The role of stratospheric processes in large-scale teleconnections

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Outline

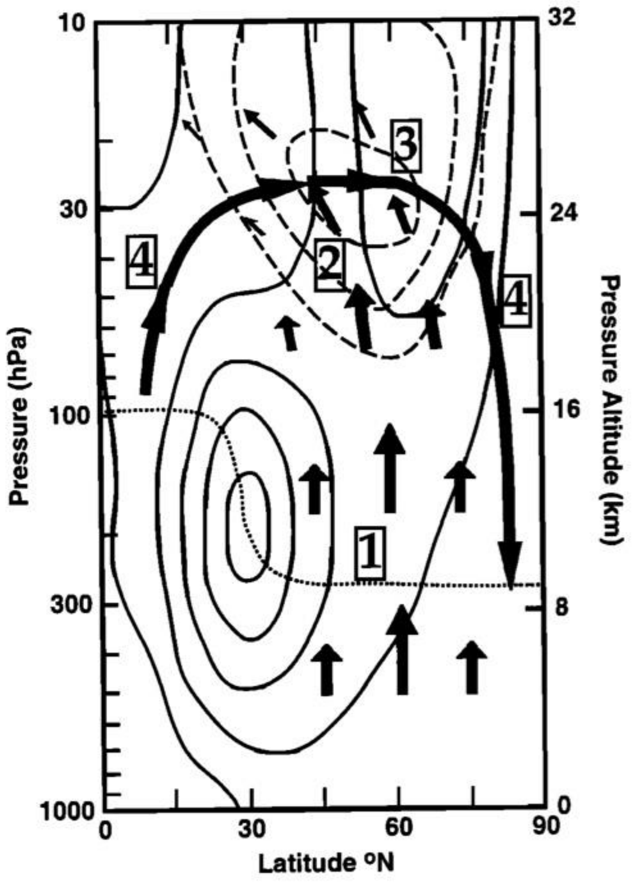
- Introduction
  - Comparison of features of stratospheric and tropospheric circulation
  - Some milestones in our understanding of stratospheric role in tropospheric climate variability and change
- Mechanisms of troposphere-stratosphere coupling
- Stratospheric processes and tropospheric climate predictability
  - Intraseasonal to interannual (strong and weak polar vortex events)
  - Seasonal to interannual (ENSO, QBO)
  - Ozone chemistry-climate interactions
- Take-home messages

Take-Home Messages

- Isolating the role of stratospheric processes in predictive skill of tropospheric circulation and teleconnections is a challenge because tropospheric and stratospheric circulation are closely coupled both upward and downward.
- The stratosphere provides an important pathway by which tropospheric circulation anomalies and teleconnections can be modified.
- A lack of proper representation of stratospheric processes degrades the potential predictive skill on subseasonal to interannual time scale in the troposphere.

Comparison of Features of Stratospheric and Tropospheric Circulation

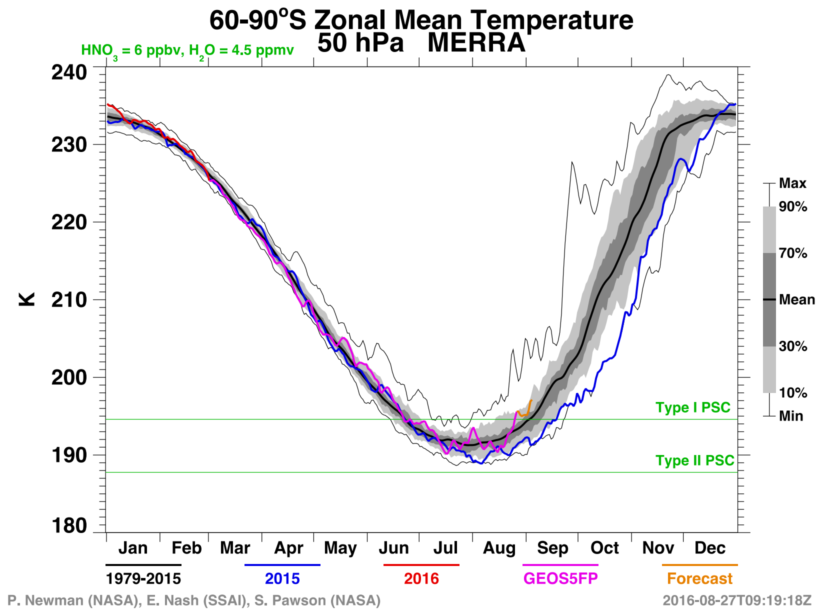
Tropospheric Control of Stratospheric Extratropical Winter Climate

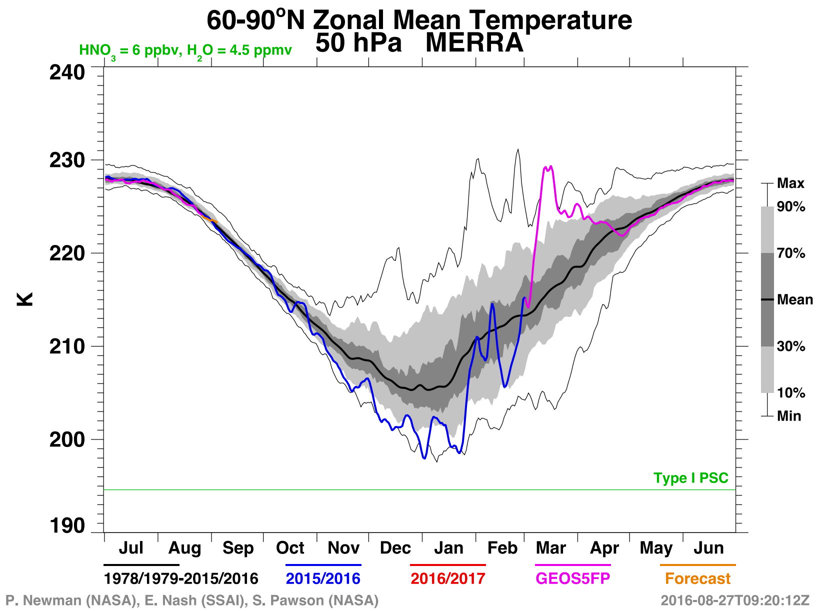


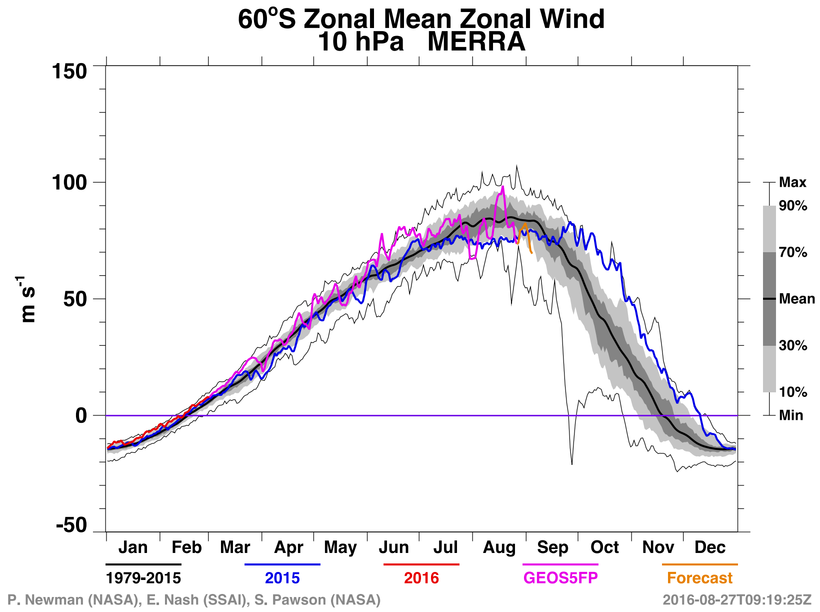
Newman et al. 2001

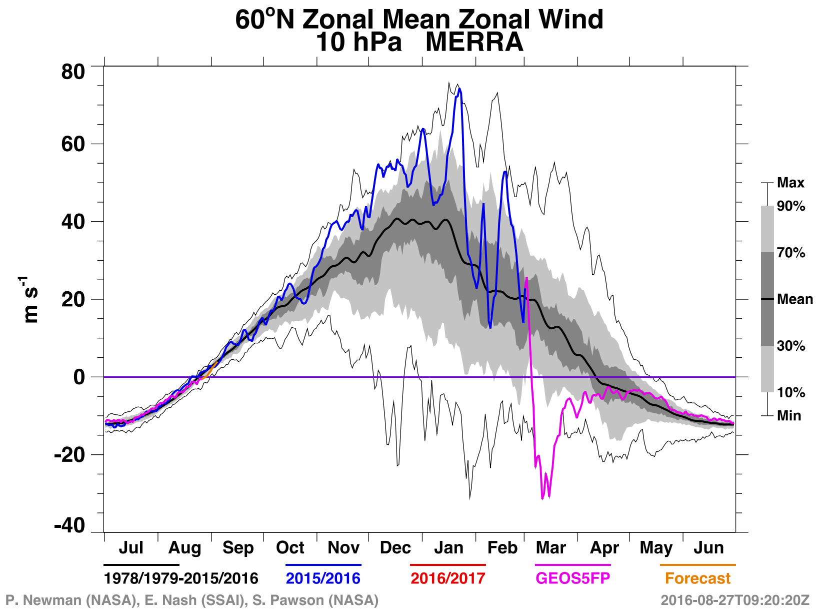
- Planetary scale waves are generated in the troposphere and may propagate upward into the stratosphere during winter when the zonal –mean flow is westerly.
- Waves dissipate in the stratosphere through wave-mean flow interaction processes
- Waves force a poleward meridional mass circulation and decelerate the zonal wind away from the radiative equilibrium state of a cold and strong stratospheric polar vortex

Seasonal Cycle of 50hPa Polar Cap Temperatures and 10hPa Zonal Mean Zonal Wind





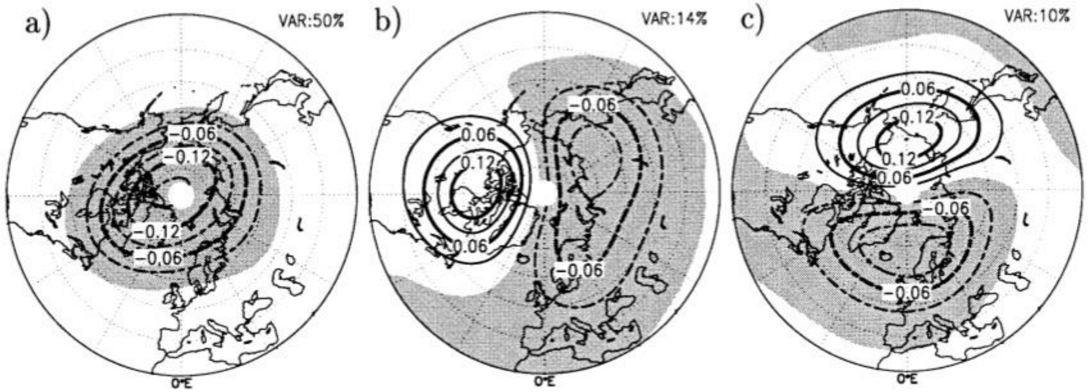




Leading Modes of Variability of Monthly (D,J,F) 50 and 500hPa Geopotential Heights

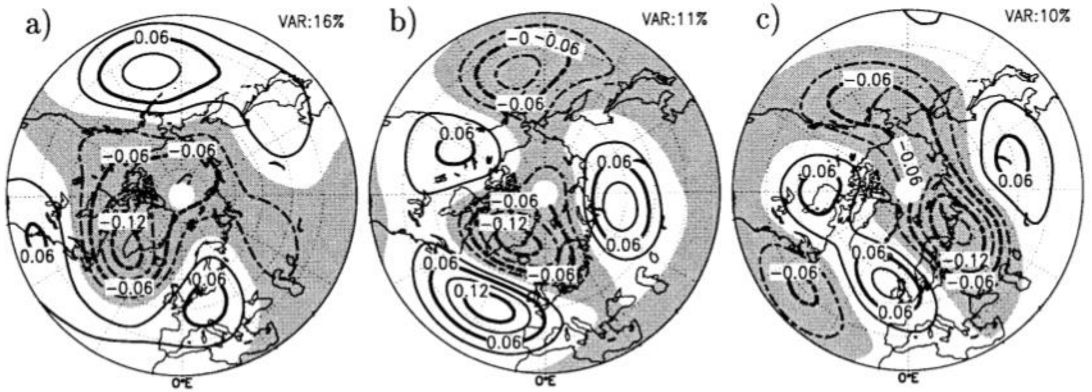
50hPa

1. EOF 50% | 2nd EOF 14% | 3rd EOF 10%



500hPa

1st EOF 16% | 2nd EOF 11% | 3rd EOF 10%



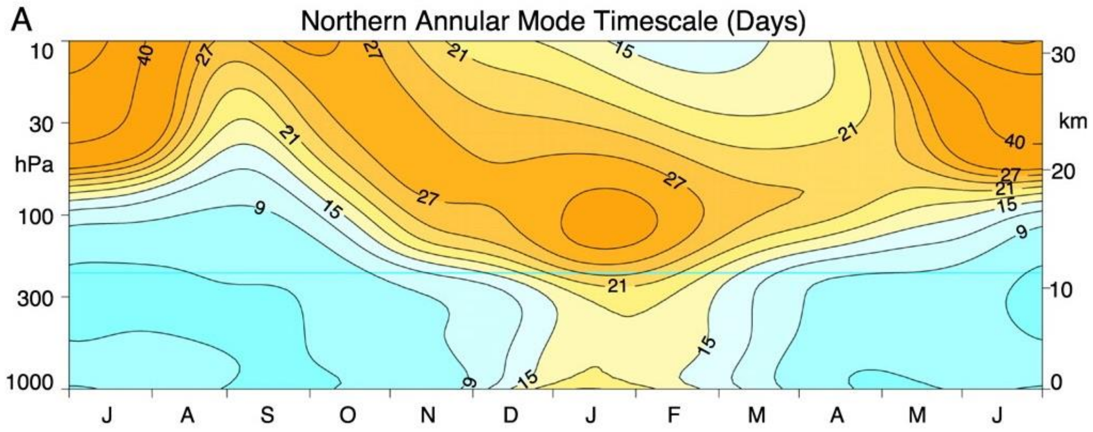
Perlwitz and Graf, 2000

Spatial Degrees of Freedom of Northern Hemisphere Circulation

	Daily		Daily (low-pass)		Monthly	
	DJF	JJA	DJF	JJA	DJF	JJA
Z_{50}	9	4	8	3	5	2
Z_{500}	29	46	21	36	13	19
Z_{1000}	29	37	20	27	13	15

Perlwitz and Graf, 2000

Time scale of Leading Mode of Variability



Baldwin et al. 2003

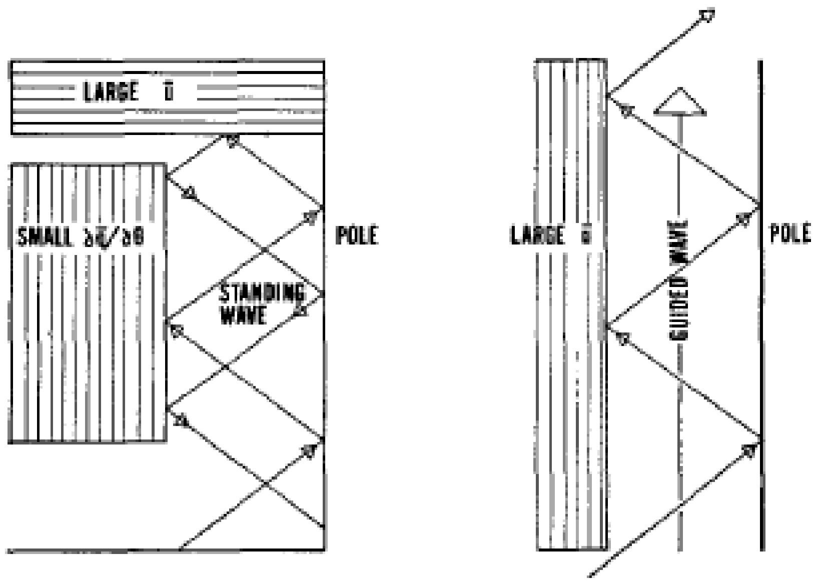
Some milestones in our understanding of stratospheric role in tropospheric climate variability and change

A Possible Mechanism for the Production of Sun-Weather Correlations (Hines et al. 1974, JAS)

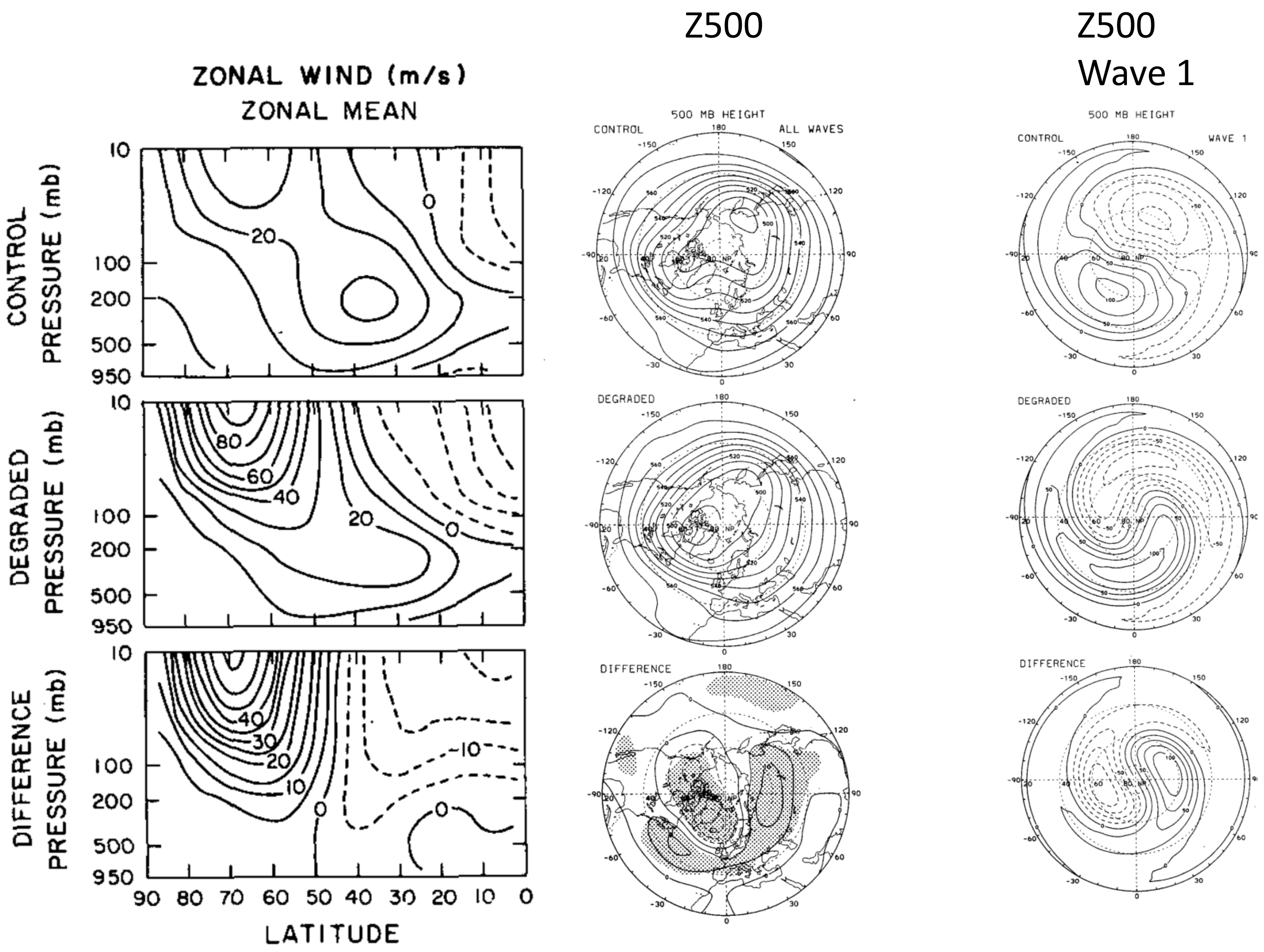
The essential point to be made is that the meteorological systems in question can be analyzed as planetary waves, that these waves propagate their energy upward, that they can then return their energy to lower levels and there interfere constructively or destructively with the initial systems that gave them their being.

Impact of Stratospheric Basic State on Tropospheric Waves

- Stratospheric winds play a dominant role in determining the transmission-refraction properties (refractive index) of planetary-scale waves that propagate vertically into the stratosphere (Charney and Drazin, 1961; Matsuno, 1970).
- Impact of strength of stratospheric polar vortex on planetary wave structure illustrated based on linear wave propagation models (Bates, 1977, Geller and Alpert, 1980, Schmitz and Grieger, 1980)



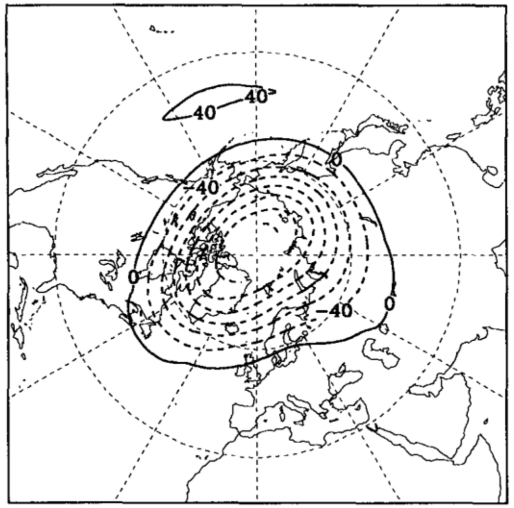
Impact of Stratospheric Basic State on Tropospheric Wave Structure



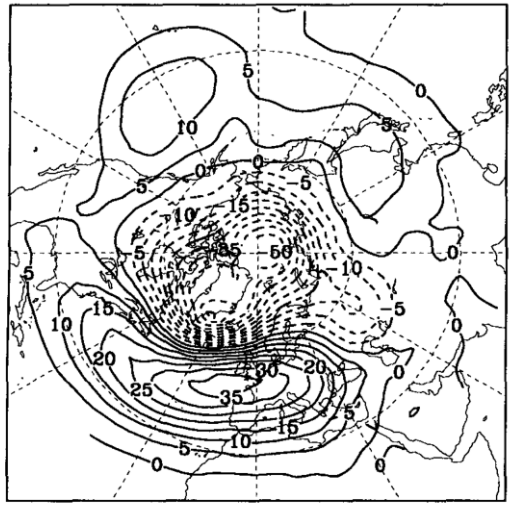
Boville, 1984

Leading Coupled Mode of Variability of Tropospheric and Stratospheric Circulation

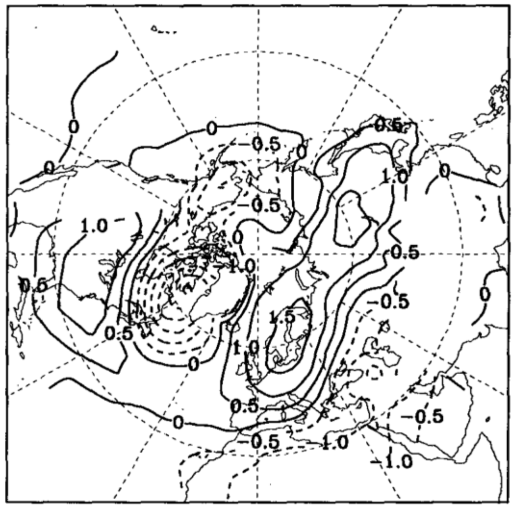
a) Z500



Z1000



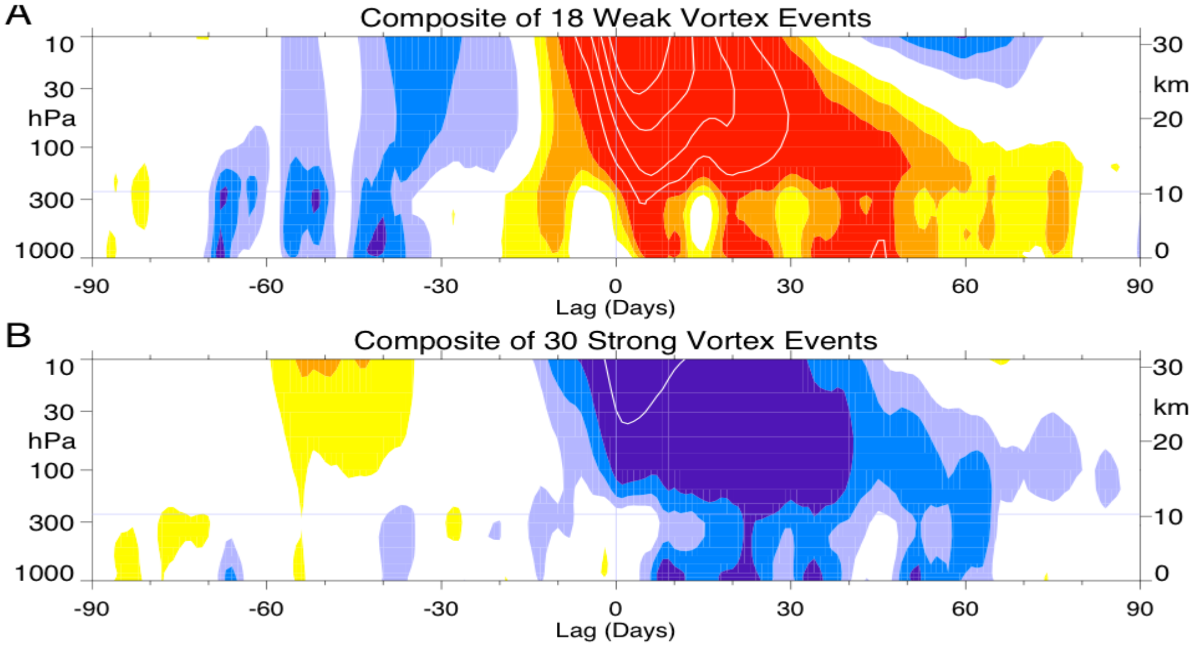
T850

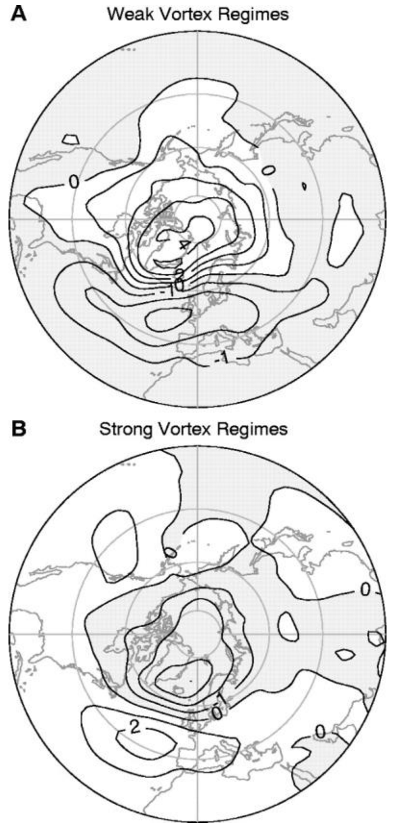


Baldwin et al. 1994, Perlwitz and Graf, 1995;
Thompson and Wallace 1998, 2000

Perlwitz and Graf, 1995

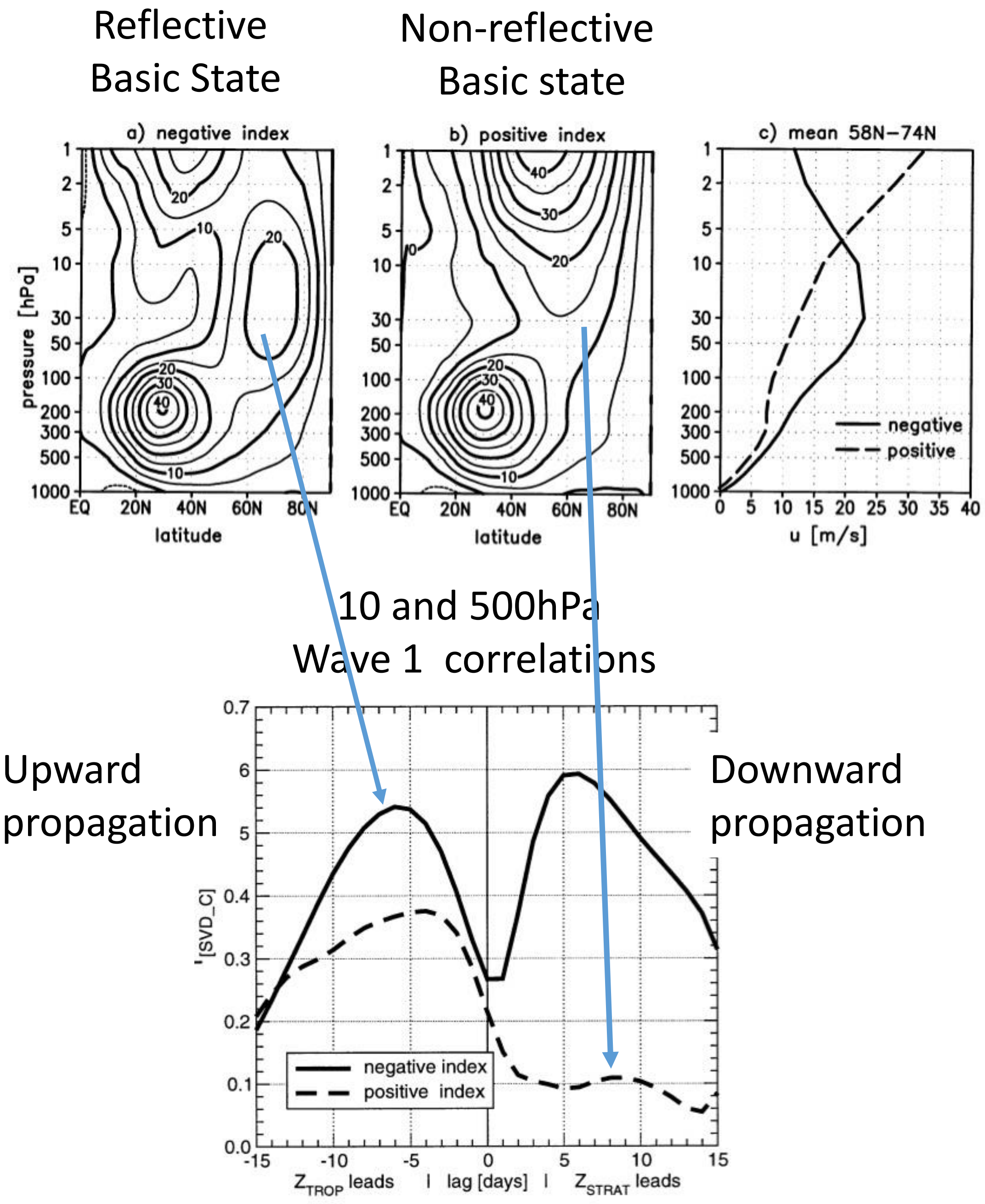
Observational Evidence for Downward progression of Northern Hemisphere Annular Mode (NAM) (Baldwin and Dunkerton, 2001)





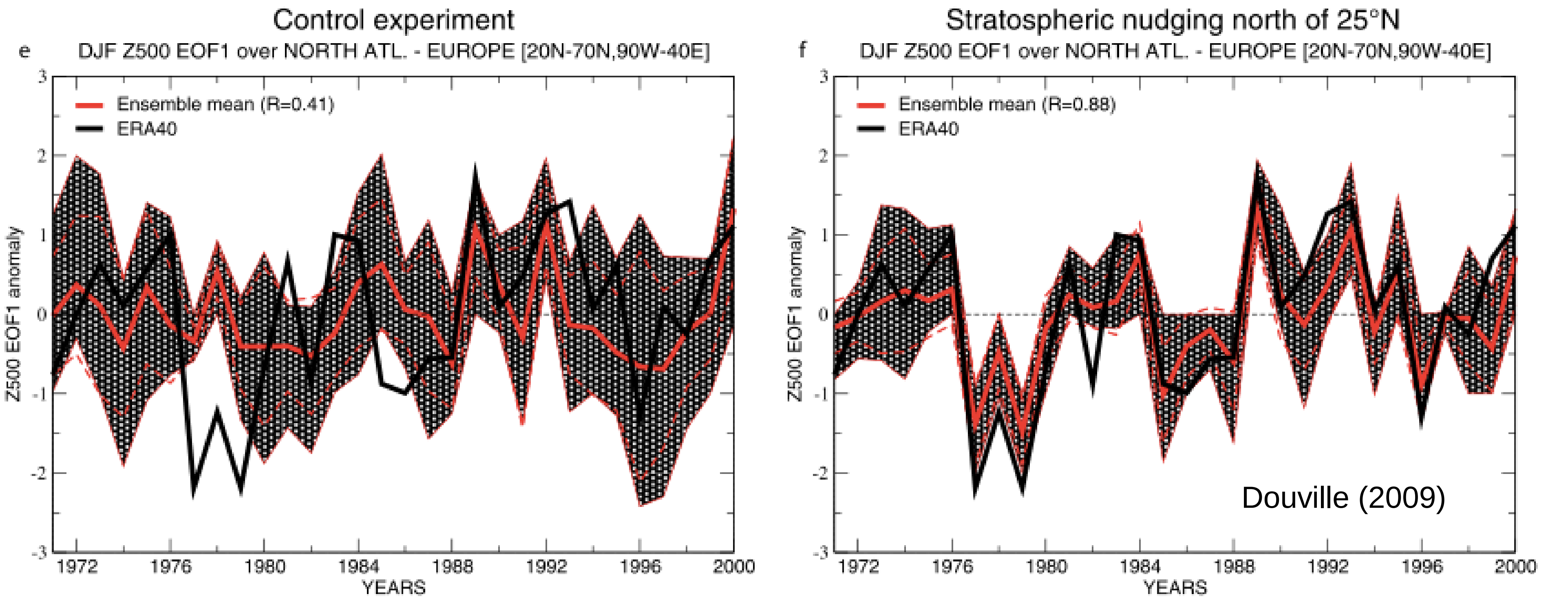
- Extreme events in the stratosphere are followed by anomalous pattern at the surface that resemble the NAM
- Extreme stratospheric events may provide forecast potential for up to two months

Observational Evidence for Downward Reflection of Planetary Wave 1 (Perlwitz and Harnik, 2003;2004)



- Process most important on weather time scale
- Leads to poleward shift of tropospheric jet over the North Atlantic for up to 4 weeks (Shaw and Perlwitz, 2015)

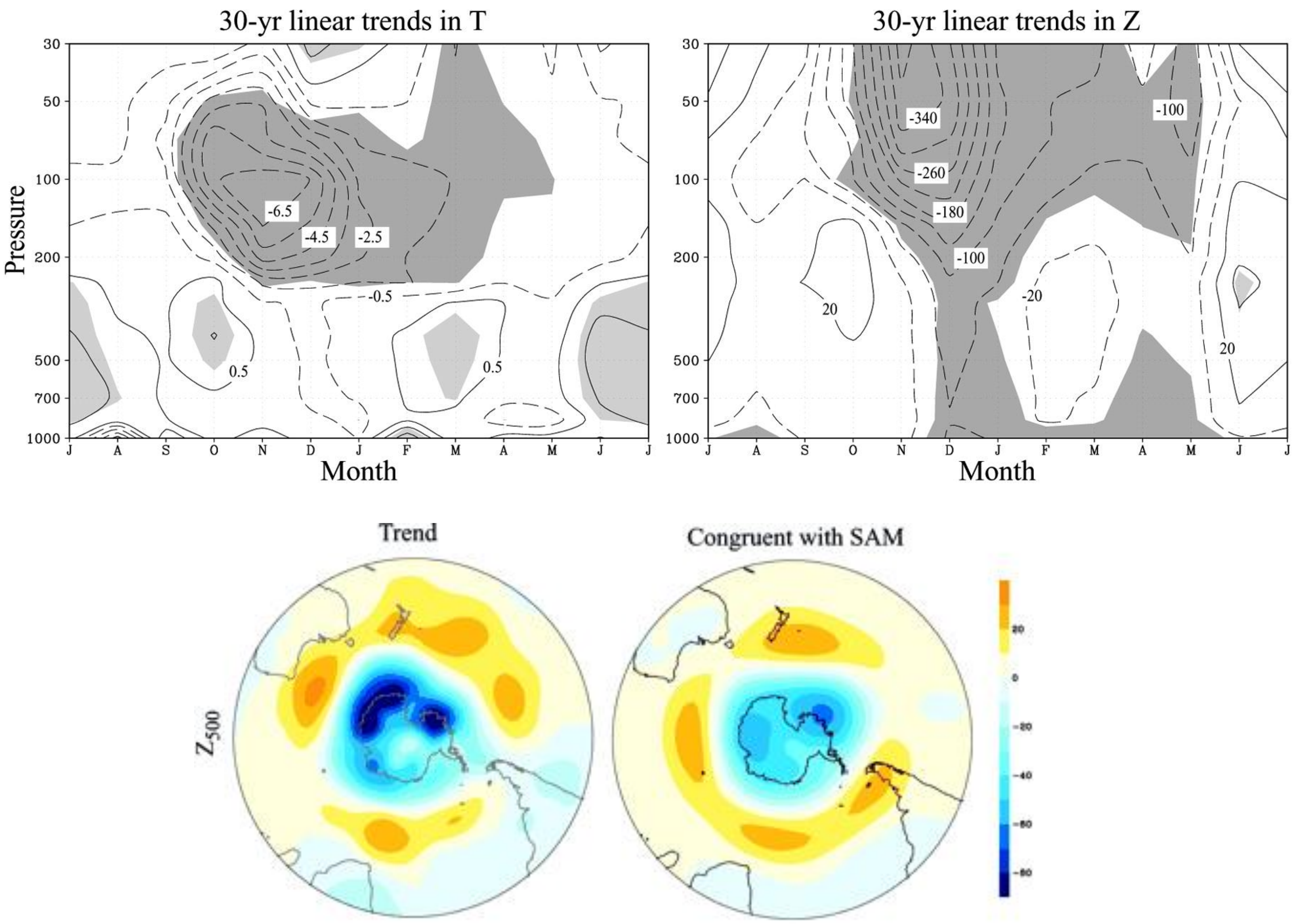
Evolution of NAO Closer to Observations when Stratosphere is Nudged to Reanalysis



Douville (2009)

See also Greatbatch et al. (2012), Scaife et al (2005)

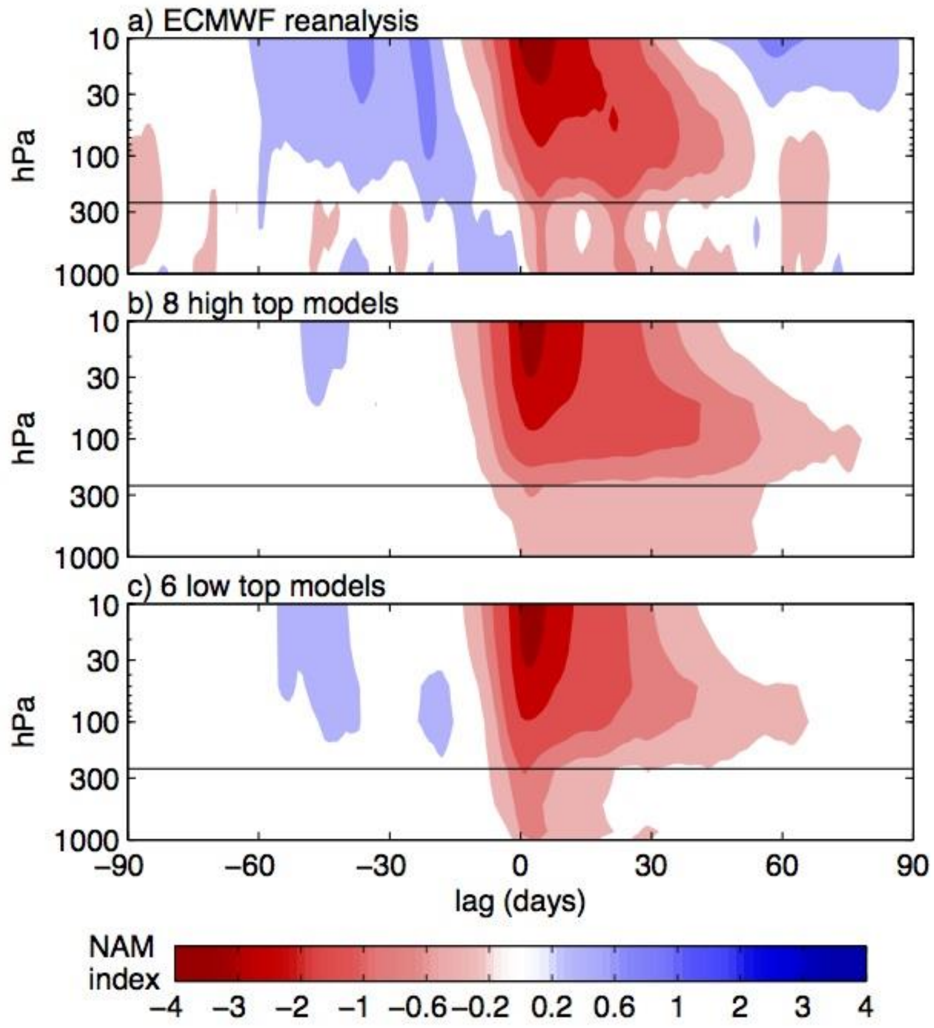
Impact of Antarctic Ozone Loss on Tropospheric Circulation During Austral Summer



Thompson and Solomon, 2002

Comparison of High and Low Top Models- A Tool to Improve our Understanding of Role of Stratospheric Processes on Tropospheric Climate

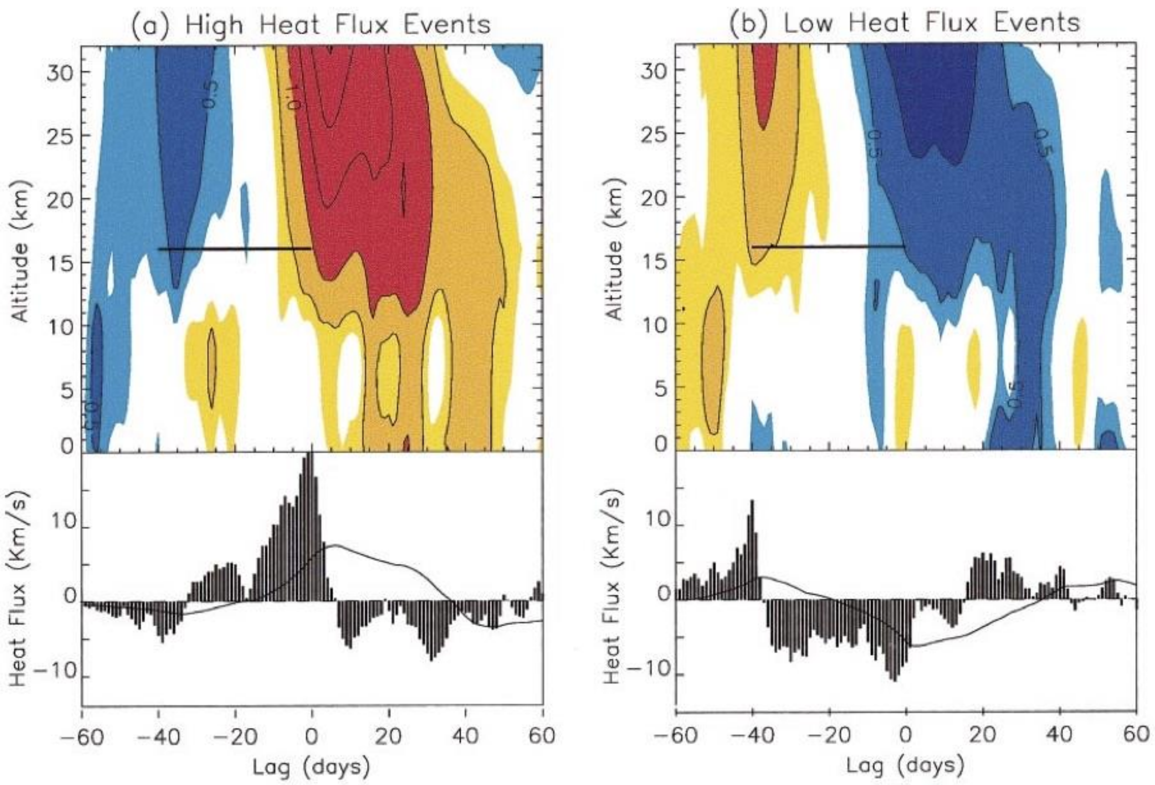
- Upper boundary effects in a general circulation model (Boville and Cheng 1988)
- Climate change impact (Shindell et al. 1999; Sigmond et al. 2008)
- Multi-model comparisons
  - CMIP5 models (Charlton-Perez et al. 2013, Manzini et al. 2014)
  - Seasonal forecast models (e.g. Butler et al. 2016)



Mechanisms of Troposphere-Stratosphere Coupling

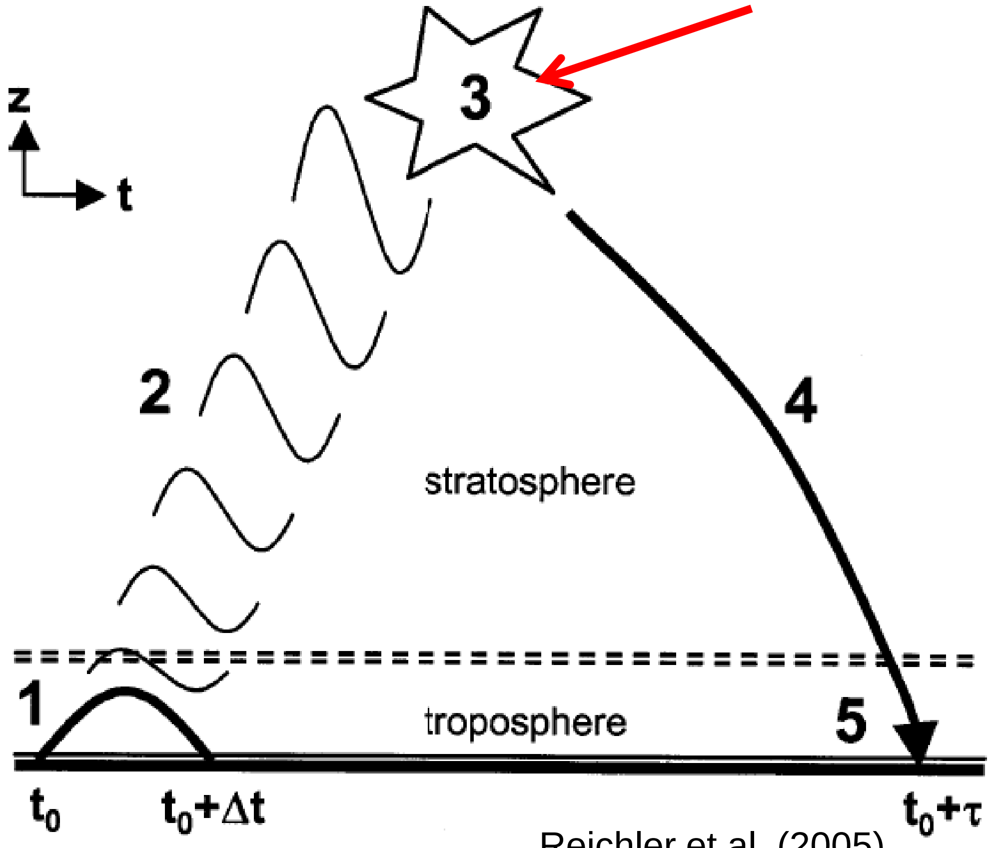
- Non-local balanced response to a **given** stratospheric torque
  - Downward control (Haynes et al. 1991)
  - PV inversion (Hartley et al. 1998, Black 2002, Ambaum & Hoskins 2002)
- Wave behavior determined by **given** zonal-mean flow via index of refraction (e.g. Charney & Drazin 1961, Matsuno 1970)
  - Dissipation at critical layer (e.g. McIntyre & Palmer 1983)
  - Reflection (e.g. Perlwitz & Harnik 2003, 2004, Shaw et al. 2010)
  - Resonance (e.g. Tung & Lindzen 1979, Plumb 1981, Esler & Scott 2005)
- Importance of synoptic scale wave feedbacks (Lorenz and Hartmann 2001, 2003: Wittman et al. 2007, Simpson et al. 2009, Thompson & Birner 2012, Chen & Held 2007)

Importance of Transiently Evolving Extreme Stratospheric Vortex Events



Polvani and Waugh (2004)

Extreme events dominate dynamics and exhibit coupling to troposphere



Reichler et al. (2005)

Stratospheric Processes and Tropospheric Climate Predictability on Subseasonal to Seasonal Time Scale

- Intraseasonal to interannual (extreme stratospheric vortex events)
- Seasonal to interannual (stratospheric ENSO pathway, QBO)
- Ozone chemistry-climate interactions

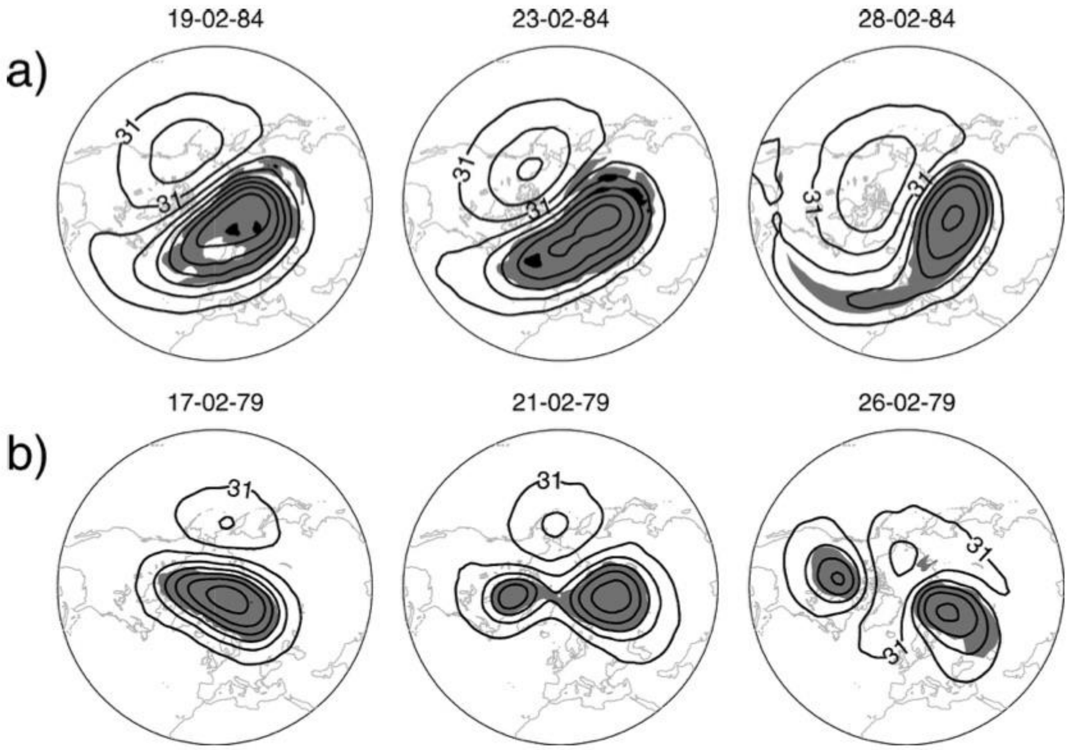
Major Stratospheric Sudden Warmings

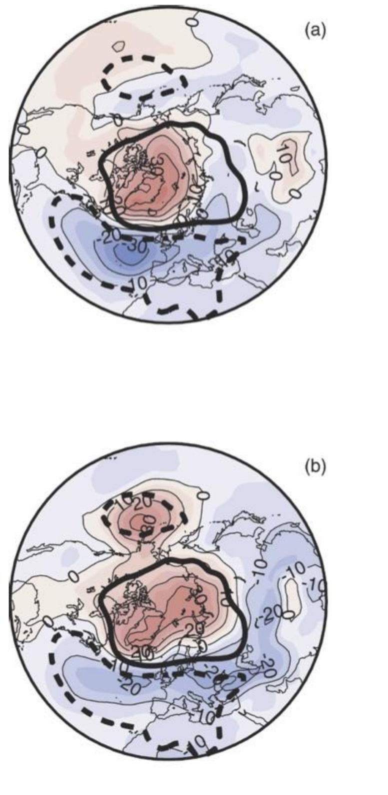
Stratospheric Evolution (10hPa)

SLP
Days 1-60 after Event onset

Vortex Displacements

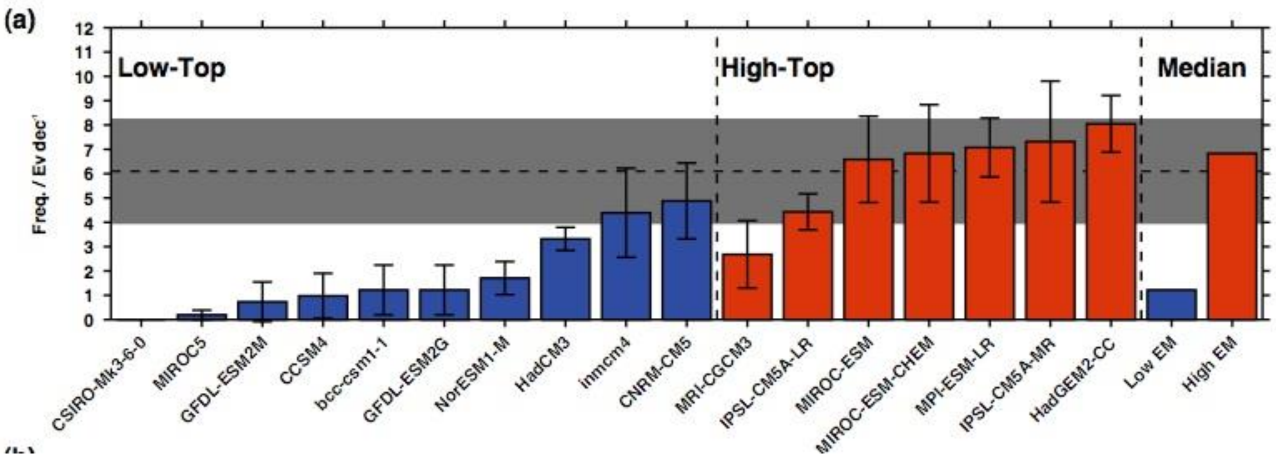
Vortex Splits

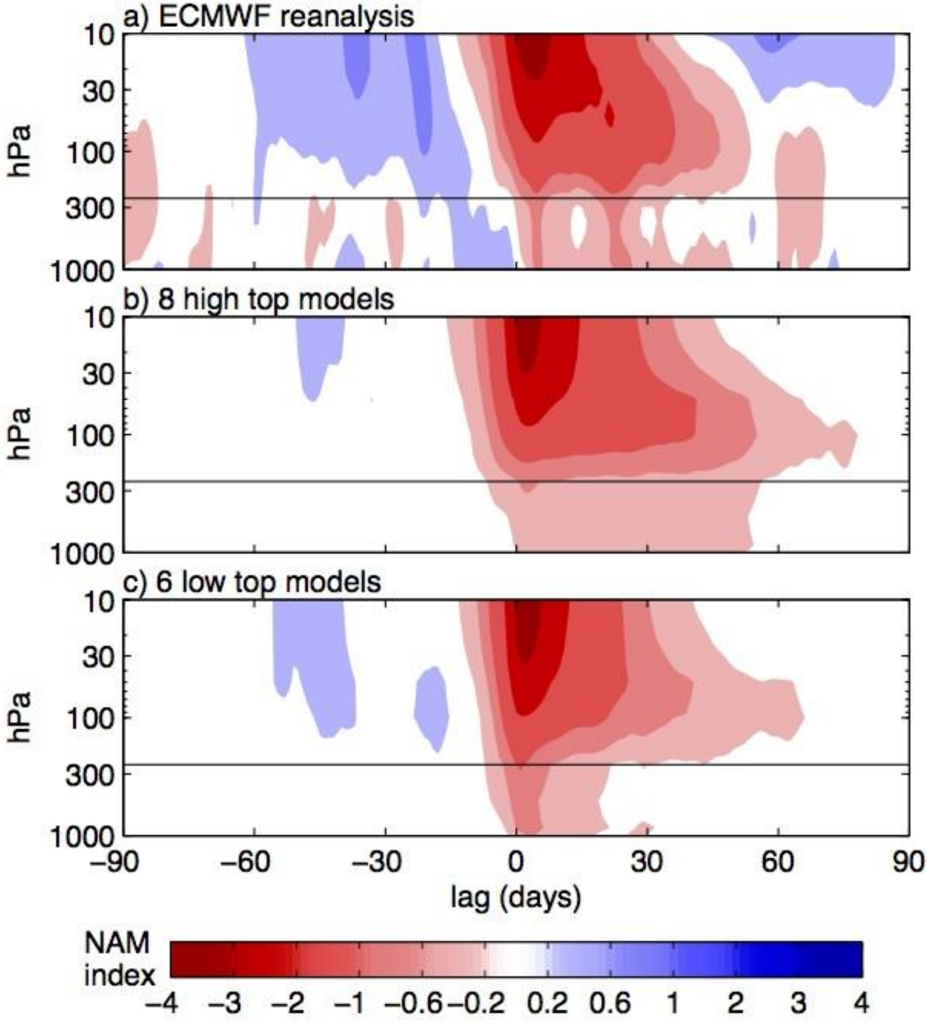




Charlton et al. 2007

Representation of SSWs and Their Downward Progression in Low and High Top Models



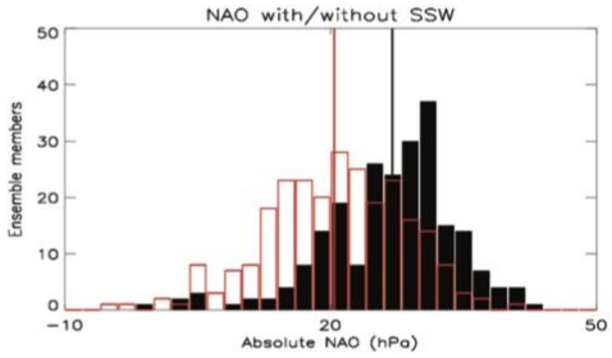


- Occurrence of SSWs is considerably better represented in high- than in low top climate models

(Charlton-Perez et al. 2013)

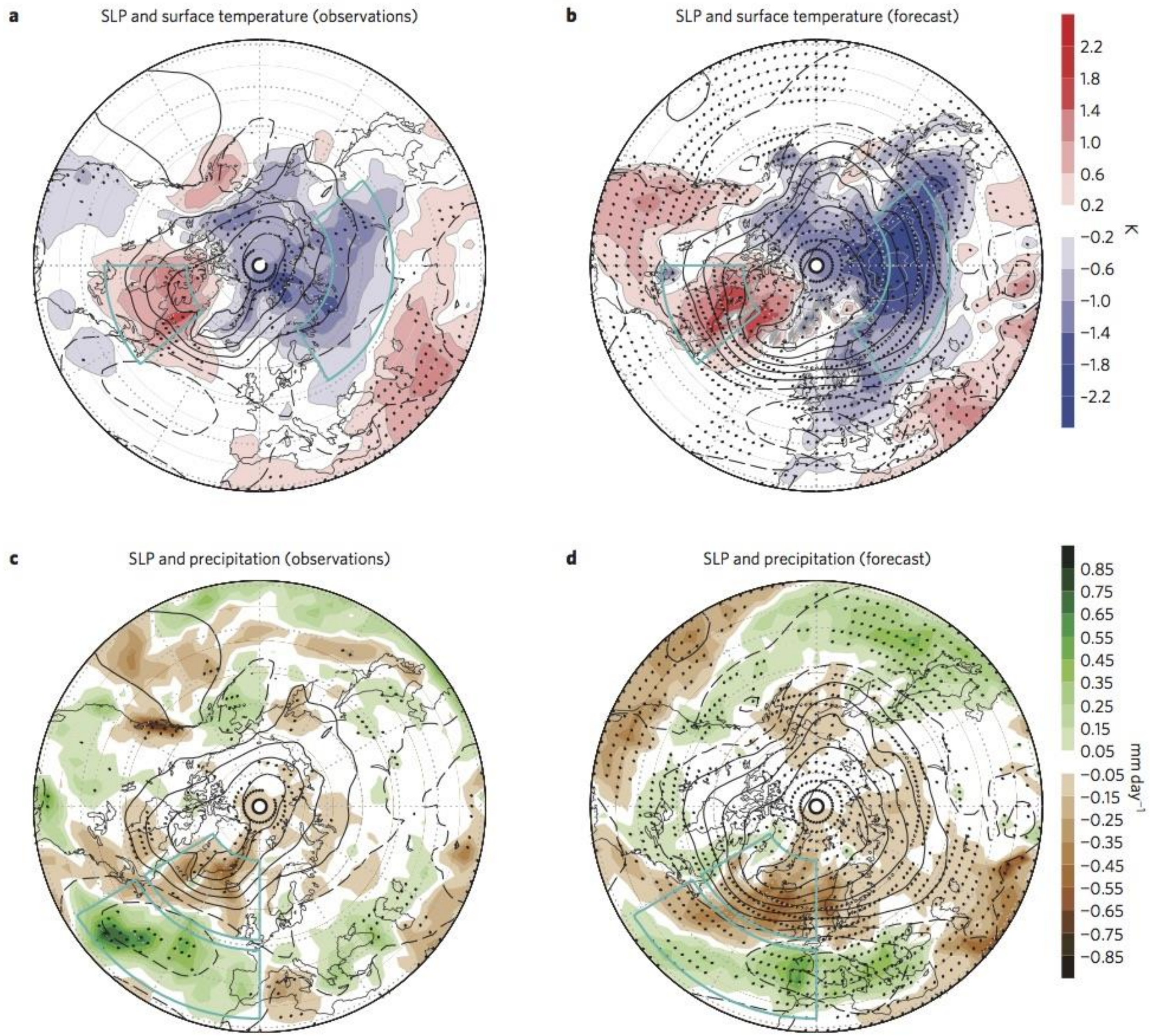
Impact of SSW on the Troposphere in Seasonal Forecast Models

NAO conditioned by SSWs



Scaife et al. 2016

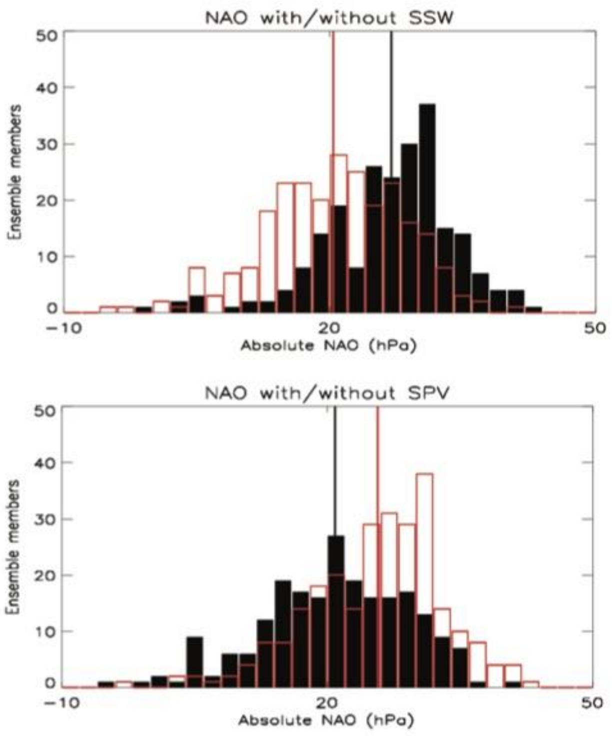
Observations and Forecast after initialized SSWs



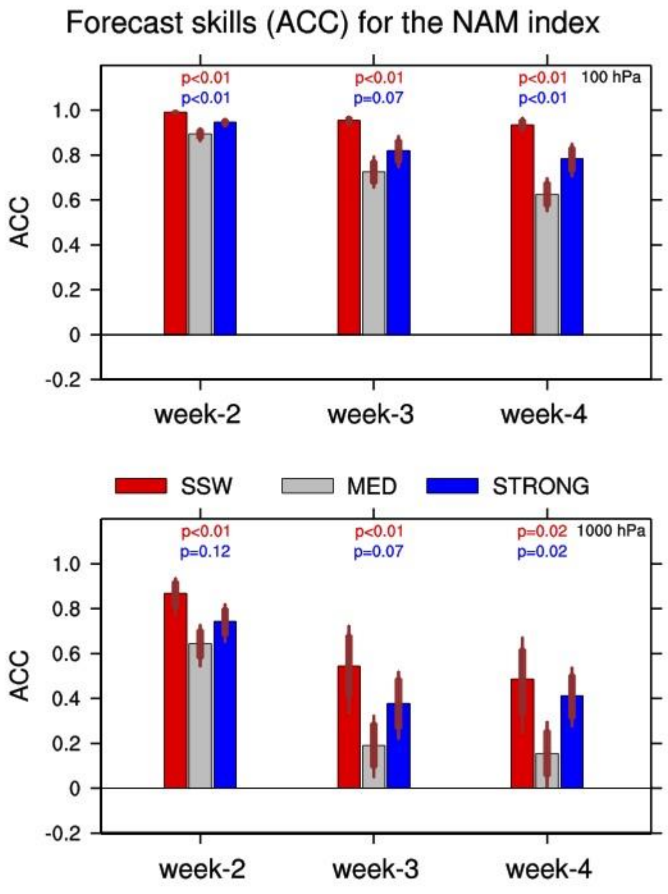
Sigmond et al. 2013

Sensitivity of Conditioned Stratosphere for SSWs and Strong Vortex Events

- Shows improved forecast skill of tropospheric large-scale circulation on subseasonal to seasonal time scale
- Skill is less clear for climate effects (temperature, precipitation)



Scaife et al. 2016

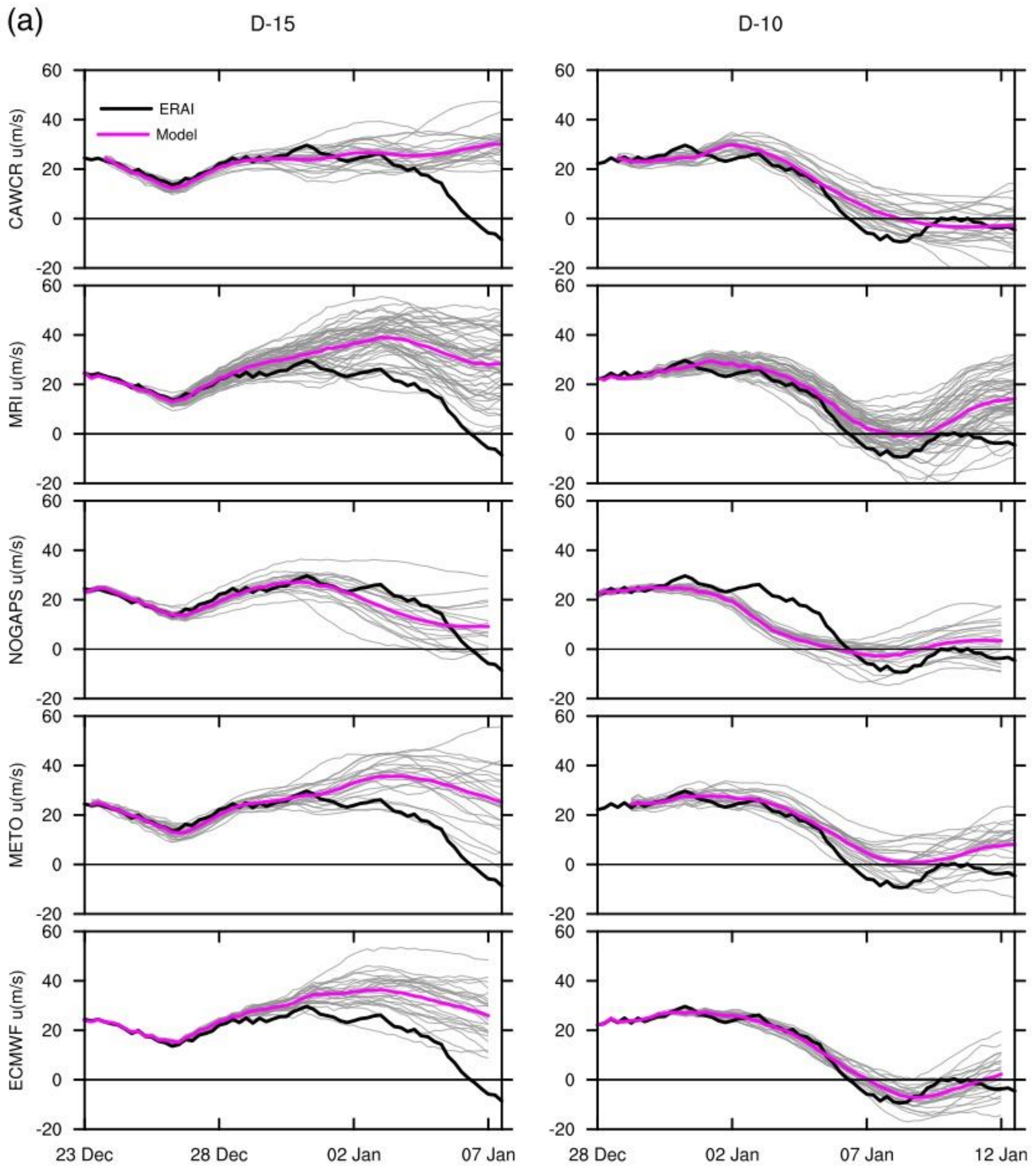


Tripathi et al. 2015

Forecast Skill of Extreme Stratospheric Vortex Events

Forecast skill is beyond 5 days and Within the subseasonal range up to 30 days (Tripathi et al. 2014)

Predictability of January 2013

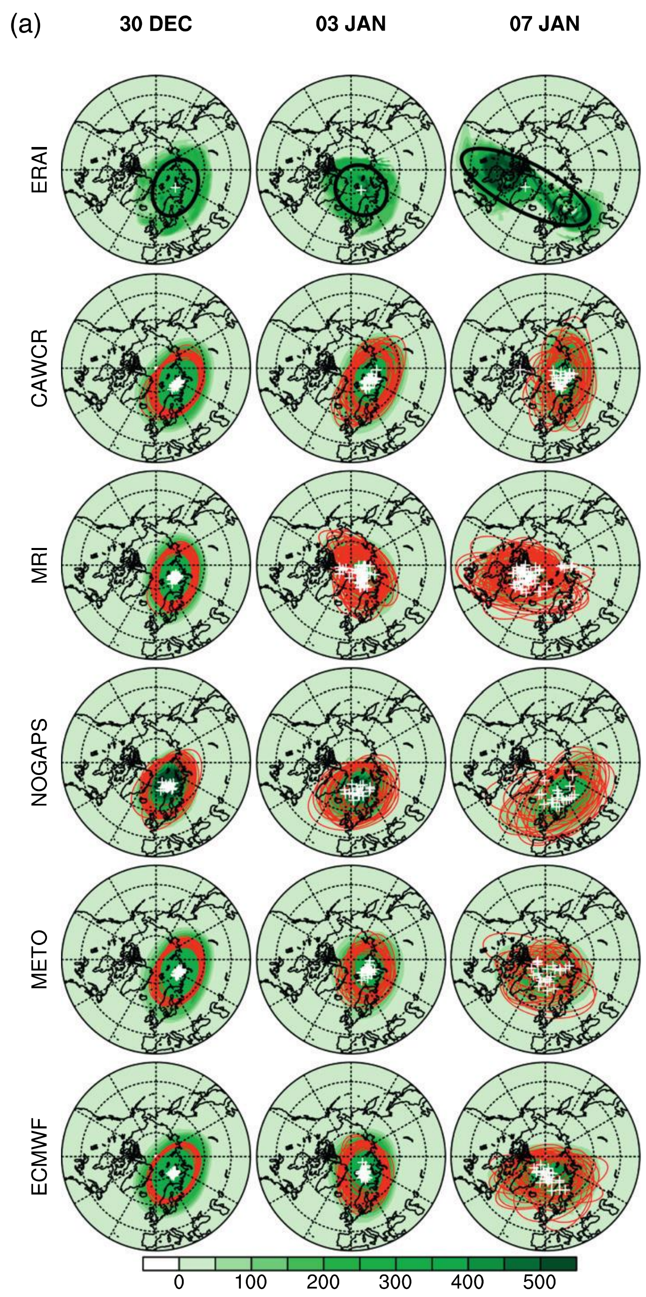


Tripathi et al. 2016

What limits forecast skill of stratospheric extreme events?

- Stratospheric model biases
- Tropospheric planetary waves

Stratospheric Vortex Structure

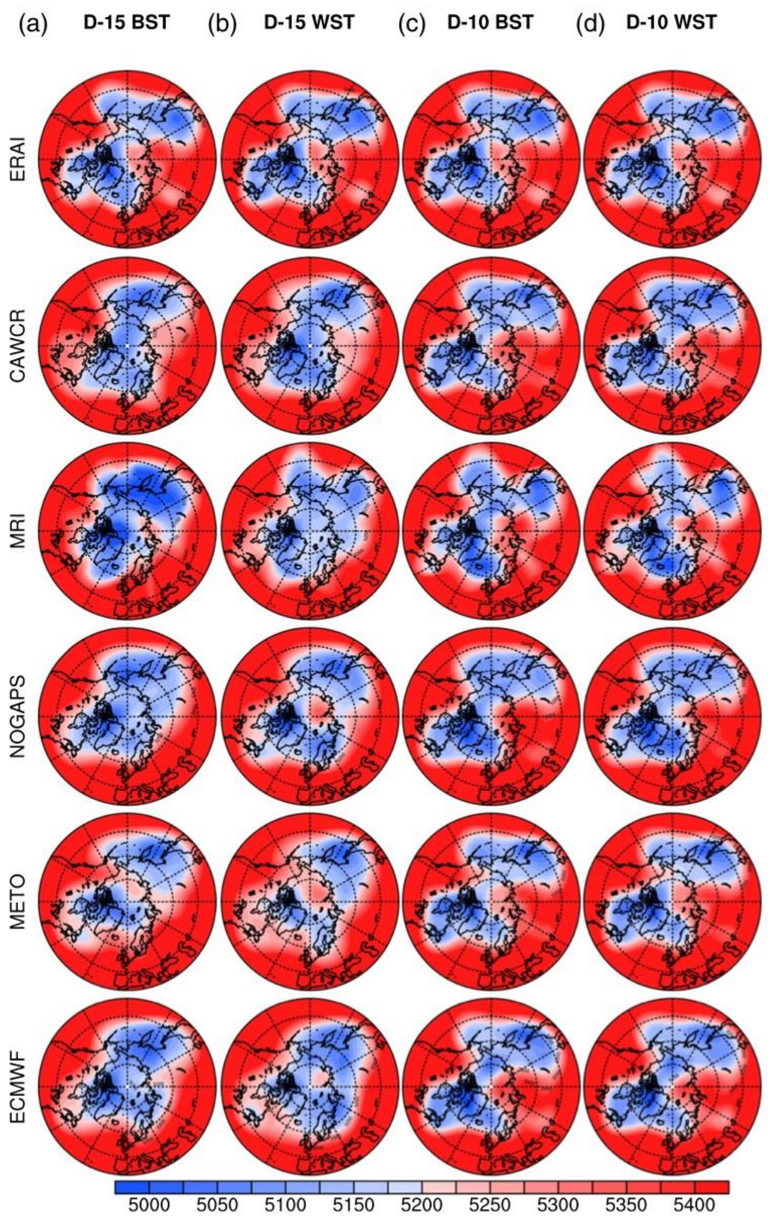


Tripathi et al. 2016

What limits forecast skill of stratospheric extreme events?

- Stratospheric model biases
- Tropospheric planetary waves, and their predictability

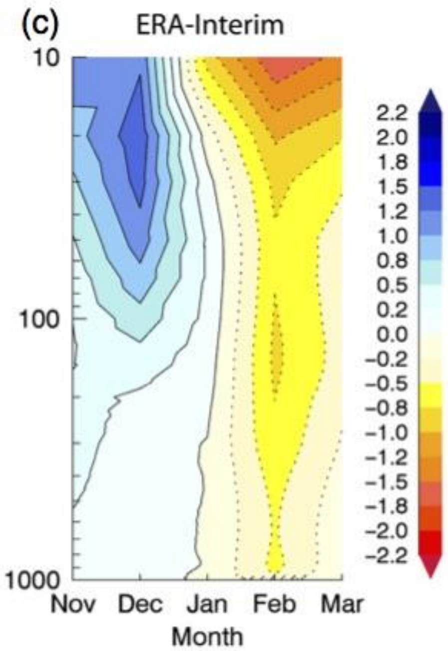
Z500

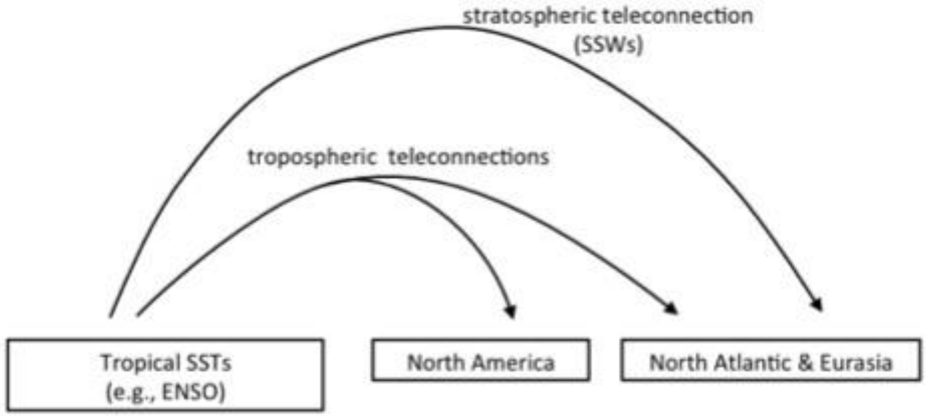


Scaife et al. 2016

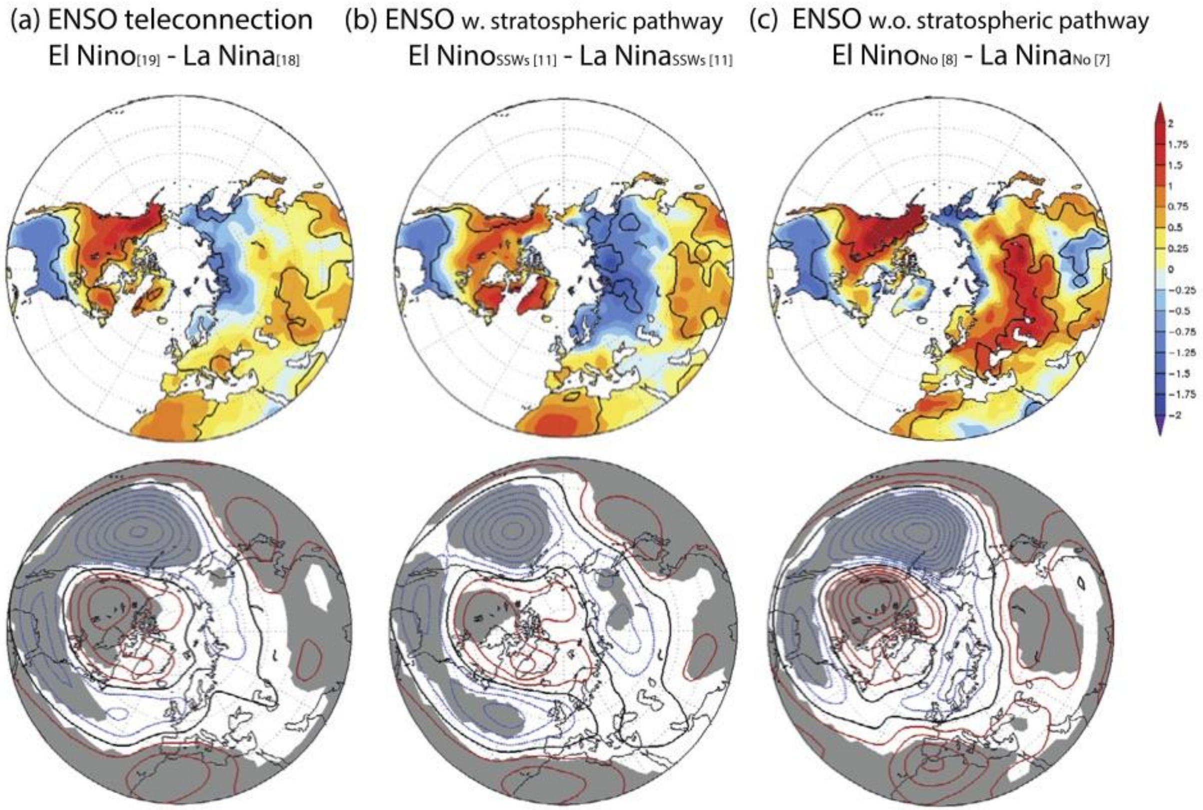
ENSO-NAO Connection and the Stratospheric Pathway

50-80N Zonal wind
El Nino-La Nina





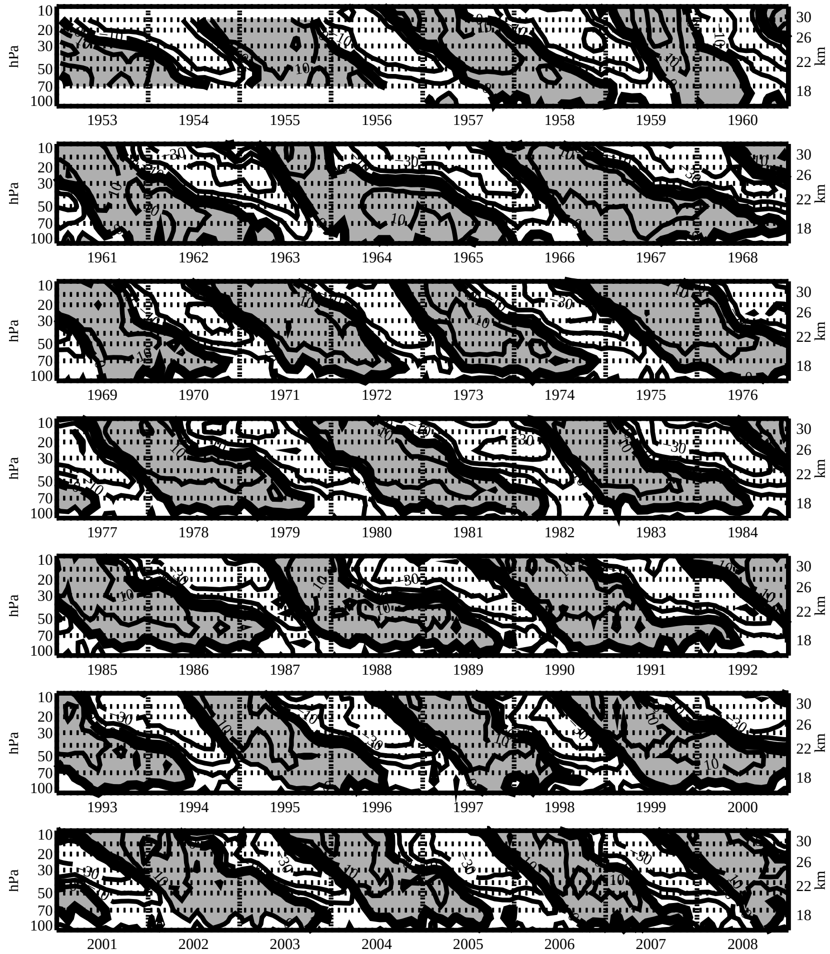
All | With Strat. Pathway | Without Strat. Pathway



Ineson and Scaife, 2009; Butler et al. 2014

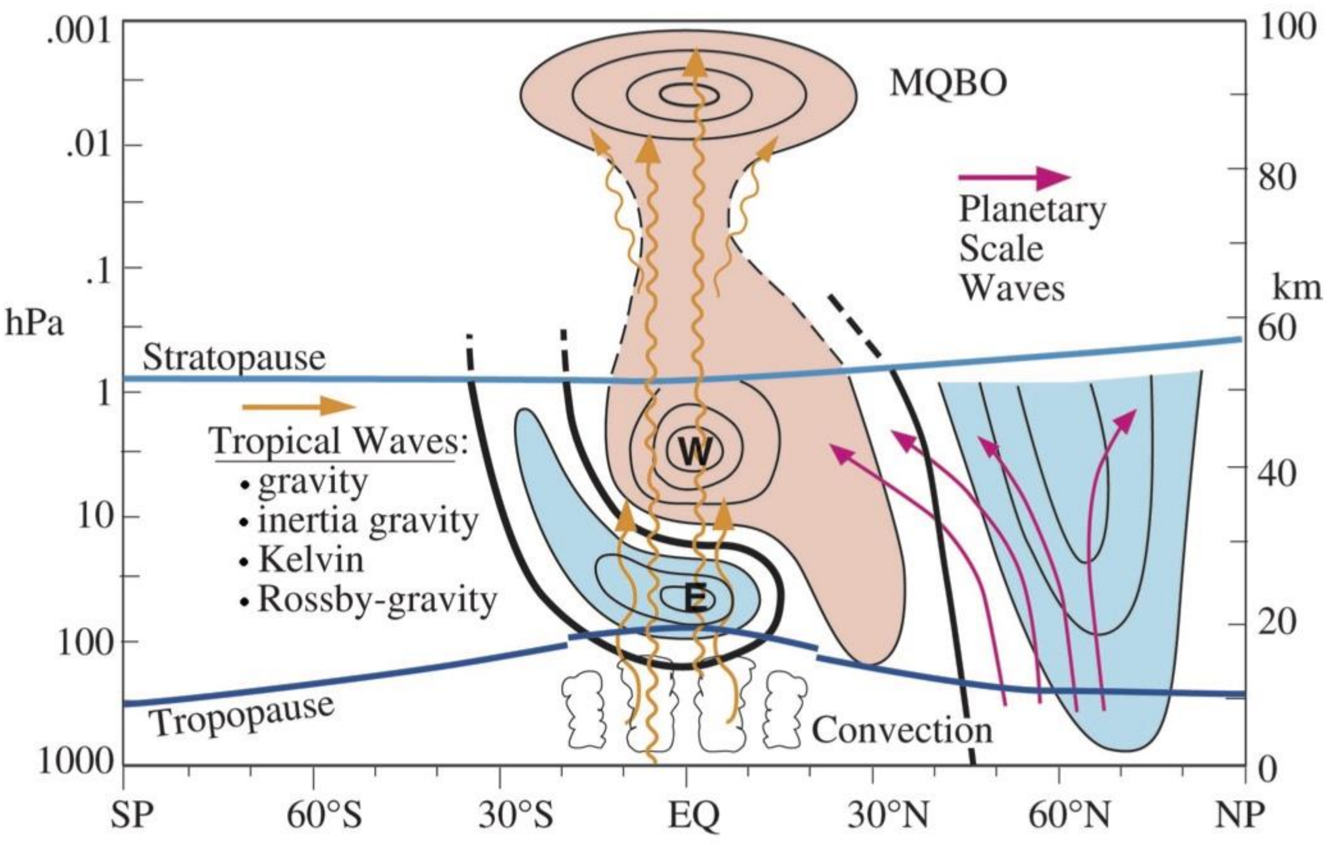
Quasi-biennial Oscillation

- Discovered in late 1950s (Graystone, 1959)
- alternating westerly and easterly zonal wind regimes that descend from the tropical upper stratosphere to the tropical tropopause at a rate of ~ 1km per month
- Mean period of 26 to 29 months



Quasi-biennial Oscillation

- Mainly driven by upward propagating tropospheric waves in the tropics and their interaction with the mean flow
- Modulates the position of subtropical zero-wind line

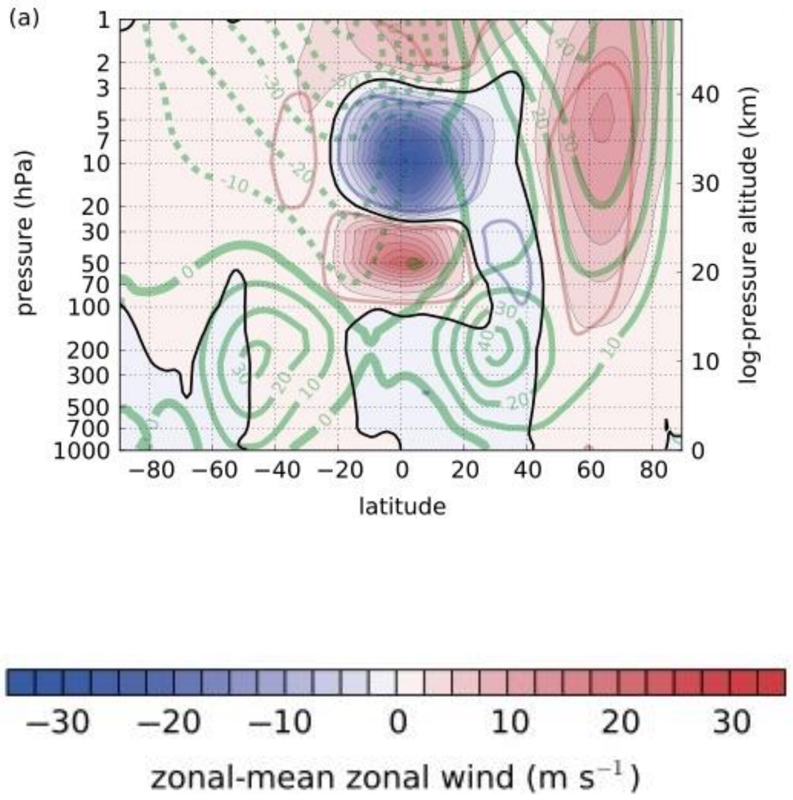


QBO-Stratospheric Polar Vortex Connection and Link to the Troposphere

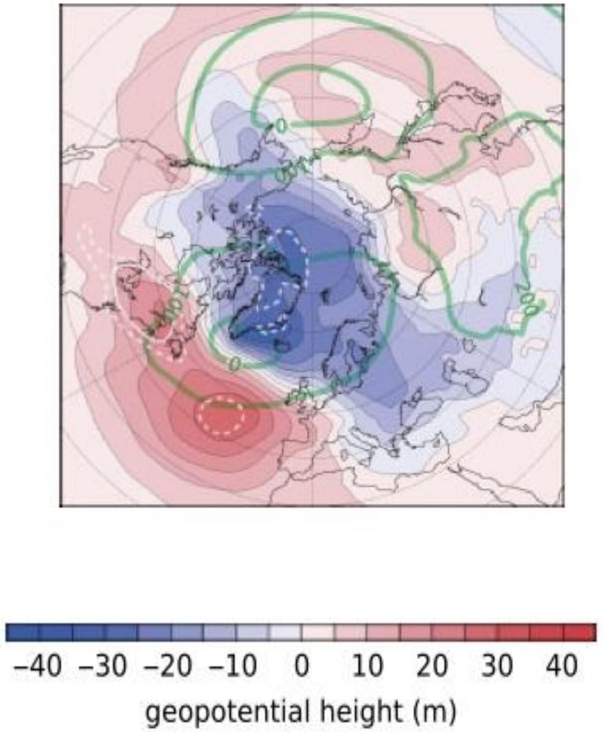
- Causal effect of the QBO on the extratropical winter stratosphere
- Coupling interacts with other sources of interannual variability

W-E QBO composite (U_E50hPa)

January (Zonal Wind)

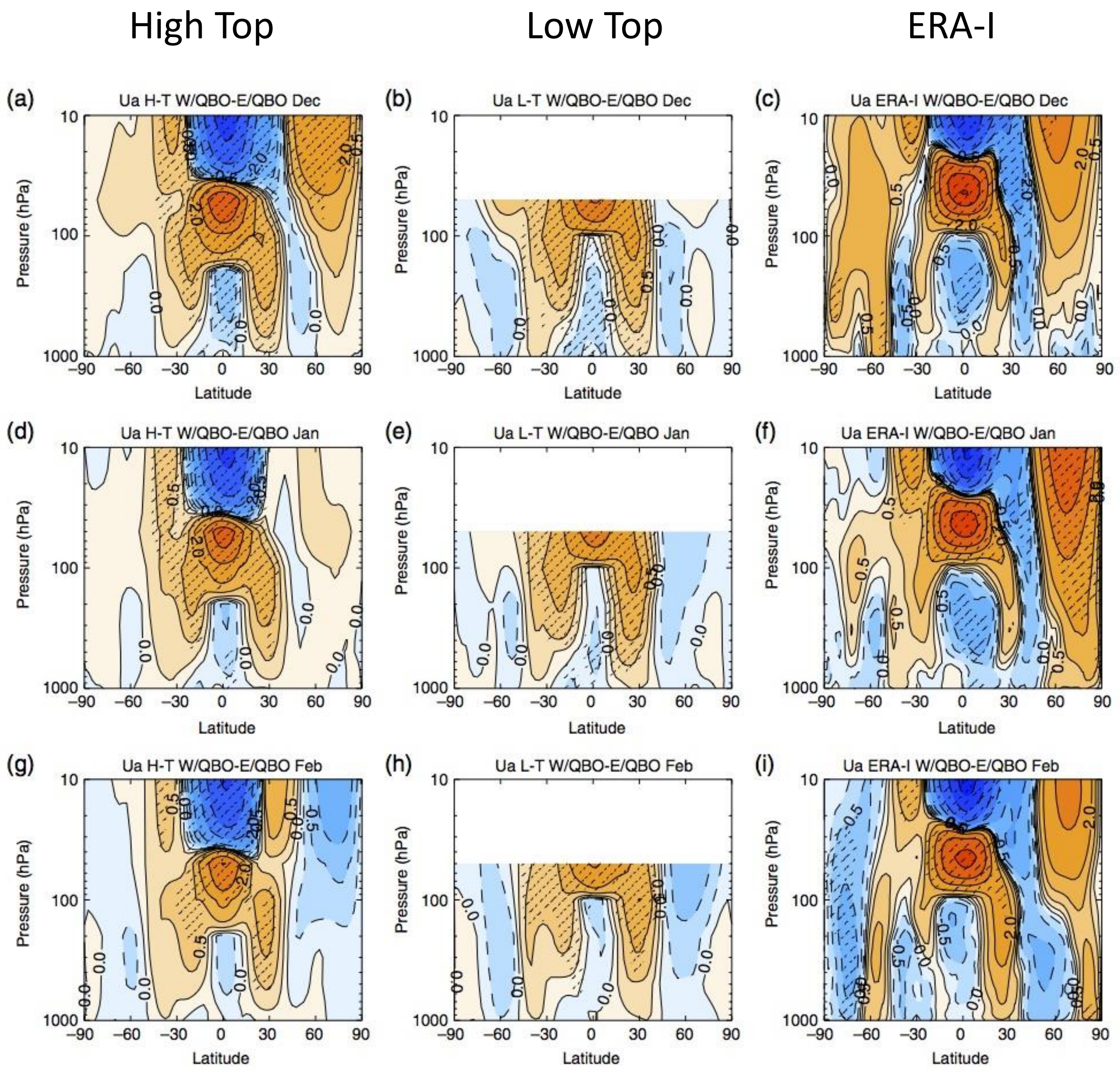


January (Z1000)



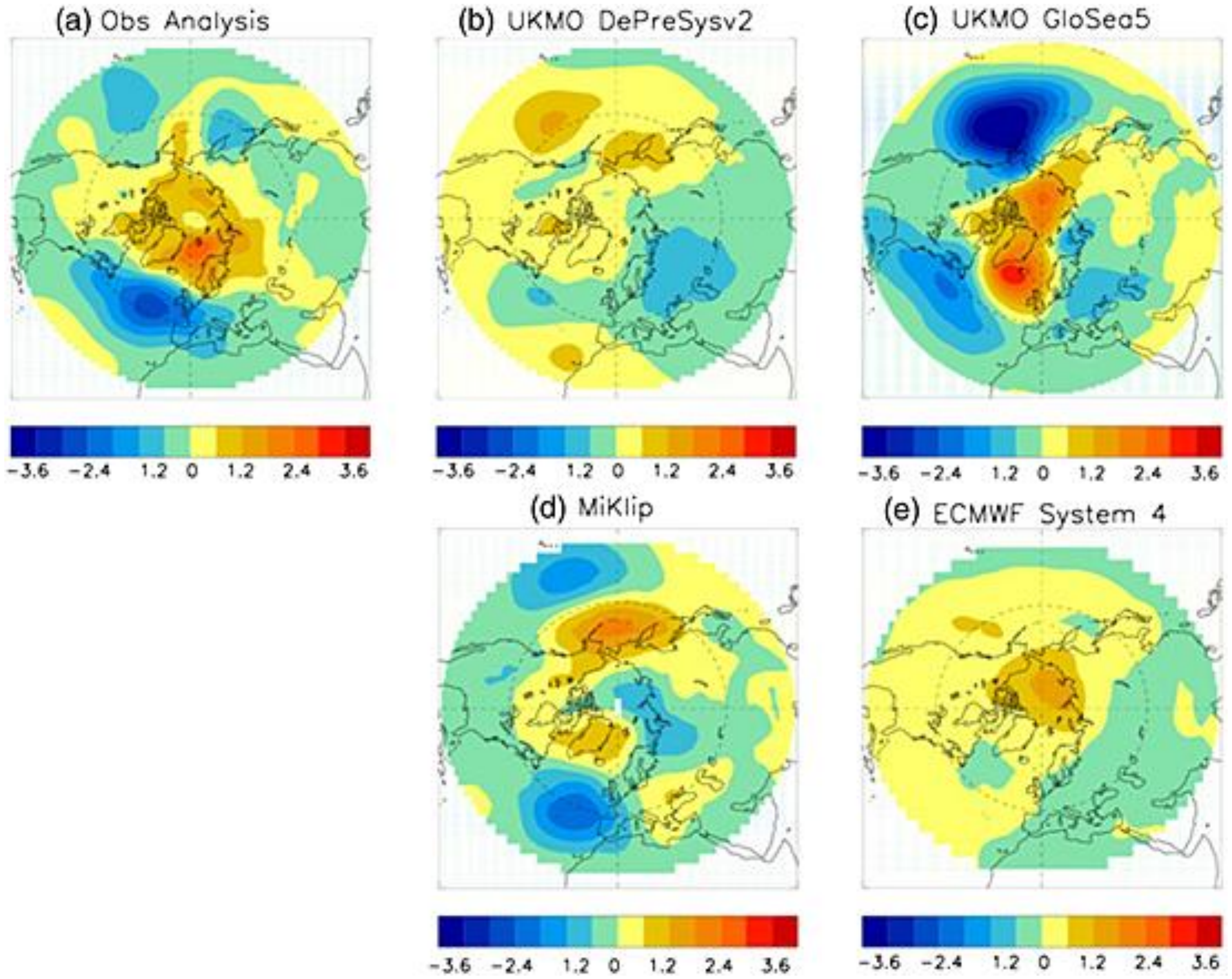
Anstey and Shepherd 2014

QBO-Stratospheric Polar Vortex Connection in Seasonal Prediction Models



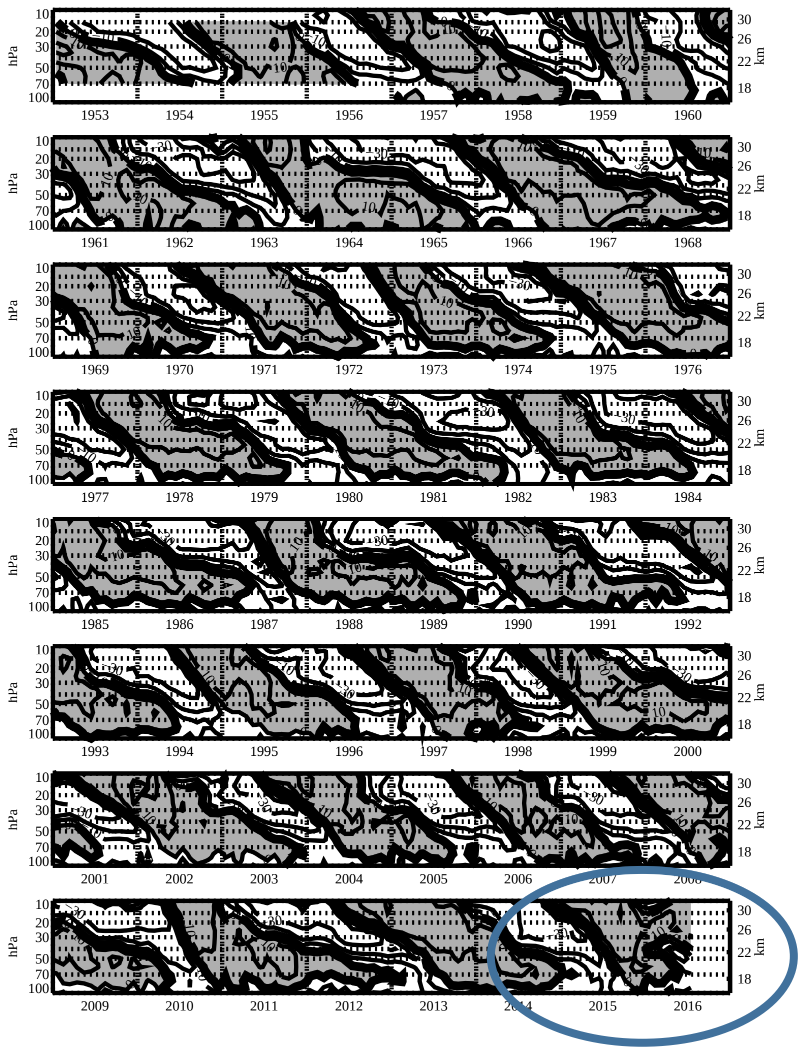
Butler et al. 2016

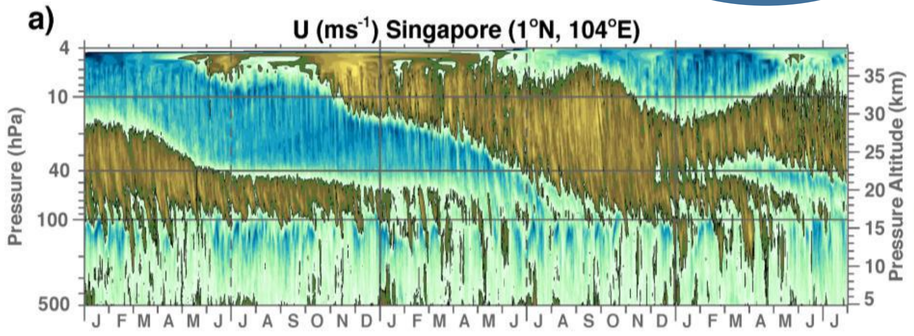
Predictability of the quasi-biennial oscillation and its northern winter teleconnection on seasonal to decadal timescales



Scaife et al. 2014

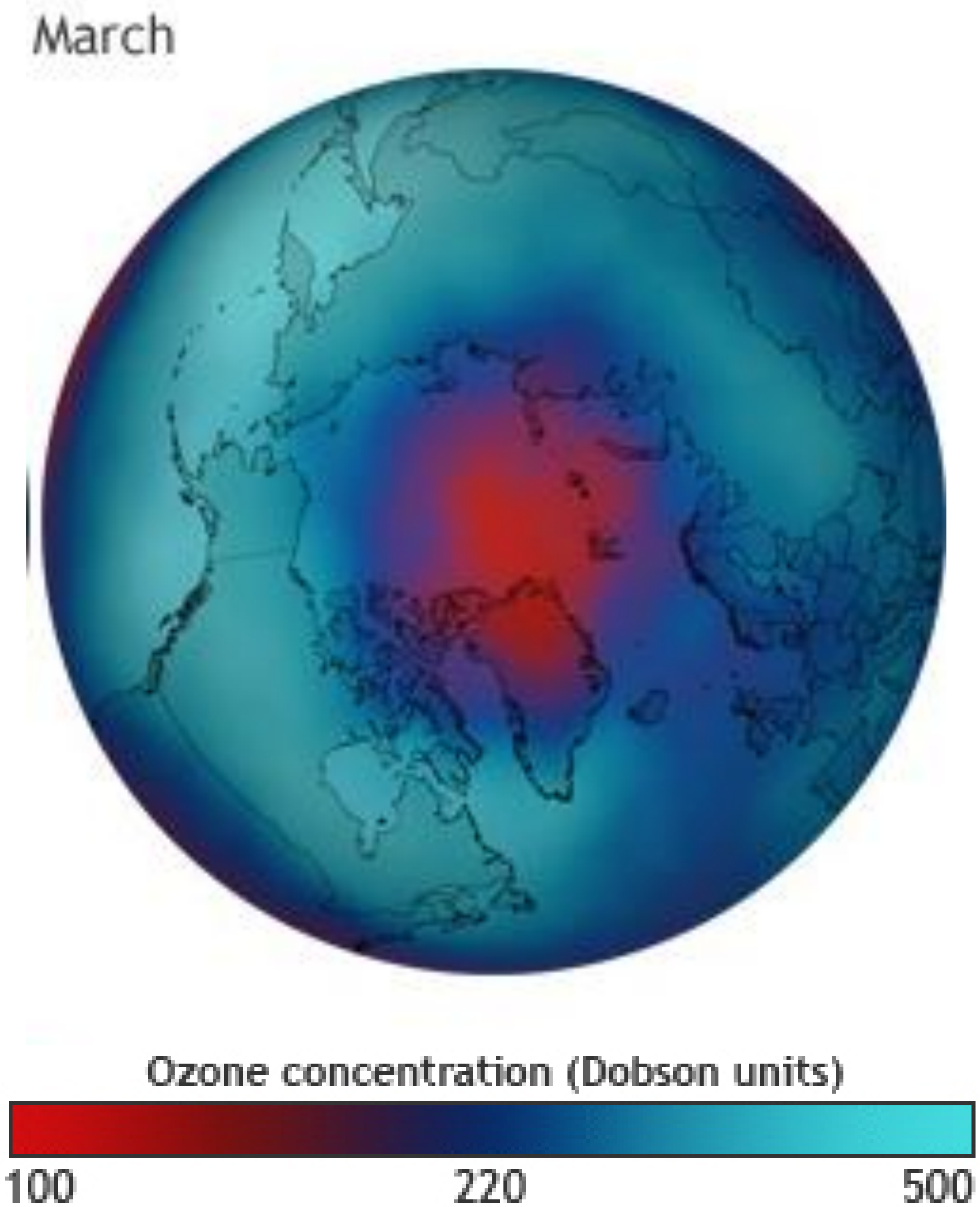
Unprecedented QBO evolution in 2015-2016 (Newman et al. 2016)

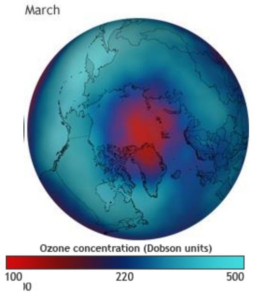




- The anomalous 2015-16 QBO evolution may prove to be a challenge to future QBO predictability studies.

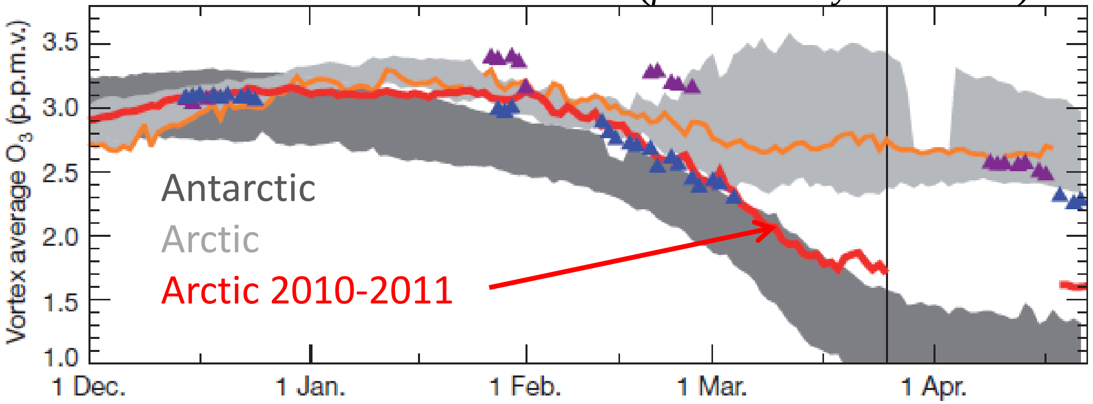
Chemistry
Climate Interactions





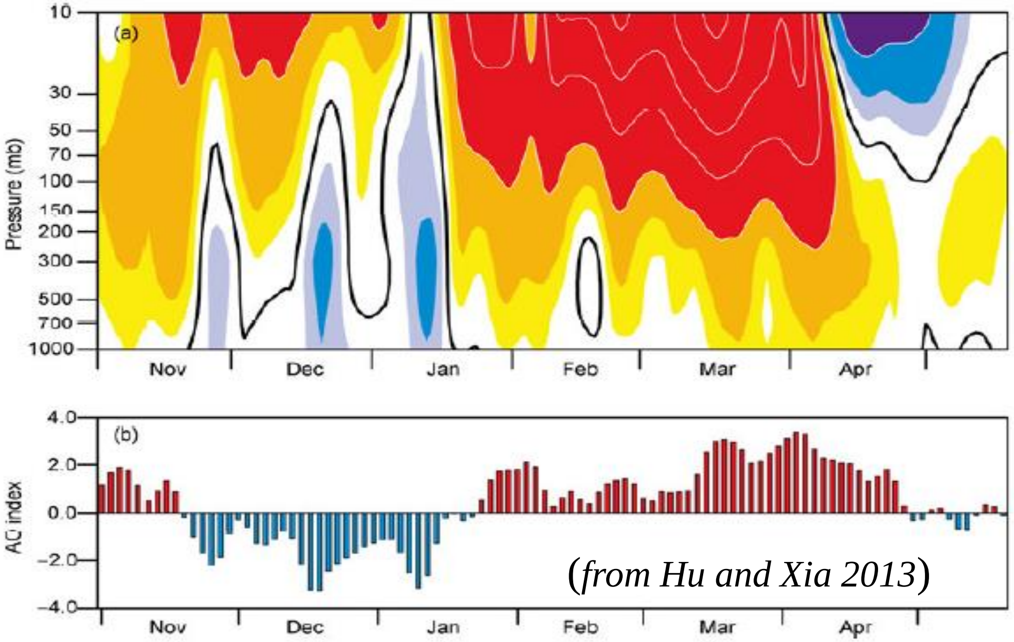
Arctic winter/spring 2011

Ozone *(from Manney et al. 2011)*



- Arctic ozone in 2011 was well below typical Arctic values and almost reached the Antarctic values

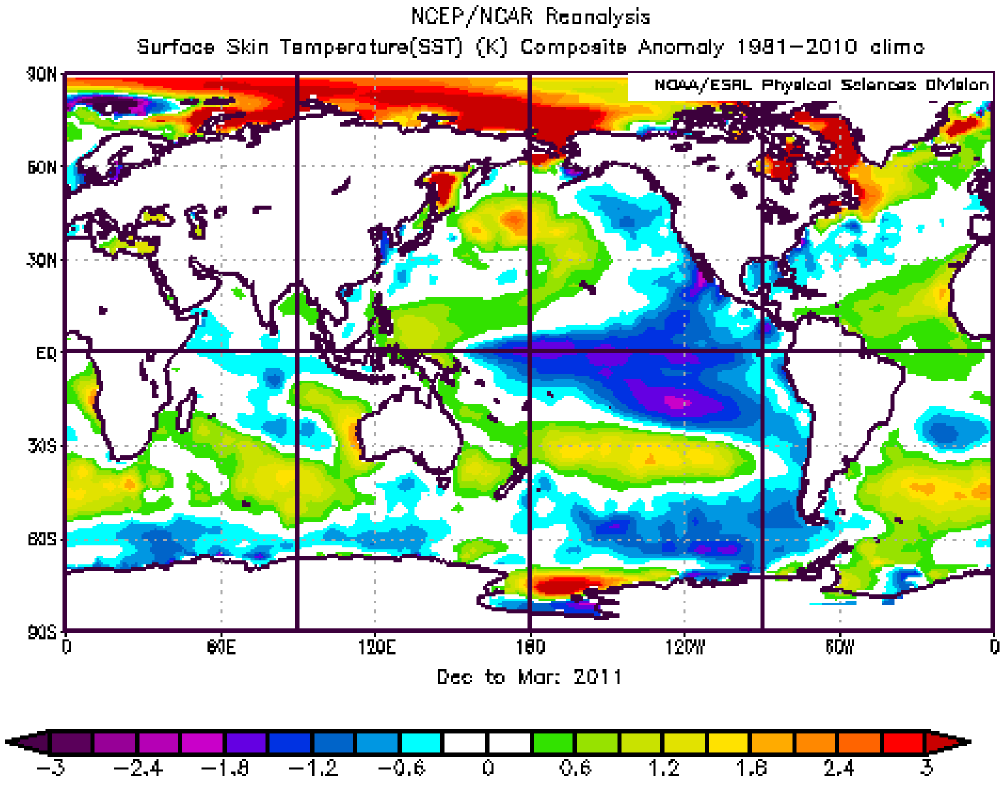
NAM index



- Polar vortex was very strong from January to early April (see e.g. Manney et al. 2011, Hurwitz et al. 2011, Strahan et al. 2013)
- Tropospheric circulation was characterized by positive NAO/NAM anomalies
- April NAO/NAM was record breaking in NOAA/CPC records since 1950 (2.48/2.27 std)

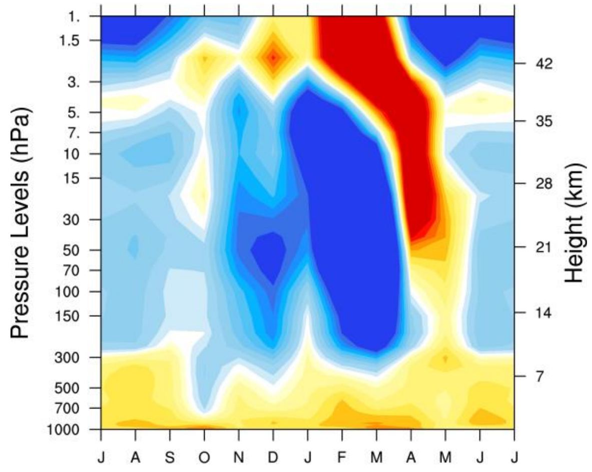
Was the Arctic ozone hole the primary driver of the record tropospheric circulation event?

Dec 2010-March 2011 SST

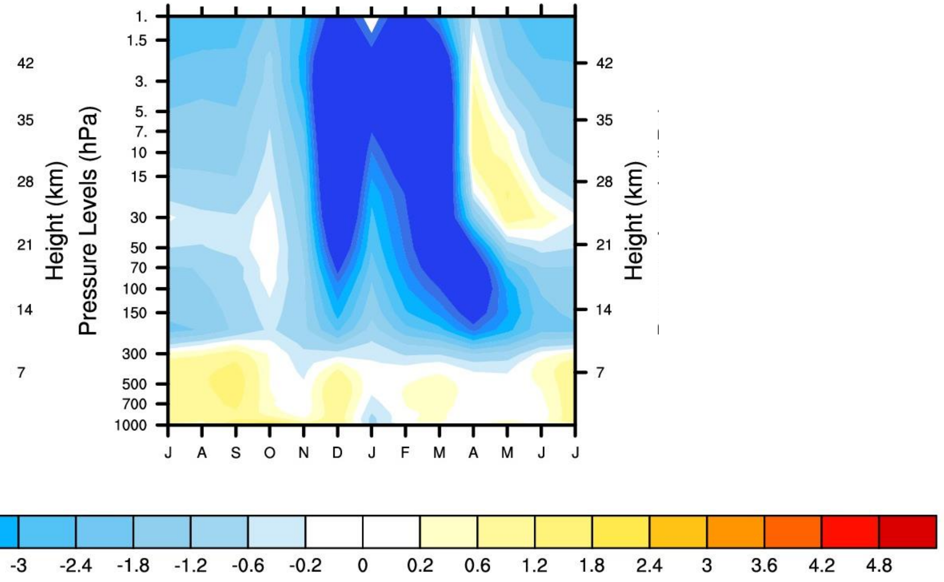


Polar Cap-Temperature Year 2010/11 (K)

Merra



CCM (2011)

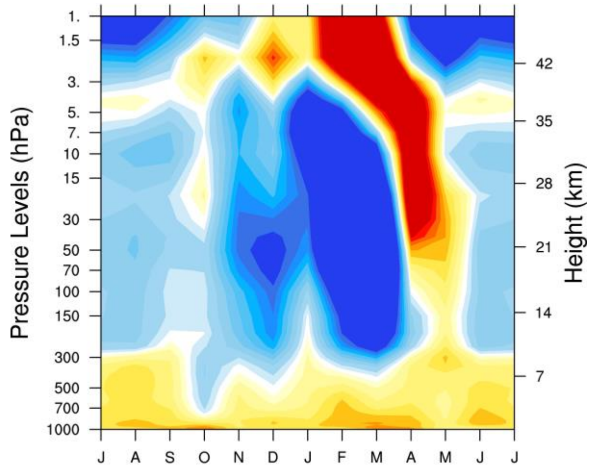


GEOS5 Chemistry Climate Model Study

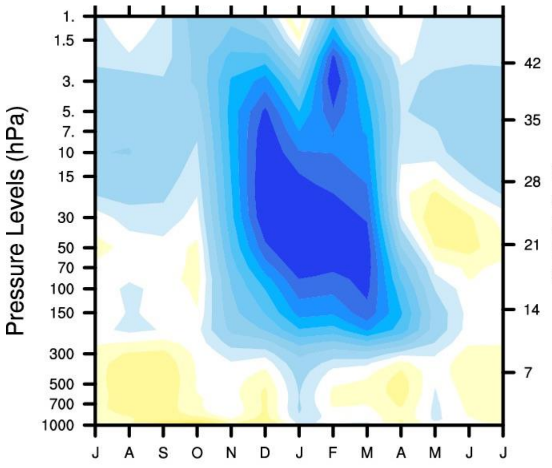
Polar Cap-Temperature Year 2010/11 (K)

GEOS5 Study

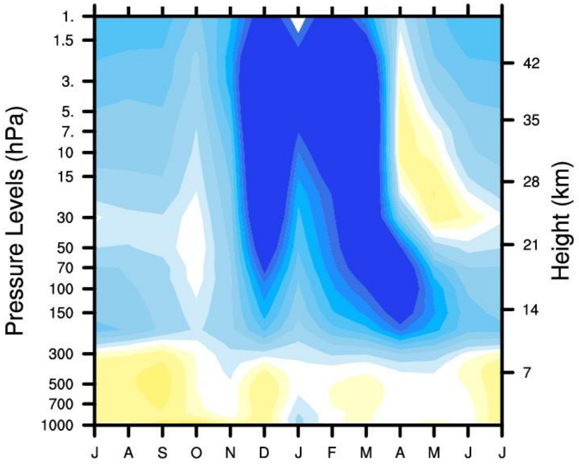
Merra



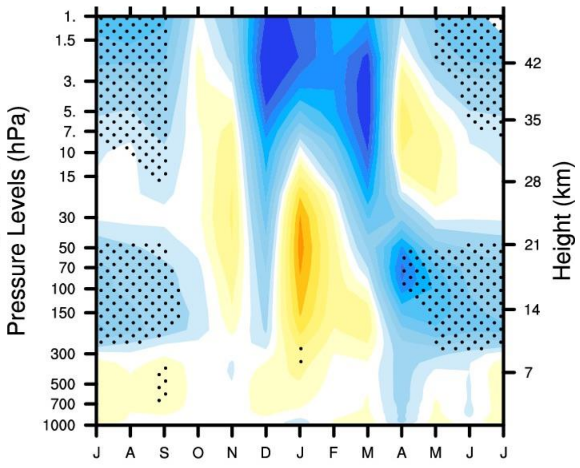
CCM(2011) ODS 1960

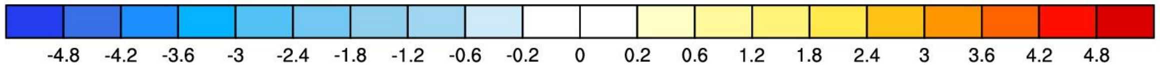


CCM (2011)



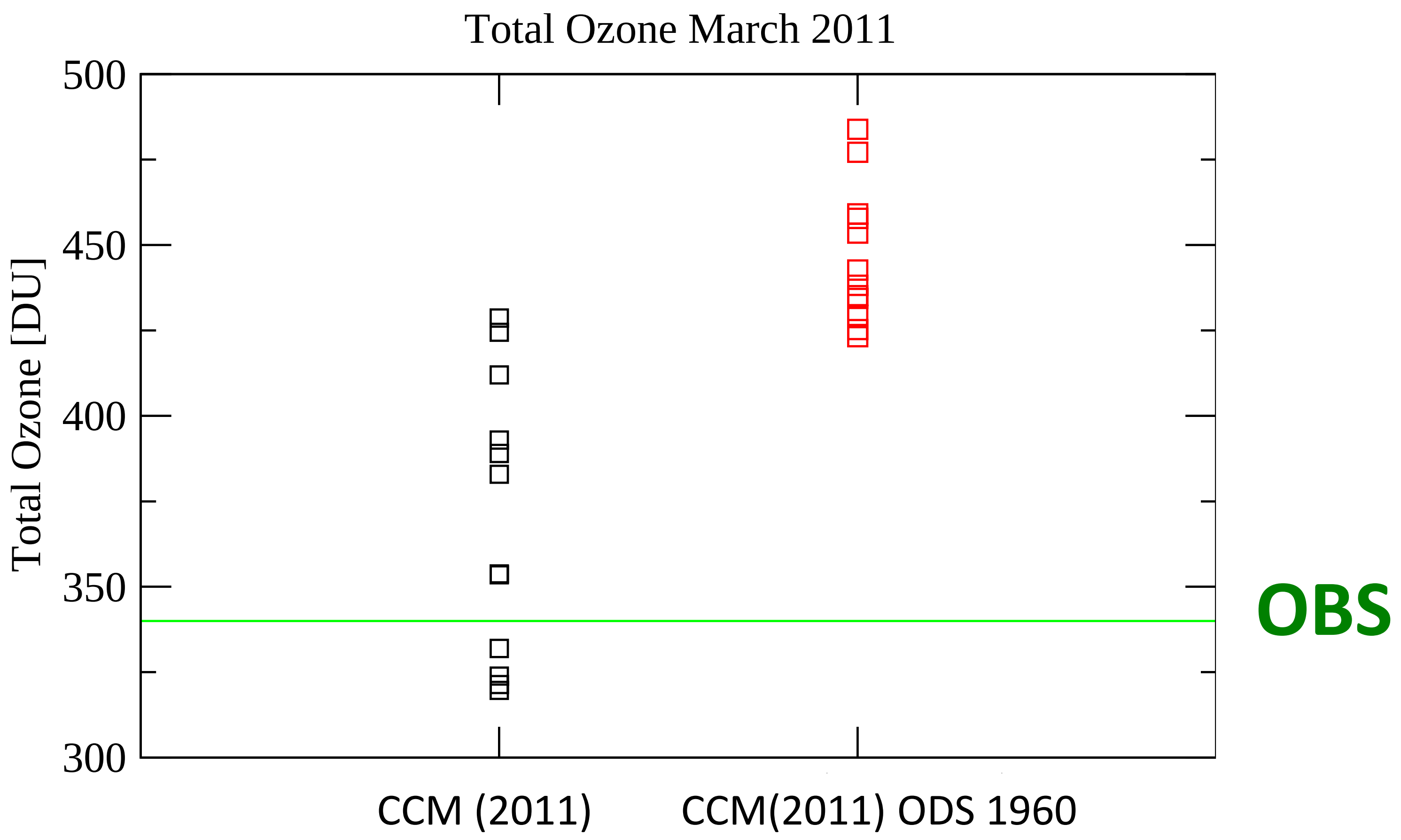
ODS Impact





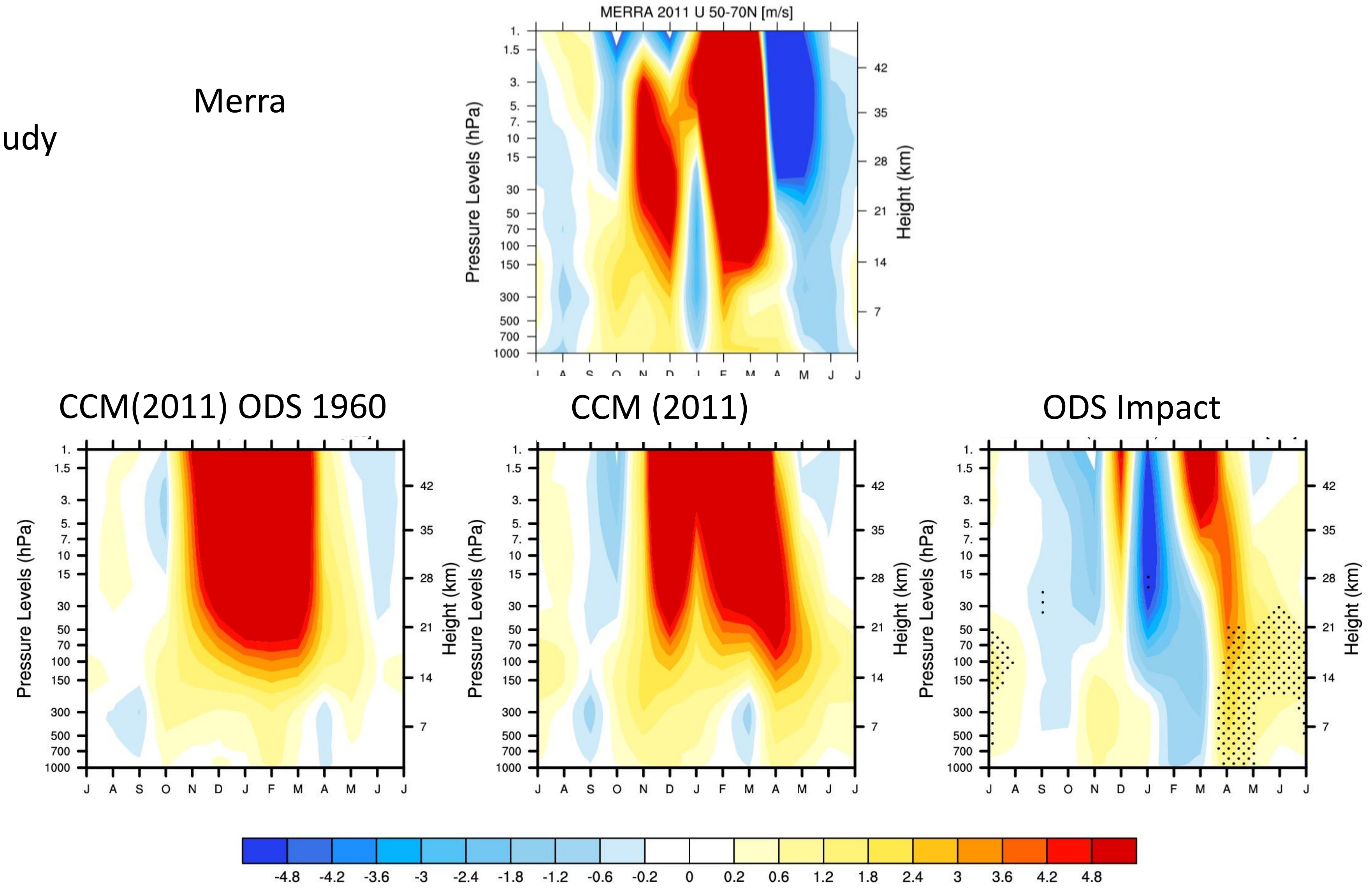
Total Ozone March 2011

GEOS5 CCM Study



U (50-70N) Year 2010/11 (m/s)

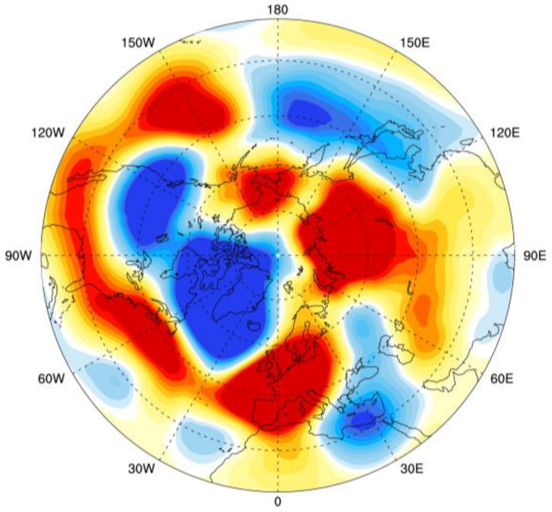
GEOS5 CCM Study



Apr-May Z500 (m)

GEOS5 Study CCM

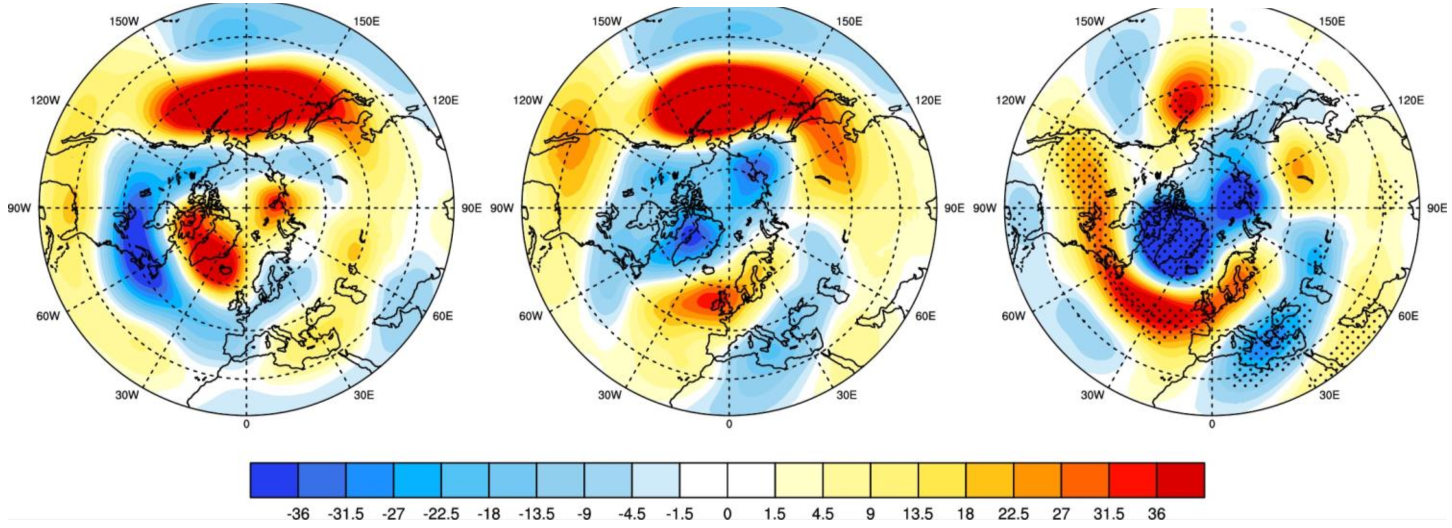
Merra



CCM(2011) ODS 1960

CCM (2011)

ODS Impact

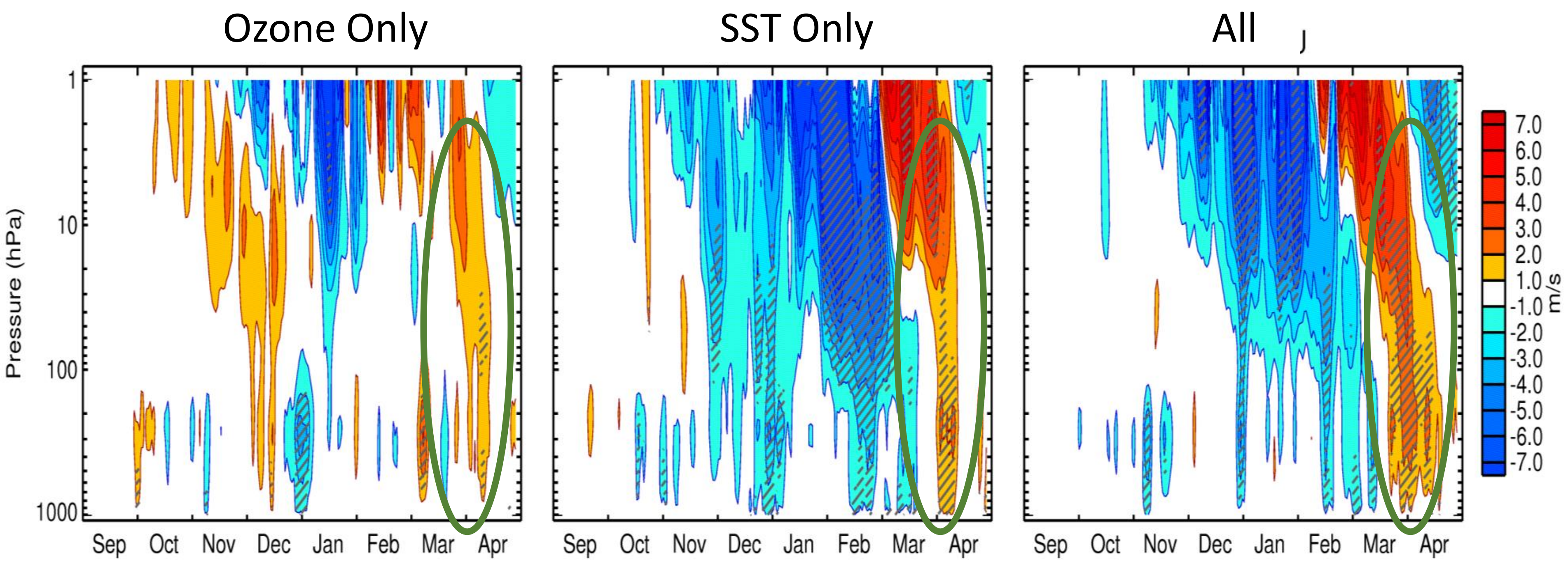


Take-Home Messages

- Isolating the role of stratospheric processes in predictive skill of tropospheric circulation and teleconnections is a challenge because tropospheric and stratospheric circulation are closely coupled both upward and downward.
- The stratosphere provides an important pathway by which tropospheric circulation anomalies and teleconnections can be modified.
- A lack of proper representation of stratospheric processes degrades the potential predictive skill on subseasonal to interannual time scale in the troposphere.

Backup slides

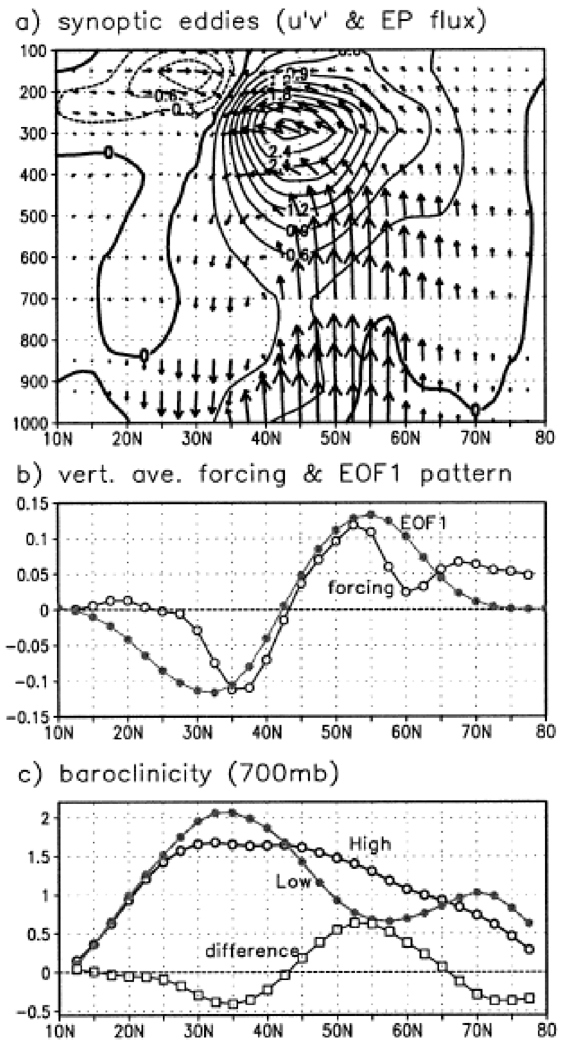
Mid-latitude (50°-70°N) Zonal Wind Response in ECHAM5



- Strengthening of the westerly stratospheric winds and downward anomaly propagation to the troposphere in March/April is simulated in all experiments
- The strongest response is simulated in the ALL experiment
  - ✓ (*ALL response is stronger than the sum of O3 and SST*)
- E.g. the mid-March/mid-April response at 1000hPa: O3 -0.02m/s; SST 0.17m/s; **ALL 0.33m/s**

Karpechko et al. 2014

Role of synoptic-scale eddies



Lorenz & Hartmann (2003)

- In the troposphere variability dominated by annular modes, which are sustained by synoptic eddy feedbacks (Lorenz and Hartmann 2001, 2003)
- Mean flow conditions in the vicinity of the tropopause affect synoptic eddies via changes in
  - Lower stratospheric shear (Wittman et al. 2007)
  - Index of refraction (Simpson et al. 2009)
  - Isentropic slope (Thompson & Birner 2012)
  - Eddy length scale (Kidston & Vallis 2010)
  - Eddy phase speed (Chen & Held 2007)
- Synoptic eddies can serve as an “amplifier” of stratospheric forcing