

Exploring the Impact of CO₂ and Ozone Changes on the QBO in Aqua-Planet Simulations

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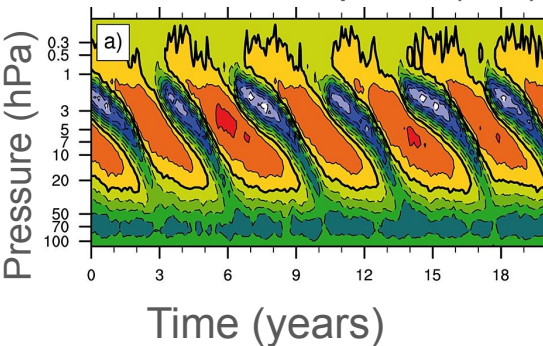
Goal: Explore QBO response to CO₂ and O₃ in an idealized model

Model Complexity



Dry Held Suarez

Zonal Wind at Equator (m/s)

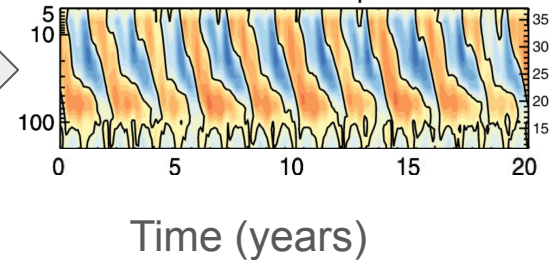


Yao and Jablonowski (2013, 2015)



Fully-Coupled

Zonal Wind at Equator (m/s)



Richter et al., 2020 - QBOi Experiment

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Model Complexity

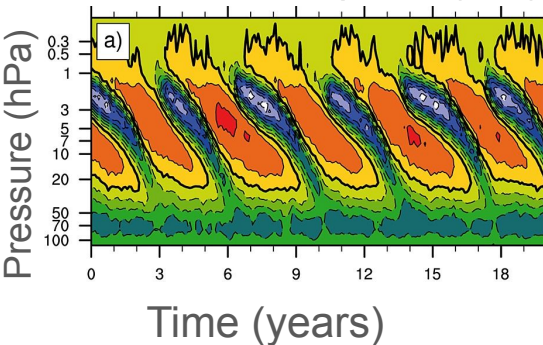


Dry Held-Suarez configuration

Aquaplanet

Fully-Coupled

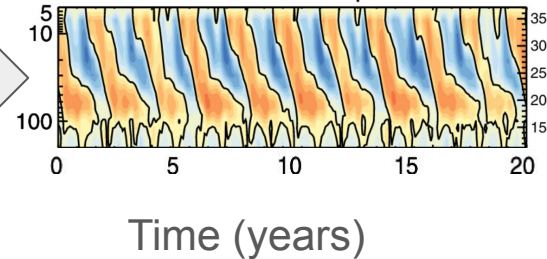
Zonal Wind at Equator (m/s)



- Water-covered Earth
- No topography
- Prescribed Sea Surface Temperatures (SSTs)
- No seasons



Zonal Wind at Equator (m/s)



Yao and Jablonowski (2013, 2015)

Richter et al., 2020 - QBOi Experiment

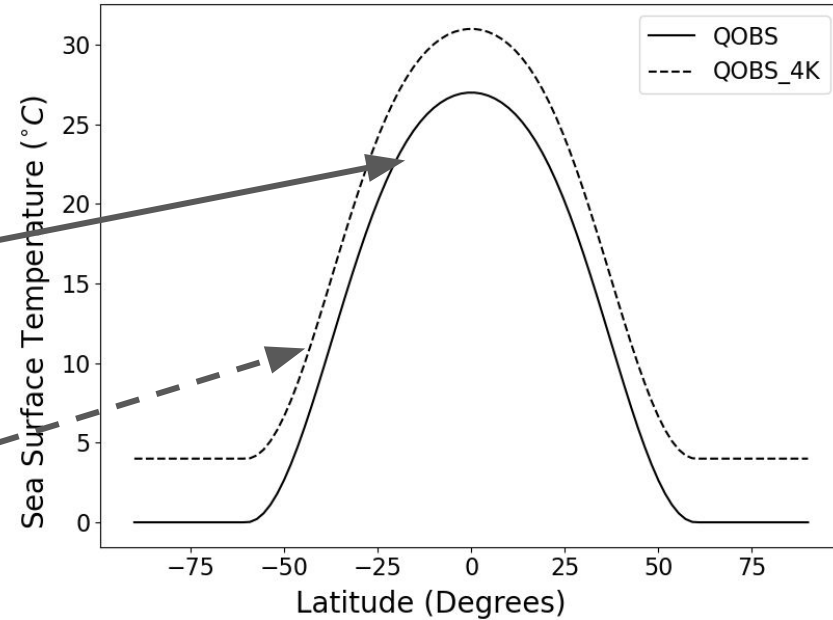
Aquaplanet Experimental Setup

- Development version of NCAR's upcoming **Community Earth System Model version 3** (CESM3) with the **Community Atmosphere Model version 7** (CAM7)
- Spectral Element (SE) dynamical core
- CAM7 physics package
- 110 km ($\sim 1^\circ$) horizontal spacing
- 72 levels with model top at 0.1 hPa (~ 61 km model top), developed for DoE's E3SMv2 model
- Incorporates recent (Feb. 2025) fix to the convective gravity wave drag scheme (Beres scheme)
- Aerosol-radiation and aerosol-cloud interactions are removed
- 20-year simulations after 2-year spin-up
20-year climatologies or composites are shown

Aquaplanet Experimental Setup

Experiment Name	CO ₂ Concentration	O ₃ Level	SST Profile
1xCO ₂	348 ppmv	1xO ₃	QOBS
4xCO ₂	1392 ppmv	1xO ₃	QOBS
4xCO ₂ _4K	1392 ppmv	1xO ₃	QOBS_4K
4xO ₃	348 ppmv	4xO ₃	QOBS

Prescribed ocean temperatures (SSTs)

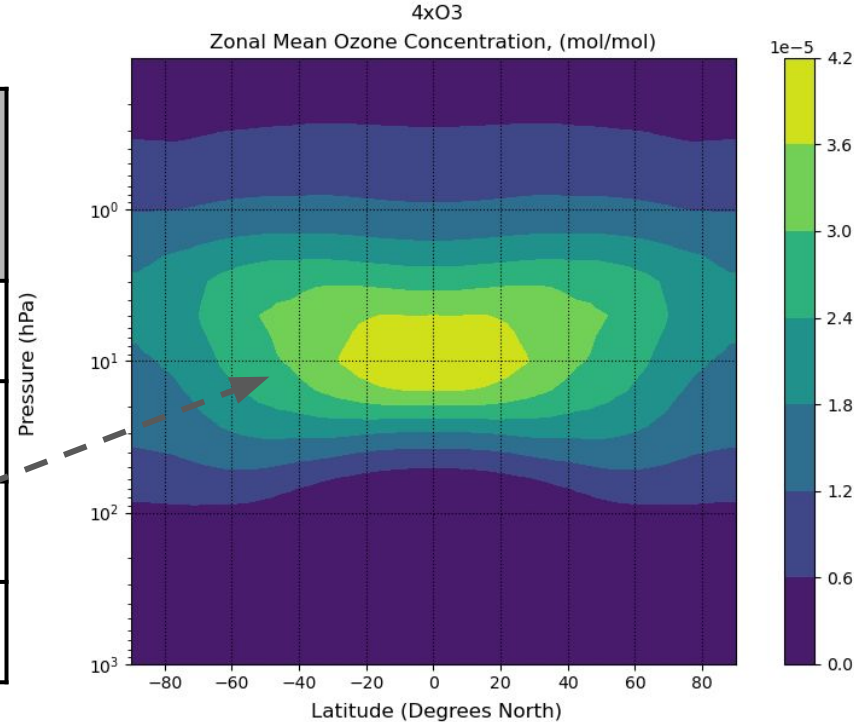


SST increase mimics the approach of the QBOi protocol

Aquaplanet Experimental Setup

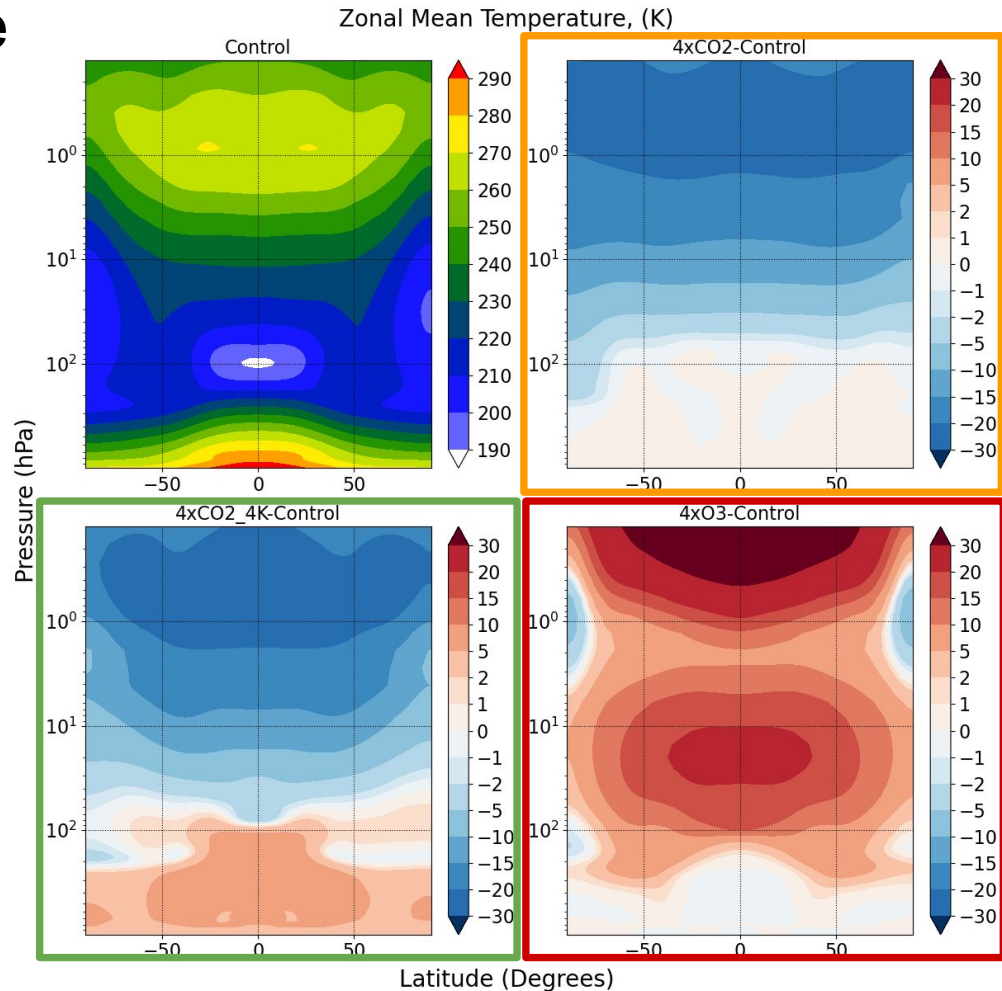
Experiment Name	CO ₂ Concentration	O ₃ Level	SST Profile
1xCO2	348 ppmv	1xO3	QOBS
4xCO2	1392 ppmv	1xO3	QOBS
4xCO2_4K	1392 ppmv	1xO3	QOBS_4K
4xO3	348 ppmv	4xO3	QOBS

Prescribed ozone concentration: 4xO3



Mean aquaplanet temperature anomalies match expected response to CO₂ and O₃

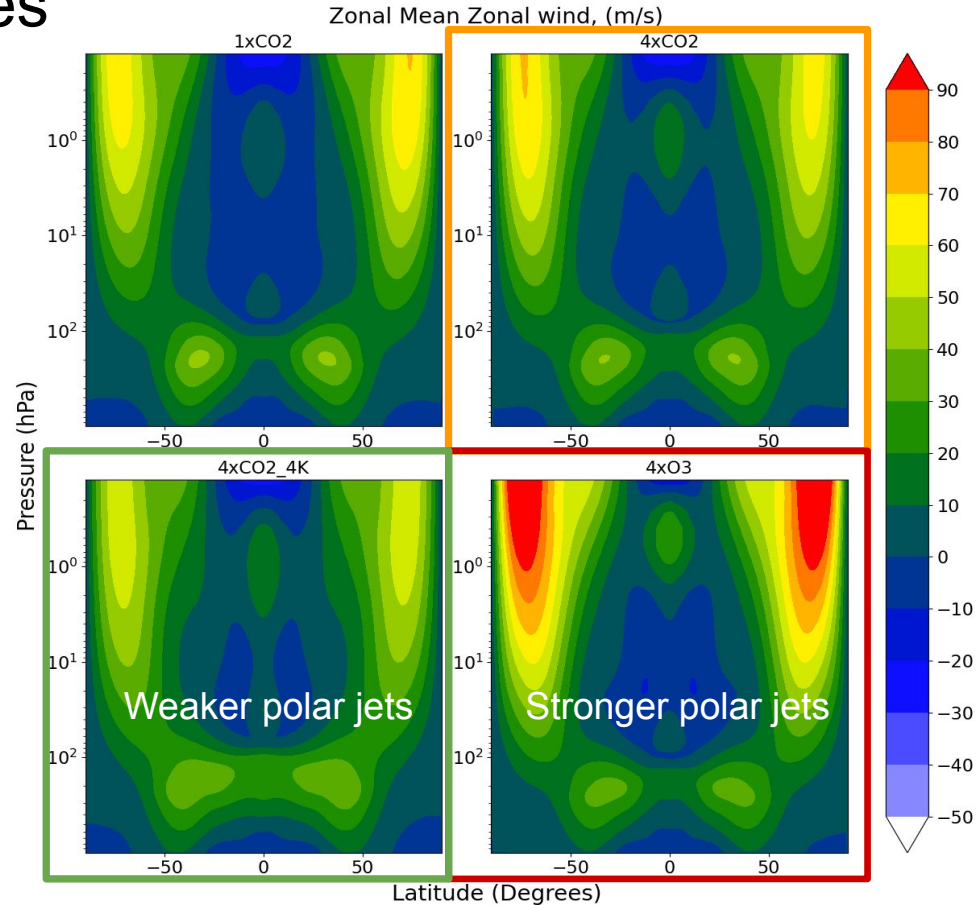
- **4xCO2** and **4xCO2_4K** show stratospheric cooling due to increased outgoing radiation from CO₂
- **4xCO2_4K** exhibits pronounced tropospheric warming due to the increased SSTs
- The **4xO3** stratosphere warms due to increased absorption of solar radiation by O₃.
- Asymmetries caused by SSWs



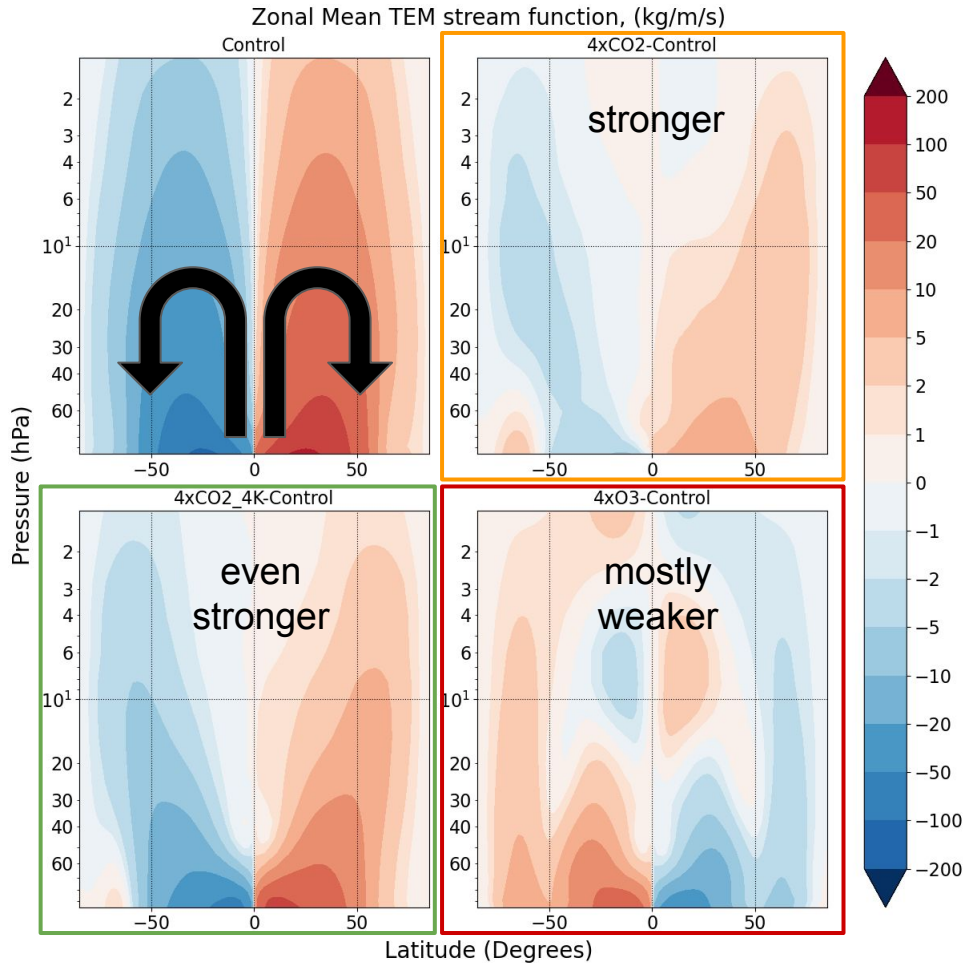
CO₂ and O₃ impact the strength of the stratospheric polar vortices

- Stratospheric cooling in **4xCO2** and **4xCO2_4K** decreases the meridional temperature gradient, which results in **weakened polar vortices**
- Stratospheric warming in **4xO3** increases the meridional temperature gradient, which results in **strengthened polar vortices**
- Asymmetries in the polar vortex response due to frequent sudden stratospheric warmings (SSWs)

Zonal-mean zonal wind climatology

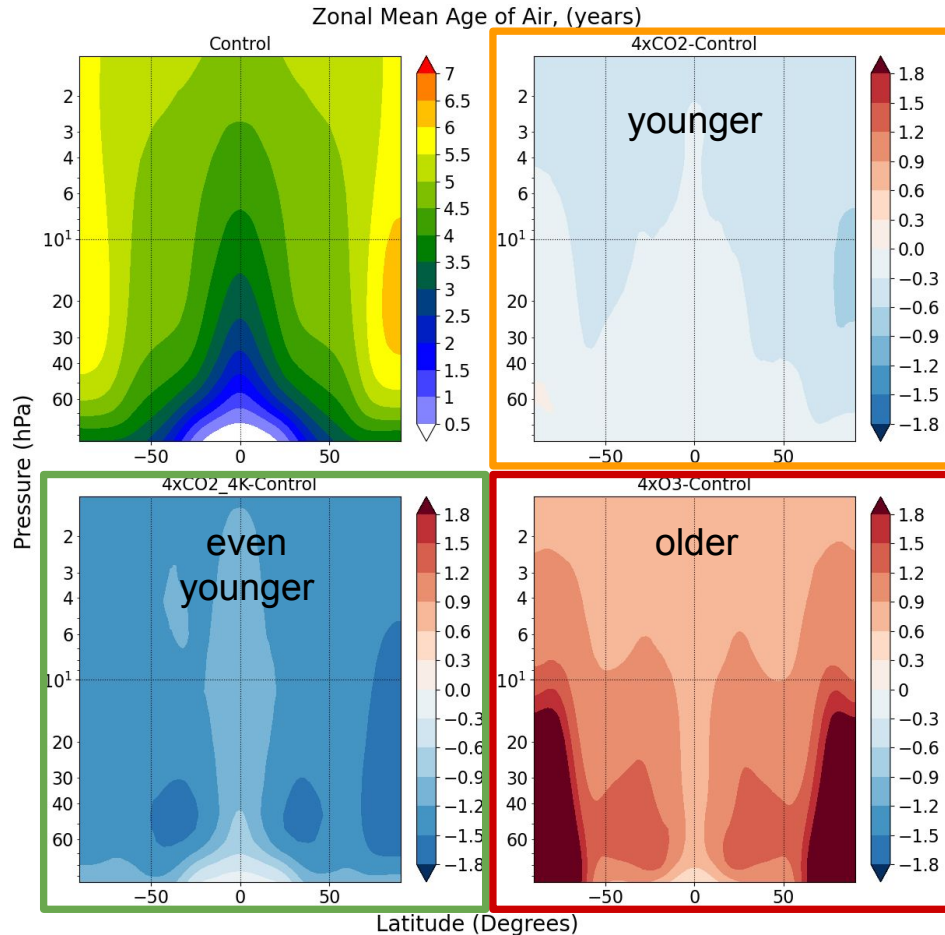


The mean meridional **Brewer Dobson Circulation (BDC)** is modulated by CO_2 and O_3



- Increased residual stream function in the **4xCO₂** and **4xCO₂_4K** simulations relative to the control represents **BDC strengthening**, consistent with many other modeling studies
- Decreased residual stream function in the **4xO₃** simulation relative to control represents **BDC weakening**

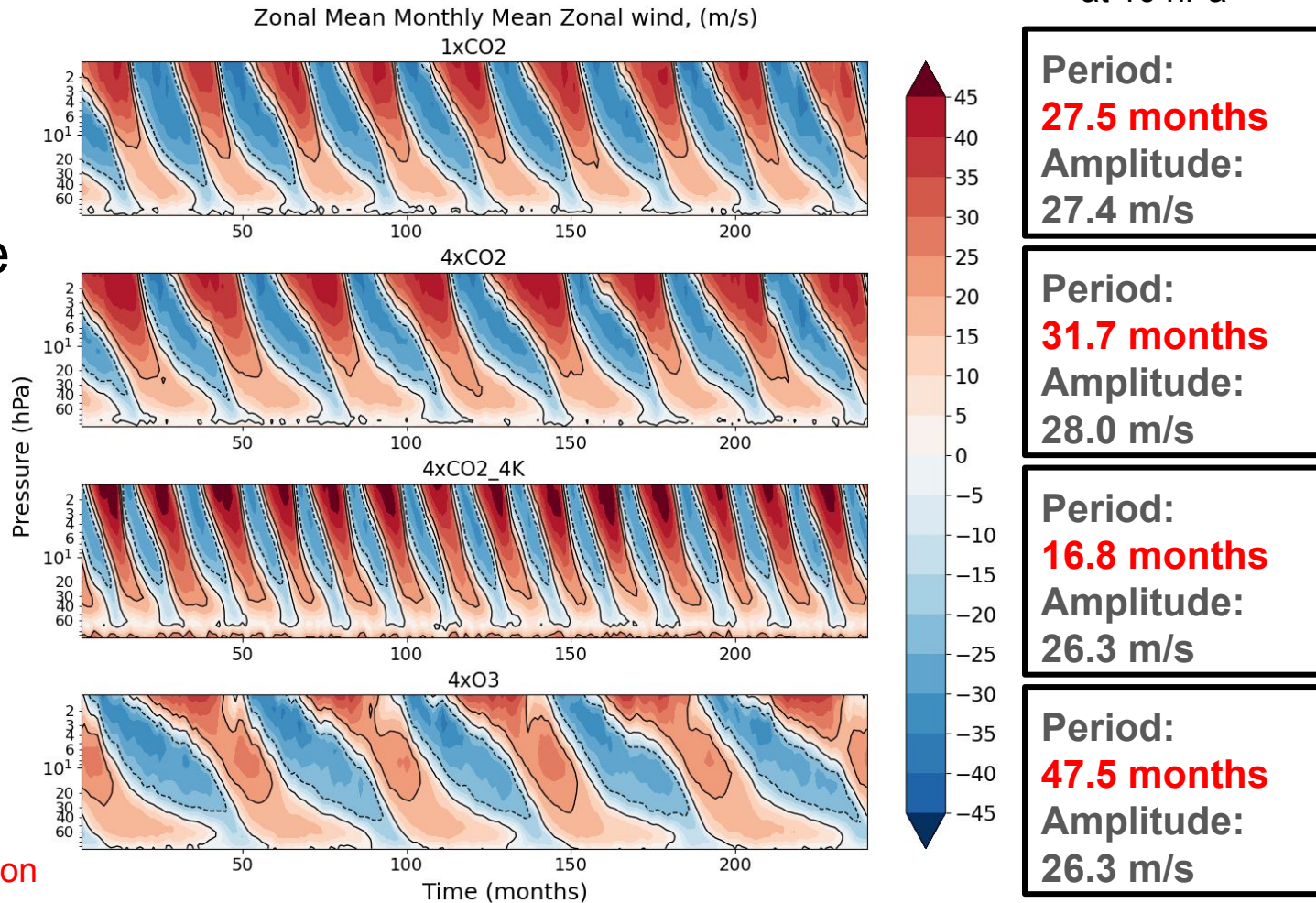
Zonal-mean Age of Air climatology



Brewer-Dobson Circulation (BDC) changes are confirmed by **age of air** analysis

- Decreased age in the **4xCO2** and **4xCO2_4K** simulations relative to the control indicates faster transport (**strengthened BDC**)
- Increased age in the **4xO3** simulation relative to control indicates slower transport (**weakened BDC**)

Aquaplanet QBO period* is sensitive to CO₂ and ozone

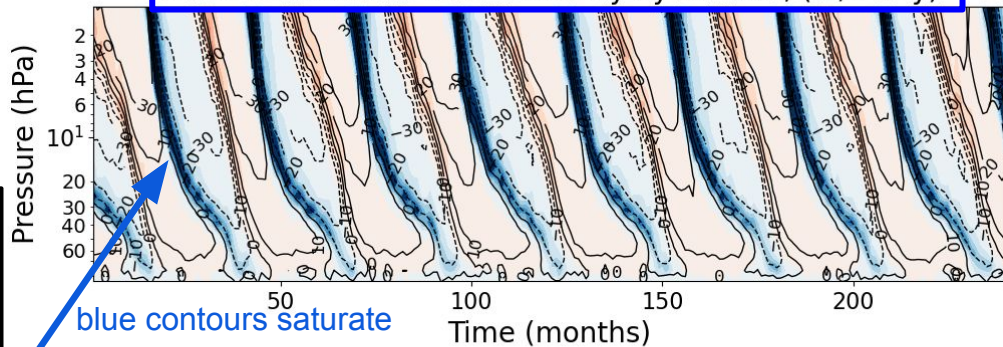


* Calculated using transition times method at 10 hPa

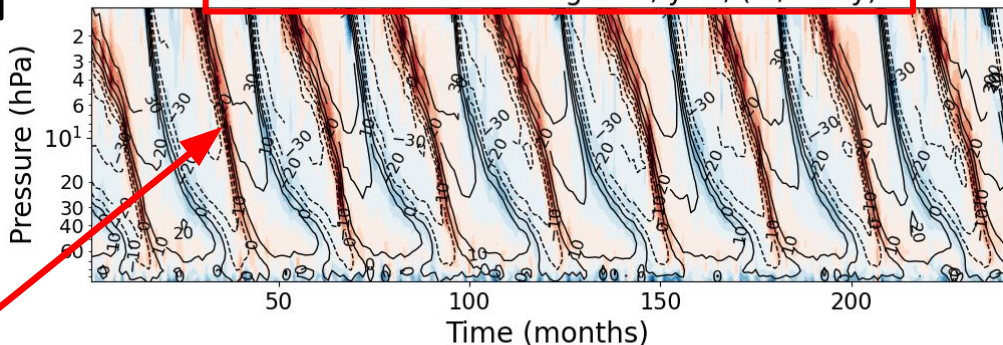
The aquaplanet QBO is driven by **resolved** and **parameterized** waves

1xCO2

Zonal Mean Zonal wind tendency by all GWs, (m/s*day)



Zonal Mean EP-flux divergence, y+z, (m/s*day)

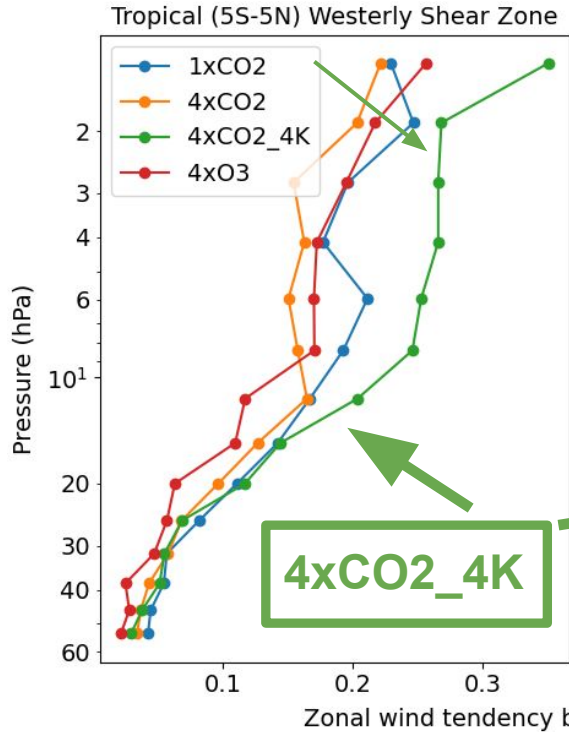


$$\bar{u}_t = \bar{v}^* [f - (a \cos \phi)^{-1} (\bar{u} \cos \phi)_\phi] - \bar{w}^* \bar{u}_z + (\rho_0 a \cos \phi)^{-1} \nabla \cdot \mathbf{F} + \text{GWD} + \bar{X}$$

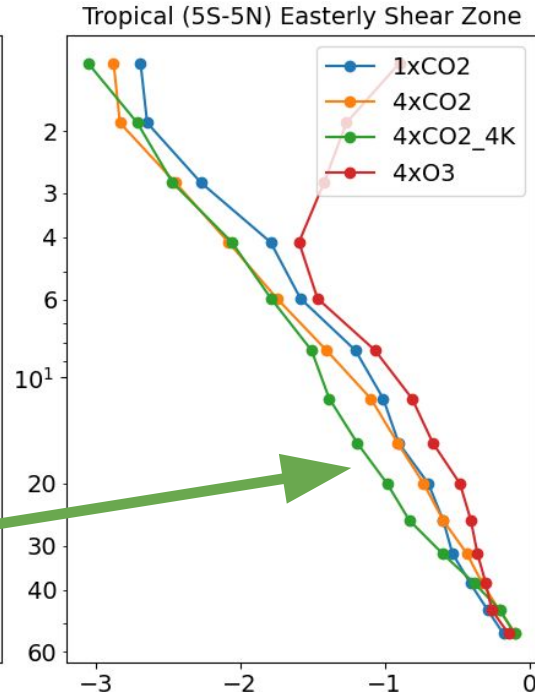
- Equatorial easterly zonal wind tendency is predominantly due to **parameterized gravity waves**
- Equatorial westerly zonal wind tendency is primarily due to **resolved Kelvin waves**

Parameterized gravity wave drag is primary driver of period changes.

Along E-W transition zone at each level



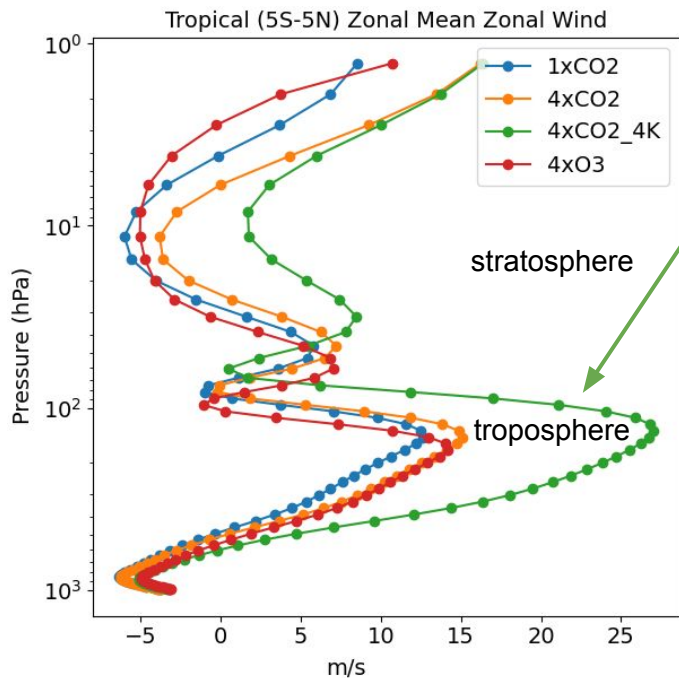
Along W-E transition zone at each level



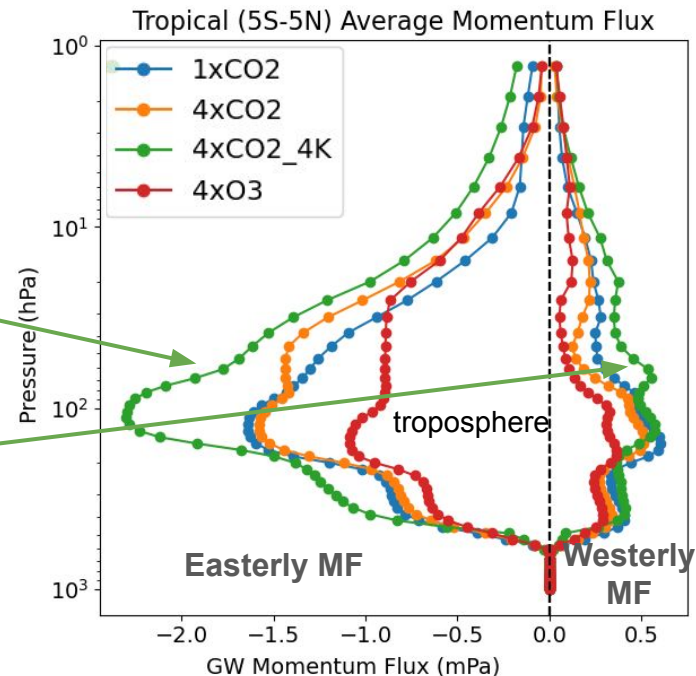
Increased gravity wave drag magnitude compared to the **control simulation** shortens 4xCO2_4K QBO period

Strengthened GW forcing in **4xCO2_4K** may be a result of amplified tropical westerlies in the troposphere.

Zonal wind amplitudes

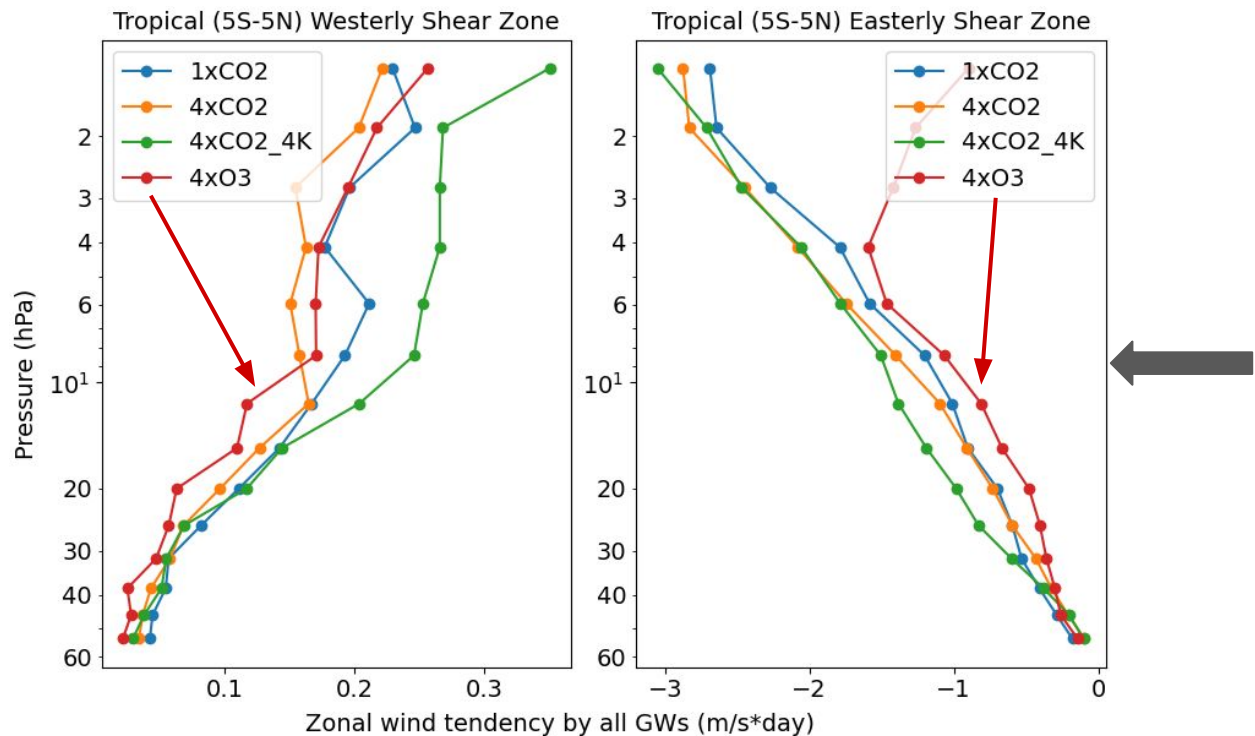


Increased tropical westerlies in the **4xCO2_4K** simulation enhance the **asymmetry of the GW momentum flux spectrum** and may **reduce critical level filtering** of westerly GWs with lower phase speeds



Mean zonal wind at GW source level impacts spectrum of parameterized GW waves

Parameterized gravity wave forcing is primary driver of period shifts



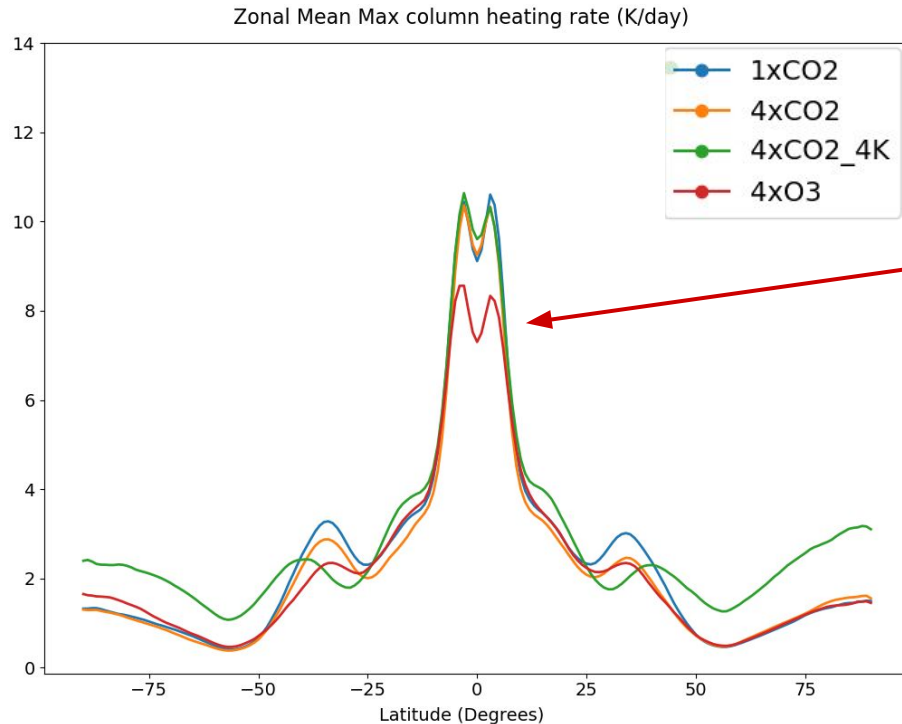
4xO3

Decreased gravity wave drag magnitude compared to the control simulation **lengthens** **4xO3** QBO period

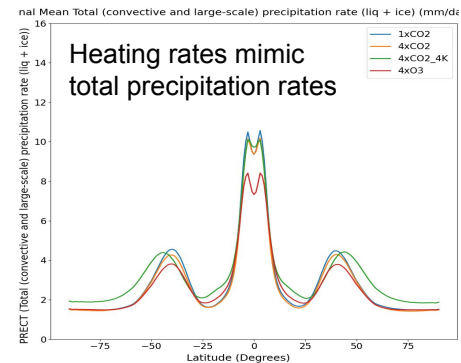
Weakened GW forcing in **4xO3** aligns with a decreased convective heating rate (from deep convection scheme)

Weakened and shallower* tropical convection in **4xO3** may be driven by the decrease in tropopause height due to stratospheric expansion

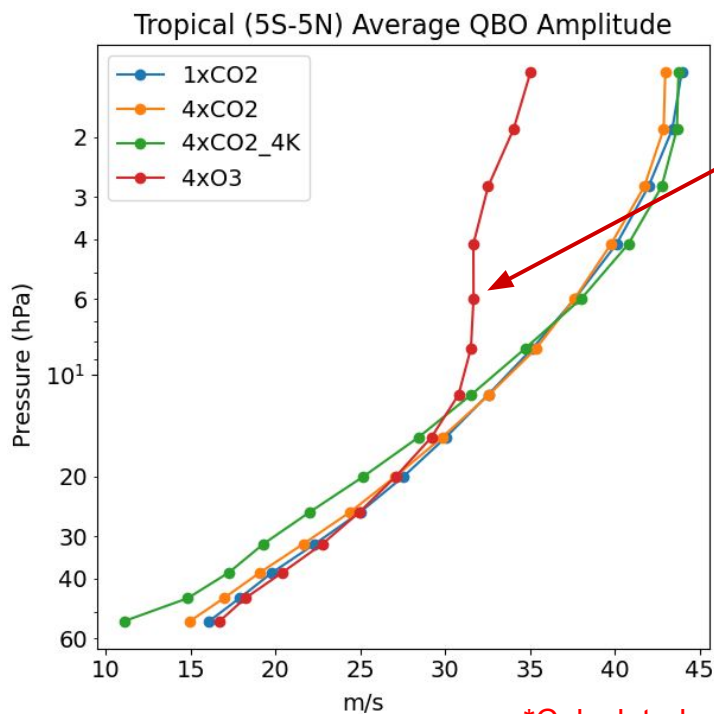
*Not pictured



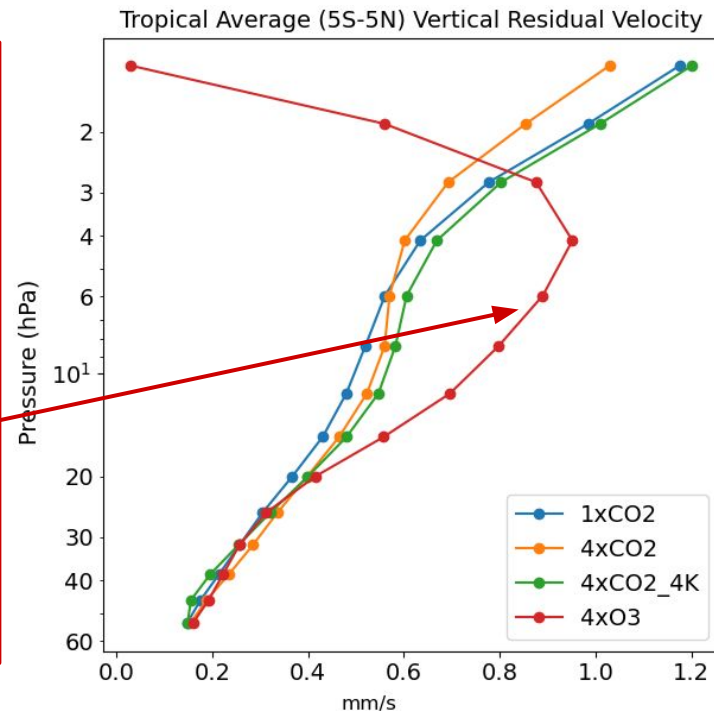
CAM's **GW** momentum flux magnitude is proportional to the **square of the maximum heating rate**.



QBO amplitude changes in **4xO3** may be connected to the vertical residual velocity.



A decreased QBO amplitude* in the **4xO3** simulation compared to the **control** overlaps an increase in the vertical residual velocity below 3 hPa



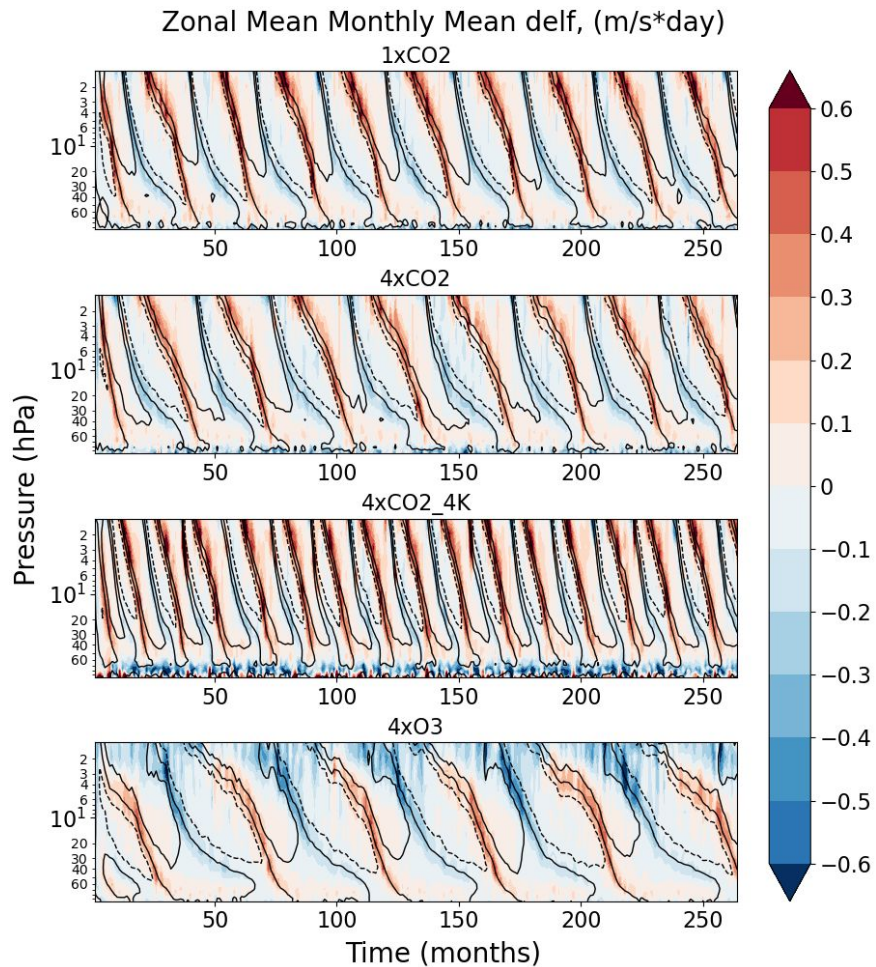
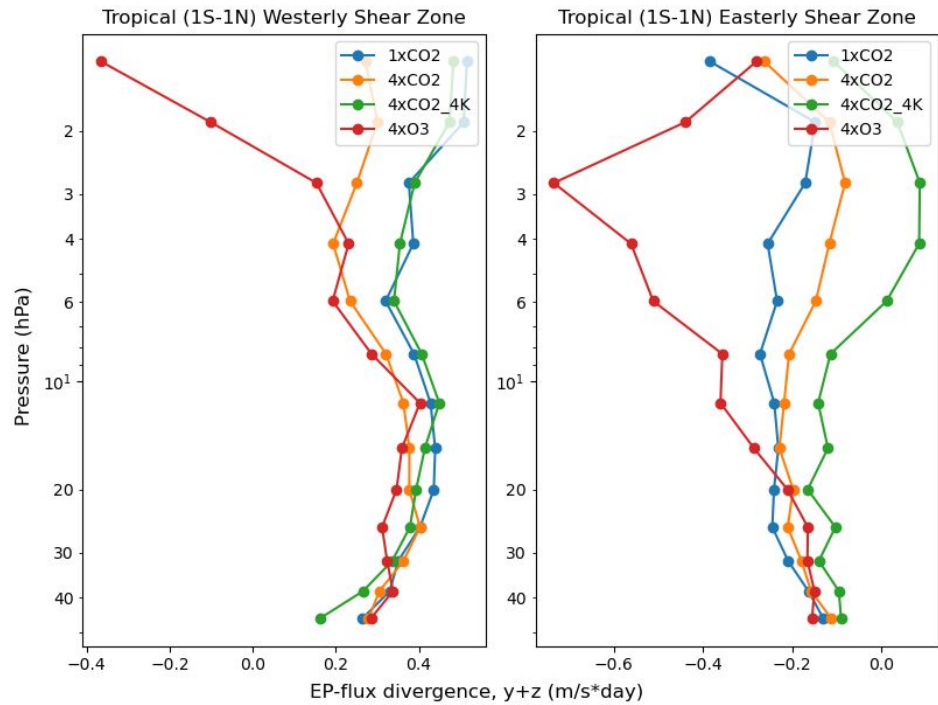
*Calculated using Dunkerton and Delisi (1985) method

Summary

- Aquaplanet is a useful simplified framework for testing the response of the stratosphere to idealized radiative forcing: CO₂ and ozone changes
- Aquaplanet mimics behavior seen in complex climate change model experiments, e.g. BDC strengthens under global warming
 - ➡ Idealized testbed which is easier to understand
- QBO response is mainly driven by GW drag forcing changes
 - Shorter QBO periods in 4xCO₂ and 4xCO₂_4K
 - Longer QBO period in 4xO₃
- Changes of the QBO forcing due to resolved waves are present but have lower magnitudes than GW forcing
- Increased vertical residual velocity in the 4xO₃ simulation may contribute to a decrease in QBO amplitude

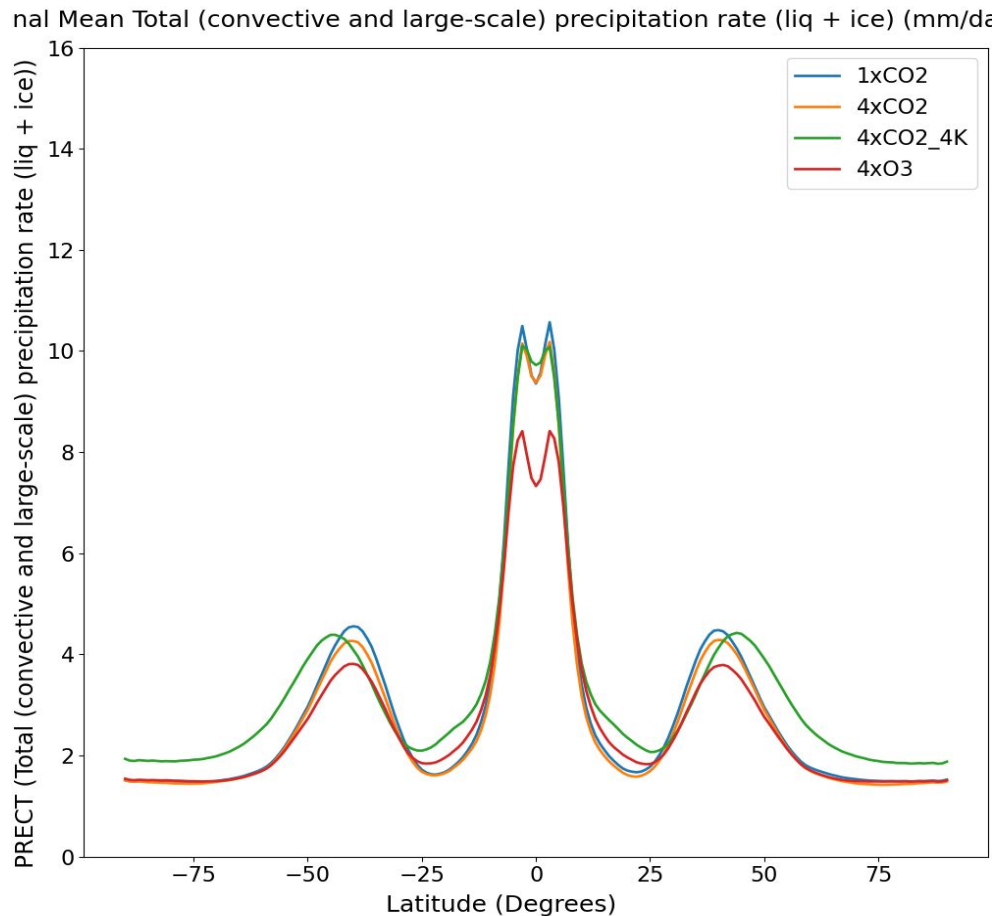
Extra Slides

EP Flux Divergence



Precipitation changes

- Marginal mean precipitation changes in the increased CO₂ experiments
- Surprising that 4xCO2 does not exhibit increased precipitation (is warmer with more water vapor), behavior is different with an older 'CAM4' physics package
- Decrease in precipitation rate for 4xO3 simulation
- 4xCO2_4K and 4xO3: Hadley cell becomes wider



Static stability changes

