"Understanding Ozone-QBO Feedbacks: A New Joint SPARC Quasi-Biennial Oscillation Initiative (QBOi) and Chemistry Climate Modeling Initiative (CCMI) Activity"

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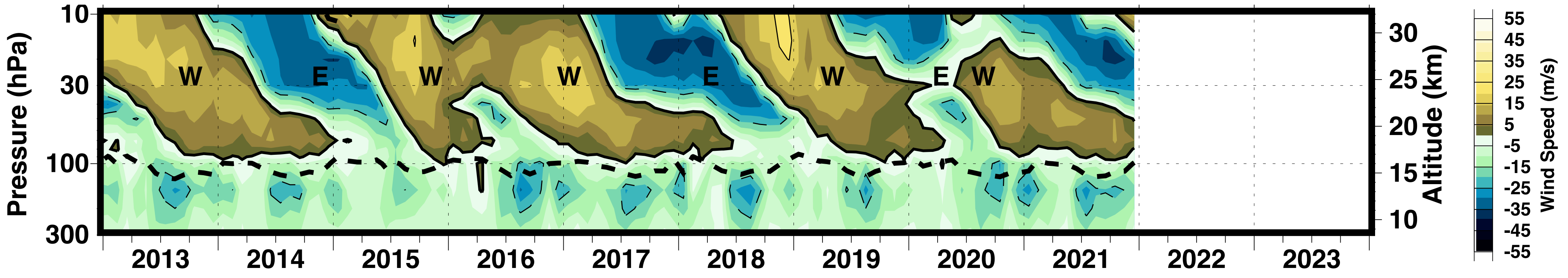
Motivation

- The Quasi-biennial Oscillation (QBO) contributes to the variability of stratospheric (*Butchart et al. (2003)*) and surface (*Ray et al. (2020)*) trace gases and modulates teleconnections to the stratospheric polar vortex (*Naito et al. (2003)*) and to tropospheric high latitudes (*Gray et al. (2017)*, *Garfinkel et al. (2012)*).
- The QBO Initiative (QBOi) is oriented toward improving the QBO in global climate models. One key takeaway from the QBOi workshop held in Oxford, UK (March 27-31, 2023) was the need for "***experiments to test QBO sensitivity to ozone feedbacks***".

Singapore Sonde Monthly Mean QBO

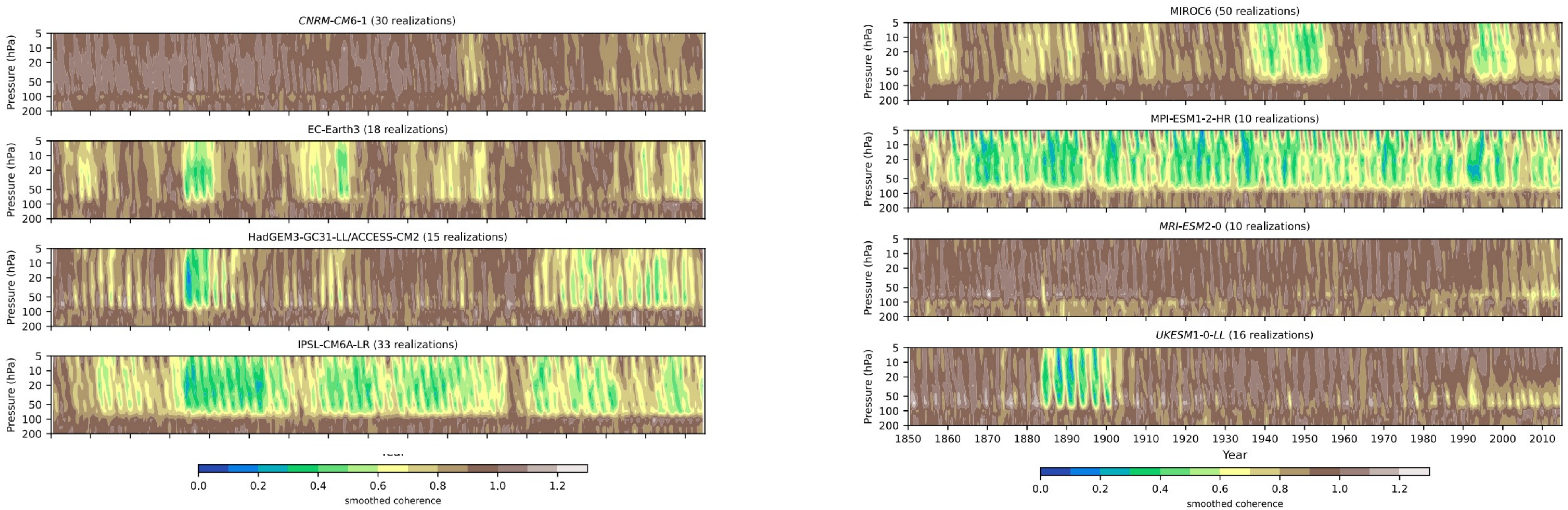


Source: Paul A. Newman, Larry Coy, Leslie R. Lait, Eric R. Nash (NASA/GSFC)

Motivation

- This renewed interest in understanding ozone feedbacks on the QBO partly reflects reports of a curious QBO synchronization among CMIP6 models constrained with CCMI ozone forcing (*Butchart and Andrews (2023)*).
- Models using the CMIP6 ozone forcing set showing more ensemble coherence (blue/green), compared to those that do not (brown).

Smoothed Ensemble Coherence of Equatorial U

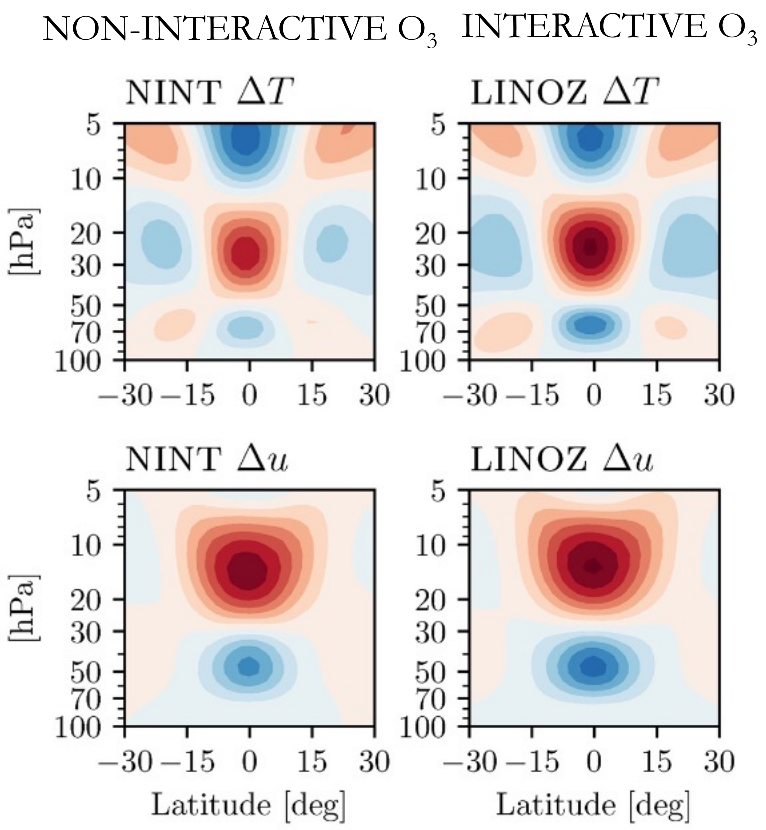


Modified from *Butchart and Andrews (2023)*

Motivation

More generally, improved understanding of ozone feedbacks on the QBO are important for:

- Self-Consistent Representations of Lower Stratospheric Dynamical and Compositional Variability
- Understanding the Ozone Response to Volcanic Forcing (e.g., *Klobas et al. (2017), Tie and Brasseur (1995)*).
- QBO Biases: Ozone feedbacks may enhance QBO amplitudes in the lower stratosphere (*DallaSanta et al. (2021)*), where models exhibit persistent biases (*Richter et al. (2020)*).



Modified from *DallaSanta et al. (2021)*

Historical Ozone Feedback on QBO Winds and Temperatures

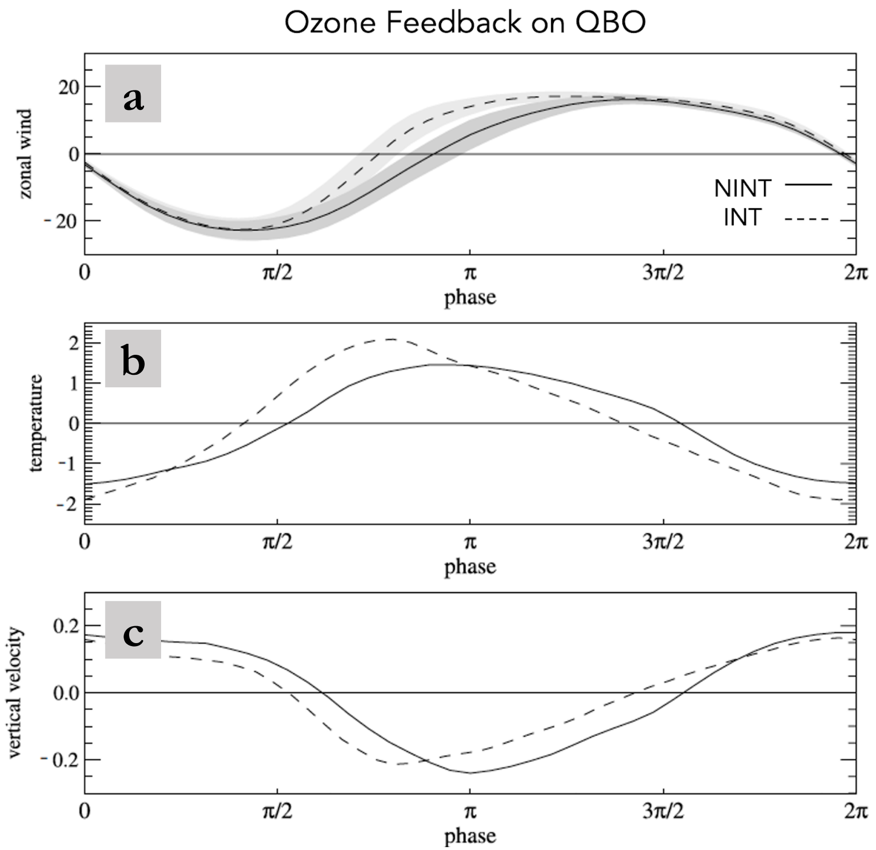
- Several studies have examined ozone feedbacks on the QBO, almost exclusively using single models run during the recent historical era (e.g., *Butchart et al. (2003), Shibata and Deushi (2005), Shibata (2021), Butchart and Andrews (2023)*).

- These studies show little consensus on how ozone feedbacks modulate:

#1. QBO periods: longer (*Butchart et al. (2003), DallaSanta et al. (2021)*) vs. shorter (*Cordero et al. (1998)*) vs. negligible impact (*Cordero and Nathan (2000)*)

#2. QBO temperature amplitude: as large as 35% (right **b**, *Butchart et al. (2003)*) and as weak as 2% (*Shibata and Deushi (2005)*).

#3. QBO meridional circulation: weaker (right **c**, *Butchart et al. (2003)*) vs. negligible impact (*Shibata (2021)*).

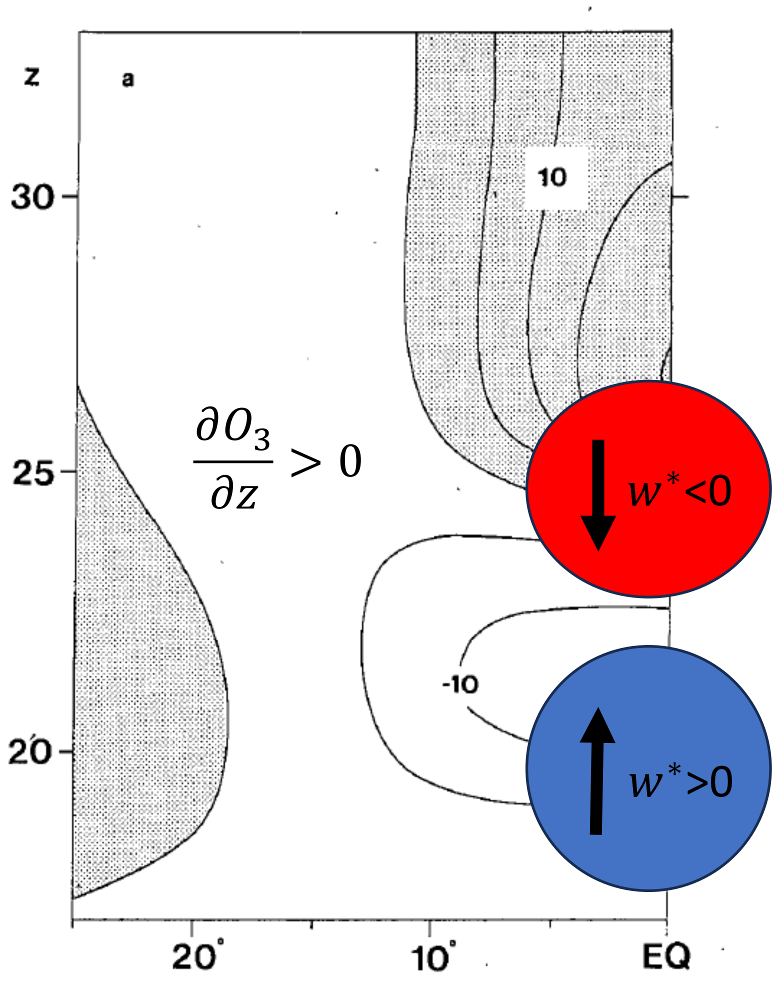


Modified from *Butchart et al. (2003)*

Historical Ozone Feedback on QBO Meridional Circulation

- Proposed mechanism for a weakened QBO meridional circulation: the additional diabatic heating produced by the ozone QBO offsets the heating that is required to maintain thermal balance in the presence of radiative cooling (*Dunkerton (1985)*). The downward transport of ozone (in the presence of strong $\frac{\partial O_3}{\partial z}$) will elevate radiative equilibrium temperatures, reducing the vertical motion that is needed to maintain the temperature perturbation against radiative damping.

- This is a ***direct*** zonal mean ozone feedback that occurs via changes in diabatic heating. However, ***indirect*** zonal mean ozone feedbacks may alter the absorption and damping of Kelvin and Rossby-gravity waves and, thus, indirectly affect both the QBO and the wave-driven meridional circulation. Direct and indirect effects can offset one another (*Cordero and Nathan (2000)*).



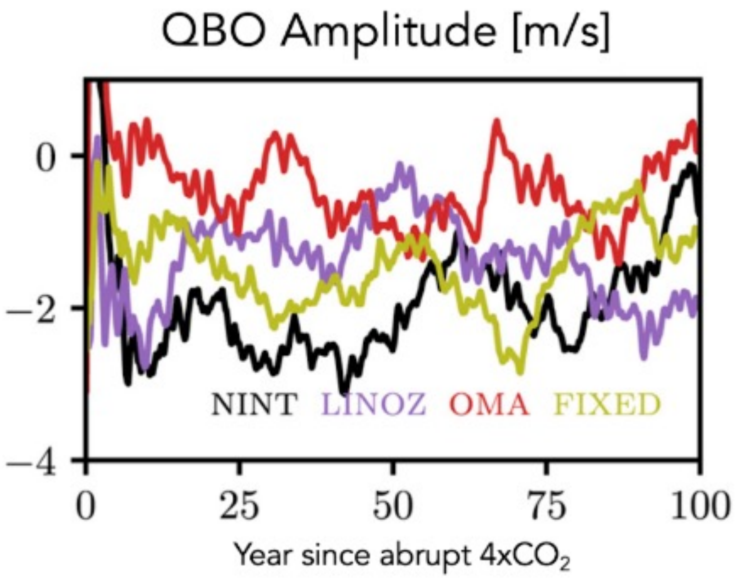
Modified from *Dunkerton (1985)*

$4xCO_2$ Ozone Feedbacks on QBO Amplitude

- Compared to the historical era, ozone-QBO feedbacks in future climate have been relatively unexplored.

- In response to $4xCO_2$, QBO amplitudes are projected to weaken, although the magnitude of this weakening is highly uncertain (*Richter et al. (2020)*).

- One recent study shows that ozone feedbacks may ***dampen*** this response (*DallaSanta et al. (2021)*, right). Linked to a dampening of CO_2-induced increased residual mean upwelling (w^*) in the mid-stratosphere (*DallaSanta et al. (2021)*), also reported in *Hufnagl et al. (2023)*.



DallaSanta et al. (2021)

NINT: non-interactive
INT: interactive O_3 and aerosols
LINOZ: interactive O_3

Limitations from Previous Studies

- Overall, large uncertainties persist in our understanding of how ozone feedbacks modulate the QBO in both historical and future climates.

- Inconsistent methodologies among studies precludes a clean attribution of drivers of these uncertainties. Furthermore, some previous studies have the following limitations:

  #1. Inconsistent definitions of ozone-QBO feedbacks (i.e., comparing interactive ozone simulations with simulations driven by a prescribed observational climatology).

  #2. Misattribution of ozone-QBO feedbacks to ozone variability and trends unrelated to the QBO. Correcting for this requires definition of the historical ozone field in the absence of the QBO.

  #3. Complexity of the coupled atmosphere-ocean 4xCO_2 response reflects compound uncertainties in both the SST-driven mean circulation and in parameterized gravity wave forcing from convection.

Proposed QBOi-CCMI Experiments: Key Science Questions

- In light of these limitations from previous studies, we propose a joint QBOi-CCMI endorsed protocol for examining ozone-QBO feedbacks in a more ***consistent*** and ***simplified*** framework.

- This framework focuses on defining ozone feedbacks consistently between non-interactive (NINT) and interactive (INT) chemistry simulations, accounting for non-QBO related ozone variability and employing a simplified atmosphere-only (AMIP) framework to minimize intermodel differences associated with differences in SSTs.

Proposed QBOi-CCMI Experiments: Key Science Questions

- To this end, 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, amplitude and meridional circulation?

  Q2) What is the ozone 4xCO_2 feedback on QBO period and amplitude? How is this coupled to ozone feedbacks on the mean meridional circulation, temperatures and winds in the stratosphere?

  Q3) What are the mechanisms associated with the changes in 1) and 2)? How do these differ between models with interactive vs. specified NOGWD parameterizations? For 2) what is the relative importance of direct radiative CO_2 changes vs. SST adjustments?

Why Now and Why CCMI?

The existing archives of both CMIP6 and QBOi simulations **cannot** be used to adequately address science questions ***Q1-Q3***.

- In particular, while 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)*), clean pairs of "non-interactive" and "interactive" simulations do not exist across the CMIP6 archive.
- At the same time, most of the QBOi models do not run with interactive chemistry.
- We propose that this gap be filled by CCMI, which includes at least 7 models capable of running both fully interactive chemistry and interactive QBOs (*Morgenstern et al. (2017), Ayarzaguena et al. (2018)*).

CCMI models	Model resolution	QBO	Solar variability	SSTs	
GEOS-CCM	2.5° x 2°, L72 (top:0.01hPa)	Internally generated	No	Prescribed (CESM1)	★
CNRM-CCM	T42L60 (top: 0.07 hPa)	Internally generated	Yes	Prescribed (CNRM)	★
NIWA-UKCA	3.75° x 2.5°, L60 (top: 84 km)	Internally generated	No	Coupled to ocean model	★
CCSRNIES-MIROC 3.2	T42L34 (top: 0.012 hPa)	Nudged	Yes	Prescribed (MIROC 3.2)	
IPSL-LMDZ-REPROBUS	3.75° x 2.5°, L39 (top: 70 km)	Nudged	--	Prescribed (SRES A1b IPSL)	
ACCESS-CCM	3.75° x 2.5°, L60 (top: 84 km)	Internally generated	No	Prescribed (HadGEM-ES2)	★
HadGEM3-ES	1.875°x1.25°, L85 (top: 85 km)	Internally generated	Yes	Coupled to ocean model	★
SOCOL3	T42L39 (top: 0.01hPa)	Nudged	Yes	Prescribed (CESM1(CAM5))	
MRI-ESM1r1	TL159L80 (top: 0.01hPa)	Internally generated	Yes	Coupled to ocean model	★
EMAC-L47	T42L47 (top: 0.01hPa)	Nudged	Yes	Prescribed (HadGEM2-ES)	
EMAC-L90	T42L90 (top: 0.01hPa)	Internally generated (slightly nudged)	Yes	Prescribed (HadGEM2-ES)	★
CMAM	T47L71 (top: 0.0575 hPa)	Internally generated	No	Prescribed (CanCM4)	★

Ayarzaguena et al. (2018)

Proposed Protocol: Present-Day AMIP* Simulations

Present-Day "Interactive" Experiment (PD INT) is nearly identical to the (1960 - 2018) REF-D1 CCMI hindcast simulation, except that the QBO is ***interactive***, not nudged. For modeling groups contributing to QBOi, this experiment mimics QBOi Phase 1 Experiment 1, except run with interactive chemistry and using CMIP6 (not CMIP5) forcings.

Tier 1

Present-Day "Non-interactive" Experiment (PD NINT): PD NINT is identical to PD INT, except prescribing a "QBO-filtered" (QBOf) three-dimensional ozone field derived from PD INT and keeping all other compositional and boundary forcings identical. QBOf is constructed using a 3-year running mean (i.e., January Year 2 smoothed ozone equals the average of January Year 1, January Year 2, and January Year 3) from each PD INT member and then used to constrain each respective PD INT ensemble member.

Tier 1

Present-Day "Eddy" Experiment (PD EDDY**)** is identical to PD NINT, but only prescribes the zonal mean QBOf ozone.

Tier 2

*3 ensemble members all exps

Proposed Protocol: Present-Day AMIP Simulations

Experiment Name	Simulation Length [years]	Ozone	CO_2	Other Comp. Forcings (ODS,CH_4,NO_2)	SSTs	SICs	Priority
PD INT	60	Interactive	CMIP6	CMIP6 (REF-D1)	HadISST1	HadISST1	**Tier 1**
PD NINT	60	QBOf	CMIP6	CMIP6 (REF-D1)	HadISST1	HadISST1	**Tier 1**
PD EDDY	60	Zonal Mean QBOf	CMIP6	CMIP6 (REF-D1)	HadISST1	HadISST1	Tier 2

PD INT – PD NINT = present day ozone feedback on QBO (***Q1***)

PD EDDY – PD INT = influence of eddies on present day ozone feedback on QBO (***Q3***)

Proposed Protocol: 4xCO_2 AMIP* Simulations

Future "Interactive" Experiment (FT CTRL): 30-year-long AMIP simulation constrained using the 1960s decadal mean annual cycles of SSTs, SICs, volcanic and solar forcing and other external compositional forcings (e.g., CH_4, N_2O, ODS) derived from the inputs used in PD NINT.

Tier 1

Future 4xCO_2 "Non-Interactive" Experiment (FT NINT 4xCO_2): FT NINT 4xCO_2 is identical to FT CTRL, with two exceptions: 1) CO_2 concentrations are quadrupled from the values prescribed in FT CTRL and 2) a spatially uniform perturbation of +4K is applied to all SST grid points. Sea ice concentrations (SICs) are kept fixed to the values used in FT CTRL.

Tier 1

Future 4xCO_2 "Interactive" Experiment (FT INT 4xCO_2): Identical to FT NINT 4xCO_2, except with ozone responding to 4xCO_2 and +4K SSTs.

Tier 1

Future FixSST 4xCO_2 "Interactive" Experiment (FT INT 4xCO_2 FIXSST) is identical to FT INT 4xCO_2, except using SSTs from FT CTRL.

Tier 2

Future 1xCO_2 + 4K SST "Interactive" Experiment (FT INT 1xCO_2+4KSST) is identical to FT INT 4xCO_2, except that CO_2 concentrations are from FT CTRL.

Tier 2

*3 ensemble members all exps

Proposed Protocol: $4xCO_2$ AMIP* Simulations

FT NINT $4xCO_2$ – FT CTRL: = $4xCO_2$ response of QBO (***Q2***)

FT INT $4xCO_2$ – FT NINT $4xCO_2$ = $4xCO_2$ ozone feedback on QBO (***Q2***)

FT INT $4xCO_2$ FIXSST– FT INT = contribution of CO_2 to $4xCO_2$ ozone feedback (***Q3***)

FT INT $1xCO_2$ + 4K SST – FT INT = contribution of SSTs to $4xCO_2$ ozone feedback (***Q3***)

Experiment Name	Simulation Length [years]	Ozone	CO_2	Other Comp. Forcings (ODS,CH_4,NO_2)	SSTs	SICs	Priority
FT CTRL	30	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	**Tier 1**
FT NINT $4xCO_2$	30	PD NINT 1960s annual cycle	4xCO2, relative to PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle + uniform 4K	PD NINT 1960s annual cycle	**Tier 1**
FT INT $4xCO_2$	30	Interactive	4xCO2, relative to PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle + uniform 4K	PD NINT 1960s annual cycle	**Tier 1**
FT INT $4xCO_2$ FIXSST	30	Interactive	4xCO2, relative to PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	Tier 2
FT INT $1xCO_2$+4KSST	30	Interactive	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle	PD NINT 1960s annual cycle + uniform 4K	PD NINT 1960s annual cycle	Tier 2

Requested Diagnostics

Diagnostics follow the requests from both DynVarMIP (*Gerber and Manzini (2016)*) and QBOi (*Butchart et al. (2020)*), with special focus placed on:

- Transformed Eulerian Mean (TEM) circulation
- Eastward wind tendencies (orographic gravity waves, non-orographic gravity waves, TEM advection, resolved Eliassen-Palm flux convergence)
- Additional diagnostics for assessing impacts on Madden-Julian Oscillation (MJO) and surface teleconnections
- Ozone and idealized tracer output (e90, AOA, st8025) (*Orbe et al. (2018)*)

Planned Analysis

The requested experiments and diagnostics will service the following analysis:

- Analysis of Present Day (PD) Ozone Feedback on QBO (PD NINT, PD INT, PD EDDY)
- Analysis of $4xCO_2$ Ozone Feedback on QBO (FT CTRL, FT $4xCO_2$ NINT, FT $4xCO_2$ INT, FT $4xCO_2$ INT FIXSST, FT INT $1xCO_2$+4KSST)
- Analysis of QBO Passive and Chemical Tracer Responses to $4xCO_2$
- Analysis of $4xCO_2$ Ozone Feedback of Brewer-Dobson Circulation
- Fixed Dynamical Heating Assessment of Ozone Feedback on Temperature $4xCO_2$ Response
- Impact of Enhanced Ozone QBO on Teleconnections

Summary

Here we propose to address long-standing uncertainties in ozone feedbacks on QBO via a more ***consistent*** and ***simplified*** framework of joint QBOi-CCMI experiments.

- Understanding processes and mechanisms is one of the core missions of CCMI.

- Improved understanding of QBO biases can help the broader global modeling community.

- The proposed experiments can more generally be used to understand ozone feedbacks on the Brewer-Dobson circulation and the troposphere.

- No existing QBOi or CMIP6 experiments can cleanly address these questions. Our goal is to maximize intersection with other CCMI efforts so that these simulations can be optimally responsive to the science interests of the broader CCMI community.

Summary

Protocol is currently being reviewed by the QBOi and CCMI steering committees. After this review, the protocol will be made available for public review.

Where does this fit within the broader CCMI landscape? Let's discuss!

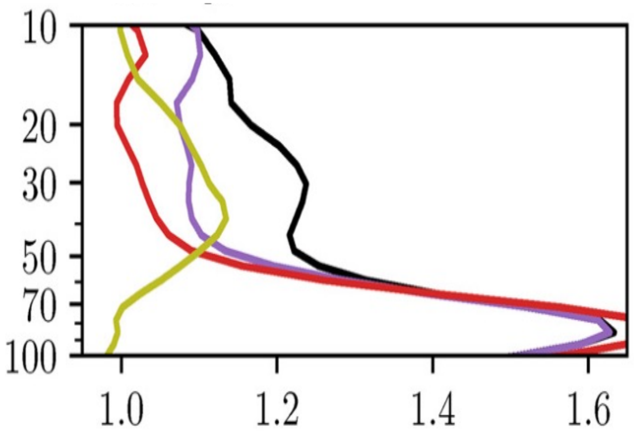
Please contact me with questions at **clara.orbe@nasa.gov**

$4xCO_2$ Ozone Feedbacks on QBO Amplitude

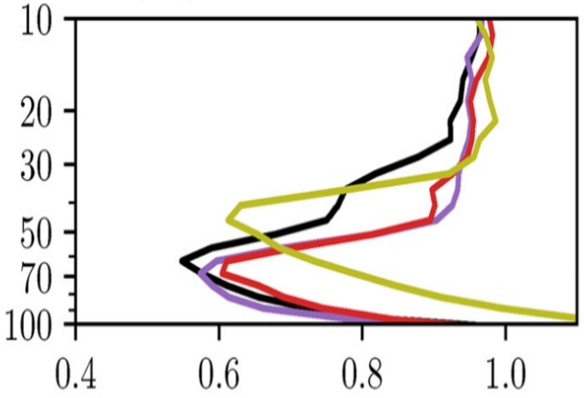
The proposed mechanism involves:

- #1. Ozone feedbacks dampen the CO_2-induced increase in residual mean upwelling (*w**) in the mid-stratosphere (*DallaSanta et al. (2021)*, right), also reported in *Hufnagl et al. (2023)*.
- #2. Stronger *w** from #1 in interactive ozone runs primarily affects easterly QBO (eQBO), which increases the easterly momentum deposition from parameterized convective waves. This further mitigates a reduction of eQBO amplitudes (*DallaSanta et al. (2021)*, below)

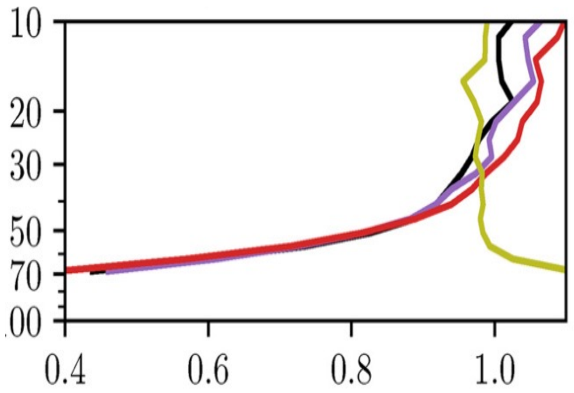
Tropical *w**
$4xCO_2$/PiControl



Tropical eQBO U
$4xCO_2$/PiControl



Tropical wQBO U
$4xCO_2$/PiControl



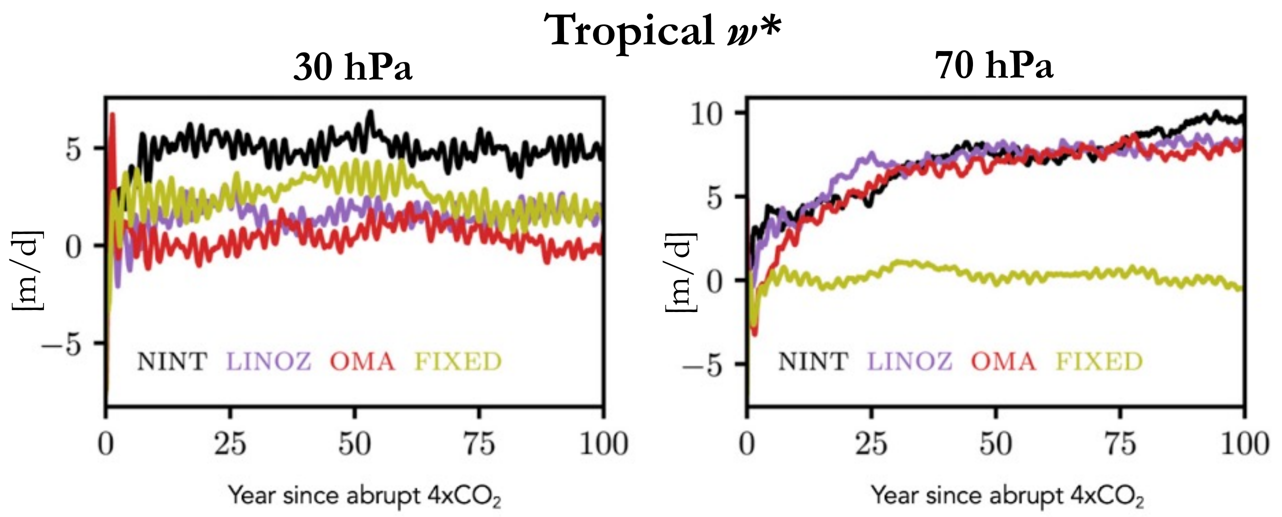
NINT: non-interactive
INT: interactive O_3 and aerosols
LINOZ: interactive O_3

DallaSanta et al. (2021)

$4xCO_2$ Ozone Feedbacks on Brewer-Dobson Circulation

Recent studies show that ozone feedbacks dampen the BDC response to $4xCO_2$:

- #1. *DallaSanta et al. (2021)* report reduced tropical residual mean upwelling (*w**) in the mid-stratosphere (but not lower stratosphere) in simulations in which ozone responds to $4xCO_2$.



NINT: non-interactive
INT: interactive O_3 and aerosols
LINOZ: interactive O_3

DallaSanta et al. (2021)

- #2. *Hufnagl et al. (2023)* report that ozone changes dampen the CO_2-induced BDC strengthening throughout the stratosphere (5-100 hPa). They attribute this weakening to attenuated vertical wave propagation during boreal summer, when ozone feedbacks enhance stratospheric easterlies.