The effect of coupled chemistry in the quasi-biennial oscillation simulated with WACCM

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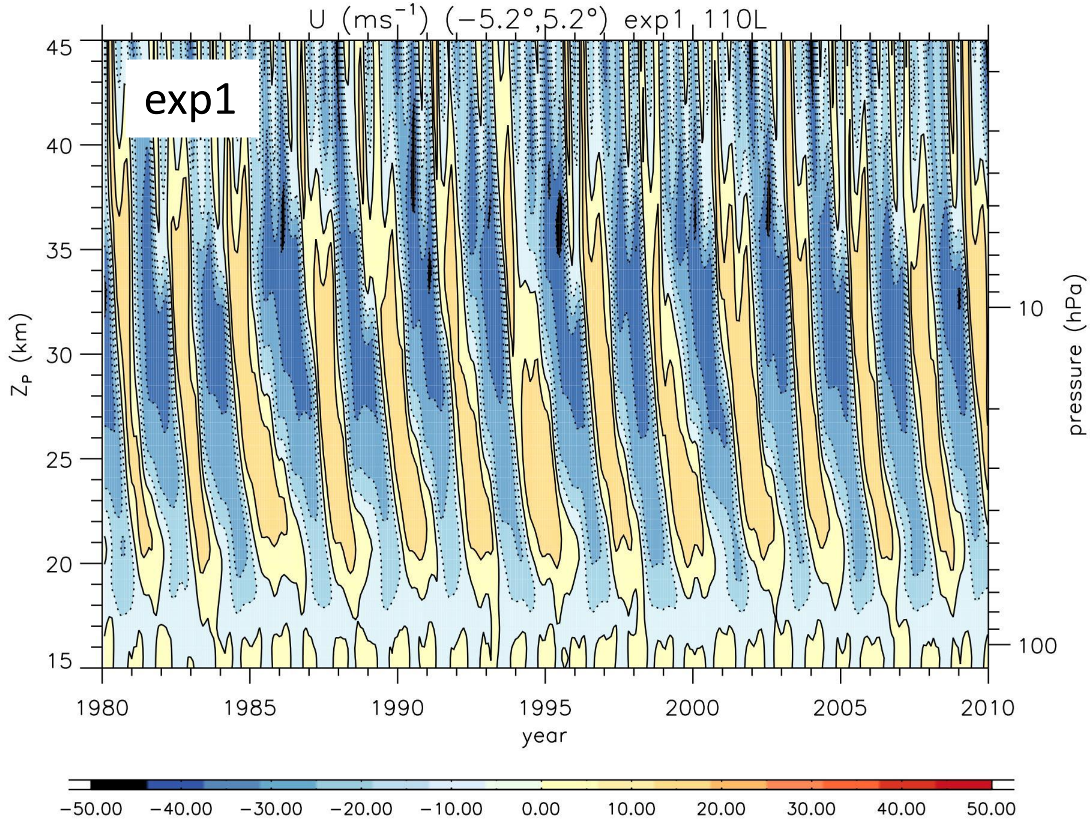
- use Whole Atmosphere Community Climate Model (WACCM), v. 5.4
    - high vertical resolution (500 m) from boundary layer through ∼10 hPa

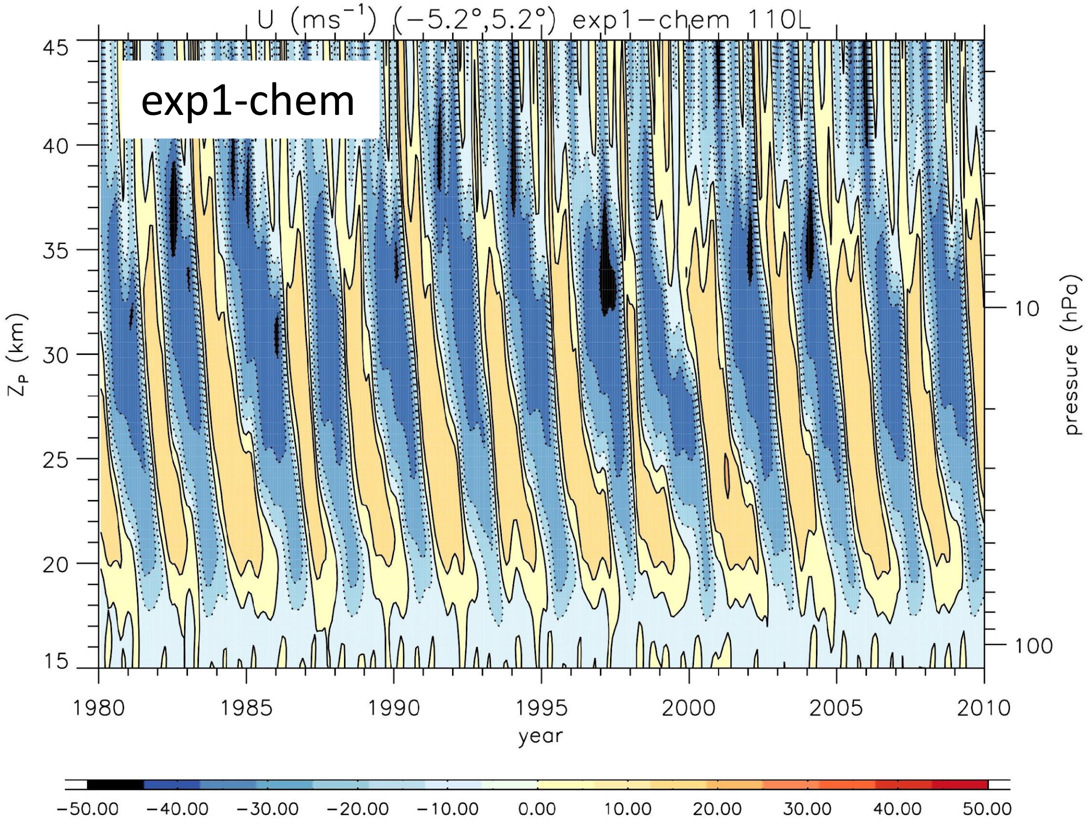
- model is run with SST specified from observations, 1980-2010:
    - this is the “experiment 1” protocol of QBOi (“present-day climate”)

- two identical simulations (BCs, GW parameterization, etc.) except for:
    - **specified chemistry** (**exp1**): O_3 and other chemical species specified
    - **coupled chemistry** (**exp1-chem**): O_3 and other species calculated explicitly

- **in this talk:** examine the effect of interactive chemistry on the QBO

zonal wind QBO, Equator

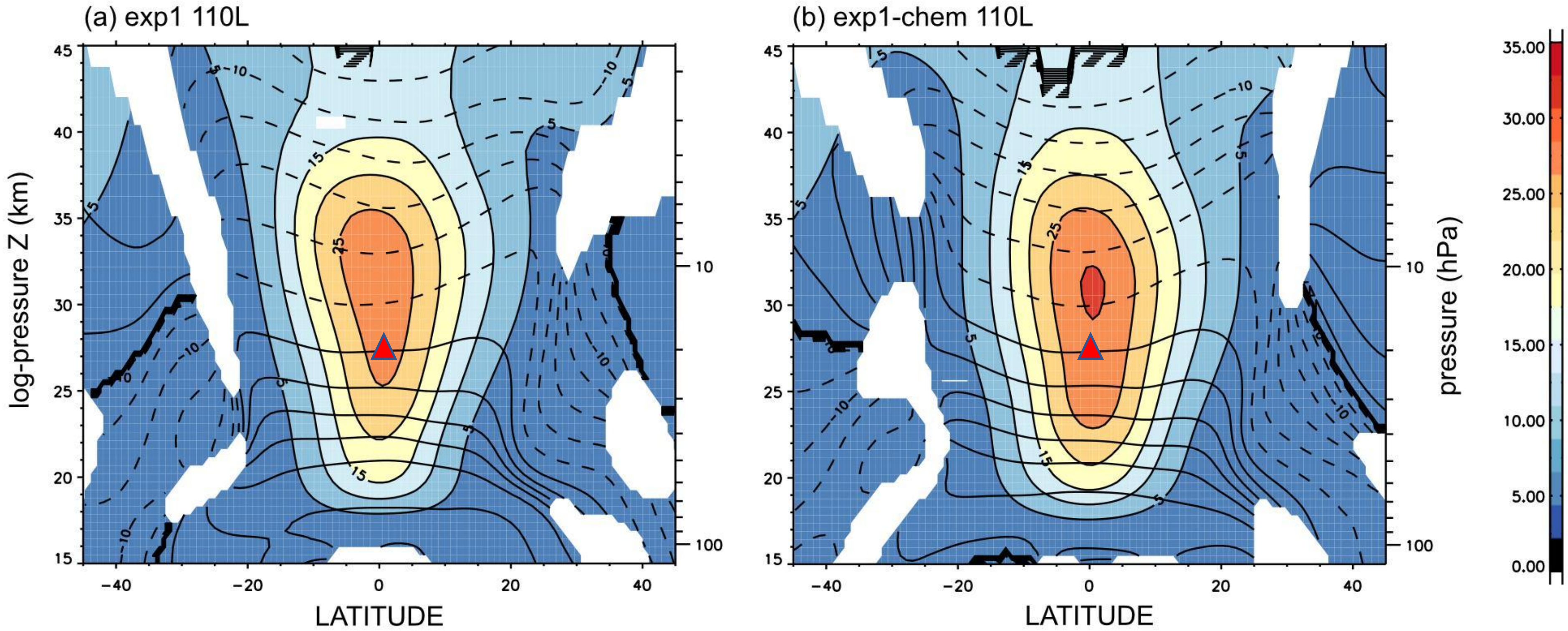




- realistic QBO in both runs (descent past 70 hPa; E-W asymmetry; amplitude)
- coupled chemistry has larger amplitude than specified chemistry
- the same is true for QBO in *T* (not shown)
- period remains approximately constant (~28 months)

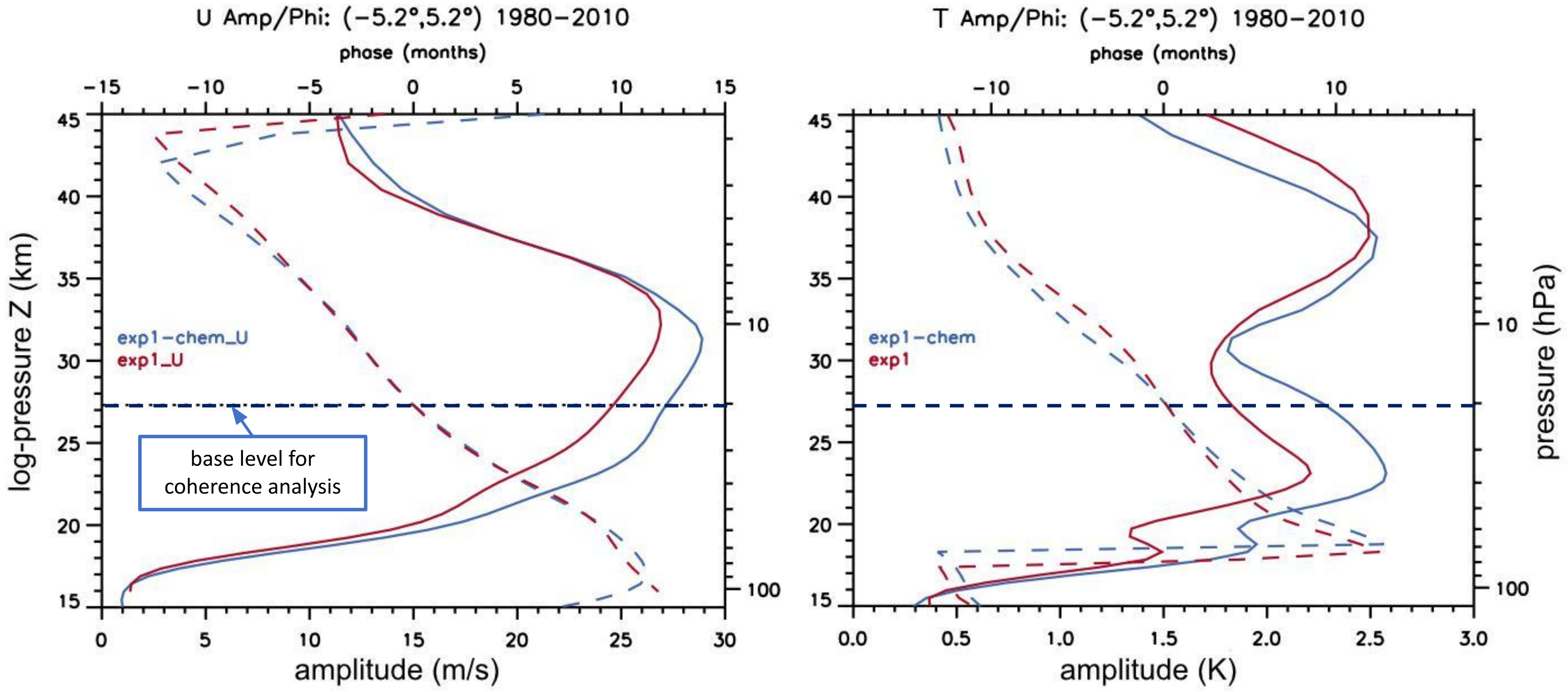
Zonal wind QBO from coherence analysis

QBO amplitude and phase, 1980-2010



- coherence analyses over QBO period band (15 – 50 months)
- triangles denote base point for coherence analysis
- QBO amplitude is larger, especially below ~10 hPa, in exp1-chem

U, T QBO structure, Equator



- coherence analyses over QBO period band (15 – 50 months)
- QBO in both *U* and *T* is stronger with coupled chemistry (exp1-chem)
  - ✔ *T* up to 30-35% stronger near 60-70 hPa; 15% stronger near 20-40 hPa
  - ✔ *U* not appreciably stronger at 70 hPa; about 10-20% stronger at 10-40 hPa
  - ✔ phase behavior (and period) are very similar in exp1 and exp1-chem

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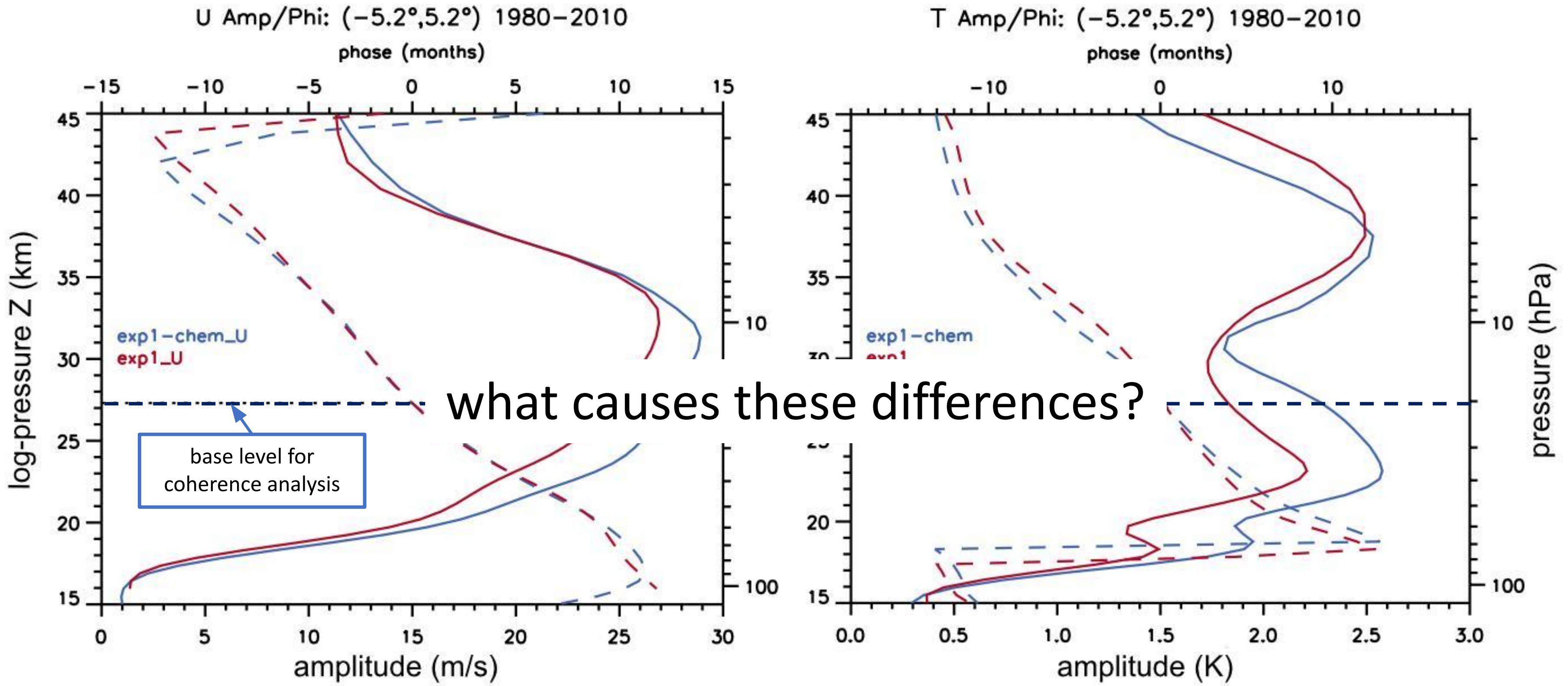

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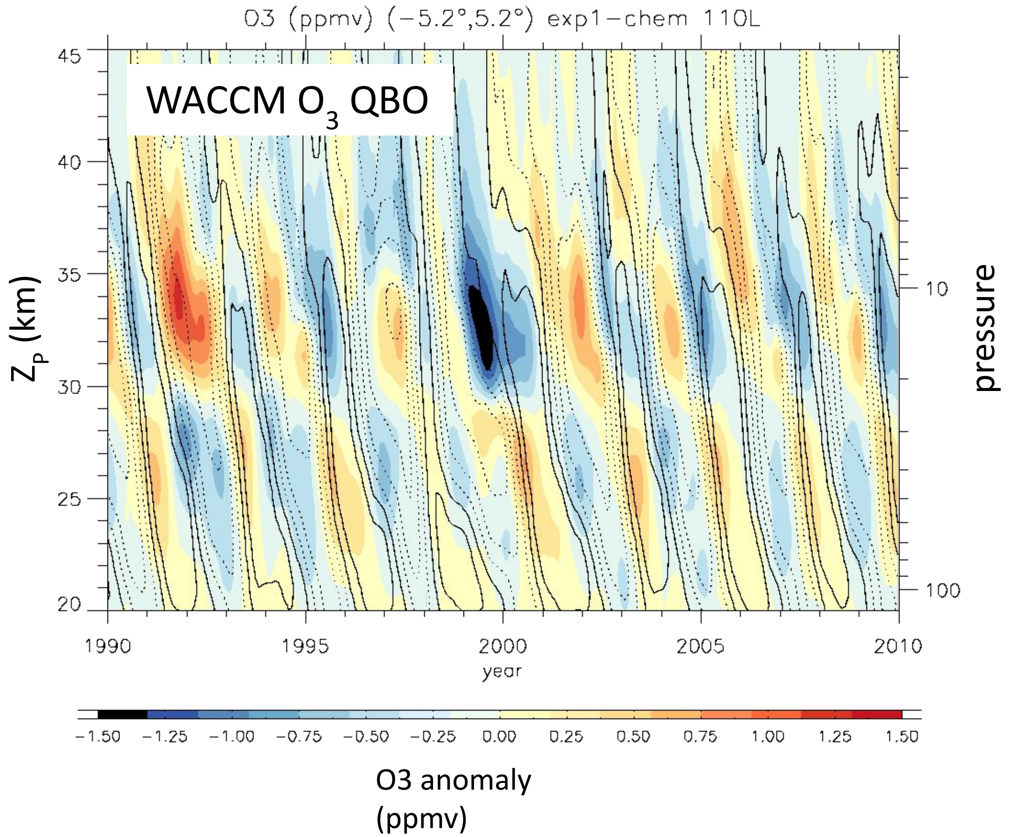
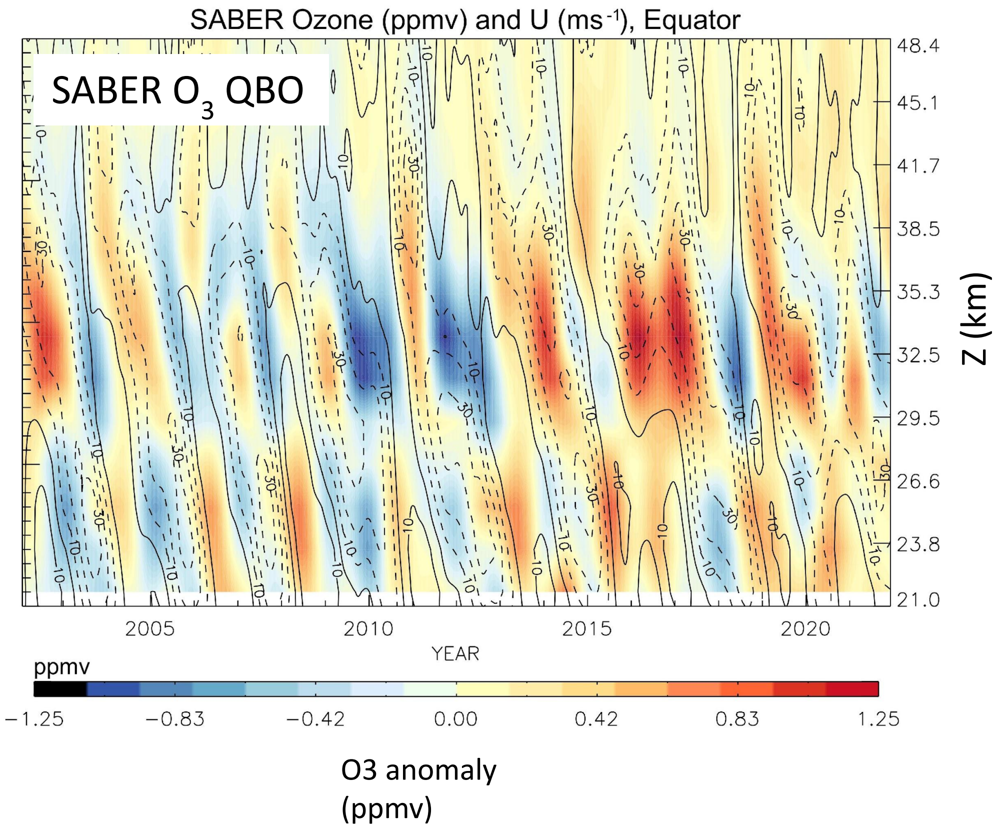
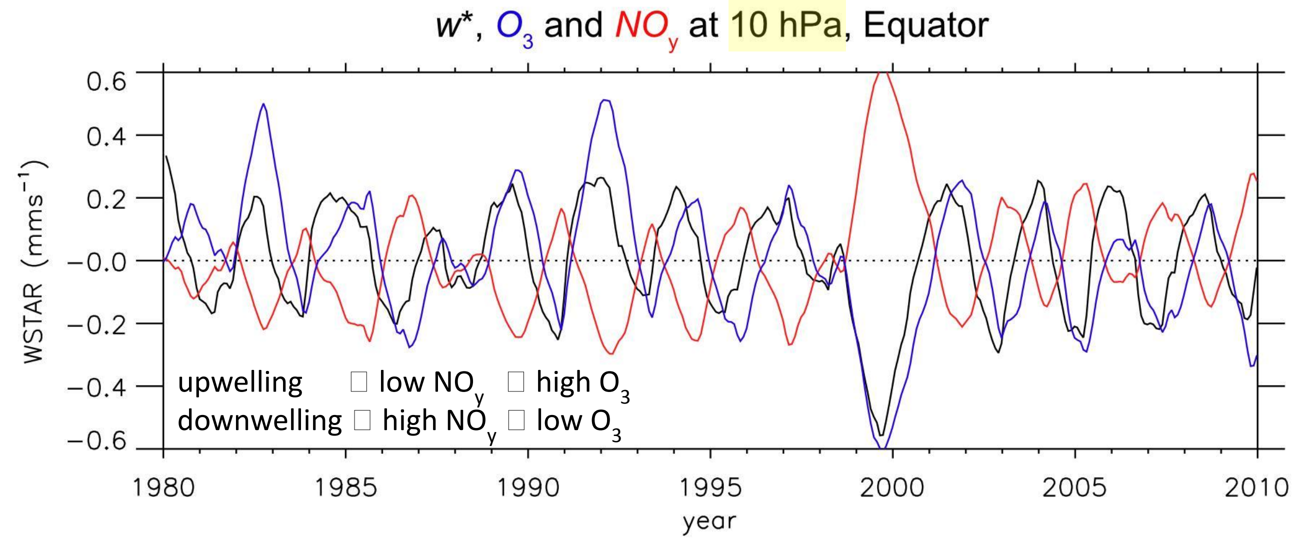
QBO in Ozone, Equator: exp1-chem vs. SABER

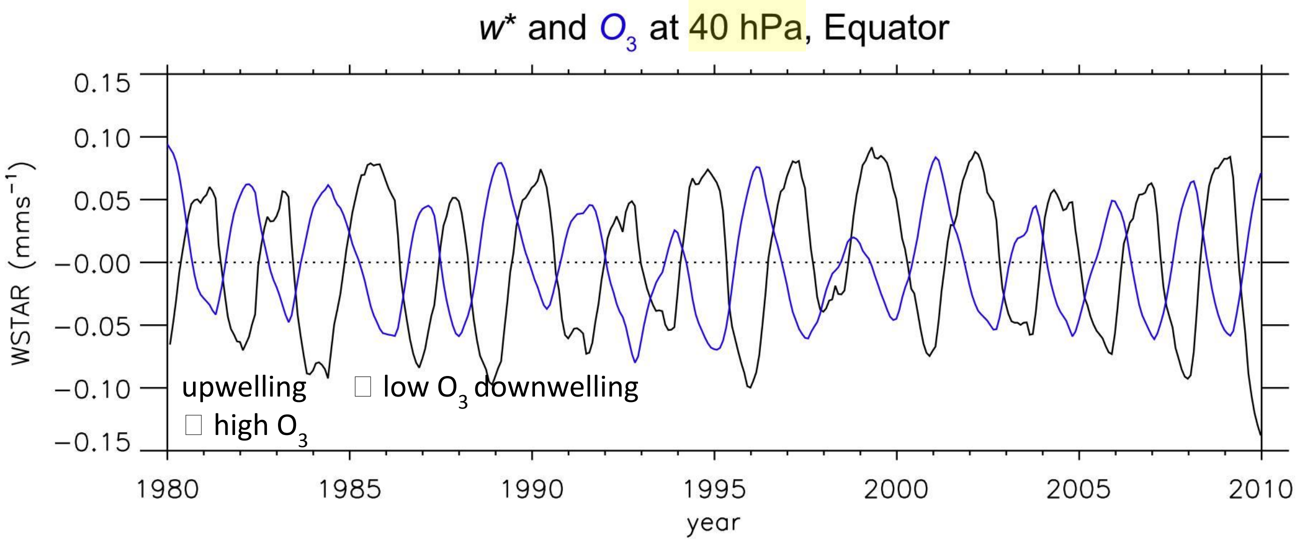




- SABER instrument on NASA's TIMED satellite (observations for 2002-2021)
- WACCM exp1-chem (1990-2010 shown) on left panel
- Ozone QBO in WACCM is in excellent overall agreement with SABER
- Ozone QBO signals are out of phase above / below ~20 hPa due to transport of NO_y / O_3

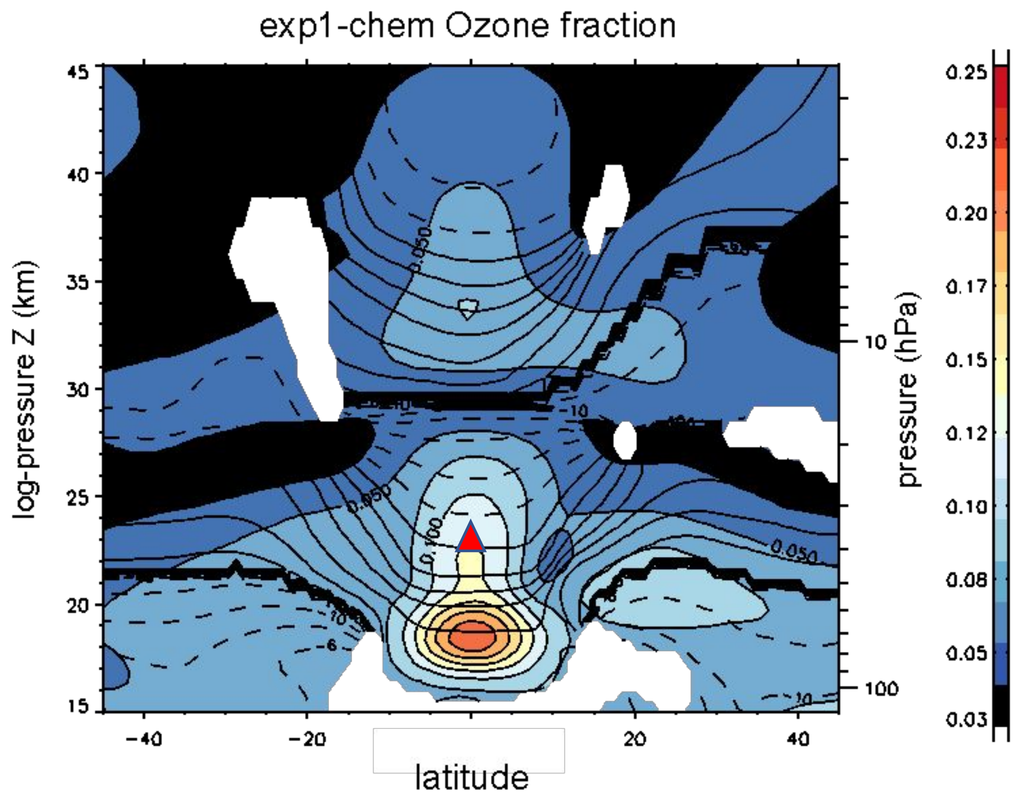
vertical transport and the ozone QBO

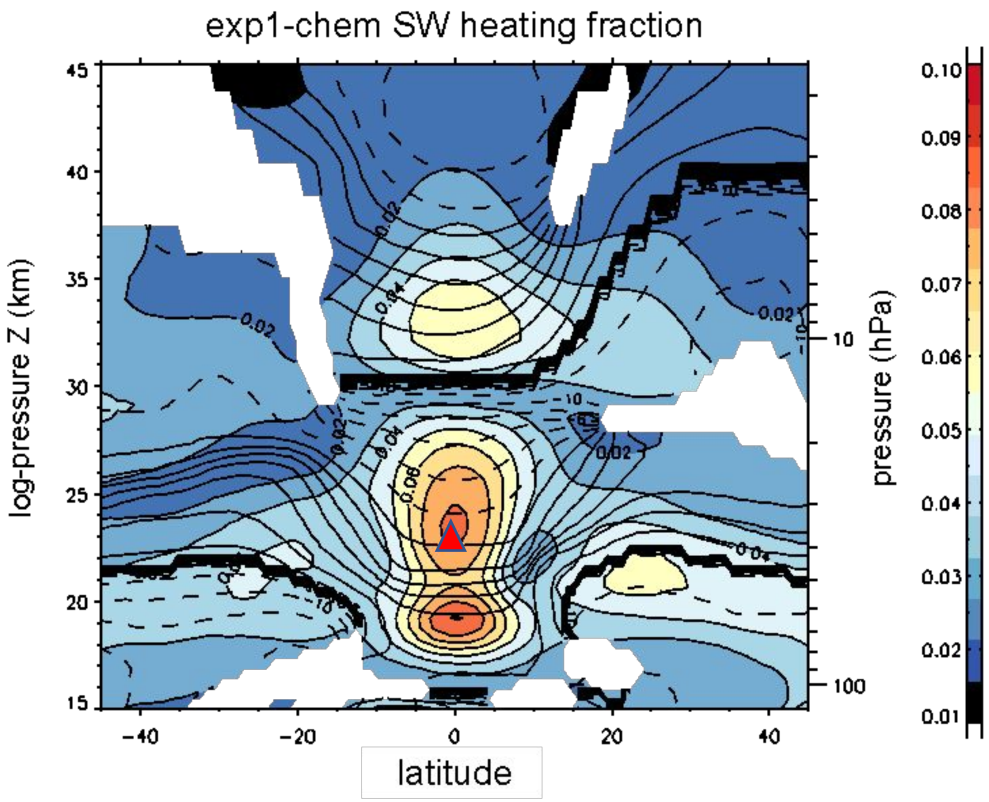




- QBO secondary circulation and O_3 anomalies:
  - ✔ **above ~20 hPa**: upward/downward **transport of NO_y** produces positive/negative O_3 anomalies
  - ✔ **below 20 hPa**: upward/downward **transport of O_3** produces negative/positive O_3 anomalies
- These processes are well known and understood, e.g., Gray and Pyle (*JAS* 1989); Chipperfield et al (*GRL* 1994); Li et al. (*QJRMS* 1995); Tian et al. (*JGR* 2006); Park et al. (*JGR* 2017); Zhang et al. (*Atmos. Env*. 2020); etc.
- They are well simulated in WACCM
- How does the O_3 QBO affect the dynamical QBO?

structure of the QBO in O_3 and O_3 heating





- coherence analysis over QBO period band (15 – 50 months)
- ozone QBO is largest, as a **fraction of local time-mean** ozone, below 20 hPa
- the resulting QBO in ozone heating is
  - ✔ relatively large below 20 hPa (~ 8-10% of time-mean)
  - ✔ relatively small above 20 hPa (≤ 5%)

linearized analysis for the lower stratosphere

$i\sigma T + w^* S = -\alpha T + Q_3$ (1) thermodynamic equation

$i\sigma T + w^* S = -\alpha T + \gamma O_3$ (2) linearized ozone heating

$i\sigma O_3 + w^* O_{3z} = -\delta O_3$ (3) (approximate) ozone balance

Combine (2) and (3)

$$(i\sigma + \alpha)T = -w^* \left\{ S + \gamma \cdot \frac{O_{3z}}{i\sigma + \delta} \right\}$$

Solve for T:

$$T = -\left\{ \frac{S + \gamma \cdot \frac{O_{3z}}{i\sigma + \delta}}{i\sigma + \alpha} \right\} \cdot w^*$$

where:

S: static stability parameter

γ: linear ozone heating coefficient

δ: ozone loss rate

α: Newtonian cooling coefficient

σ: QBO frequency

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compare with T without O_3 heating

$$T = -\frac{Sw^*}{i\sigma + \alpha}$$

 ozone heating effectively increases static stability

… linearized analysis

Ratio T(O_3) / T (no O_3), assuming constant w*:

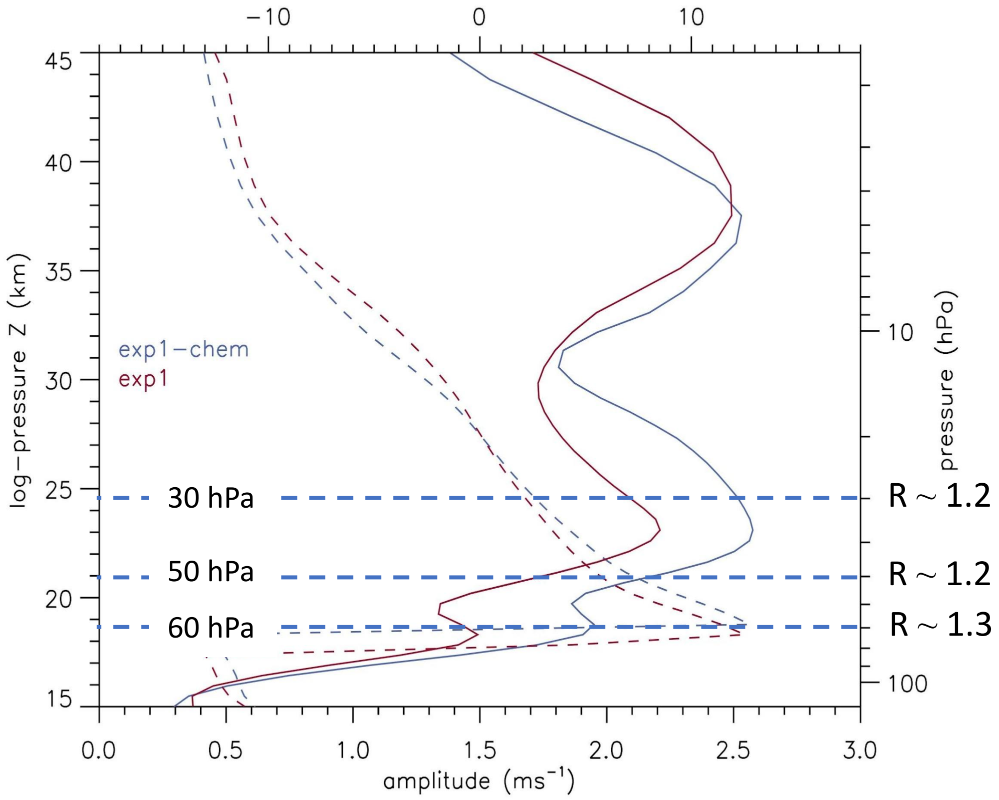
$$R = \frac{-\left\{\frac{S + \gamma \cdot \frac{O_{3z}}{i\sigma + \delta}}{i\sigma + \alpha}\right\} w^*}{-\frac{S w^*}{i\sigma + \alpha}} = \frac{S + \gamma \cdot \frac{O_{3z}}{i\sigma + \delta}}{S}$$

using representative values for the various parameters one gets:

p (hPa)	T(O_3)	T(no O_3)	ratio
30	3.1	2.6	1.22
50	3.1	2.6	1.23
60	2.5	2.0	1.40

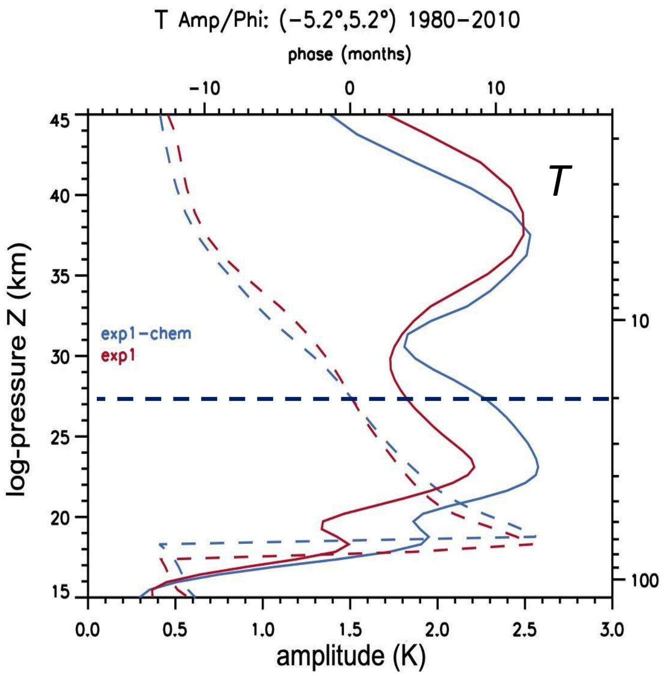
values in the table are in reasonable agreement with model values for *T* and for the ratio *T*(O_3) / *T*(no O_3)

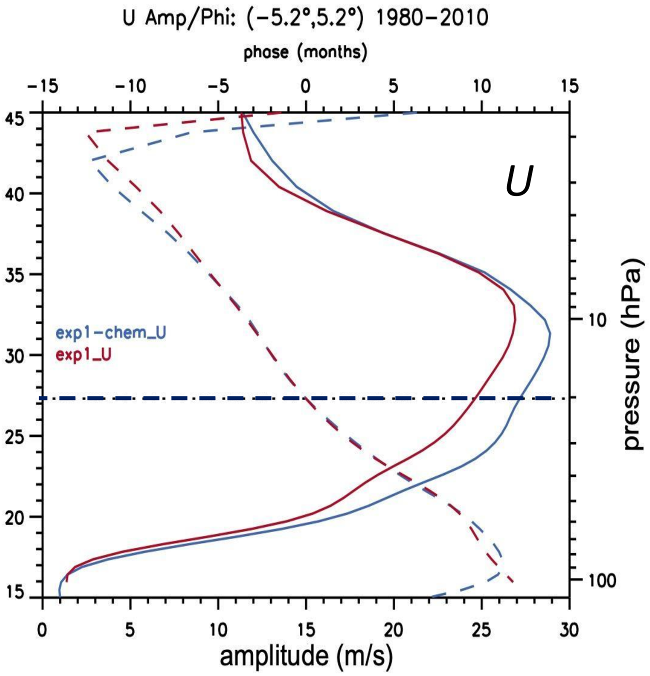
compare with model results:



zonal wind QBO

enhancement of QBO in *U* in exp1-chem occurs at higher altitude





near the Equator:

$$U_z = \frac{1}{\beta} \cdot \frac{R}{H} \cdot \frac{T}{L^2}$$

such that $U(z)$ is the integral of the T anomaly between the lower boundary of the QBO, z_0, and any level z:

$$U(z) = U(z_0) + \int_{z_0}^{z} \frac{1}{\beta} \cdot \frac{R}{H} \cdot \frac{T(z')}{L^2} dz'$$

summary

- WACCM with coupled chemistry simulates a realistic QBO in U, T, O_3
  - ✔ larger amplitude U and T than in the same model without chemistry
- QBO in ozone modulates ozone heating by 8-10% below 20 hPa
  - ✔ amplifies QBO temperature signal by 15-35%, depending on altitude
  - ✔ amplifies zonal wind signal by 10-20%
- a simple, linearized analysis is qualitatively consistent with model results