FDEPS 2012, Lecture 3

Rossby waves and the stratospheric Brewer-Dobson circulation

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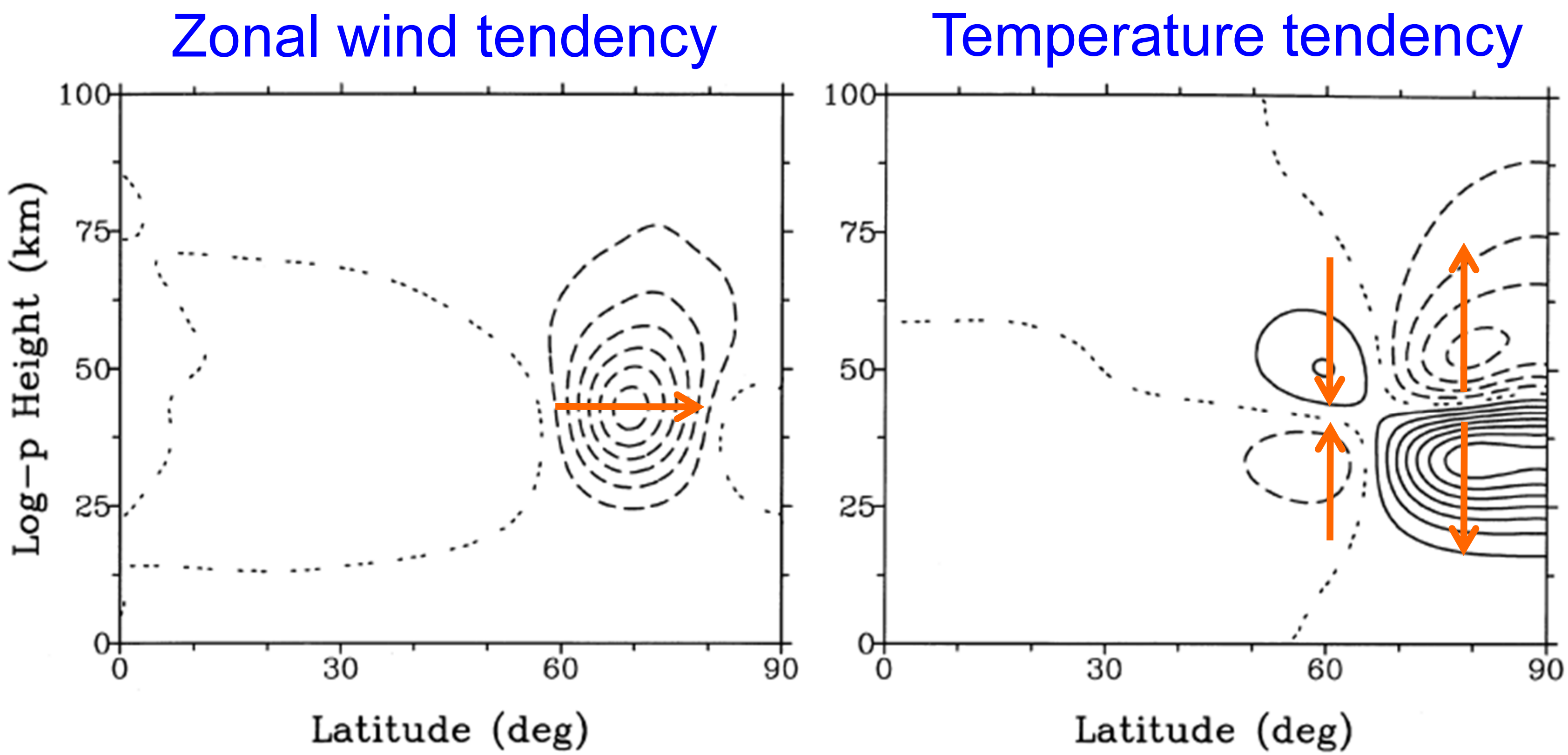
- Rotating, stratified geofluids are characterized by waves (especially Rossby and inertia-gravity)
  - Waves transfer angular momentum and energy
  - For the atmosphere, energy can be radiated to space but the angular momentum budget is closed
- The middle atmosphere is (mainly) dynamically stable, so forced by waves and damped by radiation
  - Circulation is mechanically driven: a refrigerator
- The zonal (axisymmetric) flow filters the angular momentum transfer, inducing differential torques
  - Feedback on zonal flow is wave-mean interaction
  - The two-way interaction provides mechanisms for global-scale teleconnections
- Often the torques act as a drag, but not always
  - Super-rotation is certainly possible

- **‘Eliassen adjustment’**: The instantaneous zonal-mean response to an imposed torque or radiative heating involves a residual circulation to maintain thermal-wind balance: case shown here is for a negative torque (arrows depict the induced circulation)



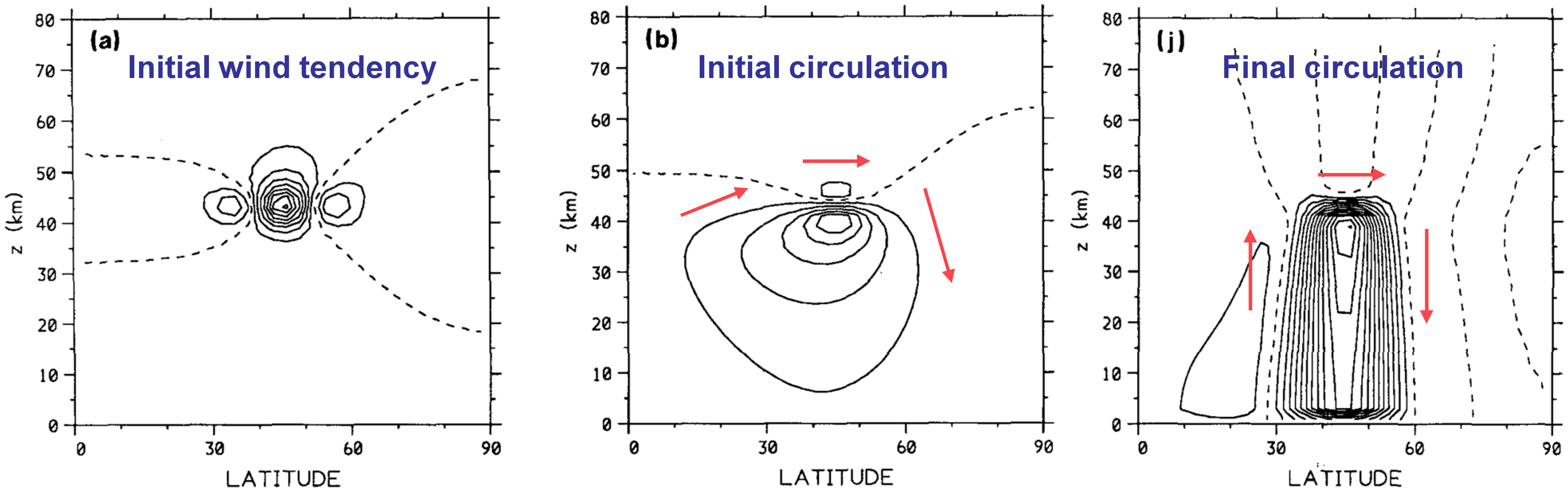
Shepherd (2000 JASTP)

- In the extratropics, persistent torques lead to downward 'burrowing' of the mean meridional circulation; negative torque $\Rightarrow$ poleward flow

$$\tau = \frac{d}{dt}(ru) = u\frac{dr}{dt} + r\cancelto{0}{\frac{du}{dt}}$$

Radiative cooling and surface drag, which are relaxational, 'accommodate' the circulation

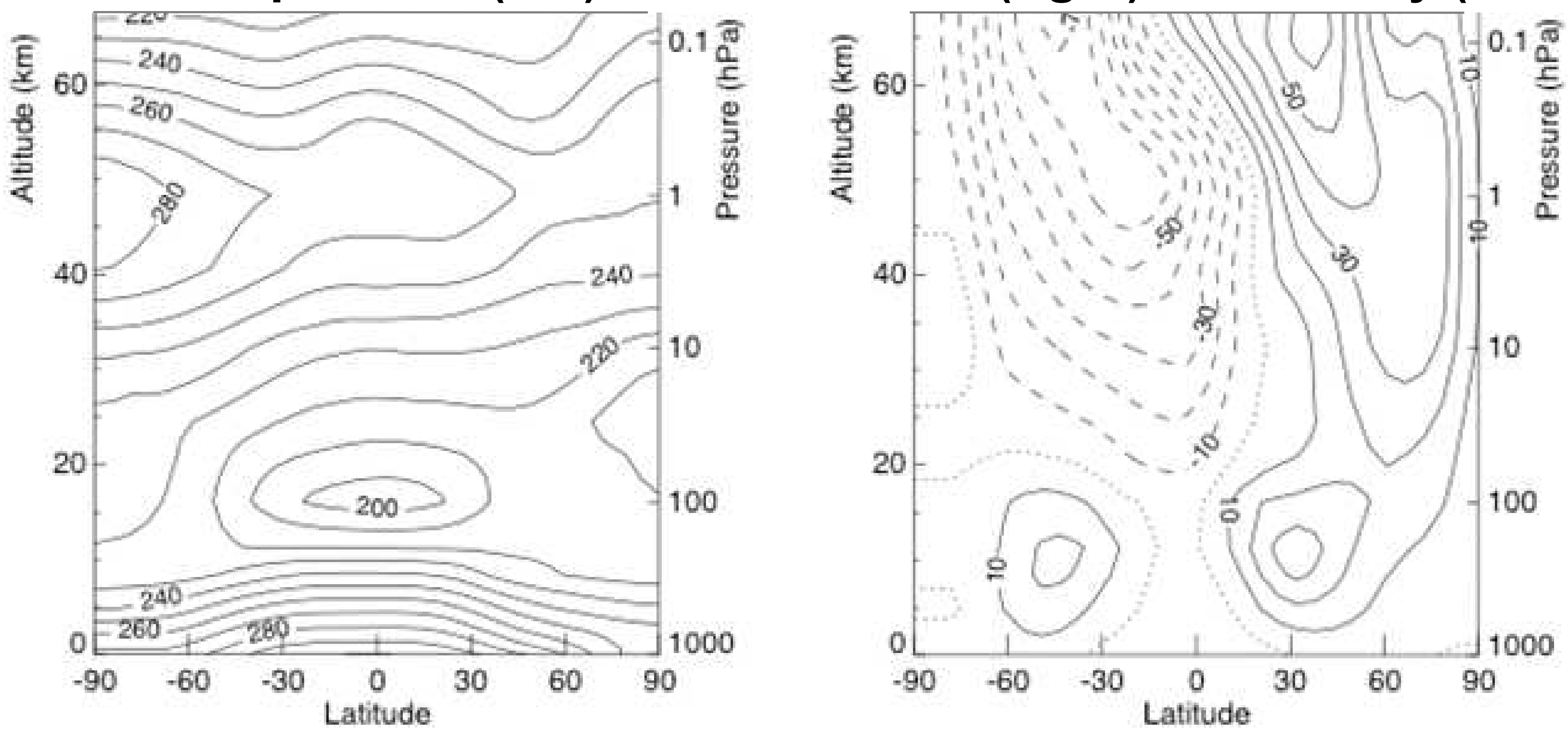
(u is absolute velocity)



Zonally symmetric calculations from Haynes et al. (1991 JAS)

- In the stratosphere, the small thermal inertia means temperatures follow the Sun: warm at the summer pole and cold at the winter pole
- Thermal wind balance implies eastward (westerly) flow in the winter hemisphere, and westward flow in the summer hemisphere

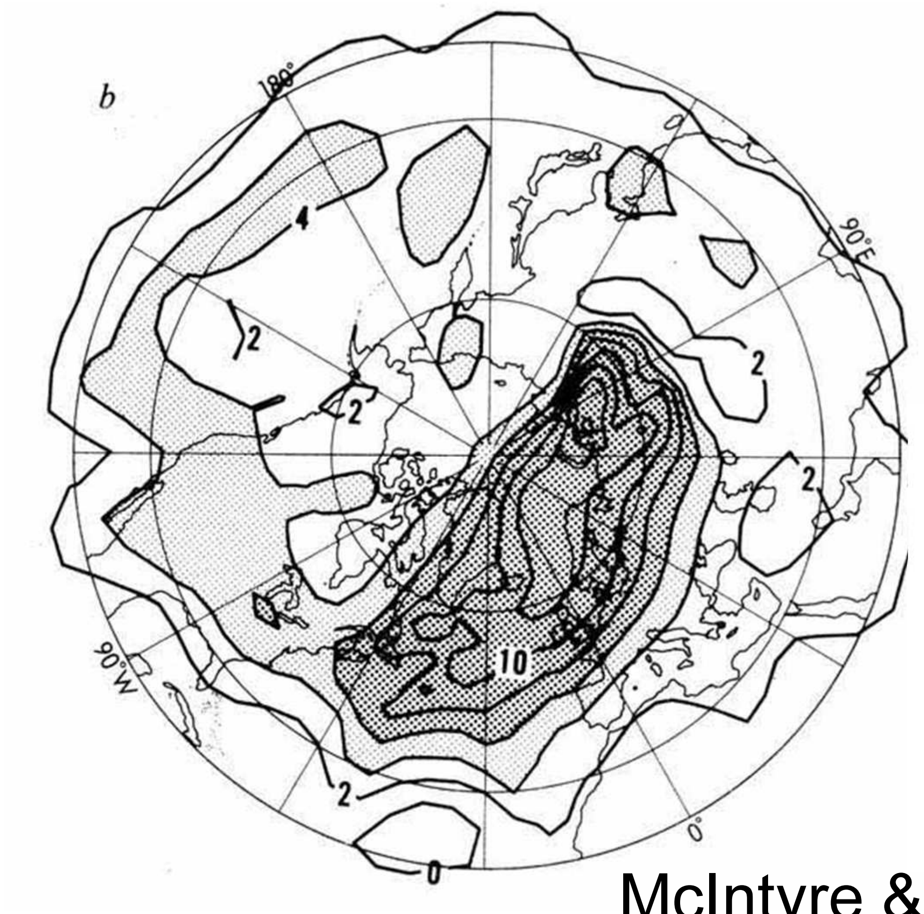
Observed temperature (left) and zonal wind (right) for January (CIRA)



Shepherd (2003 Chem. Rev.)

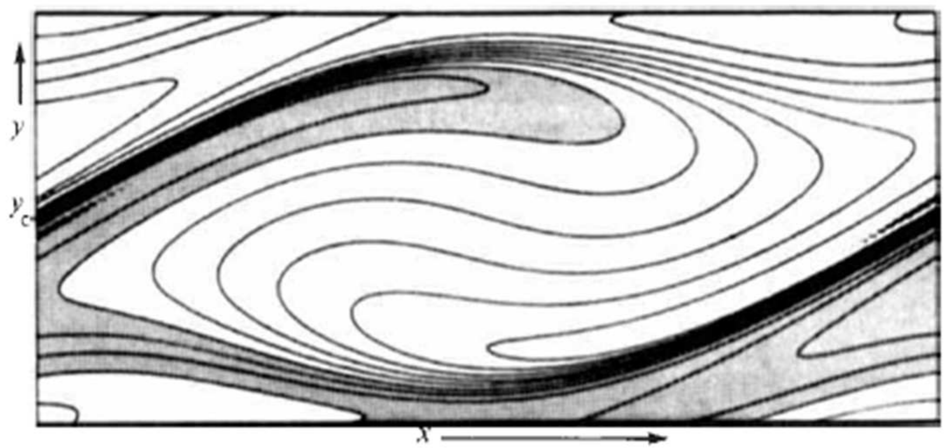
- When the flow is westerly, planetary-scale Rossby waves can propagate into the stratosphere (Charney & Drazin 1961 JGR), where they break in a hemispheric-wide ‘surf zone’ (McIntyre & Palmer 1983 Nature)

PV on 850 K isentropic surface



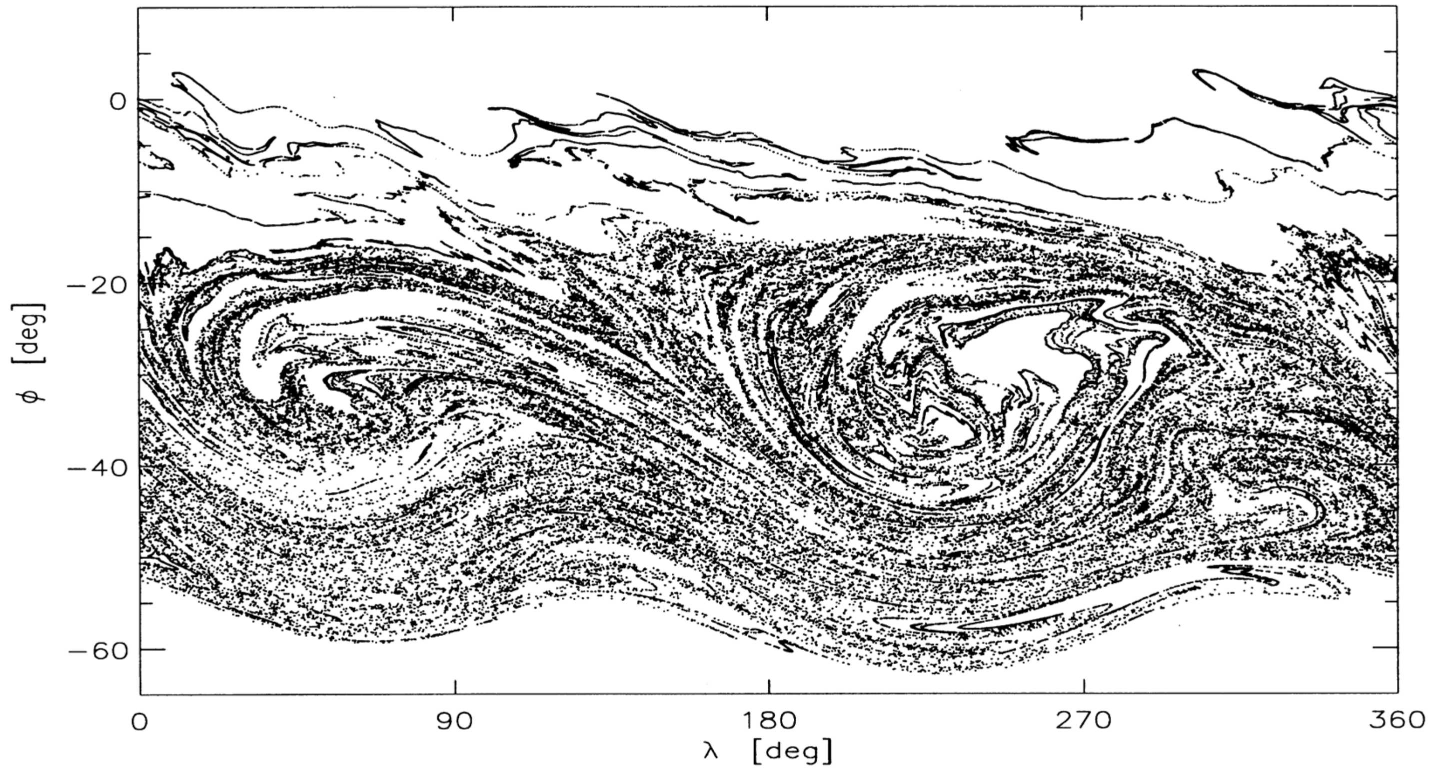
- This behaviour was argued to be that of a nonlinear critical layer (see below)

Critical layers occur where the wave phase speed equals the flow speed



McIntyre & Palmer (1987 Nature)

- The "surf zone" in the Canadian Middle Atmosphere Model, a realistic climate simulation model
  – 30-day particle advection at 1000 K (approx 35 km)
- Where the waves break, they exert a torque from the angular momentum transfer



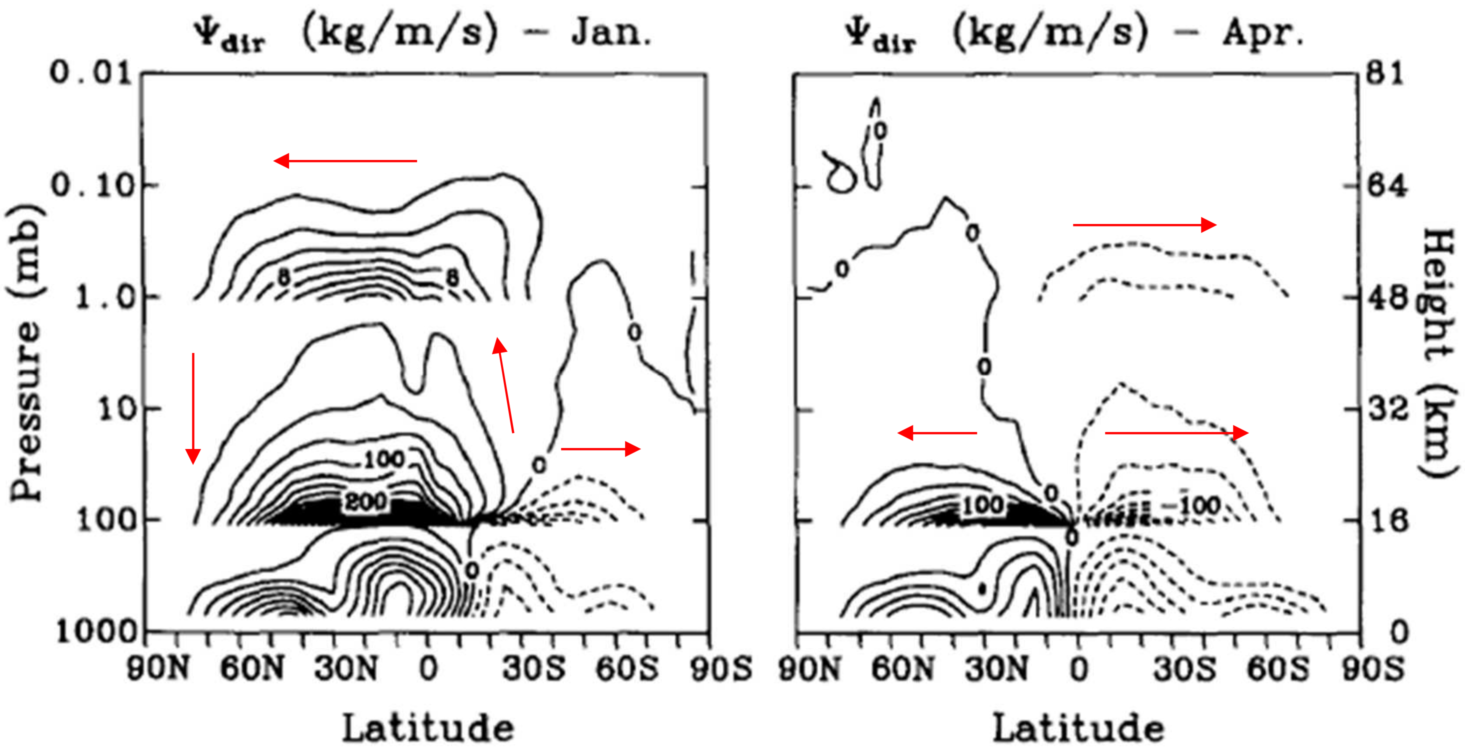
Ngan & Shepherd (1999 JAS)

- For Rossby waves, the momentum deposition is always *negative*. For barotropic dynamics, it is easy to show that

$$\frac{\partial \bar{u}}{\partial t} = -\frac{\partial}{\partial y}\left(\overline{u'v'}\right) = \overline{v'q'} = \nabla \bullet \vec{F}$$

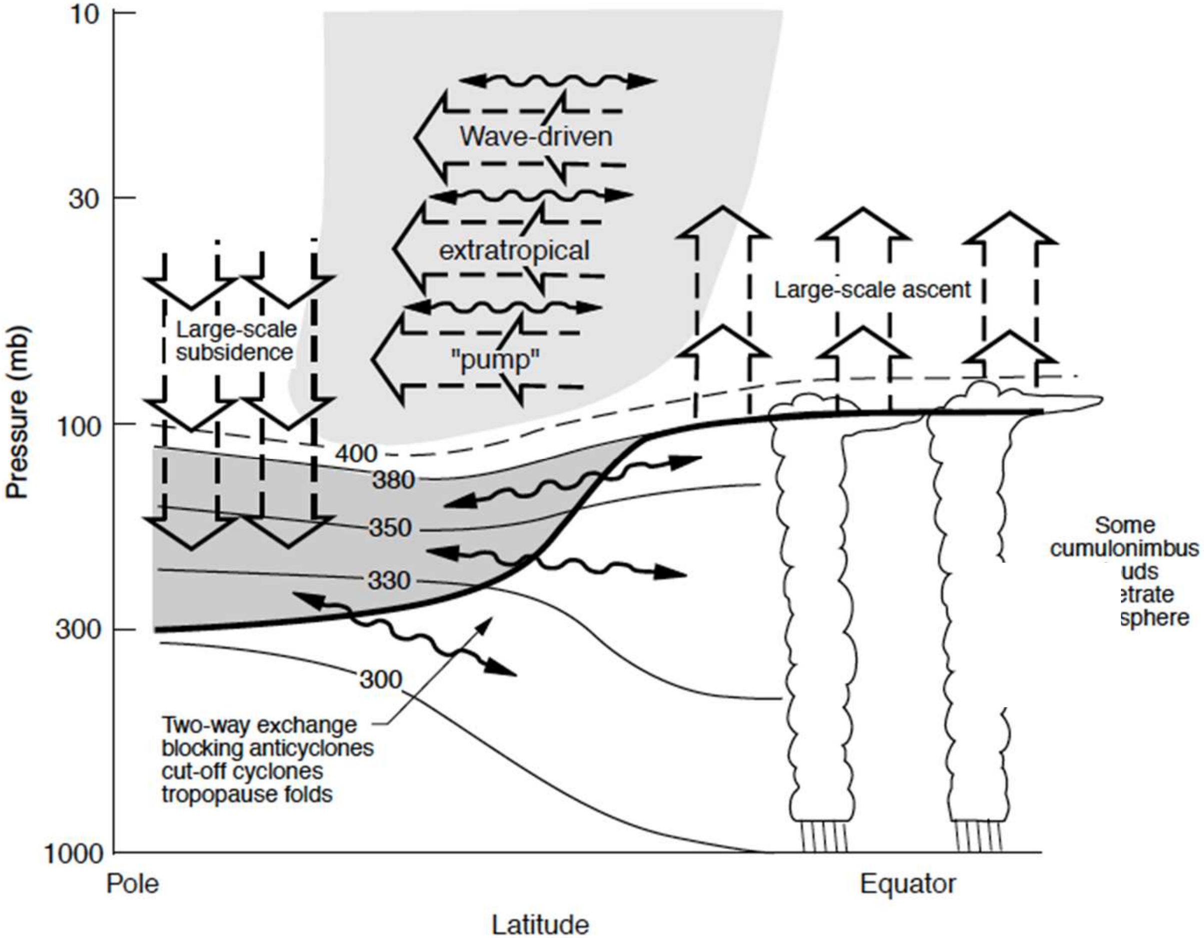
  where *q* is potential vorticity (PV) and *F* is EP flux
- An analogous relation holds for stratified flow (Dickinson 1969 JAS; Andrews & McIntyre 1976 JAS), although the zonal-wind response is then non-local (Eliassen 1951 Astrophys. Norv.)
- Breaking Rossby waves mix PV downgradient, hence the induced torque is negative
- N.B. In the stratosphere, PV mixing cannot happen spontaneously

- Wave-induced torques drive a middle atmosphere circulation with a strong seasonal dependence
  - Mainly from Rossby waves in the stratosphere
  - Mainly from gravity waves in the mesosphere



CMAM results from Beagley et al. (1997 Atmos.-Ocean)

- This is the origin of the stratospheric “Brewer-Dobson circulation”, which cools the tropics and warms the poles

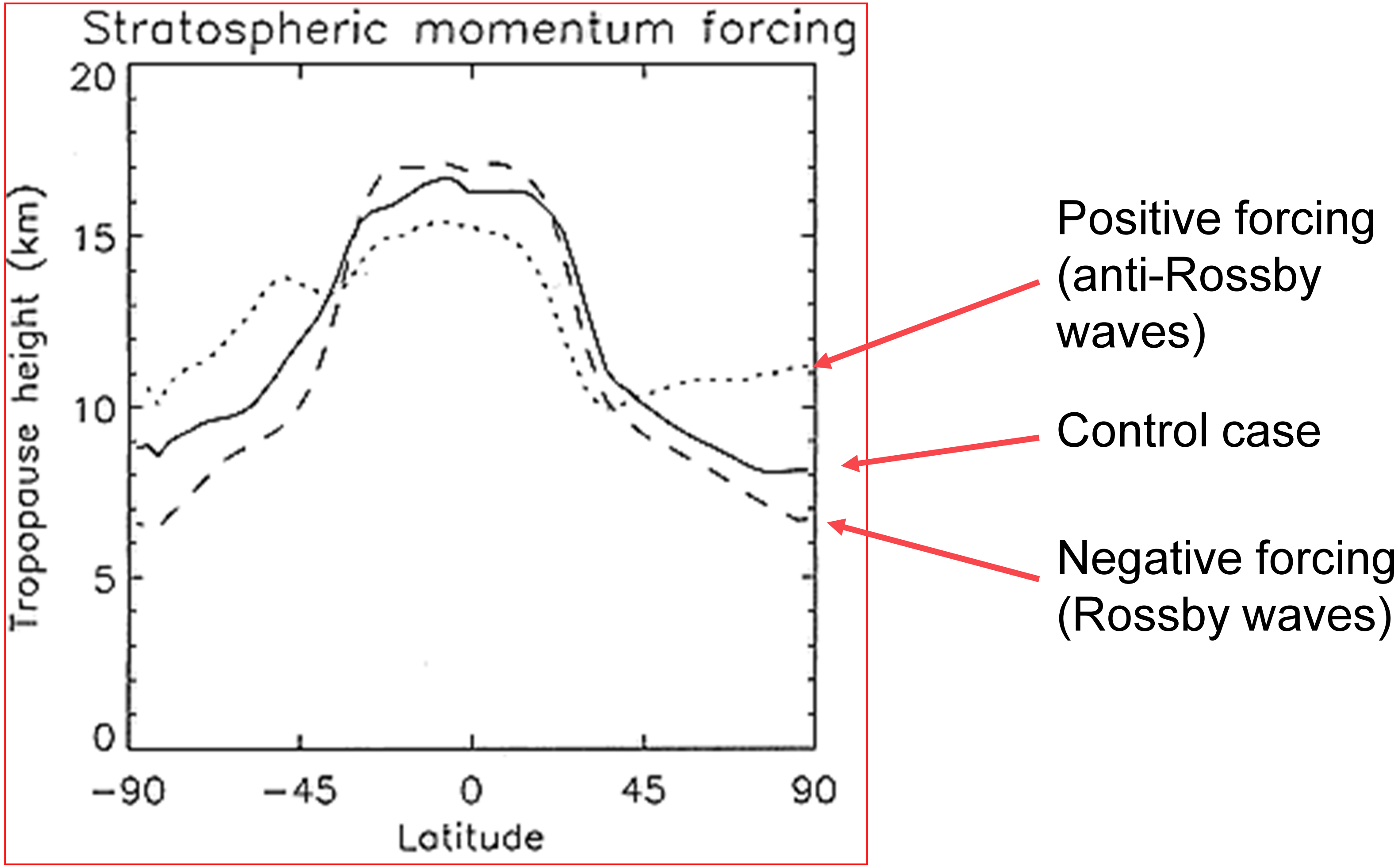


Mainly operates in the winter hemisphere

The circulation is thermally indirect: a ‘refrigerator’

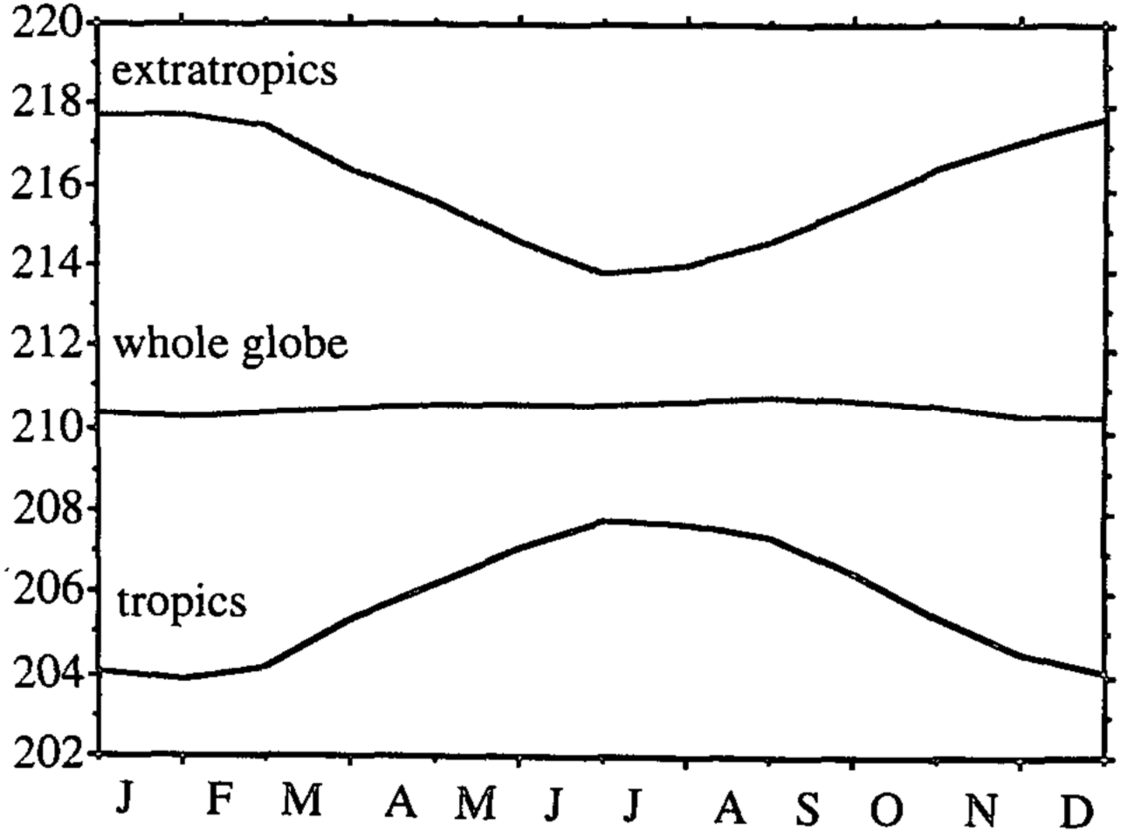
Holton et al. (1995 Rev. Geophys.)

• The BDC raises and cools the tropical tropopause, and lowers and warms the extratropical tropopause



GCM calculations by Thuburn & Craig (2000 JAS)

- The seasonal variation in the BDC leads to a seasonal variation in lower stratospheric temperature
  - Tropical temperatures are lowest in boreal winter, when the tropical upwelling is the strongest

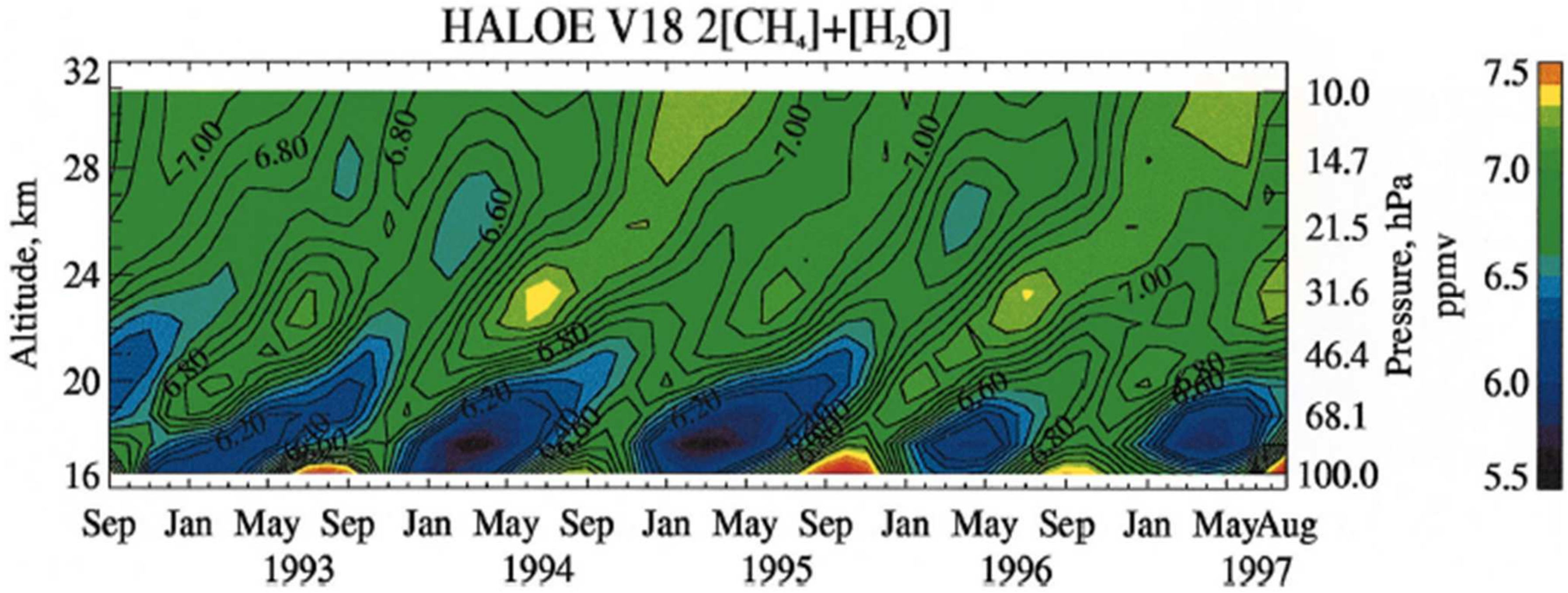


Yulaeva, Holton & Wallace (1994 JAS)

MSU Channel 4 temperature (approx 100 hPa)

Compensation between tropics and extratropics suggests the influence of the BDC

- The seasonal cycle in tropical tropopause temperature causes a seasonal cycle in dehydration, which is imprinted on the water vapour entering the stratosphere: the “water vapour tape recorder” (Mote et al. 1996 JGR)



Mote et al. (1998 JGR)

- Tropical tropopause temperature also controls stratospheric water vapour on interannual timescales

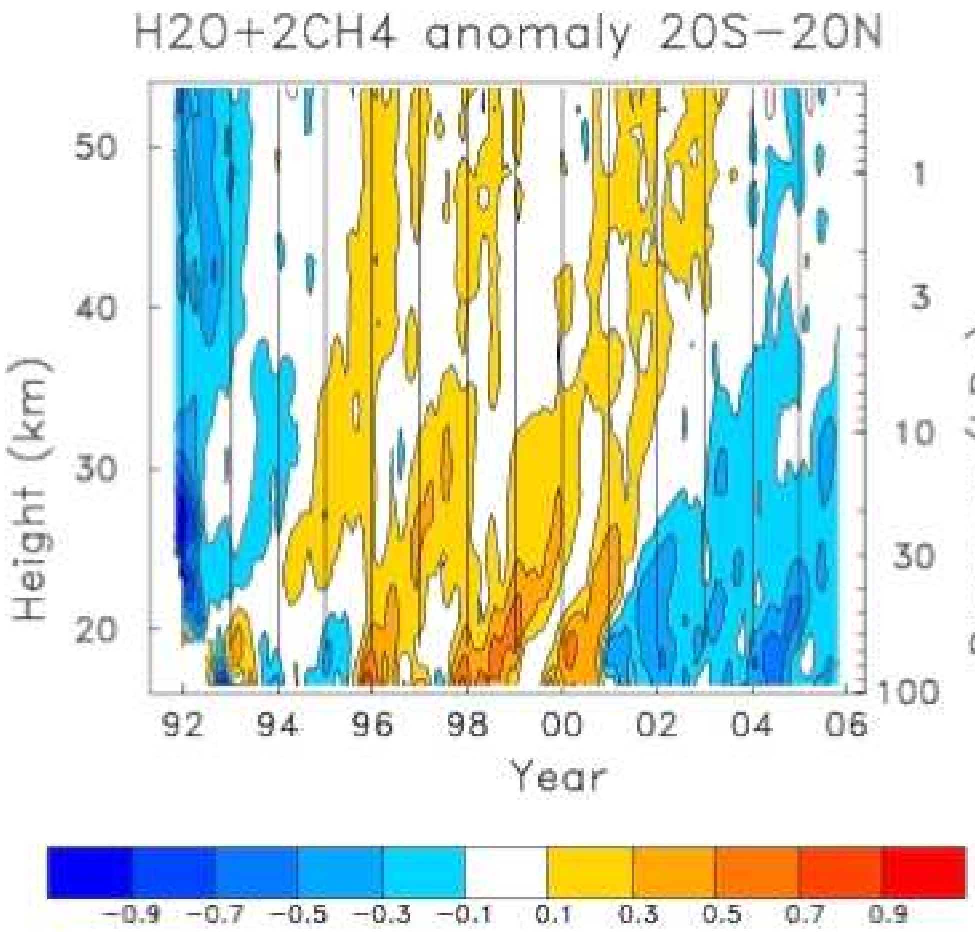


Figure shows interannual anomalies in the "tropical tape recorder" as seen in HALOE measurements from the UARS satellite

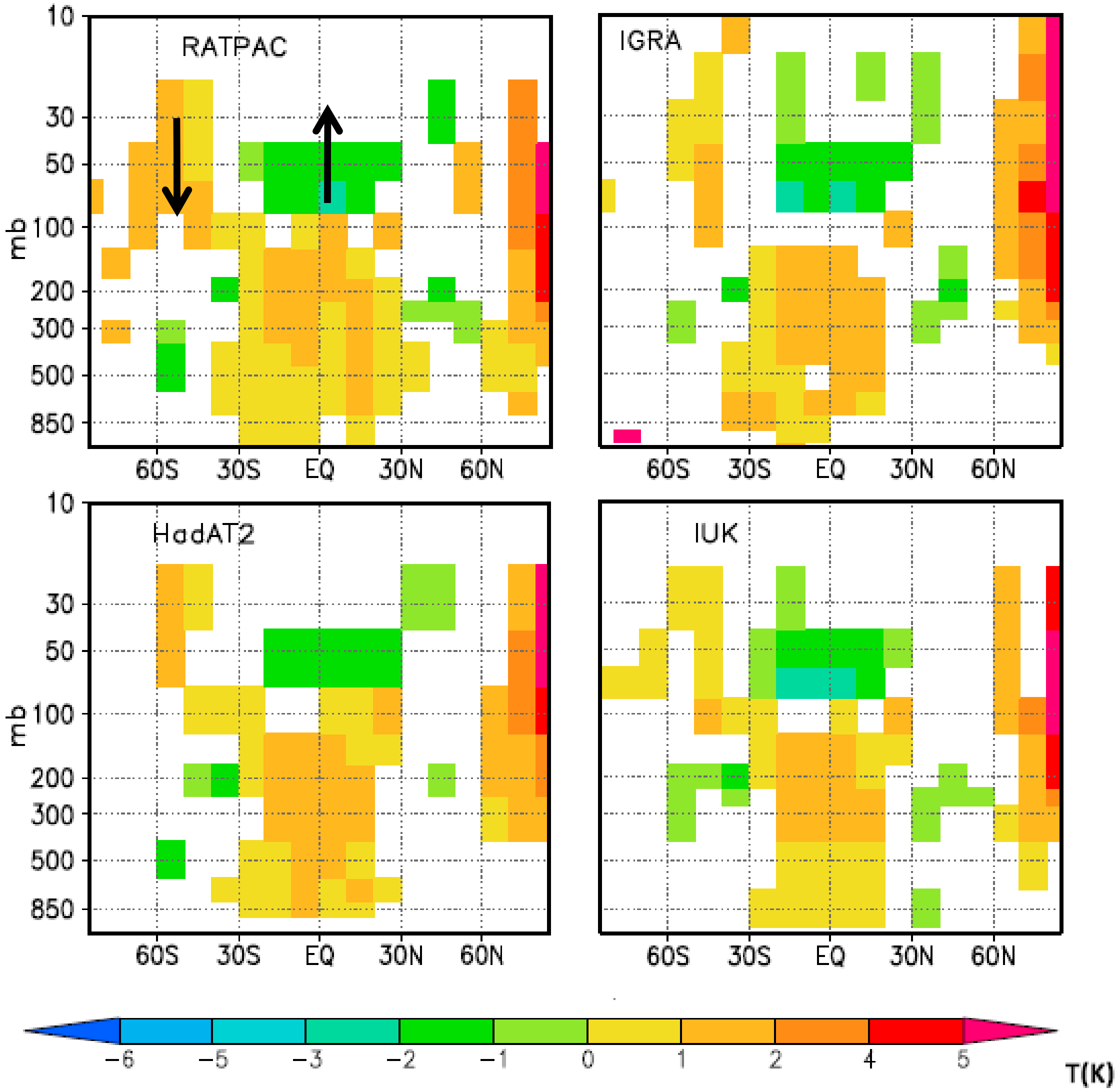
Updated from Randel et al. (2004 JAS)

- Radiosonde observations reveal variations in the BDC associated with El Niño

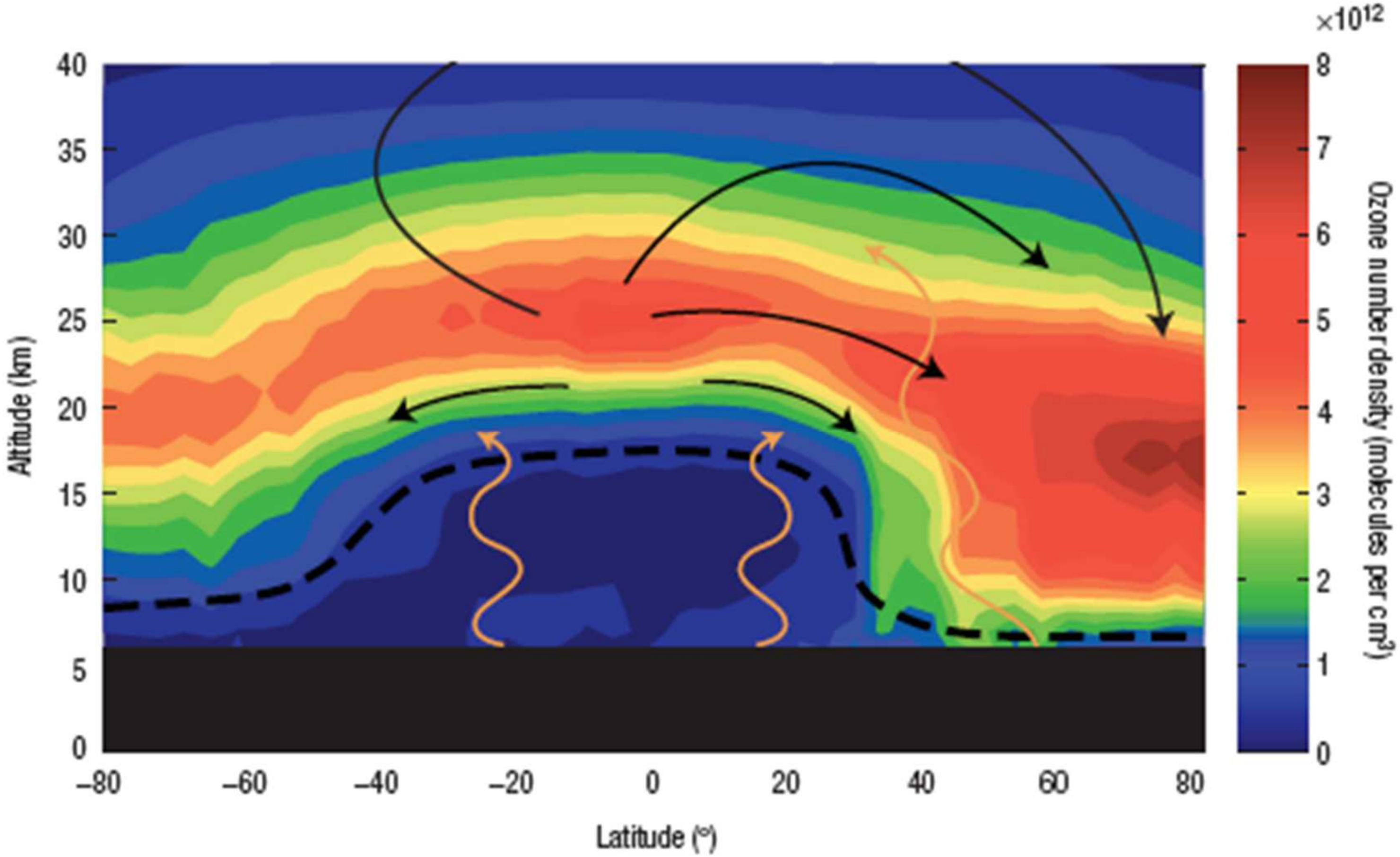
Regression of DJF temperature onto Nino 3.4 index

These stratospheric features must be dynamically driven

Free & Seidel (2009 JGR)



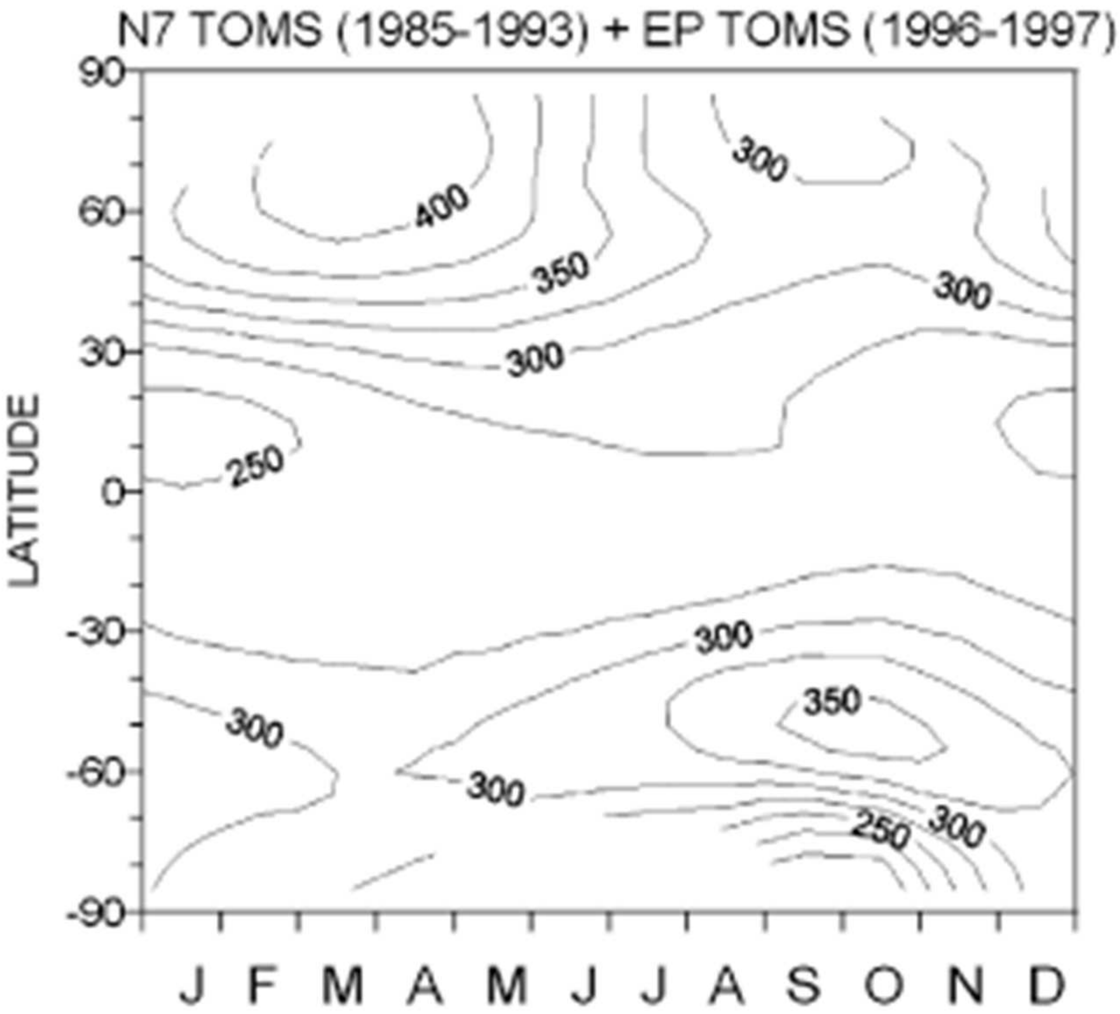
- The Brewer-Dobson circulation was originally inferred from observations of water vapour and ozone
  - Dryness of stratosphere implies tropical entry
  - Ozone distribution implies poleward motion



March 2004 OSIRIS ozone

Shaw & Shepherd (2008 Nature Geosci.)

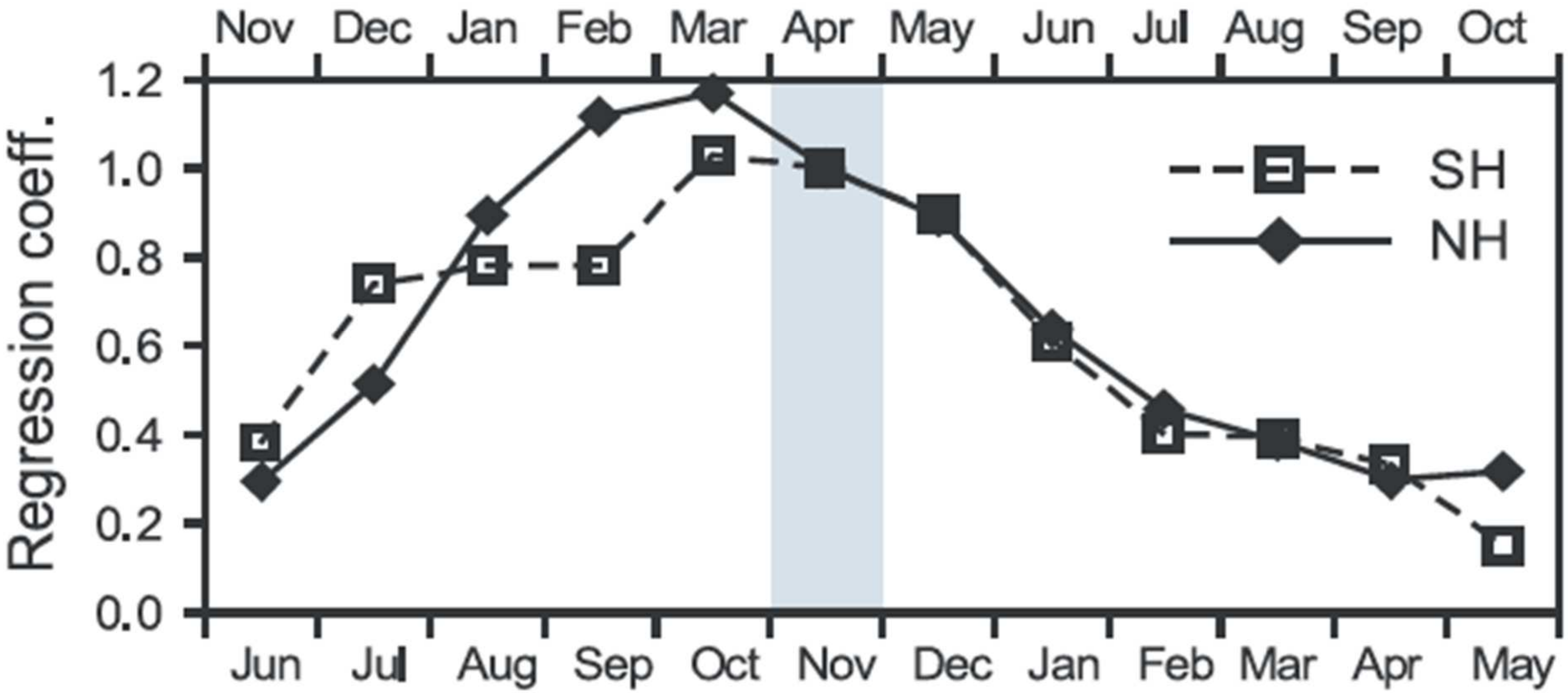
- Transport by the BDC explains the seasonal and interhemispheric differences in ozone



TOMS total ozone data (1985-1997)

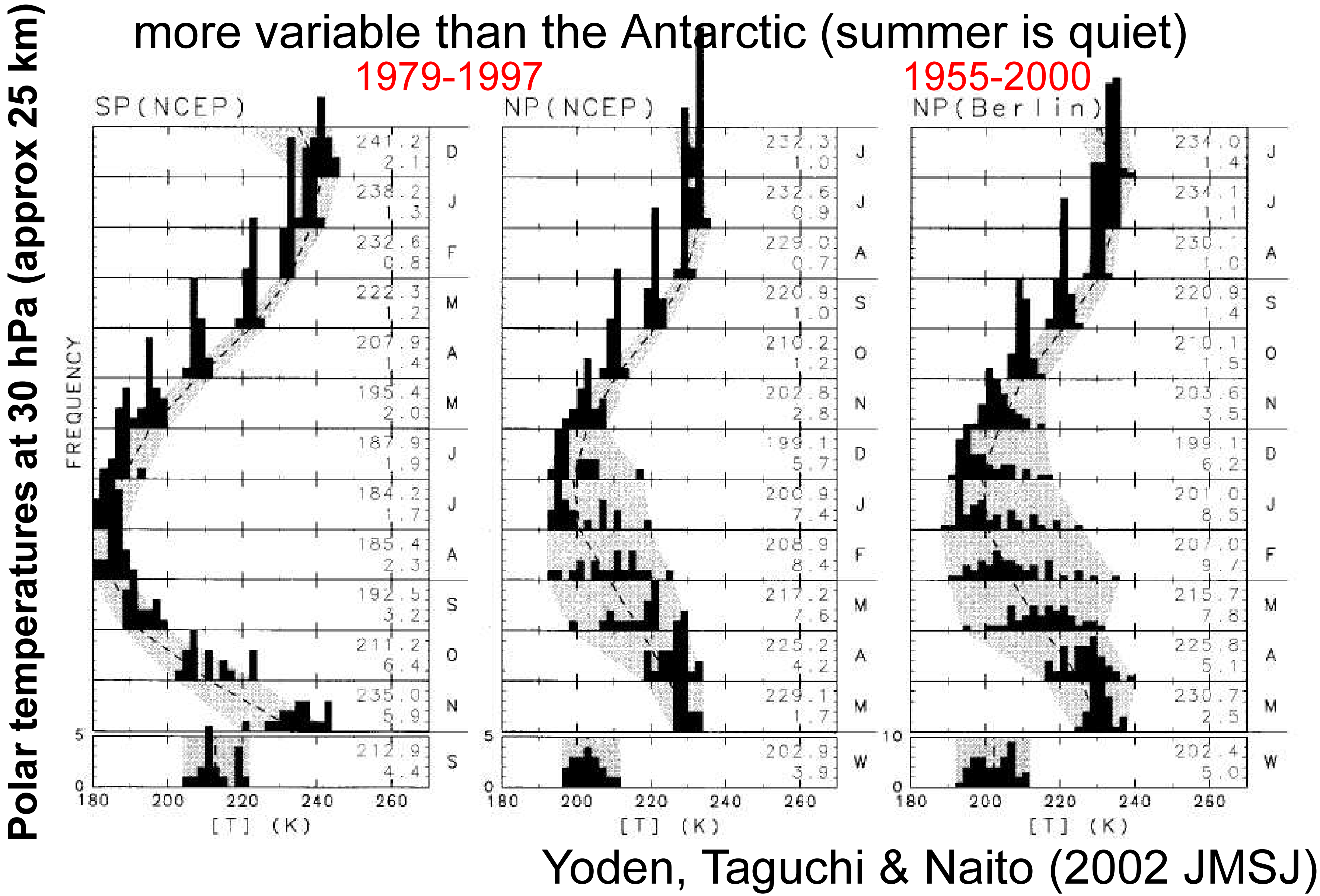
Figure courtesy of Vitali Fioletov, Environment Canada

- The seasonal cycle of stratospheric variability implies a seasonal cycle in the Brewer-Dobson circulation
  - Midlatitude column ozone anomalies build up through winter and spring, and decay photochemically during the quiescent summer (several-month timescale)

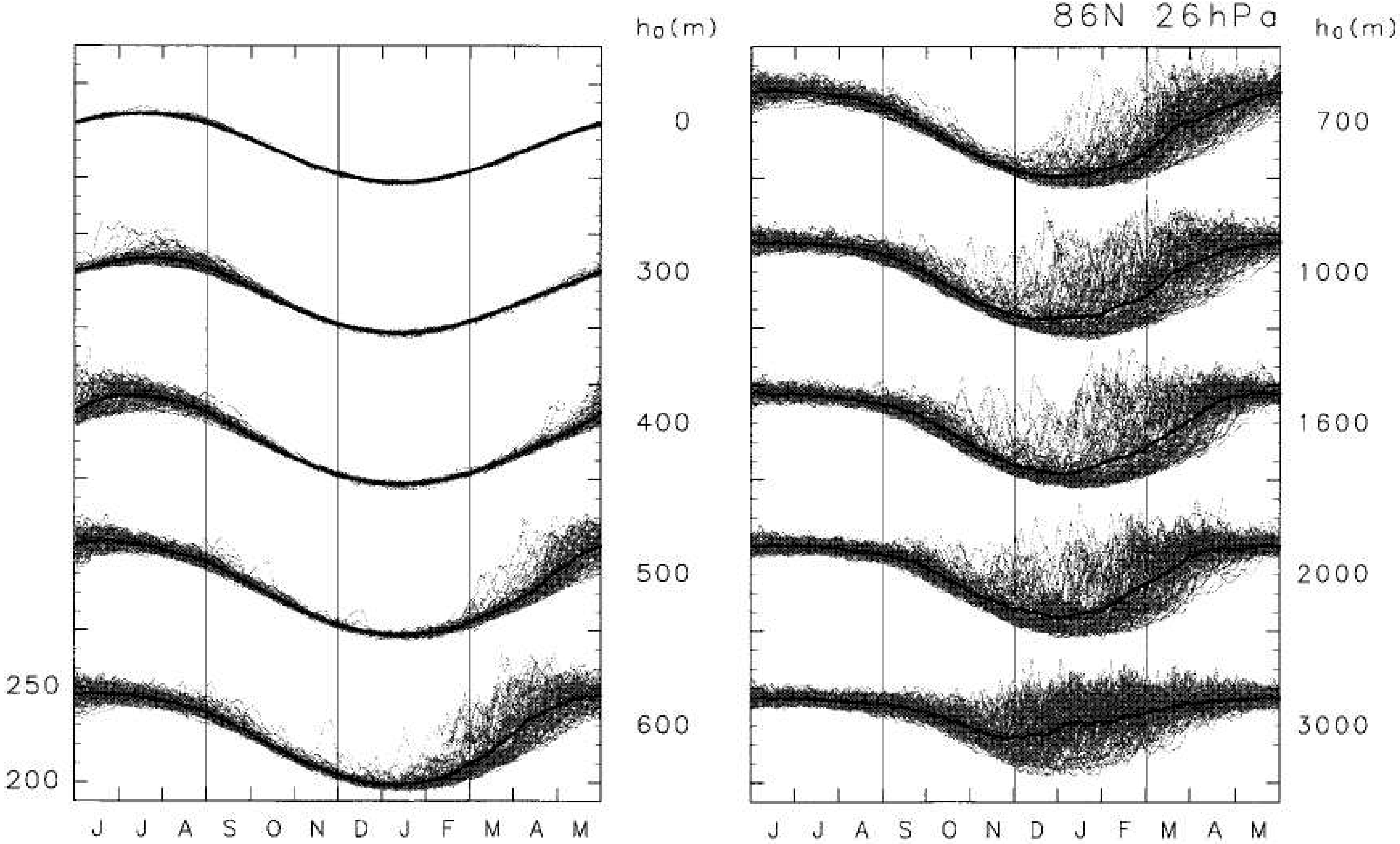


TOMS total ozone, from Fioletov & Shepherd (2003 GRL)

- Forcing of planetary Rossby waves is stronger in the NH than in the SH, so the Arctic winter is warmer and more variable than the Antarctic (summer is quiet)



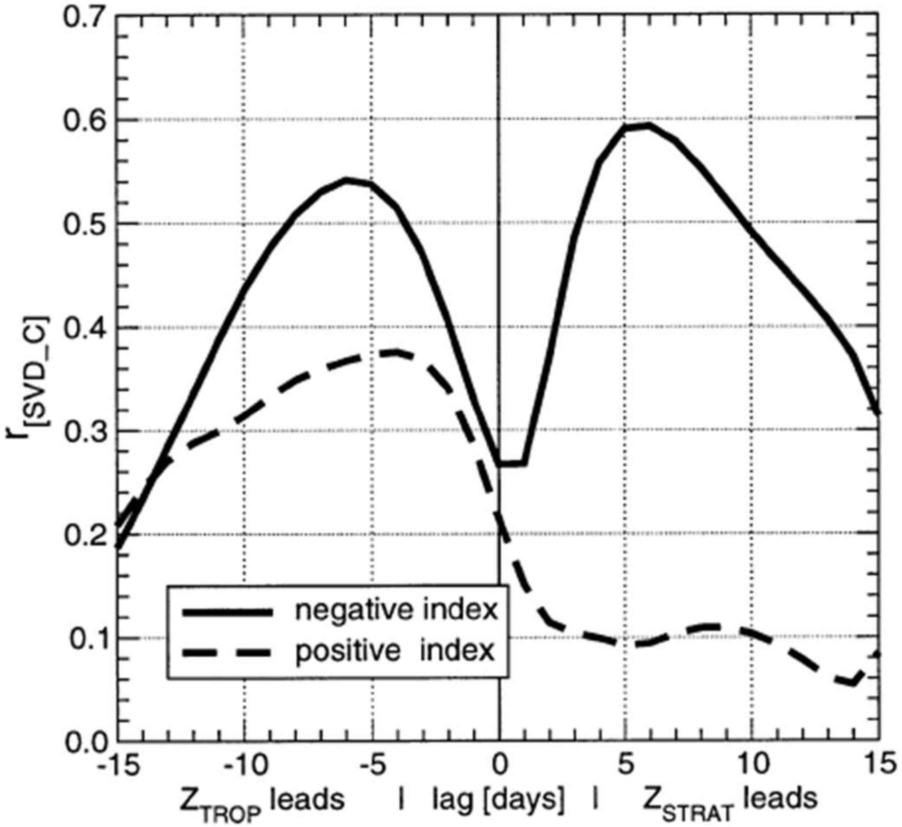
- Response of polar temperatures to increasing wave forcing h_0 in a mechanistic model reveals complex dynamics

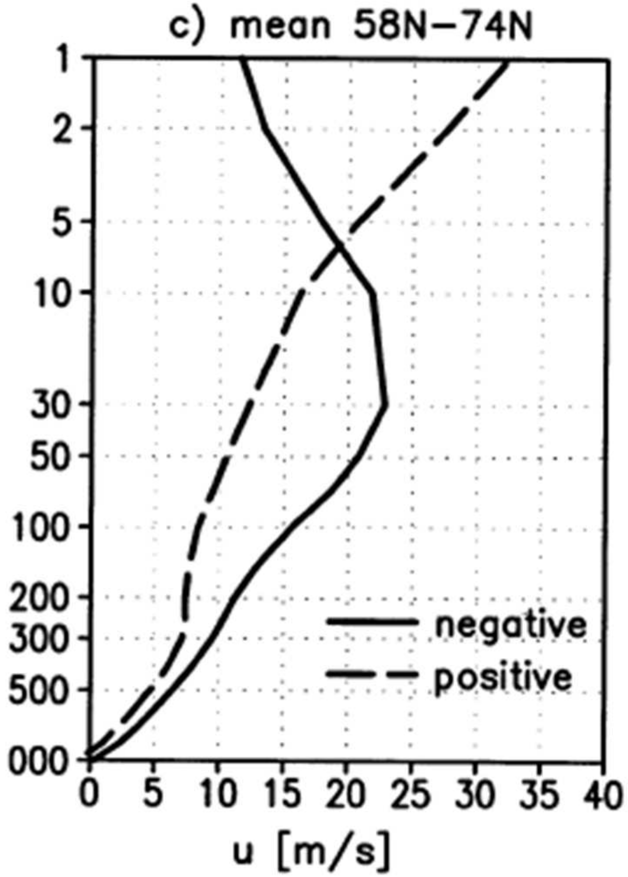


Yoden, Taguchi & Naito (2002 JMSJ)

- Observations suggest that the upward EP flux depends in part on the state of the stratosphere
  - This challenges the accepted paradigm

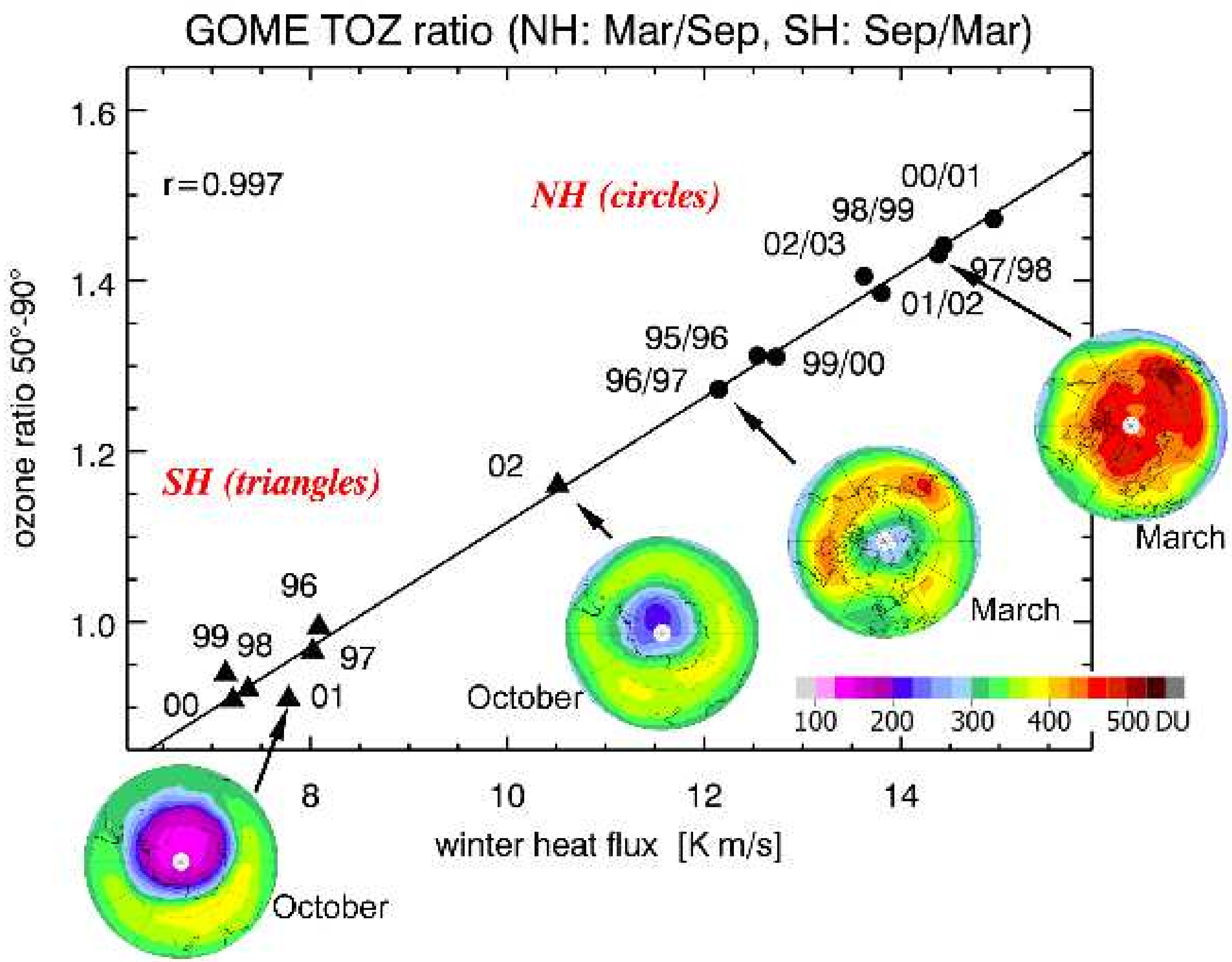
Correlation between k=1 variability in troposphere and stratosphere





Perlwitz & Harnik (2003 J Clim)

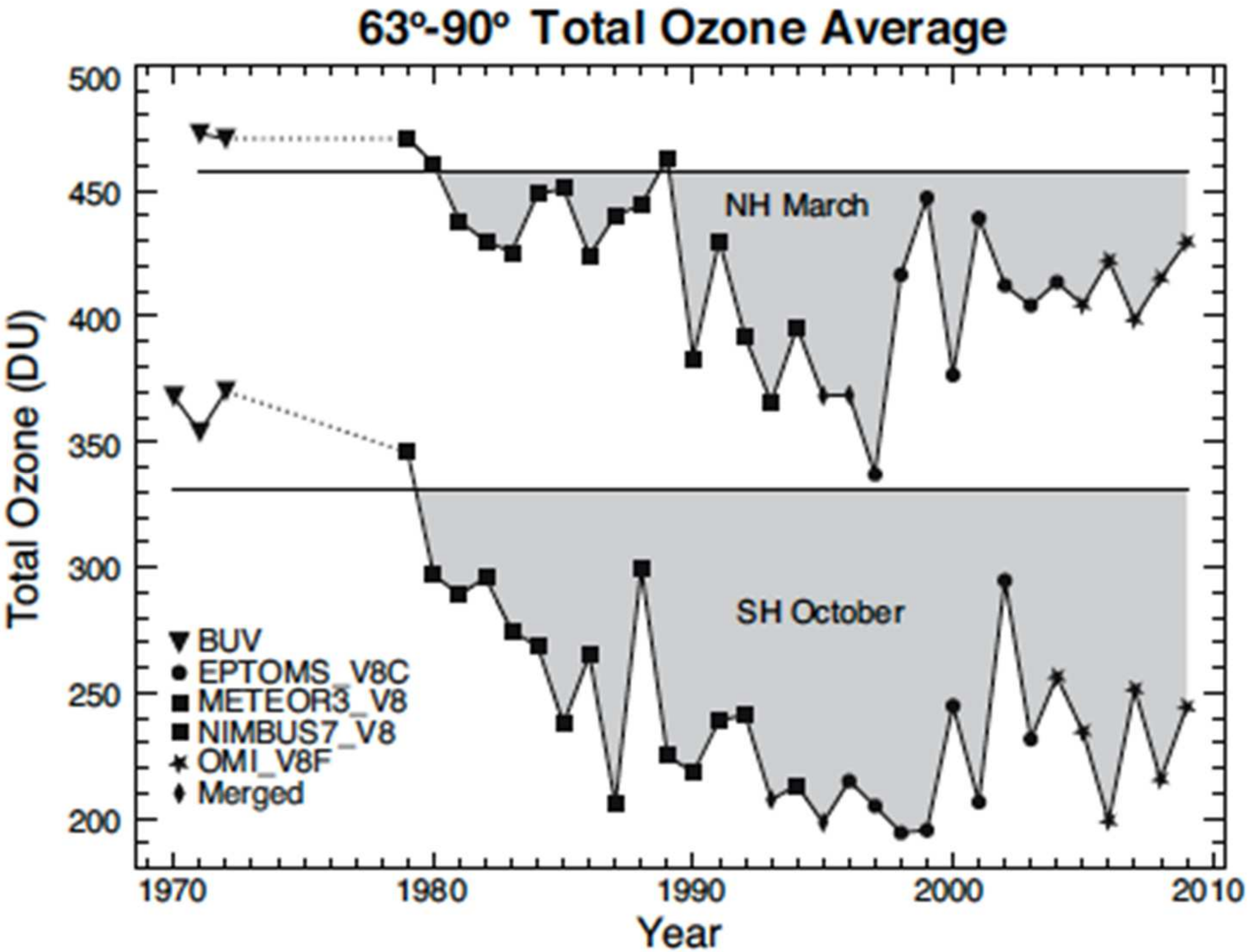
- Variations in the upward wave forcing ("winter heat flux", proportional to vertical EP flux) are associated with variations in polar downwelling, hence in polar vortex strength and in polar ozone abundance



There is a continuous transition between the two hemispheres

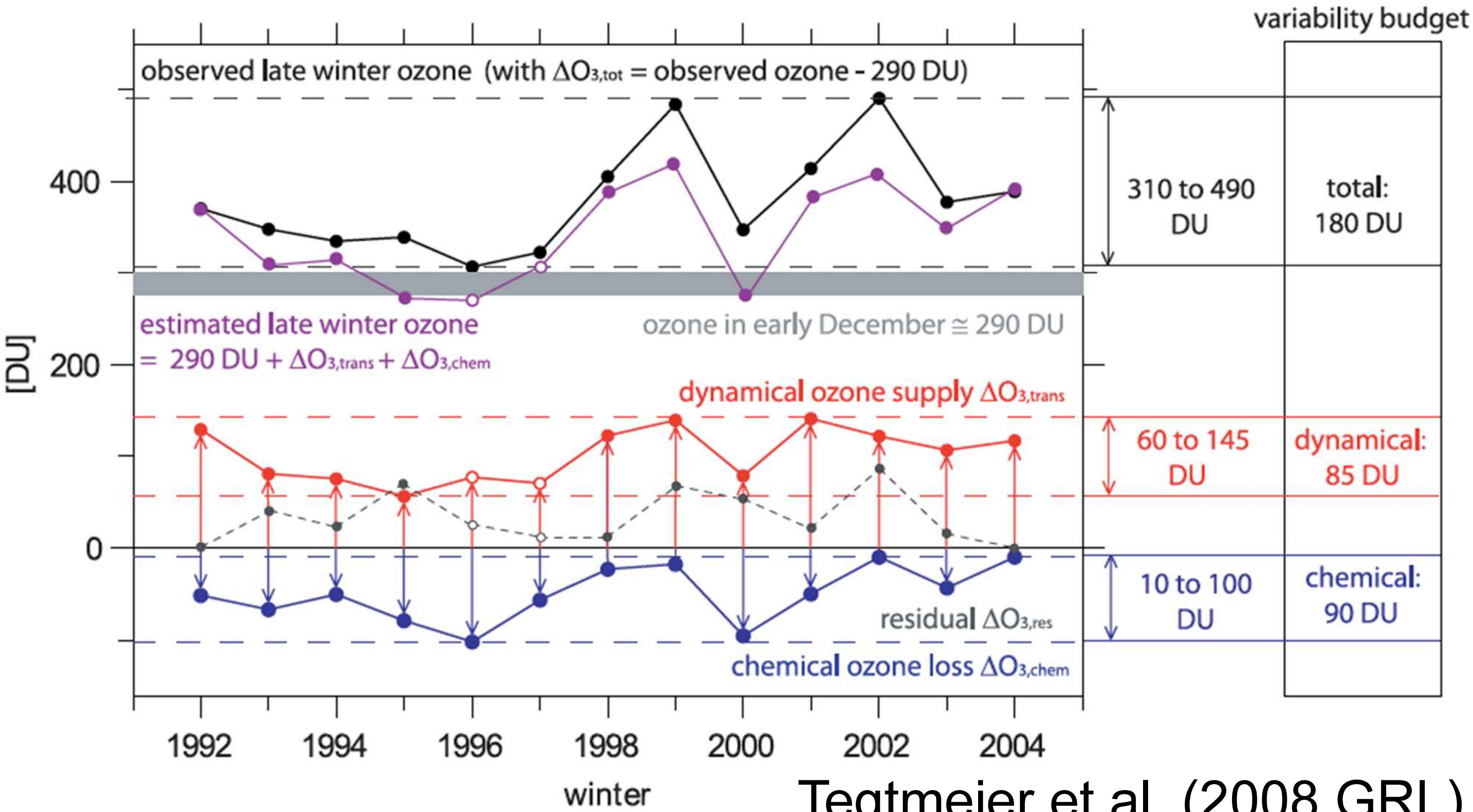
Adapted from Weber et al. (2003 GRL)

- This inter-annual variability in the polar downwelling is most pronounced in the NH, and leads to decadal timescale changes in ozone



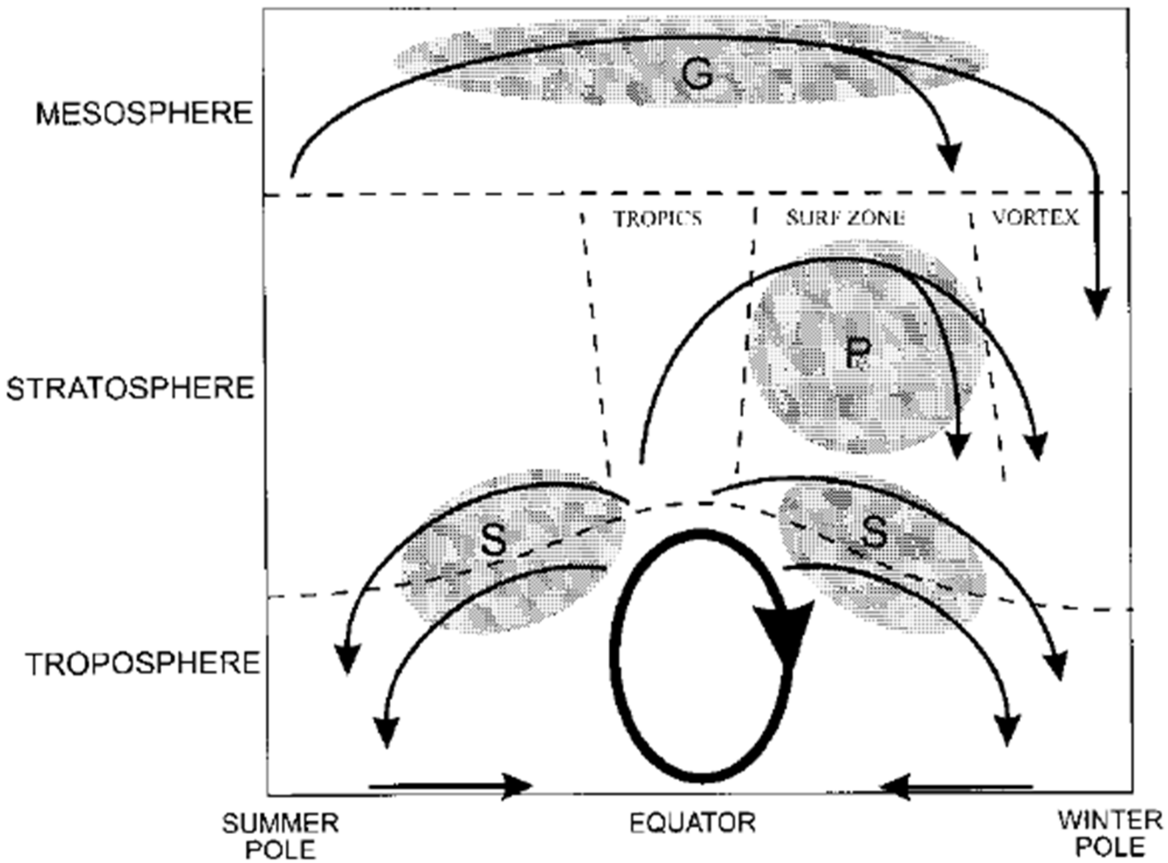
WMO (2011)

- For the Arctic, anomalies in transport and in (temperature-induced) chemical loss act in phase and contribute equally to the observed ozone variability (while chlorine loading is high)

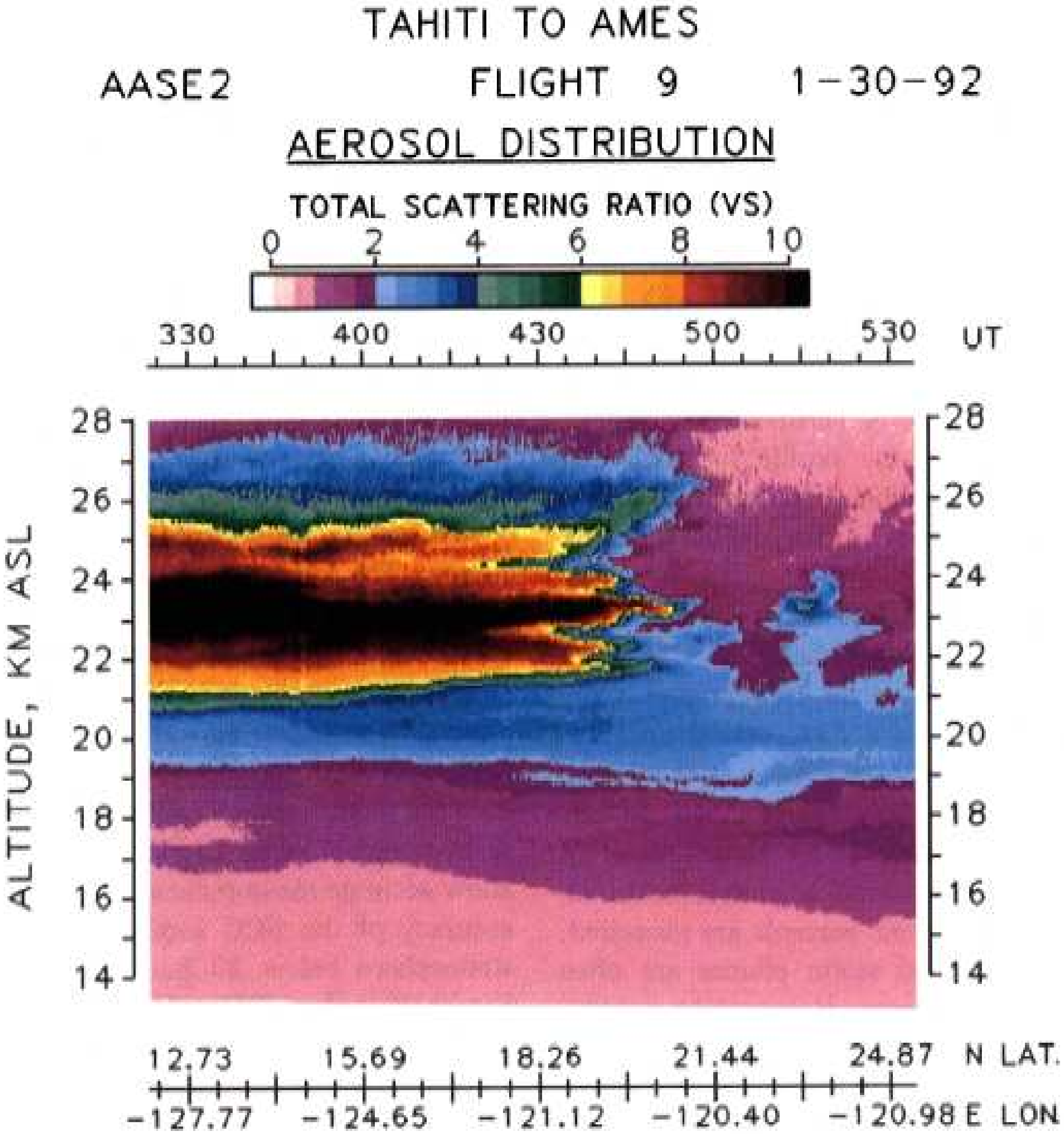


Tegtmeier et al. (2008 GRL)

- In addition to the “deep” branch of the BDC driven by planetary-wave drag, there is also a “shallow” branch for which synoptic-scale wave drag is important



Plumb (2002 JMSJ)

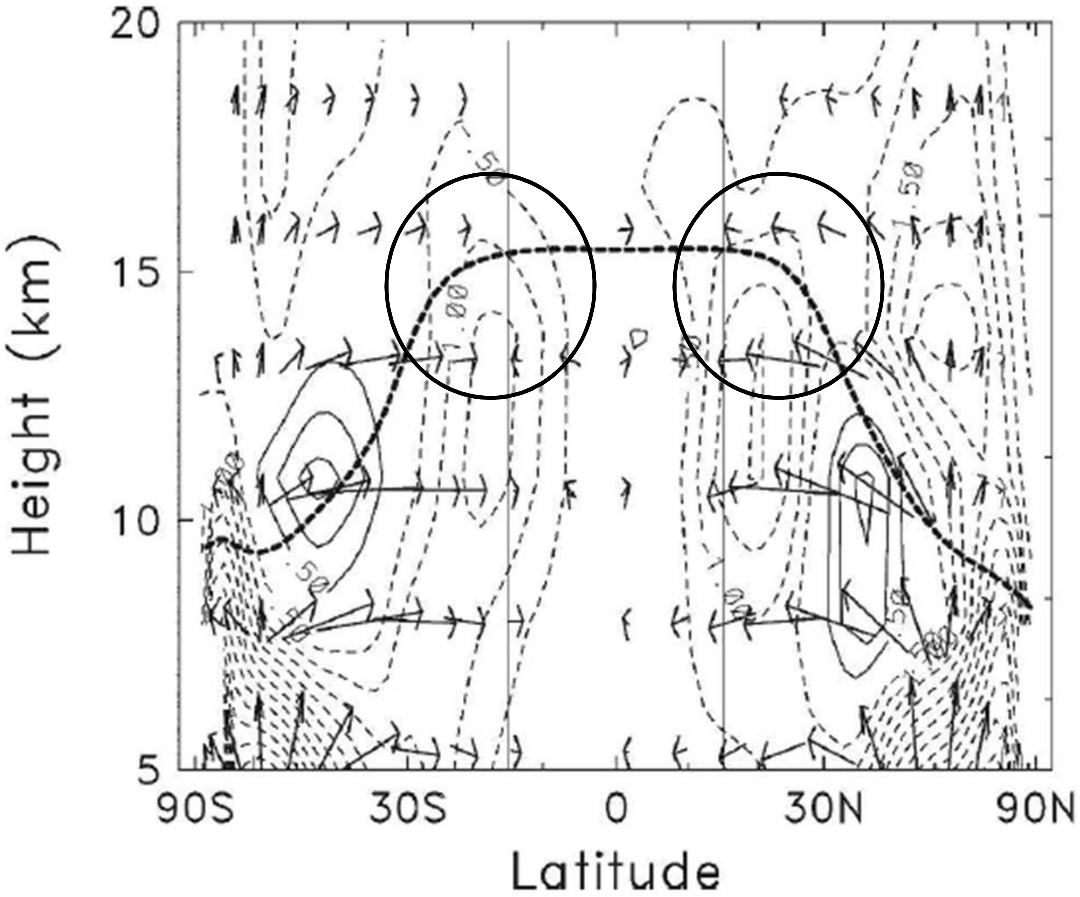


Synoptic-scale waves are presumably a major contributor to the observed outflow just above the tropical tropopause, which occurs year-round

Seen in airborne lidar measurements after Mt Pinatubo eruption

Grant et al. (1994 JGR)

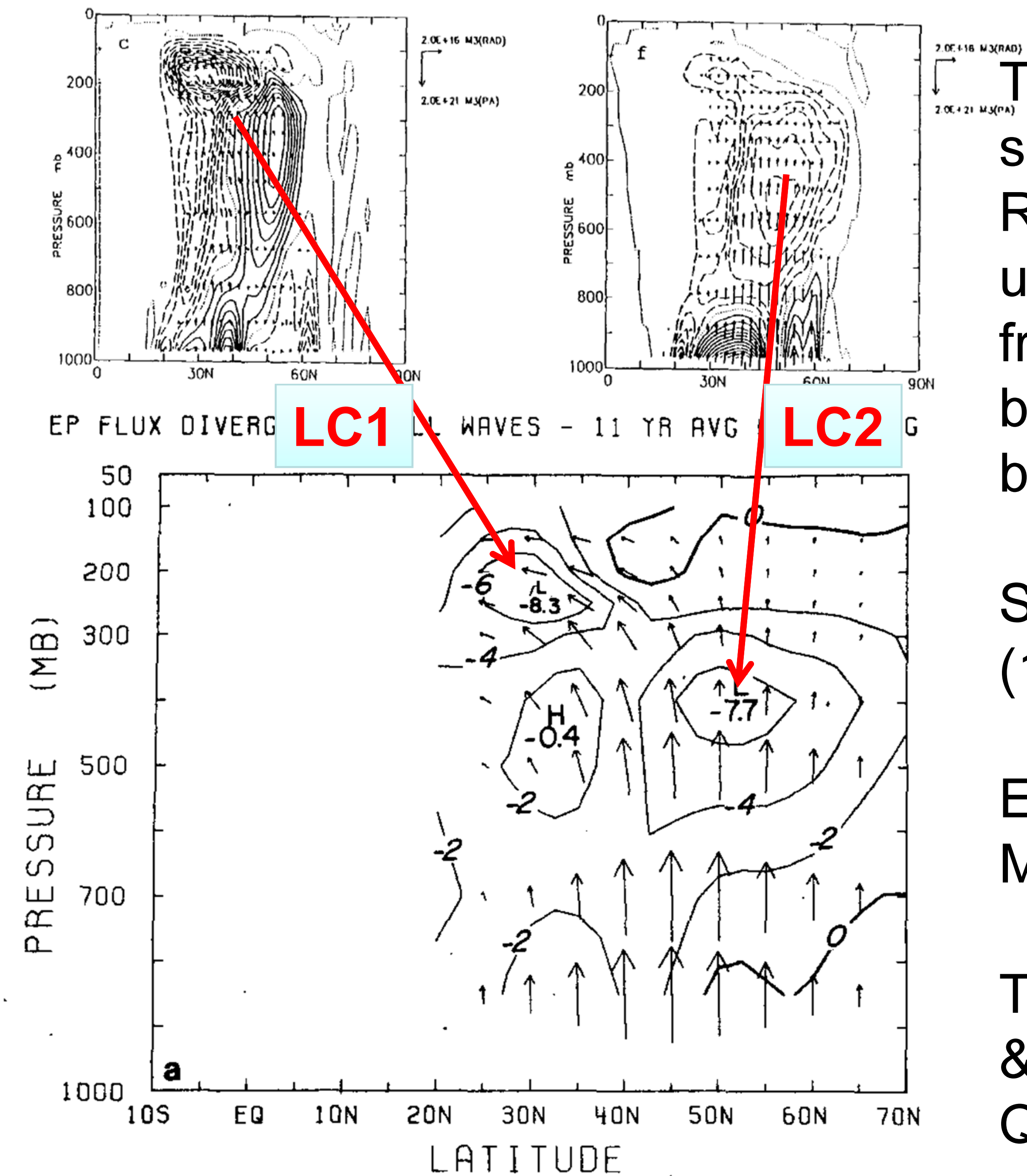
- The importance of synoptic-scale Rossby waves to the BDC may seem surprising, but the drag from synoptic-scale waves extends continuously into the subtropical lower stratosphere



Annual mean observed EP flux and flux divergence from ERA-40

Tropopause shown with thick line

Randel, Garcia & Wu (2008 JAS)



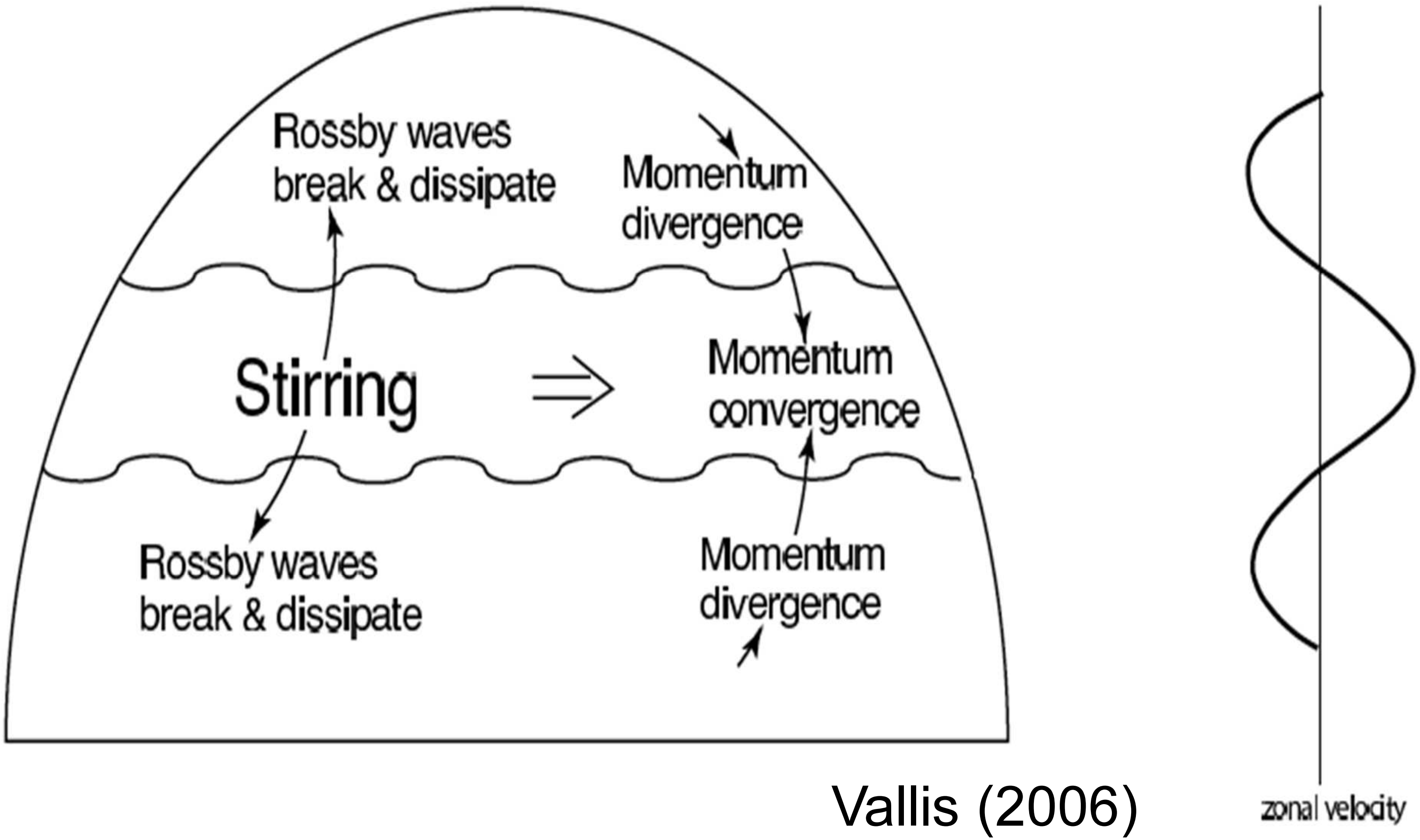
The subtropical synoptic-scale Rossby wave drag is understood to arise from the nonlinear breaking of growing baroclinic waves

Simmons & Hoskins (1978 JAS)

Edmon, Hoskins & McIntyre (1980 JAS)

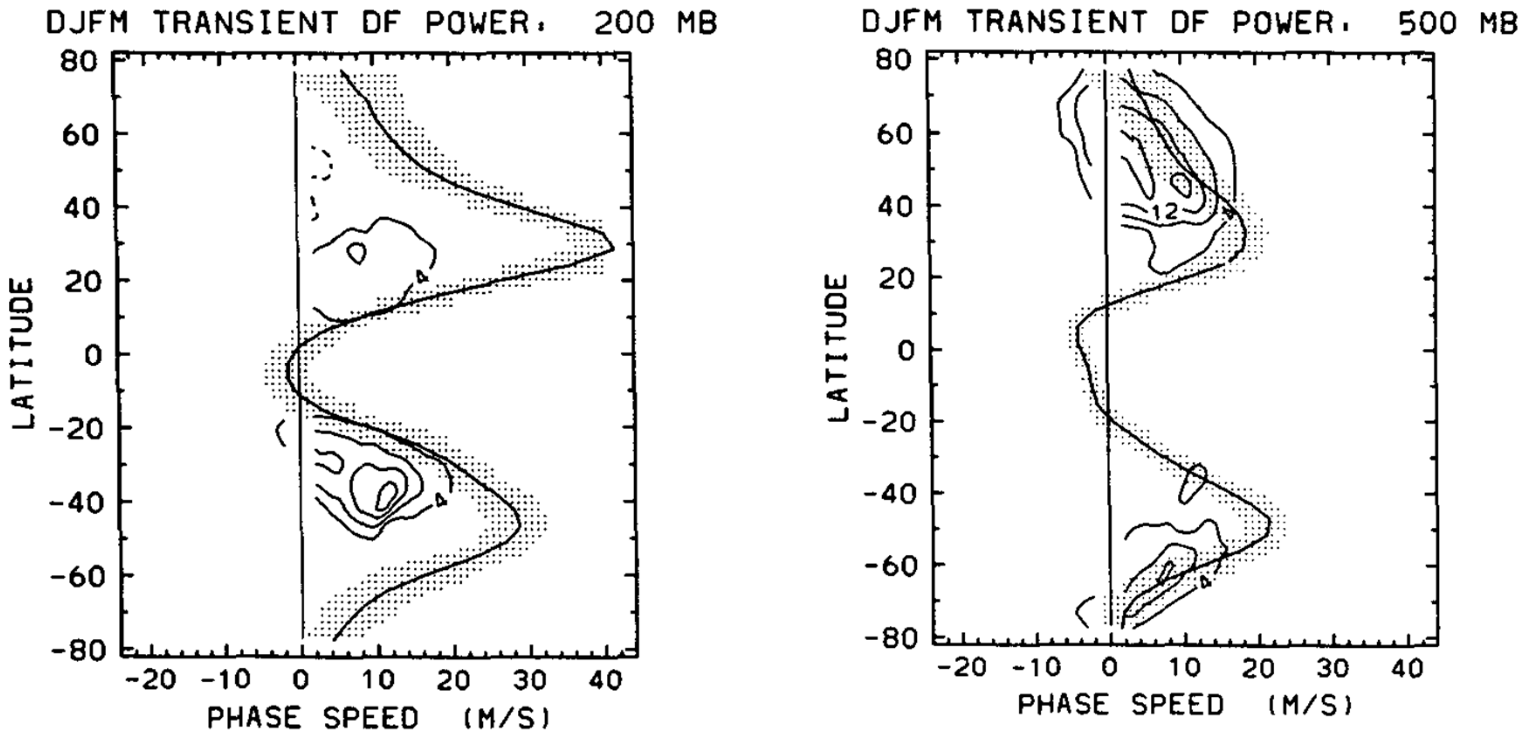
Thorncroft, Hoskins & McIntyre (1993 QJRMS)

- The breaking of synoptic-scale Rossby waves on the flank of the jet is a fundamental phenomenon, which is responsible for the maintenance of eddy-driven jets



Vallis (2006)

- Just as with stationary planetary waves, the breaking of synoptic-scale waves occurs in nonlinear critical layers
  – The subtropical critical layer in the upper troposphere, and the midlatitude critical layer in the middle troposphere
  – Here for northern winter; northern summer is similar



Randel & Held (1991 JAS)

- Don’t you see zonal wave 5-6 ‘cat’s eyes’ here at 21 km in the NH?

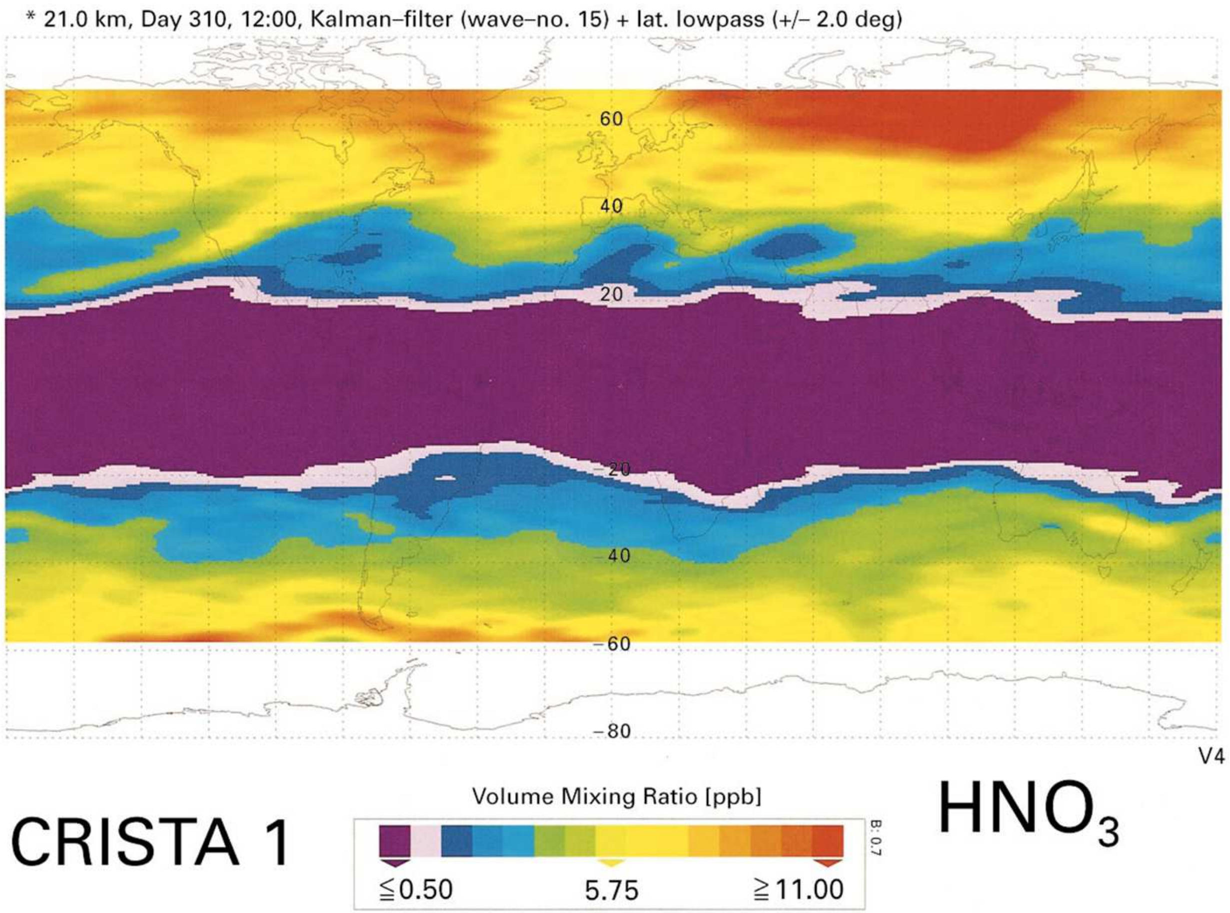


Figure courtesy of Dirk Offermann, University of Wuppertal

Shepherd (2000 JASTP)

Summary

- Rossby waves propagate from the troposphere into the stratosphere and provide a negative torque where they dissipate (‘Eliassen-Palm flux convergence’)
  - The waves generally dissipate by breaking *sideways* in nonlinear critical layers
- Negative torques drive poleward flow: the origin of the ‘Brewer-Dobson circulation’ important for chemical species
- Planetary waves propagate deep into the stratosphere during the winter season, and drive polar downwelling
- Synoptic-scale waves propagate into the subtropical lower stratosphere year-round, and drive a shallow branch of the BDC
  - The tropical upwelling undergoes year-to-year variations

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