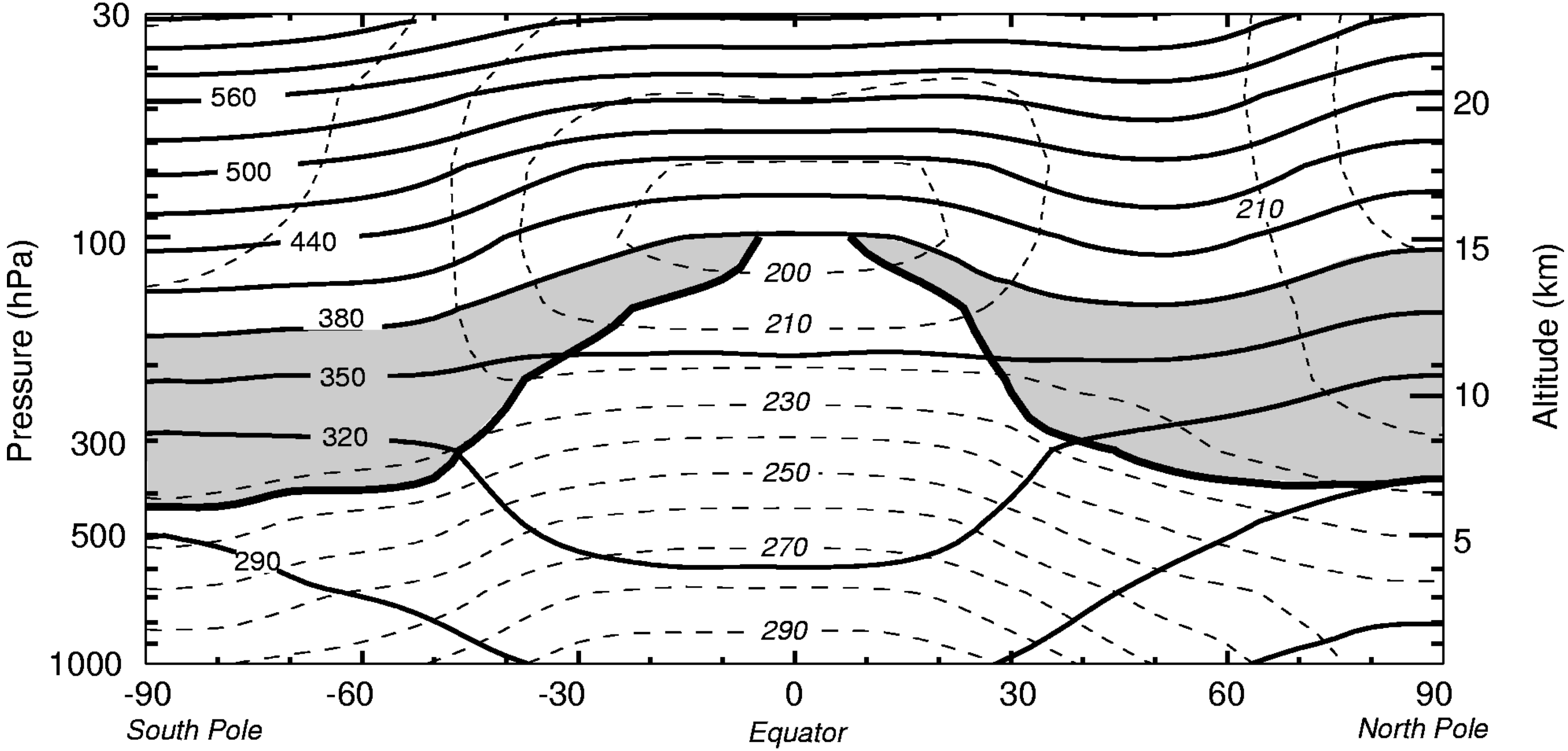
Long-memory processes in the stratosphere

Ted Shepherd

Dept of Physics, Univ of Toronto

- Basic aspects of stratospheric variability
- Polar vortex variability
- Tropical variability
- Tropical-polar interactions

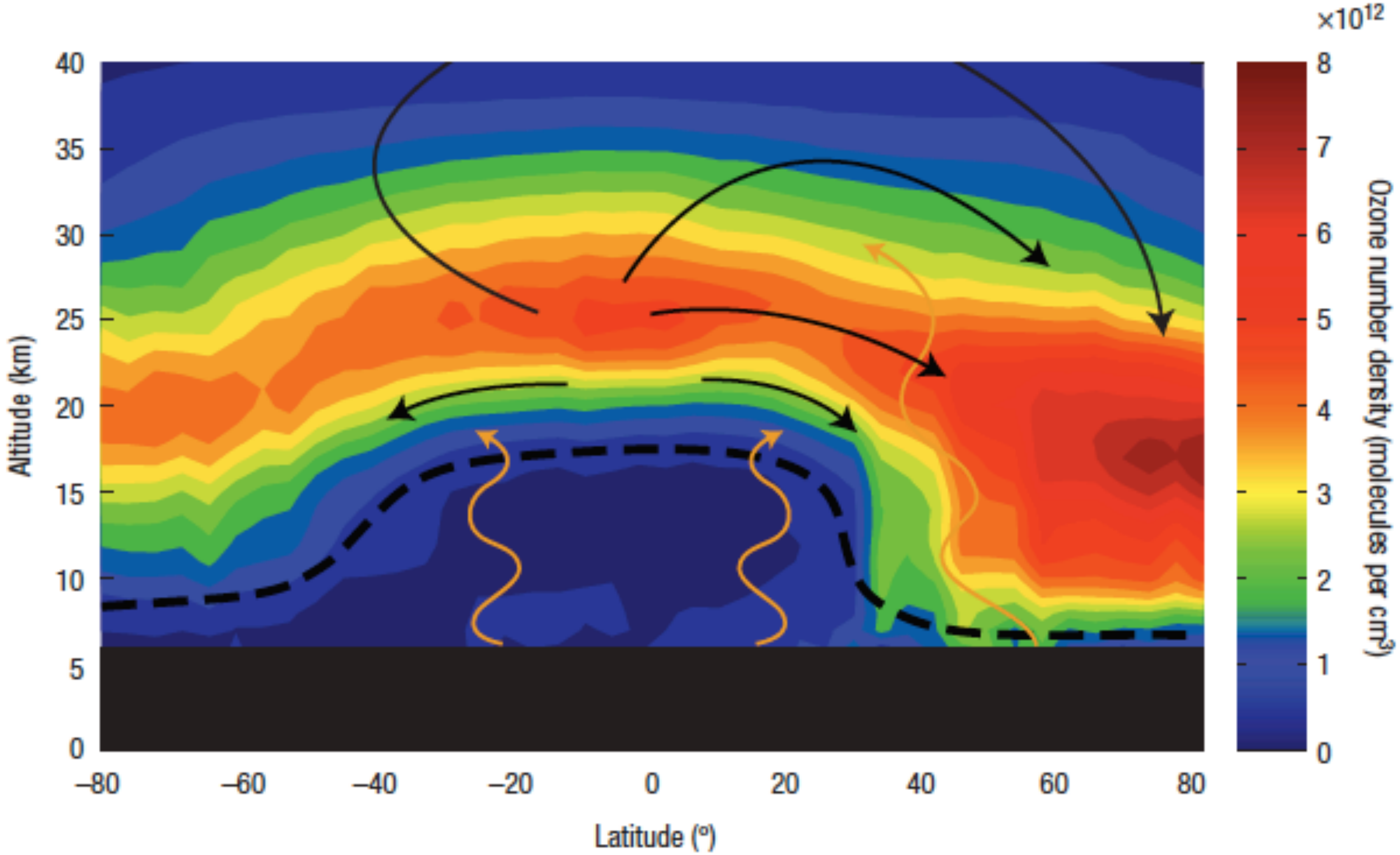
- The stratosphere is, for the most part, dynamically stable
  - Its variability comes from the troposphere
  - It acts as an upper boundary condition for waves propagating upward from the troposphere



Holton et al. (1995 Rev Geophys)

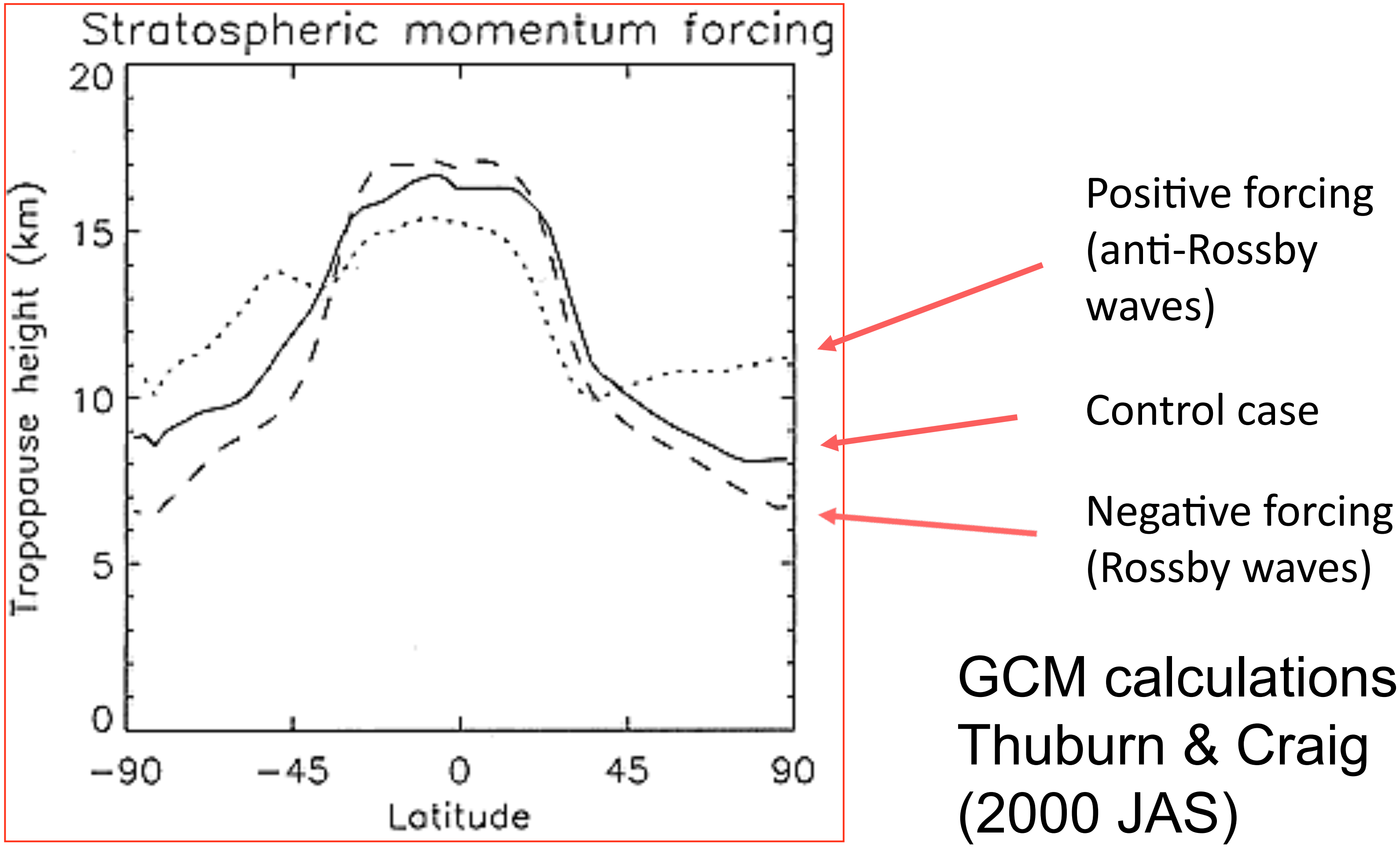
- The momentum transferred by these upward propagating waves drives the meridional (Brewer-Dobson) circulation
  – Shapes the ozone distribution in the lower stratosphere, providing a radiative memory

March 2004 ozone from OSIRIS



Shaw & Shepherd (2008 Nature Geosci)

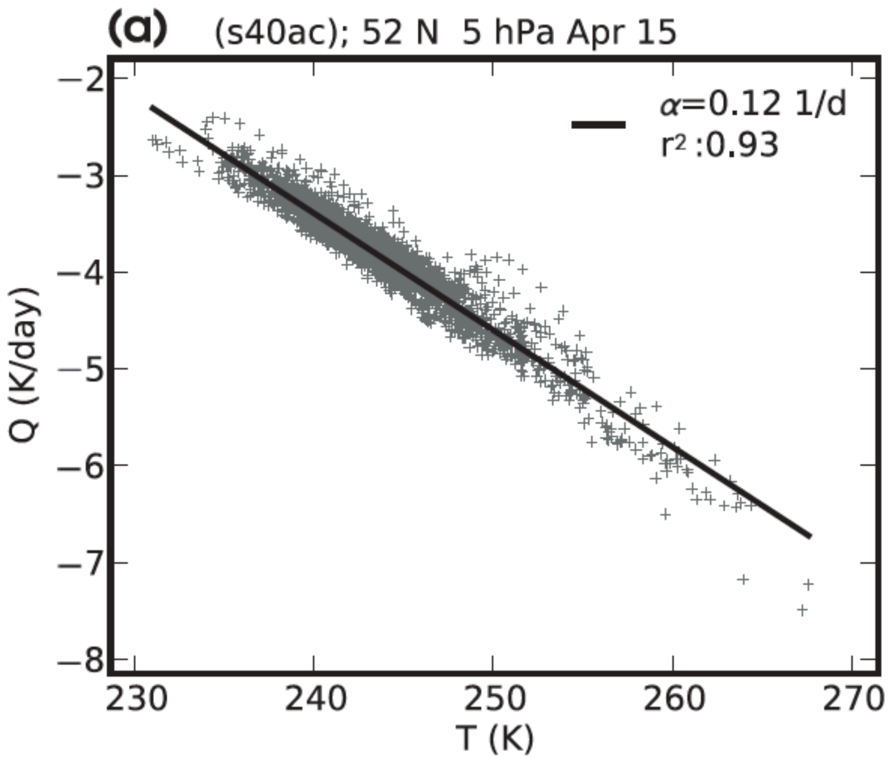
- The Brewer-Dobson circulation raises and cools the tropical tropopause, and lowers and warms the extratropical tropopause, also affecting the upper boundary condition of the troposphere

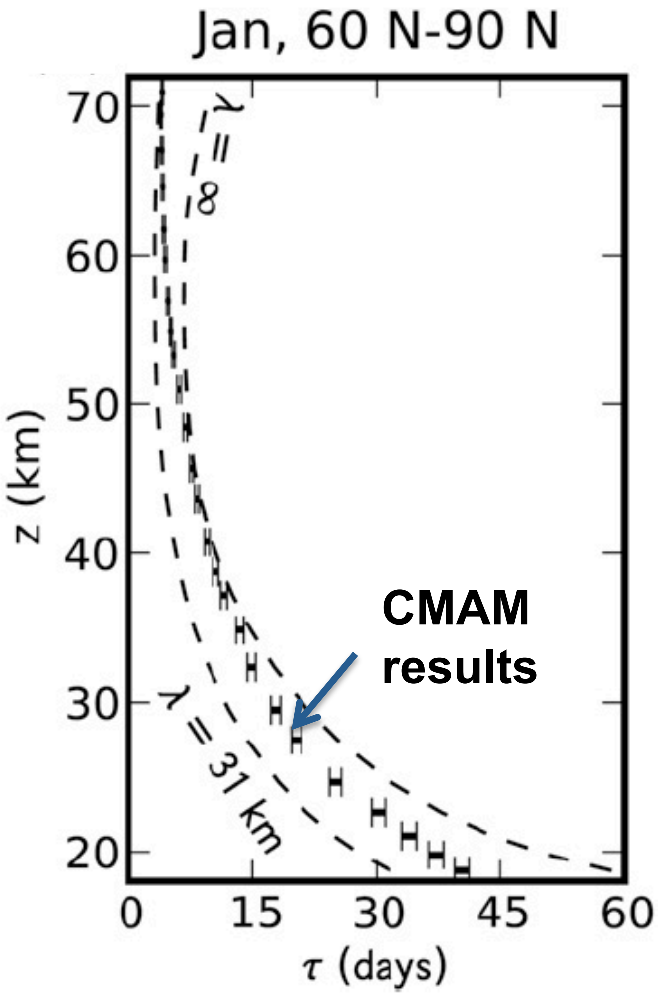


GCM calculations by Thuburn & Craig (2000 JAS)

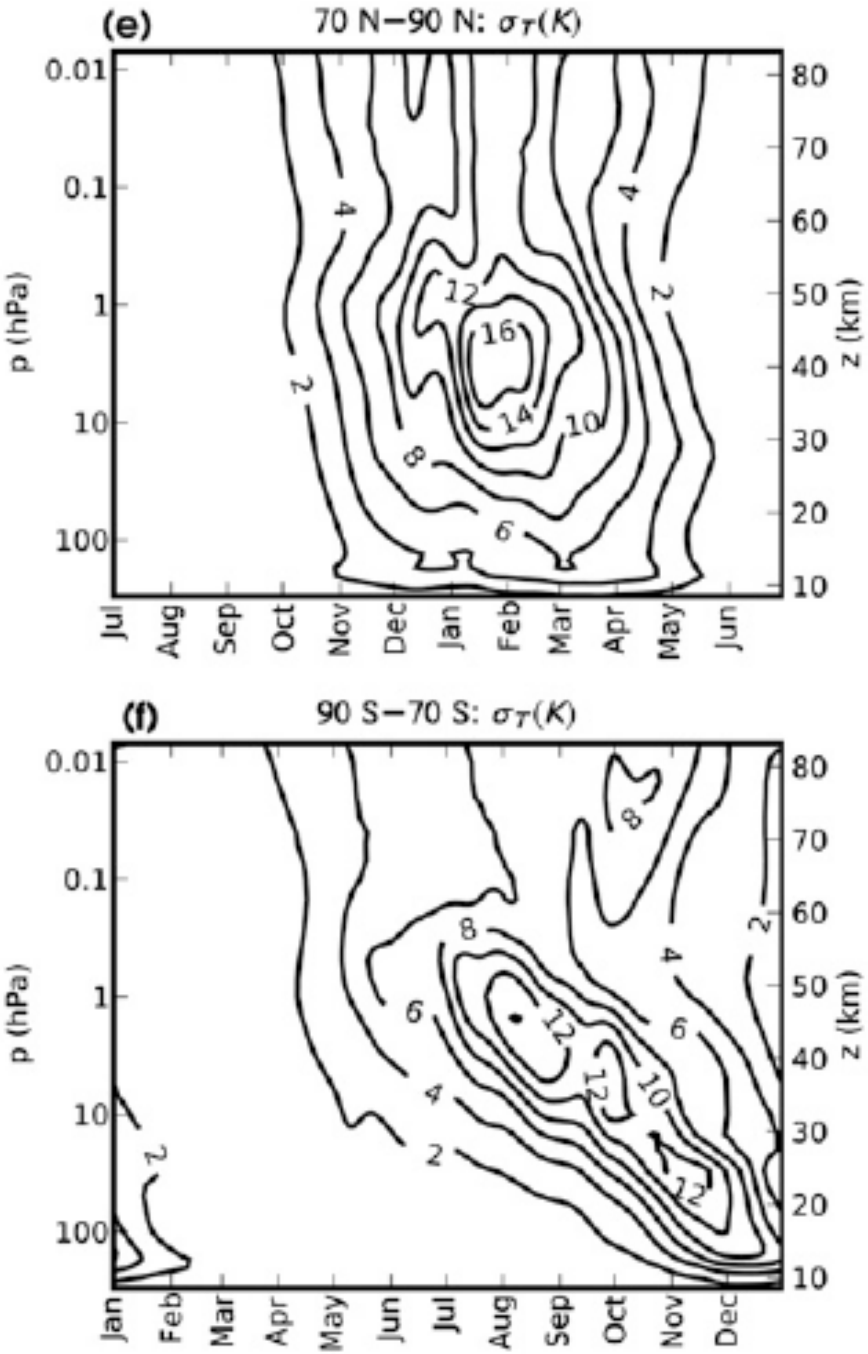
- The radiative damping timescale ranges from a few days in the upper stratosphere to a month or more in the lower stratosphere

Estimated from variability in radiative cooling rates in a comprehensive chemistry-climate model (CMAM)





Hitchcock, Shepherd & Yoden (2010 JAS)



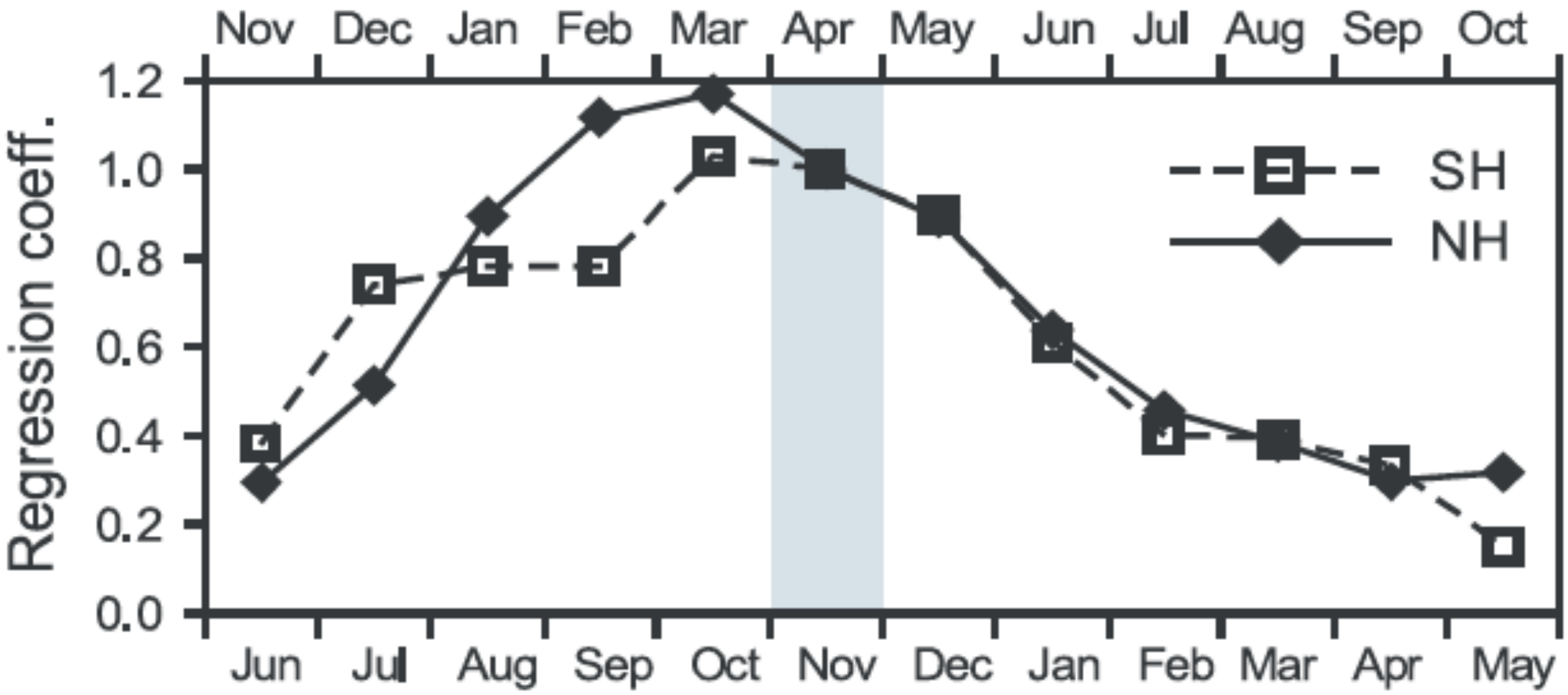
Extratropical stratospheric variability has a strong seasonal cycle, as the stratosphere is largely undisturbed during the summer when zonal winds are easterly

The SH is more complex…

Figure shows polar temperature RMS variances (in K) from the CMAM

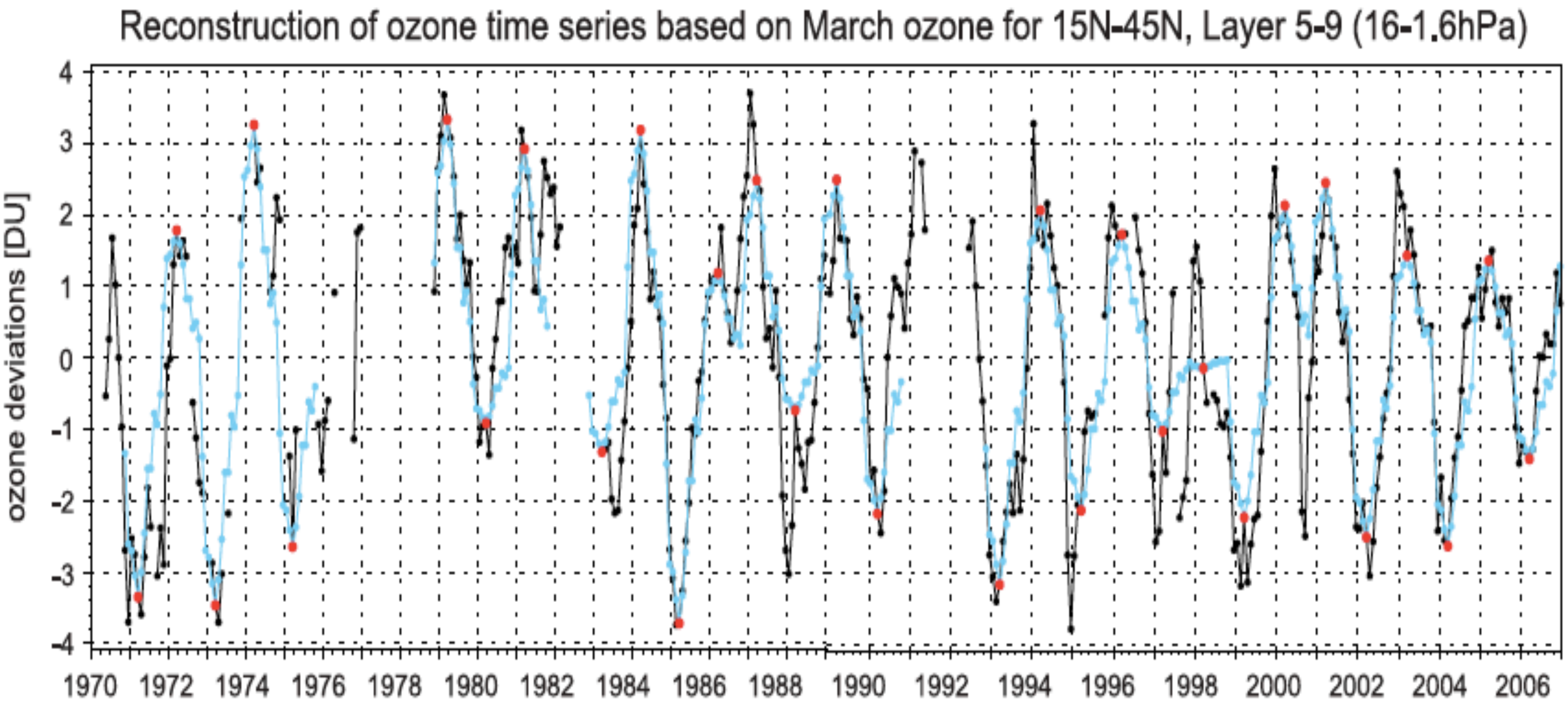
Hitchcock, Shepherd & Yoden (2010 JAS)

- 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)



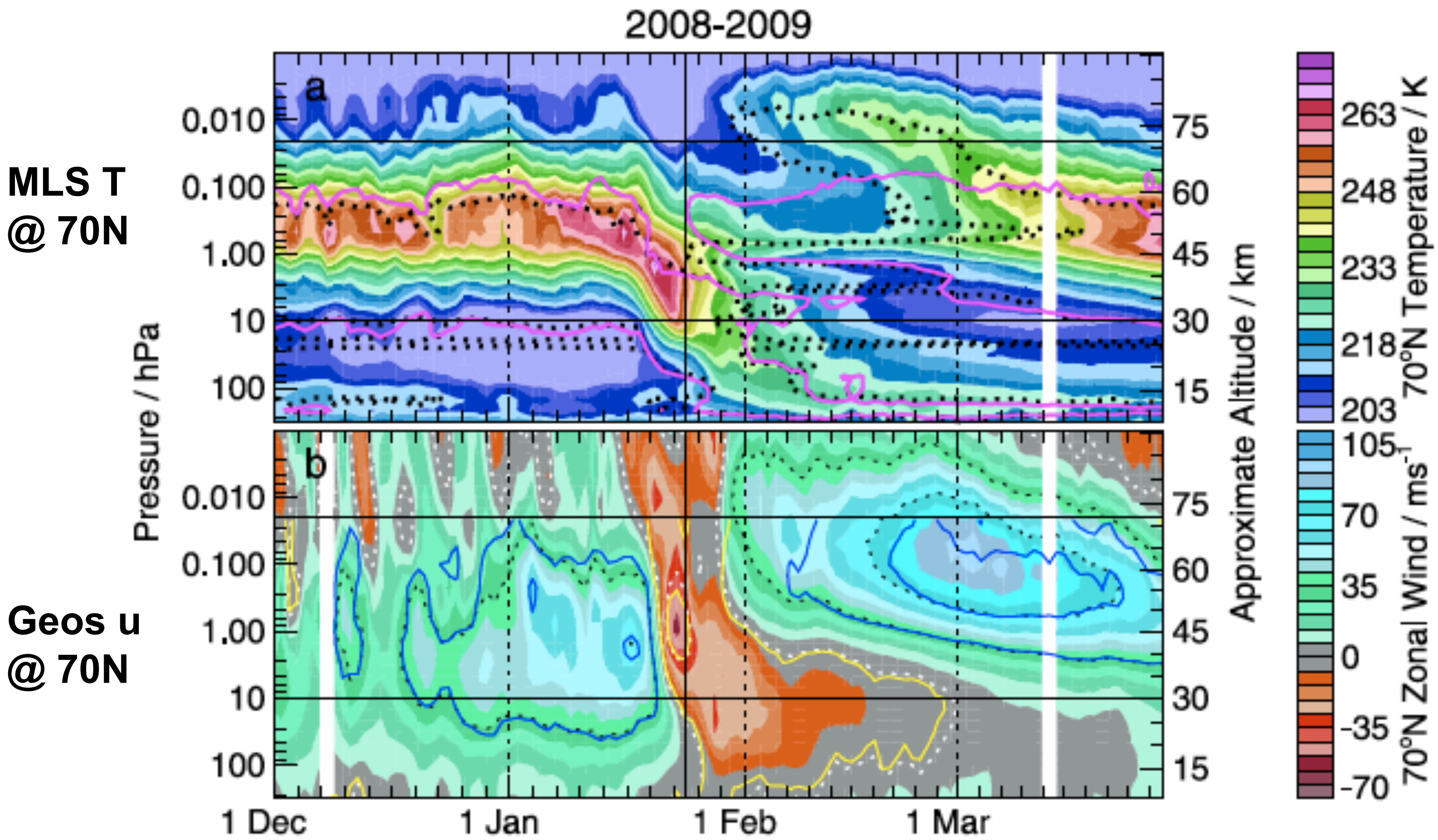
TOMS total ozone, from Fioletov & Shepherd (2003 GRL)

- This ozone "memory" is so strong that one can reconstruct (blue) the subtropical upper stratospheric SBUV(/2) ozone anomaly time series (black) from March measurements alone (red)



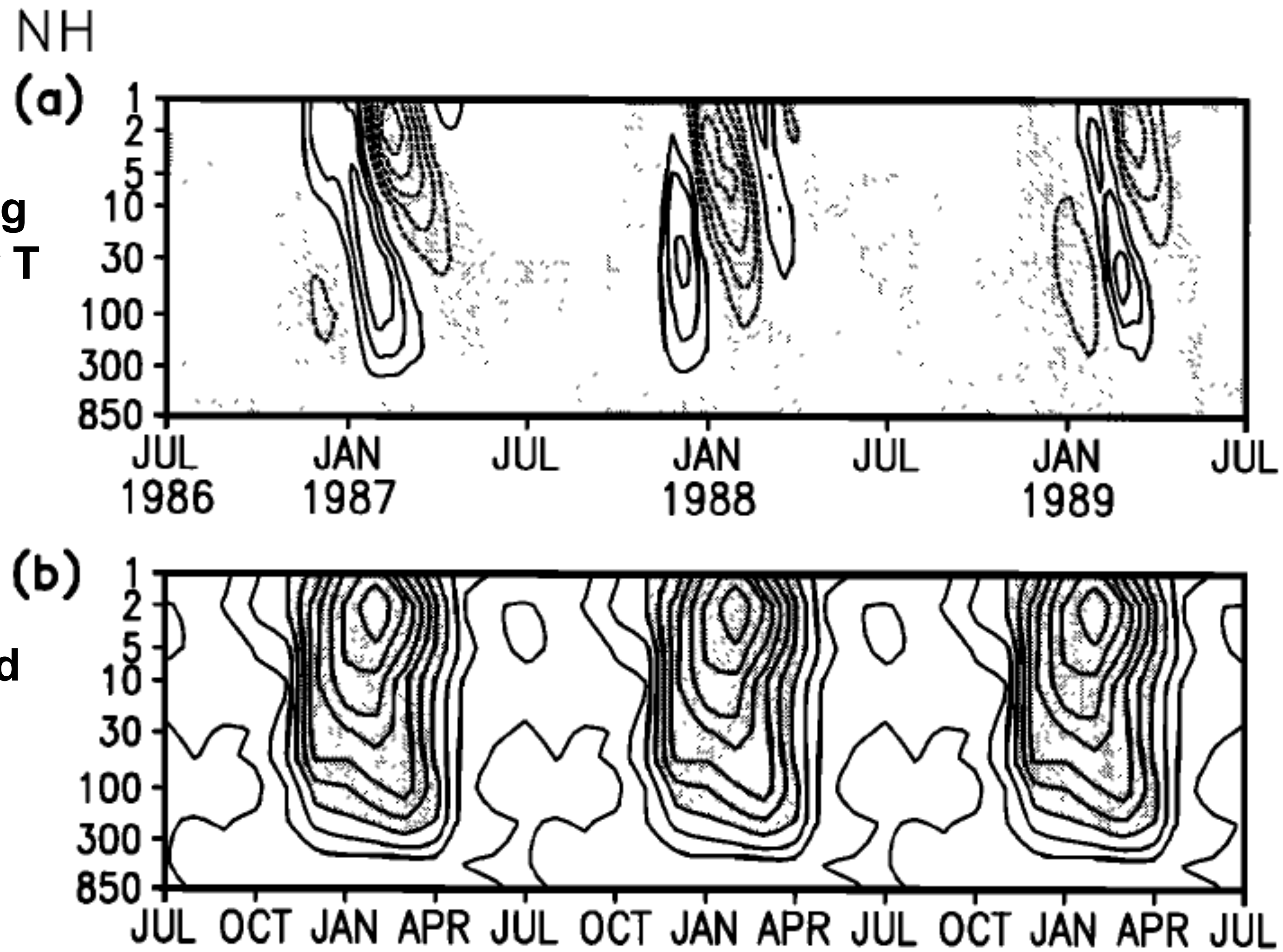
Tegtmeier, Fioletov & Shepherd (2008 JGR)

- The most dramatic polar disturbances are Stratospheric Sudden Warmings (SSWs); because the winds become easterly, it can take the rest of the winter to recover



Manney et al. (2009 GRL)

- More generally, NH polar vortex disturbances propagate downwards, but there is only time for one oscillation in a winter



30 day running average polar T anomaly

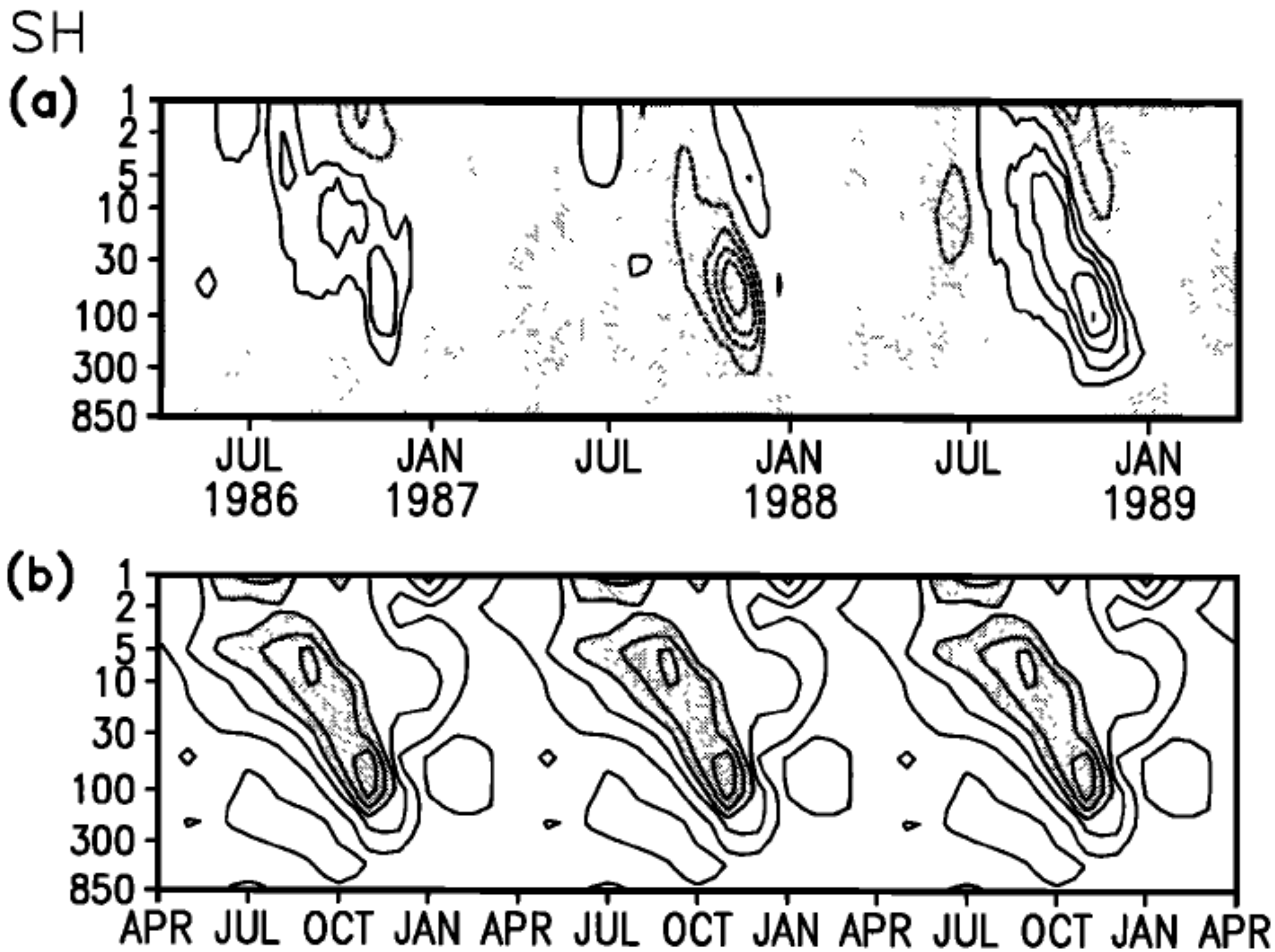
Interannual std of monthly mean polar T

Kuroda & Kodera (2001 JGR)

- In the SH, the variability is confined to springtime and represents variability in the annual breakdown of the vortex

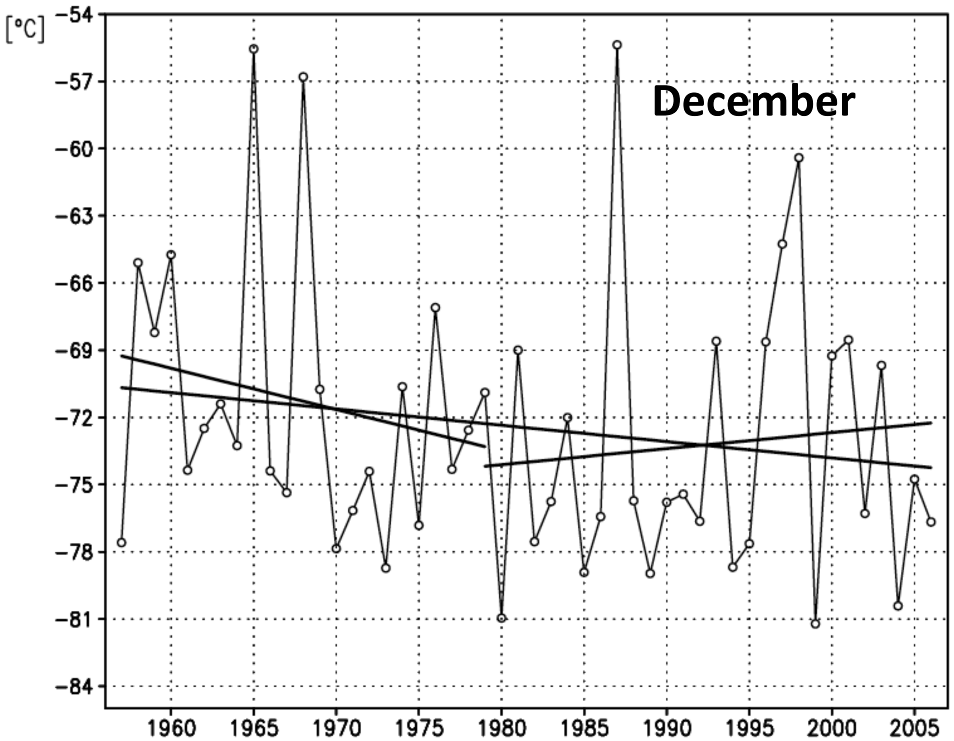
30 day running average polar T anomaly

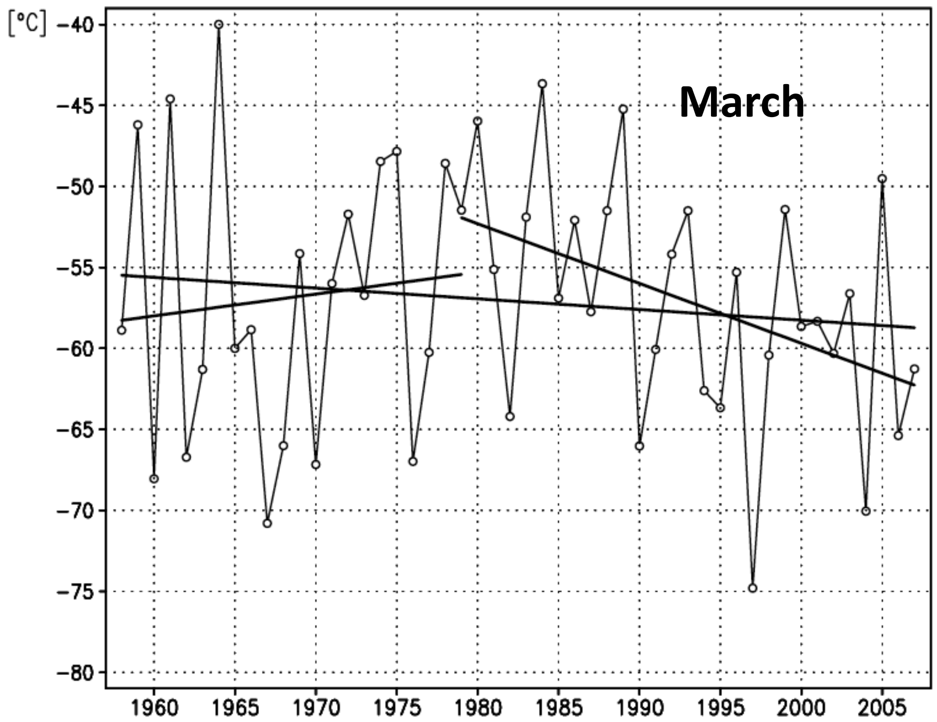
Interannual std of monthly mean polar T



Kuroda & Kodera (2001 JGR)

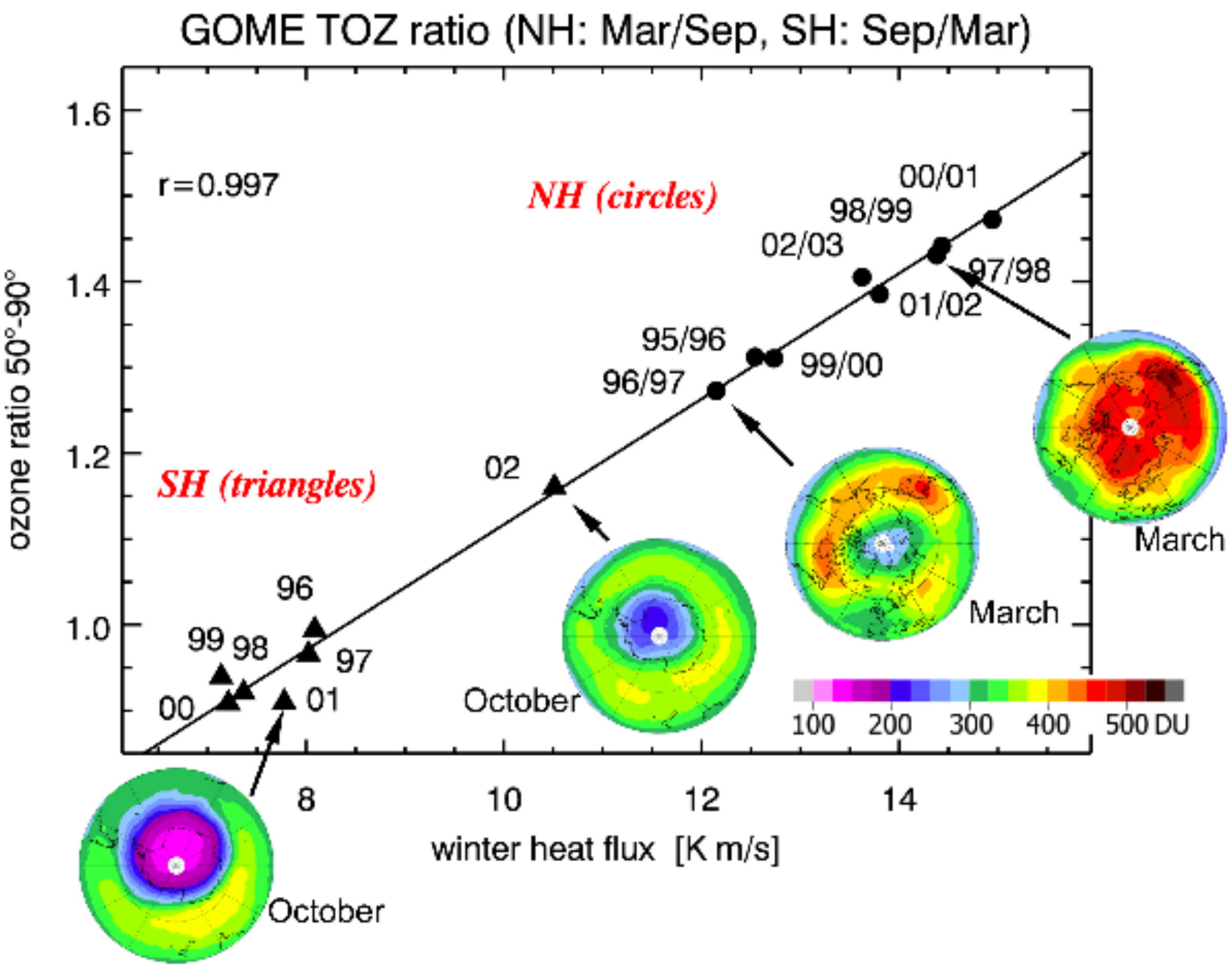
- The oscillatory nature of NH polar vortex variability leads to a see-saw relationship between early-winter and late-winter decadal variability (here in 30 hPa polar T)
  - There is a lot of power in the decadal variations, which have tended to be interpreted as trends





Updated from Labitzke & Kunze (2005 Meteor. Z.)

- 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

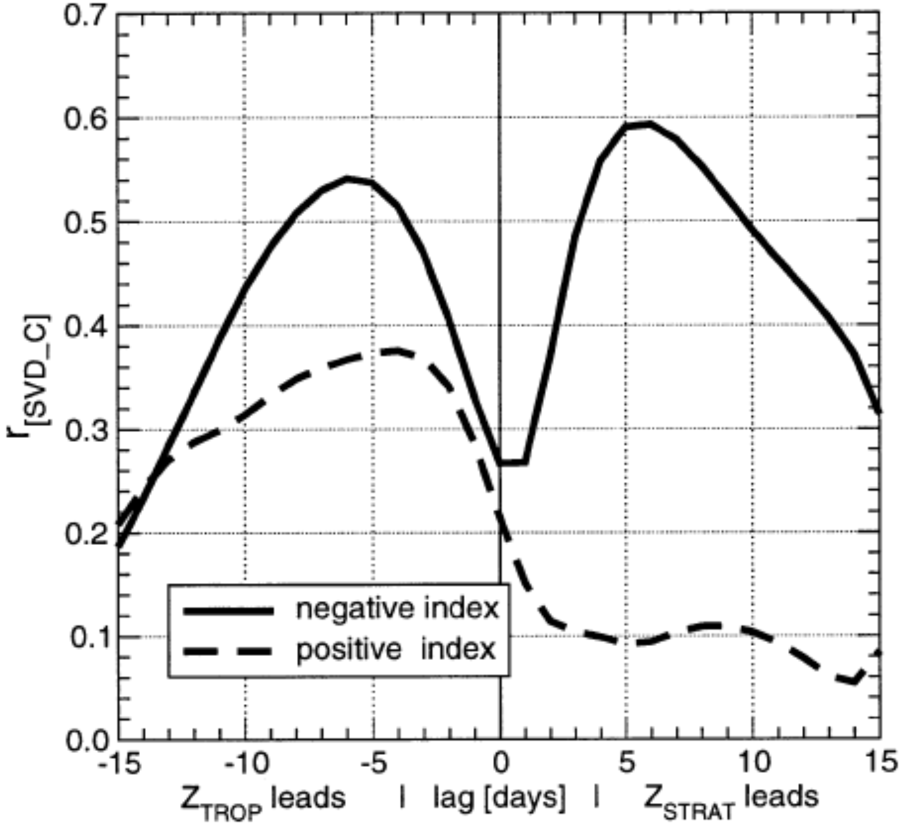


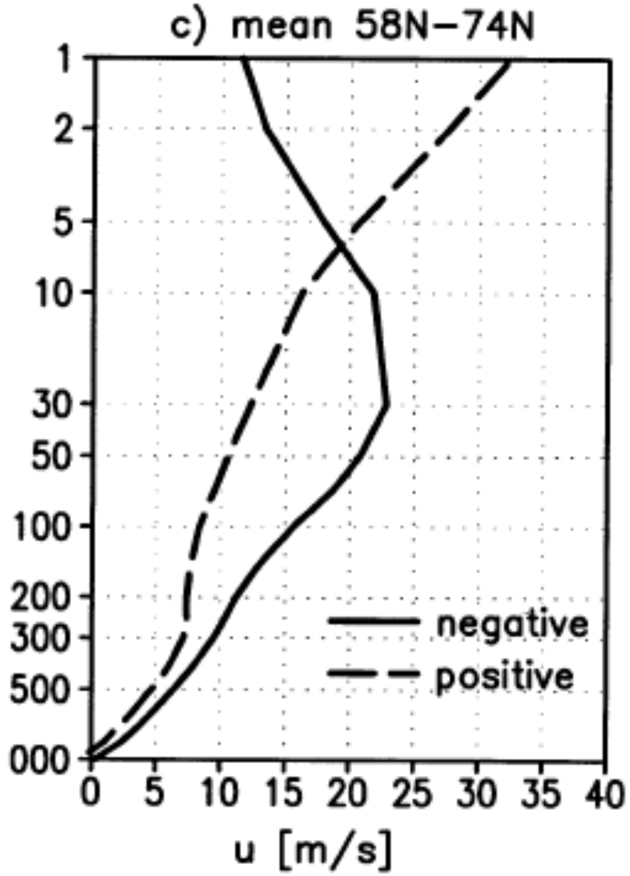
There is a continuous transition between the two hemispheres

Adapted from Weber et al. (2003 GRL)

- However it seems likely that the upward EP flux depends in part on the state of the stratosphere
  - This challenges the accepted paradigm

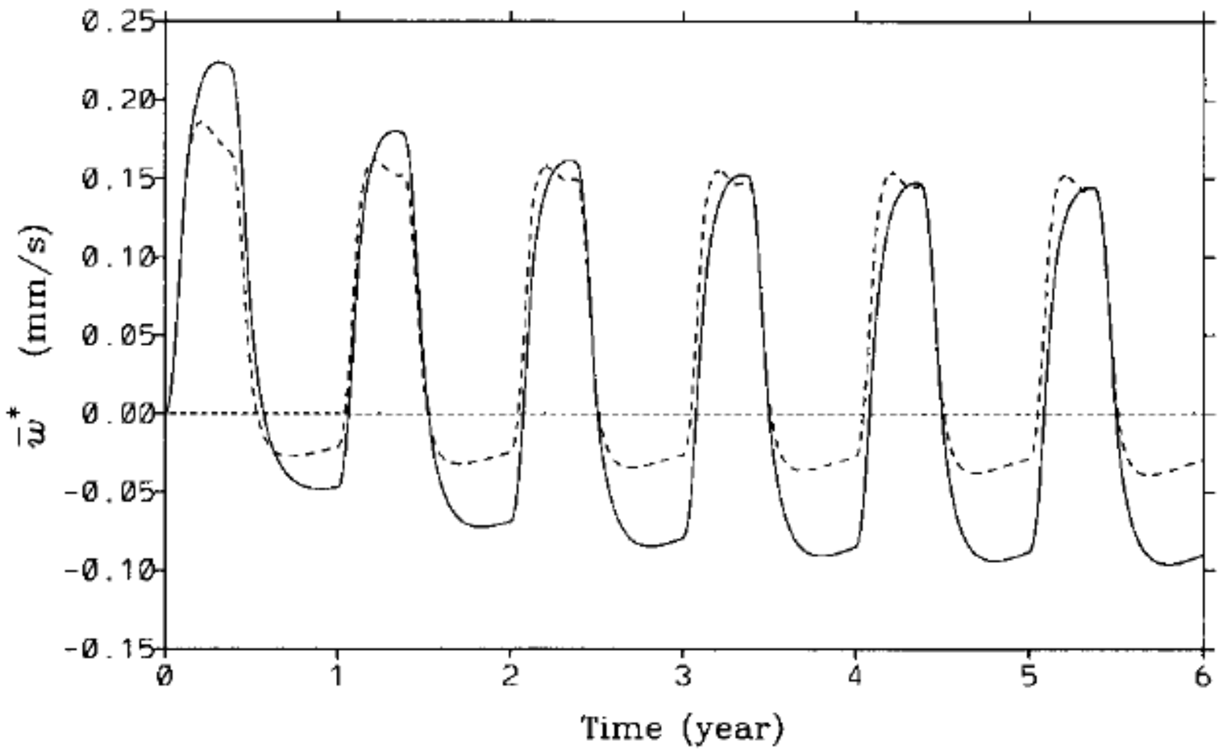
Correlation between k=1 variability in troposphere and stratosphere





Perlwitz & Harnik (2003 J Clim)

- In the tropics, zonal wind anomalies have tremendous inertia because radiative cooling damps them only weakly: the “tropical flywheel” (Scott & Haynes 1998 QJRMS)
  - It takes several years for the response to a switch-on oscillatory subtropical wave forcing to equilibrate

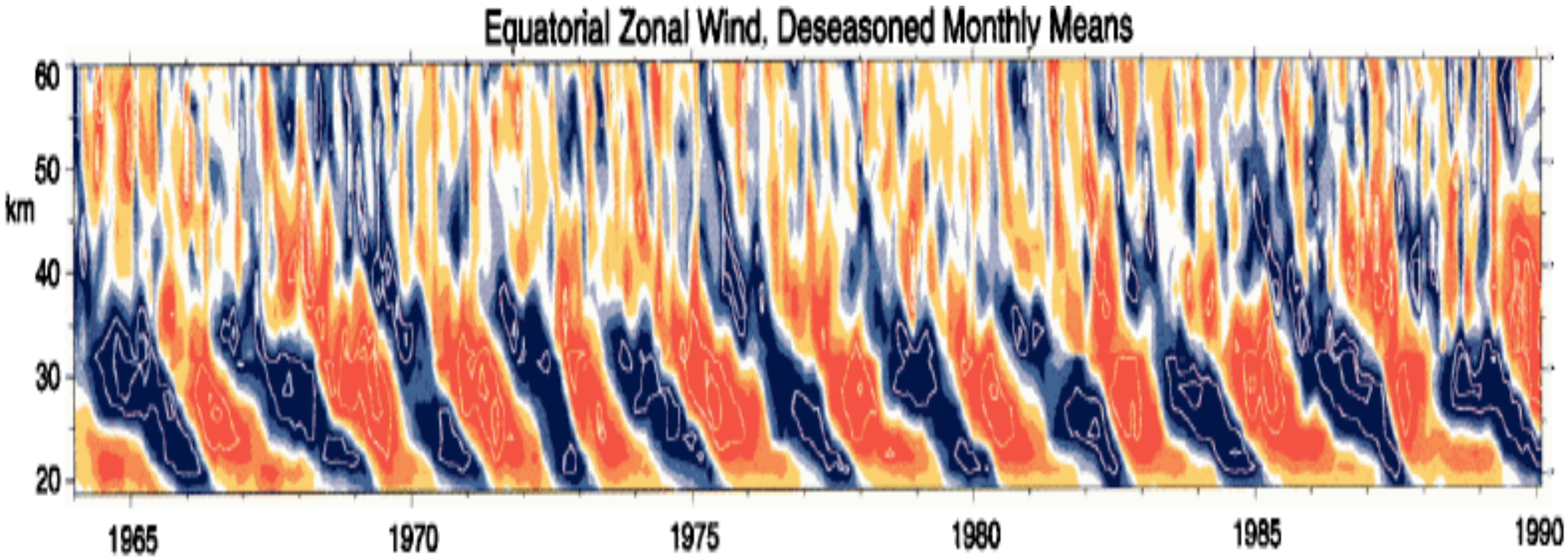


Equatorial upwelling in linear (solid) and nonlinear (dashed) zonally symmetric model

Linear model equilibrates to zero annual mean

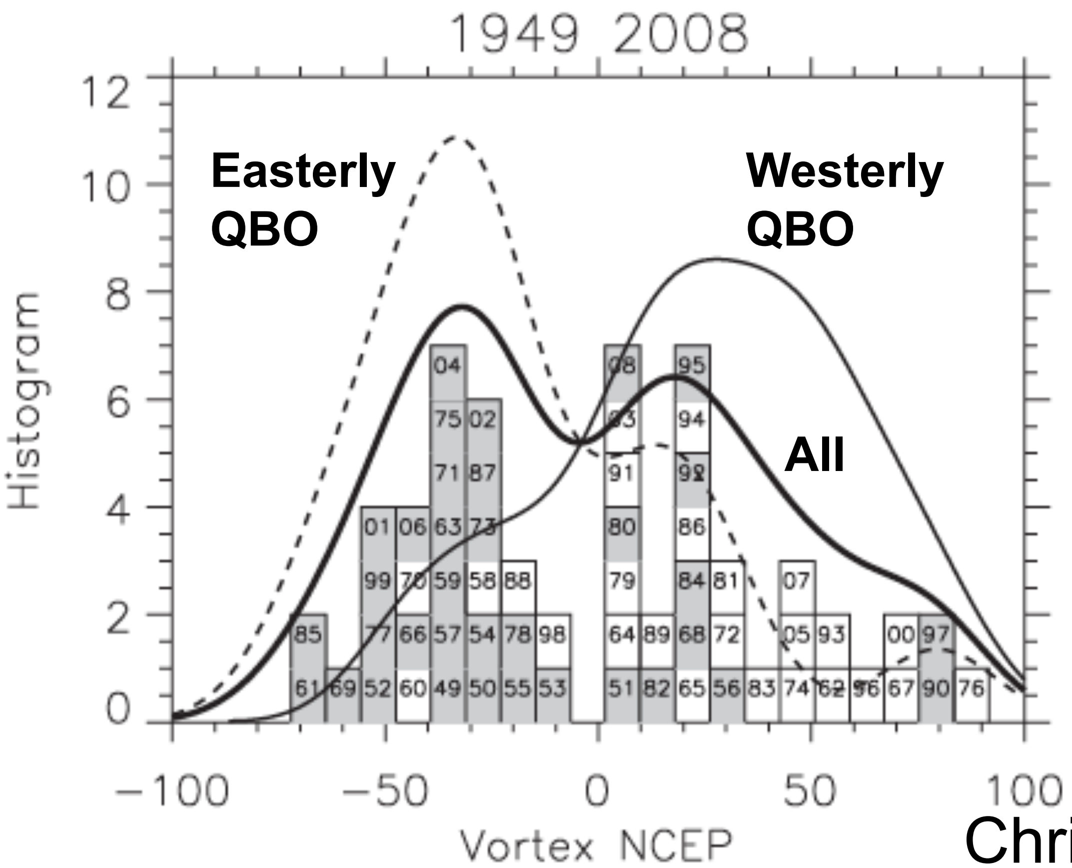
Semeniuk & Shepherd (2001 JAS)

- At the equator, a spectrum of wave forcing generically leads to oscillating zonal winds: the stratospheric QBO
  - Period from 22 to 34 months, average around 28
- Information mainly propagates upward, though there is some evidence for role of the upper stratosphere
  - Also modulated by the Brewer-Dobson circulation



Baldwin et al. (2001 Rev Geophys)

- The QBO affects polar vortex variability through the Holton-Tan effect (1981 JAS)
  - Qualitatively, results from meridional displacement in region of planetary wave breaking (stratospheric 'surf zone') in response to shifted subtropical critical layers

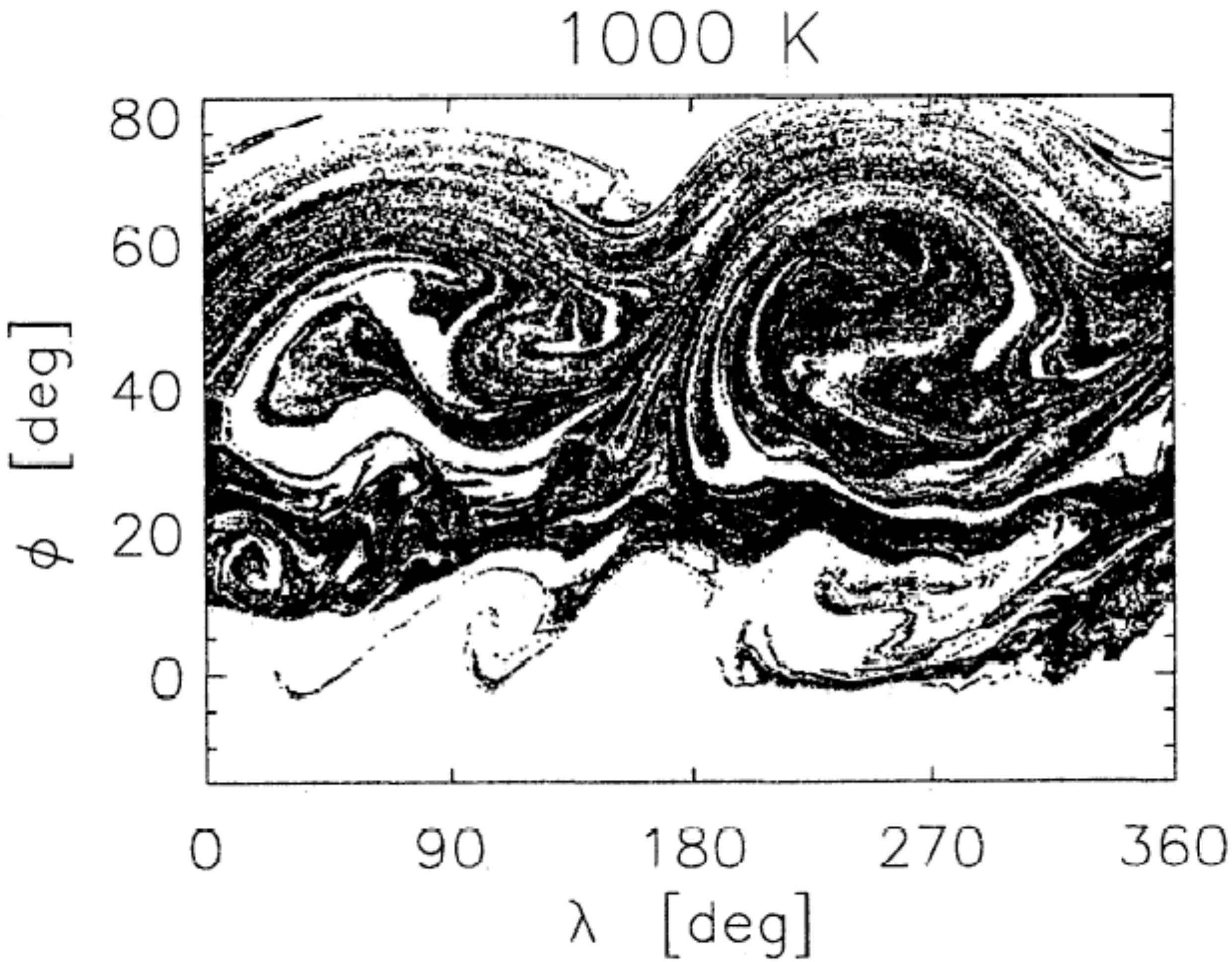


Is the origin of the observed bimodality in NH variability (here based on NAM index at 20 hPa)

Years segregated by FUB QBO index (shaded is easterly)

Christiansen (2010 J Clim)

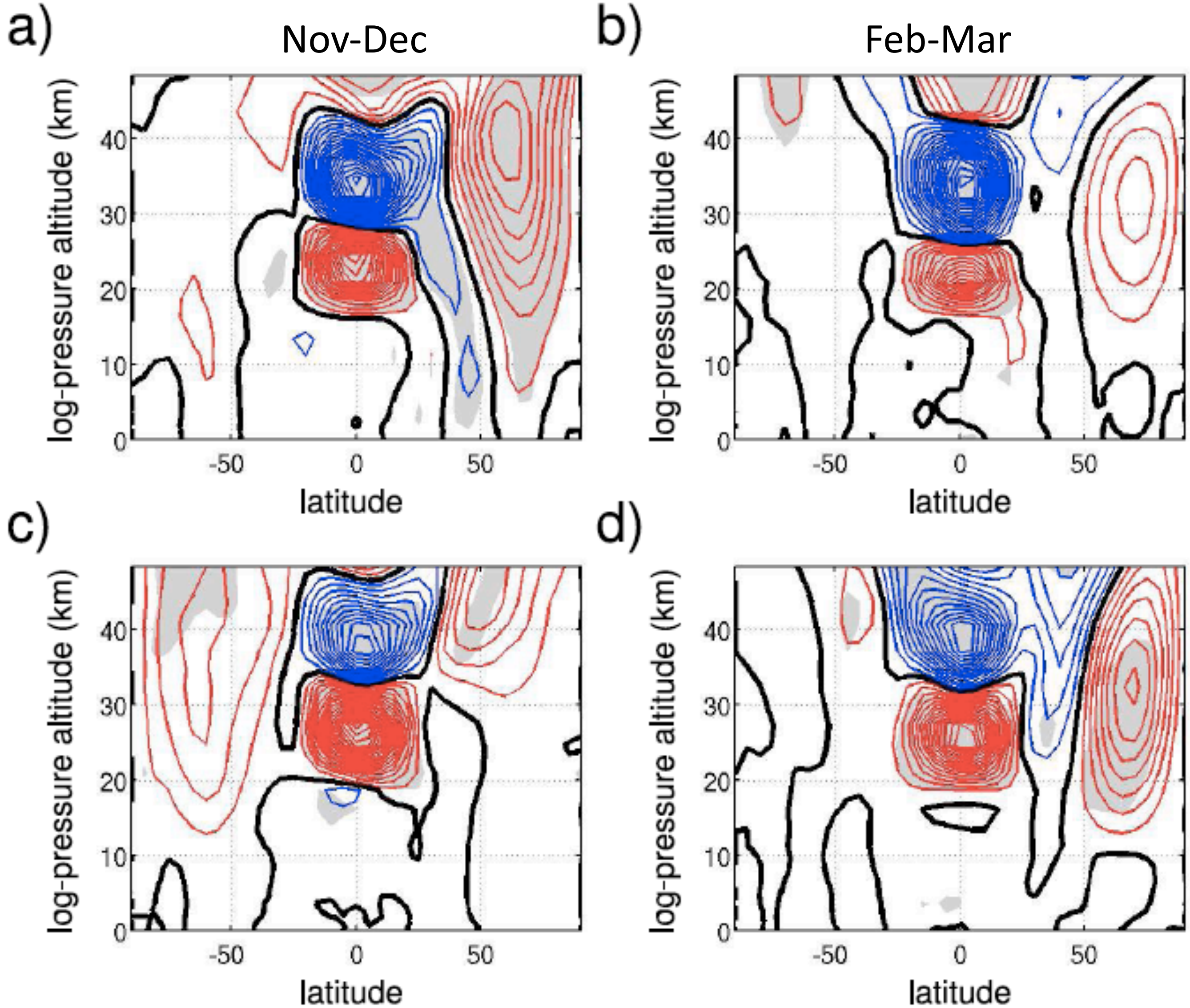
- Tropical-polar coupling is possible because planetary-wave drag occurs in a hemispheric-wide ‘surf zone’ (McIntyre & Palmer 1983 Nature)



Off-line isentropic particle advection at approx. 35 km altitude driven by winds from the CMAM

Shepherd, Koshyk & Ngan (2000 JGR)

- The Holton-Tan effect has a sensitive seasonal dependence (seen here in ERA-40 W-E zonal wind differences)

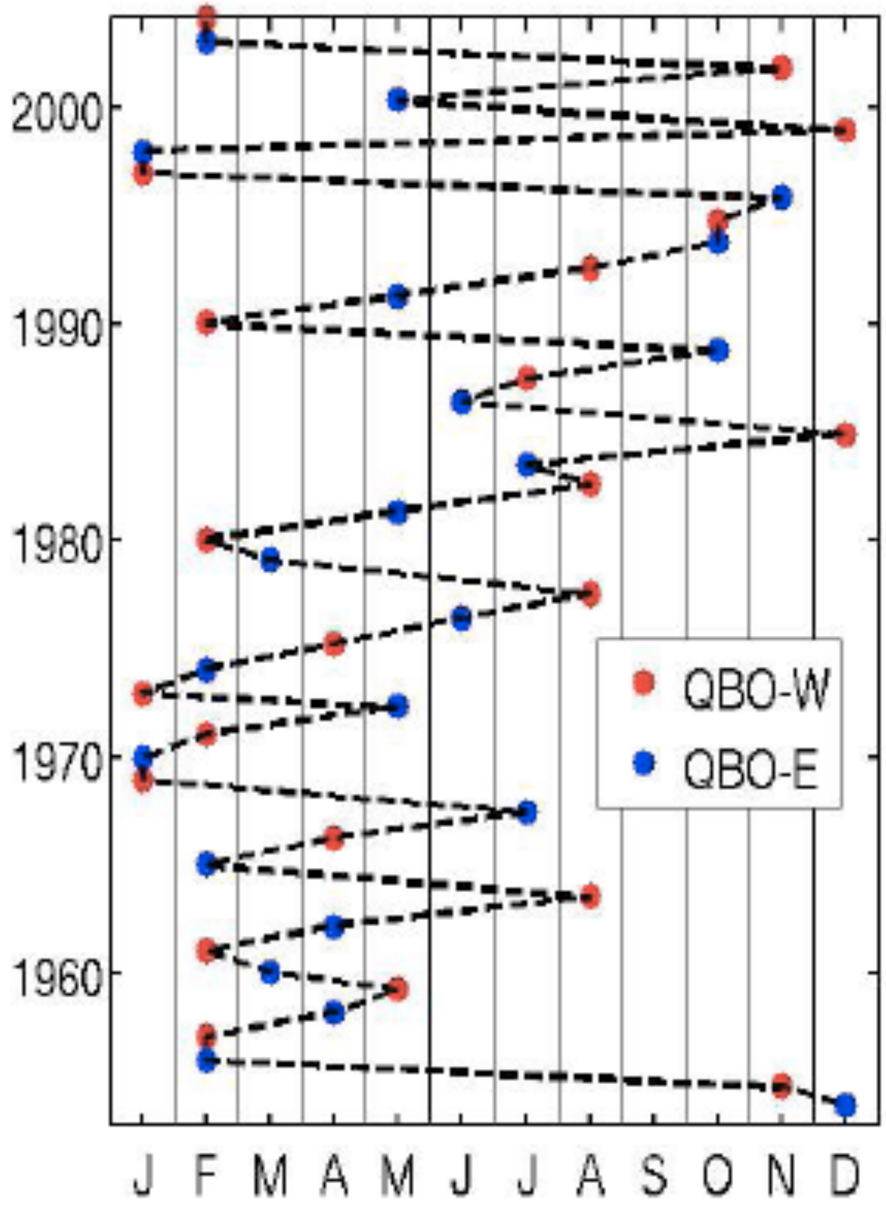


C.I. = 2 m/s

30 hPa phase transitions between November and April in the previous year

Between April and September in the previous year

Anstey & Shepherd (2008 GRL)



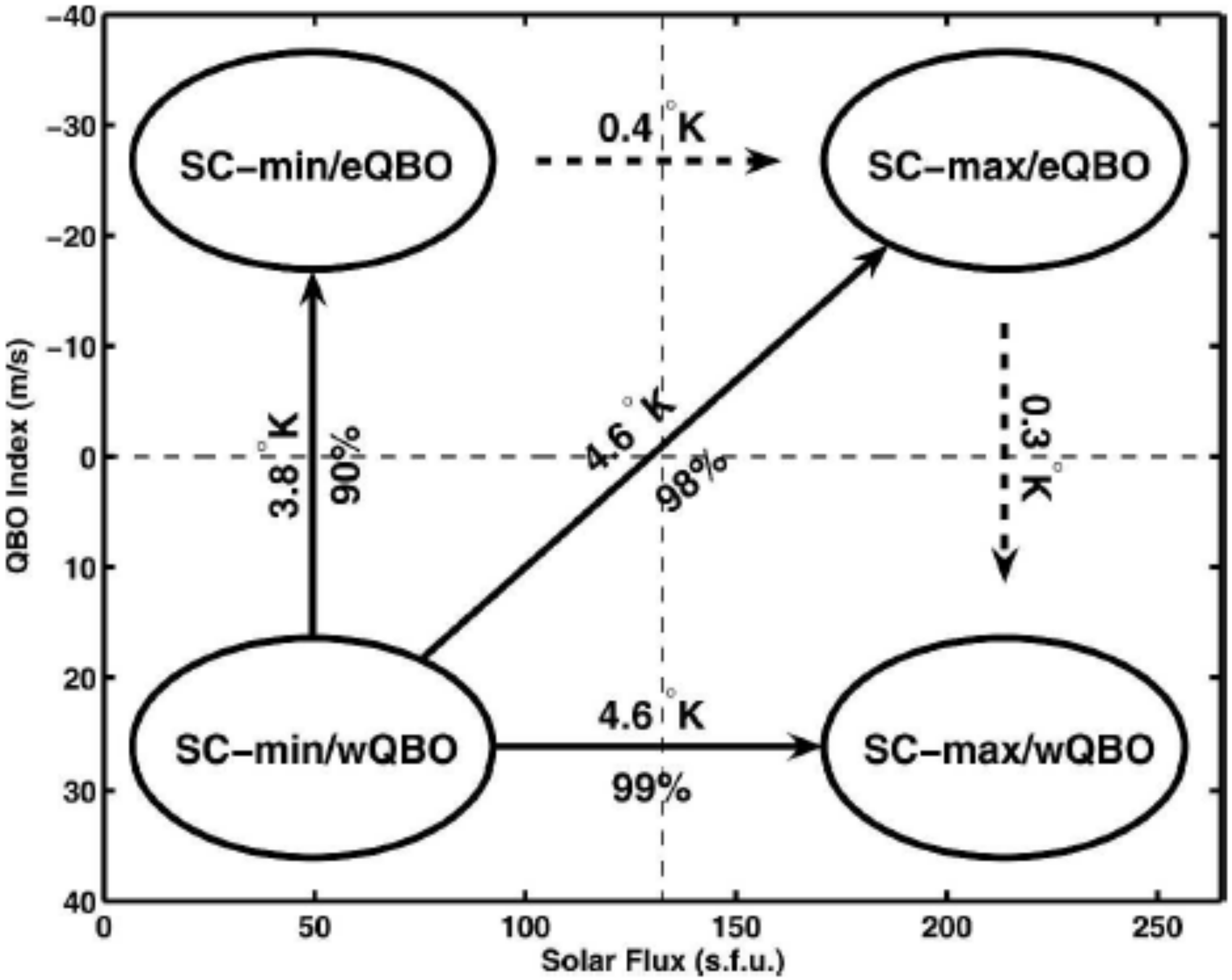
Anstey & Shepherd (2008 GRL)

Seasonality of observed QBO phase transitions exhibits an interesting decadal variability

May explain why QBO-vortex coupling seems non-robust (Lu et al. 2008 JGR)

Non-robustness of QBO-vortex coupling has been attributed to solar variability, but CMAM shows the same behaviour with no external variability (Anstey, Shepherd & Scinocca 2010 JAS)

- Because SSWs disturb the NH vortex so strongly, perturbations do not add (a second “trigger” is redundant)

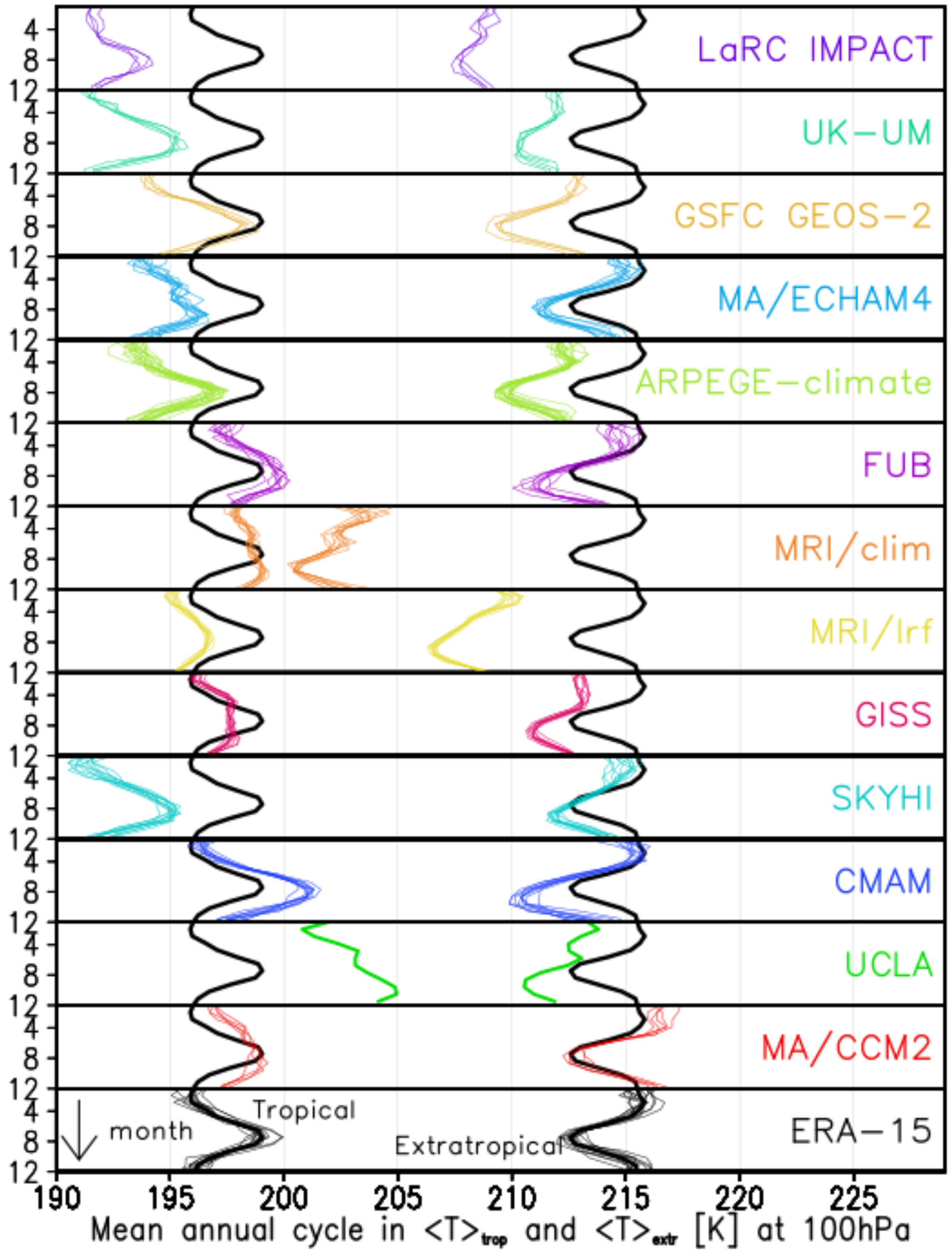


Mean warming of NH pole (Feb-Mar over 10-50 hPa) from different combinations of solar and QBO perturbations (based on NCEP/NCAR, 1954-2005)

Camp & Tung (2007 JAS)

Summary

- The stratosphere has several internal mechanisms for providing “memory” in polar regions
  - Long radiative timescale (several weeks in LS)
  - Seasonal memory of ozone anomalies
  - Intraseasonal coherence in polar vortex anomalies
  - Inertia of tropical winds (“tropical flywheel”)
  - Quasi-biennial oscillation
  - Coupling between annual cycle of extratropical dynamical forcing and QBO leads to decadal variability (though not simply “beats”)
- Stratospheric models (whether simple or complex) and observations both exhibit strong decadal timescale variability: but how predictable is it?

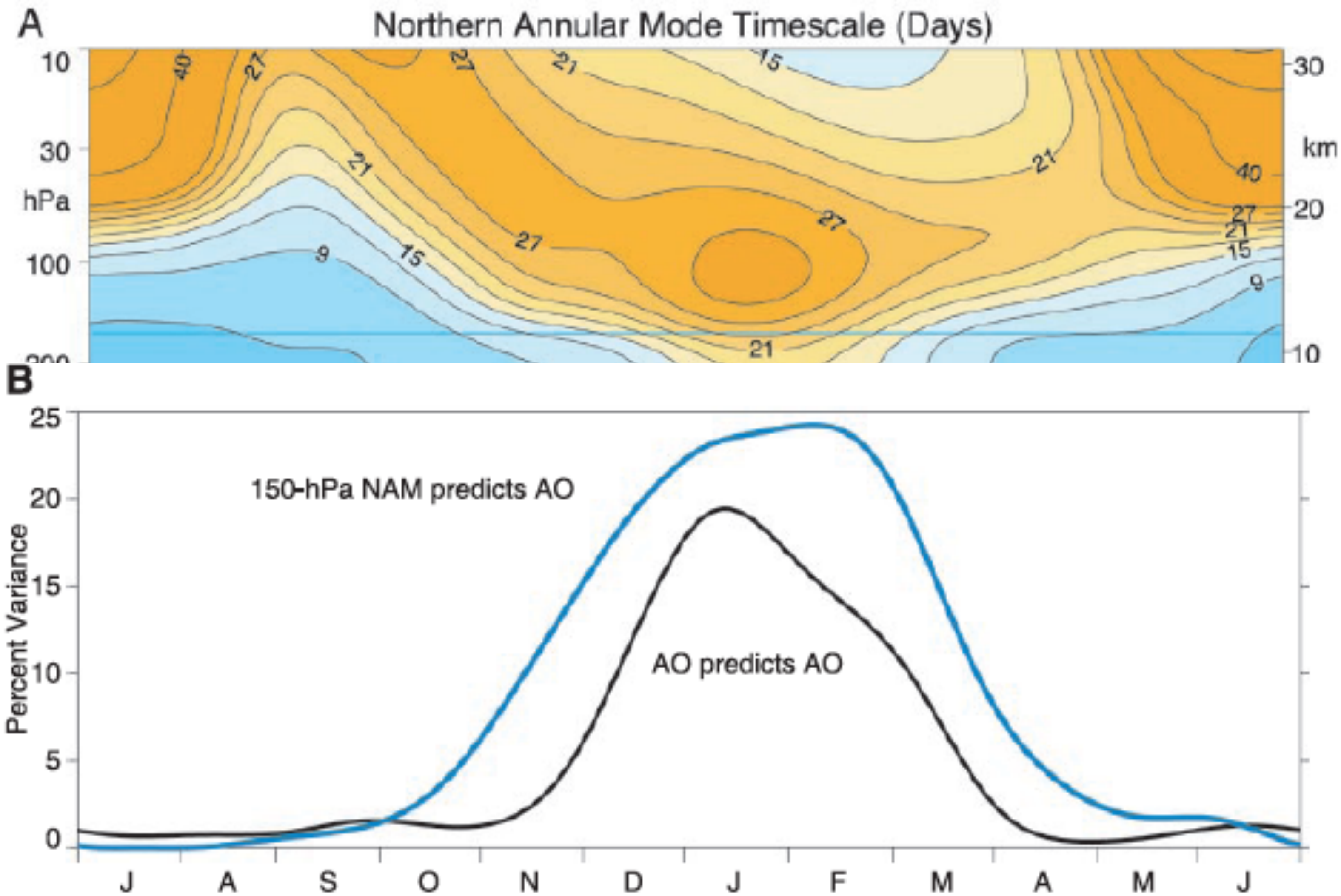


Seasonal cycle of 100 hPa temperature for various middle atmosphere climate models, from the SPARC GRIPS intercomparison, circa 10 years ago

Annual cycle should show an exact compensation between the tropics and extratropics (Yulaeva et al. 1994 JAS), as in ERA-15

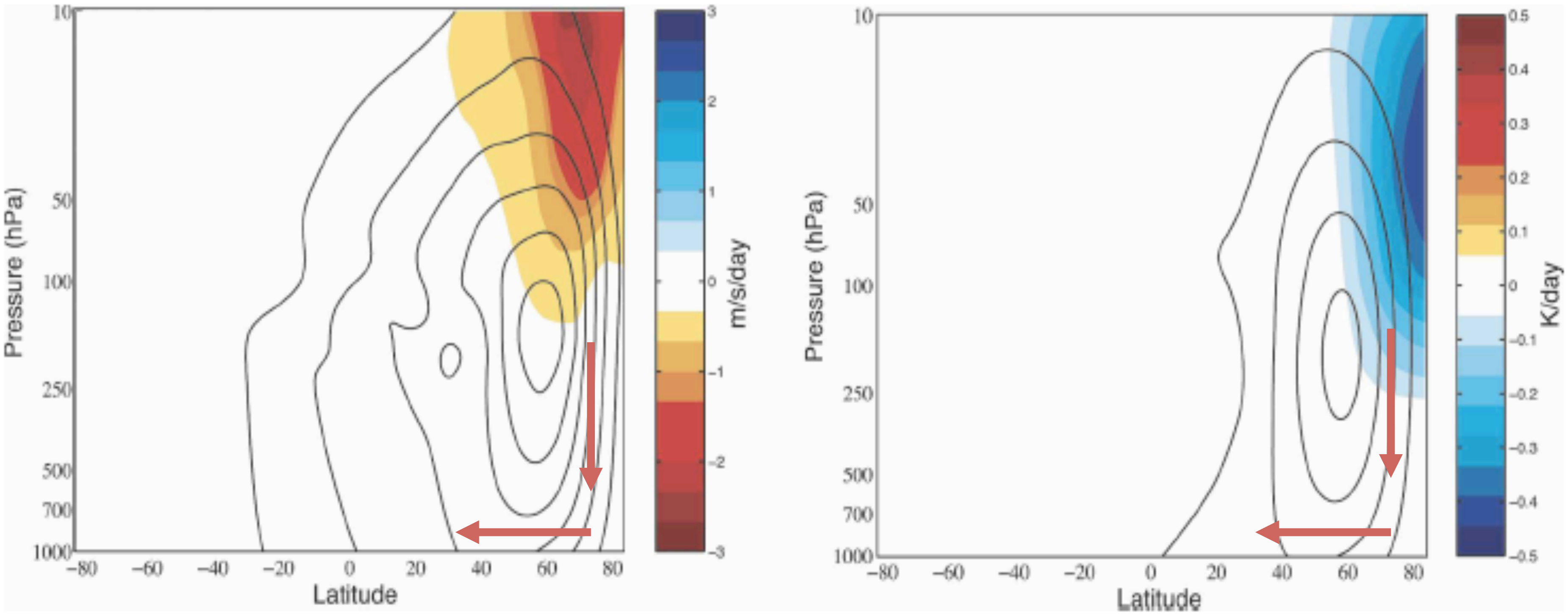
Some models show rather strange errors

Pawson et al. (2000 BAMS)

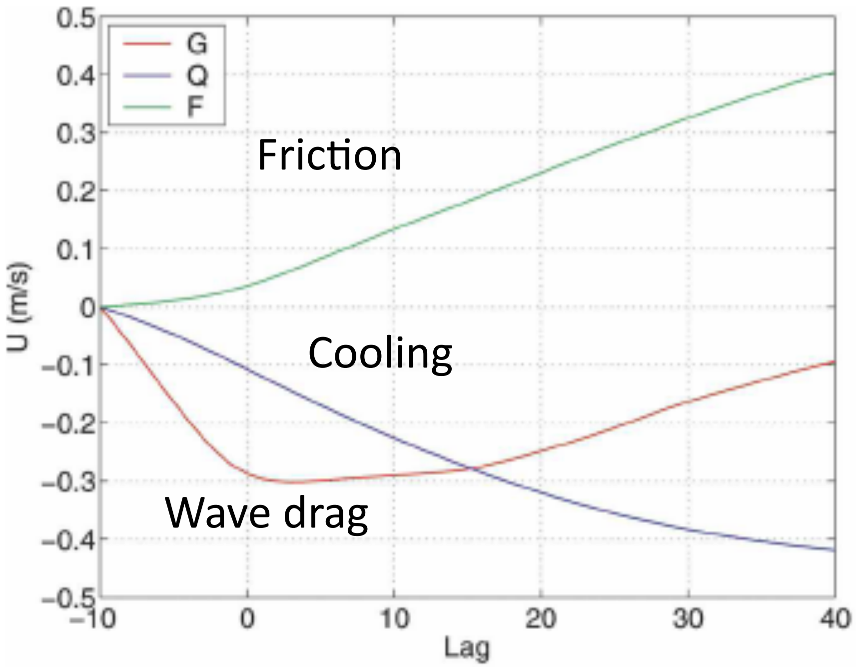


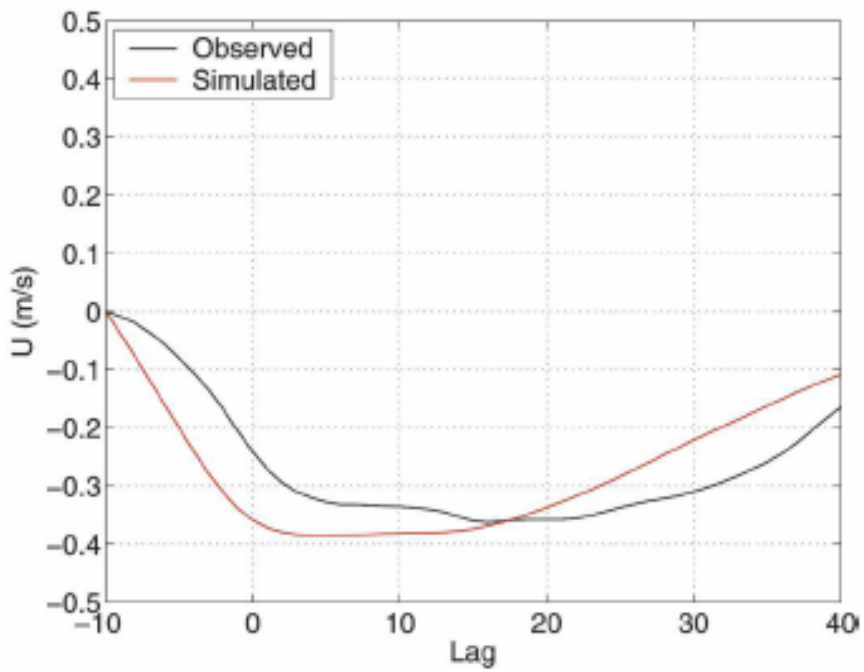
Baldwin et al. (2003 Science)

- A negative NAM anomaly is preceded by anomalous wave drag (left, colours), which warms the polar lower stratosphere and leads to radiative cooling (right, colours)
- Both stratospheric forcings weaken the surface zonal wind through their induced meridional circulations (lines)



Thompson, Furtado & Shepherd (2006 JAS)

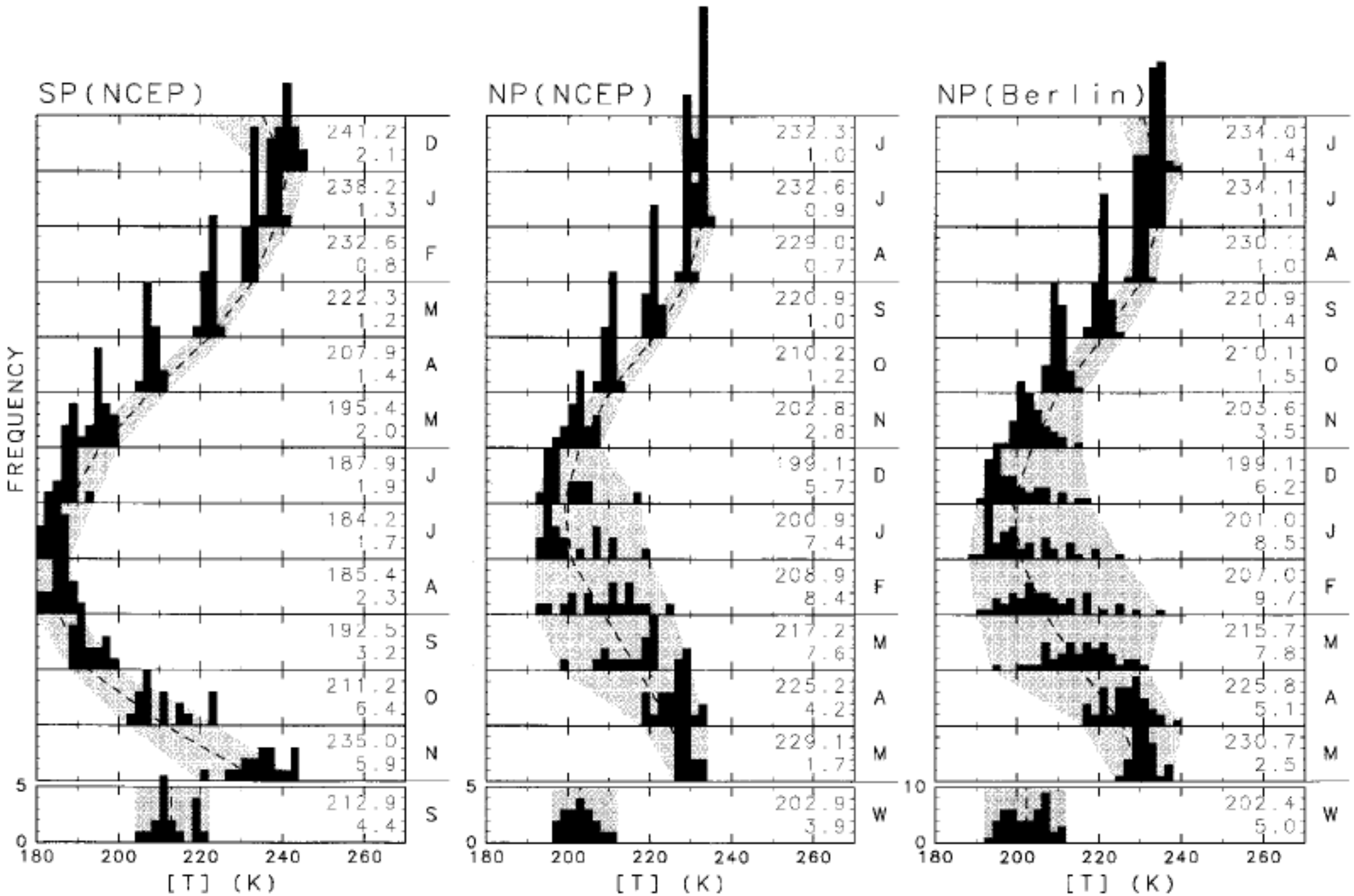




The surface wind reduction is initiated by the wave drag and maintained by the cooling, and damped by surface friction

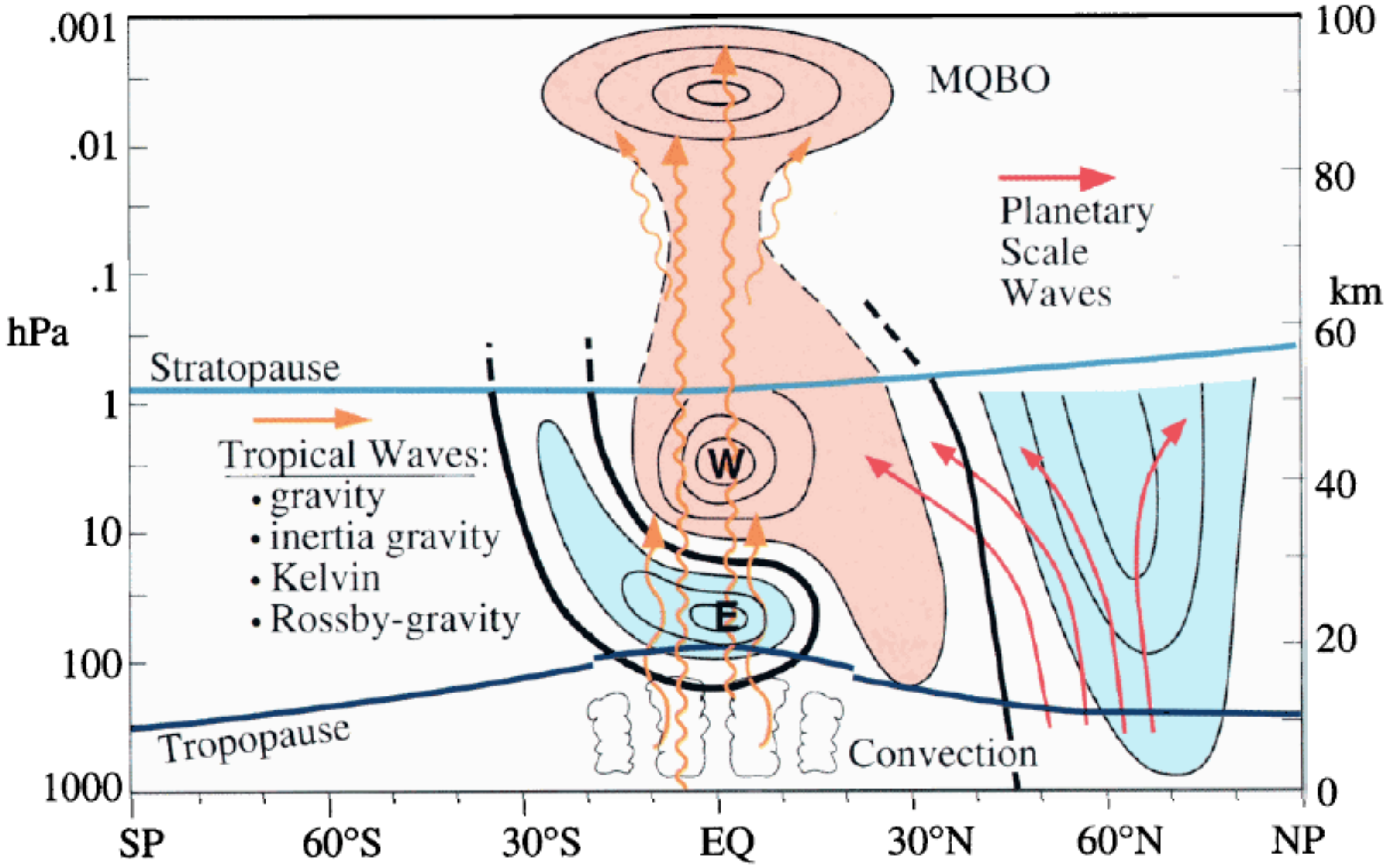
Surface wind anomalies are computed from the zonal-mean QG response to the observed forcings

Thompson, Furtado & Shepherd (2006 JAS)



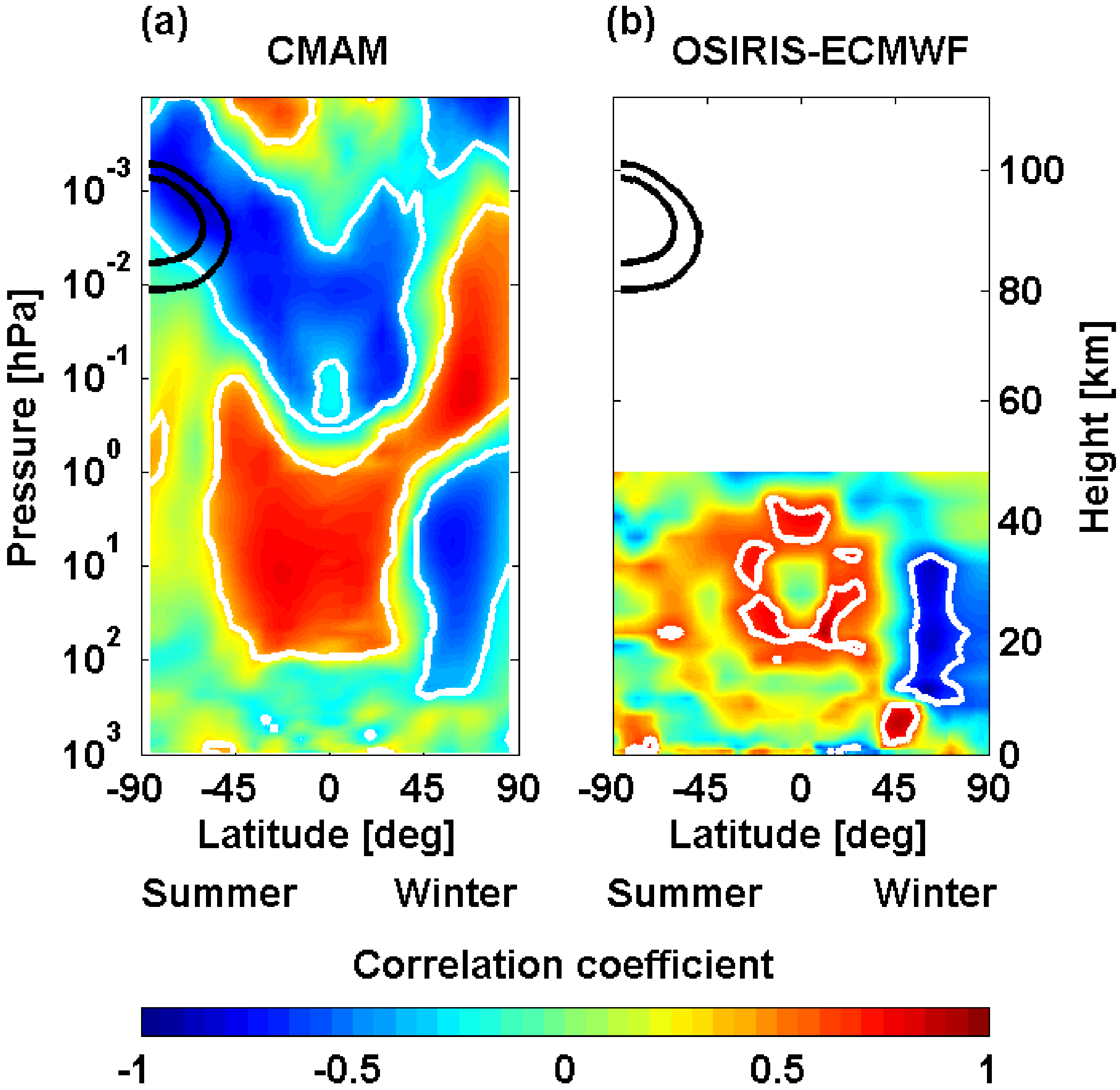
Yoden et al. (2002 JMSJ)

- The quasi-biennial oscillation (QBO) in equatorial winds is a source of Arctic variability



N.B. W is westward!

Baldwin et al. (2001 Rev Geophys)



Simulations with the extended CMAM show a similar correlation pattern to the obs (associating NLC radius with low temperature)

Here the two hemispheres are combined

Black lines indicate summer mesopause

Karlsson, McLandress & Shepherd (2009 JASTP)