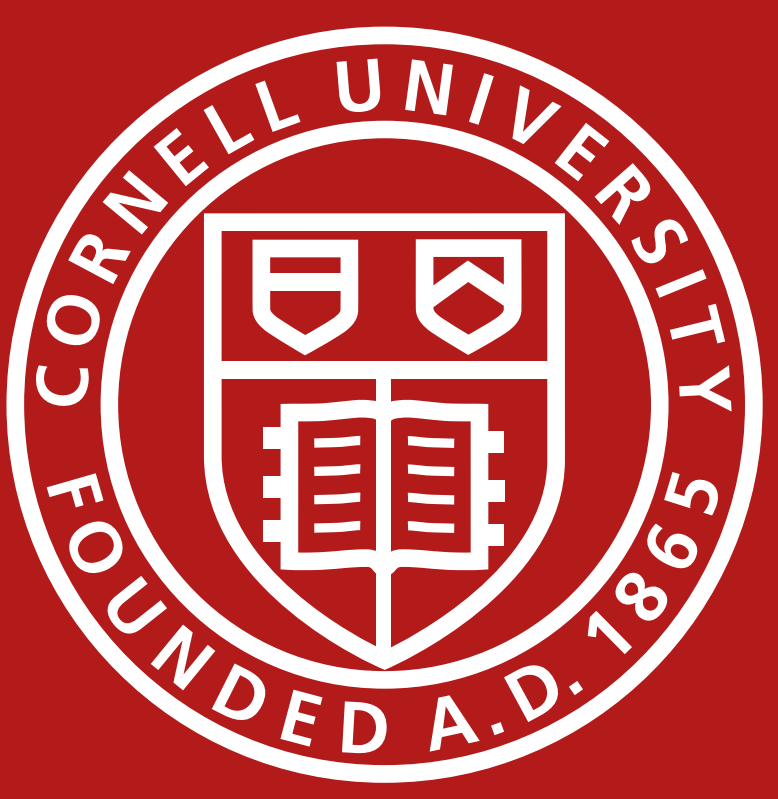




Modeling the effects of ozone on the QBO secondary circulation

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1. Motivation, Background

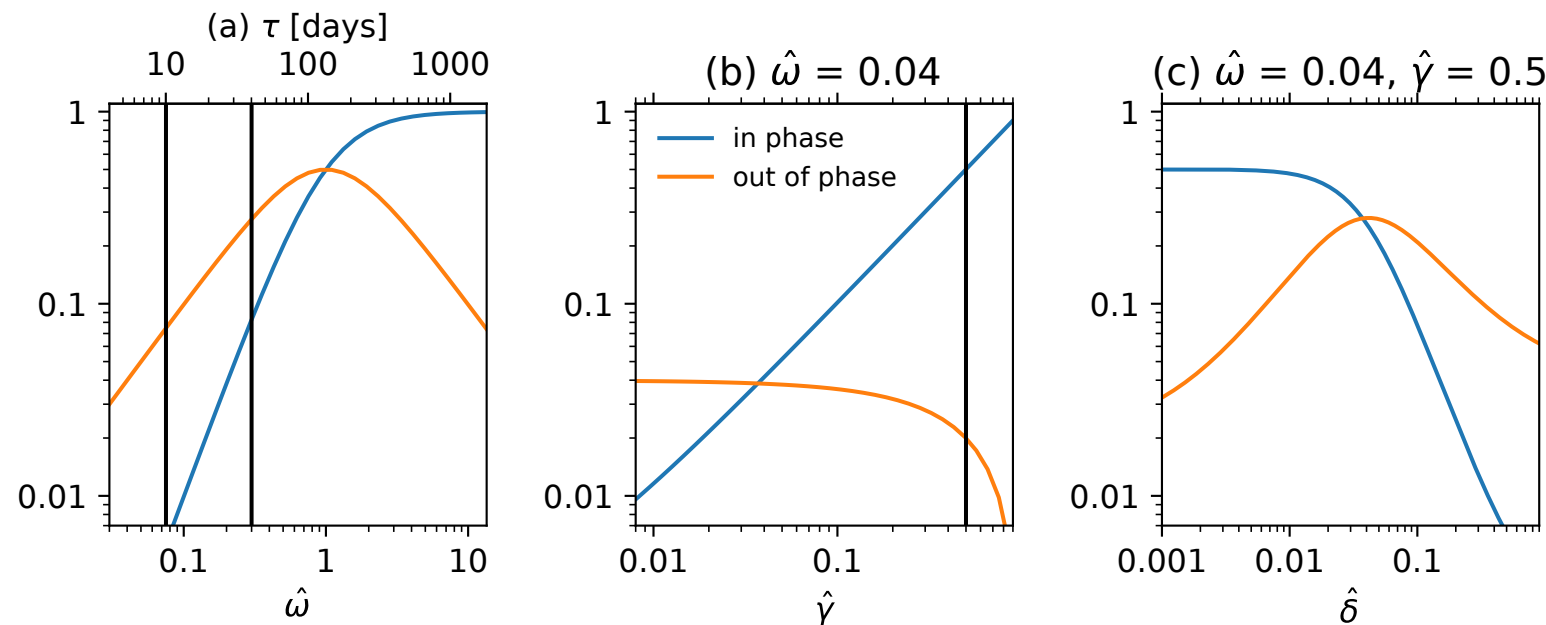
The **secondary circulation of the QBO** is key to understand the two way coupling between ozone and the QBO. It can be modeled as a response to imposed wave driving using the zonally-averaged, linearized primitive equations on an equatorial beta plane. The strength of the secondary circulation is determined by the aspect ratio of the imposed forcing; for values appropriate to the QBO, the wave driving nearly entirely goes into accelerating the winds [1,2,3], and produces a circulation in phase with the zonal winds, rather than the shear zones.

If the radiative heating induced by temperature anomalies are included, the scaling for the circulation is modified by the factor (1). This is much more efficient at generating a secondary circulation, and predicts circulation out of phase with the winds, as is observed..

$$\begin{aligned} \partial_t T + \frac{H}{R} N^2 w &= -\alpha T \\ \partial_t u - \beta y v &= \mathcal{F} \\ -\beta y \partial_z u &= \frac{R}{H} \partial_y T \\ \partial_t T + \frac{H}{R} N^2 w &= -\alpha T + \gamma \chi' \\ \partial_t \chi' + w \partial_z \chi_0 &= -\delta \chi' \end{aligned}$$

$$\frac{\hat{\omega}^2 + i\hat{\omega}(\hat{\delta} + \hat{\gamma})}{\hat{\omega}^2 - \hat{\delta} + i\hat{\omega}(1 + \hat{\delta})}$$

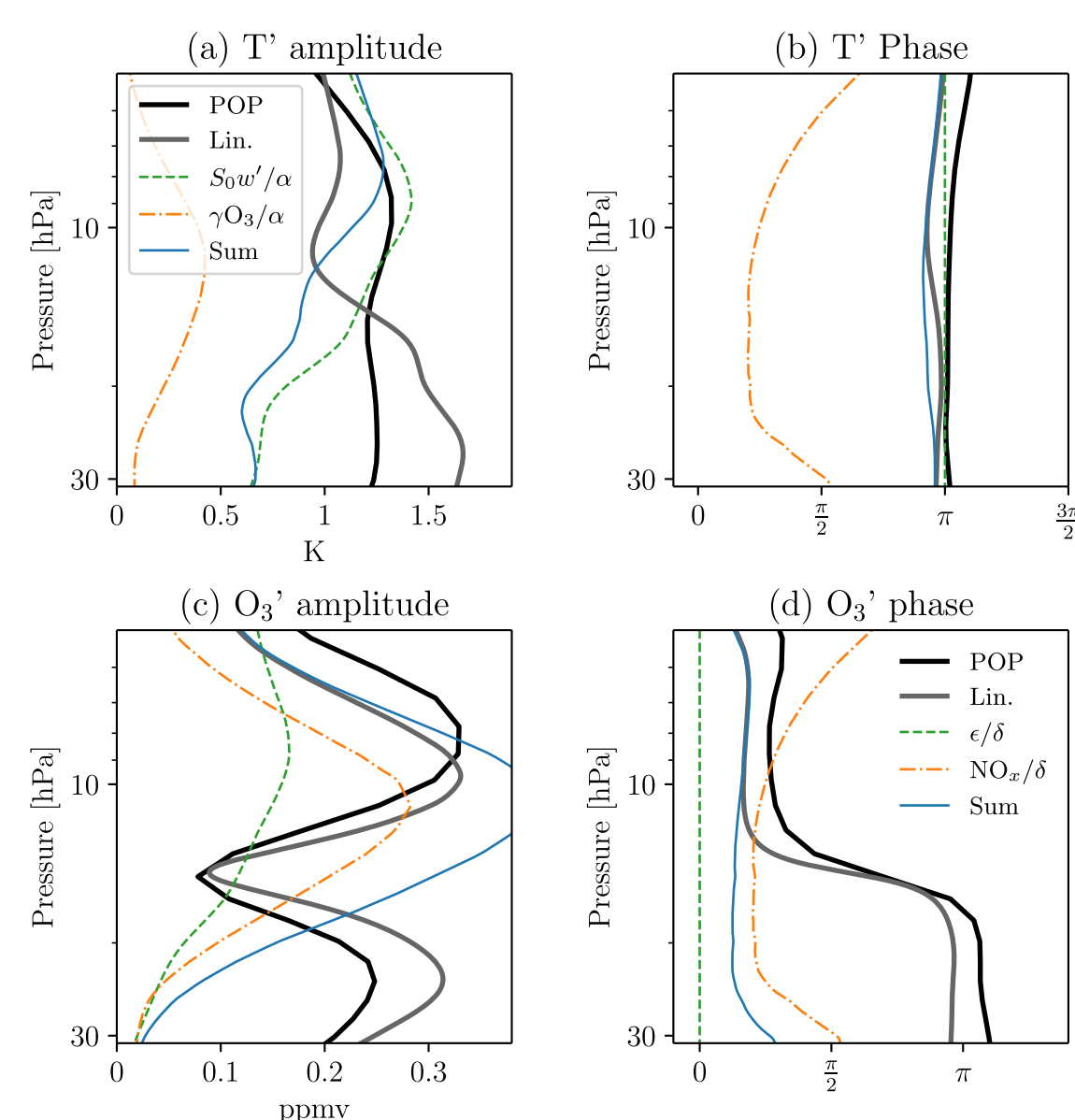
Coupling this system to a simple ozone budget raises difficulties: in some parameter regimes, the ozone heating compensates for radiative relaxation, eliminating the secondary circulation.



3. Temperature and Ozone QBO

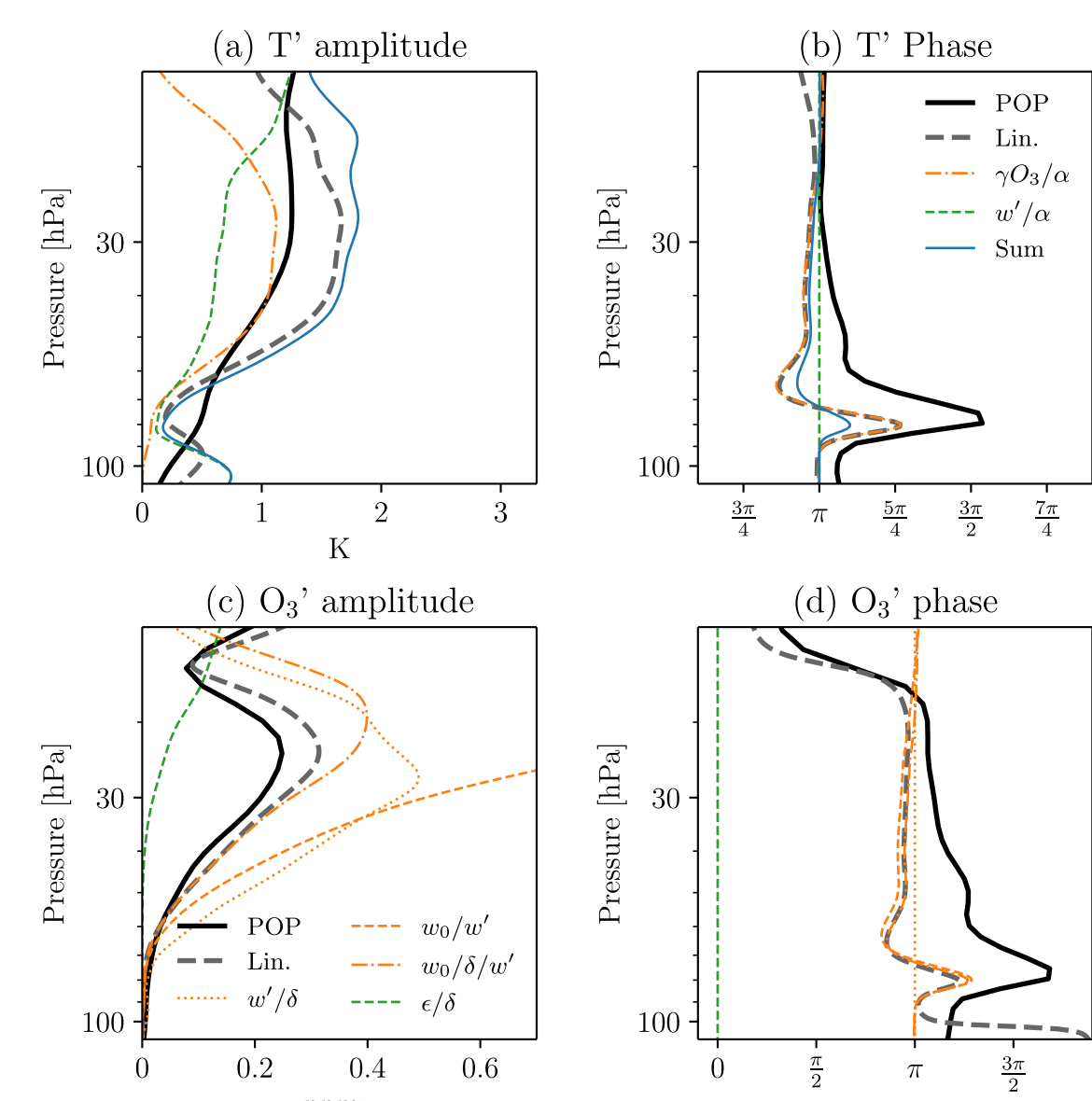
The linearized thermodynamic and ozone budgets can be solved to predict a temperature and ozone QBO given an imposed secondary circulation [4]. Using the secondary circulation from ERA 5 and the coefficients above produces far too strong a signal in both. This response is much improved if w is reduced by 50% in the dynamically controlled region.

$$\begin{aligned} \tilde{T} &= -\frac{S_0 \tilde{w}}{\alpha} \frac{\hat{\Delta}}{\hat{\Delta}} - \frac{S_0 \tilde{w}}{\alpha} \frac{\hat{\gamma}}{\hat{\Delta}} \\ \tilde{\chi} &= -\frac{\partial_z \chi_0 \tilde{w}}{\alpha} \frac{\hat{\epsilon}}{\hat{\Delta}} - \frac{\partial_z \chi_0 \tilde{w}}{\alpha} \frac{i\hat{\omega} + 1}{\hat{\Delta}} \\ \hat{\Delta} &= i\hat{\omega}(1 + \hat{\delta}) + \hat{\delta} - \hat{\gamma}\hat{\epsilon} - \hat{\omega}^2 \end{aligned}$$



In the photochemically-controlled regime (above about 12 hPa), temperature is determined by a balance between radiative damping and adiabatic heating. The photochemical equilibrium is perturbed by these temperature anomalies, and by variations in NO_x.

$$\tilde{T} = -\frac{S_0 \tilde{w}}{\alpha} \quad \tilde{\chi} = \frac{\hat{\epsilon}}{\hat{\delta}} \tilde{T} \quad \tilde{\chi}_N = -\frac{\nu}{\delta} \tilde{N}$$

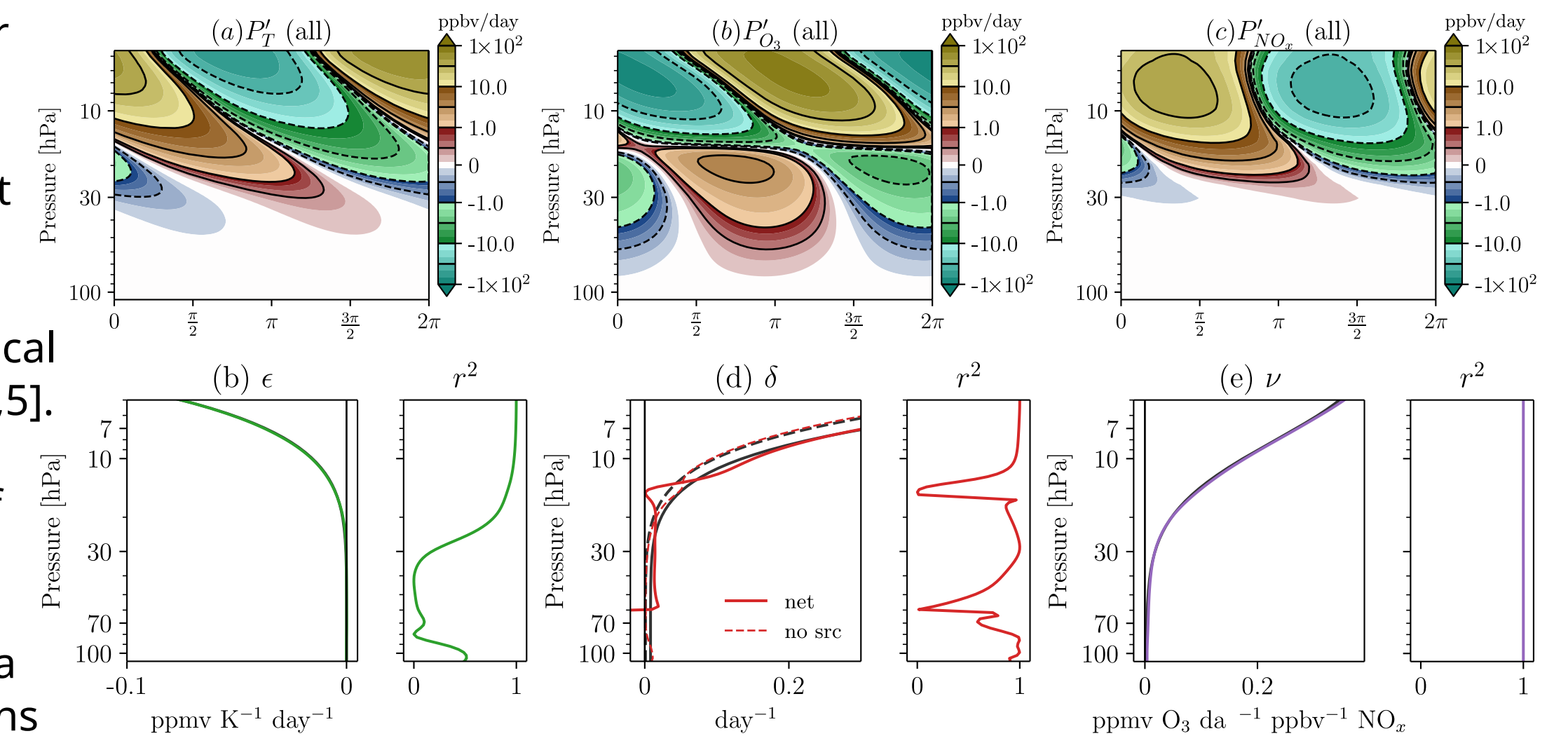


In the dynamically-controlled regime (below about 12 hPa), temperature is determined by a balance between radiative relaxation and ozone heating. Ozone is determined by advection by both the background upwelling and the secondary circulation, as well as by photochemical damping; all three are important.

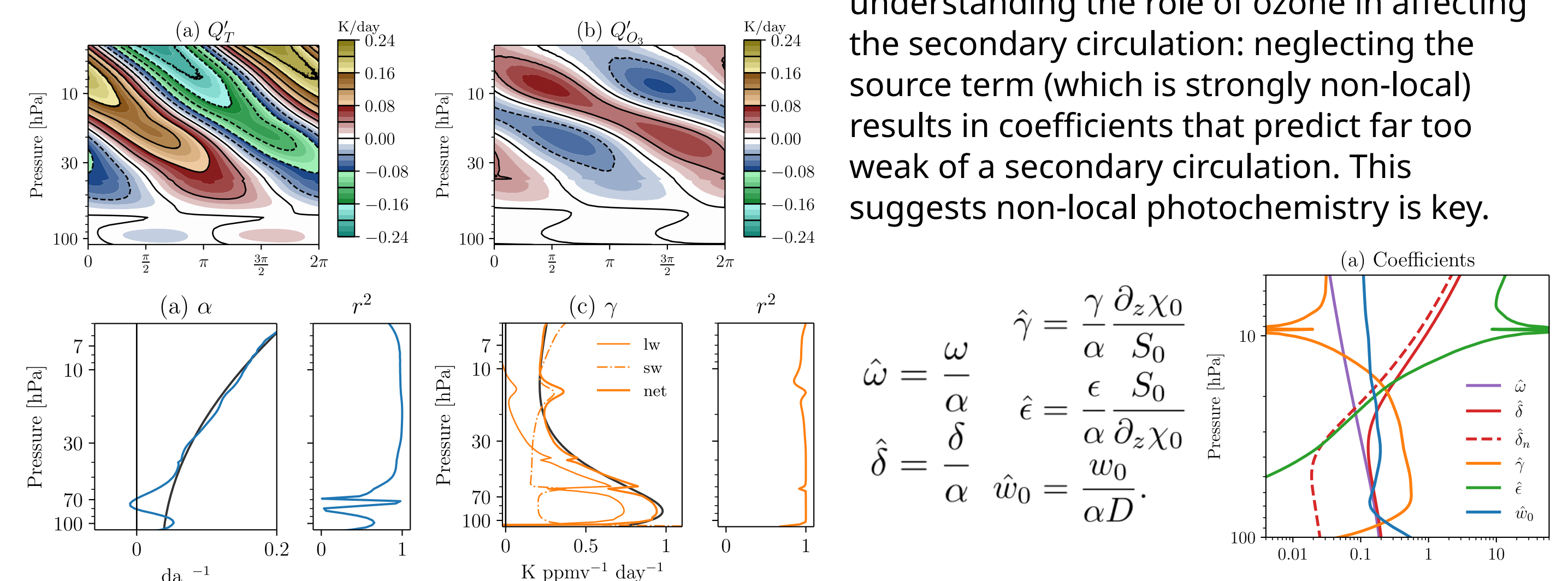
$$\begin{aligned} \tilde{T} &= \hat{\gamma} \tilde{\chi} \\ \tilde{\chi} &= -\frac{\partial_z \chi_0 \tilde{w}}{\delta} \\ \tilde{\chi} &= -\int_{z_t}^z \frac{\tilde{w}}{w_0} \partial_z \chi_0 \exp \left\{ -\int_{z'}^z \frac{\delta}{w_0} dz'' \right\} dz' \end{aligned}$$

2. Linear Coefficients

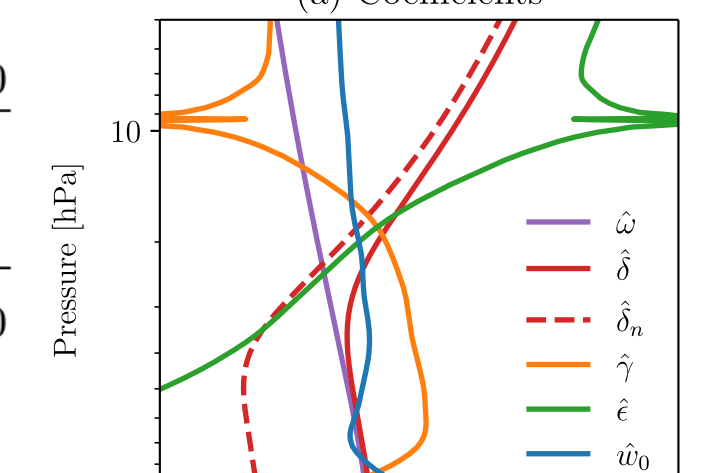
Linear coefficients for the ozone and thermodynamics budgets have been fit to output from a radiative-convective/radiative photochemical equilibrium model [4,5]. The fits are additive, and through much of the domain are reasonably accurate, through below 70 hPa non-local contributions dominate.



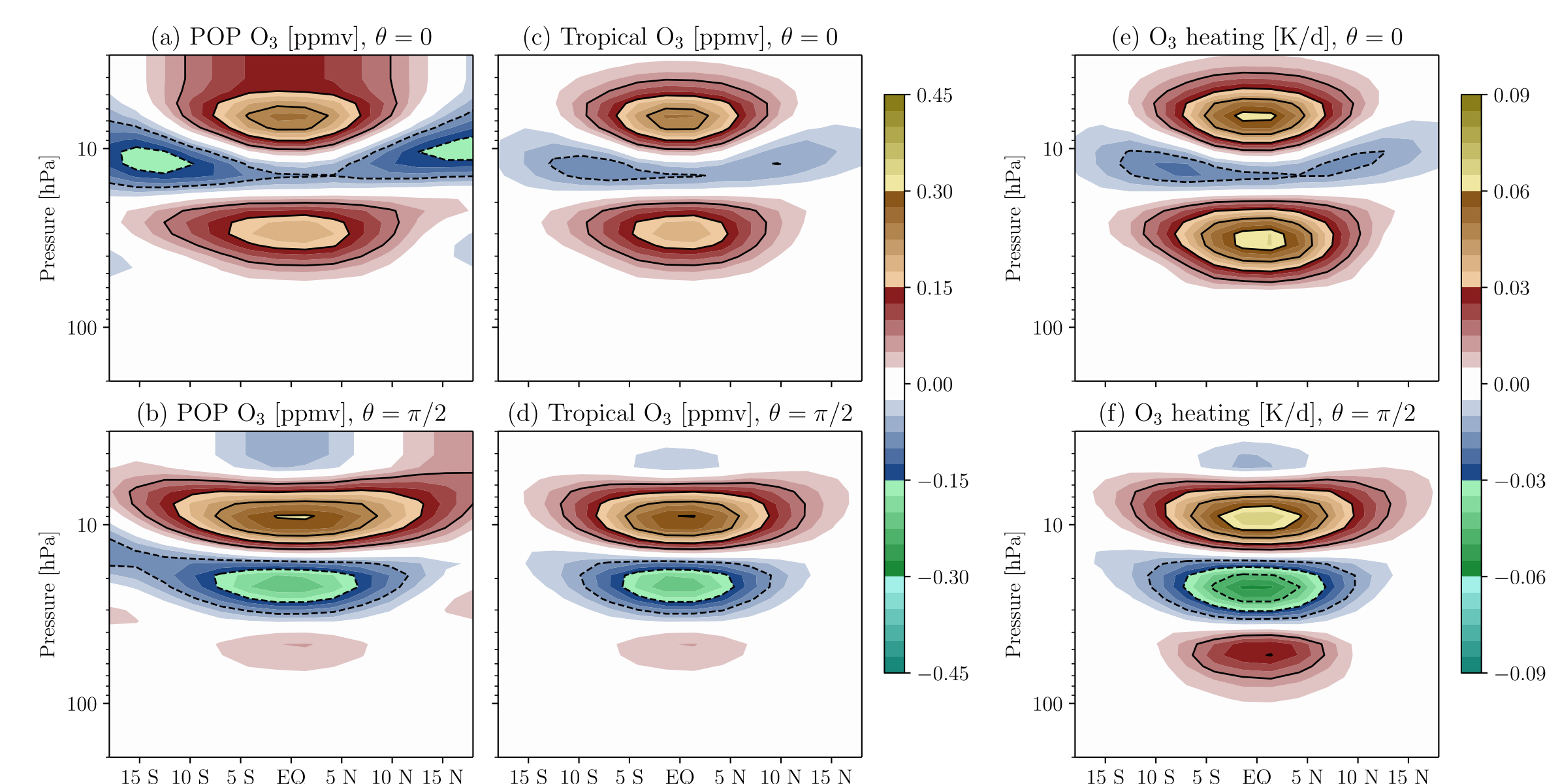
Photochemical sensitivities are key to understanding the role of ozone in affecting the secondary circulation: neglecting the source term (which is strongly non-local) results in coefficients that predict far too weak of a secondary circulation. This suggests non-local photochemistry is key.



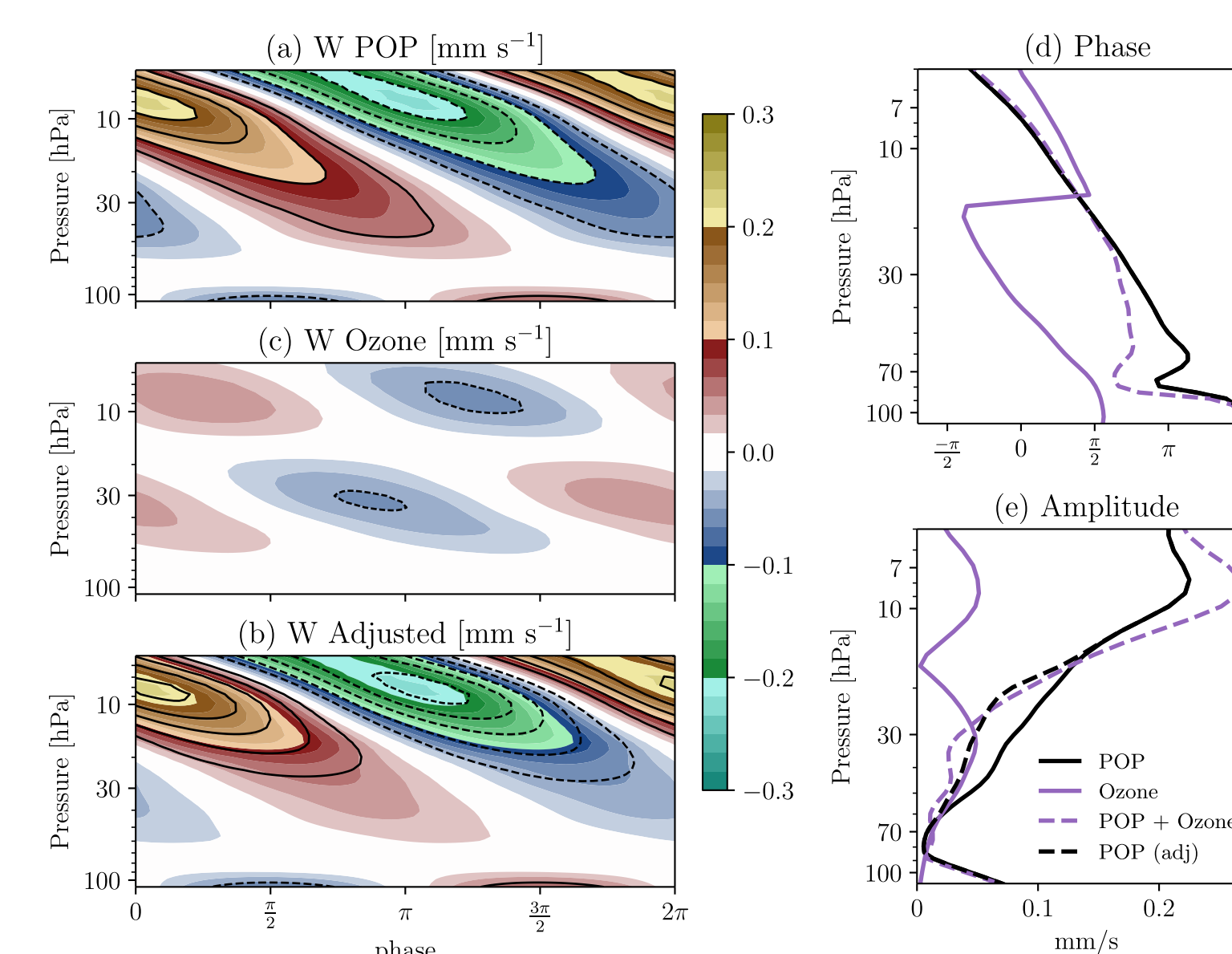
$$\begin{aligned} \hat{\omega} &= \frac{\omega}{\alpha} \\ \hat{\delta} &= \frac{\delta}{\alpha} \\ \hat{\gamma} &= \frac{\gamma}{\alpha} \frac{\partial_z \chi_0}{S_0} \\ \hat{\epsilon} &= \frac{\epsilon}{\alpha} \frac{\partial_z \chi_0}{S_0} \\ \hat{w}_0 &= \frac{w_0}{\alpha D} \end{aligned}$$



4. Overestimation of QBO w* in ERA5



The overestimation of the QBO secondary circulation in ERA5 is due to the fact that only climatological ozone is used for radiative heating rates. The missing circulation can be estimated using (a) observed ozone anomalies [6], (b) the linear coefficients estimated above, and (c) a zonally symmetric primitive equation solver. The ozone QBO in the tropics and its associated heating rate anomalies are shown above. The secondary circulation induced by these heating rates is shown below, along with an estimate of the adjusted secondary circulation. Use of the adjusted circulation provides a much better fit in the linear model of the temperature and ozone QBO.



This work is published [4,7]. A more satisfying theory of the secondary circulation would start from the wave driving directly, or be explicitly coupled to a model of the wave forcing. Nonetheless, this model should be useful for diagnosing the QBO secondary circulation in the QUOCA models with imposed vs linear vs interactive ozone. Ongoing effort is pursuing such an approach.

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