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Projected strengthening of the extratropical surface impacts of the stratospheric Quasi-Biennial Oscillation

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Revised to *Geophysical Research Letters*
(August 2020)
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Key Points:

- The impact of the QBO on the stratospheric polar vortex is projected to be stronger in the future by CMIP5/6 models.
- The NAO-like response during QBO winters are enhanced eastward in the RCP85/SSP585 scenarios, implying a stronger impact of QBO on the near surface.
- This strengthening is not due to a change in the QBO amplitude, as indeed most models project a weaker QBO.

Abstract

Using state-of-the-art models with a spontaneous quasi-biennial oscillation (QBO) from the Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5/6), this study explores projected changes in the Holton-Tan (HT) relationship and the near surface response to the QBO. Most models project an enhanced surface response to the QBO via a strengthened HT relationship in the future. Specifically, the North Atlantic Oscillation-like response is projected to double and shift eastward in the future in the high-end emissions scenarios compared with the historical simulation. This strengthening occurs even as the amplitude of the QBO in the tropical stratosphere weakens from the historical simulation to the future projections. The seemingly contradictory projections of future changes in the QBO and the HT relationship might imply that the HT relationship changes nonlinearly with the QBO intensity, and the coherent changes in the background circulation structure should also be highlighted.

Key words: Quasi-Biennial Oscillation (QBO); CMIP5/6; Polar vortex; Global warming

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1029/2020GL089149

Plain language summary

Projecting the weather on sub-seasonal and seasonal timescales is extremely difficult yet is essential for certain applications. Forecasting skill on these timescales relies on features in the climate system that persist for longer than two weeks, and one such feature is the quasi-biennial oscillation (QBO). Here, we use Earth system model simulations from the Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5/6) to demonstrate that the surface response to the QBO via the Holton-Tan (HT) relationship is projected to strengthen. Specifically, the North Atlantic Oscillation response is projected to double and shift eastward in the future in the high-end emissions scenarios compared with the historical simulation. This strengthening is not due to a change in the QBO amplitude, as indeed most models project a weakening trend for the QBO amplitude, and also a shortening trend for the QBO periodicity. The seemingly contradictory projections of future weakening of the QBO yet strengthening of the HT relationship suggests that the HT relationship will change nonlinearly with the QBO intensity, and the coherent changes in the background circulation structure should also be highlighted.

1. Introduction

It is more difficult to forecast the weather on sub-seasonal and seasonal timescales as compared to shorter timescales, but these predictions on longer time scales are of essential importance for certain applications (Rayner et al., 2005; Morss et al., 2008; Vitart et al., 2017). The Quasi-Biennial Oscillation (QBO) can impact near-surface climate and weather in the Northern Hemisphere (NH) winter by modulating the variability of the stratospheric polar vortex (Holton & Tan, 1980; Baldwin et al., 2001; Ruzmaikin et al., 2005; Marshall & Scaife, 2009). The connection between the QBO and the polar vortex is the so-called Holton-Tan relationship (HT relationship hereafter), although the mechanism originally proposed by HT may not explain the entirety of the polar stratospheric response (Garfinkel et al., 2012; Watson & Gray, 2014; White et al., 2015; Rao et al., 2019). In addition to this polar stratospheric pathway, there are other pathways whereby the QBO influences the tropospheric circulation (Garfinkel & Hartmann, 2011a, 2011b; Anstey & Shepherd, 2014; Andrews et al., 2015; Rao et al., 2020a, 2020b).

While possible changes in the QBO have been considered by several studies (Kawatani & Hamilton, 2013; Butchart et al., 2020; Richter et al., 2020a), the changes in the HT relationship and surface impacts of QBO have not been studied in detail. Due to the decadal and multi-decadal variability in the HT relationship associated with solar activity (Gray et al., 2001; Lu et al., 2008) or the alignment of the QBO phases with the seasons (Anstey et al., 2010; Christiansen, 2010; Rao et al., 2020a, 2020b), the evidence for changes in the future magnitude of the stratospheric HT relationship in the one study that has examined this issue (Naoe & Shibata, 2012) is not robust. The possibility of future changes in the corresponding surface impact of the QBO via the HT mechanism has not been reported yet, especially in the North Atlantic–European region.

As there has been a rapid increase in the number of state-of-the-art models that are capable of simulating a spontaneous QBO (Bushell et al., 2020; Rao et al., 2020a, 2020b; Richter et al., 2020b), an understanding of the future changes in the QBO and in its impact on the North Atlantic–European climate has only now become possible. Given the importance of accurate seasonal forecasts for a range of applications (Rayner et al., 2005; Morss et al., 2008; Vitart et al., 2017), and the inherent predictability of the QBO on seasonal and annual timescales (Scaife et al., 2014; Garfinkel et al., 2018), it is important to assess how the surface impacts of the QBO will change. Rao et al. (2020a) considered in detail the ability of these models to capture the HT relationship in the historical integrations, and found that if one considers the phase of the QBO with peak winds in the lower stratosphere, the models' HT relationship is of similar strength to that in reanalysis data. The main purpose of this paper is to demonstrate a strengthened future response of the surface to the QBO via the HT relationship.

2. Model datasets and methods

2.1 QBO-resolving CMIP5/6 models used in this study

Output from twenty QBO-resolving models are used in this study (Table S1), including 7 CMIP5 models (i.e., from CESM1-WACCM to MPI-ESM-MR) and 13 CMIP6 models (from BCC-CSM2-MR to UKESM1-0-LL) performing the historical and future scenario simulations. Four of the CMIP5 models used by Kawatani and Hamilton (2013) are HadGESM2-CC, MIROC-ESM-CHEM, MIROC-ESM, and MPI-ESM-MR. Note that the first CMIP5 model, CESM1-WACCM, cannot internally simulate the QBO, and the QBO zonal winds between 86 and 4 hPa are nudged toward the observed QBO with an approximate 28-month cycle period (Marsh et al., 2013). All the CMIP5 models have a model top at or above the 1 hPa pressure level and have at least 60 vertical levels. Most of the 13 CMIP6 models that have a QBO are also high-top models with a model top at or above the 1 hPa pressure level or higher than ~50 km, except that BCC-CSM2-MR has a relatively lower model top. The horizontal resolution in CMIP6 models is generally higher than in CMIP5 models, though a finer horizontal resolution appears less important than a finer vertical resolution to simulate the QBO.

The historical and future scenario experiments are available for almost all CMIP5/6 models. The affiliation, nationality, horizontal resolution, model top and levels for each CMIP5/6 model are listed in Table S1. The historical simulation begins in 1850 and ends in 2005 for CMIP5, whereas the historical simulation ends in 2014 for CMIP6. The future scenarios are termed differently: it is called Representative Concentration Pathways (RCPs; Taylor et al., 2012) with a representative radiative forcing value in 2100 (e.g., 2.6, 4.5, 6, and 8.5 W/m^2) for CMIP5, and it is called Shared Socioeconomic Pathways (SSPs; Gidden et al., 2019) for CMIP6. The RCP45 (a moderate warming simulation) and RCP85 (a strong warming simulation) future scenarios are provided by nearly all of the seven CMIP5 models (no RCP85 for GEOSCCM); the SSP245 (a moderate warming simulation) and SSP585 (a strong warming simulation) scenarios are provided by all of the 13 CMIP6 models (Eyring et al., 2016). It is estimated that the RCP45/SSP245 and RCP85/SSP585 provide concentrations of greenhouse gases for the moderate- and high-end scenarios that achieve climate forcings of 4.5 and 8.5 W m^{-2} by 2100, respectively (O'Neill et al., 2016). The three-dimensional monthly mean data were obtained from the CMIP5/6 database during 2006/2015–2100 for the two scenarios (RCP45/SSP245 and RCP85/SSP585).

2.2 *Methods*

The monthly QBO time series are defined as the area-weighted zonal winds over the near-equator latitude band (5°S–5°N). To filter out the intraseasonal variability that might confound our procedure to isolate QBO westerly and easterly peaks (i.e., several adjacent peaks might appear in the original raw data), the time series are smoothed using a five-month running-mean. To track the long-term trend in the QBO timeseries and to compare the long-term change of the QBO easterly and westerly phases, the QBO time series are not deseasonalized. Since the QBO variability is more realistic at 30hPa than that at 50hPa in CMIP5/6, and considering that the observed HT relationship is evident both for 50hPa and 30hPa winds (Holton & Tan, 1980; Baldwin et al., 2001), this paper will mainly use zonal winds at 30 hPa to define QBO. Sensitivity to using the QBO index at 50 hPa is explored in the supplemental material.

Two methods of defining the QBO amplitude are described as follows. All the QBO westerly and easterly extrema at a given pressure level are identified and marked. If no easterly (westerly) extrema interrupt two adjacent westerly (easterly) extrema, the weaker one of the two westerly (easterly) extrema is deleted. Then all QBO westerly and easterly extrema are re-identified. In this way, only the largest one of several adjacent westerly extrema without an easterly interruption is chosen as the QBO westerly amplitude (A_W) in a complete QBO cycle. Similarly, only the most negative of several adjacent easterly extrema without a westerly interruption is chosen as the QBO easterly amplitude (A_E). Following the above steps, only westerly and easterly peaks are kept and the other extrema are not stored. The time axes of those peaks are saved for calculation of the QBO period for each QBO cycle. The QBO amplitude is estimated as $1/2(A_W - A_E)$ in a complete QBO cycle, constructing a nonuniform discrete series. The second method of quantifying the QBO amplitude used here is to multiply the 8-year running standard deviation of the smoothed monthly QBO index by $\sqrt{2}$ (Kawatani & Hamilton, 2013), constructing a continuous month-by-month series ($\sqrt{2}\sigma$).

The cycle period of the QBO is the difference in the time axis between two neighboring QBO westerly (or easterly) peaks. The dominant QBO period can also be extracted from a spectral analysis on the QBO index.

To reveal the HT relationship in different simulations, the QBO index at 30 hPa is deseasonalized. The westerly QBO winter is selected if the winter-mean (December–February) QBO index exceeds 5 m s^{-1} for each model, and the easterly QBO winter is selected if the winter-mean QBO index falls below –5 m s^{-1}. The sensitivity of the composite HT pattern to a smaller threshold has been tested (Rao et al., 2020a, 2020b), but the composite pattern is nearly unchanged. The ERA-Interim reanalysis (Dee et al., 2011) is used as a baseline when we assess the surface response to QBO in the present-day climate system from historical runs by CMIP5/6 models.

3. An enhanced Holton-Tan relationship in the future

One of the most noticeable impacts of the QBO is on the stratospheric polar vortex (as discussed in the introduction). Two metrics are used to quantify the stratospheric polar vortex: the polar cap temperature in the Arctic stratosphere (70–90°N, 100–10 hPa) and the circumpolar zonal wind in the stratosphere (55–75°N, 70–5 hPa). These metrics are evaluated in the long historical runs, the moderate future warming scenario simulations, and the strong future warming scenario simulations from twenty models in CMIP5/6. The composite differences for the two metrics between easterly and westerly QBO winters are shown in Figure 1 for historical (gray), RCP45/SSP245 (dark blue), and RCP85/SSP585 (light blue) simulations. The composite difference in the QBO winds decreases in the future scenario simulations relative to the historical simulation for most models (Figure 1a), implying a decreasing trend in the QBO amplitude in agreement with previous work (Kawatani & Hamilton, 2013; Butchart et al., 2020; Richter et al., 2020a). Compared with the westerly QBO, the Arctic stratosphere is anomalously warm (Figure 1b) and the polar night jet decelerates (Figure 1c) in the easterly QBO winters in historical simulations for most models (Rao et al. (2020a) discusses the HT relationship in the historical simulations in detail). The HT relationship can be simulated by 17 models, and the multimodel ensemble mean (MME) is also shown (excluding CESM1-WACCM, due to QBO nudging in this model). The key point is that the polar vortex response to the QBO in the future projections (especially in the RCP85/SSP585 scenarios) will be enhanced in nearly all models as compared to the historical simulation. While the HT relationship will not hold for either of the future scenarios in three models (MIROC-ESM, CESM2-WACCM, CNRM-CM6-1), the MME indicates that the extratropical stratospheric response to the QBO will be significantly enhanced in both future scenarios, and the enhancement of the HT relationship in RCP85/SSP585 is larger than in RCP45/SSP245.

The composite latitude-pressure cross section of the zonal-mean zonal wind difference between the easterly and westerly QBO winters (December–February) is shown in Figure 2 for the MME (excluding CESM1-WACCM) and ERA-Interim. The composite QBO structure in the tropical stratosphere is nearly unchanged from the historical to future simulations, but the QBO central anomaly at 30 hPa weakens (Figures 2e, 2f). However, the extratropical wind anomalies in the future simulations are larger and more significant than in the historical simulations. It can be concluded that the enhanced HT relationship in the future is not attributed to the change in the QBO amplitude, and changes in the extratropical dynamics in a warming climate system are probably responsible for this enhanced HT relationship, left for future study. For example, the climatological subtropical tropospheric jet is projected to be stronger than the present-day one (purple contours in Figure 2), although the jet center does not shift.

The large MME composite from the three scenarios allows us to reject the possibility that the apparent changes in the HT relationship are merely due to long-term natural variability in the climate system, unlike the single-model study of Naoe and Shibata (2012). In addition, Naoe and Shibata (2012) found the maximum HT effect shifts to the early spring in the future in a single model, whereas the projected HT relationship in the CMIP5/6 MMEs is enhanced in both the moderate- and high-emissions future scenarios, and the maximum HT effect still appears in the winter season (not shown).

4. Projected strengthening of the extratropical surface response to the QBO

Does the strengthened HT relationship lead to a strengthened surface response too? Rao et al. (2020a, 2020b) showed that the surface impacts of the QBO associated with the HT effect is generally captured in the historical simulation in models that simulate the stratospheric response. Composite MSLP differences between the easterly and westerly QBO winters from multimodel ensemble (MME) of CMIP5/6 models (excluding CESM1-WACCM) and a representative model are shown in Figure 3 for the North Atlantic-Europe region (shadings, units: Pa). The HT effect can descend to the troposphere, especially in the North Atlantic region, so the HT relationship has implications for the seasonal prediction of North Atlantic-Europe climate (Marshall & Scaife, 2009; Garfinkel et al., 2018; Rao et al., 2020a, 2020b). In both models and the reanalysis, the negative North Atlantic Oscillation (NAO) tends to develop during strong easterly QBO, due to the downward impact of the associated weak stratospheric polar vortex. Specifically, a high mean sea level pressure (MSLP) anomaly center is modelled in the Arctic Ocean and North Greenland by the MME of historical runs (Figure 3a). As an example of the CMIP5/6 models with a decent HT relationship (Figure 1), the UKESM1-0-LL model also simulates a high center at high latitudes in the Atlantic sector (Figure 3d). Contrastingly, a low MSLP anomaly band develops at midlatitudes (Figures 3a, 3d). Although the QBO amplitude is projected to weaken in the future (see the supporting information file), the HT effect in the troposphere is projected to become stronger, especially in the RCP85/SSP585 scenarios and also shift eastward (Figures 3b, 3e). The projected change in the HT effect by UKESM1-0-LL largely resembles that by the MME (Figures 3c, 3f). Namely, the polar vortex response to the QBO is much stronger in the RCP85/SSP585 future scenario than the present day. Consistent with the much stronger projection of the circumpolar jet response in the stratosphere by UKESM1-0-LL than by the MME, the MSLP response magnitude is correspondingly much larger in UKESM1-0-LL than in the MME (cf. UKESM1-0-LL and MME in Figure 3). More remarkably, both UKESM1-0-LL and the MME project that the near-surface NAO-like but eastward-shifted response to QBO in the future will be more than twice of their present-day response (Figures 3a, 3b vs Figures 3d, 3e). This difference in the magnitude of the surface response is statistically significant at the 90% confidence level (Figures 3c, 3f).

5. QBO amplitude changes in historical and future simulations

Our discussion above indicated a weakening of the QBO itself, and we now confirm this finding using a variety of metrics. We show the individual time series of the QBO index at 30 hPa in the moderate-emissions scenario simulations in Figure 4 for seven CMIP5 models and 13 CMIP6 models. The first model, CESM1-WACCM cannot simulate the QBO internally but with the equatorial zonal winds nudging toward the observed QBO cycle, so the long-term trend of the QBO amplitude is nearly zero for both westerly and easterly phases (Figure 4a). A trend of the QBO amplitude is also undetectable in GEOSCCM and CNRM-ESM2-1 for both phases (Figures 4c, 4l). The positive regressed slopes of QBO westerly and easterly amplitudes in CMCC-CMS and HadGEM2-CC might imply a change in the tropical climatology (i.e., zonal winds shift toward westerlies) rather than any change in the QBO amplitude (Figures 4b, 4d). However, this cannot be determined from the analysis here. Similarly, the negative slopes of QBO westerly and easterly amplitudes in MIROC-ESM and BCC-CSM2-MR can be explained by the climatological zonal wind shift toward easterlies (Figures 4f, 4h). For the other 13 models, however, the QBO magnitude weakens unambiguously. The weakening of the easterly phase is particularly pronounced for most models; that is, the trend of the QBO westerlies is somewhat weaker than that of the QBO easterlies (Figures 4e, 4g, 4i–4k, 4m, 4n, 4p–4s). In contrast, the weakening trend of the QBO westerly amplitude is more prominent than that of the QBO easterly amplitude in only two CMIP6 models (4o, 4t).

Most models project a weakening QBO in the moderate-emission future scenario, with a multi-model ensemble (excluding CESM1-WACCM with a QBO nudged rather than generated) mean (MME) trends of -0.13/0.37 m/s per decade for westerly and easterly phases. However, the long-term trend in the historical simulation is rather inconsistent (MME trends = -0.03/0.14 m/s per decade), and nine models (e.g., MIROC-ESM-CHEM, MIROC-ESM, MPI-ESM-MR, CESM2-WACCM, CNRM-CM6-1, HadGEM3-GC31-LL, IPSL-CM6A-LR, MPI-ESM1-2-HR, UKESM1-0-LL) project a prominent weakening of the QBO amplitude (< -0.1 m/s per decade, Figure S3). In contrast, the weakening of the QBO from most models (excluding CESM1-WACCM, CMCC-CMS, MPI-ESM1-2-HR) is projected to be much larger in RCP85/SSP585 scenarios (Figure S4) with the MME trends of -0.17/0.69 m/s per decade.

The supplemental material also examines other metrics [e.g., A_W, A_E, $1/2(A_W - A_E)$] of the QBO amplitude to demonstrate the robustness of the projected weakening of QBO amplitude (Figures S5–S7).

The weakening amplitude of the QBO cycle in most models and the MME can be explained by the increase in tropical upwelling accompanied with a strengthening Brewer-Dobson circulation in response to more accumulated greenhouse gas concentration (Butchart et al., 2006; Kawatani et al., 2011; Kawatani & Hamilton, 2013). Although Gabriel (2019) identified that the QBO remains nearly unchanged in MPI-ESM-MR, we find that the QBO amplitude weakens in this model (Fig. 4g). Latest studies provide more evidence that the QBO amplitude will weaken in the high-emissions scenario and 4×CO_2 simulations (Giorgetta, 2005; Butchart et al., 2020; Richter et al., 2020a; 2020b), although our results further reveal that the QBO will also weaken in the moderate-emissions scenario, and that the amplitude of the QBO easterlies will weaken more than that of the westerlies. Therefore, the enhanced change in the HT effect and the surface response is not due to the QBO itself strengthening. Instead, the QBO actually is projected to weaken. As for the projected change in the QBO cycle period, it is still debatable in earlier studies (Watanabe et al., 2012; Kawatani & Hamilton, 2013; Schirber et al., 2015; Richter et al., 2020a), but most models show that the QBO period will shorten (Figures S8–S10).

6. Conclusions

Taking advantage of the rapid increase in state-of-the-art models which can spontaneously simulate a QBO in the tropical stratosphere, here we project the long-term changes of the HT relationship and the impact of the QBO on the surface in the North Atlantic–European region. Most models project a significantly enhanced HT relationship in both the moderate- and high-end future scenarios. The composite QBO central wind amplitude decreases from the historical to the RCP45/SSP245, and then to the RCP85/SSP585 simulations in the MME, but the extratropical stratospheric response gradually strengthens. Consistent with the stronger stratospheric HT relationship in the future, the projected surface response by the RCP85/SSP585 scenario in the North Atlantic–European region (i.e., the NAO) will double in the future, implying that seasonal predictive skill for the North Atlantic and European region based on the phase of the QBO will increase. Gabriel (2019) suggests that the extratropical QBO signature changes towards the disappearance of the HT relationship based on one model, but we use a larger model ensemble and find a strengthened HT relationship. The different conclusions between Gabriel (2019) and this study might be caused by their different projected background circulations, periods of interest, model numbers, and experiment setups.

To test if the enhanced HT relationship is related to the strengthening of the QBO amplitude, different metrics [i.e., A_W, A_E, $1/2(A_W - A_E)$ and $\sqrt{2}\sigma$] are adopted to extract the QBO trends for each QBO-resolving CMIP5/6 model. Most QBO-resolving CMIP5/6 models project a weakening trend for the QBO amplitude in the future scenario simulations [~-0.25 m/s and -0.5 m/s per decade in the two future scenarios; consistent with recent studies (Kawatani & Hamilton, 2013; Butchart et al., 2020; Richter et al., 2020a)]. Building on these previous studies, we show that the weakening trend of the QBO easterly peak is stronger than that of the QBO westerly peak for most models, which might be mixed with the climatological shift for the tropical wind towards westerlies. The seemingly contradictory projections of future changes in the QBO and its impact might be attributed to the coherent changes in the background circulation structure. However, the mechanism for the HT relationship in the present climate is highly uncertain with at least four different possibilities in the literature (Garfinkel et al., 2012; Watson & Gray, 2014; White et al., 2015; Rao et al., 2019), and hence a discussion of how these mechanisms will change under climate change is left for a future investigation. These results demonstrate that a linear viewpoint for the projected changes in the QBO and the extratropical response might be invalid, because our results have shown a weaker QBO but a stronger HT relationship in the future.

Acknowledgments

JR was funded by the National Key R&D Program of China (2016YFA0602104) and the National Natural Science Foundation of China (41705024). CIG, IW, and JR are also funded by the ISF-NSFC joint research program (3259/19) and the European Research Council starting grant under the European Union’s Horizon 2020 research and innovation programme (677756). All data used in this study are publicly available. The CMIP5/6 simulations are available through the ESGF (https://esgf-node.llnl.gov/projects/esgf-llnl/). Those QBO-resolving CMIP5/6 models are developed by different agencies from different countries, listed in Table S1.

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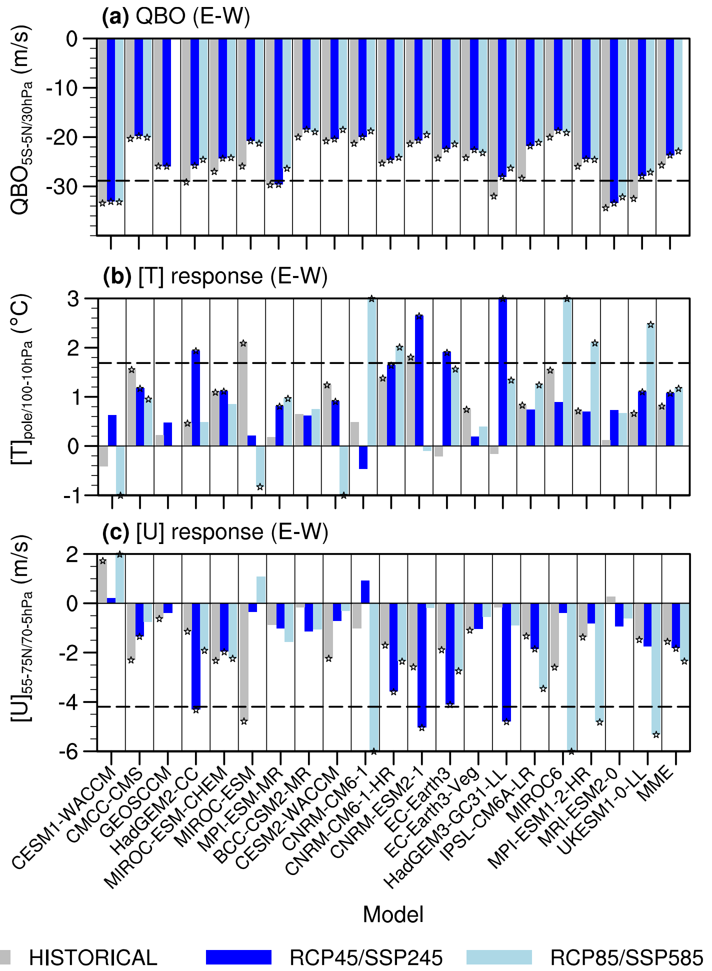

Figure 1. Changes in the composite QBO amplitude and the stratospheric polar vortex response in the historical and future simulations for CMIP5 and CMIP6 models. (a) Composite equatorial zonal wind difference at 30 hPa between the easterly and westerly QBO winters. (b) Composite difference in the polar cap temperature (70–90°N, 100–10 hPa) between the easterly and westerly QBO winters. (c) Composite difference in the circumpolar zonal wind (55–75°N, 70–5 hPa) between the easterly and westerly QBO winters. The gray bar shows the composite for the historical simulation, the dark blue bar shows the composite for the moderate future emissions scenario (RCP45/SSP245), and the light blue bar shows the composite for the strong future emissions scenario (RCP85/SSP585). The pentagram marks the composite difference at the 95% confidence level ($\alpha \leq 0.05$). The horizontal dashed line shows the composite from ERA-Interim.

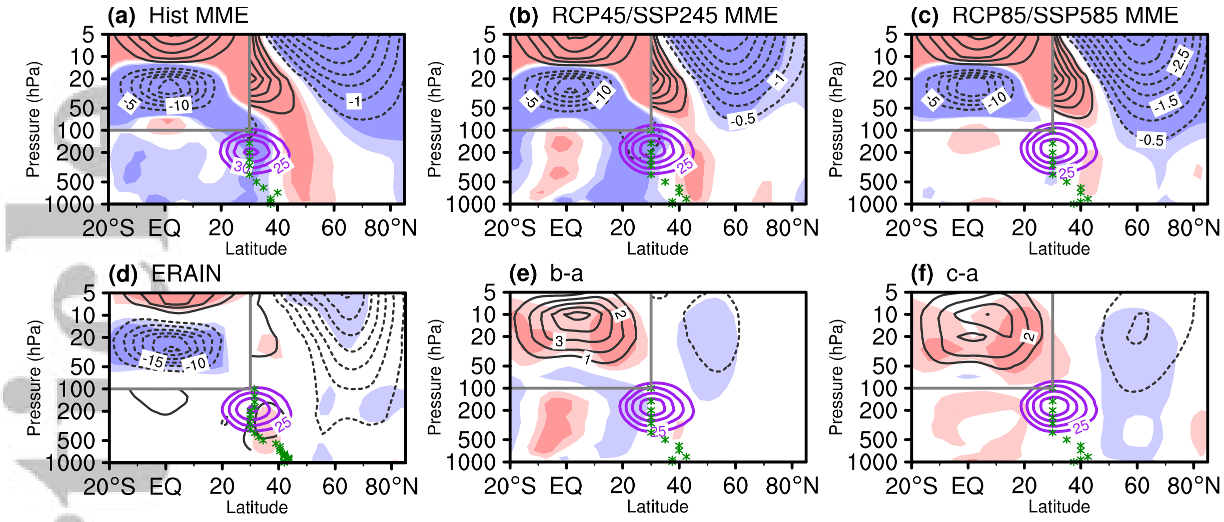

Figure 2. Changes in the Holton-Tan (HT) relationship from historical simulations to future simulations. (a) Composite latitude-pressure cross-sections of the zonal-mean zonal wind differences (contours, units: m/s; contour interval: 5 inside the gray box and 0.5 outside) between the easterly and westerly QBO winters in the historical simulations. (b, c) As in (a) but in the moderate-emissions scenario (moderate future warming) and high-emissions scenario (strong future warming) simulations. (d) As in (a) but for the composite from ERA-Interim. The purple contours (≥25 m/s, interval: 5) show the climatological subtropical tropospheric westerly jet, and the green asterisks mark the tropospheric jet maximum center at each pressure level from 1000–100 hPa. (e, f) Changes in the zonal-mean zonal wind responses (contour interval: 1.0 inside the gray box and 0.5 outside) to the QBO from the historical simulations to the future scenario simulation. Only the multiple model ensemble means (MMEs) are shown. The zero contours are skipped for clarity. The light and dark shadings denote the difference value at the 90 and 95% confidence levels.

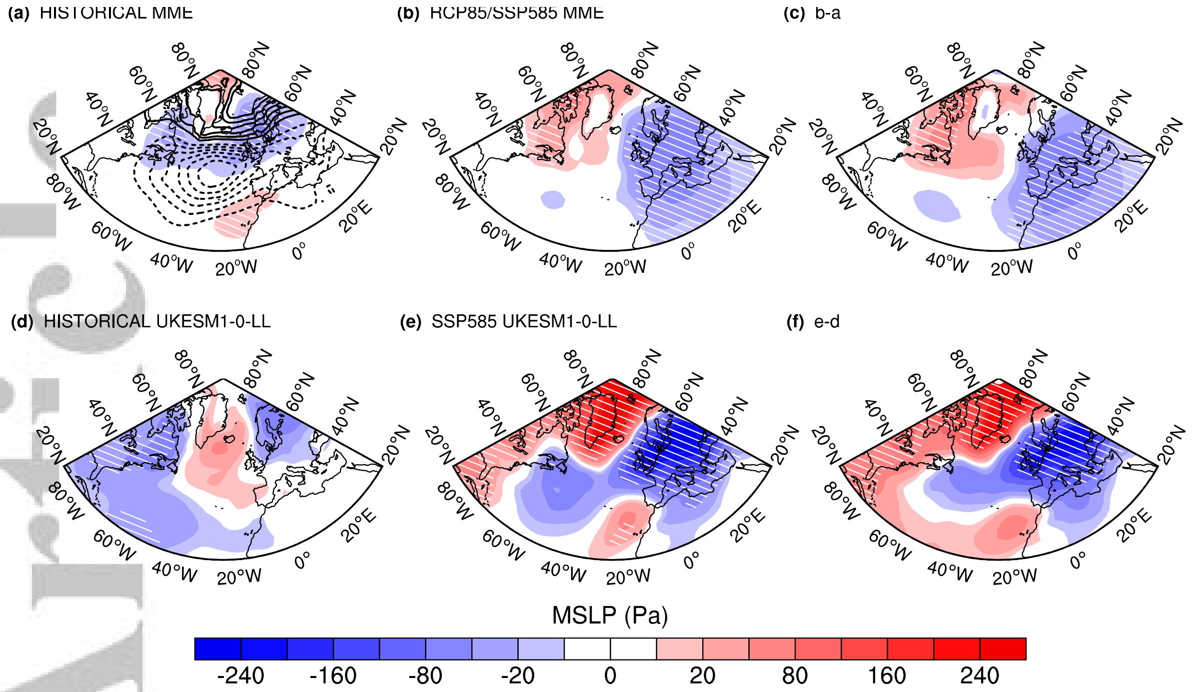

Figure 3. Composite mean sea level pressure (MSLP) differences in the North Atlantic-Europe region (shadings, units: Pa) between the easterly and westerly QBO winters. (a, d) the historical simulations; (b, e) high-emission scenario (strong future warming) simulations; (c, f) Changes in the MSLP response from the historical simulations to high-emission scenario simulations. Both the MME (a–c) and a representative model (i.e., UKESM1-0-LL) (d–f) are shown. The hatched regions mark the MSLP difference value at the 90% confidence level. The contours in (a) show the composite from ERA-Interim as a reference in the present-day climate system.

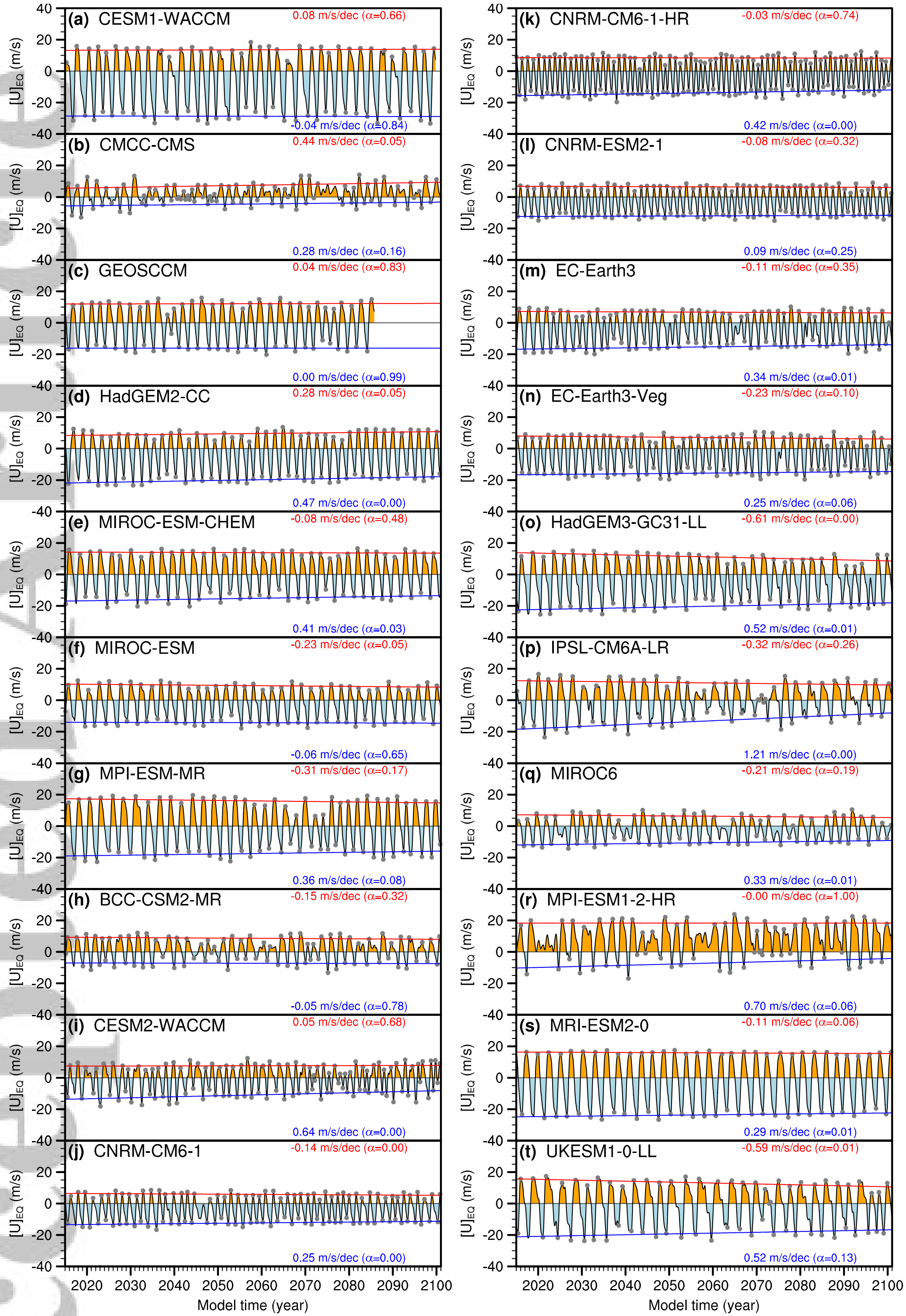

Figure 4. Long-term trend of the QBO westerly and easterly amplitudes at 30 hPa in the moderate future emissions scenario. (a–g) RCP45 for CMIP5 models; (h–t) SSP245 for CMIP6 models. The black curve is the QBO index denoted by the zonal-mean zonal wind in the equator (5°S–5°N) at 30 hPa. The red (blue) line is the linear trend of the QBO westerly (easterly) amplitudes with its value and significance level (α) printed for each model using the same color. A positive trend denotes an increase in the QBO westerlies and a decrease in the easterlies, and a negative trend denotes a decrease in the QBO westerlies and an increase in the easterlies.