How Does the Stratosphere Influence the Annular Mode Response to Climate Change?

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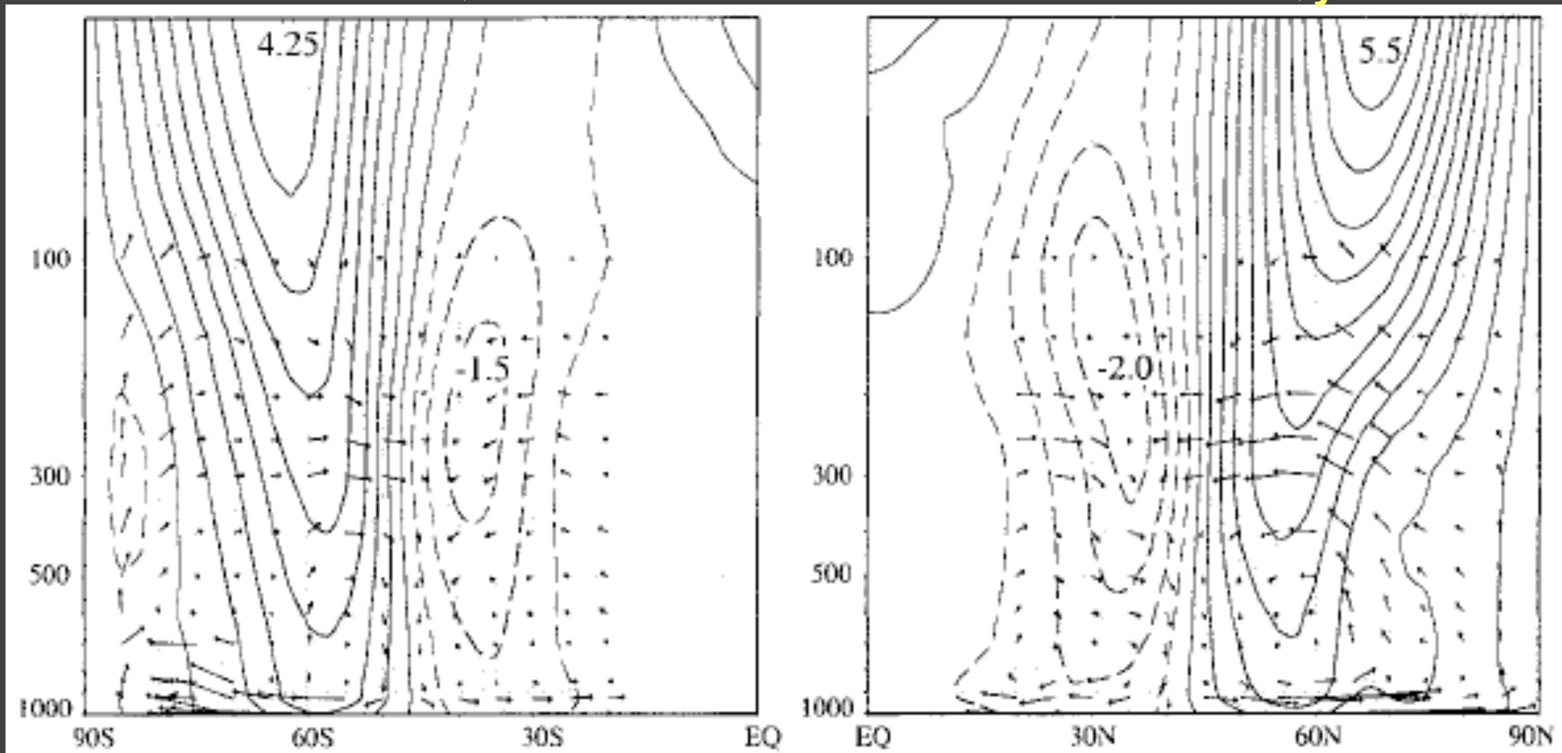
Review highlighting work of CSPARC (CCCma & U. Toronto)

Sigmond et al., GRL, 2008.
Sigmond and Scinocca in prep.
Shaw et al., J. Climate submitted.
Fletcher et al., JGR in press.
Hardiman et al., JGR submitted.

Southern and Northern Annular Modes

AM+ in Zonal Wind, U

SAM+ in U, Nov. NAM+ in U, JFM



Thompson and Wallace 2000

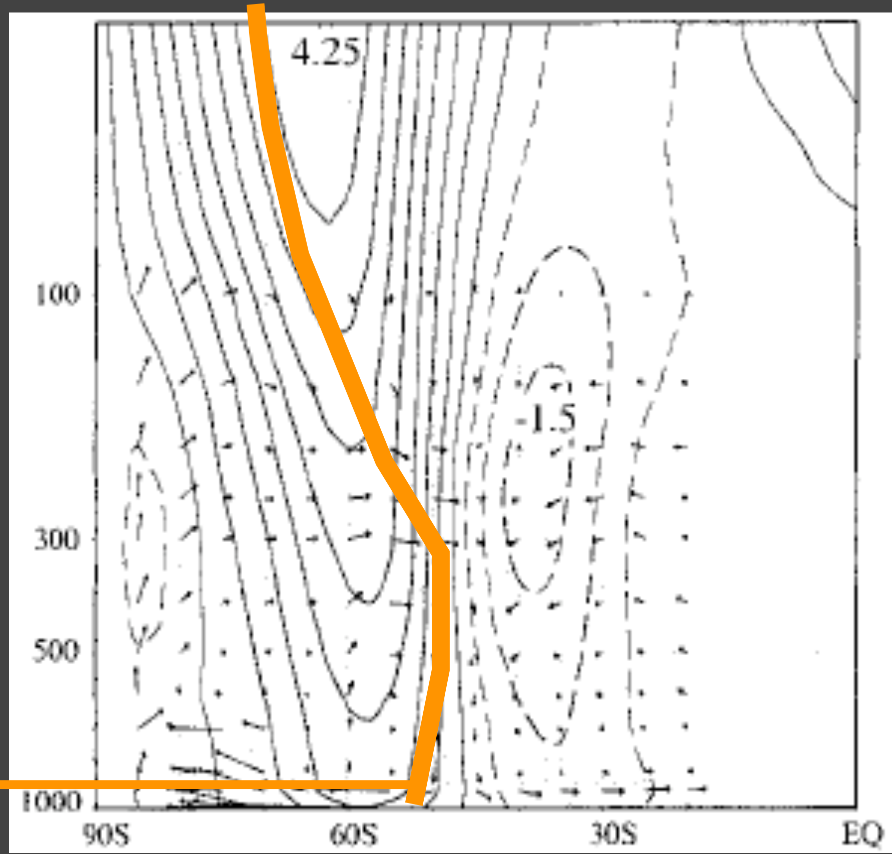
- Symmetric about equator in active seasons.
- Notice stratosphere-troposphere link.

Stratosphere-Troposphere AM Signatures

Stratosphere:
Stronger polar night jet, colder polar stratosphere.

Troposphere:
Poleward intensified jet stream.

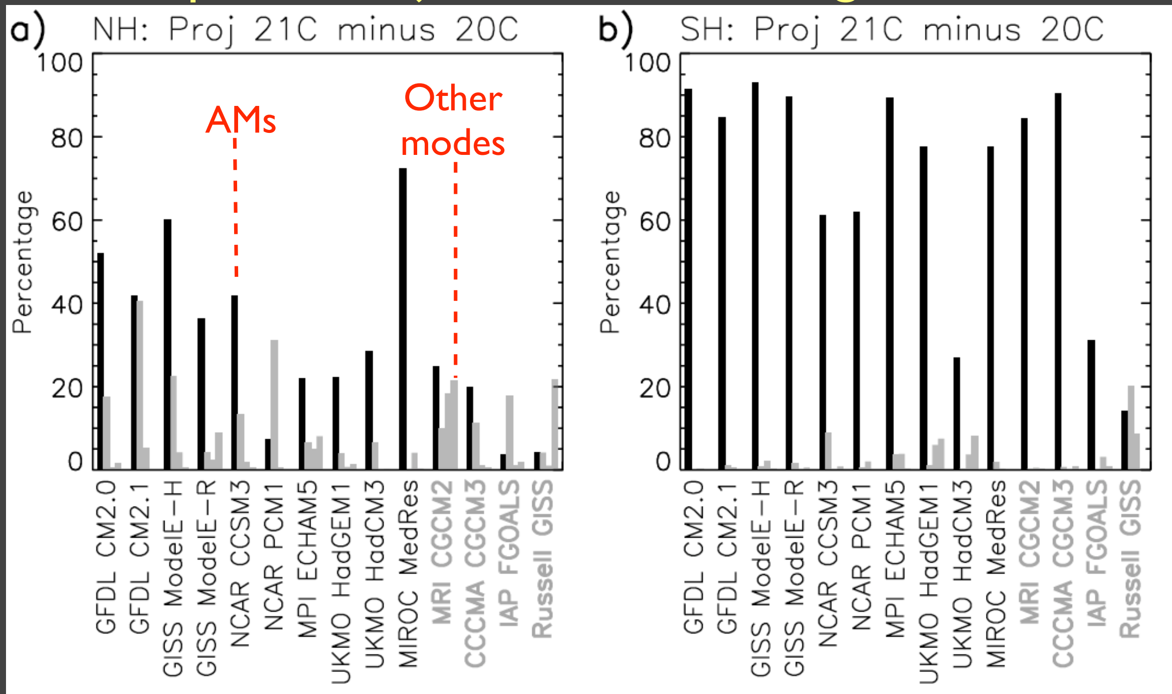
SAM+ in U, Nov.



Thompson and Wallace 2000

Can We Predict the Pattern of Extratropical Climate Change?

SLP Response Projected onto Leading EOFs, CMIP3



Miller et al. 2006

- The Annular Mode (AM) response to climate change remains a key uncertainty in extratropical climate prediction.
- *How can we explain and constrain the range of predictions?*

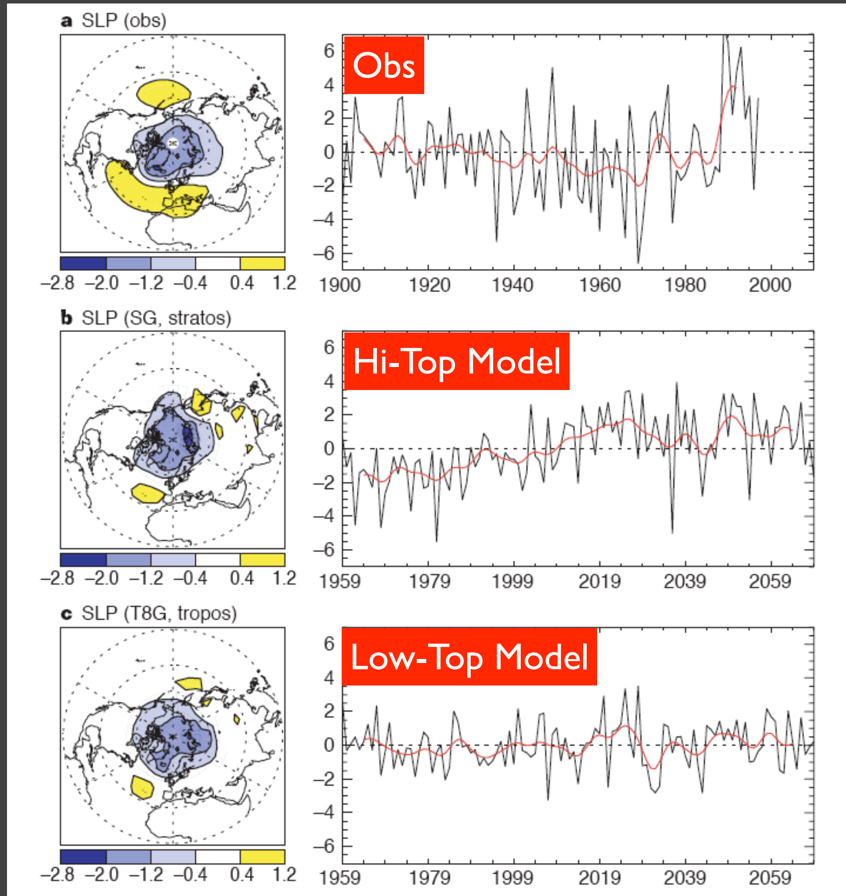
AM Signatures: Greenhouse Warming

Hurrell, Thompson and others observed multi-decadal NAO and NAM trends.

Shindell et al. found that a climate model with relatively good stratospheric representation gets a positive NAM response to greenhouse warming.

But in precisely what way is the stratosphere key to the response?

GISS GCM Climate Change Projection for NAM



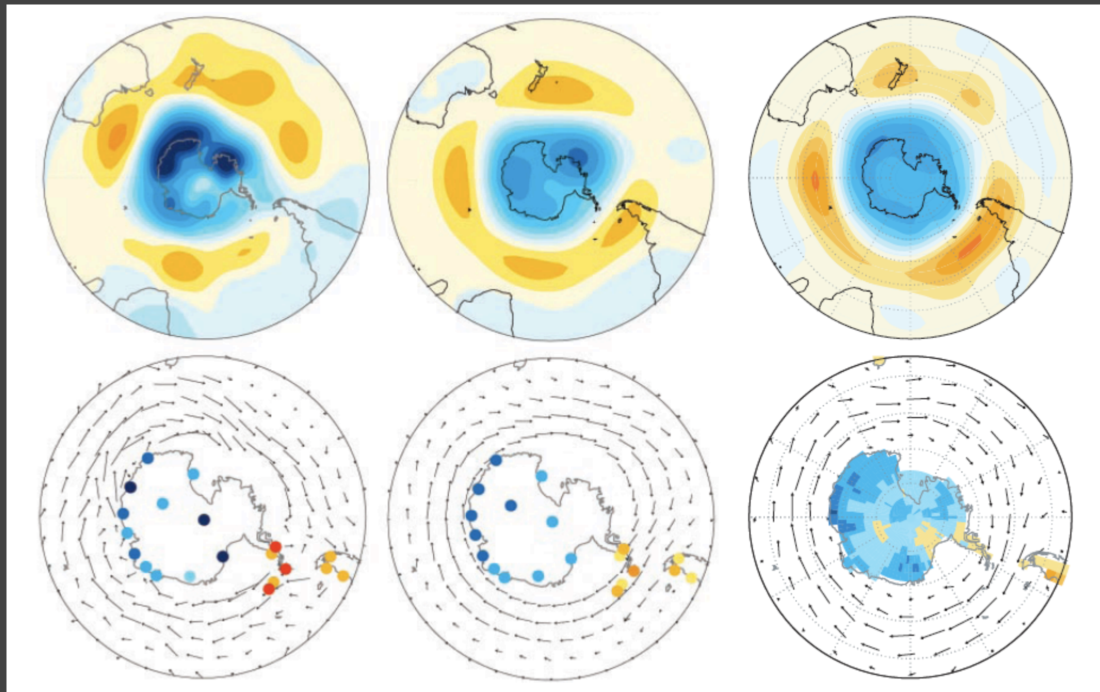
Shindell et al. 1999

AM Signatures: Ozone Depletion

Trend, 1968-1998 | Projection of Trend onto SAM | GCM Response to Ozone Depletion

Z500

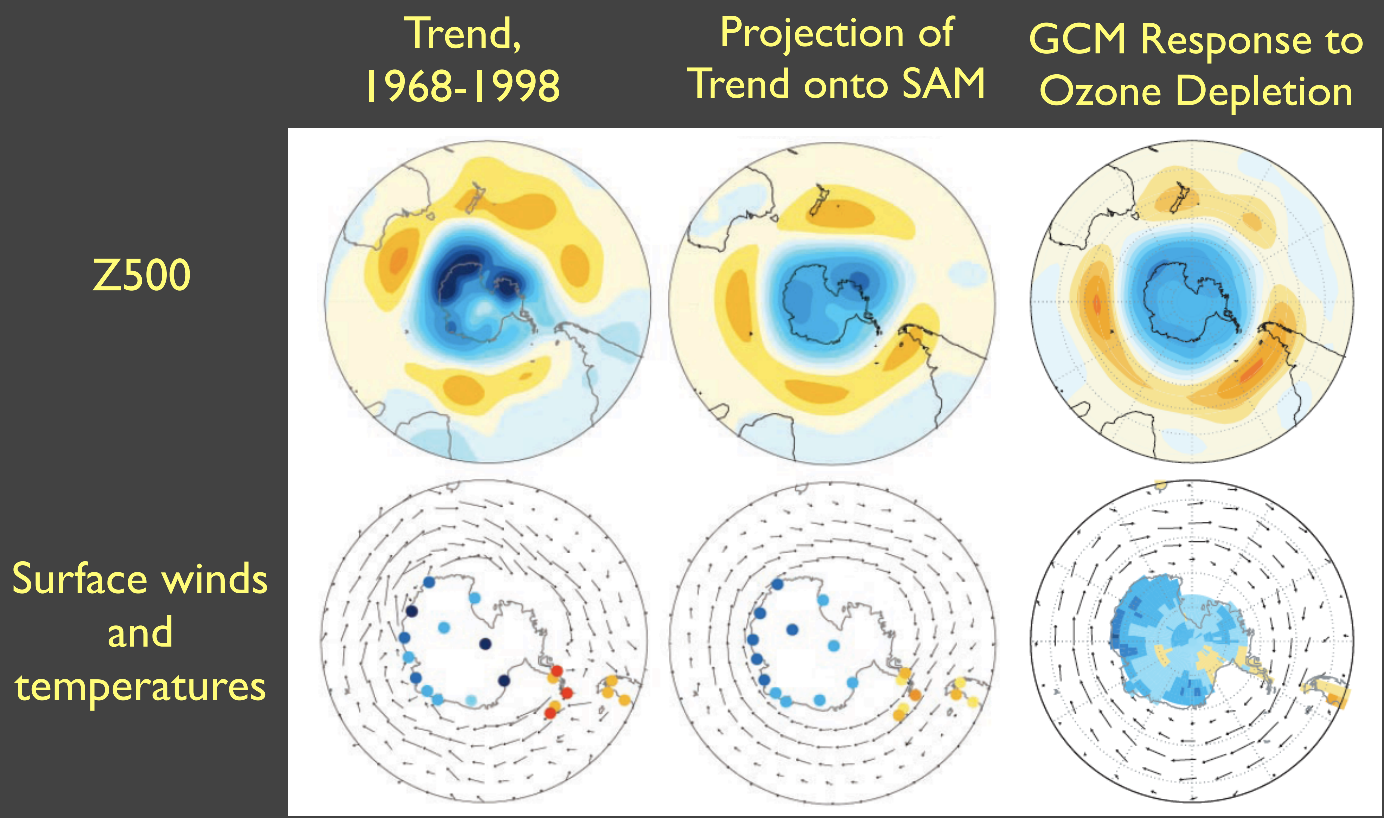
Surface winds and temperatures



Thompson & Solomon 2002, Gillett and Thompson 2003

- Southern Hemisphere trends are strongly SAM related.
- Photochemical ozone loss and recovery control a lot of this (see Son et al., Perlwitz et al.).

AM Signatures: Ozone Depletion



Thompson & Solomon 2002, Gillett and Thompson 2003

- *But how well do we understand this response, and how robust is it?*

Questions & Ideas for Today

Can we explain and constrain the predictions of the AM response to climate change?

What is the dynamical role of the stratosphere in the AM response?

AM responses to climate forcings have many causes.

The stratosphere often influences the tropospheric response, but in various ways.

Theory and modelling to sort through these issues are developing rapidly.

We must remember the non-AM part of the response.

Direct/Indirect Decomposition
&
Fluctuation Dissipation Theory

Direct/Indirect Decomposition

We can separate climate response patterns into

- ✳An "indirect" part: projection onto internal modes (positive NAM here). This part is often dominant.

- ✳A "direct" part: the residual

  We can often interpret the direct part as the forcing that causes the indirect part.

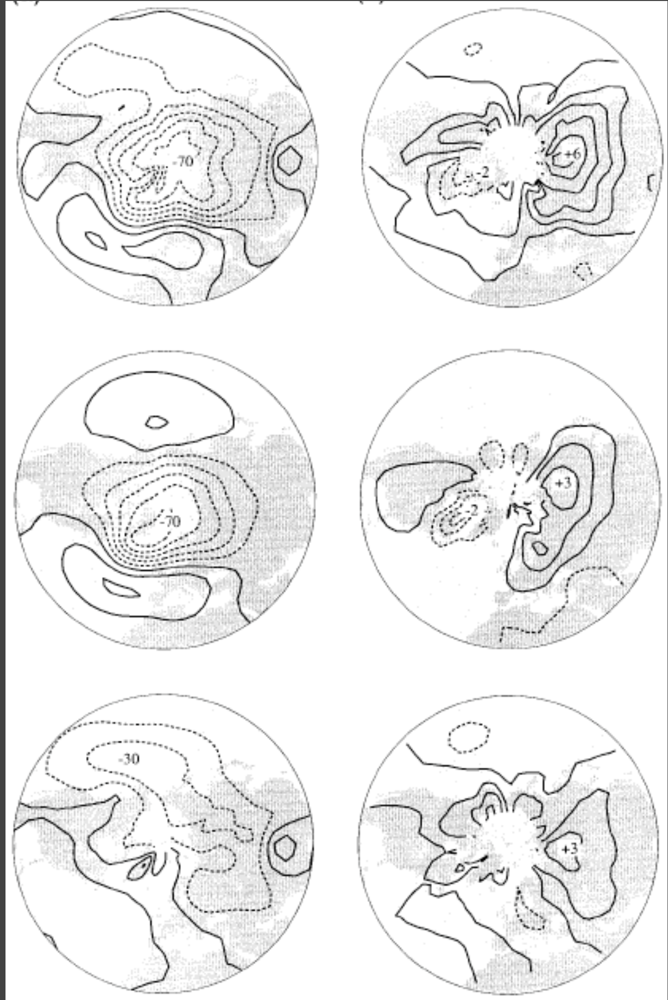
NH Trends, JFM 1968-1998

SLP SAT

Trend

NAM+ (indirect)

Residual (direct)



Thompson et al. 2000

Southern Hemisphere Response to Global Warming

The GFDL R30 "low-top" GCM gets a SAM+ response to greenhouse warming.

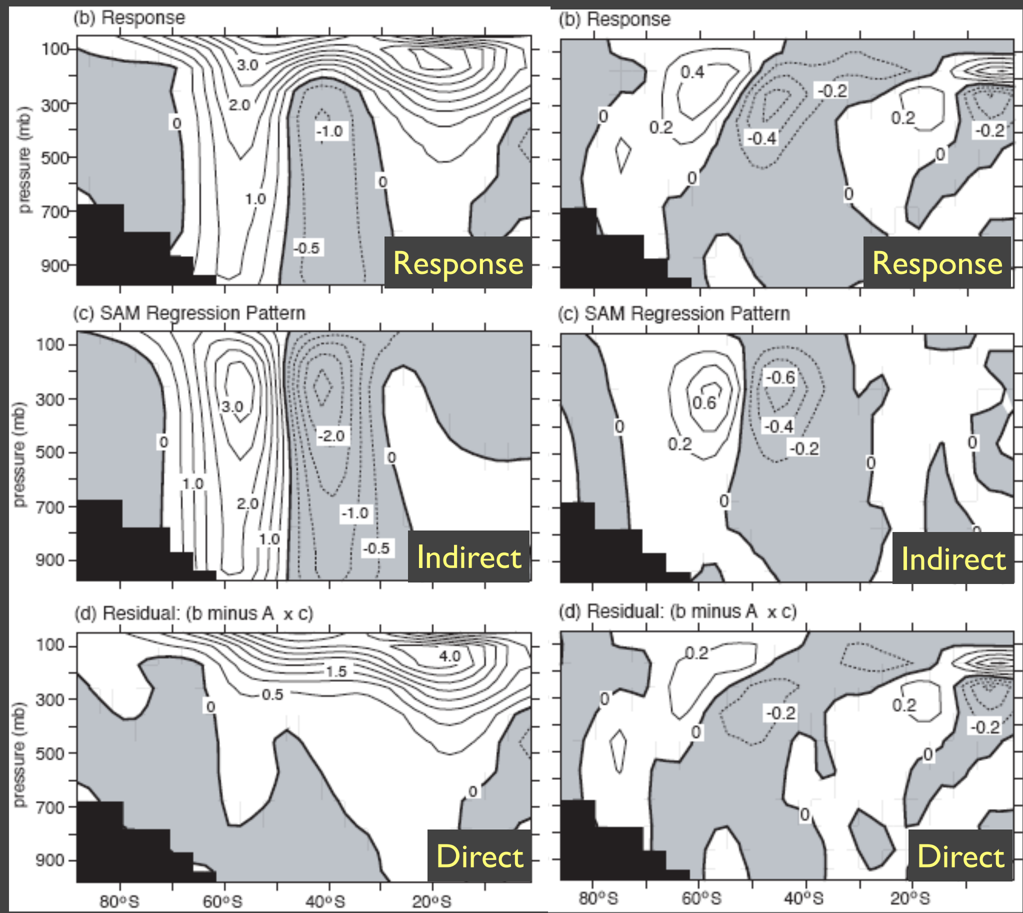
- It is linked to changes in upper tropospheric eddy momentum fluxes (see Gang Chen's work).

The direct response is thermally forced (tropical warming/extratropical stratospheric cooling).

Here is an example of extratropical climate change without strong stratospheric dynamical influence.

GFDL R30 GCM Response to Greenhouse Warming (low-top tropospheric model)

U $\qquad$ $-\partial[u'v']/\partial y$



Kushner et al. 2001

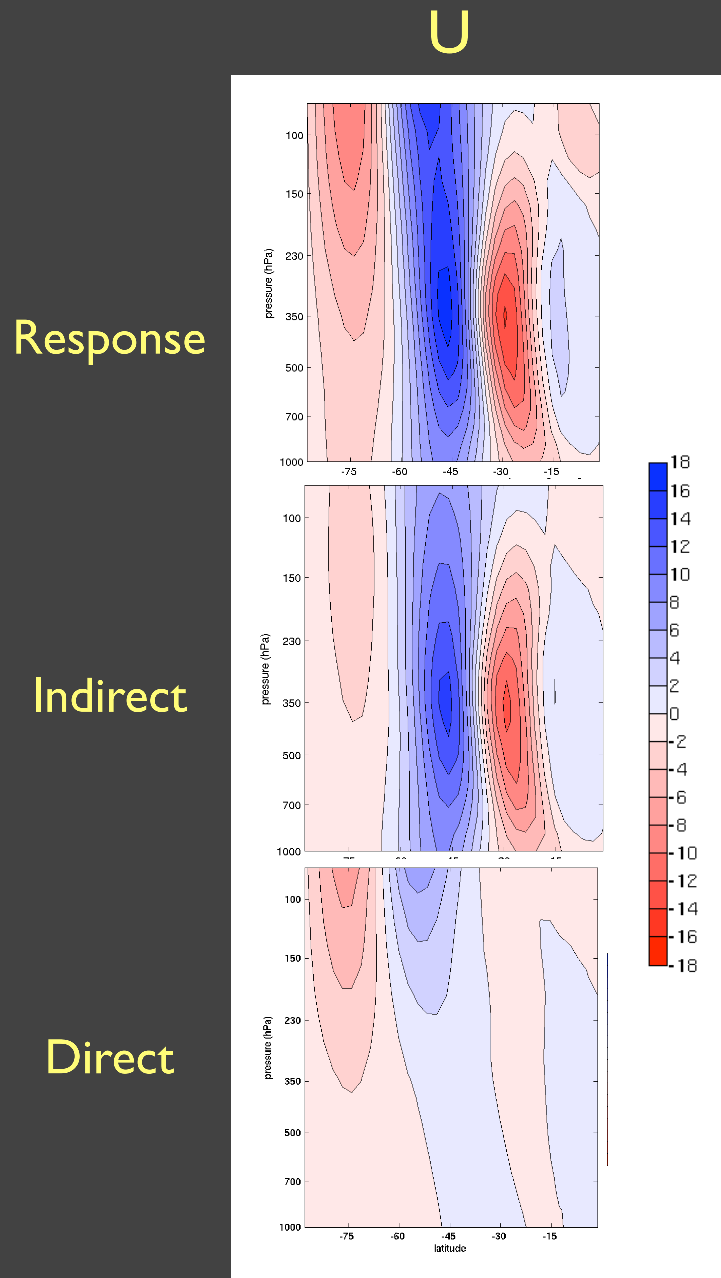
Stratospheric Cooling in a Simple GCM

This simple Hi-Top GCM, gets a huge AM response to stratospheric cooling.

The direct response reflects the imposed stratospheric cooling.

The indirect AM response is eddy driven and *unrealistically* large.

(We'll get back to this point.)

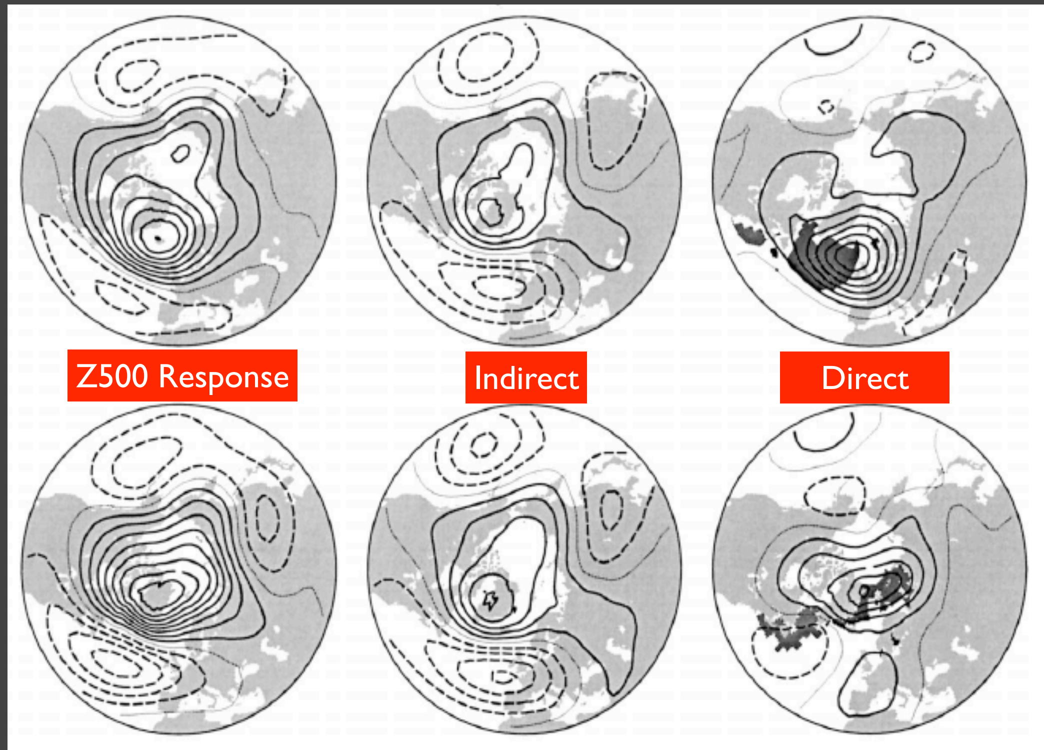


Polvani & Kushner 2002

Deser et al. 2004: Response to Surface Forcing

Response to SST Forcing in a Low-Top AGCM

Response to Sea Ice Forcing



Deser et al. 2004

- We see a similar total response to different forcings.
- Indirect response: nonlinear, induced in various ways, unpredictable.
- Direct response: localized to forcing regions, predictable.

Fluctuation Dissipation Theory (FDT)

AM indirect responses are unpredictable and can be triggered in many ways such as

- Tropospheric warming (CO_2)
- Stratospheric cooling (O_3, CO_2)
- Surface forcing (Cryosphere & SSTs)
- Directly applying torques (Ring and Plumb, Chen and Zorita-Gotor, Sigmond & Scinocca).

The direct/indirect decomposition is useful but empirical and diagnostic.

FDT offers a predictive and systematic framework.

Fluctuation Dissipation Theory (FDT)

Leith, Palmer, Ring & Plumb, Gritsun & Branstator . . .

Idea: use internal variability to predict the response to external forcing.

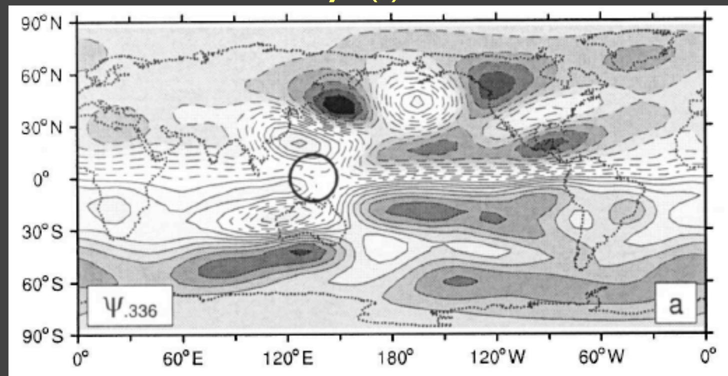
Response of a mode
$\propto$
(Projection of forcing onto the mode)
x
(Persistence timescale of the mode)

AMs are persistent and large scale, so we often see a strong AM response.

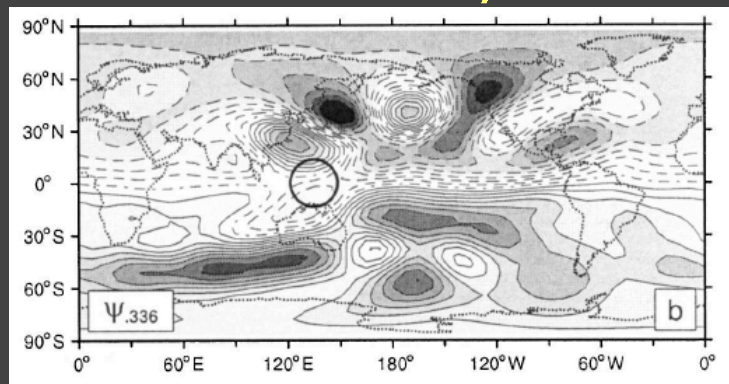
The response is a product of uncertain terms, so predictions are even more uncertain.

Circulation Response to Tropical Heating

4,000,000 day (!) AGCM run



Reconstruction by FDT



Gritsun & Branstator 2007

Stratospheric Influence on the AM Responses

- FDT helps us understand why AM responses are so common and so uncertain.
- This is one reason why extratropical climate prediction will always be hard.
- But there has been recent progress on pinning down what controls the AM response, and what the role of the stratosphere is.

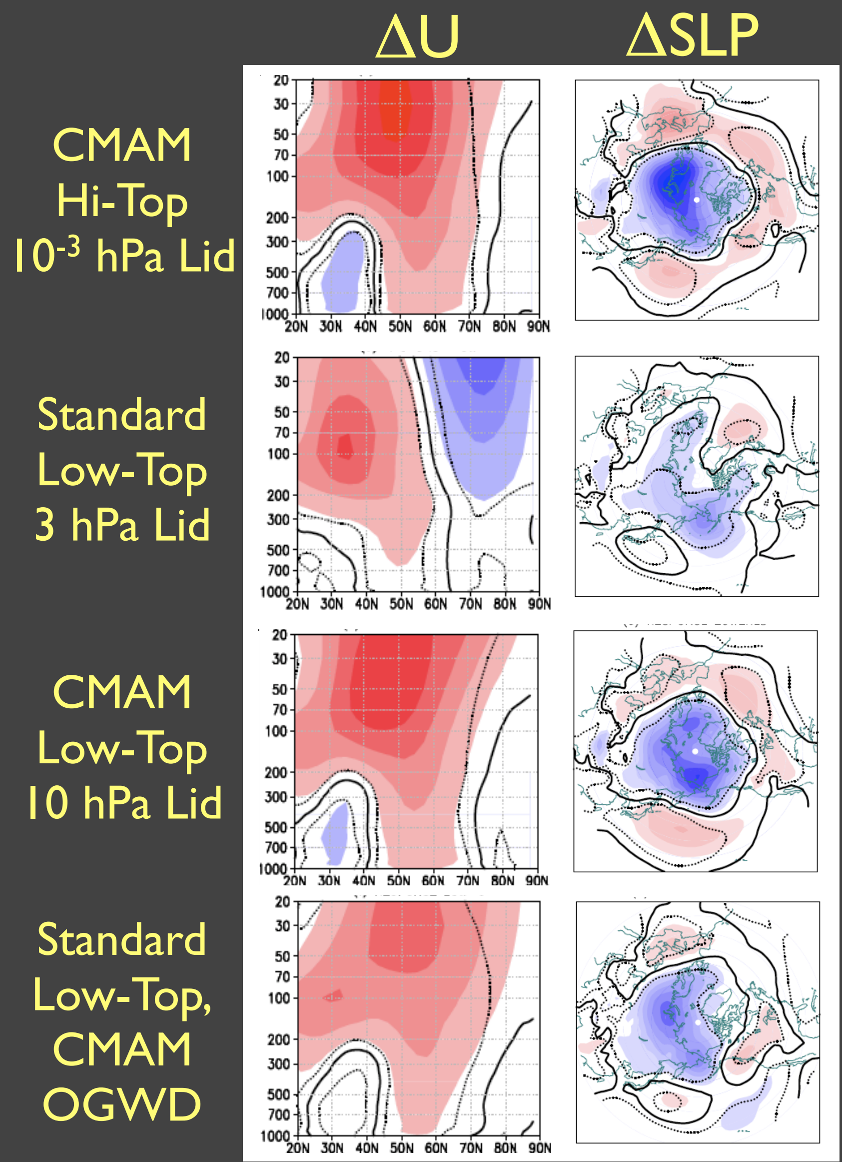
Bottom-Up Control of the AM Response

The Hi-Top Canadian GCM (CMAM) gets a tropospheric NAM response to 2XCO2.

The Low-Top Canadian GCM (Standard) does not.

But a Low-Top version of CMAM also gets the NAM response.

Orographic GWD (OGWD) settings turn out to control the response.



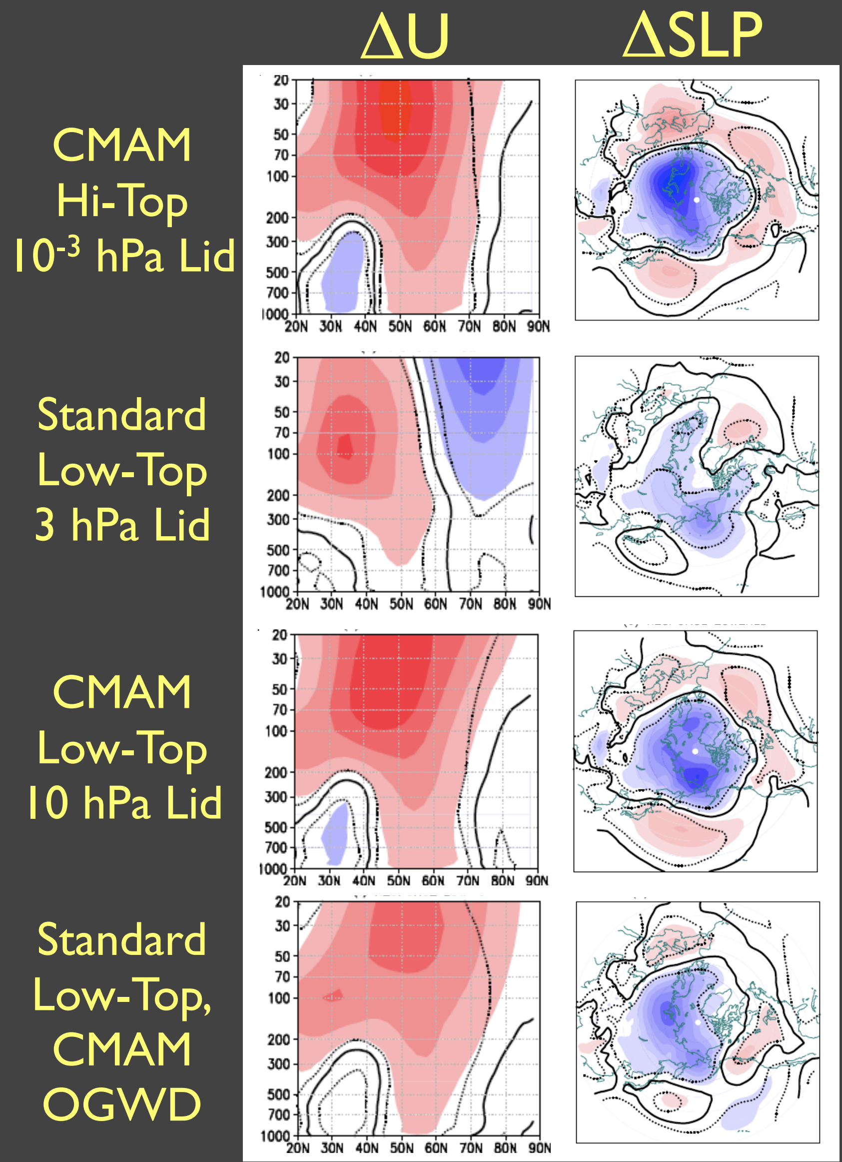
Sigmond et al. 2008

Bottom-Up Control of the AM Response

If the CMAM GWD settings are put in the Standard GCM, it gets a NAM response too.

The OGWD controls lower stratospheric winds; stratospheric *resolution* is secondary here.

See Michael Sigmond's posters AP95 & AP96.



Sigmond et al. 2008

Top-Down Control of the AM Response

Hi- and Low-Top CMAM get similar tropospheric SAM+ responses to Antarctic Stratospheric Cooling.

But non-orographic GWD can control the response.

When the GW flux is allowed to escape to space for the Low-Top CMAM, the SAM response is reduced.

The flux-to-space boundary condition is not momentum conserving; again, vertical resolution is secondary.

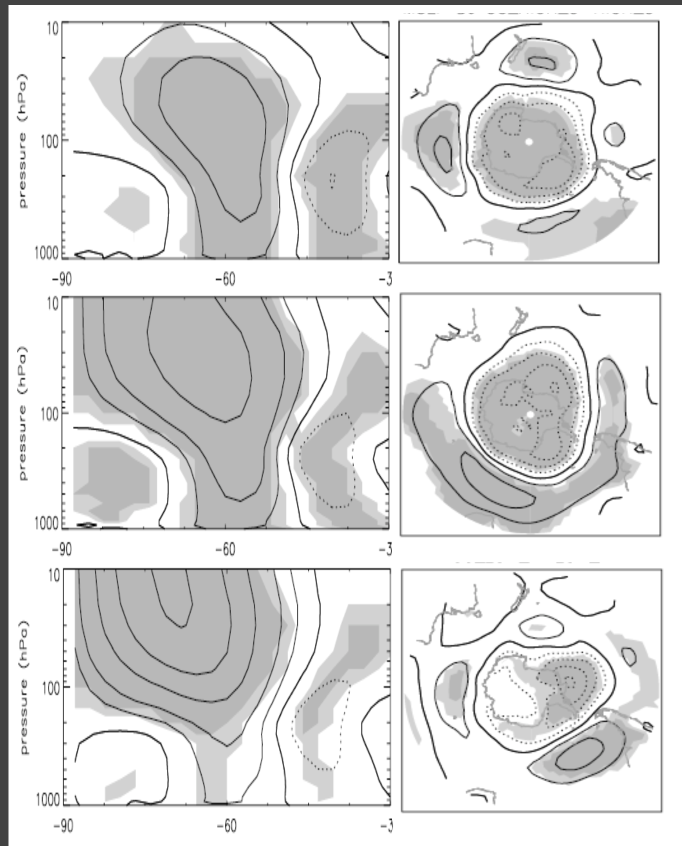
See Tiffany Shaw's poster AP93.

ΔU ΔSLP

CMAM Hi-Top

CMAM Low-Top

CMAM Low-Top; Flux GWs to Space!



Shaw et al. 2008

Stratospheric Control of the Response to Surface Forcing

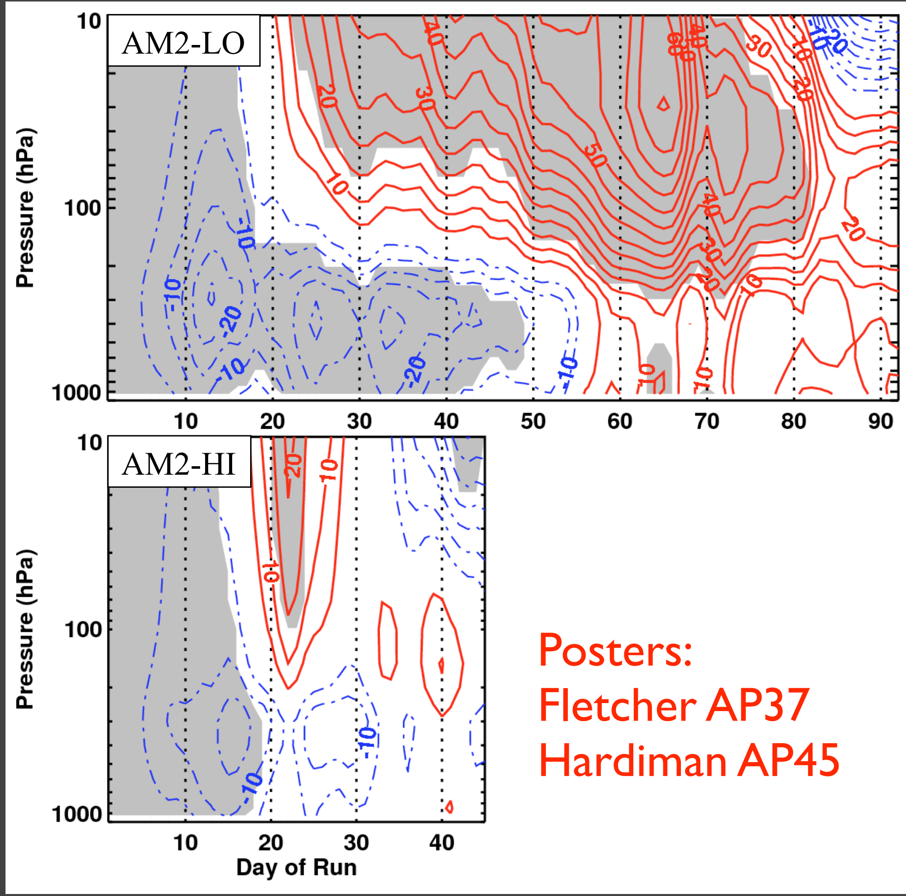
We switch on Eurasian snow forcing to excite transient stratosphere-troposphere NAM events.

The low-top GFDL GCM (AM2-LO) response is vertically coupled and long lived, especially if the polar vortex is relatively weak.

The high-top GCM (AM2-HI) response is vertically uncoupled and brief.

Lower stratospheric winds and decorrelation timescales control the difference; these are less realistic in AM2-HI.

NAM Response to October Snow Forcing



Posters:
Fletcher AP37
Hardiman AP45

Fletcher et al. 2007, 2008
Hardiman et al. 2008

Tuning AM Responses in a Simple GCM

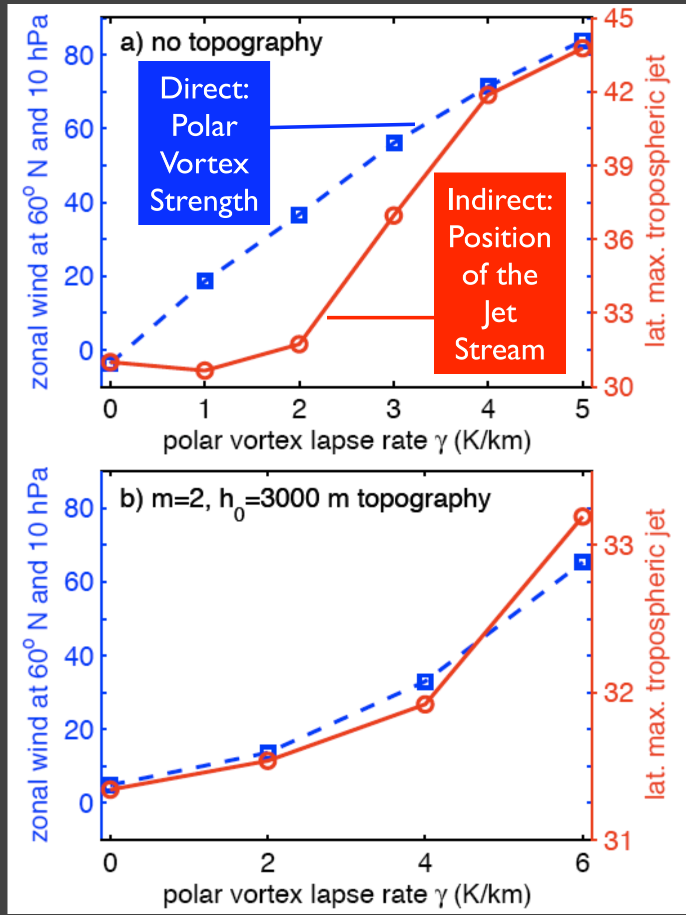
Gerber & Polvani look at the effect of topography on the response to stratospheric cooling in a simple GCM.

Introducing reasonable topography reduces the tropospheric AM response by a factor of 6.

Multiple-jet states in the troposphere and the tropospheric AM timescale control the sensitivity (FDT).

See Cegeon Chan poster AP13.

Polar Vortex Strength and Tropospheric Jet Position



Gerber and Polvani 2008

Conclusion

The stratosphere influences AM responses in many ways via the mean climate state and GWD parameterizations.

To understand this influence, it is useful to:

- Use the direct/indirect decomposition to isolate the "forcing" from the AM part of the response.
- Carry out careful Low-Top/Hi-Top GCM comparisons (SPARC DynVar Project).
- Force the models in novel ways.
- Use simplified GCMs, FDT and other theory.

Thanks to . . .

Natural Science and Engineering Research Council of Canada (NSERC).

Canadian Foundation for Climate and Atmospheric Science (CFCAS).

The Conference Organizers, for the invitation.

You, for your attention!

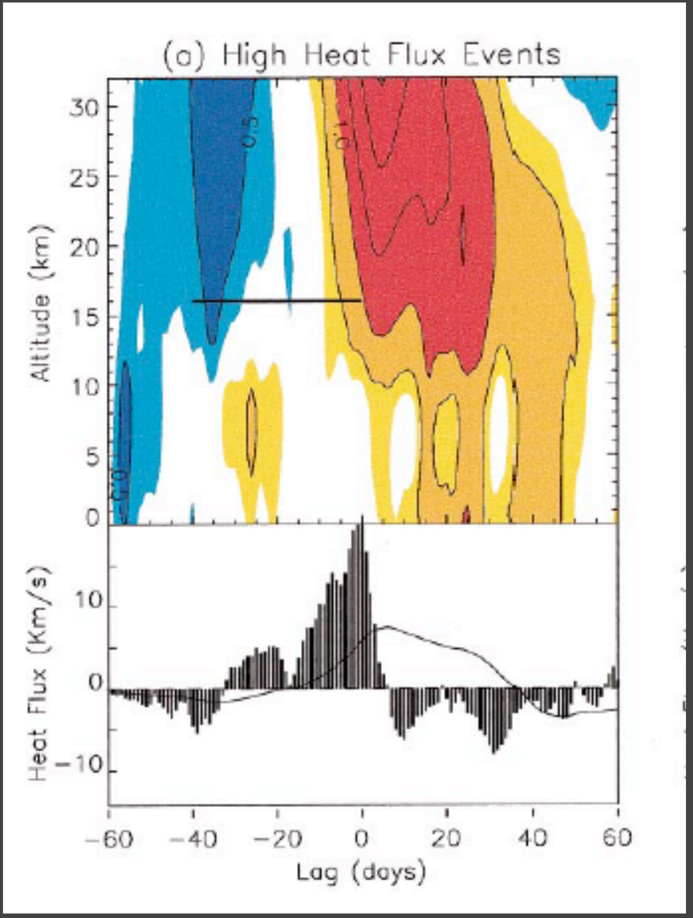
Stratosphere-Troposphere AM Signatures

The climatological AM structure reflects a fast (multiple week) process:

AM signals propagate downwards from the stratosphere to the troposphere (Baldwin and Dunkerton).

Planetary wave driving events get things going.

Time Lag Regressions of NAM and EP Flux



Polvani and Waugh 2004

Stratosphere-Troposphere AM Signatures

Some wave driving events occur spontaneously

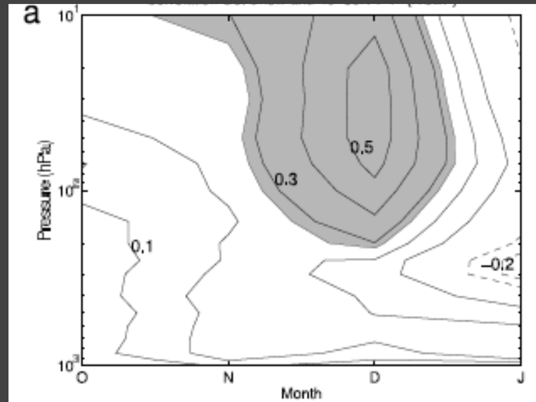
✳ E.g., stratospheric vacillations of Holton-Mass model.

Other wave driving events are externally forced.

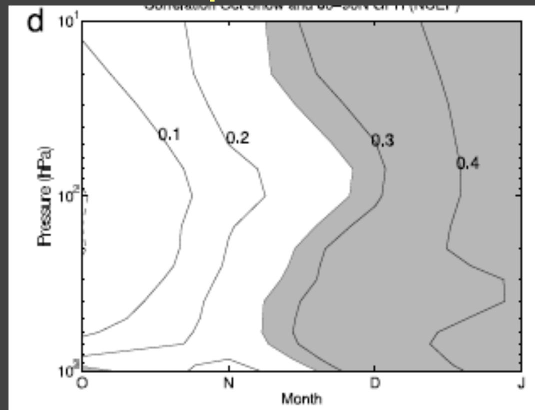
✳ E.g., variations in snow-extent over Eurasia in October can stimulate coupled stratosphere-troposphere NAM events.

October Eurasian Snow Correlated with . . .

. . .Vertical EP Flux



. . . Simple NAM Index



Hardiman et al. 2008

Fluctuation Dissipation Theory (FDT)

Leith, Palmer, Ring & Plumb, Gritsun & Branstator . . .

Climate responses project onto internal modes.

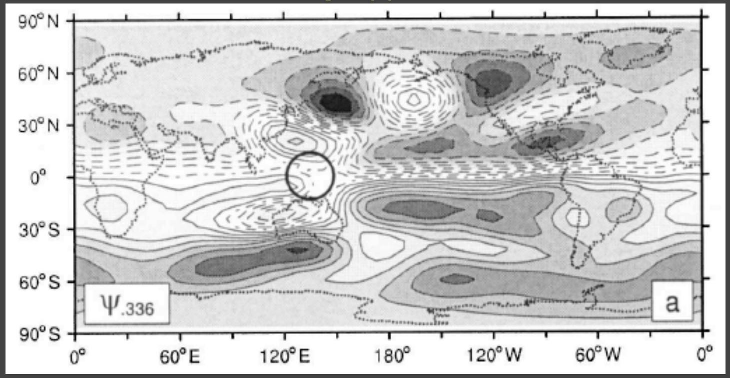
Look to the internal variability of the climate system to predict the response to climate forcings.

The empirical direct/indirect decomposition is consistent with FDT.

FDT is technically difficult, but appears to work accurately.

Circulation Response to Tropical Heating

4,000,000 day (!) AGCM run



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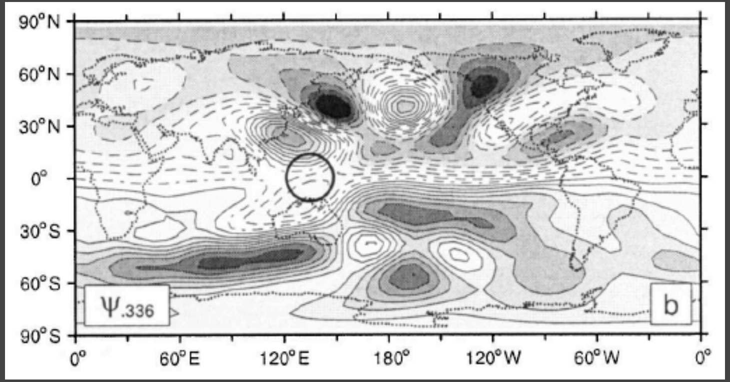

Gritsun & Branstator 2007