Evaluation of Troposphere-Stratosphere Interactions in the CFS

Judith Perlwitz
Cooperative Institute for Research in Environmental Sciences, University of Colorado and NOAA Earth System Research Laboratory, Physical Sciences Division

Preamble

- First-year status report on CTB proposal “CFS Stratosphere Improvement”
- Joint project between NOAA/ESRL/PSD (Judith Perlwitz, Tao Zhang), NOAA/NCEP/EMC (Jordan Alpert) and NOAA/NCEP/CPC (Craig Long, Shuntai Zhou, Amy Butler)
- Thanks to Tiffany Shaw for calculating the wave geometries for CFS

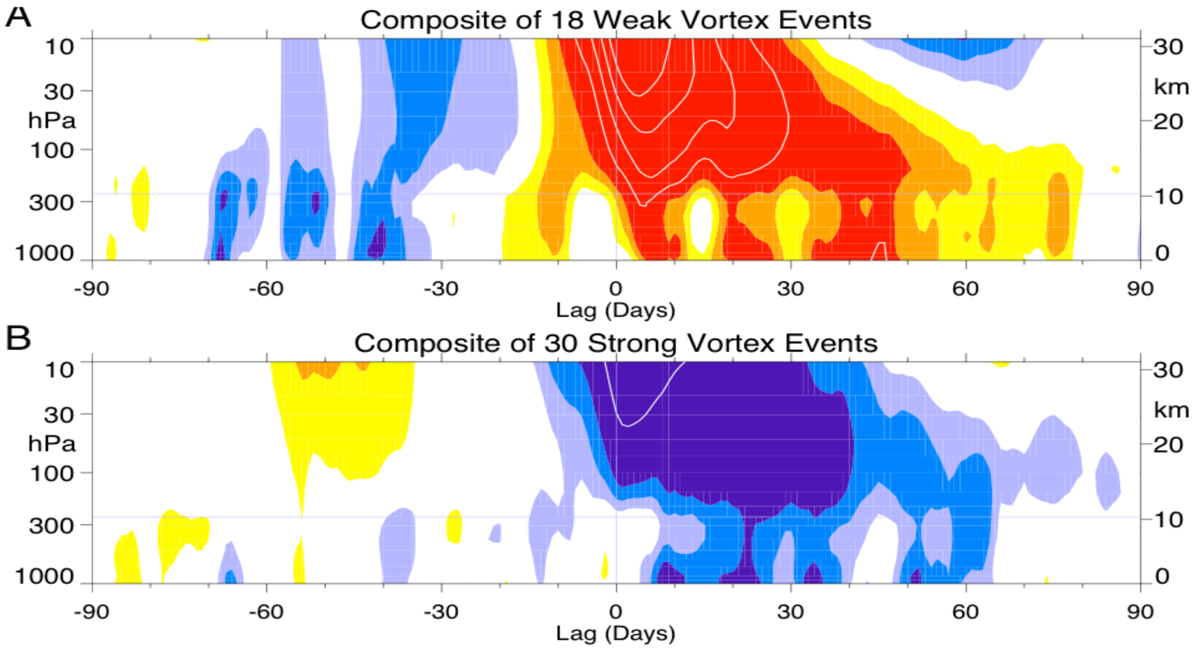
Outline

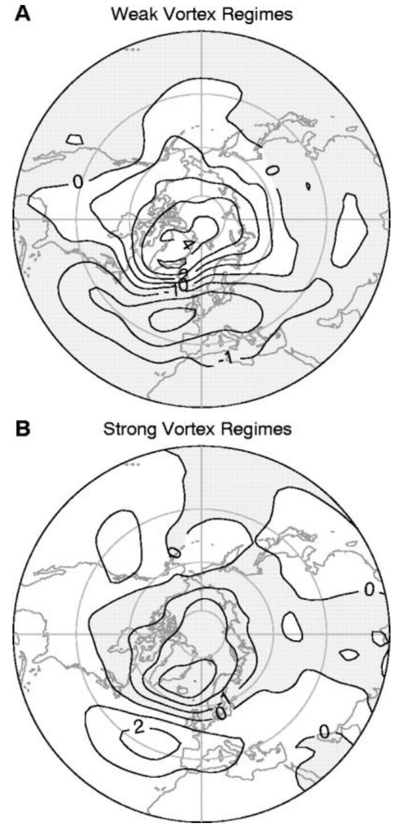
- Introduction
  - NAS Assessment of intraseasonal to interannual (ISI) climate prediction and predictability
  - Troposphere-Stratosphere coupling
- First year accomplishments
  - Evaluation of troposphere-stratosphere coupling in atmospheric component of CFS (GFS_{CFS})
  - Sensitivity to orographic gravity wave drag parameterization
- Summary
- Next steps

NAS Assessment of intraseasonal to interannual (ISI) climate prediction and predictability

- ***Operational ISI prediction models should be improved to represent stratosphere- troposphere interactions.***
  - *Relatively long-lived (up to two months) atmospheric anomalies can arise from stratospheric disturbances*.
  - In sensitive areas such as Europe in winter, experiments suggest that the influence of stratospheric variability on land surface temperatures can exceed the local effect of sea surface temperature.
  - Additionally, while our weather and climate models do not often resolve or represent the stratospheric Quasi-Biennial Oscillation very well, it is one of the more predictable features in the atmosphere, and it has been found to exhibit a signature in ISI surface climate.

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



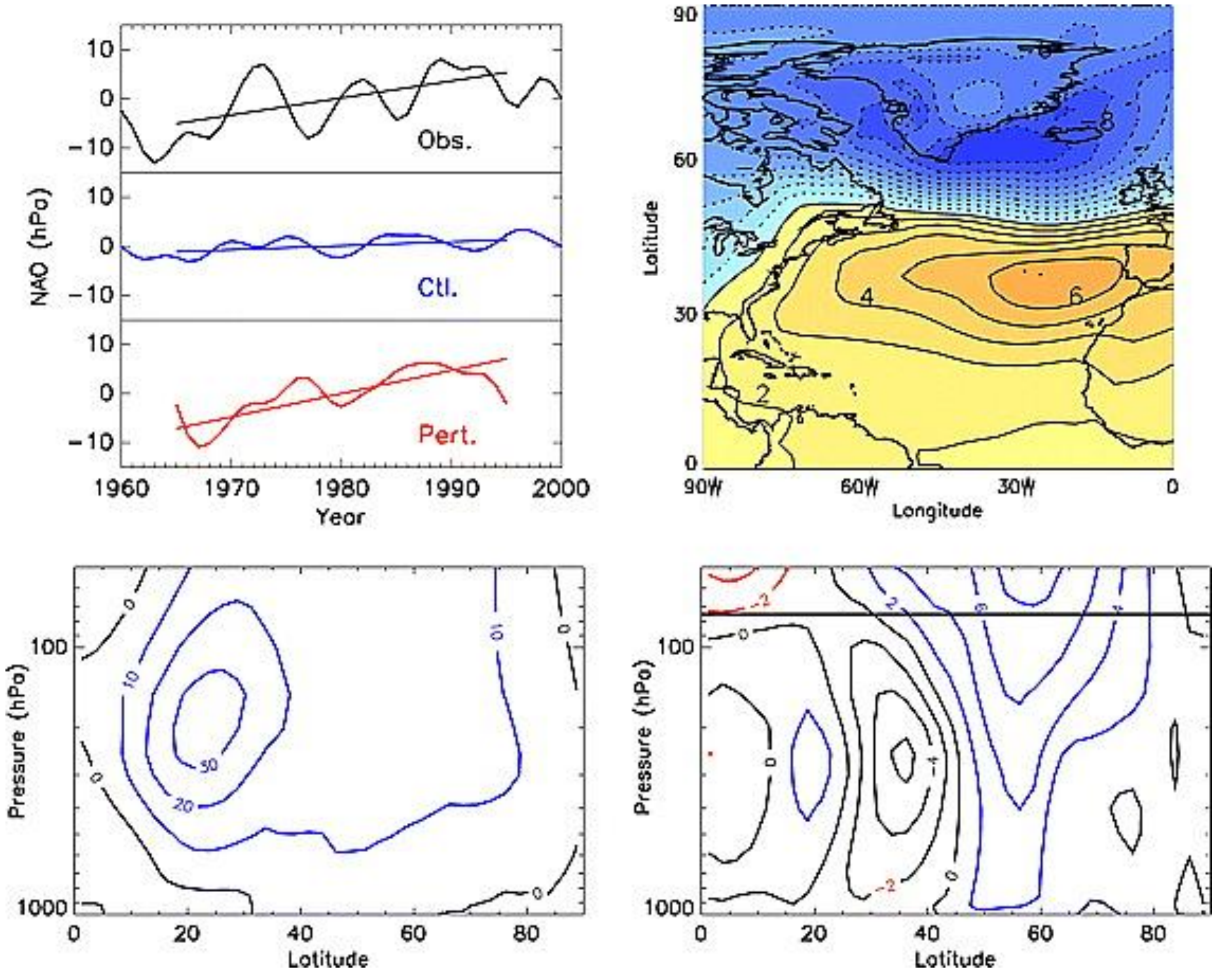


- Extreme events in the stratosphere are followed by anomalous pattern at the surface that resemble the NAM
- Extreme stratospheric events may provide forecast potential for weak 3 to 4

NAS Assessment of intraseasonal to interannual (ISI) climate prediction and predictability

- ***Operational ISI prediction models should be improved to represent stratosphere- troposphere interactions.***
  - *Relatively long-lived (up to two months) atmospheric anomalies can arise from stratospheric disturbances.*
  - ***In sensitive areas such as Europe in winter, experiments suggest that the influence of stratospheric variability on land surface temperatures can exceed the local effect of sea surface temperature.***
  - *Additionally, while our weather and climate models do not often resolve or represent the stratospheric Quasi-Biennial Oscillation very well, it is one of the more predictable features in the atmosphere, and it has been found to exhibit a signature in ISI surface climate.*

Stratospheric Circulation Changes and NAO trends (Scaife et al. 2005)



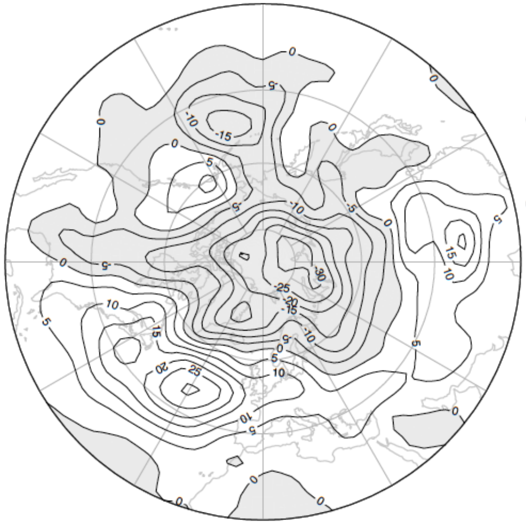
- Magnitude of NAO trends can only be simulated when prescribing observed variations in stratospheric circulation

NAS Assessment of intraseasonal to interannual (ISI) climate prediction and predictability

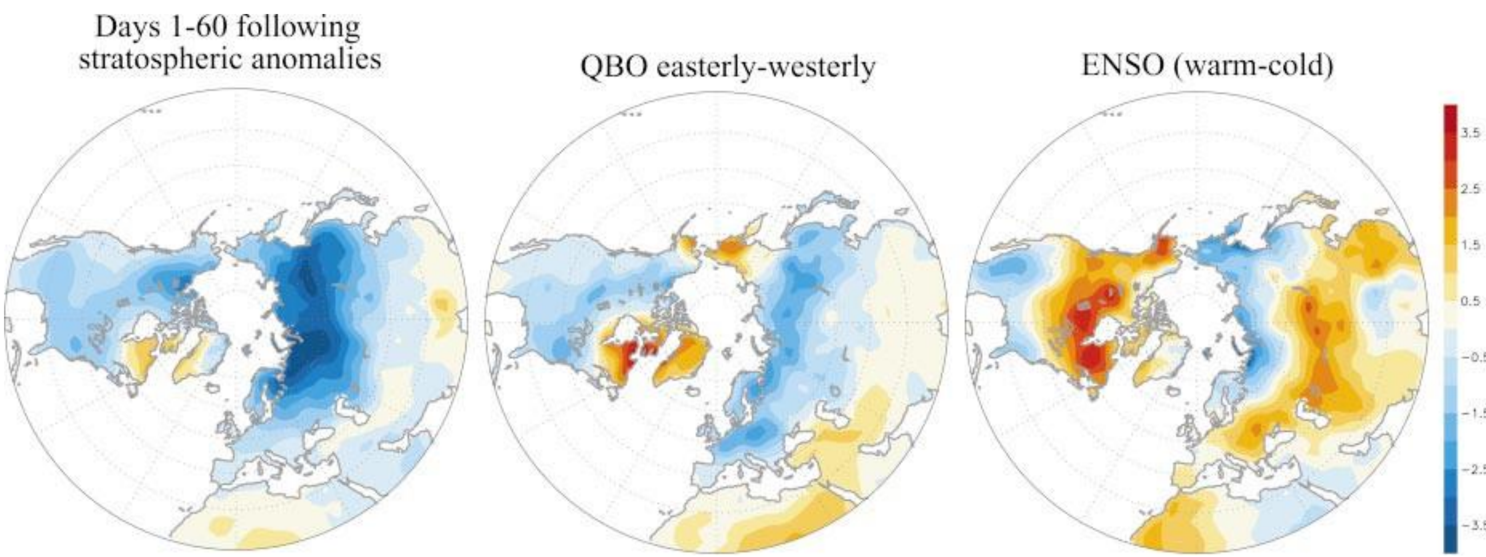
- ***Operational ISI prediction models should be improved to represent stratosphere- troposphere interactions.***
  - *Relatively long-lived (up to two months) atmospheric anomalies can arise from stratospheric disturbances.*
  - *In sensitive areas such as Europe in winter, experiments suggest that the influence of stratospheric variability on land surface temperatures can exceed the local effect of sea surface temperature.*
  - ***Additionally, while our weather and climate models do not often resolve or represent the stratospheric Quasi-Biennial Oscillation very well, it is one of the more predictable features in the atmosphere, and it has been found to exhibit a signature in ISI surface climate.***

QBO Signal in the troposphere

Baldwin et al. 2001,
Thompson et al. 2002



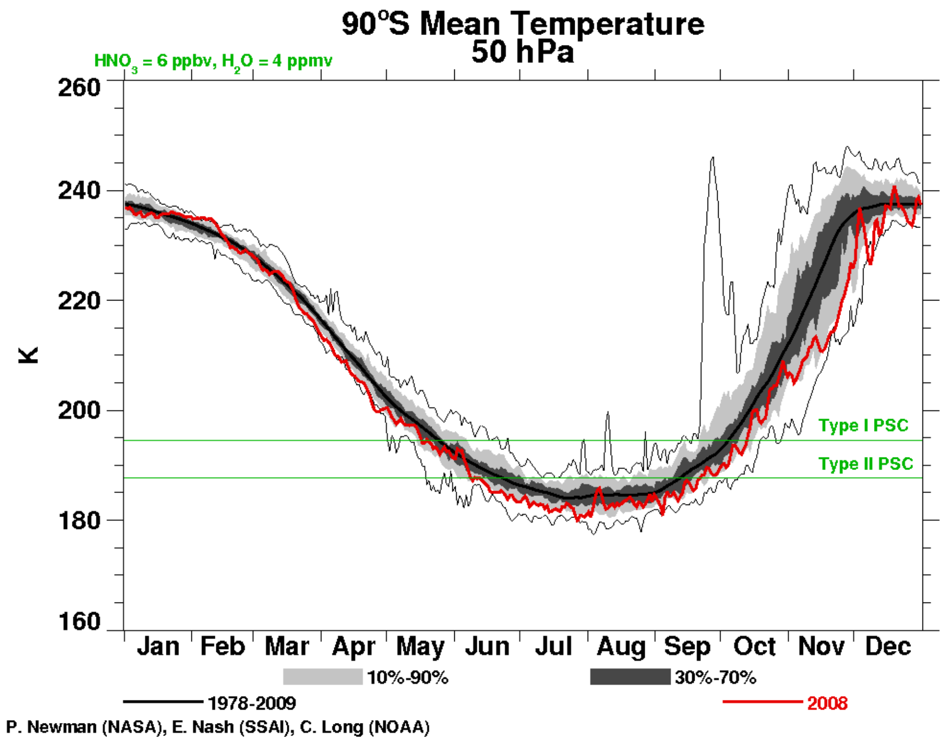
W-E QBO Composite of 1964-96 1000-hPa Z

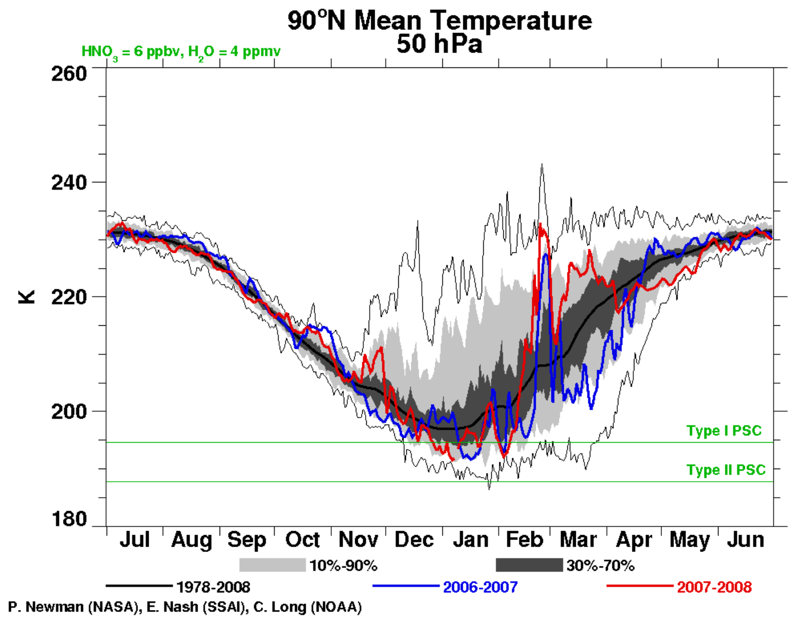


Role of the Stratosphere in the Climate System

- **Troposphere and stratosphere are closely coupled with impact of the troposphere on the stratosphere dominating.**
- Stratosphere provides an important pathway by which tropospheric circulation anomalies can be modified.
- Impact of stratosphere on the troposphere via changes in the stratospheric basic state (due to ozone depletion, volcanic aerosols)
- Degrading the representation of stratospheric processes in GCMs has important implication for modeling the tropospheric climate state, its variability and its sensitivity to external forcing.

Seasonal Cycle of 50hPa Polar Temperatures





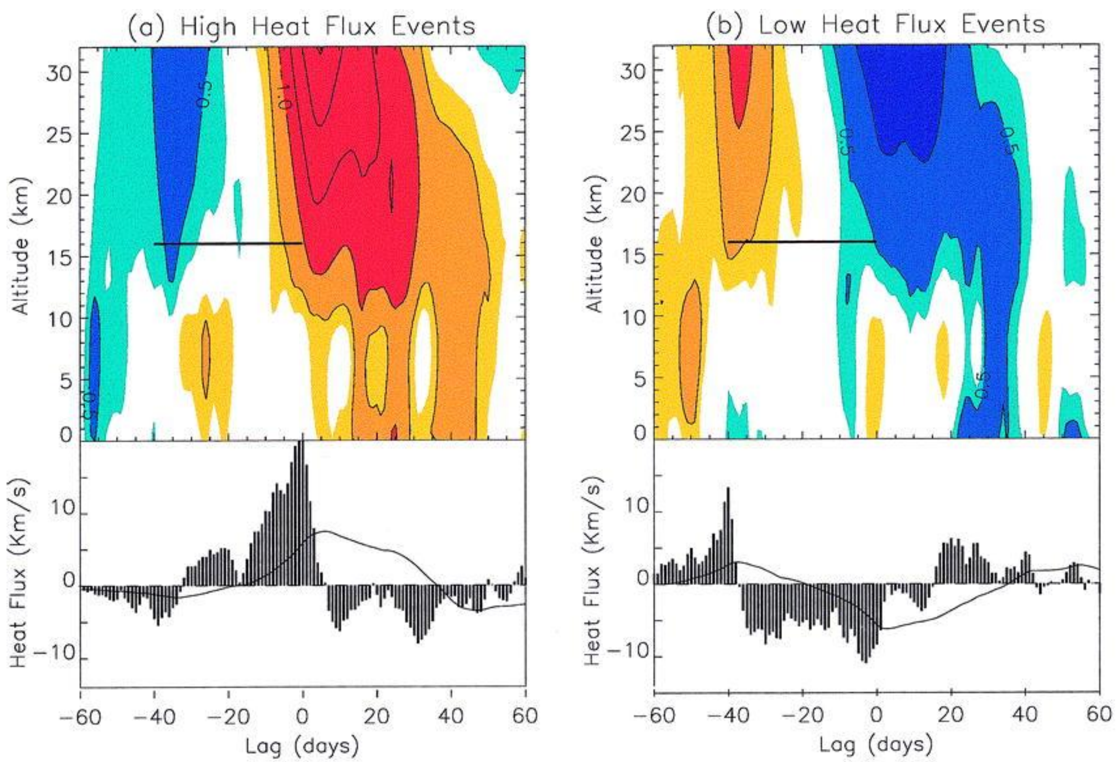
- Large differences between Northern and Southern Hemisphere stratospheric climatologies due to differences in strength of tropospheric wave forcing

Role of Stratosphere in the Climate System

- Troposphere and stratosphere are closely coupled with impact of the troposphere on the stratosphere dominating.
- **Stratosphere provides an important pathway by which tropospheric circulation anomalies can be modified.**
- Impact of stratosphere on the troposphere via changes in the stratospheric basic state (due to ozone depletion, volcanic aerosols).
- Degrading the representation of stratospheric processes in GCMs has important implication for modeling the tropospheric climate state, its variability and its sensitivity to external forcing.

Downward Zonal Mean Coupling

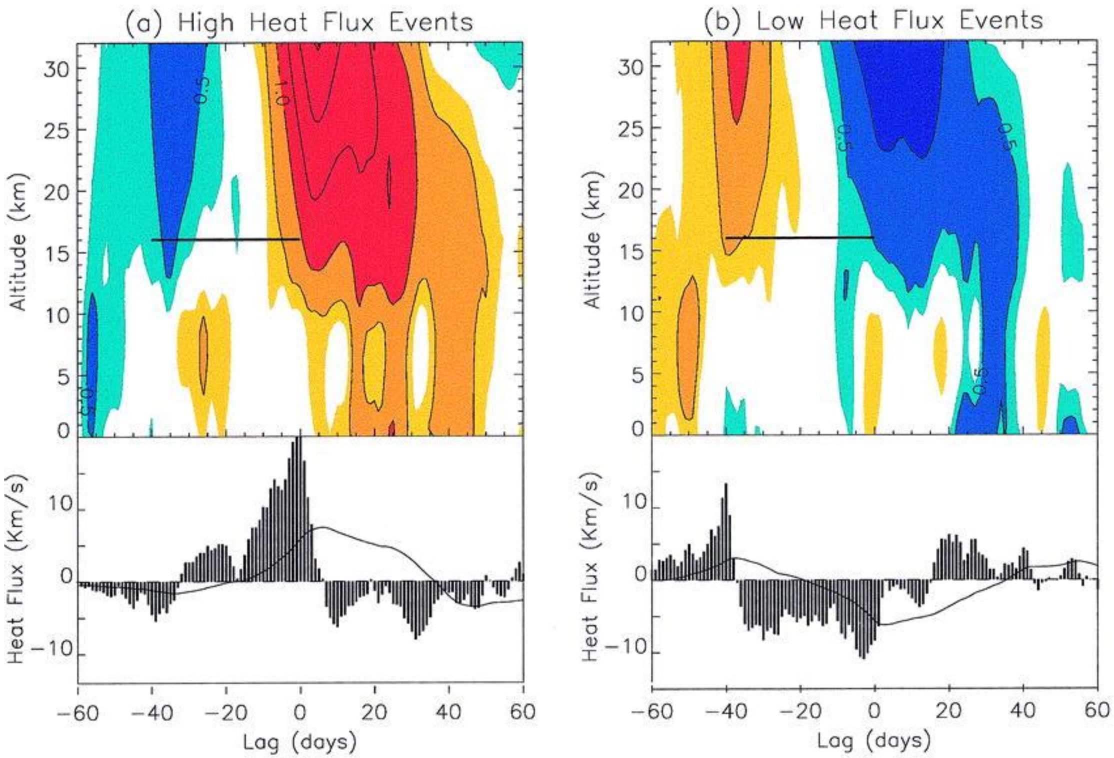
- •Dissipation of wave activity in the stratosphere
- •Westward acceleration of the stratospheric flow
- •Downward progression of westward zonal mean anomalies
- •Lack of wave activity relates to downward progression of eastward zonal wind anomalies



Downward progression of NAM anomalies is determined by upward flux of wave activity (Polvani and Waugh, 2004)

Downward Zonal Mean Coupling

- Dissipation of wave activity in the stratosphere
- Westward acceleration of the stratospheric flow
- Downward progression of westward zonal mean anomalies
- Lack of wave activity relates to downward progression of eastward zonal wind anomalies



Downward progression of NAM anomalies is determined by upward flux of wave activity (Polvani and Waugh, 2004)

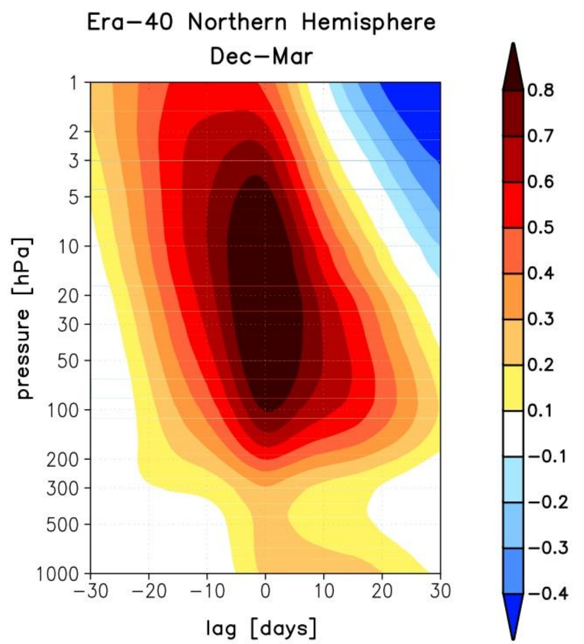


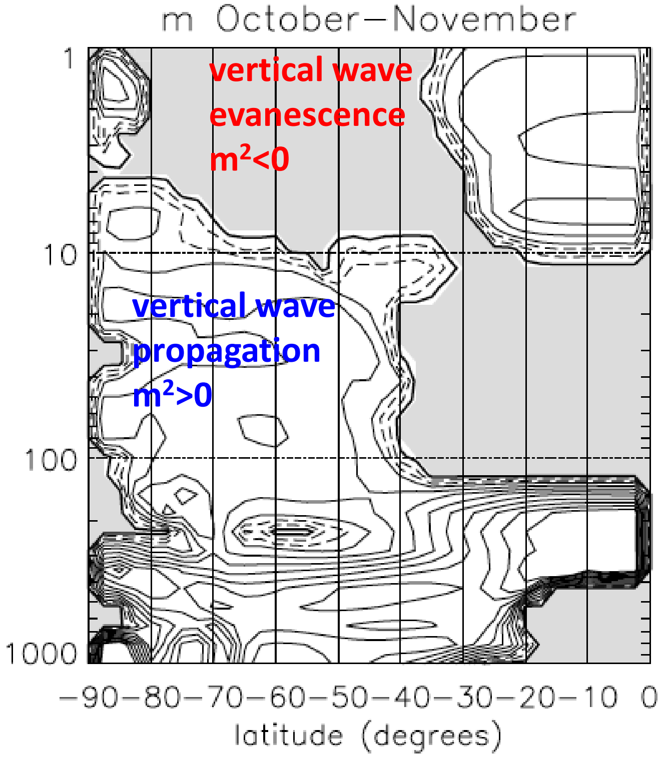
Illustration of downward zonal mean coupling based on correlations of NAM index at 20 hPa with NAM index from 1000 to 1 hPa
(Perlwitz and Harnik, 2003)

Downward Wave Coupling

- Wave activity that propagates into the stratosphere can approach a vertical reflective surface
- Wave activity then gets reflected back into the troposphere where it modifies the tropospheric flow
- Downward wave coupling only occurs when there is a bounded wave geometry of the basic state
- Process can be illustrated using wave geometry diagnostic (Harnik and Lindzen, 2001) and cross spectral correlation analysis (Randel, 1987)

Downward Wave Coupling

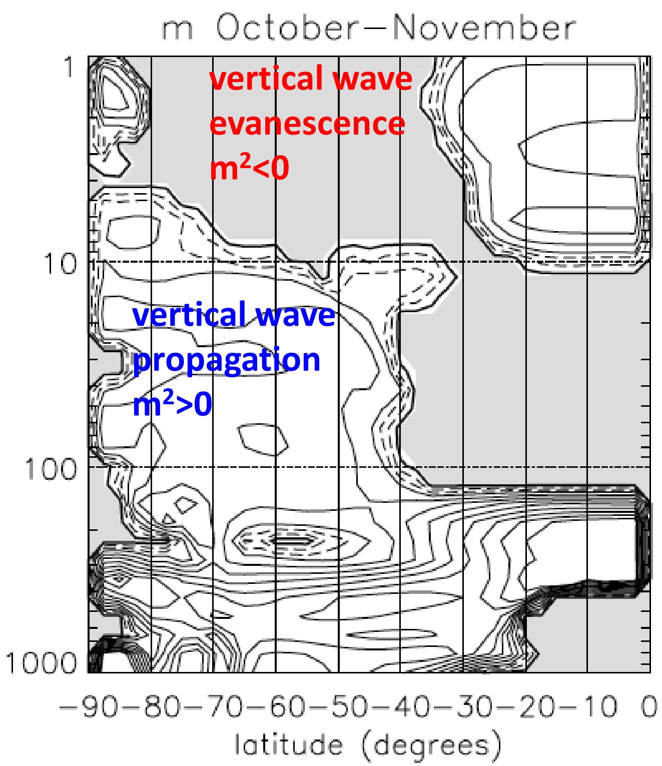
- Wave activity that propagates into the stratosphere can approach a vertical reflective surface
- Wave activity then gets reflected back into the troposphere where it modifies the tropospheric flow
- Downward wave coupling only occurs when there is a bounded wave geometry of the basic state
- Process can be illustrated using wave geometry diagnostic (Harnik and Lindzen, 2001) and cross spectral correlation analysis (Randel, 1987)

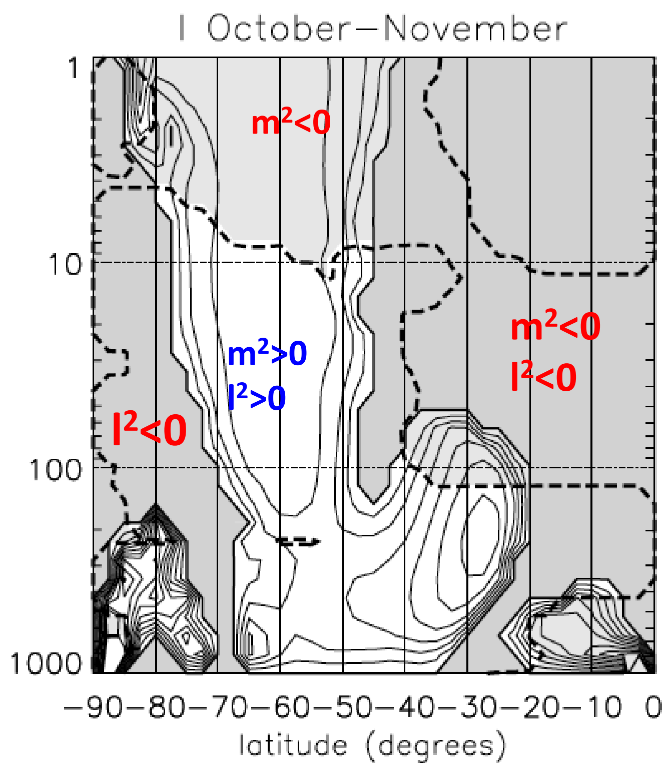


Wave geometry diagnostic separates index of refraction into vertical (m) and meridional (l) wave number. Shown is wave geometry for stationary wave 1 (c=0).

Downward Wave Coupling

- Wave activity that propagates into the stratosphere can approach a vertical reflective surface
- Wave activity then gets reflected back into the troposphere where it modifies the tropospheric flow
- Downward wave coupling only occurs when there is a bounded wave geometry of the basic state
- Process can be illustrated using wave geometry diagnostic (Harnik and Lindzen, 2001) and cross spectral correlation analysis (Randel, 1987)

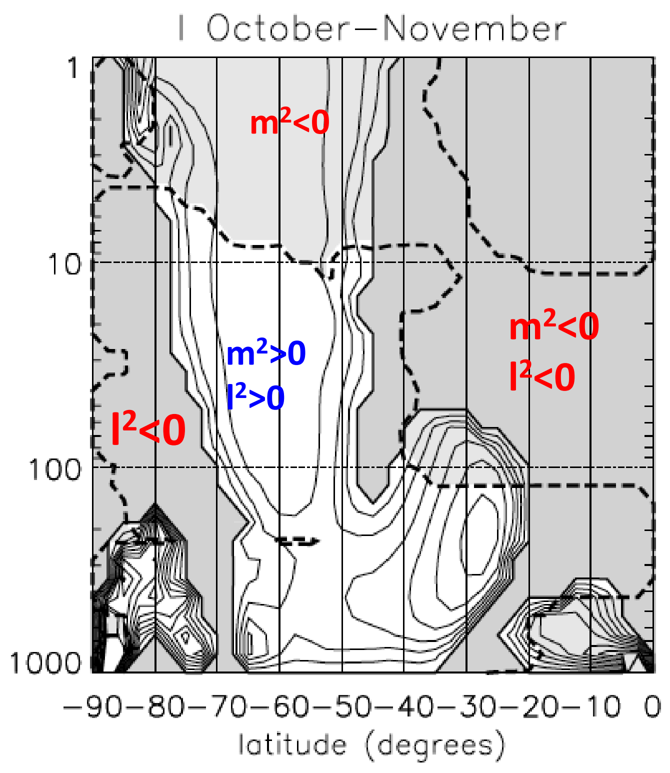




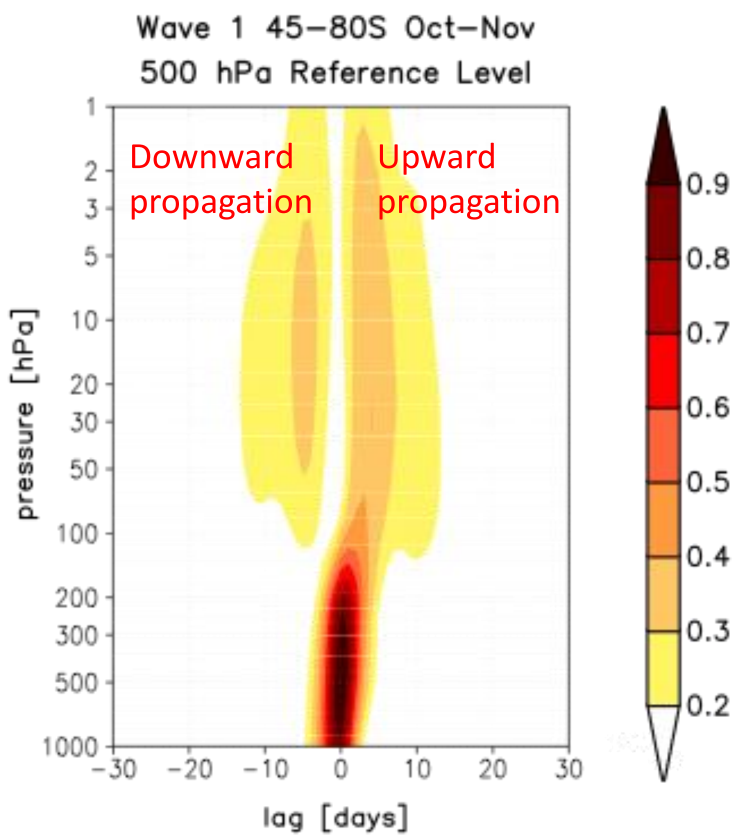
Wave geometry diagnostic separates index of refraction into vertical (m) and meridional (l) wave number. Shown is wave geometry for stationary wave 1 (c=0).

Downward Wave Coupling

- Wave activity that propagates into the stratosphere can approach a vertical reflective surface
- Wave activity then gets reflected back into the troposphere where it modifies the tropospheric flow
- Downward wave coupling only occurs when there is a bounded wave geometry of the basic state
- Process can be illustrated using wave geometry diagnostic (Harnik and Lindzen, 2001) and cross spectral correlation analysis (Randel, 1987)



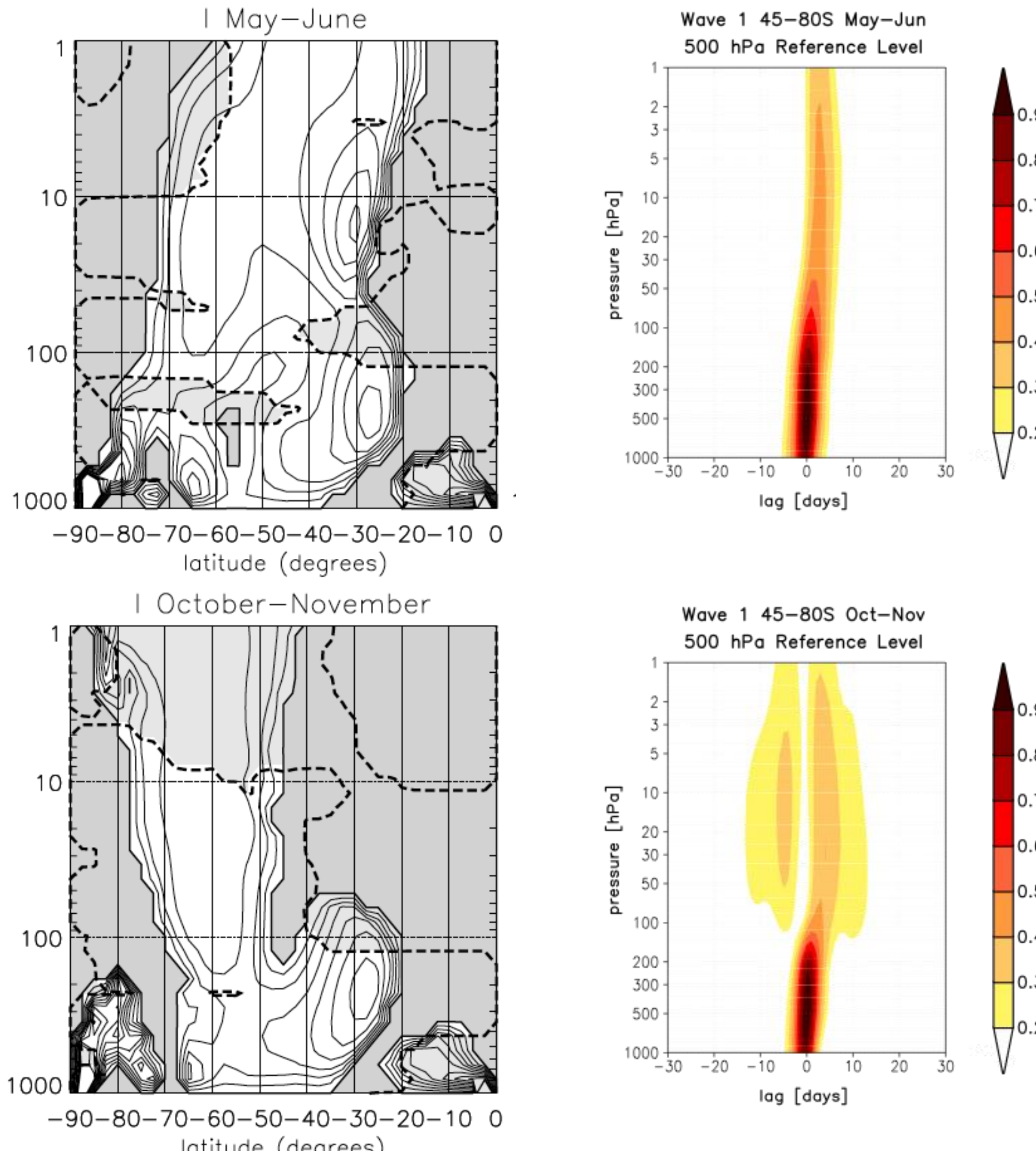
Wave geometry diagnostic for wave 1 (c=0)



Correlation coherence between Z500hPa Fourier coefficients of wave 1 and respective values from 1000 to 1 hPa as a function of time lag

Downward Wave Coupling

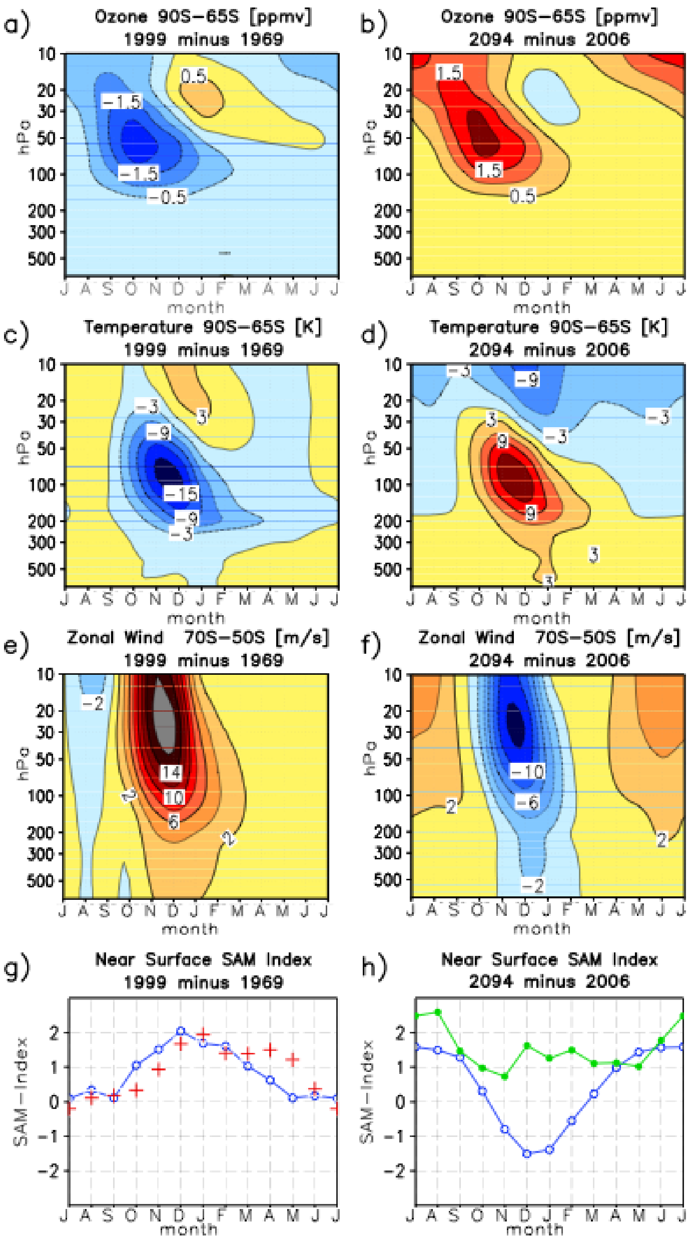
Bounded wave geometry is required for downward wave coupling.



Role of Stratosphere in the Climate System

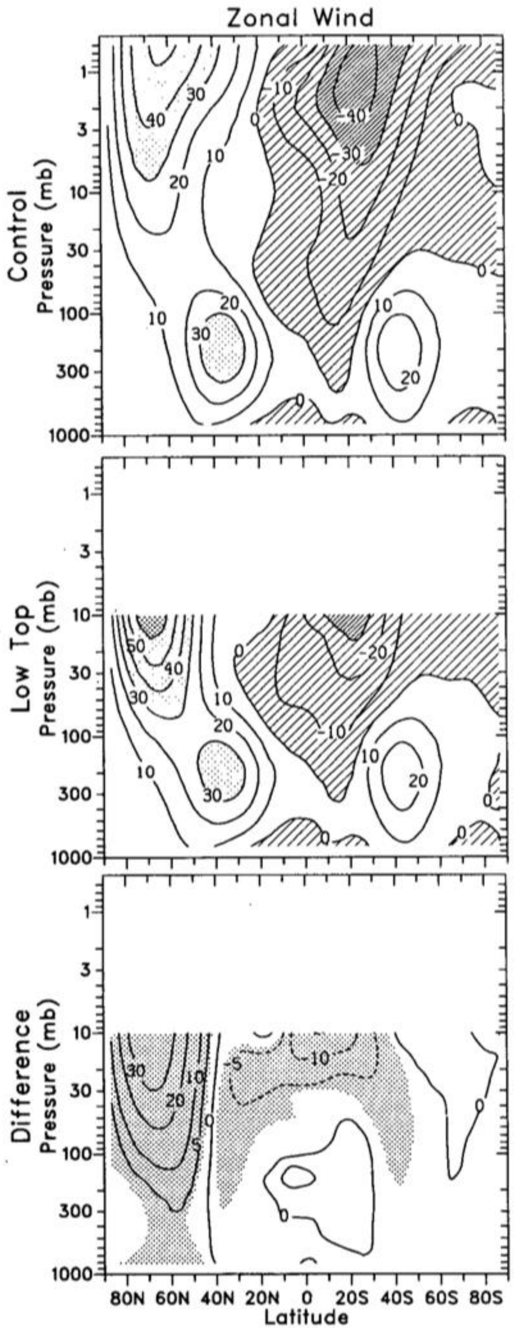
- Troposphere and stratosphere are closely coupled with impact of the troposphere on the stratosphere dominating.
- Stratosphere provides an important pathway by which tropospheric circulation anomalies can be modified.
- **Impact of stratosphere on the troposphere via changes in the stratospheric basic state (due to ozone depletion, volcanic aerosols).**
- Degrading the representation of stratospheric processes in GCMs has important implication for modeling the tropospheric climate state, its variability and its sensitivity to external forcing.

Impact of Stratospheric Ozone Changes (Depletion and Recovery) on Southern Hemisphere Circulation (Perlwitz et al. 2008



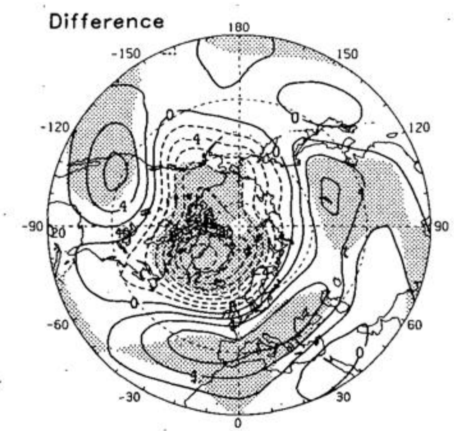
Role of Stratosphere in the Climate System

- Troposphere and stratosphere are closely coupled with impact of the troposphere on the stratosphere dominating.
- Stratosphere provides an important pathway by which tropospheric circulation anomalies can be modified.
- Impact of stratosphere on the troposphere via changes in the stratospheric basic state (due to ozone depletion, volcanic aerosols).
- **Degrading the representation of stratospheric processes in GCMs has important implication for modeling the tropospheric climate state, its variability and its sensitivity to external forcing.**



Impact of Stratosphere Representation in Climate Models on the Simulation of Tropospheric Climate (Boville, 1984, Boville and Cheng, 1988)

Z500



First Year Results

- Problem: CFS version 2 was not available during first year, thus we worked with interims versions of the model.
- Evaluation of troposphere-stratosphere coupling based on AMIP simulation using atmospheric component of CFS (GFS_{CFS})
- Sensitivity experiments with CFS (model used for hurricane forecast)

Some Basic Features of the Atmospheric General Circulation Model

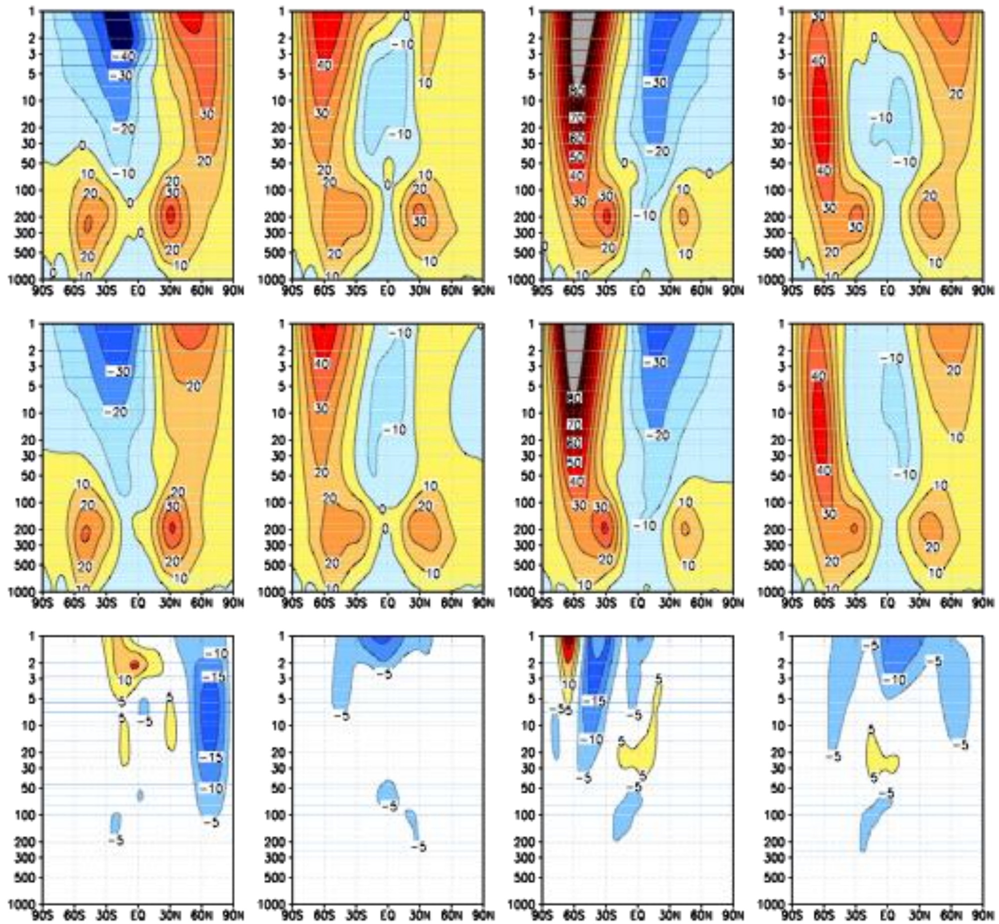
- Resolution T162/L64
- Model Top 0.2 hPa
- Orographic Gravity wave drag parameterization
- There is no non-orographic gravity wave drag parameterization
- Vertical diffusion and Rayleigh friction are applied at the model top for numerical stability

Evaluation of Troposphere-Stratosphere Coupling in GFS_{CFS}

- AMIP simulation (1970-2008) using observed SST and sea ice
- Evaluation based on ERA40 Reanalysis (1979-2002)
- Troposphere-stratosphere coupling in Northern and Southern Hemisphere based on ERA40 is documented in Shaw et al. 2010

Zonal Mean Zonal Wind

DJF MAM JJA SON



ERA40

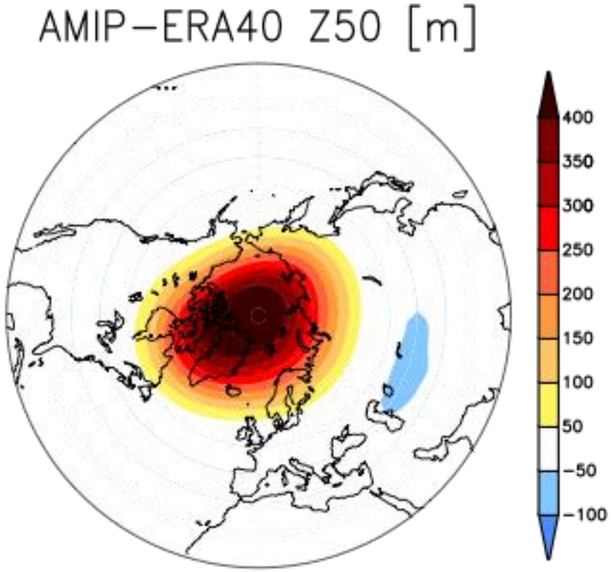
AMIP

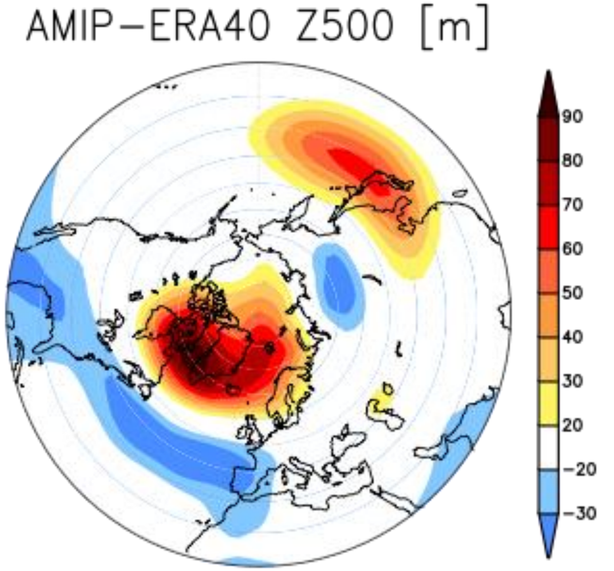
AMIP minus ERA40

The models Northern Hemisphere polar night jet is too weak.
The models Southern Hemisphere polar night jet is shifted poleward.

DJF Height Fields at 50 and 500 hPa levels

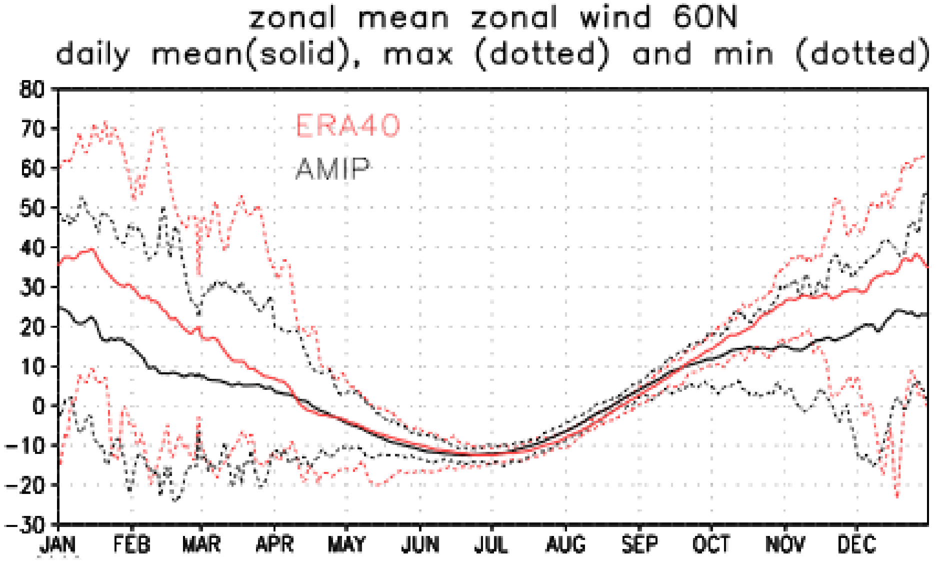
- Stratospheric polar winter vortex is too weak.
- Negative NAO bias in the troposphere





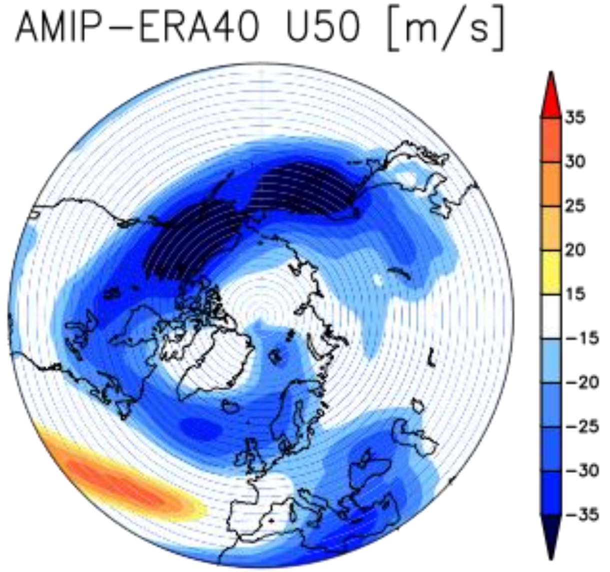
Seasonal cycle of daily zonal mean zonal wind at 60N and 10hPa

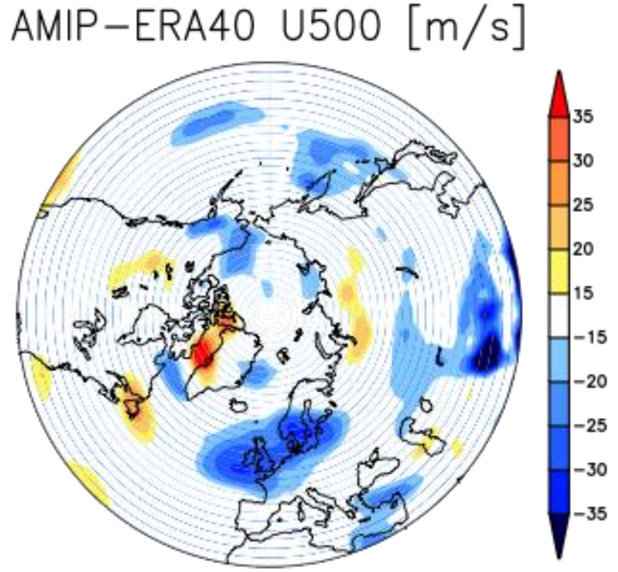
- Model captures stratospheric sudden warmings
- Model lacks occurrence of strong polar night jet.



Monthly Standard Deviation of D,J,F Zonal Wind Fields

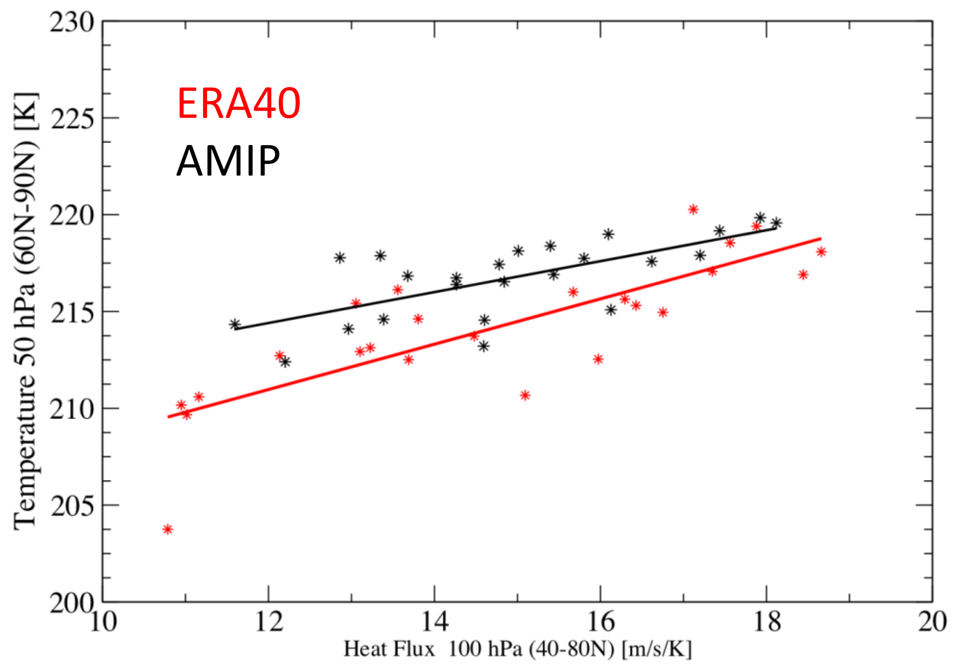
Reduced variability of polar night jet in model also affects variability of tropospheric zonal wind over Europe (lacks zonal strong winds).





Northern Hemisphere Jan/Feb Heat-Flux 100hPa-Feb/Mar 50 hPa Polar Cap Temperature relationship

- Model lacks low heat flux values at 100 hPa and very low polar cap temperatures at 50 hPa
- Slope is larger in ERA40 than in the model
- Results suggest that sensitivity of stratospheric anomalies to tropospheric wave forcing is not correctly represented.



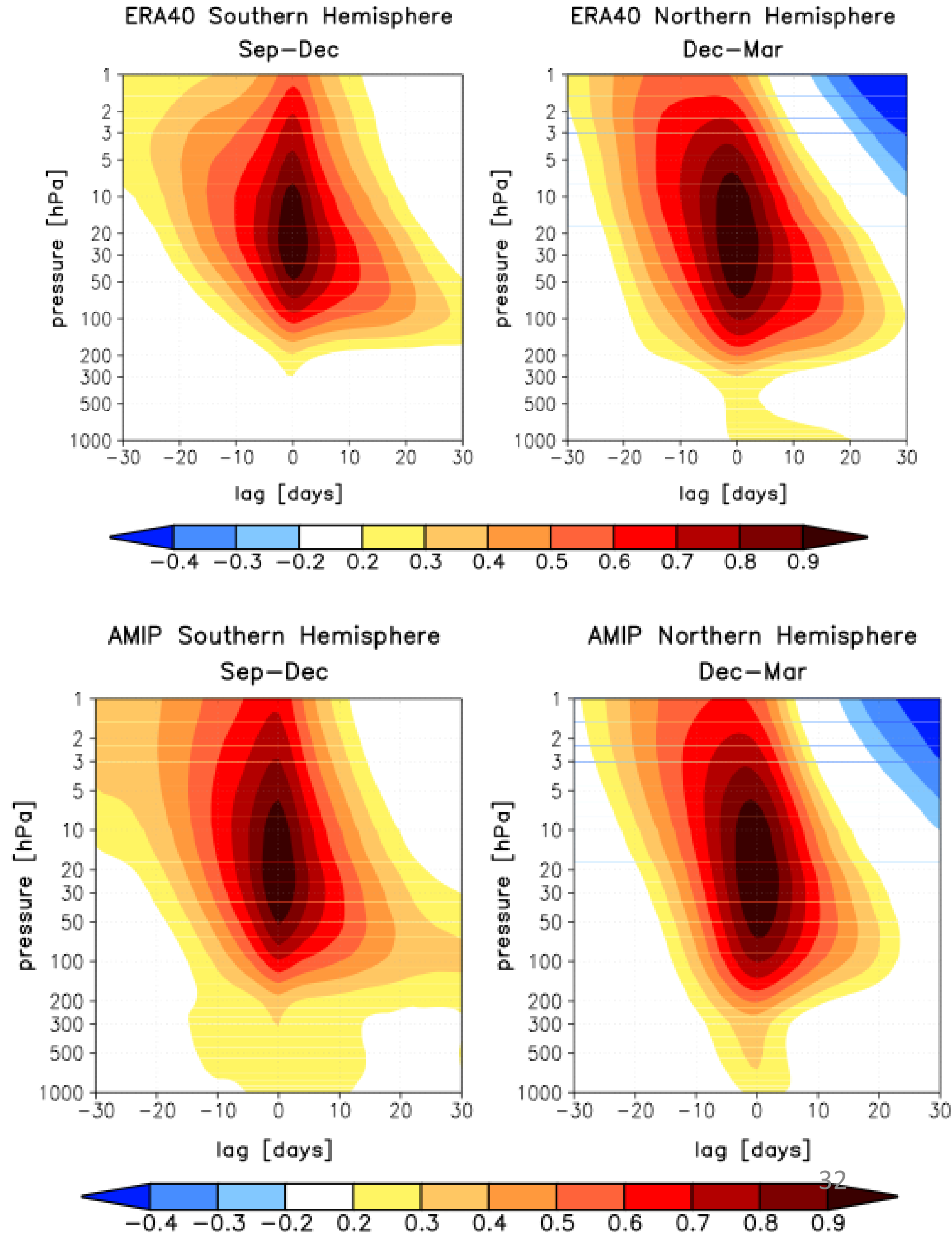
Zonal Mean Downward Coupling

Southern Hemisphere:

- In reanalysis, there is no downward wave coupling on intra-seasonal time scale.
- The model shows significant instantaneous relationship between tropospheric and stratospheric annular mode variability.

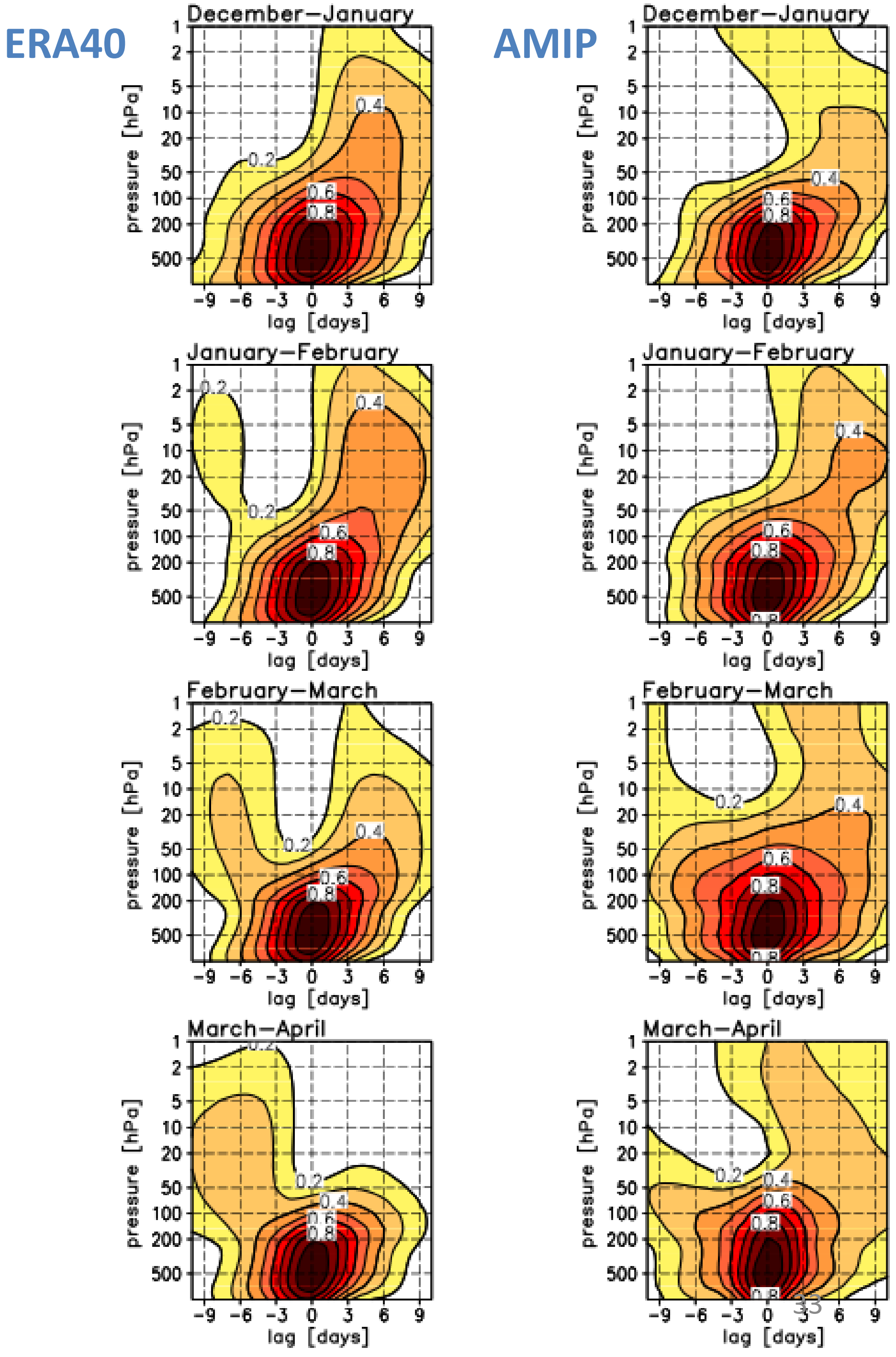
Northern Hemisphere:

- Reanalysis show significant correlations at positive time lags near the surface up to about 20 days .
- The model shows significant correlations only up to about 6 days.



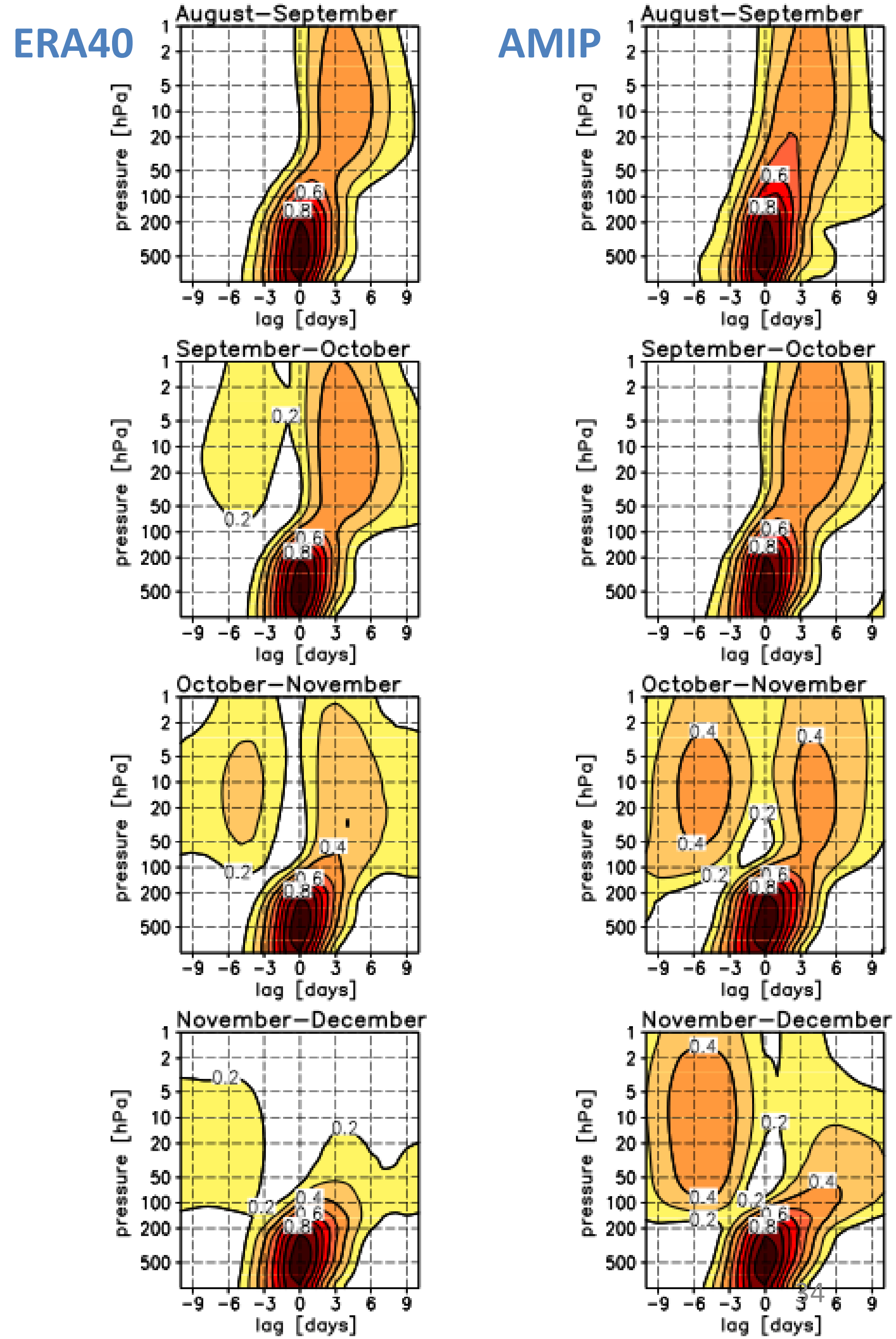
Wave One Propagation in Northern Hemisphere

- In model, upward propagation of wave activity is more disperse, especially in Feb-Mar
- Model does not capture downward wave coupling, most likely due to lack of formation of reflective configuration of stratospheric basic state
- In Mar-April, model shows very different propagation characteristics for planetary wave 1 than reanalysis



Wave One Propagation in Southern Hemisphere

- Model captures downward wave coupling
- Bias in timing of downward wave coupling
- Downward wave coupling starts too late and lasts too long in the season most likely due to a delay in the descent of vertical reflective surface and delay in vortex breakup



CFS Sensitivity Experiments

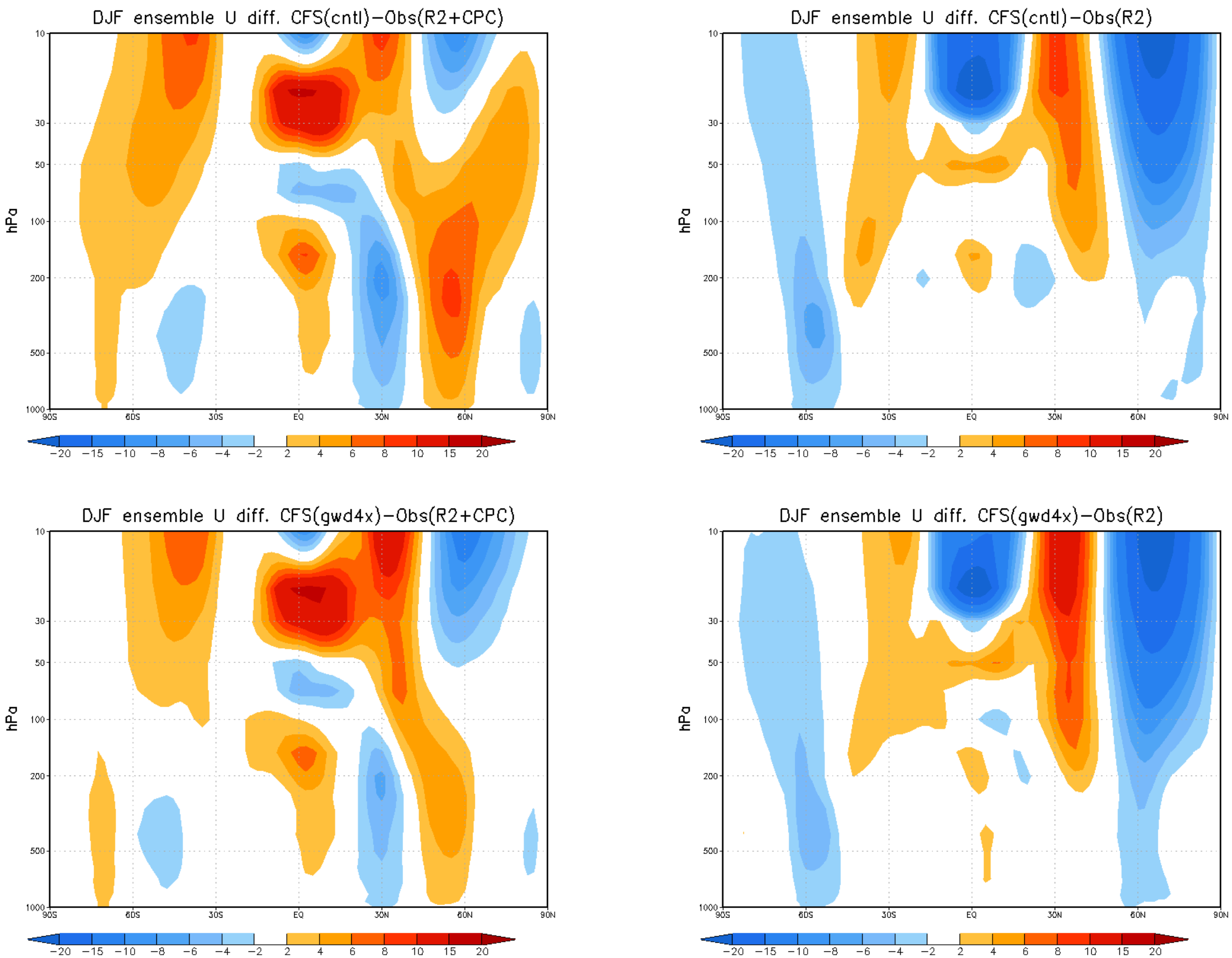
1. Sensitivity to initial conditions
   - ***Results indicate that model biases are not very sensitive to initial conditions.***
2. Sensitivity to orographic wave drag parameterization
   - Six member base line experiments both for 2009/10 (El Nino year) and 2007/08 (La Nina year)
   - Six member experiments for both years with increased orographic gravity wave drag (4x).
   - ***Results indicate that an increased orographic gravity wave drag increases stratospheric biases with mixed results for the troposphere.***

Zonal Mean Zonal Wind (CFS minus NCEP R2)

2009/10 (El Nino) | 2007/08 (La Nina)

Control

OGWDx4



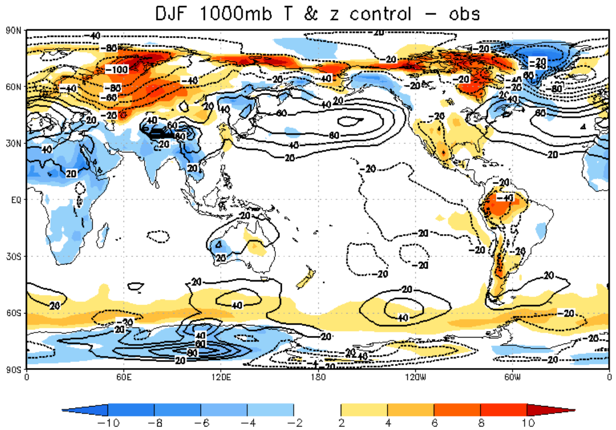
- Biases in tropics result from lack of the model to simulate QBO.
- Control: Enhanced weak polar vortex bias in La Nina case compared to El Nino case.
- Experiment: Stratospheric bias in NH is enhanced due to increased orographic GWD

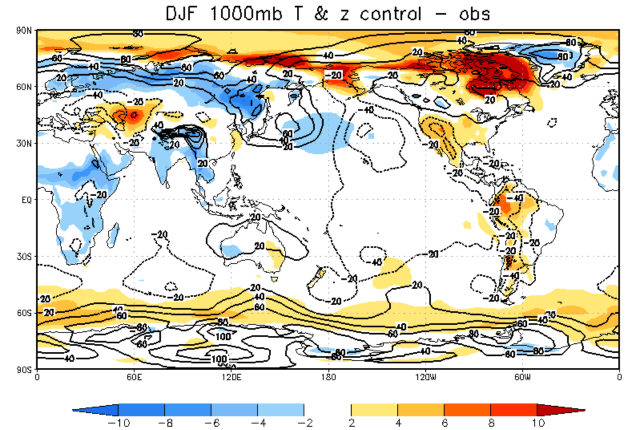
DJF 1000 hPa Heights (contours) and Temperatures (shading) CFS– NCEP R2

2009/10 (El Nino)

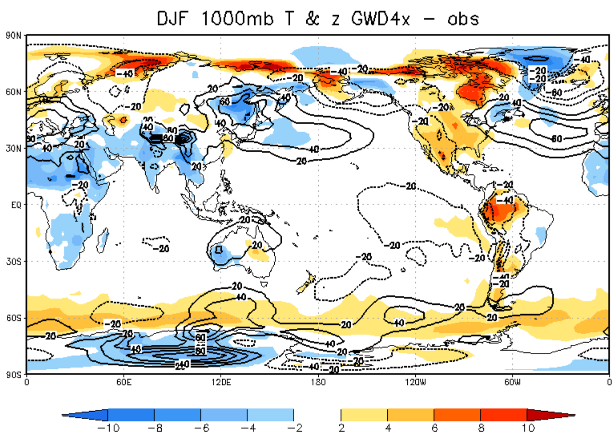
2007/08 (La Nina)

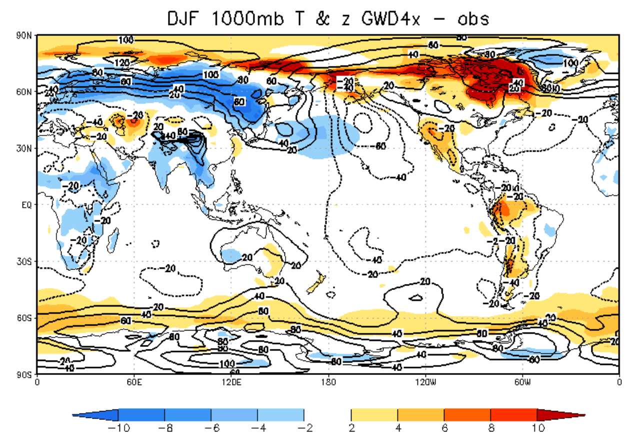
Control





OGWDx4





- Model is too warm over NH mid-latitudes.
- Tropospheric jet is shifted poleward (e.g., doesn't capture (-) AO very well).
- Increased OGWD reduces T bias over most of Eurasia but increases T bias slightly over U.S.

- Model is too cold over Eurasia and has positive bias in heights over poles (e.g., doesn't capture (+) AO very well).
- Biases increase due to increased OGWD.

Summary

- Results are based on interims version of the model.
- CFS is not able to simulate a strong polar vortex in the Northern Hemisphere which affects the model's tropospheric climatology.
- In the Southern Hemisphere, polar vortex breaks up too late.
- CFS exhibits large biases in the dynamic troposphere-stratosphere coupling which limits the models capability of a stratospheric pathway to modify tropospheric circulation anomalies.
- Increased orographic GWD increases biases in the Northern Hemisphere stratospheric basic state.

NOAA-SPARC DynVar Workshop NOAA/ESRL in Boulder, Nov 3-5, 2010

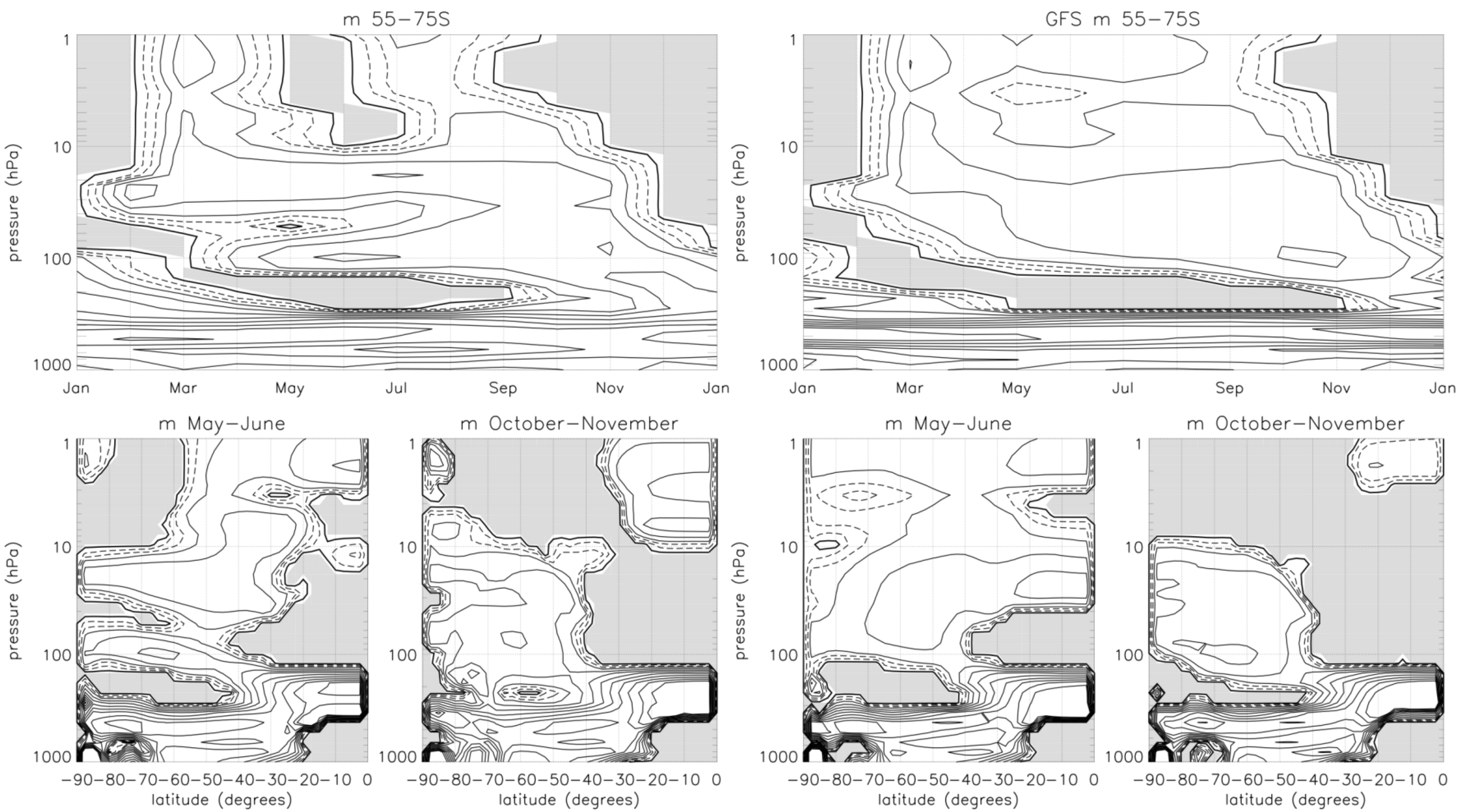
- The activity uses general circulation models to ask:
  - How does the stratosphere affect the tropospheric mean climate?
  - How does the stratosphere impact climate variability on all timescales?
  - How does the stratosphere impact climate change?
- Presentations are called for:
  - Presentation of the status of the CMIP5 runs with models with a well-resolved stratosphere;
  - Discussion on how to best analyze, make full use, and exchange knowledge from the ensembles of CMIP5 runs, with the role of the stratosphere in focus;
  - Discussion how to best analyze Stratosphere resolving Historical Forecast Project runs;
  - New results and reports on experience gained from the analysis of the SPARC Chemistry-Climate Model Validation Activity (CCMVal)-2 simulations.

Next Steps

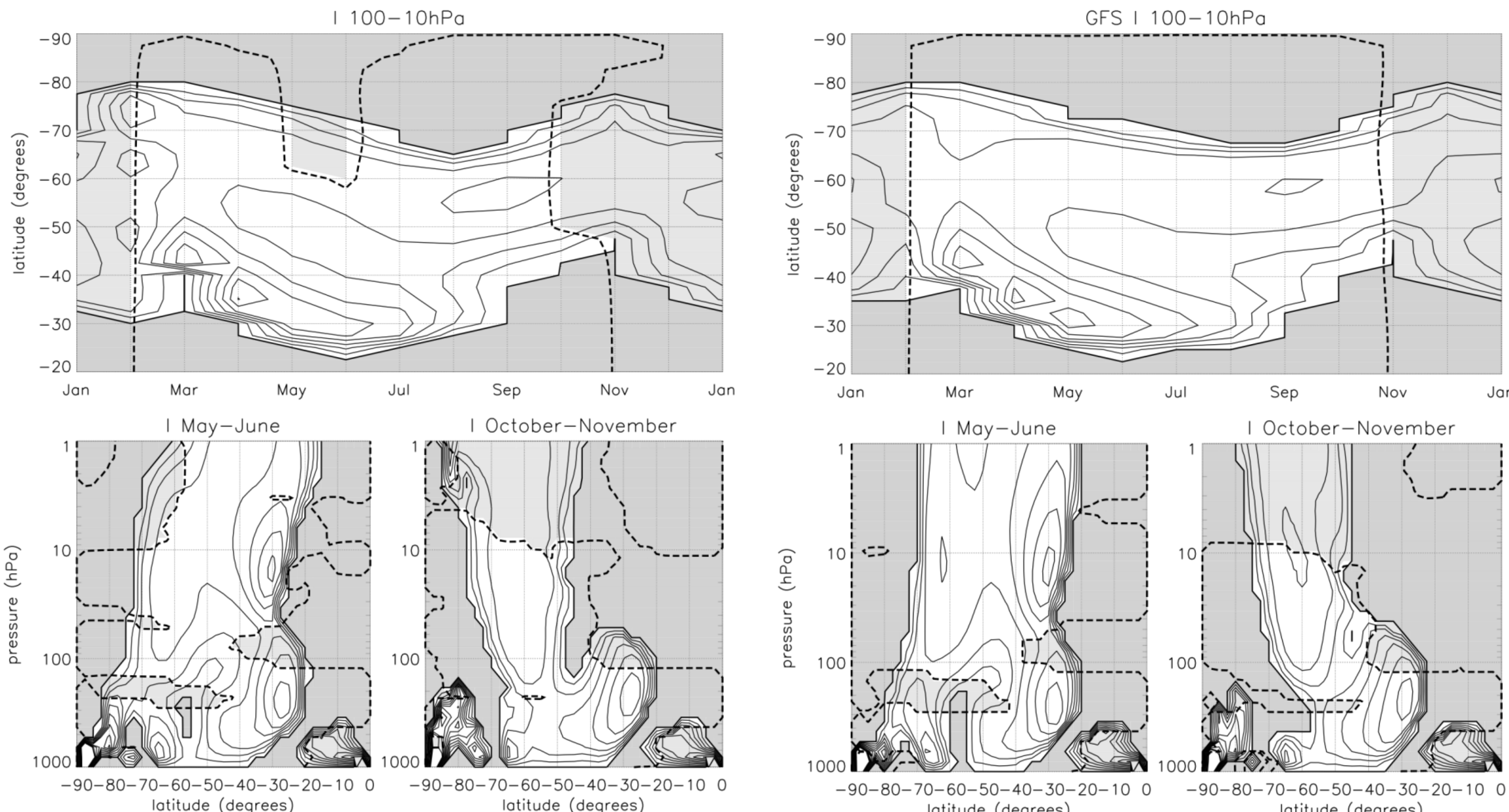
- Carry out baseline experiments with CFS version 2 (both La Nina and El Nino cases)
- Carry out AMIP run with GFS_{CFS}
- Increase number of layers to 91 and lift model top to 0.006 hPa (80km)
- Include non-orographic gravity drag parameterization
- Incorporate parameterizations for gravity wave sources (convection, frontal zones)
- Analyze troposphere-stratosphere coupling in hindcast experiments

Backup Slides

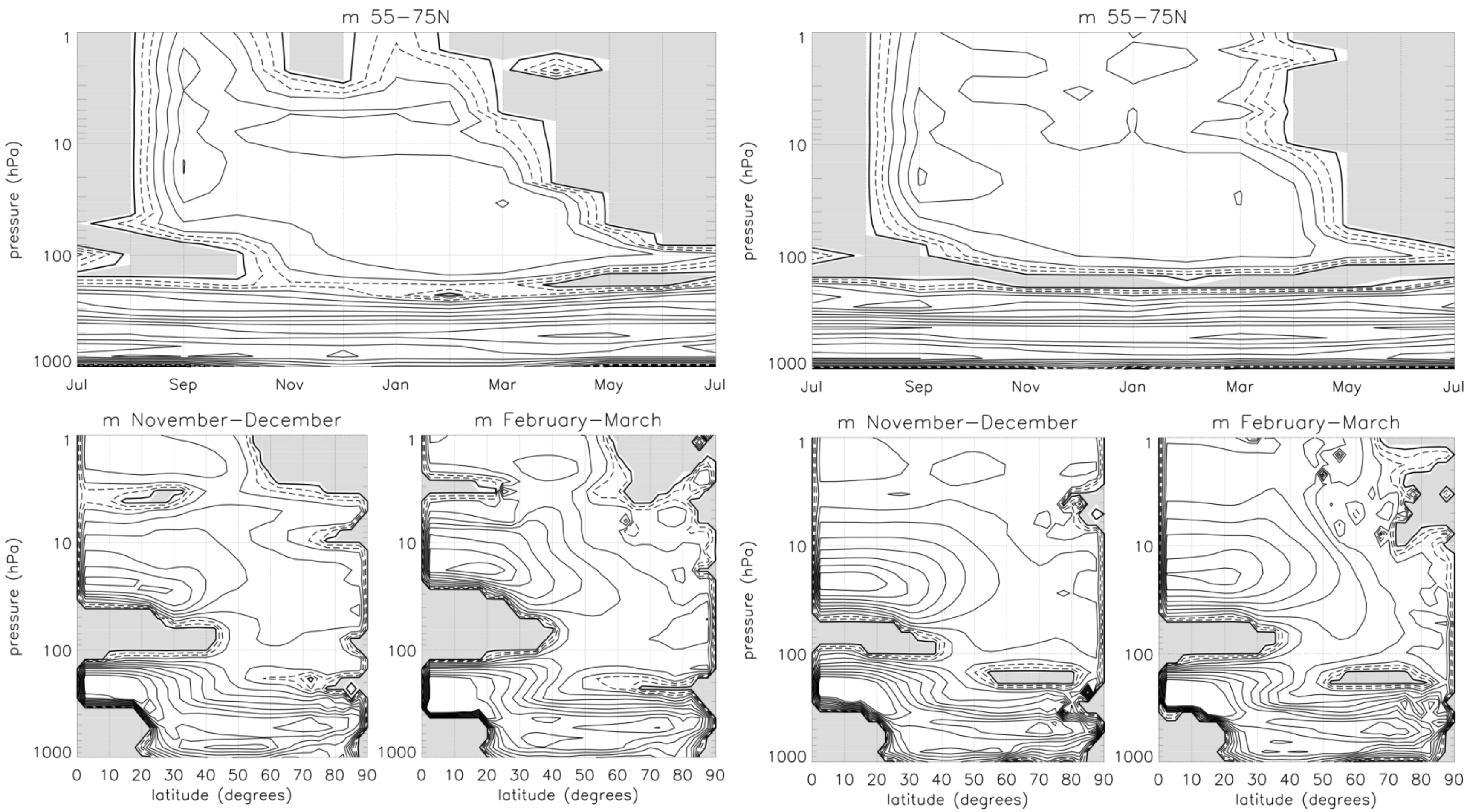
SH Vertical Wave Number



SH Meridional Wave Number



NH Vertical Wave Number



NH Meridional Wave Number