Proposed Joint QBOi-CCMI Ozone Feedback Protocol

I. Motivation

It has long been recognized that radiative and dynamical feedbacks from stratospheric ozone can impact the Quasi-Biennial Oscillation (QBO). In other words, the changes in stratospheric ozone caused by QBO-driven changes in temperature and circulation alter the heating rates and overall QBO structure. The ozone feedback on the QBO has been examined mainly in the context of recent historical climate (e.g., Butchart et al. (2003), Shibata and Deushi (2005), Shibata (2021), Butchart et al. (2023)), but a review of this literature reveals large uncertainties in the magnitude – and even sign – of the ozone feedback on both the QBO period and amplitude (Section IIIa). One recent study has examined how ozone feedbacks on the QBO may change during rapid climate change, modeled as an abrupt quadrupling of atmospheric carbon dioxide concentrations (4xCO_2) (DallaSanta et al. (2021)), but this topic remains relatively unexplored (Section IIIb). In general, methodological differences make it difficult to pinpoint and understand the drivers of conflicting conclusions drawn from previous studies. This suggests that a common experimental protocol is needed in order to assess the robustness of QBO-ozone feedbacks.

II. Timeliness

Compared to its predecessor activity, the Stratospheric Processes and their Role in Climate (SPARC) CCMVal multi-model comparison project (Eyring et al. (2008)), the SPARC Chemistry Climate Modeling Initiative (CCMI) includes more (8) models running with both fully interactive stratospheric ozone chemistry and self-generated QBO cycles (Eyring et al. (2013), Plummer et al. (2021)). This should have presented a unique opportunity to systematically assess QBO-ozone feedbacks in these models, although none of the completed (Phase 1) nor in-progress (Phase 2) experiments would enable this type of analysis.

At the same time, there has been a marked improvement in the simulation of the QBO in climate models, moving from Phase 5 to Phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Orbe et al. (2020), Richter et al. (2020)). Highlighting the presence of QBO-ozone feedbacks in historical climate, Butchart et al. (2023) show that CMIP6 models running historical simulations with self-generating QBOs, but non-interactive CMIP6-prescribed stratospheric ozone (Checa-Garcia et al. (2018)), feature a curious synchronization of the QBO across ensemble members. Ozone feedbacks might also modulate the projected future response of the QBO amplitude to an abrupt quadrupling of CO_2, at least in the one CMIP6 model examined in DallaSanta et al. (2021). Though reflective of different forcings, both examples of QBO-ozone feedbacks have emerged in the latest generation of coupled climate models and require further understanding.

The QBO synchronization across the CMIP6 prescribed-ozone historical realizations reported in Butchart et al. (2023) may involve adjustments to QBO descent rates via ozone-induced changes in the QBO secondary circulation, but this is highly speculative and a tested mechanism is still missing. At the same time, the robustness of the results presented in DallaSanta et al. (2021) is hard to assess in the broader CMIP6 archive. In particular, comparisons between the 10 CMIP6 models including interactive stratospheric ozone with those running with prescribed ozone are instructive (Wang et al., (In Prep.)) by e.g. following the approach of Morgenstern et al., (2022) of taking differences between pairs of models. However, such analysis does not cleanly distinguish intermodel differences due to ozone from other contributors to model structural uncertainty. That is, clean pairs of "non-interactive" and "interactive" simulations within the same GCM do not exist broadly across the CMIP6 archive.

To summarize: The CMIP6 and CCMI experiments have limited utility for addressing longstanding uncertainties in QBO-ozone feedbacks. To this end, we propose a new joint QBOi-CCMI activity aimed at identifying robustness and improving understanding of QBO-ozone feedbacks in present-day and future climates.

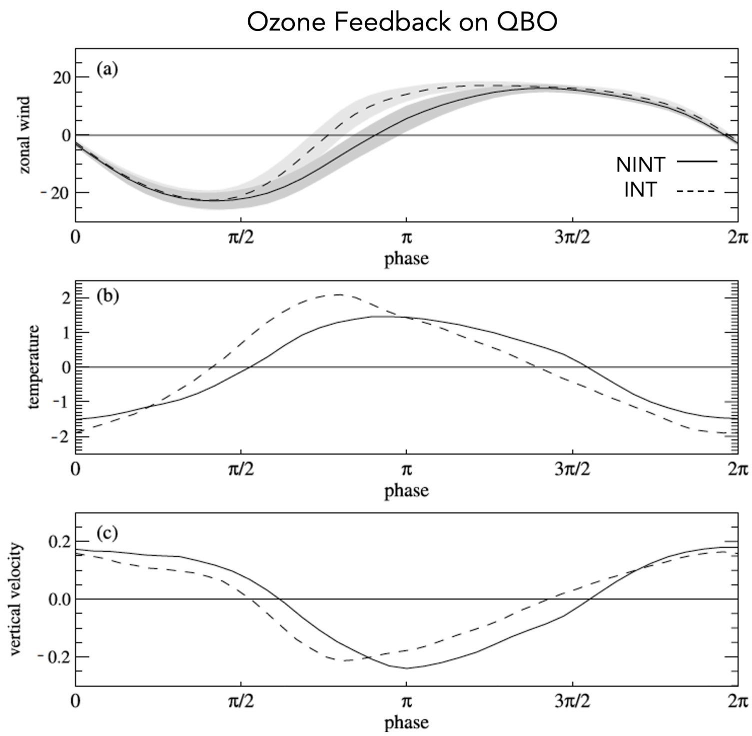

Figure 1: Comparisons of the tropical zonal mean zonal wind [ms^{-1}] (a) and anomalies in temperature (K) (b) and vertical residual velocity (mms^{-1}) (c) between simulations using specified (NINT, solid line) versus coupled (INT, dashed line) ozone. Fields are evaluated at the equator and at 21.5 hPa and plotted as a function of QBO phase. Adapted from Butchart et al. (2003).

III. Background: Ozone Feedbacks on the QBO

a) Present-Day Climate

Ozone feedbacks on the QBO under present-day and recent historical conditions have been examined in several studies. Nonetheless, large uncertainties remain. In particular, while some studies show that ozone feedbacks result in an increased QBO period of ~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 (Cordero and Nathan (2000)) on QBO period. Even among the former, studies are inconsistent in whether the lengthened QBO period reflects a prolongation of the westerly (Butchart et al. (2003)) or easterly (Shibata and Deushi (2005)) phases. At the same time, the temperature QBO amplitude is also sensitive to ozone feedbacks since ozone is the major heating source of the stratosphere, featuring a 35% peak-to-peak increase in temperature amplitude in the middle stratosphere (Butchart et al. (2003), **Figure 1b**) which may also extend to the lower stratosphere (~70 hPa) (DallaSanta et al. (2021)). However, other studies find only a 2% increase at 30 hPa (Shibata and Deushi (2005)). Among the more consistent findings, nearly all studies report no substantial QBO wind amplitude change (**Figure 1a).**

In addition to the mean winds and temperatures, the QBO meridional circulation also responds to feedbacks from ozone (**Figure 1c**). Cordero and Nathan (2000) show that zonal mean direct ozone feedbacks weaken the QBO meridional circulation because the additional diabatic heating produced by the ozone QBO offsets the heating required to maintain thermal balance in the presence of radiative cooling (Dunkerton (1985)). That is, the downward transport of ozone (in the presence of strong background ozone gradients) will elevate radiative equilibrium temperatures so that less vertical motion is needed to maintain the temperature perturbation against radiative damping. While this physical argument is compelling, it is not clearly borne out in all models, as Shibata et al. (2021) find no significant changes in the residual mean upwelling associated with the QBO across simulations of varying ozone feedback strength.

Part of the discrepancy in the residual circulation response to ozone feedbacks may reside in differences related to zonal mean versus eddy ozone feedbacks (Cordero and Nathan (2000)). Here eddy feedbacks refer to how the eddy ozone (not zonal mean) heating interacts with the wave fields and how these in turn change the forcing of the QBO via changes in damping (Echols and Nathan (1996)). That is, how do ozone eddies modify the damping of Kelvin and Rossby-gravity waves that force regions of descending westerlies and easterlies, respectively? As in Echols and Nathan (1996), Butchart et al. (2003) reported a 25/45% increase in the westerly/easterly wave forcing of the QBO when ozone feedbacks were included, but whether or not these results bear out consistently across other models is unknown.

To summarize: There are large uncertainties in how feedbacks from stratospheric ozone modulate the QBO period, QBO amplitude (both with respect to temperature and wind), QBO meridional circulation and QBO wave forcing in present-day climate. Furthermore, among those models simulating enhanced QBO temperature amplitudes in the lower stratosphere with ozone feedbacks, implications for tropospheric dynamical teleconnections and potential feedbacks on tropospheric ozone remain largely unexplored.

b) 4xCO_2 Climate

Most studies examining QBO-ozone feedbacks have focused on either present-day or historical climate. By comparison, how ozone feedbacks modulate the QBO response to future climate change has been relatively unexplored. Nonetheless, initial results are compelling, with DallaSanta et al. (2021) showing that ozone feedbacks may dampen the response of the QBO amplitude to increased CO_2 in a coupled atmosphere-ocean model in which CO_2 affects climate both through its direct radiative impact and via changes in SSTs (**Figure 2, top panel**). The contribution of ozone feedbacks to uncertainties in predictions of future QBO amplitude changes (Richter et al. (2020)), however, remains unexplored.

DallaSanta et al. (2021) propose a mechanism for an ozone feedback on the QBO amplitude in a 4xCO_2 altered climate, consisting of two parts. First, ozone induces relative enhancement of meridional temperature gradients in the lower stratosphere, which dampen the response of the Brewer-Dobson Circulation (BDC) to increased CO_2, resulting in weaker upwelling in the mid-stratosphere (30 hPa; **Figure 2, bottom left panel**). This "dampened BDC response" in the middle stratosphere primarily affects the QBO through its influence on the QBO meridional circulation associated with the easterly phase of the QBO (eQBO), as eQBO is typically associated with enhanced upwelling in the lower tropical stratosphere (and vice versa for westerly QBO) (Figure 5 in that study). Second, this reduced amplitude of eQBO, associated with the weakened QBO meridional circulation, itself causes a reduction in easterly momentum deposition from parameterized convective waves, further reducing the amplitude of eQBO. The latter occurs because in the convective non-orographic gravity wave drag (NOGWD) parameterization employed in the model used in that study – in which when easterlies achieve magnitudes near -20 m/s additional easterly momentum is obtained from the c=-20 convectively launched gravity wave – even a slight QBO amplitude weakening will block convective waves from obtaining additional easterly momentum.

The second component of the mechanism proposed in DallaSanta et al. (2021) is most obviously likely to be model-dependent and sensitive to the details of how NOGWD is implemented across models. The first component – that is, how ozone feedbacks dampen a strengthening of the BDC in response to increased CO_2 – may also be model dependent as the literature suggests mixed results. In particular, Hufnagl et al. (2023) showed that ozone changes damp the CO_2-induced BDC increase by up to 20% throughout the lower and middle stratosphere, with the damping of the BDC strengthening being linked to ozone-induced relative enhancement of meridional temperature gradients in the lower stratosphere, resulting in stronger stratospheric easterlies which suppress wave propagation (and, hence, wave forcing of the BDC). By comparison, neither Nowack et al. (2015) (see their Figure S2) nor DallaSanta et al. (2021) (**Figure 2, bottom right panel**) identified an ozone feedback on the BDC in the lower stratosphere , suggesting that this response is likely to be level-dependent and/or vary across models. Overall, given these uncertainties in both parts 1 and 2 of the proposed mechanism, it is important to revisit the role of ozone feedbacks on future BDC and QBO changes in other models.

As the previous results highlight, understanding the role of ozone feedbacks on the QBO response to a 4xCO_2 climate raises more general questions about how stratospheric ozone feedbacks modify the temperature, wind and mean meridional circulation responses to increased CO_2 in the stratosphere (both via direct radiative impacts and through changes in SSTs). To this end, the experimental protocol proposed in Section V will also provide an opportunity to examine more generally the influence of ozone feedbacks on stratospheric winds and temperatures (Chiodo et al. (2018), Chiodo and Polvani (2019)), as well as shifts in the tropospheric midlatitude jets (Chiodo and Polvani (2019)); Li and Newman (2022); Orbe et al. (2024)) and surface climate.

IV. Guiding Questions for Proposed QBO-Ozone Experiments

Some limitations from previous studies, which contribute to our lack of understanding of QBO-ozone feedbacks, are:

a) Inconsistent definitions of QBO-Ozone Feedbacks

Some previous studies have quantified ozone feedbacks by examining the QBO differences between transient interactive full ozone chemistry (hereafter "INT") simulations and transient "non-interactive" (hereafter NINT) simulations, in which a climatological ozone annual cycle forcing is prescribed from an observational dataset (e.g., Butchart et al. (2003), Deushi and Shibata (2005)). This approach is problematic in that the ozone climatology prescribed in NINT may not be consistent with the ozone climatology generated from the INT simulation, i.e., the differences between the ozone distributions used in the INT and NINT experiments likely swamp the QBO-driven ozone anomalies.

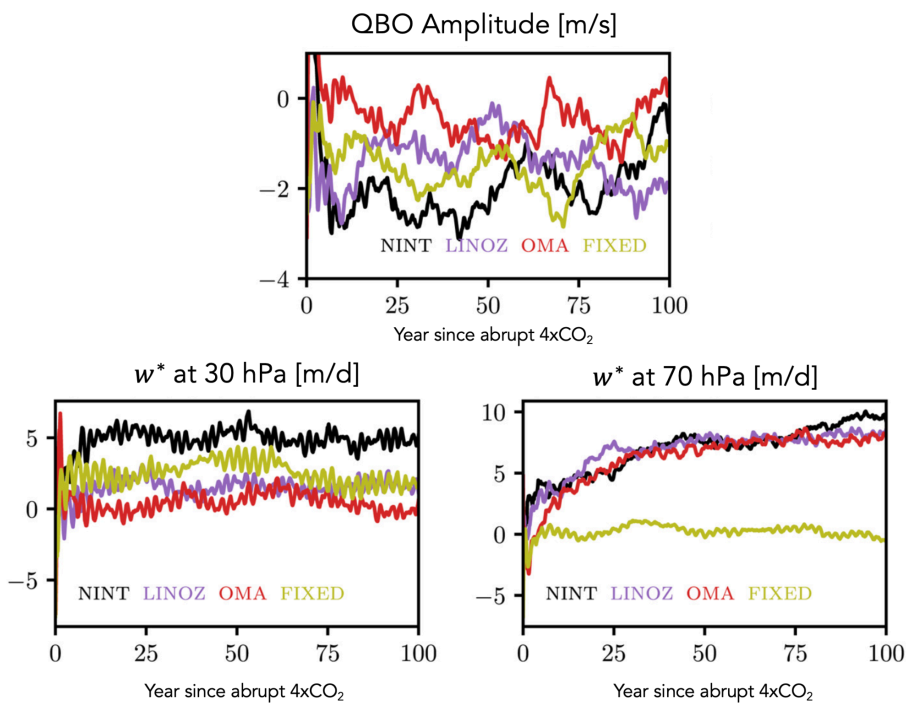

Figure 2: The response of the QBO amplitude (top) to an abrupt quadrupling of CO_2 in the CMIP6 GISS E2-2-G climate model (adapted from DallaSanta et al. (2021)). The 4xCO_2 reduction in QBO amplitude is larger in the non-interactive simulation (NINT, black), compared to in the interactive full chemistry (OMA, red) and linearized ozone (LINOZ, purple) simulations. This is associated with a dampened increase in tropical residual mean upwelling (w^*) at 30 hPa (bottom left), although no ozone feedback on w^* is captured at 70 hPa (bottom right). Tropical averages are taken from −10° to 10° and the yellow line shows results from a non-interactive simulation constrained with preindustrial SSTs (FIXED, denoted as PDSST in the experimental protocol outlined in Section V).

b) Complexity of Coupled Atmosphere-Ocean 4xCO_2 Response

In addition to limitation a), the experiments performed in DallaSanta et al. (2021) are difficult to meaningfully interpret due to the complexity of the coupled atmosphere-ocean system's 4xCO_2 response. This is because there is a strong coupling between changes in sea surface temperatures (SSTs), lower stratospheric tropical upwelling and ozone in response to increased CO_2, which all contribute to subsequent ozone feedbacks on the circulation. In particular, Chiodo and Polvani (2018) showed a large spread in the tropical lower stratospheric ozone response to 4xCO_2 across 4 CMIP5 models, which they related to a spread in the response of upwelling in that region (see their Figure 6b), although preliminary analysis suggests that this relationship may be weaker in the CMIP6 models (Wang et al., in prep). As the upwelling response is itself related to changes in SSTs (Abalos et al. (2021), Chrysanthou et al. (2020)), this suggests that ozone feedbacks in some models may be weaker than others, simply because of their global surface temperature responses, which renders isolating stratospheric mechanisms of ozone-circulation feedbacks in models challenging. In addition, there are other important subtleties introduced when running coupled atmosphere-ocean frameworks – namely using different tunings for NINT and INT preindustrial control simulations – that can potentially alter the ozone distribution as well as the influence of ozone on the QBO climate response.

Given the limitations posed by a) and b), here we propose a protocol for examining QBO-ozone feedbacks in a more consistent and simplified framework. This framework focuses on defining ozone feedbacks consistently between NINT and INT simulations and employing a simplified AMIP framework to minimize inter-model differences associated with differences in SSTs. Using an AMIP framework also presents the obvious benefit that models that do not run coupled to a dynamic ocean, sea ice or land surface model are encouraged to participate.

Here we propose a set of both present-day and 4xCO_2 AMIP experiments oriented at examining these three key questions:

Q1) What is the present-day ozone feedback on QBO period and amplitude?
How do QBO-driven ozone changes alter the stratospheric residual mean meridional circulation, temperatures, and winds, as well as stratosphere-troposphere exchange (STE) of ozone?

Q2) For the 4xCO_2 climate, what are the ozone feedbacks on QBO period and amplitude?
Again, how do QBO-driven ozone changes alter the stratospheric circulation, temperatures and STE flux under a 4xCO_2 climate?

Q3) What mechanisms are associated with the ozone feedbacks found in Q1) and Q2)?
How do these differ between models where NOGWD is parameterized to remain fixed vs. respond to changes in the atmospheric base state? For Q2) what is the relative importance of the direct stratospheric radiative and chemical changes caused by CO_2 (cooling) vs. overall climate change (warming SSTs)?

V. Proposed Experimental Protocol

Focusing on the questions ***Q1-Q3*** above, we propose a set of both "Present Day" (hereafter PD) experiments and "Future" (hereafter FT) experiments (**Table 1**). Simulations designated as "Tier 1" and "Tier 2" are required and voluntary, respectively.

Both PD and FT experiments are proposed using time-slice frameworks. While the committee's recommendation is to pursue a time-slice approach for the PD experiments, an alternative transient approach may be preferred by certain modeling centers that participated in CCMI and is presented in the Appendix. We strongly discourage this approach, however, since analysis of transient experiments will be seriously complicated by the presence of large non-stationary trends in ozone that are not easy to remove, as well as events that may trigger anomalies in the QBO (e.g., volcanoes, ENSO, wildfires).

Table 1: The proposed list of "Present-Day" (PD) and "Future" (FT) experiments. Tier 1 experiments are in bold. 3 ensemble members per experiment are requested, with the exception of PD_INT.

Experiment Name	**Simulation Length [years] (x Ens. Mem)**	**O_3**	**CO_2**	**Other trace gases (ODS,CH_4,N_2O, tropospheric pollutants)**	**SSTs**	**SICs**	**Tier**
PD_INT	90 (x1)	Interactive	CMIP6 (2000-2020 mean)**	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean)	HadISST1 (2000-2020 mean)	**Tier 1**
PD_NINT	30 (x3)	Climatological PD_INT*	CMIP6 (2000-2020 mean)	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean)	HadISST1 (2000-2020 mean)	**Tier 1**
FT_NINT_4xCO_2	30 (x3)	PD_NINT (Climatology from PD_INT)	4xCMIP6 (2000-2020 mean)	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean) + uniform 4K	HadISST1 (2000-2020 mean)	**Tier 1**
FT_INT_4xCO_2	30 (x3)	Interactive	4xCMIP6 (2000-2020 mean)	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean) + uniform 4K	HadISST1 (2000-2020 mean)	**Tier 1**
FT_INT_4xCO_2+PDSST	30 (x3)	Interactive	4xCMIP6 (2000-2020 mean)	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean)	HadISST1 (2000-2020 mean)	Tier 2

FT_INT_ $1xCO_2$+4 KSST	30 (x3)	Interactive	CMIP6 (2000-2020 mean)	CMIP6 (2000-2020 mean)	HadISST1 (2000-2020 mean) + uniform 4K	HadISST1 (2000-2020 mean)	Tier 2

Notes for Table 1:
*Each PD_NINT ensemble is constrained with the climatological mean annual cycle of ozone, derived from each non-overlapping 30-year-long segment of the PD_INT integration.
**All uses of (2000-2020 mean) include the annual cycle for SSTs and SICs, but just a single annual mean value for CO_2 and other long-lived trace gases. For tropospheric chemistry (if included), emissions of short-lived pollutants including aerosols should use a monthly mean (or equivalent) annual cycle that repeats.

The experiments are designed such that:

PD_INT minus PD_NINT is used to quantify the present-day ozone feedbacks on the QBO (Q1).

FT_NINT_4xCO_2 minus PD_NINT is used to quantify the impact of 4xCO_2 (both the direct radiative response and warmer SSTs) on the QBO with ozone fixed, while FT_INT_4xCO_2 minus FT_NINT_4xCO_2 is used to quantify the ozone feedback on the 4xCO_2 response of the QBO (Q2).

FT_INT_4xCO_2+PDSST minus FT_INT_4xCO_2 and FT_INT_1xCO_2+4KSST minus FT_INT_4xCO_2 are used to separate the QBO-ozone feedbacks into contributions from global warming (+4K uniform SSTs) versus stratospheric cooling (4xCO_2), respectively (Q3).

a) Present-Day (PD) AMIP Simulations:

PD "Interactive" Experiment (PD_INT, Tier 1):

The PD "Interactive" Experiment is a time-slice "present-day" 90-year-long integration run using full interactive chemistry and forced with boundary conditions used in CMIP6 available through input4MIPs, see **Table 1**. Specifically, year 2000-2020 mean values are prescribed, with the monthly seasonal cycles retained for sea surface temperatures (SSTs) and sea ice concentrations (SICs). A single annual mean value should be used for the long-lived gases (CO_2, CH_4, N_2O, ozone depleting gases) as well as solar, volcanic and (if used) biomass burning emissions, although the annual cycle in tropospheric emissions of short-lived species over 2000-2020 should be used. A 10-year spin up for chemistry is recommended. Note that the CMIP6 historical forcings were also used in the CCMI REF-D1 hindcast experiment.

It is imperative that all participating models run with at least interactive stratospheric ozone. For models using more simplified chemical mechanisms, at least ozone needs to run interactively coupled with the model's internal dynamics and radiation, no matter how simplified its treatment.

PD "Non-interactive" Experiment (PD_NINT, Tier 1):

The PD "Non-interactive" Experiment is identical to PD_INT, except that a single, monthly annual cycle of three-dimensional ozone fields are prescribed, based on a 30-year climatology derived from the PD_INT experiment, keeping all other compositional and boundary forcings identical. The 90-year-long PD_INT experiment should generate three successive 30-year ozone climatologies, which are used to constrain three 30-year-long PD_NINT ensemble members. Initialization is up to the modeling group. The difference PD_INT minus PD_NINT is used to quantify the present-day ozone feedbacks on the QBO. Note that this approach is distinct from previous studies in which an ozone climatological seasonal cycle is prescribed from an observational dataset (Buchart et al. (2003), Deushi and Shibata (2005)) and is thus certain to be different from the underlying model (in this case, PD_INT).

b) Future (FT) 4xCO_2 AMIP Simulations

FT 4xCO_2 "Non-Interactive" Experiment (FT_NINT_4xCO_2,Tier 1): The FT_NINT_4xCO_2 experiment is based on a climate change scenario and builds off the PD_NINT experiment in two main ways: 1) CO_2 concentrations are quadrupled from the values prescribed in PD_NINT and 2) a spatially uniform perturbation of +4K is applied to all SST grid points. Sea ice concentrations are kept fixed to the values used in PD_NINT. Three 30-year-long ensemble members are initialized from the three PD_NINT ensemble members and constrained with their corresponding three-dimensional ozone fields (all other chemical species are the same as in PD_NINT). See **Section XI** for an explanatory note on the use of prescribed PD_NINT ozone values in this experiment.

FT 4xCO2 "Interactive" Experiment (FT_INT_4xCO_2, Tier 1): The 3 member 30-year-long FT 4xCO_2 "Interactive" experiment is identical to FT_NINT_4xCO_2, except that ozone is allowed to respond interactively to the quadrupled CO_2 concentrations and +4K SST perturbations. Each ensemble member is initialized from a different point in the PD_INT experiment to ensure that the chemistry is sufficiently spun-up. The difference between FT_INT_4xCO_2 - FT_NINT_4xCO_2 is used to quantify 4xCO_2 ozone feedbacks on the QBO.

Note that for whole atmosphere chemistry models running with tropospheric chemistry care will need to be taken in diagnosing the influence of the FT climate change on tropospheric chemistry and its subsequent impacts on climate forcing and tropopause stability (primarily through ozone and aerosols). Changes in upper tropospheric and stratospheric water vapor associated with warmer SSTs will also represent a confounding factor by influencing both temperatures and ozone chemistry in the stratosphere. If modeling centers can take measures to avoid these complications we advise that they do so.

FT 4xCO2 "Interactive" Present-Day SST Experiment (FT_INT_4xCO_2+PDSST, Tier 2): The FT 4xCO_2 "Interactive" Fixed SST experiment is identical to FT_INT_4xCO_2, except that SSTs are fixed to the present-day values used in PD_INT.

FT 1xCO2 "Interactive" +4K SST Experiment (FT_INT_1xCO_2+4KSST, Tier 2): The FT 1xCO_2 "Interactive" +4K SST experiment is identical to FT_INT_4xCO_2, except that CO_2 concentrations are identical to those used in PD_INT.

Ensemble Members: For all experiments except PD_INT, 3 ensemble members are requested (Col. 2, **Table 1**).

VI. Diagnostics

The proposed diagnostics (**Tables 2-6**) are selections from diagnostics requested from related multi-model intercomparison projects, including DynVarMIP (Gerber and Manzini (2016)), QBOi (Butchart et al. (2018)), CCMI (Plummer et al. (2021)) and SNAPSI (Hitchcock et al. (2022)). Json files for the requested output are being constructed and will be made available in May.

a) Spatial Resolution

Output is requested for all variables in **Tables 2-3** and **Table 5** on a standard 42 pressure level grid (hereafter "plev42") that reflects a slight modification to the 39-pressure level grid used in DynVarMIP to account for more levels in the vicinity of the QBO and fewer levels above the stratopause: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 170, 150, 130, 115, 100, 90, 80, 70, 60, 50, 40, 35, 30, 25, 20, 17, 15, 13, 11, 10, 9, 8, 6, 5, 4, 3, 2, 1.5, 1, 0.7, 0.5, and 0.4 hPa.

In addition to the plev42 pressure-level output, **Table 4** consists of quantities requested as close to the native model pressure grid as possible (i.e., hereafter "plevTEM") as these will be used to calculate the TEM circulation offline in order to verify consistency with the TEM fields provided by the modeling centers in **Table 3**. Finally, the 6-hourly instantaneous output in **Table 6** is also requested on the plevTEM vertical grid and for only a subset of latitudes (15ºS to 15ºN) and for pressure levels above 150 hPa, following the analogous request from QBOi. Horizontal resolution of all output should be the same as the model.

b) Temporal Resolution and Output Periods

For all years monthly mean output is requested for all variables and ensemble members. 6-hourly mean and daily mean data is requested for subsets of the diagnostics for the entire duration of the experiment, but for only one ensemble member. The 6-hourly (3-D) instantaneous output (**Table 6**) is also requested for one ensemble member, but for only 10 years (although 30 years is strongly encouraged).

c) Diagnostics

Table 2 is identical to Table 1 from the QBOi Phase 1 protocol (Butchart et al. (2018)), except for a few additional requests (e.g., outgoing longwave radiation, tropopause air pressure and tropopause air temperature).

Table 2: Requested climate variable output. For variables with a vertical dimension, output is requested on the plev42 vertical grid.

Variable Name	Long name [units]	Spatial Dimension	Temporal Resolution
psl	Sea Level Pressure [Pa]	2-D (lat, lon)	Monthly, Daily
ps	Surface Air Pressure [Pa]	2-D (lat, lon)	Monthly, Daily
prc	Convective Precipitation Flux [$kgs^{-1}m^{-2}$]	2-D (lat, lon)	Monthly, Daily
pr	Total Precipitation Flux [$kgs^{-1}m^{-2}$]	2-D (lat, lon)	Monthly, Daily
rlut	Outgoing Longwave Radiation [Wm^{-2}]	2-D (lat, lon)	Monthly, Daily
tas	Near-Surface Air Temperature [K]	2-D (lat, lon)	Monthly, Daily
uas	Eastward Near-Surface Wind [ms^{-1}]	2-D (lat, lon)	Monthly, Daily
vas	Northward Near-Surface Wind [ms^{-1}]	2-D (lat, lon)	Monthly, Daily
ptp	Tropopause Air Pressure [Pa]	2-D (lat, lon)	Monthly, Daily
tatp	Tropopause Air Temperature [K]	2-D (lat, lon)	Monthly, Daily
ta	Air Temperature [K]	3-D	Monthly, Daily
ua	Eastward Wind [ms^{-1}]	3-D	Monthly, Daily
va	Northward Wind [ms^{-1}]	3-D	Monthly, Daily
wap	Vertical velocity, Omega (=dp/dt) [Pas^{-1}]	3-D	Monthly, Daily
zg	Geopotential Height [m]	3-D	Monthly, Daily

Table 3 identifies key radiative and dynamical quantities to be saved. As in the prescriptions in the QBOi Phase 1 (Butchart et al. (2018)) and DynVarMIP (Gerber and Manzini (2016)) protocols, we ask that modeling groups submit their online calculations of the TEM circulation and Eliassen-Palm fluxes. However, in order to account for potential inconsistencies that may arise due to different TEM formulations among the modeling centers, **Table 4** identifies the necessary zonal mean 6-hourly quantities needed to calculate the TEM offline (Ming (2016)).

Table 3: Requested radiative output and dynamical fields. For variables with a vertical dimension, output is requested on the plev42 vertical grid.

Variable Name	**Long name [units]**	**Spatial Dimension**	**Temporal Resolution**
zmtnt	Total Temperature Tendency [Ks^{-1}]	2-D zonal mean	Monthly
tntlwas	All sky longwave Heating Rate [Ks^{-1}]	2-D zonal mean	Monthly
tntlwcs	Clear sky longwave Heating Rate [Ks^{-1}]	2-D zonal mean	Monthly
tntswas	All sky shortwave Heating Rate [Ks^{-1}]	2-D zonal mean	Monthly
tntswcs	Clear sky shortwave Heating Rate [Ks^{-1}]	2-D zonal mean	Monthly
ua	Eastward wind [ms^{-1}]	2-D zonal mean	Monthly
va	Northward wind [ms^{-1}]	2-D zonal mean	Monthly
wap	Vertical velocity, Omega (=dp/dt) [Pas^{-1}]	2-D zonal mean	Monthly
*v**	Residual Northward Winds [ms^{-1}]	2-D zonal mean	Monthly, Daily
*w**	Residual Upward Wind [ms^{-1}]	2-D zonal mean	Monthly, Daily
ψ *	Transformed Eulerian Mean Mass Streamfunction [kgs^{-1}]	2-D zonal mean	Monthly
epfy	Northward Component of the Eliassen-Palm Flux [m^3s^{-2}]	2-D zonal mean	Monthly
epfz	Upward Component of the Eliassen-Palm Flux [m^3s^{-2}]	2-D zonal mean	Monthly
ta	Air temperature [K]	2-D zonal mean	Monthly
zg	Geopotential height [m]	2-D zonal mean	Monthly, Daily
v’T’	Northward Flux of Temperature [$ms^{-1}K$]	2-D zonal mean	Monthly
u’v’	Northward flux of Eastward Momentum [m^2s^{-2}]	2-D zonal mean	Monthly

u’w’	Upward Flux of Eastward Momentum [m^2s^{-2}]	2-D zonal mean	Monthly
utendnet	Eastward wind net tendency due to all parameterized processes [ms^{-2}]	2-D zonal mean	Monthly, Daily
utendogw	Eastward wind tendency by orographic gravity waves [ms^{-2}]	2-D zonal mean	Monthly, Daily
utendnogw	Eastward wind tendency by non-orographic gravity waves [ms^{-2}]	2-D zonal mean	Monthly, Daily
vtendnet	Northward wind net tendency due to all parameterized processes [ms^{-2}]	2-D zonal mean	Monthly, Daily
vtendogw	Northward wind tendency by orographic gravity waves [ms^{-2}]	2-D zonal mean	Monthly, Daily
vtendnogw	Northward wind tendency by non-orographic gravity waves [ms^{-2}]	2-D zonal mean	Monthly, Daily
precip	Precipitation flux [kg m-2 s-1]	3-D	Monthly, Daily
cod	Cloud optical depth [1]	3-D	Monthly, Daily
convec_cloud_area_frac	Convective Cloud Area [%]	3-D	Monthly, Daily
cloud_area_frac	Total Cloud Cover Area [%]	3-D	Monthly, Daily

Table 4: Requested 6-hourly instantaneous output needed to compute the TEM circulation offline as validation of the online TEM output requested in **Table 3**. Data is requested at a vertical resolution equivalent to the underlying model resolution (i.e., plevTEM).

Variable Name	**Long name [units]**	**Spatial Dimension**	**Temporal Resolution**
ta	Air Temperature [K]	2-D zonal mean	6-hourly
ua	Eastward Wind [ms^{-1}]	2-D zonal mean	6-hourly

va	Northward Wind [ms^{-1}]	2-D zonal mean	6-hourly
wap	Vertical velocity, Omega (=dp/dt) [Pas^{-1}]	2-D zonal mean	6-hourly
v'T'	Northward Flux of Temperature [$ms^{-1}K$]	2-D zonal mean	6-hourly
u'v'	Northward flux of Eastward Momentum [m^2s^{-2}]	2-D zonal mean	6-hourly
u'w'	Upward Flux of Eastward Momentum [m^2s^{-2}]	2-D zonal mean	6-hourly

To interpret the influence of ozone on the QBO (and vice versa) we will examine the associated transport circulation using both chemical tracers, as well as a subset of the passive idealized tracers requested for Phase 1 of CCMI (Eyring et al. (2013), Orbe et al. (2018)). This output request is summarized in **Table 5**.

Table 5: Requested chemical and idealized tracer output. For variables with a vertical dimension, output is requested on the plev42 vertical grid.

Variable Name	**Longname [units]**	**Spatial Dimension**	**Temporal Resolution**
O_3	Ozone [ppm]	2-D zonal mean	Monthly, Daily
H_2O	Water Vapor [ppm]	2-D zonal mean	Monthly, Daily
O3S	Stratospheric ozone tracer [ppm]	2-D zonal mean	Monthly
O3STE	Net stratosphere-to-troposphere exchange O3 flux (Tg/year)	2-D zonal mean	Monthly
AOD	Aerosol Optical Depth	2-D (lat, lon)	Monthly
e90	e90 [ppb]	2-D zonal mean	Monthly
AOA	Stratospheric Mean Age-of-Air [years]	2-D zonal mean	Monthly
ST80_25	ST80_25 [ppb]	2-D zonal mean	Monthly
O3_col	Total Column Ozone [DU]	2-D (lat, lon)	Monthly
NO	NO volume mixing ratio	2-D zonal mean	Monthly

	[ppb]		
NO_2	NO_2 volume mixing ratio [ppb]	2-D zonal mean	Monthly
N_2O	N_2O volume mixing ratio [ppb]	2-D zonal mean	Monthly
N_2O_5	N_2O_5 volume mixing ratio [ppb]	2-D zonal mean	Monthly
HNO_3	HNO_3 volume mixing ratio [ppb]	2-D zonal mean	Monthly
NOy	Total reactive nitrogen volume mixing ratio [ppb]	2-D zonal mean	Monthly
Cly	Total inorganic chlorine volume mixing ratio [ppb]	2-D zonal mean	Monthly
Bry	Total inorganic bromine volume mixing ratio [ppb]	2-D zonal mean	Monthly
Cl	Cl volume mixing ratio [ppb]	2-D zonal mean	Monthly
Br	Br volume mixing ratio [ppb]	2-D zonal mean	Monthly
O	O volume mixing ratio [ppb]	2-D zonal mean	Monthly
Total Cl	Total Cl volume mixing ratio [ppb]	2-D zonal mean	Monthly
Total Br	Total Br volume mixing ratio [ppb]	2-D zonal mean	Monthly
ClO	ClO volume mixing ratio [ppb]	2-D zonal mean	Monthly
$ClNO_2$	$ClNO_2$ volume mixing ratio [ppb]	2-D zonal mean	Monthly
$ClONO_2$	$ClONO_2$ volume mixing ratio [ppb]	2-D zonal mean	Monthly
HCl	HCl volume mixing ratio [ppb]	2-D zonal mean	Monthly
BrO	BrO volume mixing ratio	2-D zonal mean	Monthly

	[ppb]		
OH	OH volume mixing ratio [ppb]	2-D zonal mean	Monthly
HO_2	HO_2 volume mixing ratio [ppb]	2-D zonal mean	Monthly
CH_4	CH_4 volume mixing ratio [ppb]	2-D zonal mean	Monthly
SO_2	SO2 volume mixing ratio [ppb]	2-D zonal mean	Monthly
J_O3	O3 photolysis frequency [s^{-1}]	2-D zonal mean	Monthly
J_O2	O2 photolysis frequency [s^{-1}]	2-D zonal mean	Monthly
O3_prod	Ozone production [ppbv s^{-1}]	2-D zonal mean	Monthly
O3_loss	Chemical ozone loss [ppb s^{-1}]	2-D zonal mean	Monthly
O3_loss_Ox*	Chemical ozone loss by Ox [ppb s^{-1}]	2-D zonal mean	Monthly
O3_loss_HOx*	Chemical ozone loss by HOx [ppb s^{-1}]	2-D zonal mean	Monthly
O3_loss_NOx*	Chemical ozone loss by NOx [ppb s^{-1}]	2-D zonal mean	Monthly
O3_loss_ClOx*	Chemical ozone loss by ClOx [ppb s^{-1}]	2-D zonal mean	Monthly
SAD	Surface Area Density of Sulfate Aerosol [m^{-1}]	2-D zonal mean	Monthly
NAT	Surface Area Density of NAT PSC Particles [m^{-1}]	2-D zonal mean	Monthly
PSC	Surface Area Density of Water Ice PSC Particles [m^{-1}]	2-D zonal mean	Monthly

Notes for Table 5:
*These quantities will not make sense for tropospheric ozone, and if not diagnosed as such, need not be reported below the tropopause.

Finally, **Table 6** includes the same requests for 6-hourly instantaneous 3-D wind and temperature fields as in QBOi (see Table 4 in Butchart et al. (2018)) and will enable quantification of ozone feedbacks on equatorial wave spectra (e.g. Horinouchi et al., (2003); Lott et al., (2014)). Note that this data is requested for a specific subset of latitudes (15ºS to 15ºN) and on the plevTEM grid above 150 hPa, as in QBOi Phase 1. Output for one ensemble member is requested for at least 10 years (30 years strongly encouraged).

Table 6: The 6-hourly instantaneous 3-D equatorial output for assessing equatorial wave spectra. Data is requested only for a subset of latitudes (15ºS to 15ºN), pressure levels (vertical resolution equivalent to underlying model resolution between 150 hPa and 0.4 hPa), and 10 years of one ensemble member (although 30 years is strongly encouraged).

Variable Name	**Long name [units]**	**Spatial Dimension**	**Temporal Resolution**
ta	Air Temperature [K]	3-D	6-hourly
ua	Eastward wind [ms^{-1}]	3-D	6-hourly
va	Northward wind [ms^{-1}]	3-D	6-hourly
wap	Vertical Velocity, Omega (=dp/dt) [Pas^{-1}]	3-D	6-hourly

VII. Data Storage

Data will be uploaded and stored to the QBOi collective workspace on JASMIN, with eventual long-term archiving to the CEDA permanent archive. The current estimate of required data storage for 8 models contributing all Tier 1 and Tier 2 experiments is ~15 TB and is broken down here, where the same byte-per-grid-cell estimate used in estimating storage for the CCMI Phase 2 experiments has been used. Note that, while CMORizing of data is strongly encouraged, it is not required for hosting on the CEDA archive.

VIII. Participating Models

Models participating in this activity will need to be able to run with *both* interactive ozone (however simple the scheme may be) and with an interactive QBO.

Current contributing modeling centers and associated models are:

#1. NASA GEOS-CCM (Contact: Feng Li)

#2. EMAC (Contacts: Tobias Kerzenmacher and Stefan Versick; if not EMACL90 then ICON)

#3. NASA GISS E2.2 (Contact: Clara Orbe)

#4. MIROC-ES2H (Contact: Shingo Watanabe)

#5. AGCM3-CMAM (Contact: James Anstey)

#6. CESM2 (WACCM6) (Contacts: Gabriel Chiodo and Rolando Garcia)

#7. UKESM1-StratTrop (Contact: James Keeble)

#8. E3SM (Contact: Qi Tang)

IX. Proposed Analysis, Associated Experiments and Potential Leads

A more formal designation of working group leads will be made during a virtual workshop in Fall 2024 (date TBD) and the following represents only a tentative draft of topic titles and potential contributors to the associated analysis.

#1. Description of Overall Effort (Everyone)

#2. Analysis of Present Day (PD) Ozone Feedback on QBO (PD_NINT, PD_INT) (Everyone)

#3. Analysis of Future (FT) 4xCO_2 Ozone Feedback on QBO (PD_NINT, FT_4xCO_2_INT, FT_4xCO_2 _NINT, FT_4xCO_2_INT+PDSST, FT_INT_1xCO_2+4KSST) (Everyone)

#4. Analysis of PD and 4xCO_2 QBO Passive and Chemical Tracers (C. Orbe, M. Diallo)

#5. Analysis of 4xCO_2 Ozone Feedback of Brewer-Dobson Circulation, as well as polar vortex, and large-scale circulation (G. Chiodo, S. Kaeslin, N. Calvo, A. Chrysanthou)

#6. Fixed Dynamical Heating Assessment of Ozone Feedback on Temperature 4xCO_2 Response and other Idealized Calculations. (A. Ming, P. Hitchcock)

#7. Impact of Enhanced Ozone QBO on Teleconnections (M. Diallo, N.Calvo (polar vortex))

Broader interest in analysis:

Amy Butler, Dillon Elsbury, Ewa Bednarz, Young-Ha Kim, Thomas Reichler, Seok-woo Son

X. Proposed Timeline

February 2024: Initial release of experimental protocol and community meeting
March 2024: Time for receipt of community feedback
April 2024: Final protocol is released
April 2024-Spring 2025: Modeling centers run experiments and upload to the QBOi JASMIN workspace
Summer-Fall 2024: Identification of working groups and associated leads
Fall 2024: Submission of experimental protocol to GMD

Fall 2024: Virtual workshop, joint with QBOi, to discuss proposed analysis and present preliminary result
Summer 2025: Presentation of results at the QBOi workshop (location tentatively set for Cornell U., Ithaca, NY)

XI. Prescribed Ozone Values in the FT_NINT_4xCO_2 Experiment

Note that prescribing PD_NINT ozone concentrations in the FT_NINT_4xCO_2 integration will result in a disconnect between the 4xCO_2 (heightened) dynamical tropopause and the chemical tropopause implied in the prescribed ozone distribution. While this inconsistency can be corrected for either through prescription of the FT_INT_4xCO_2 ozone concentrations and/or ozone redistribution (for an example see Hardiman et al. (2019)), we clarify that the 4xCO_2 ozone feedback we seek to capture targets the following question: "How does the ozone response to 4xCO_2 (consisting of an ozone response to *both* a rise in tropopause height and an acceleration of the BDC) modulate the QBO-ozone feedback?" This question is distinct from asking how the ozone feedback captured by the PD_NINT and INT experiments (i.e., the mechanism initially proposed in Butchart et al. (2003)) changes under climate change. We privilege the former question mainly because it more directly challenges the CMIP6 prescription to use preindustrial control ozone concentrations in the 4xCO_2 experiment. As such, it more practically addresses potential issues that may have surfaced in the CMIP6 ensemble when ozone feedbacks on the climate's response to CO_2 were ignored.

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