Stratospheric Influence on Polar Climate

Paul Kushner, Dept. of Physics, University of Toronto

Aims for Today

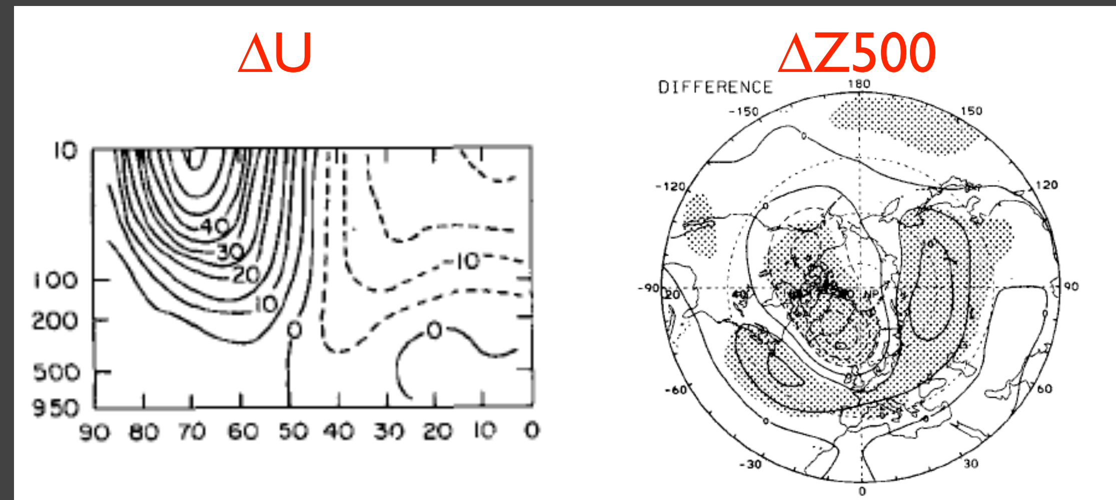
1. Discuss different types of stratospheric influence.
2. Describe some dynamical aspects.
3. Mention limits of stratospheric influence.

Types of Stratospheric Influence

Direct and Indirect Stratospheric Influence

Direct: change in stratosphere leads to change in troposphere.

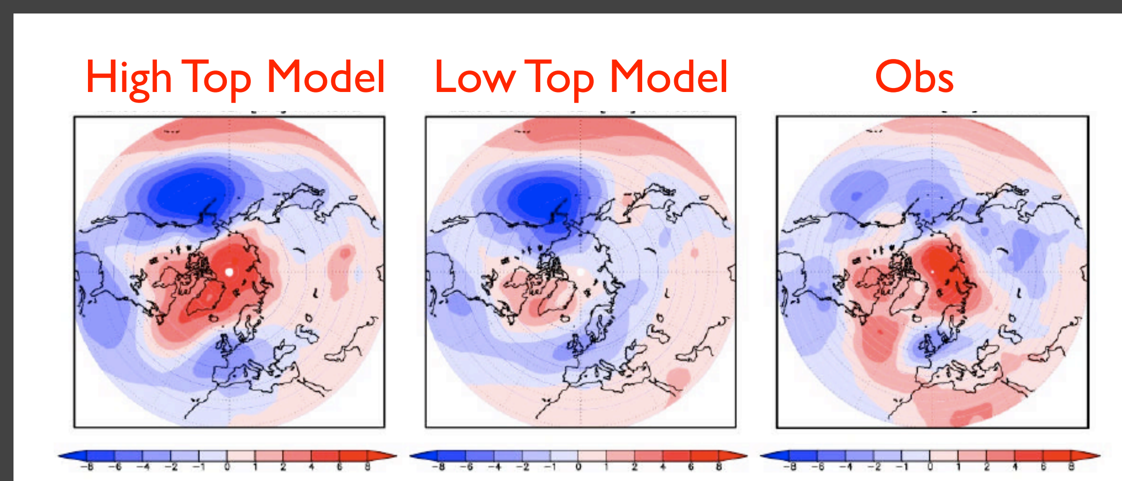
GCM Response to Reduced Stratospheric Diffusion



Boville 1984

Indirect: stratosphere exerts influence on tropospheric perturbations.

ENSO Teleconnections in SLP



Cagnazzo & Manzini 2008

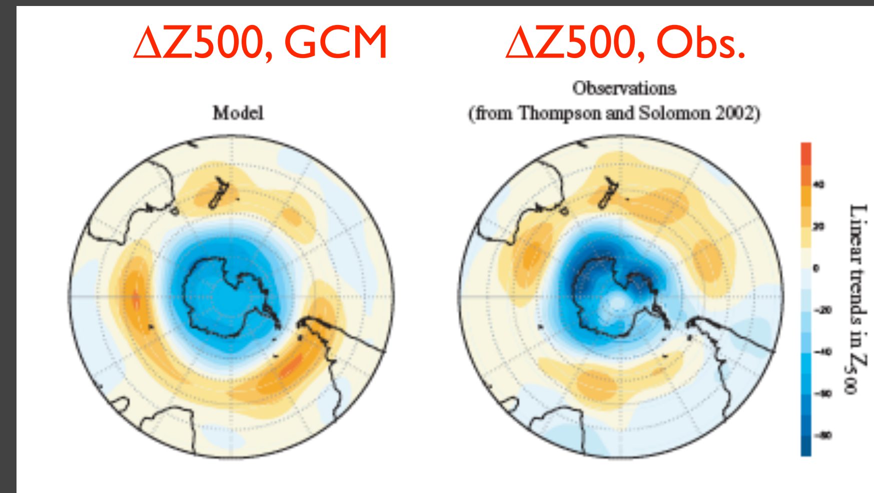
Scales of Stratospheric Influence

Stratosphere can have a hemispheric-scale influence (via Annular Modes).

It can also have a regional-scale influence.

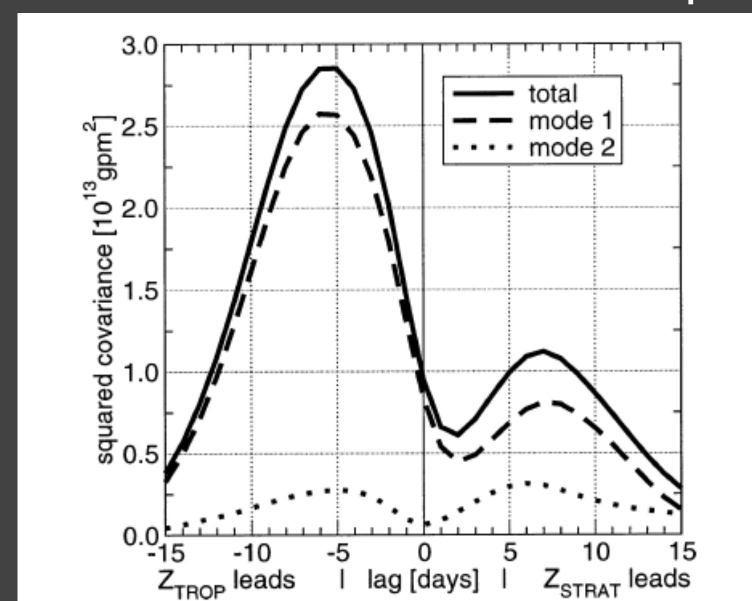
- This deserves more attention.

Response to Ozone Depletion



Thompson & Solomon, Gillett & Thompson

Wave Reflection from the Stratosphere



Perlwitz & Harnik 2003

Dynamical Ideas

QG Dynamics: Active, Eddy Driven Circulation

Extratropical circulation satisfies:

$$q_t + \nabla \cdot (\vec{u} q) = S$$

PV, *q*, linearly related to met. fields: "invertibility"

Zonal mean PV anomalies driven by eddy PV flux:

$$\overline{q}_t + (\overline{v'q'})_y = \overline{S} \;\Rightarrow\; \frac{d}{dt}\left\langle \frac{1}{2}(\overline{q^a})^2 \right\rangle = -\left\langle (\overline{v'q'})^a_y \cdot \overline{q^a} \right\rangle + \left\langle \overline{S^a} \cdot \overline{q^a} \right\rangle$$

a is anomaly, <> is spatial average

Under general conditions:

$$\left\langle \overline{S^a} \cdot \overline{q^a} \right\rangle \leq 0 \Rightarrow -\left\langle (\overline{v'q'})^a_y \cdot \overline{q^a} \right\rangle \geq 0$$

for time mean (Kushner 2010).

- PV fluxes converge to reinforce PV anomalies.

PV Flux: Meridional/Vertical Split

Eddy PV flux splits naturally:

$$(\overline{v'q'}) = \nabla \cdot \vec{F} = [F_{(y)}]_y + [F_{(z)}]_z = \overline{v'\zeta'} - f_0\overline{v'h'}/\overline{h}$$

EP wave activity flux, meridional and vertical components — *Vorticity/ momentum flux* — *Thickness/ heat flux: form stress*

Stratospheric PV fluxes:

- Dominated by vertical component (heat flux/form stress).

Tropospheric PV fluxes:

- Involve both components.
- Simplest models (Vallis et al. 2004) focus on meridional component — vorticity flux.

Hemispheric (Zonal Mean) Stratospheric Influence: Annular Mode Dynamics

AM Characteristics

Dominant extratropical zonal modes.

Stratosphere: variation in strength of polar vortex and vertical EP flux (Holton-Mass model).

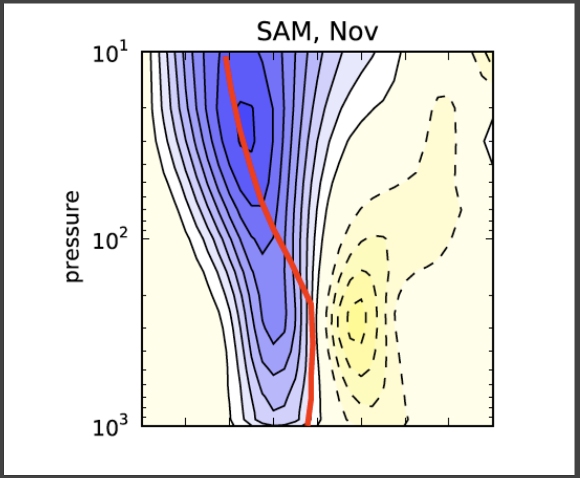
Troposphere: variation in position of eddy-driven jet and meridional EP flux (Vallis et al. 2004 model).

AM propagation occurs continually in both hemispheres.

- Couples vertical and meridional EP flux (Song and Robinson 2004, Thompson et al. 2006).
- Modulated by tropospheric influences, radiative influences.

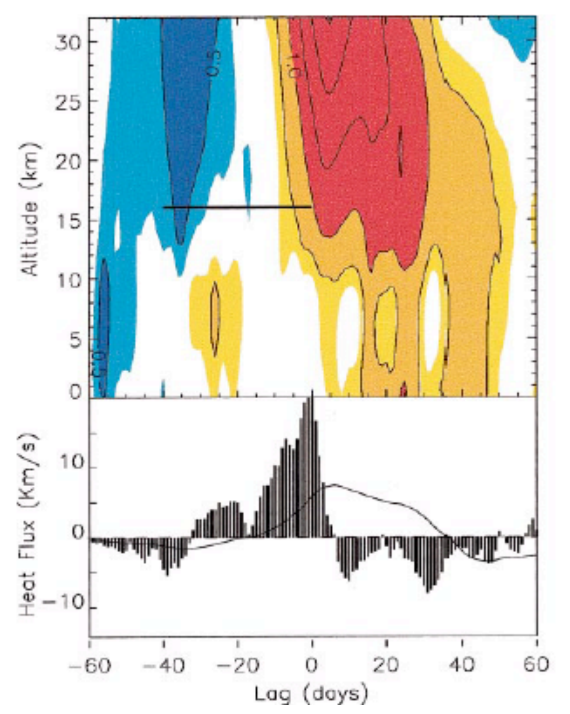
SAM in U and SH Jet Axis

Thompson & Wallace 2000, Kushner 2010



NAM Composited on $F_{(z)}$

Baldwin & Dunkerton 2001, Polvani & Waugh 2004



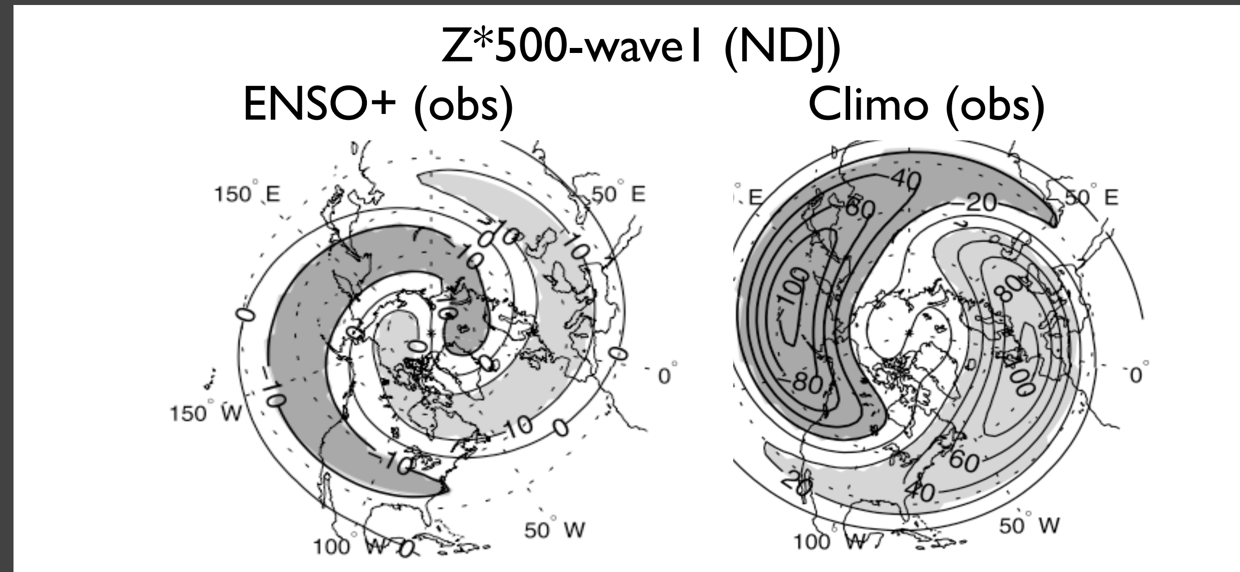
Seasonal NAM Variability: Interference

Wave anomaly lines up with climatological wave, increases wave activity flux into stratosphere.

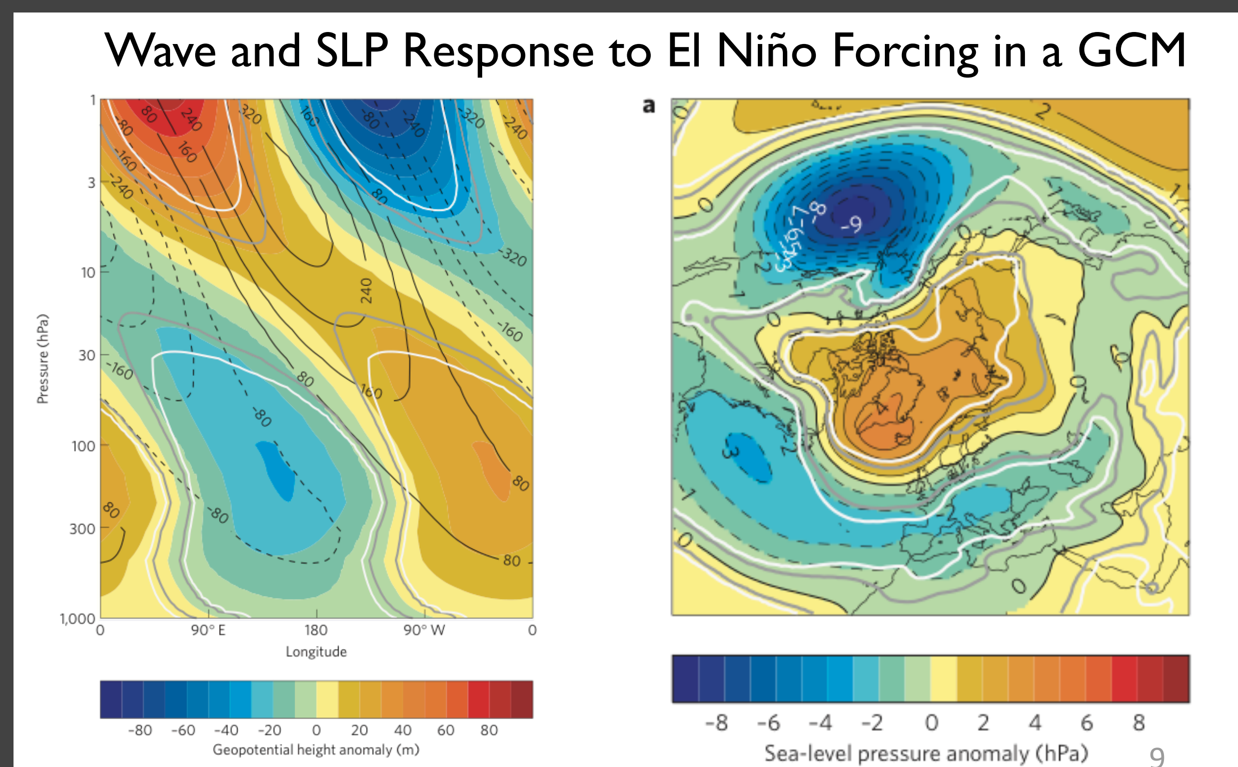
Leads to negative NAM response in stratosphere and troposphere.

The zonal mean signal scales *linearly* with the wave anomaly.

E.g.’s: ENSO, snow, blocking, West Pacific driving of NAM (Garfinkel and Hartmann, Ineson and Scaife, Smith et al., Fletcher and Kushner, Martius & Polvani, Nishii et al., Orsolini poster).



Garfinkel and Hartmann 2009



Ineson and Scaife 2009

PV Flux: Linear/Nonlinear Split

Decompose fields into climatology and anomaly:

$$q = q^c + q^a$$

PV flux anomalies satisfy:

$$(\overline{v'q'})^a = \overline{v'^a q'^c} + \overline{v'^c q'^a} + \overline{v'^a q'^a}$$

LIN: linear in the wave anomalies ($\overline{v'^a q'^c} + \overline{v'^c q'^a}$)

NONLIN: nonlinear in the wave anomalies ($\overline{v'^a q'^a}$)

LIN: zonal coherence between wave anomaly and climatological wave --- linear interference

NONLIN: PV flux intrinsic to wave anomaly.

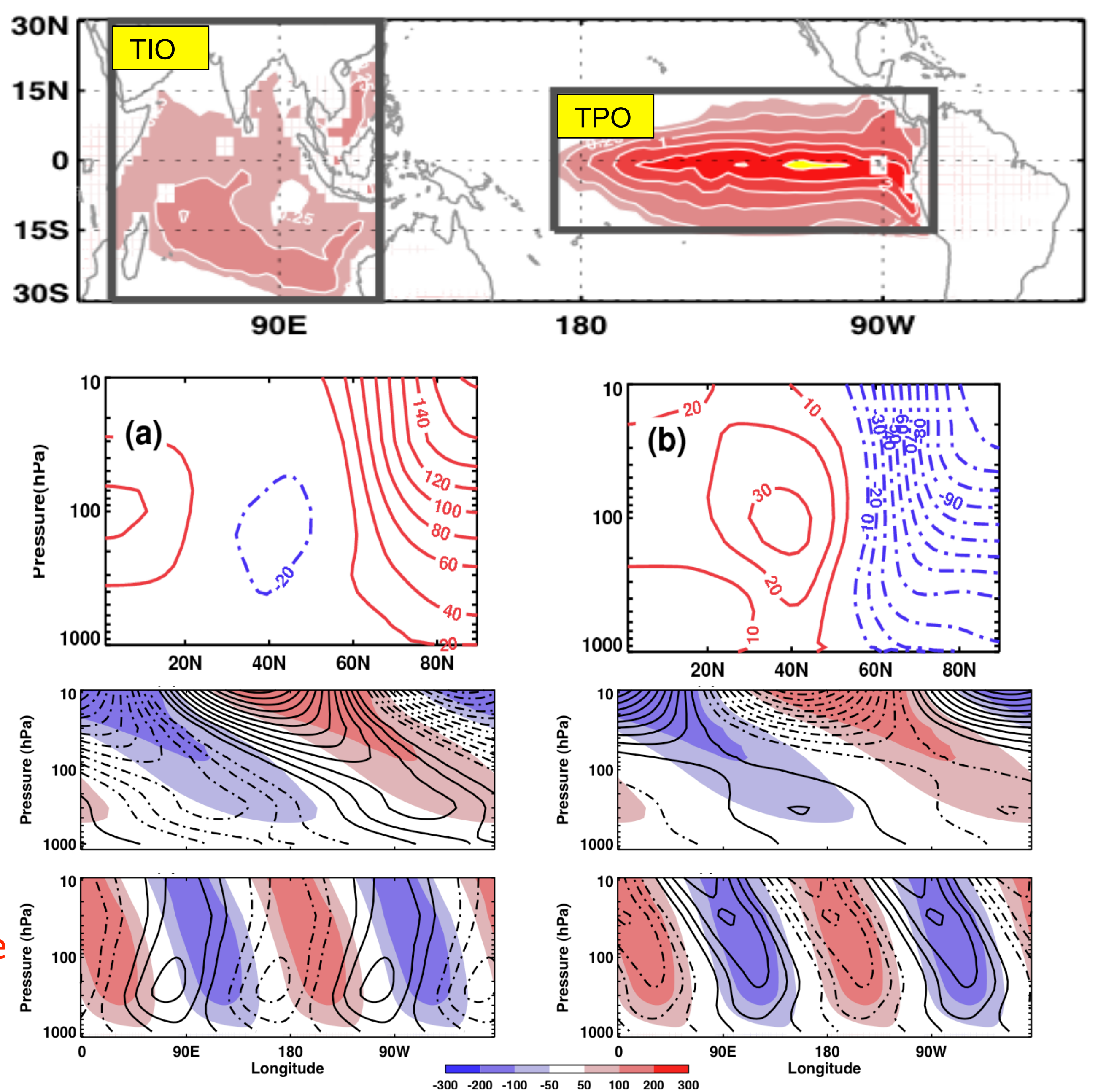
NAM Response to Tropical Forcing

Imposed Tropical Forcing

Zonal Mean Z Response

60N Wave-1 Response (Climatological wave shaded)

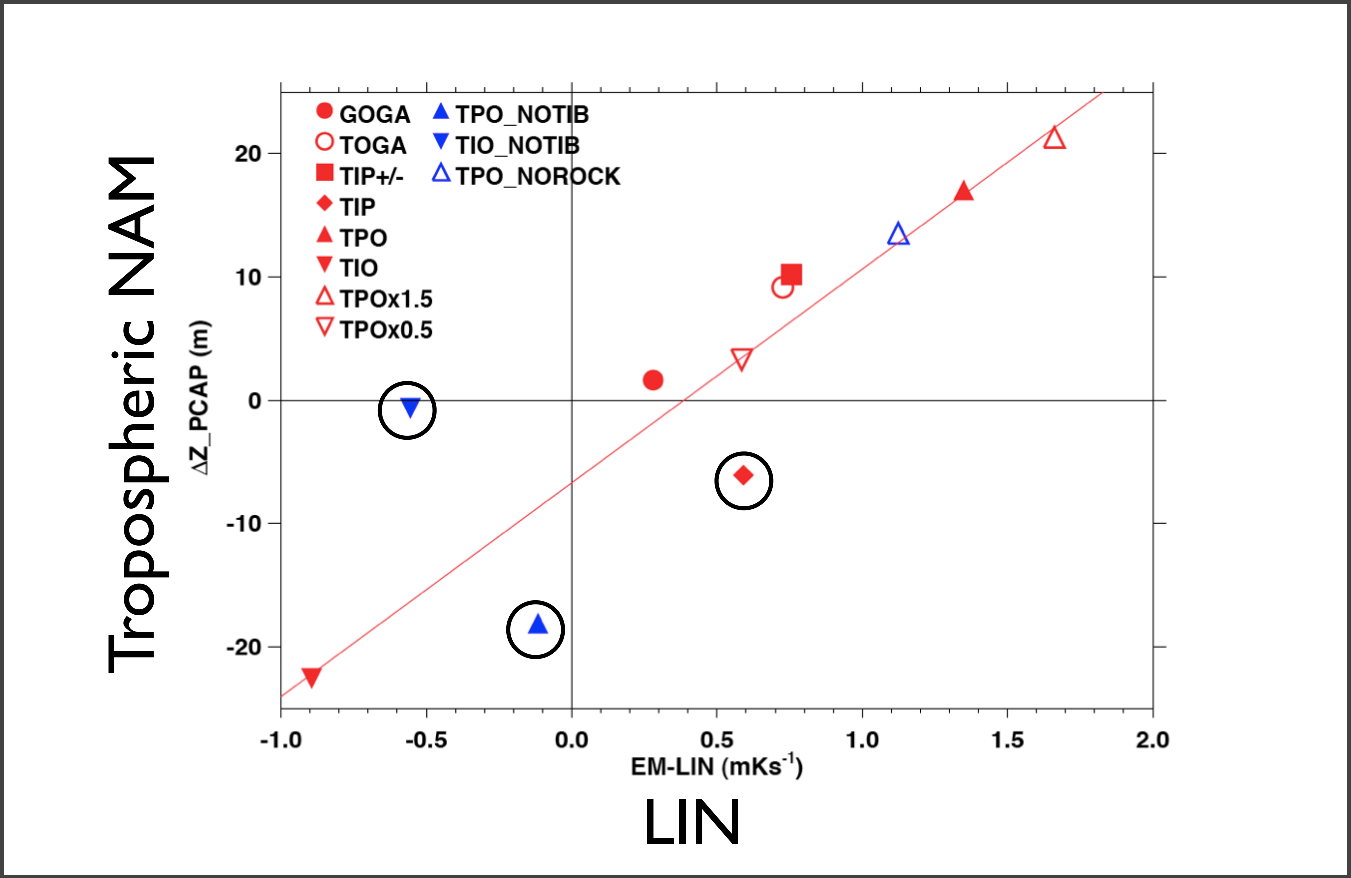
60N Wave-2 Response



Fletcher and Kushner in press

NAM Response to Tropical Forcing

Tropospheric NAM Response v. LIN Component of $\Delta F_{(z)}$



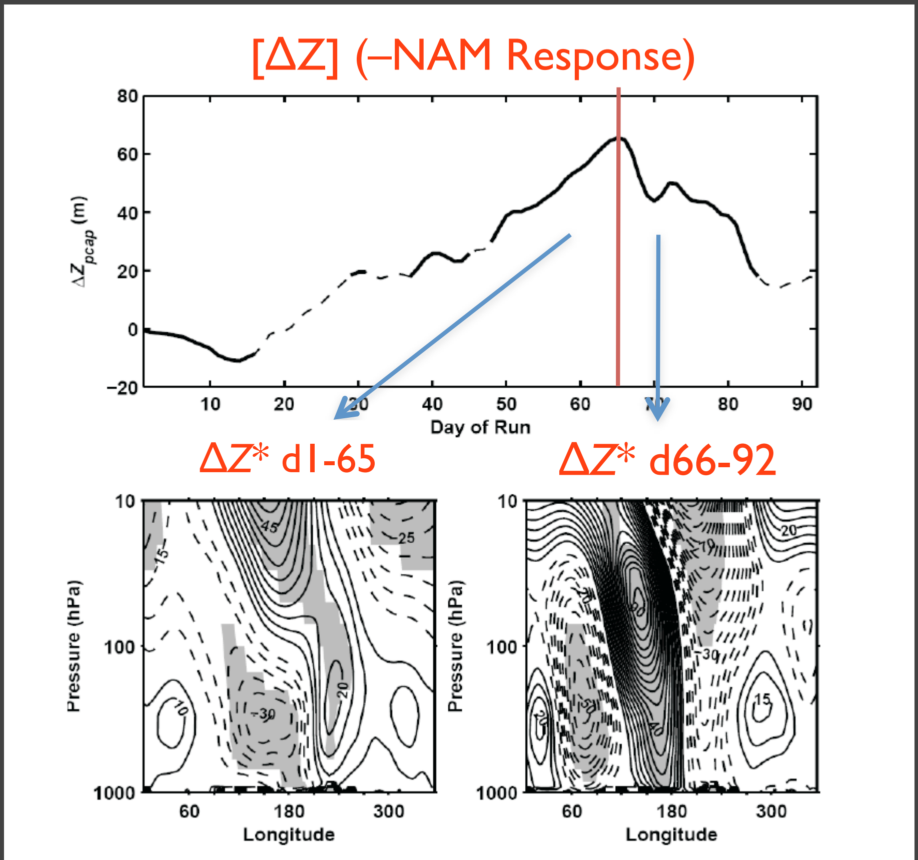
Fletcher and Kushner in press

Linear interference effect can be tuned by tuning background wave or forcing.

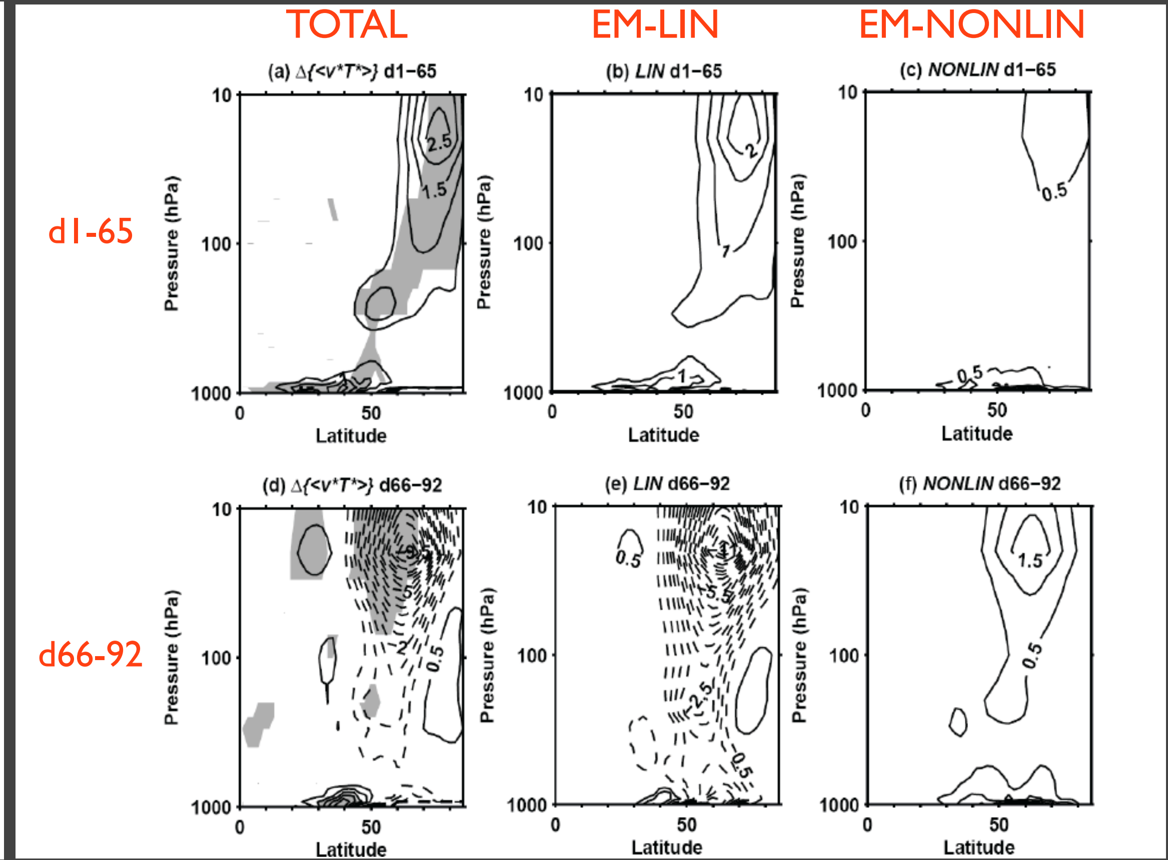
Similar dynamics operates in seasonal response to Siberian snow anomalies (Smith et al., in press).

Response to snow forcing in GFDL AM2

Stratospheric NAM and Wave Response



Δv^*T^* Response



Smith et al. in press

SAM Response to Radiative Forcings

Robust, (mainly) ozone driven.

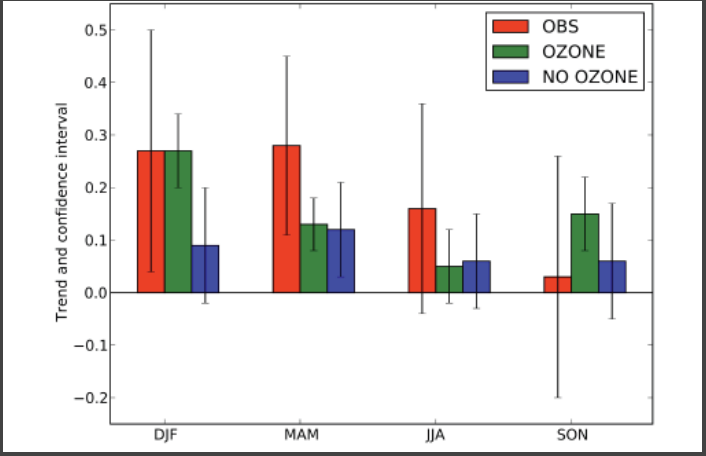
Reversible under ozone/GHG recovery, and involves both radiative and dynamic aspects (Cai et al. 2003, Son et al., Grise et al. 2009).

Ozone, GHG responses have distinct seasonality and model dependence (Perlwitz et al. 2008, Son et al.).

Projected SAM trend: ozone/GHG opposite signs (Shindell & Schmidt 2004, Son et al. 2010, Arblaster talk).

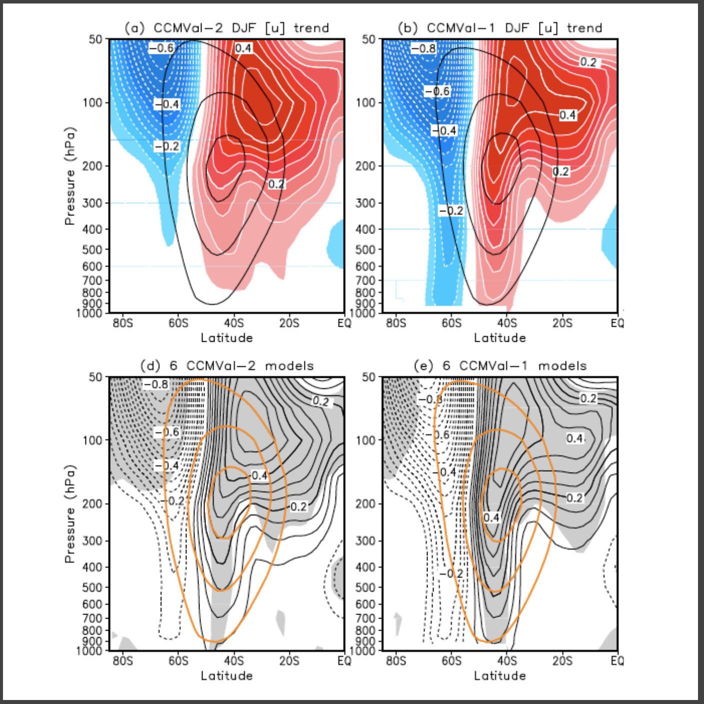
Historic SAM Trends (Obs/CMIP3)

Fogt et al. 2009

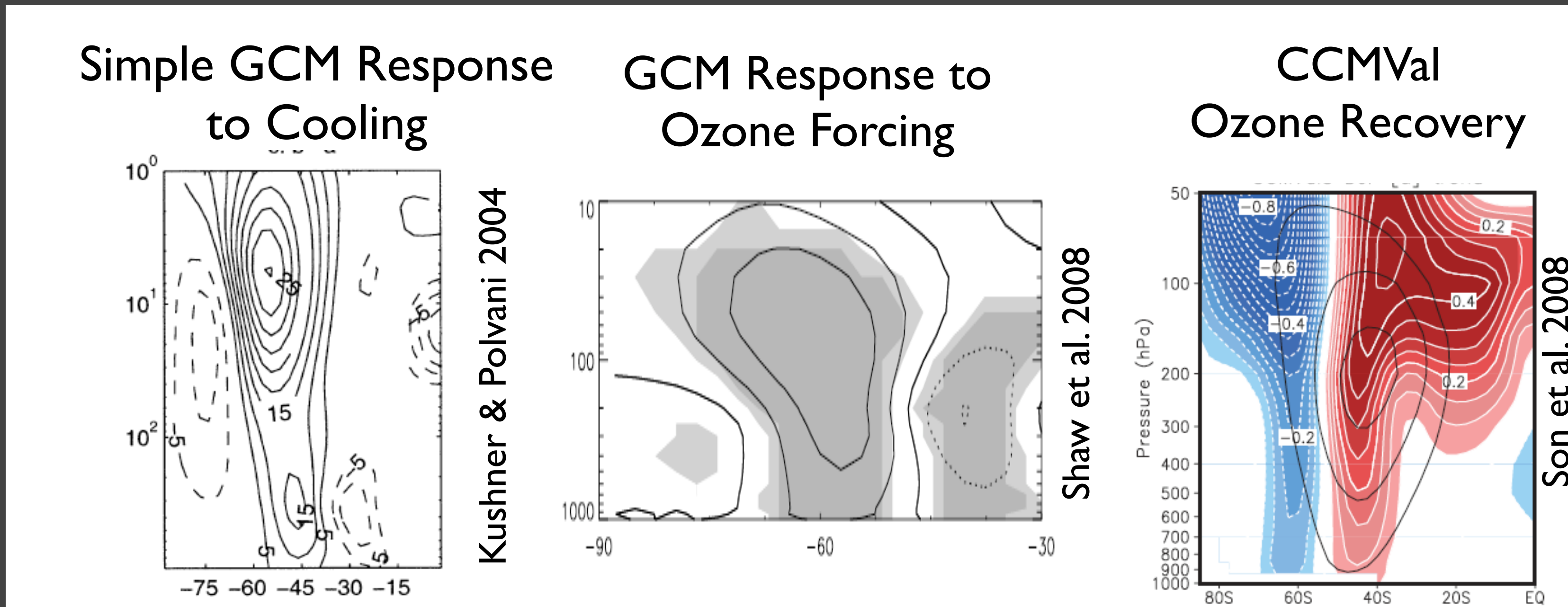


Projected 21st century U Trends (CCMVal)

Son et al. 2010



Characterizing Tropospheric Sensitivity to Stratospheric Change

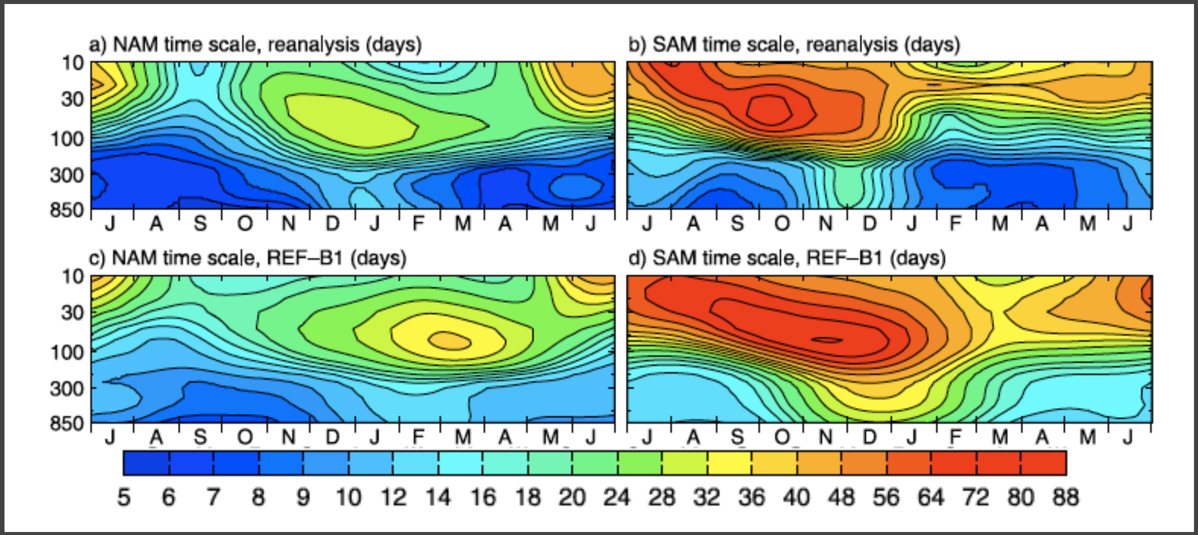


$$R = \Delta U_{50}/\Delta U_{850}$$

CCMVal1 (Son et al. 2008)	R ~ 5
CCMVal2 (Baldwin et al. SPARC, Son et al. 2010)	R ~ 4
GEOS CCM (Perlwitz et al. 2008)	R ~ 6
Idealized GCM cooling (Polvani & Kushner)	R~1.5
Idealized GCM cooling (Gerber & Polvani)	R ~ 8
CMAM ozone forcing (Shaw et al. 2008)	R~2 - 7
SAM Trend	R~1-2

Annular Mode Timescale

Seasonal Cycle of AM Timescale, Obs & CCMVal Models



Baldwin et al. 2003, Gerber et al. 2010

AM timescale related to persistence of strat-trop coupling events in winter.

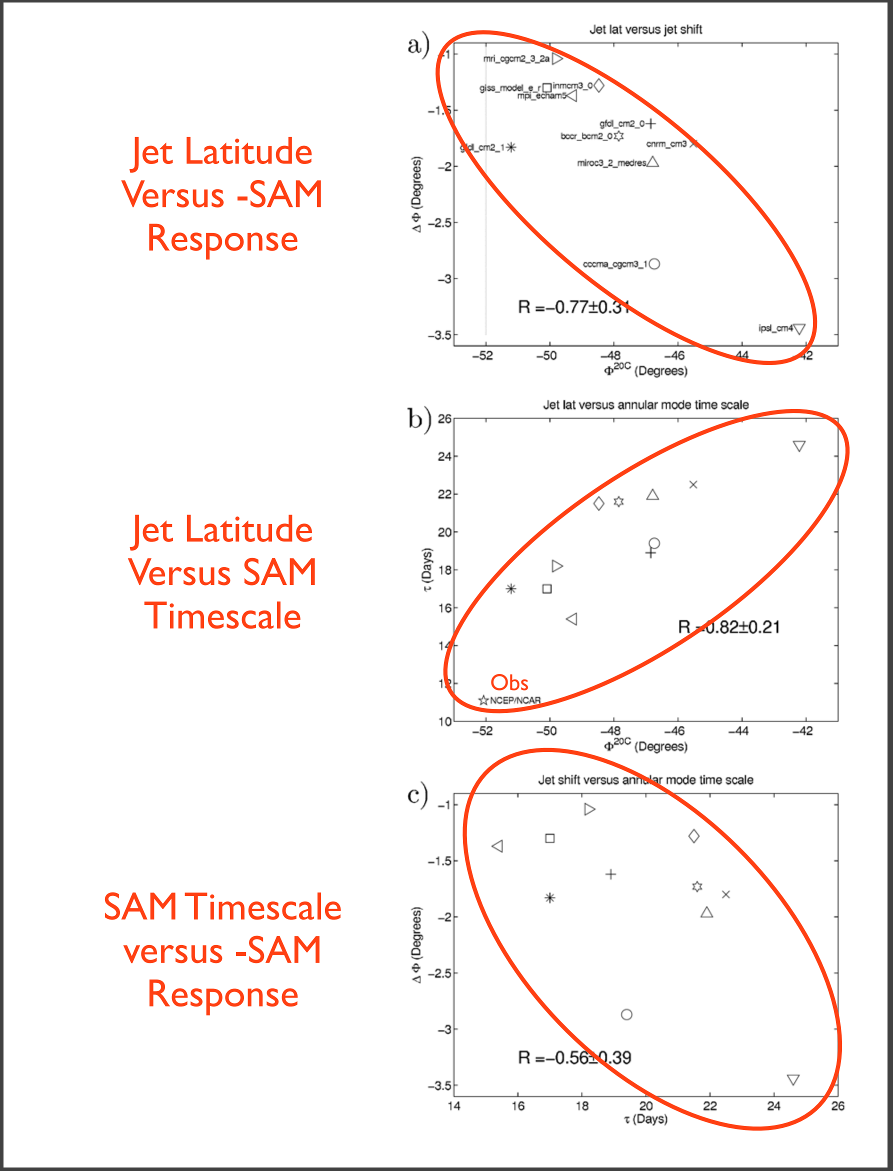
- Implications for AM response to climate change.

AM Timescales and the SAM Response

Amplitude of SAM response, SAM timescale, and climatological jet position all linked.

- Fluctuation-Dissipation theory, jet regimes (Ring and Plumb, Gerber et al.)

SAM Response in CMIP3



Kidston & Gerber, 2010

Regional (Wave) Stratospheric Influence

Stratospheric Influence by Wave Reflection

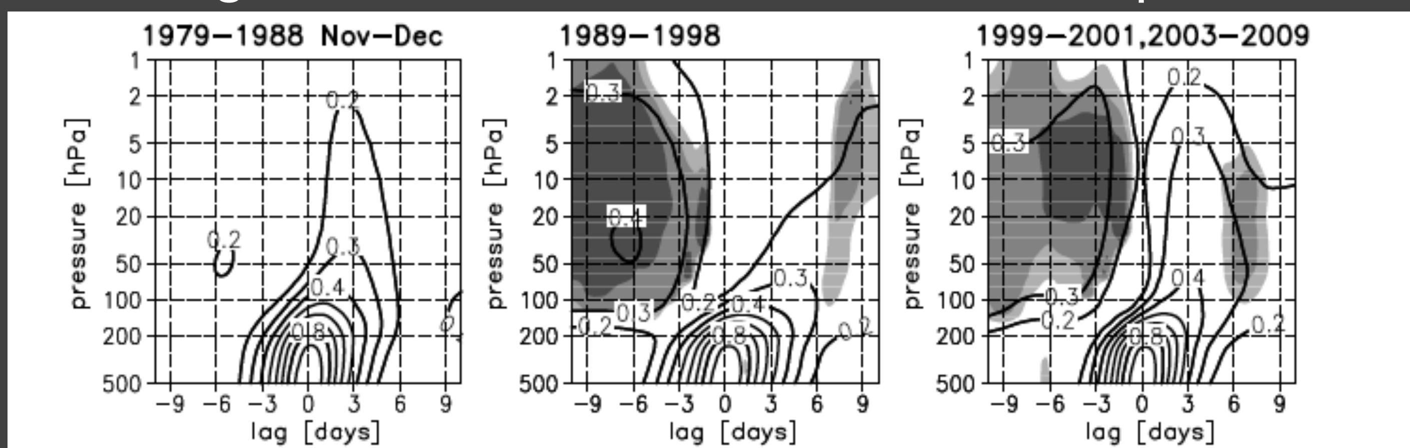
QG wave equation

$$q'_t + \overline{u} q'_x + v' \overline{q}_y + [\nabla \cdot (\vec{u}' q')]' = S'$$

linear dynamics   wave-wave

Southern Hemisphere wave reflection trends:

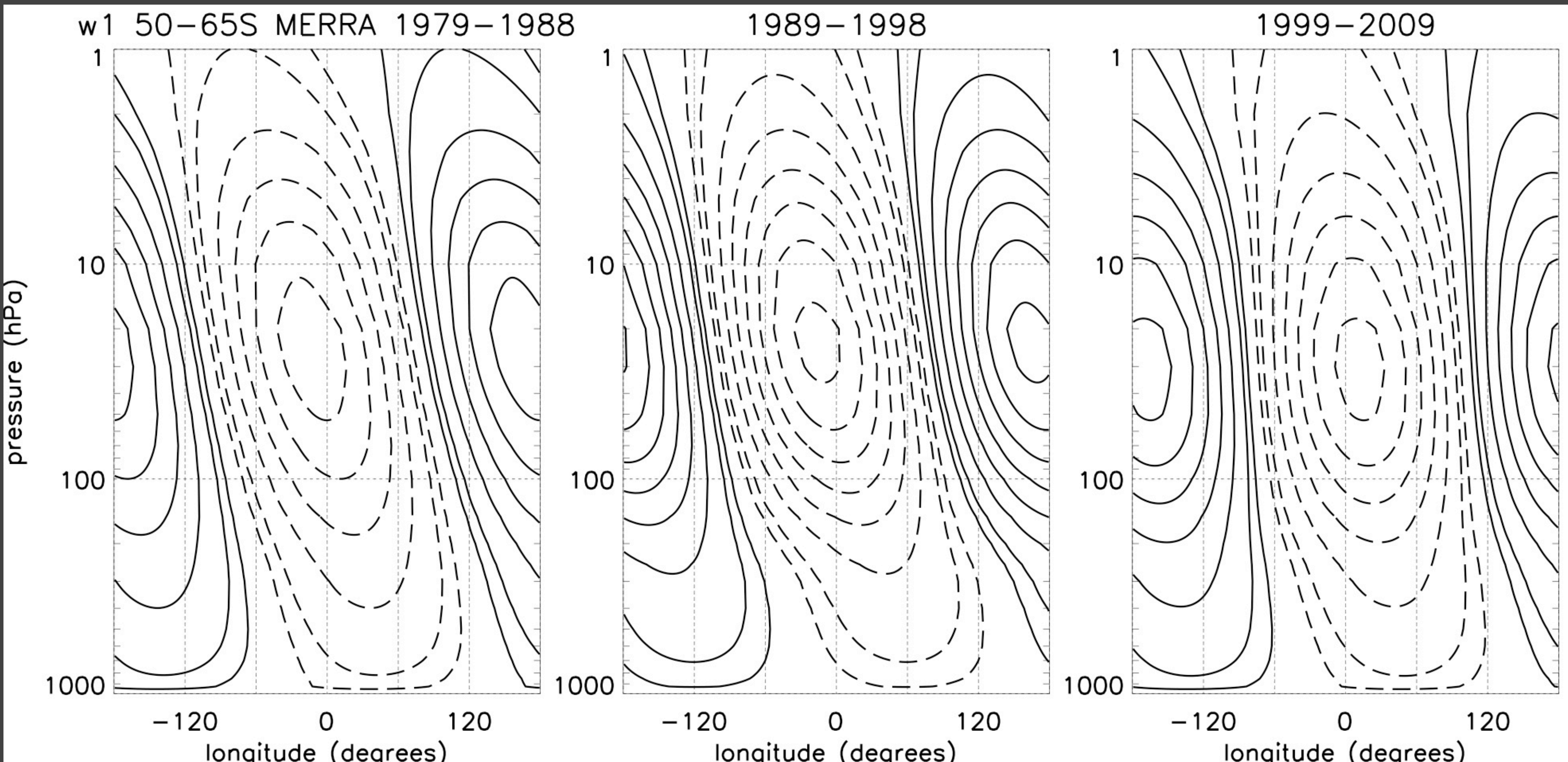
Lag correlation of Wave 1, Southern Hemisphere



Perlwitz & Harnik 2004, Shaw et al. 2010, Harnik et al. 2010

Ozone depletion delays time of vortex breakup; reflective surfaces form in stratosphere.

Decadal Changes in Vertical Structure of Wave 1 (Nov 1-Dec 16)



Shaw et al. in prep

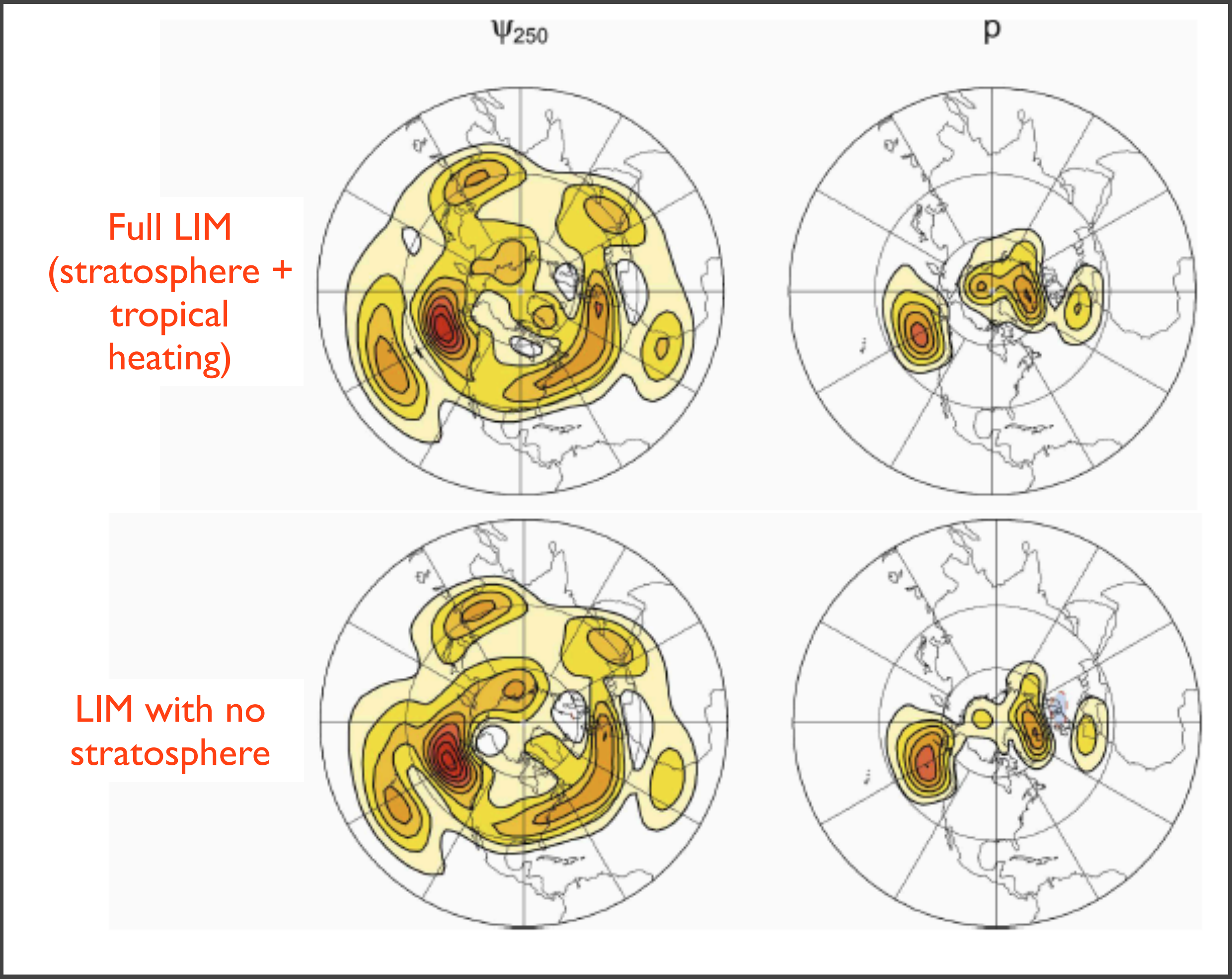
Limits of Stratospheric Influence

Limits of Stratospheric Influence

Newman and Sardeshmukh's statistical forecast model:

- Little stratospheric impact away from polar region.

21-Day Lag Covariance from Linear Inverse Model



Newman and Sardeshmukh 2008

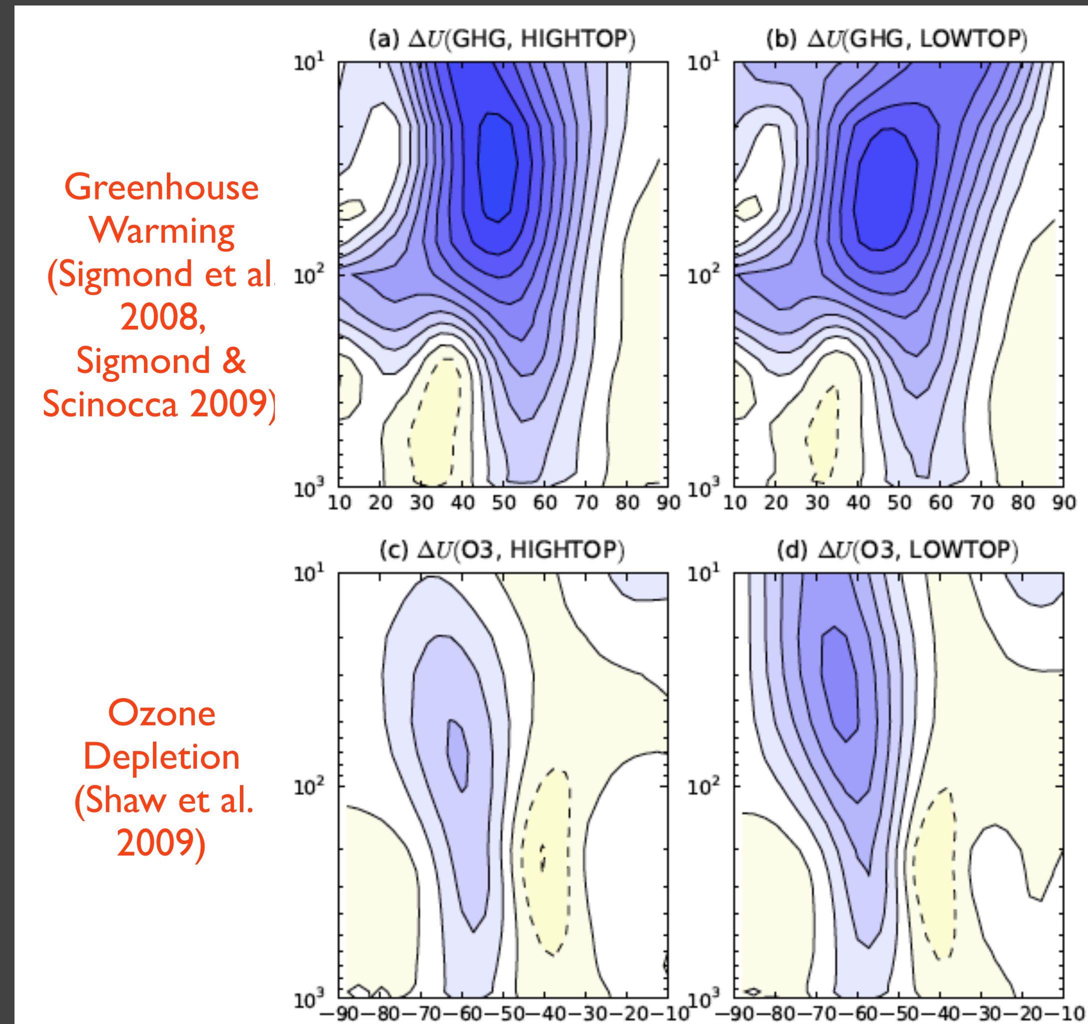
Can We Parameterize the Stratosphere?

AM climate responses captured in carefully constructed (momentum-conserving) “Low-Top” model.

- Some reported stratospheric influences (Shindell et al. 1999) might be model artefacts.

Sigmond and collabs now looking at stratosphere/ ocean/sea ice coupling.

CMAM *U* Response to Climate Forcing



Reviewed by Kushner 2010

Conclusions

Stratosphere matters even if "forcing" is tropospheric.

Useful to think separately about hemispheric (zonal-mean) and regional (wave) influences.

For predictability, need simple metrics relating stratospheric to tropospheric variability.

Linear theory is relevant.

- Wave reflection/linear interference.

Seasonal timescale variability is relevant to decadal.

- Biases influence AM climate responses.

Limits of stratospheric influence need to be recognized and characterized.

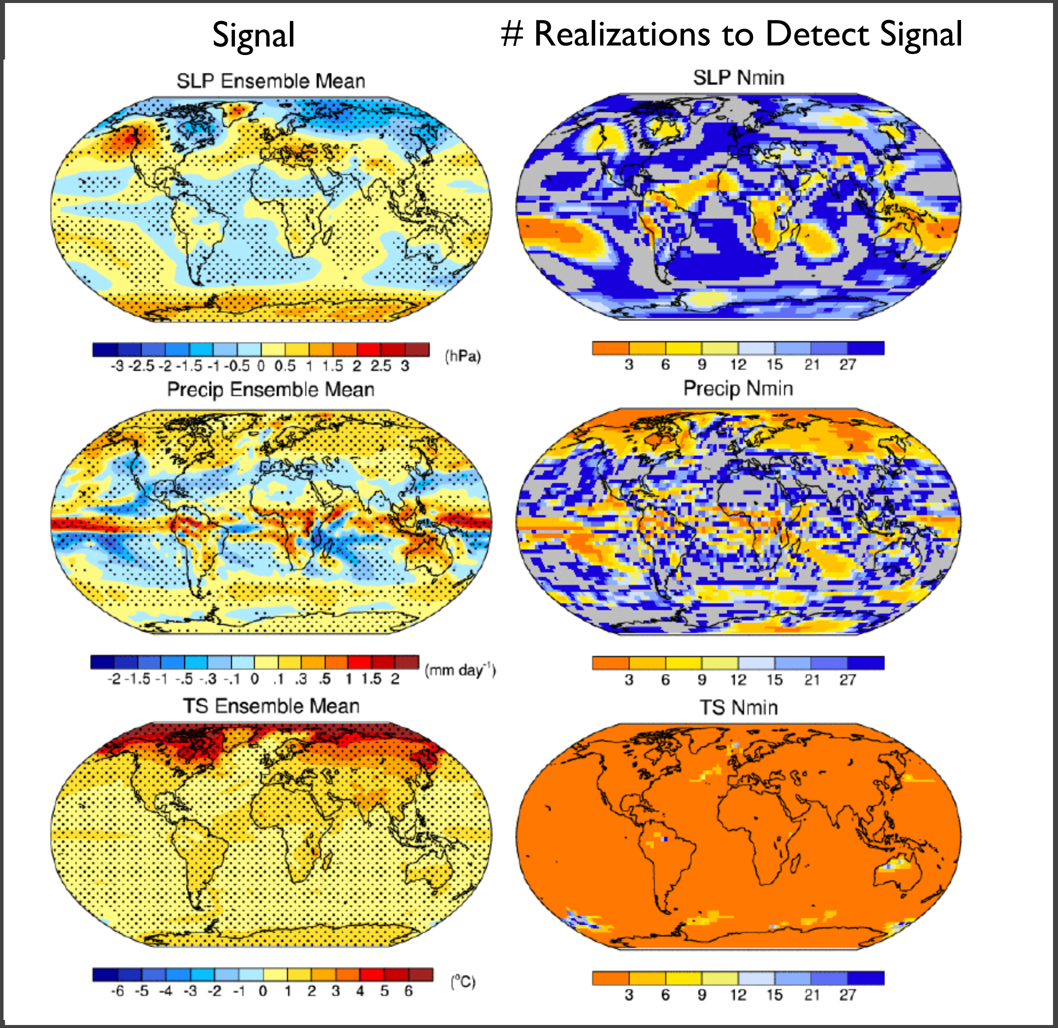
Extratropical Circulation is Hard to Predict

21st Century Wintertime Climate Response,
NCAR CCSM3 "Large" Ensemble

SLP

Precip

T_s



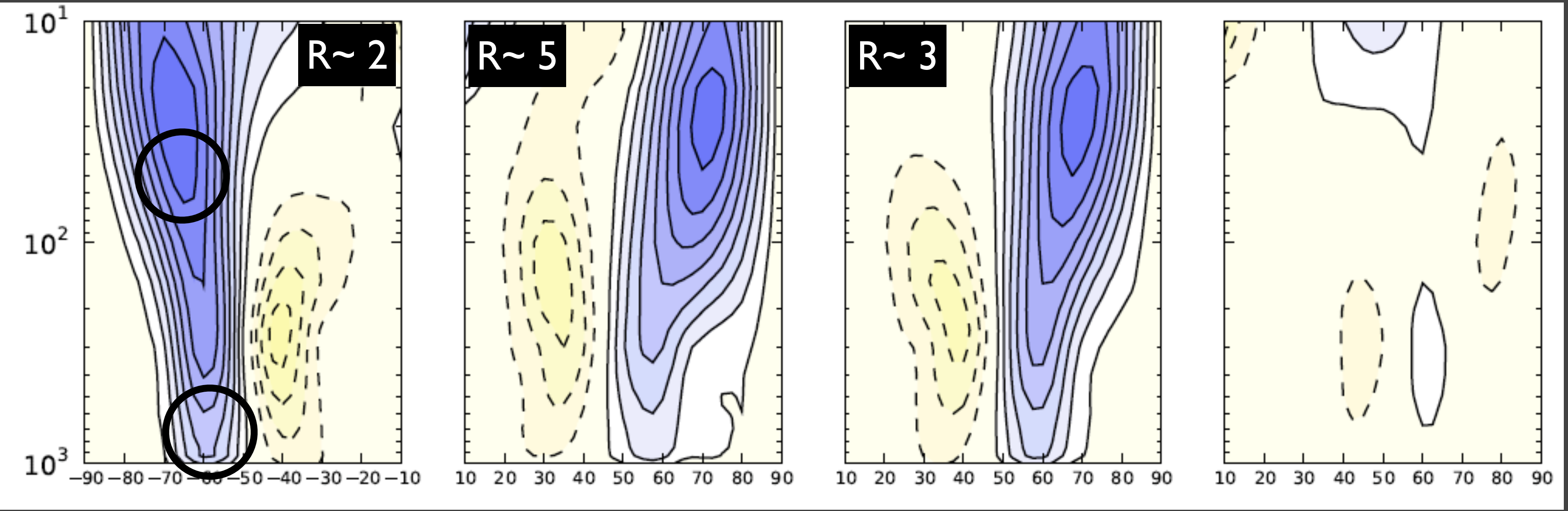
Deser et al., submitted

Scaling for Stratosphere-Troposphere AM Responses

For the annular mode in zonal wind, U, we can define a rough measure of high-latitude coupling (as proposed by W. Robinson):

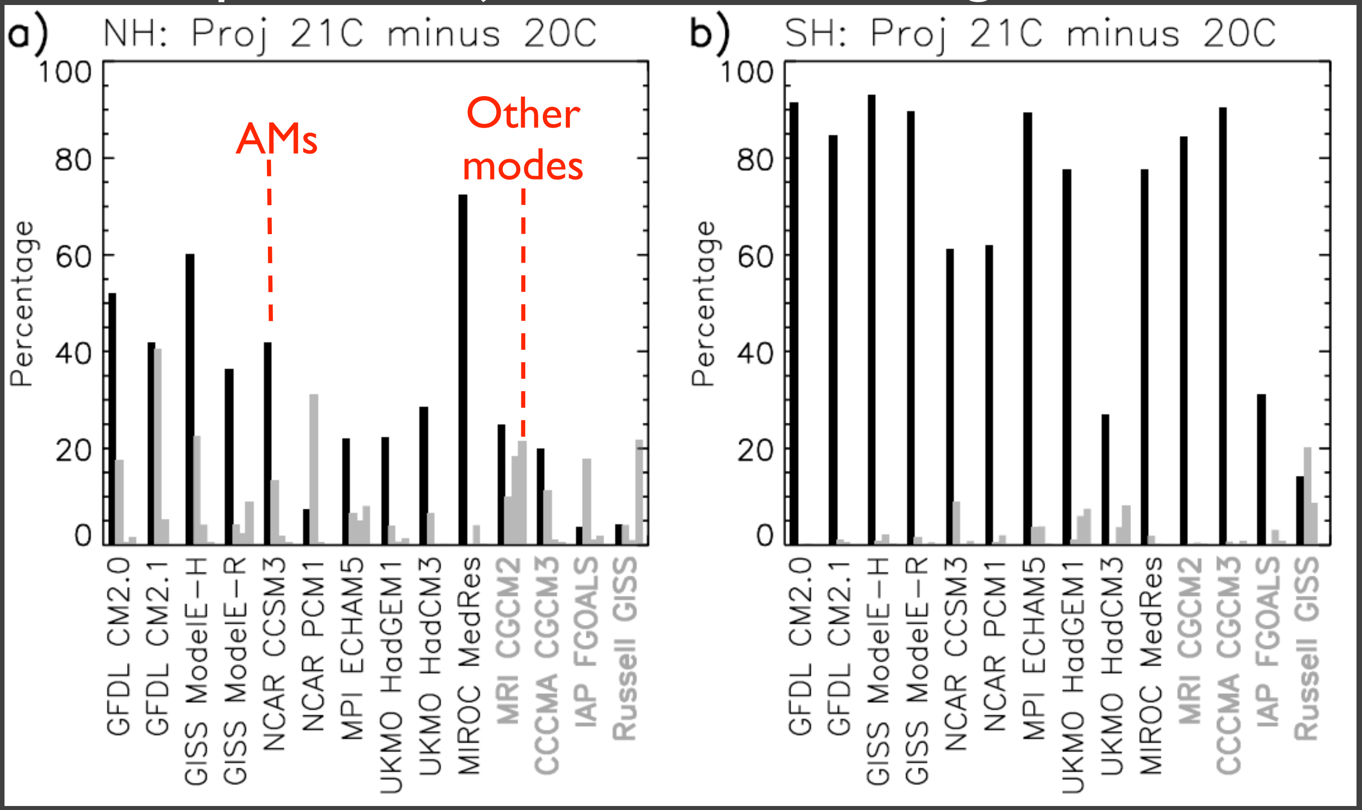
$$R = \Delta U_{50}/\Delta U_{850}$$

SAM, Nov. NAM, JFM Symmetric Antisym.



AM Responses to Climate Change

SLP Response Projected onto Leading EOFs, CMIP3



Miller et al. 2006

- Both GHG increases and ozone depletion lead to positive SAM trends.
- SAM response more robust than NAM response.
- Direct and indirect stratospheric influence.