The Whole Atmosphere Community Climate Model (WACCM)

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OUTLINE

- Scientific motivation
- Model development
  - –Physical processes
  - –Chemistry
- Some initial results
  - –Mesospheric thermal inversions
  - –Tides in the mesosphere and lower thermosphere
  - –The 2-day wave
  - –Water vapor in the lower stratosphere
  - –The winter stratosphere and the "annular mode"
- The WACCM Workshop

WACCM Motivation

Roble, Geophysical Monographs, 123, 53, 2000

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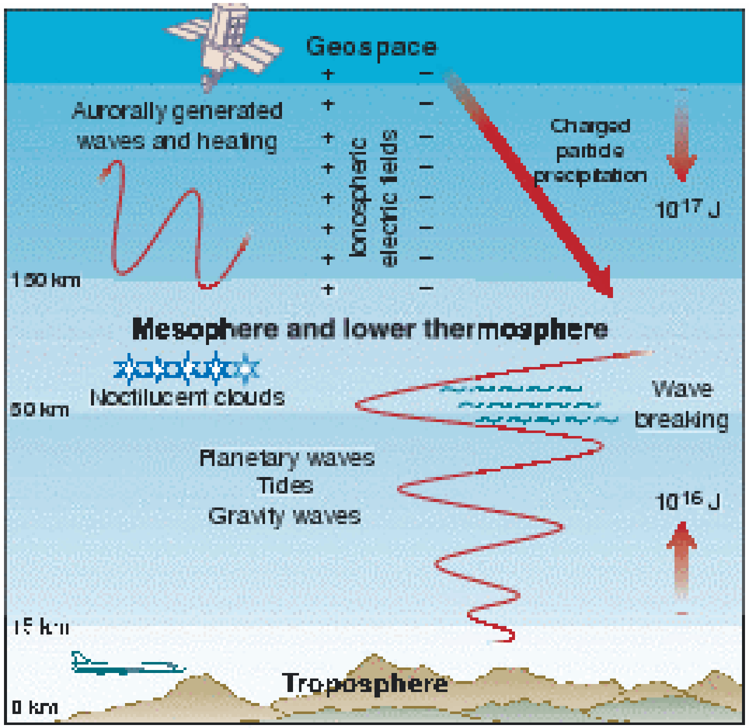
•Coupling between atmospheric layers:

- Waves transport energy and momentum from the lower atmosphere to drive the QBO, SAO, sudden warmings, mean meridional circulation
- Solar inputs, e.g., auroral production of NO in the mesosphere and downward transport to the stratosphere
- Stratosphere-troposphere exchange

• Climate Variability and Climate Change:

- What is the impact of the stratosphere on tropospheric variability, e.g., the Artic oscillation or "annular mode"?
- How important is coupling among radiation, chemistry, and circulation? (e.g., in the response to O_3 depletion or CO_2 increase)



Energy transfer in the mesosphere and lower thermosphere. About 10^{16} J of energy propagates up daily from the atmosphere below in the form of waves and tides. During a geomagnetic storm (which occurs about every 5 days), about 10^{17} J is injected per day from space through auroral processes.

Jarvis, "Bridging the Atmospheric Divide"
Science, **293**, 2218, 2001

WACCM Motivation

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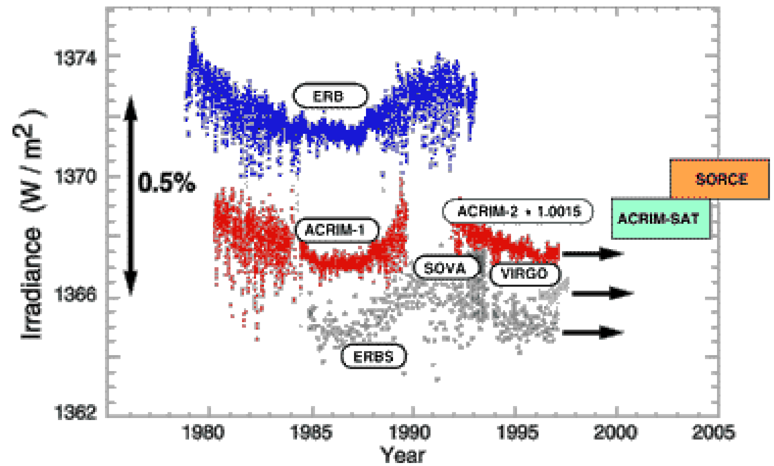
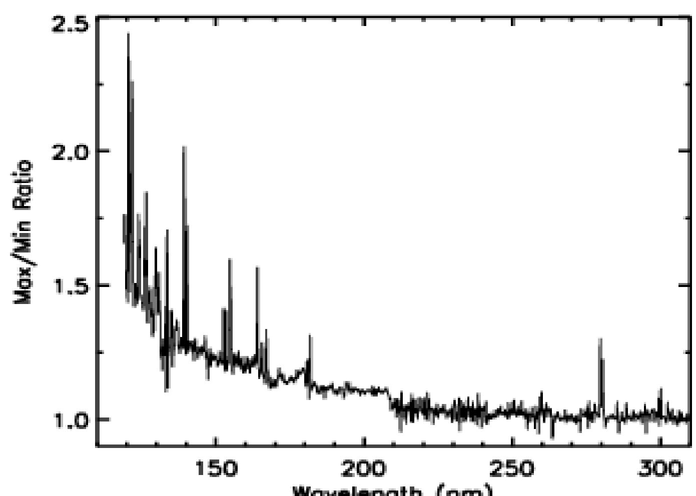
- Response to Solar Variability:
  - Recent satellite observations have shown that solar cycle variation is:

    0.1% for total Solar Irradiance

    5-10% at ≈ 200nm
  - Radiation at wavelengths near 200 nm is absorbed in the stratosphere

  => Impacts on global climate may be mediated by stratospheric chemistry and dynamics
- Satellite observations:
  - There are several satellite programs that can benefit from a comprehensive model to help interpret observations
  - e.g., UARS, TIMED, EOS Aura





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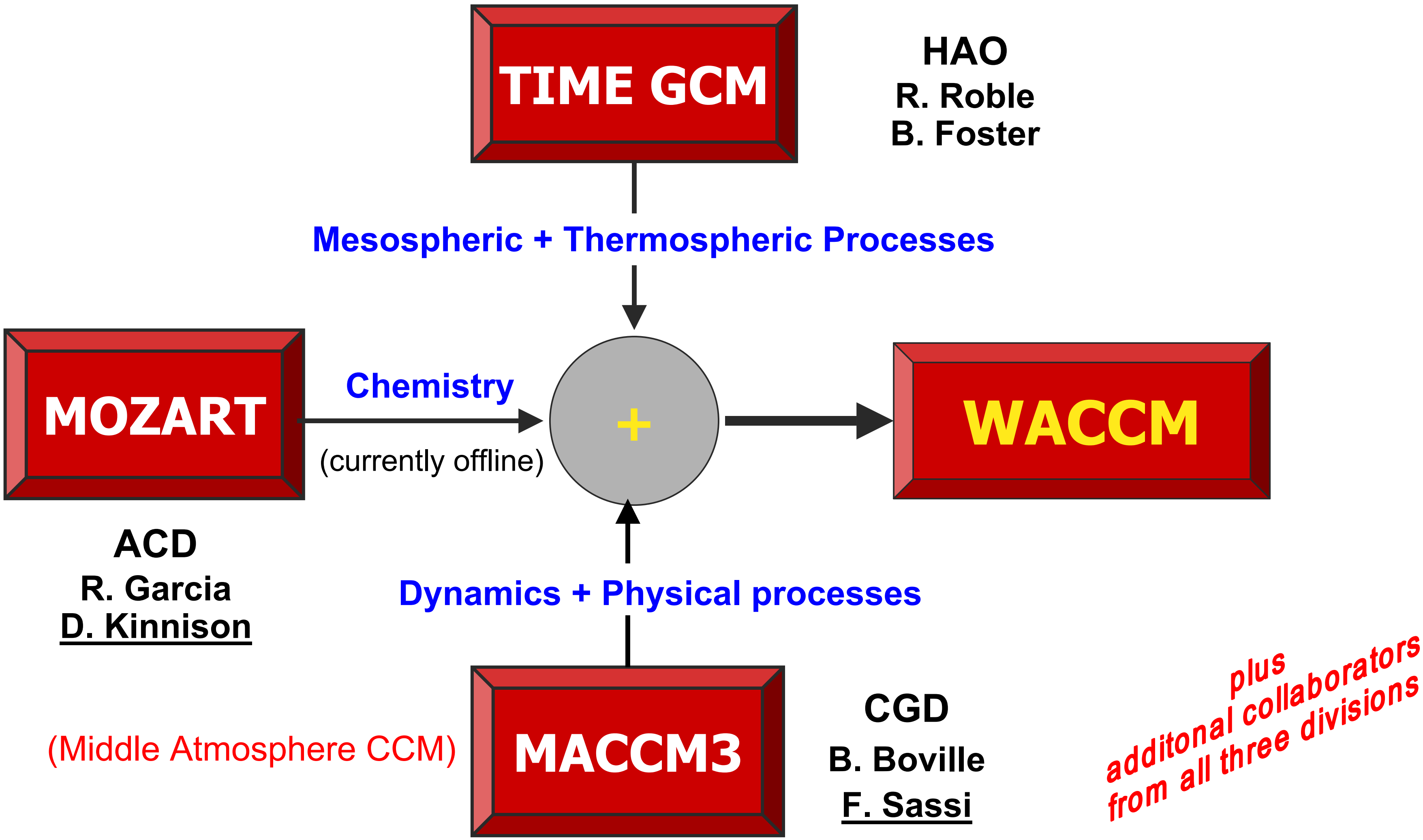
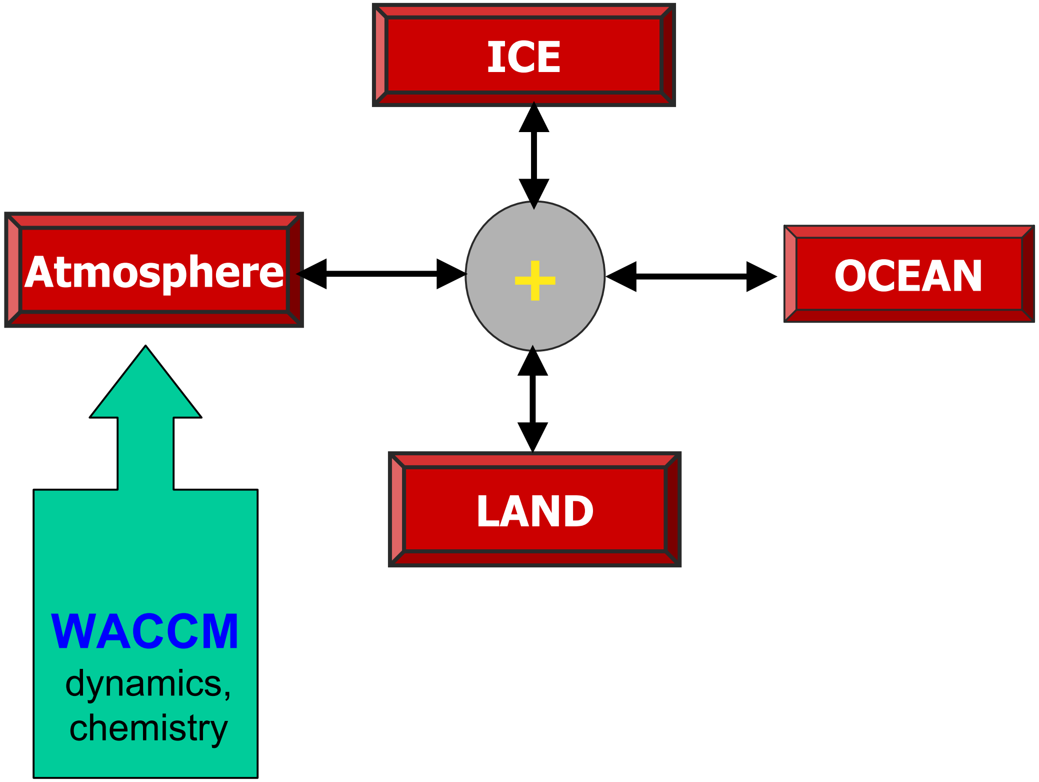
WACCM Components:
A collaboration among 3 NCAR Divisions



WACCM and the NCAR Community Climate System Model



WACCM uses the *software framework of the NCAR CCSM*. May be run in place of the standard CAM (Community Atmospheric Model)

Dynamics Module

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Additions to the original MACCM3 code:

• A parameterization of non-LTE IR (15 μm band of CO_2 above 70 km) merged with CCSM IR parameterization (below 70 km)

• Short wave heating rates (above 70 km) due to absorption of radiation shortward of 200 nm and chemical potential heating

•Gravity Wave parameterization extended upward, includes dissipation by molecular viscosity

• Effects of dissipation of momentum and heat by molecular viscosity (dominant above 100 km)

• Diffusive separation of atmospheric constituents above about 90 km

• Simplified parameterization of ion drag

WACCM
Zonal Mean Wind and Temperature

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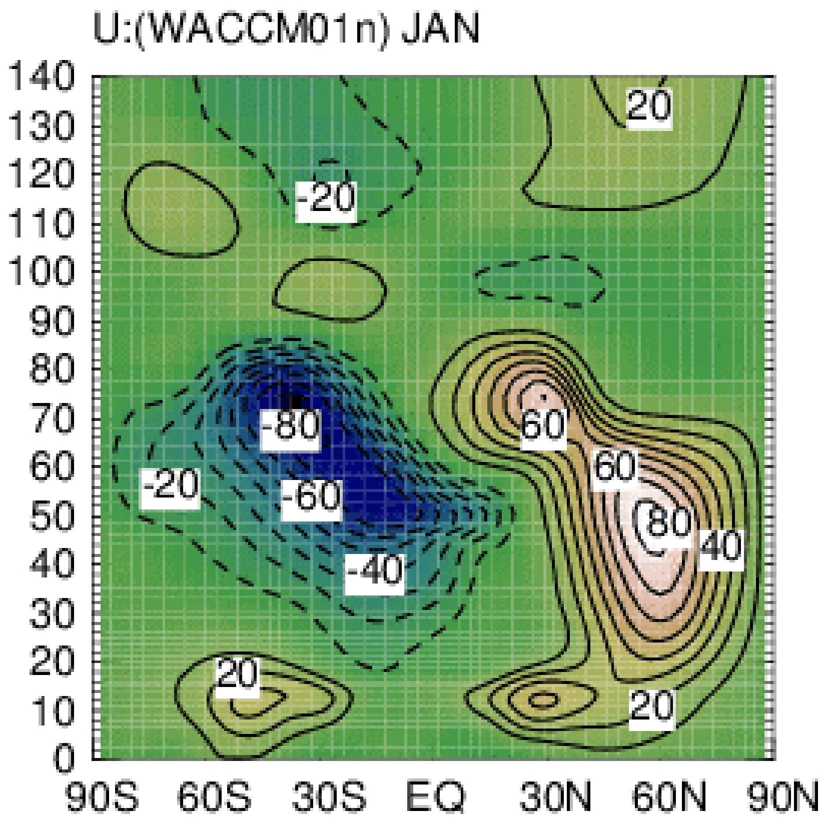

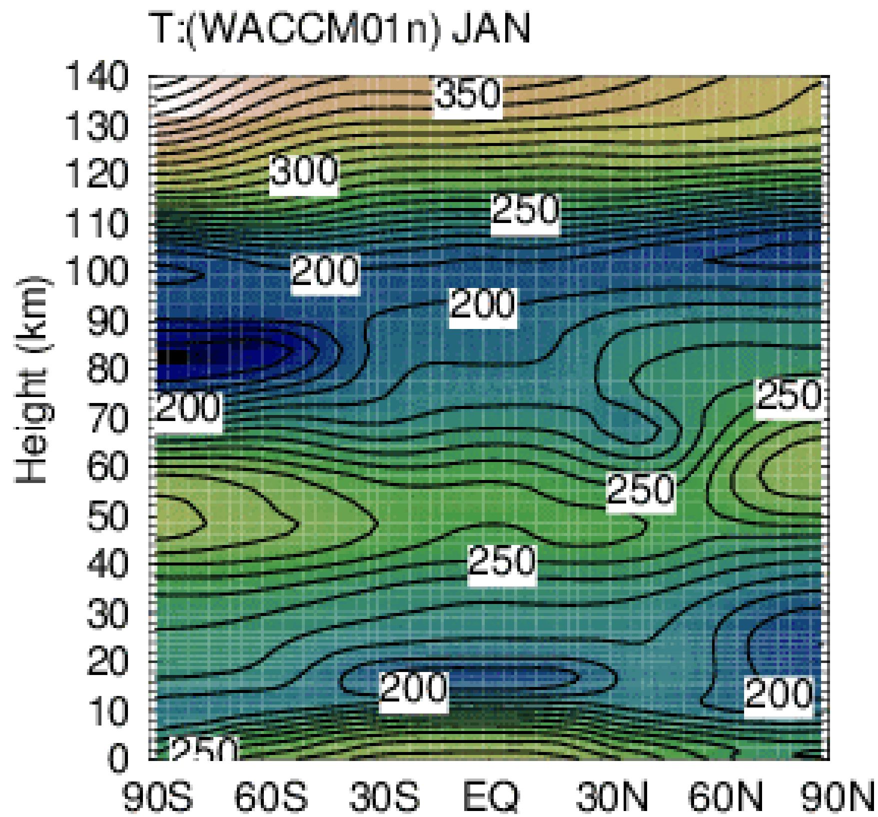

Gross diagnostics (zonal mean behavior)
Complete climatological analysis is planned

Solstice Temperature Distribution

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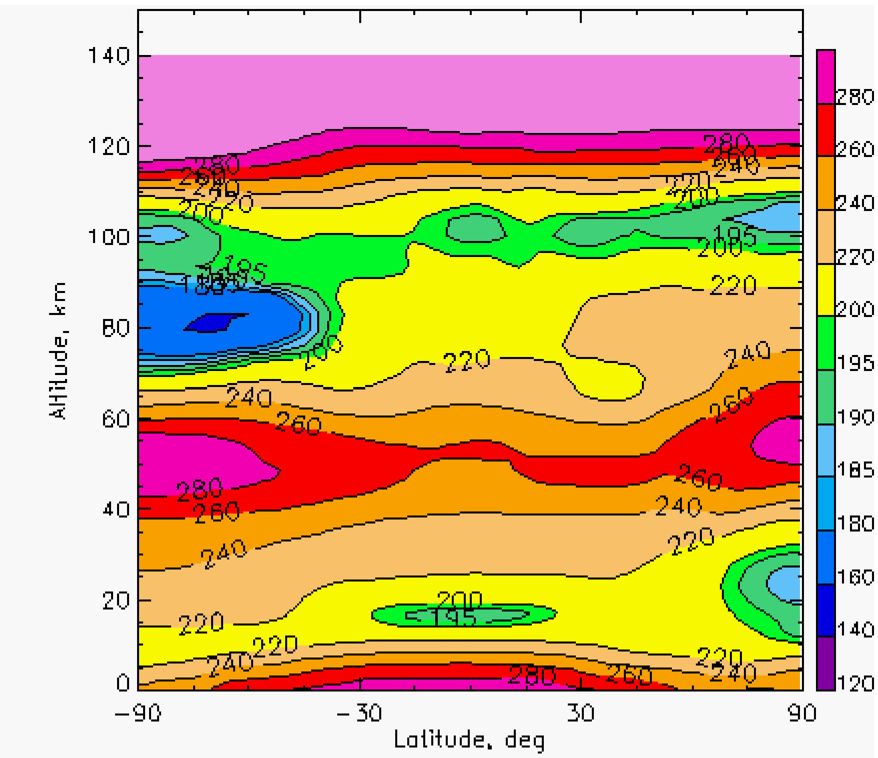
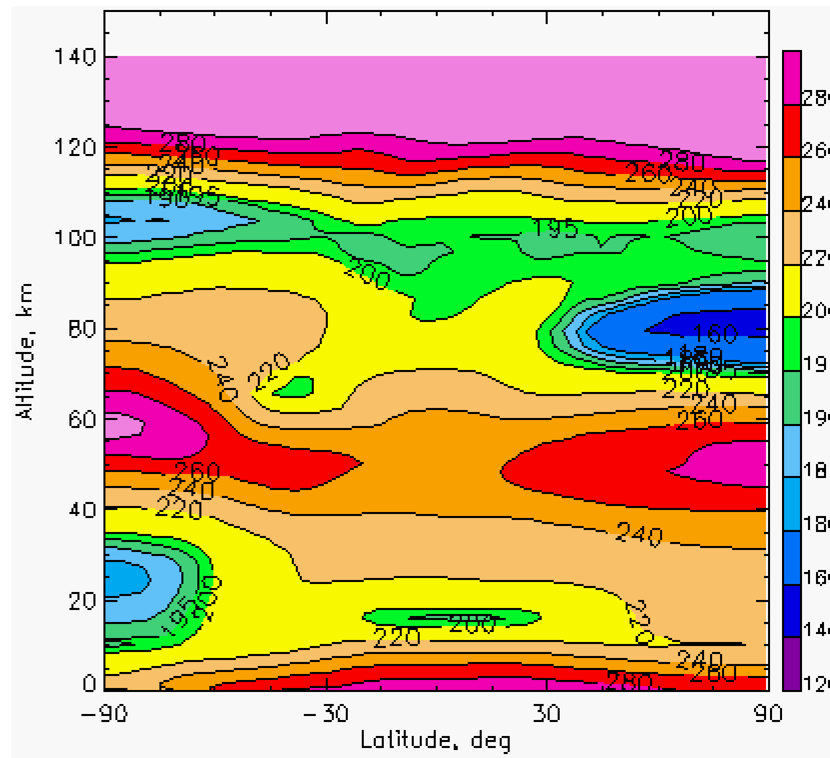
January



July



Chemistry Module (MOZART-3)

(50 species; 41 Photolysis, 93 Gas Phase, 17 Hetero. Rx)

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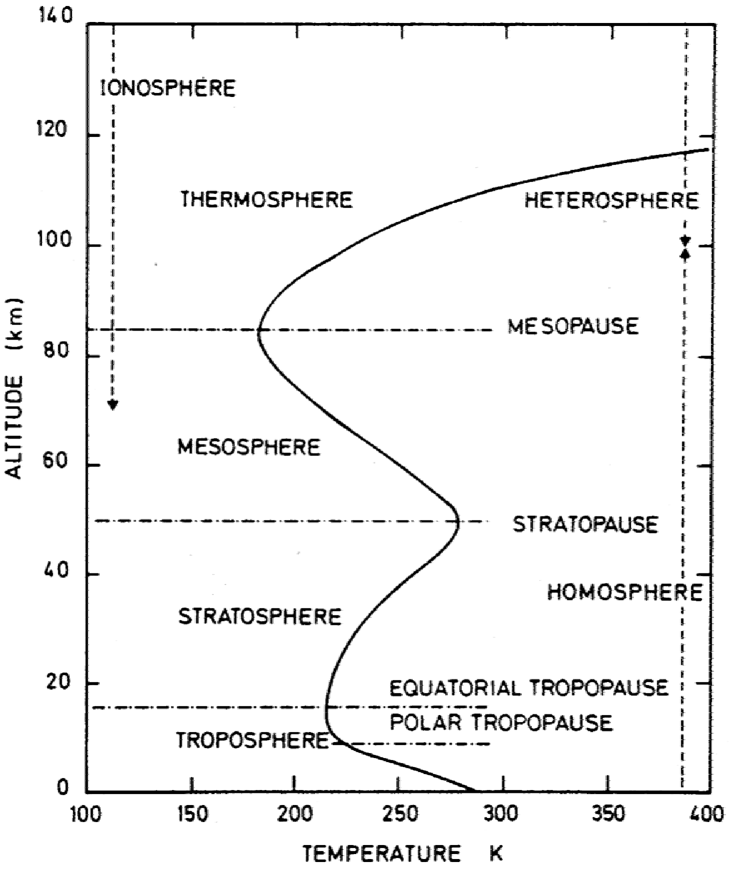
Our goal was to represent the chemical processes considered important in the:

- Troposphere, Stratosphere, and Mesosphere:
  - Ox, HO_x, NO_x, ClO_x, and BrO_x
  - Heterogeneous processes on sulfate, nitric acid hydrates, and water-ice aerosols
- Thermosphere (limited):
  - Auroral NO_x production
  - Currently do not include ion-molecule reactions



WACCM Chemical Species

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Long-lived Species: (17-species, 1-constant)

– Misc: CO_2, CO, CH_4, H_2O, N_2O, H_2, O_2

– CFCs: CCl_4, CFC-11, CFC-12, CFC-113

– HCFCs: HCFC-22

– Chlorocarbons: CH_3Cl, CH_3CCl_3,

– Bromocarbons: CH_3Br

– Halons: H-1211, H-1301

– Constant Species: N_2

Short-lived Species: (32-species)

- O_X: O_3, O, $O(^1D)$
- NO_X: N, $N(^2D)$, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2
- ClO_X: Cl, ClO, Cl_2O_2, OClO, HOCl, HCl, $ClONO_2$, Cl_2
- BrO_X: Br, BrO, HOBr, HBr, BrCl, $BrONO_2$
- HO_X: H, OH, HO_2, H_2O_2
- HC Species: CH_2O, CH_3O_2, CH_3OOH

Heterogeneous Chemistry Module

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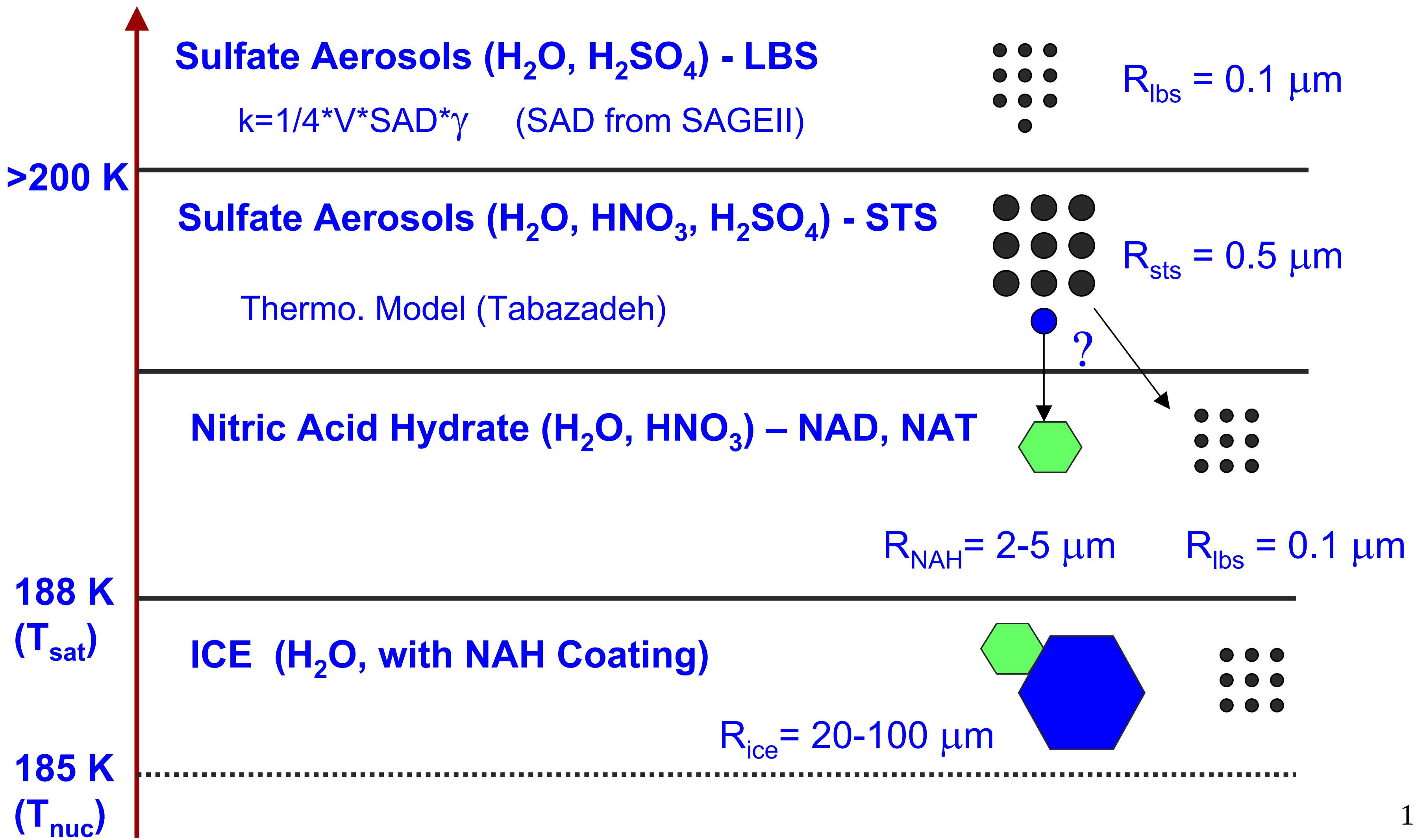

Total Column Ozone (Dobson Units)

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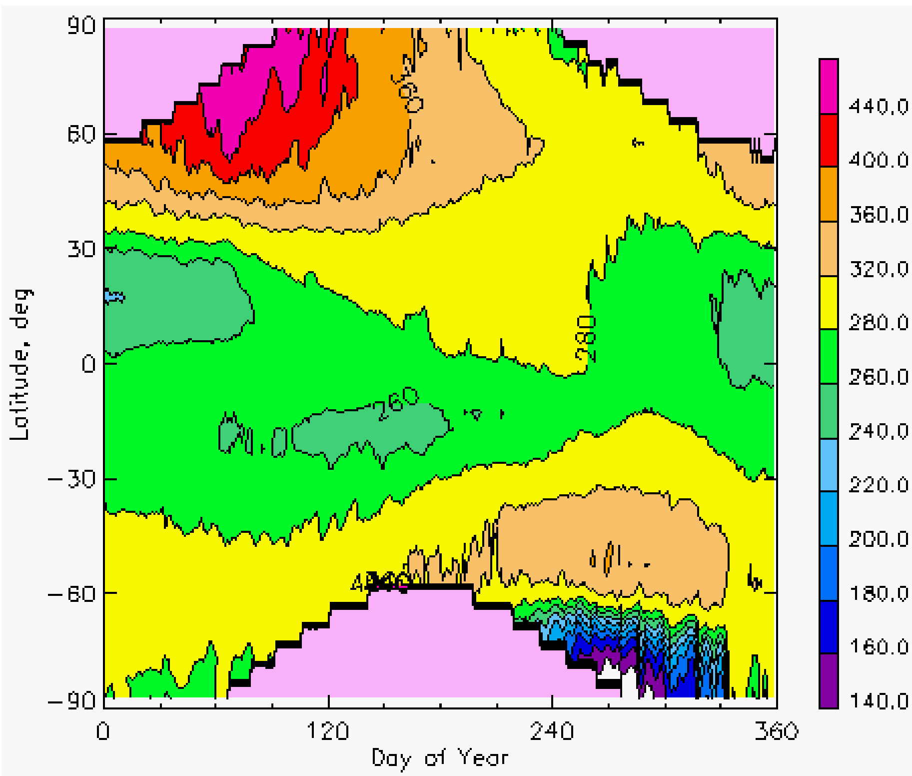
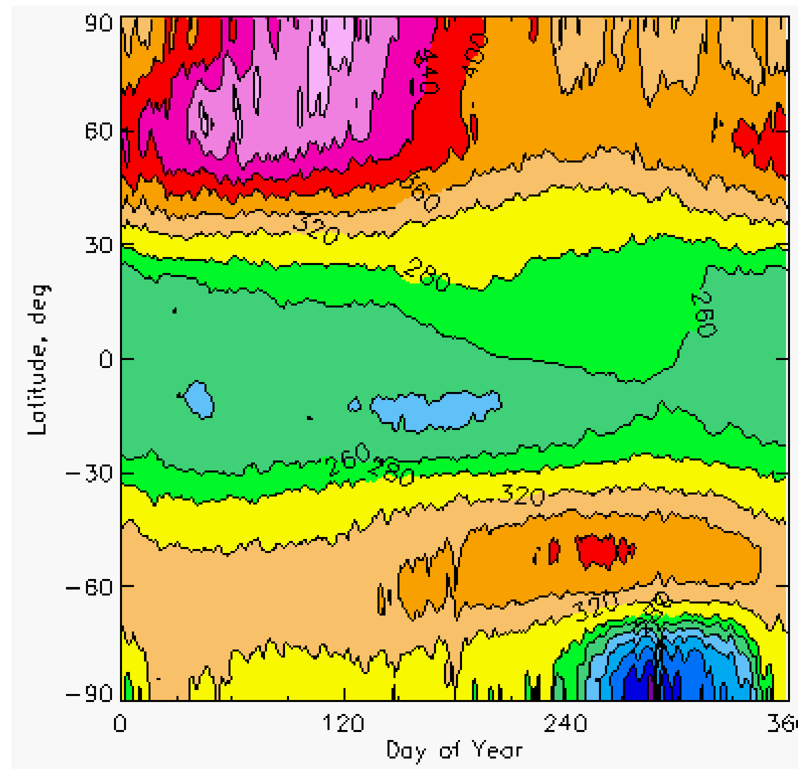
Earth Probe TOMS, 1999 (daily)



WACCM (daily)



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Vertical T profiles during inversions: Observed and modeled

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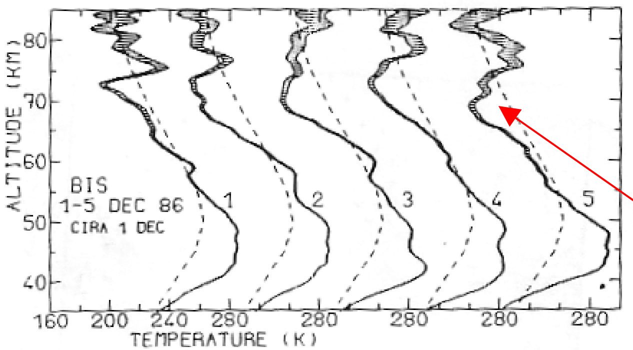
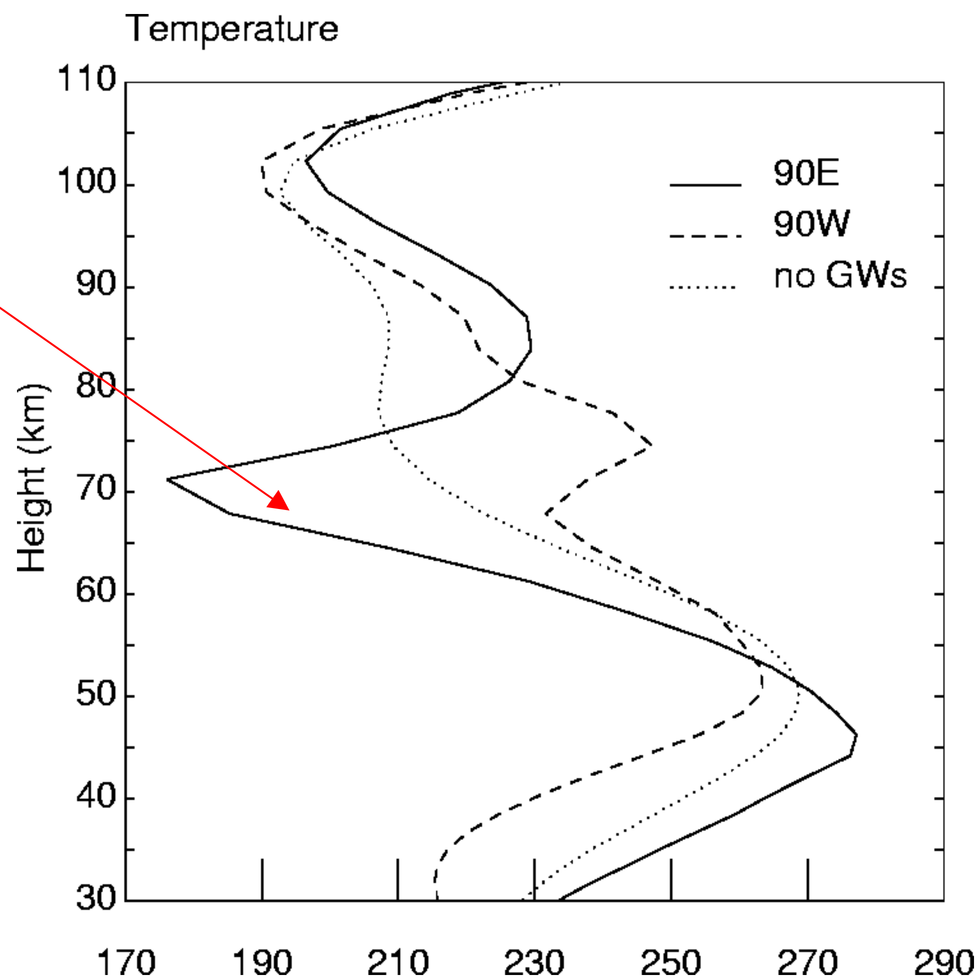


Fig. 1 Nightly mean temperature profiles at Biscarrosse from December 1 to December 5, 1986. The error bars ($\pm 1\sigma$) are indicated by the shaded area. The CIRA 1972 profile is shown for comparison (dotted line). Perturbations with vertical wavelengths shorter than 1.5 km have been filtered.



Wintertime mesospheric inversions: Observed and modeled

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Hauchecorne et al, JGR, 1987

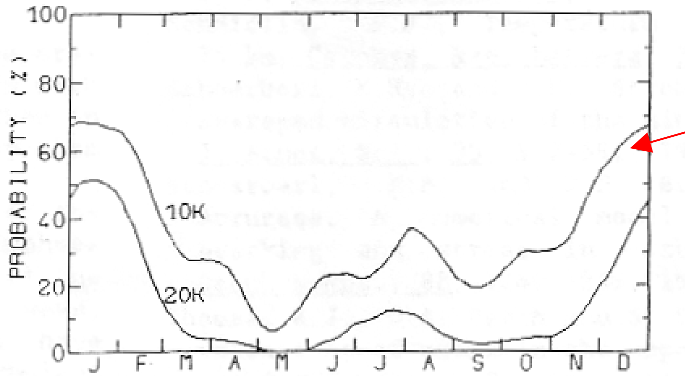


Fig. 6 Annual variation of the probability of occurrence of a mesospheric inversion for the 10 K and 20 K criteria. A ± 30 days triangular filter has been applied to smooth the data.

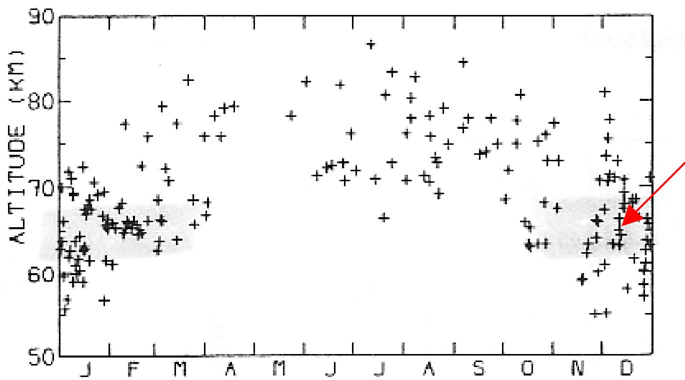
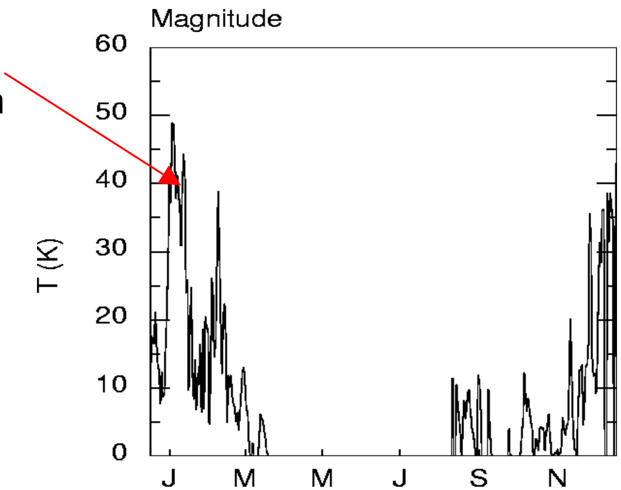


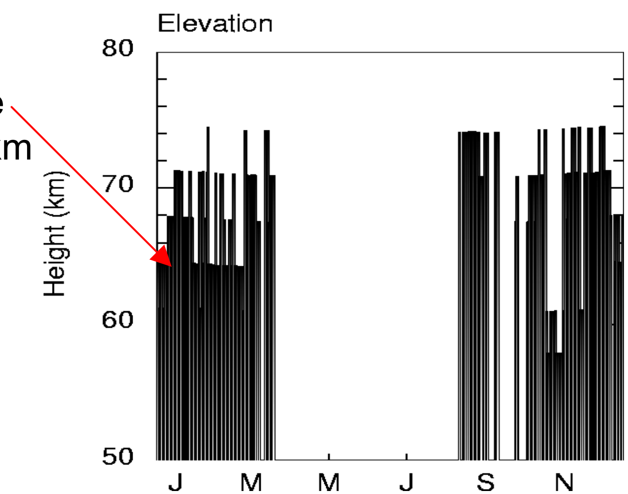
Fig. 5 Altitude of the secondary minimum of temperature versus the day of the year for all OHP profiles from June 1981 to September 1986 for which a temperature inversion has been detected (10 K criterion).

WACCM

winter maximum



winter altitude ~65-70 km



Mean zonal wind and planetary wave breaking: Standard run with GW parameterization

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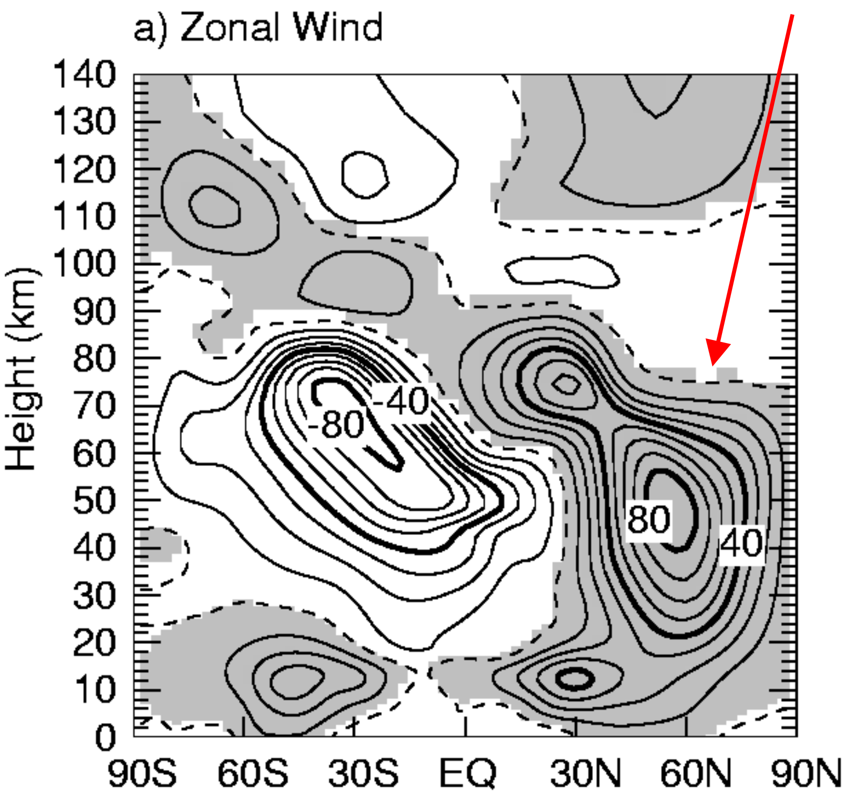
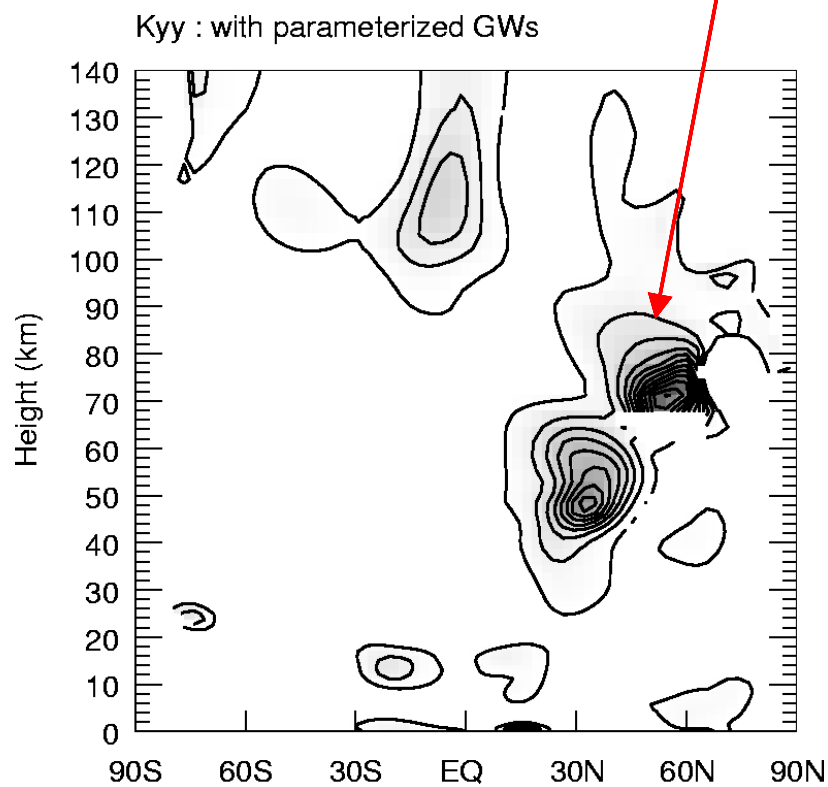
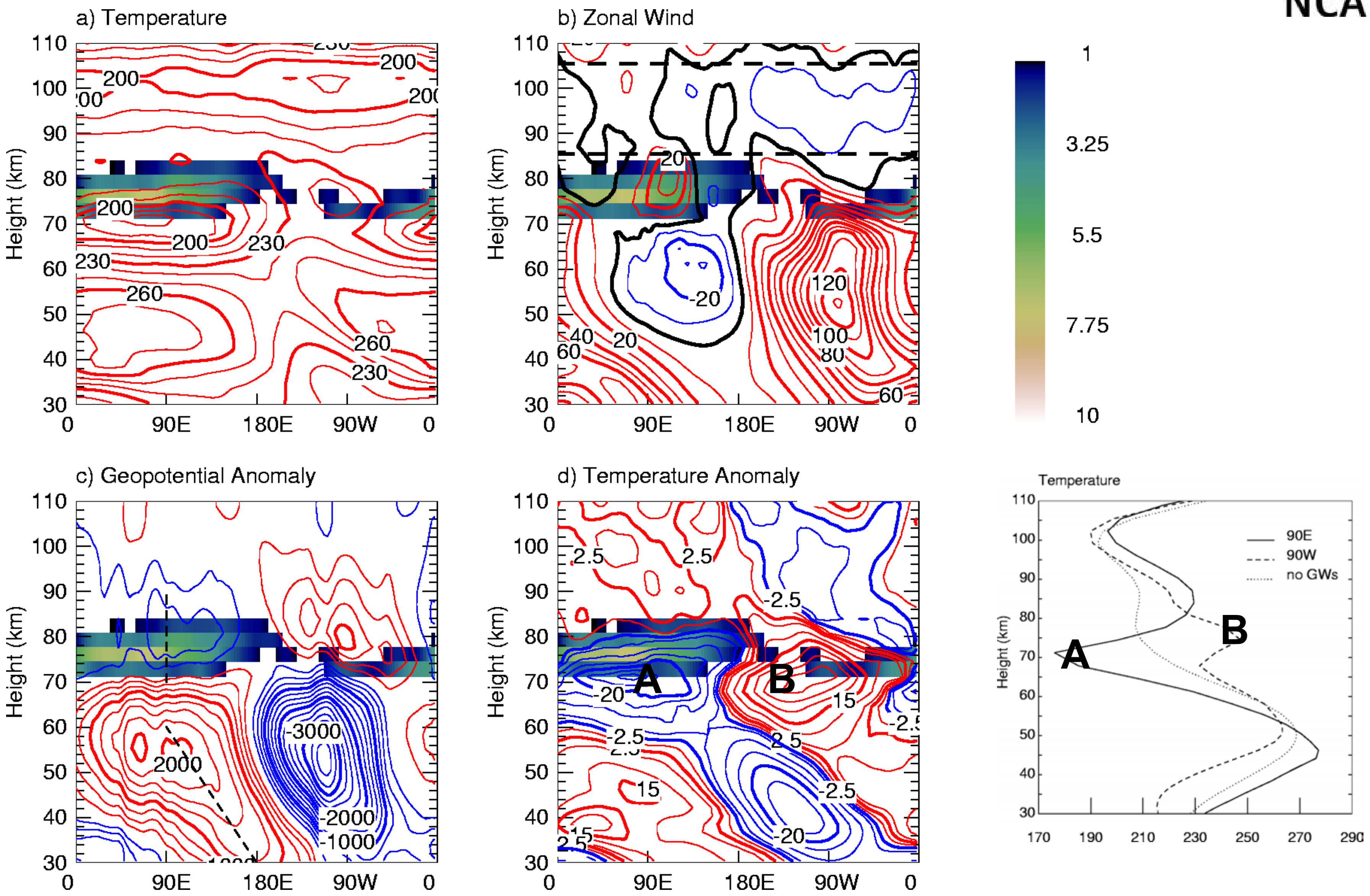
wind reversal, zero-wind line near 75 km



note "compact" mesospheric surf-zone



Structure of wintertime T inversions simulated with WACCM



Effects of removing gravity wave drag: Zonal wind and planetary wave breaking

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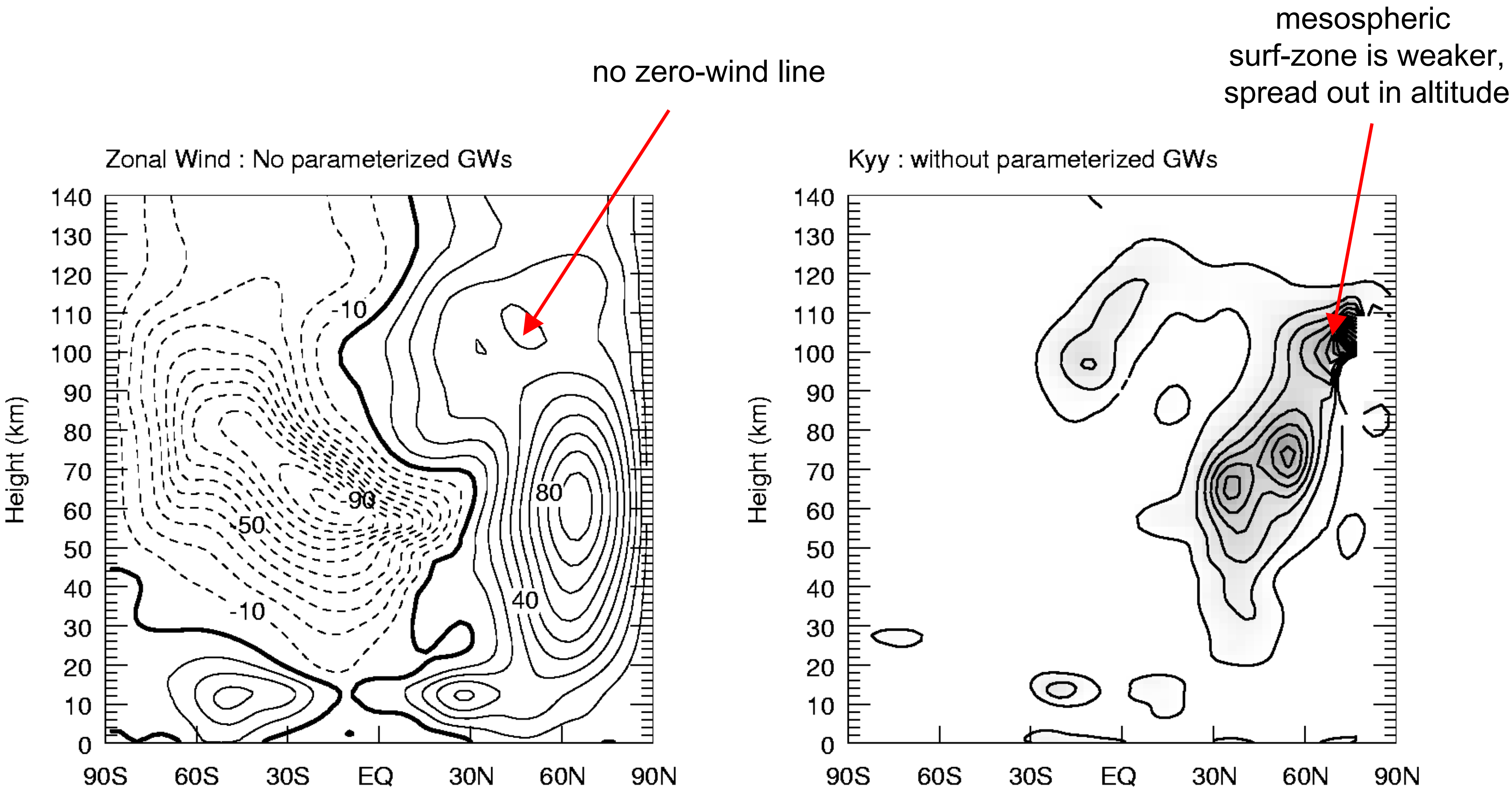
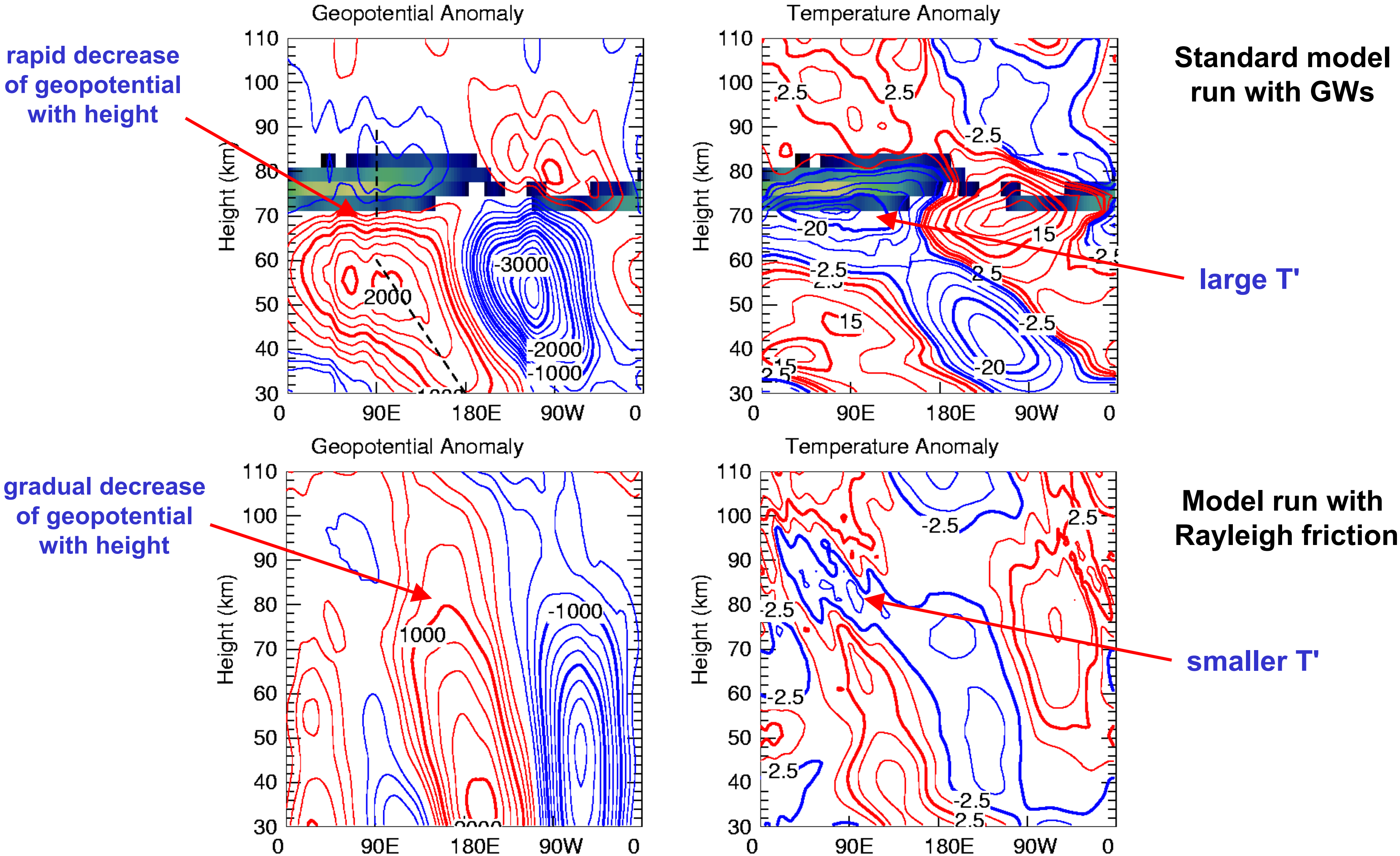
Model run with Rayleigh friction Replacing gravity wave drag



Effects of removing gravity wave drag: Planetary wave structure



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Tides: standard case

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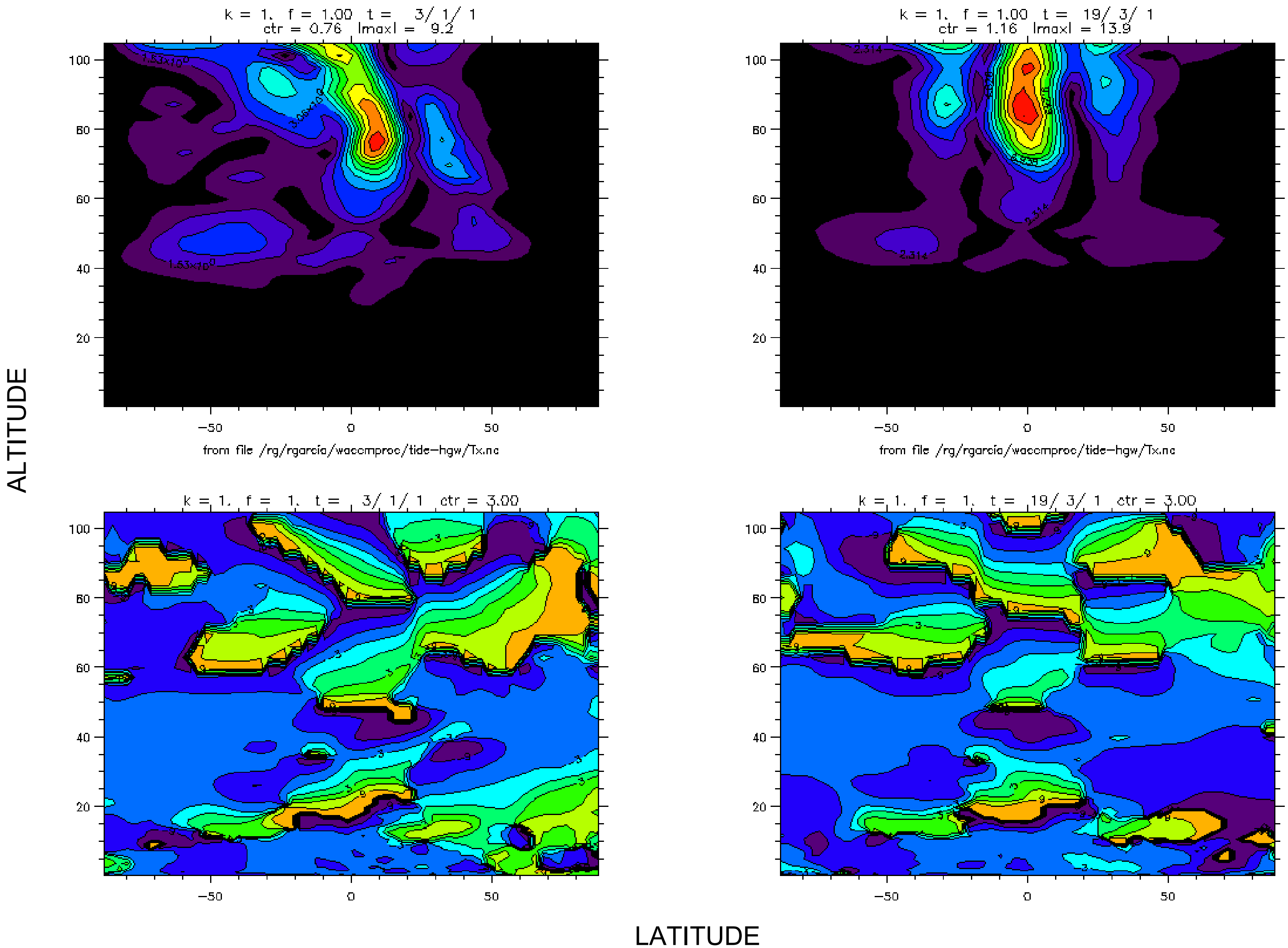
Model:

- Forcing via shortwave heating (O_3, H_2O, O_2) and convective heating
- Gravity wave parameterization
- Comparisons with observations

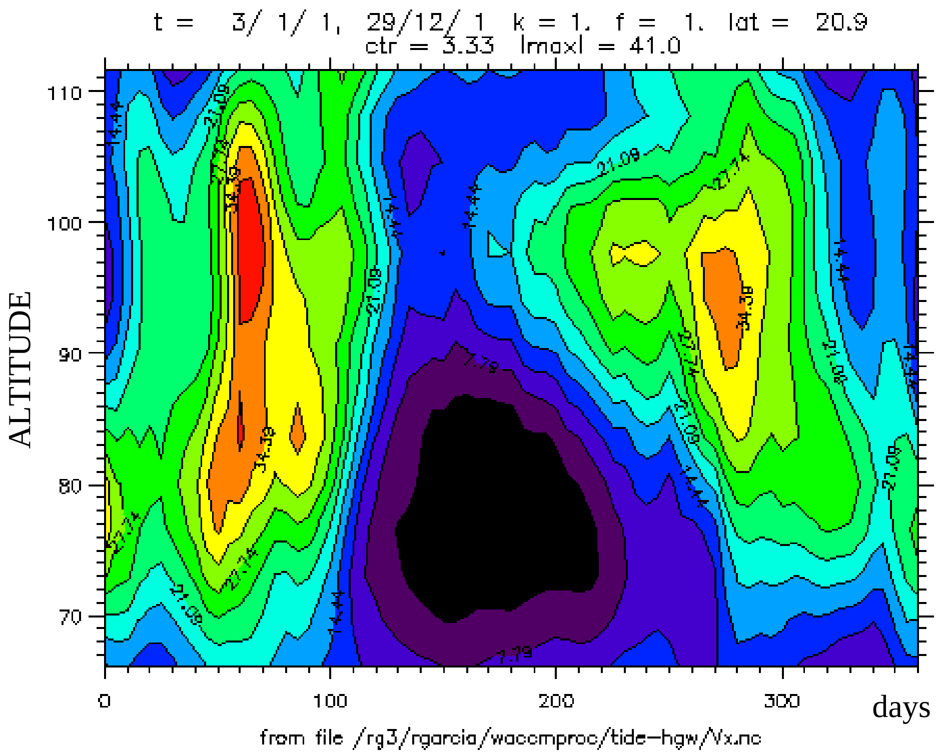
Analysis method:

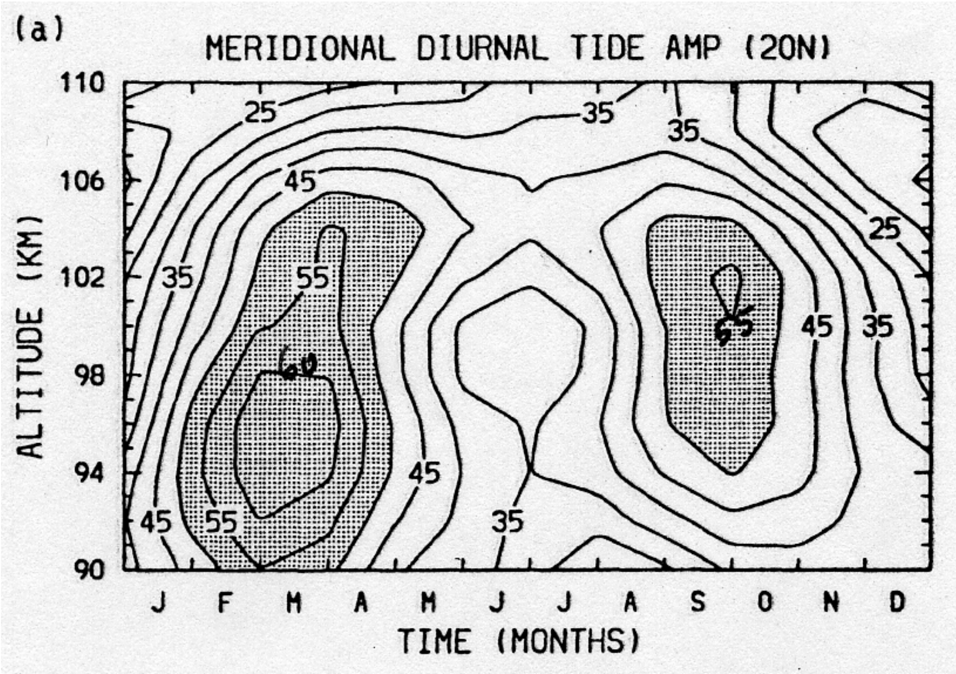
- 3-hourly output saved for successive 5-day periods throughout year
- Extract wavenumber, frequency components via Fourier analysis (k = 0, 6 and f = ±3 cpd)

Diurnal T tide (k=1 westward): January and March



Diurnal V tide - annual cycle at 20 N





V from UARS/WINDI
(McLandress et al, 1996)

Diurnal V tide – annual cycle at 20N, 95 km

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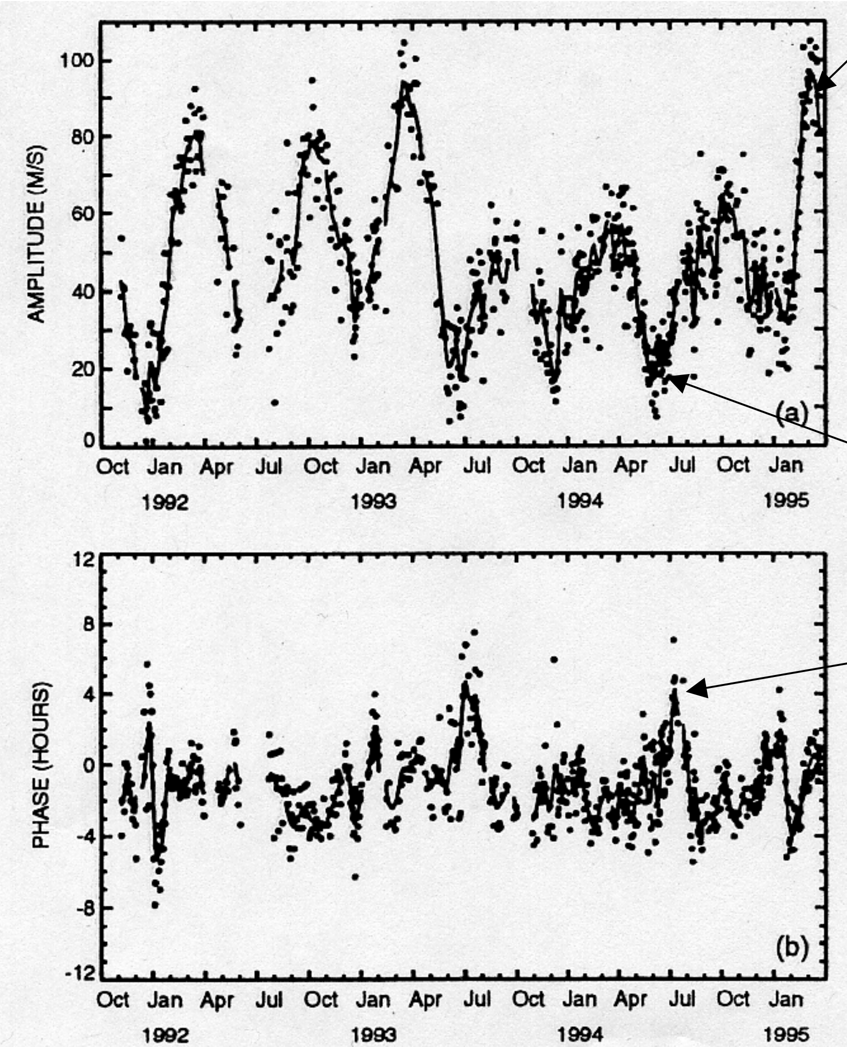
UARS/HRDI V
At 95 km, 20 N
(Burrage et al., 1995)

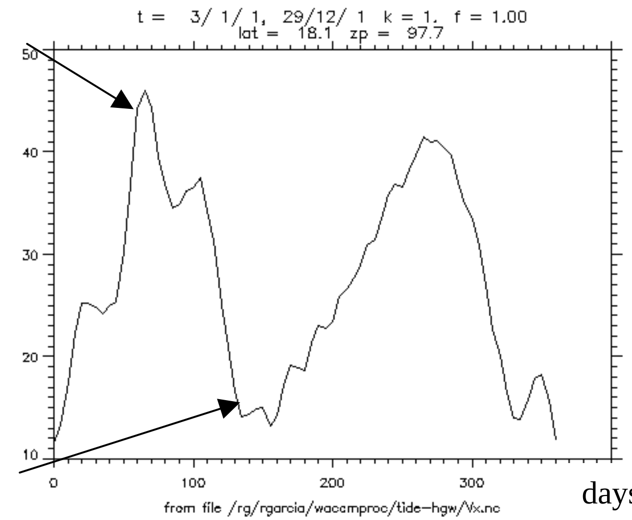
WACCM V
At 97 km, 18 N

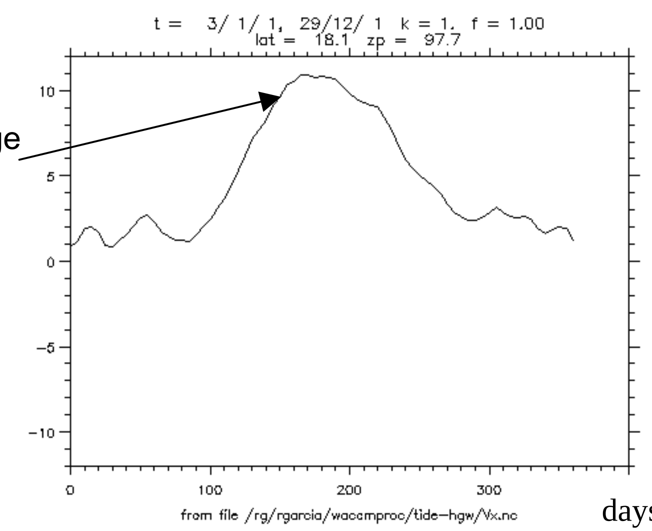


maxima at
equinoxes

deep minima
at solstices

phase change
at summer
solstice





Diurnal V tide structure - solstice

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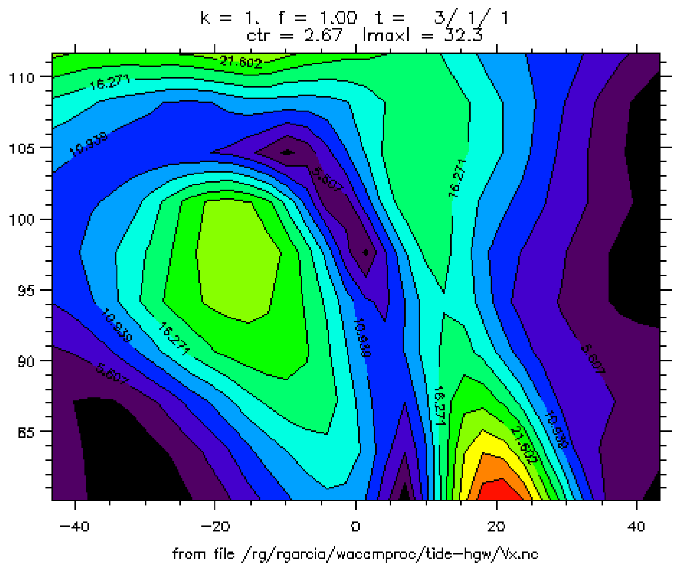
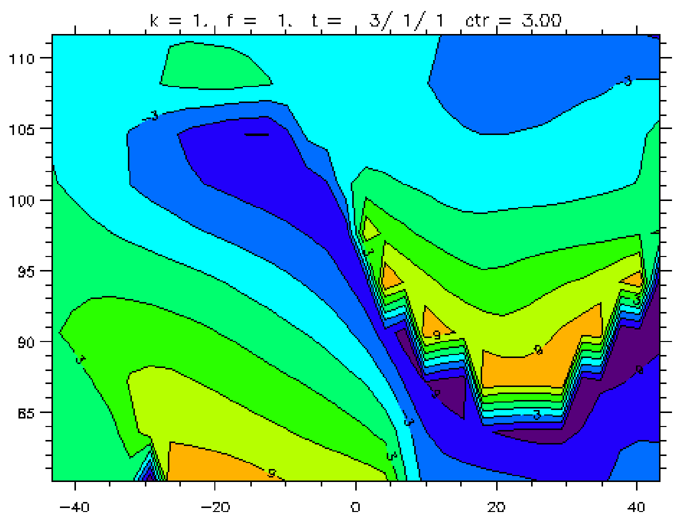
ALTITUDE





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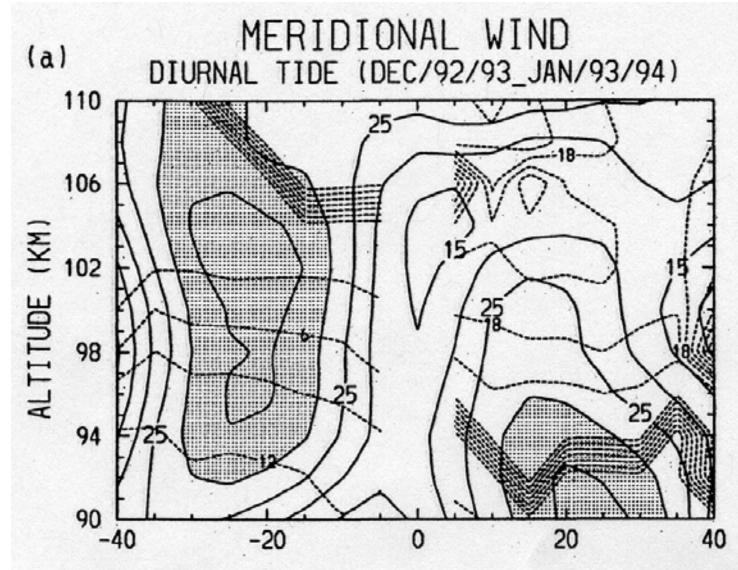

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V from UARS/WINDI
(McLandress et al, 1996)

Diurnal V tide structure - equinox

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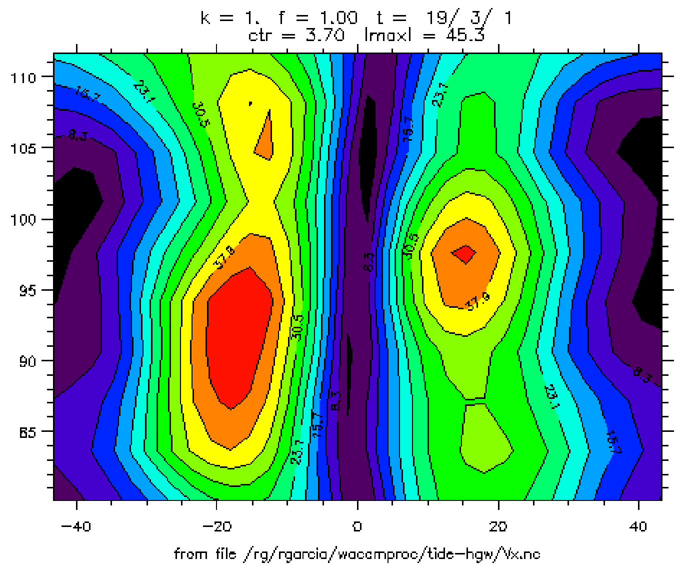

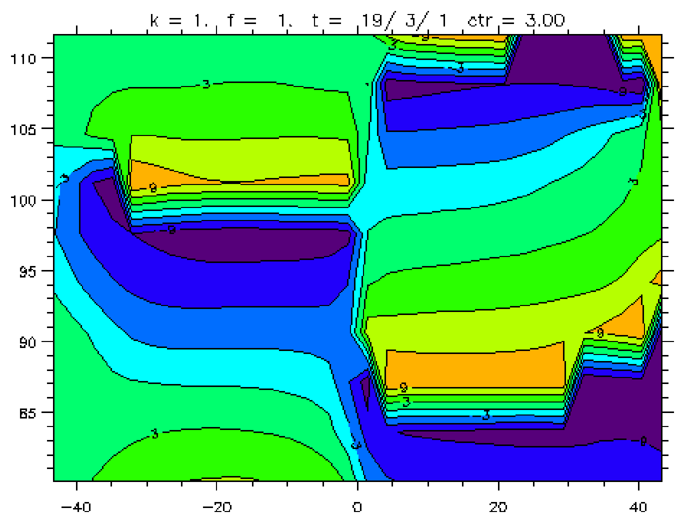

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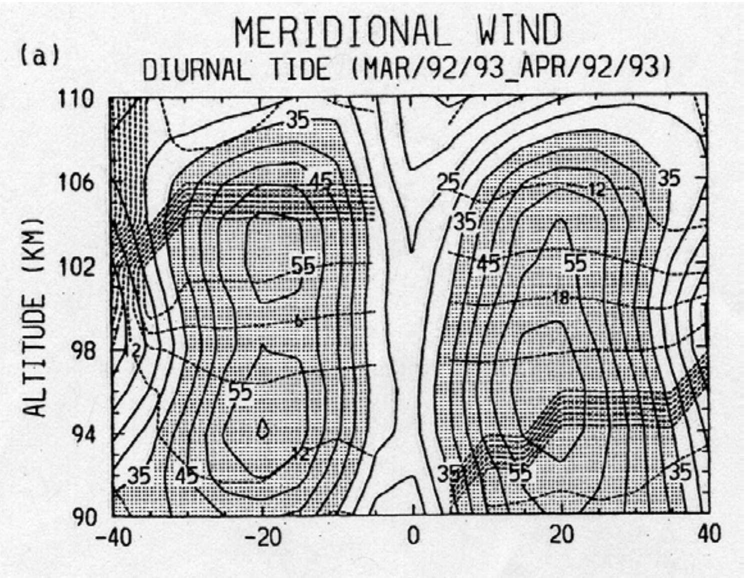

LATITUDE

V from UARS/WINDI
(McLandress et al, 1996)

Semidiurnal V Tide: Effects of dissipation mechanims (GW drag vs. Rayleigh friction)

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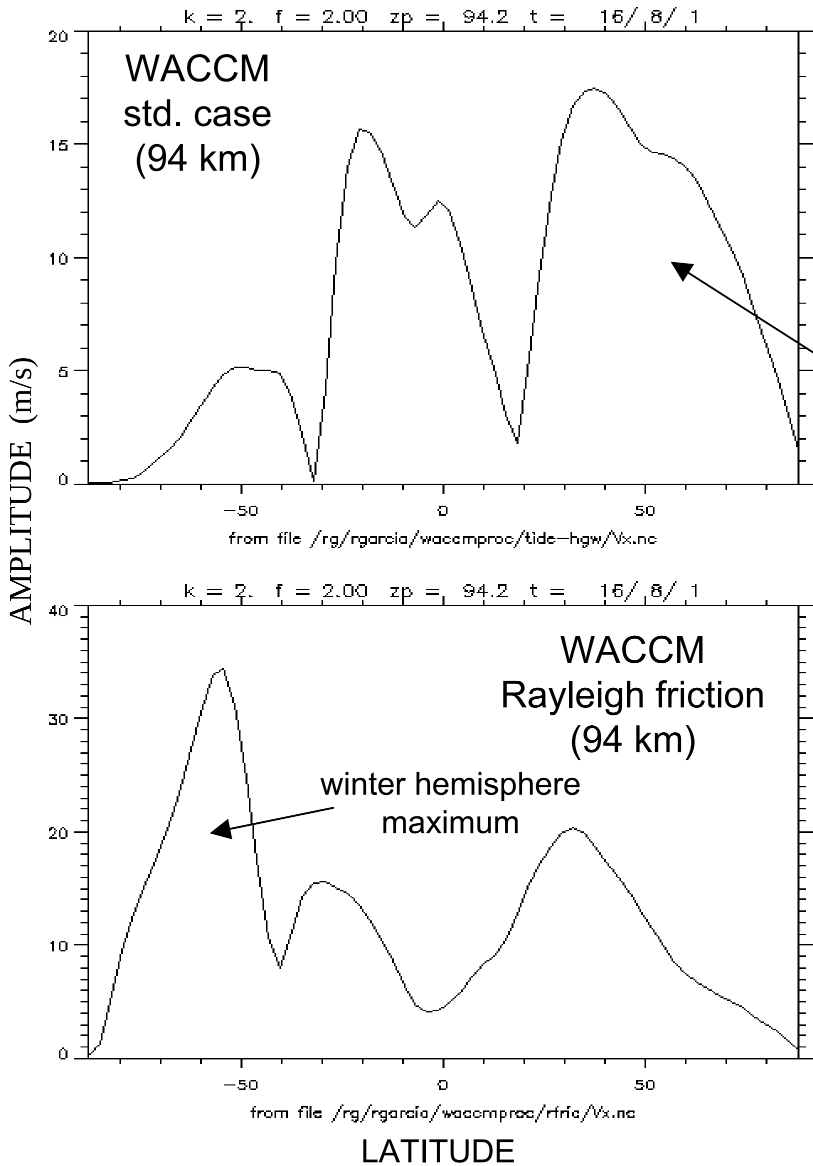
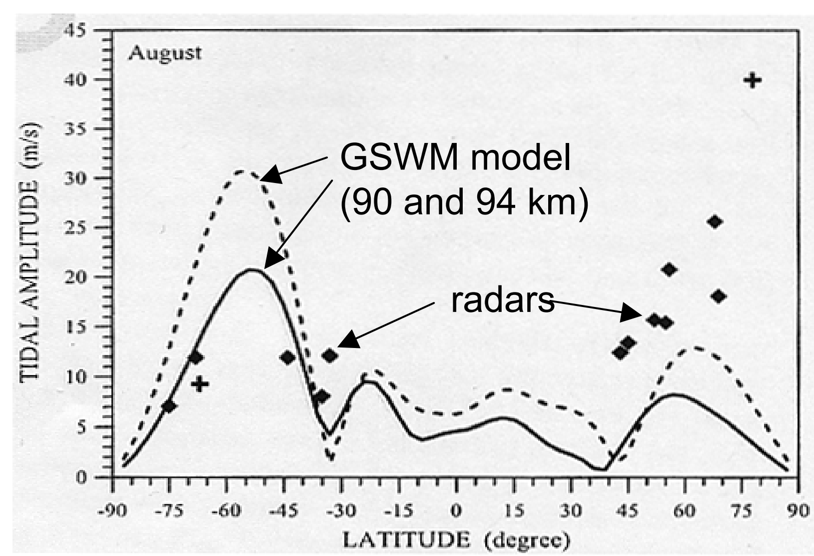


Semidiurnal V Tide
Latitudinal Structure
WACCM vs. Pancheva et al's
(JASTP, 2002) radar data (August)



Tidal contributions due to shortwave and convective heating

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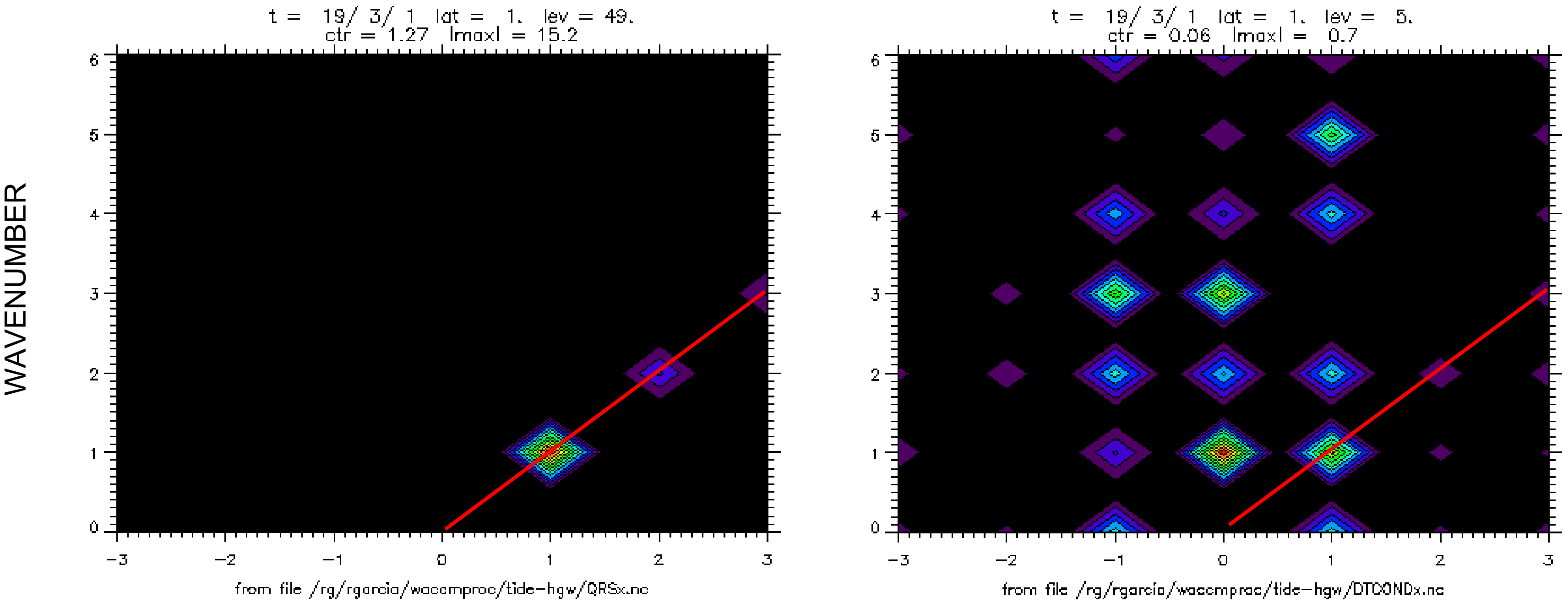
In the model,

- Shortwave heating excites mainly migrating components
- Convective heating excites migrating and non-migrating components

Short-wave (O_3) heating at 50 km

Convective heating at 5 km



FREQUENCY (cpd)

Diurnal "non-migrating" tides

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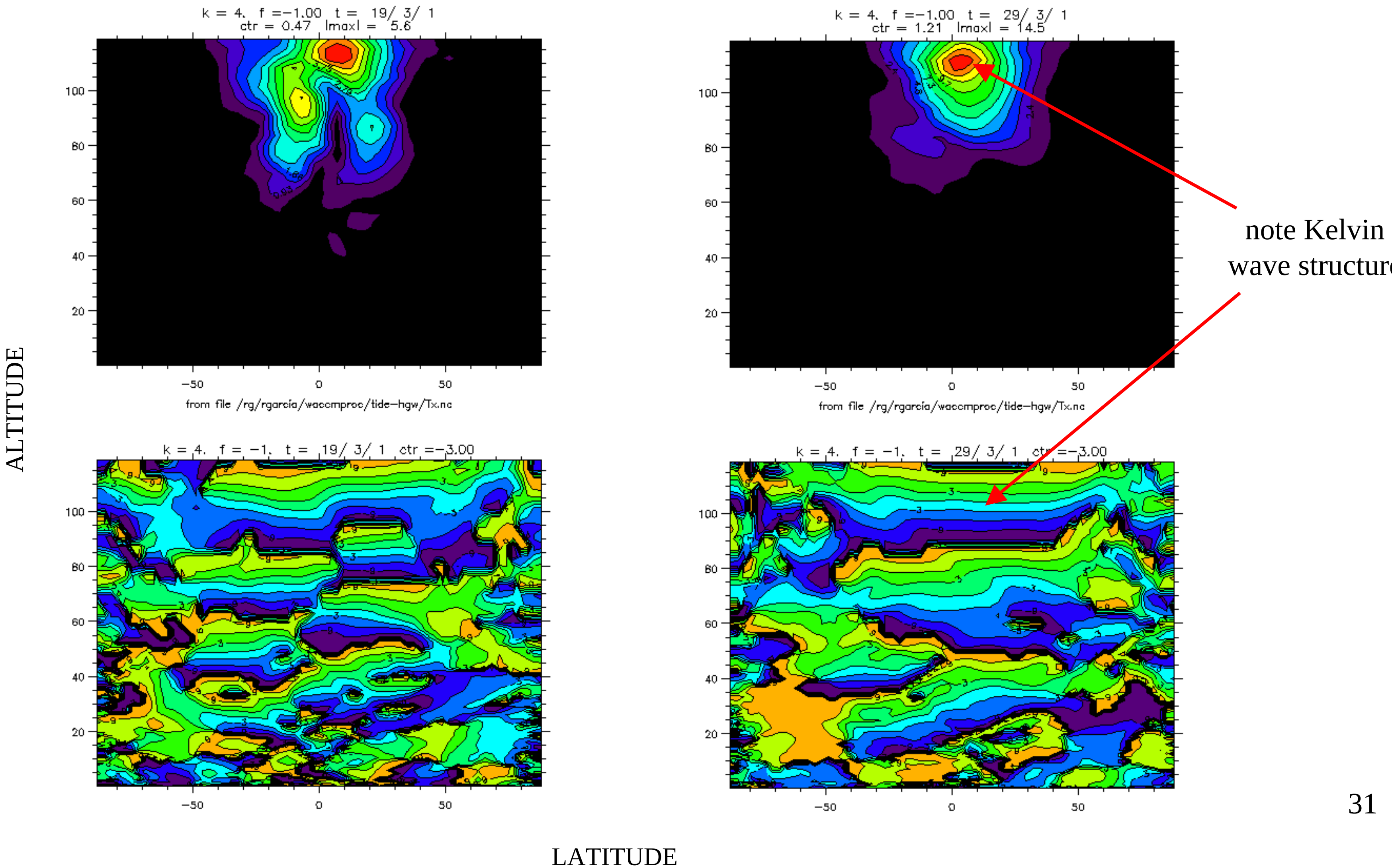
k=4 eastward T - March 19 | k=4 eastward T - March 29



Role of convective Heating in the excitation of "non-migrating" tides

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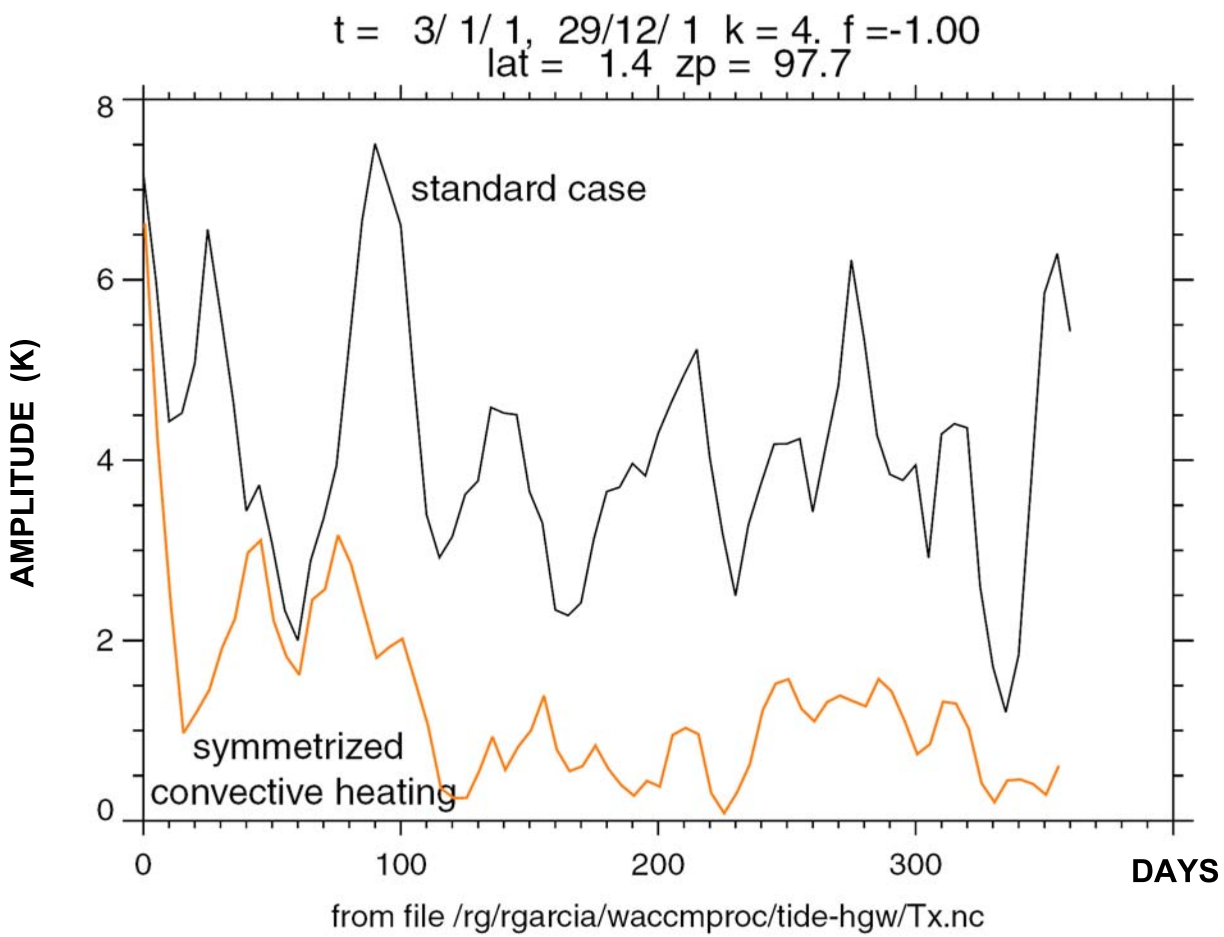
Annual Cycle: T at 98 km, Equator: k = 4 diurnal, eastward



Convective forcing of the tide is eliminated by "symmetrizing" the heating, i.e., zonally-averaging Q'_{conv} and applying the average at every longitude

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V' structure of 2-day wave (January): Modeled and observed

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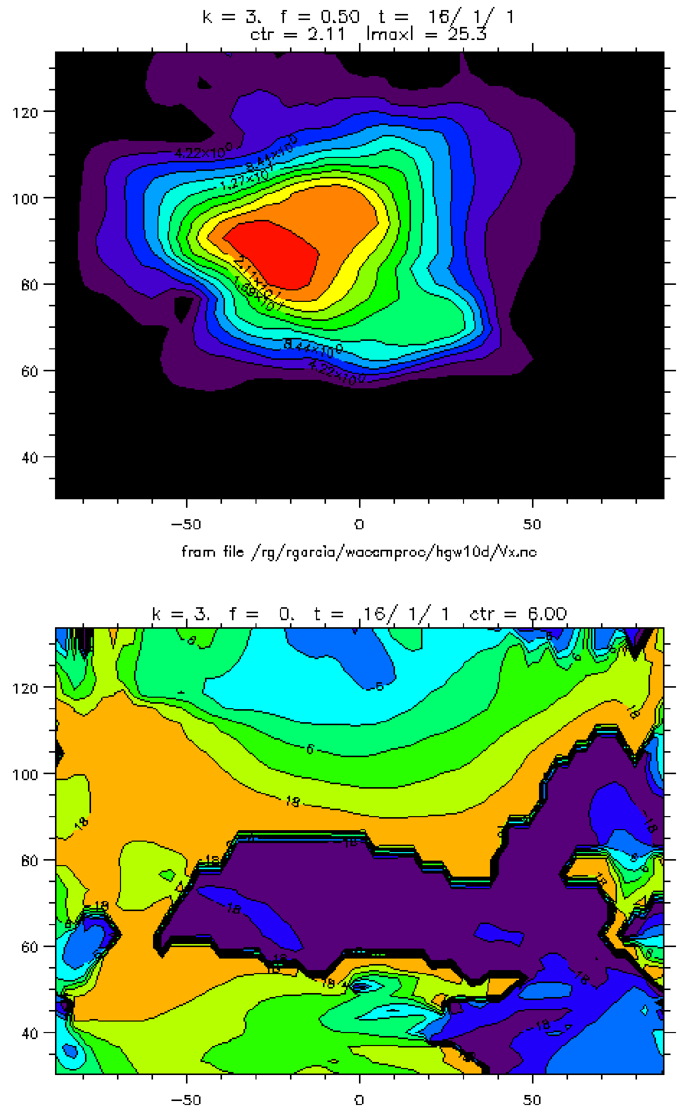
ALTITUDE



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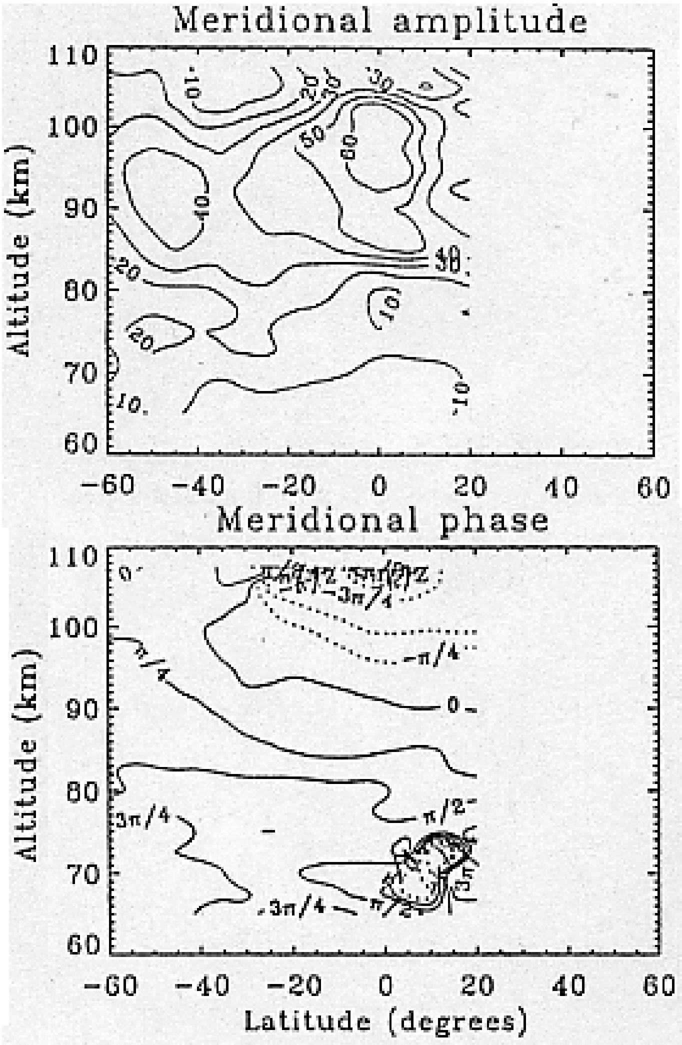

Wu et al (GRL, 1993) HRDI data

V' structure of 2-day wave (k = 3, t ~ 2days) and zonal-mean wind in January

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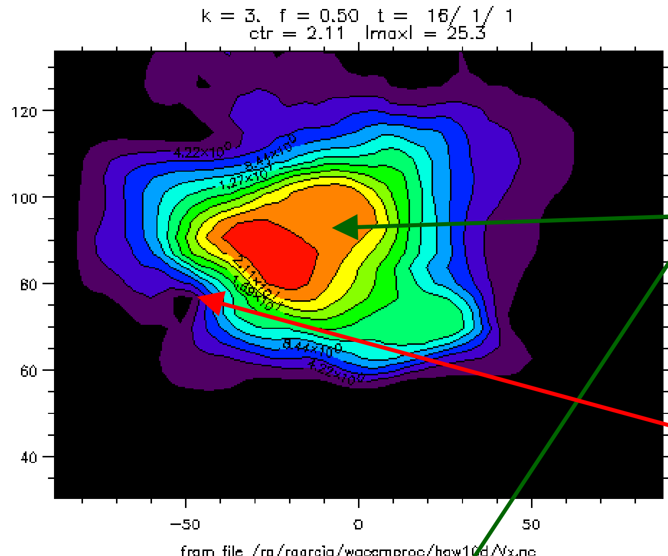
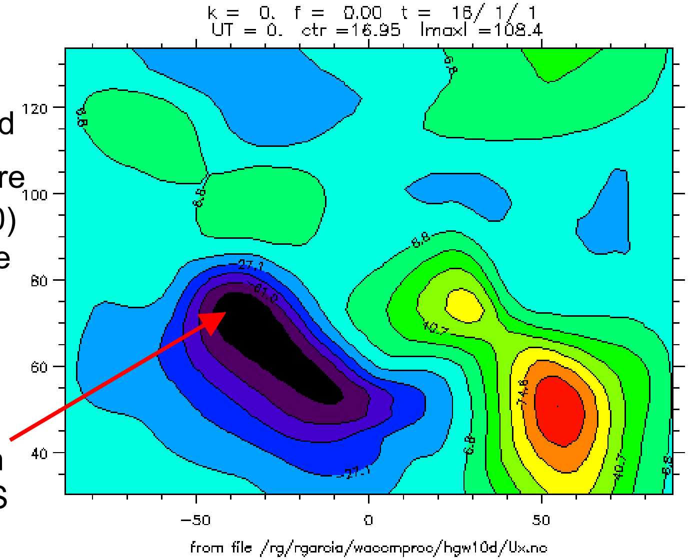


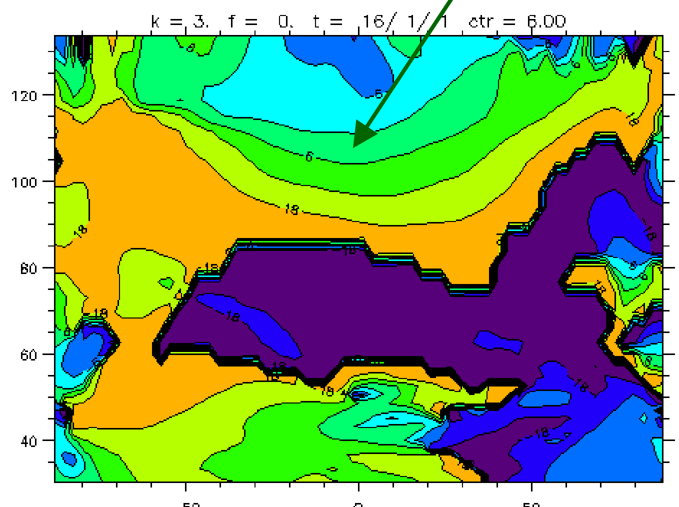


Amplitude and phase structure resemble (3,0) normal mode

q_y reverses in this region ~75 km, 45 S

ALTITUDE

LATITUDE



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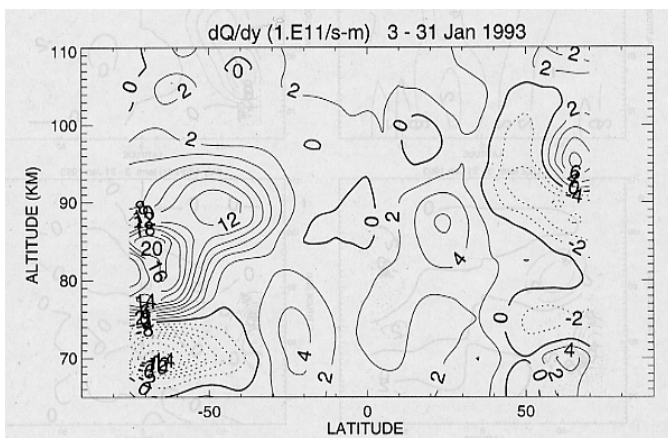

PV gradient from CIRA U (Fritts et al, JGR, 1999)

Seasonal evolution of 2-day wave amplitude (95 km) at Equator and zonal mean wind (75 km) at 30 N

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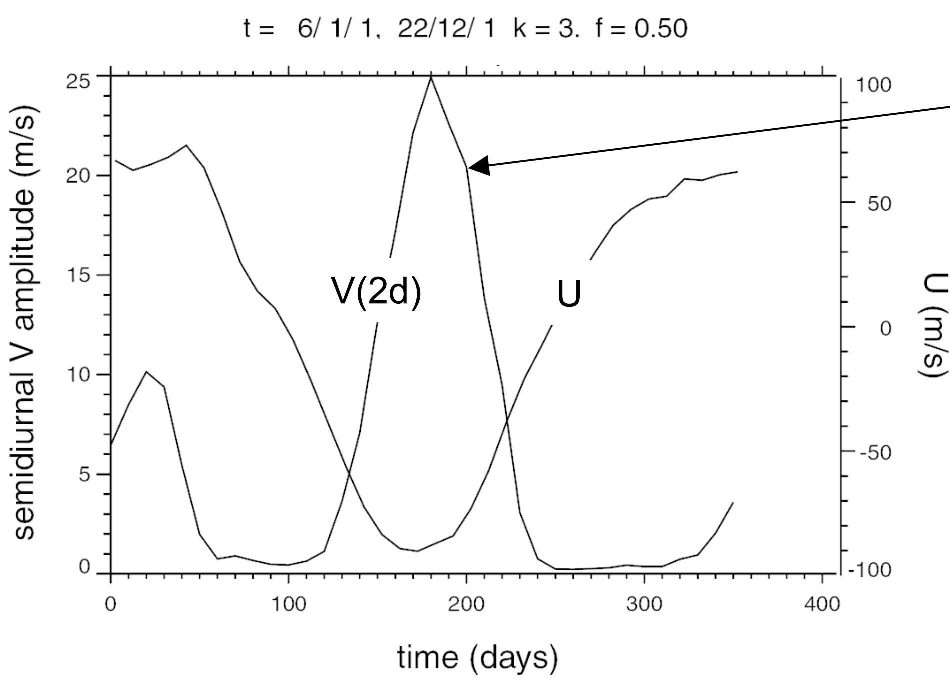
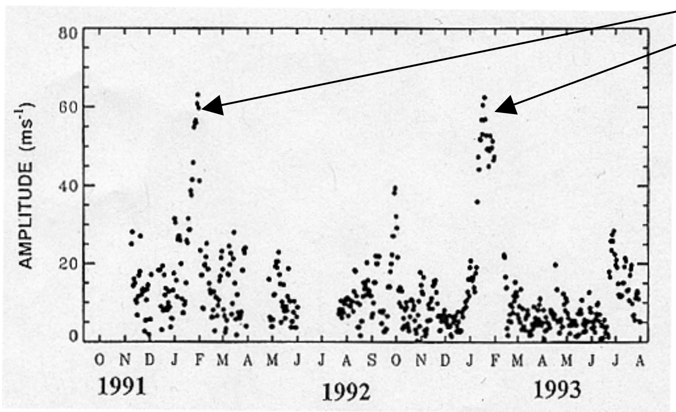


2-day amplitude maximizes at summer solstice; lags U slightly

summer solstice maxima



Wu et al (GRL, 1993)
2-day V' amplitude
10 S- 10 N average
at 95 km

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Water seasonal cycle at 100 mb
(courtesy of Mijeong Park and Bill Randel)

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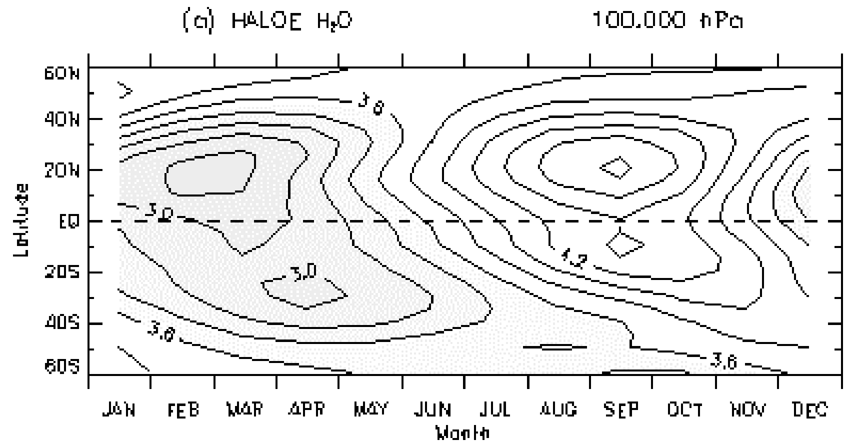
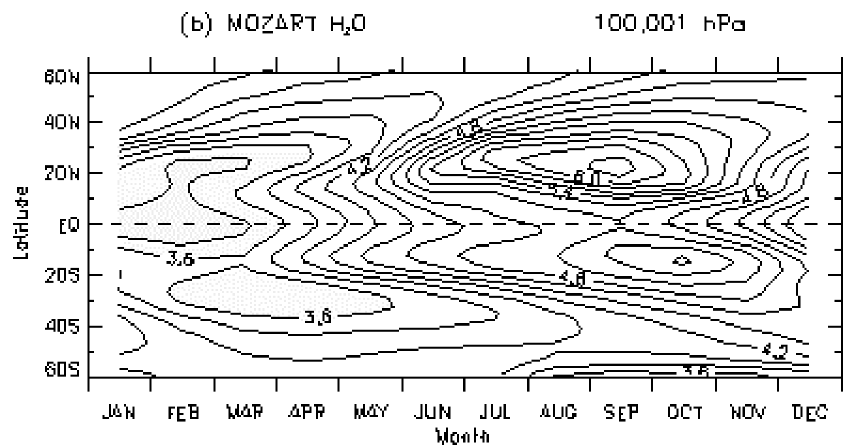
Water Vapor Distributions

HALOE

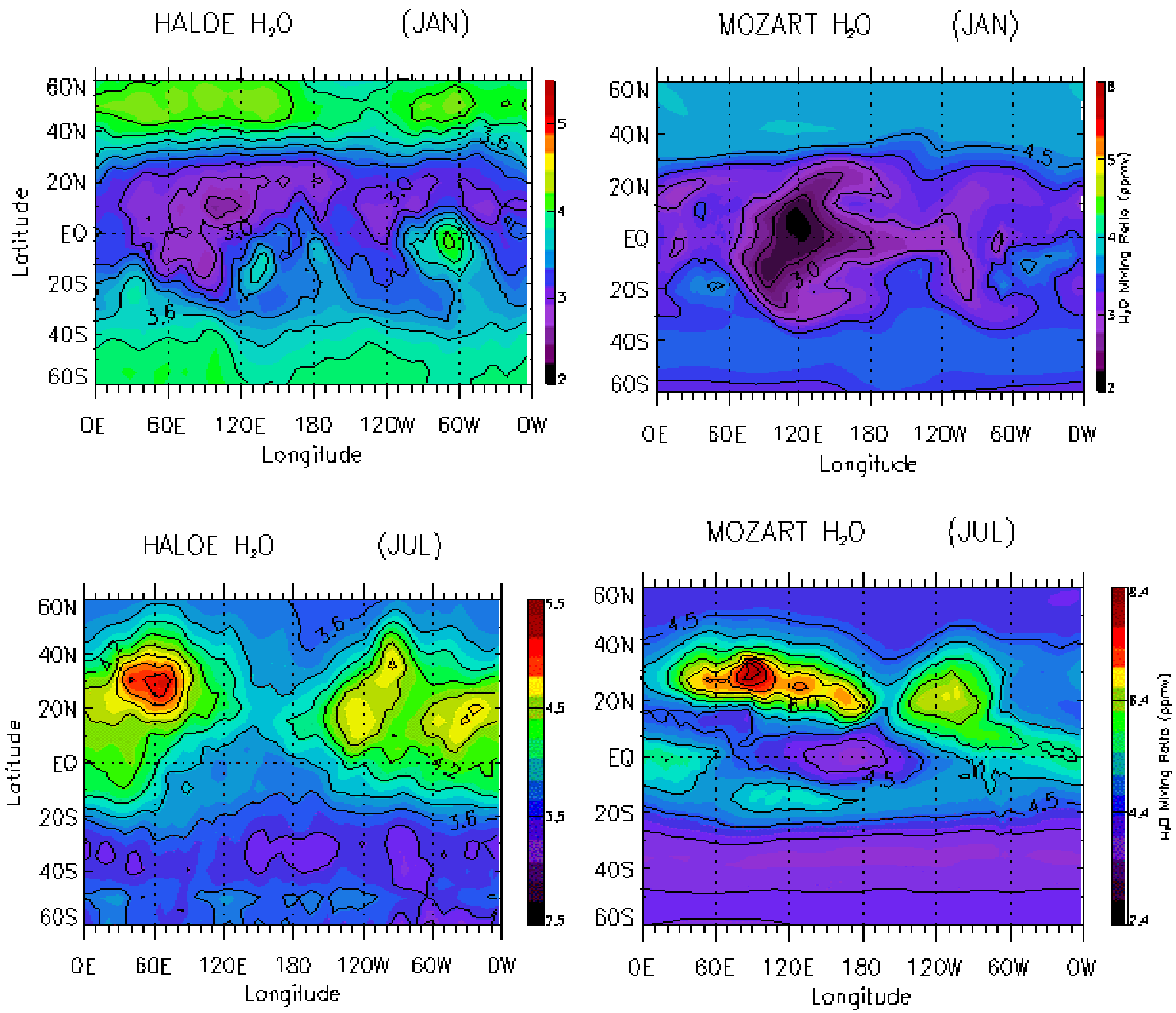


MOZART



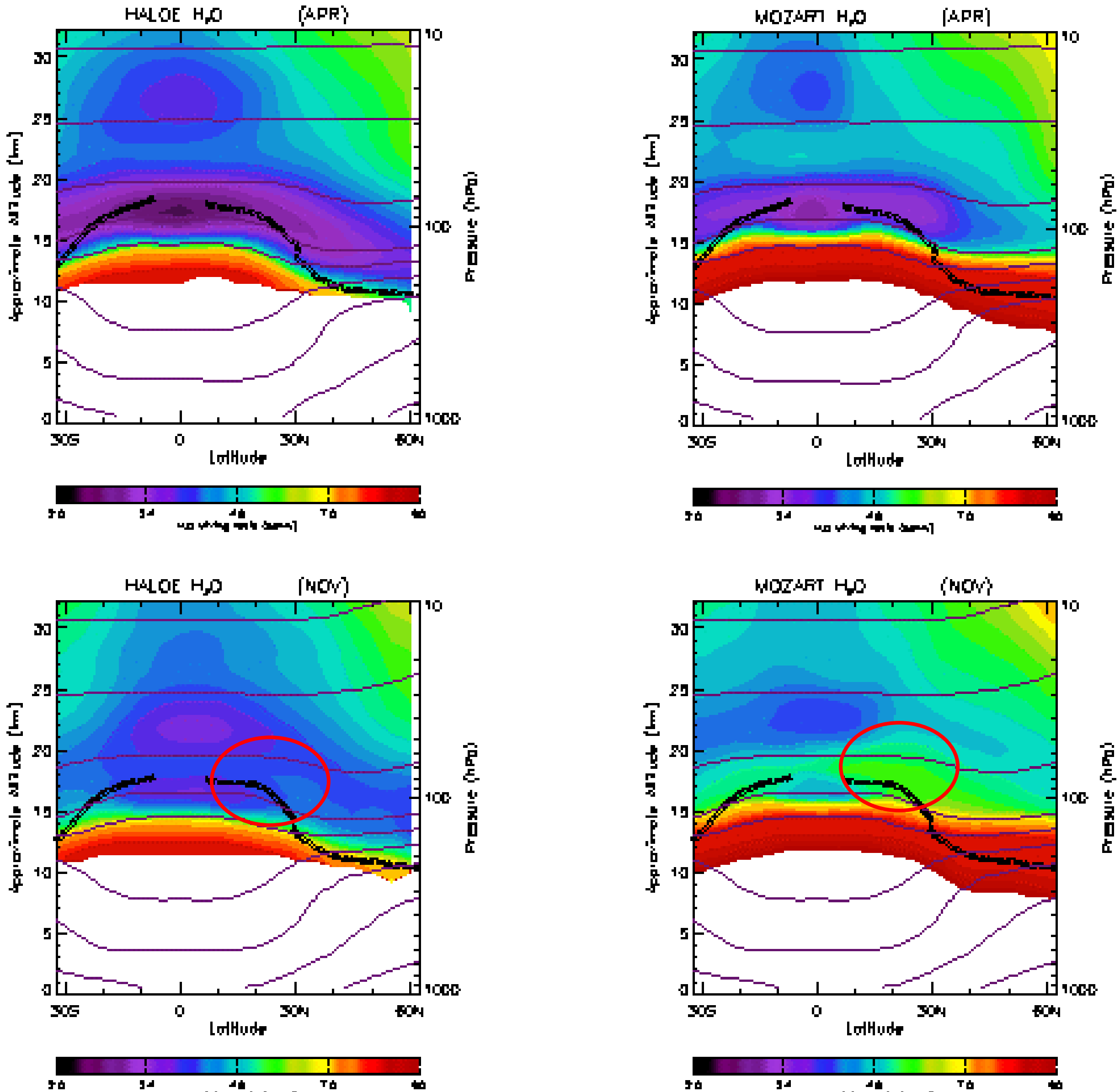
Water vapor at 100 mb: January and July (courtesy of Mijeong Park and Bill Randel)

NCAR

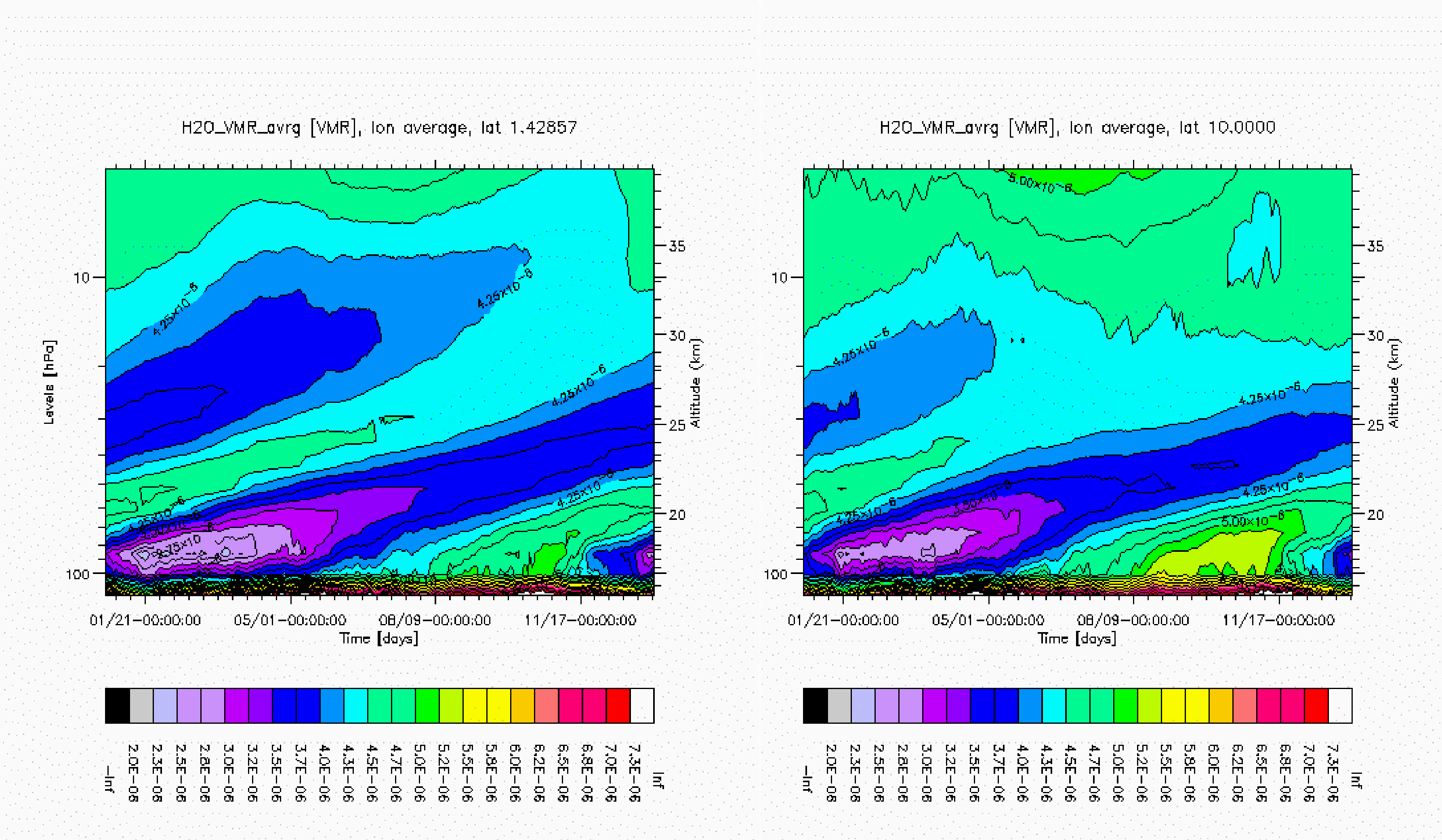


Water vapor in April, November: Meridional section through monsoon region (courtesy of Mijeong Park and Bill Randel)

NCAR



Water vapor "Tape Recorder"
Seasonal evolution at 1.4 and 10 N



Computed annual cycle of water vapor in the lower stratosphere

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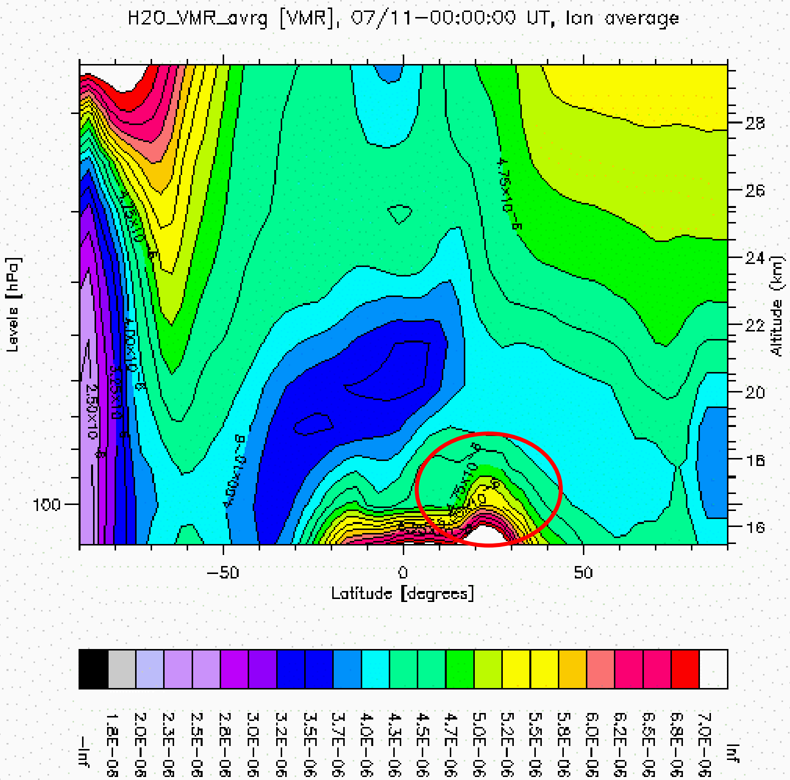
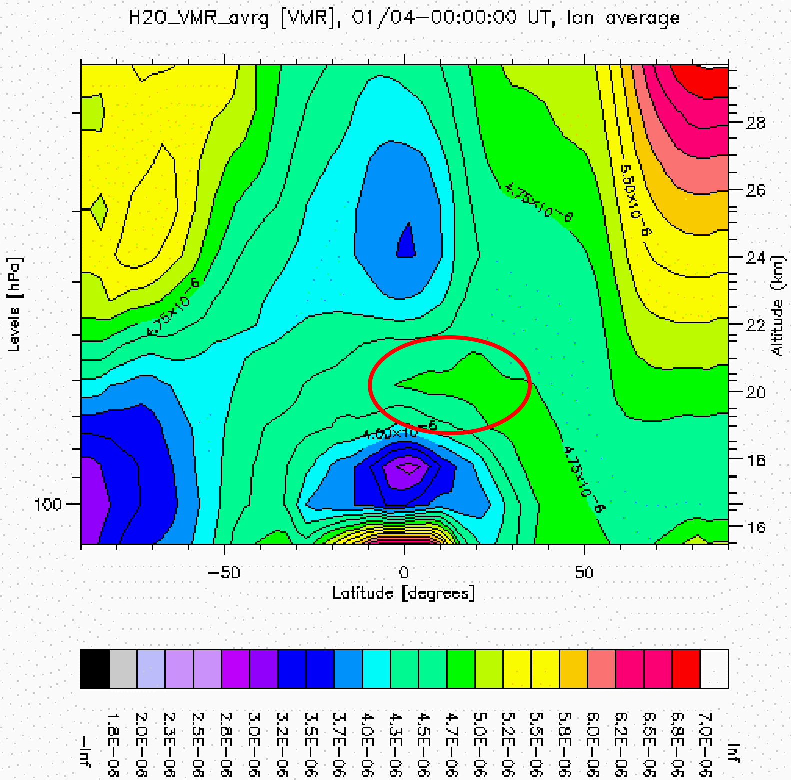
JULY



JANUARY



- Scientific motivation
- Model development
  - Physical processes
  - Chemistry
- Some initial results
  - Mesospheric thermal inversions
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The winter stratosphere and the tropospheric annular mode: Observations

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Northern annular mode in geopotential height: EOF index composites (Baldwin and Dunkerton, *Science*, 2001)

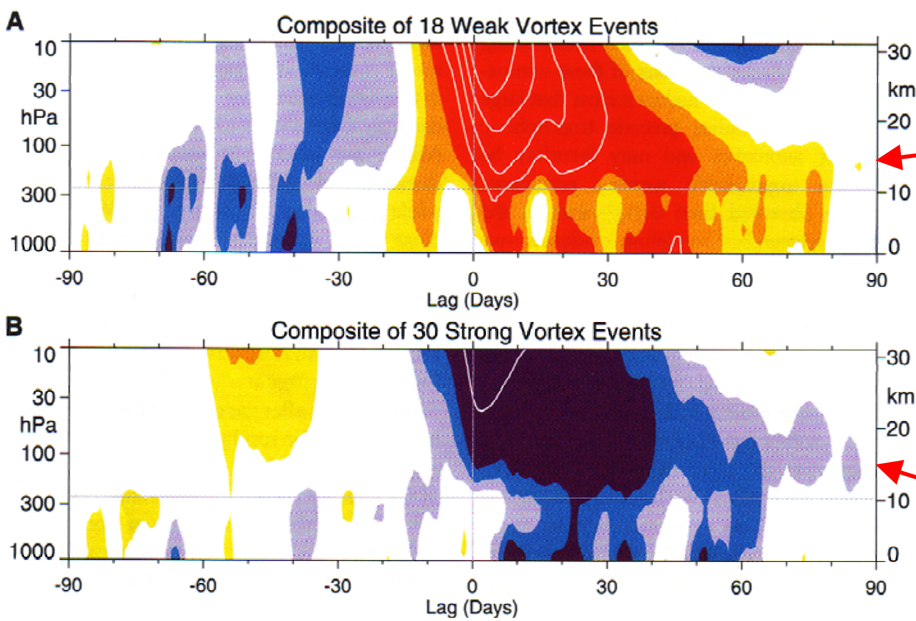

Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between −0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

annular mode in P_s

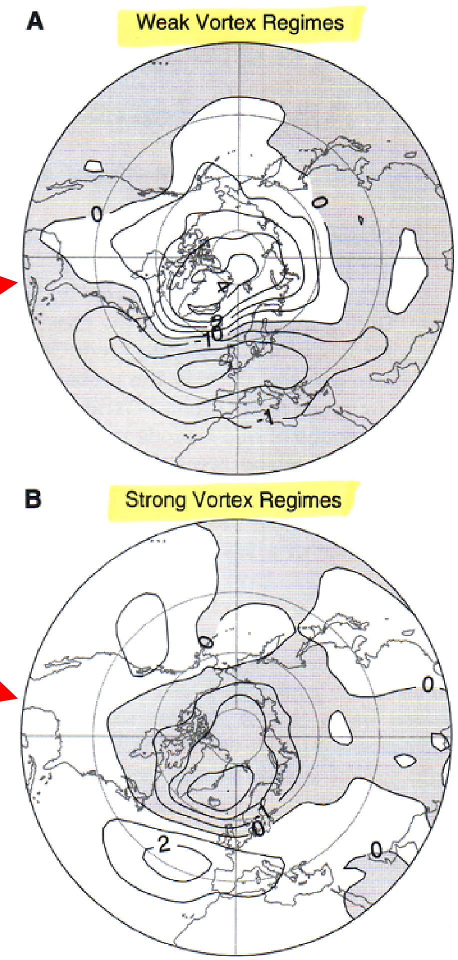

Fig. 3. Average sea-level pressure anomalies (hPa) for (**A**) the 1080 days during weak vortex regimes and (**B**) the 1800 days during strong vortex regimes.

Leading EOFs of 10 mb Geopotential and P_s from 46 yrs of WACCM monthly-mean results

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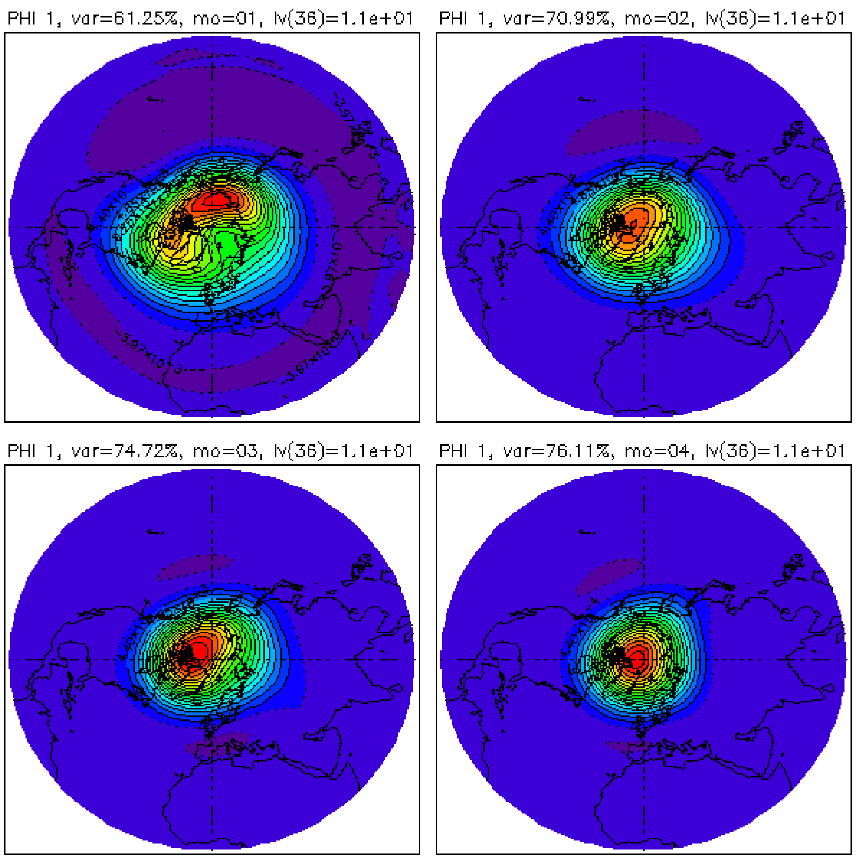
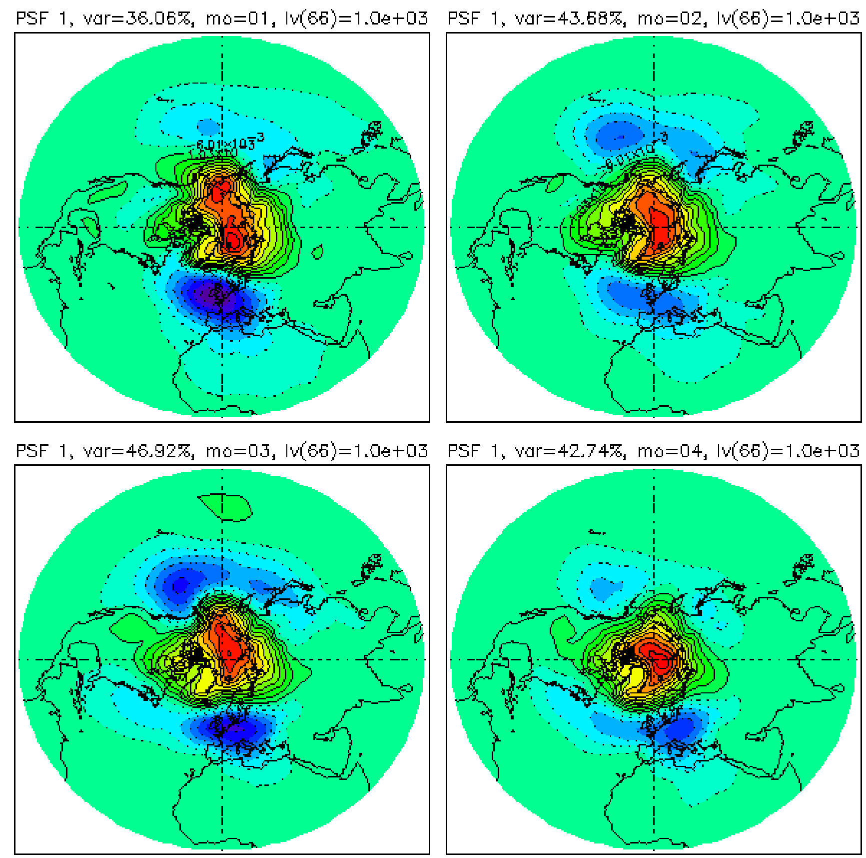
EOF1 of Geopotential at 10 mb, JAN-MAR (variance explained 61-76%)



EOF1 of Surface Pressure, JAN-MAR (variance explained 36-47%)



Correlations between monthly-mean EOF 1 of PHI (10 mb) and P_s

	P_s Jan	P_s Feb	P_s Mar	P_s Apr
Φ Jan	0.11	0.35	0.44	0.28
Φ Feb	0.27	0.45	0.65	0.56
Φ Mar	0.26	0.48	0.50	0.64
Φ Apr	0.10	0.35	0.29	0.54

Correlation coefficients > 0.4 are significant (95%)

Correlations between PHI (10 mb) EOF 1 and P_s EOF 1: two examples

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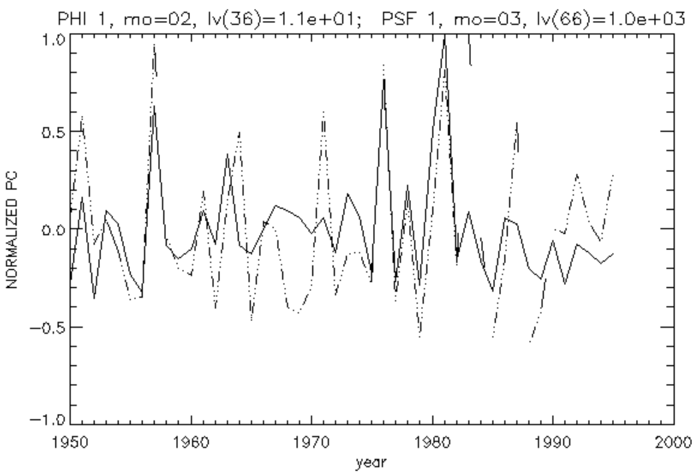
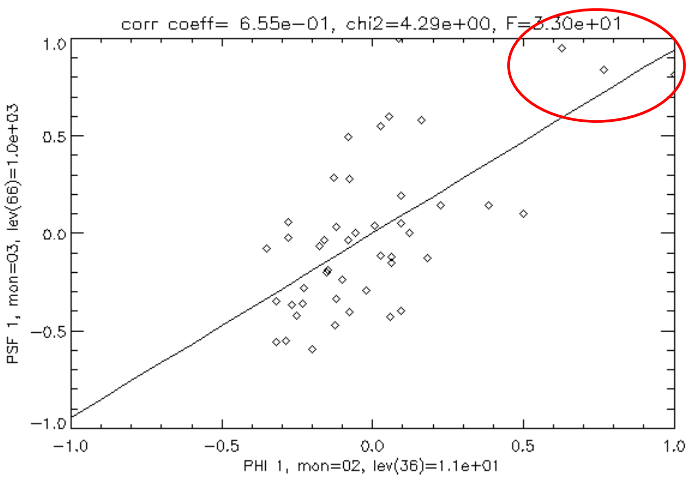
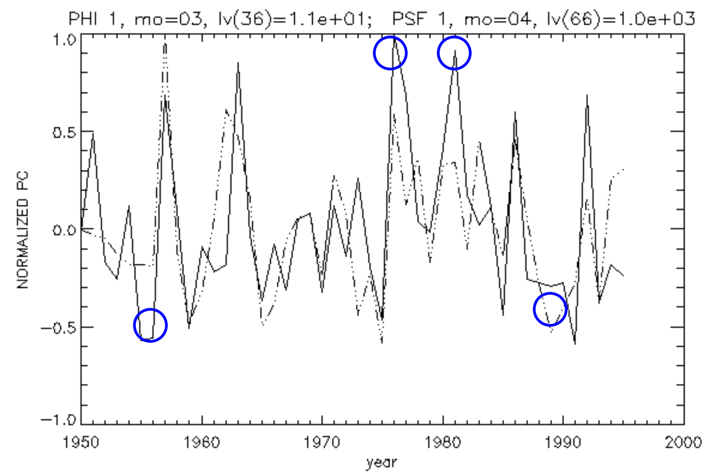
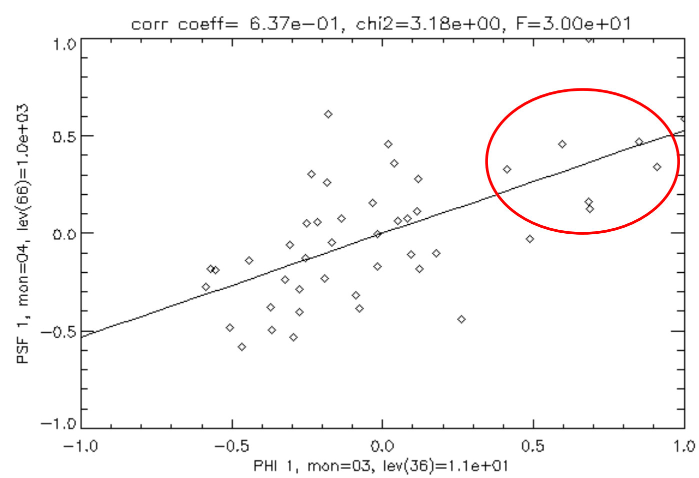
PHI (10 mb) FEB vs. Ps MAR





PHI (10 mb) MAR vs. Ps APR





Reconstruction of PHI(10 mb) and P_s (4 EOFs) for years of high and low PHI (10 mb) EOF 1

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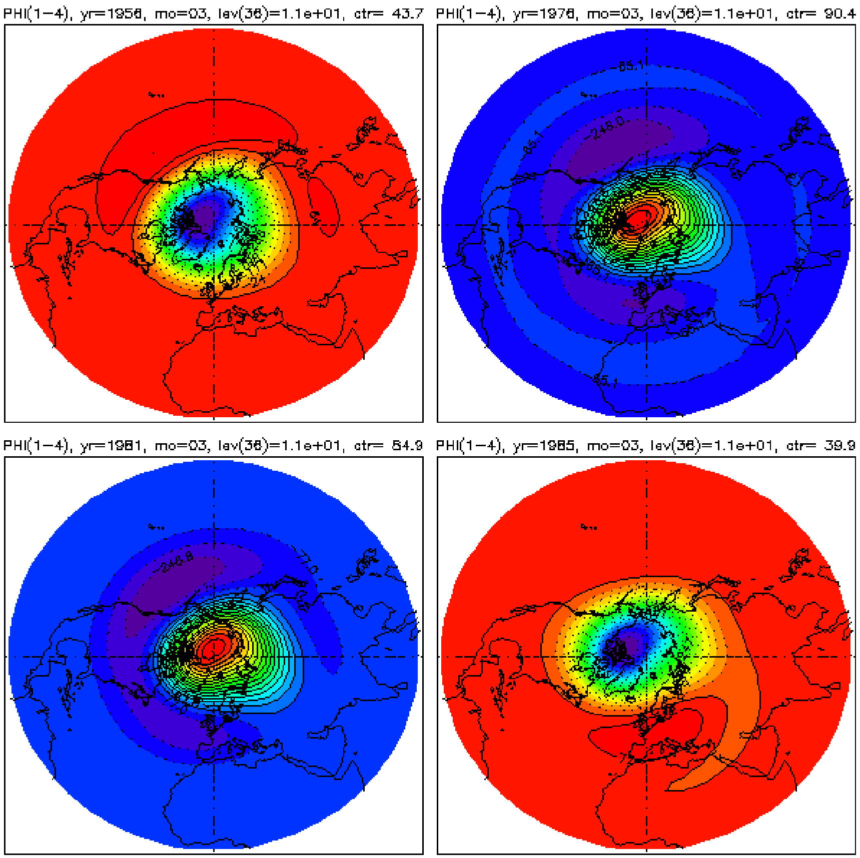
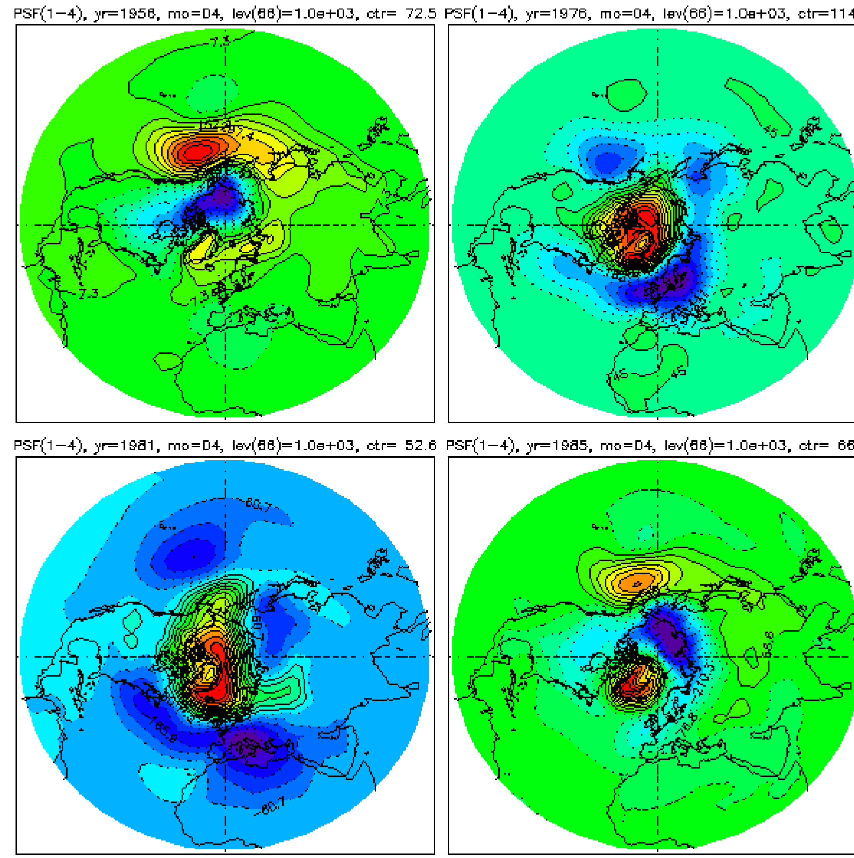
PHI (10 mb) MAR



P_s APR



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WACCM Workshop: June 20-21 (1:00 PM – 5:30 PM)

NCAR

Purpose:

- To provide a forum for scientists of diverse backgrounds to discuss topics related to coupling of atmospheric layers, from the troposphere to the lower thermosphere

- To establish guidelines for community involvement in WACCM

Format:

- A small number of invited talks (40-45 minutes), with an extended period of discussion (20 minutes) following each presentation

- No contributed talks. Workshop participants are encouraged to come prepared to contribute to the general discussion

WACCM Workshop Agenda

NCAR

THURSDAY, JUNE 20 (1:00 PM)
Front Range Theater, Radisson Hotel Conference Center

- 1:00 pm: Water vapor in the middle atmosphere
(A. Dessler, University of Maryland, USA)

- 2:00 pm: Effects of solar variability on the middle atmosphere
(K. Kodera, Meteorological Research Institute, Tsukuba, JAPAN)

- 3:00 pm: BREAK

- 3:30 pm: Dynamics of the MLTI Region
(J. Forbes, University of Colorado, Boulder, CO, USA)

- 4:30 pm: Modeling and Observations of the Atmospheric Thermal Structure, Chemical Composition, and Radiation Balance using WACCM and Satellite Data
(M. Mlynczak, NASA L.R.C., Hampton, VA, USA)

WACCM Workshop Agenda

NCAR

FRIDAY, JUNE 21 (1:00 PM)
Front Range Theater, Radisson Hotel Conference Center

- 1:00 pm: Convective parameterizations and tropical dynamics
(L. Ricciardulli, Remote Sensing Systems, Santa Rosa, CA, USA)

- 2:00 pm: Modeling the Quasibiennial Oscillation
(M. Giorgetta / E. Manzini, Max Planck Institute, Hamburg, GERMANY)

- 3:00 pm: BREAK

- 3:30 pm: The winter stratosphere and the "annular mode"
(T. Dunkerton, NorthWest Research Associates, Bellevue, WA, USA)

- 4:30 pm: General Discussion: Model Status and Guidelines for Use
(led by B. Boville, NCAR/CGD)