

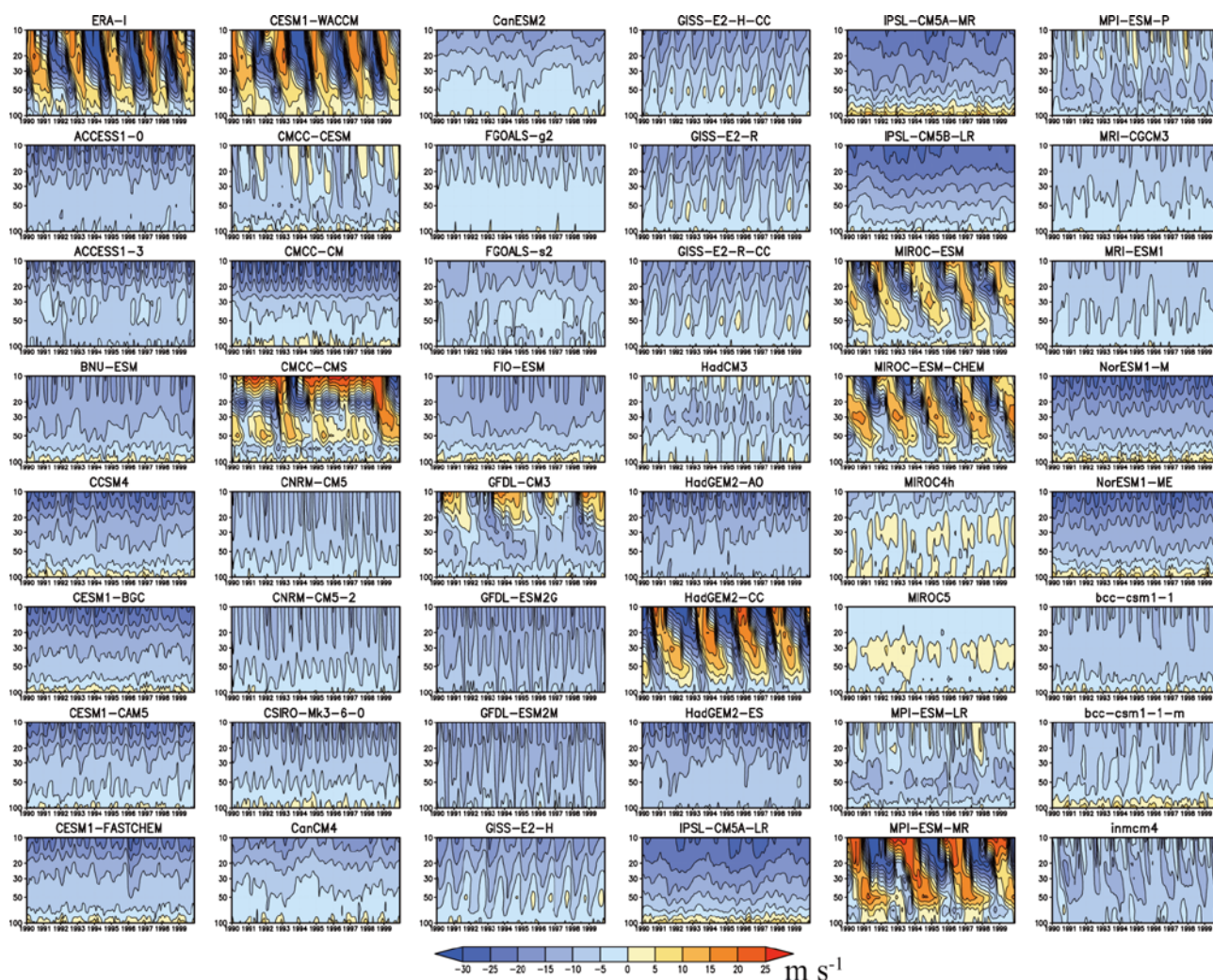
## Improving the QBO in climate models

James Anstey<sup>1</sup>, Neal Butchart<sup>2</sup>, Kevin Hamilton<sup>3</sup>, Scott Osprey<sup>4</sup>, Andrew Bushell<sup>5</sup>, Laura Holt<sup>6</sup>, Yaga Richter<sup>7</sup>, Anne Smith<sup>7</sup> and Tim Stockdale<sup>8</sup>

<sup>1</sup>Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, Canada ([james.anstey@canada.ca](mailto:james.anstey@canada.ca)), <sup>2</sup>Met Office Hadley Centre, Exeter, UK ([neal.butchart@metoffice.gov.uk](mailto:neal.butchart@metoffice.gov.uk)), <sup>3</sup> Department of Atmospheric Sciences, University of Hawaii, Honolulu, HI, USA and International Pacific Research Center (IPRC), Honolulu, HI, USA, <sup>4</sup> National Centre for Atmospheric Science, University of Oxford, Oxford, UK ([scott.osprey@physics.ox.ac.uk](mailto:scott.osprey@physics.ox.ac.uk)), <sup>5</sup> Met Office, Exeter, UK, <sup>6</sup> NorthWest Research Associates, Boulder, USA, <sup>7</sup> National Center for Atmospheric Research, Boulder, USA, <sup>8</sup> European Centre for Medium-Range Weather Forecasts, Reading, UK.

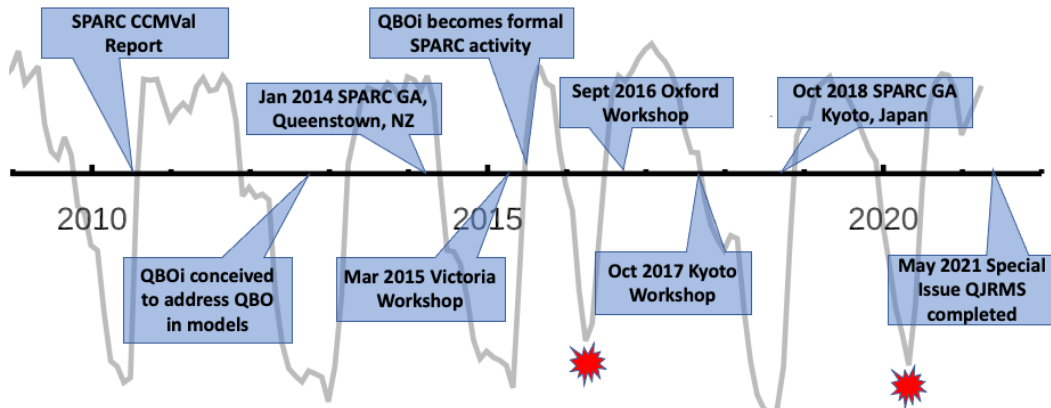
Climatic impacts of stratospheric variability and long-term change are routinely evaluated in coordinated community efforts such as the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP) supporting Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, and the World Meteorological Organization (WMO) Ozone Assessments. The large observed interannual variability of the tropical stratosphere affects distributions of con-

stituents such as water vapour and ozone and impacts regional surface climate via teleconnections. Ten years ago most of the models being used to support the IPCC and WMO assessments could not properly represent such impacts due to the absence or poor representation of the quasi-biennial oscillation (QBO; see Figure 7). To address this the Quasi-Biennial Oscillation initiative (QBOi) was conceived in 2012 to advance understanding of the QBO and the accuracy of its representation in models.



**Figure 7:** Tropical stratospheric winds in climate models at the time QBOi was conceived. Ten years (1990–1999) of equatorial vertical profiles (10–100 hPa) of zonal-mean zonal wind in 47 CMIP5 models, and ERA-Interim reanalysis at top right. CESM1-WACCM is nudged to observations. From Butchart et al. 2018.

## QBO & QBOi Milestones



**Figure 8:** Time series of the 40hPa equatorial wind with the key developments in the life of the QBOi activity marked on the same timeline. The two QBO disruption events during the Northern Hemisphere winters of 2015/16 and 2019/20 are marked with red stars.

In 2015 QBOi became a SPARC activity and the first phase began in March 2015 with a kick-off workshop in Victoria, Canada. Phase I has now concluded with a set of multi-model studies published in a Special Section of the Quarterly Journal (QJ) of the Royal Meteorological Society. In this article we give a brief overview of phase-I scientific findings, focusing on those aspects that motivate the sec-

ond QBOi phase. This new phase has just started and will examine the causes of the biases identified in phase I and the effects of these biases on QBO impacts.

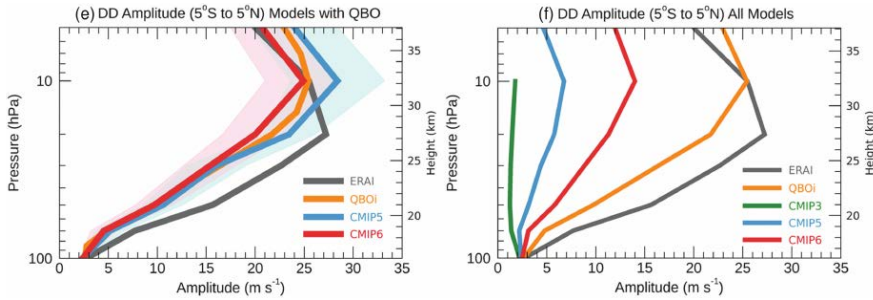
From the outset QBOi has been community-driven, with coordinated experiments and analyses developed over a series of workshops (Figure 8). Experiments for phase-I were agreed at the Victoria workshop and the lead authors for the core multi-model analyses were identified at a September 2016 workshop in Oxford, UK. Phase I was extended to include investigations of El Niño-Southern Oscillation (ENSO) impacts in October 2017 at the FISAPS/QBOi/SATIO-TCS joint SPARC workshop in Kyoto, Japan. Finalization of phase-I core analyses and preparatory discussions for phase-2 took place at the QBOi side meeting of the 2018 SPARC General Assembly, also in Kyoto.

Breakout group discussions at the workshops proved essential to moving the activity forward and helped prioritise scientific questions that could be usefully addressed using the multi-model ensemble such as:

- Are modelled QBOs realistic? Are there common biases?
- How might the QBO change under increased greenhouse gas concentrations?
- Is the QBO accurately predicted by initialized models?
- How well do models represent the equatorial waves that drive the QBO?
- Do models capture the observed linkages between the QBO and other regions (teleconnections)?

Model	Institutes	Investigators
60LCAM5	NCAR	J. Chen, J. Richter
AGCM3-CMAM	CCCma U. Toronto	J. Anstey, J. Scinocca C. McLandress
CESM1-(WACCM5-110L)	NCAR	R. Garcia, J. Richter
EC-EARTH3.1	BSC	J. Garcia-Serrano
ECHAM5sh	ISAC-CNR	F. Serva, C. Cagnazzo
EMAC	KIT	P. Braesicke, T. Kerzenmacher, S. Versick
HadGEM2-A	Ewha W. U. Yonsei U.	Y.-H. Kim H.-Y. Chun
HadGEM2-AC	Ewha W. U. Yonsei U.	Y.-H. Kim H.-Y. Chun
IFS43r1	ECMWF	T. Stockdale
LMDz6	IPSL-LMD	F. Lott
MIROC-AGCM-LL	MIROC	Y. Kawatani
MIROC-ESM	MIROC	S. Watanabe
MPI-ESM-MR	MPI U. Hamburg	H. Pohlmann M. Dobrynin
MRI-ESM2	MRI-JMA	K. Yoshida, H. Naoe, S. Yukimoto
UMGA7	Met Office MOHC U. Oxford	A. Bushell N. Butchart S. Osprey
UMGA7gws	Met Office MOHC U. Oxford	A. Bushell N. Butchart S. Osprey
UMGC2	MOHC	A. Scaife, M. Andrews

**Table 1:** Models, institutes and investigators participating in QBOi phase-I by running and providing output from the coordinated experiments. Adapted from Table 5 of Butchart et al. 2018.



**Figure 9:** Root-mean square amplitude of tropical wind variability in the ERA-Interim reanalysis and QBOi and CMIP multi-model ensembles. Averaged over the full ensemble, simulated tropical stratospheric variability has improved over time (right panel), but when the average includes only those models with QBOs, there is no discernible improvement (left panel). From Richter et al. 2020b.

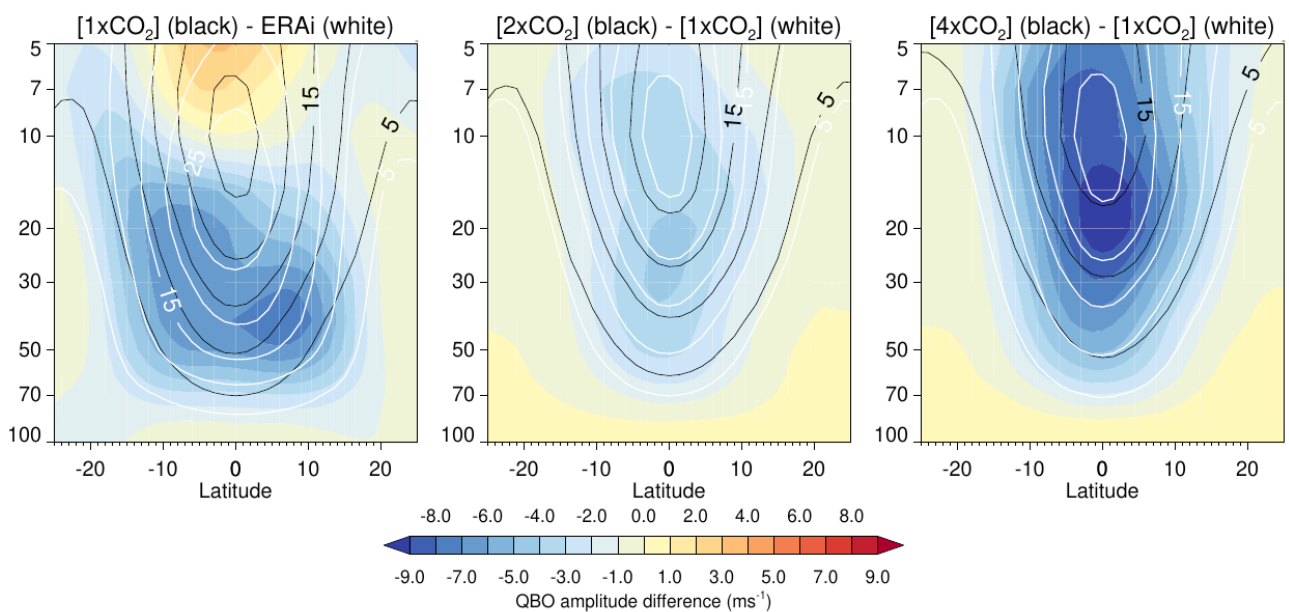
By the time of the Victoria workshop the number of global models exhibiting spontaneous QBO-like oscillations had increased sufficiently to allow a meaningful model intercomparison to address the above questions. Models that took part in this intercomparison (QBOi phase I) are listed in Table I. For the latest CMIP phase (CMIP6) there was a further increase in the number of models featuring QBO-like oscillations. Yet although QBOs are now more common in climate models, their overall quality has not improved (Figure 9), indicating a need to understand and address the common biases identified in the QBOi phase-I model intercomparison.

### Present-day simulations

Perhaps the most distinctive feature of the QBO is its long period of ~28 months. The period is

often well represented in models, but this can usually be accomplished by tuning the parametrized non-orographic gravity wave drag (GWD) that represents QBO forcing due to small-scale waves generated by tropical convection. Such tuning is justified by the large observational uncertainty in the forcing contribution from these waves. Capturing the vertical structure of the QBO appears to be more difficult. In the 10 km above the tropical tropopause the QBO amplitude is, on average, unrealistically weak in successive generations of models (Figure 9). Underestimates of around 50% near 50 hPa are common. Potentially this limits the accuracy of teleconnections that are sensitive to the QBO winds at these altitudes. These include the QBO teleconnections to the Northern Hemisphere polar vortex in the winter stratosphere, the subtropical jet, and the Madden-Julian Oscillation. The ubiquitous amplitude bias in the lowermost stratosphere suggests a pervasive problem in tuning wave parameterizations to allow the models to simulate both adequate amplitudes and the correct QBO mean period.

Another pervasive error is that the simulated QBOs are too narrow in latitude at lower altitudes (Figure 10).



**Figure 10:** QBO zonal-mean zonal wind amplitude as a function of latitude and altitude for the QBOi multi-model ensemble (MME). Left panel: MME-mean present-day experiment (black lines), ERA-Interim reanalysis (white lines), and their difference (filled contours). Centre and right panels: as left panel, but white lines are present-day and black lines are 2xCO<sub>2</sub> and 4xCO<sub>2</sub> experiments, respectively. Amplitudes are calculated as in Figure 9.

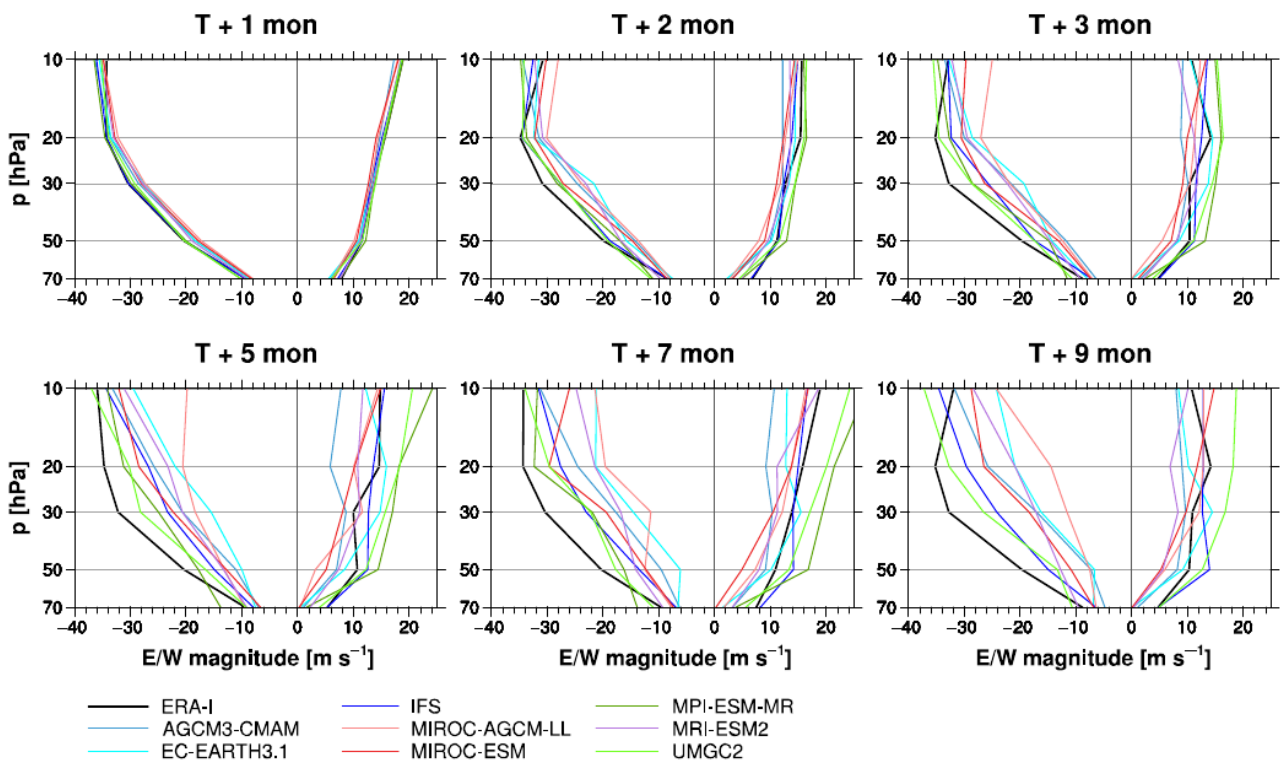
Since the westward phase is observed to be meridionally broader than the eastward phase this suggests that the low altitude amplitude biases may be linked more to that phase. The models have particular difficulty maintaining the strength of the westward QBO phase at these altitudes, as evidenced by its rapid decay in simulations initialized from reanalysis (Figure 11). Forcing of westward QBO winds is believed to come mainly from small-scale gravity waves. At resolutions typical of current climate models, the bulk of this forcing must be parametrized, although resolved waves also contribute. Dissipation of resolved waves is known to be sensitive to vertical resolution, and this is evident across the QBOi ensemble for both eastward and westward waves (Figure 12). Hence the resolved wave forcing is likely too weak in at least some of the models. However, given the amplitude biases this shortfall is clearly not being compensated by the parametrized waves. Understanding why is an important objective for QBOi phase 2.

### Projecting the future

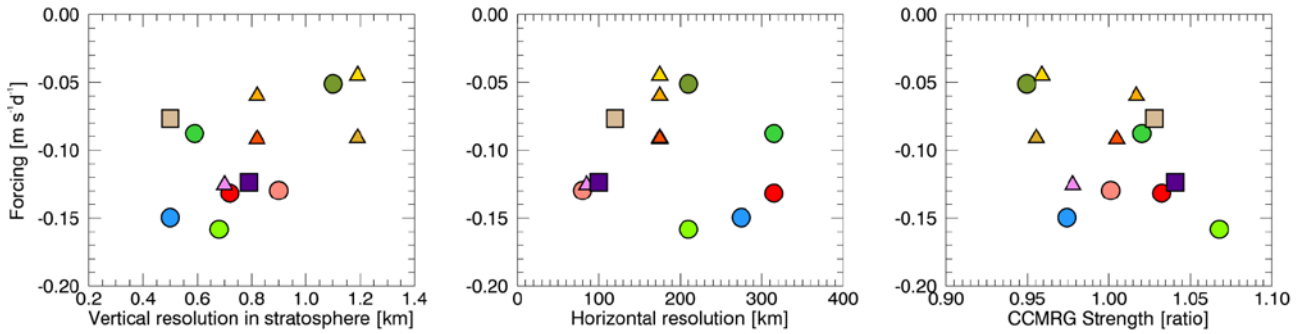
Future changes to the QBO are relevant for surface climate because of its teleconnections, for instance to the North Atlantic Oscillation. Also, because of its regularity and prominent signal, any changes in the QBO are potentially a powerful indicator (fingerprint) of a changing climate, provided that the response is

independent of the tuning. It has become evident that a robust prediction by climate models is a slowing down of QBO wind speeds. The response of QBO wind amplitude to doubled and quadrupled CO<sub>2</sub> concentrations is seen in Figure 10. Weakening amplitude is not only predicted by the QBOi models, but also by CMIP5 and CMIP6 models. Arguably this, and a speeding up of the Brewer-Dobson circulation, are among the few robust changes to the general circulation that have been obtained to date from model climate projections.

Consensus suggests confidence, but caution is warranted: according to these same models, other aspects of the QBO's future behaviour are highly uncertain. Increased CO<sub>2</sub> concentration causes a longer QBO period in some models, but a shorter period in others. In some models the oscillation becomes erratic, or retreats to higher altitudes, or even ceases. Why such varied projections? Possibly the tuning of the GWD parametrizations is only valid for a narrow range of climates and therefore there is work to be done on improving the parametrizations or reducing the dependency on them. Consequently, the models almost certainly lack predictive power when applied outside of the present-day climate forcing conditions under which models are developed and tuned. In this respect the diverging future projections have provided a useful test of modelling assumptions (*i.e.*, tuning).



**Figure 11:** Eastward and westward equatorial zonal-mean zonal wind in QBOi models, composited at each altitude for the 10 cases of strongest eastward and westward reanalysis wind at the hindcast verification time. From Stockdale et al. 2020.



**Figure 12:** Resolved westward wave forcing at 26-10hPa (26-32 km), 10S-10N in QBOi models vs. (a) vertical resolution at 20-25 km, (b) horizontal resolution, (c) convectively coupled mixed Rossby-gravity wave strength. Figure 18 of Holt et al. 2020 shows the corresponding plots for eastward waves.

Verification of future QBO projections could take some time (i.e., many cycles of  $\sim 28$  months), so any confidence in them will have to rely more on the knowledge that the models can accurately represent the QBO mechanisms in the present.

### Predicting the present

Understanding the dependency on choice of model parameters and configuration is complicated by the strong coupling between zonal-mean flow and waves that characterizes the QBO: the waves induce the mean flow to change direction, while the mean flow controls wave propagation and dissipation. Faced with a chicken-egg problem, predictions initialized from reanalysis data are a valuable tool because they allow processes influencing the QBO to be examined under realistic mean-flow conditions before biases develop. Because of the QBO's slow timescale, biases take a few months to reassert themselves - as the hindcasts by QBOi models in Figure 11 showed - and before they do, the resolved and parametrized waves respond to realistic QBO shear zones. In the first month of the QBOi model hindcasts, the strength of westward GWD forcing near 50 hPa is roughly half of that inferred from reanalysis, consistent with the models' inability to maintain westward QBO phases (Figure 11).

An important question is to what extent do mean-flow biases limit the skill of QBO predictions on seasonal-to-decadal timescales? All of the QBOi hindcasts show high skill at predicting the 20-30 hPa QBO winds, but no single model performs well at all altitudes - reinforcing the contention that models have difficulty in accurately capturing the QBO's vertical structure. Possibly greater skill could be achieved by reducing the common systematic errors shared by the models, though further investigation will be required in phase 2 to confirm this.

### Disruptions

The forecasting potential implied by the QBO's exceptionally long (28 month) timescale mainly comes about through its regional impacts. However, the occurrence of two recent disruptions to the QBO - during the NH winters of 2015/16 and 2019/20 (Figure 8) - suggests the QBO could be less predictable than previously thought. Hence it is important to understand the conditions under which the QBO's usual cycling breaks down. Based on the two observed disruptions, these conditions include strong forcing by equatorward-propagating Rossby waves. In the extratropics, from where these waves originate, the predictability timescales are much shorter (typically  $< 1$  month) than in the tropics. Therefore, a strong extratropical influence on the QBO could limit its predictability, if disruptions become more common.

With only two observed events it is hard to draw definitive conclusions about their causes or rarity, though their appearance in the last 5 years following 60 years of QBO observations without disruption raises the question of whether they are becoming more likely. These questions could be difficult to answer using the current models, as a significant finding of QBOi phase-I was that most models were unable to capture the observed variability of the QBO in the 60 years prior to disruptions. One reason for this could be that the parametrized GWD is not directly linked to deep convection in most of the models. The models also show significant amplitude errors near 40 hPa, the altitude at which shallow westward jets emerged during both of the observed disruptions.

### Moving forward

QBOi was conceived as a community effort to improve the representation of the QBO in climate models. We expect this to enable better representa-

tion of QBO impacts (teleconnections) and more skilful QBO predictions. Phase 1 revealed model biases that could degrade QBO teleconnections, potentially explaining why they are usually weak or absent in models. Phase 2 will test this with nudging experiments that bias-correct the tropical stratospheric winds. This will provide insight into what aspects of the QBO are important for its teleconnections. Using the same experiments, the behaviour of resolved and parametrized waves in the presence of realistic QBO winds will be examined. This will help identify the causes of QBO biases, and determine where further model development is needed to reduce the biases. Disruptions were not anticipated when the phase-I experiments were designed, but reducing QBO biases would likely benefit modelling studies of these events. Improving the models is expected to improve confidence in future projections of QBO behaviour.

Compared to previous generations of climate models, simulated QBOs are now relatively common, but have not substantially improved in accuracy. The QBO results from a sensitive balance of many atmospheric processes including tropical deep convection, a broad spectrum of tropical waves, vertical advection by the Brewer-Dobson circulation, radiative feedbacks (e.g., from ozone heating), and in light of the recent disruptions, large-scale waves from the extratropics. Incorporating all this complexity is a reason why comprehensive climate models are valuable for understanding the QBO and its interactions with other parts of the climate system. The complexity also means that simulating the QBO is a sensitive test of models, as many different processes must be represented accurately in order to realistically simulate the QBO. In the context of Earth System Model development, particularly as increasing horizontal resolution reduces models' dependence on parametrized tropical convection, this makes simulating the QBO a useful test case for stratosphere-resolving climate models. The two recent disruptions are a reminder that nature can be surprising. But better predictions could be on the cards with the expected improvements such as increased resolution with the next generation of models.

### Participation

Interested scientists are welcome to participate in QBOi. For more information please contact the QBOi coordinators:

James Anstey ([james.anstey@canada.ca](mailto:james.anstey@canada.ca)),  
Neal Butchart ([neal.butchart@metoffice.gov.uk](mailto:neal.butchart@metoffice.gov.uk)),  
and Scott Osprey ([scott.osprey@physics.ox.ac.uk](mailto:scott.osprey@physics.ox.ac.uk)).

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- Smith *et al.* 2019: [The equatorial stratospheric semiannual oscillation and time-mean winds in QBOi models](#). *QJR Meteorol Soc.* 2020; 1 - 17.
- Stockdale *et al.* 2020: [Prediction of the quasi-biennial oscillation with a multi-model ensemble of QBO-resolving models](#). *QJR Meteorol Soc.*, 1 - 22.

### Workshop reports

March 2015, Victoria, Canada: SPARC Newsletter no. 45 (July 2015)

September 2016, Oxford, UK: SPARC Newsletter no. 48 (January 2017)

October 2017, Kyoto, Japan (joint with the FISAPS and SATIO-TCS activities): SPARC Newsletter no. 50 (February 2018)