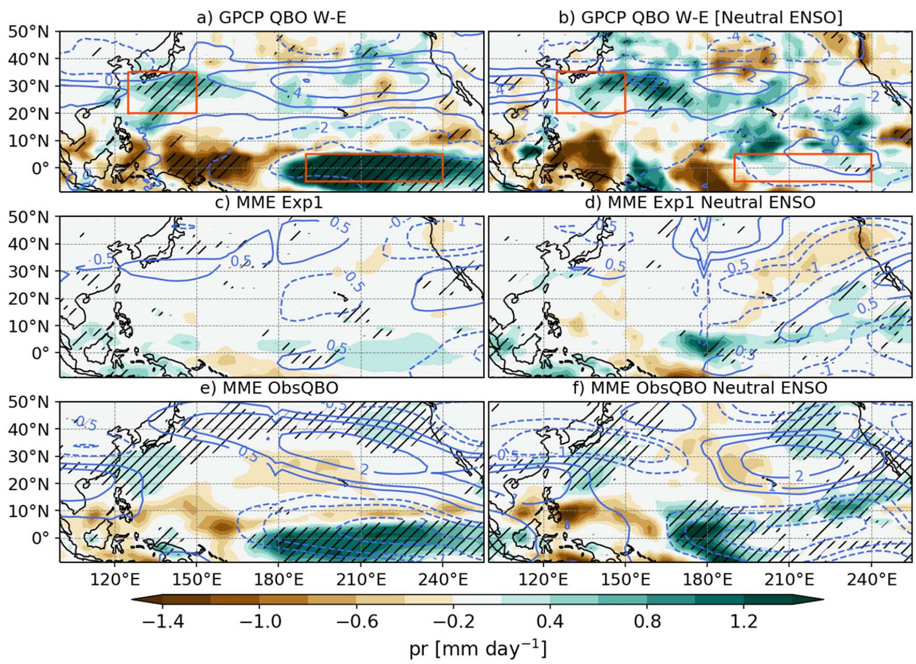

Figure 13: Nudging modifies the tropical precipitation and subtropical upper level wind response to the QBO. DJF mean differences (QBO W-E) in precipitation (shading in mm day^{-1}) and zonal wind at 200 hPa (contours in m s^{-1}). Results are shown for observations considering a) all cases and b) only neutral ENSO conditions. QBOi MME of the experiments (c-d) Exp1 and (e-f) Exp1-ObsQBO. Hatching in (a-b) denotes statistical significance of the precipitation differences to the 95% confidence level according to a bootstrap test whereas in (c-f) the hatching shows where at least 70% of the models agree on the sign of the difference.

The tropical Pacific precipitation and North Pacific zonal wind responses appear robust in the nudged experiment (Fig. 13f) even after removing the potential ENSO influence. This response, under neutral ENSO conditions, is characterised by stronger precipitation in QBOW associated with an easterly wind anomaly in the western North Pacific, and a westerly anomaly in the eastern North Pacific (Yoden et al. 2023), a response not seen in observations. The upper-level easterly wind anomaly in the tropical Pacific suggests a weakening of the Walker circulation (Bjerknes 1969), consistent with previous observational and modelling studies (Hitchman et al., 2021; García-Franco et al., 2022, 2023).

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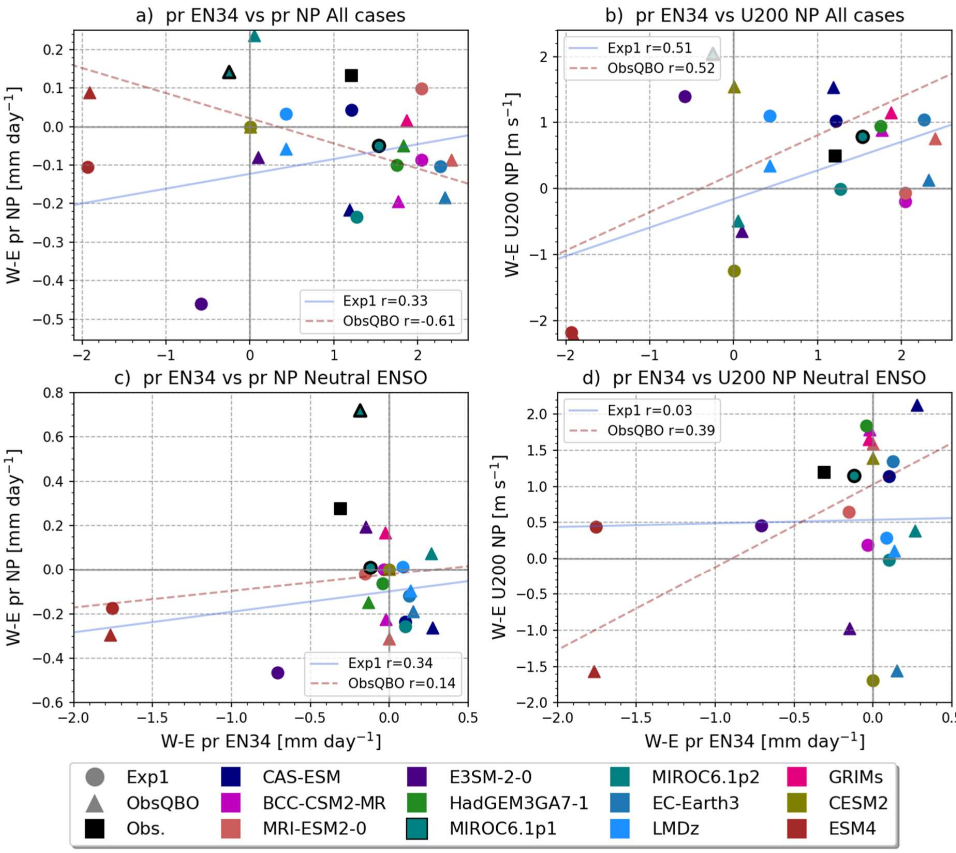

Figure 14: Scatter plots showing the relationships between precipitation in the Niño3.4 region and the precipitation and zonal wind in the subtropical North Pacific (NP; defined as [20°N – 40°N, 125°E – 150°E]) for DJF. Relationship of the QBOW-E differences of Niño3.4 precipitation and a) NP precipitation and b) NP zonal wind at 200 hPa using all cases. (c-d) As in (a-b) but only considering Neutral ENSO conditions. The Pearson correlation coefficients for each experiment are shown in the legends. Exp1 results are indicated by coloured circles, and Exp1-ObsQBO by coloured triangles. N.B. for clarity the scales differ for each panel.

If we examine the model spread of the relationship between the simulated tropical (Niño3.4) precipitation and subtropical upper-level zonal wind responses (Fig. 14 b,d), we find that the nudged experiments (Exp1-ObsQBO) show a comparable response and correlation to the free running experiment (Exp1). Specifically, the positive QBOW-E signal in the North Pacific *U200* jet response appears to be a robust feature that is positively correlated with the tropical precipitation response, except in the case of Neutral ENSO conditions in Exp1. The ESM4 model stands out as an outlier in these results because of the strongly negative tropical precipitation response, however, removing this model from the correlation analysis does not change the sign of the correlation, but does reduce the magnitude from $r = 0.52$ to 0.23.

The relationship between the simulated Niño3.4 precipitation and the subtropical precipitation (Fig. 14 a,c) shows that QBO impacts depend strongly on the background ENSO condition. Restricting the analysis to ENSO-neutral winters not only alters the strength but even reverses the sign of the subtropical QBO signal (compare Exp1-ObsQBO anomalies in Fig. 14a versus 14c). This sign change implies that both the mean state of the tropical circulation (e.g. the Walker circulation) and the ENSO phase modulate how the QBO influences precipitation beyond the deep tropics. In particular, these results

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demonstrate that the ENSO phase can be a critical influence on the tropical–subtropical QBO teleconnection pathway (Garfinkel et al., 2010, Kumar et al., 2022; García-Franco et al., 2023).

Overall, nudging the models towards the observed QBO improves the representation of the subtropical route in the Pacific. However, some aspects of the observed response and the nudged simulations are challenging to interpret given the potential aliasing of the QBO signal with the ENSO signal. Nonetheless, our results show that nudging has a relevant impact on the subtropical jet over the Pacific resulting in a stronger response compared to the free-running experiment Exp1. Finally, while the nudging generates a stronger subtropical response, nudging may not always lead to the correct spatial pattern of the QBO signals as highlighted in Fig. 13 for the extra-tropical response.

7 Conclusions

The sensitivity of QBO-extratropical teleconnections to model biases in the equatorial stratospheric zonal mean winds has been investigated. A comparison of the free-running (Exp1) experiment and the experiment where the equatorial stratosphere is nudged towards the observed QBO (Exp1-ObsQBO) over the period 1979 - 2020 indicates that the PNJ response to the QBO phase, i.e. the Holton-Tan Effect, is improved when the QBO matches observations. The response was found to be significant for both experiments. Of the contributing models, five out of the eleven models with internally-generated QBOs exhibited a negative PNJ anomaly, which increased to ten out of twelve models when the observed QBO was imposed. This provides evidence that the observed winter-mean QBO-PNJ teleconnection is more likely to be captured in models with a realistic QBO compared to an internally-generated QBO. It is plausible that, in free-running models, issues such as model bias and weaker-than-observed strength of the QBO at 50 hPa (Richter et al., 2022, Anstey et al., *in prep*.) may act as a barrier to capturing the Holton-Tan effect.

The magnitudes of the QBO-PNJ responses for individual models were similar for Exp1 and Exp1-ObsQBO, but weak compared to observations. Sub-sampling the Exp1-ObsQBO models using the same number of QBOE and QBOW winters as for observations demonstrated that the magnitude of the observed PNJ response in January cannot be captured by the models. This suggests that there is still a gap to be bridged between the strength of the teleconnection in the models and observations. It is possible that the strength of the observed January PNJ response, though significant, is relatively uncertain given the limited number of QBOE and QBOW samples. It is also plausible that the observed difference in timing of SSWs for QBOE and QBOW winters contributes to the large January response. This relationship between the timing of SSWs and the QBO phase, i.e. earlier SSWs for QBOE compared to QBOW winters, was not captured by either Exp1 or Exp1-ObsQBO experiments. Furthermore, only a small, insignificant, but robust increase in SSW frequency was found during QBOE vs QBOW in both experiments. If models were able to fully capture this timing and frequency differential it would clarify whether SSWs significantly modulate the strength of the Holton-Tan Effect.

Although the magnitudes of model QBO-PNJ teleconnections were weak, the Exp1-ObsQBO experiment was found to significantly capture part of the interannual variability of the January PNJ over the historical period 1979 - 2020. A similar analysis using Exp1-NoQBO demonstrated no skill. This suggests that seasonal/multi-annual forecasts which contain a QBO that reflects both the time-evolving phase and strength of the observed QBO is an important consideration when predicting the stratospheric polar vortex, and that any departure from the observed QBO may potentially reduce the prediction skill of the PNJ.

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The QBO-NAO teleconnection, which is small and insignificant in observations, was also found to be extremely weak and insignificant in the Exp1 and Exp1-ObsQBO experiments. If the teleconnection acts through the pathway from QBO-to-PNJ and then PNJ-to-NAO, it is plausible that the relatively weak PNJ response to the QBO phase may have contributed to the lack of QBO-NAO response. Nevertheless, the correlation between the PNJ and NAO was found to be significant when not stratified by the phase of the QBO. Additional experiments which nudge the observed historically-evolving equatorial and polar stratospheric winds into models (effectively an extension of Exp1-ObsQBO) may provide evidence of whether a bias-corrected PNJ is linked to the NAO when composited by QBO phase.

The influence of the QBO on the North Pacific STJ has been arguably linked to the QBOW-E zonal-mean zonal wind anomaly arching polewards and downwards from the lower equatorial stratosphere to the upper sub-tropical troposphere. The small but significant zonal wind anomaly on the southern flank of the STJ, only captured by the bias-corrected experiment (Exp1-ObsQBO), suggests that the models can produce a weak approximation of the observed response to the QBO. It is probably not a coincidence that the influence of the QBO on the North Pacific upper-level winds was found to be larger in the nudged experiment than in the free running experiment. Hence, it is plausible that the weak response might be attributed to a difference in strength and zonal topology of the arching zonal wind anomalies, or to some aspect of the upper-troposphere-lower-stratosphere coupling outside of the nudged region. Further experiments that bias correct the arching zonal wind anomalies in addition to the QBO may identify where the QBO-STJ connection is breaking down in models.

ENSO is likely to be an influential and potentially confounding factor when interpreting the response of the STJ and precipitation in the North Pacific. Removing ENSO events altered the sign and spatial structure of the tropospheric zonal wind QBO signal and its relationship with tropical precipitation, highlighting the role of the mean tropical state in modulating QBO teleconnections. Only the nudged experiment exhibited a zonal wind STJ response that appeared to be robust with- and without-ENSO but the spatial pattern of the anomalies varies significantly depending on the ENSO state. Further nudged simulations using climatological SSTs would enable the QBO signal to be better isolated from the effects of ENSO.

In summary, this comparison of the three QBOi phase-2 experiments has demonstrated that the QBO teleconnection to the winter stratospheric polar vortex can be improved in models when a more realistic QBO is imposed, i.e. when the QBO is bias-corrected. Perhaps surprisingly, this has failed to translate into a robust SSW frequency and timing response. Similarly, the teleconnection to the tropospheric NAO has failed to produce conclusive and consistent results for both observations and experiments. In the North Pacific, the zonal wind anomaly on the southern flank of the STJ was improved in terms of strength, although not latitudinal position, when imposing a more realistic QBO. While bias-correcting the simulated QBOs increases the strength of those concomitant extra-tropical responses that are diagnosed in this paper, these responses are still, on average, underestimated by the models. Moreover, the morphology of the response in the models is often somewhat different to that observed (e.g. the observed QBO influence on the frequency and timing of SSWs is not captured by the models). Establishing whether these errors can be attributed to model biases in the extra-tropics or are due to the poor representation of the teleconnection mechanisms by the models is quite beyond the scope of this study and is an important topic for future research.

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Appendix A

Table A1: Strength of the DJF PNJ response in models when compositing by QBOE-W. Bold indicates significance at the 2-sided 90% level (5% - 95%).

	Exp1 PNJ (m/s)	**Exp1-ObsQBO PNJ (m/s)**
BCC-CSM2-MR	**-5**	**-5**
CAS-ESM	+2	**-7**
CESM2	**-3**	**-3**
EC-EARTH3	0	-4
E3SMv2	+1	+1
ESM4	**-3**	**-3**
GRIMS 4.0	no data	-4
LMDz	+2	**-5**
MIROC6.1p1	+2	**-6**
MIROC6.1p2	0	**-4**
HadGEM3GA7.1	**-5**	-3
MRI-ESM2.0	**-5**	+3
ERA5	-	**-6**

Table A2: Slopes (*m*, unit = s/m/yr) and correlation coefficients (*r*) when regressing the frequency of SSWs (unit = yr^{-1}) against DJF zonally-averaged zonal winds at 60N and 10hPa (ms^{-1}) using the average values from each model, as in Fig. 7. The regression is performed for each experiment, using all boreal winters and SSWs (denoted by 'All'), filtering for only El Niño, La Niña, ENSO-neutral winters, and initial and non-initial SSWs.

	Exp1	**Exp1-NoQBO**	**Exp1-ObsQBO**
All	m = -0.0506 r = -0.934	m = -0.046 r =-0.937	m = -0.0410 r =-0.881
El Niño	m = -0.0494 r = -0.865	m = -0.0490 r =-0.874	m = -0.0451 r =-0.864
La Niña	m = -0.0468 r = -0.950	m = 0.0415 r =-0.914	m = -0.0434 r =-0.893
Neutral ENSO	m = -0.0512 r = -0.924	m = -0.0419 r =-0.793	m = -0.0366 r =-0.841

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Initial SSWs	m = -0.0260 r = -0.920	m = -0.0202 r =-0.895	m = -0.0191 r =-0.904
Non-initial SSWs	m = -0.0240 r = -0.847	m = -0.0259 r =-0.897	m = -0.0217 r =-0.822

Table A3: The models used in the strong-vortex (SVMM) model mean ensembles (grey cell = included, white cell = not included) for each model experiment: Exp1, Exp1-NoQBO, and Exp1-ObsQBO.

	SVMM, Exp1	**SVMM, Exp1-NoQBO**	**SVMM, Exp1-ObsQBO**
BCC-CSM2-MR			
CAS-ESM			
CESM2			
EC-EARTH3			
E3SMv2			
ESM4			
GRIMS 4.0			
LMDz			
MIROC6.1p1			
MIROC6.1p2			
HadGEM3GA7.1			
MRI-ESM2.0			

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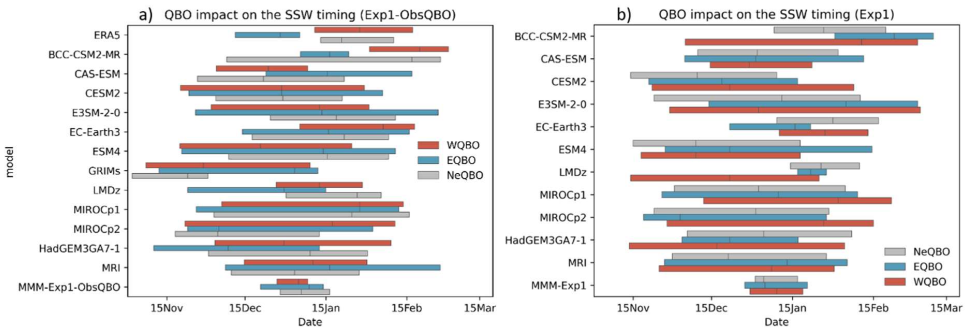

Figure A1: Models are unable to capture the observed significant shift to earlier winter SSWs under QBOE conditions. Timing distribution of mid-winter SSWs for (a) Exp1-ObsQBO and (b) Exp1, during QBOE (blue), QBOW (red) and QBO-neutral (grey) winters. Colour bars indicate the spread of SSWs and extend from the 25th to the 75th percentile with the mean indicated by a vertical line.

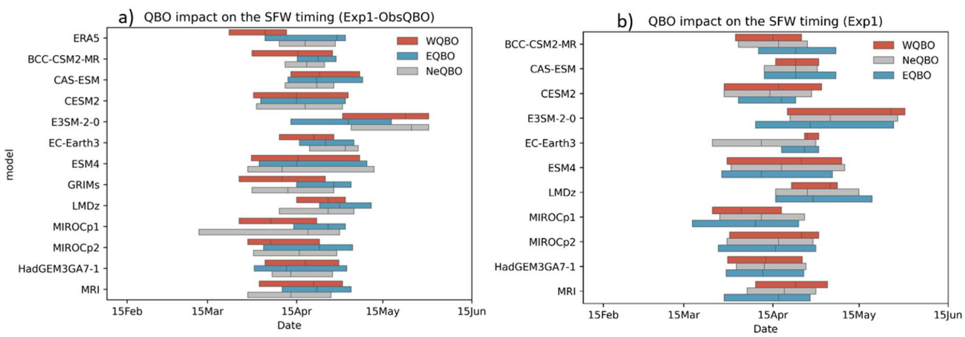

Figure A2: Models are unable to capture the observed shift to earlier SFWs under QBOW conditions. Timing distribution of SFWs for (a) Exp1-ObsQBO and (b) Exp1, during QBOE (blue), QBOW (red) and QBO-neutral (grey) winters.

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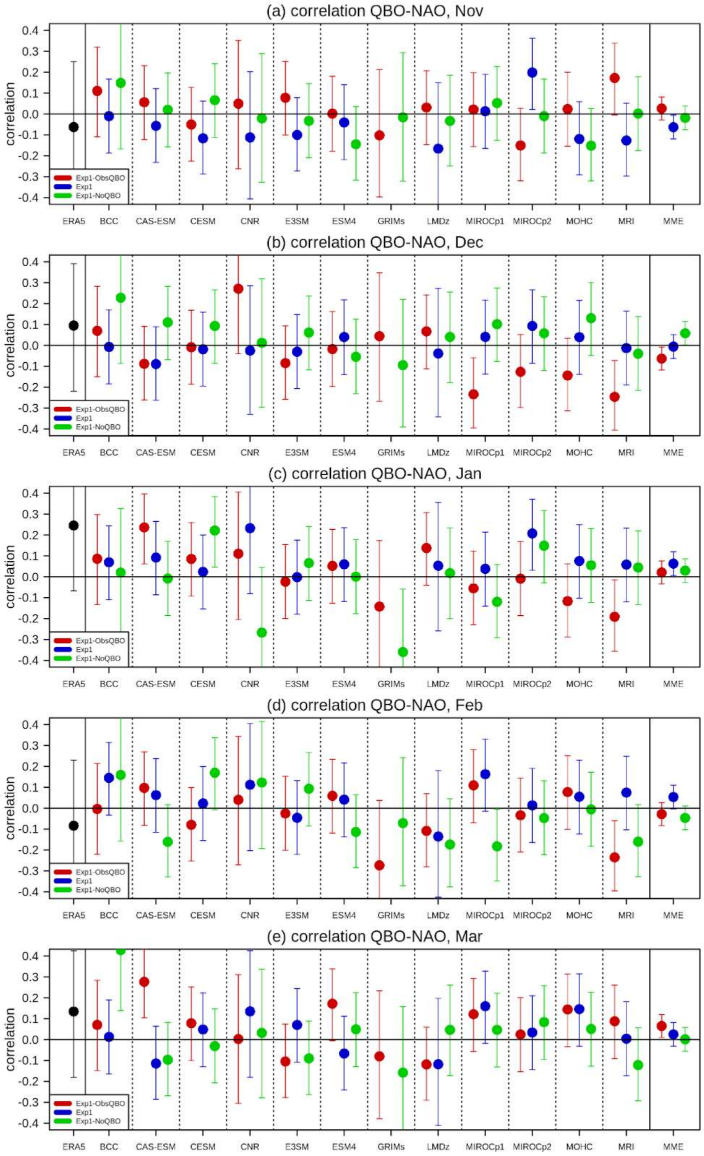

Figure A3: Correlation between the QBO (5°S-5°N and 50 hPa) and the NAO index in (top to bottom) November, December, January, February and March for ERA5, all models, and the MME for each experiment.

Data availability

The QBOi data archive was kindly hosted by the NERC Centre for Environmental Data Analysis (CEDA), UK.

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Author contribution

MA, NB, JA, EB, DE, JCF, VK, FP, NT: Conceptualization of the goals and aims of this analysis. Formal analysis of the experiments including investigation and methodology. Visualization of results and writing the manuscript.
MA, KY, ZC, DCH, KH, AJ, YK, JK, PL, FL, YL, HN, JR, FS, SWS, QT, SW, JX: Setting up individual models, running the experiments, and provision of data to the NERC CEDA archive. Reviewing the manuscript.
NB, JA, YK, SO, JR: Project management of QBOi, design of phase 2 experiments and data (diagnostic) request with input from the modellers.

Competing interests

JA serves as co-editor for the special issue to which this paper belongs. The remaining authors declare that they have no conflict of interest.

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