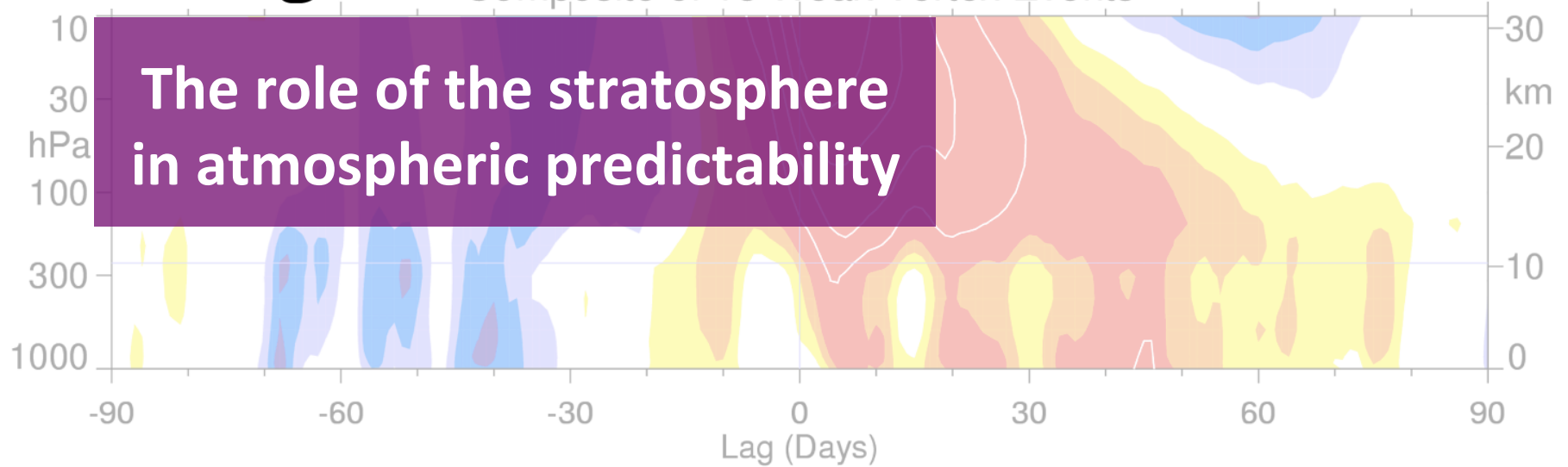


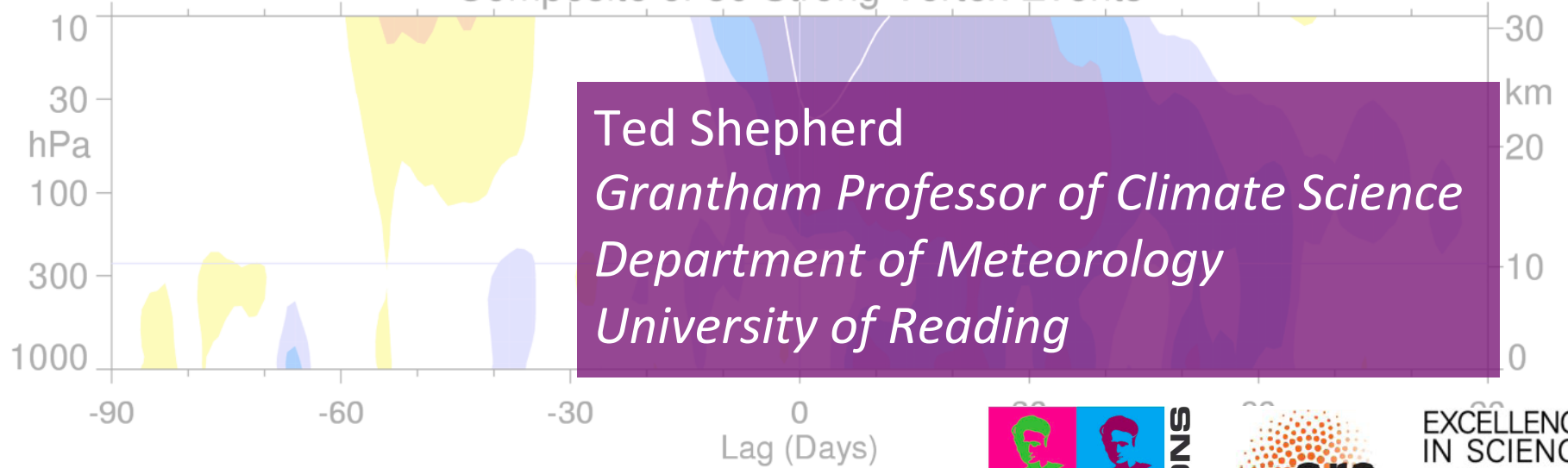


Composite of 18 Weak Vortex Events



B

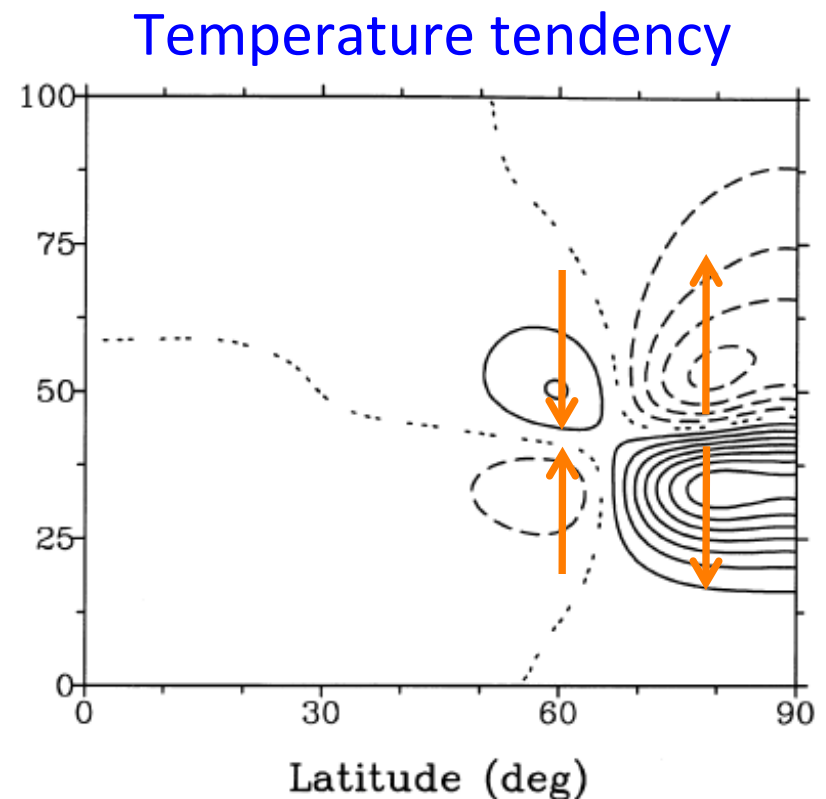
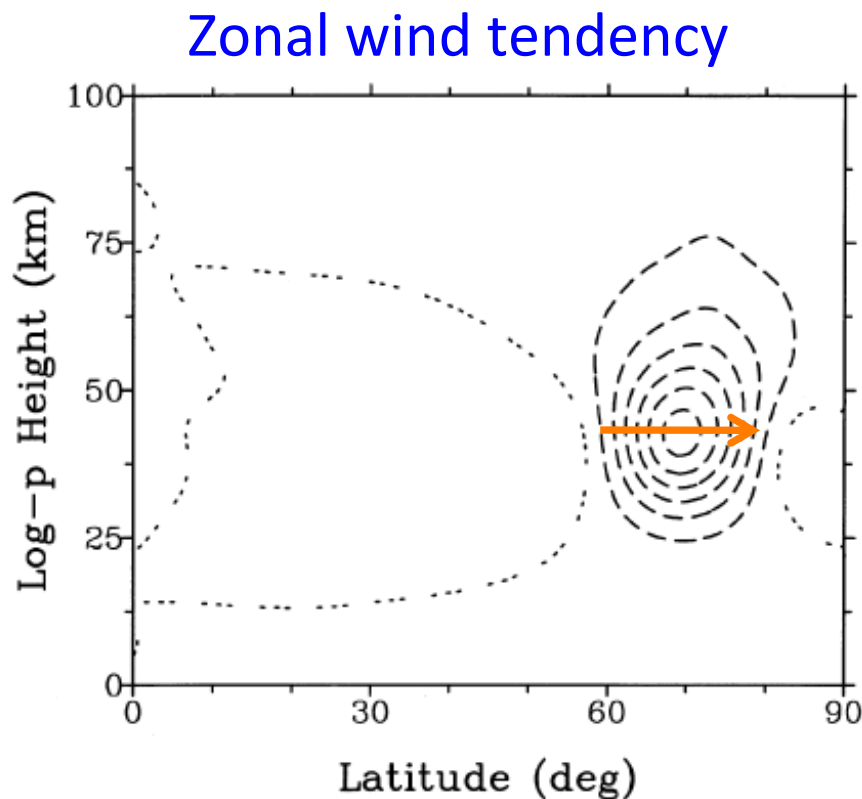
Composite of 30 Strong Vortex Events



Some dynamical basics

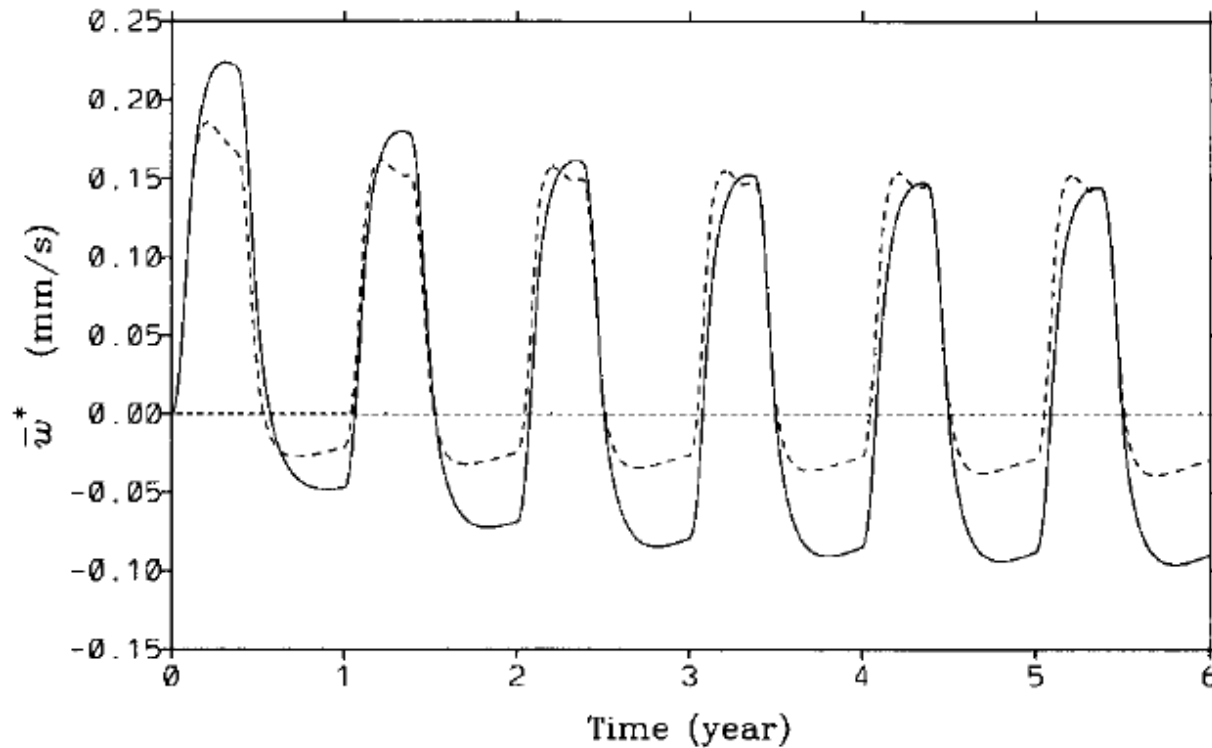
- Atmospheric waves (Rossby, equatorial, gravity) propagate from the denser troposphere up into the stratosphere
 - Waves transfer angular momentum and energy
 - The energy can be radiated to space but the angular momentum budget is closed
- The stratosphere is dynamically stable, so its circulation is 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-flow interaction**
- 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 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

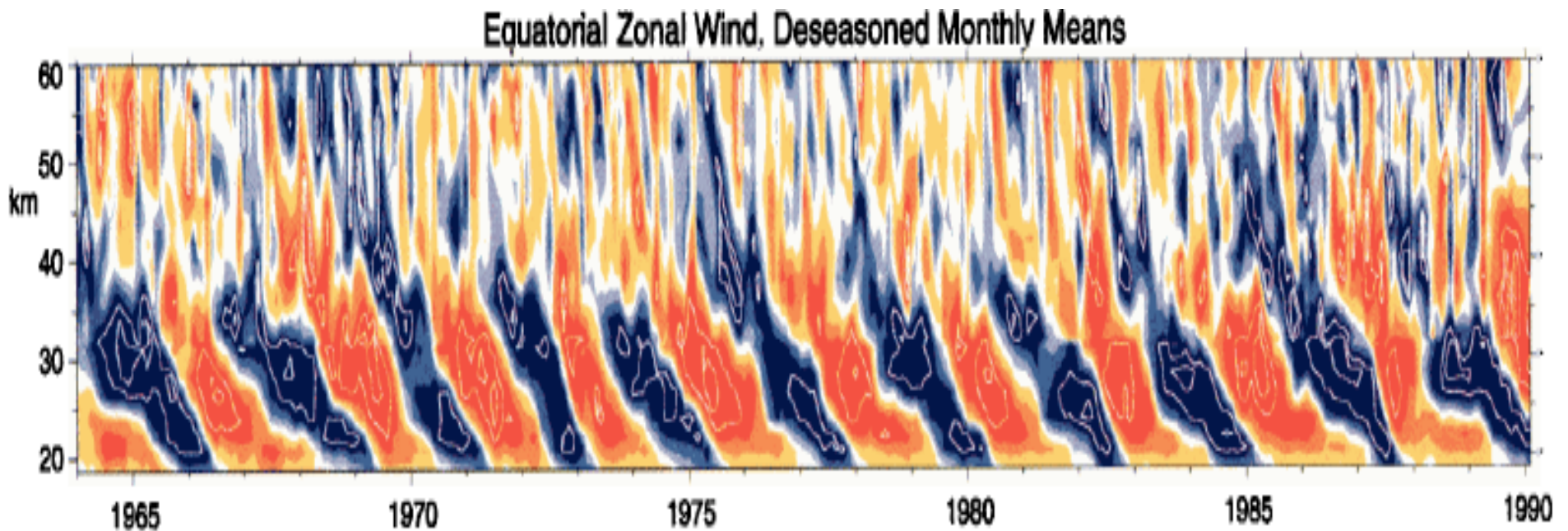


Equatorial upwelling
in linear (solid) and
nonlinear (dashed)
zonally symmetric
model

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 (see e.g. Plumb 1977 JAS), which are super-rotating in their eastward phase
- Manifested in the stratospheric **Quasi-Biennial Oscillation** (QBO) — an obvious source of seasonal predictability



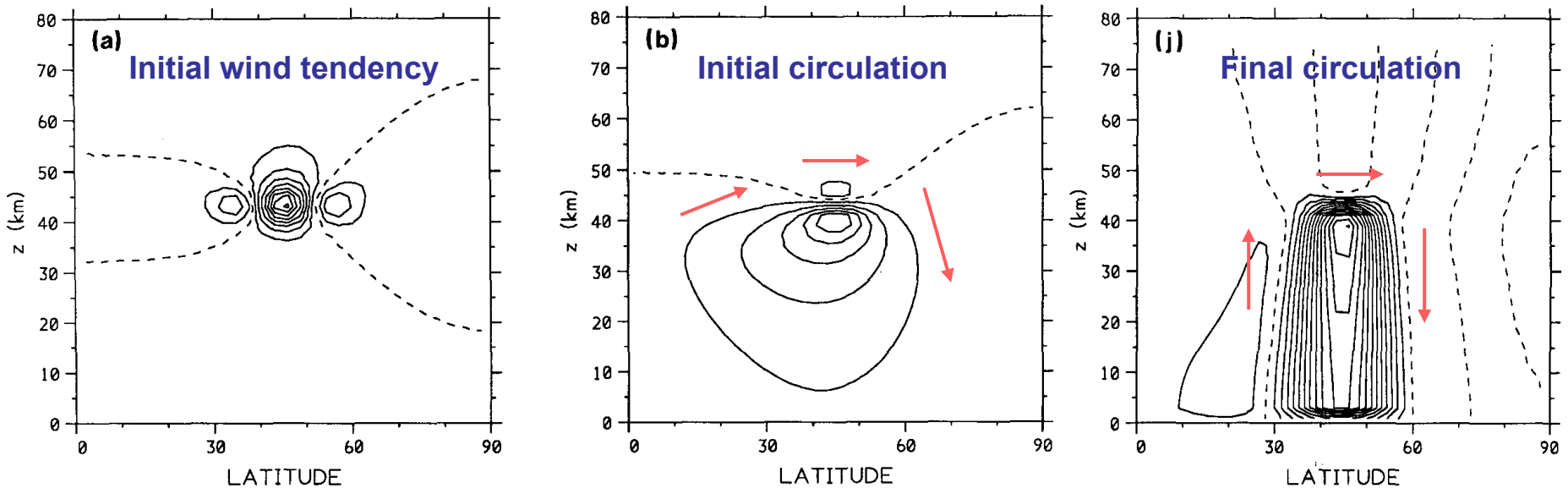
Observations from Baldwin et al. (2001 Rev. Geophys.)

- In the extratropics, persistent torques lead to downward ‘burrowing’ of the mean meridional circulation (so-called **downward control**); negative torque \Rightarrow poleward flow

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

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

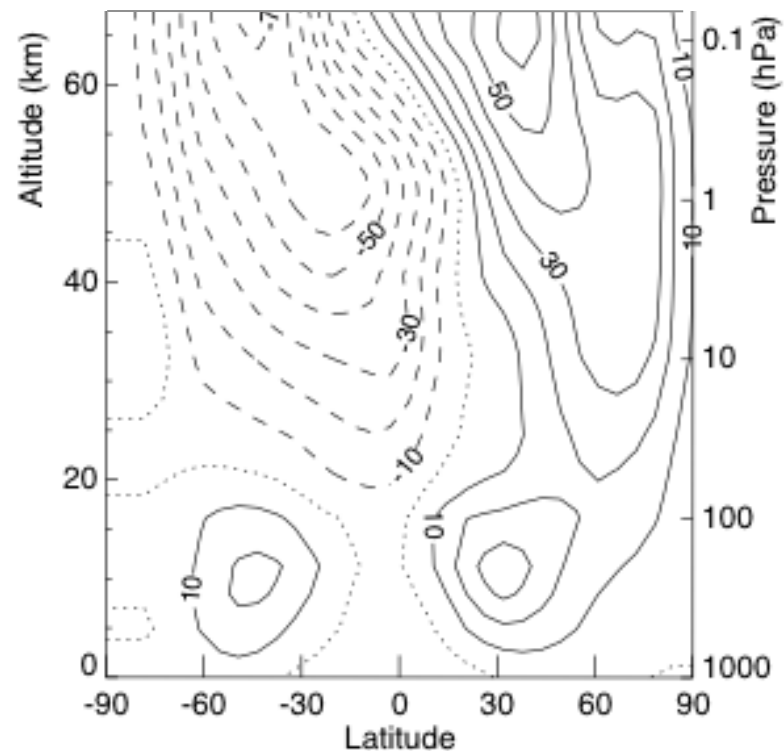
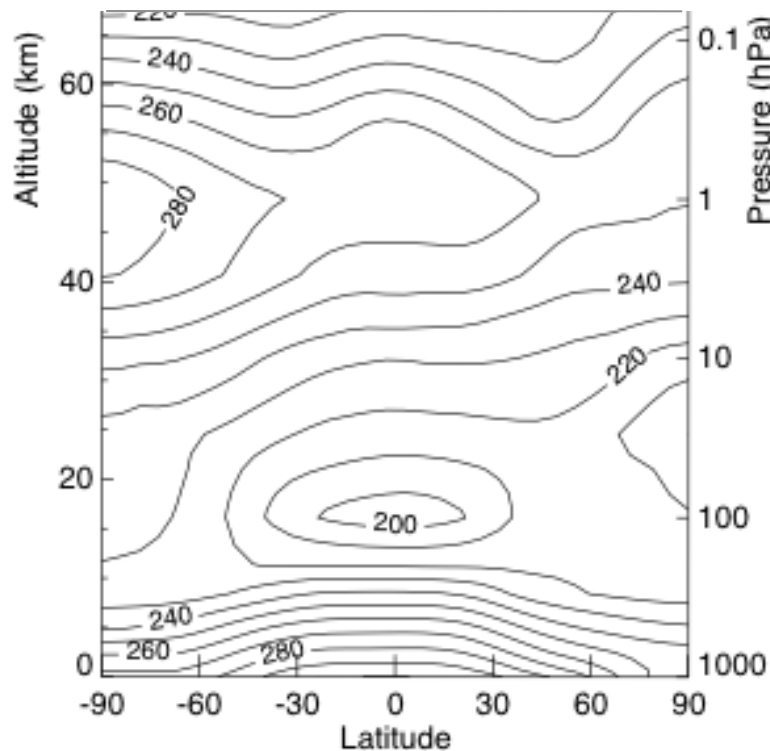
(u is absolute velocity)



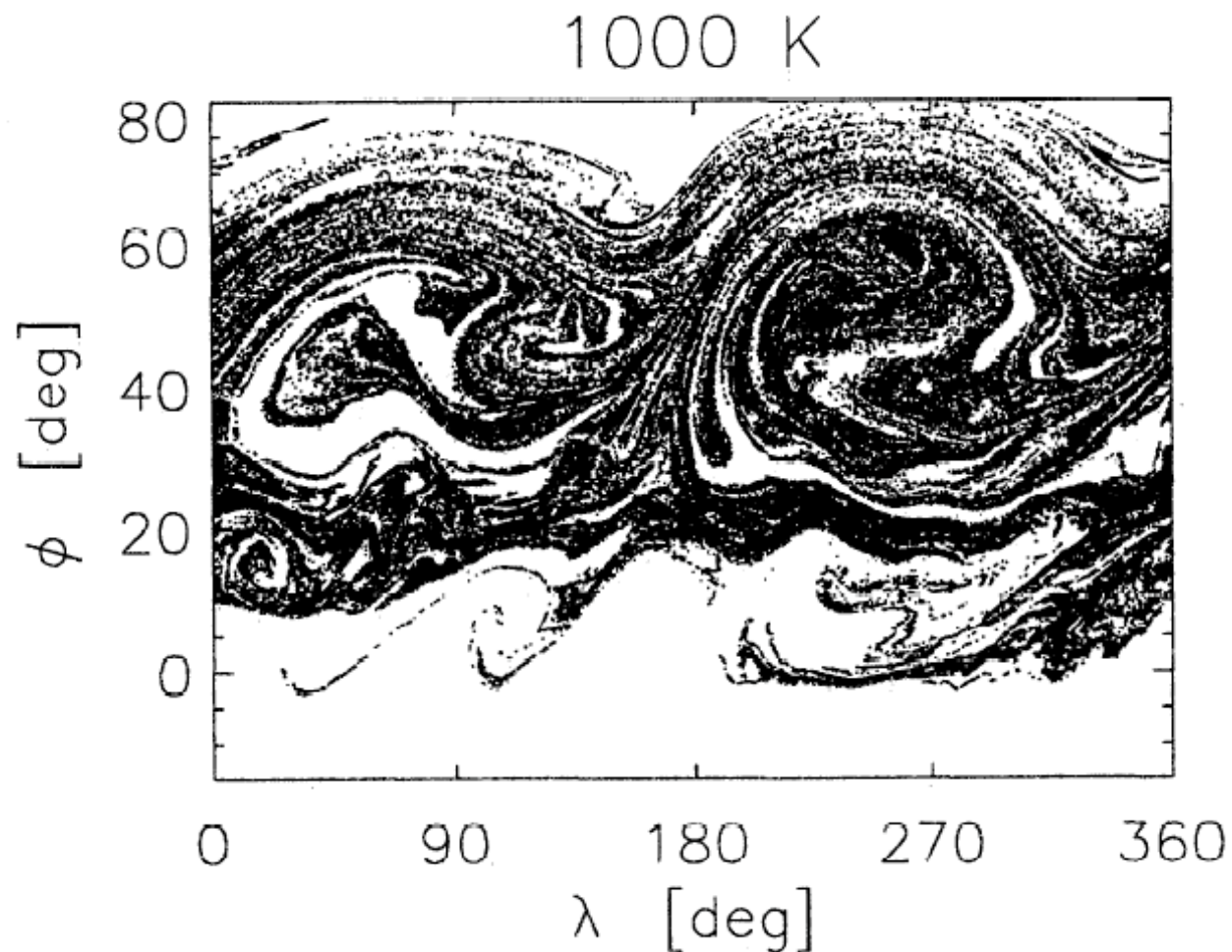
Zonally symmetric calculations from Haynes et al. (1991 JAS)

- The small thermal inertia of the stratosphere means that 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)



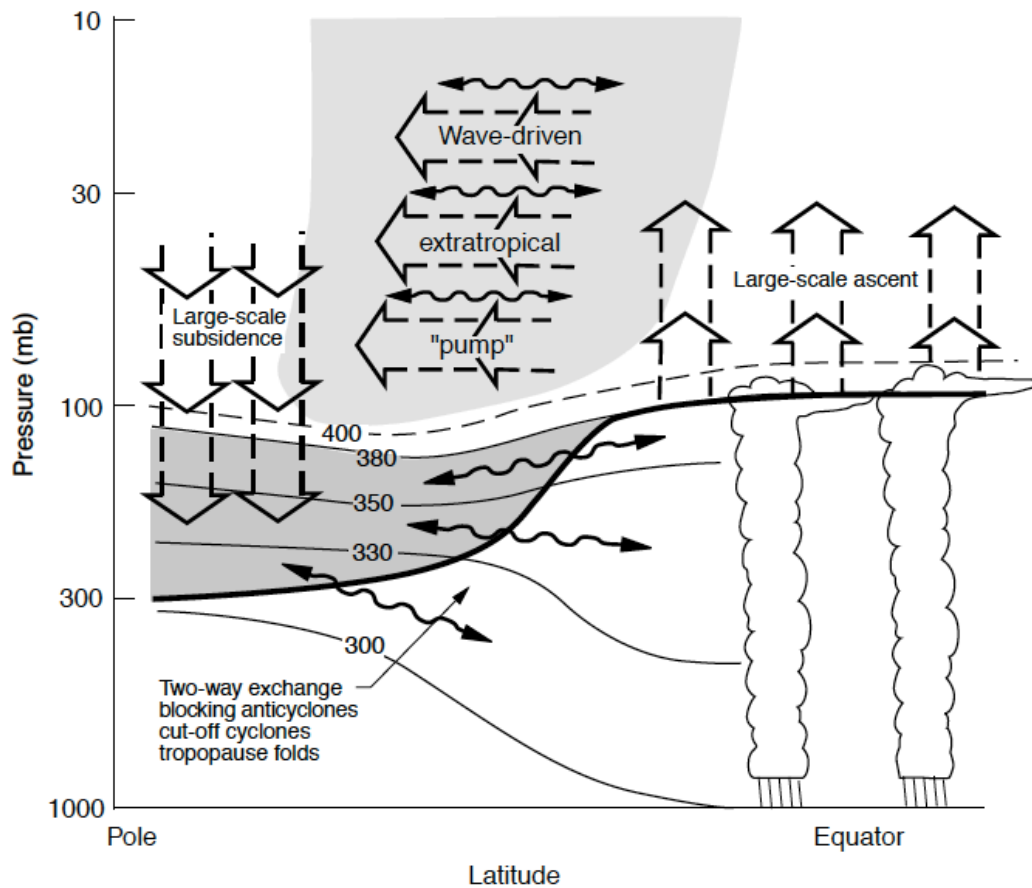
- When the flow is westerly, planetary-scale Rossby waves can propagate into the stratosphere (Charney & Drazin 1961 JGR), where they break in a hemispheric-wide ‘surf zone’ (McIntyre & Palmer 1983 Nature)



Off-line isentropic particle advection at approx. 35 km altitude driven by winds from the Canadian Middle Atmosphere Model (CMAM)

Shepherd, Koshyk & Ngan (2000 JGR)

- Rossby waves always transfer *negative* angular momentum, so drive poleward flow where they dissipate
- This is the origin of the ‘Brewer-Dobson circulation’, which cools the tropics and warms the poles



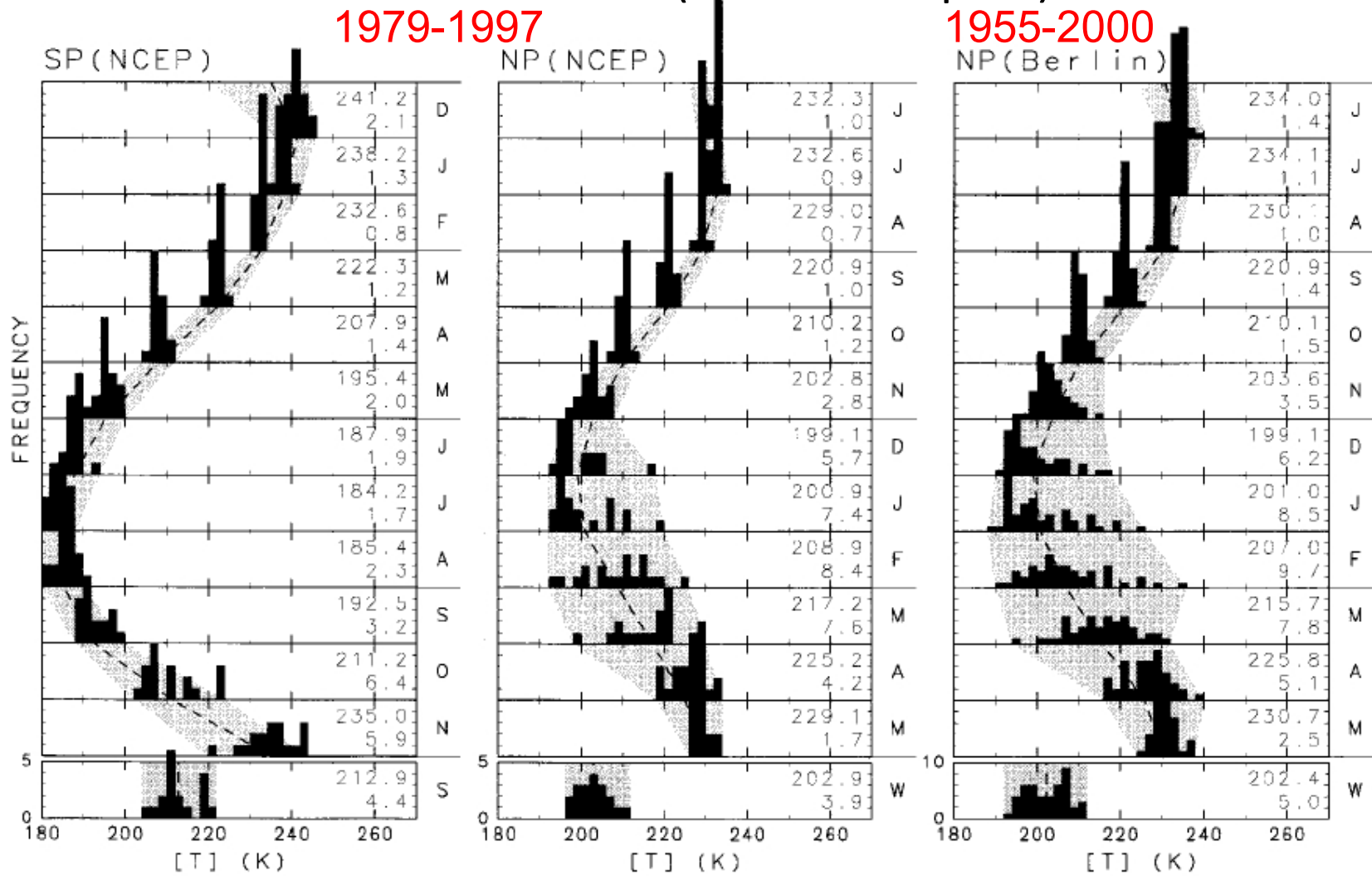
Mainly operates in the winter hemisphere

The very large width of the ‘surf zone’ provides a mechanism for coupling between tropical and polar latitudes

Holton et al. (1995 Rev. Geophys.)

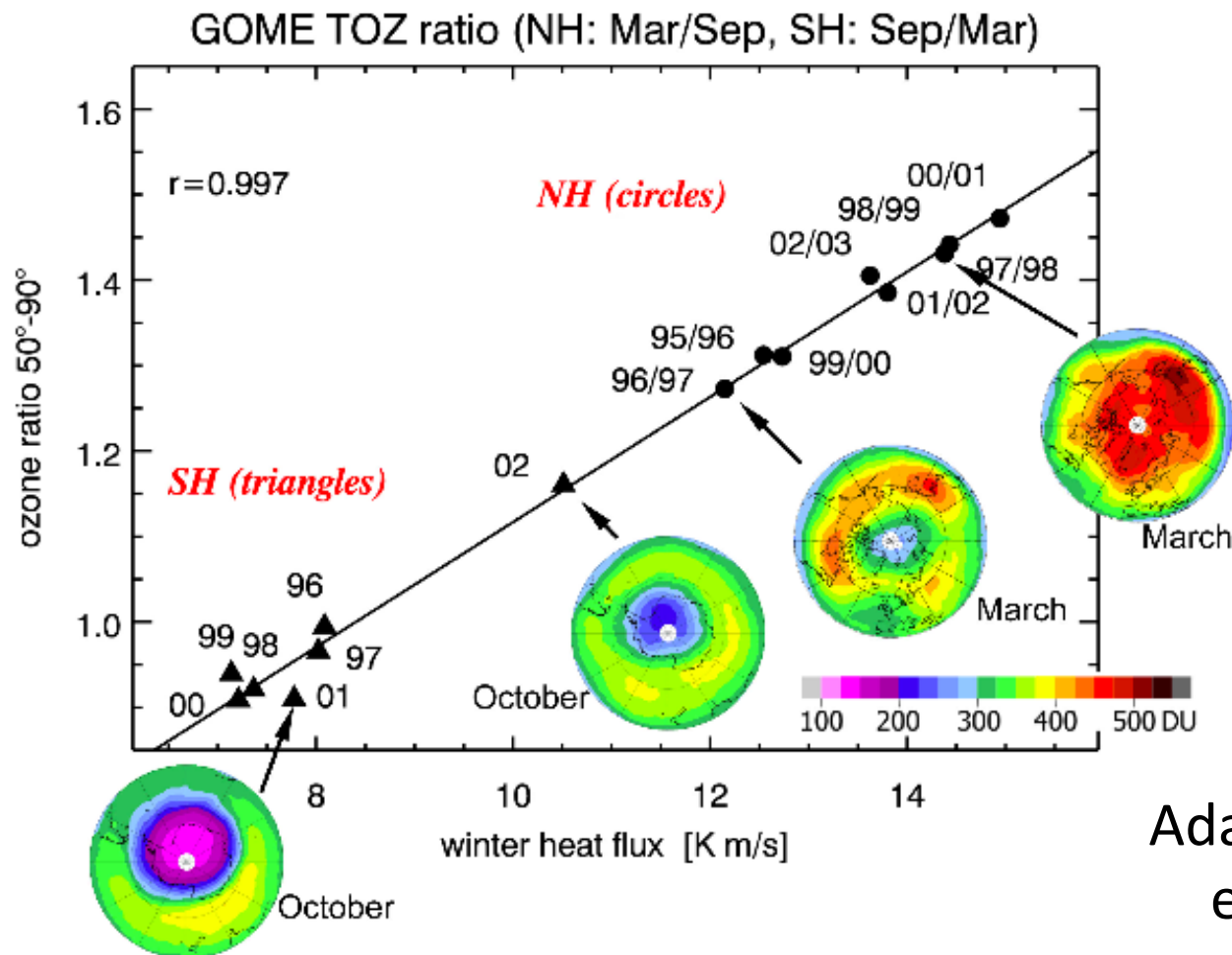
- Forcing of planetary Rossby waves is stronger in the NH than in the SH, so the Arctic winter is warmer and more variable than the Antarctic (summer is quiet)

Polar temperatures at 30 hPa (approx 25 km)



Yoden, Taguchi & Naito (2002 JMSJ)

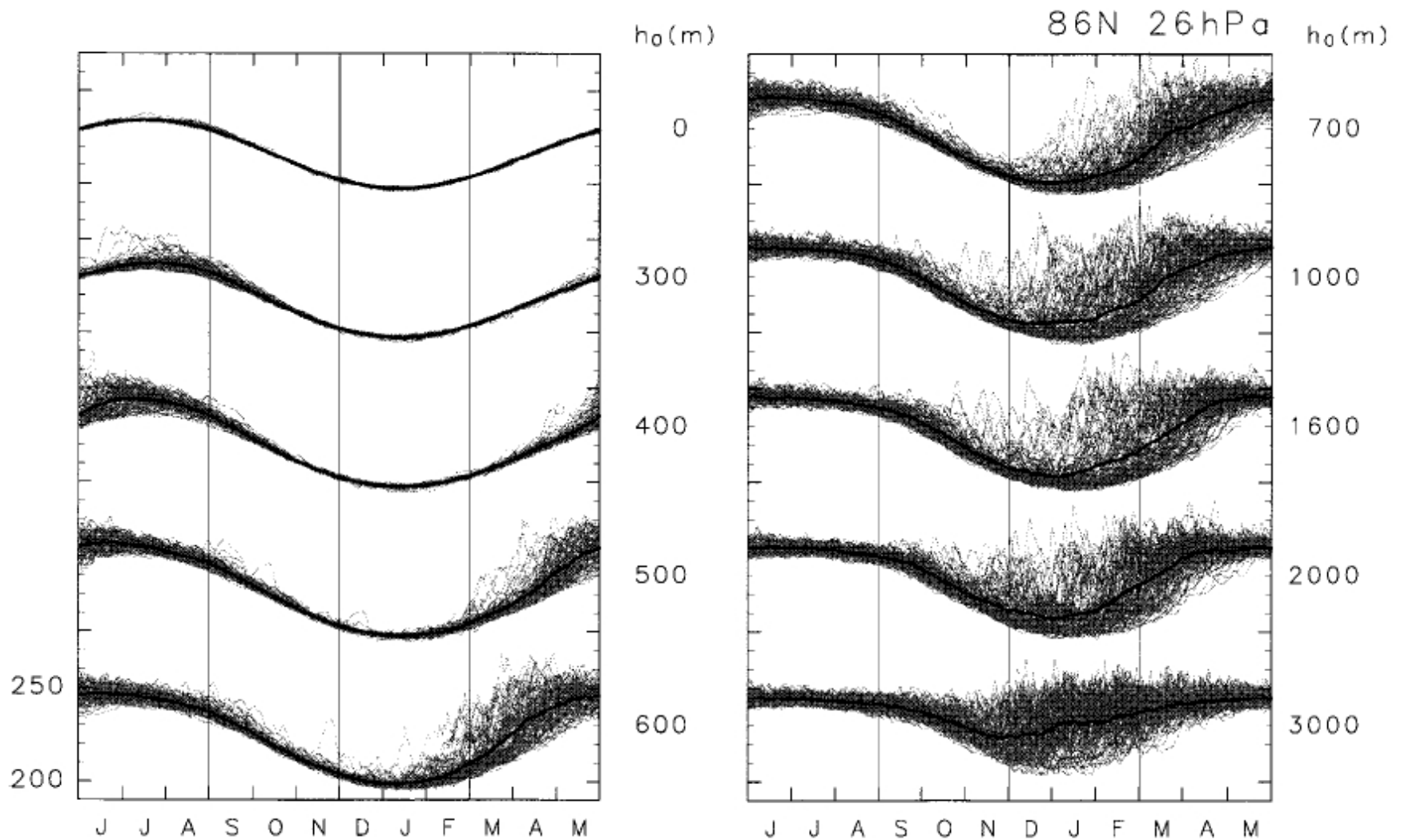
- Variations in the upward wave forcing ('winter heat flux', proportional to vertical Eliassen-Palm flux) are associated with variations in polar downwelling, hence in polar vortex strength and in polar ozone abundance



There is a continuous transition between the two hemispheres

Adapted from Weber et al. (2003 GRL)

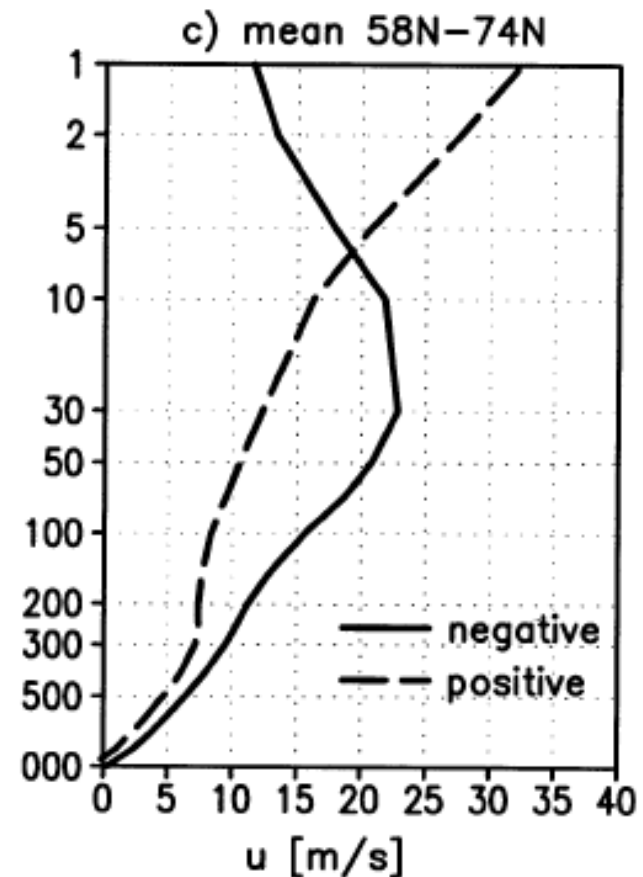
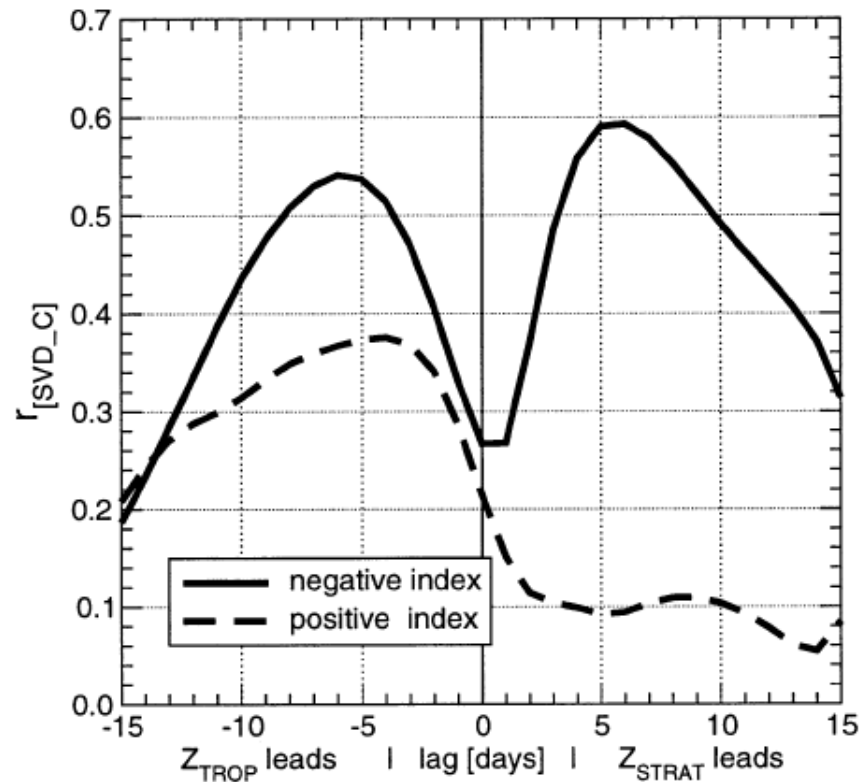
- Response of polar temperatures to increasing wave forcing h_0 in a mechanistic model reveals complex dynamics



Yoden, Taguchi & Naito (2002 JMSJ)

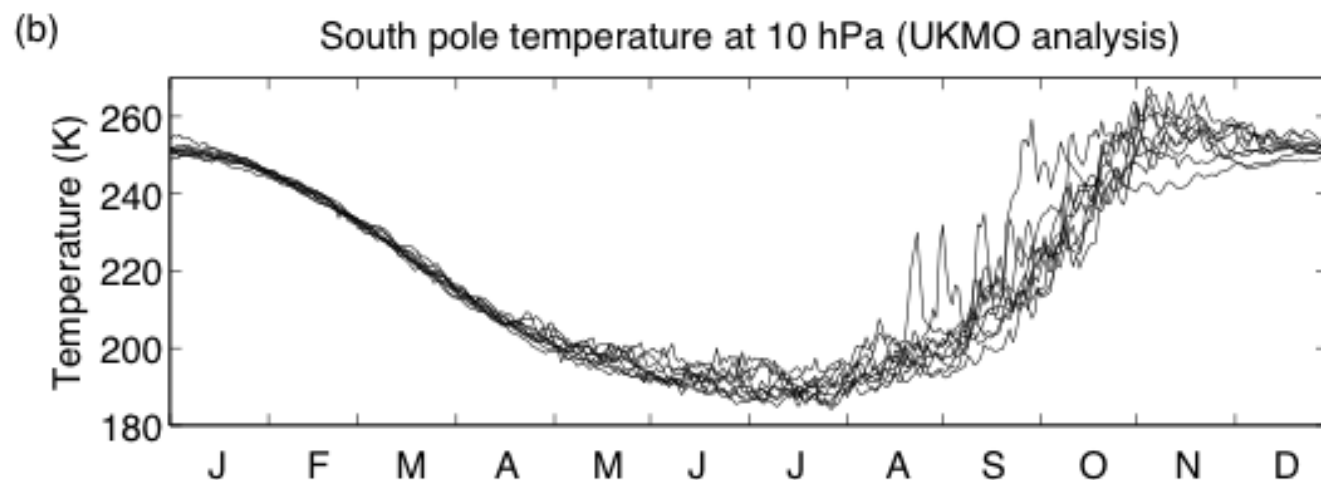
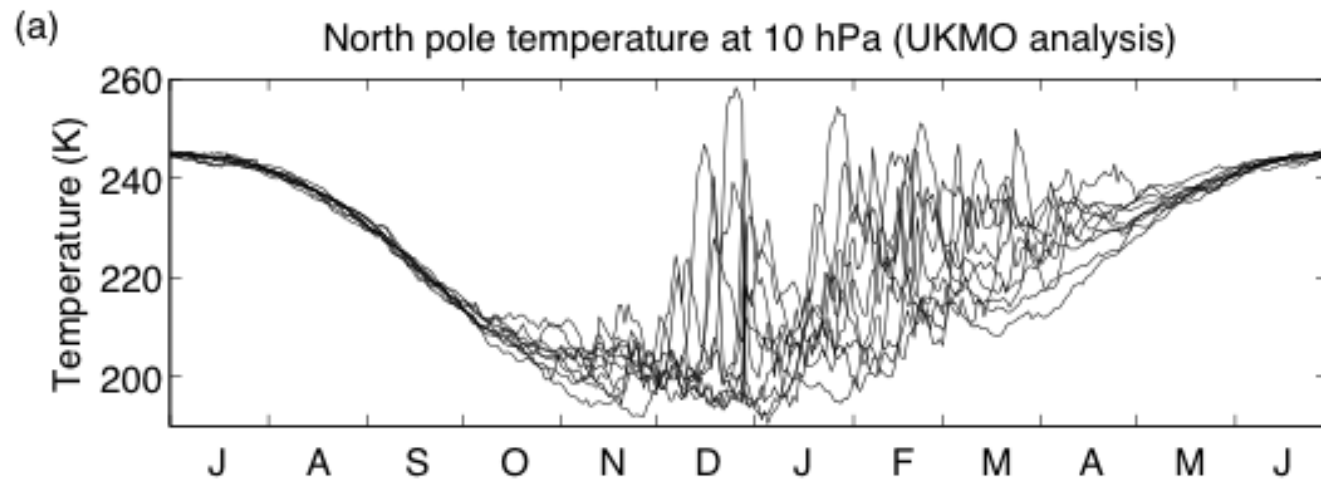
- Observations suggest that the upward EP flux depends in part on the state of the stratosphere
 - The stratosphere can provide a non-trivial upper boundary condition for tropospheric planetary waves

Correlation between $k=1$ variability in troposphere and stratosphere

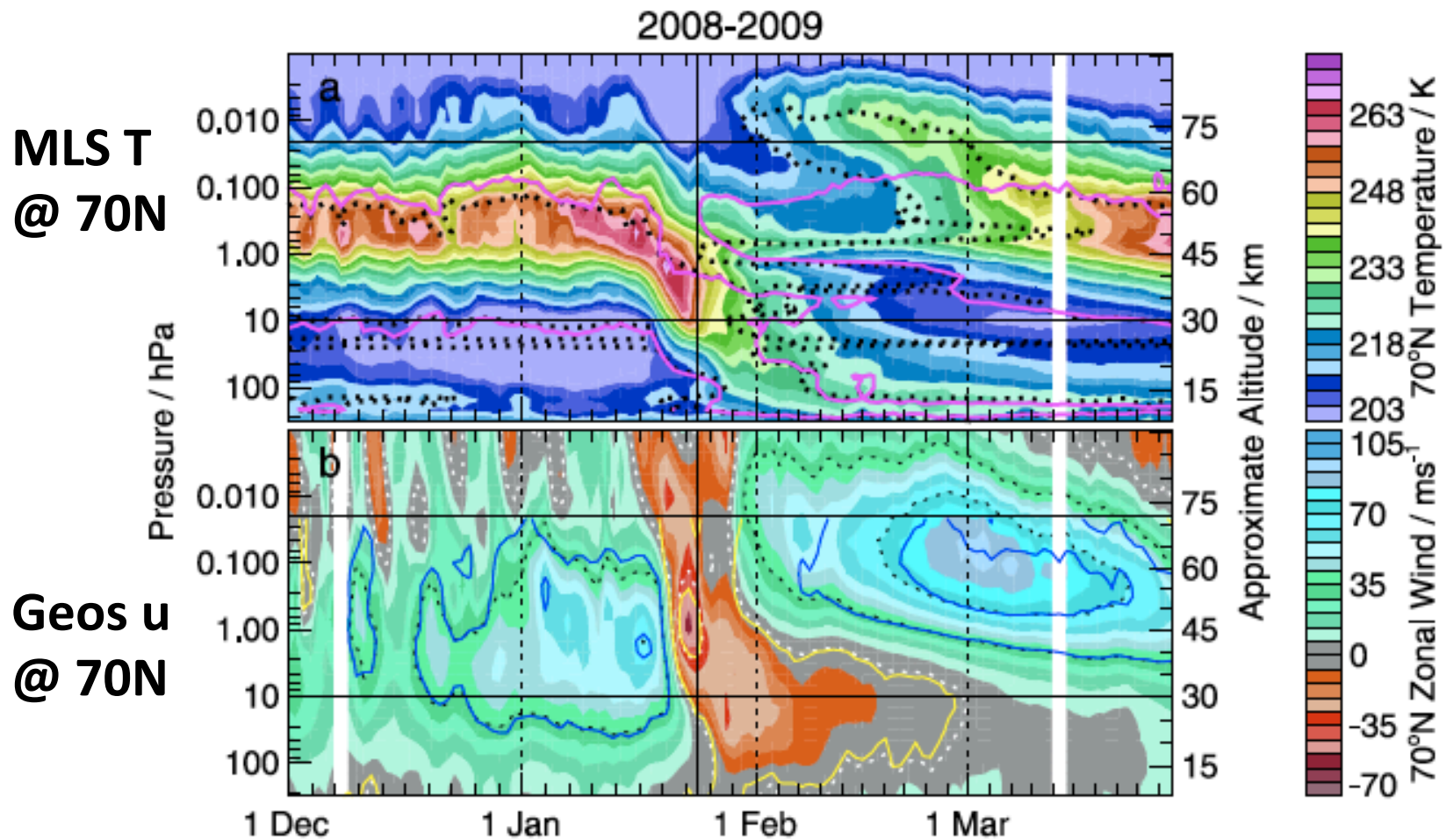


Perlwitz & Harnik (2003 J. Clim.)

- 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

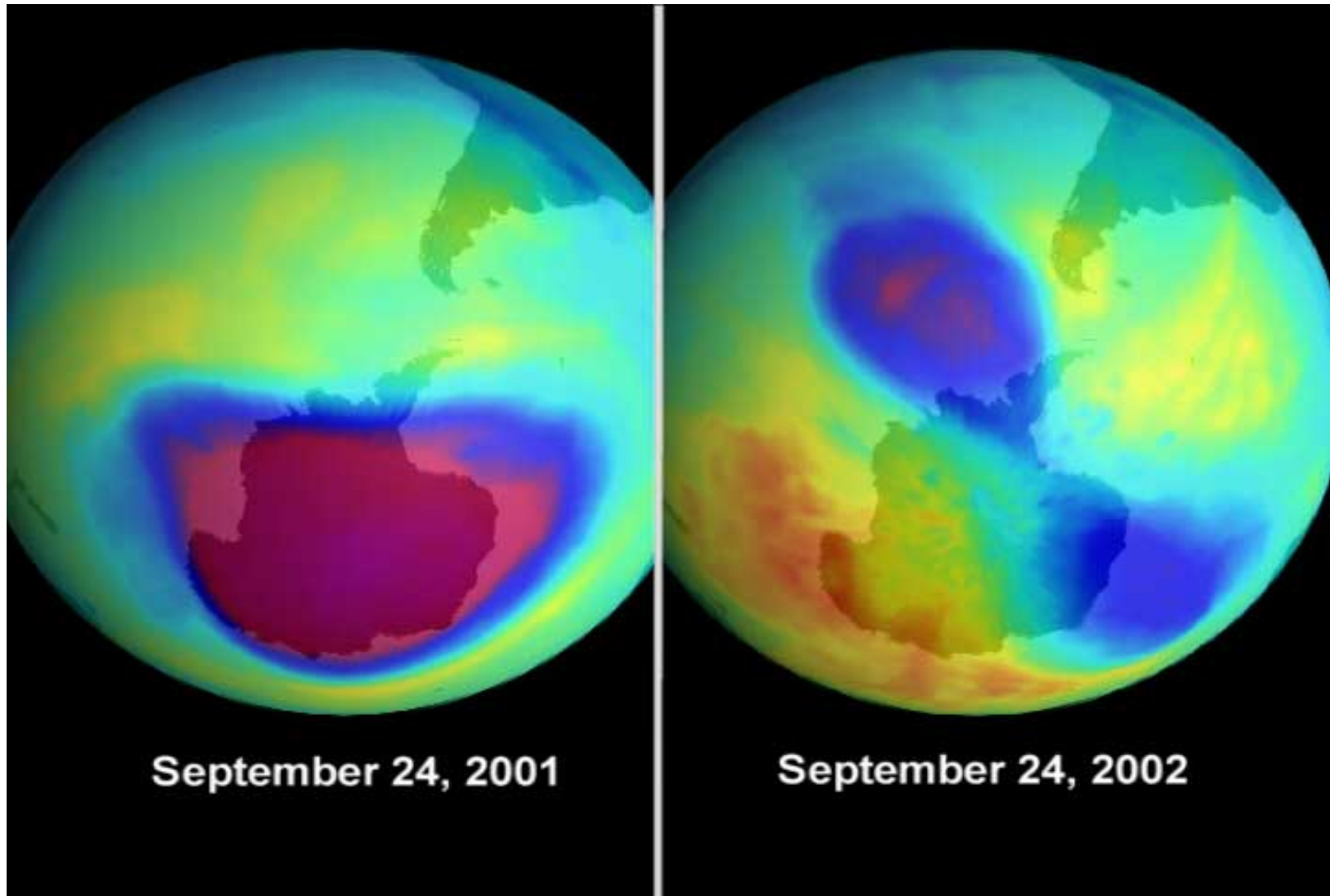


- The most dramatic polar disturbances are **Stratospheric Sudden Warmings** (SSWs); because the winds become easterly, it can take the rest of the winter to recover
 - Highly predictable life cycle (Hitchcock & Shepherd 2013 JAS)

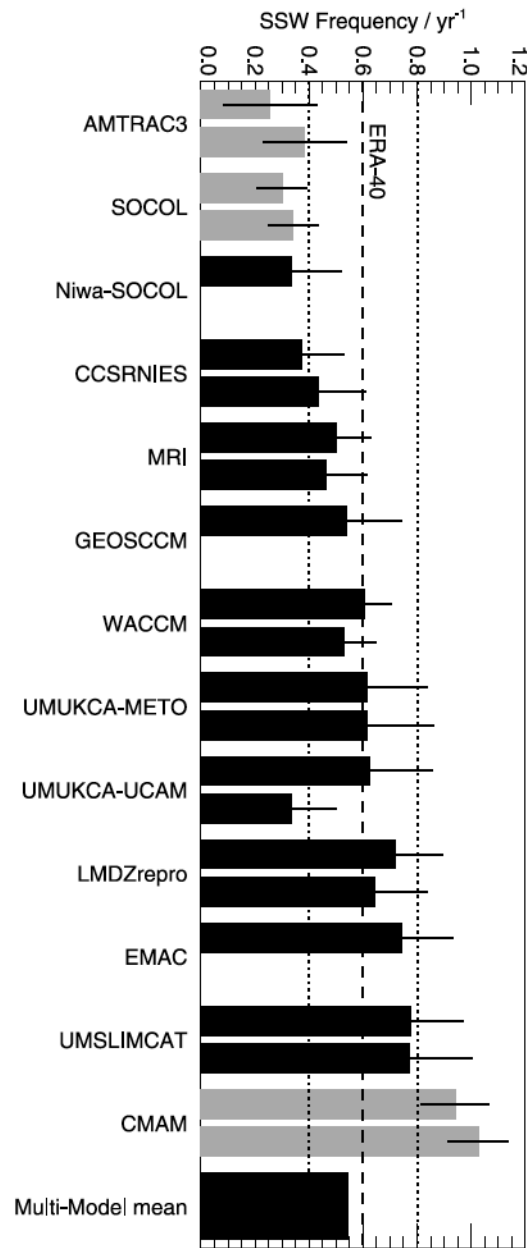


Manney et al. (2009 GRL)

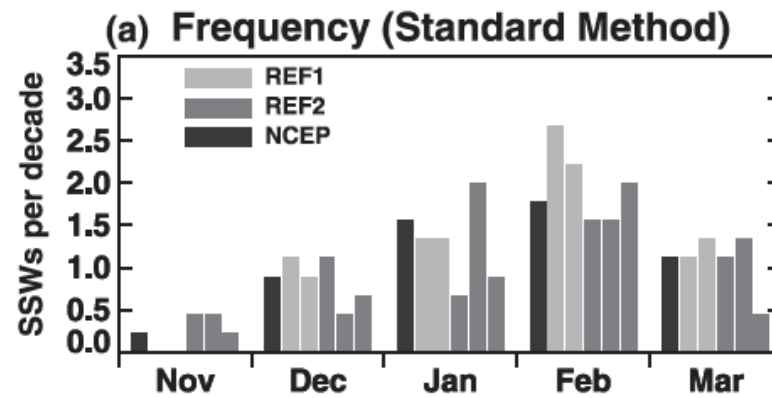
The split ozone hole of 2002: a wave-2 sudden warming



TOMS data (smoothed), from NASA GSFC web site



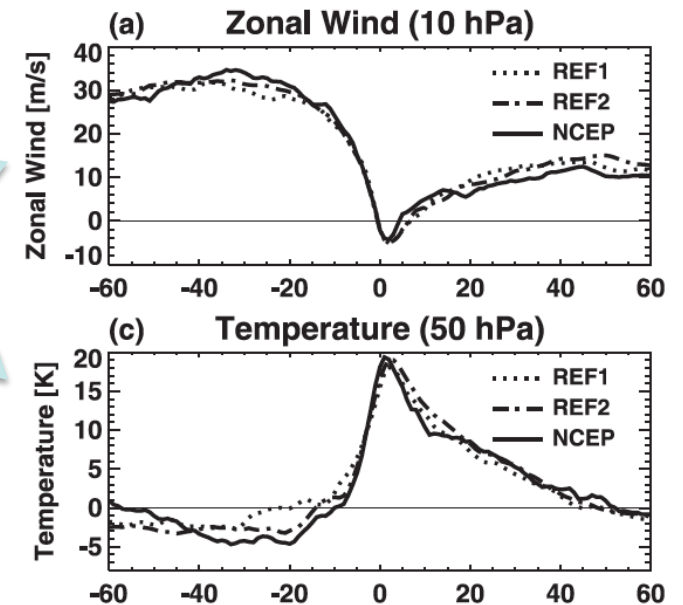
- In general, stratosphere-resolving climate models simulate SSWs fairly well
- However the models need to be tuned carefully to achieve this (gravity-wave drag)



McLandress & Shepherd
(2009 J. Clim.)

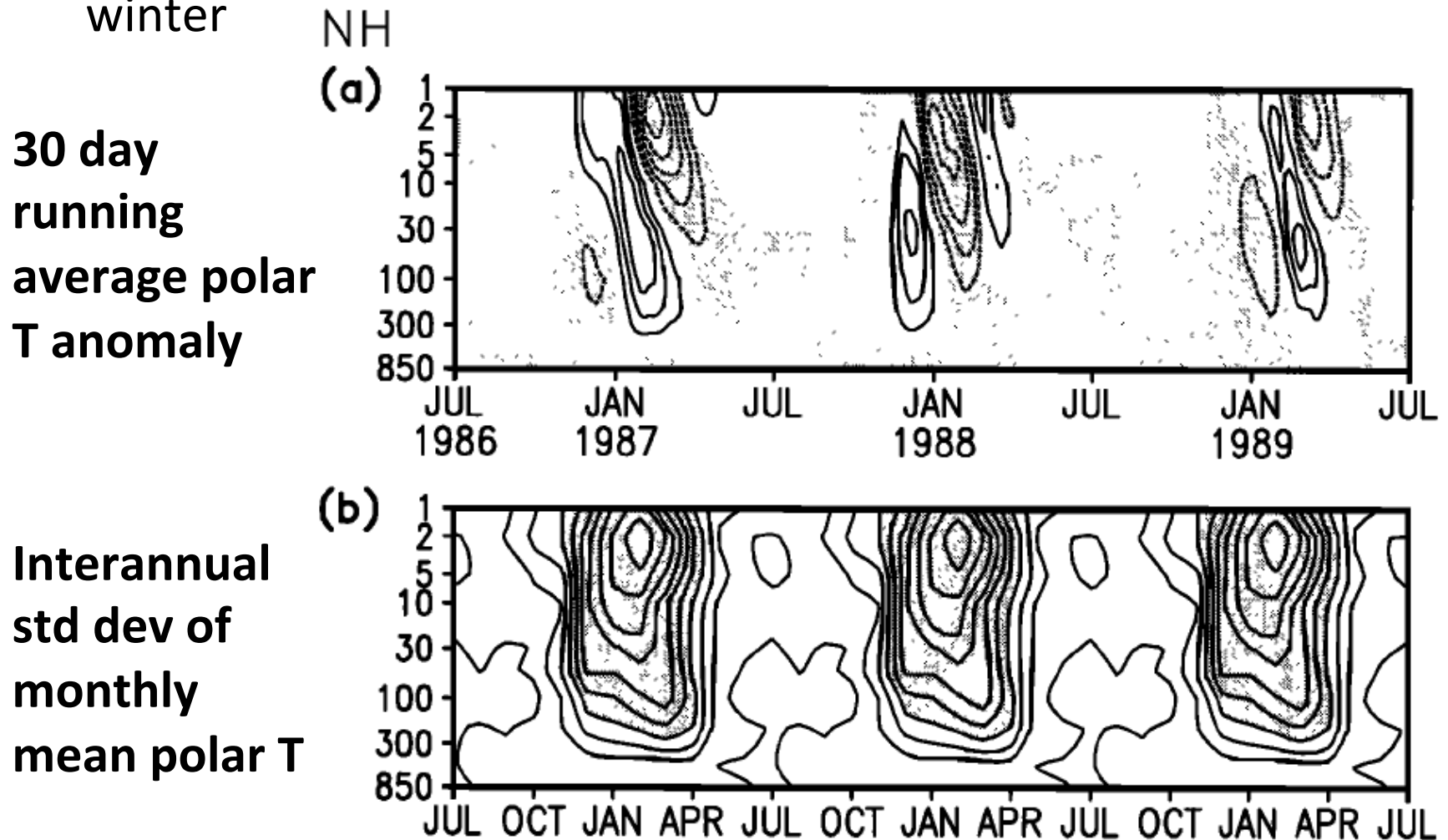
CMAM (CCMVal-1)

CMAM (CCMVal-2)



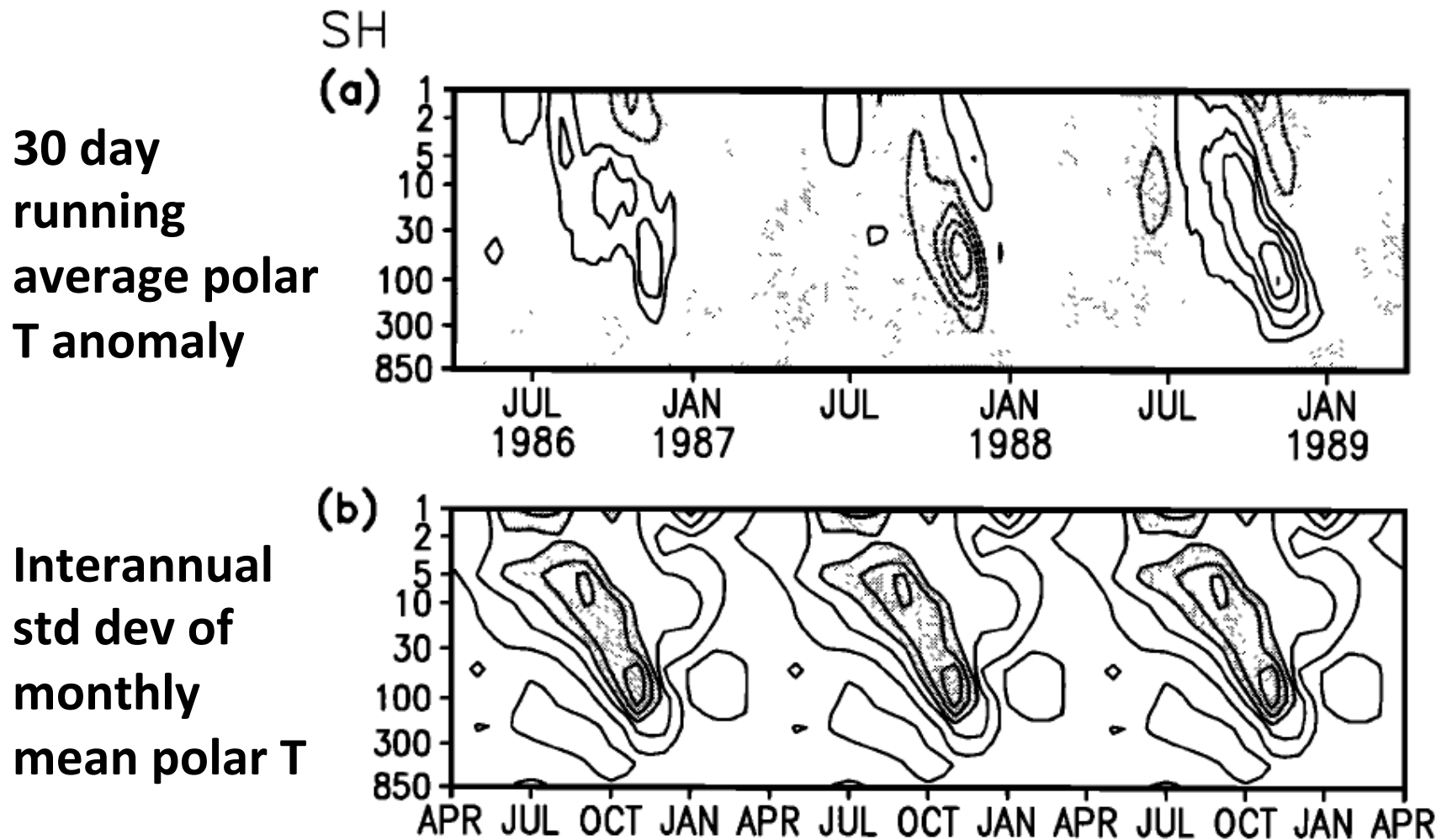
Butchart et al. (2011 JGR)

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



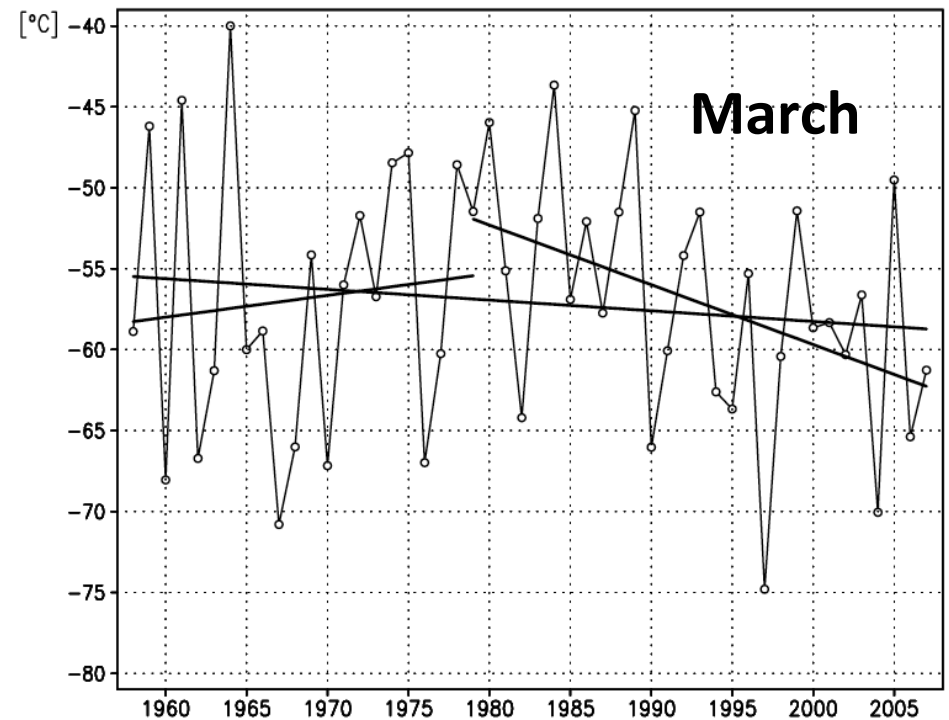
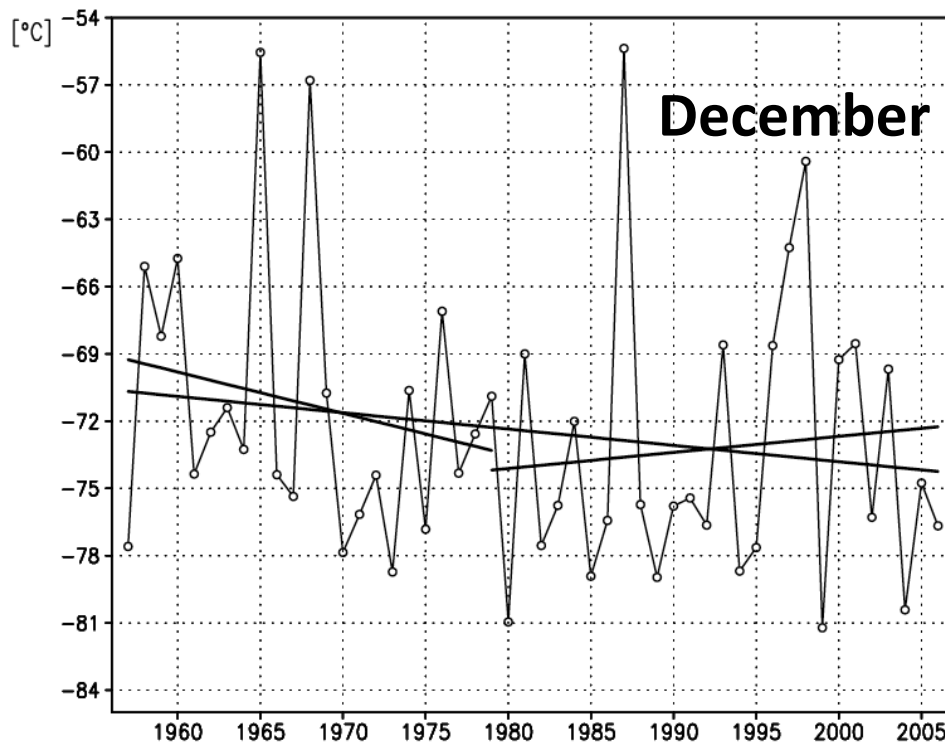
Kuroda & Kodera (2001 JGR)

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



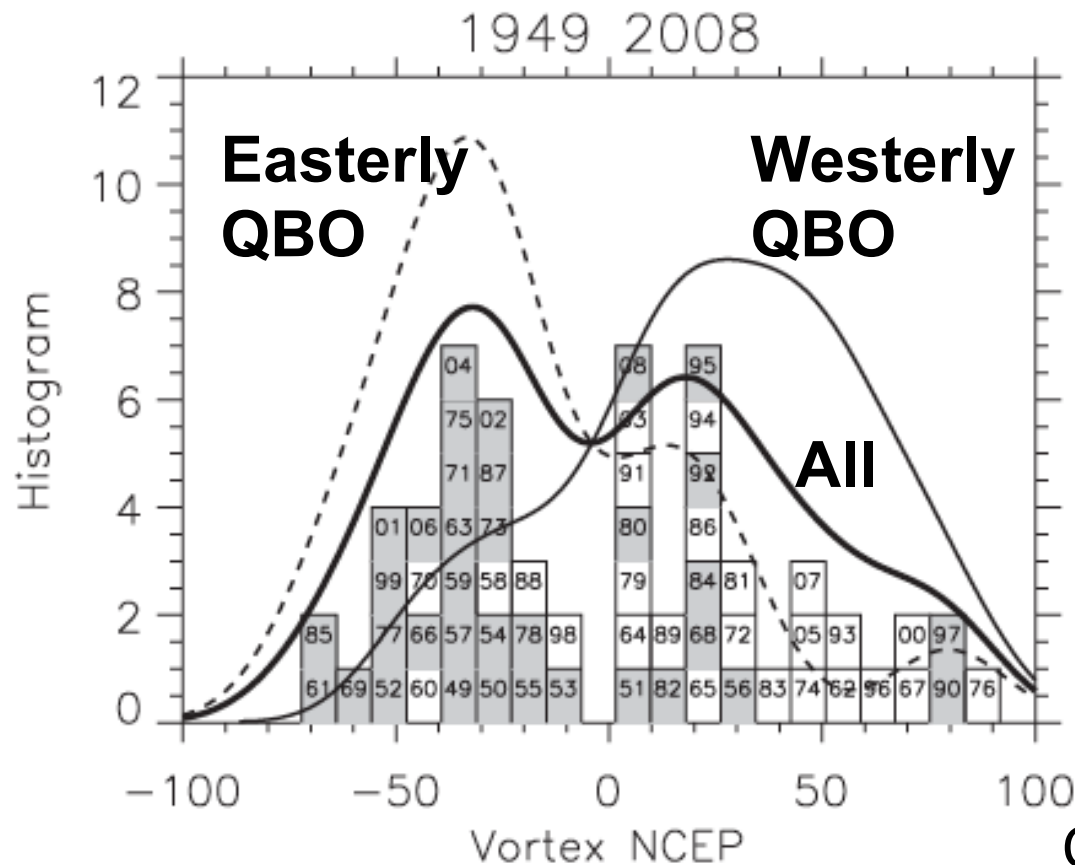
Kuroda & Kodera (2001 JGR)

- 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.)

- 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



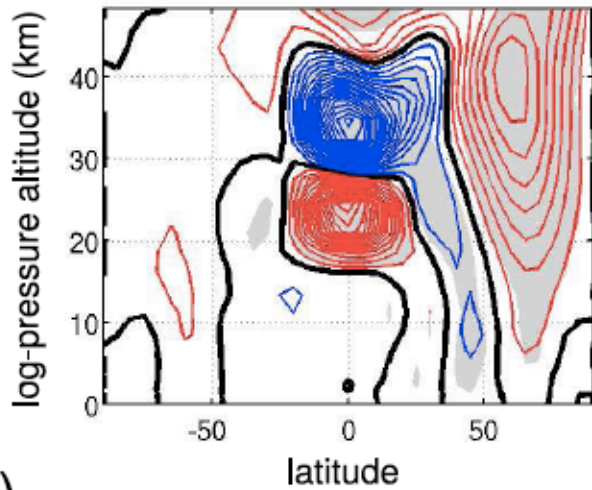
Is the origin of the observed bimodality in NH variability (here based on NAM index at 20 hPa)

Years segregated by FUB QBO index (shaded is easterly)

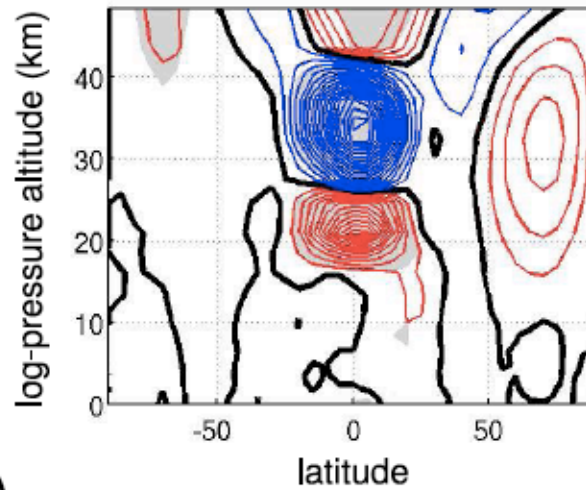
Christiansen (2010 J. Clim.)

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

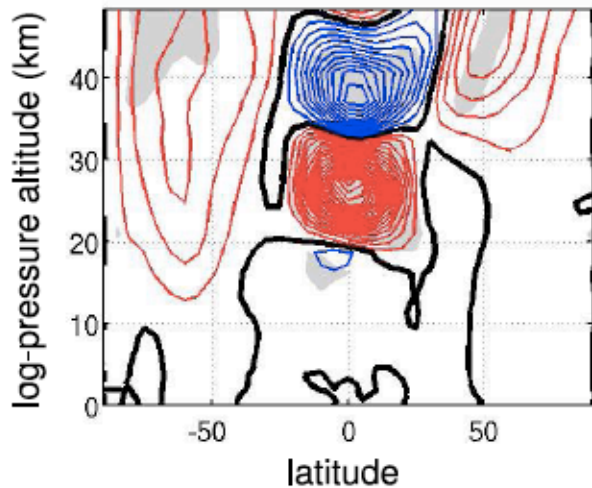
a) Nov-Dec



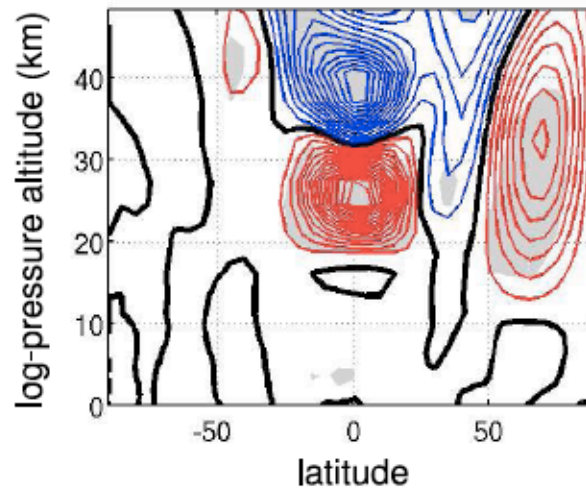
b) Feb-Mar



c)



d)

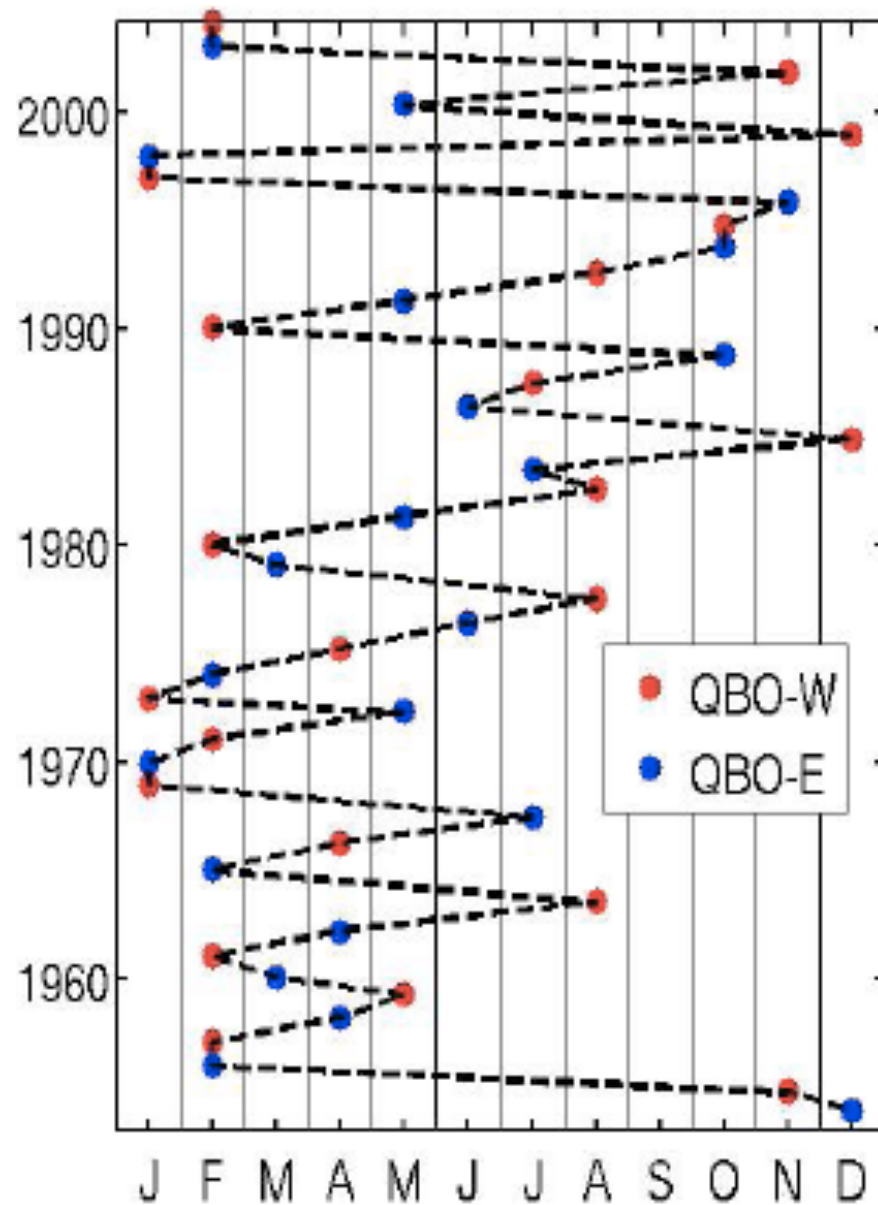


C.I. = 2 m/s

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

Between April and September in the previous year

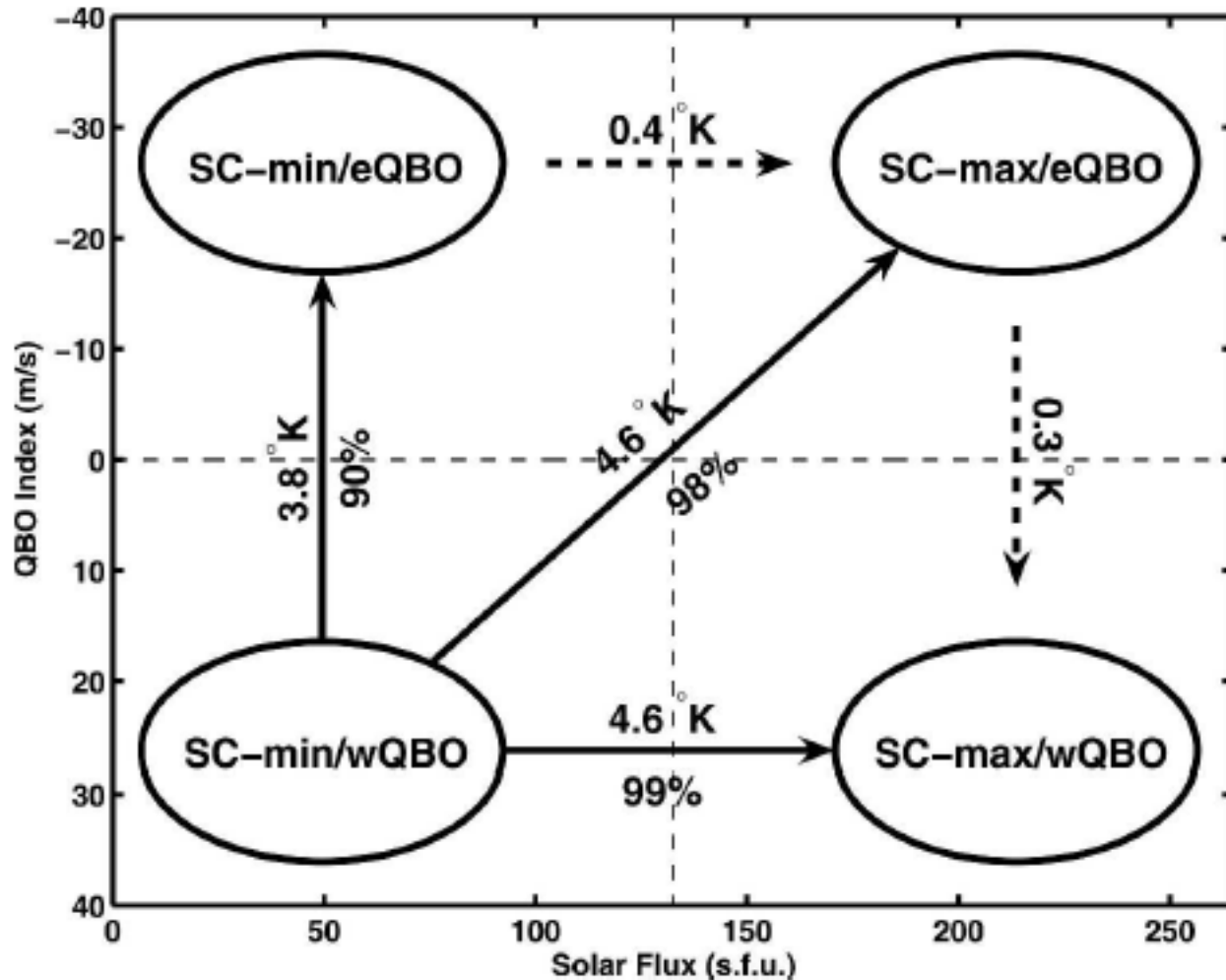
Anstey & Shepherd (2008 GRL)



- 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)

Anstey & Shepherd (2008 GRL)

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

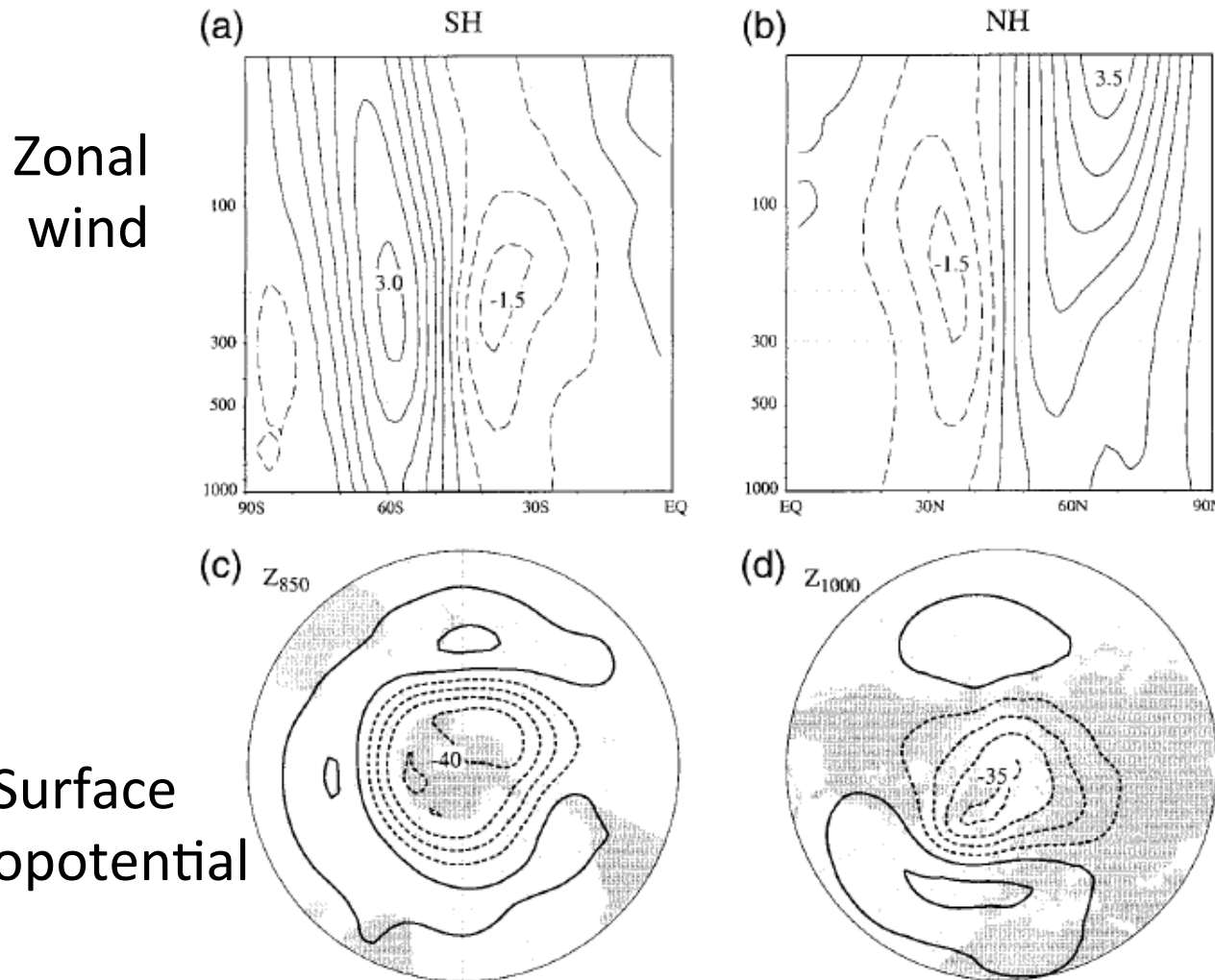


Mean warming of NH pole (Feb-Mar over 10-50 hPa) from different combinations of solar and QBO perturbations (based on NCEP/NCAR, 1954-2005)

Camp & Tung (2007 JAS)

- In both hemispheres, **stratospheric polar vortex variability is connected to the troposphere**: in NH, the effect is strongest over the North Atlantic

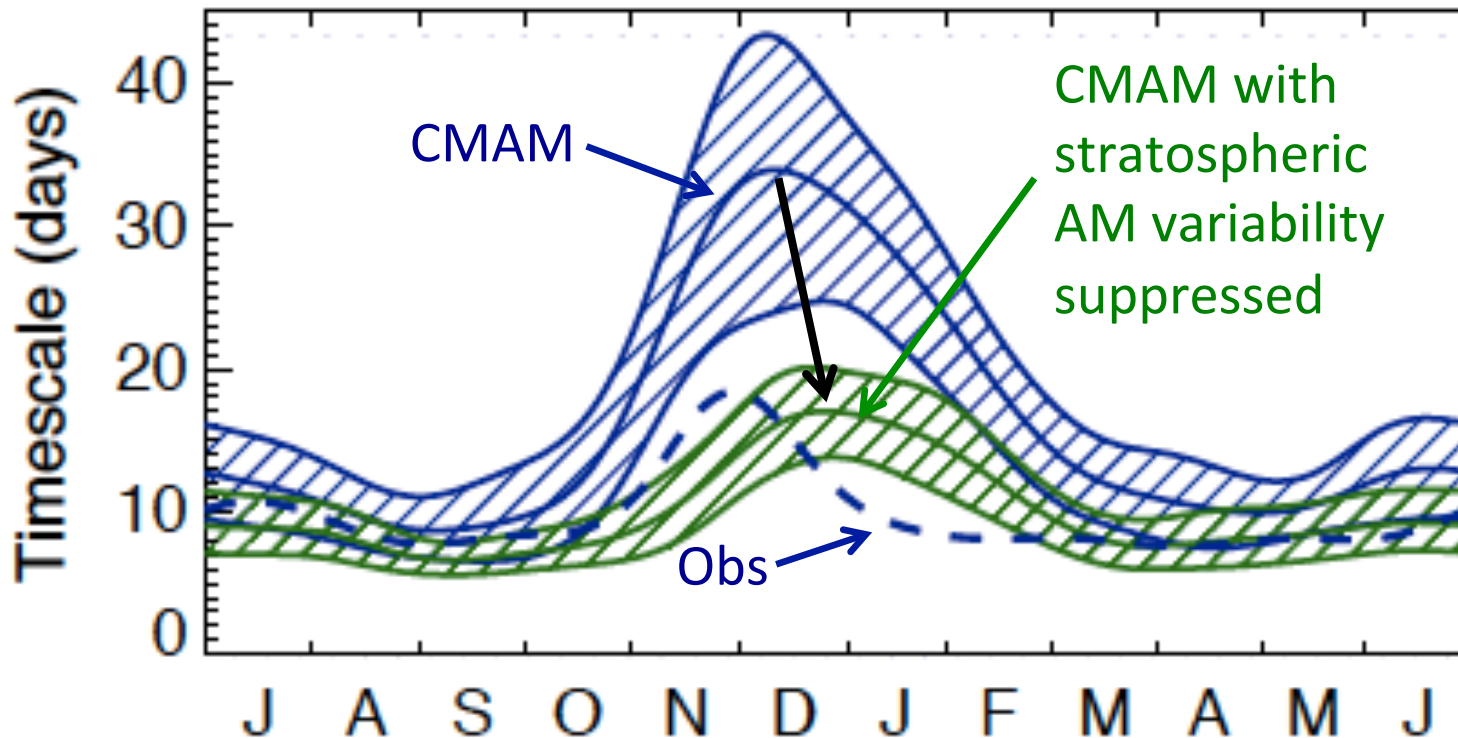
Regressions on the annular modes



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

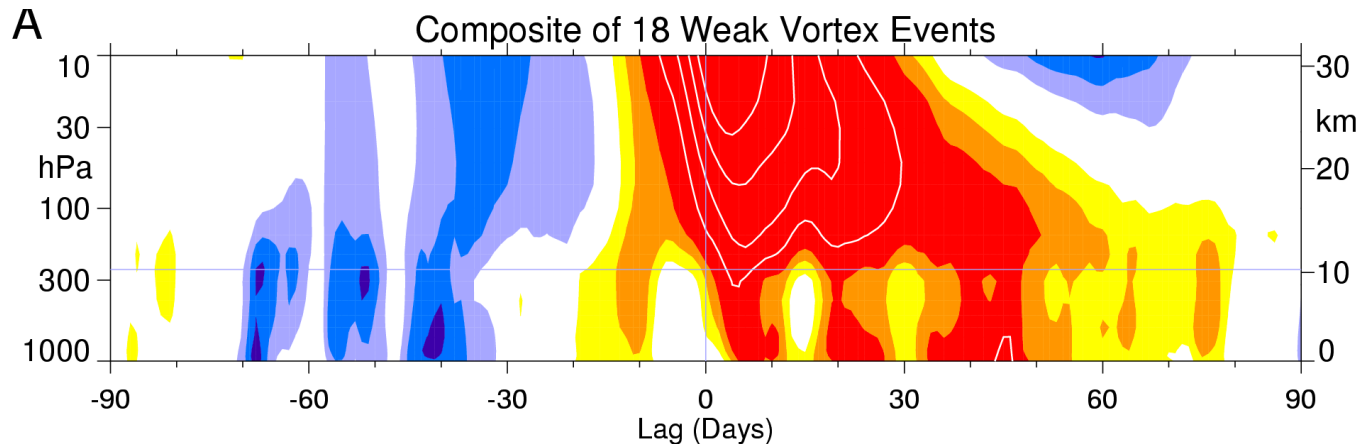
Thompson & Wallace (2000 J. Clim.)

- The late-spring variability in SH polar vortex breakdown substantially prolongs persistence of tropospheric SAM variability in late-spring/summer

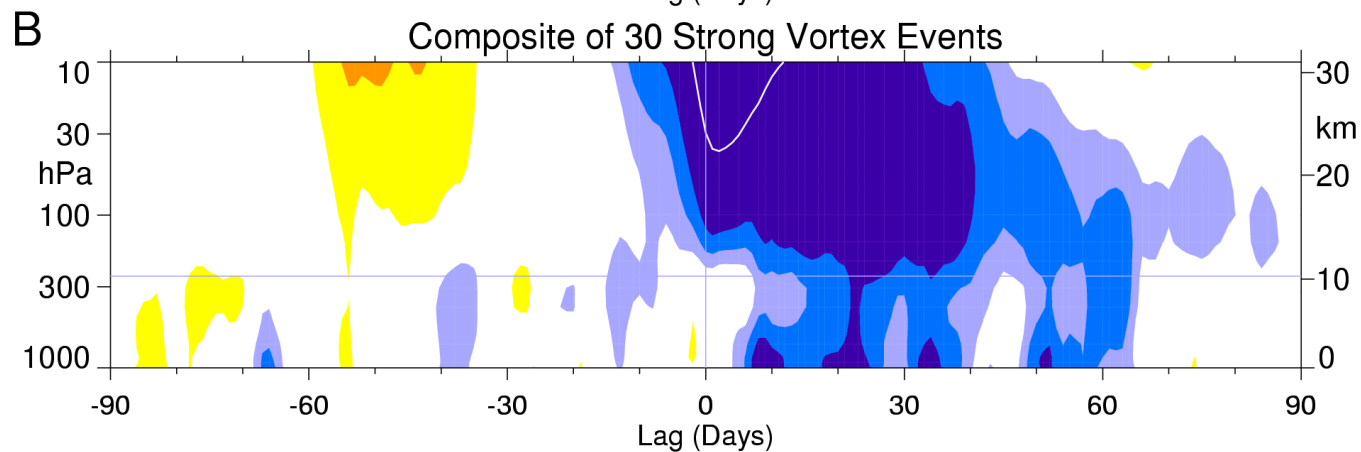


Simpson, Hitchcock, Shepherd & Scinocca (2011 GRL)

- There is an apparent downward propagation of annular mode anomalies: **stratosphere-troposphere coupling**
 - A warmer polar stratosphere (weaker vortex) leads to an equatorward shift in the midlatitude tropospheric jet

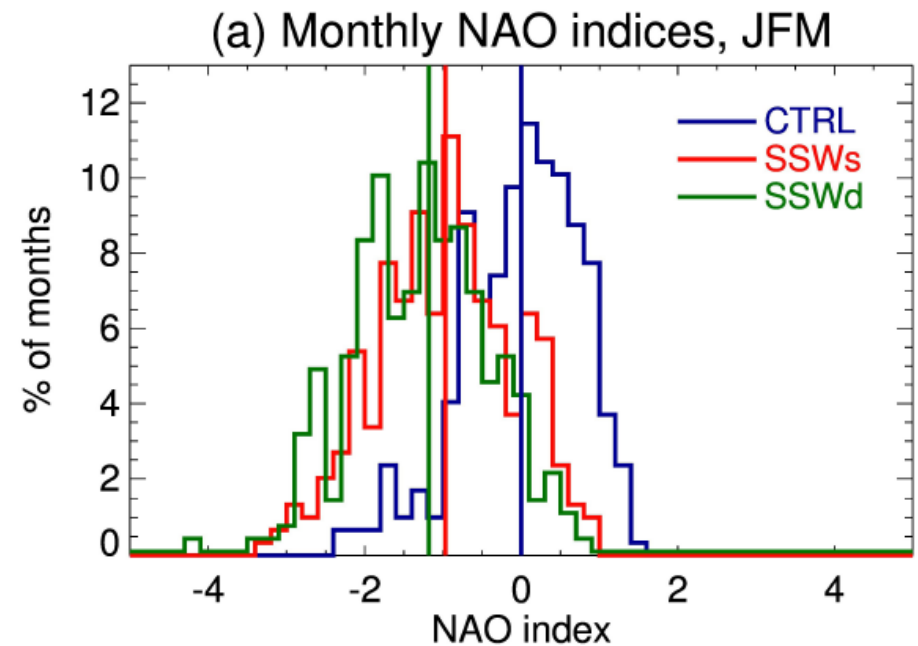
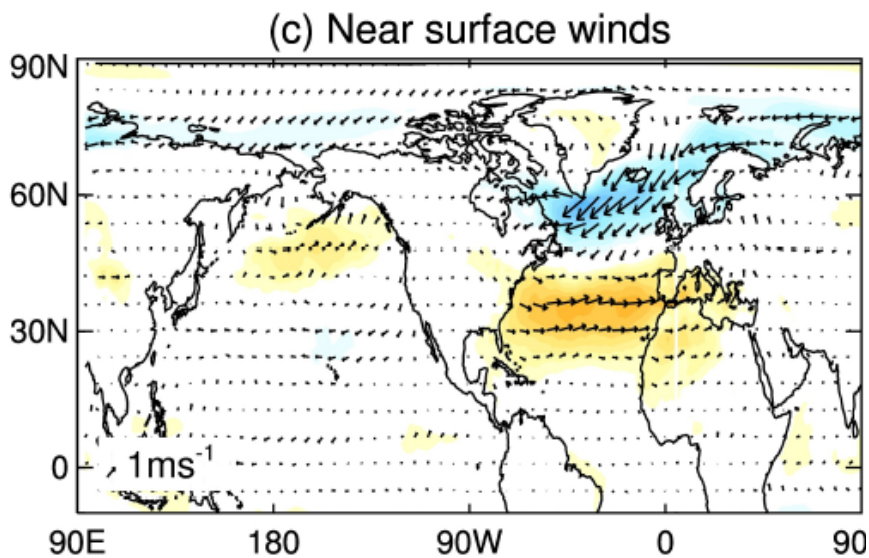


Composites of
Northern
Annular Mode
(NAM) indices



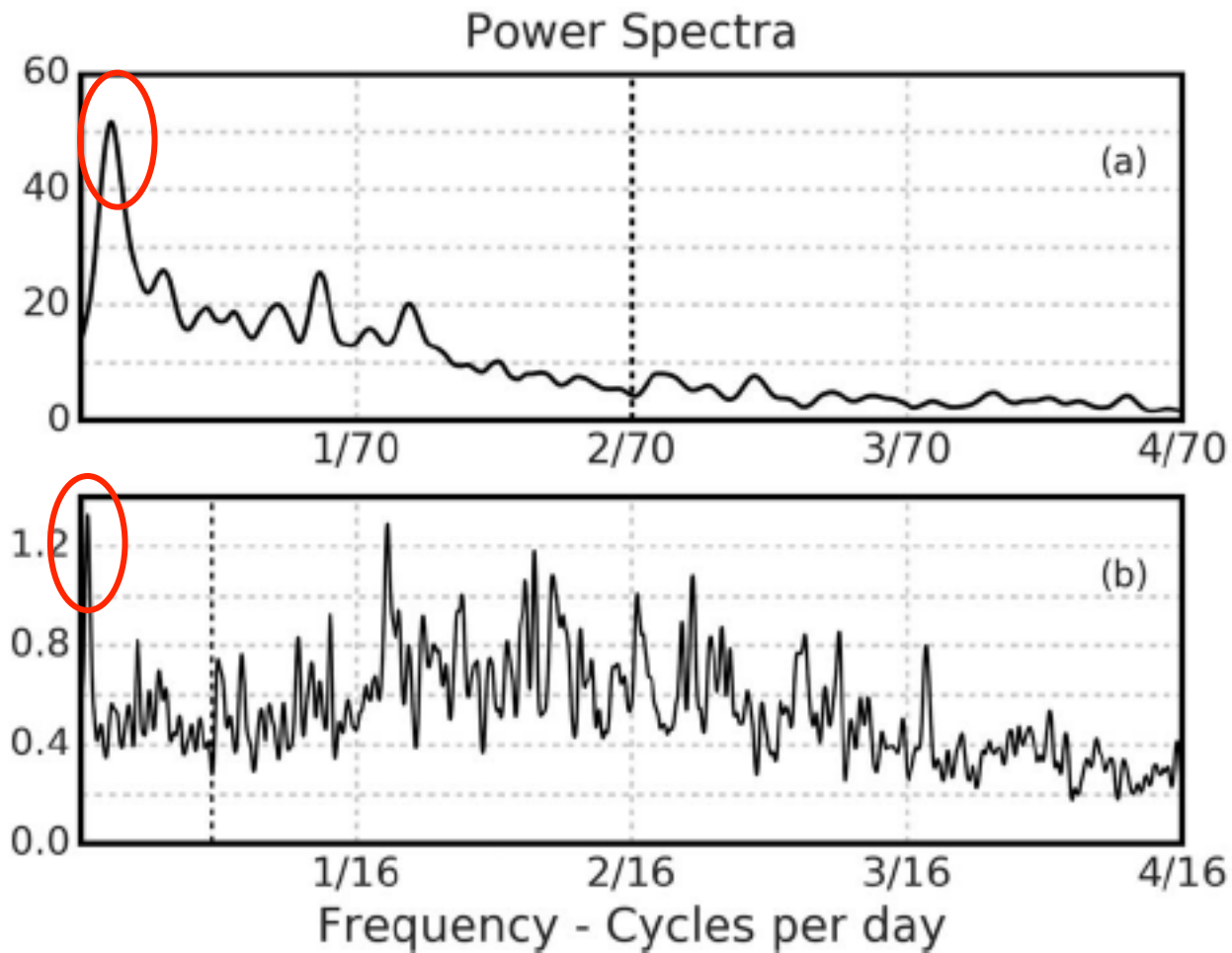
Baldwin &
Dunkerton (2001
Science)

- The NH jet shift is concentrated over the North Atlantic and can impact ocean circulation (Reichler et al. 2012 Nature Geosci.), providing inter-seasonal memory of stratospheric effects
 - Observed response for 30 days following SSWs (left)
 - NAO-like surface response is induced in models with a zonally symmetric stratospheric perturbation (right)



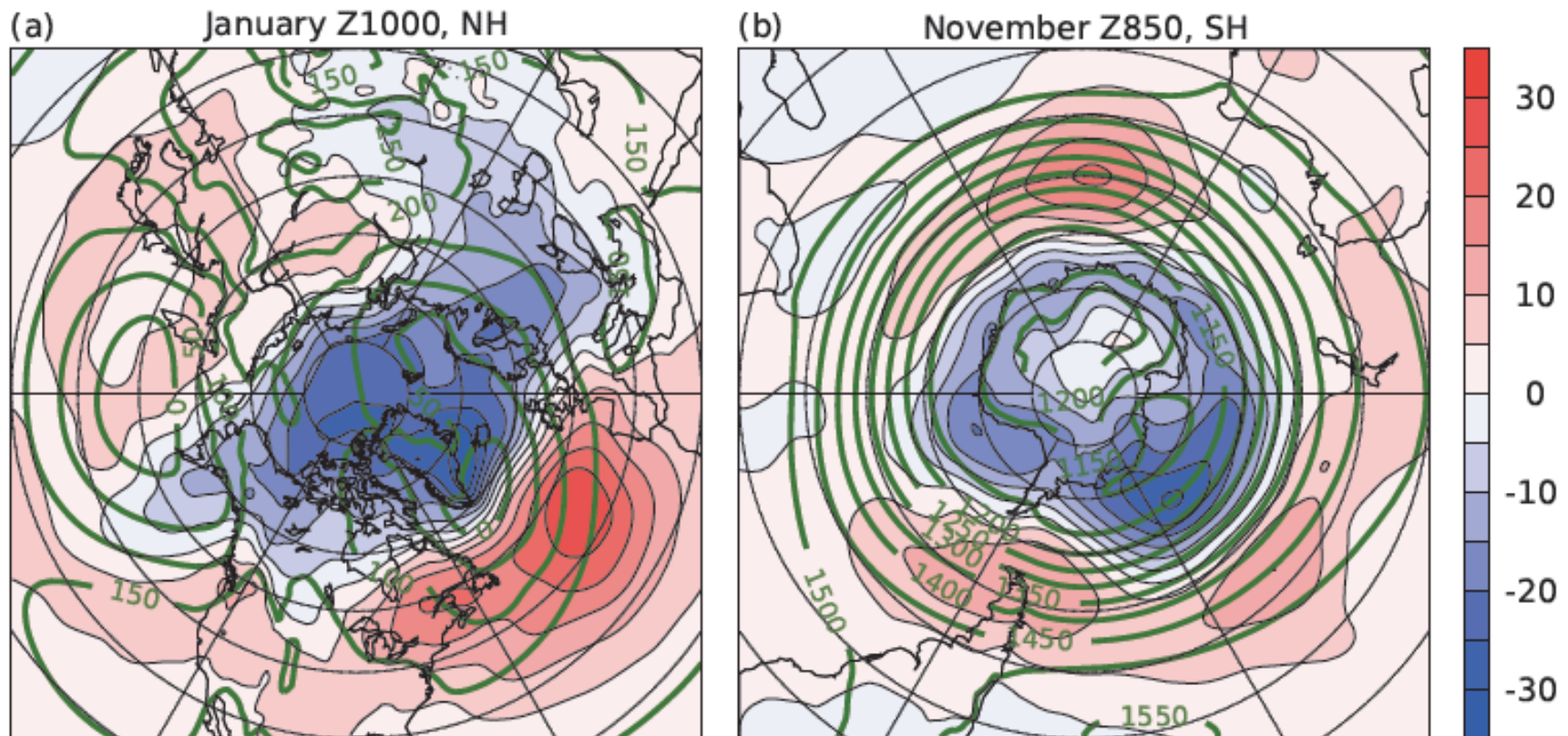
Hitchcock & Simpson (2014 JAS)

- Influence of variable SH vortex breakdown (confined to narrow time window) is ostensible reason for pronounced 2-year peak in SAM and eddy momentum flux convergence power spectra



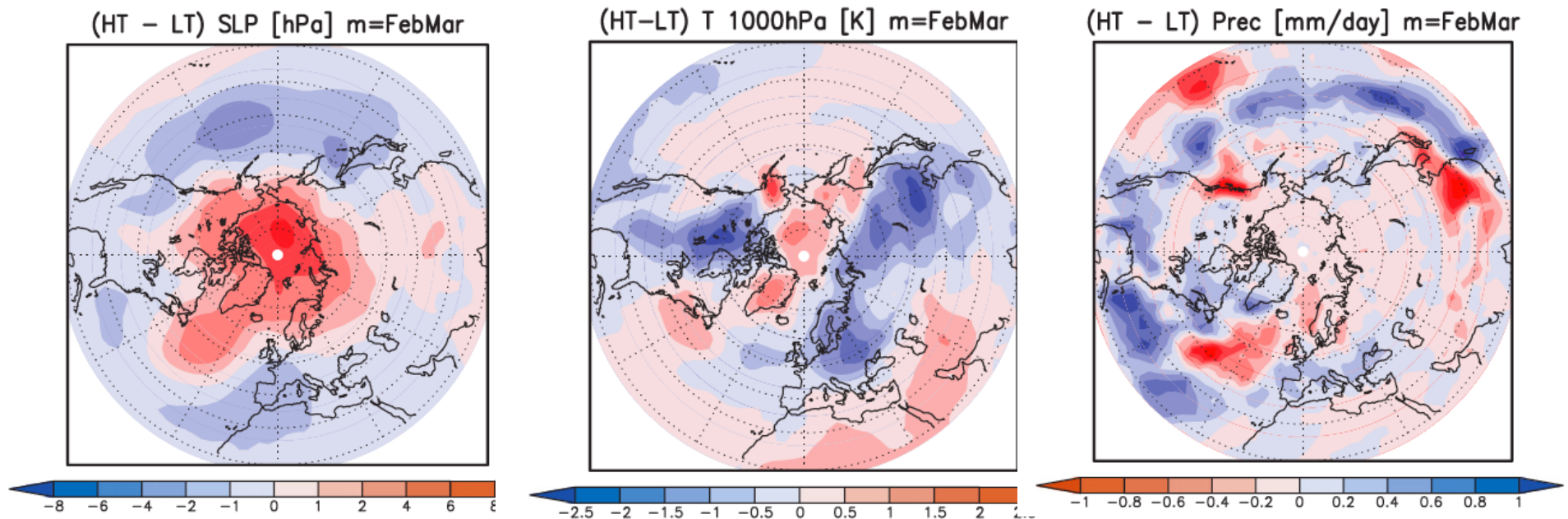
Byrne, Shepherd, Woollings & Plumb (2016 GRL)

- Through its impact on polar vortex variability, the quasi-biennial oscillation (QBO) in stratospheric tropical zonal winds affects surface climate, in both hemispheres
 - Figure shows W-E differences, updating Holton & Tan (1980)



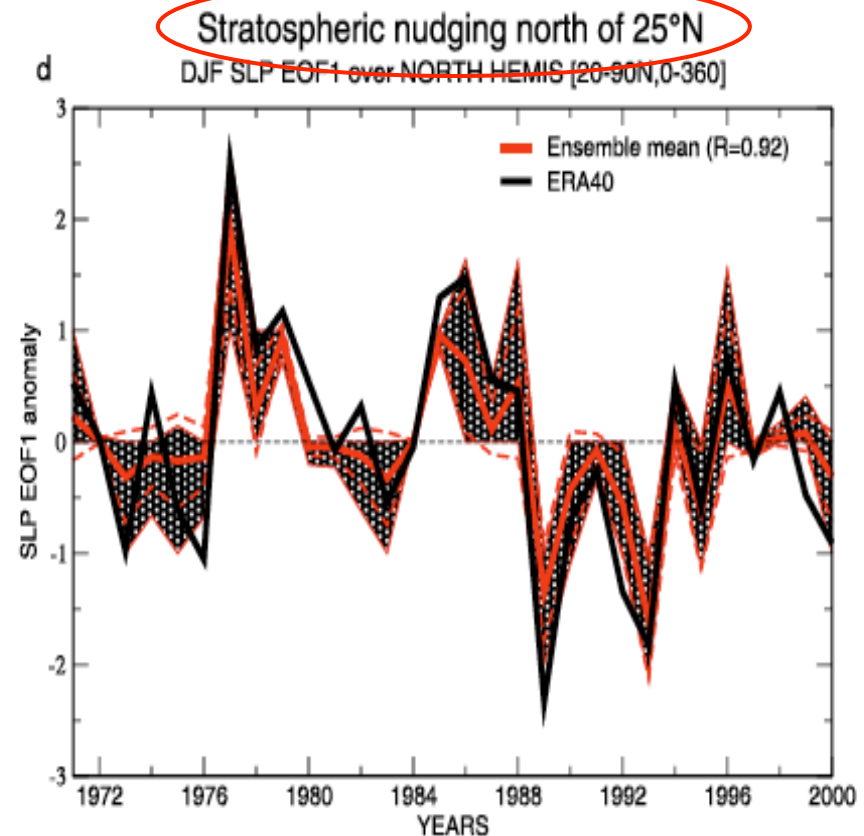
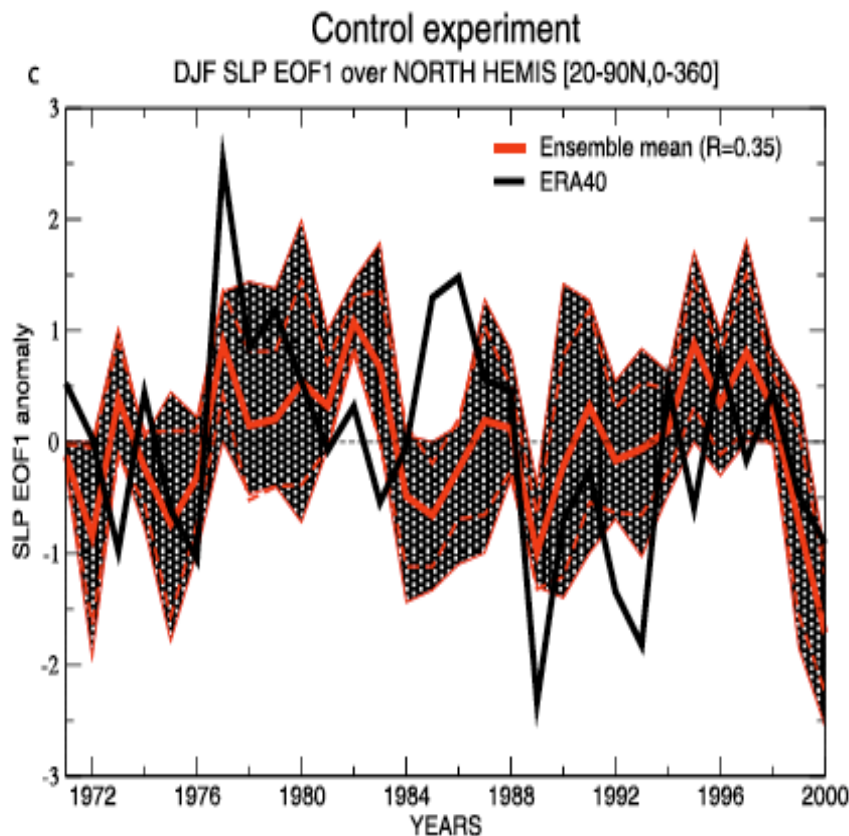
Anstey & Shepherd (2014 QJRMS)

- The European late-winter response to warm ENSO events is strongly modulated by the stratosphere
 - Figures show differences between high-top and low-top models, which represent the signature of SSWs (which the low-top model cannot produce)
 - There seems to be no robust response to cold ENSO events



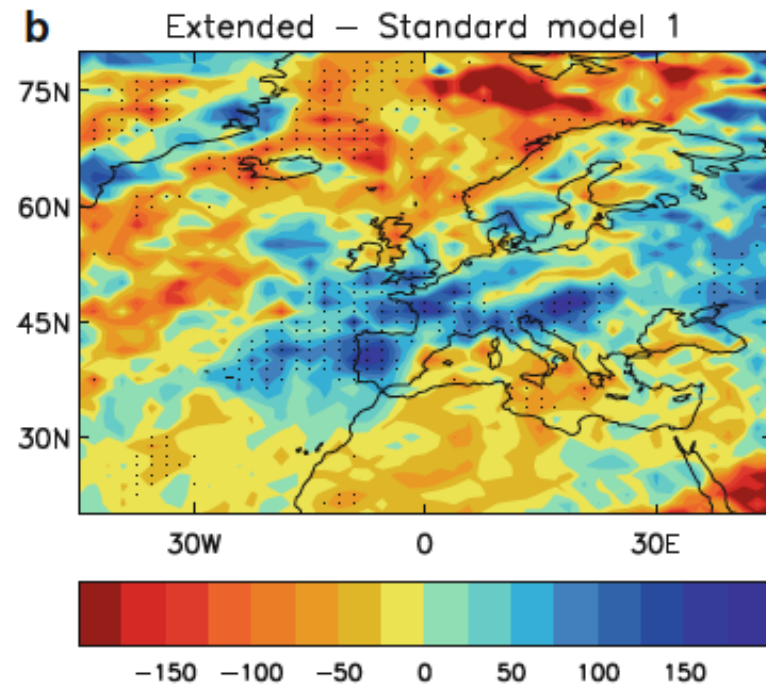
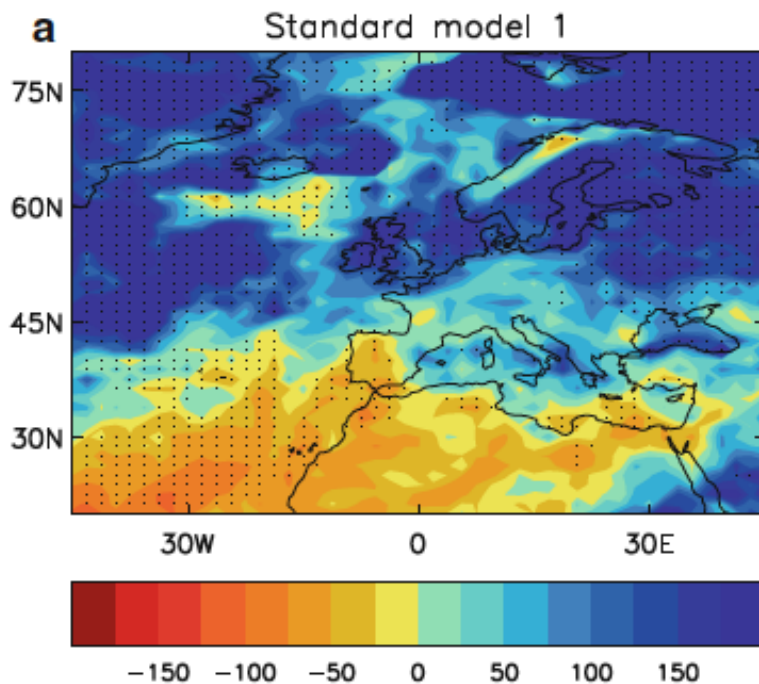
Cagnazzo & Manzini (2009 J. Clim.); see also Bell et al. (2009 J. Clim.)

- Through this seasonal stratosphere-troposphere coupling, the stratosphere appears to exert a significant control on interannual variability of wintertime Arctic circulation
 - Wintertime surface NAM index in 30-year AMIP runs with Météo-France model: SSTs alone provide little control (left)



Douville (2009 GRL)

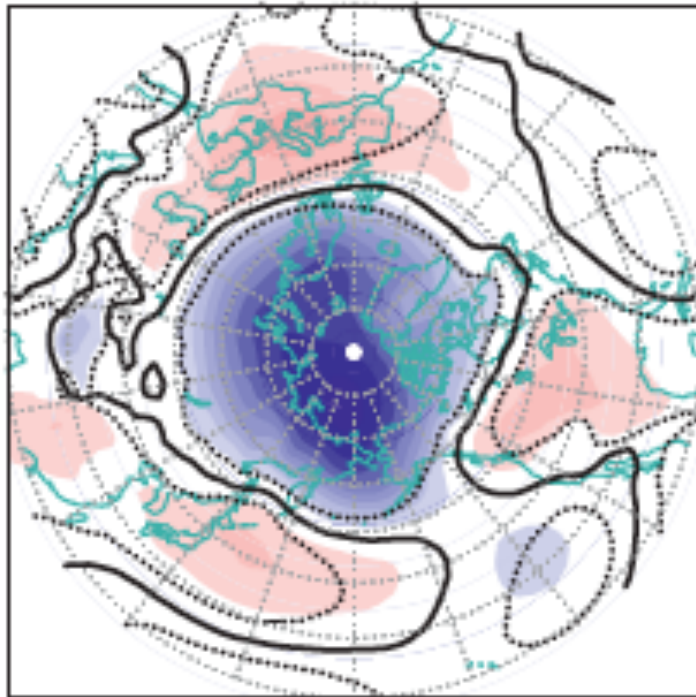
- The same control has been argued to hold on longer timescales
 - Stratosphere-resolving climate models generally predict less of a poleward shift in wintertime North Atlantic storm track, attributed to weakening of Arctic stratospheric polar vortex
 - Figure shows percentage change in frequency of extreme wintertime rainfall from 4xCO₂: right is effect of stratosphere



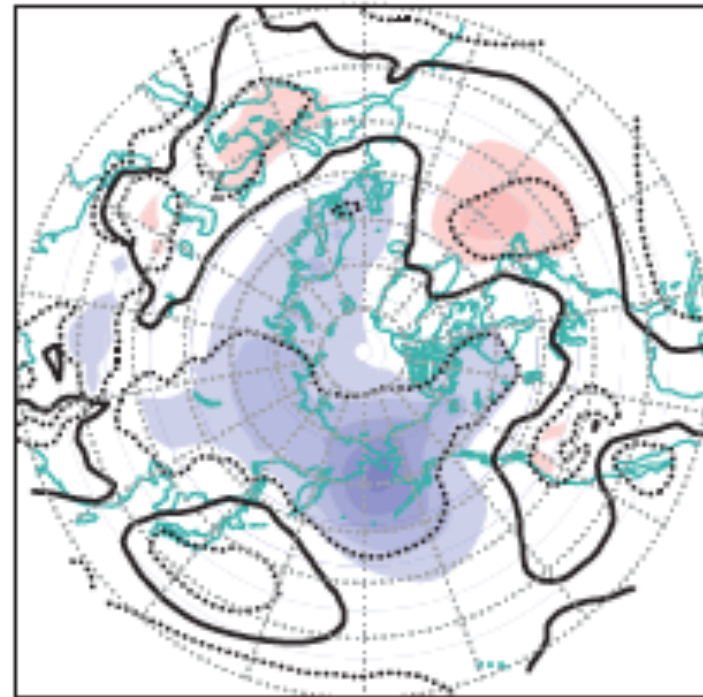
Scaife et al. (2012 Clim. Dyn.)

- In CMAM, the Arctic wintertime mean sea level response to doubled CO₂ changed dramatically between two different (but plausible) parameter settings in the orographic GWD scheme
- Difference consistent with Scaife et al. (2012): weakened stratospheric vortex / weaker poleward shift in tropospheric jet

(a) RESPONSE WEAK (DRAG)



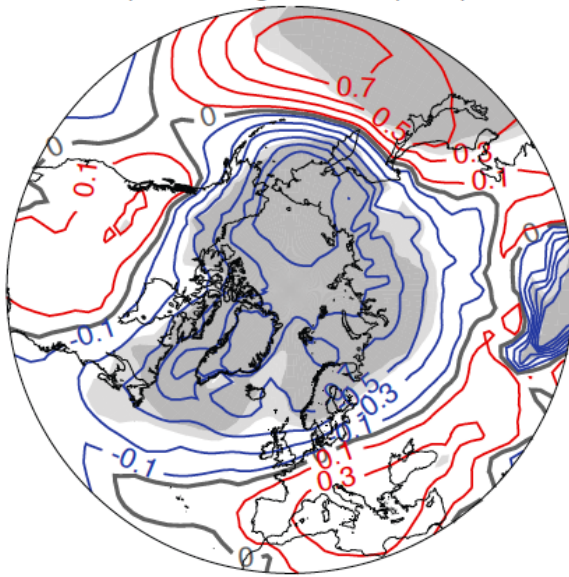
(b) RESPONSE STRONG (DRAG)



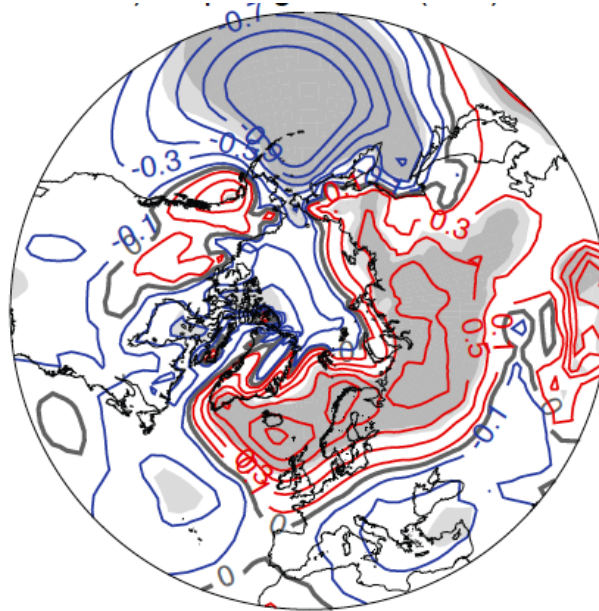
Sigmond & Scinocca (2010 J. Clim.)

- SPARC DynVar CMIP5 analysis suggests GHG-induced changes in wintertime Arctic sea-level pressure are affected as much by changes in the stratospheric polar vortex as by tropical upper tropospheric warming or by Arctic surface warming
- Response to stratosphere is NAO-like and opposite in sign to that from tropical warming, in the same sense as the response to SSWs and Scaife et al. (2012)

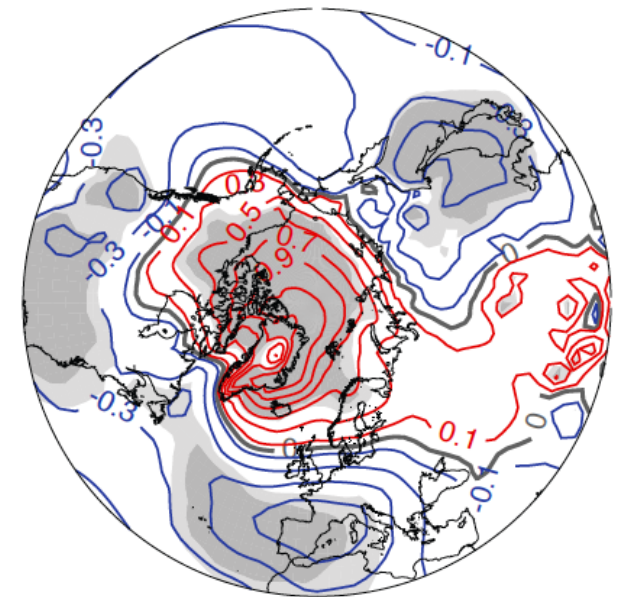
Tropical warming



Arctic warming

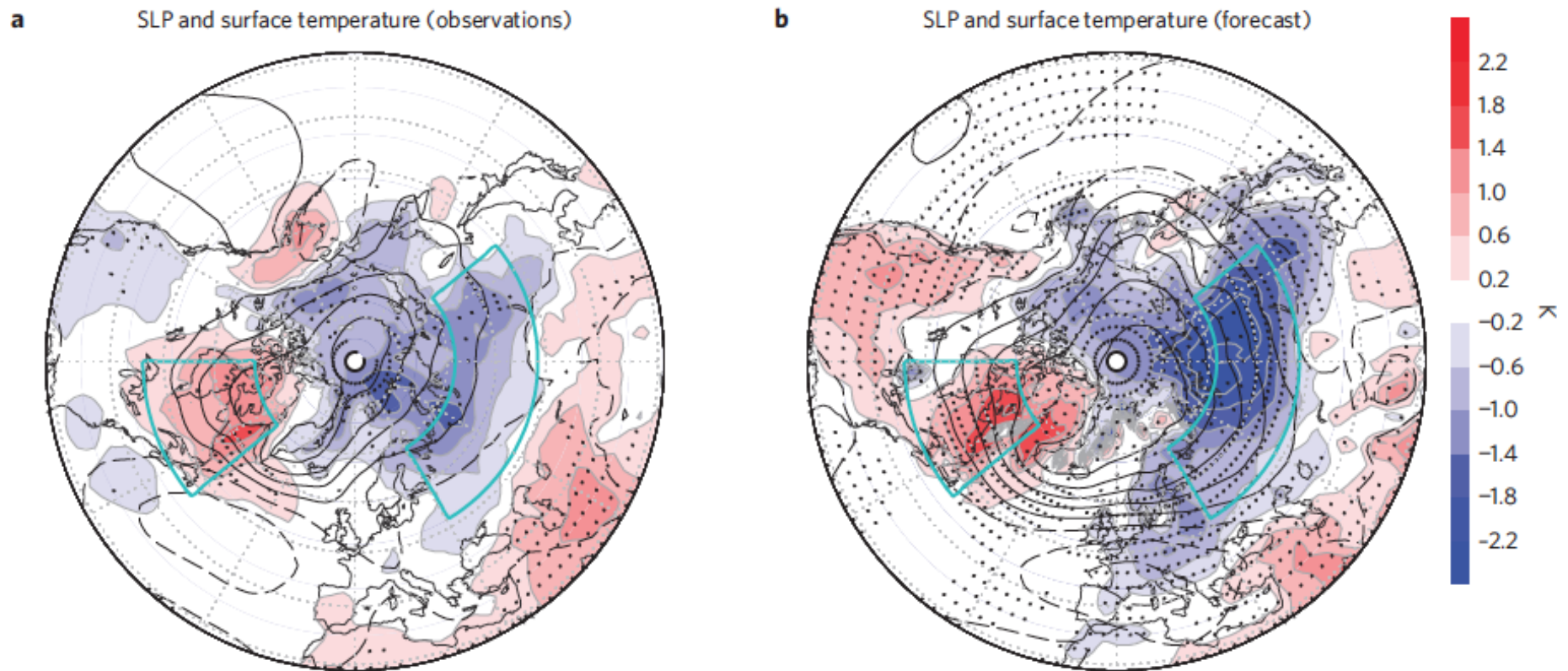


Stratosphere

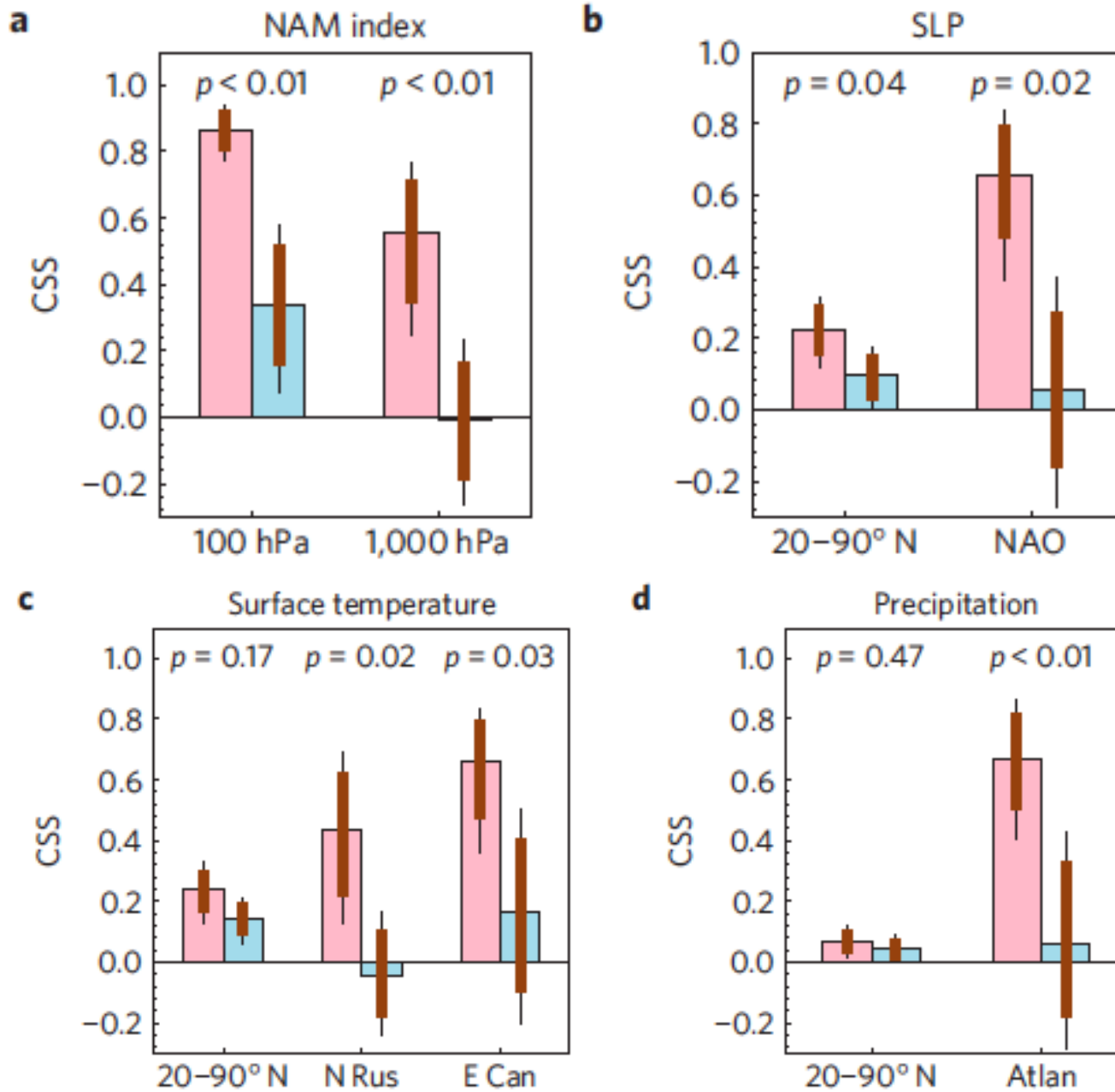


Manzini et al. (2014 JGR)

- Stratosphere-resolving models can correctly predict the surface response to SSWs when initialized at the time of the SSW
 - Figure shows response averaged over 16-60 days after the SSW, for 20 SSWs from 1970-2009 (model: ensemble of 10)



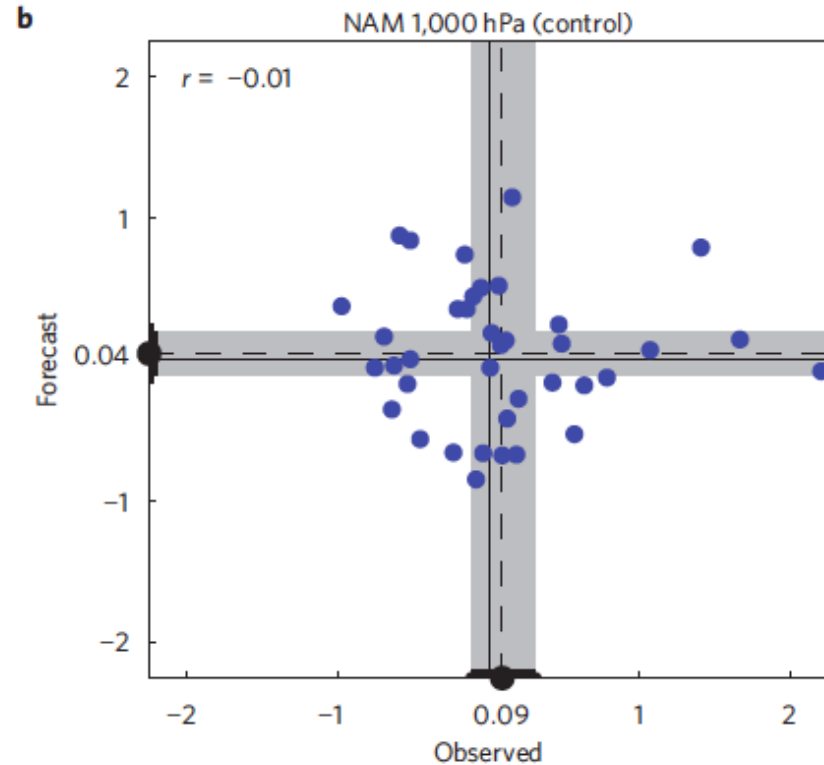
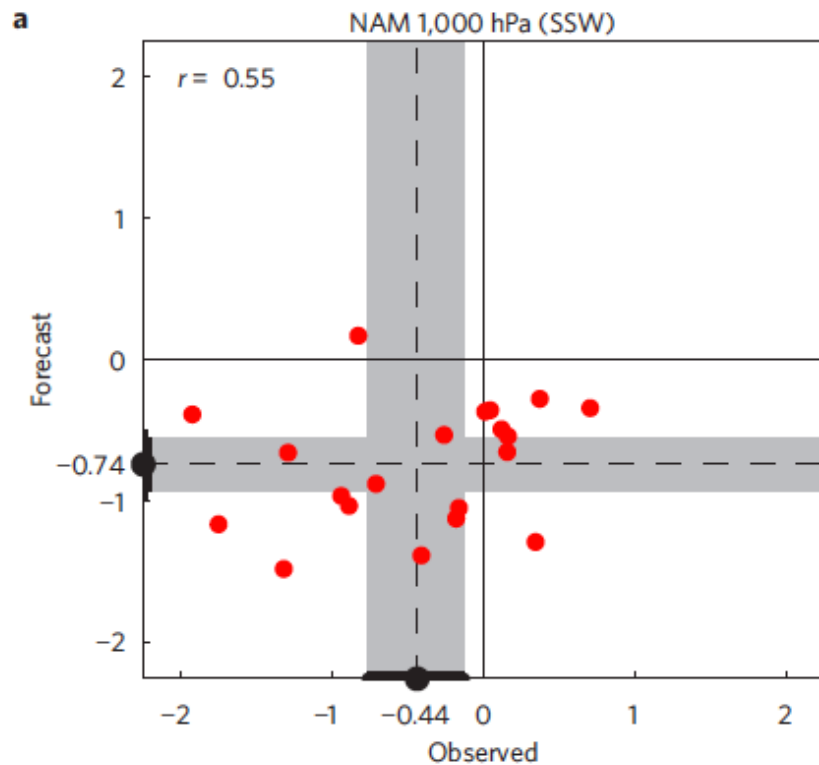
Sigmond, Scinocca, Kharin & Shepherd (2013 Nature Geosci.)



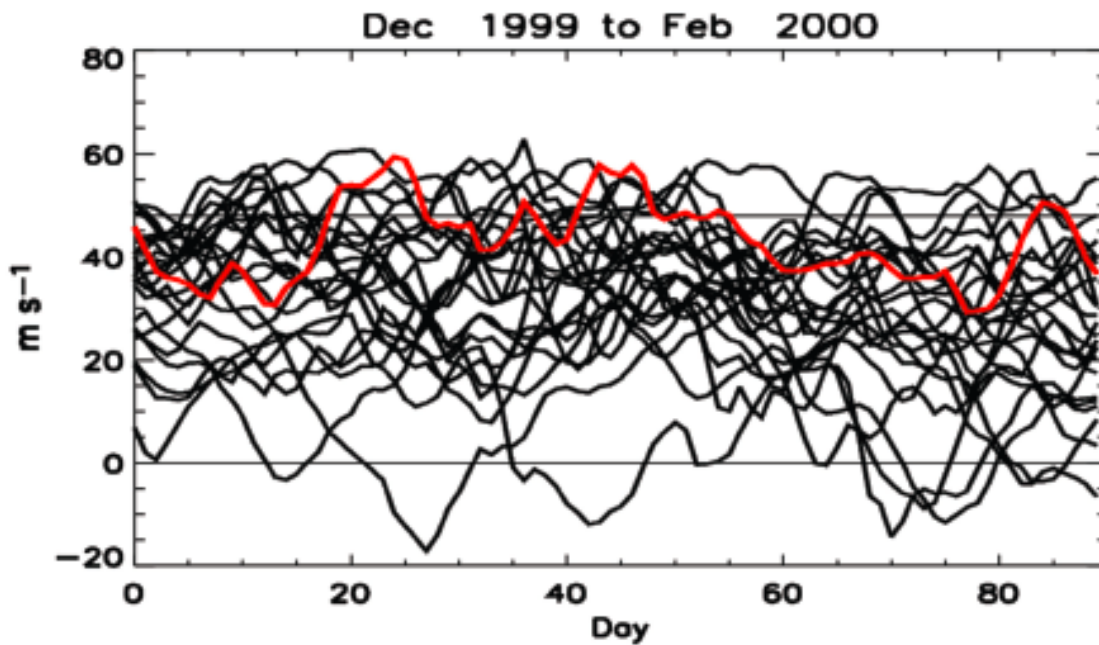
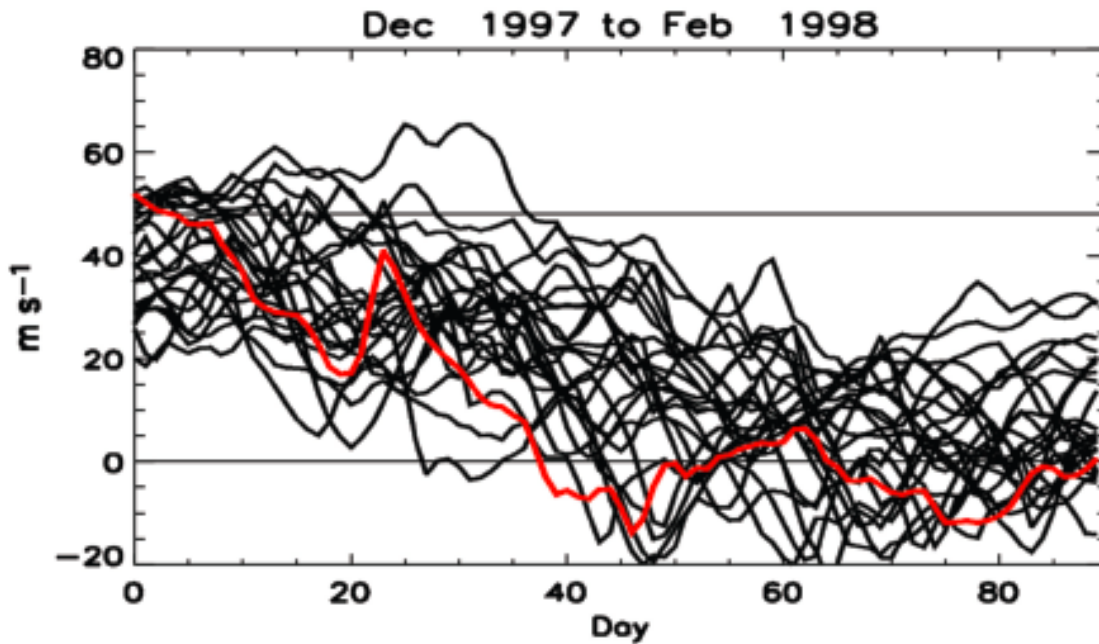
- SSWs enhance the skill of seasonal predictions of a variety of surface climate fields, especially in certain regions
 - Blue is the control, pink is after SSWs

Sigmond et al. (2013 Nature Geosci.)

- Predictability of the NAM is not increased after an SSW (the scatter is not reduced)
 - The SSW just loads the dice in one direction



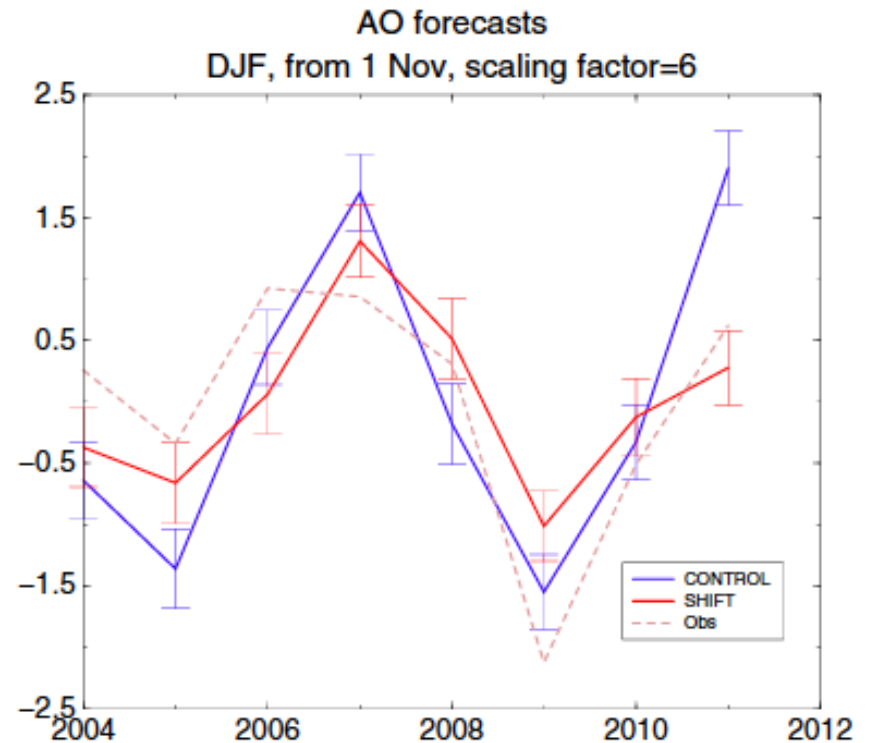
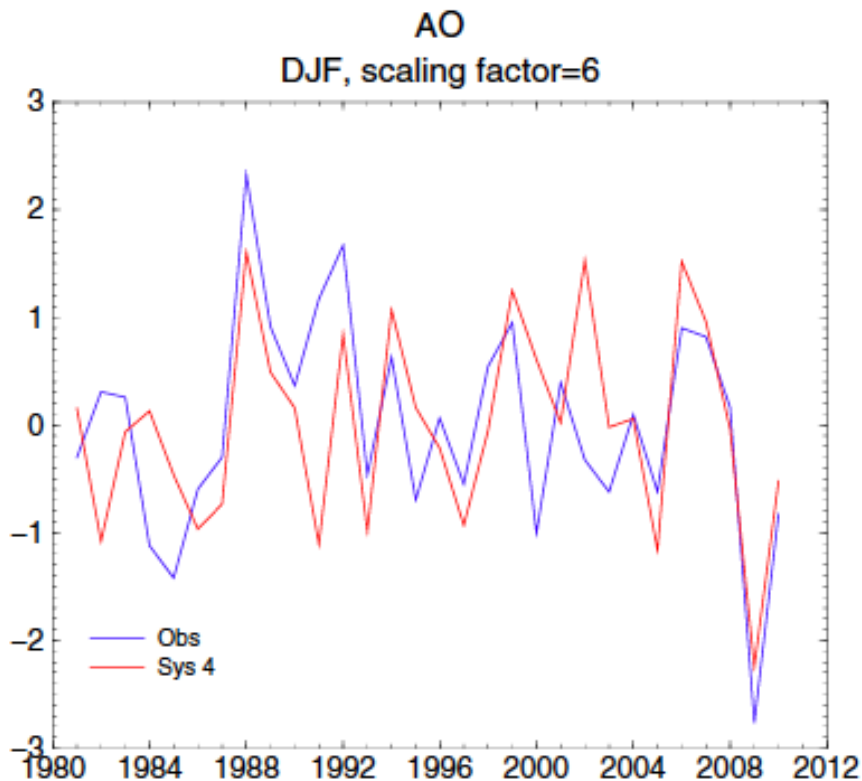
Sigmond, Scinocca, Kharin & Shepherd (2013 Nature Geosci.)



- Deterministic prediction of a SSW is generally limited to about two weeks, but probabilistic prediction is possible for the winter season
 - Makes sense given the known factors influencing the probability of SSWs
- Plots show ensemble forecasts (initialized on Nov. 1) from the Met Office system, for two quite different winters

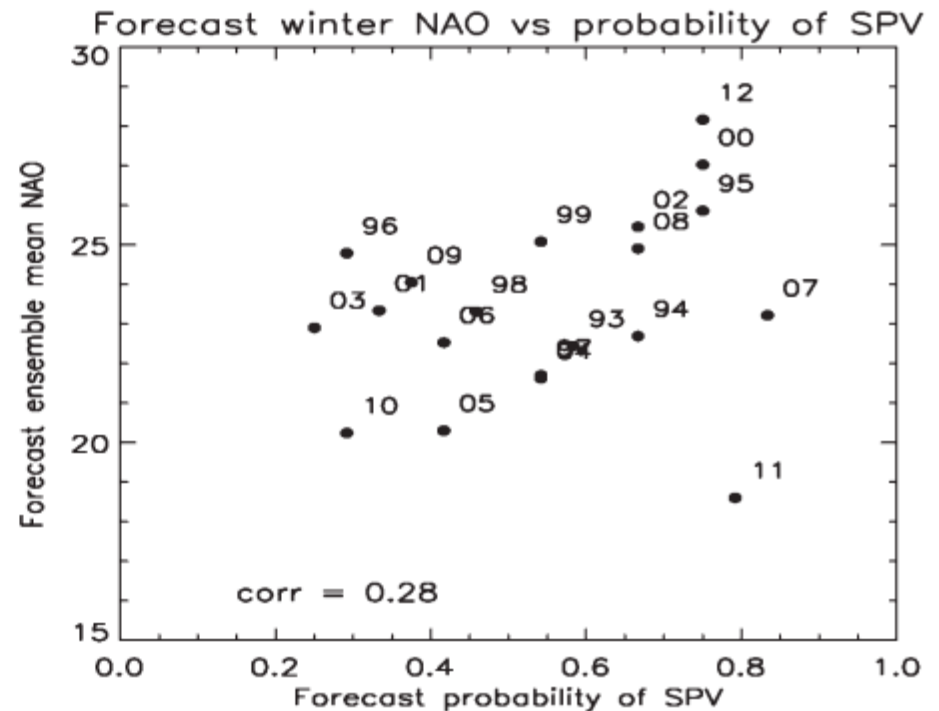
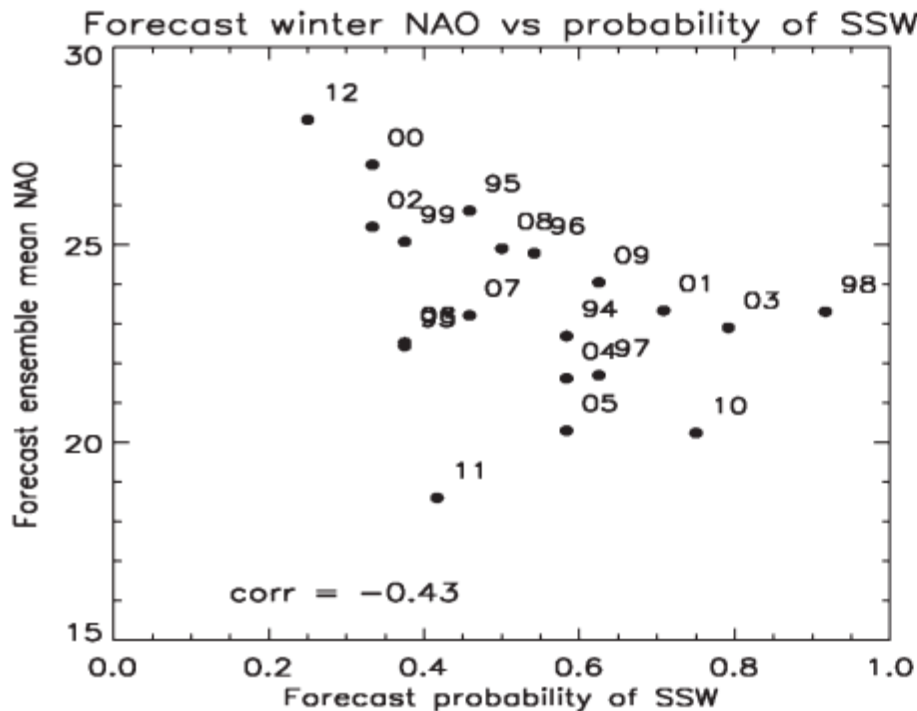
Scaife et al. (2016 ASL)

- ECMWF seasonal forecast system shows high skill in DJF AO (or NAM) index (left), which, perhaps surprisingly, **comes from the atmospheric initial conditions!** (right)
- Skill originates in the stratosphere but model error leads to underestimation of predictability (cf. Eade et al. 2014 GRL)



Stockdale, Molteni & Ferranti (2015 GRL)

- Met Office system likewise shows strong predictability of the DJF NAO index, which is highly correlated with SSW probability
 - Forecast skill of NAO vanishes completely when years with SSWs are excluded from the record!
- There is also some relation with Strong Polar Vortex (SPV) events, though their probability is less predictable



Scaife et al. (2016 ASL)

Summary

- The stratosphere contains radiative-dynamical mechanisms for memory, and response to forcing, relevant for predictability
 - External forcing comes from solar variability, aerosol loading from volcanic eruptions, and ozone depletion (SH)
 - Internal forcing comes from the QBO
- The primary pathway for influencing the troposphere is polar vortex variability
 - Active season is winter-spring for NH, late spring for SH
- Most dramatic events are SSWs (for SH, mainly ‘final warmings’)
 - Long-lived events have a predictable life cycle of 2 months
- SSW recovery phases thus provide subseasonal predictability after a deterministic prediction (or occurrence) of a SSW
- Altered SSW probabilities also provide a mechanism for seasonal predictability during the active season