Zonal Mean Models

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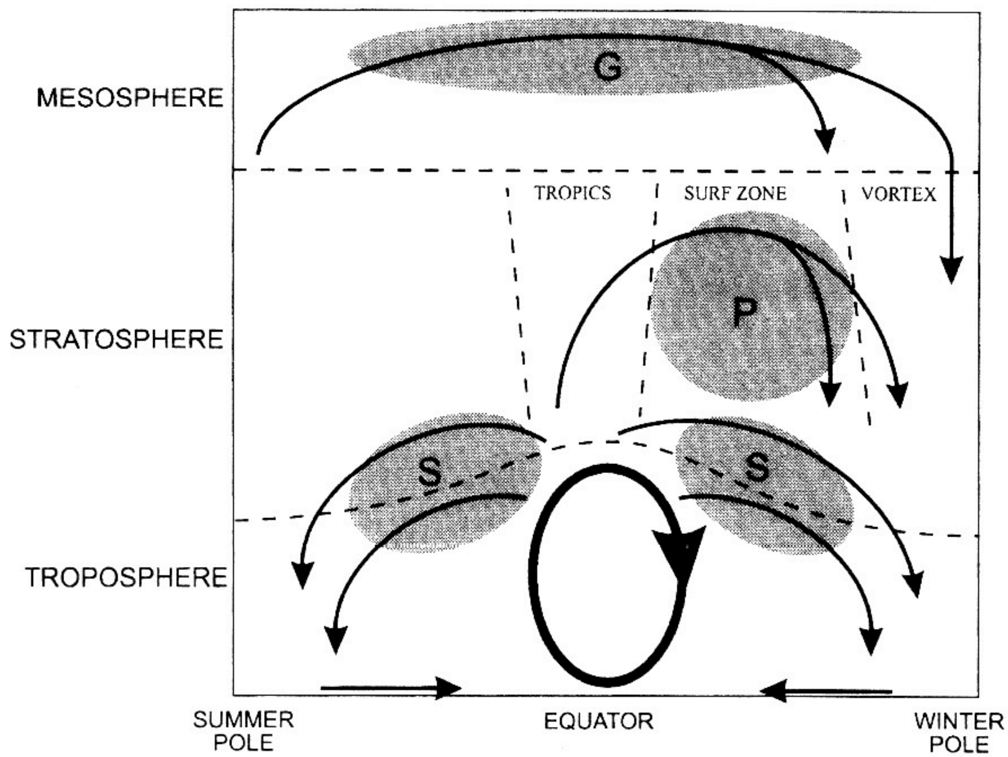
The Zonal Mean Circulation



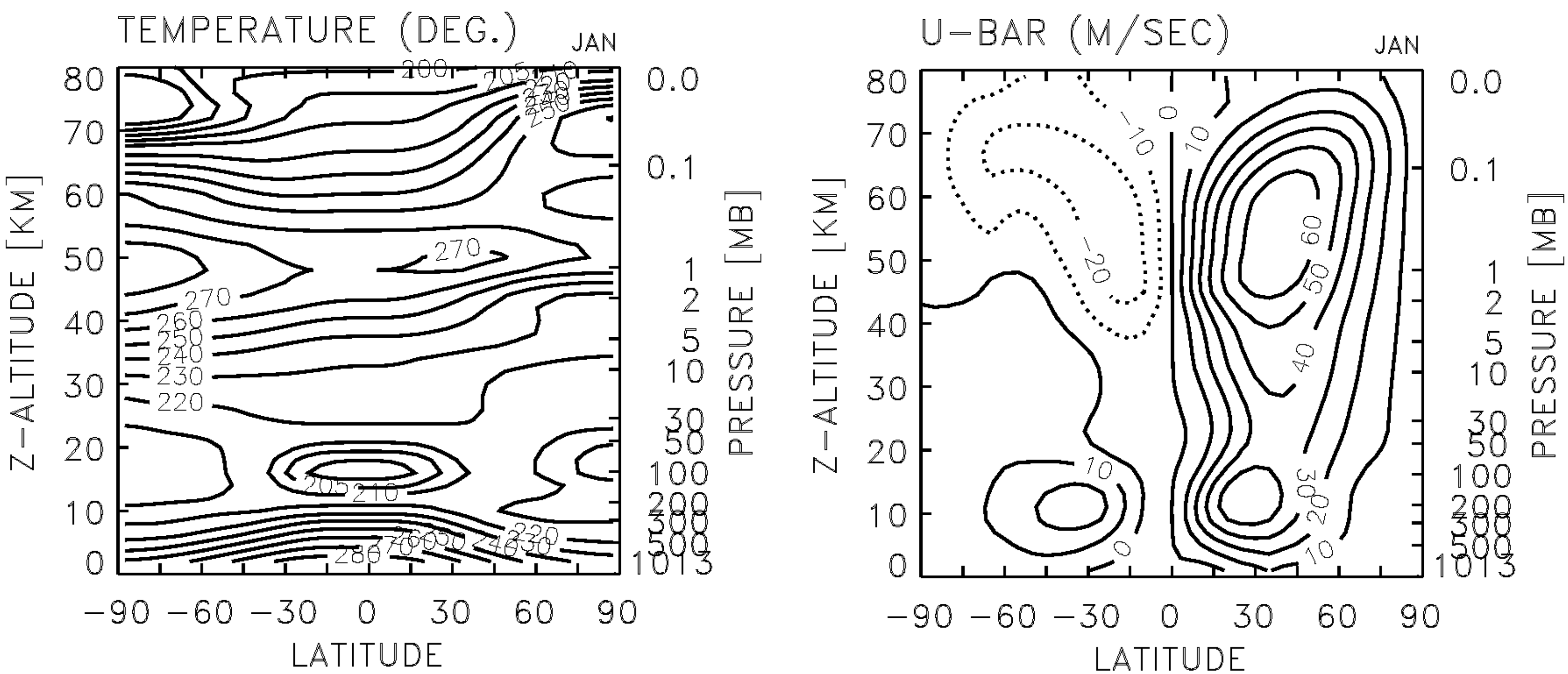
[Plumb, 2002]

- **The challenge: How to describe the wave driving, which is fundamentally a 3-D process, in a 2-D framework?**
- **There have been a number of approaches, of varying degrees of sophistication:** **e.g. Harwood and Pyle, *QJRMS*, 1975; Schoeberl and Strobel, *JAS*, 1978; Tung, *JAS*, 1982; Garcia and Solomon, *JGR*, 1983; Plumb and Mahlman, *JAS*, 1987; Jackman et al., *JGR*, 1988; Kinnersley and Harwood, *QJRMS*, 1993**

Modelled Fields

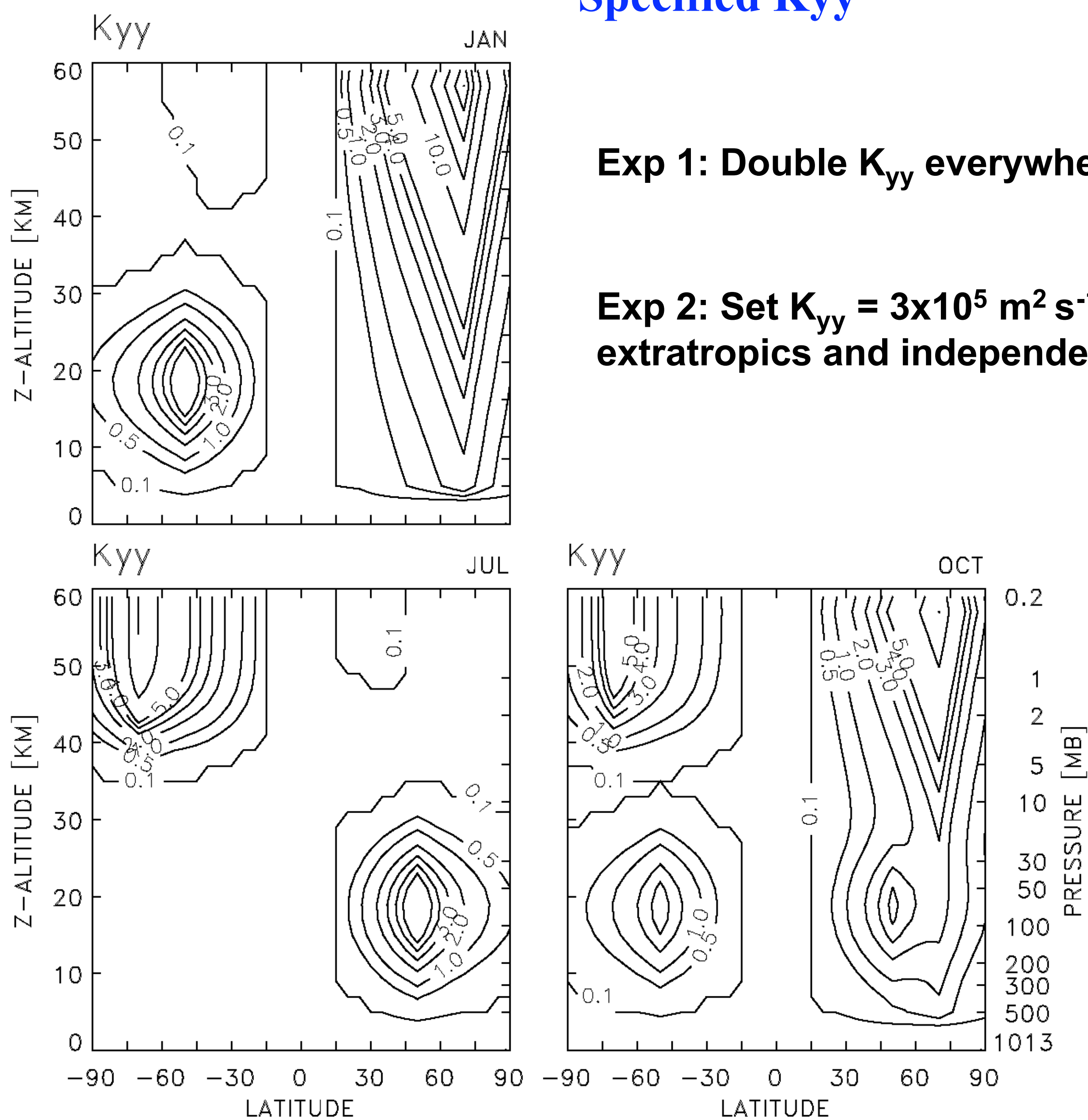
Zonal momentum equation

$$\partial_t \bar{u} + \frac{1}{\cos\theta}\partial_y(\overline{uv}^* \cos\theta) + \frac{1}{\rho_o}\partial_z(\rho_o \overline{uw}^*) - f\bar{v}^* - \frac{\overline{uv}^*}{a}\tan\theta = -\beta_R \bar{u} - K_{yy}\partial_y \bar{q}_y$$



[Schneider et al., 2000]

Specified Kyy



Exp 1: Double K_{yy} everywhere outside the tropics

Exp 2: Set $K_{yy} = 3x10^5\ m^2\ s^{-1}$ everywhere in extratropics and independent of season

[Based on Newman et al., 1988]

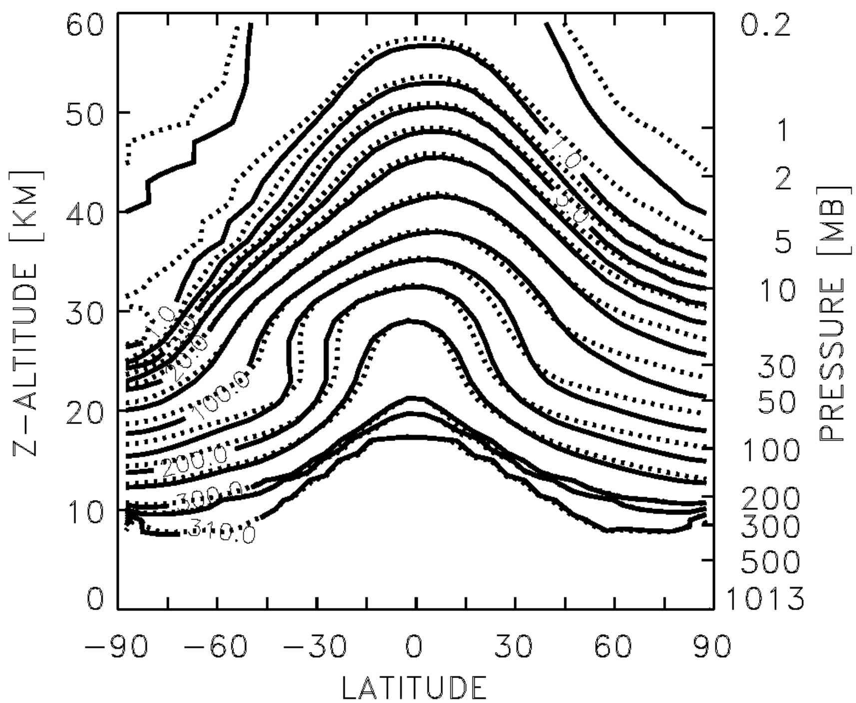
Units: $10^5\ m\ s^{-2}$

[Schneider et al., 2000]

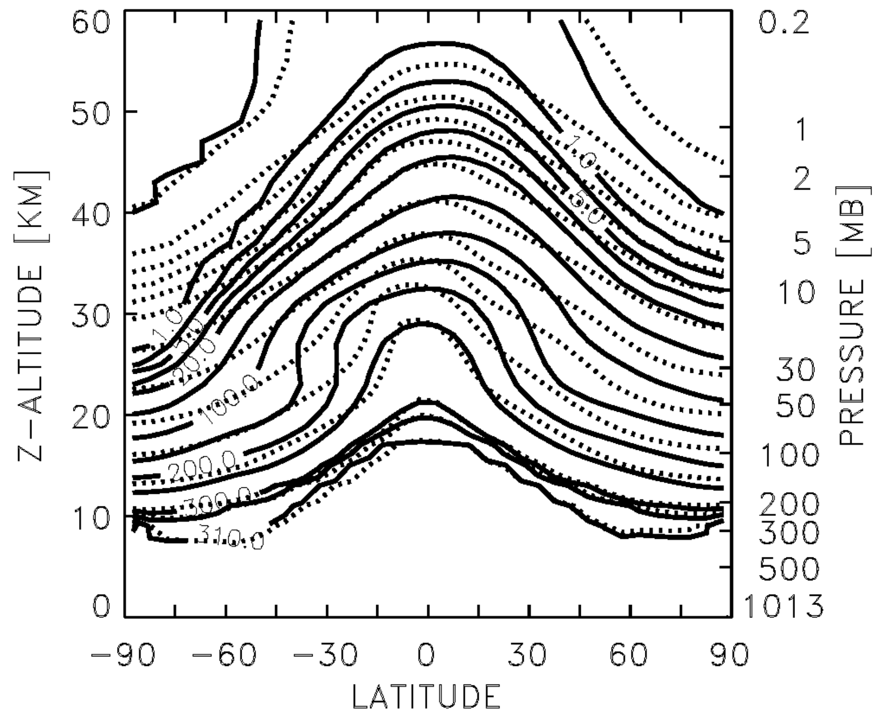
Sensitivity to K_{yy}

Modelled N_2O for September

Double Kyy (dotted line)

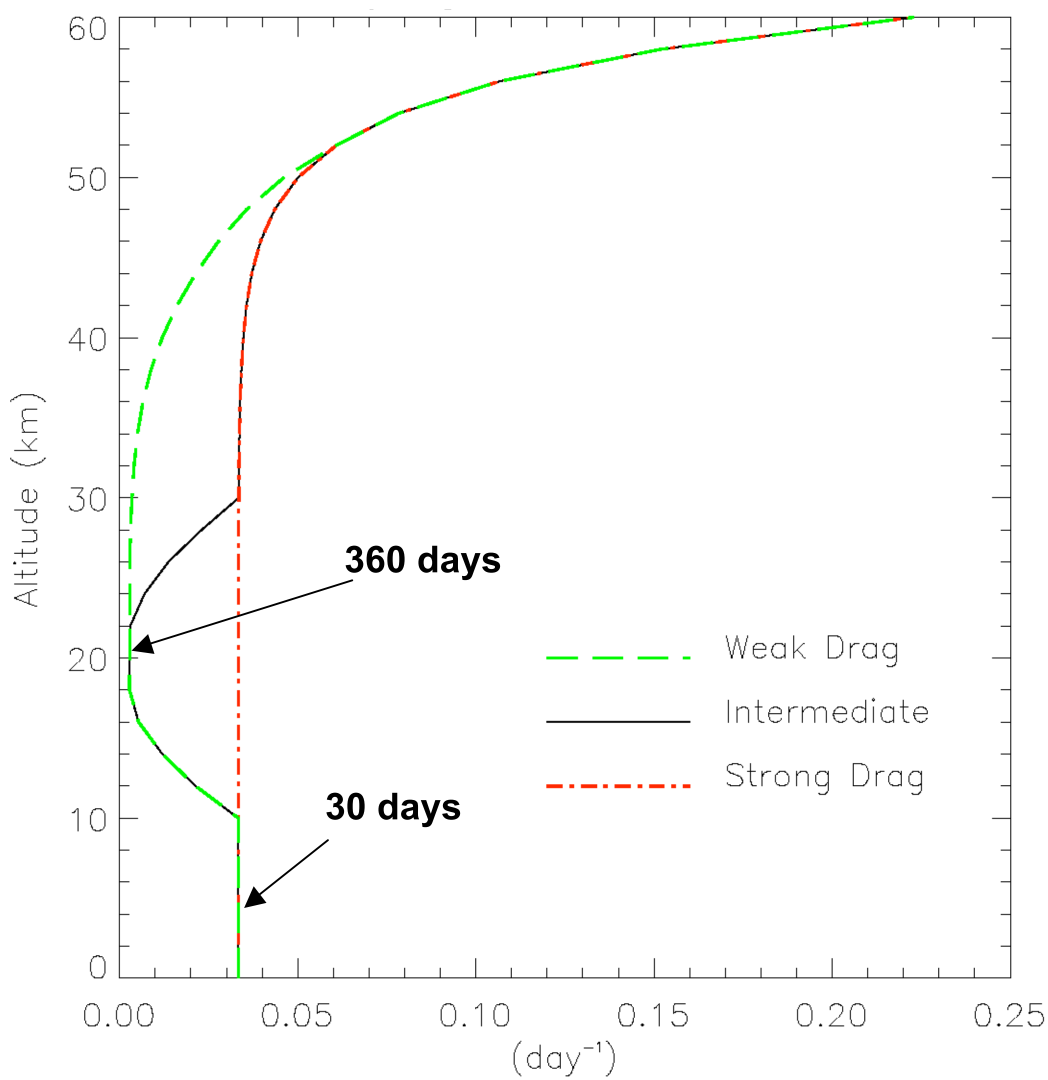


Constant Kyy (dotted line)

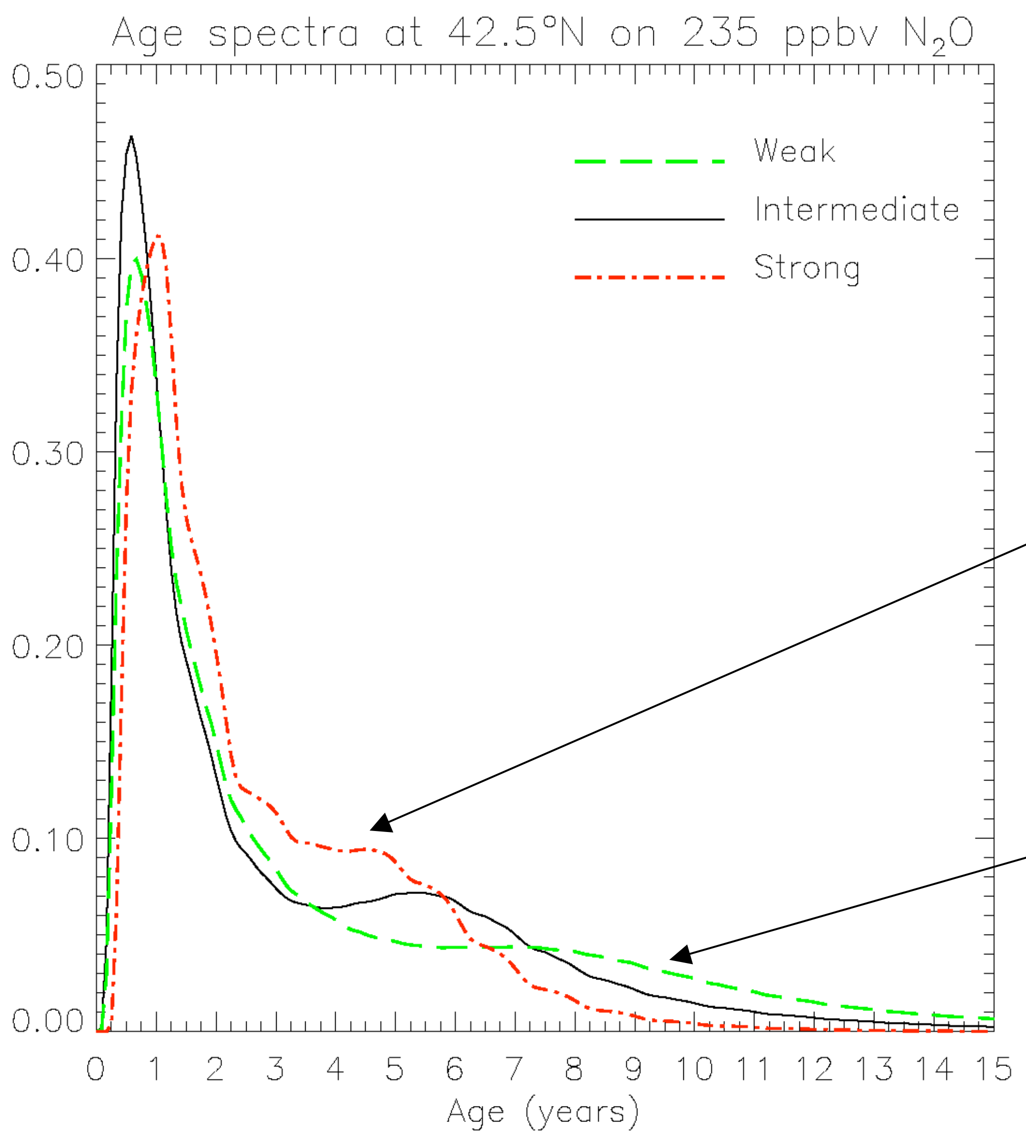


- **Doubling Kyy everywhere outside the tropics does not significantly influence the N_2O distribution because the Kyy are used for the mixing of both the PV and the chemical tracer**
- **Constant Kyy (which results in increased Kyy in subtropics) reduces the subtropical gradients in N_2O**

Sensitivity to the Rayleigh Friction (β_R)



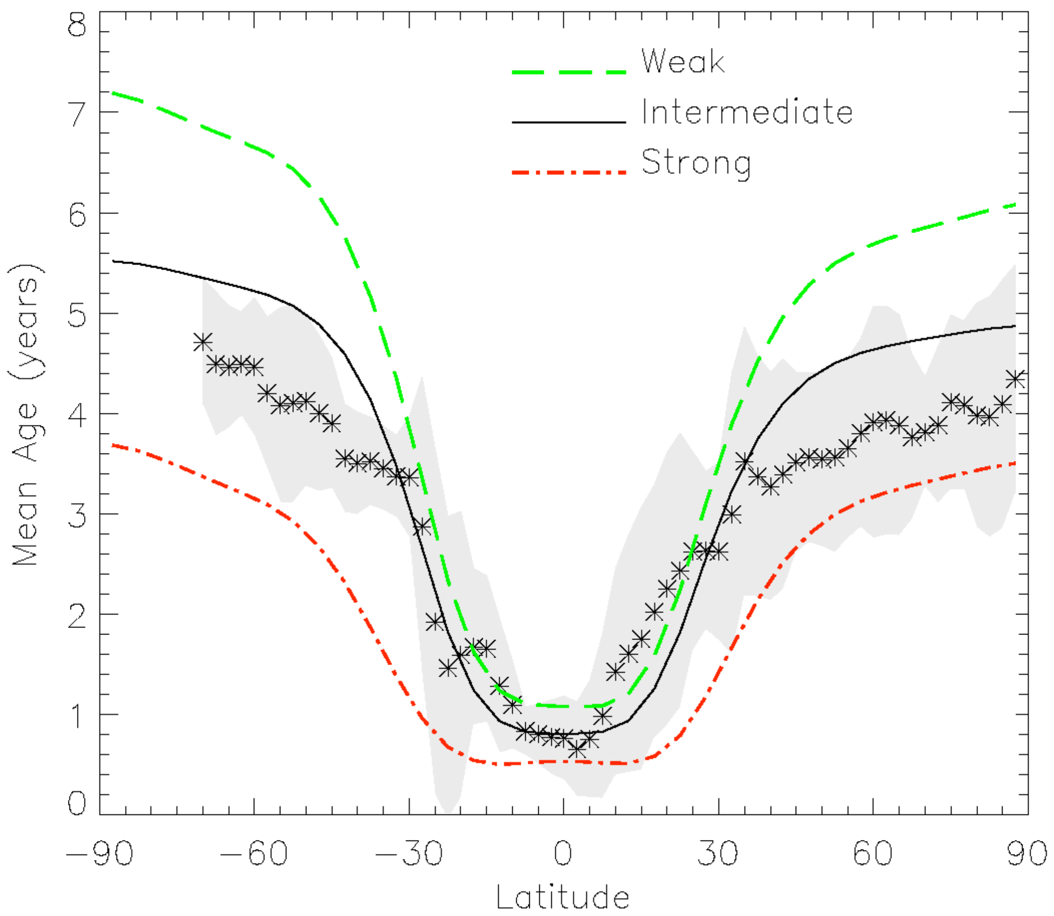
Age Spectrum



stronger outflow from the tropics in strong drag case results in shorter transit times to the extratropical lower stratosphere

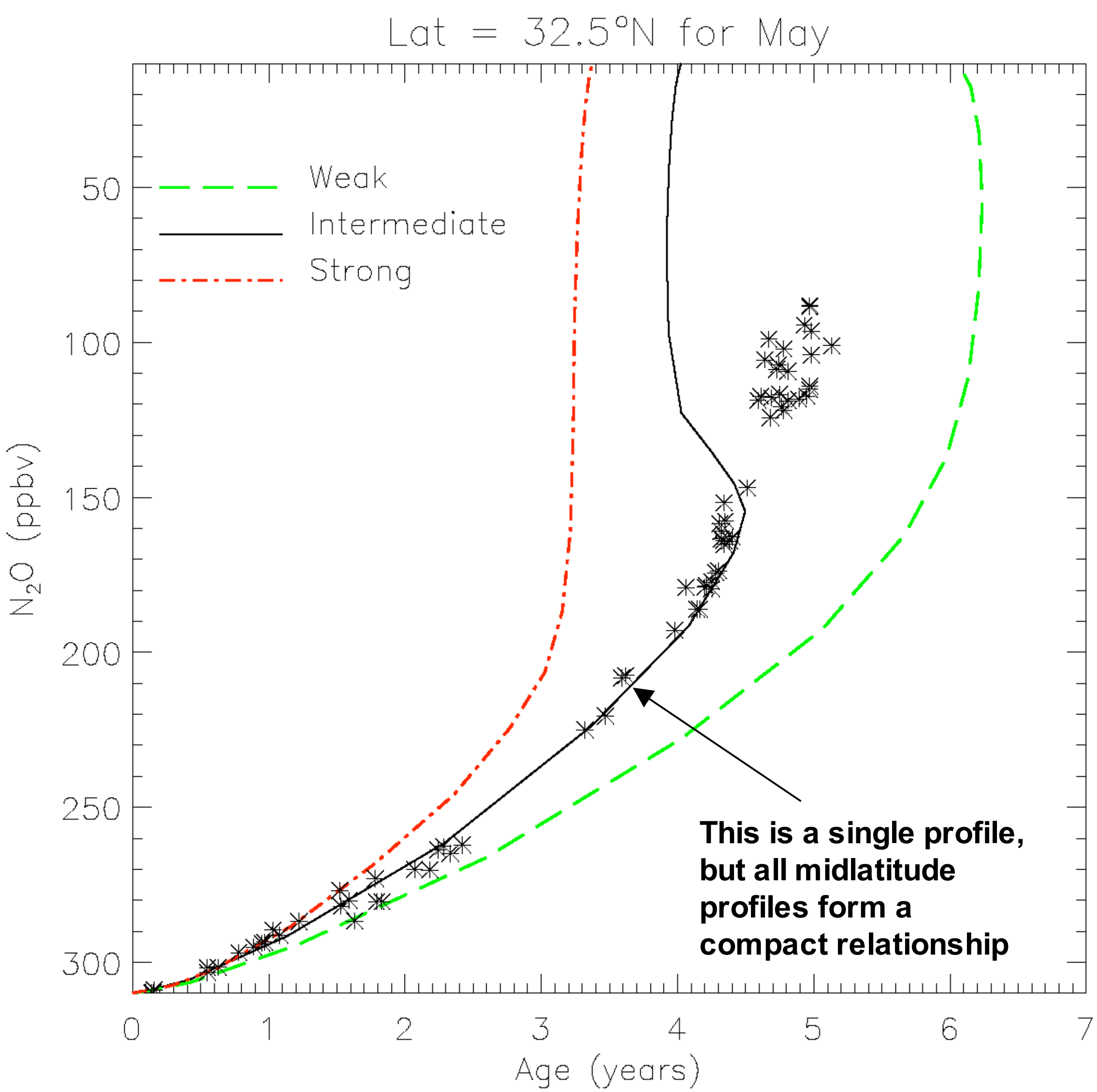
Reduced outflow from tropics in weak drag case results in longer transit times

Mean Ages



- Weak (strong) friction case significantly older (younger) everywhere in the extratropical lower stratosphere
- The intermediate drag case also overestimates the mean age

Correlation Between N_2O and Age

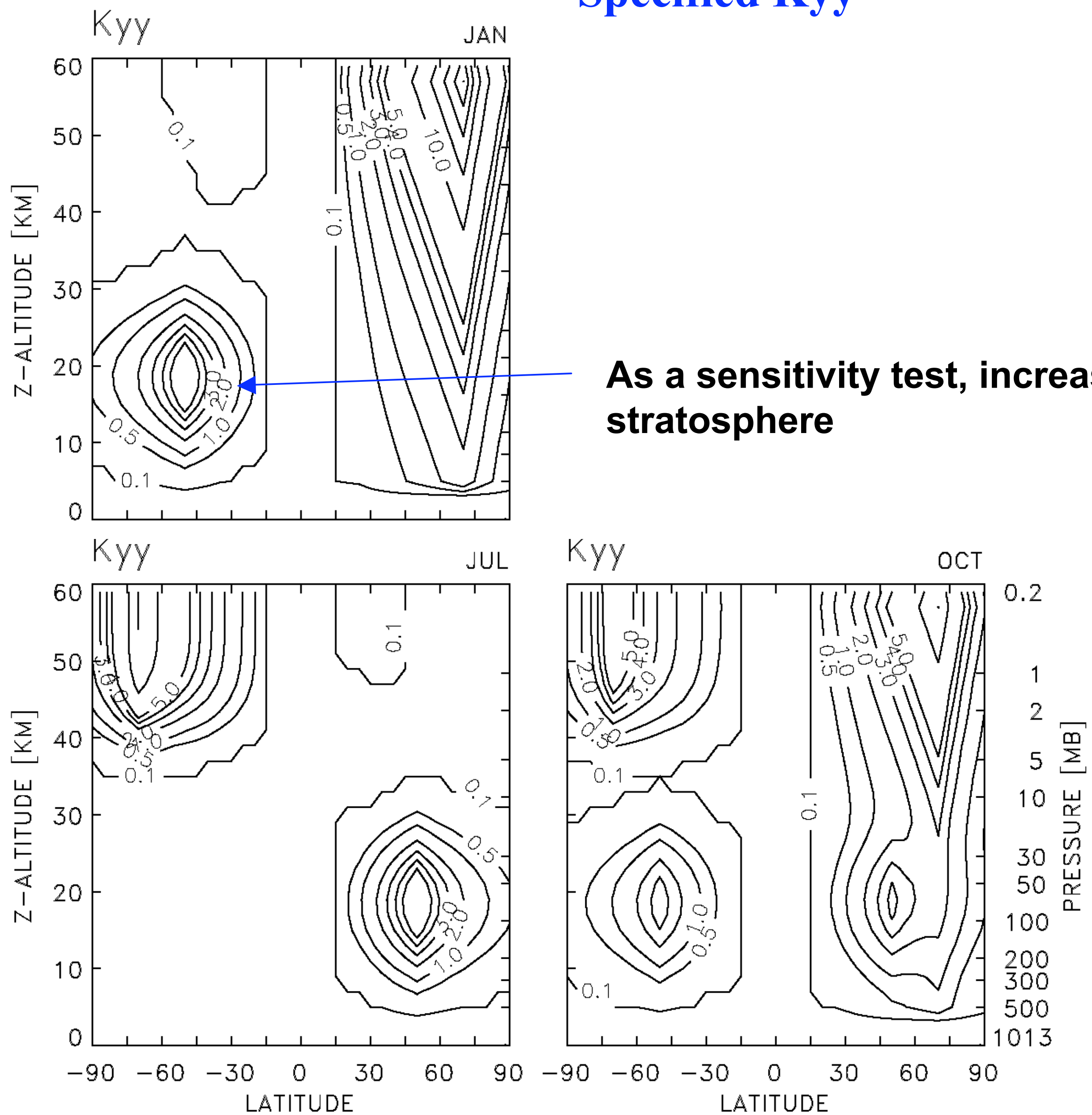


Sensitivity runs cannot reproduce age/N2O correlation

- The strong and weak simulations are extreme cases
- The friction is only one component of the forcing

N_2O and age data (1 balloon flight) are for 18 May 1998, at 34ºN, by Scott et al. [1999] and Andrews et al. [2001], respectively

Specified Kyy

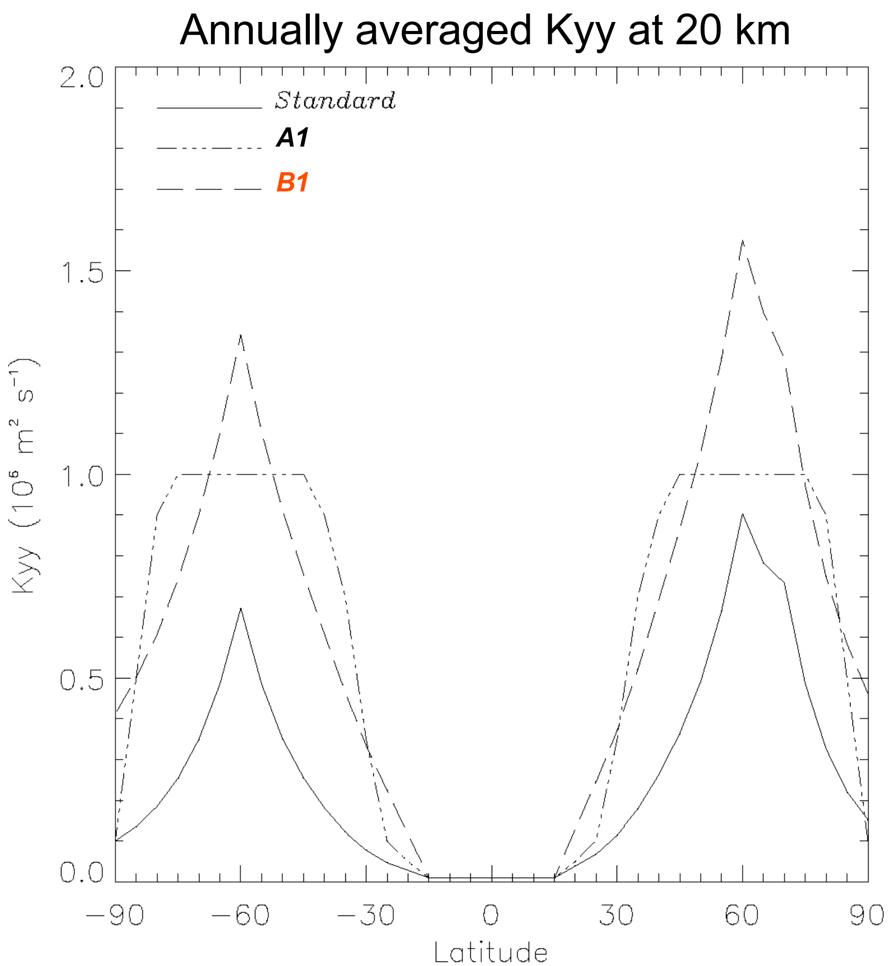


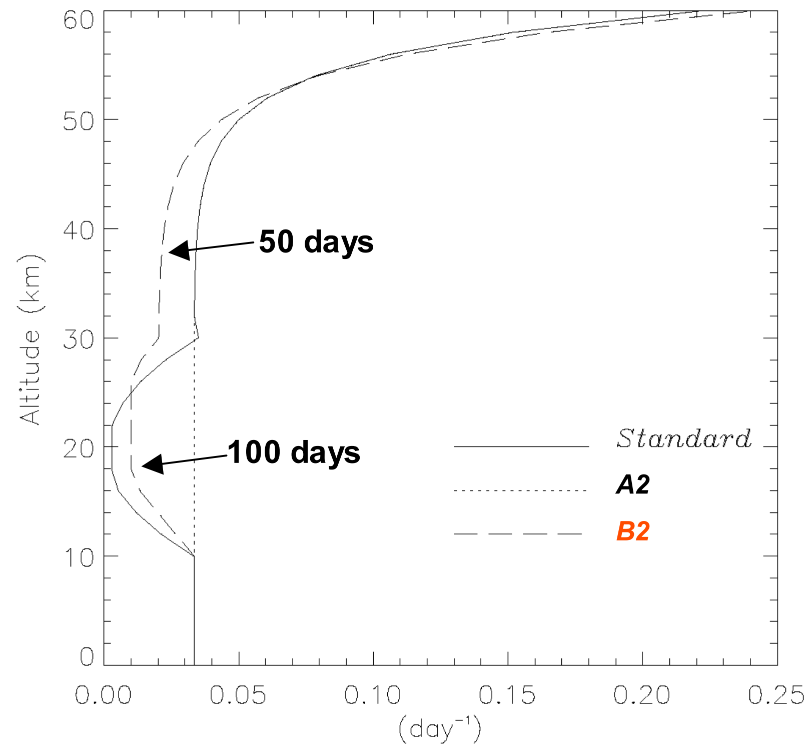
As a sensitivity test, increase Kyy in lower stratosphere

Units: 10^5 m s^{-2}

[Schneider et al., 2000]

Combined Friction and Kyy Experiment

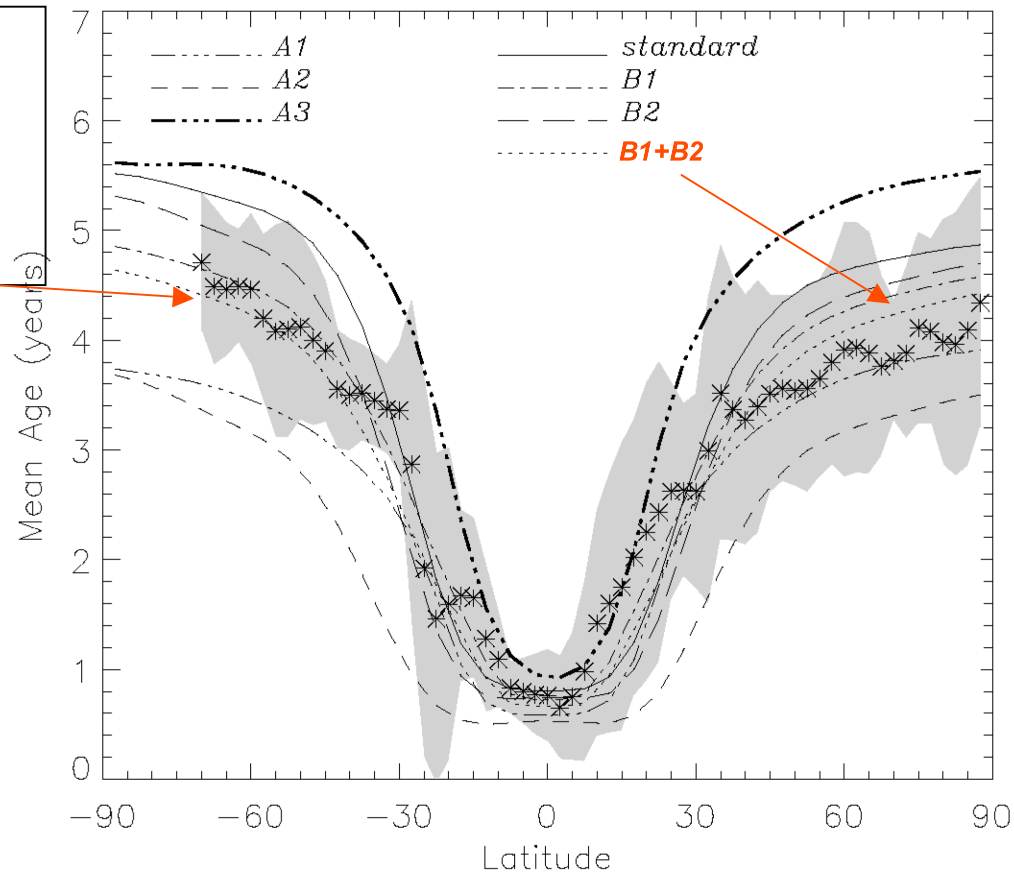




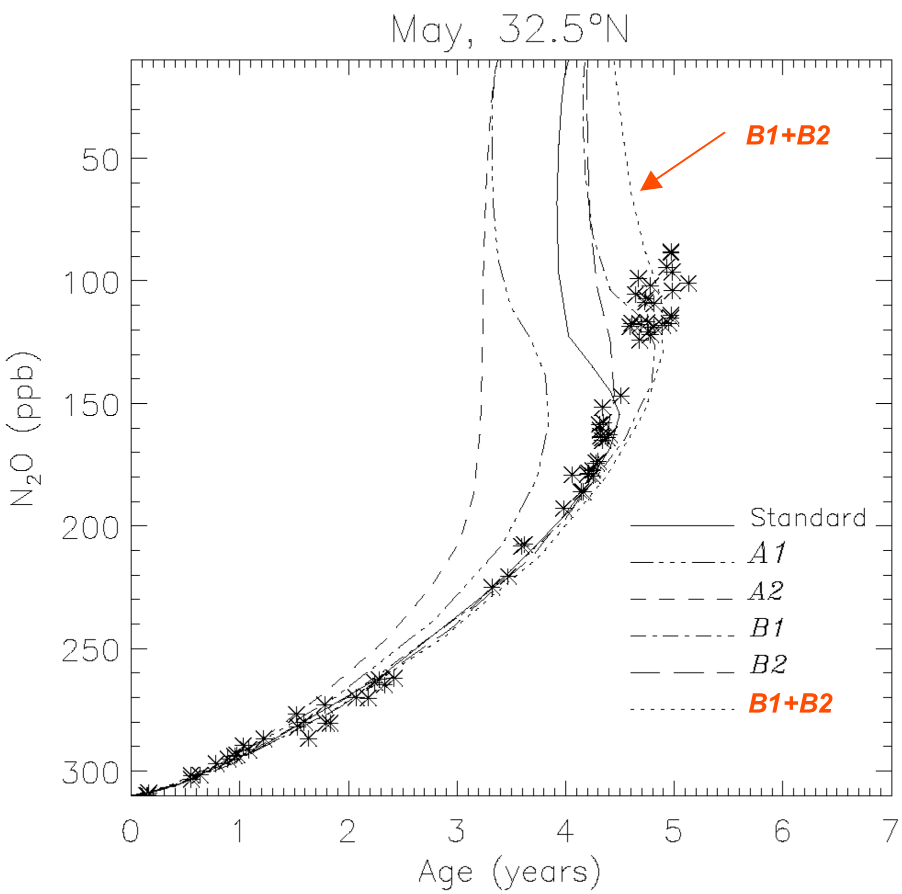
B1+B2: Double lower stratospheric Kyy maximum + increased drag below 30 km with reduced drag at higher levels

Meridional Age Gradient

Enhanced meridional transport in the lower stratosphere Improves modelled mean ages in extratropical lower stratosphere

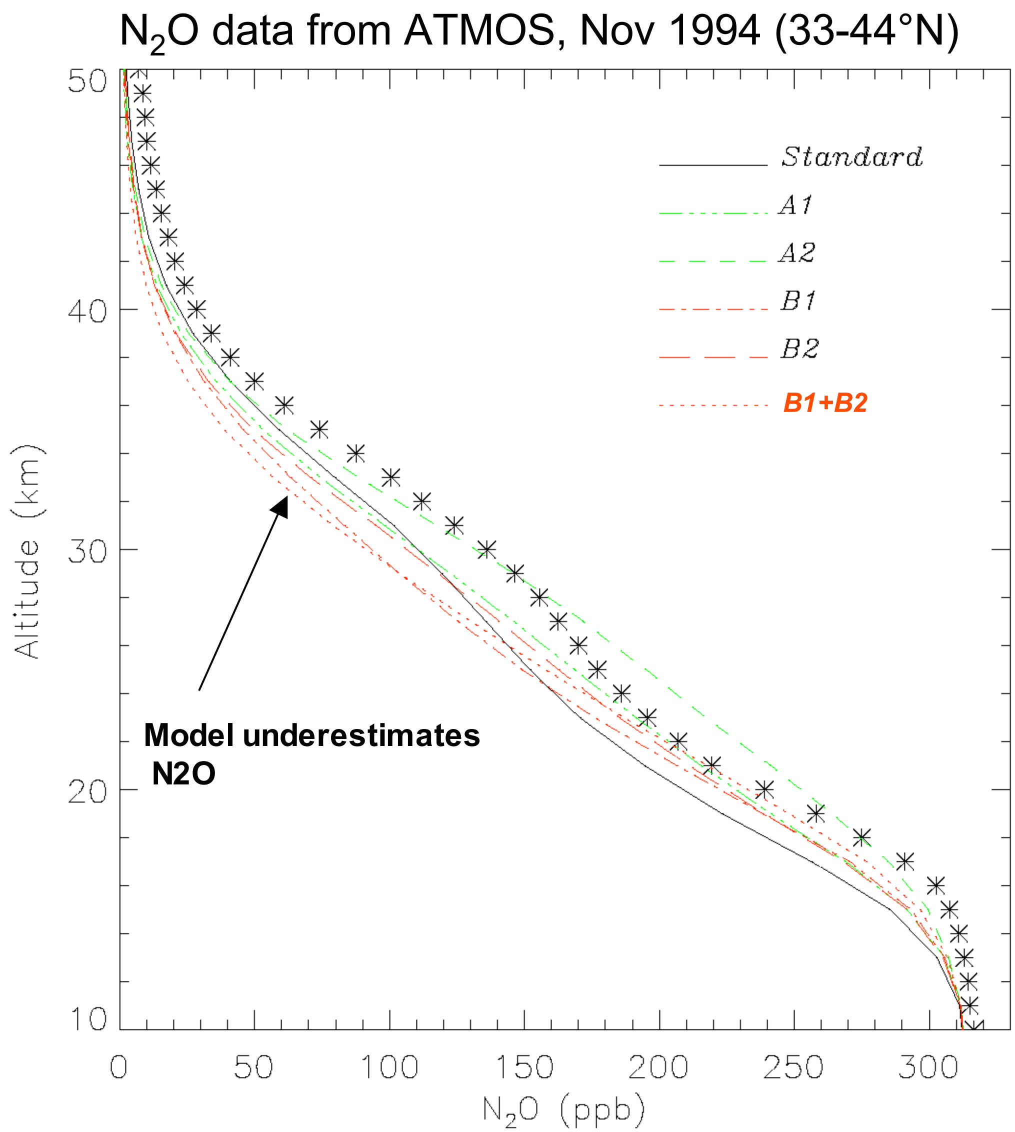


Correlation Between N_2O and Age



Unlike the weak and strong drag cases, B1+B2 reproduces the age/N2O correlation

Modelled N_2O Profile (averaged 30-45°N)



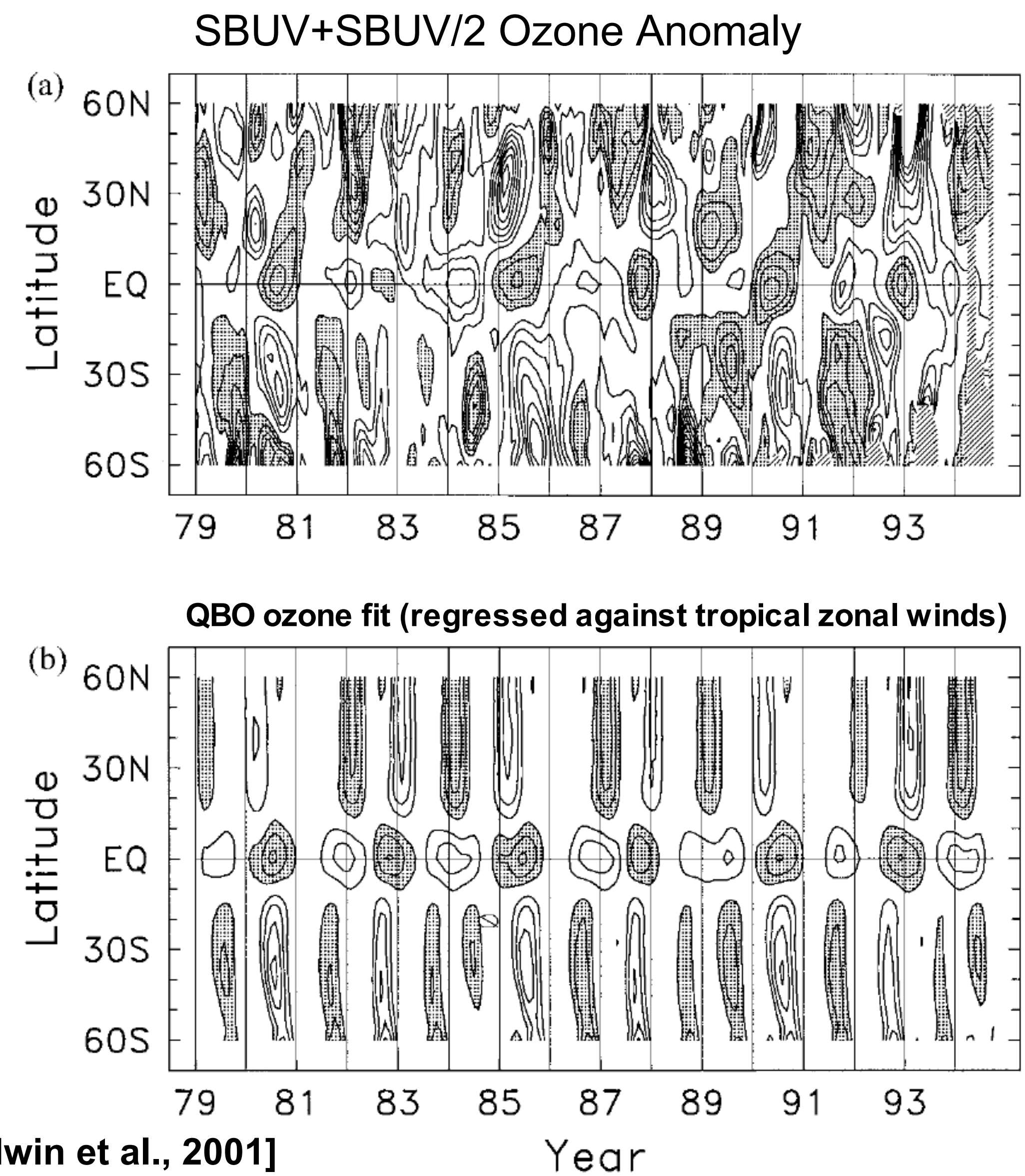
[Jones et al., 2001]

By increasing the outflow in the lower stratosphere we have tuned the model to reproduce the age and N_2O in the lower stratosphere at the expense of the upper stratosphere

We could modify Kyy and β_R to also match the N_2O data in the upper stratosphere, but how do you ensure that this tuning is physically meaningful?

Try to limit tuning! But when you do it, interpret the model results carefully

QBO in Column Ozone



[Baldwin et al., 2001]

Example of the utility of a simple model (and useful tuning)

Why is the QBO in extratropics strongest in the winter hemisphere?

QBO in Zonal Winds

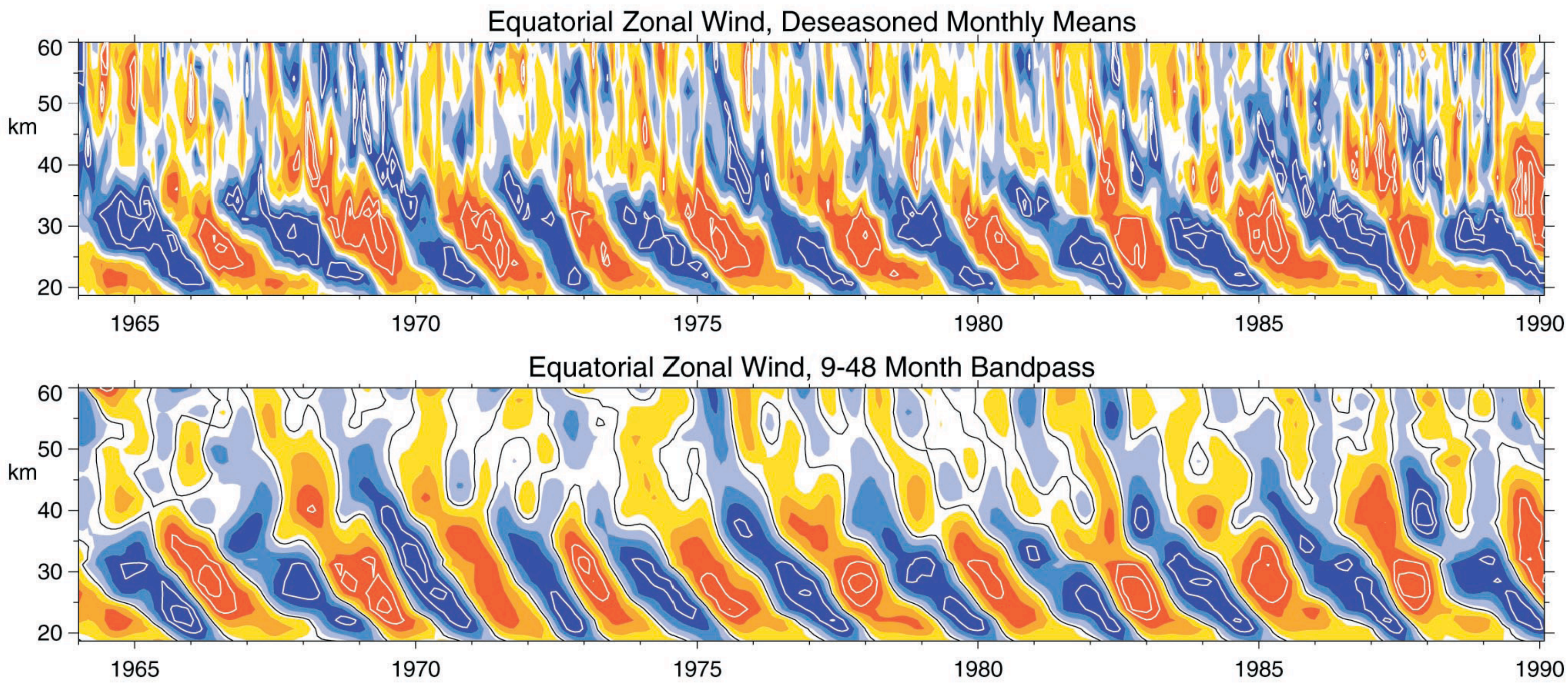
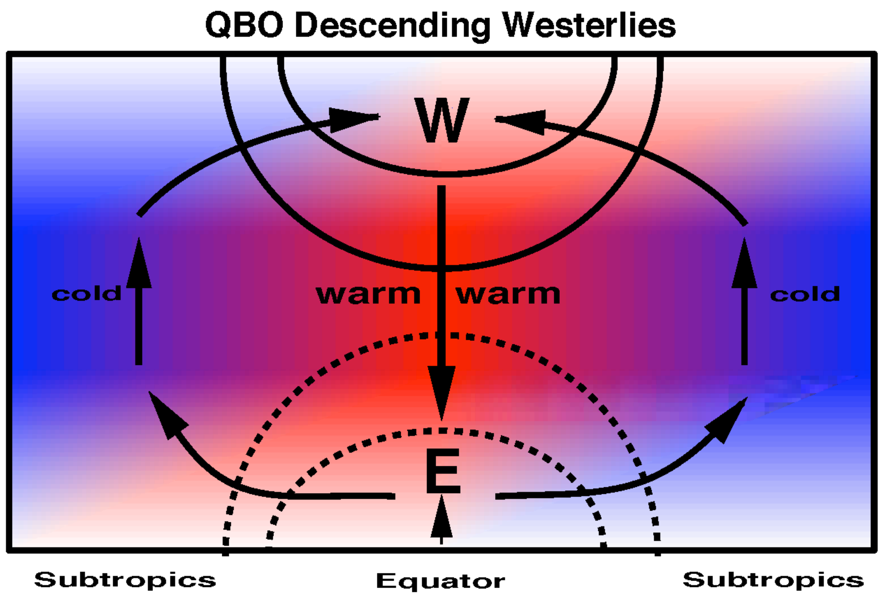
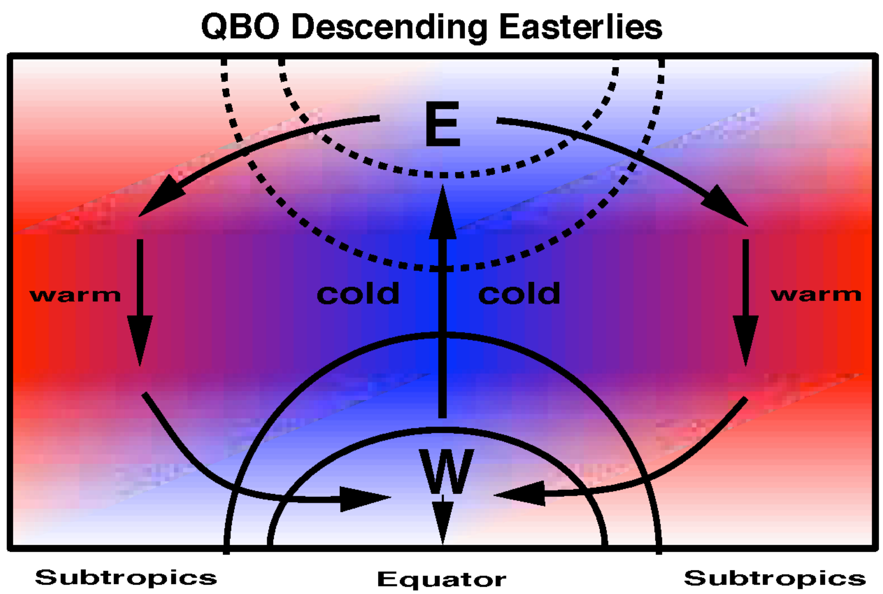


Plate 1. (top) Time-height section of the monthly-mean zonal wind component (m s^{-1}), with the seasonal cycle removed, for 1964–1990. Below 31 km, equatorial radiosonde data are used from Canton Island (2.8°N, January 1964 to August 1967), Gan/Maledive Islands (0.7°S, September 1967 to December 1975), and Singapore (1.4°N, January 1976 to February 1990). Above 31 km, rocketsonde data from Kwajalein (8.7°N) and Ascension Island (8.0°S) are shown. The contour interval is 6 m s^{-1}, with the band between −3 and +3 unshaded. Red represents positive (westerly) winds. After *Gray et al.* [2001]. In the bottom panel the data are band-pass filtered to retain periods between 9 and 48 months.

[Baldwin et al., 2001]

QBO Meridional Circulation





In the middle stratosphere:

- **Lower temperatures (associated with ascent) slows down chemical loss of O_3**
- **Ascent results in a reduction in NO_y (and NO_x) and therefore less O_3 loss**

In the lower stratosphere:

Descent in the tropics will result an increase in tropical ozone, whereas ascent in subtropics will result in reduced subtropical ozone

Why are the subtropical O3 anomalies larger in winter?

The QBO Mechanism

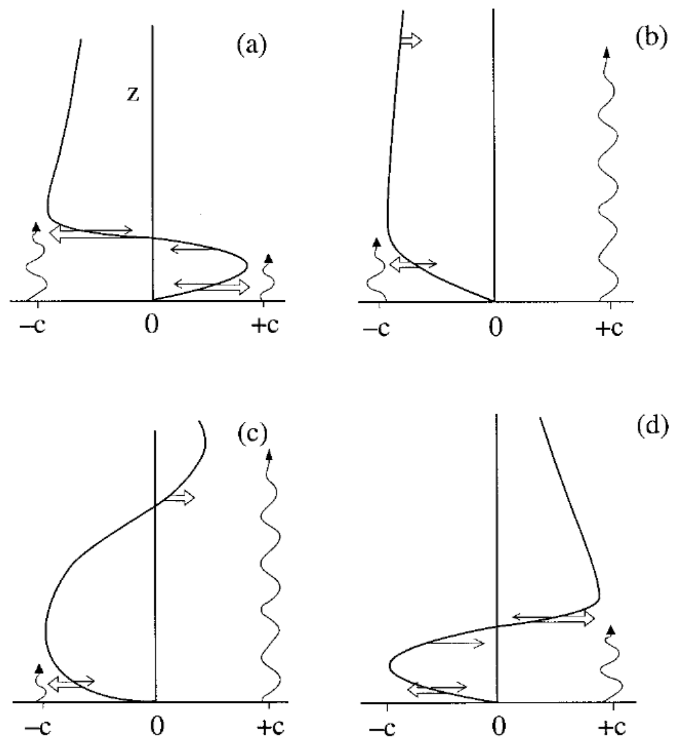


Figure 7. Schematic representation of the evolution of the mean flow in *Plumb*'s [1984] analog of the QBO. Four stages of a half cycle are shown. Double arrows show wave-driven acceleration, and single arrows show viscously driven accelerations. Wavy lines indicate relative penetration of eastward and westward waves. After *Plumb* [1984]. Reprinted with permission.

Forced by vertically propagating gravity waves in the tropics

Simulating the QBO

Forcing the QBO in the 2-D Model [Holton and Lindzen, 1972]

$$F = \left[A\exp\left(\frac{z - z_o}{H}\right) R(z) \exp\left(-\int_{z_o}^{z} R(z')dz' \right) \right] + k_z \frac{\partial^2 \overline{u}}{\partial z^2}$$

QBO zonal forcing

where

$$R(z) = \frac{\alpha(z)N}{k(\overline{u} - c)^2} \left[\frac{\beta}{k^2(\overline{u} - c)} - 1 \right]$$

Rossby-gravity wave

$$R(z) = \frac{\alpha(z)N}{k(\overline{u} - c)^2}$$

Kelvin wave

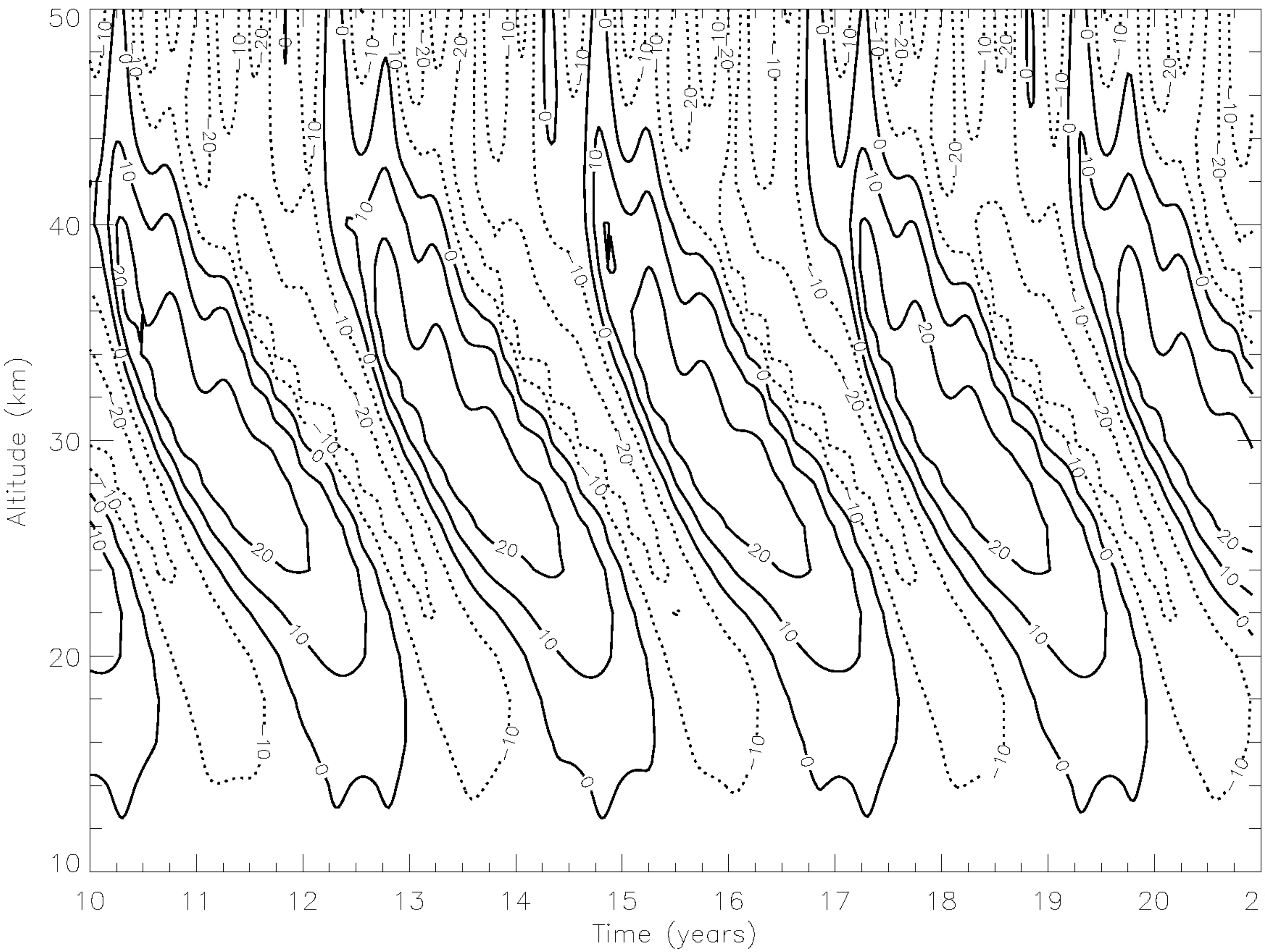
	Kelvin Wave	Rossby-Gravity Wave
k	2	4
c (m s^{-1})	+30	−30
A (m^2 s^{-2})	12.0×10^{-3}	-19.0×10^{-3}

The simplification

The large scale Kelvin and Rossby-gravity waves account for a small fraction of the actual momentum flux - the QBO is forced by a broad spectrum of waves

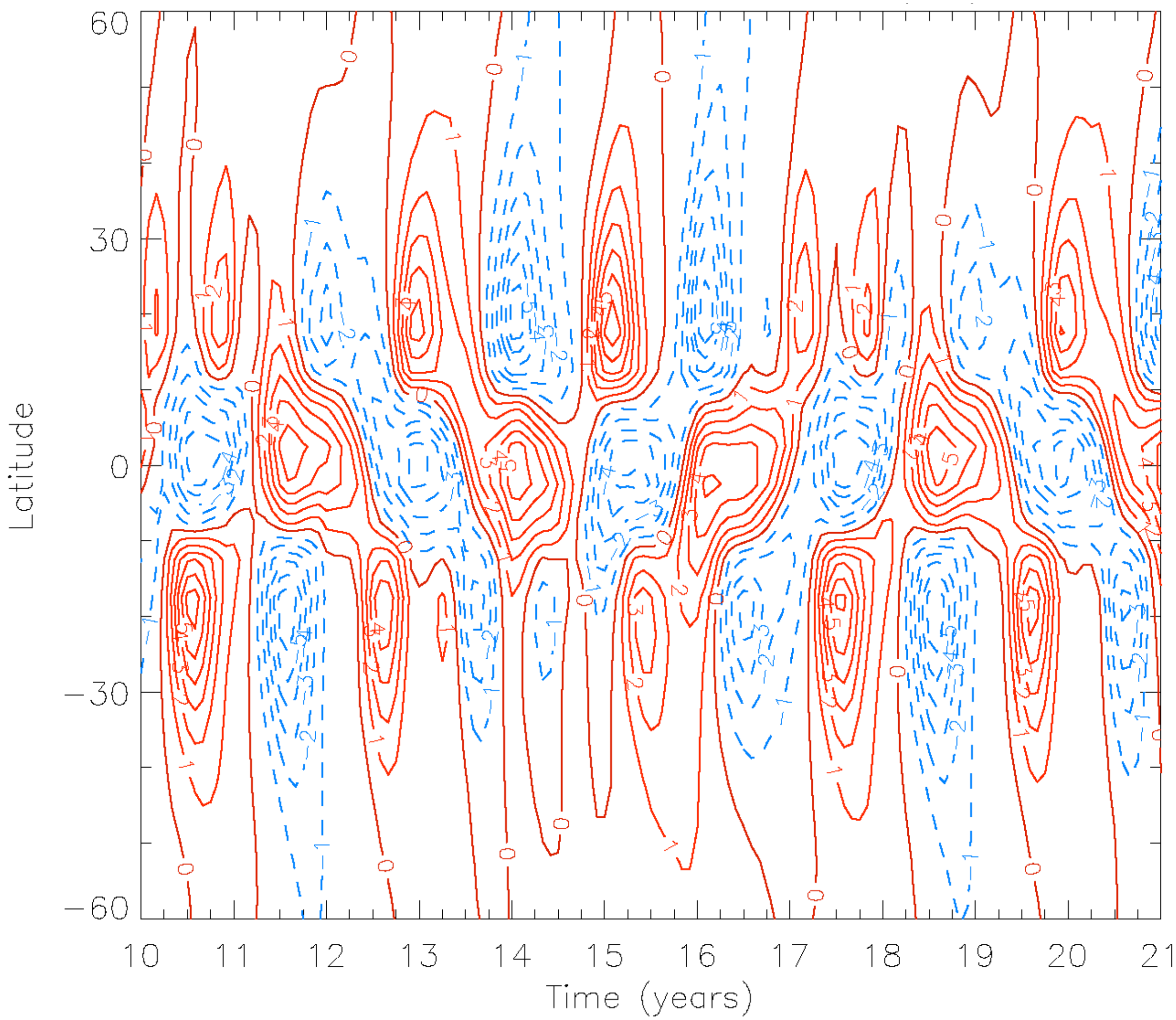
Momentum flux (*A*) and k_z chosen to provide a "reasonable QBO"

Modelled Equatorial Zonal Winds (m/s)



Period of modelled QBO = 28 months

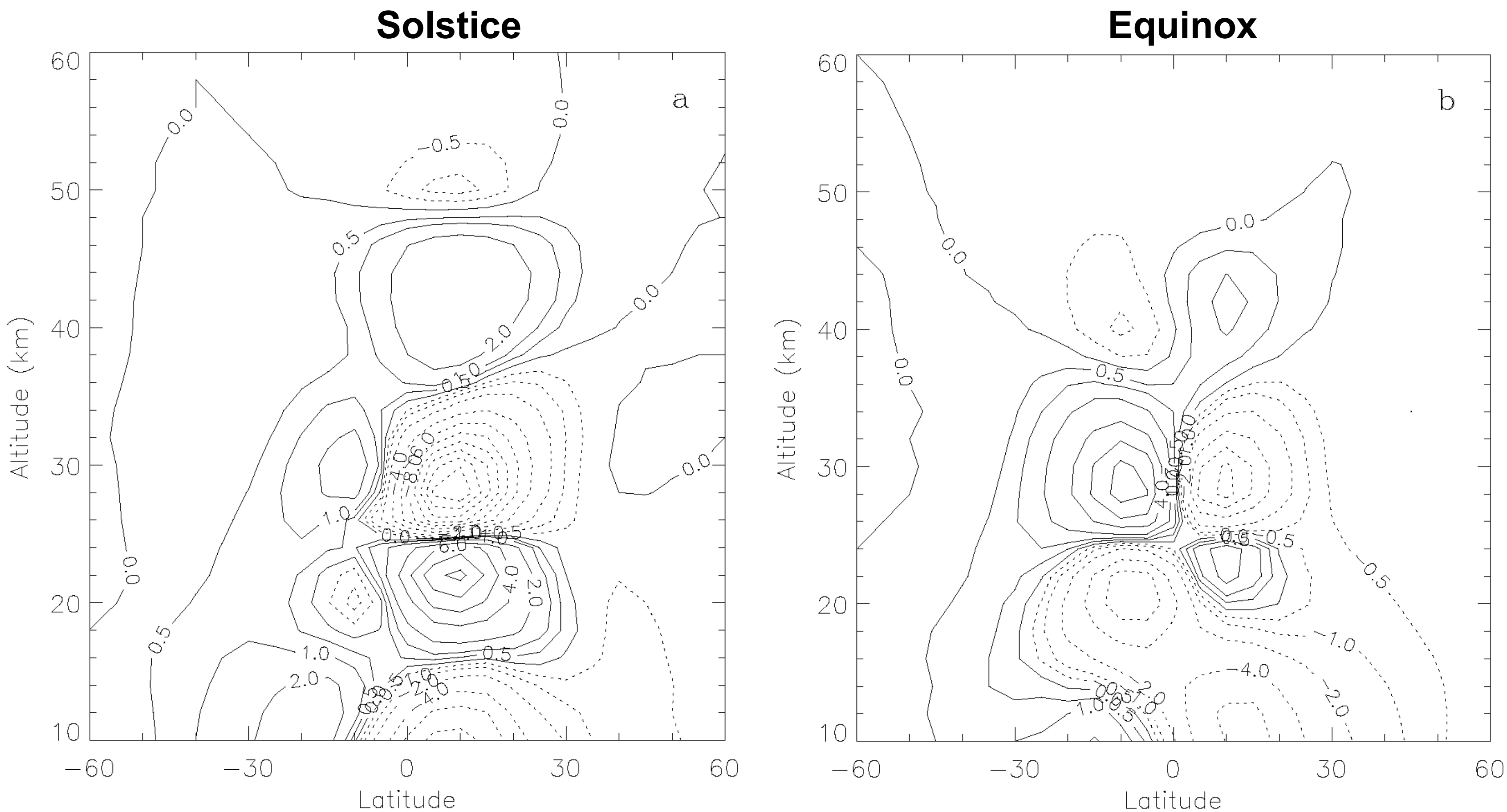
Modeled QBO Anomalies in O_3 (in DU)



No QBO at midlatitudes since Kyy is constant

With the simplified QBO forcing, the model adequately reproduces the seasonal dependence of the anomalies; modelled amplitude=5-6 DU, observations = 6-10 DU

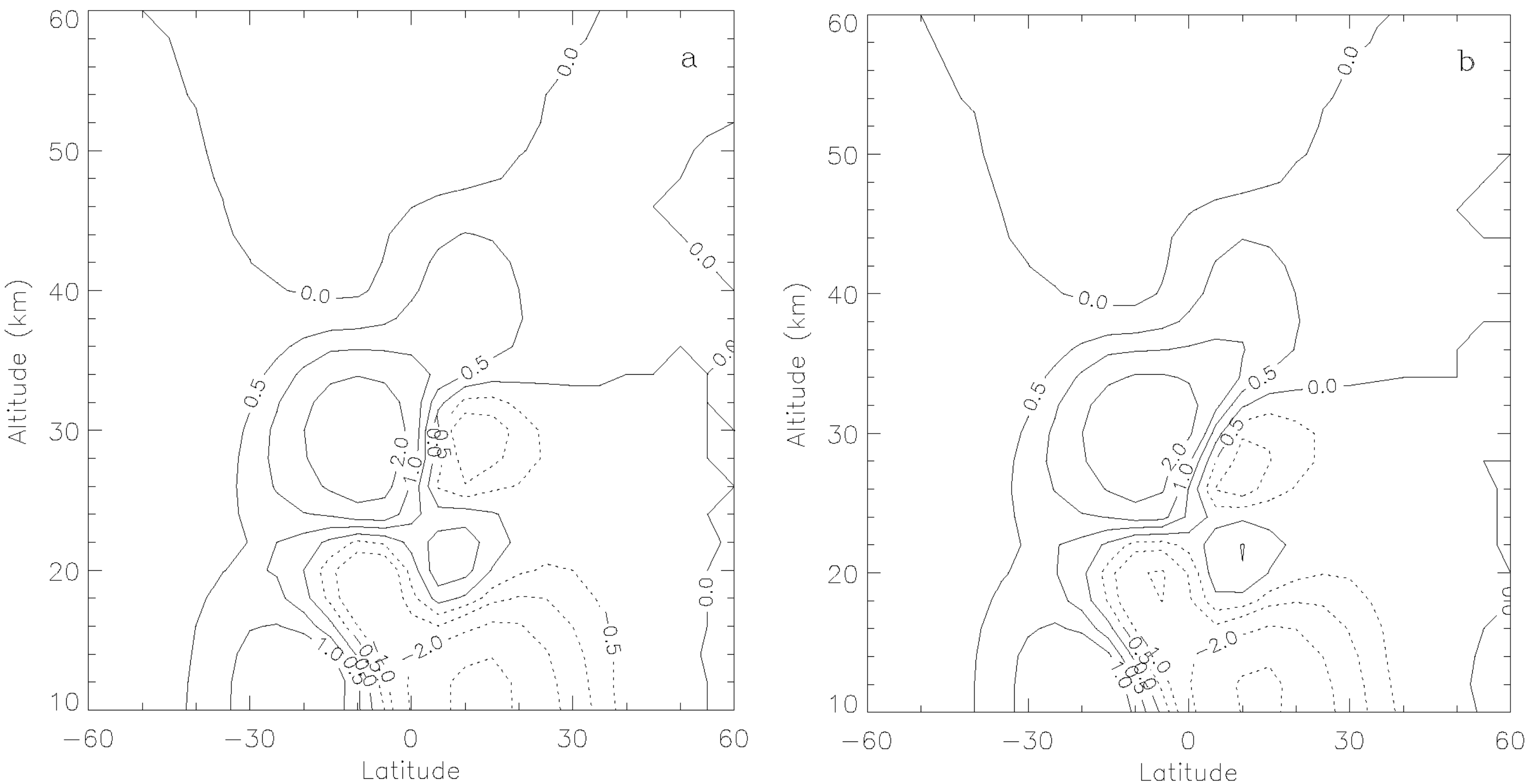
Modeled QBO Meridional Circulation



[Jones et al., 1998]

- **QBO meridional circulation seasonally dependent ⇒ induced O_3 anomalies will have seasonal dependence**
- **A 2-D model provides a ideal tool with which to diagnose the source of the seasonal dependence**

Modeled QBO Meridional Circulation



[Jones et al., 1998]

Seasonal dependence of QBO circulation is significantly less without the nonlinear momentum advection terms in model

Main Points of Lecture

- **Zonal mean models (and simple models in general) are useful tools for interpreting observations**
- **These models are highly parameterized and therefore it is easy to tune them in an arbitrary and unphysical manner**
- **Must carefully consider your application of the models, given their limitations - do not try to overly interpret the model results**