Dynamics and Modeling of the Middle Atmosphere

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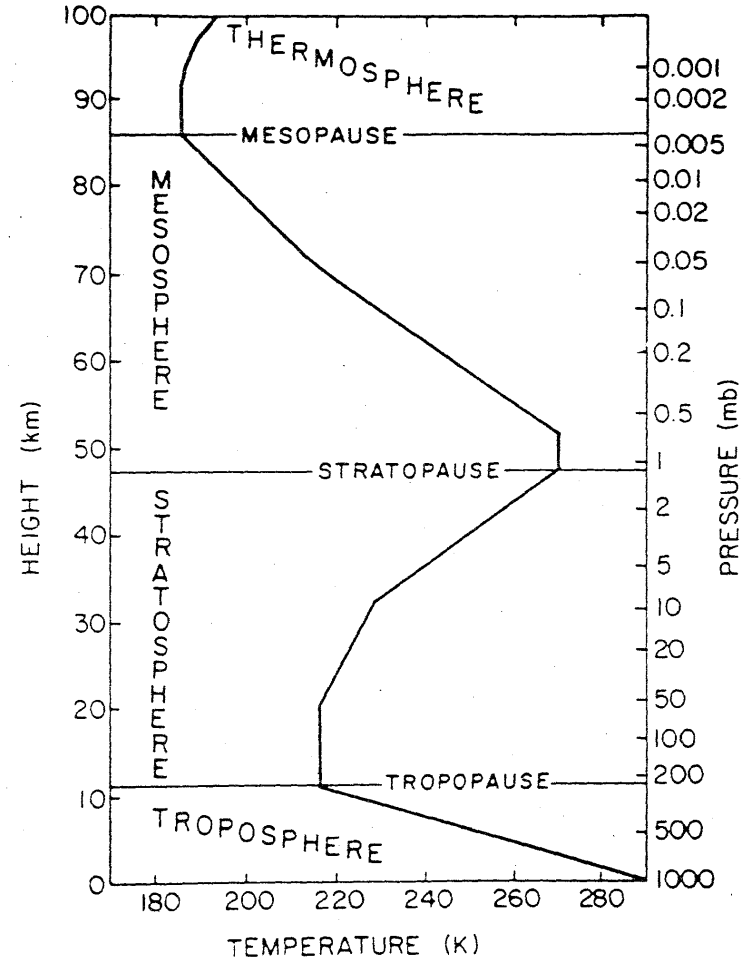
Outline

- Mean circulation and temperature structure
- Atmospheric waves
- Fundamental dynamical concepts
- Modeling the middle atmosphere

the Middle Atmosphere

- Global-average temperature profile is shown on right
- Atmospheric layers are defined by changes in the vertical gradient of temperature
- Layering is a result of radiative heating and convection
- Middle atmosphere: stratosphere, mesosphere and lower thermosphere (~15 –130 km)

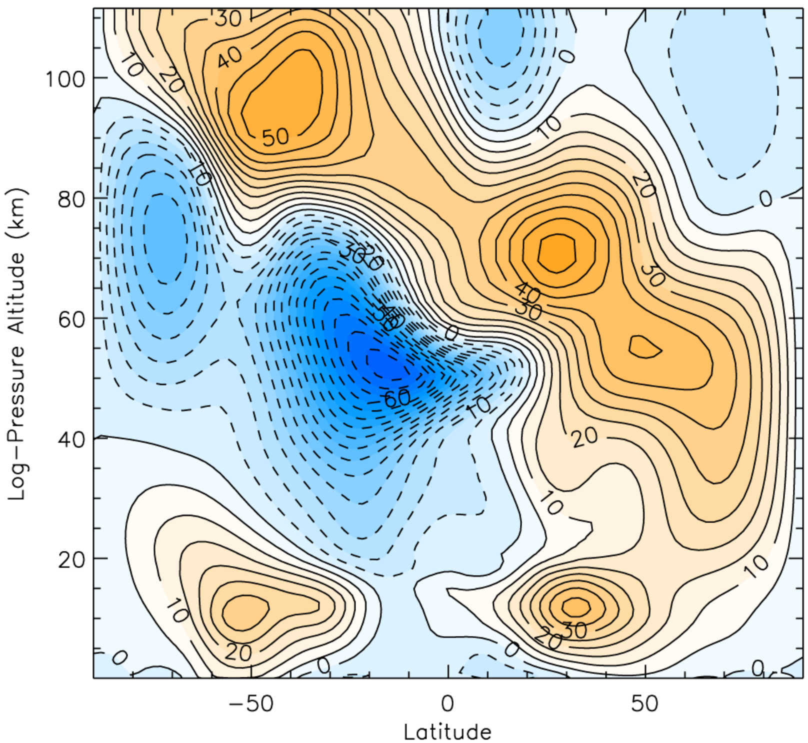


Midlatitude temperature profile. Based on the *U.S. Standard Atmosphere* (1976)

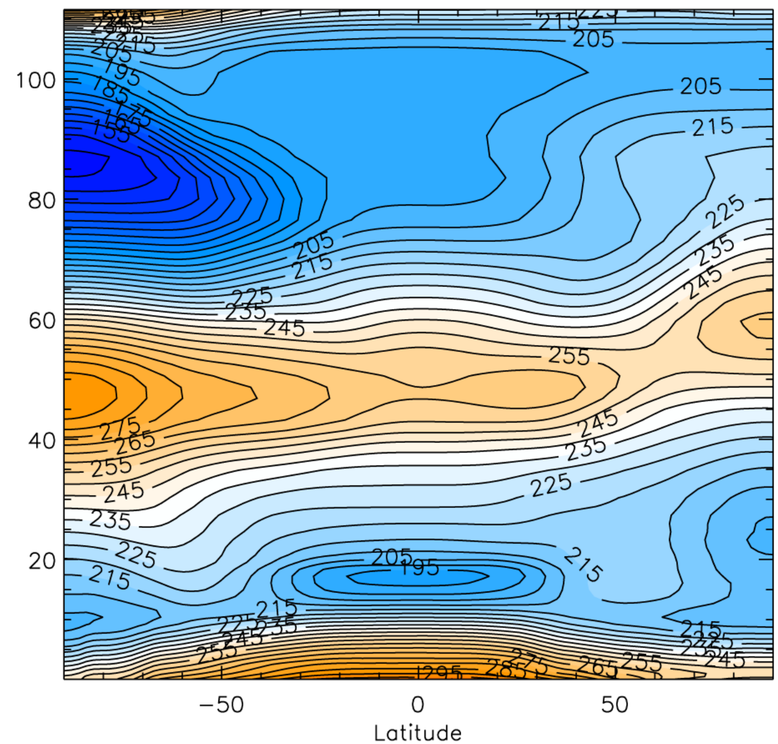
Mean Circulation and Temperature Structure

Zonally-mean wind and temperature

Time-mean WACCM U for NH winter 1953-2006

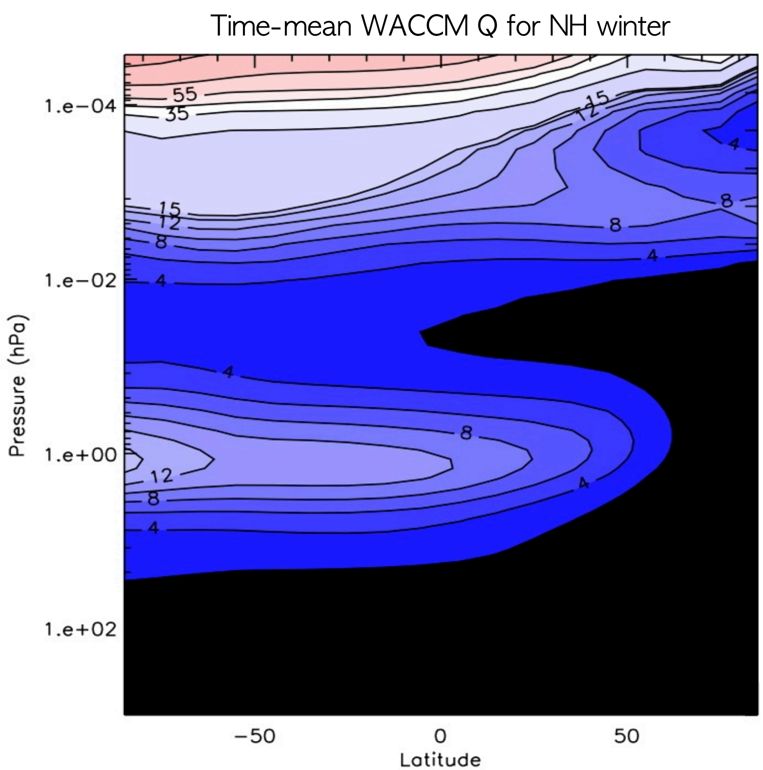


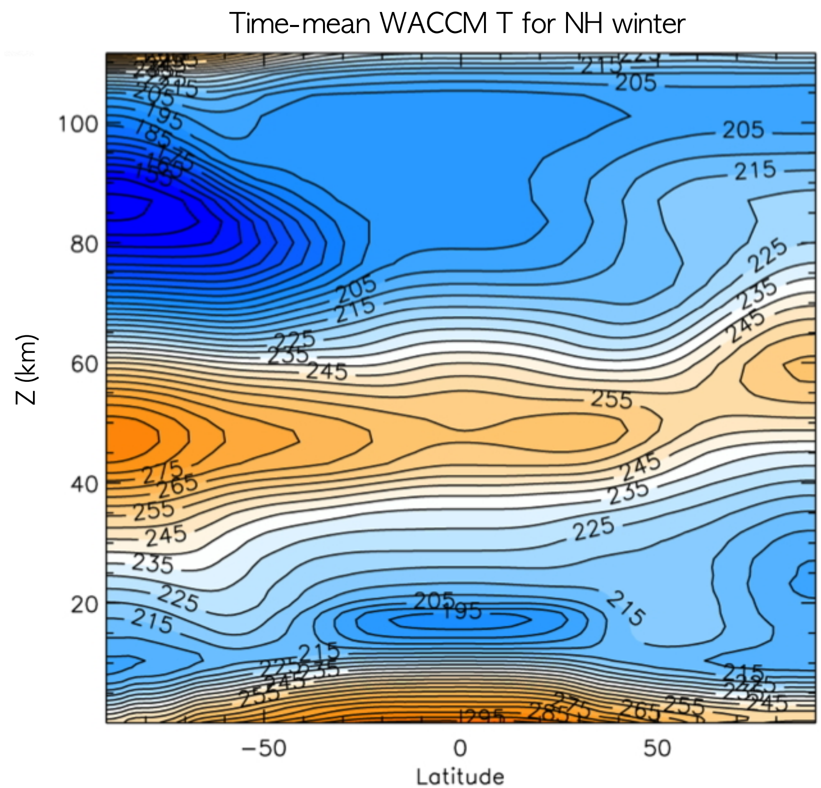
Time-mean WACCM T for NH winter 1953-2006



- Zonal-mean U and T for NH winter simulated with the Whole Atmosphere Community Climate Model (WACCM4)
- The zonal-mean wind is in *geostrophic balance* with the zonal-mean temperature distribution
- The zonal mean wind / temperature outside the Tropics varies mainly with the *annual cycle* (driven by solar heating)
- Quasi-steady-state during the solstice seasons

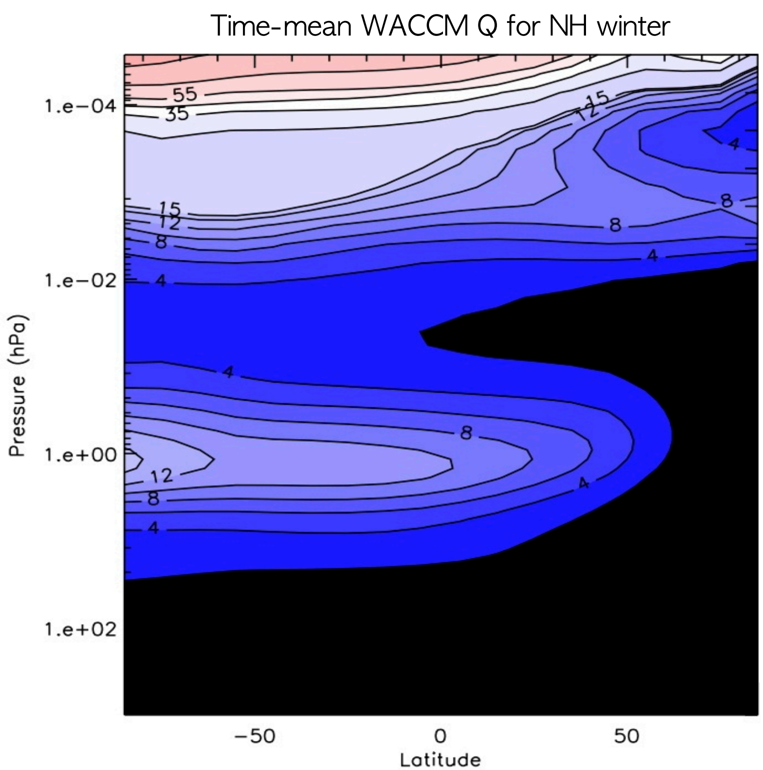
Zonally-mean solar heating and temperature

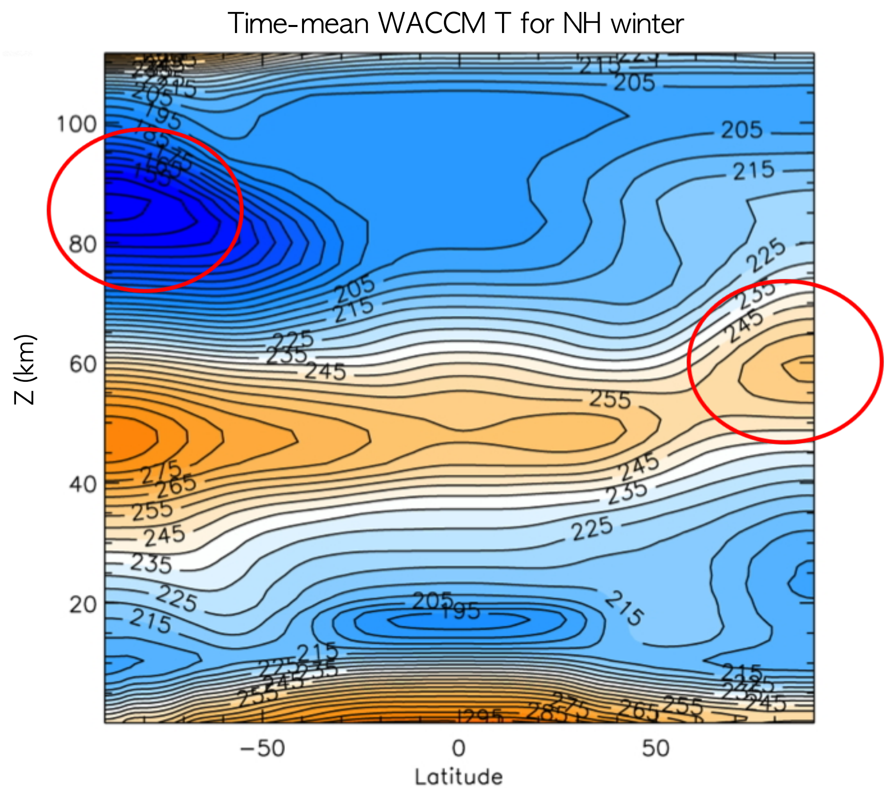




- The basic temperature distribution is determined by the latitudinal gradient of the radiative drive

Zonally-mean solar heating and temperature





- The basic temperature distribution is determined by the latitudinal gradient of the radiative drive
- But it is *strongly modified by adiabatic cooling/warming* associated the vertical component of the mean circulationin the mesosphere and lower thermosphere (discussed later)

Tropical variability: QBO and SAO

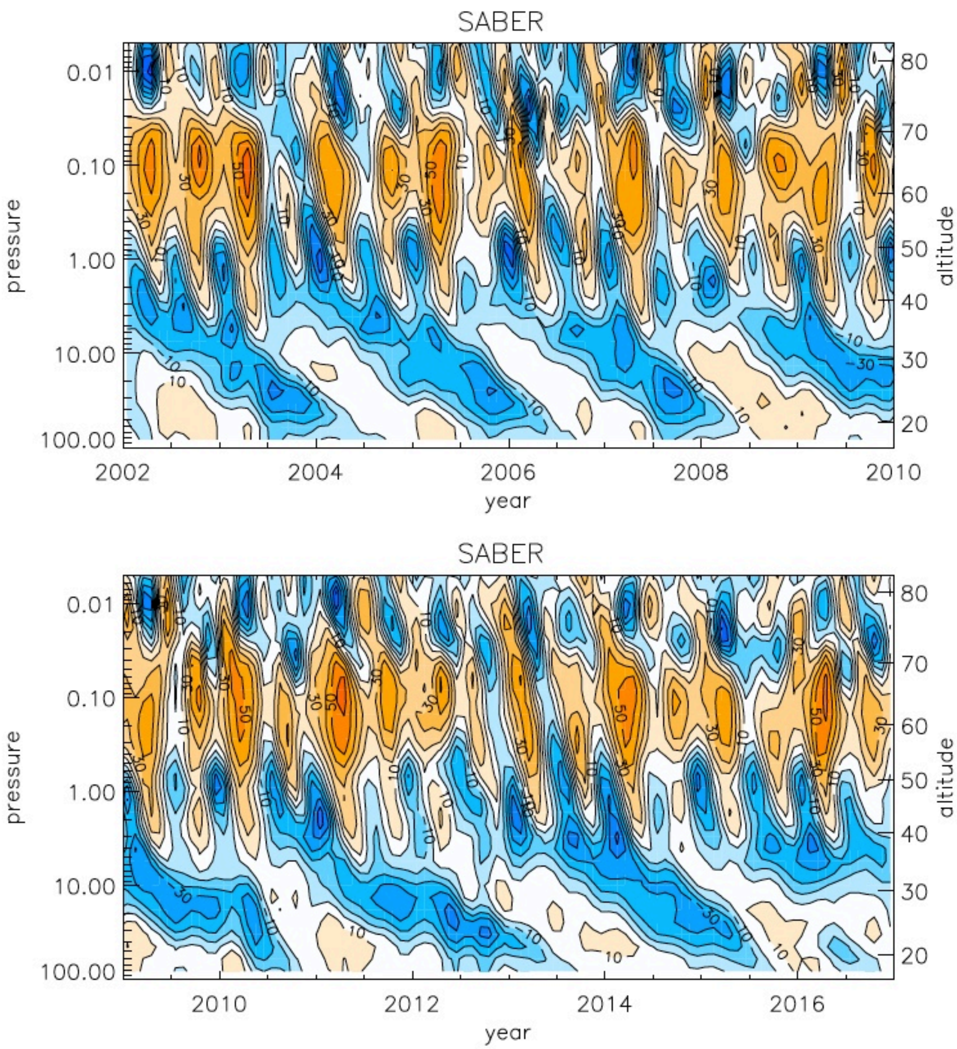


FIG. 6. Time series of SABER monthly mean wind at the equator.

Smith et al., *JAS*, 2017

- In the Tropics the zonal-mean circulation is never steady; it is dominated by winds that reverse sign in altitude and time periodically or quasi-periodically
- The plot at left shows the zonal-mean zonal wind, U, averaged within 8° of the Equator
- The behavior of U is dominated by the quasi-biennial oscillation (QBO) in the stratosphere and by the semi-annual oscillation (SAO) in the mesosphere

Waves in the middle atmosphere

Waves …

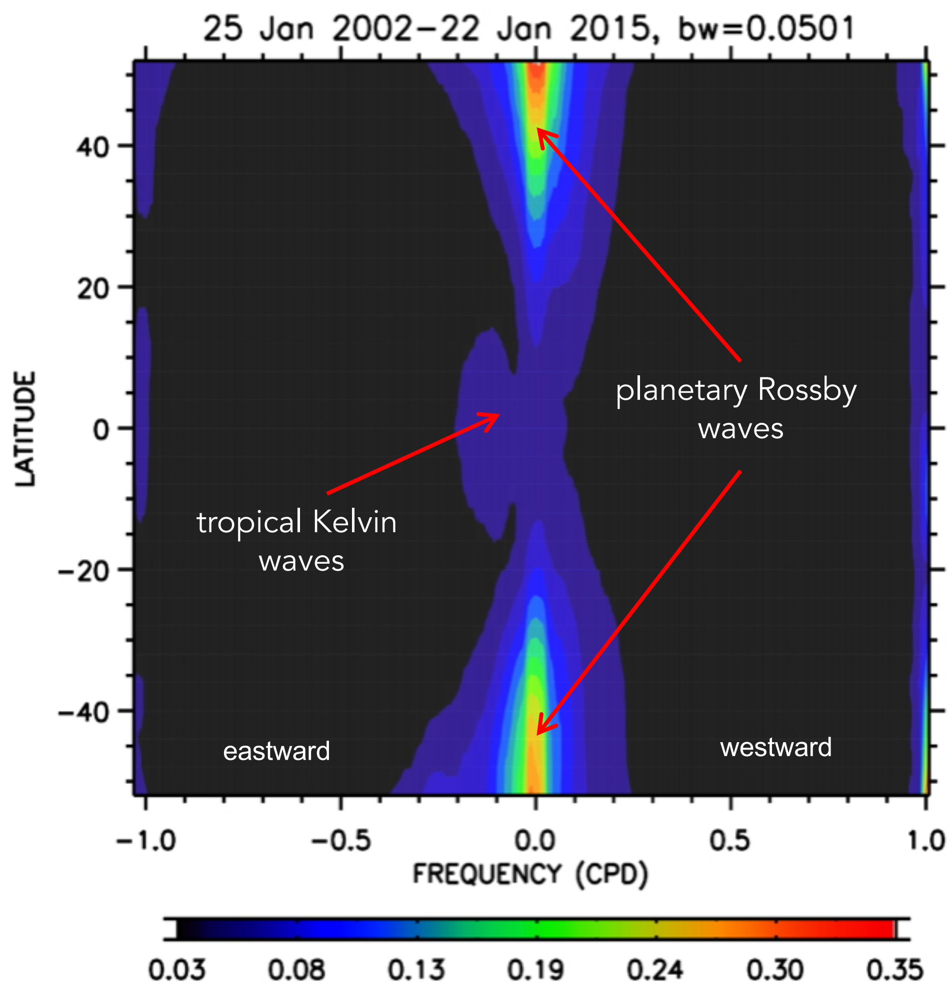
- are an essential component of the circulation of the middle atmosphere
- transport momentum and energy from the lower atmosphere
- drive the mean meridional circulation outside the Tropics, and drive the SAO and QBO in the Tropics
- induce advective transport and mixing of atmospheric constituents

Large-scale wave spectrum in the stratosphere (45 km)

- the figure shows the RMS temperature spectrum at 45 km as a function of latitude and frequency
- positive frequencies correspond to westward-propagating waves; negative frequencies correspond to eastward-propagating waves

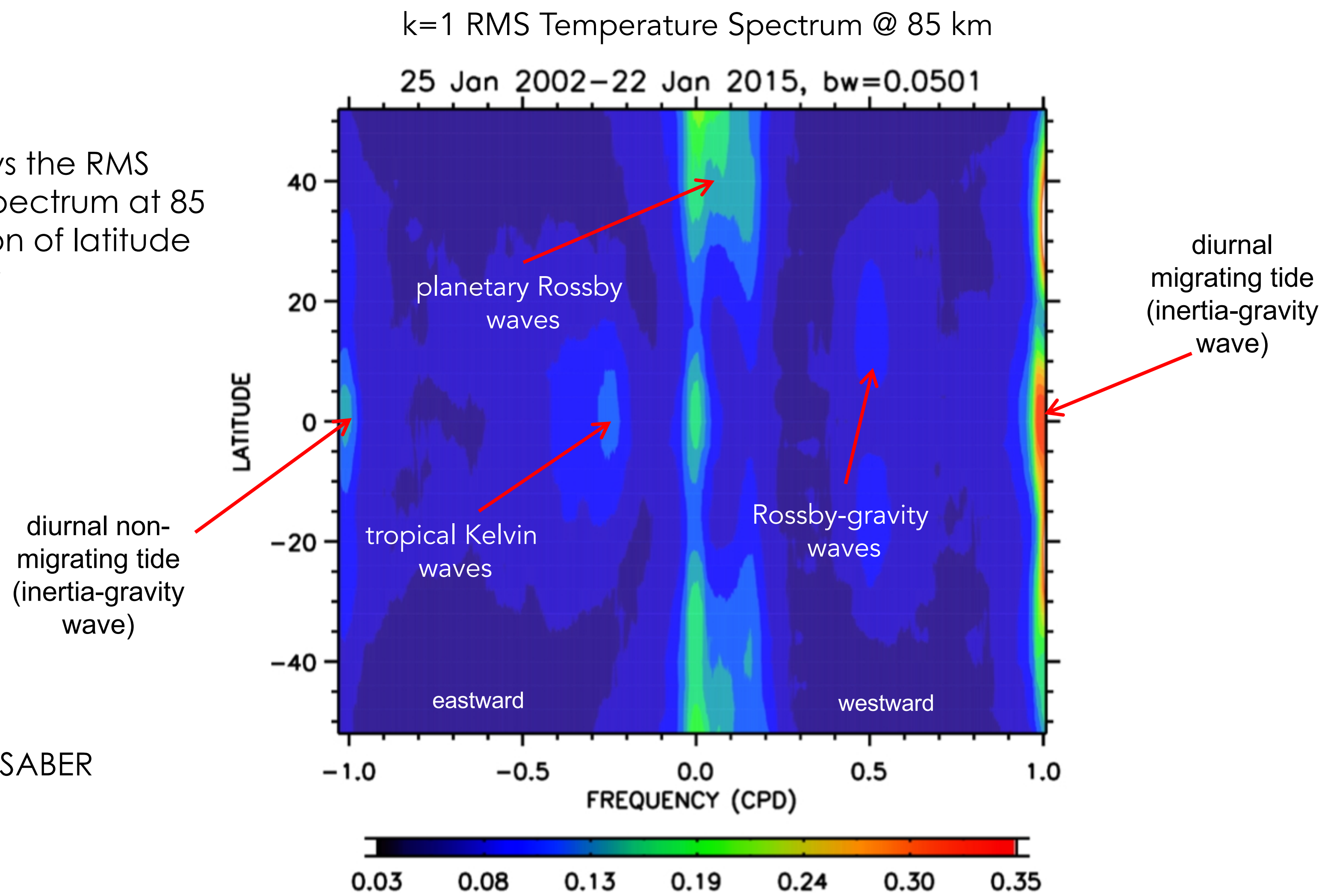
data: TIMED/SABER

k=1 RMS Temperature Spectrum @ 45 km



Large-scale wave spectrum in the upper mesosphere (85 km)

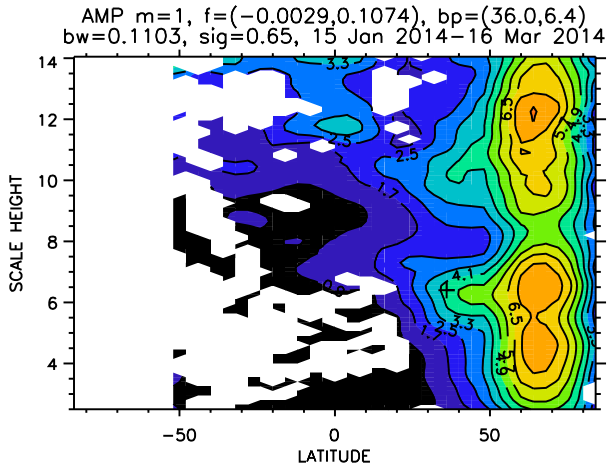
- the figure shows the RMS temperature spectrum at 85 km as a function of latitude and frequency

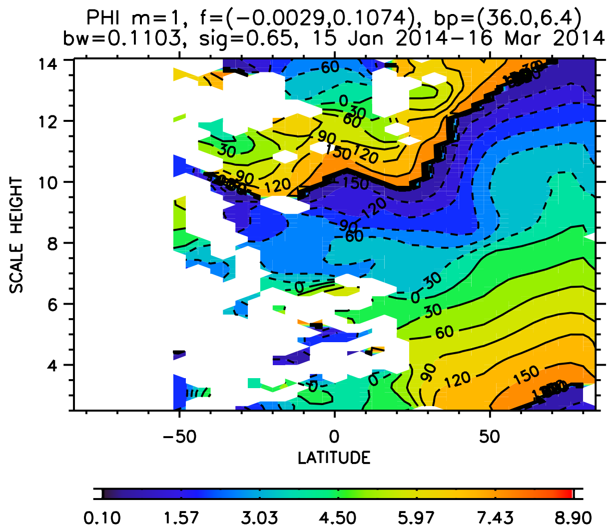


data: TIMED/SABER

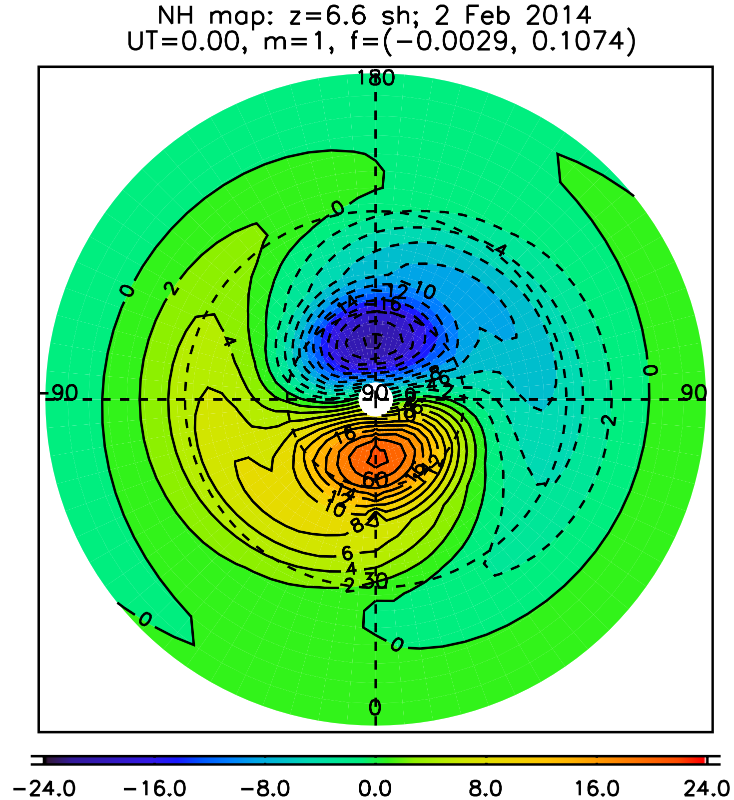
Rossby waves

mean amplitude/phase Jan-Mar 2014





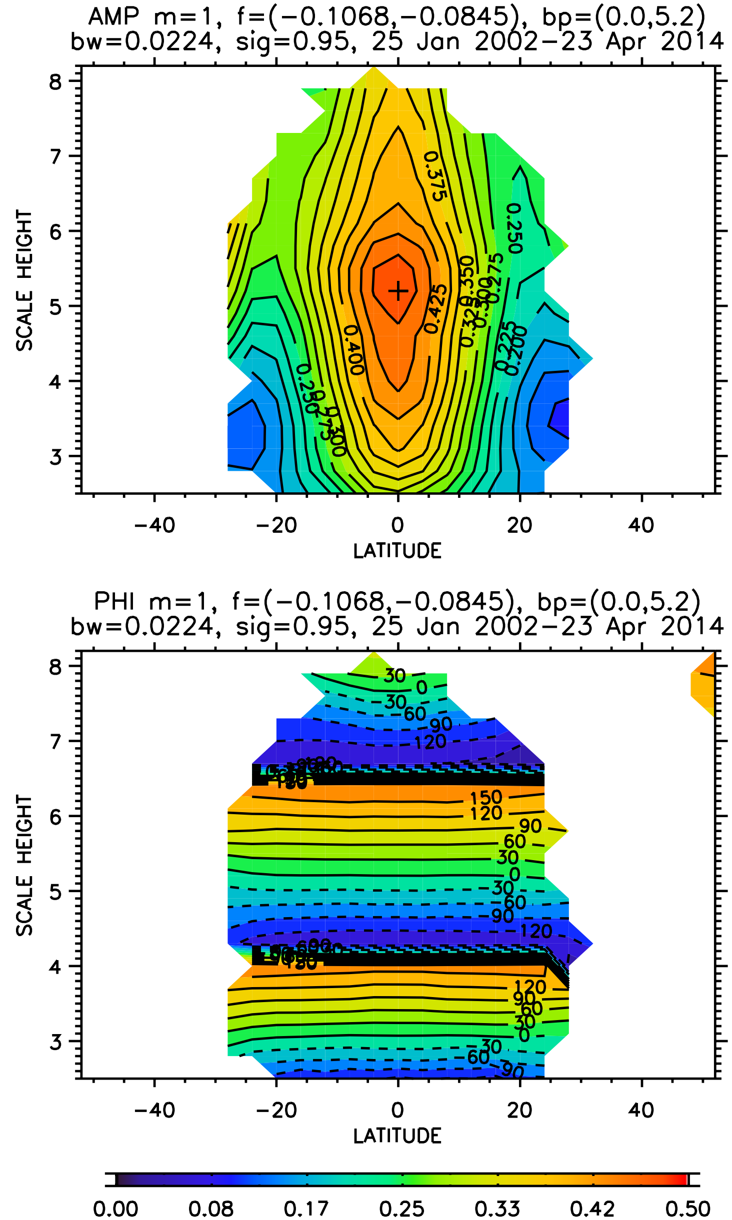
- Rossby planetary-scale waves are a major component of the *extra-tropical* circulation in winter; they are absent in summer (left panel)
- Instantaneous amplitudes can be large: T'~20 K in the example shown below for *k* = 1



data: TIMED/SABER

equatorial Kelvin waves

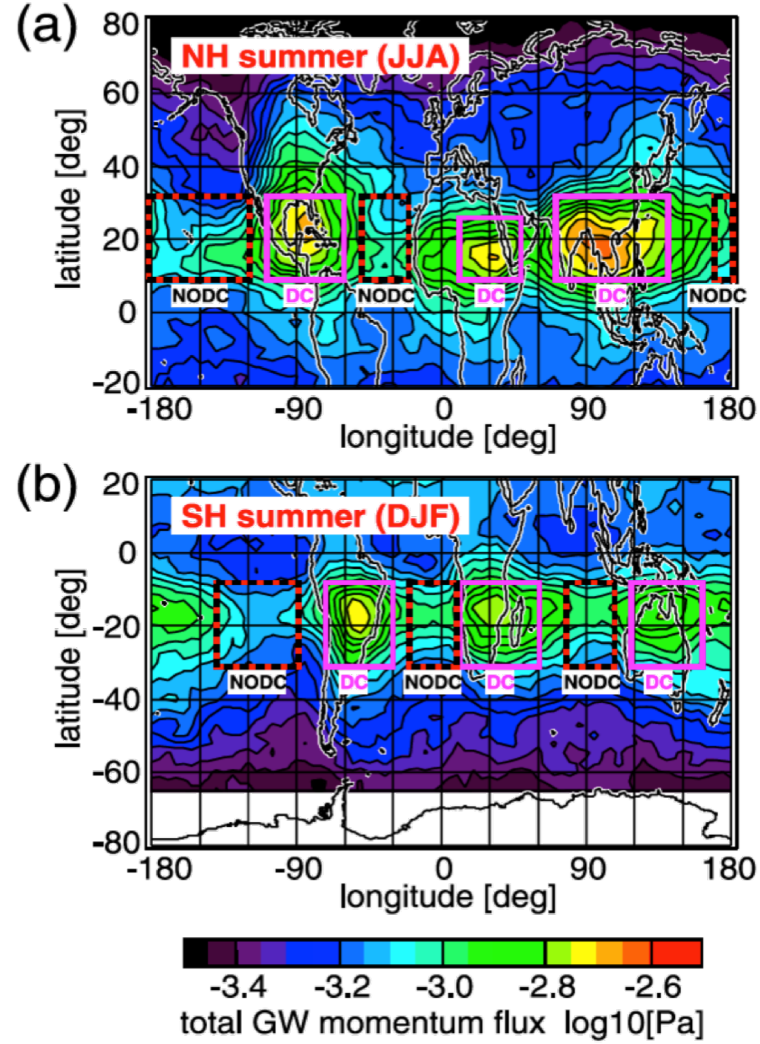
- Equatorial Kelvin waves are prominent in the tropical middle atmosphere
- They help drive the westerly phase of the stratospheric QBO



data: TIMED/SABER

Mesoscale gravity waves

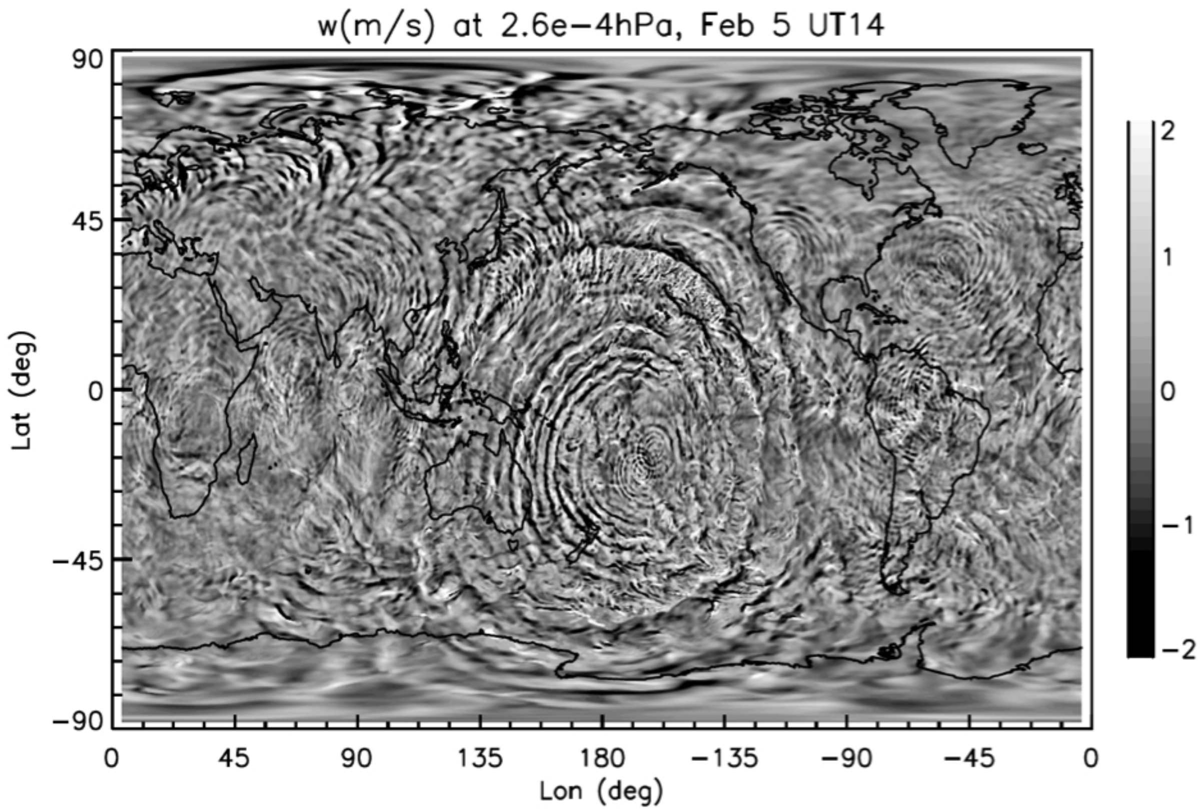
- figure shows an analysis of HIRDLS satellite temperature data
- momentum flux is associated with small-scale waves excited by deep convection
- important for driving the QBO



Horizontal distribution of HIRDLS total GW momentum flux on a logarithmic scale in (a) the northern and (b) the southern hemisphere at 25 km altitude

Ern and Preusse (GRL, 2012)

Mesoscale gravity waves



Vertical winds on 5 February at 14:00 UT and 2.6×10^{-4} hPa (~105 km) (maximum value is 7.3 m s^{-1}).

- mesoscale gravity waves in a very high horizontal resolution run (0.25˚) of the Whole Atmosphere Community Climate Model

- w' attains very large amplitude in the lower thermosphere

(Liu et al., *GRL* 2014)

Some Fundamental Dynamical Concepts

Wave-zonal mean interaction

- The zonally-averaged temperature and wind structure of the atmosphere is ultimately determined by the distribution of solar heating
- Departures from the zonal averages are *of first order importance*, and they are associated with *transport of momentum by atmospheric waves*
- Therefore, it is natural to approach the problem of the general circulation of the middle atmosphere in terms of the interaction between the zonal-mean state and the wave motions
- Formally, this consists of writing the relevant fields as the sum of zonal means and departures therefrom, X = <X> + X', and substituting these into the governing equations (momentum, thermodynamics, continuity)

Transformed Eulerian Mean (TEM) Equations

The TEM momentum equation is:

$$\frac{\partial u}{\partial t} + v^*\left(\frac{1}{cos\theta}\frac{\partial\,\bar{u}cos\theta}{\partial y} - f\right) + w^*\frac{\partial u}{\partial z} = \boxed{\frac{1}{\rho\cos\theta}\nabla\cdot\mathcal{F} + \frac{1}{\rho}\frac{\partial\,\overline{u'w'}}{\partial z}}$$

where $\mathcal{F}$ is the *Eliassen-Palm flux*, a vector in the latitude/height plane $\mathcal{F} = (\mathcal{F}_y, \mathcal{F}_z)$, with

$$\mathcal{F}_y = \rho_o \cos\phi\left(\overline{u}_z\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'v'}\right) \qquad \text{(T2)}$$

$$\mathcal{F}_z = \rho_o \cos\phi\left[\left(f - \frac{1}{\cos\phi}\frac{\partial\overline{u}\cos\phi}{\partial y}\right)\frac{\overline{v'\theta'}}{\overline{\theta}_z} - \overline{u'w'}\right] \qquad \text{(T3)}$$

The TEM thermodynamic energy equation is:

$$\frac{\partial\overline{\theta}}{\partial t} + \overline{v}^*\frac{\partial\overline{\theta}}{\partial y} + \overline{w}^*\frac{\partial\overline{\theta}}{\partial z} = \frac{\overline{\theta}}{\overline{T}}\,\overline{Q} - \frac{1}{\rho_o}\frac{\partial}{\partial z}\left[\rho_o\left(\overline{v'\theta'}\frac{\overline{\theta}_y}{\overline{\theta}_z} + \overline{w'\theta'}\right)\right] \qquad \text{(T4)}$$

and the continuity equation is given by:

$$\frac{1}{\cos\phi}\frac{\partial\cos\phi\,\overline{v}^*}{\partial y} + \frac{1}{\rho_o}\frac{\partial\rho_o\overline{w}^*}{\partial z} = 0 \qquad \text{(T5)}$$

(see Andrews et al., 1987)

- The components of the Eliassen-Palm (EP) flux vector (T2)-(T3) are proportional to momentum and heat fluxes

- According to Eqn. (T1) the eddies can produce an acceleration of the zonal mean flow, $\overline{u}_t$, only when the divergence of the EP flux is nonzero. It can be shown that for steady, conservative waves the EP flux divergence vanishes so the waves have no effect on the mean flow. This result is known as the *nonacceleration theorem*.

- Similarly, the eddy flux terms on the RHS of the thermodynamic equation vanish for steady, conservative waves (Andrews and McIntyre, 1978b). Aside from these terms in the thermodynamic equation, wave forcing in the TEM system appears only in the zonal momentum equation. These properties of the TEM system simplify considerably the physical interpretation of the interaction between the mean state and the waves.

- Wave forcing terms appear principally in the momentum equation, as divergences of *pseudo-momentum fluxes* (e.g., the Eliassen-Palm flux and small-scale GW fluxes)

- The TEM equations provide clear, physically-intuitive insights into the role of waves in the zonal mean budgets of momentum and thermodynamics

Tropical vs. extra-tropical dynamics

Outside the Tropics, the time-mean momentum balance during the solstices may be approximated as:

$$\bar{v}^* \left(\frac{1}{a\cos\phi} \frac{\partial \bar{u}\cos\phi}{\partial y} - f \right) = \frac{1}{\rho\cos\phi} \nabla \bullet \mathbf{F}$$

such that $\nabla \bullet \mathbf{F} = 0 \Leftrightarrow \bar{v}^* = 0$

In the deep Tropics (equatorward of ~15-20°), it is possible to have a steady circulation, $\bar{v}^* \neq 0,$ even if $\nabla \bullet \mathbf{F} = 0,$ provided that the quantity in brackets above vanishes (e.g., the mean Hadley Cell in the troposphere)

But, in general, tropical zonal-mean circulations are not in steady-state and must be described by the full TEM zonal momentum equation,

$$\frac{\partial \bar{u}}{\partial t} + \bar{v}^* \left(\frac{1}{a\cos\phi} \frac{\partial \bar{u}\cos\phi}{\partial y} - f \right) + \bar{w}^* \frac{\partial \bar{u}}{\partial z} = \frac{1}{\rho\cos\phi} \nabla \bullet \mathbf{F}$$

This is typical of the quasi-biennial and semi-annual oscillations mentioned earlier

Wave-forcing and angular momentum: quasi-steady state

The result $\bar{v}^*\left(\frac{1}{a\cos\varphi}\frac{\partial\bar{u}\cos\varphi}{a\partial\varphi} - f\right) = \frac{1}{\rho\cos\varphi}\nabla\bullet\mathbf{F}$ is actually a statement about conservation of angular momentum.

This may be seen by multiplying the above equation times $a\cos\varphi$, and rearranging terms, which leads to the equivalent expression:

$$\bar{v}^*\frac{\partial\overline{m}}{a\partial\varphi} = \frac{a}{\rho}\nabla\bullet\mathbf{F}$$

where $\overline{m} = a\cos\theta(\bar{u} + a\Omega\cos\theta)$ is the zonal-mean angular momentum. This equation states that a mean meridional circulation $\bar{v}^*$ can cross isolines of $\overline{m}$ only if there exists a zonal–mean wave force, $\nabla\bullet\mathbf{F}$.

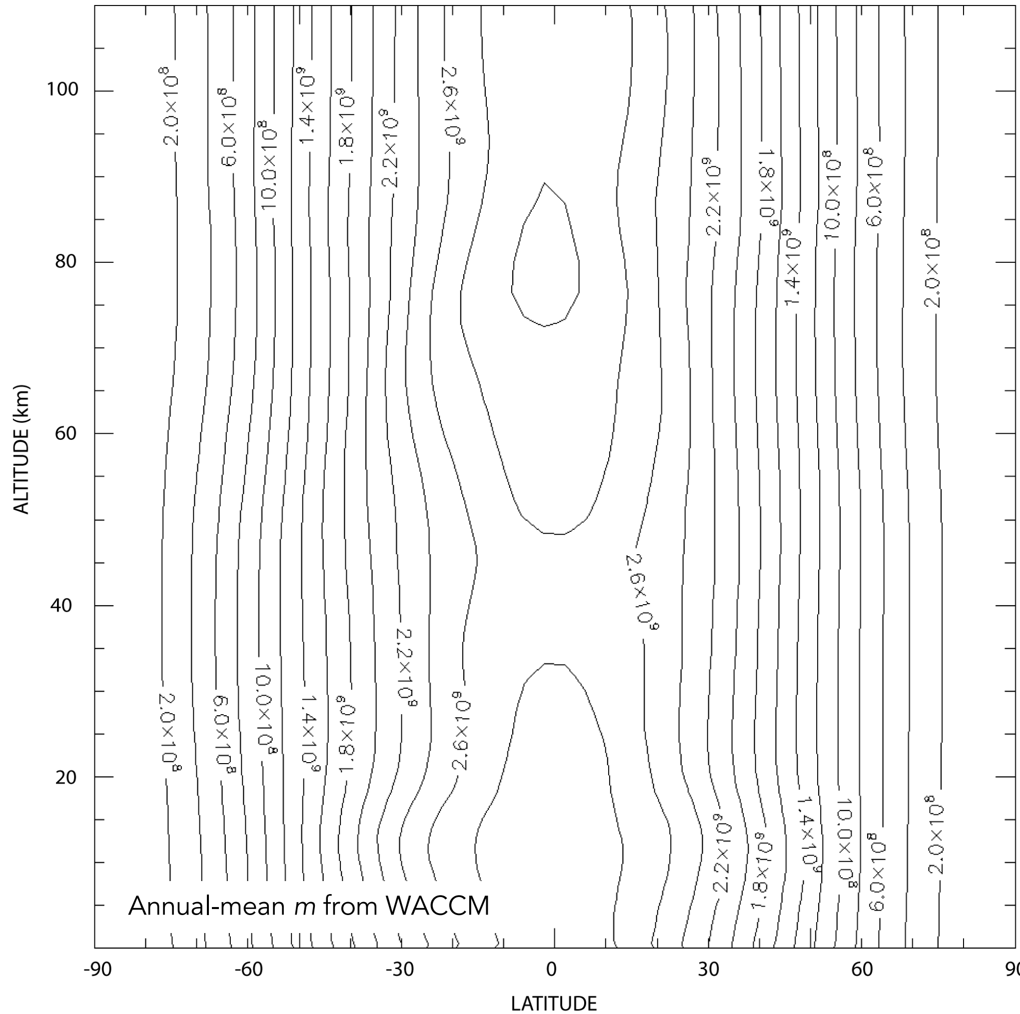
Wave driving of the MMC and wave dissipation

In steady-state, $\bar{v}^* \dfrac{\partial \bar{m}}{a\partial\phi} = \dfrac{a}{\rho}\nabla \bullet \mathbf{F}$

such that $\bar{v}^* \neq 0 \Leftrightarrow \nabla \bullet \mathbf{F} \neq 0$ (if $\bar{m}_\phi \neq 0$)

This constraint can be visualized by considering the distribution of in the atmosphere, as shown on right

Annual-mean *m*



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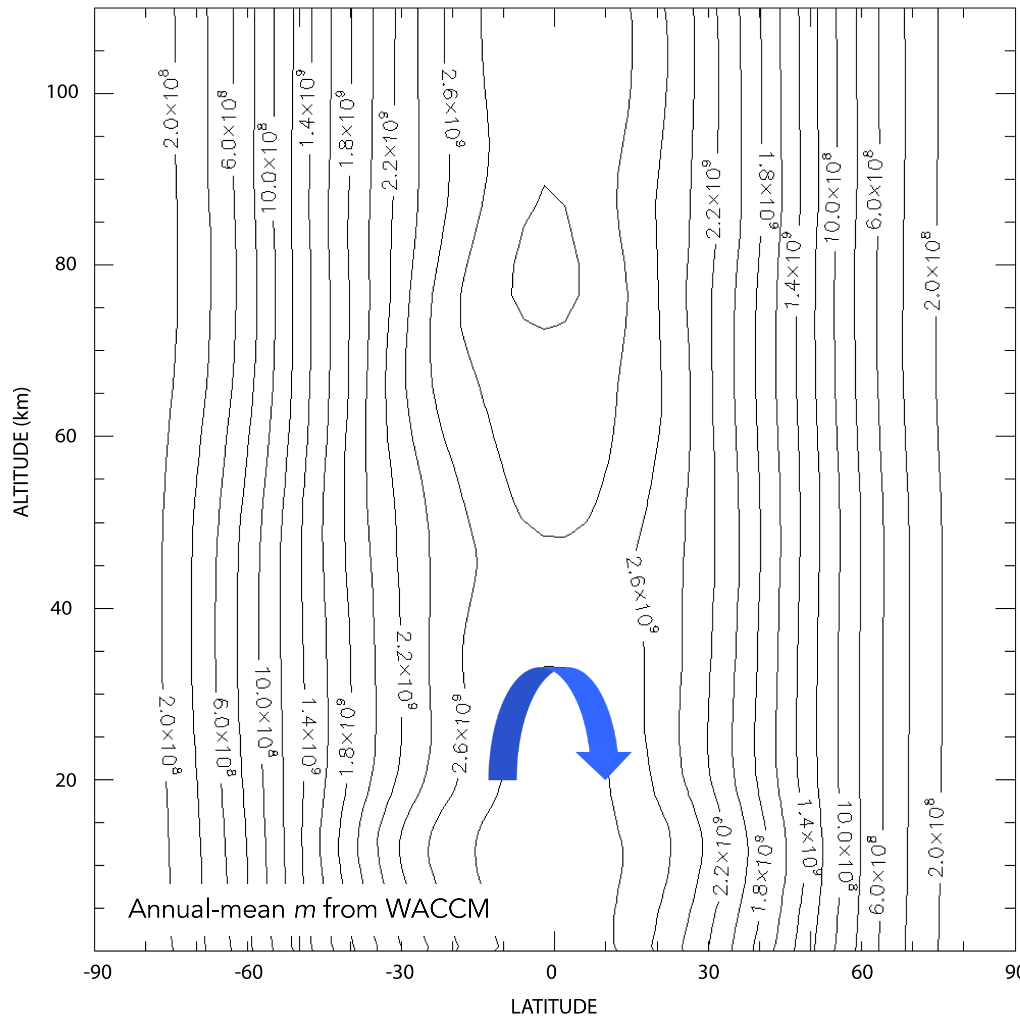
- in the Tropics, it is possible in principle to have an *angular momentum conserving* circulation even in the absence of wave forcing (v* may be ≠ 0 in regions where ∂*m*/∂ϕ = 0)

Annual-mean *m*



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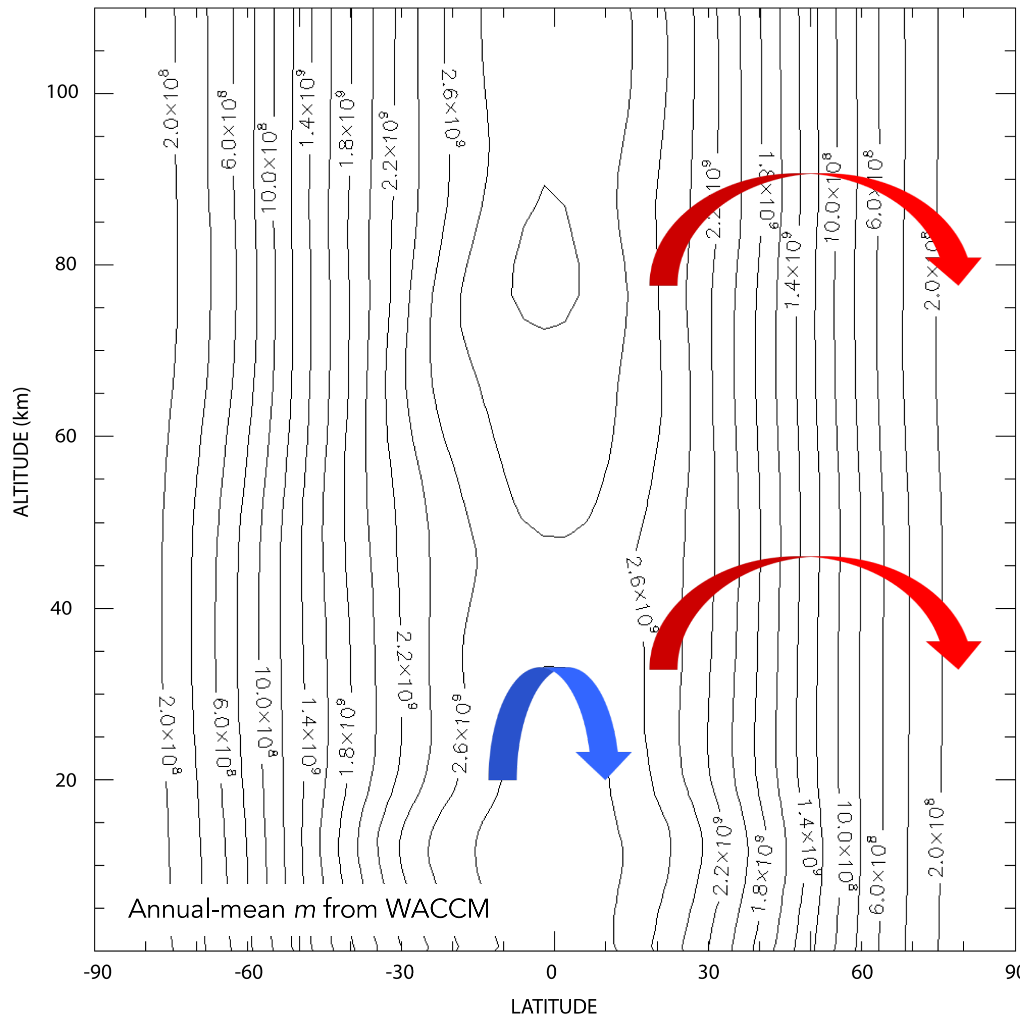
- in the Tropics, it is possible in principle to have an *angular momentum conserving* circulation even in the absence of wave forcing (v* may be ≠ 0 in regions where ∂*m*/∂ϕ = 0)

- outside the Tropics, the quasi-steady state mean meridional circulation *is always wave-driven* because it must cross contours of *m* (∂*m*/∂ϕ ≠ 0).

Annual-mean *m*



Waves and the zonal-mean structure of the middle atmosphere

under quasi-steady state conditions,

$$\overline{v}^*\left(\frac{1}{\cos\phi}\frac{\partial u\cos\phi}{\partial y}-f\right)=\frac{1}{\rho\cos\phi}\nabla\bullet F$$

$$\nabla\bullet F=0\Rightarrow\overline{v}^*$$

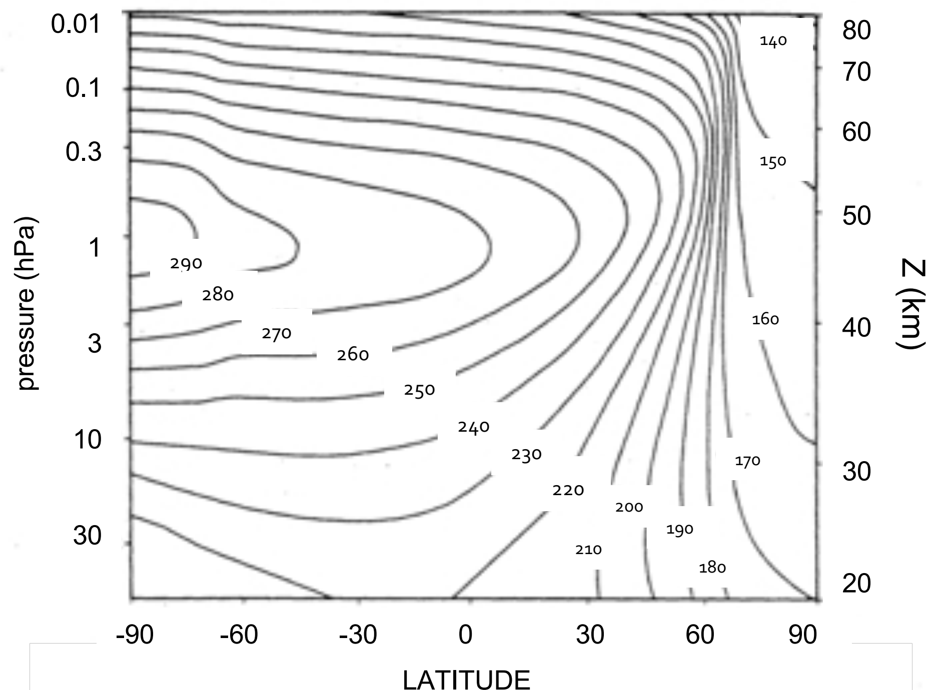
$$\Rightarrow\overline{w}^*=0\quad\text{(by continuity)}$$

and, from the simplified thermodynamic equation,

$$\overline{w}^*\frac{HN^2}{R}=-\alpha(T-T_E)$$

$$\overline{w}^*=0\Rightarrow T\rightarrow T_E$$

radiative equilibrium T distribution: Jan



- the observed mean state of the middle atmosphere is very far from radiative equilibrium (shown above)
- → wave-driven circulations have a profound effect on the zonal-mean state of the middle atmosphere

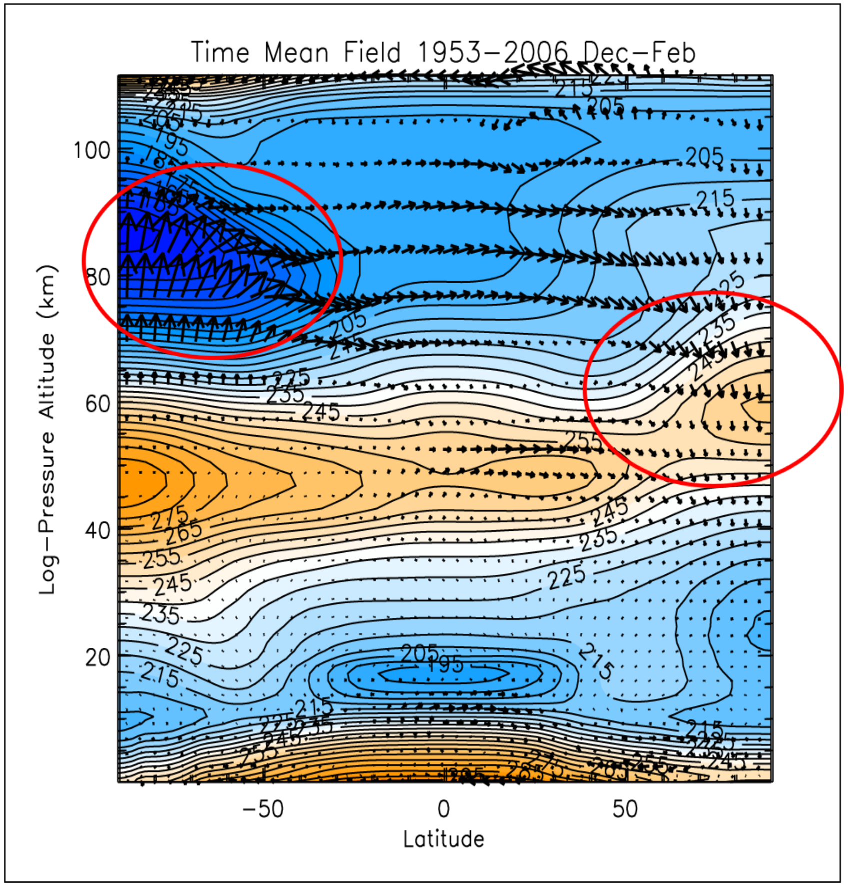
Mean meridional circulation and temperature structure

From the steady-state, zonal-mean thermodynamic equation we have:

$$\bar{w}^*\left(\frac{HN^2}{R}\right) = -\alpha(\bar{T} - \bar{T}_E)$$

It follows that $\bar{w}^*$ will induce departures of the zonal-mean temperature $\bar{T}$ from its radiative equilibrium value $\bar{T}_E$, such that $\bar{T} > \bar{T}_E$ if $\bar{w}^* < 0$ (downwelling) and vice-versa.

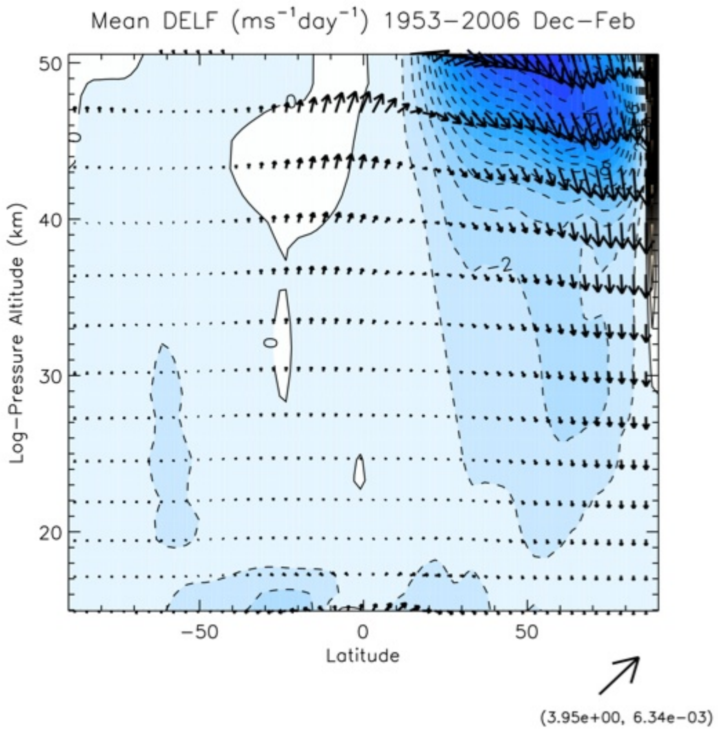
- The cold summer mesopause and warm winter stratopause are *prima facie* evidence of the existence of a vigorous mean meridional circulation in the middle atmosphere



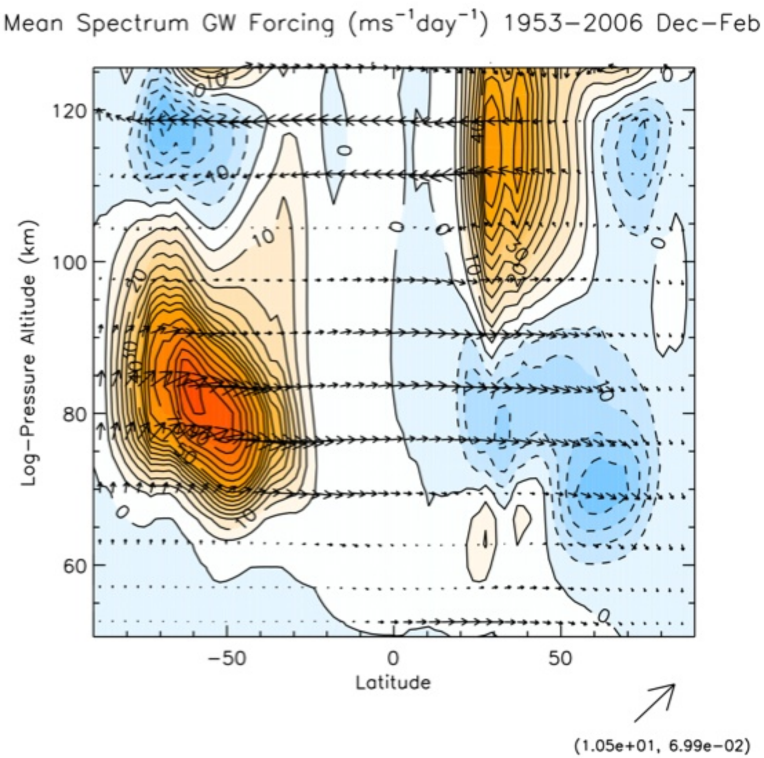
Time-mean, zonal-mean NH winter Temperature from WACCM

Wave dissipation and the mean meridional circulation

stratosphere

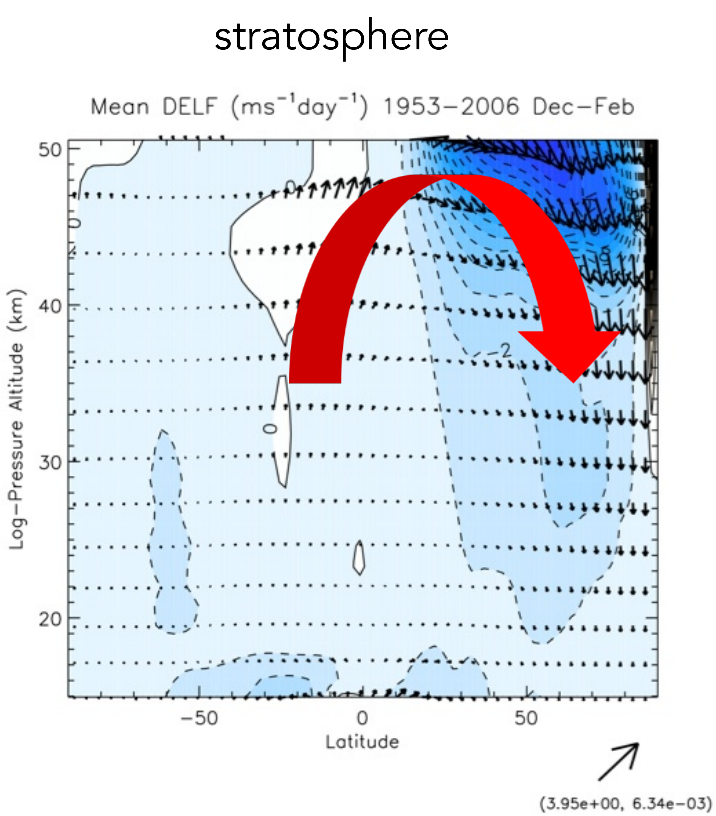


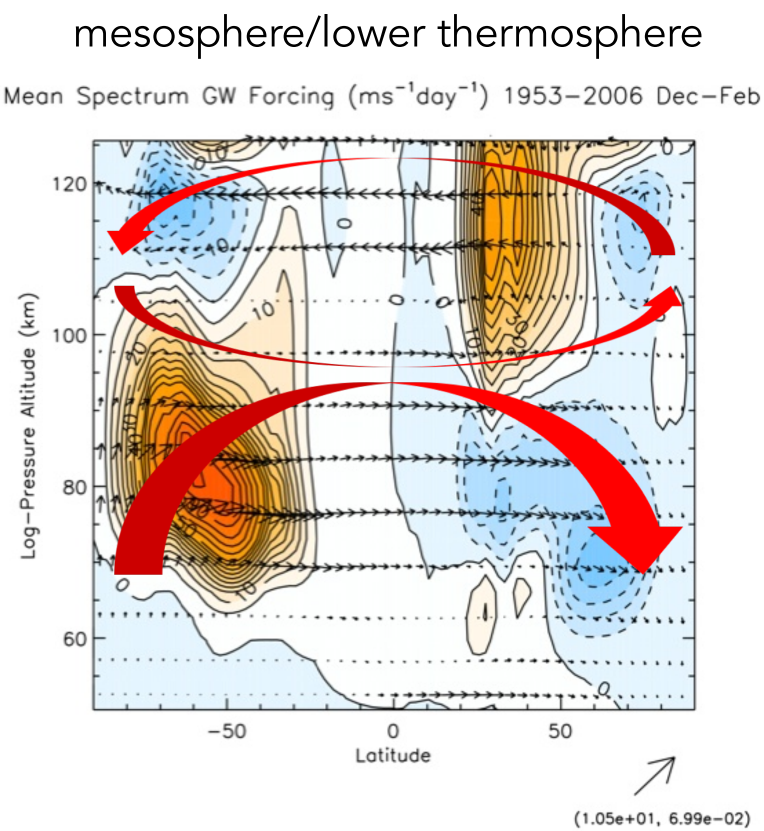
mesosphere/lower thermosphere



- the figure shows results from the Whole Atmosphere Community Climate Model (WACCM) for the zonal-mean force due to planetary wave dissipation in the stratosphere (left) and gravity wave dissipation in the mesosphere and lower thermosphere (right) superimposed on the mean meridional circulation vectors

Wave dissipation and the mean meridional circulation





- the figure shows results from the Whole Atmosphere Community Climate Model (WACCM) for the zonal-mean force due to planetary wave dissipation in the stratosphere (left) and gravity wave dissipation in the mesosphere and lower thermosphere (right) superimposed on the mean meridional circulation vectors
- outside the Tropics, there is a clear correspondence between wave forcing and v^* expected from the quasi-steady-state momentum balance: $-fv^* = \mathrm{div}(F)$

the Whole Atmosphere Community Climate Model (WACCM)

Whole Atmosphere Community Climate Model, v.4 (WACCM4)

Model Framework	Dynamics	Tracer Advection	Resolution	Chemistry	Other Processes
Based upon Community Atmosphere Model, V.4 (CAM4) Part of the NCAR Community Earth System Model, v.1 (CESM1)	Finite Volume Dynamical Core (Lin, 2004) Fully-interactive, i.e., consistent with model-derived, radiatively active gases: O_3, CO_2, CH_4, N_2O, H_2O, CFC11, CFC12, O_2, NO QBO may be specified from observations Coupled to full ocean model (NCAR POP)	Flux-form Finite Volume (Lin, 2004)	Horizontal: 1.9° x 2.5° (lat x lon) Vertical: 66 levels 0-140km < 1.0km in UTLS 1-2 km in stratosphere 3 km in MLT	Middle Atmosphere Mechanism 57 Species including Ox, HOx, NOx, BrOx, and ClOx No NMHCs Includes het. chemistry on LBS, STS, NAT, ICE E-region Ion Chemistry	Gravity-wave parametrization (for unresolved, mesoscale gravity waves) Molecular diffusion (Banks and Kockarts, 1973) Auroral processes, including ion drag, and Joule heating Longwave, shortwave, and chemical potential heating

Curent version, used for CCMI

Major CESM WACCM/WACCM-X Components

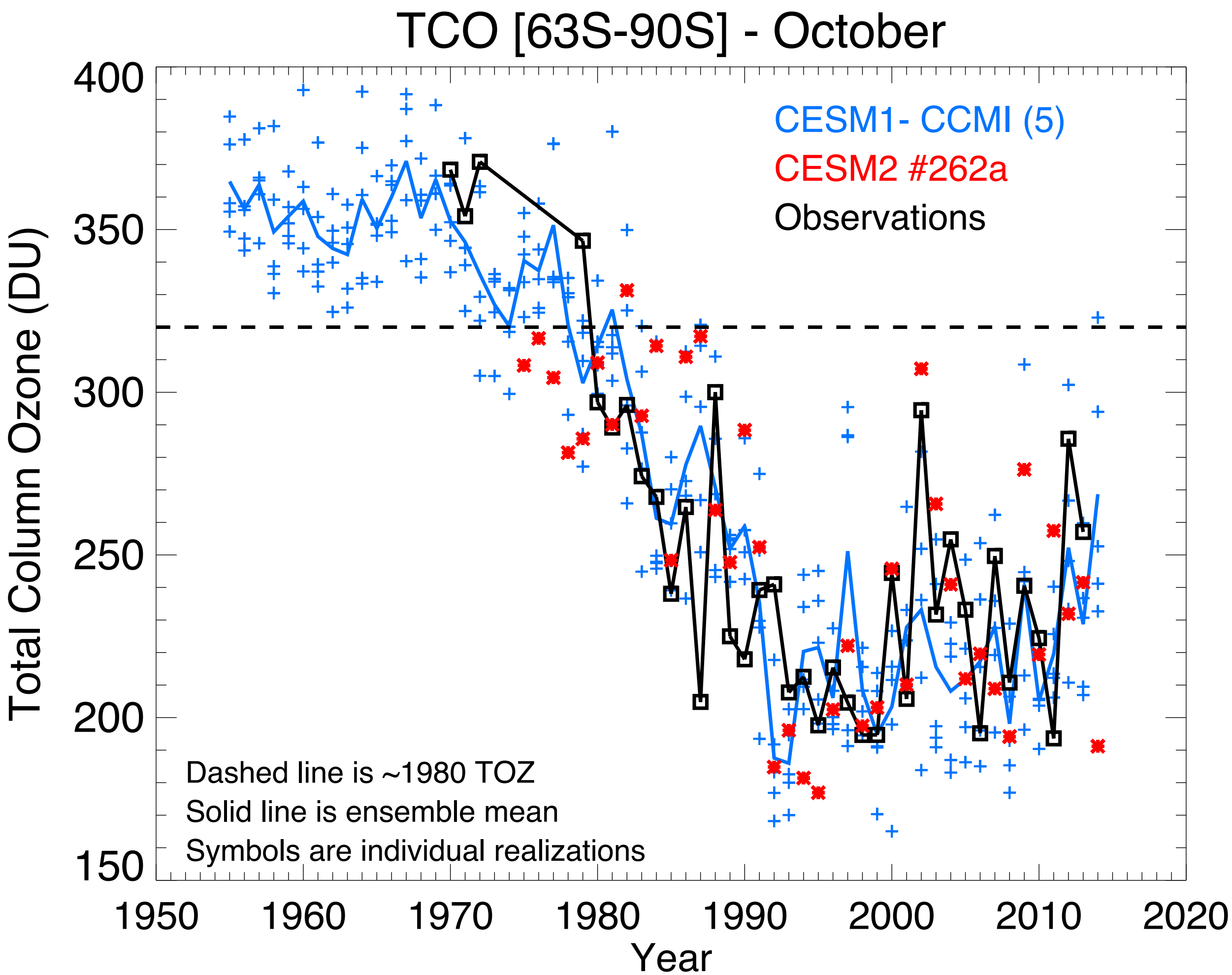
Model Framework	Chemistry	Physics	Physics	Resolution
Atmosphere component of NCAR Community Earth System Model (CESM) Extension of the NCAR Community Atmosphere Model, v.4 (CAM4) Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m) Spectral Element Dynamical Core	MOZART+ Ion Chemistry (~60+ species) Fully-interactive with dynamics.	Long wave/short wave/EUV RRTMG IR cooling (LTE/non-LTE) Modal Aerosal CARMA Convection, precip., and cloud param. Parameterized GW Major/minor species diffusion (+UBC) Molecular viscosity and thermal conductivity (+UBC) Species dependent Cp, R, m.	Parameterized electric field at high, mid, low latitudes. IGRF geomagnetic field. Auroral processes, ion drag and Joule heating Ion/electron energy equations Ambipolar diffusion Ion/electron transport Ionospheric dynamo Coupling with plasmasphere/ magnetosphere	Horizontal: 1.9° x 2.5° (lat x lon configurable as needed) Vertical: 66 levels (0-140km) 81/126 levels 0-~600km Mesoscale-resolving version:0.25 deg/0.1 scale height.

Whole Atmosphere Community Climate Model, v.6 (WACCM6)

- Based on Community Atmosphere Model, v.6 (CAM6), 1.25° x 0.95° resolution
- New IR transfer scheme (RRTMG)
- New boundary layer, shallow convection, and cloud macrophysics parameterization (CLUBB)
- New cloud microphysics parameterization (Morrison-Gettelman)
- New orographic gravity wave source parameterization
- New boundary layer form drag parameterization (Beljaars)
- Prognostic, interactive aerosols (MAM4)
- Internally generated QBO
- Updated tropospheric and D-region chemistry
- Part of CESM2, Released for CMIP6

Some recent modeling work

Antarctic spring O_3 column evolution



plot by D. Kinnison, ACOM

Ozone recovery

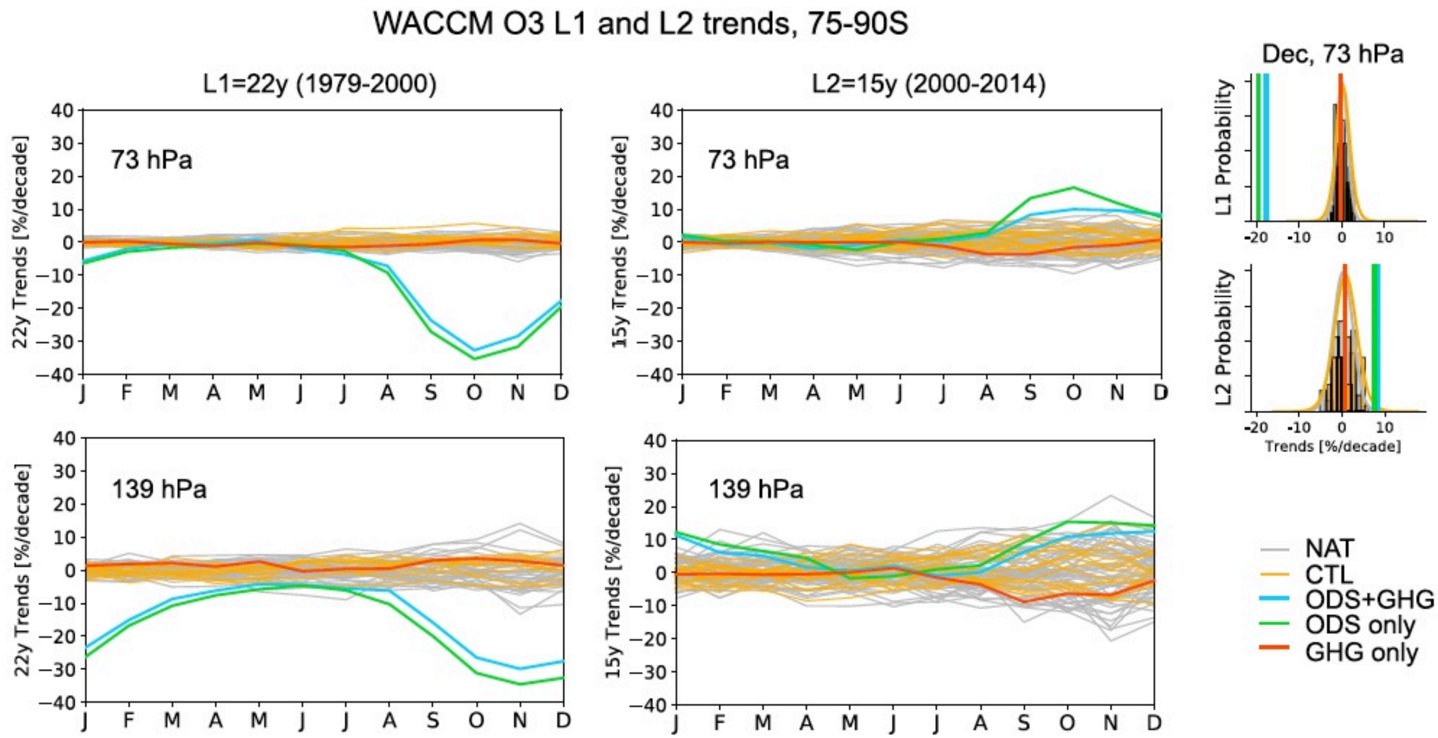


Figure 3. Modeled polar-cap average (75-90S) seasonality of ozone trends (% per decade by month) at 73 and 139 hPa in the lower stratosphere for 22 year (L1) and 15 year (L2) segments. The solid heavy colored lines show the ensemble means of forced FR-WACCM simulations for the depletion era and healing eras (denoted L1 and L2, respectively) including both ODS and GHG forcing (cyan), ODS only (green), and GHG only (red). The light lines show consecutive nonoverlapping L1- and L2-length segments in the long control runs for solar plus internal variability (NAT, light gray) and internal variability only (CTL, light orange). The probability distributions of the long control run trends for the month of December at 73 hPa only are shown in the small histograms at the right, together with the December trends from the ODS + GHG, ODS only, and GHG only simulations. The smooth curves in the histogram figure show the NAT and CTL distributions modeled with a Student's *t* distribution (based on the distribution of individual segments). Solomon et al., *JGR*, 2017

- pattern of ozone depletion and recovery is explained mainly by the effect of ODS

Brewer-Dobson circulation changes

- Age of air (AoA) as a proxy for strenght of the BDC
- Decreasing AoA => strengthening BDC
- Acceleration of the BDC is dominated by the effect of ozone depleting substances (ODS)
- Modified by the effect of non-ODS GHG

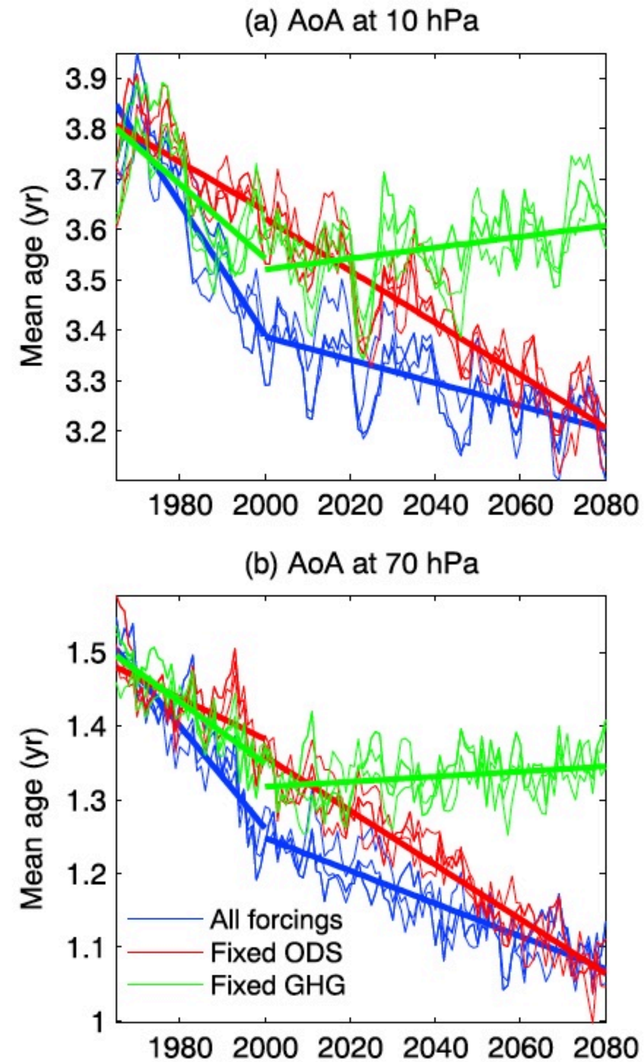
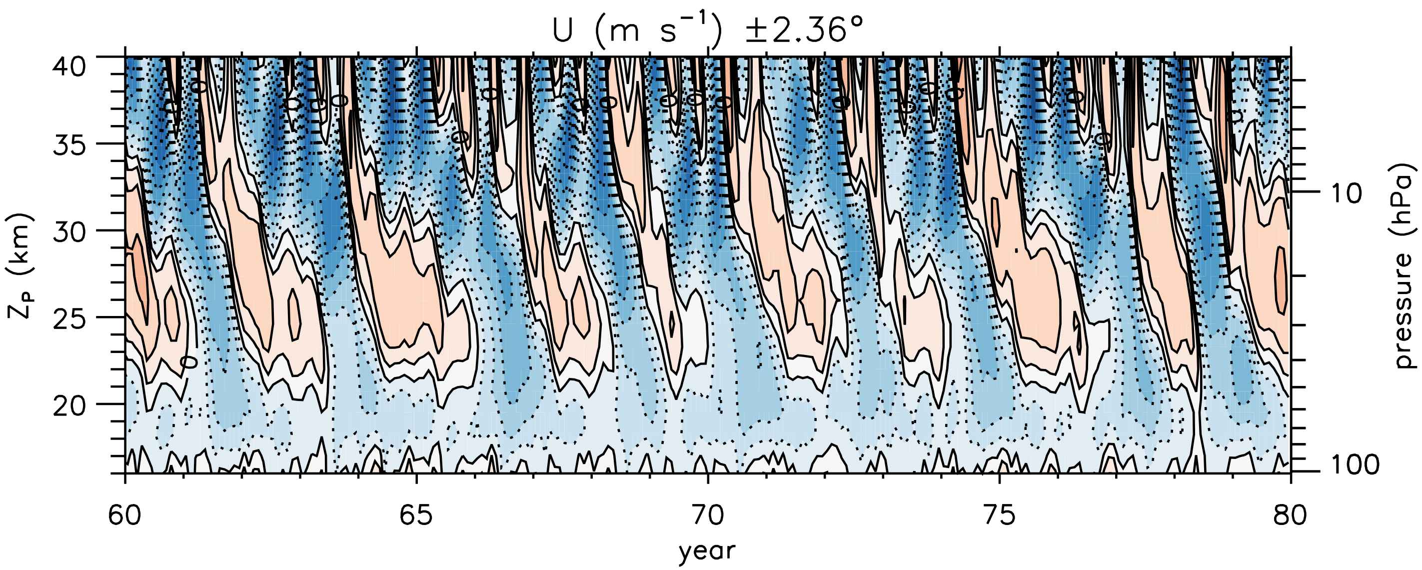


Figure 3. Annual and global mean AoA at (a) 10 hPa and (b) 70 hPa. Blue: All forcings. Red: Fixed ODS. Green: Fixed GHG. For clarity, the yearly values have been smoothed with a three-point running mean. Straight lines show linear fits to the ensemble means, for the past and the future: all trends are statistically significant at the 95% level.

Polvani et al., *GRL*, 2018

quasi-biennial oscillation (70L)

WACCM6 Pre-industrial Control

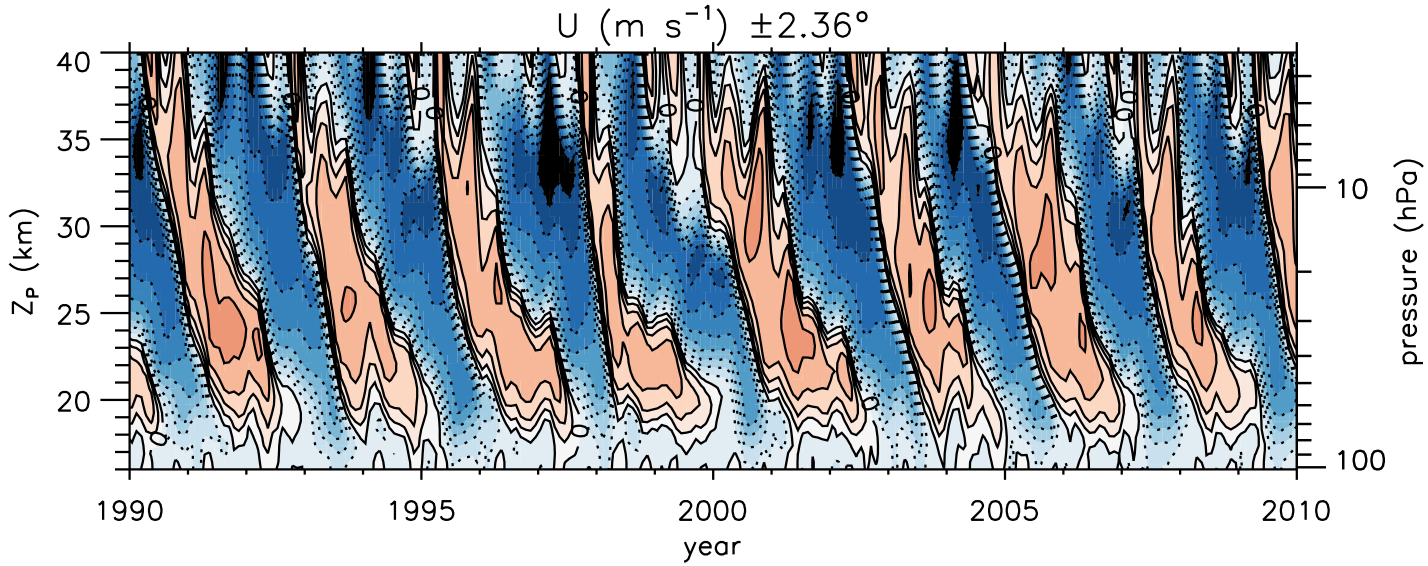


qbo period ~ 26 months

- WACCM6 generates a QBO internally, period is realistic
- driven mainly by parameterized GW
- QBO does not reach the lowermost stratosphere

a better QBO

WACCM5.4, 110L

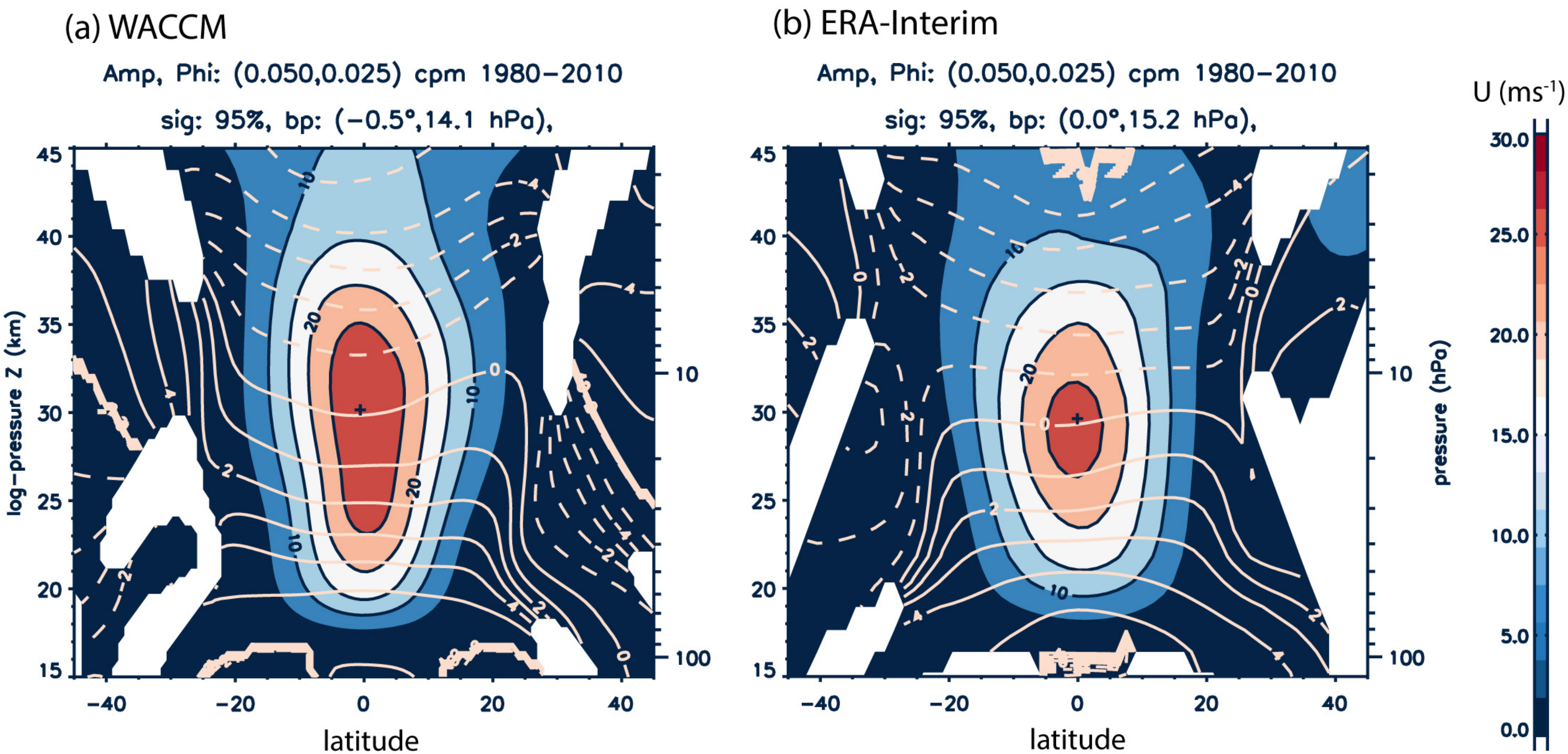


qbo period 27.5 months

- 110L model (v. 5.4) has physics similar to WACCM6
- much finer vertical resolution (500 m) through the middle stratosphere
- not a supported release at this time

- the QBO is realistic throughout stratosphere; period agrees very well with obs
- (resolved) low-frequency Kelvin waves help drive the QBO below 20 km

QBO structure in 110L model



Garcia and Richter, *JAS 2018*

questions?