Impacts, processes and projections of the quasi-biennial oscillation

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Abstract | In the tropical stratosphere, deep layers of eastward and westward winds encircle the globe and descend regularly from the upper stratosphere to the tropical tropopause. With a complete cycle typically lasting almost 2.5 years, this quasi-biennial oscillation (QBO) is arguably the most predictable mode of atmospheric variability that is not linked to the changing seasons. The QBO affects climate phenomena outside the tropical stratosphere, including ozone transport, the North Atlantic Oscillation and the Madden–Julian Oscillation, and its high predictability could enable better forecasts of these phenomena if models can accurately represent the coupling processes. Climate and forecasting models are increasingly able to simulate stratospheric oscillations resembling the QBO, but exhibit common systematic errors such as weak amplitude in the lowermost tropical stratosphere. Uncertainties about the waves that force the oscillation, particularly the momentum fluxes from small-scale gravity waves excited by deep convection, make its simulation challenging. Improved representation of the processes governing the QBO is expected to lead to better forecasts of the oscillation and its impacts, increased understanding of unusual events such as the two QBO disruptions observed since 2016, and more reliable future projections of QBO behaviour under climate change.

High above the Equator, alternate layers of eastward and westward winds descend through the stratosphere from near the stratopause down to the tropical tropopause region (at an altitude of approximately 16 km; FIG. 1a). At each altitude the winds typically take between 20 and 37 months to change from eastward to westward and back again, averaging around 28 months to do so[1]. Since this duration is close to 2 years, these repeating irregular cycles, which extend about 5° either side of the Equator[2], are referred to as the quasi-biennial oscillation (QBO). Despite its irregular period, the QBO is one of the most repeatable fluctuations of the large-scale circulation seen anywhere in Earth's atmosphere other than those associated with the changes in season and from day to night. Consequently, the QBO, or at least its phase progression, is one of the most predictable modes of large-scale internal variability in the atmosphere[3].

The QBO was discovered in the early 1960s[4,5], although evidence for its existence extends back to the nineteenth century[6,7]. The basic theoretical framework for an understanding of the QBO followed soon after its discovery[8,9], and by the time of the first comprehensive review of the QBO[10] a canonical model for the oscillation was well established (BOX 1). This simplified canonical model explains the underlying oscillation in the equatorial winds; however, the observed evolution and detailed structure of the QBO is affected by contributions from several other processes and phenomena (FIG. 1b).

Since the discovery of the QBO, its signal or influence has been identified in many other atmospheric phenomena, such as the strength of the stratospheric polar vortex[11–13], the distribution of stratospheric ozone[14,15] and other trace gases (BOX 2), the subtropical jets[16,17], the tropical troposphere[18–21], the Madden–Julian oscillation (MJO)[22] and semi-annual oscillations in the stratosphere and mesosphere[23,24]. Much research has sought to identify the pathways and mechanisms controlling the QBO's impacts and to improve their representation in models[11,20,21,25]. Improved modelling of the QBO could bring societal benefits with better predictions and projections that utilize the QBO's long timescales. For example, improved predictions of the North Atlantic Oscillation (NAO) could result from better model representation of QBO–NAO dynamical linkages[26,27], increasing the reliability of foreknowledge of the NAO's substantial impacts on Europe and eastern North America[28].

At the start of the twenty-first century, most state-of-the-art numerical models that included the stratosphere were unable to represent the QBO[29]. In the following two decades, parameterizations of unresolved gravity waves

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Key points

- The quasi-biennial oscillation (QBO) is a periodic wind variation in the equatorial stratosphere with a timescale of almost 2.5 years.
- The QBO affects predictability globally owing to its teleconnections to phenomena outside the tropical stratosphere.
- Many climate models are now able to simulate QBO-like oscillations, but with systematic errors including weak amplitude in the lowermost stratosphere.
- Improving the representation of the QBO in models is challenging owing to uncertainties in observations and in understanding of the waves that drive the oscillation.
- Climate models project a future weakening of the QBO amplitude.
- Although the QBO has historically been very predictable, since 2016 its regular cycling has been disrupted twice, for reasons not yet well understood.

and improved vertical resolution, which enable models to represent the rudiments of the canonical QBO model, have led to an increasing number of stratosphere-resolving models with realistic QBOs[30–32]. Indeed, at least 15 of the climate models used to support the current Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) feature a QBO, compared with none for the Fourth Assessment Report (AR4)[32].

Developing an understanding of the QBO and its reliability as a source of predictability became more challenging when the descending cycles were unexpectedly interrupted during the 2015/16 Northern Hemisphere winter[33–36], and again during the 2019/20 Northern Hemisphere winter[37,38] (circled events in FIG. 1a). These interruptions were associated with an anomalously high injection of wave momentum from the extratropics, temporarily dominating the wind evolution[39]. Importantly, the QBO's predictable signal was lost during the interruptions and when the oscillation re-emerged after a few months the phase was substantially shifted from that predicted without the disruption. Two interruptions occurring in the space of 4 years raises the question of whether these events are not 'once-in-a-lifetime' but rather that the QBO's behaviour is evolving owing to the changing climate[37].

In this Review, we describe the processes governing the QBO, the physical modelling of these processes, the effects of the QBO on other parts of the climate system, and future projections of the QBO under climate change. We focus on the past two decades of progress, referring readers to a comprehensive earlier review[10] for a more in-depth presentation of fundamental aspects of the QBO. We first discuss QBO impacts (teleconnections), which are the subject of considerable practical interest owing to the QBO's high predictibility. Realizing this predictability will require accurate representation of the QBO's governing processes in physical models, which we discuss next, followed by examination of future projections and their uncertainties. We conclude with some perspectives on future directions for QBO research.

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Impacts

Various mechanistic pathways have been proposed to explain QBO teleconnections (FIG. 2) but the processes involved remain uncertain. Determining the strength of impacts, either from observations or models, can be challenging. The QBO has been reliably observed since the 1950s, effectively limiting the observational record to only about 70 years. (Although a reconstruction of the QBO back to 1900 exists, its reliability prior to the 1950s is unclear[40,41]). Metrics for observed impacts (for example, a subtropical jet shift) can usually be obtained from reanalyses, and systematic inter-reanalysis differences are generally small enough that, in most cases, different modern reanalyses are equally suitable for characterizing an observed teleconnection over a given time period[42,43]. The uncertainty in observed QBO impacts is, therefore, primarily due to the limited sample size available (that is, the limited observational record). Distinguishing the influence of the QBO from other sources of interannual variability such as the El Niño–Southern Oscillation (ENSO), large tropical volcanic eruptions, and the 11-year solar cycle is often not straightforward, although the QBO's distinct timescale is helpful[44,45]. Observations show that QBO impacts can differ in their sensitivity to the height region of the QBO. Some impacts are maximized using winds at 50 hPa (around 21 km) to identify the QBO phase while others are maximized using winds at 20 hPa (around 27 km) or 70 hPa (around 19 km), suggesting that different physical mechanisms are present. Many of the proposed pathways for QBO impacts overlap and interact, creating substantial challenges in identifying the dominant pathways and mechanisms. Models can provide larger samples than observations and can be configured to exclude competing influences such as the ENSO, but are affected by modelling uncertainties in both the pathway mechanisms and the representation of the QBO.

If the processes underlying the QBO and its teleconnections are simulated with sufficient accuracy, long-range weather forecasting can benefit from the QBO's high predictability, which can extend to several years[12,46,47]. We first give an overview of tropical and subtropical impacts that could potentially be forecast more skilfully, followed by extratropical impacts.

Tropical and subtropical impacts. A QBO modulation of seasonal-mean tropical deep convection has been observed in the atmospheric layer directly beneath the QBO region (FIG. 2, pathway 1)[18–20,48]. Increased precipitation in the western tropical Pacific, and a southward shift of the Inter-tropical Convergence Zone, are found under QBO eastward winds at 70 hPa (REF.[20]). Precipitation differences between the QBO phases are about 1 mm per day but with strong regional and seasonal variation. Diagnosing this signal requires careful separation of the

QBO signal from the much larger ENSO impact[20,49]. A stronger QBO response is observed in the variability of deep convection associated with the MJO, which is about 40% stronger during the Northern Hemisphere winter when QBO winds at 50 hPa are westward[22,49,50]. This latter signal has only become apparent over the

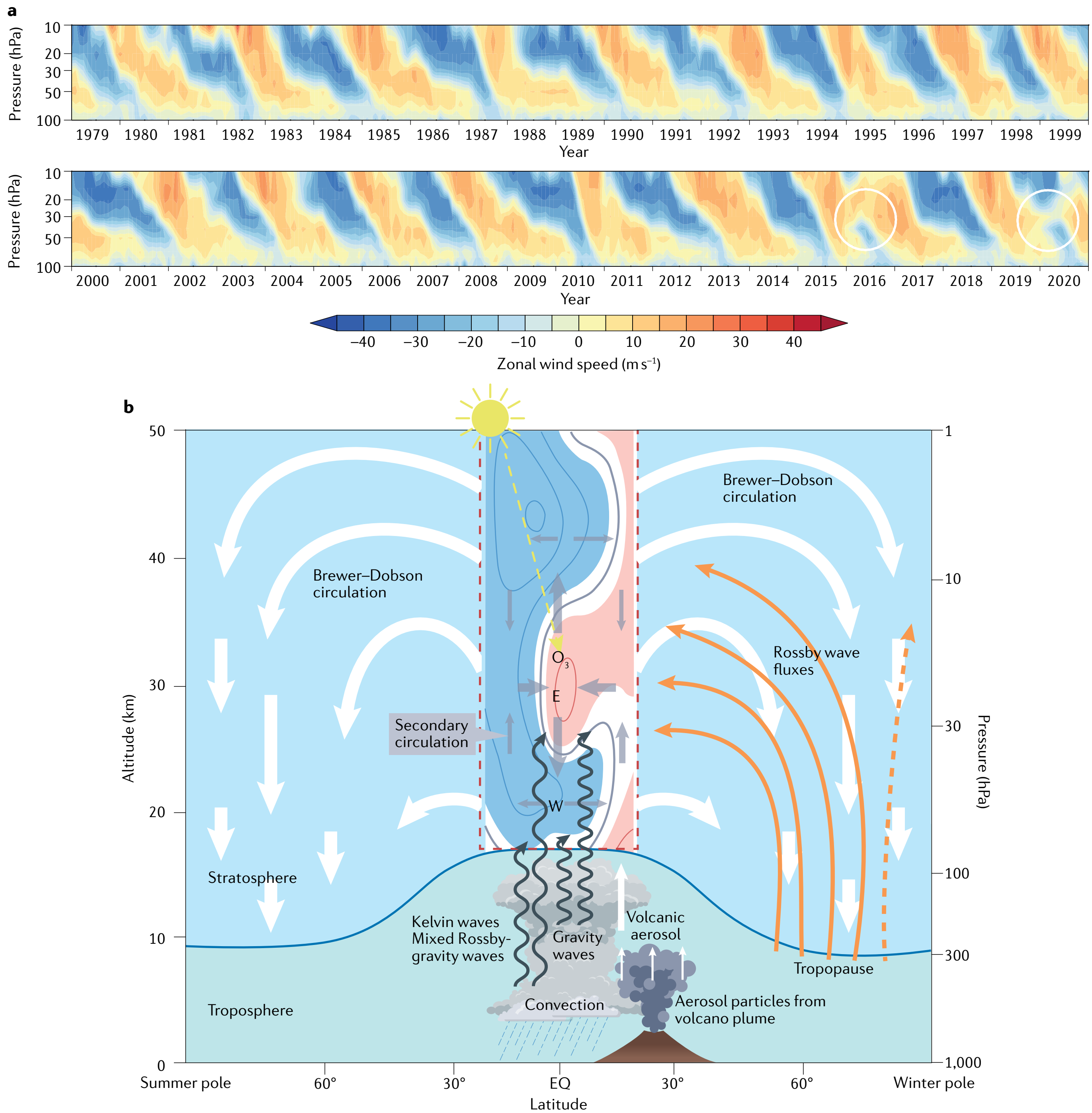
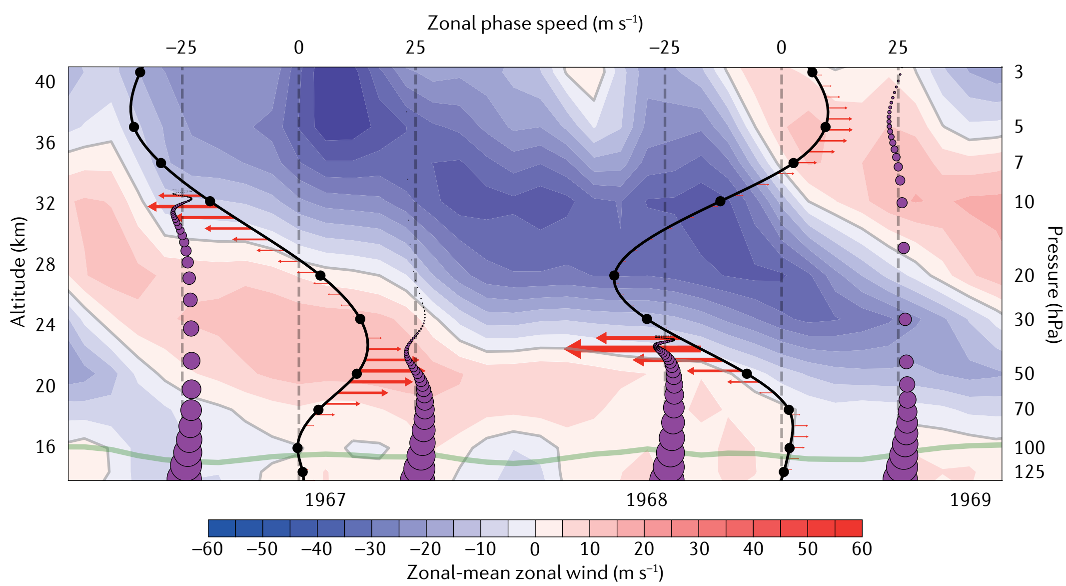


Fig. 1 | **The QBO in tropical stratospheric zonal wind and global circulation of the stratosphere. a** | Monthly means of daily observations (generally twice per day at 0Z and 12Z) of zonal winds above Singapore for 1979–2020. White circles indicate the only two occasions when the sequence of quasi-regular oscillations in the zonal winds over the Equator have been disrupted since regular observations became available in the 1950s. **b** | Eastward (E) and westward (W) zonal winds (red and blue, respectively) in the tropical stratosphere (box bounded by dashed red line) when the QBO phase is transitioning from westward to eastward at 30 hPa (zero-wind line, thick grey contour), and the semi-annual oscillation (SAO) in the upper stratosphere is in its westward phase. Rossby waves propagate through the winter extratropical stratosphere (orange arrows), transporting westward momentum equatorwards that can be important for 'QBO disruption' events. Black wavy arrows represent upwards-propagating tropical waves that drive the QBO in the canonical model (see BOX 1). The QBO is also affected by the overturning circulation of the stratosphere (Brewer–Dobson circulation, thick white arrows) and the QBO mean-meridional circulation maintaining thermal wind balance, hereinafter referred to as the QBO secondary circulation (grey arrows inside red dashed box), which modulates the distribution of ozone (see BOX 2). Data for part **a** is from https://acd-ext.gsfc.nasa.gov/Data_services/met/qbo/QBO_Singapore_Uvals_GSFC.txt.

Box 1 | **QBO mechanism**

Since its discovery, the QBO has correctly been surmised to be a wave-driven circulation[5]. The characteristic descending eastward and westward shear zones are caused by the dissipation of eastward and westward wave momentum fluxes, respectively. The schematic[192] shows a 3-year time series of monthly mean zonal-mean zonal wind vertical profiles in the tropical stratosphere (filled contours) from the JRA-55 reanalysis[189], and overlays two idealized profiles (thick black lines) corresponding to December 1966 and June 1968 along with two assumed waves with ±25 m s^{-1} zonal phase speed for each profile (upper axis in the figure). For an eastward wave propagating upwards in eastward wind shear (or a westward wave propagating upwards in westward shear), the vertical wavelength and vertical group velocity of the wave both decrease as the wind speed approaches the wave phase speed with altitude. Dissipation of the wave due to various mechanisms, including radiative damping and wave breaking owing to convective or dynamical instability, increases under these conditions. The dissipation reduces the momentum flux carried by the wave (purple dots), leading to momentum deposition that drags the mean flow (red arrows) towards the phase speed of the wave. Therefore, over time, the shear zone descends. This two-way interaction between the waves and the mean flow drives the QBO. The descent of shear zones also requires that the wave drag forces exceed advection by upwelling in the tropical branch of the Brewer–Dobson circulation[164,174] (not shown on the schematic, but see FIG. 1b).

Despite a clear understanding of these fundamentals, the details of which waves drive the QBO and the relative importance of different dissipation mechanisms remain murky. Contrary to the simple two-wave schematic, the relevant waves range from small-scale (tens of kilometres) short-period (minutes) gravity waves to global-scale long-period (days to weeks) Kelvin, Rossby and mixed Rossby and gravity waves. Estimates from high-resolution global models and reanalyses suggest that Kelvin waves contribute approximately half of the QBO eastward forcing, with the remainder contributed by gravity waves, and that gravity waves provide the majority of the westward forcing with smaller contributions from Rossby and mixed Rossby and gravity waves[107,109,115,116,137,193]. Improved global observing systems are needed to verify these results and to quantify global wave momentum fluxes, but vertical resolution limits satellite views of the important short-vertical-wavelength waves (<4 km)[111–113,194]. New results from long-duration, super-pressure balloons overcome these limitations, shedding new light on the details of wave driving of the QBO at very short vertical wavelengths[124,186].



past four decades, possibly associated with cooling of the stratosphere induced by changing greenhouse gas concentrations[51]. The QBO signal at the tropical tropopause is a peak-to-peak temperature variation of around 1 K (REF.[52]), yielding an anomalously cold and high tropical tropopause during QBO westward wind shear (when the MJO is enhanced) that can plausibly induce a tropospheric convection response[53]. However, the mechanisms remain uncertain and are a focus of active research[21].

The presence of the QBO also influences the passage of vertically propagating tropical waves into the upper stratosphere and beyond (FIG. 2, pathway 2). The QBO modulates the semi-annual oscillation (SAO) in the upper stratosphere: the SAO amplitude is roughly 5–10 m s^{-1} larger near 3 hPa (about 41 km) when QBO winds at 10 hPa (about 32 km) are westward than when they are eastward, although many models fail to reproduce this effect[54]. QBO influence on equatorial wind oscillations at higher altitudes is expected owing to the same mechanism that causes the QBO: winds at lower altitudes alternately restrict or permit the upwards propagation of waves whose phase speeds fall within the range of QBO wind speeds (BOX 1). Evidence exists that mesospheric zonal winds exhibit quasi-biennial variability coherent with the stratospheric QBO and consistent with this mechanism[55].

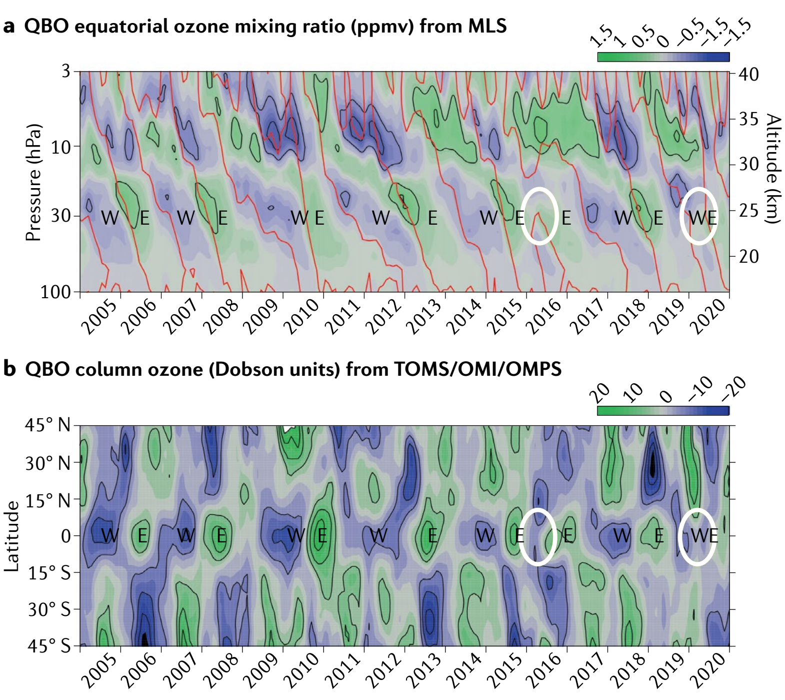
In the subtropics, seasonally dependent QBO signals have been found in the subtropical jet and mean sea level pressure in both Pacific and Atlantic basins[16,17,20]. When the lower stratospheric (about 50 hPa) QBO winds are westward, the Pacific subtropical jet tends to be further poleward during the Northern Hemisphere early and late winter (when the jet is weaker than in midwinter)[16]. This response is probably associated with the QBO-induced mean-meridional circulation[56] (or secondary circulation; FIG. 1b) that induces zonal wind anomalies in the subtropics[16] (FIG. 2, pathway 3). The Pacific storm track shifts polewards, while the Atlantic storm track contracts vertically, when the 50 hPa QBO is westward during the Northern Hemisphere winter[17].

Box 2 | **QBO in ozone and other trace gases**

The QBO is enormously important for year-to-year variability of trace gases and aerosols in the tropical stratosphere, and also for their global distributions. Exposing and removing this QBO-driven ozone variability is necessary to calculate the underlying stratospheric ozone trends caused by ozone-depleting substances[195]. Satellite observations of vertical profiles of ozone concentration show equatorial anomalies (top panel of the figure, parts per million by volume (ppmv); NASA Aura satellite Microwave Limb Sounder, MLS) associated with eastward and westward QBO phases (labelled E and W, respectively, with zonal wind zero contours in red). Ozone anomalies are driven by the QBO's impact on stratospheric circulation and temperature[10] (FIG. 2). However, because ozone absorbs both shortwave and longwave radiation, ozone anomalies feed back on the QBO's period and amplitude[165,166,196]. The vertical component of the QBO secondary circulation (FIG. 1b) produces a negative ozone anomaly in westward shear zones and a positive anomaly in eastward shear zones. The ozone anomalies change sign above 15 hPa owing to temperature control of the NO_x catalytic ozone loss process[165,197,198].

The QBO influence on composition extends from the tropics into the mid-to-high latitudes of both hemispheres. Satellite observations of total ozone column over 45° S to 45° N (bottom panel of the figure, Dobson units; Nimbus-7 TOMS, Meteor-3 TOMS, Earth Probe TOMS, Aura OMI, Suomi OMPS and SBUV) show positive and negative anomalies associated with eastward and westward winds, respectively, in the tropics (8° S to 8° N). The associated subtropical return branch of the QBO secondary circulation results in ozone anomalies of the opposite sign at higher latitudes. The anomalies in total ozone column are formed because ozone density is largest in the lower stratosphere, making the ozone column anomaly most sensitive to the QBO-driven circulation at these altitudes.

Satellite and balloon profile observations show the QBO influence on advection and distributions of other trace gases and particles[199,200], including an effect on stratospheric water vapour[15]. The QBO disruption of 2015/16 (white ellipses) had a direct impact on stratospheric composition[201,202]. Recognition that the QBO influences polar stratospheric composition and surface concentrations continues to grow. The QBO partially controls the Antarctic ozone hole by altering the year-to-year variability of ozone-depleting chlorine and bromine[203] and can influence atmospheric transport from the stratosphere into the troposphere, confounding emission estimates of key ozone depleting substances such as chlorofluorcarbon-11 ($CFCl_3$)[204].



Observed QBO-related variations in East Asian climate are probably related to the Pacific jet response[57–60], including an eastward shift of western North Pacific tropical cyclone tracks near 30° N during the westward 50 hPa QBO[61]. However, an early statistical association between the QBO and Atlantic tropical cyclones[62] disappeared when a longer data record (by approximately 25 years) became available[63]. The QBO can modulate the regions in which MJO teleconnections occur[64–66], and combining information about the MJO and the QBO can increase the predictability of atmospheric river events that funnel water vapour from the subtropics to the west coast of North America[67].

Extratropical impacts. The QBO influence on the Northern Hemisphere winter stratospheric polar vortex (FIG. 2, pathway 4), often referred to as the Holton–Tan effect[68], is a well studied route for influence on the underlying tropospheric mid-latitude weather and climate. Anomalously strong or weak polar vortex winds result in an annular impact on the tropospheric winds and mean sea level pressure[28,69,70]. This impact is particularly evident in the Atlantic sector, where 60-day composite mean sea level pressure anomalies of about 4 hPa following sudden stratospheric warming (SSW) events show a pattern resembling the NAO[28]. Forecasts of the NAO are valuable owing to its large effect on the European and eastern North American climate. During Northern Hemisphere winter, eastward QBO winds in the lower tropical stratosphere (about 50 hPa) favour a stronger stratospheric polar vortex, leading to a positive NAO phase (normally associated with a polewards-shifted Atlantic jet), whereas westward QBO winds favour a negative NAO[26,46] and greater likelihood of extreme cold surface temperatures[71]. The average difference in stratospheric vortex strength in January is about 5–10 $m\,s^{-1}$ between the eastward and westward QBO phases[11], with corresponding NAO-like mean sea level pressure differences of about 5 hPa (REF.[20]). Forecasts of the NAO are improving[72,73], but whether all processes underlying NAO predictability are well represented by the atmospheric models used in current forecasting systems is unclear. The predictable signal in these forecasts is usually weaker than observed, necessitating large ensembles for its extraction and to achieve skillful predictions[74]. The QBO is expected to contribute skill to NAO forecasts[26], but could also be a source of this signal-to-noise problem if processes underlying QBO teleconnections are not well represented in the models[27].

The underlying mechanisms for QBO influence on stratospheric winds at higher latitudes (FIG. 2, pathway 4) are uncertain, because predicting the effects of different tropical wind states on planetary waves from first principles is difficult[11,68]. One proposed mechanism involves a latitudinal shift in the zero-wind line, which acts as an effective waveguide for planetary-scale Rossby waves by modulating the occurrence of low-latitude wave breaking[68,75,76]. During the westward QBO phase the zero-wind line shifts into the subtropics of the winter hemisphere, constraining these waves to higher latitudes and resulting in a weaker, warmer polar vortex

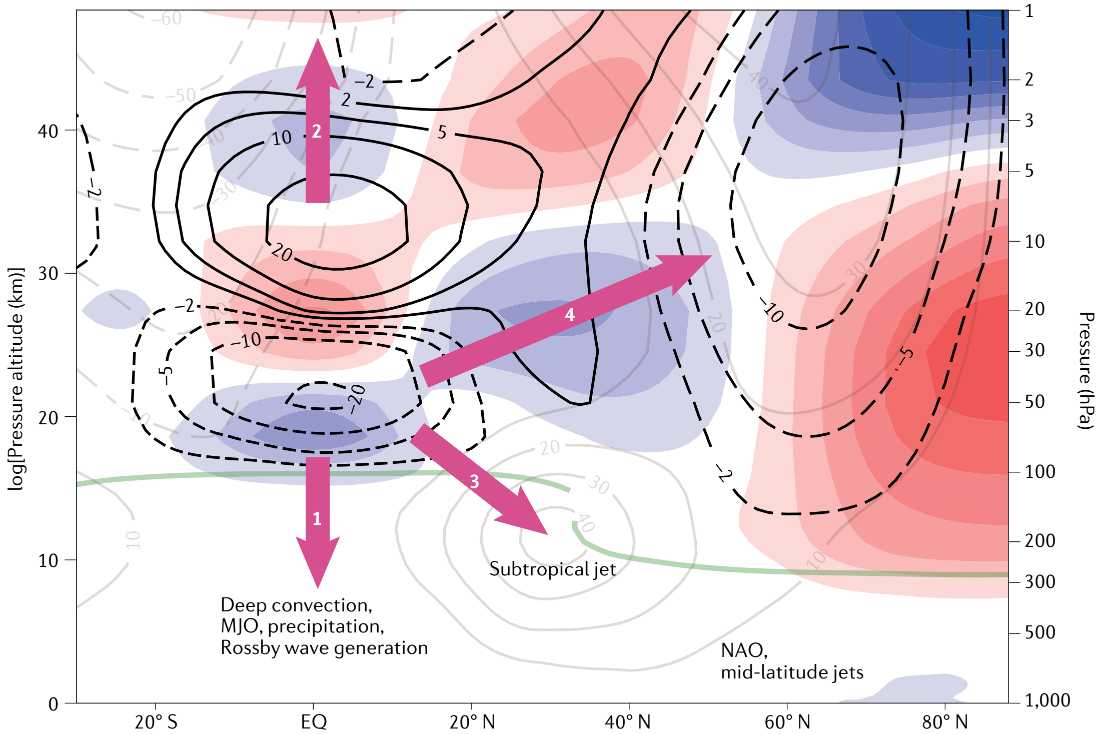


Fig. 2 | **Global QBO teleconnections and their pathways.** January difference between westward and eastward QBO composites for 1958–2016 using the JRA-55 reanalyses[189], defining QBO phase by 50 hPa equatorial wind (westward minus eastward). Black contours represent zonal-mean zonal wind difference (westward dashed, eastward solid, units of metres per second), filled contours represent zonal-mean temperature difference (warmer is indicated by red and colder by blue, 1 K contours starting at ±0.5 K). Also shown are the January climatogical zonal-mean zonal wind (light brown contours, zero contour omitted, units of metres per second) and thermal tropopause (light green). Numbered arrows (purple) indicate pathways for QBO influence by modulating tropical tropopause temperature or wind (pathway 1), filtering upwards-propagating waves that reach the SAO near the stratopause and above (pathway 2), modulation of the subtropical jet by the QBO secondary circulation (pathway 3), and modulating planetary-scale waves that distort the stratospheric polar vortex (pathway 4).

than in eastward QBO years. This mechanism (often referred to as the Holton–Tan mechanism) has been demonstrated in a general circulation model by artificially introducing horizontal wind shear in the vicinity of the zero-wind line; however, as the response is highly nonlinear, within a few days feedback processes rapidly alter the background winds, thus obscuring direct evidence of the mechanism[77]. Another proposed mechanism involves planetary waves interacting with the zonal wind anomalies associated with the QBO secondary circulation (FIG. 1b), not requiring zero-wind-line-induced wave breaking[78,79]. An ambiguity with both mechanisms is that planetary waves have deep vertical wavelengths and prevailing tropical winds typically change direction with altitude (because the QBO consists of descending wind layers). Which QBO altitudes exert the strongest influence on the extratropical stratosphere is unclear, and even tropical winds at very high altitudes near the stratopause that are influenced by pathway 2 might be important[80,81]. The strength of the Northern Hemisphere QBO–vortex relationship also appears to vary on decadal timescales[82] and the source of this longer-term modulation is not fully understood[83–86].

Although most research has focused on the Northern Hemisphere response, the Southern Hemisphere winter stratospheric polar vortex is also affected by the QBO[87]. The late-winter vortex breakdown is delayed when QBO winds near 20 hPa are eastward; November-average differences in stratospheric vortex winds between eastward and westward QBO phases are around 5–8 m s^{-1} (REF.[11]), The Southern Hemisphere response indicates that the high-latitude circulation can respond to tropical wind anomalies at different altitudes (20 hPa, compared with 50 hPa for the Northern Hemisphere vortex). The timing of the Southern Hemisphere response (late winter) also differs from that in the Northern Hemisphere (early to mid-winter). The vortex response to QBO phase could depend on the vortex state itself, as suggested by modelling[11,88], and the Southern Hemisphere winter stratospheric polar vortex is much stronger and colder than the Northern Hemisphere vortex. Highly nonlinear vortex variability — as occurs during Northern Hemisphere midwinter, including SSW events — might respond differently to a more quiescent vortex[75,89–91]. The seasonal evolution of the Northern Hemisphere response[83,92–94] is often not captured by models[13,95].

Clarifying the coupling mechanisms between tropical and high-latitude stratospheric winds should help to clarify the efficacy of the polar vortex route (FIG. 2, pathway 4) for generating extratropical surface impacts. However, in addition to this well studied (at least in the Northern Hemisphere) route, evidence is growing that tropical and subtropical pathways can also cause extratropical surface impacts. QBO influence on tropical convection (FIG. 2, pathway 1) can influence the generation of Rossby waves that propagate to higher latitudes, which in turn directly influence extratropical weather systems, including the Aleutian low-pressure region in the North Pacific and the NAO[96]. Given that Rossby waves are the main source of winter stratospheric variability, this pathway can also influence stratospheric polar vortex variability, and hence pathway 4, in either hemisphere[97–99]. Additionally, QBO modulation of the subtropical jet (FIG. 2, pathway 3) could also affect the southern component of the NAO, and affect wave propagation into the winter stratosphere governing the vortex response[100]. The various pathways impacting the tropospheric extratropics are difficult to disentangle, and climate models vary widely in their ability to represent them[25]. A judicious choice of multi-linear regression indices can help to isolate the different pathways[20], but more research is needed to determine which pathways dominate.

Processes and modelling

Increasingly, climate prediction models are being developed to include an internally generated QBO to represent more realistic modes of internal variability at sub-seasonal to seasonal (S2S) and interannual timescales[101]. However, impacts (teleconnections) tend to be weaker in models than is observed[65,102,103], and deficiencies in simulated QBOs could be at least partly responsible[13,95,104]. Simulating a self-consistent QBO in global forecast and prediction models — that is, atmospheric general circulation models (GCMs) — requires accurate representation of a multitude of processes and their mutual interactions, and hence can be considered a sensitive test of model fidelity[10]. QBOs in current models exhibit common biases, suggesting common systematic errors in their representations of the underlying physical processes driving the QBO.

The QBO is forced by wave dissipation (see BOX 1) involving wave scales ranging from global-scale Kelvin waves to mesoscale gravity waves. High vertical resolution (<1 km) is needed in models to capture realistic wave–mean flow interactions of resolved large-scale waves such as Kelvin waves and mixed Rossby and gravity waves[105–110]. As the descent of eastward QBO shear zones is driven by approximately equal parts Kelvin wave and gravity wave forcing, and the descent of westward shear zones is driven primarily by gravity waves, most global models require parameterization of unresolved gravity waves to simulate an internally generated QBO[109,111–116]. Exceptions include research models with specific conditions including: highly active and variable convective rain/latent heating (parameterized and/or resolved); high horizontal resolution; weak implicit and explicit grid-scale dissipation; and high vertical resolution[107,117]. The first two of these conditions are required to generate a broad spectrum of tropical waves[118,119], and the latter conditions are required to support wave propagation without excessive dissipation, allowing waves to get reasonably close to their critical levels[109,120–124]. Most state-of-the-art climate model experiments and even ultrahigh-resolution global models without all four ingredients require specially tuned non-orographic gravity wave drag parameterizations to obtain a QBO[30,32,122]. Simulated QBO-like oscillations are sensitive to small changes in model details such as horizontal and vertical resolution[121–123,125,126], dynamical core[120], location of the model top[127], filtering of upwards-propagating waves by tropical winds below the QBO[121], and the strength of the tropical wave convective sources[110,128]. Therefore, arriving at a simulation of a QBO with realistic period and amplitude in a climate model can be a difficult and time-consuming task. As yet, no consensus exists on what model configuration — and especially, what choice of non-orographic gravity wave drag parameterization and its parameter settings — is optimal for simulating the QBO.

The number of climate models that are able to simulate the QBO has increased in the past two decades. Fifteen models in the sixth phase of the Coupled Model Intercomparison Project (CMIP6) were able to simulate a QBO[32], compared with five models in CMIP5[1]. Although the mean period of the QBO in these models and those participating in the SPARC QBO Initiative (QBOi)[129] is represented quite well, the vertical structure of its amplitude is not: models systematically underestimate the QBO wind amplitude in the lowermost stratosphere (about 50 hPa), and often overestimate it above 10 hPa (FIG. 3). The latitudinal extent of the amplitude tends to be well represented near 10 hPa but underestimated near 50 hPa (REF.[129]). Weak QBO amplitude in the lowermost stratosphere is often manifested by the development of weak westward winds (FIG. 4) and a lack of downward descent of shear zones to the tropopause[47], both of which could be linked with the under-representation of QBO teleconnections in models[95,104]. Insufficient vertical resolution can lead to weak QBO amplitude in the lowermost stratosphere[121,123,125,126], but the reasons for this systematic model error have not been fully clarified.

The finer features of the QBO are not well captured by models. In observations, eastward phases of the QBO descend approximately twice as fast as westward phases, which sometimes stall in the lower stratosphere[130], whereas most models have comparable eastward and westward descent rates, and under-represented (or less pronounced) stalling[1,129]. The vertical depths of QBO phases in models are often shallower than observed[95], possibly owing to errors in descent rate, which could weaken the QBO teleconnection to high latitudes if deep QBO phases are important[131,132]. The variability in the duration and amplitude of individual cycles is less than in observations[129,133], which is probably related to over-reliance on parameterized gravity wave forcing.

The contribution of large-scale equatorial wave modes, such as Kelvin waves, mixed Rossby and gravity waves, and inertia-gravity waves, to the driving of the QBO is generally underestimated by models. The distributions of equatorially trapped waves in the stratosphere with equivalent depths <90 m (zonal phase speeds $|c| < \sim 30\,\mathrm{m\,s^{-1}}$, those most relevant to QBO forcing) generally correspond to sources resulting from tropospheric convection[134]. Only approximately half of the QBOi models showed realistic convectively coupled Kelvin waves and only a few models (4 of 13) have convectively coupled mixed Rossby and gravity waves[110]. Those models with stronger convectively coupled waves and higher vertical resolution tend to produce stronger resolved wave forcing in the QBO region.

Reanalyses can provide observation-based estimates of QBO driving by different equatorial wave modes[115,135,136]. Although tropospheric convection in reanalyses is parameterized and, hence, the sources of resolved waves in reanalyses are somewhat

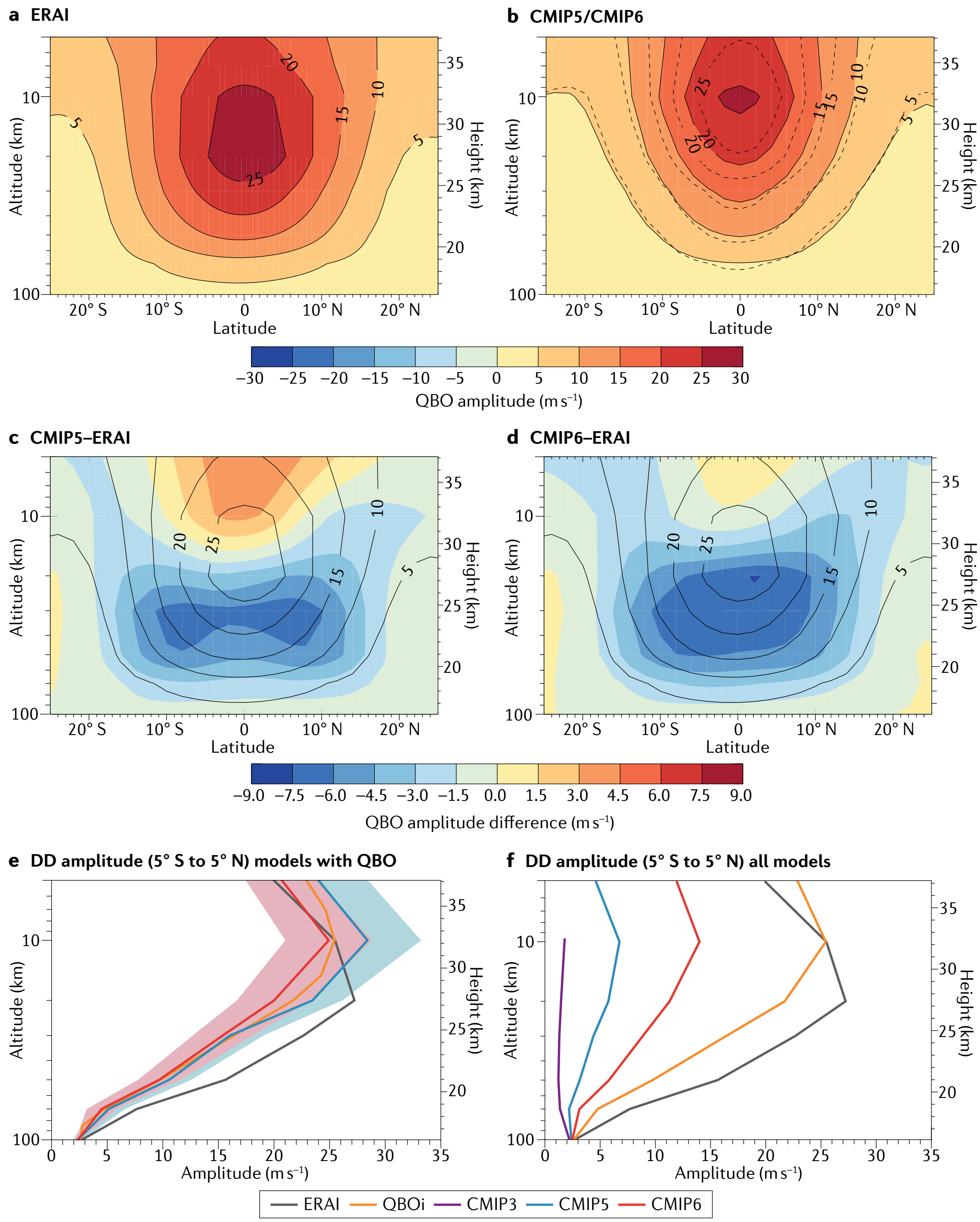


Fig. 3 | **Model biases in tropical stratospheric wind variability.** QBO biases in QBOi, CMIP5 and CMIP6 models[32]. QBO amplitude derived from deseasonalized zonal-mean zonal wind following[2] (DD) for ERA-Interim (ERAI) reanalysis[190] (part **a**), CMIP6 (shading and solid line) and CMIP5 (dotted line) models with QBOs (part **b**), CMIP5 minus ERAI (shading) (part **c**), and CMIP6 minus ERAI (shading) (part **d**). Solid contours in parts **c** and **d** show the ERAI amplitude from part **a** for comparison with the model biases. In part **e** the vertical profile of DD amplitude averaged over 5° S–5° N is for ERAI (black), QBOi models (orange), and CMIP5 and CMIP6 models with QBOs (blue and red). Blue and pink shading represent the ±2 standard error for CMIP5 and CMIP6, respectively (twice the multi-model standard deviation divided by $\sqrt{n}$ for n models). In part **f**, the DD amplitude is averaged for all CMIP5 and CMIP6 models (whether or not they have QBOs) and CMIP3 models (none of which have QBOs; purple line). Reprinted with permission from REF.[32], Wiley.

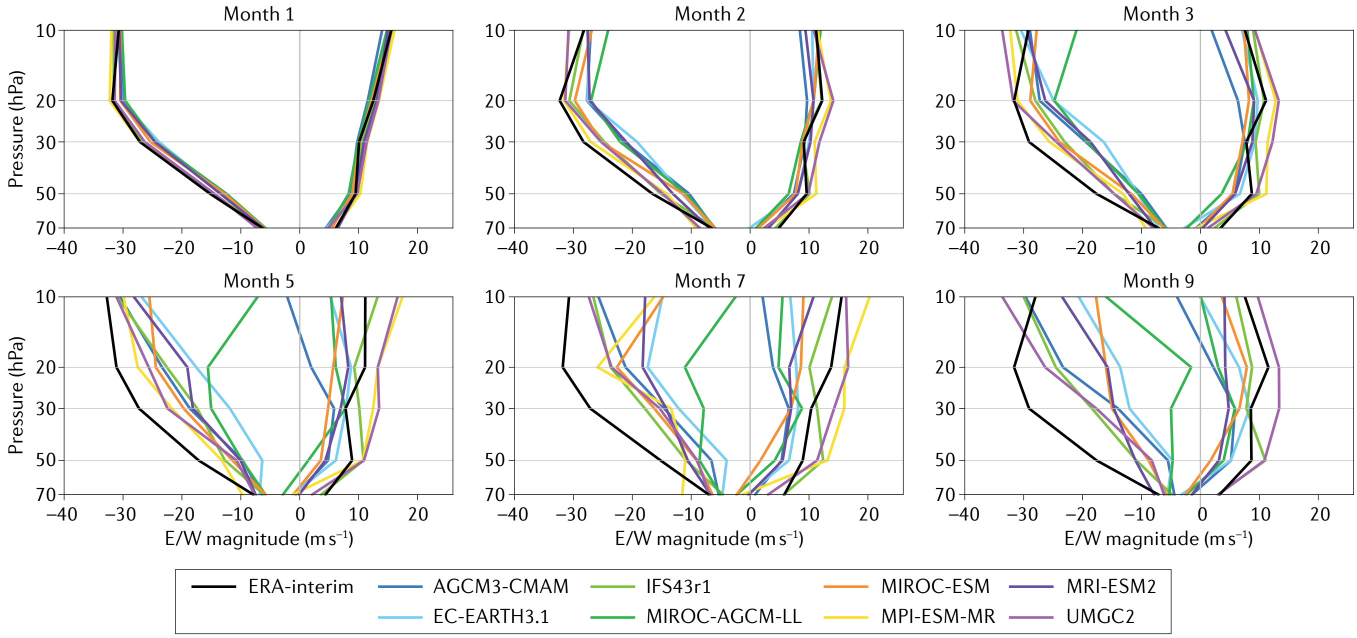


Fig. 4 | **Predictability of QBO evolution affected by model biases.** Westward and eastward monthly mean equatorial wind composited for the cases of the ten strongest analysed monthly mean eastward and westward winds at each level and forecast verification time for hindcasts by QBOi models. Systematic westward wind biases develop with time in a majority of seasonal forecasts. Data analysis follows REF.[47]. Figure reprinted with permission from REF.[32], Wiley (American Geophysical Union).

model-dependent, observational constraints on the large-scale circulation are provided by data assimilation. In particular, stratospheric temperatures are observationally constrained by the assimilation of satellite radiances, leading to reasonable agreement on equatorial wave spectra among modern reanalyses[135], although diagnosed QBO driving can still differ appreciably between reanalyses owing to other modelling issues (for example, vertical resolution). Modern reanalyses agree on broad aspects of the forcing by different equatorial wave modes, such as Kelvin waves driving approximately 50% of eastward phase onsets, and systematic inter-reanalysis differences are generally smaller than the variations between different QBO cycles[43,135,137]. These findings could be consistent with the waves propagating through very similar and realistic background QBO winds in all modern reanalyses, owing to the strong constraint on equatorial winds provided by the assimilation of tropical radiosonde wind observations[138,139], although the timing of QBO phase transitions can differ slightly between reanalyses and eastward phase onsets are often delayed by approximately 1–2 months compared with radiosonde winds[43,139]. Improved assimilation of radiosonde winds has led to dramatic improvements in the quality of QBOs in modern reanalyses compared with earlier generations of global reanalyses[43,140], but the degree to which the highly inhomogeneous spatial coverage of tropical radiosonde stations might bias reanalysis representations of the QBO remains unclear[139,141].

Models using parameterized gravity wave drag with wave sources that are fixed in time and space typically simulate QBOs with less cycle-to-cycle variability and less asymmetry in the descent rates of eastward and westward shear zones than observations and reanalyses[1,129]. Consequently, the QBO can be too regular in such models[46]. Variability in tropical waves, including gravity waves[133,142–146], as well as variations in tropical upwelling[147], lead to period and amplitude variations that make the QBO an irregular oscillation. The ENSO is one source of these variations, and faster QBO phase propagation and weaker amplitude are observed during El Niño conditions[148]; models vary in their ability to reproduce this behaviour[149,150]. Low-latitude volcanic eruptions (FIG. 1b) are another source: aerosol-induced heating warms the tropical lower stratosphere and drives increased upwelling, biasing the QBO towards increased eastward shear and modulating its period, although the exact response depends on the QBO phase at the time of the eruption[151,152]. The response of modelled QBOs to stratospheric sulfate geoengineering is qualitatively similar but model-dependent in its details, as well as depending on the magnitude and latitude of aerosol injection[153–156]. In the case of observed extreme deviations from typical QBO behaviour (circled events in FIG. 1a), anomalous tropical wave activity might have preconditioned the eastward QBO phase to be disrupted by large Rossby wave fluxes from the extratropics during the 2015/16 Northern Hemisphere winter[36,157,158], and substantially weakened the eastward QBO phase during the three months prior to the emergence of 40 hPa westward winds during the 2019/20 Northern Hemisphere winter[38]. The ability of extratropical Rossby waves to interact with the QBO is also sensitive to the subtropical winds[159,160], which are critical for forecasting QBO disruptions[161]. The general lack of QBO disruptions in models is consistent with their QBOs being too regular.

Disruptions aside, skilful predictions of QBO phase out to 3 or 4 years have been demonstrated, and a longer horizon could be feasible if model representation of the QBO's driving processes were to be improved[46,162]. Models do not predict the QBO equally well at all altitudes or for both QBO phases[47,163]. When initialized with realistic winds, models have particular difficulty maintaining the westward QBO phase (FIG. 4), which is driven mainly by small-scale gravity waves. Descent of the westward phase is opposed by tropical upwelling more strongly than during eastward phase descent because the QBO secondary circulation is upward in westward shear[56,164] (FIG. 1b), and substantial uncertainty exists regarding the observed upwelling speed[43] and, hence, whether this speed is well represented in models. The vertical component of the QBO secondary circulation also leads to a QBO in ozone in the lower stratosphere (BOX 2), producing radiative heating anomalies that in turn influence the dynamical evolution. This feedback can alter the duration of QBO cycles[165–167] or increase the QBO amplitude[168] and might increase predictive skill[169].

In summary, simulating the QBO requires high horizontal resolution for realistic tropical convection and a broad spectrum of tropical waves, and also requires high vertical resolution and minimal numerical diffusion to simulate stratospheric waves and wave–mean flow interactions. In lieu of such high resolution, substantial developments in gravity wave parameterization, informed by high-resolution observations, will be needed. Although a wide variety of gravity wave parameterizations and tunings can all simulate a similar realistic QBO under current conditions, the details of the parameterized gravity waves can lead to very different predictions of the response of the QBO to climate change[101,170], as discussed in the next section.

Projected changes

One goal of comprehensive climate modelling is to simulate the response of the climate system to external forcing, with a particular practical focus on understanding and projecting the response to greenhouse-gas-induced global warming. Given that the QBO is an important aspect of climate variability, the question of how the QBO responds to anthropogenic warming has been assessed in various GCM simulations[32,171–176]. Some research included a detailed specification of atmospheric greenhouse gas concentrations based on historical data and standard IPCC future scenarios, and others have compared control simulations with runs using enhanced, typically doubled or quadrupled, CO_2 concentration. A robust aspect of the global warming effect — that is, one that GCMs agree on — is weakening of the QBO amplitude in the lower stratosphere, which is seen in present and future climate simulations running without non-orographic gravity wave parameterization, in which the QBO is driven only by the resolved waves of the models[172]. The weakening of the QBO in these simulations has been attributed to increased mean tropical upwelling in the lower stratosphere, which overwhelms counteracting influences from strengthened wave fluxes associated with increased tropical precipitation in a warming climate[101,172].

Weakening of the QBO appears to be ubiquitous among GCMs that have investigated this issue, including models from CMIP5[174], QBOi[32] and CMIP6[175–177]. The time series of QBO amplitude at 70 hPa (around 9 km) in four CMIP5 models showed a weakening of the QBO between 1.9% and 2.7% per decade in historical simulations continued up to 2100 using the IPCC RCP4.5 scenario[178] (FIG. 5a). The global-warming-related QBO amplitude trends in models with approximately 200-year integrations or in extensive ensembles of integrations can be determined with confidence. Determining the trends in the observed record, which begins in 1953, is much more challenging. The weakening of the QBO amplitude was found with 60 years of near-equatorial radiosonde observations during 1953–2012 (REF.[174]). The black curve in FIG. 5a updates this analysis with the record extended to September 2021. The observed decreasing amplitude trend is $3.5 \pm 3.0\%$ per decade with 95% confidence. This trend is smaller than previously reported by using 1953–2012 data, possibly owing to, in part, somewhat larger amplitude coinciding with two anomalous QBO disruptions in 2015/16 and 2019/20. A negative trend in the 1953–2020 period is different from zero with only 93% confidence using a somewhat different definition for QBO amplitude and a bootstrapping approach to estimating natural variability[176]. Quasi-decadal variability imposed on a long-term decreasing trend is found in both observations and models (FIG. 5a). The 70 hPa trends in the QBO amplitude and mean upwelling in pre-industrial CMIP5 runs with fixed climate forcing are extremely small, indicating that the trends in these models are externally forced[174].

CMIP6 models, which use non-orographic gravity wave parameterizations, project a weakening of the QBO ranging from $5.8 \pm 0.5\%$, $4.3 \pm 0.5\%$ and $2.0 \pm 0.5\%$ per decade at 50 hPa for the SSP585, SSP370 (REF.[179]), and historical simulations, respectively[175] (FIG. 5b). The weakening of the QBO amplitude was also found in simulations of the QBO in doubled and quadrupled CO_2 simulations that were performed by eleven GCMs participating in QBOi[32]. The observed trend in QBO amplitude is significantly negative only in the lower stratosphere (FIG. 5b). On the other hand, data from approximately 200-year simulations of CMIP5[174] and CMIP6[175] models simulating the QBO show weakening trends at all altitudes between 70 and 10 hPa (FIG. 5b). The positive trends at 30–10 hPa in observations disagree with the models, and whether this indicates model deficiencies or the imprint of quasi-decadal natural variability on the observed trends is unclear.

In contrast with the QBO amplitude, no consistent response in the simulated QBO period change in a warming climate occurs among GCMs. Early single-GCMs showed a decrease in QBO period under doubled CO_2 forcing, with the caveat that the degree of shortening is dependent on the prescribed increase in the strength of parameterized GW momentum flux at the source level[171]. However, other GCM experiments without non-orographic GW parameterization[172] or with constant parameterized wave sources[173] suggest that the QBO period might lengthen in a warming climate. In a 60-year observational record no significant trend in QBO period was detected, and the trends are inconsistent in sign among the multi-century CMIP5 model

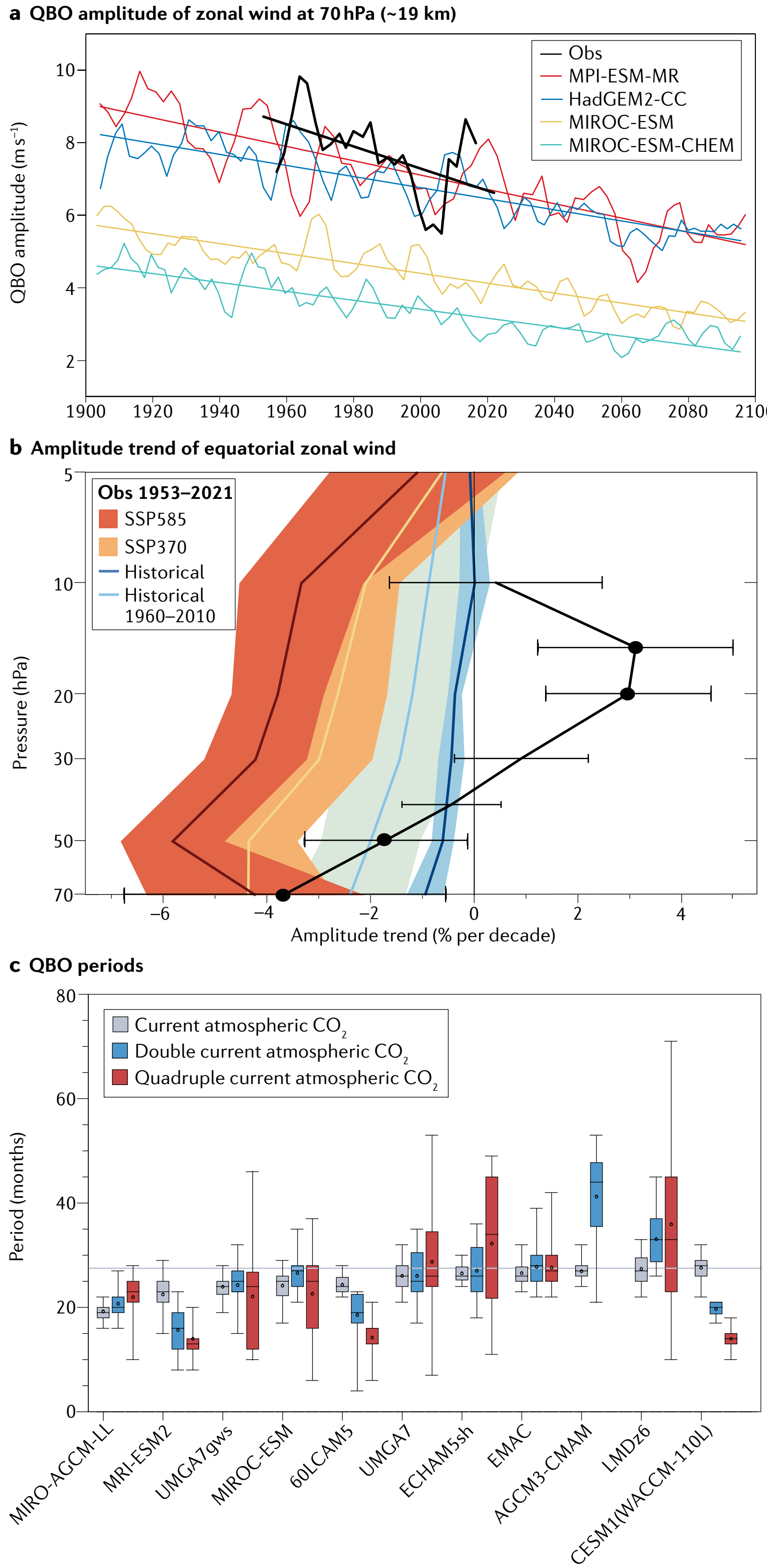


Fig. 5 | **QBO changes under future climate change scenarios. a** | Time variation in the mean QBO amplitude in observations (Obs, black) and four CMIP5 models (colours) at 70 hPa (about 19 km). Observations are radiosonde data provided by FUB[191] (https://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html) from January 1953 to September 2021. CMIP5 output is from historical simulations and future simulations with the RCP4.5 scenario ('business as usual'). The linear regression trends are all statistically significant ($P \leq 0.05$). **b** | The multi-model mean trend (percentage per decade) in QBO amplitude in CMIP6 historical (blue), SSP370 (yellow) and SSP585 (red) simulations and FUB observations from January 1953 to September 2021 (black) as a function of altitude. Shading denotes the uncertainty in the multi-model mean (±2 standard error) and error bars of black lines are ranges of 95% significance (filled circles satisfy 95% significance). **c** | Distribution of QBO periods in the present day (grey), doubled CO_2 (blue) and quadrupled CO_2 (red) simulations from QBOi models[101]. Box edges mark the lower and upper quartiles, box whiskers mark the minimum and maximum values, and black dots represent mean values. Part **a** adapted from REF.[174], Springer Nature Limited. Part **b** is adapted from REF.[175], CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). Part **c** reprinted with permission from REF.[101], Wiley (Royal Meteorological Society).

simulations[174]. The projected QBO period changes in eleven QBOi models range from a decrease of 8 months to a lengthening by 13 months in a doubled CO_2 climate (FIG. 5c). In the quadrupled CO_2 simulations, some models showed a QBO period reduction with periods as short as 14 months, whereas in others a tropical oscillation was no longer easily identifiable[101]. The wide spread in response of the QBO period to warmer climate was also found in the most recent generation of GCMs used in CMIP6[175].

Uncertainty in projections of the QBO is in large part due to uncertainties in gravity wave parameterizations[101,170]. Parameterized non-orographic gravity wave momentum flux at the source level in GCMs is poorly constrained even in present-day conditions and difficult to project in a warming climate. A majority of existing models prescribe a fixed value of gravity wave momentum flux at the source level and hence miss the effects of changing gravity wave sources on the QBO[101]. However, the magnitude of the change of source-level gravity wave momentum flux is a key determinant of whether the QBO period will increase or decrease in a warming climate[101,171]. Several GCMs have implemented gravity wave parameterizations that link the properties of gravity waves to the properties of convection (in the tropics) and fronts (in the extratropics)[143,145,180]. These parameterizations were developed to capture the effects of changing gravity wave sources not only on the QBO but on other aspects of the middle atmospheric circulation. However, three QBOi models with source-dependent gravity wave parameterizations showed vastly different changes to gravity wave momentum flux at the source level with doubled and quadrupled CO_2, and very different changes to the QBO in these simulations[101]. Hence, reducing uncertainty in gravity wave parameterizations is crucial to reducing the uncertainty in the projections of the QBO period in the warming climate.

Uncertainty in QBO projections can also arise from deficiencies in representation of large-scale tropical waves in GCMs, as well as the shortcomings of other model elements such as resolution and dynamical core. Large-scale tropical waves are likely to change in a warming climate owing to changes in tropospheric convection and latent heating[181]. However, because the generation of Kelvin and mixed Rossby and gravity waves is often underestimated in GCMs[110] (see section 'Processes and modelling'), changes to these waves in a warming climate as represented in models are quite uncertain[101].

If weak QBO amplitude in the lowermost stratosphere is a source of error for teleconnections, the observed amplitude trend suggests that teleconnections might weaken in the future. However, evidence exists that QBO impacts on the extratropics in the Northern Hemisphere winter could strengthen under climate change[177,182,183]. Although future changes in stratospheric vortex variability are not robust across models and should be treated with caution[184], the multi-model mean of 20 CMIP5/6 climate models shows a strengthened QBO influence on the Northern Hemisphere winter stratospheric vortex and a strengthened surface impact in the Atlantic (however, not all models agree on the sign of this change)[177]. In the tropics, the emergence of the QBO–MJO linkage has been suggested to be caused by climate change[51], although this is difficult to verify because current climate models generally do not capture this teleconnection[104].

Summary and future perspectives

The QBO is an exceptionally long-duration mode of atmospheric variability that affects the predictability of other phenomena such as the stratospheric polar vortex and the MJO. Accurate modelling of the QBO and its impacts could provide societal benefits by realizing this predictability. Many more climate and forecasting models are now able to represent the QBO, largely owing to the inclusion of parameterizations of small-scale tropical waves. However, the overall quality of these simulated QBOs has not substantially improved, and models show common biases, including persistently weak QBO amplitude in the lowermost tropical stratosphere. Future projections by climate models consistently show the QBO amplitude weakening under increased greenhouse-gas forcing, and observations show a weakening of QBO amplitude at lower altitudes (about 70 hPa). Two disruptions of the QBO have occurred, during the Northern Hemisphere winters of 2015/16 and 2019/20, which are unprecedented in the observational record that started in 1953.

Further advances in understanding and simulating the QBO will require better quantitative knowledge of how the real QBO is forced by the whole spectrum of atmospheric waves, from small-scale gravity waves up to planetary-scale modes. In the canonical model, all waves with zonal phase speeds within or near the range of QBO wind speeds can drive the QBO, and so a QBO may occur in a numerical model even if the tropical wave spectrum (the mix of different wave types driving the QBO) is unrealistic. However, the precise mix of driving waves can affect important details such as the QBO's vertical extent or its sensitivity to climate forcings such as ENSO or changing greenhouse gas concentrations. Simulating a realistic QBO for realistic reasons requires the reduction of the quantitative uncertainty in the forcing contributions by different wave types.

Increasing the horizontal resolution of models can help by improving the representation of the wide spectrum of tropical wave sources, although this is not guaranteed, because tropical convection can be model-dependent even as resolutions of about 10 km or finer are approached[185]. The vertical resolution in the lower stratosphere sufficient to realistically represent the mechanisms causing stratospheric dissipation of the waves remains unclear[126]. Analyses of novel observational datasets such as long-duration balloon flights[124,186] and lidar satellite wind observations[187] can help to address these questions by providing better observational constraints on the waves driving the QBO. These constraints should narrow the range of physically defensible parameter values used in non-orographic gravity wave parameterizations. Weak constraints allow modellers substantial freedom to adjust these parameters, such as by tuning a model's average QBO period to be about 28 months. However, the pervasive model bias towards weak QBO amplitude in the lowermost stratosphere (about 50 hPa), which has not improved in the most recent generation of climate models (CMIP6), suggests that optimizing the vertical structure of the amplitude is more challenging than merely optimizing the QBO period. Understanding the origins of errors in QBO vertical structure (and why it is less amenable to tuning than the QBO period) is a priority for future research.

A greater understanding of the modelling sensitivities of the QBO, and improved observational constraints on gravity wave parameterizations, could create more confidence in future projections of QBO behaviour. Gravity wave parameter settings tuned to achieve a realistic QBO period in the present-day climate might not be valid in a changed climate, leading to non-robust projected changes in QBO period. The projected weakening of QBO amplitude is robust, but the vertical structure of QBO amplitude trends differs between observations and models. Whereas models project decreasing QBO wind amplitude at all altitudes in response to global warming, the 69-year radiosonde record shows a negative amplitude trend with highest significance in the lowermost stratosphere (about 70 hPa) but a positive trend at higher levels (about 20 hPa) (FIG. 5a). This discrepancy might be due to natural variability obscuring the true forced response in the real atmosphere, although the statistical significance of observed trends suggests that this is unlikely. Understanding the origin of the pervasive present-day model biases in QBO vertical structure could elucidate how those biases might affect future projections.

The consequences of QBO biases in models of the simulation of QBO impacts remain unclear. Observed tropospheric teleconnections tend to be most significant when QBO winds at lower levels (for example, 50 hPa) are used as predictors. Given that models systematically underestimate the QBO amplitude at these lower levels, reducing their biases could improve the simulation of teleconnections, which are often found to be weak in models[25,95,103,104]. Complicating the issue is that multiple pathways (mechanisms) for QBO teleconnections are plausible, the dominant pathways are not yet clear, and a single pathway might not dominate. Depending on the relevant pathways, other model biases — for example, biases in the strength and position of tropospheric jets or the spatio-temporal variability of tropical deep convection — could also affect simulated teleconnections[188]. A promising approach to disentangling these questions is to bias-correct model QBOs by nudging them towards observations (this refers to artificially constraining a model by adding a forcing term that relaxes its equatorial winds towards observed winds) so that teleconnections can be compared across different models that have the same unbiased QBO winds, but differ in their other biases. Such experiments will help to determine what aspects of the QBO, as well as other aspects of the climate system, need to be improved in order to simulate QBO impacts accurately.

Realizing the QBO's potential benefits for improving forecasting on sub-seasonal, seasonal and decadal timescales will depend not only on accurate simulation of its teleconnections but also, of course, on predicting the QBO itself. The QBO's most notable feature is its extremely long timescale, and skilful predictions out to several years might be possible using GCMs[46,162,169]. The impact of model biases on QBO predictability should be investigated further. A promising approach is to run QBO-resolving climate models in hindcast mode — that is, to initialize the models with realistic QBO winds — to test the validity of their modelling assumptions and process representations (for example, parameterized wave driving)[47]. An important outstanding question concerns how well the onset of the disruptive events resembling the evolution of tropical stratospheric wind during the 2015/16 and 2019/20 Northern Hemisphere winters can be predicted.

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Author contributions

S.M.O. led the writing of the first draft. J.A.A. led the revisions and reviewer responses. All authors individually led the compilation of specific sections, figures and boxes within the manuscript. All authors contributed to researching data for the article, discussion of content, writing the article and reviewing/editing the article before submission.

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