Stratospheric Variability & Prediction on Sub-seasonal Timescales

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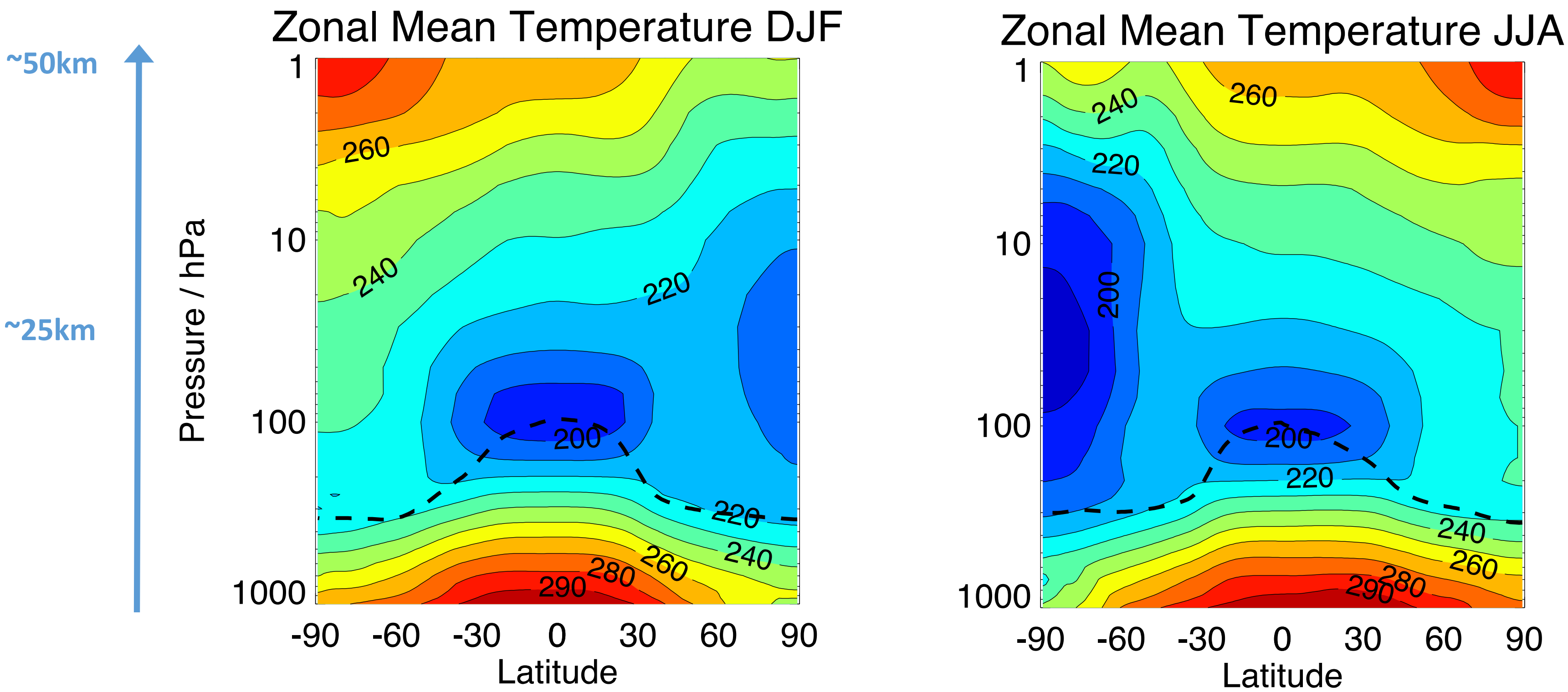
with special thanks to Andrew Charlton-Perez

Outline

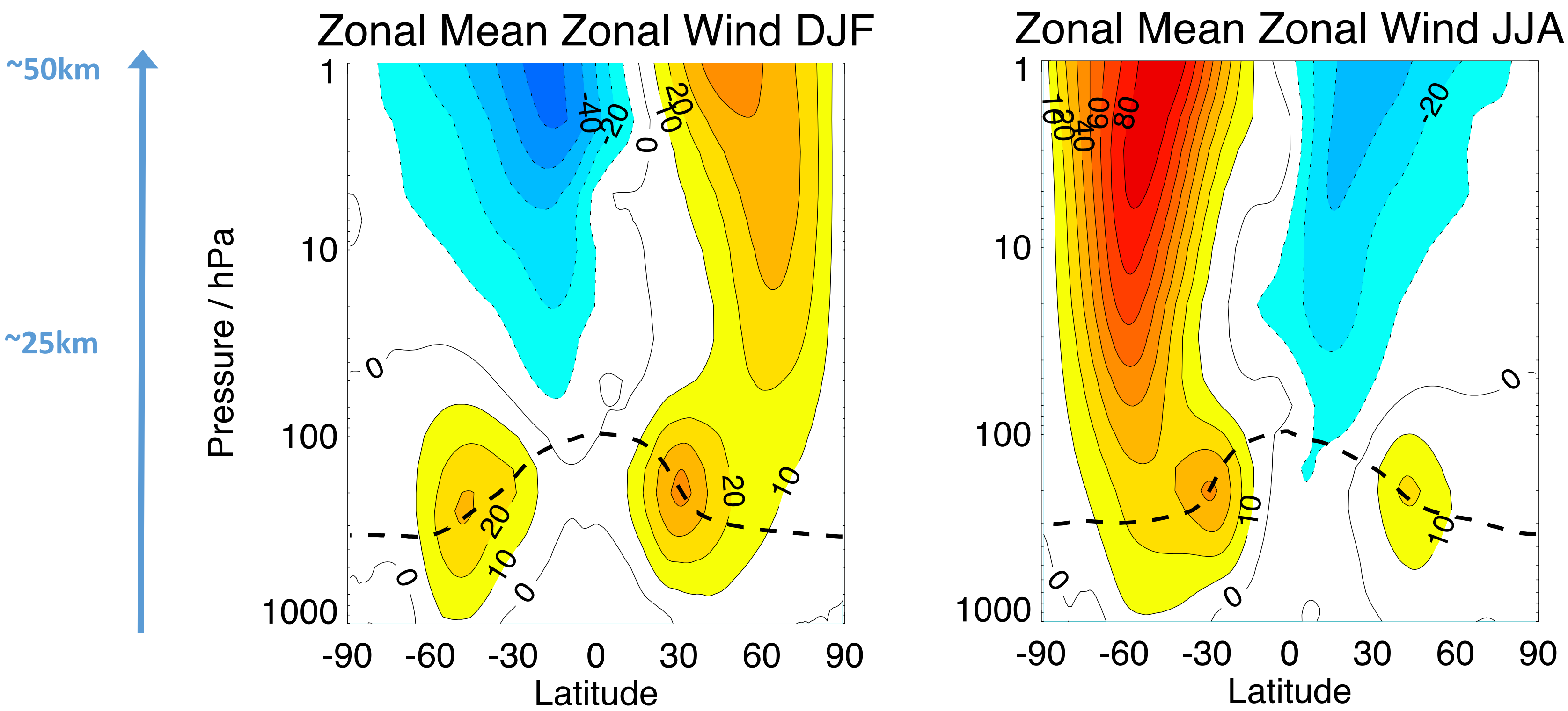
- Structure of the Stratosphere
- Variability in the Stratosphere
- Relationships between Stratospheric & Tropospheric Variability
- Impact of Stratosphere on Tropospheric Prediction on Sub-seasonal timescales
- Prediction of Polar Vortex on Sub-seasonal Timescales
- Summary

Structure of the Stratosphere - Temperature



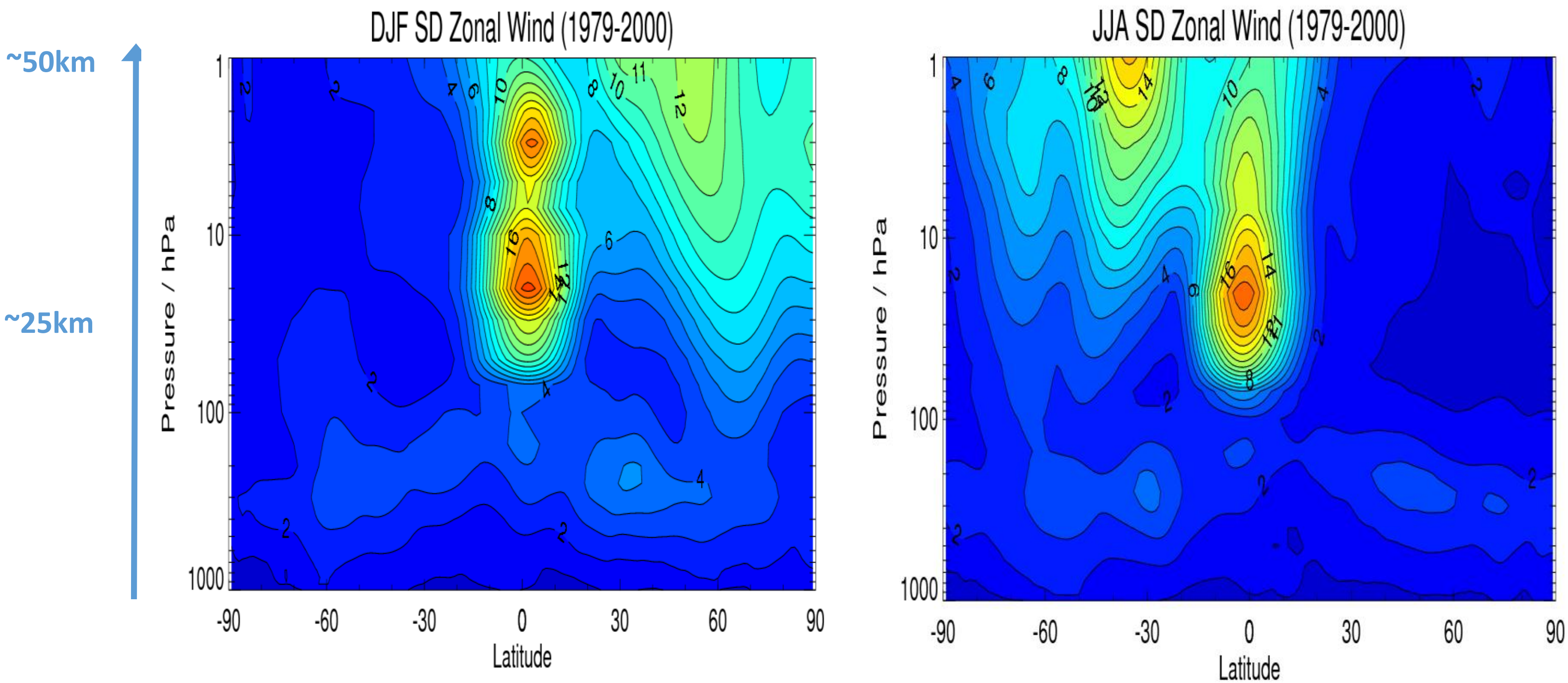
- Tropopause height varies from about 9km at the poles to 17km in the tropics
- Temperature nearly constant or increasing with height in the stratosphere
- Winter pole has coldest temperatures above about 20km
- Warmest temperatures are at the summer pole

Structure of the Stratosphere - Winds



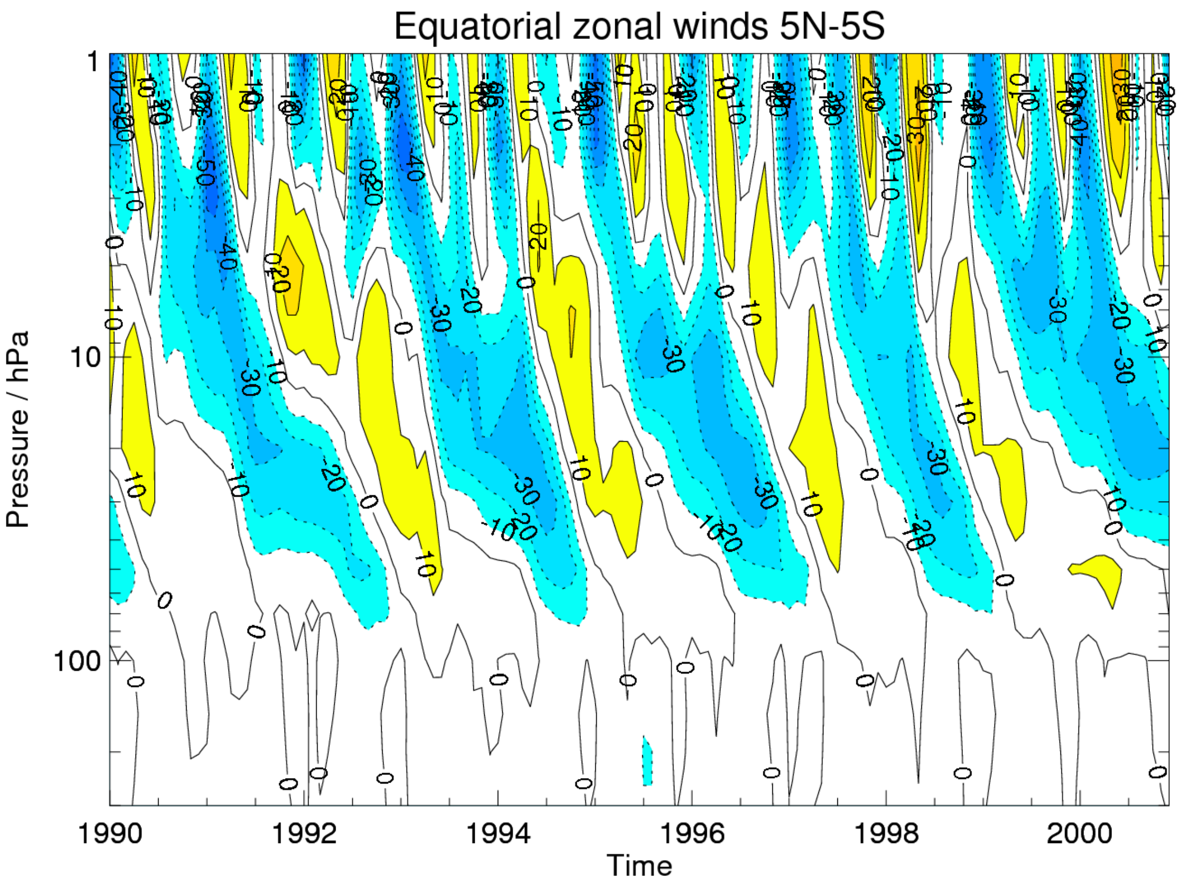
- Strong Westerly Winds in Winter Hemisphere in thermal wind balance
- Stratopsheric Jet poleward of the tropospheric jet
- Jet describes the edge of the polar vortex
- Southern Hemisphere Jet much stronger than Northern Hemisphere
- Easterly winds in Summer Hemisphere

Variability of the Stratosphere – Zonal Mean Winds



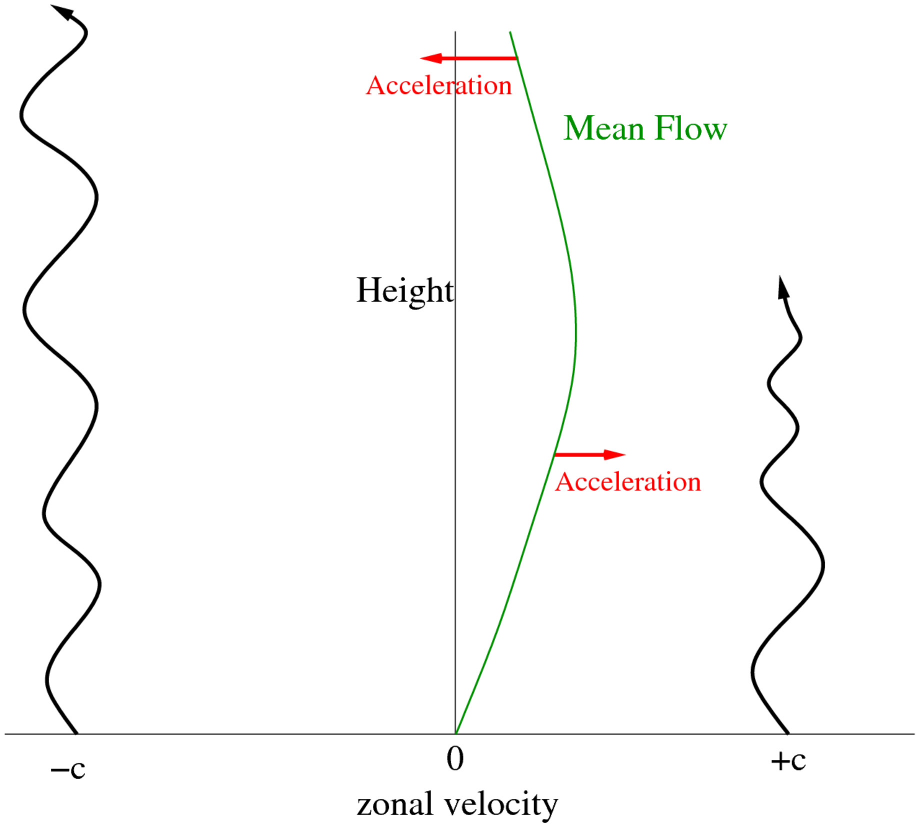
- Variability concentrated in
  - the equatorial region
  - The edge of the polar vortex (winter hemisphere)
- Significant variability in the Winter Northern Hemisphere Polar Cap
- Weak Variability in the Winter Southern Hemisphere Polar Cap

Equatorial Variability – The Quasi-biennial Oscillation



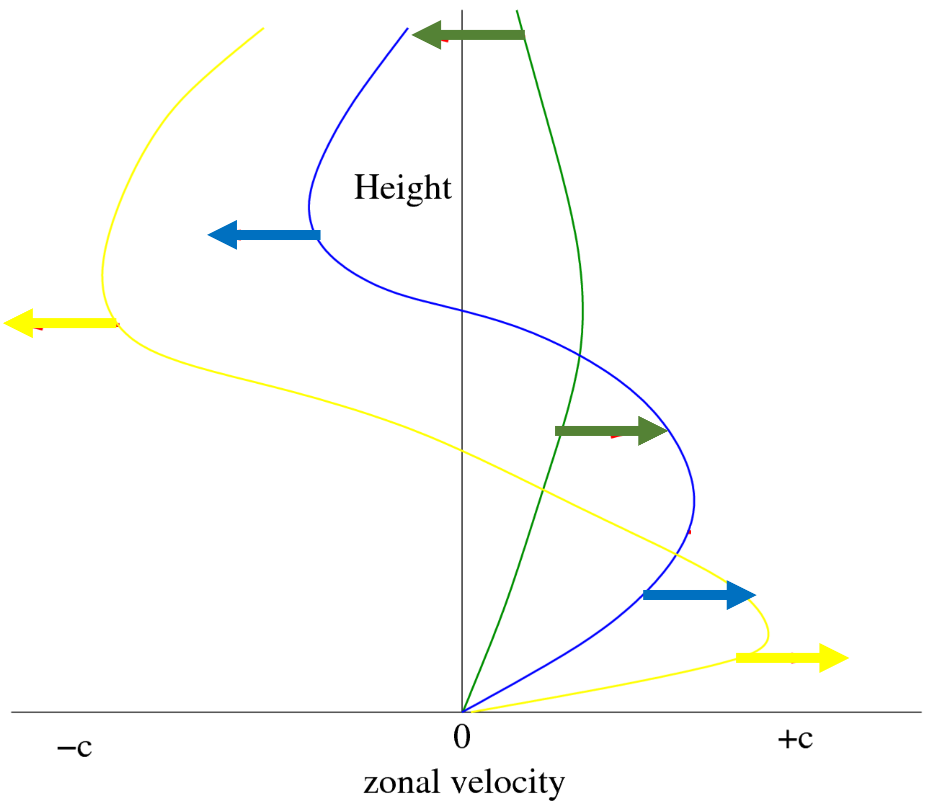
- Fairly regular oscillation in the zonal mean zonal wind at the Equator
- Period is approximately 27 months (but varies between 24-30)
  - Quasi-biennial Oscillation

Quasi-biennial Oscillation - Mechanisms



- QBO arises through interaction between gravity waves and the mean wind
- Waves can propagate vertically in regions where their phase speed is opposite to the mean wind or small
- As waves break they accelerate the mean flow in the direction of their zonal propagation
- Eastward propagating waves exert and eastward (westerly) acceleration in regions of eastward (westerly) shear and vice-versa

Quasi-biennial Oscillation - Mechanisms



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- Regions of westerly and easterly descend

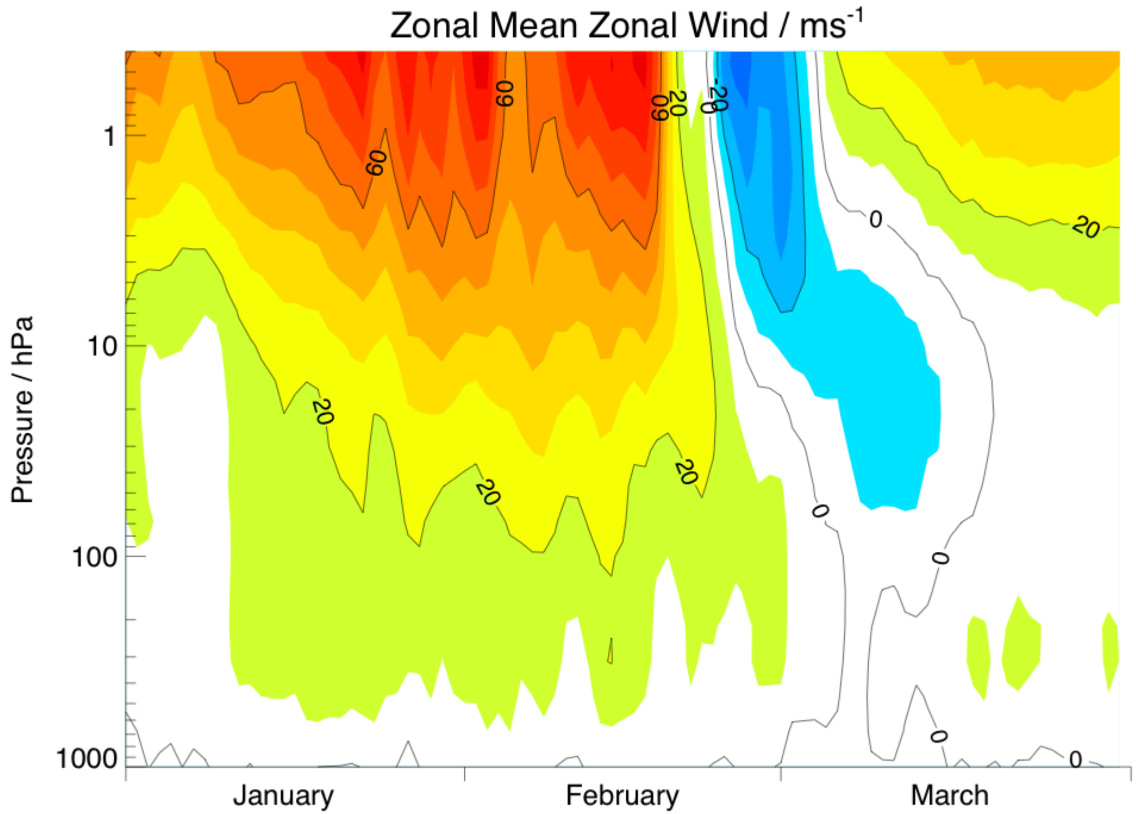
Stratospheric Variability – The Extratropics

- Extra-tropical stratospheric variability dominated by Rossby-Waves
- Rossby-waves can propagate vertically in sufficiently weak westerly winds (Charney-Drazin Theory)

$$0 < [u] < [u_c]$$

- Critical velocity u_c depends on wavelength with shorter wavelength waves having a smaller critical velocity
- When wind speed is less than zero or greater than the critical velocity the waves break and decelerate the mean westerly flow
- Changes in wave activity and breaking can lead to variations in the strength of the polar vortex

Stratospheric Variability – Sudden Stratospheric Warmings



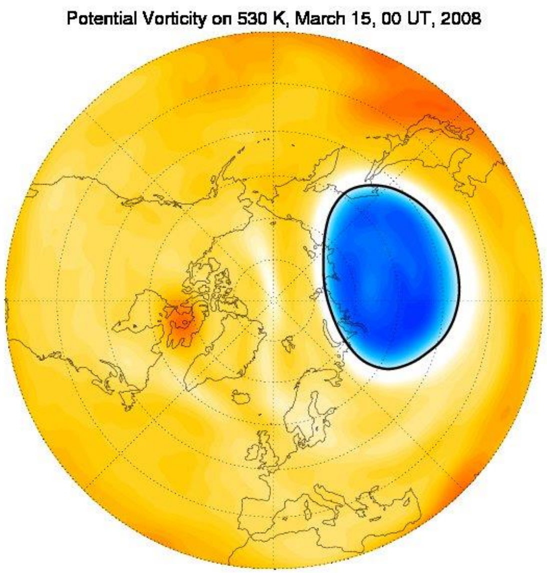
- Northern Winter Polar Vortex occasionally breaks down on sub-seasonal timescales
- Reversal of wind is associated with warming of polar stratosphere (thermal wind balance – " Sudden Stratospheric Warming"
- Southern hemisphere wave forcing generally not strong enough to produce SSW

Sudden Stratospheric Warmings - Classification

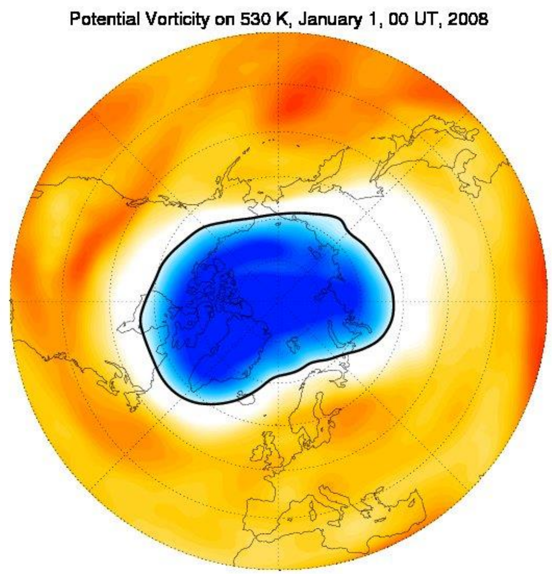
- **Major Warming** - zonal wind is reversed over the polar cap and climatological westerlies are replaced by easterlies (about 1 every 2 years)
- **Minor Warming** - no reversal of flow (occur most years)

- **Displacement Warming** (or wave one warming) - vortex is moved off the pole
- **Split Vortex** (or wave two warming) – polar vortex splits

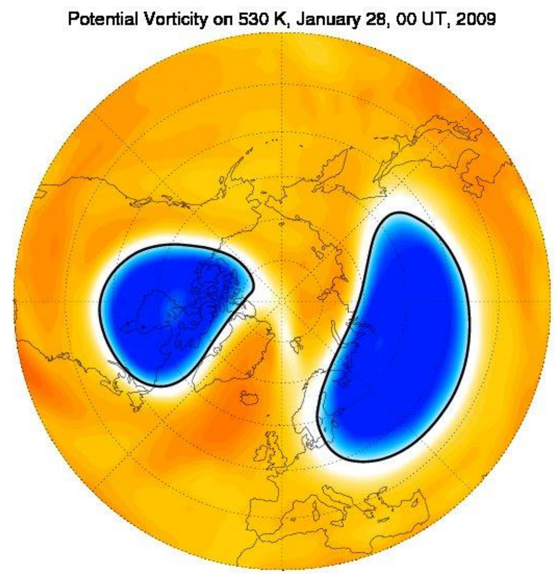
Displaced Vortex



Undisturbed Vortex



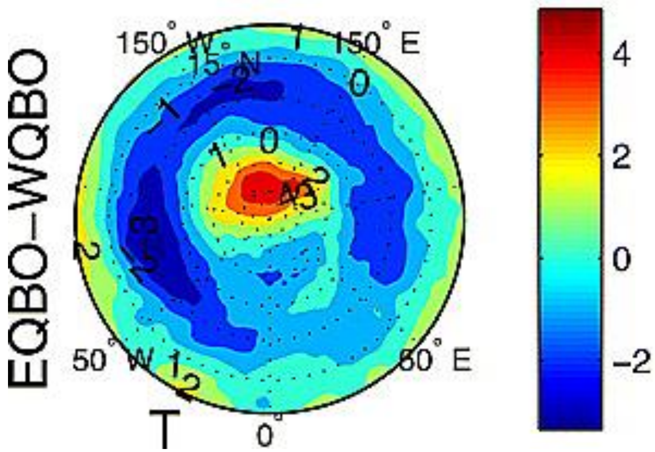
Split Vortex



Images from animations on Thomas Birner's webpage
http://birner.atmos.colostate.edu/ssw.html

Influence of the QBO on the polar vortex

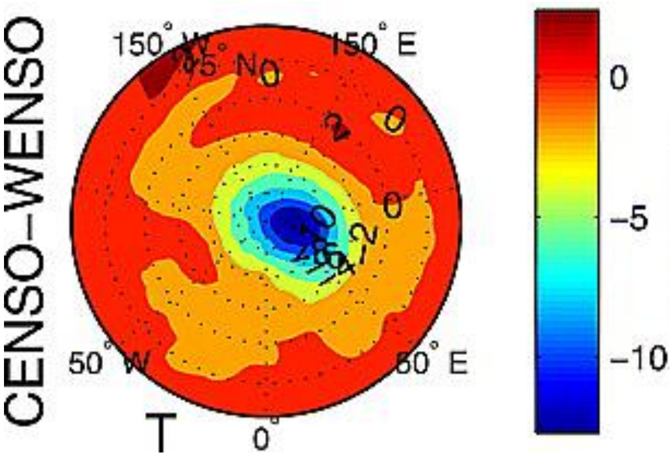
- Meridional Propagation of Rossby waves is influenced by the background state zonal wind
- Easterly Phase of the QBO confines Rossby Wave activity to the winter hemisphere
- NH winter wave activity tends to be stronger during Easterly phase of the QBO
- Stronger wave activity tends to lead to a more disturbed vortex during Easterly Phases of the QBO



10hPa OND Temperature differences for Easterly QBO – Westerly QBO from Garfinkel and Hartmann, *JGR,* 2007.
The reduced temperature equator to pole temperature gradient is indicative of a weaker polar vortex

Influence of the QBO on seasonal predictability

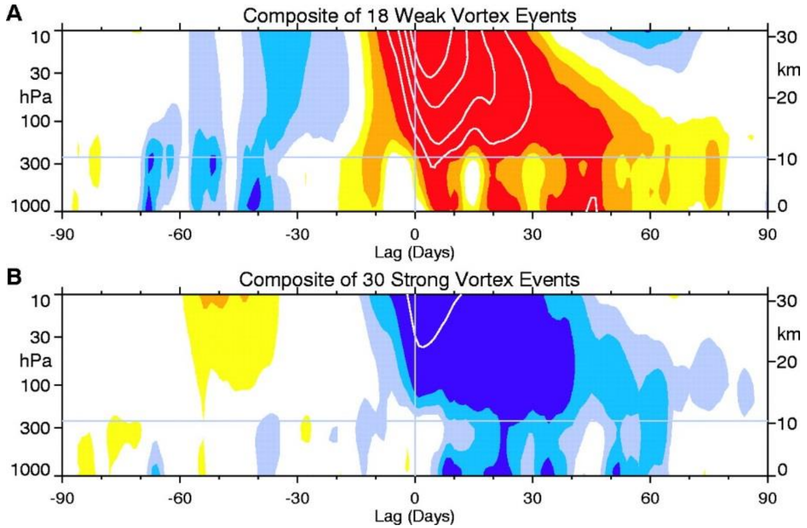
- The influence of the Phase of the QBO on wave propagation may also impact the response of the QBO to ENSO
- Garkinkel and Hartmann (2007) found that under easterly phases of the QBO there was no significant impact of ENSO on the polar vortex
- Under Westerly phases of the QBO, La Niña (El Niño) tends to be associated with a colder and stronger (warmer and weaker) vortex



10hPa NDJF Temperature differences for La Niña - El Niño in the westerly phase of the QBO from Garfinkel and Hartmann, *JGR,* 2007.
The increased equator to pole temperature gradient is indicative of a stronger polar vortex

Relationship between the polar vortex and the troposphere

- The variations in the stratospheric polar vortex are well characterized by “annular modes” - coherent hemispheric scale pressure variations with one sign of anomaly over the pole and the opposite sign at low lattitudes
- At the surface these annular models are related to the North Atlantic Oscillation (NAO) or Arctic Oscillation (AO)
- Following a SSW (weak vortex) or a strong vortex event there is a signal in the annular mode at the surface

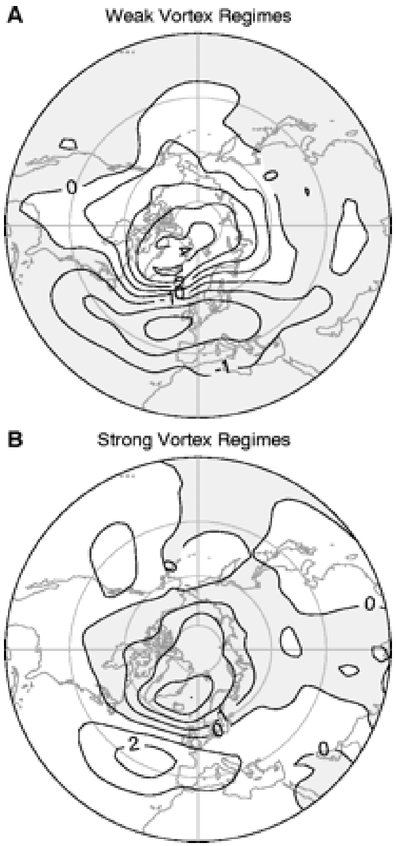


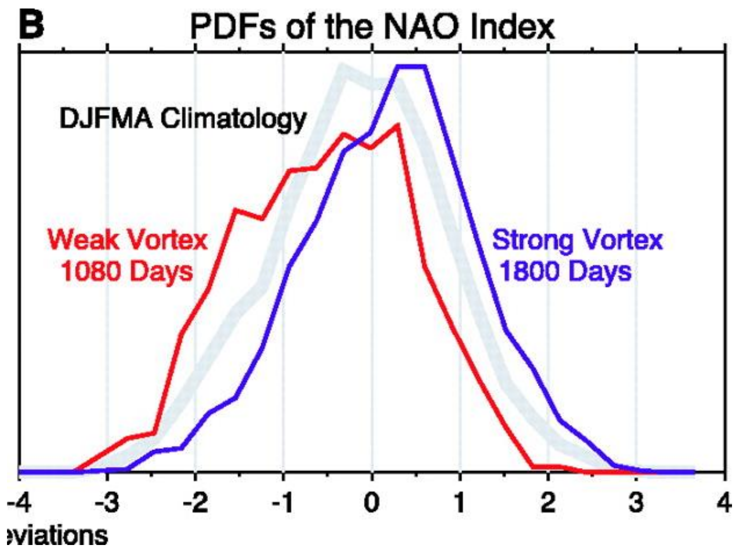
Time height cross section of the Northern Annular Mode index for 18 weak vortex events and 30 Strong vortex events from Baldwin and Dunkerton, *Science,* 2001.

Mechanisms for stratosphere-troposphere teleconnection

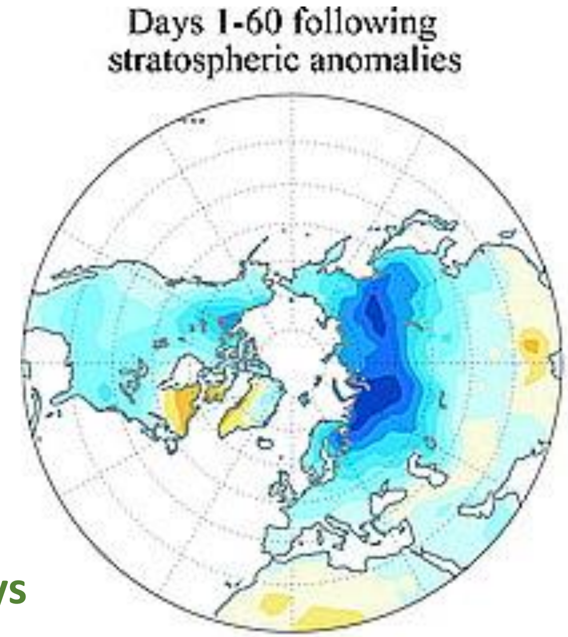
- The mechanisms by which the stratosphere influences the troposphere are not fully understood but different mechanisms can be characterised as
  - Influence of stratospheric on the development of tropospheric baroclinic eddies
  - Large-scale tropospheric adjustment to stratospheric PV anomalies
  - Planetary-scale wave-mean flow interaction in which the propagation of vertically propagating planetary-scale waves is influenced by variations in the stratospheric winds
- As yet there is no consensus on which is the dominant mechanism and it is possible that more than one play a role

Relationship between the polar vortex and the troposphere





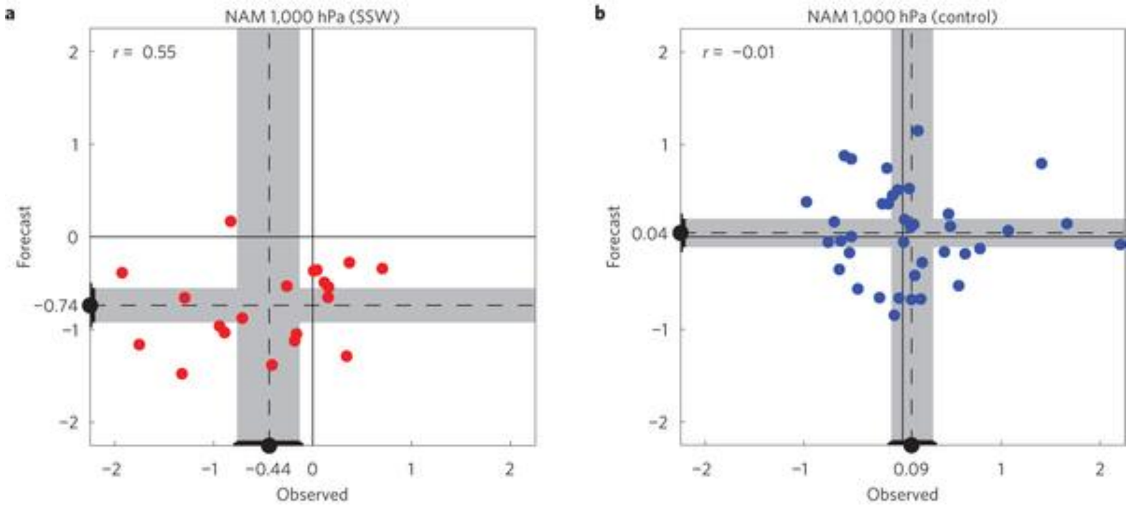
Surface variability averaged over 60 days following weak and strong vortex events



Left: Surface pressure anomalies after weak and strong vortex events.
Middle: PDF of NAO index following weak and strong vortex events
(both from Baldwin and Dunkerton, *Science*, 2001)
Right: Difference in daily mean surface temperature for weak-strong vortex events
(from Thompson et al., *J. Climate*, 2002)

Impact on seasonal predictability

- Sigmond et al. (*Nature Geosciences, 2013)* explored the impact of SSWs on seasonal prediction in the Canadian Middle Atmosphere Model
- 10 ensemble members are initialized on the dates of 20 SSWs and compared to a set of control forecasts initialized on the same date of the preceding and following years

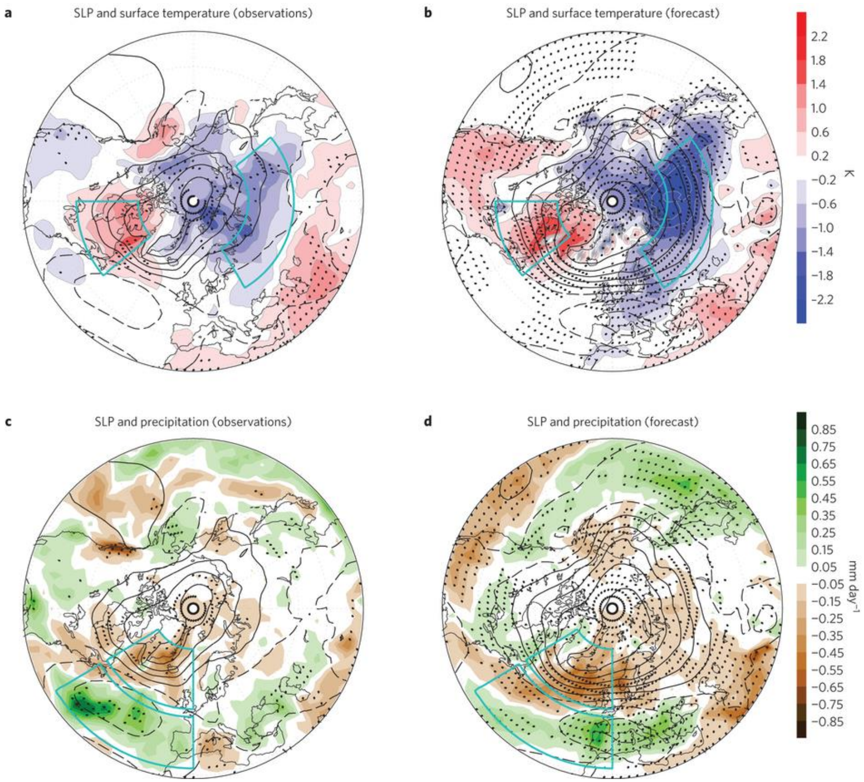


Ensemble mean forecast vs observed 1000hPa NAM index for forecasts 16-60 days after SSW (left) and for control forecasts (right) from Sigmond et al (2013)

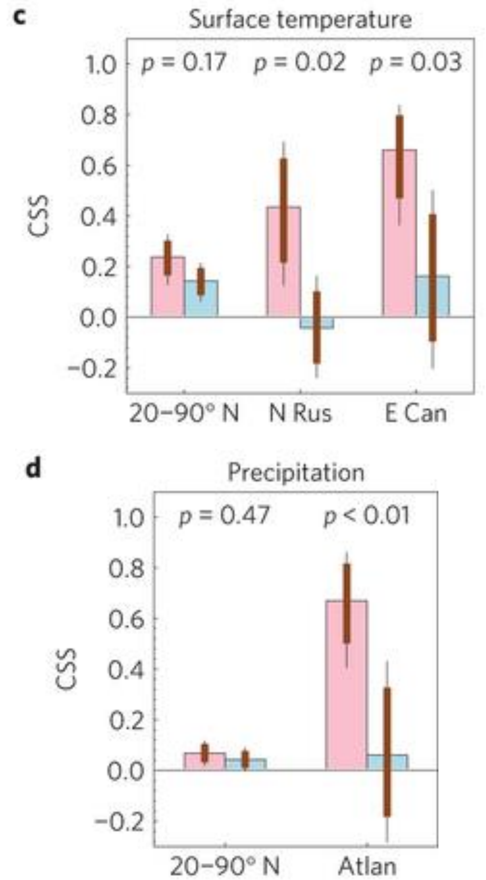
Impact on seasonal predictability

Temperature

Precipitation



Observed Forecast



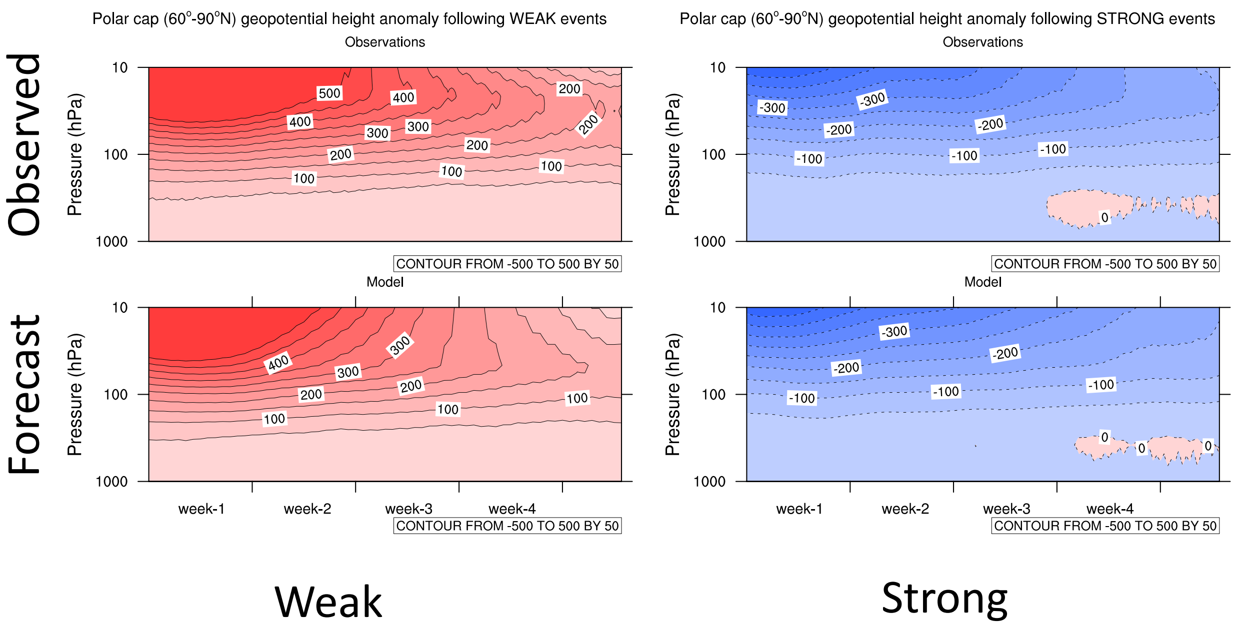
Left: Mean observed forecast surface pressure, temperature and precipitation anomalies after SSWs

Middle: Correlation Skill scores for surface temperature and precipitation for forecasts following SSWs and control forecasts

(from Sigmond et al., *Nature Geosciences* 2013)

Impact on sub-seasonal predictability

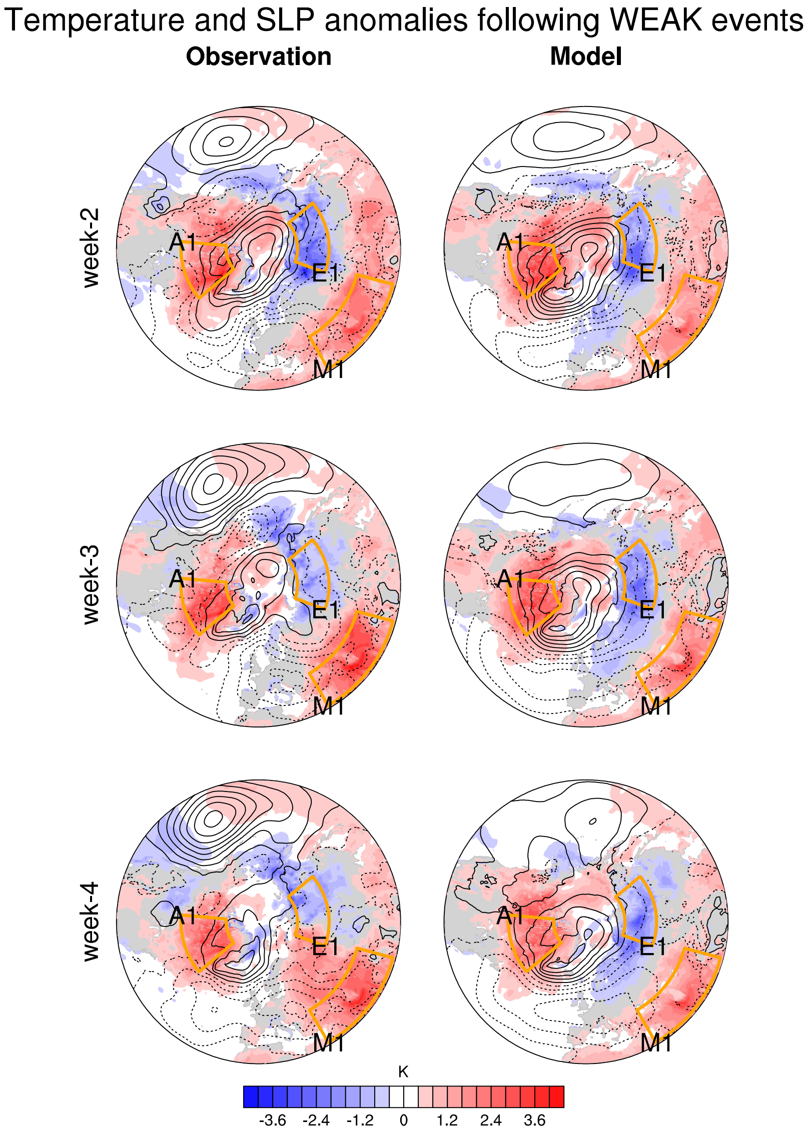
- Does this improved skill on seasonal timescales also occur on sub-seasonal timescales
- Recently Tripathi et al (*ERL*, 2015) explored the impact of SSWs on sub-seasonal predictability in the ECMWF monthly forecasting system
- Composite based on Strong (103), Medium (199) and weak (36) … a and 60N



Polar cap anomalies in geopotential well captured by ECMWF system throughout the stratosphere and troposphere *(figure courtesy Andrew Charlton-Perez)*

Impact on sub-seasonal predictability

- Strong negative (positive) NAM anomaly in sea-level pressure for weak (strong) vortex events
- Warm anomalies over NE Canada and Middle East following weak vortex events
- Cold Anomalies over Northern Russia following weak vortex events
- Signal remains in observations and forecasts out to week 4



from Tripathi et al (*ERL*, 2015)

Impact on sub-seasonal predictability

- Forecasts able to reproduce size of surface temperature anomalies for some regions
- Warm anomalies in Eastern Canada and Middle East following weak events
- Warm (cold) anomalies in Northern Eurasia following strong (weak) events
- Also able to capture the lack of signal over Eastern Canada following strong events

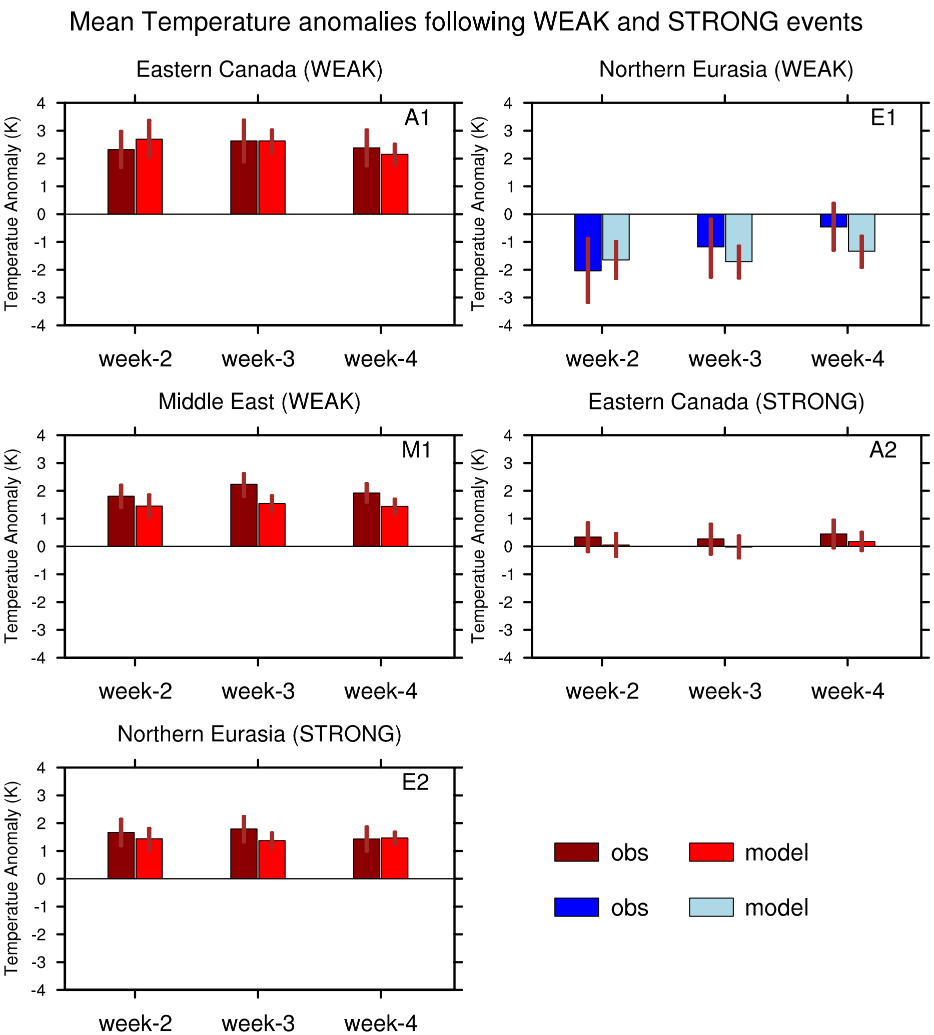
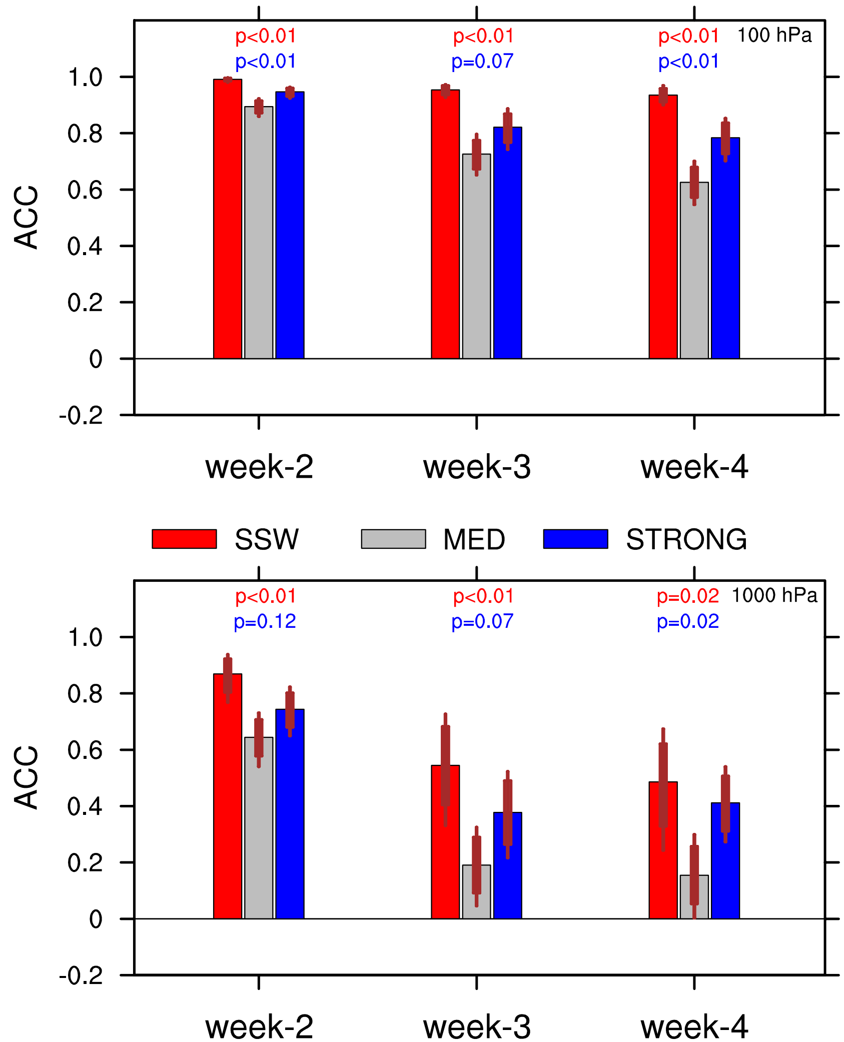


Figure courtesy Andrew Chalrton-Perez

Impact on sub-seasonal forecast skill

Forecast skills (ACC) for the NAM index

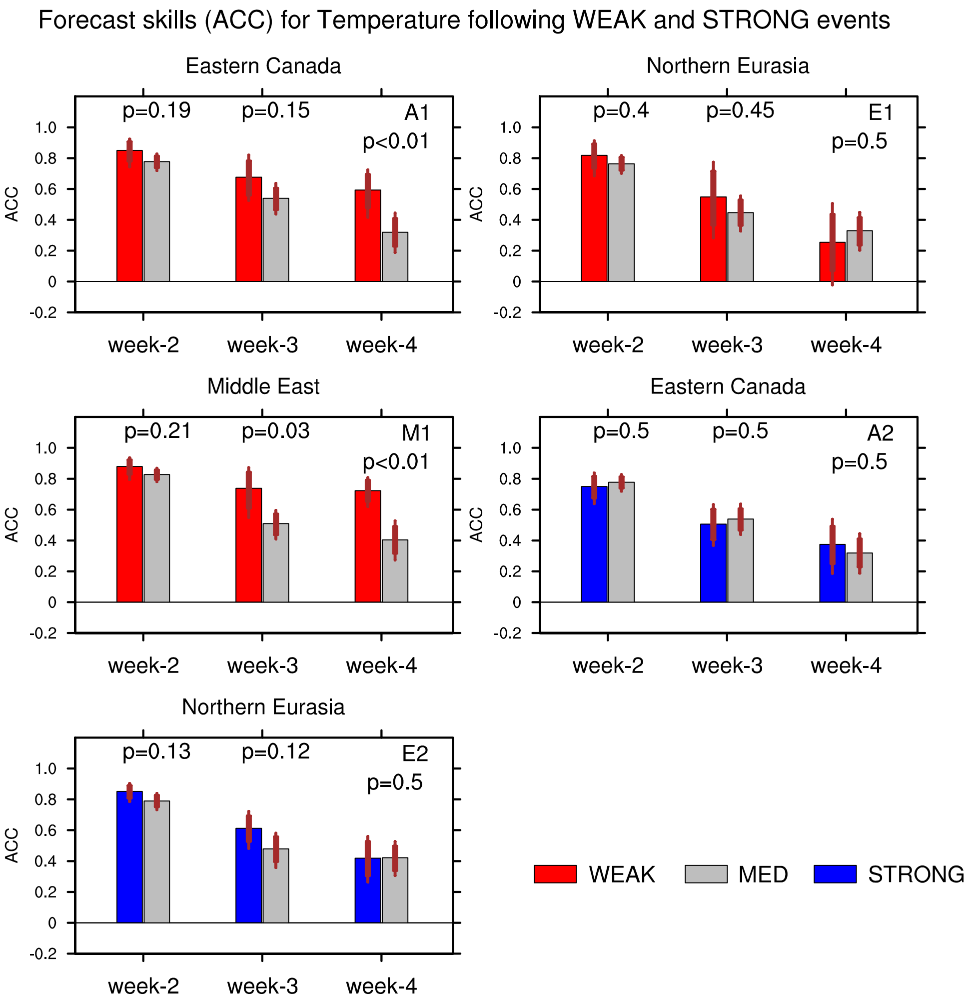
- Significant increases in skill for NAM index at 100hPa and surface when forecast initialized with strong or weak vortex
- Particular large improvements in skill at the surface in weeks 3-4



from Tripathi et al (*ERL*, 2015)

Impact on sub-seasonal forecast skill

- Significant improvements in skill for surface temperature over Eastern Canada (week 4) and Middle East (weeks 3-4) following weak vortex events
- Little or no significant impact on skill in for other regions or lead times



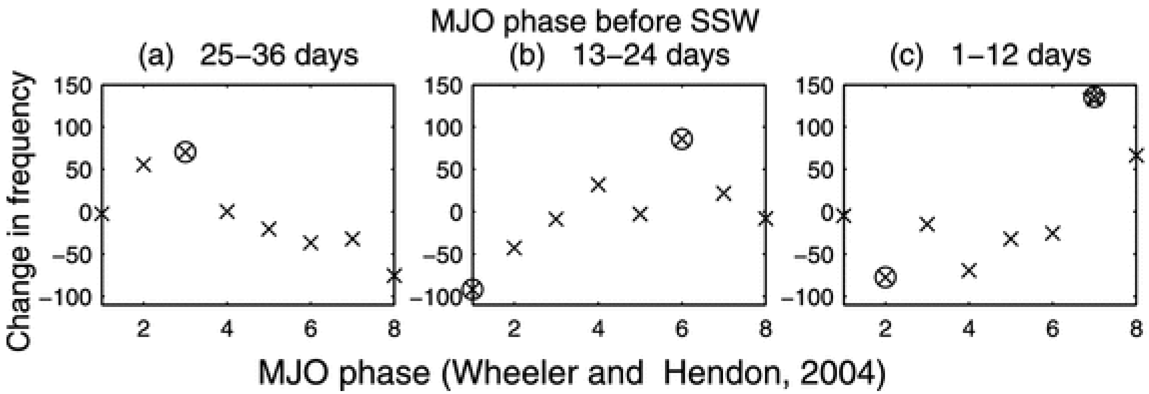
from Tripathi et al (*ERL*, 2015)

How predictable are SSW?s

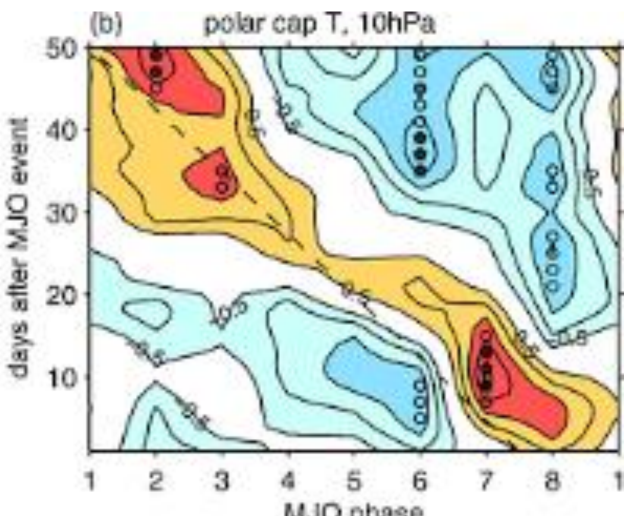
- There has been little systematic evaluation of the predictability of SSWs on sub-seasonal timescales
- Studies focussing on the prediction of individual events suggest skill at lead-times of 5-15 days depending on event and model (Tripathi et al, *QJRMS, 2014)*
- Predictability likely depends on model resolution (vertical and horizontal) and representation of stratospheric mean state
- Improved representation of the stratosphere will improve both the representation of the stratospheric dynamics and the ability to assimilate satellite data

How predictable are SSW?s

- One potential source of predictability for SSWs is the MJO
- Garfinkel et al, (*QJRMS*, 2012) explored the link between the MJO and SSWs



Change in frequency of MJO phase compared to climatology before major NH SSWs from Garfinkel et al. (2012)



10hPa Polar cap temperature as a function of lag follow particular MJO phases from Garfinkel et al. (2012)

Summary

- Stratosphere characterized by strong static stability with uniform or increasing temperature with height
- Strong seasonality in zonal winds and temperature in thermal wind balance
  - strong westerly polar vortex in winter hemisphere
  - weak easterlies in summer hemisphere
- Equatorial variability dominated by Quasi-Biennial Oscillation (QBO) driven by interaction between vertically propagating gravity waves and mean flow
- Weak variability in summer hemisphere
- Winter polar vortex variability driven by interaction between vertically propagating Rossby-waves and the mean zonal wind

Summary

- For strong wave forcing winter vortex can break down leading to a Sudden Stratospheric Warming (SSW)
- Polar vortex has strong teleconnection to tropospheric annular models leading to potential predictability on sub-seasonal to seasonal timescales
- Operational prediction systems are able to capture some of the tropospheric response to polar vortex variability on seasonal and sub-seasonal timescales
- Strong and Weak vortex conditions can improved forecast skill in Northern Hemisphere at weeks 2-4 depending on variable and region
- Potential to predict SSWs at lead times of 5-15 days provides possibility of skill tropospheric forecasts at even longer leadtimes