FDEPS 2012, Lecture 4

Polar vortex variability and stratosphere-troposphere coupling

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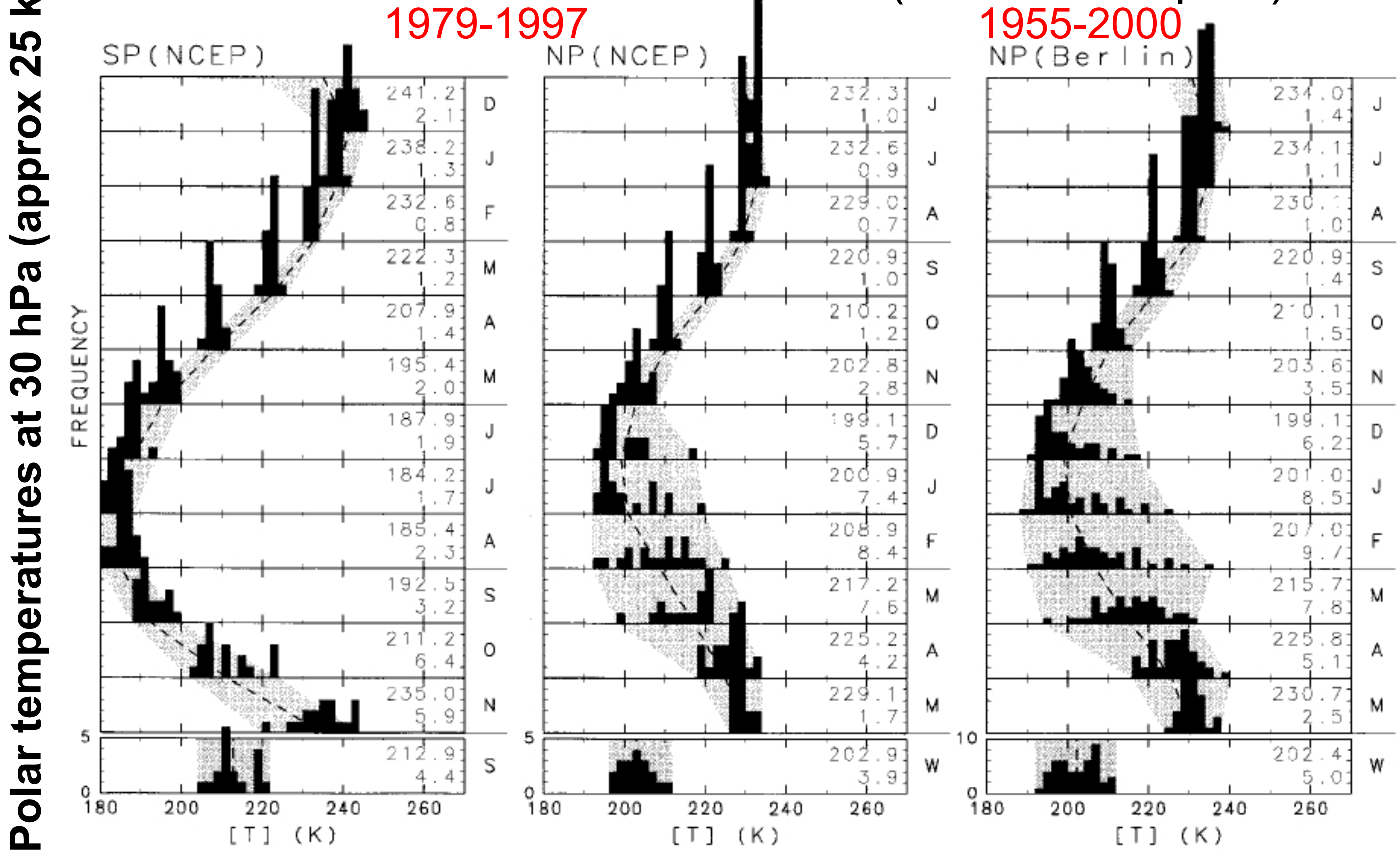
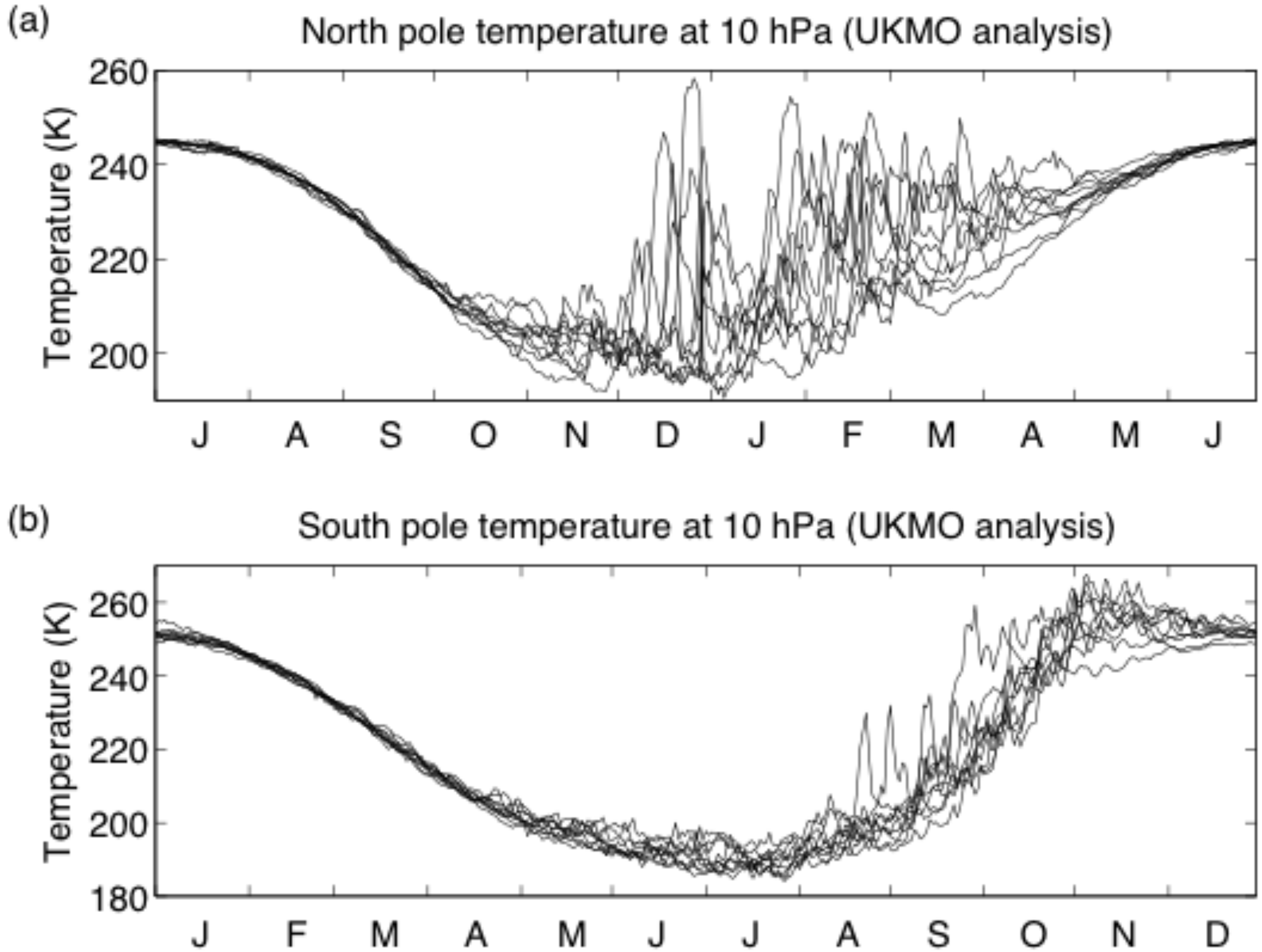
- Forcing of planetary Rossby waves is stronger in the NH than in the SH, so the Arctic winter is warmer and more variable than the Antarctic (summer is quiet)



Yoden, Taguchi & Naito (2002 JMSJ)

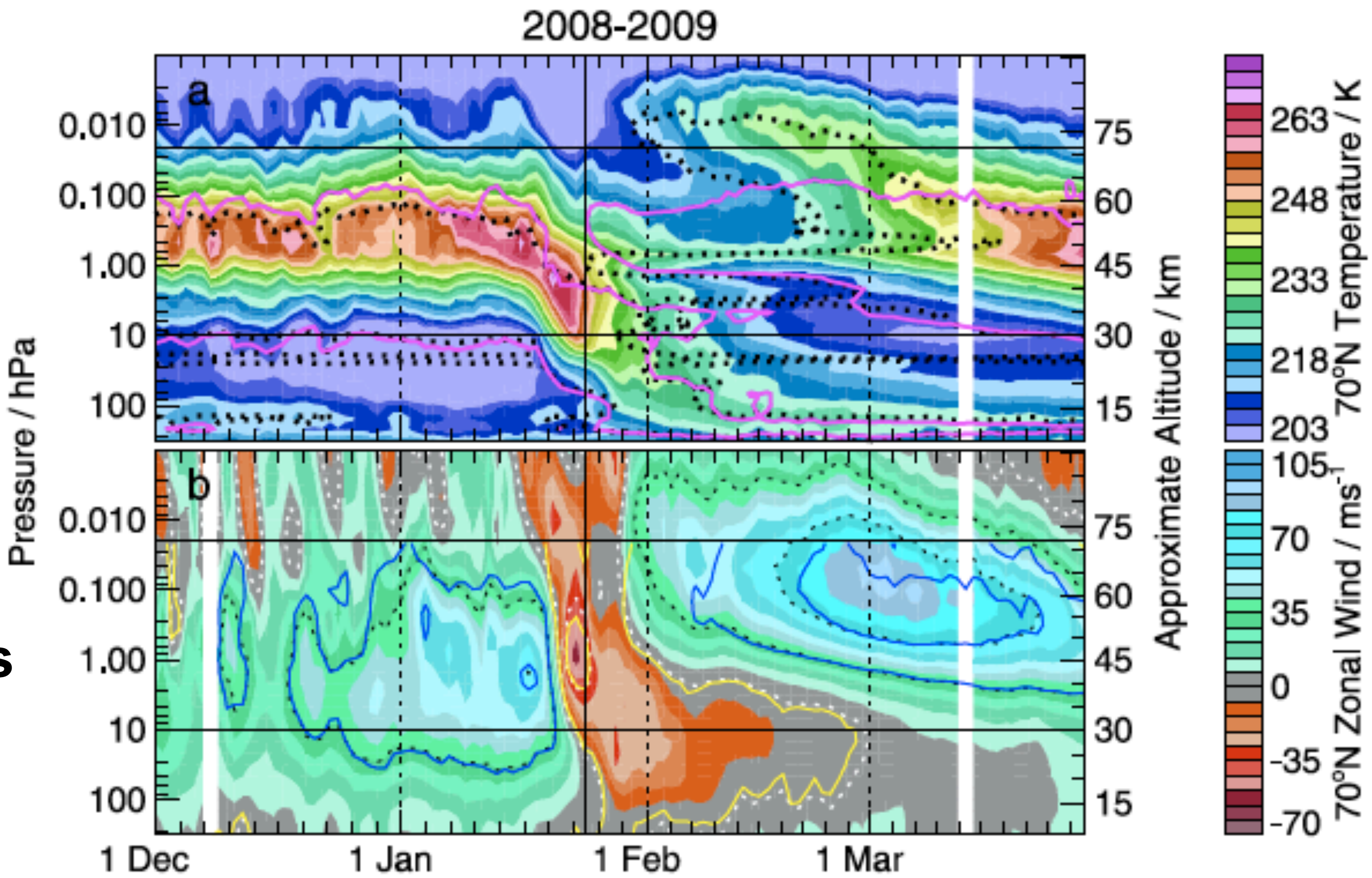
- Time series of polar temperatures exhibit ‘spiky’ behaviour
  - Rapid warming caused by a focusing of Rossby wave drag at high latitudes, a highly nonlinear process



- 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

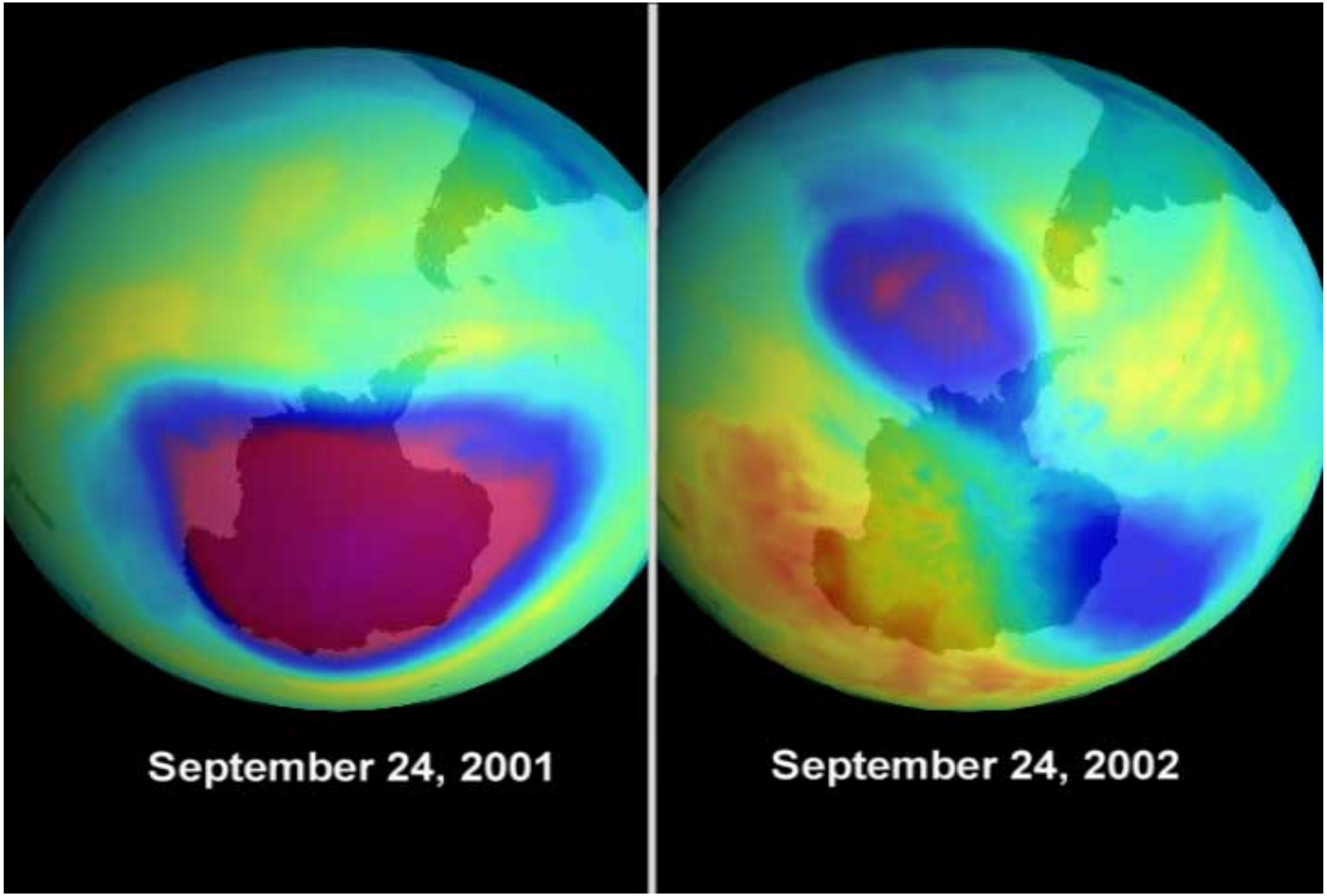
MLS T @ 70N

Geos u @ 70N



Manney et al. (2009 GRL)

The split ozone hole of 2002: a wave-2 sudden warming

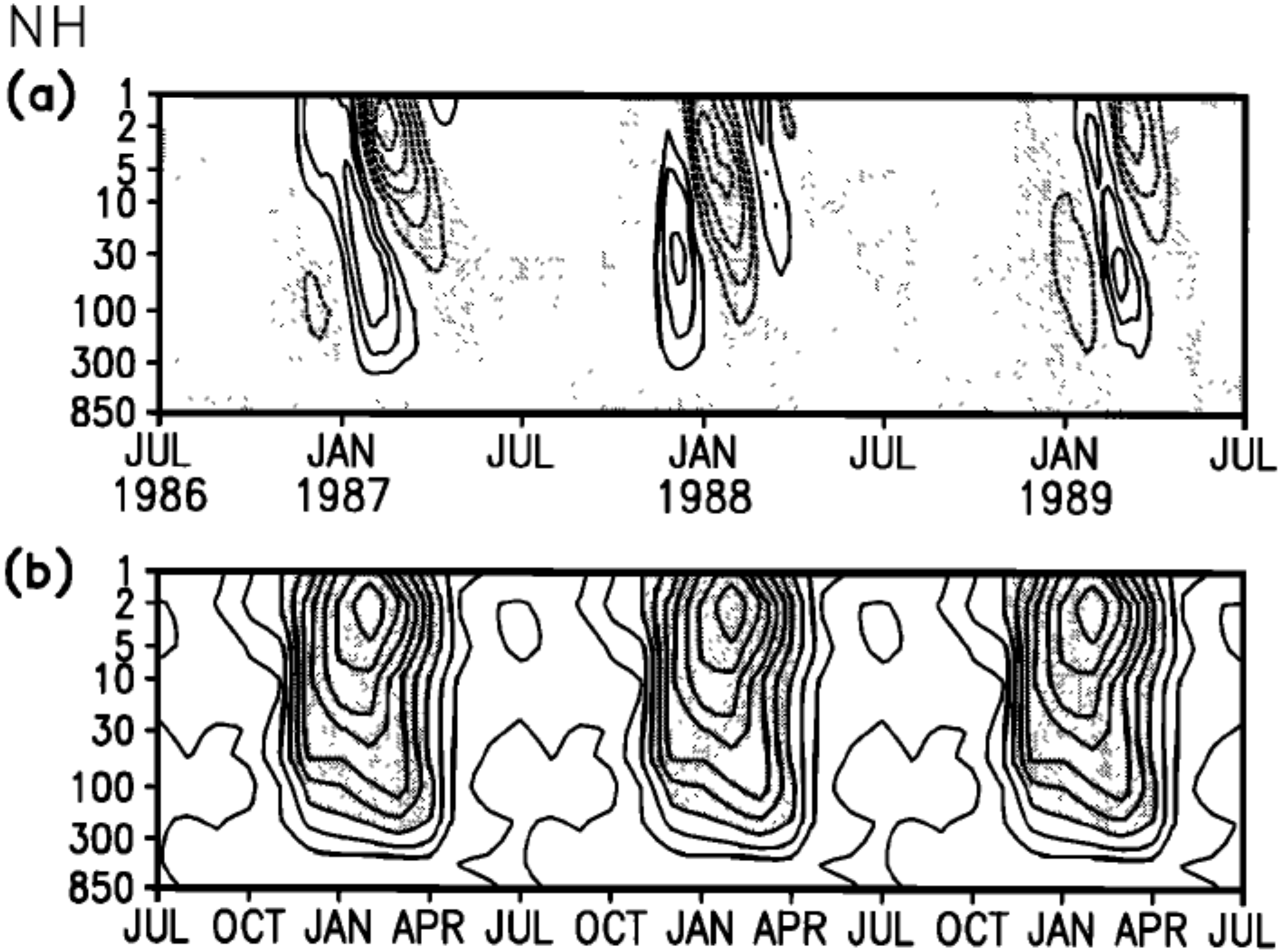


TOMS data (smoothed), from NASA GSFC web site

- 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 dev of monthly mean polar T

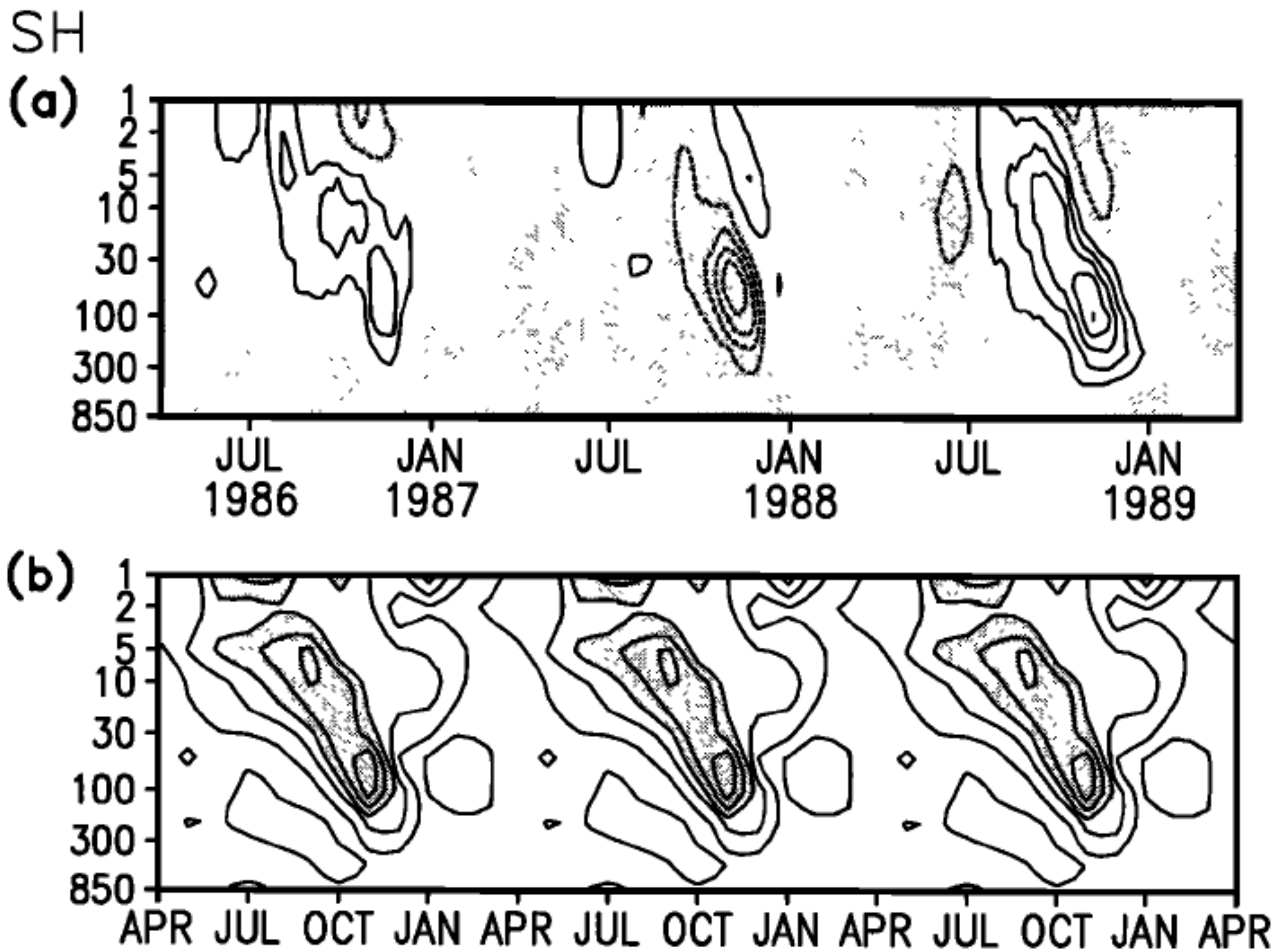


Kuroda & Kodera (2001 JGR)

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

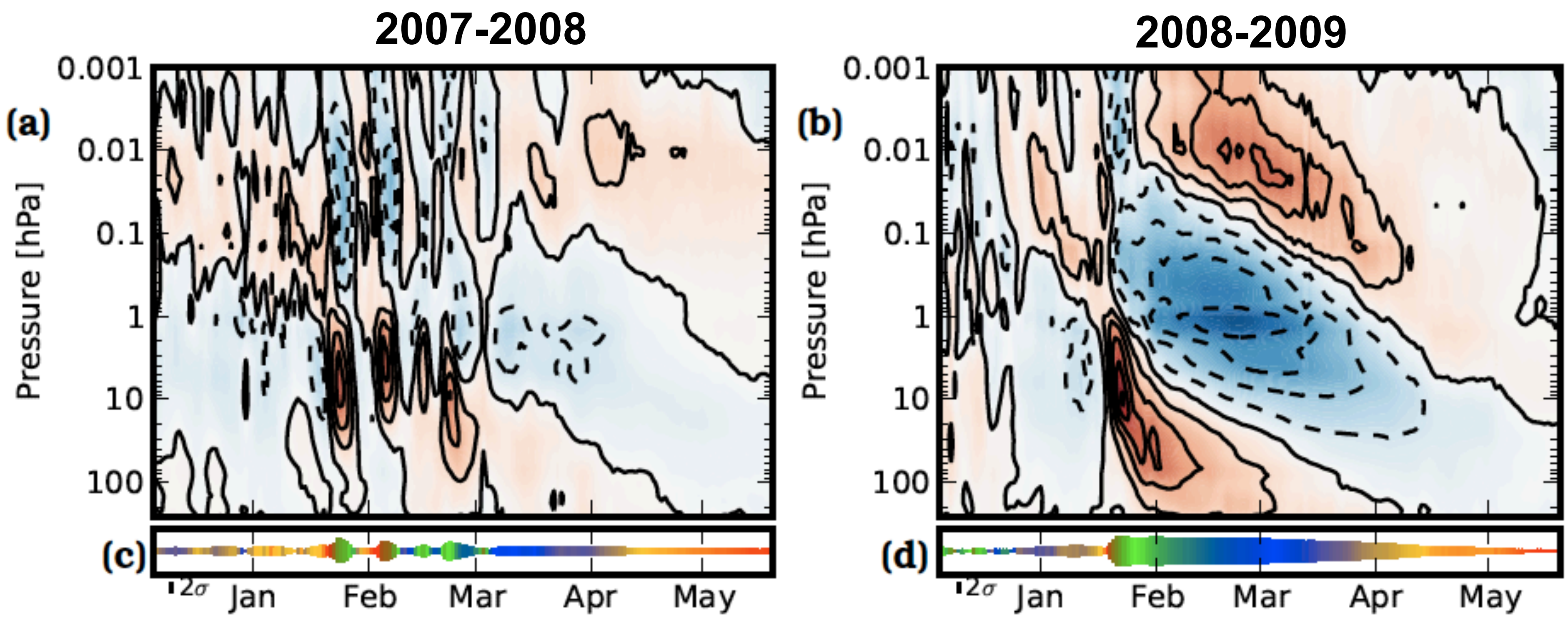
30 day running average polar T anomaly

Interannual std dev of monthly mean polar T

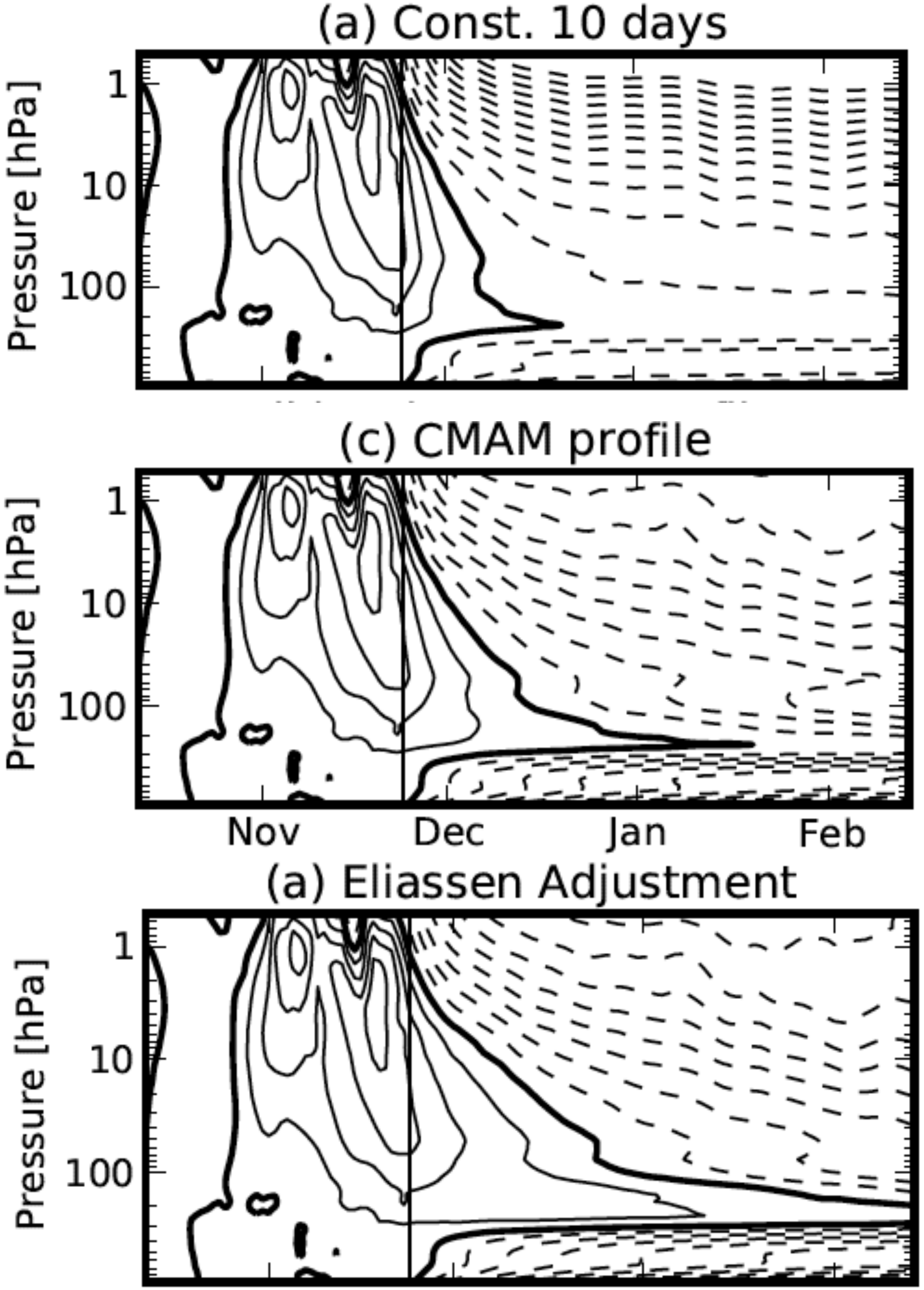


Kuroda & Kodera (2001 JGR)

- About half of all SSWs are short-lived, as in 2007-2008 (left), while half have extended recovery periods, as in 2008-2009 (right)
  - Figures show MLS polar-cap average temperatures
  - Note opposite response in the mesosphere



Hitchcock, Shepherd & Manney (J Clim, in press)

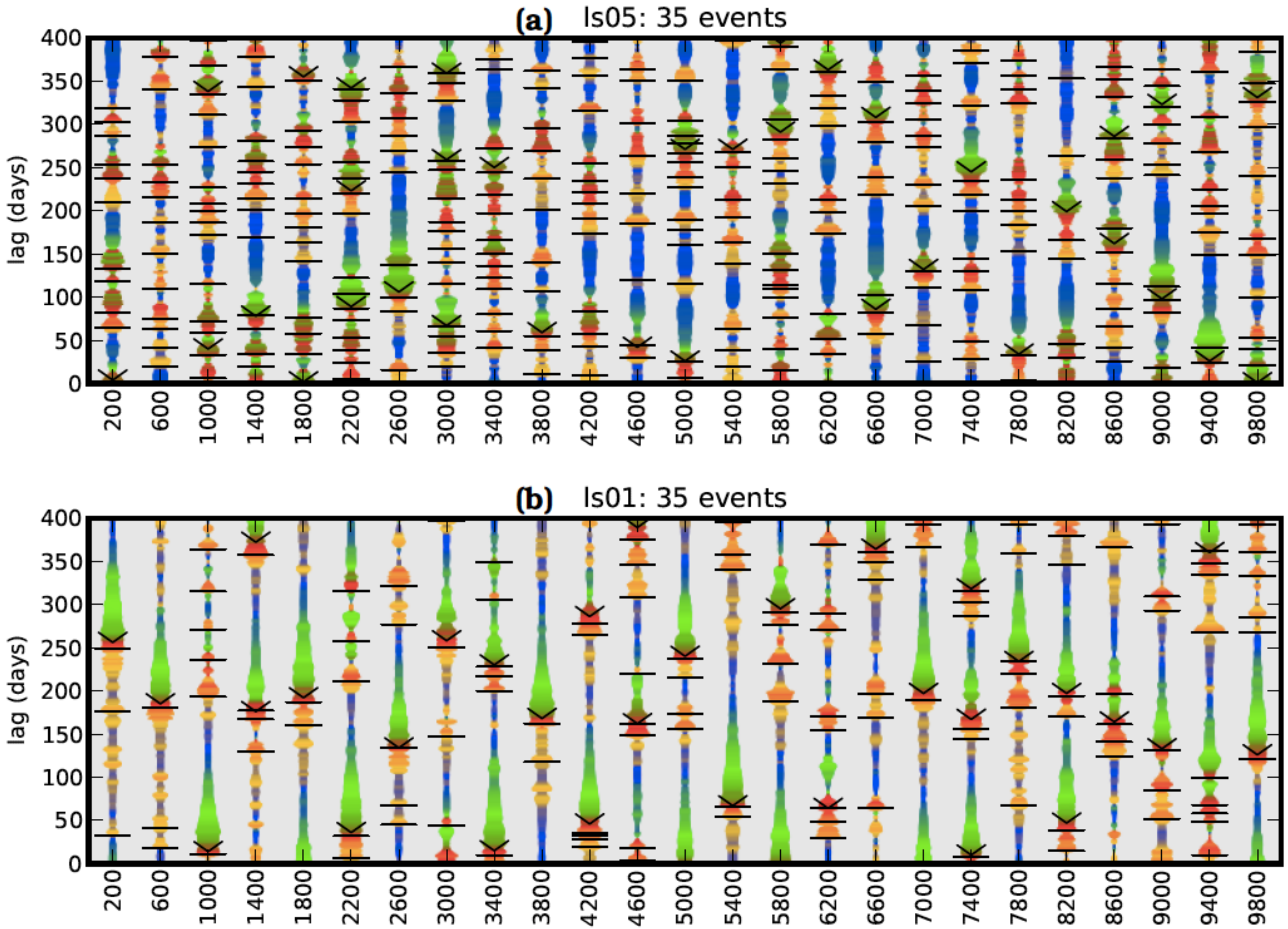


- Solving the zonal-mean QG equations forced by wave drag from the Canadian Middle Atmosphere Model (CMAM) shows that the long timescales result from:
  - Long radiative timescales in the lower stratosphere
  - Continued descent from induced radiative cooling
  - Absence of planetary-wave forcing

Plots show polar T anomaly

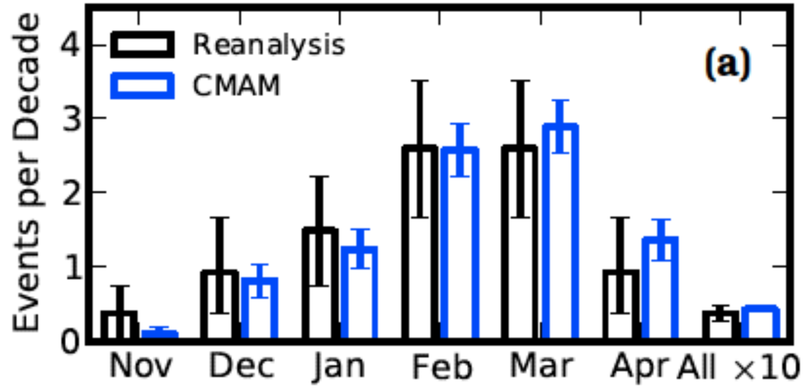
Hitchcock & Shepherd (JAS, in press)

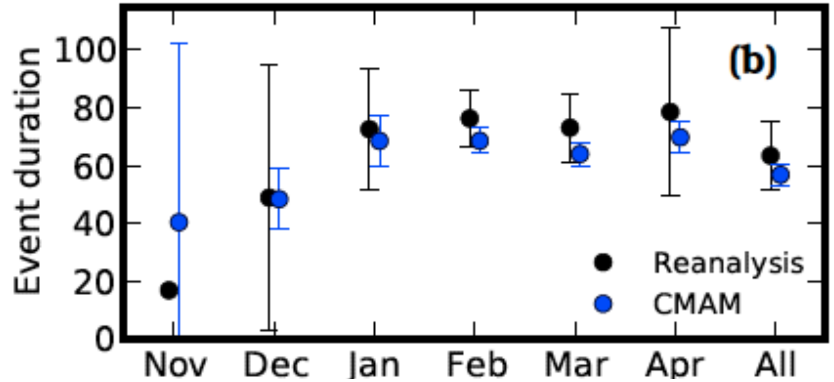
- Only with long radiative damping timescales in the lower stratosphere does a simplified GCM exhibit such events

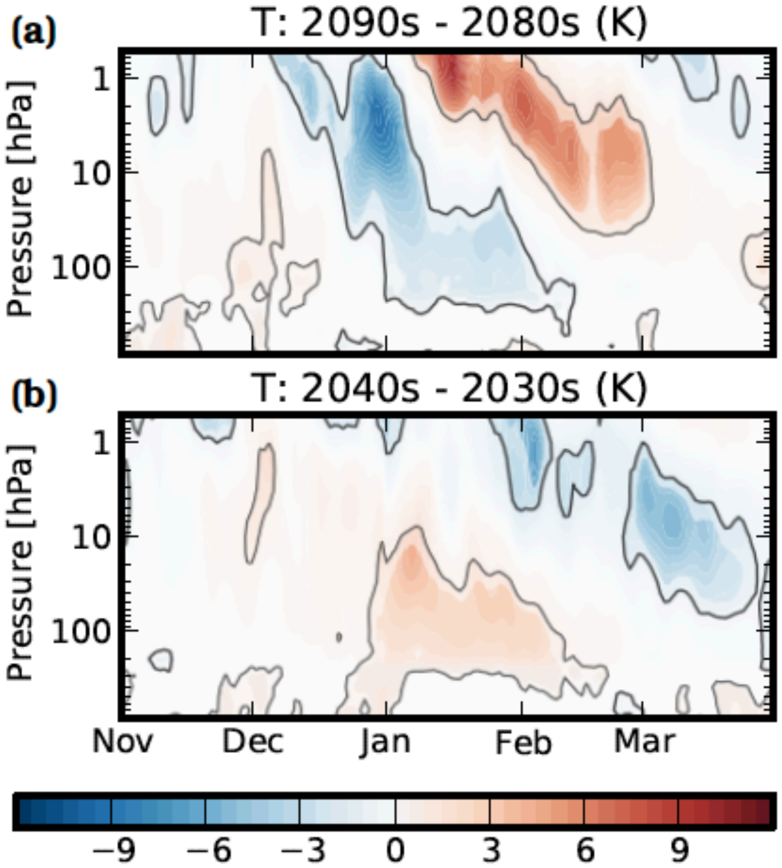


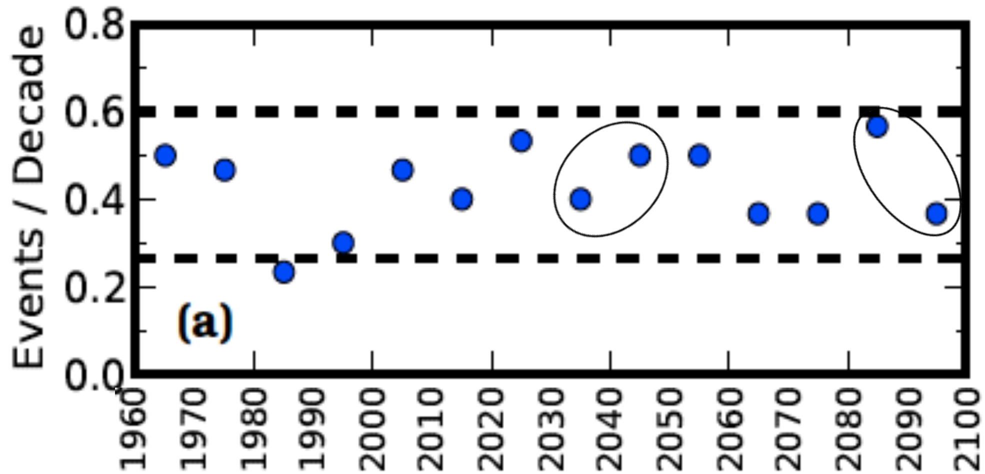
Hitchcock, Shepherd, Yoden, Noguchi & Taguchi (JAS, submitted)

- In CMAM, this variability leads to apparent decadal trends in Arctic temperatures even for 3-member ensembles (below)



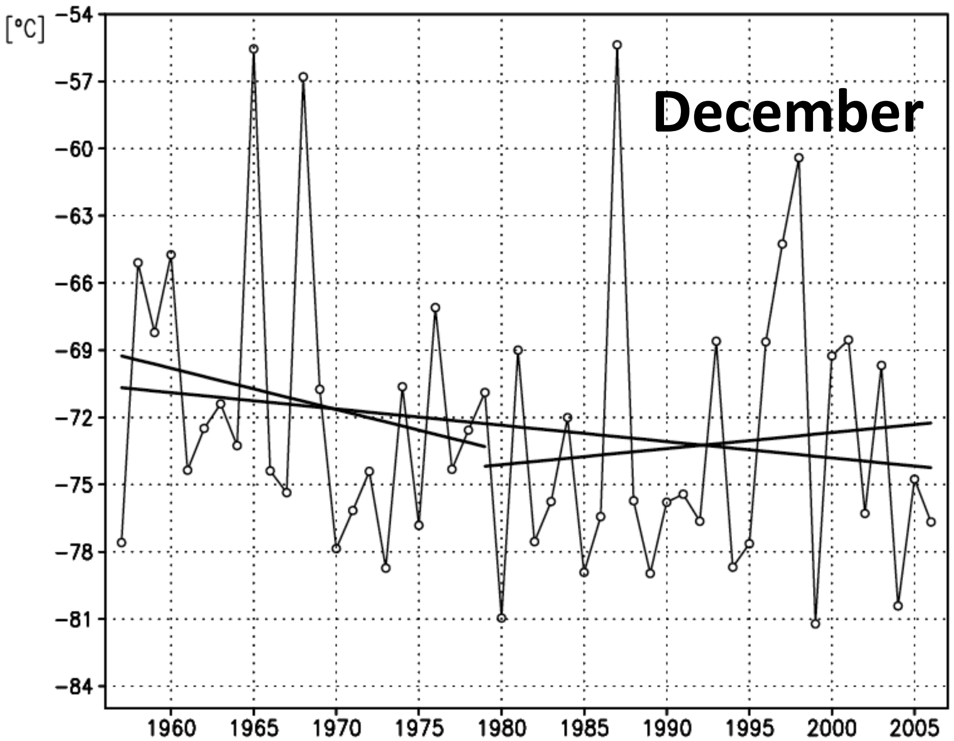


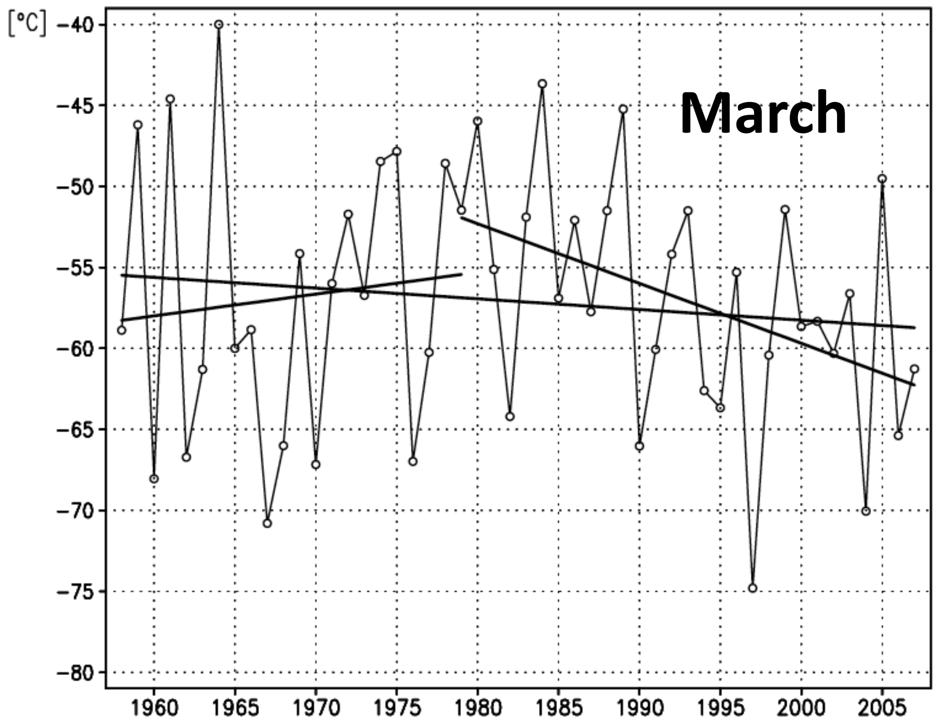




Ph.D. thesis of Peter Hitchcock, University of Toronto (2012)

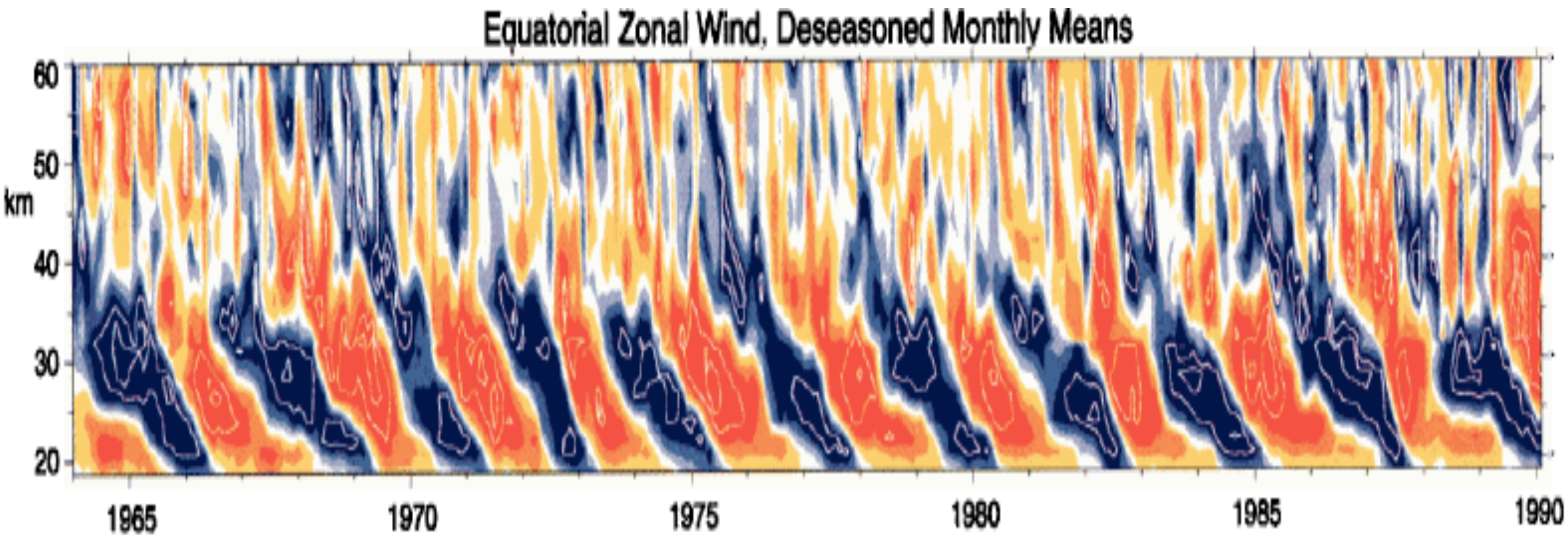
- The oscillatory nature of NH polar vortex variability leads to a see-saw relationship between early-winter and late-winter decadal variability (here in 30 hPa polar T)
  - There is a lot of power in the decadal variations, which have tended to be interpreted as trends





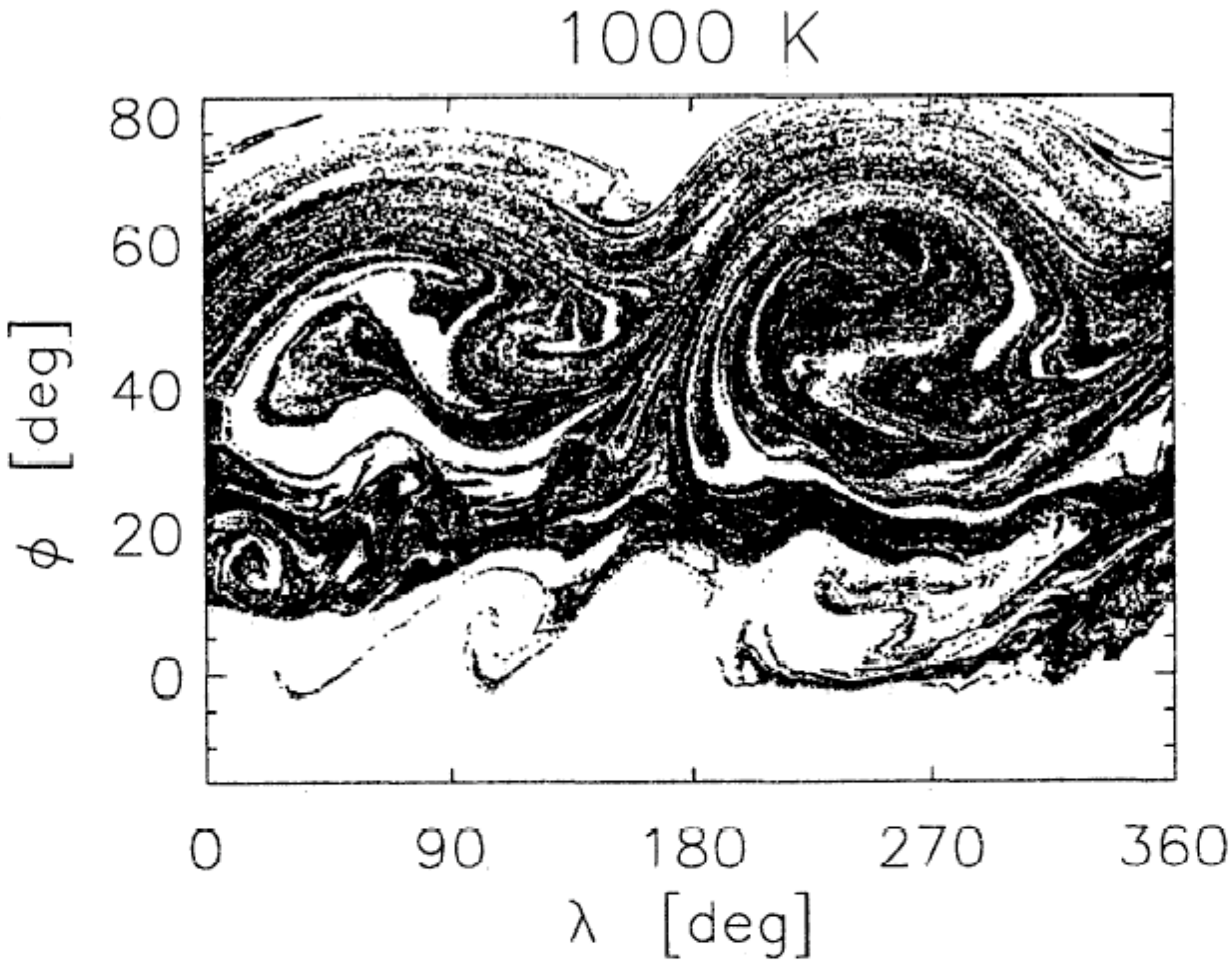
Updated from Labitzke & Kunze (2005 Meteor. Z.)

- At the equator, a spectrum of wave forcing generically leads to oscillating zonal winds (see e.g. Plumb 1977 JAS), which are super-rotating in their eastward phase
- Manifested in the stratospheric Quasi-Biennial Oscillation (QBO)



Observations from Baldwin et al. (2001 Rev. Geophys.)

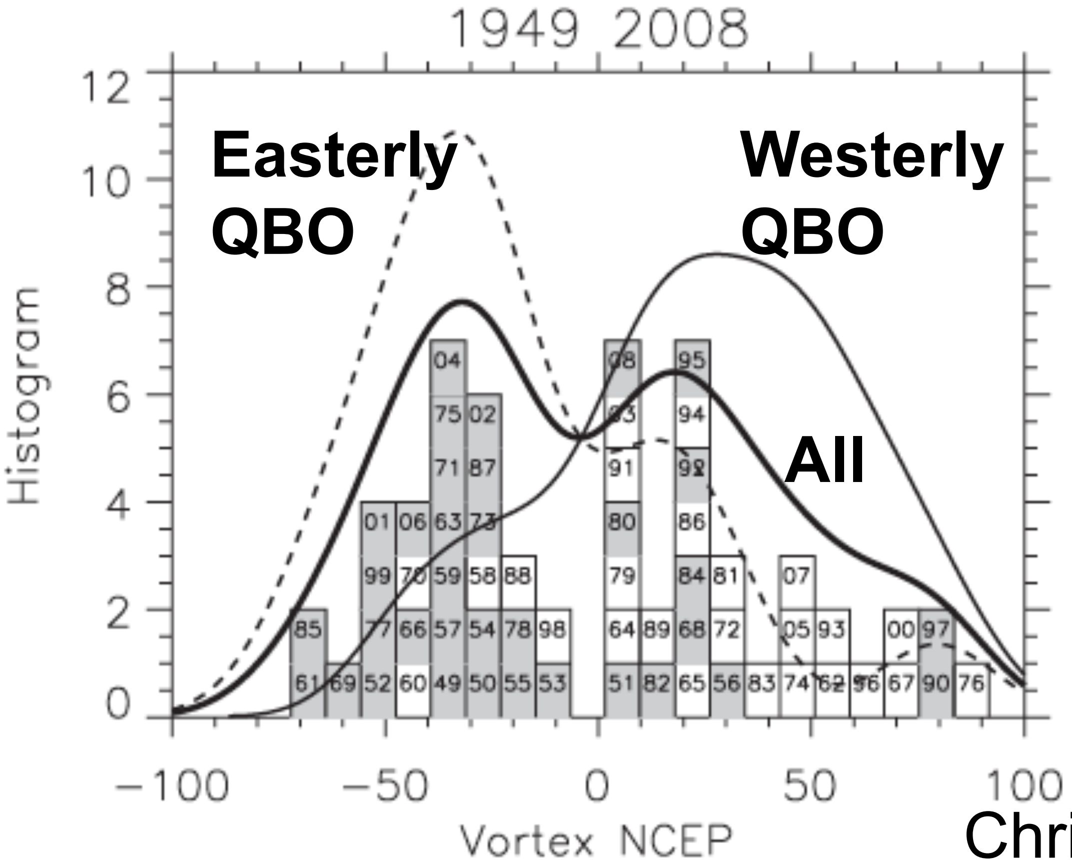
- The hemispheric scale of the stratospheric surf zone provides a mechanism through which changes in tropical winds can directly affect the polar vortex



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

Shepherd, Koshyk & Ngan (2000 JGR)

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

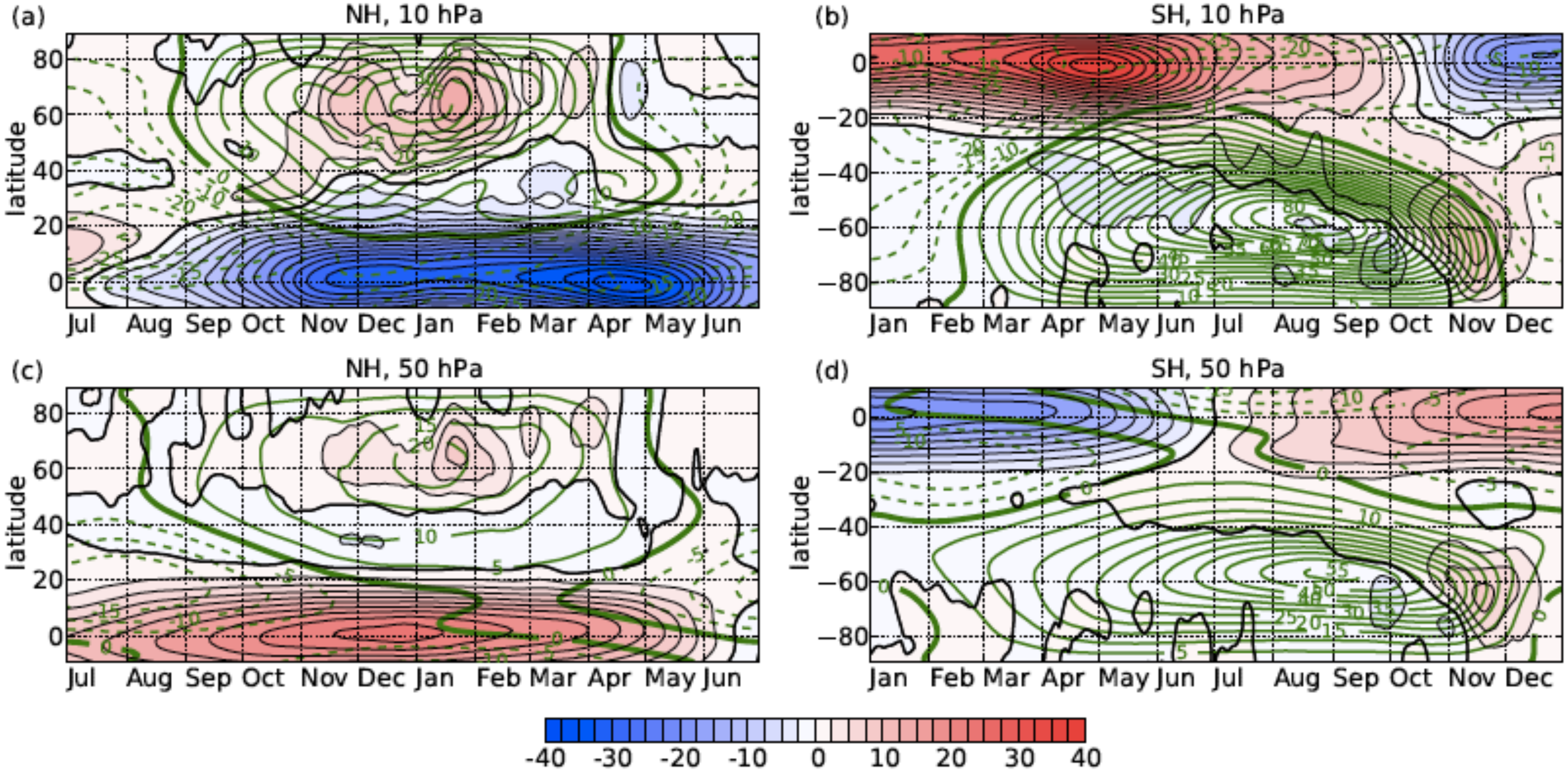


Is the origin of the observed bimodality in NH variability (here based on NAM index at 20 hPa)

Years segregated by FUB QBO index (shaded is easterly)

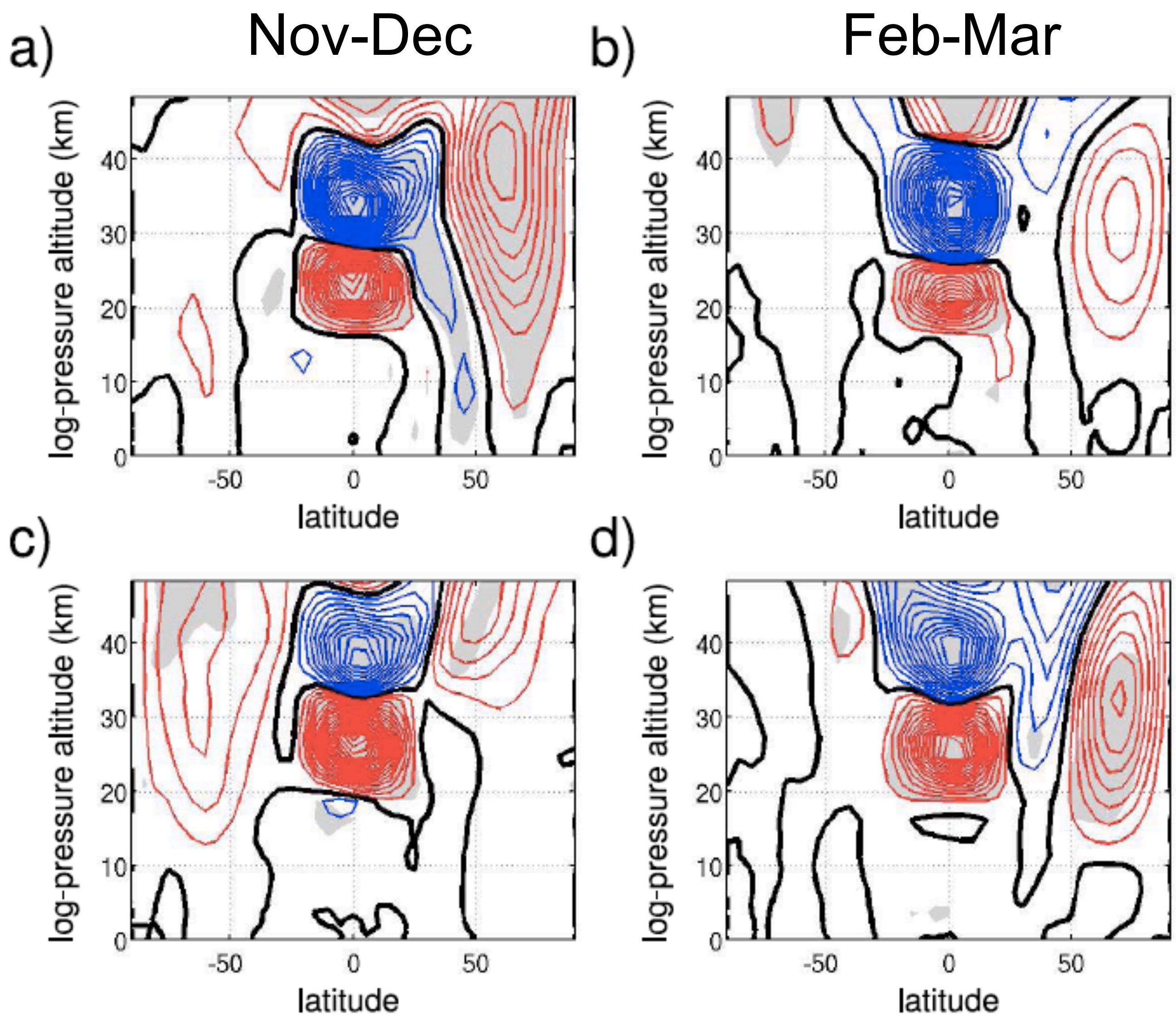
Christiansen (2010 J Clim)

- The NH vortex is affected from late fall to early spring, the SH vortex only in late spring
  - QBO phase defined here at 50 hPa in January for NH and at 20 hPa in July for SH; which levels are causal?



Anstey & Shepherd (QJRMS, submitted)

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

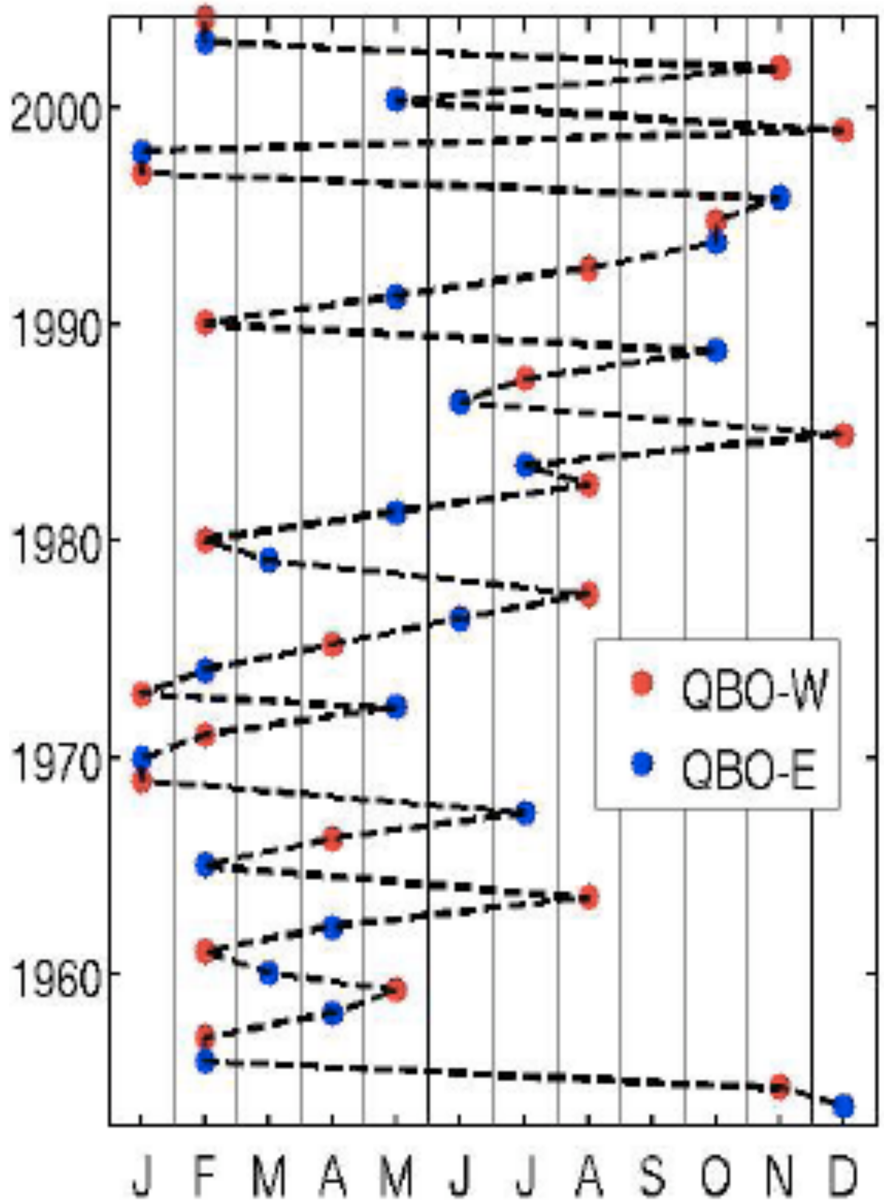


C.I. = 2 m/s

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

Between April and September in the previous year

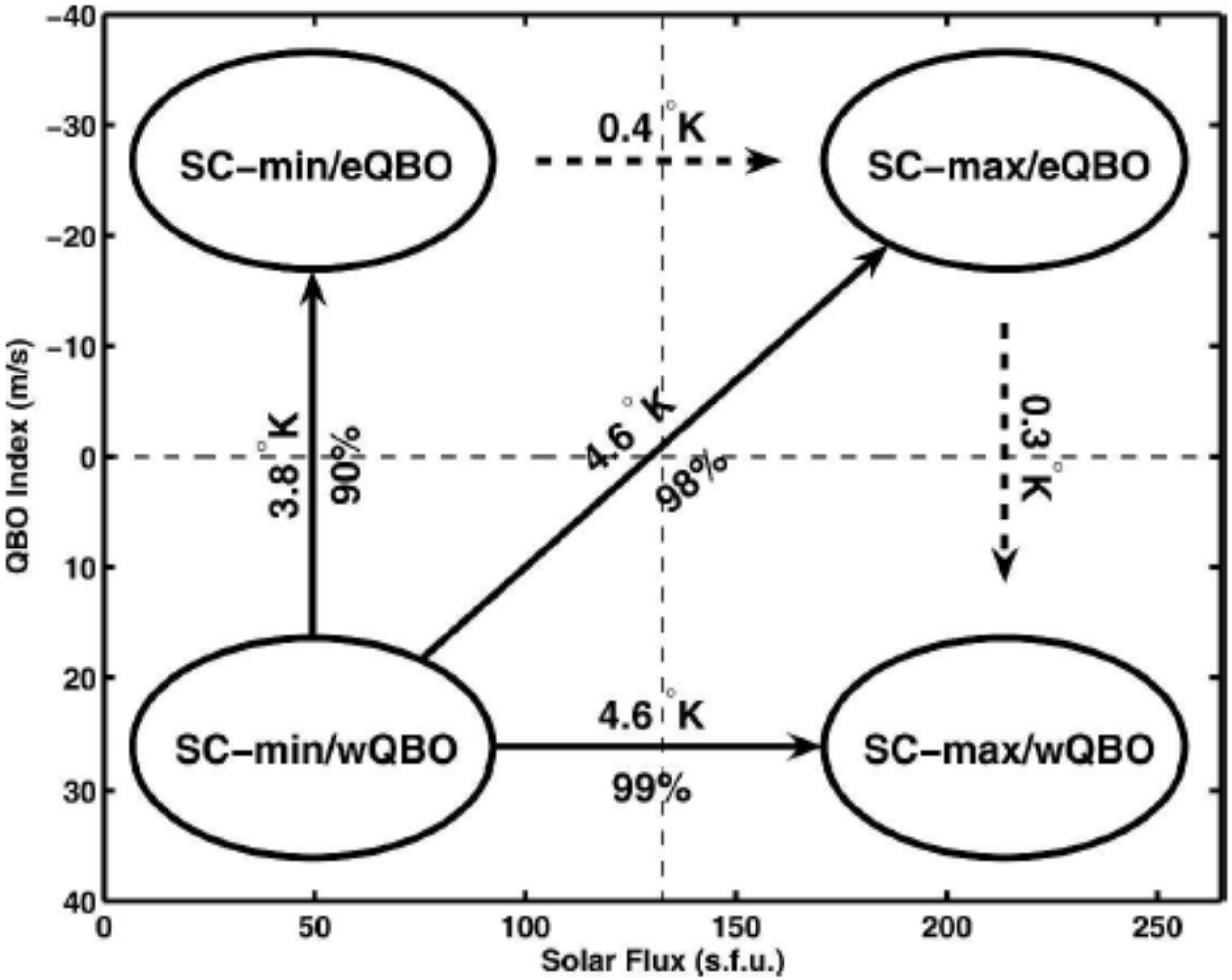
Anstey & Shepherd (2008 GRL)



Anstey & Shepherd (2008 GRL)

- The seasonality of observed QBO phase transitions exhibits an interesting decadal variability
- May explain why the QBO-vortex coupling seems non-robust
- Non-robustness of QBO-vortex coupling has been attributed to solar variability, but CMAM shows the same behaviour with no solar variability (Anstey, Shepherd & Scinocca 2010 JAS)

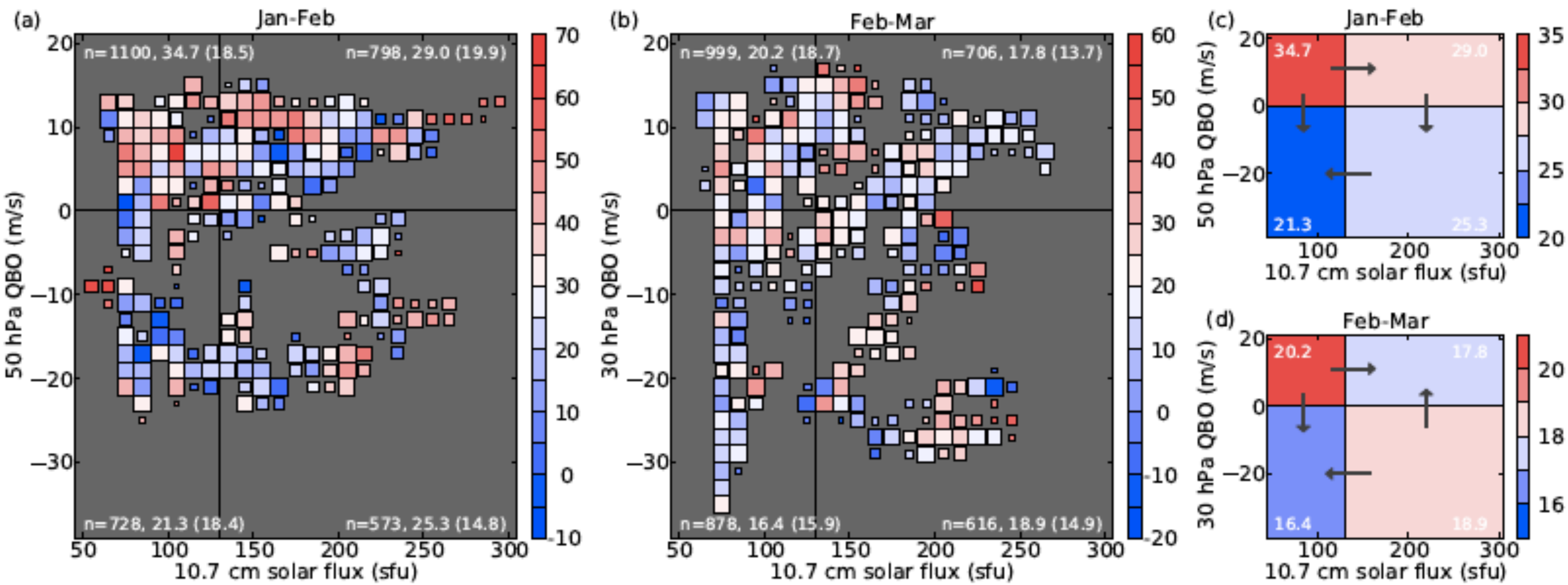
- Because SSWs disturb the NH vortex so strongly, perturbations do not add (a second “trigger” is redundant)



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)

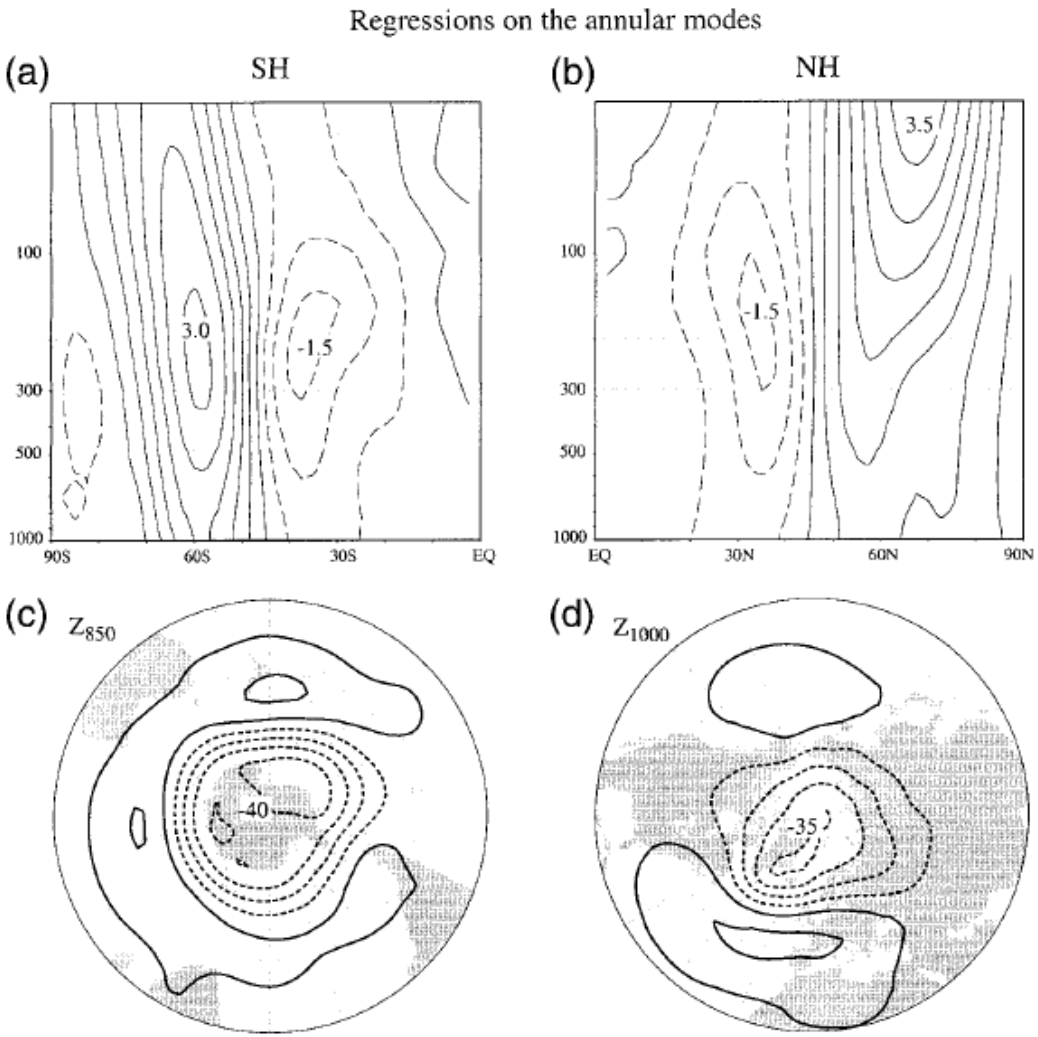
Camp & Tung (2007 JAS)

- The only differences that seem robust in the data are between QBO-W/SC-min and the other quadrants
- However we have not sampled very much of phase space in the observational record



Anstey & Shepherd (QJRMS, submitted)

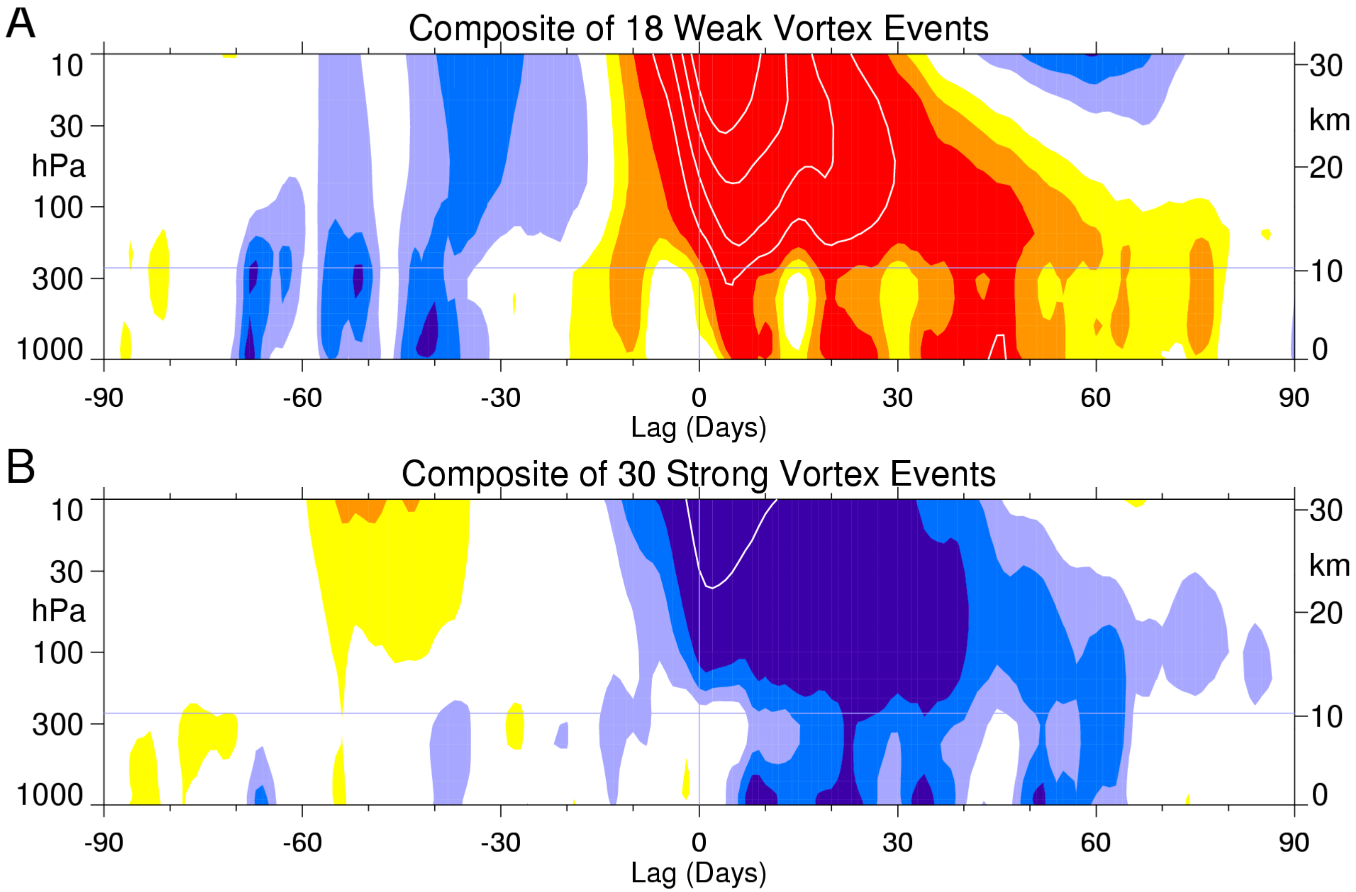
- In both hemispheres, the stratospheric polar vortex variability is connected to the troposphere (where it affects the subtropical jet)



Southern and Northern Hemisphere "annular modes" (SAM and NAM), based on hemispheric EOFs

Thompson & Wallace (2000 J Clim)

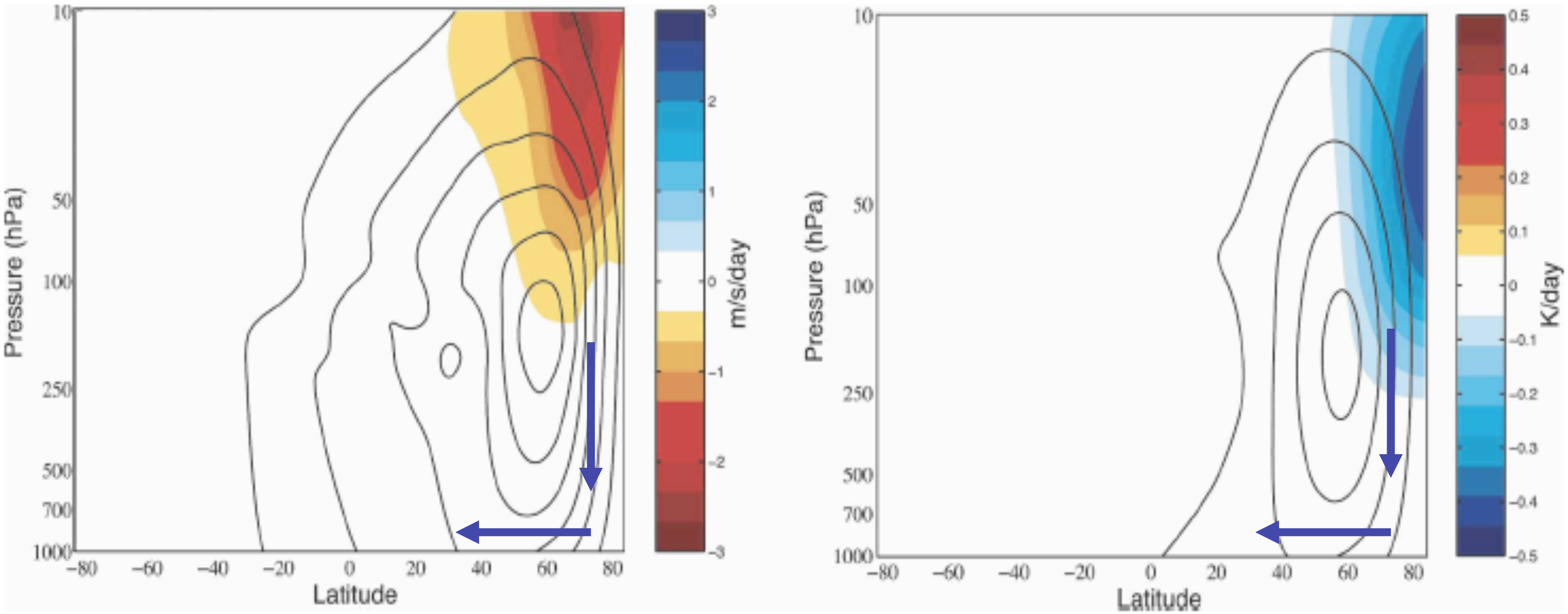
- Variations in the stratospheric polar vortex appear to influence tropospheric weather regimes for several months
- Must be wave-mean flow interaction, but beyond that, the mechanism has not yet been clearly elucidated



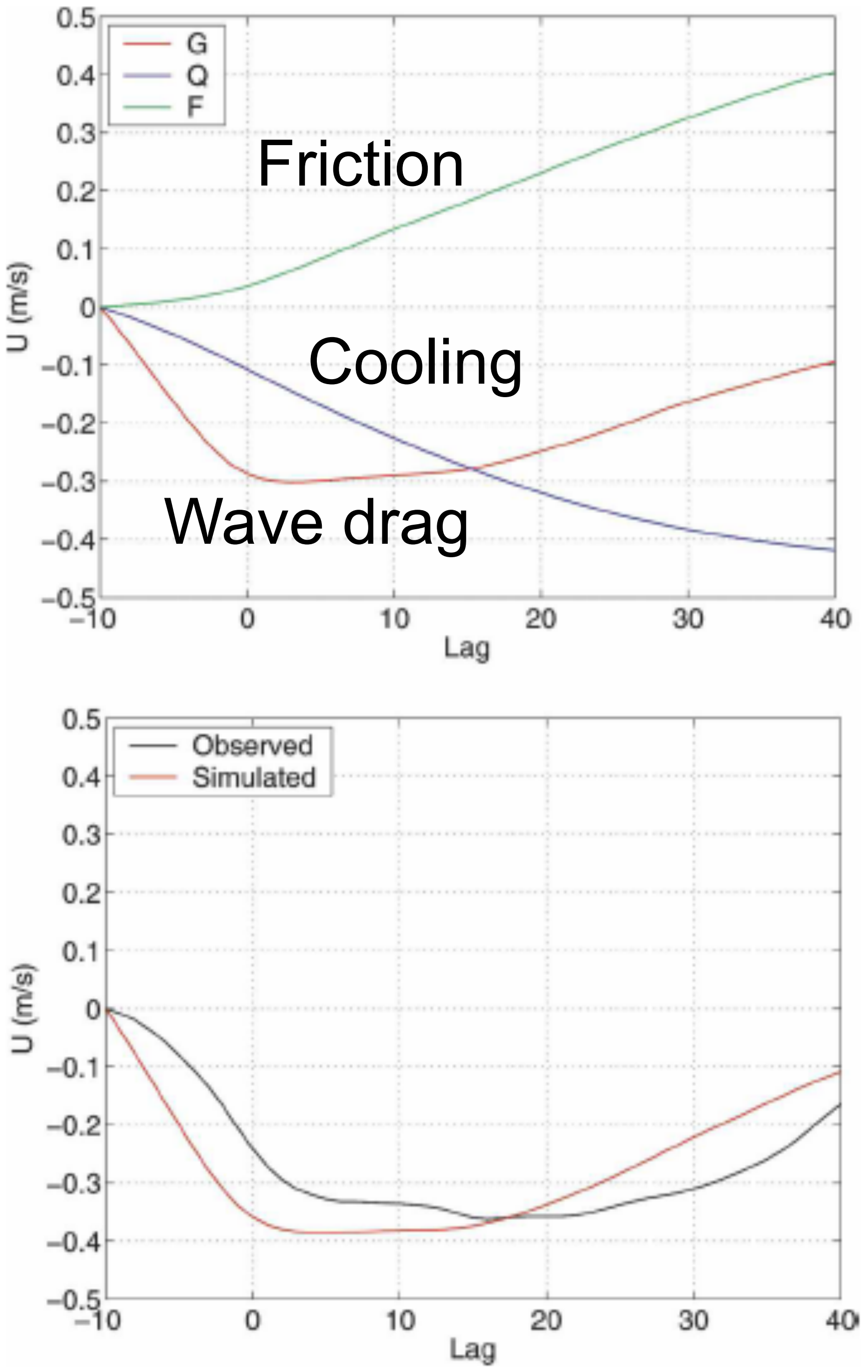
Composites of Northern Annular Mode (NAM) indices

Baldwin & Dunkerton (2001 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)

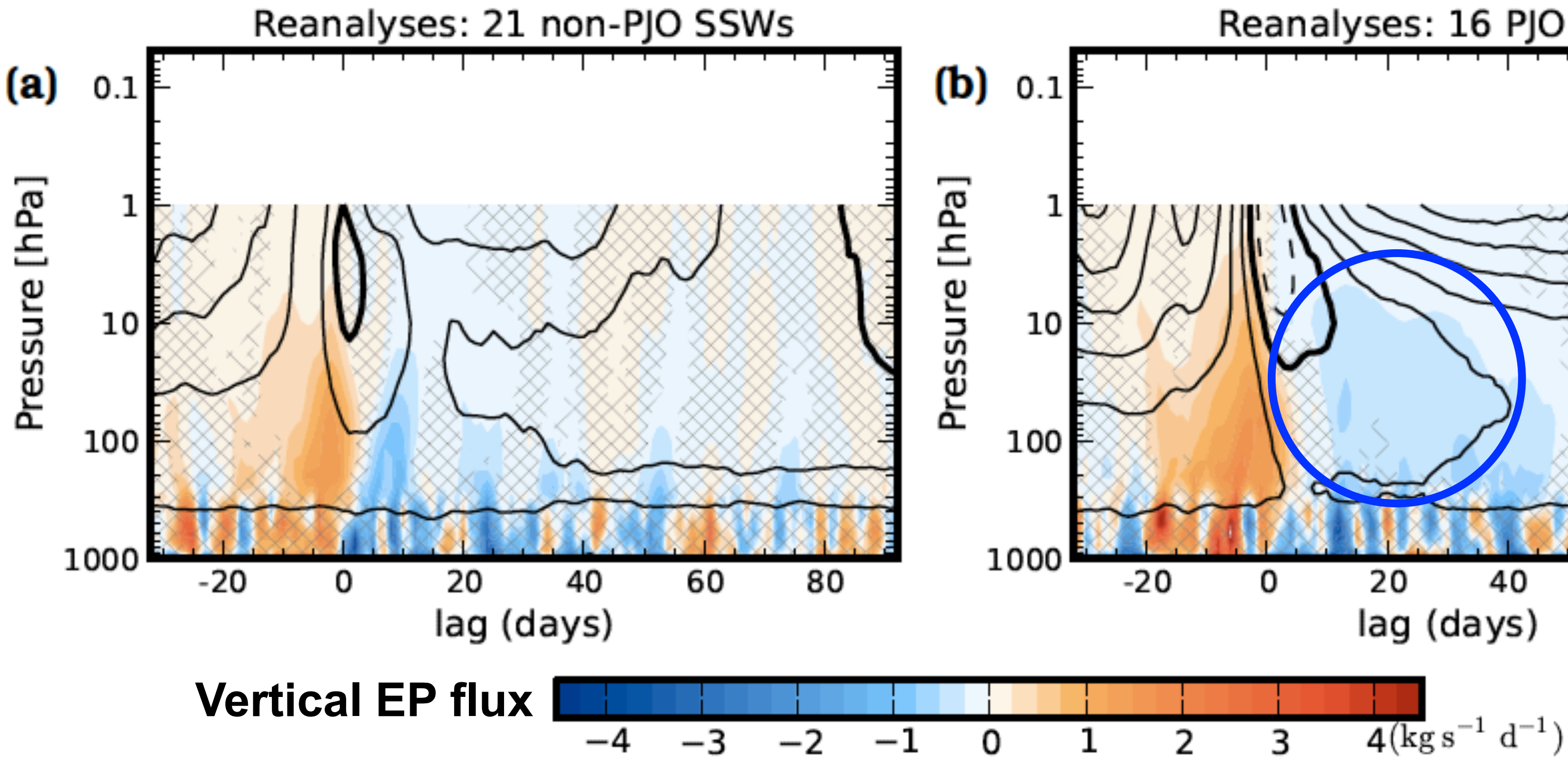


The surface wind reduction is initiated by the wave drag and maintained by the cooling, and damped by surface friction

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

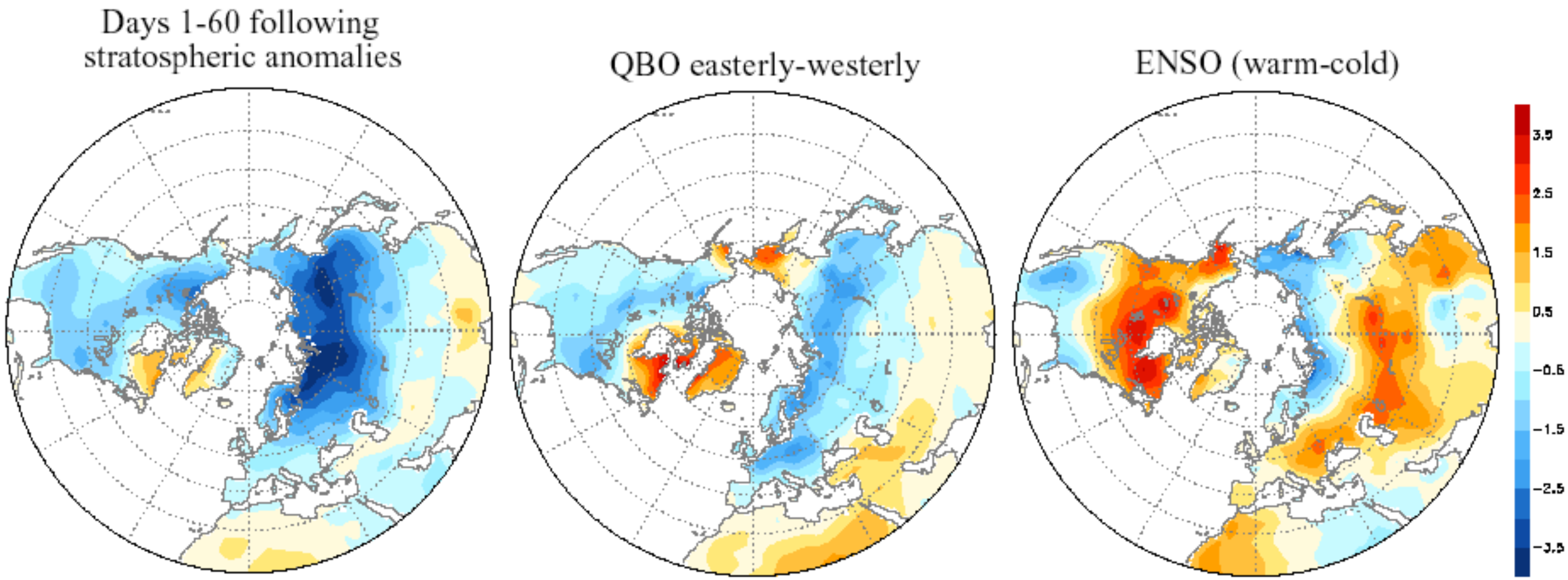
Thompson, Furtado & Shepherd (2006 JAS)

- The extended recoveries from SSWs (right) are associated with a strong suppression of planetary-wave fluxes (colour) into the stratosphere — more than can be explained by the Charney-Drazin theorem (contours show zonal winds)



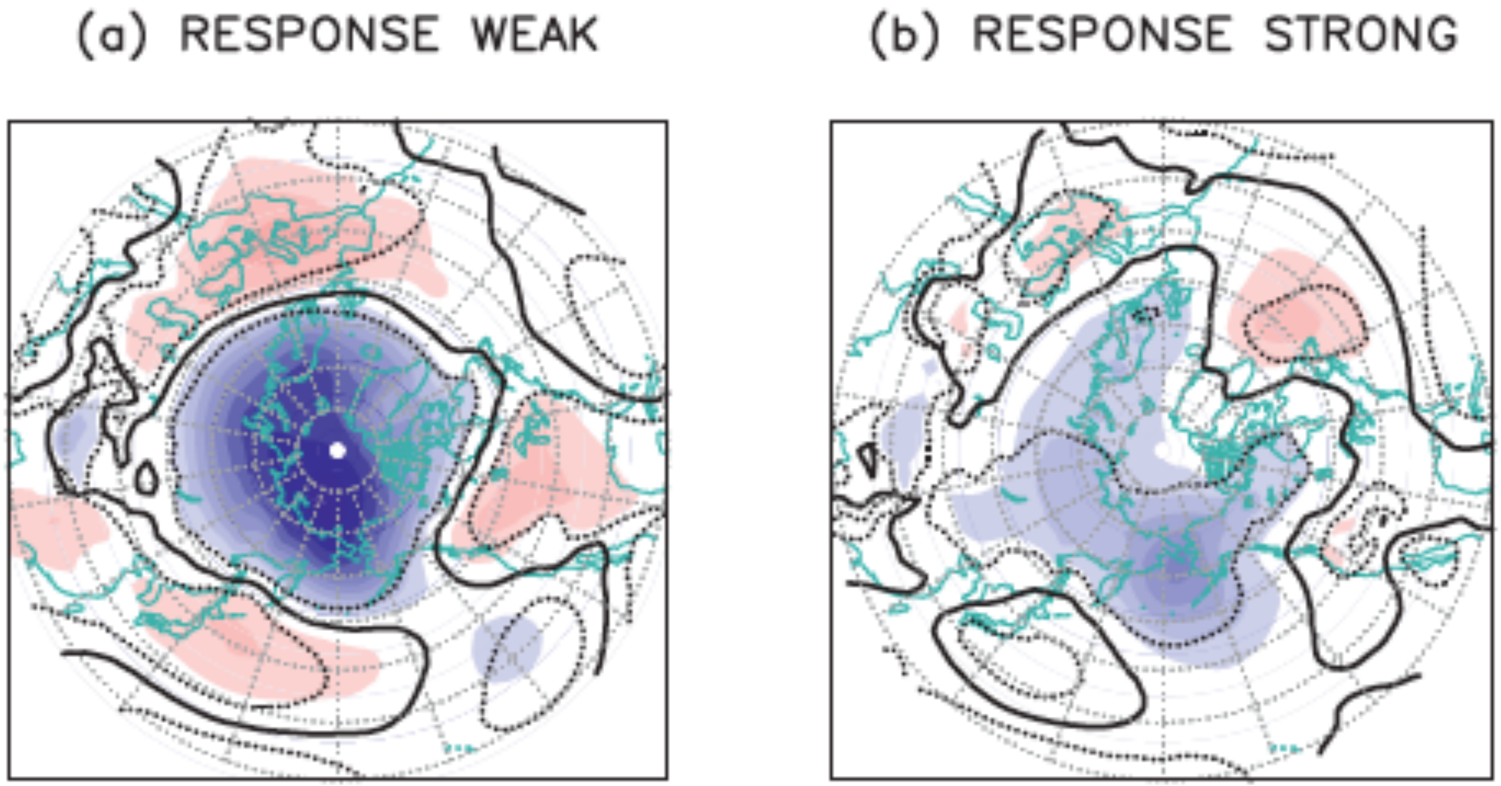
Hitchcock, Shepherd & Manney (J Clim, in press)

- Over Europe, the surface effects of stratospheric variability are comparable to those from ENSO
- Provides a mechanism for effect of QBO on high-latitude surface climate, through the Holton-Tan effect
  - Figure shows wintertime surface air temperature differences (in K) between circulation regimes



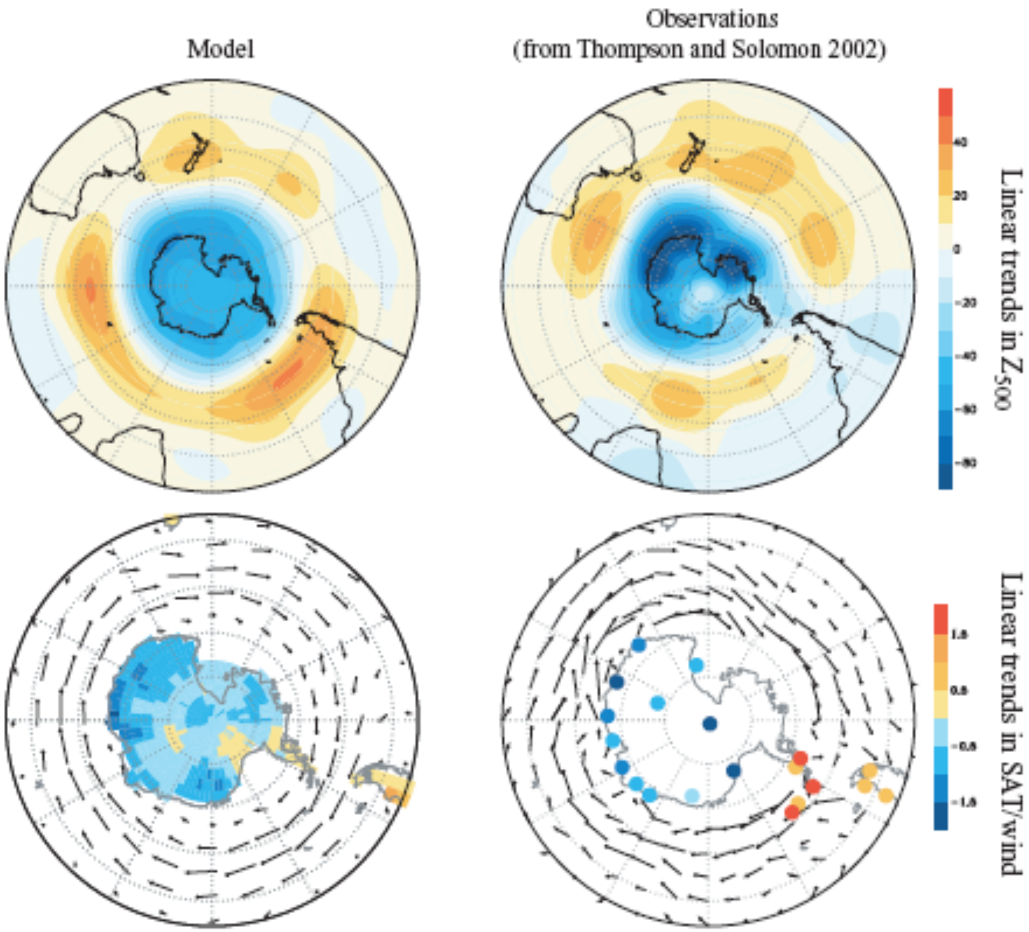
Thompson, Baldwin & Wallace (2002 J. Clim.)

- In the Arctic, the predicted wintertime surface response (here MSLP) to doubled CO_2 depends sensitively on the settings of the orographic gravity-wave drag scheme
  - Mechanism is effect on stratospheric planetary-wave drag via effect of OGWD on climatological zonal flow



CMAM results from Sigmond & Scinocca (2010 J Clim)

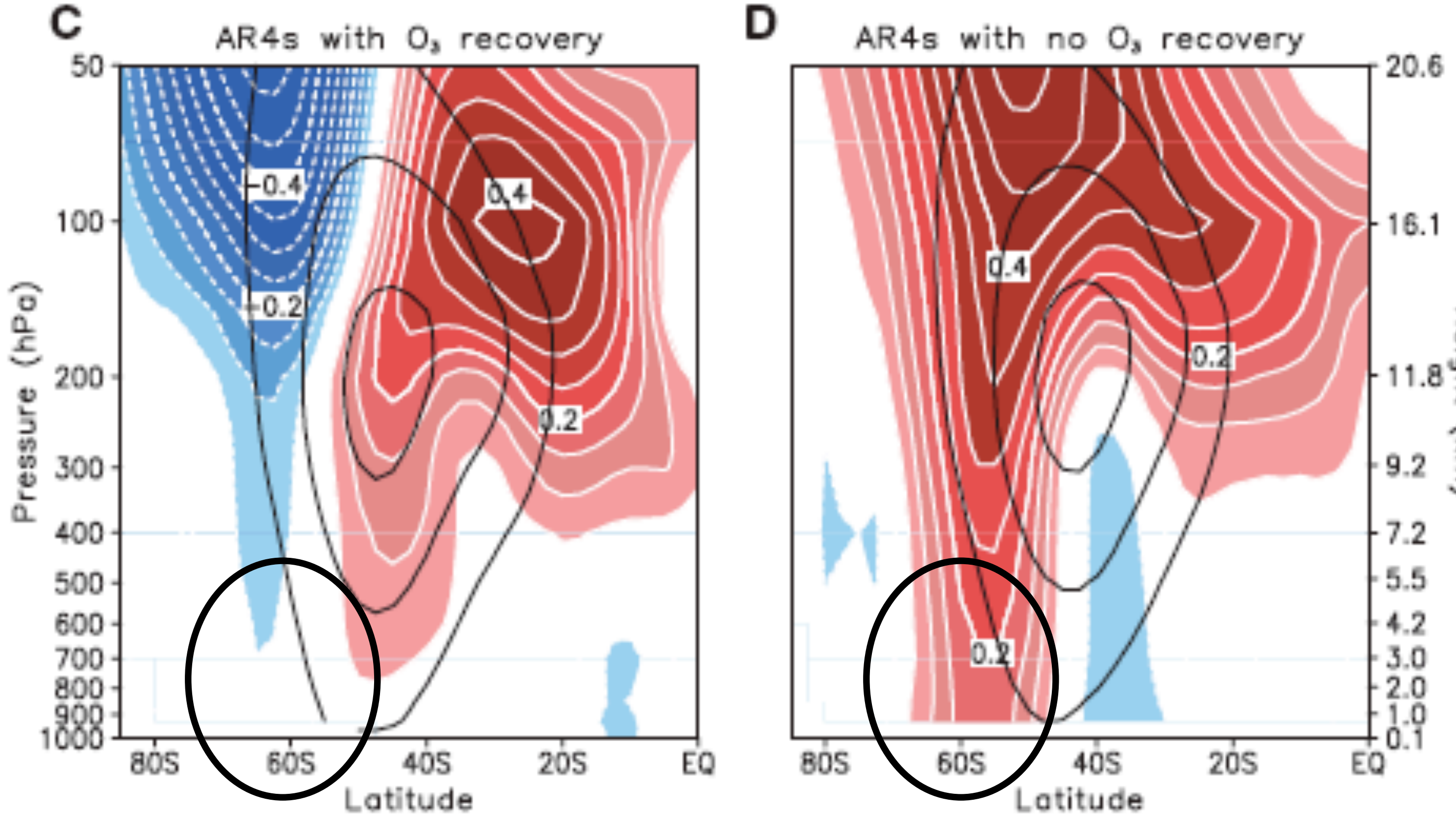
- The ozone hole has been the primary driver of recent trends in SH high-latitude summertime surface climate
  - Mechanism is not clear, but is presumably analogous to the Baldwin-Dunkerton effect



Linear trends up to 2000

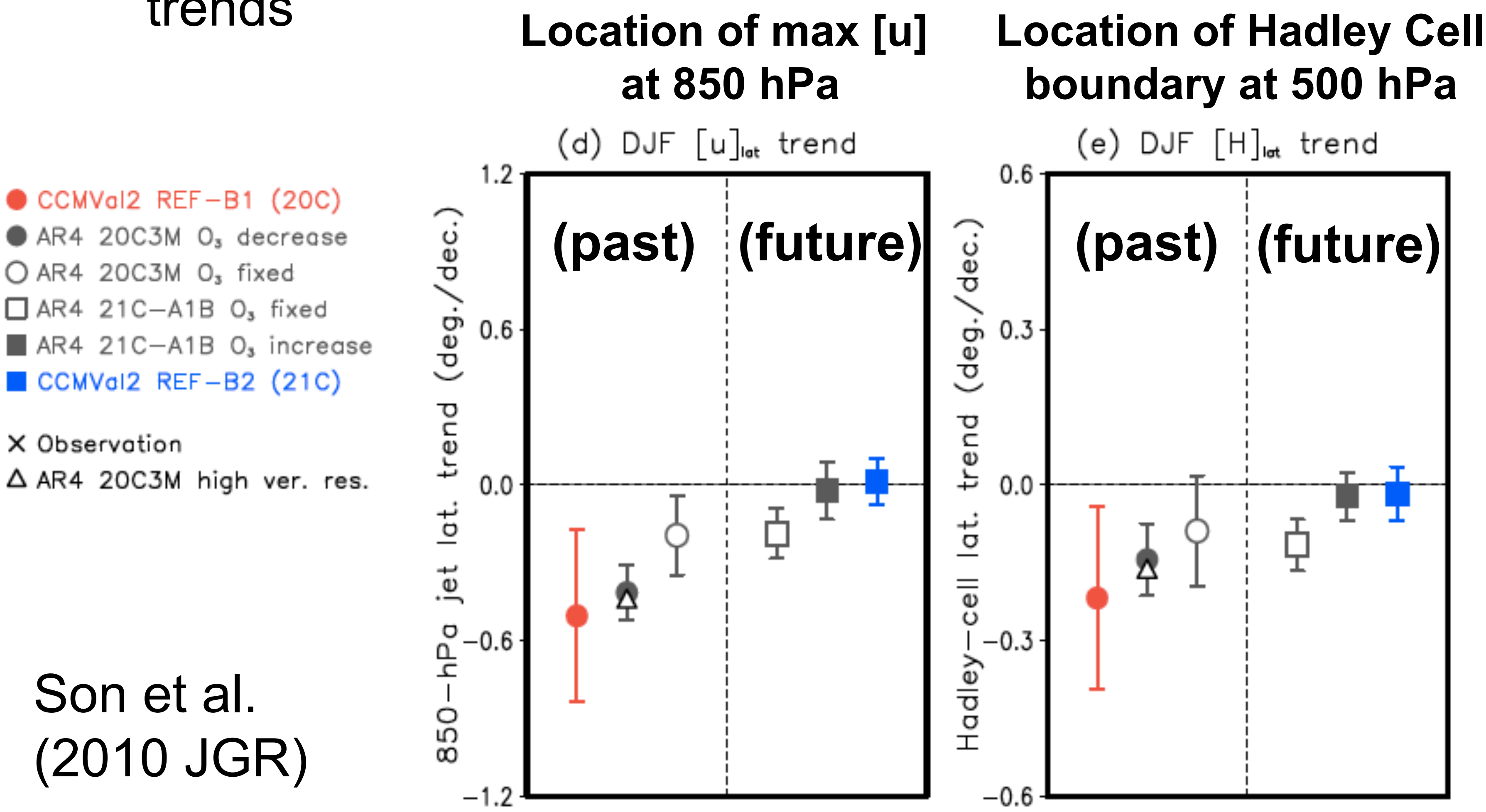
Gillett & Thompson (2003 Science)

- It follows that ozone recovery will weaken or possibly even reverse the summertime SAM trends in the future
  - Plots show DJF zonal wind trends (in m/s/decade) over 2000-2050 for IPCC AR4 models with (left) and without (right) prescribed ozone recovery



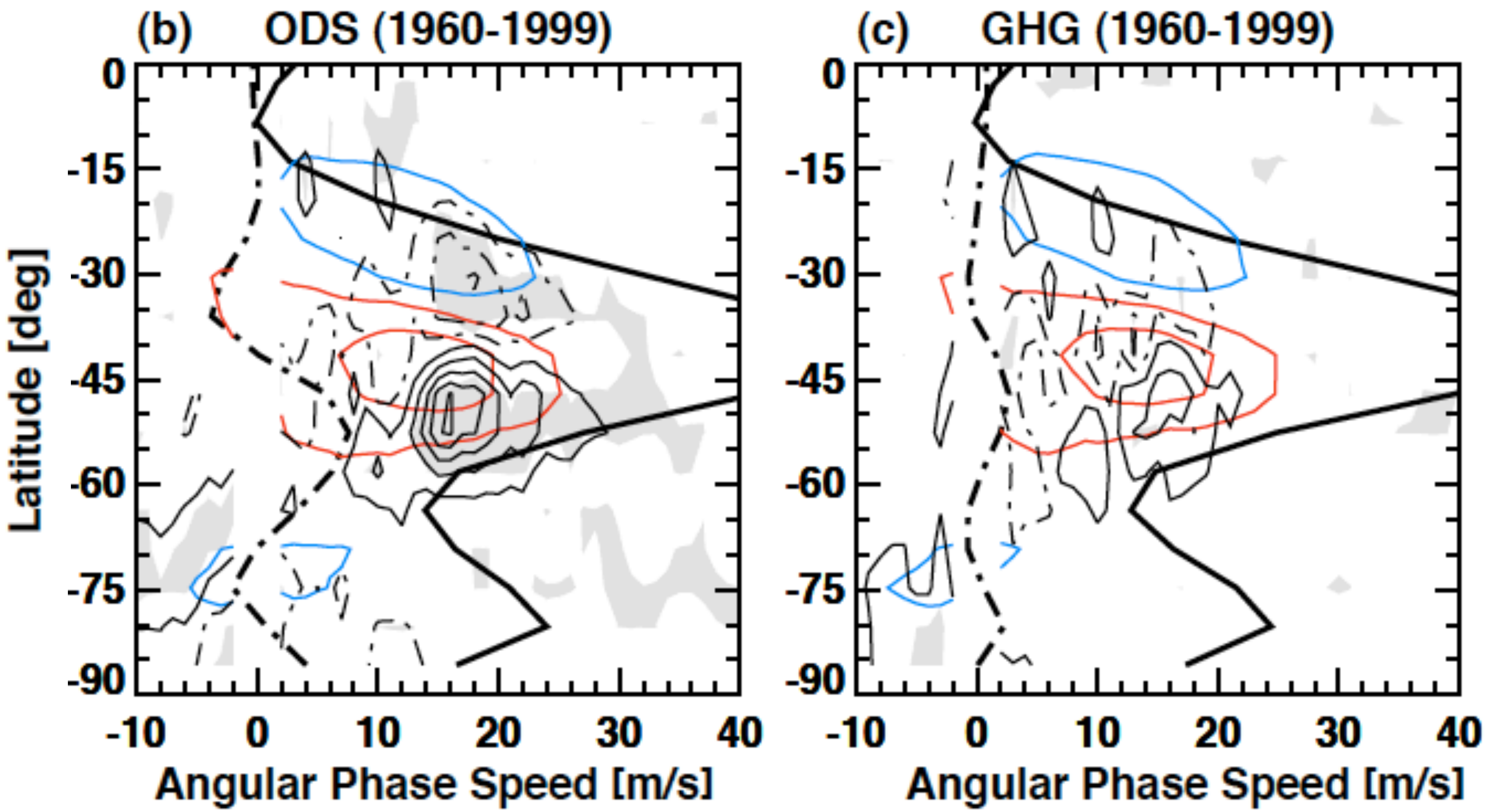
Son et al. (2008 Science)

- Models show that the ozone hole has had a major effect on the width of the Hadley cell
  - Reflected in differences between past and future trends



Son et al. (2010 JGR)

- The ozone hole causes a poleward shift in upper tropospheric eddy momentum flux convergence at subpolar latitudes, which can explain the SAM trend
  - DJF trends at 250 hPa; colours show climatology (red is positive)

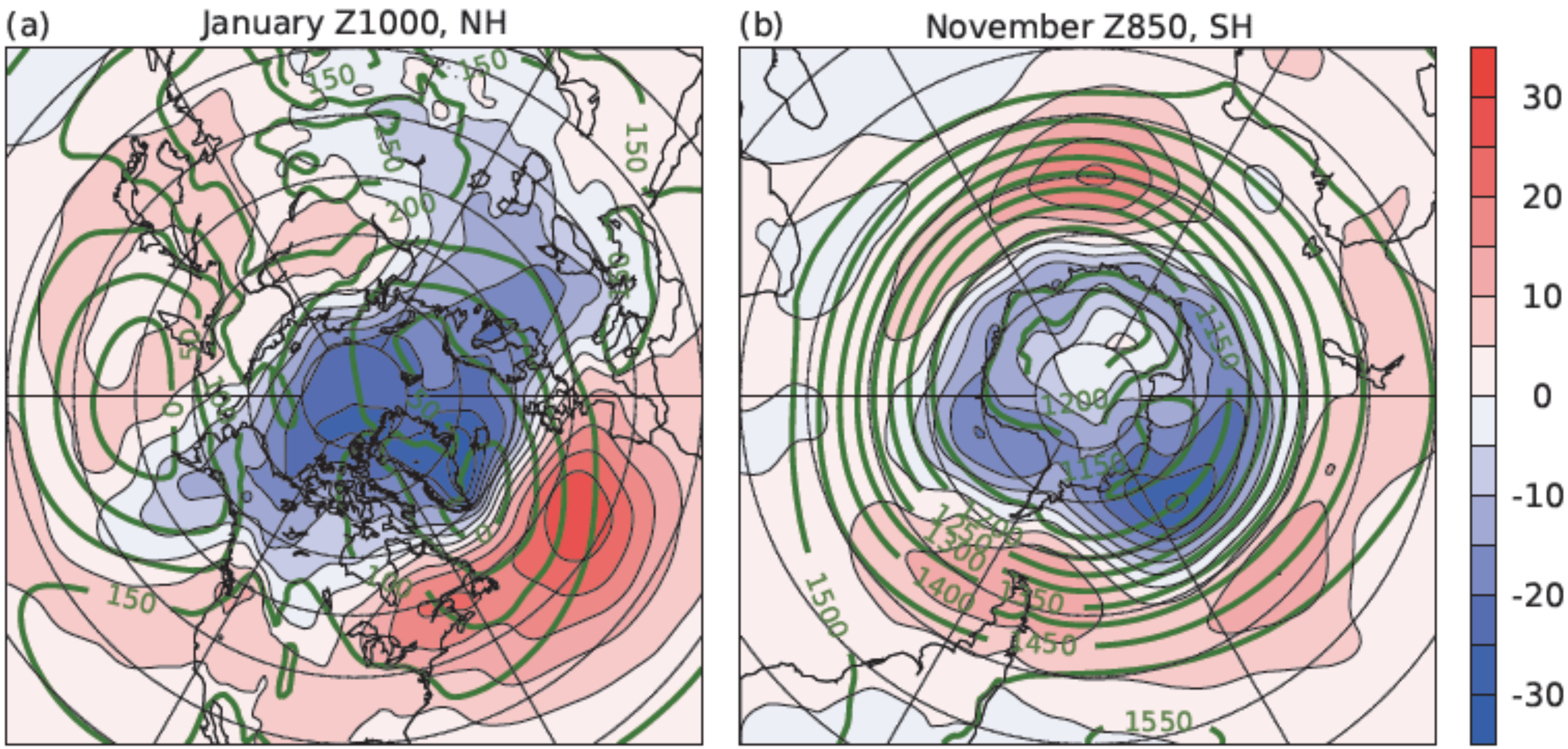


McLandress et al. (2011 J. Clim.)

Summary

- Variations in Rossby-wave forcing in the stratosphere lead to polar vortex variability
  - This variability is modulated by the QBO through the ‘Holton-Tan effect’
  - Most dramatic events are ‘Stratospheric Sudden Warmings’, about half of which exhibit extended recoveries lasting up to two months
  - The extended recoveries result from the long radiative timescales in the lower stratosphere, together with the suppression of tropospheric wave forcing
- Stratospheric polar vortex variability couples to the surface
  - Provides seasonal predictability; also effect of ozone hole on summertime SH climate

- The QBO affects surface climate, in both hemispheres (W-E differences)



Anstey & Shepherd (QJRMS, submitted)