INFO-QBO: INvestigating the Feedback from Ozone in the Quasi-Biennial Oscillation

Abstract The Quasi-Biennial Oscillation (QBO) is the main source of year-to-year variability in the tropical stratosphere with far reaching teleconnections to other parts of the climate system from extratropical variability to tropical convection. Historically it has exhibited a remarkably regular period of ~28 months, but recent, unprecedented disruptions indicate this periodicity may be fragile. It has long been recognized that radiative and dynamical feedbacks from stratospheric ozone can impact the QBO but a clear mechanistic description is still lacking. Moreover, simulating a realistic QBO in climate models is still challenging and many numerical models only include a simplified version by nudging their tropical winds to observations.The ozone feedback on the QBO has been examined mainly in the context of recent historical climate, with one recent study on the future changes in response to an increase in carbon dioxide. A review of the literature reveals *large uncertainties* in the magnitude of the ozone feedback on both the QBO period and amplitude. A new international model intercomparison project has recently been launched to study ozone–QBO feedbacks with data expected by the end of 2024. *The main aim of this team is to use high-resolution satellite observations of tropical stratospheric temperature and composition to assess the representation of ozone-QBO feedbacks and associated dynamical processes in these new model runs.* The outcome of this activity will improve our understanding of the interactions between composition and the QBO, contributing to improving the fidelity of future model projections of the QBO and its teleconnections.

Scientific rationale The Quasi-biennial Oscillation manifests as a pattern of alternating eastward and westward winds that descend from roughly 40 km to 17 km, with a period of about 28 months, Figure 1(a). It dominates the variability of the tropical stratosphere (Baldwin et al. 2001). The QBO has broad effects on the circulation and composition of the stratosphere (Punge et al 2009; Diallo et al 2018; Diallo et al 2022), and influences surface weather and climate in both the tropics and the extratropics (Gray et al. 2018, Butler et al., 2019; Anstey et al. 2021). For example, in surface temperatures these effects can be regionally as strong as 2K, i.e., as strong as climate change scenarios (Marshall and Scaife, 2009).

The remarkable predictability of the QBO (Scaife et al. 2014), along with its far-reaching impacts on the climate system, make its representation in global climate models critical. Moreover, observations indicate that the amplitude of the QBO has changed significantly in the last decades (Kawatani and Hamilton 2013), and the recent disruptions (Osprey et al. 2016, Anstey et al. 2021) further raise prospects of further changes in its behaviour. However, obtaining an accurate representation of the QBO in a global climate model remains a major challenge, and models often produce divergent projections of how the QBO might respond to perturbations (Butchart et al 2018). Understanding and modelling the processes that drive the QBO is thus critical to improving the predictability of both surface weather and climate (Marshall and Scaife, 2009).

The basic dynamic framework describing the interaction between waves and mean-flow in the QBO is well established (Baldwin et al., 2001 and references therein). It has also long been recognised that ozone feedbacks impact the QBO period, amplitude and response to perturbations (Gray and Pyle, 1989; Li et al., 1995; Shibata, 2021). Nonetheless, large uncertainties remain. For example, while several studies show that ozone feedbacks result in a longer QBO period by ~10% (Butchart et al., 2003; DallaSanta et al., 2021) or more (Shibata and Deushi, 2005), other studies show smaller (Cordero et al., 1998) and nearly negligible impacts on QBO period (Cordero and Nathan, 2000). Similar disagreements exist for the temperature amplitude change (Butchart et al., 2003; DallaSanta et al., 2021; Shibata and Deushi, 2005). There is a critical need for a holistic assessment of ozone feedbacks in state-of-the-art chemistry climate models, validated against up to date satellite observations of the structure and composition of the QBO. This proposal aims to address these multifaceted difficulties.

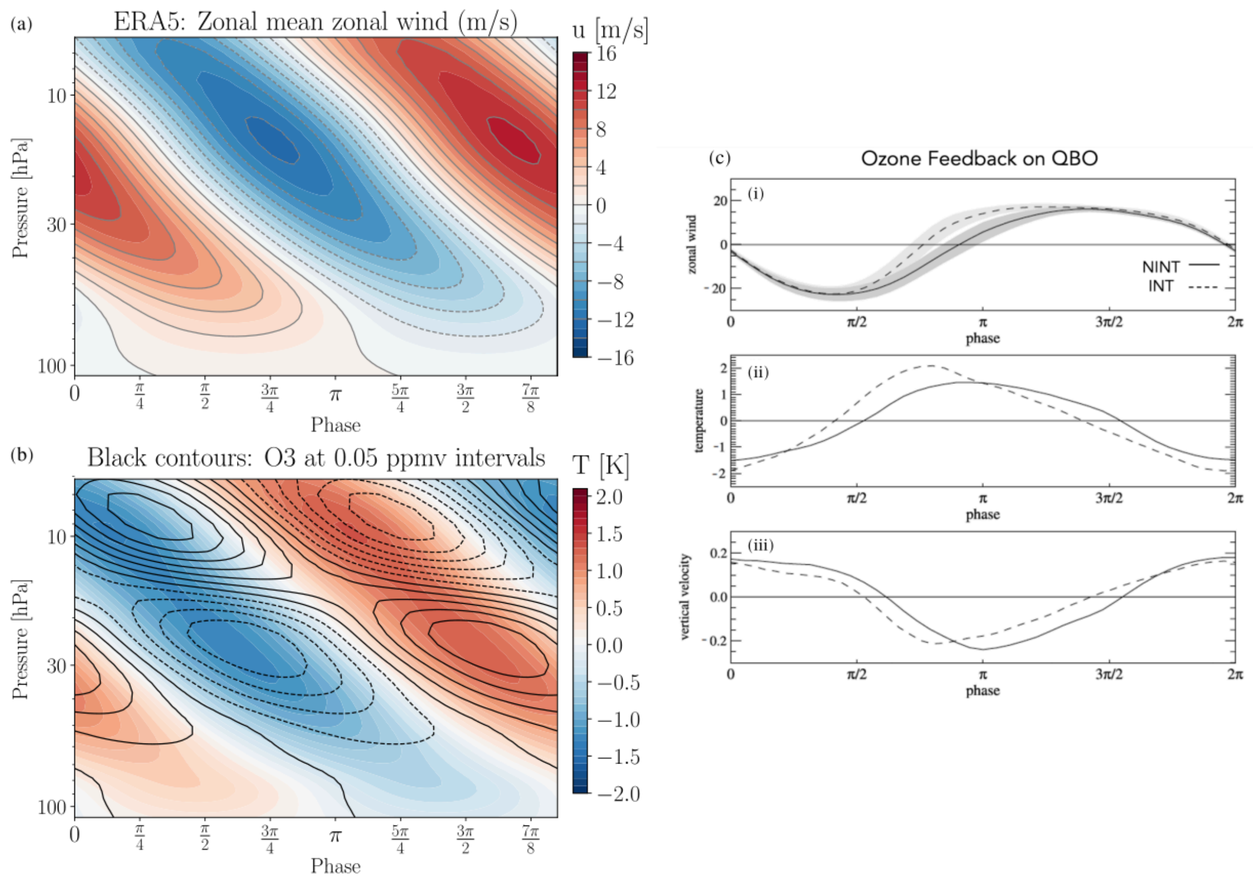

Figure 1: All plots show one oscillation of the QBO (a) Zonal mean zonal wind leading QBO principal oscillation pattern (POP) from ERA5 reanalysis data averaged between 5N-S, 1979 to 2023 (b) Coloured contours show temperature POP from ERA5. Black lines show ozone POP from the merged satellite dataset SWOOSH. (c) Figure adapted from Butchart et al (2003) showing comparisons of the (i) zonal mean zonal wind (ii) temperature and (iii) vertical residual velocity between simulations using specified (NINT, solid line) versus coupled (INT, dashed line) ozone.

Firstly, whilst we now have high quality satellite, radiosonde and novel reanalysis datasets of trace gases and temperature that span many QBO cycles, we do not have a methodology to assess from these observations the nature of the ozone feedback on the QBO.

Secondly, only a few state-of-the-art climate models are able to spontaneously generate a QBO and even then, the phase, strength and downward extent differ significantly from observations (Richter et al., 2022). Only 15 of 30 such models used in the latest Intergovernmental Panel on Climate Change report have any sort of QBO (and only about 7 include interactive chemistry). Amongst the models that do simulate a QBO, none capture the observed QBO phase and amplitude in the lower stratosphere. It is also clear that models with interactive and non-interactive chemistry show different QBO behaviours in the current climate, Figure 1(c). Furthermore, there is no consistency in predictions of how the QBO behaves under a doubling of carbon dioxide. In addition, Butchart et al. (2023) show that CMIP6 models running with internally-generated QBOs, but non-interactive chemistry, exhibit a curious synchronisation of the QBO across ensembles run with prescribed CMIP6 historical ozone forcing, resulting in non-physical QBO-related temperature and winds in those models. Though reflective of different mechanisms and forcings, these examples illustrate new pathways whereby ozone can feedback onto the circulation that have emerged in the latest generation of coupled climate models and that require further understanding.

Finally, the processes driving the QBO are highly complex, finely balanced and intricately coupled. QBO winds are mostly driven by small-scale gravity waves and planetary-scale equatorially trapped waves. Via thermal wind balance, the vertical shear of zonal winds caused by wave-mean flow interactions produce equatorial temperature anomalies, Figure 1(b). These in turn modify the radiative heating and a secondary meridional circulation with vertical motion on the equator is required to maintain the temperature anomaly against radiative relaxation. The vertical motion then advects ozone, Figure 1(c), and other chemical tracers, feeding back on the radiative heating and thus the secondary circulation. The net effect of these feedbacks on the temperature and secondary circulation modifies the profile of zonal winds, modifying the propagation and attenuation of the waves. A full understanding of the effects of ozone on the QBO must account for how all of these components respond in concert. Before we can reliably predict how the QBO may change, we must first verify that climate models are capturing this highly coupled set of feedbacks with sufficient fidelity.

This proposal aims to deliver a systematic study of QBO-ozone interactions using observational data, modelling tools, theoretical frameworks and leveraging our joint expertise in atmospheric dynamics, radiative processes and atmospheric chemistry to push the limits of our understanding of the QBO.

It is particularly timely since a substantial modelling effort is underway to generate clean simulations of the ozone feedback. This has gathered the support of six modelling centres worldwide (with two more centres pending approval) and is endorsed by the QBOi and Chemistry Climate Model Initiatives (CCMI). Together with these new model simulations, we now have available long (20 years+) high resolution radio occultation measurements of temperature and homogenised ozone (and other chemical tracers) satellite measurements. We are therefore presented with a unique opportunity to test key QBO-ozone coupling mechanisms and quantify the strength of those feedbacks in the climate.

Main goals and project work plan The work plan is designed such that there will be close collaboration between team members with dynamics, chemistry and observational expertise.

1. Assess nature of QBO-ozone feedback in high resolution in the observational record

We will make use of a combination of datasets including SWOOSH (Davis et al., 2016), MLS (Waters et al, 2006), TOMS/OMI (both column ozone and vertical profiles, as well as other trace gases; McPeters, 1996), SAGE and OSIRIS (NO_2; Dube et al., 2022), GNSS radio occultations (e.g., COSMIC, temperature; Anthes et al., 2008) as well as the new M2SCREAM stratospheric composition reanalysis dataset (Wargan et al, 2023). A combined study of the QBO in trace gases across a range of our best available observational data will allow us to develop the methodology to evaluate the ozone feedback as well as identify any gaps in measurement. Observation constraints on the wave forcing (Holt et al. 2022), decomposed into extratropical Rossby waves, equatorial planetary waves and small-scale convective gravity waves will also be brought up to date. For this exercise to be successful, we propose bringing together domain experts and contrast the observed QBO response with the carefully designed new model experiments.

2. Validate the new model simulations against observations and determine the sign of the ozone feedback under climate change

Progress on understanding the QBO-ozone feedback has so far been limited by the lack of clean pairs of interactive and non-interactive model simulations. The experimental protocol of this new QBOi/CCMI modelling effort has been chosen to precisely address the role of ozone in setting the present day QBO amplitude and period as well as under a $4xCO_2$ scenario. This work will involve investigating the impact of ozone feedbacks on the large-scale circulation, including coupling to stratospheric composition (e.g. water vapour, changes in chemical depletion cycles including NO_x

and HO_x, and evaluating their role in the ozone-QBO signal). The wave forcing in the interactive and non-interactive model simulations will also be decomposed and evaluated. This assessment of wave decomposition in simulations with and without ozone feedbacks and in observations will provide insight about the underlying relationship between the dynamical and chemical coupling mechanisms, which modulates the secondary meridional circulation and can impact QBO teleconnections outside the tropics. We will validate these new model simulations against observations and then combine our firm understanding of the mechanisms in the current climate to determine the sign of ozone feedback under climate change. We will evaluate the robustness of our results among models, as well as the relative importance of chemical, radiative and transport processes.

3. Identify the key dynamical and chemical coupling mechanisms

Because of the highly coupled nature of the ozone feedback on the QBO, it will be essential to interpret both the observations and the climate models in the context of appropriate conceptual models. Such models exist for various aspects of QBO dynamics, but a full theoretical framework still remains to be developed. Here we will bring together experts to construct this full framework and test each component against the observations and climate models. It will in turn help to better identify how well observations constrain key sensitivities in the chemical, radiative, and dynamical processes that drive the QBO, to explain differences between climate models, and to project how the character of the QBO may evolve in the future.

4. Community recommendations on areas of future work

We will identify gaps in measurement, in particular focussing on upcoming satellite campaigns such as the CAIRT ESA mission and recommend key processes on which to focus in order to best monitor the ozone feedback on the QBO. We will also recommend areas for future scientific analysis on this new modelling dataset as well as for the upcoming CMIP7 project.

Schedule of the project We have scheduled two 5-day meetings in Bern. Prior to the first meeting, participants will gather the observational datasets and compute time series of QBO variability in various dynamical and chemical quantities. During the initial meeting, there will be overview presentations of existing work related to the main themes, with the majority of time dedicated to discussing the best approach to extracting the QBO ozone feedback from the observational record. We will devise a research plan for the first year. Ahead of the second meeting, analyses will be conducted, and rough drafts of the two manuscripts will be prepared. Group members will present their findings at the second meeting. During this session, we will finalise the writing and establish a work plan for any remaining analyses to be completed shortly thereafter. We will also form a subgroup tasked with drafting the community recommendations.

List of the expected outputs e.g., scientific papers, reviews, books, software, etc.
Research paper: *How do we define the QBO-ozone feedback in observations and how well is it captured in models?*
Research paper: *What is the sign of the future QBO-ozone feedback?*
Report synthesising the community recommendations

Financial support requested from ISSI We require a meeting space equipped with internet access and a projector for team presentations. Additionally, we seek assistance in setting up a website and ongoing IT support. Regarding financial support, we request funding for hotel accommodations and per diem expenses for a team consisting of 12 members. Additionally, we anticipate the inclusion of two additional young scientists to the team in the future, as outlined in the proposal guidelines. Per diem will be necessary for approximately 6 days per participant for each of the two scheduled meetings. Furthermore, travel support is requested for one of the team leaders or a designated participant.

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