NCAR WACCM Whole Atmosphere Community Climate Model

WACCM studies of the upper atmosphere

Dan Marsh
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CEDAR, 2009

Outline

- WACCM-3 description
- A summary of current research:
  - Tides in WACCM
  - WACCM-X
  - PMC studies
  - Sodium Chemistry
- How to obtain WACCM
- Summary

Winter, 1999

UCAR Quarterly

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH
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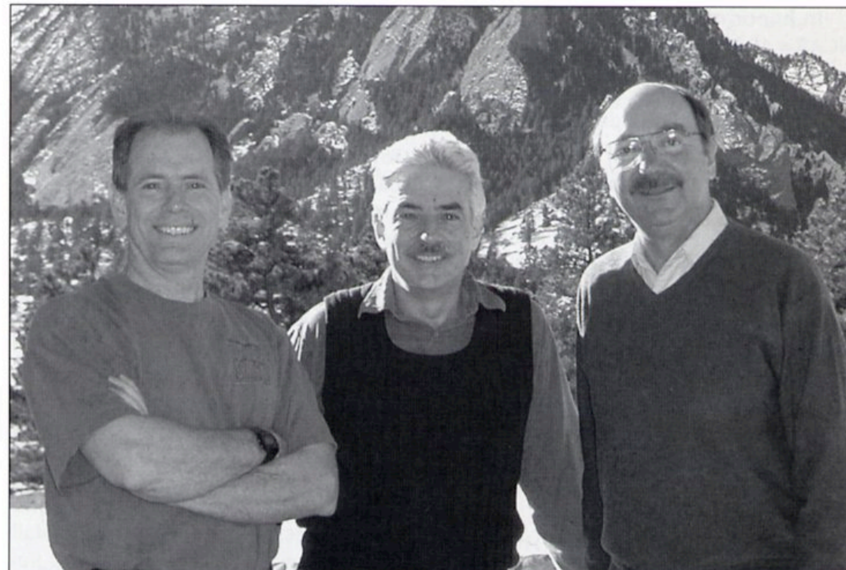
It's about TIME: A new upper-atmosphere model

by Carol Rasmussen

Ray Roble, a senior scientist in the High Altitude Observatory, has spent the last 20 years or so creating and refining a general circulation model of the upper atmosphere—the transition zone between the bulk of the atmosphere below 30 kilometers and the void above 500 km. Now, the knowledge Roble has amassed in developing his thermosphere-iono-sphere-mesosphere electrodynamics general circulation model (TIME-GCM) is being incorporated into the middle atmosphere community climate model, an offspring of NCAR's CCM family that was created by Byron Boville (Climate and Global Dynamics Division). A third co-principal investigator, Rolando Garcia, and colleagues in NCAR's Atmospheric Chemistry Division (ACD) will be adding chemistry components to the model.



Byron Boville, Rolando Garcia, and Ray Roble. (Photo by Carlye Calvin.)

"A year from now, we expect to have a model that extends from the surface to 120 kilometers and includes ozone chemistry," says Boville. The yet-unnamed composite model will be one of only two or three general circulation models to reach that altitude. Some GCMs only extend to 30 km, including the troposphere and part of the lower stratosphere; a few have been extended into the mesosphere, with upper boundaries in the range of 60–80 km. The new model will include the entire mesosphere as well as the lower thermosphere. But the plan doesn't stop there. Further into the future, the scientists will add thermos-

electrically charged atoms and molecules of the ionosphere are ionized by solar radiation and aurora particle precipitation. This happens throughout the atmosphere, but in the denser air lower down, charged particles quickly bump into oppositely charged particles and recombine. In the sparsely populated ionosphere, ionized parti-

WACCM Project Goals

Develop a state of the art, “high-top”, numerical model with coupled chemistry that will serve the needs of the scientific community

Conduct research to understand the coupling between atmospheric layers, the role of chemical and physical processes in defining these couplings, and the interaction between the Earth’s atmosphere and the Sun

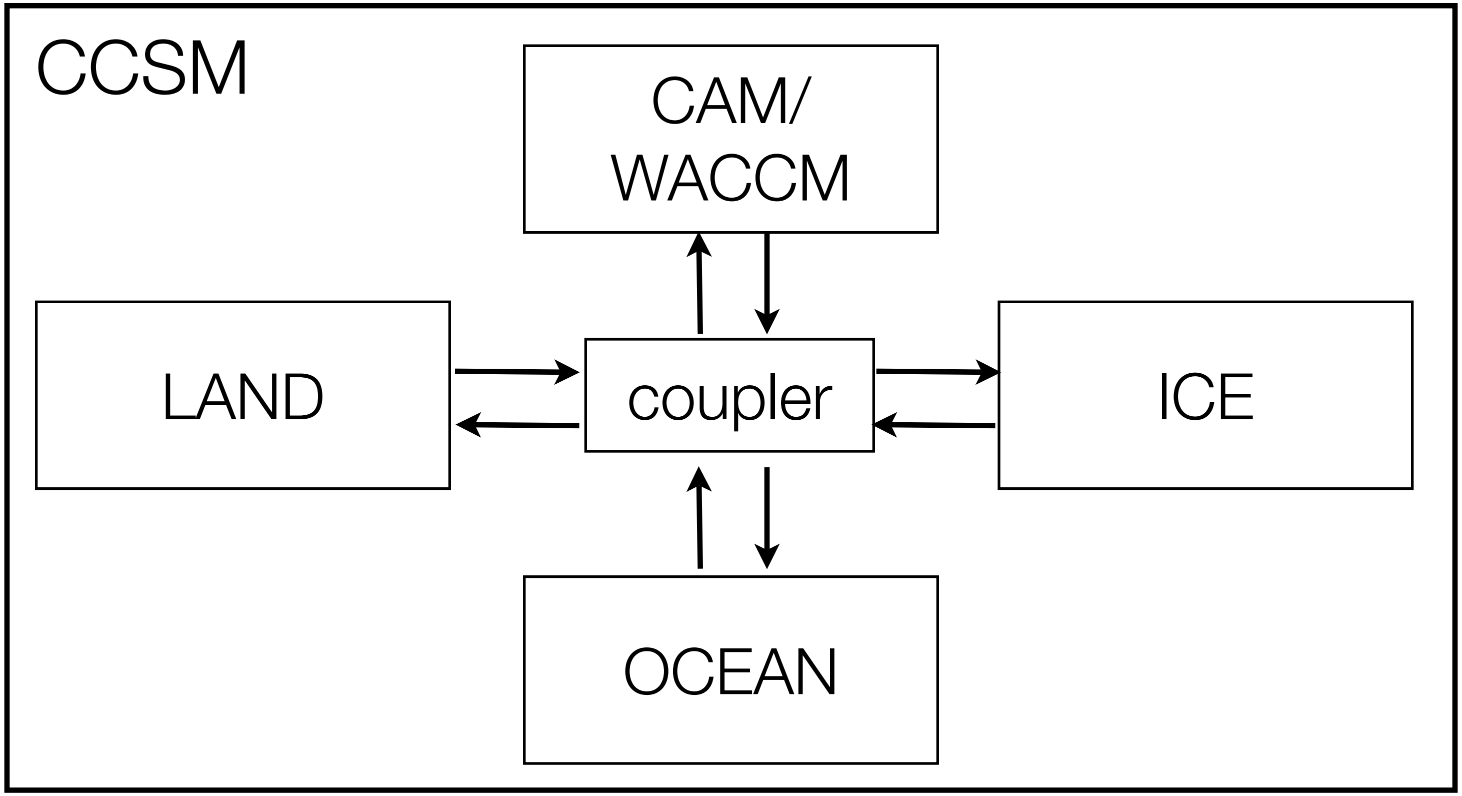
Acknowledgement

WACCM Development Contributors:

Charles Bardeen, Byron Boville, Chris Fischer, Benjamin T. Foster, Rolando R. Garcia, Andrew Gettelman, Maura E. Hagan, Charles Jackman, Douglas E. Kinnison, Han-Li Liu, Jospeph M. McInerney, Daniel R. Marsh, Astrid Maute, Aimee Merkel, Mike Mills, Liying Qian, Cora Randall, Arthur D. Richmond, Jadwiga H. Richter, Raymond G. Roble, Fabrizio Sassi, Anne K. Smith, Stanley C. Solomon, Francis Vitt

WACCM description

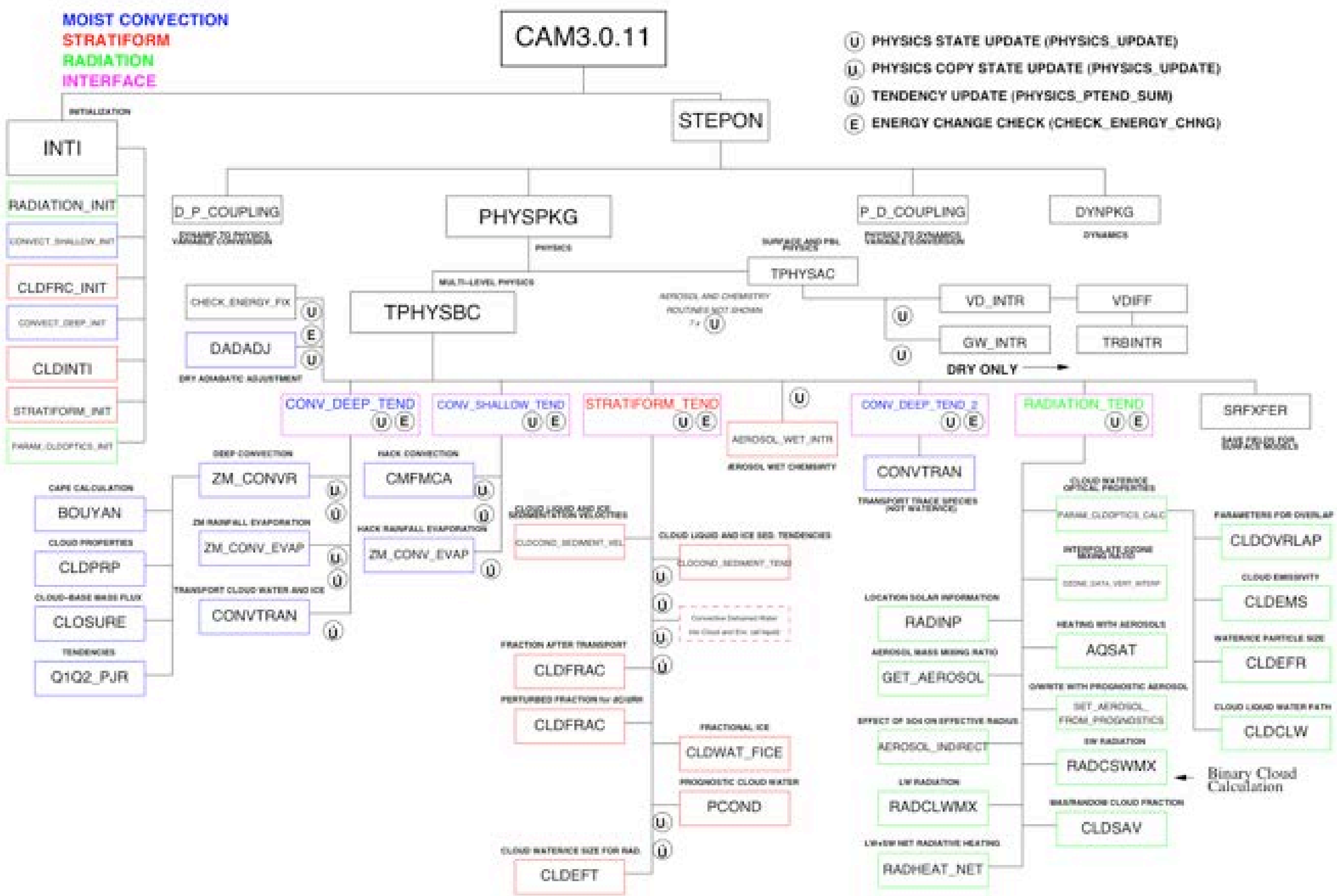
- WACCM is an extension of the Community Atmosphere Model (CAM) - the atmospheric component of the Community Climate System Model



WACCM
Whole Atmosphere Community Climate Model

NCAR

Community Atmosphere Model Flowchart



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WACCM-3.5

Model Framework	Dynamics	Tracer Advection	Resolution	Chemistry	Other Processes
Extension of the NCAR Community Atmosphere Model version 3 (CAM3) Based upon CAM3.5.48	Finite Volume Dynamical Core (Lin, 2004) Fully-interactive with chemistry, i.e., consistent with model-derived, radiatively active gases: O3, CO2, CH4, N2O, H2O, CFC11, CFC12, O2, NO	Flux-form Finite Volume (Lin, 2004)	Horizontal: 1.9° x 2.5° (lat x lon) Vertical: 66 levels 0-140km < 1.0km in UTLS 1-2 km in stratosphere ~3 km in MLT	Middle Atmosphere Mechanism: 57 Species including Ox, HOx, NOx, BrOx, and ClOx Heterogeneous chemistry E-region Ion Chemistry	GW Param.: convection-, frontal-, and orographically-generated Molecular Diffusion: Banks and Kockarts, 1973 Auroral processes, including ion drag, and Joule heating LW/SW and chemical potential heating

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WACCM-3 Chemical Constituents in MA Mechanism

Long-lived Species: (17-species)

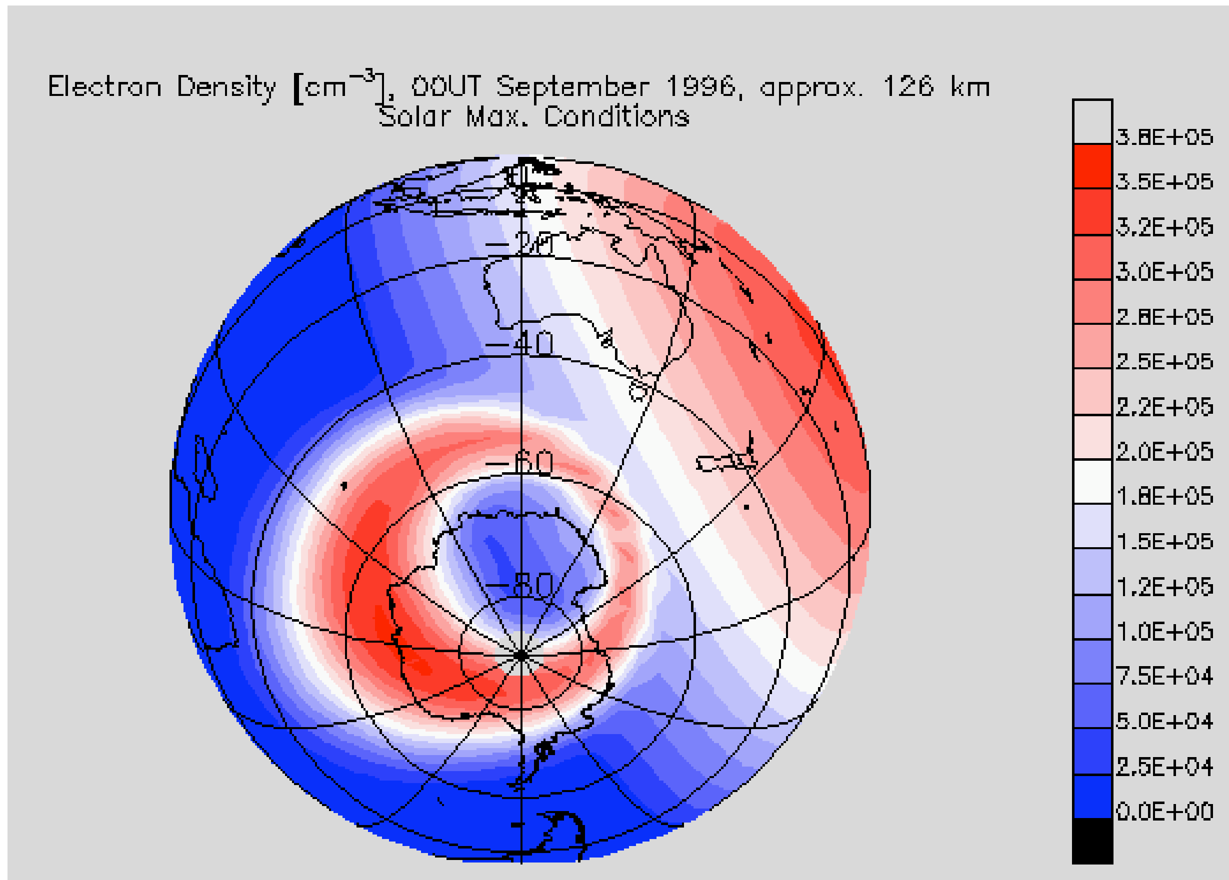
- Misc: CO_2, CO, CH_4, H_2O, N_2O, H_2, O_2
- CFCs: CCl_4, CFC-11, CFC-12, CFC-113
- HCFCs: HCFC-22
- Chlorocarbons: CH_3Cl, CH_3CCl_3,
- Bromocarbons: CH_3Br
- Halons: H-1211, H-1301
- Constant Species: N_2

Short-lived Species: (34 neutrals + 5 ions + electrons)

- O_X: O_3, O, $O(^1D)$
- NO_X: N, 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
- HC Species: CH_2O, CH_3O_2, CH_3OOH
- Ions: N^+, N_2^+, NO^+, O^+, O_2^+
- Other: $O_2(^1\Sigma)$, $O_2(^1\Delta)$, $N(^2D)$, e

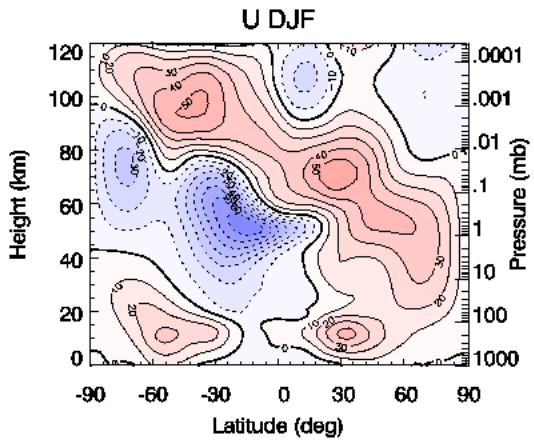
WACCM-3

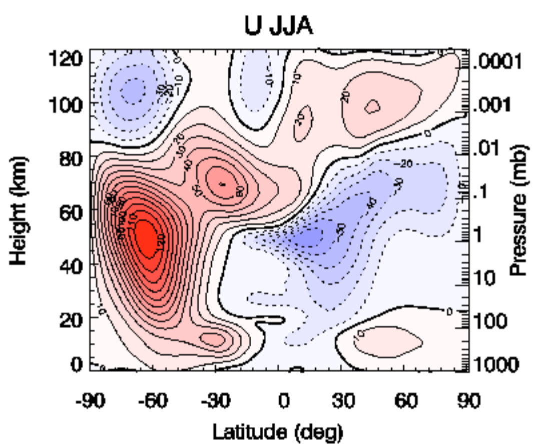
- WACCM modifications for the upper atmosphere:
  - Variability of solar spectrum
  - Chemical heating
  - Airglow
  - E-region ion chemistry (5 ions & electrons)
  - EUV and x-ray ionization
  - Auroral processes
    - Particle precipitation
    - Ion drag
    - Joule heating



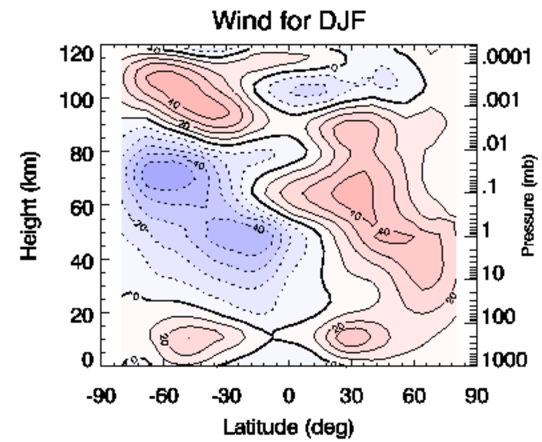
Zonal winds 0-120 km

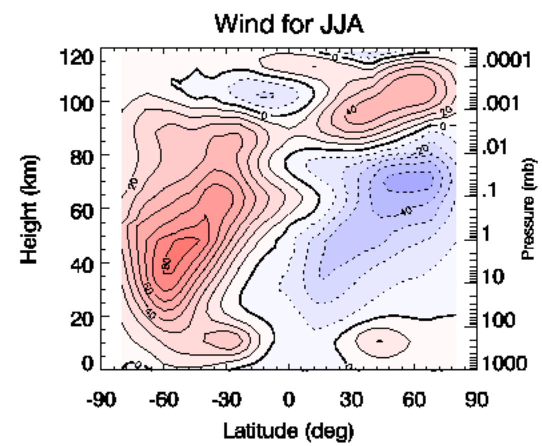
WACCM3.6





URAP





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Atmospheric Tides in WACCM

with R.R. Garcia and A.K. Smith

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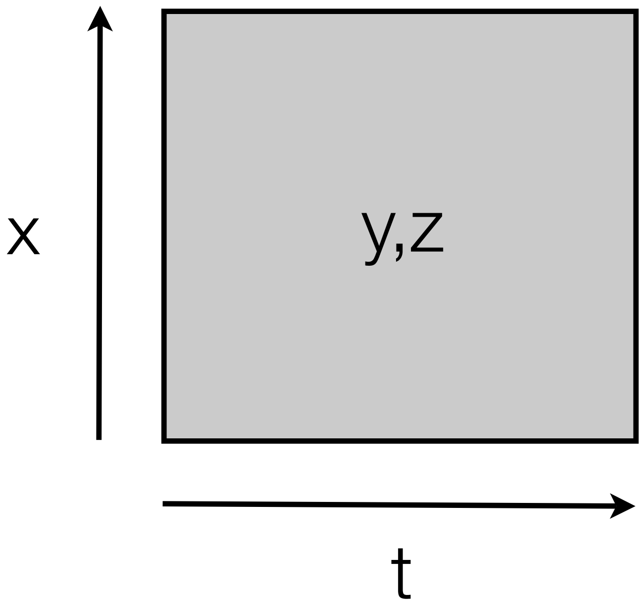
Monthly mean tidal diagnostics



Applied to u, v, T, and PS. Calculated and output once per month

Amplitude and phase calculated at each height (z) and latitude (y)

Post-processing:
migrating and non-migrating modes can be separated by FFT expansion in longitude of the tidal coefficients

Example for the diurnal tide:

The diurnal tide for each month of output can be represented with two coefficients, C_{24} and S_{24}, at each gridpoint (x, y, z):

$$T_d = C_{24} \cdot \cos\left(\frac{2\pi t}{24}\right) + S_{24} \cdot \sin\left(\frac{2\pi t}{24}\right)$$

t **= universal time (hr)**

During the model run, calculate C_{24} and S_{24} by accumulating the following sums at each time step:

$$C_{24} = \frac{2}{N} \sum_1^N T(t_n) \cos\left(\frac{2\pi t_n}{24}\right)$$

$$S_{24} = \frac{2}{N} \sum_1^N T(t_n) \sin\left(\frac{2\pi t_n}{24}\right)$$

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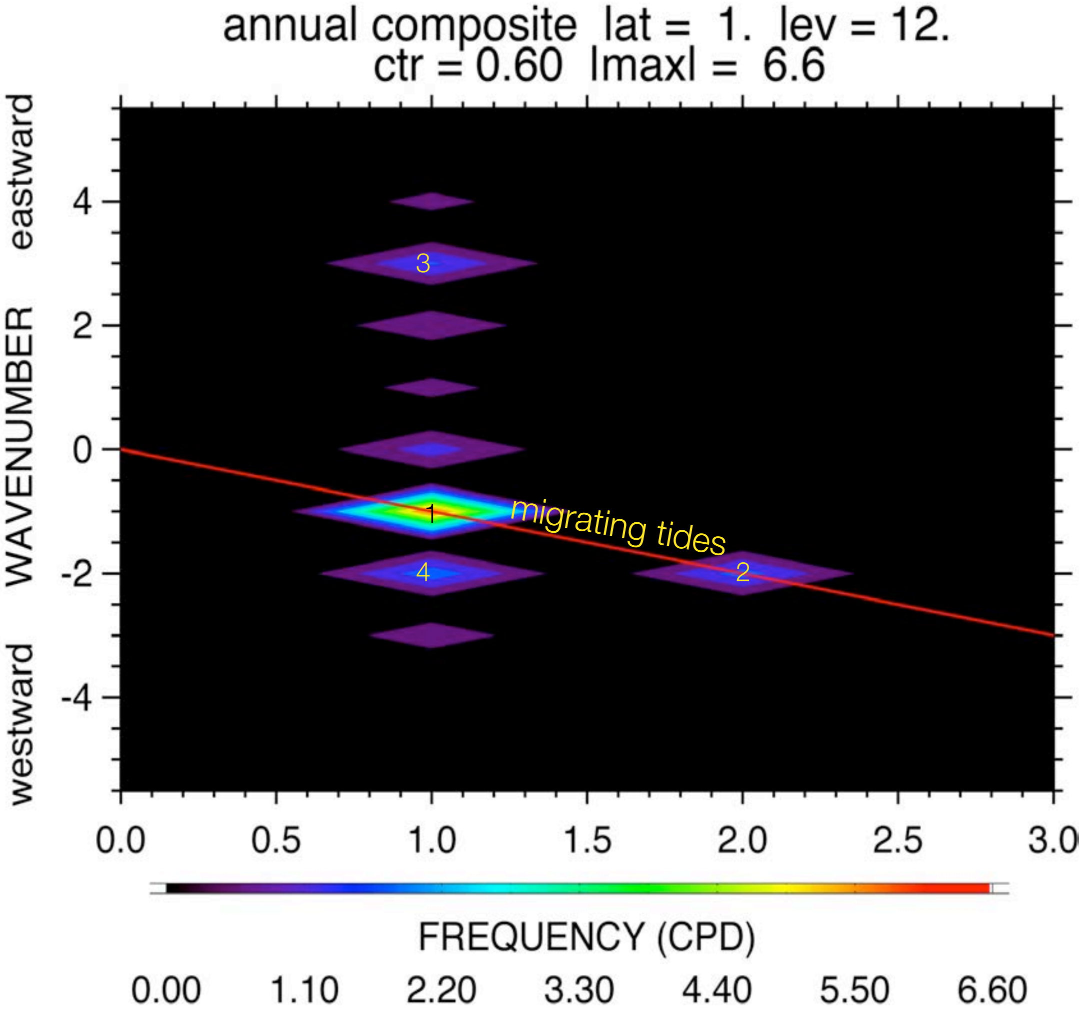
Equatorial spectrum at 12 SH (~85 km)



1: m=1 migrating diurnal
2. m=2 migrating SD
3. m=3 diurnal eastward
4. m=1 SD westward

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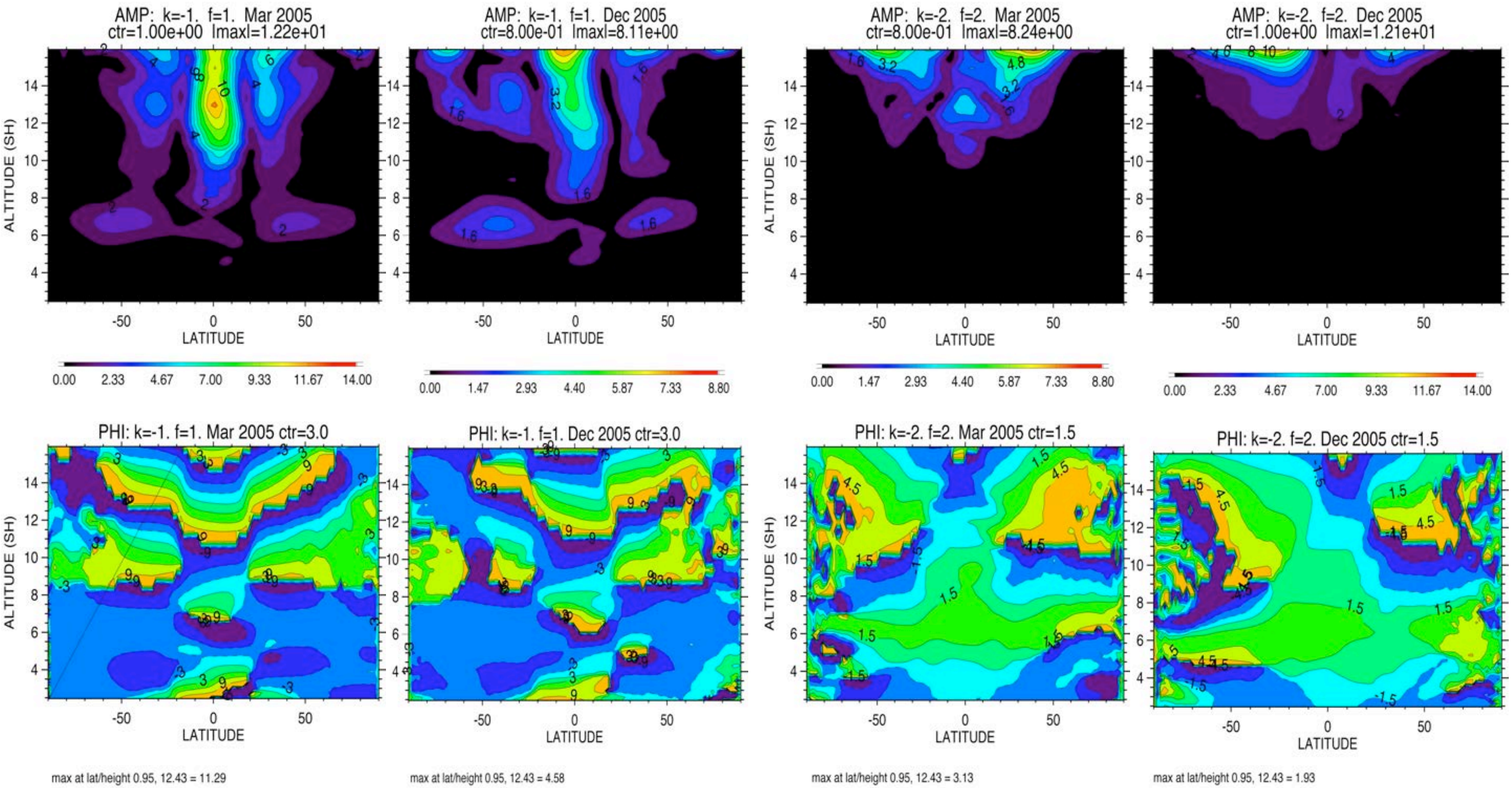
Structure of modeled migrating temperature tides

T diurnal westward 1 — March, December

T semidiurnal westward 2 — March, December



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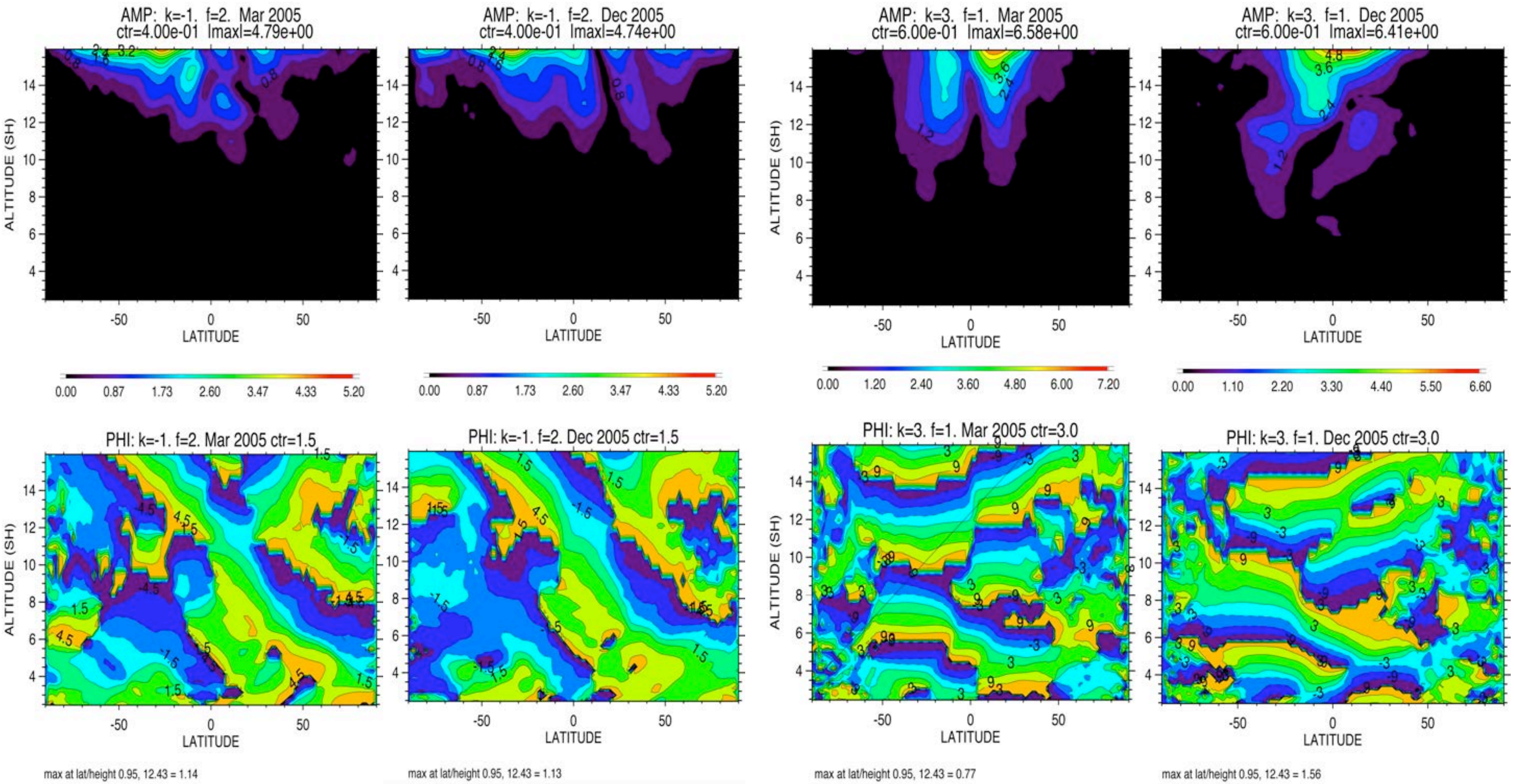
Structure of two modeled "non-migrating" tides

T semidiurnal westward 1 — March, December

T diurnal Eastward 3 — March, December



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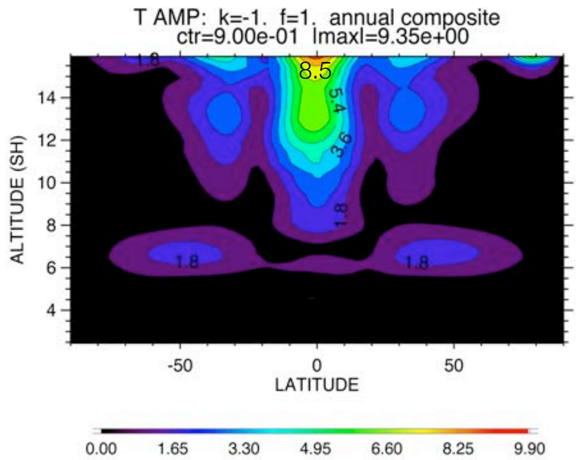
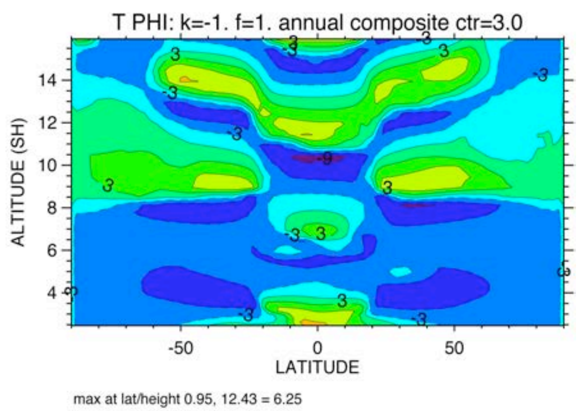
Diurnal migrating T tide: WACCM vs. SABER

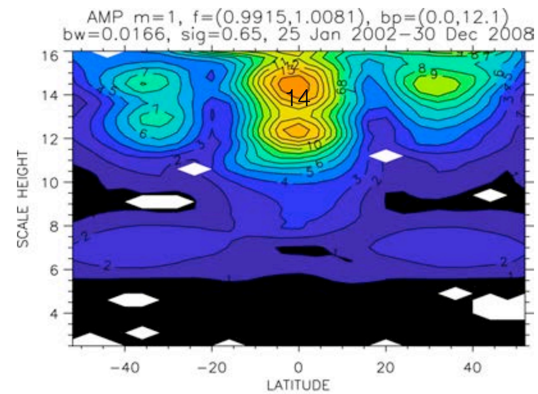
WACCM diurnal tide obtained from monthly amplitude/phase over period of simulation (50 yr)
Structure shown here is the time-mean over the entire simulation period

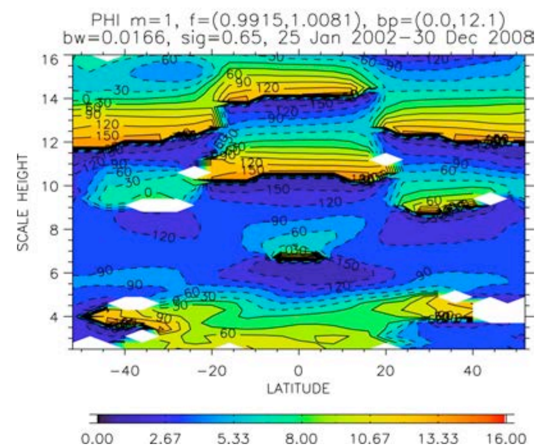
WACCM diurnal T tide





SABER diurnal T tide



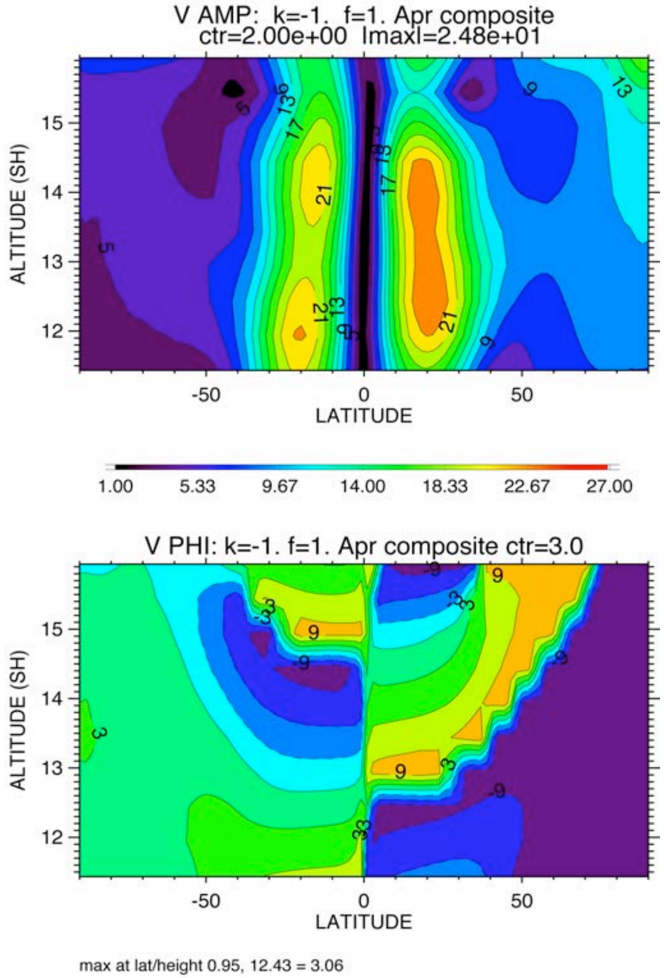


SABER diurnal tide from Salby spectral analysis of SABER data
Tide structure determined from coherence of spectrum over a band centered at 1 cpd westward
Results may be viewed as long-term mean over SABER period, 2002-2007

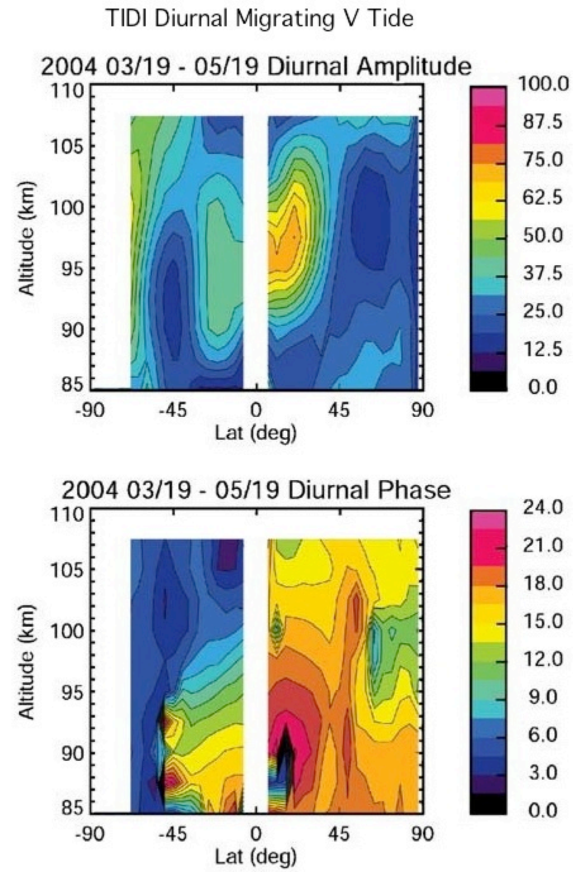
The morphology of the tide is generally consistent between WACCM and SABER
WACCM amplitudes are considerably smaller, especially in the mesosphere and lower thermosphere

Diurnal migrating V tide structure : TIDI vs. WACCM

WACCM may composite



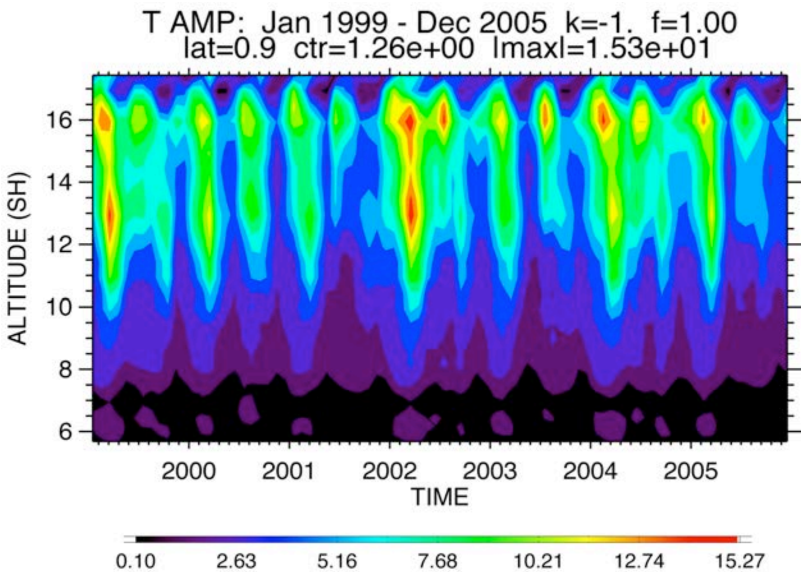
TIDI march-may 2004



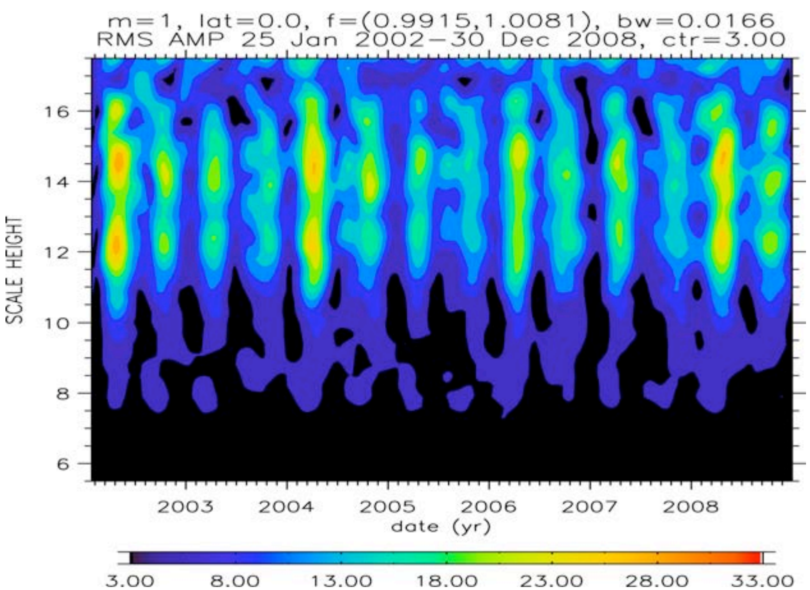
Liu et al. (JASTP, 2006)

- Similar structure in WACCM and TIDI observations, but smaller amplitudes in the model

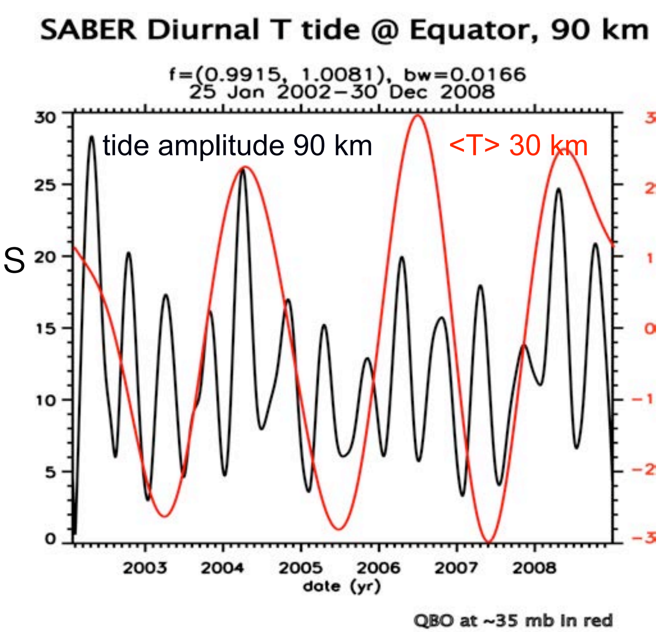
Altitude-time variability of the diurnal tide at the Equator



model and observations display a clear semi-annual variation, with maxima at the equinoxes amplitudes observed by SABER are about 2X larger than calculated with WACCM there is also considerable interannual variability (quasi-biennial)

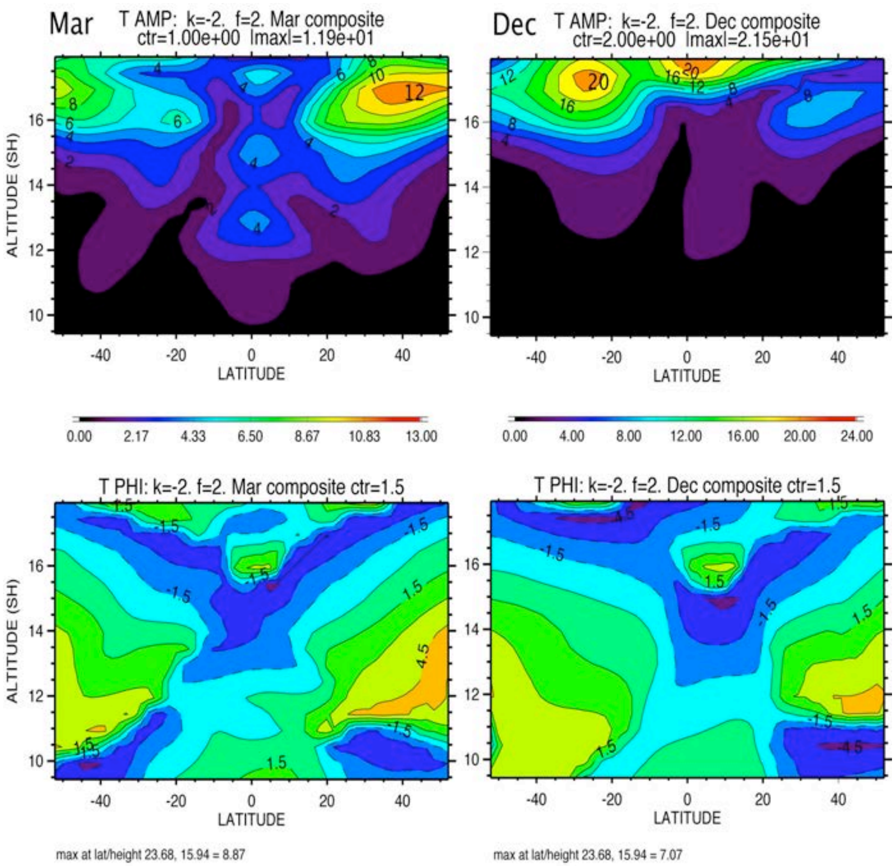


Similar behavior is seen in SABER data

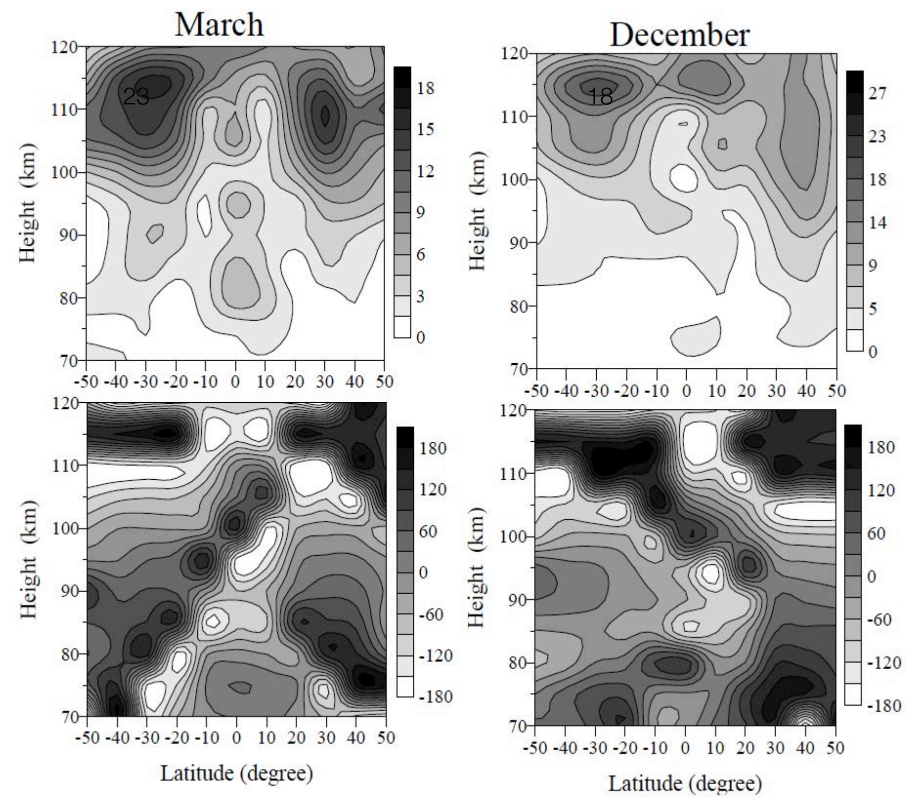


Semidiurnal migrating T tide: WACCM vs. SABER

WACCM Semidiurnal migrating T tide



SABER Semidiurnal migrating T tide



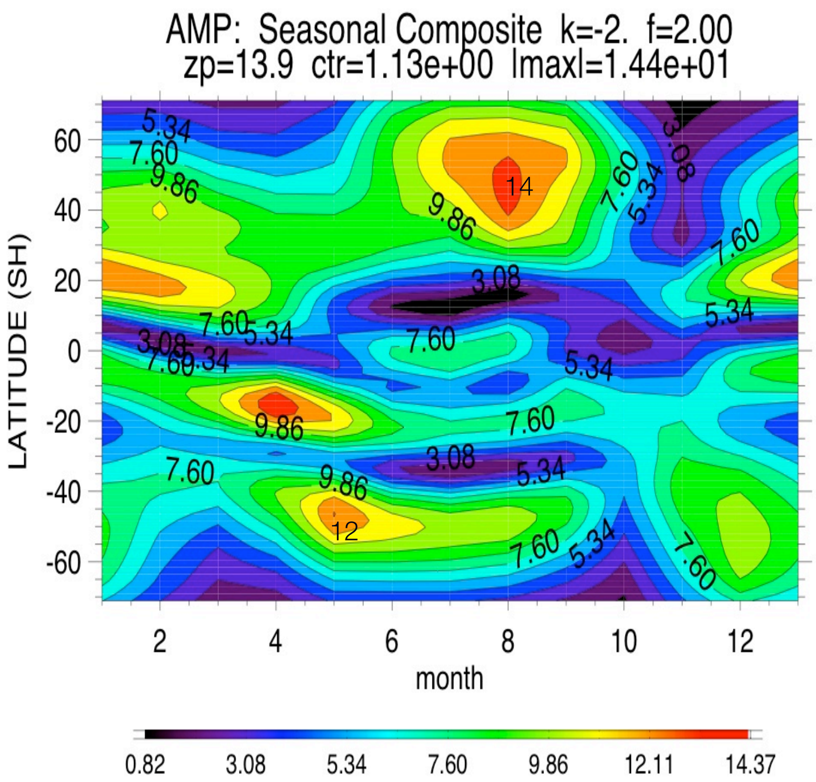
Pancheva et al., 2009

As with diurnal tide, structures are generally consistent; but WACCM amplitudes are smaller

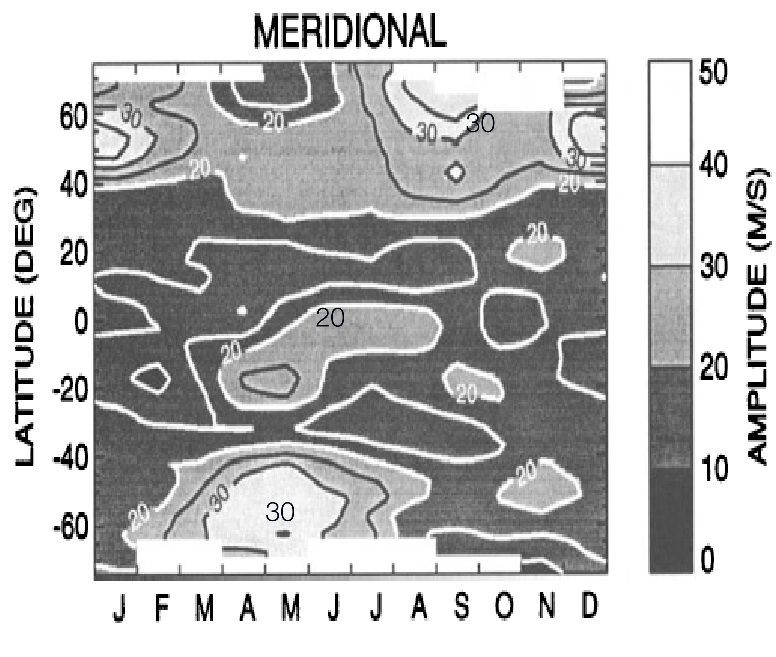
WACCM Whole Atmosphere Community Climate Model

Seasonal variability of the semidiurnal V tide, 95 km

WACCM composite V seasonal cycle, ~95 km



HRDI composite V seasonal cycle @ 95 km



Burrage et al, GRL, 1995

WACCM: 50-year mean
UARS/HRDI: Nov 1991 – July 1994

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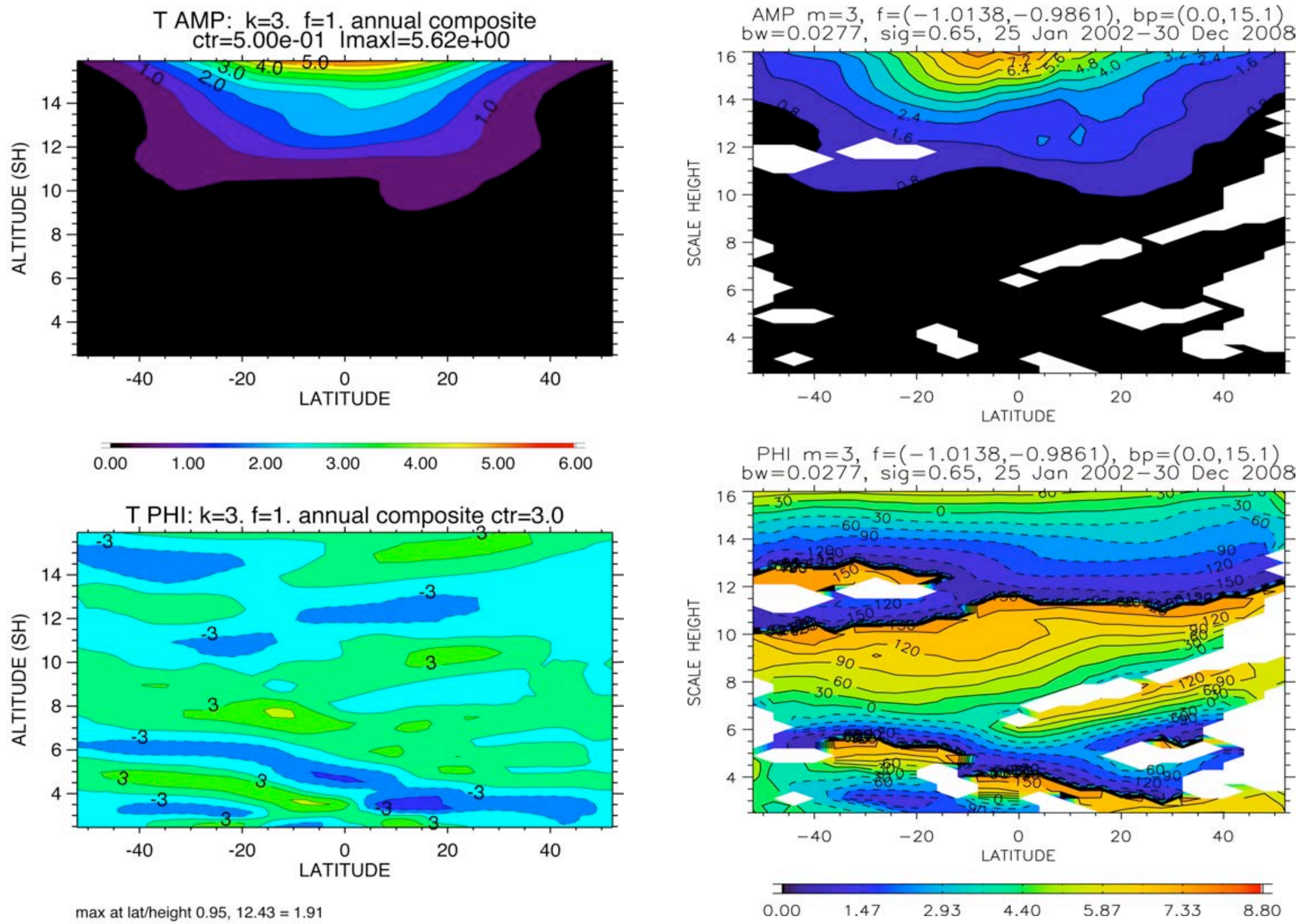
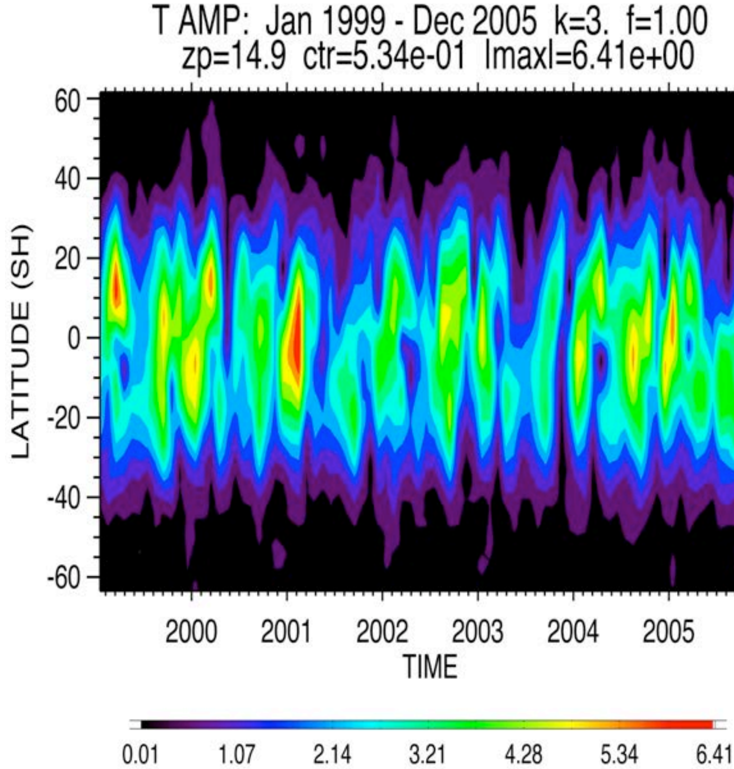
Diurnal eastward-3 T tide: WACCM vs. SABER



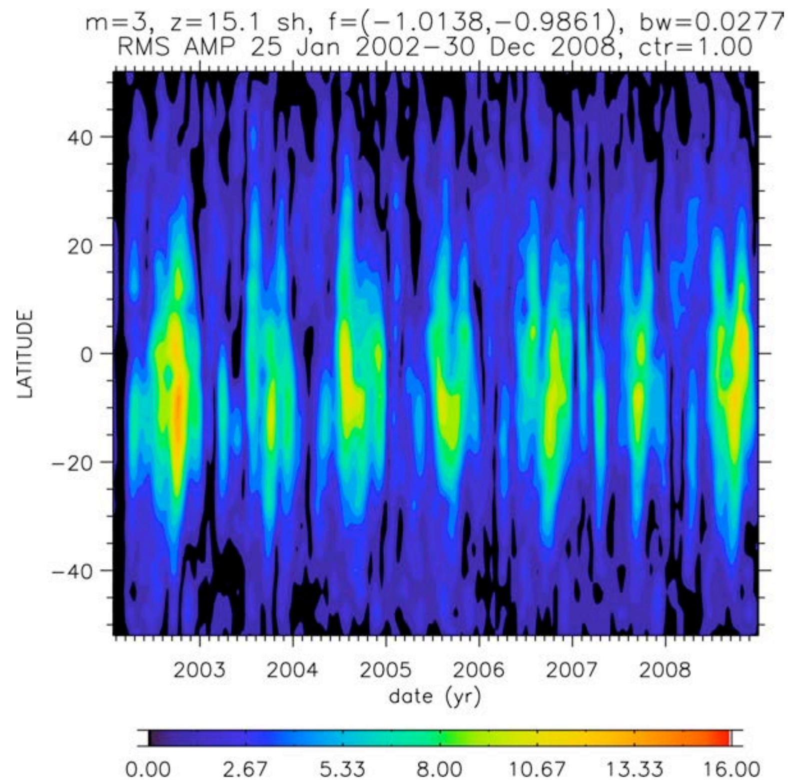
WACCM: 50 year mean
SABER: 2002-2007
large-amplitude above ~ 10 sh (70 km) has the structure of a Kelvin wave
phase behavior suggests also RG structure at lower altitudes

Seasonal variation of eastward-3 T tide at equator

WACCM m=3 diurnal at 105 km



SABER m=3 diurnal at 105 km



SABER: regular seasonal, maxima always in late NH summer (~August)
WACCM: semiannual variation, with maxima in August and January

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WACCM-X:
Thermosphere and Ionosphere Extension of WACCM

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led by Han-Li Liu (HAO)

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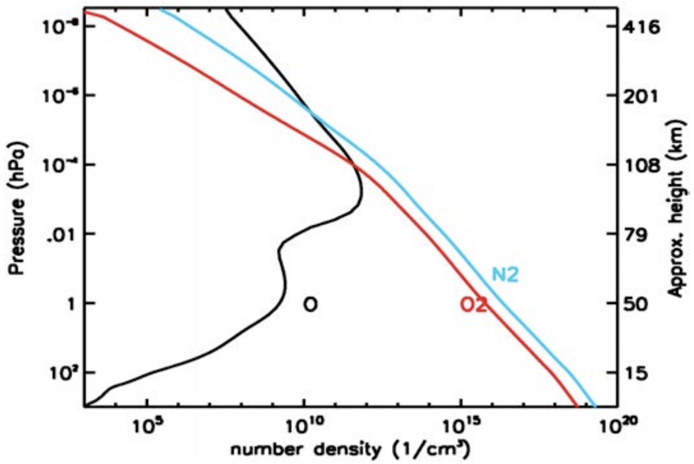
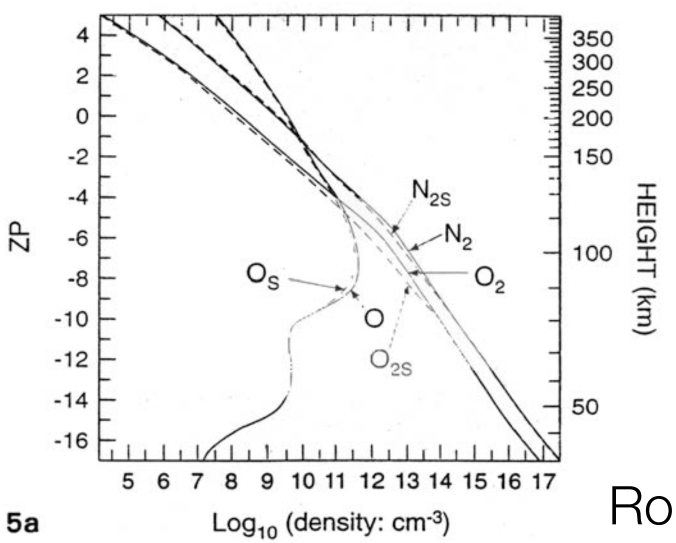
WACCM-X modifications

- 81 or 125 vertical levels (0-~500 km) ✔
- Major/minor species diffusion ✔
- Species dependent Cp, R, m ✔
- Ambipolar diffusion
- Ion/electron transport due to Lorentz force
- Ion/electron energy equations
- Coupling with plasmasphere (GIP) / magnetosphere (GAIM/CISM)

WACCM-X: Compositional Structures

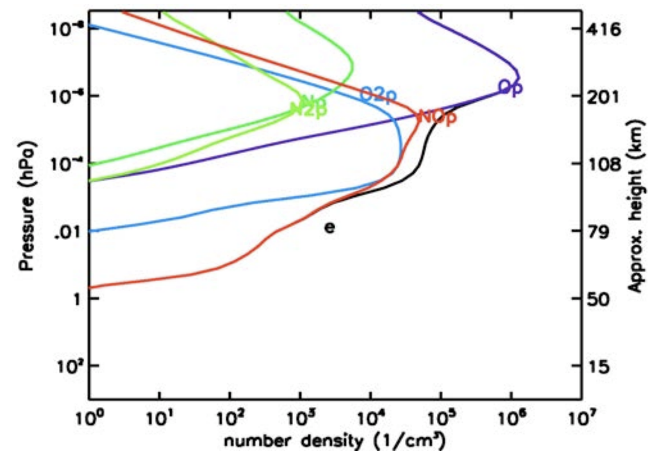
Major Species

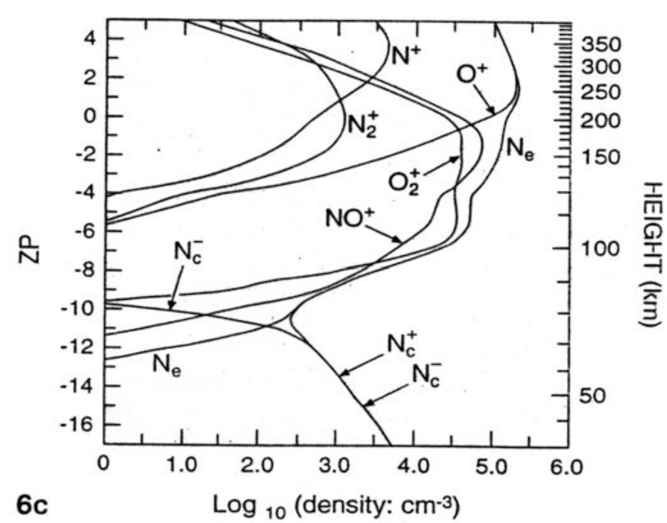




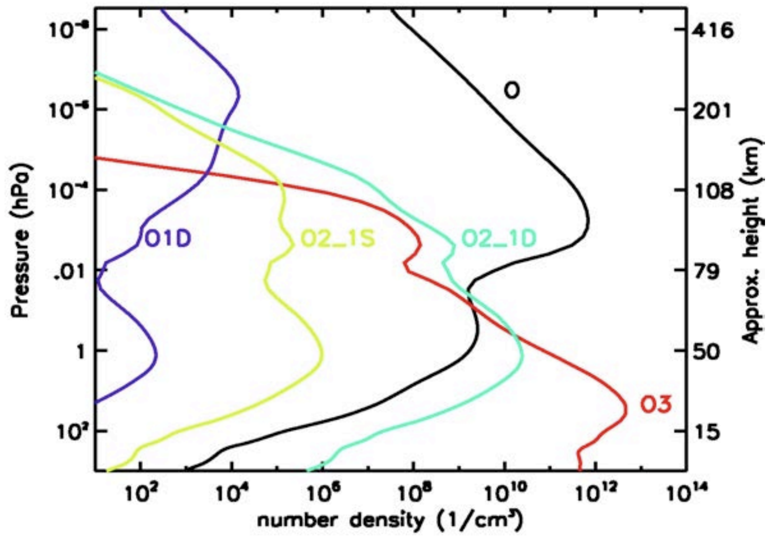
Roble, 1995

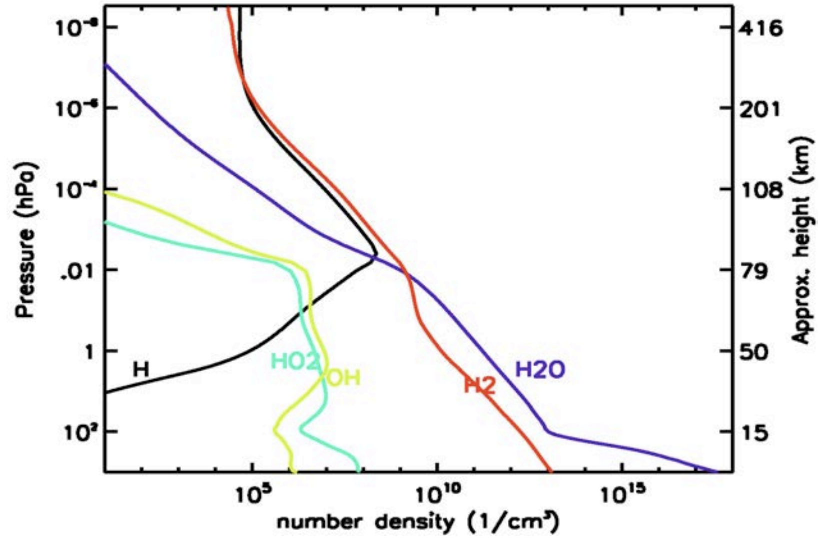
Ions and Electrons

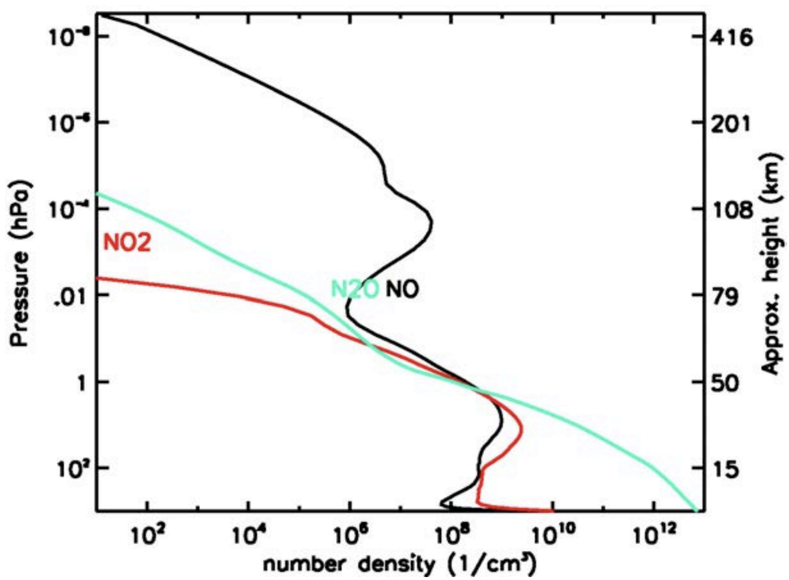


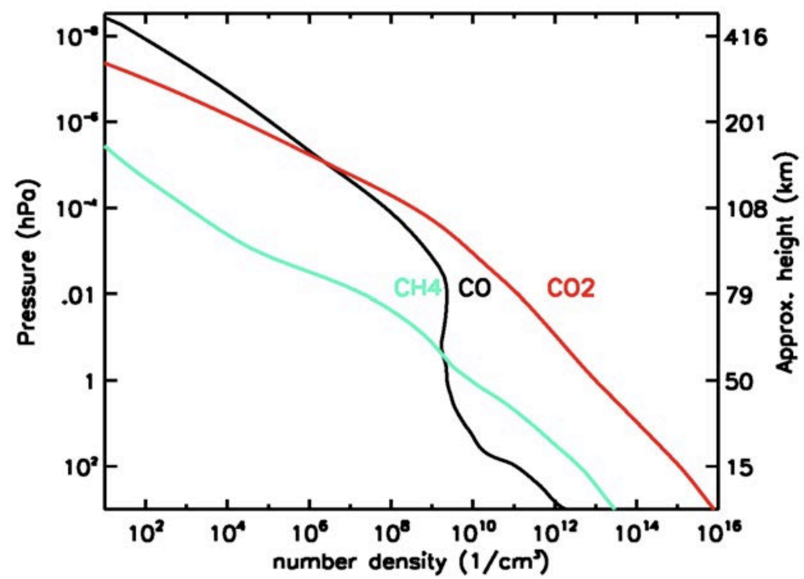


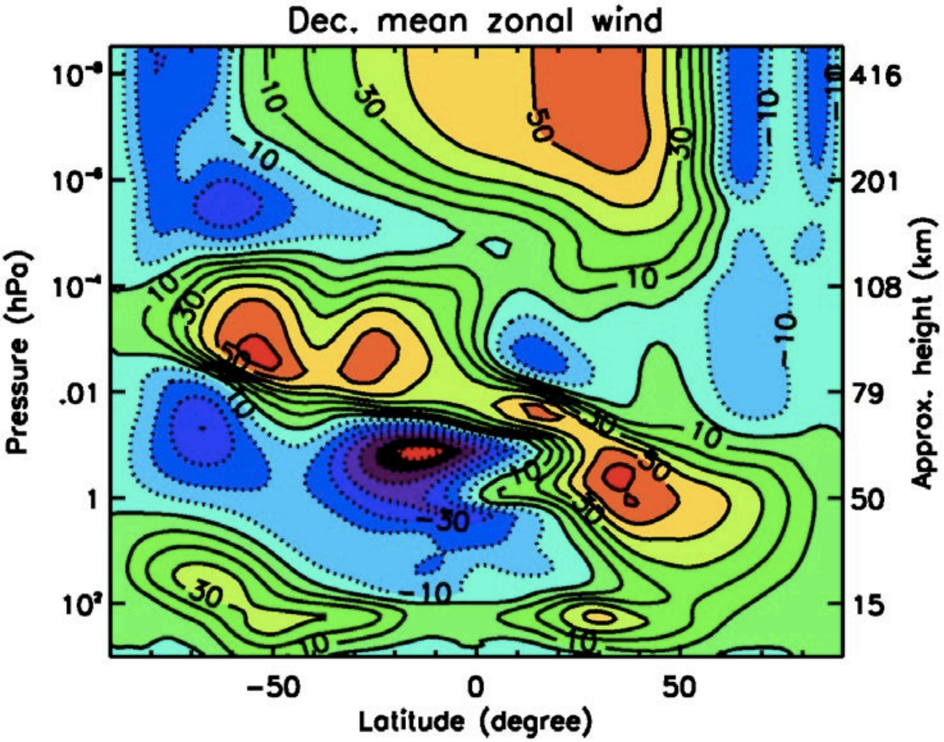
Minor species

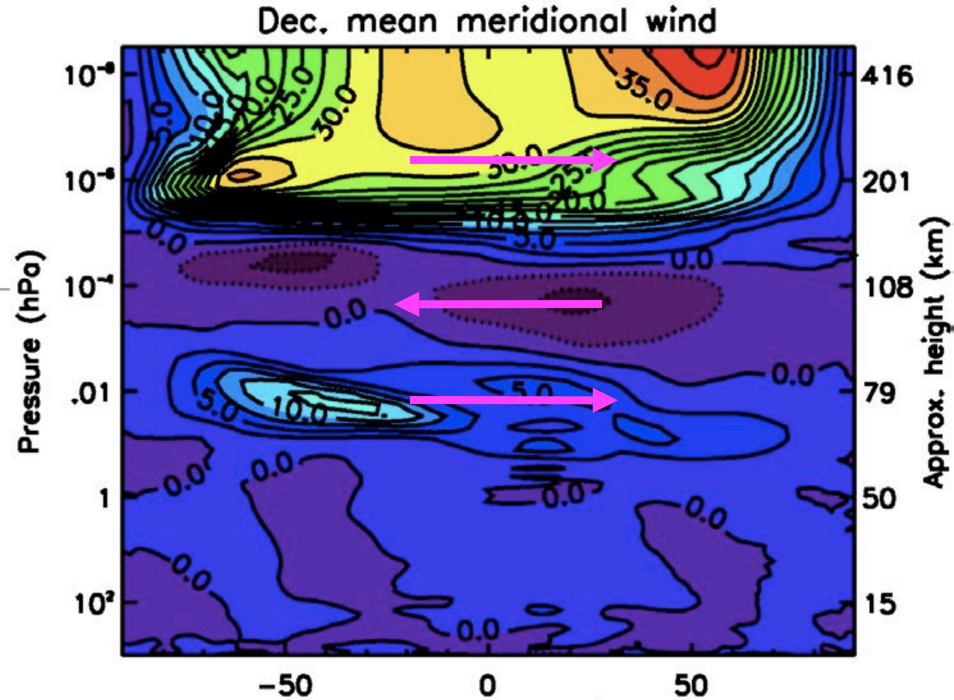




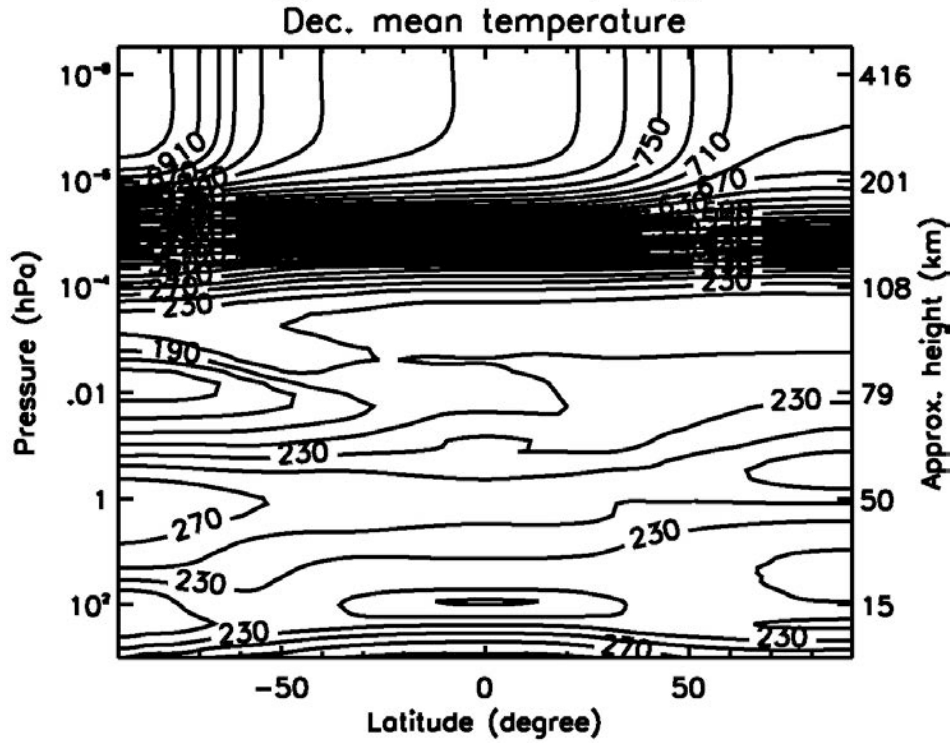


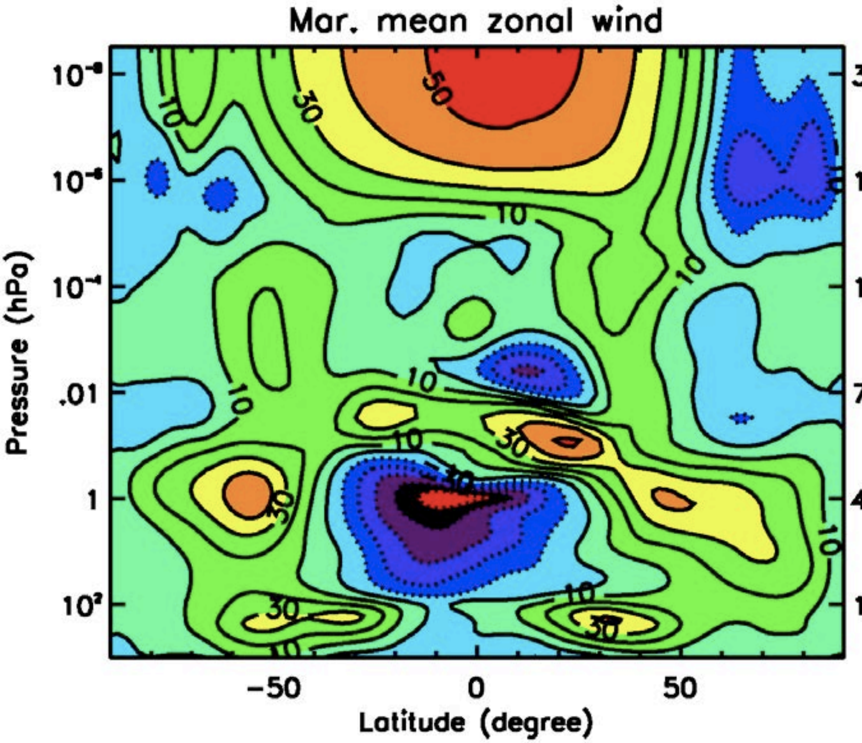


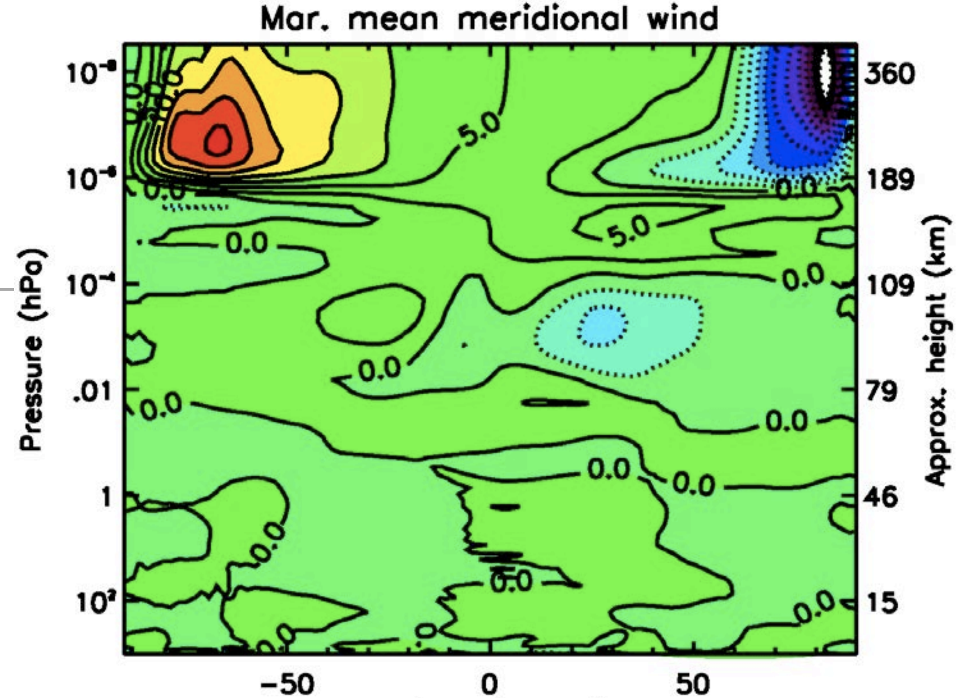




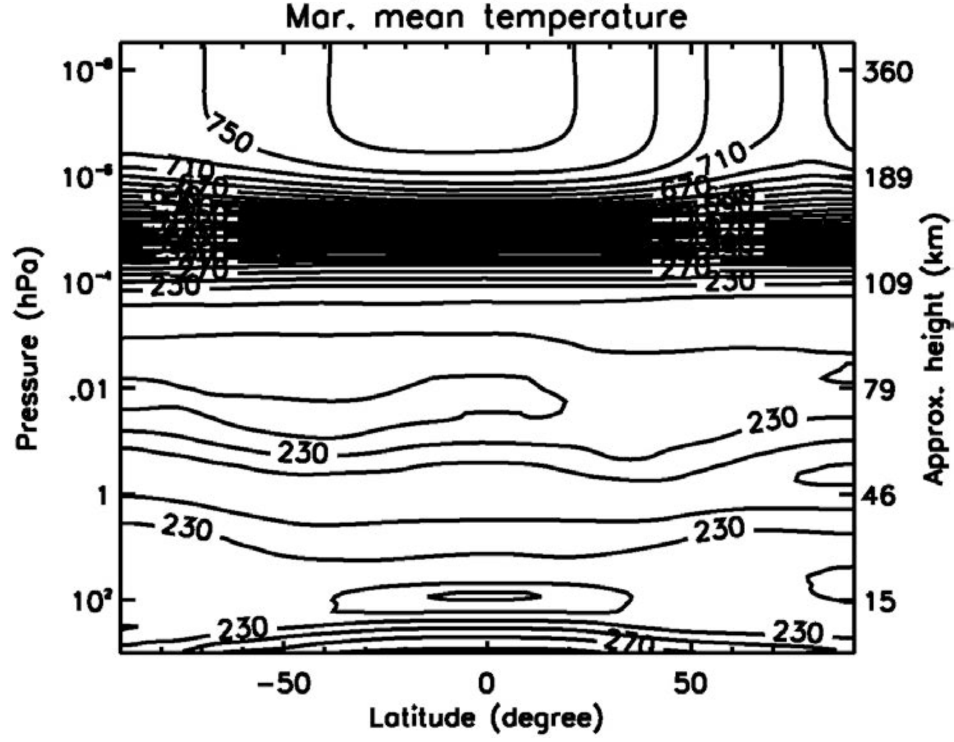
WACCM-X: Winds and Temperature (December)





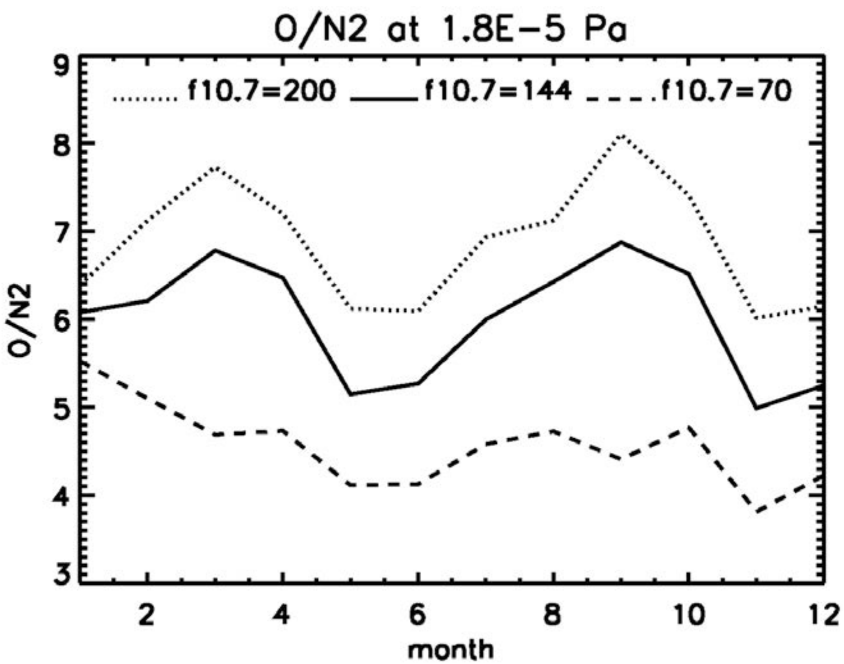


WACCM-X: Winds and Temperature (March)

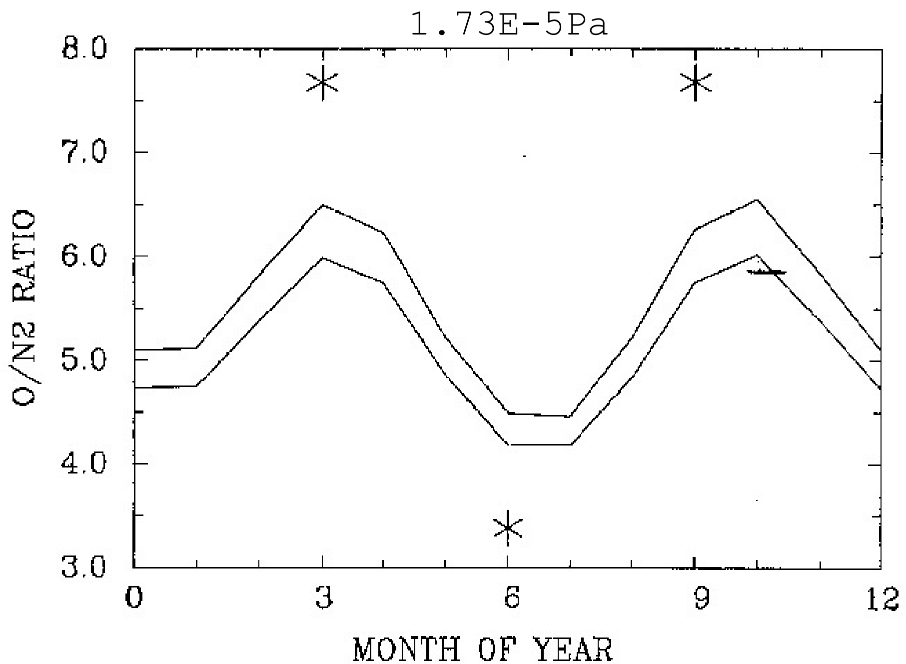


Thermosphere O/N_2 Semi-annual Variation (~250 km)

WACCM



MSIS



Fuller-Rowell, 1998

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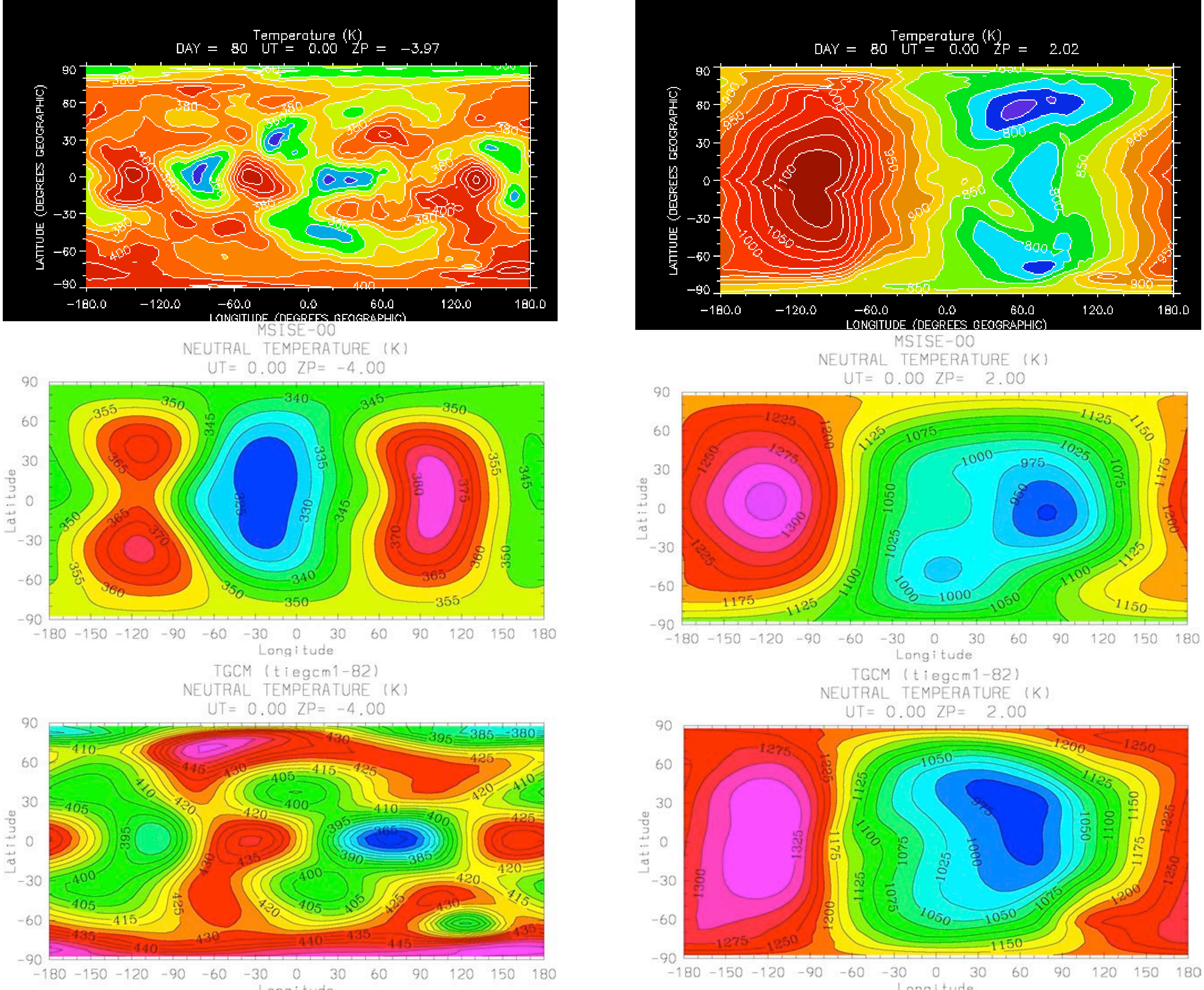
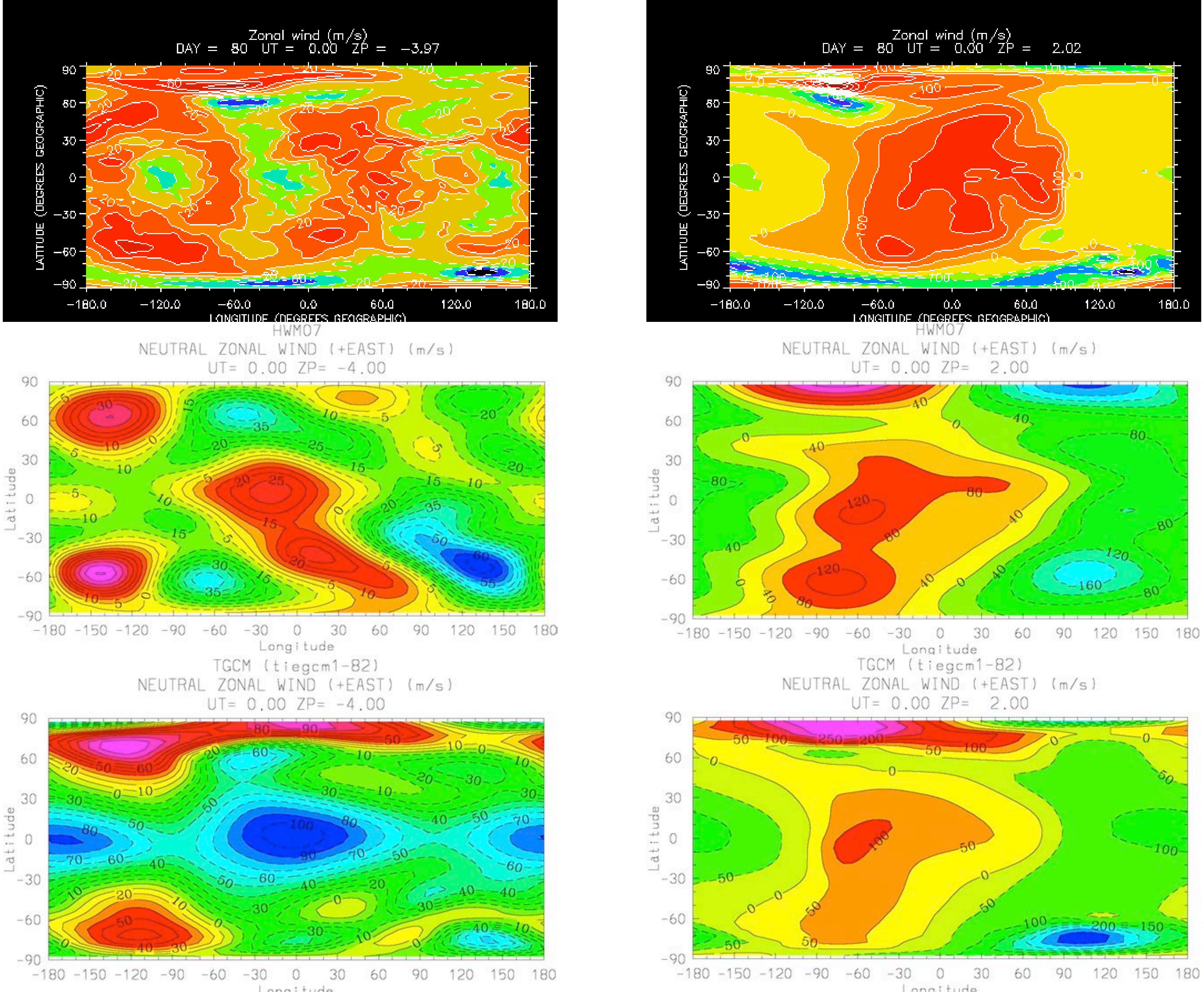
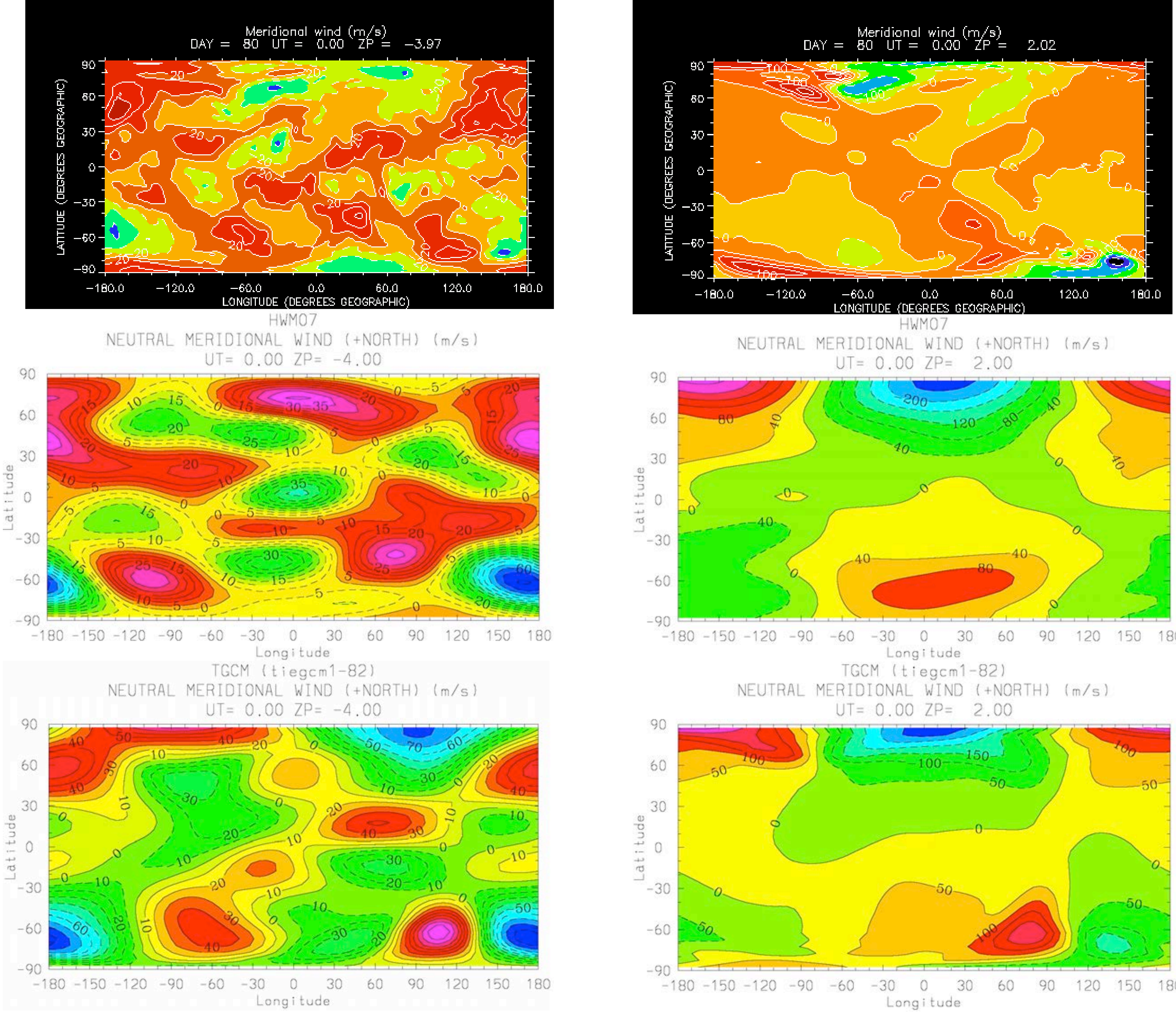
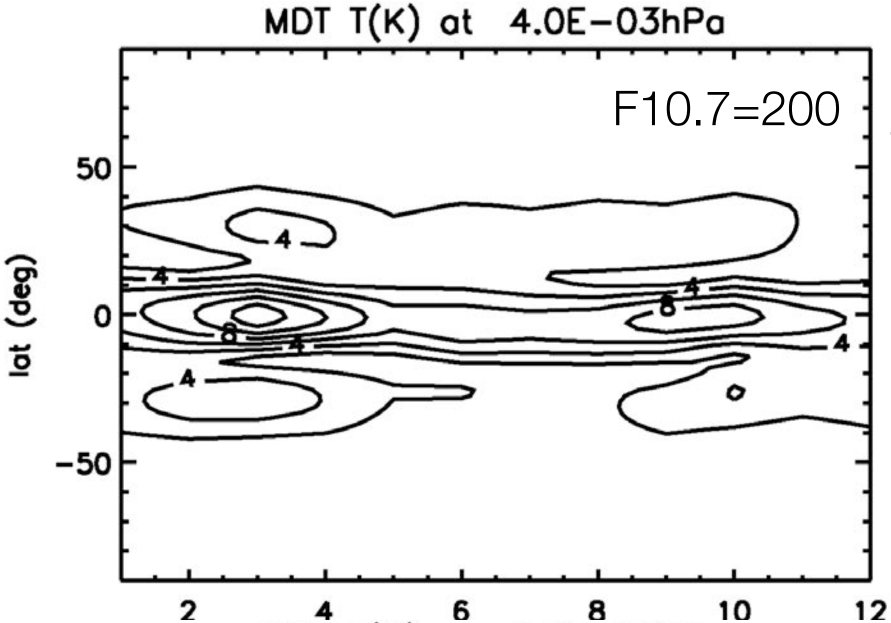

Temperature (K)
DAY = 80 UT = 0.00 ZP = -3.97
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
Temperature (K)
DAY = 80 UT = 0.00 ZP = 2.02
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
MSISE-00
NEUTRAL TEMPERATURE (K)
UT= 0.00 ZP= -4.00
Latitude
Longitude
MSISE-00
NEUTRAL TEMPERATURE (K)
UT= 0.00 ZP= 2.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL TEMPERATURE (K)
UT= 0.00 ZP= -4.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL TEMPERATURE (K)
UT= 0.00 ZP= 2.00
Latitude
Longitude

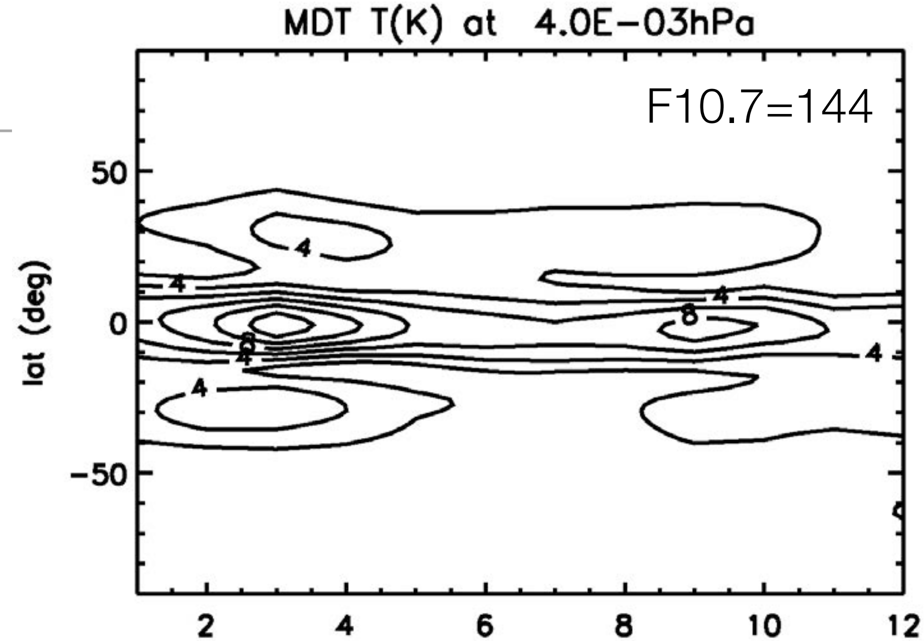

Zonal wind (m/s)
DAY = 80 UT = 0.00 ZP = -3.97
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
Zonal wind (m/s)
DAY = 80 UT = 0.00 ZP = 2.02
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
HWM07
NEUTRAL ZONAL WIND (+EAST) (m/s)
UT= 0.00 ZP= -4.00
Latitude
Longitude
HWM07
NEUTRAL ZONAL WIND (+EAST) (m/s)
UT= 0.00 ZP= 2.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL ZONAL WIND (+EAST) (m/s)
UT= 0.00 ZP= -4.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL ZONAL WIND (+EAST) (m/s)
UT= 0.00 ZP= 2.00
Latitude
Longitude

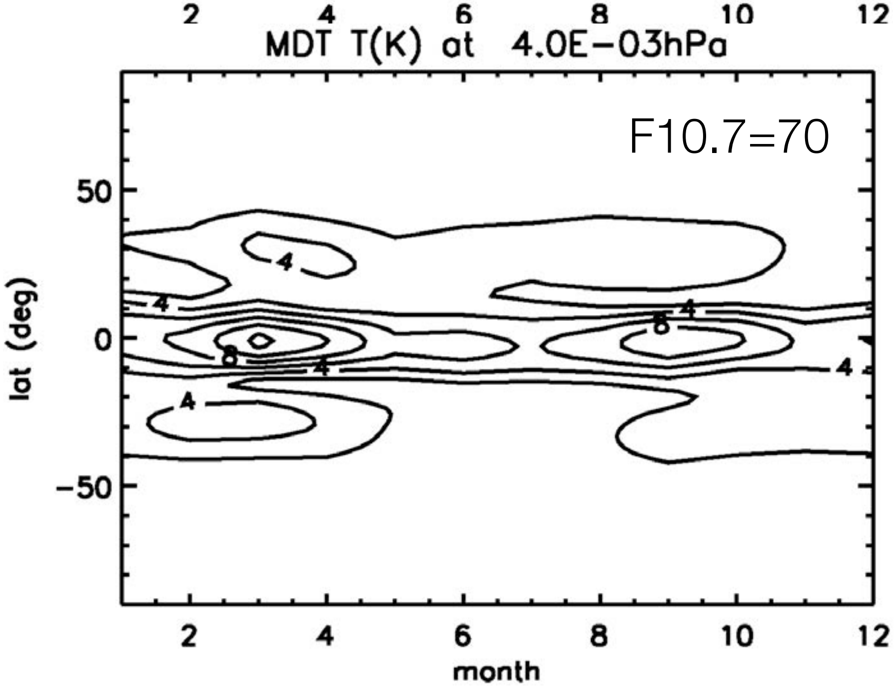


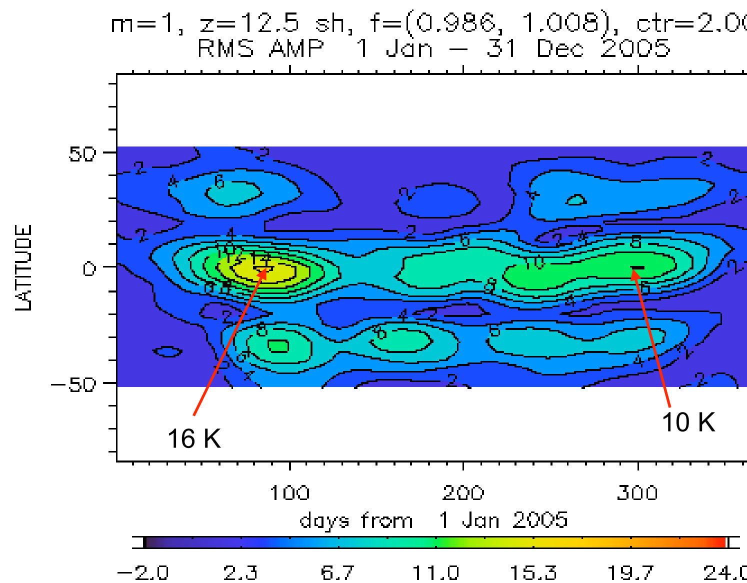
Meridional wind (m/s)
DAY = 80 UT = 0.00 ZP = -3.97
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
Meridional wind (m/s)
DAY = 80 UT = 0.00 ZP = 2.02
LATITUDE (DEGREES GEOGRAPHIC)
LONGITUDE (DEGREES GEOGRAPHIC)
HWM07
NEUTRAL MERIDIONAL WIND (+NORTH) (m/s)
UT= 0.00 ZP= -4.00
Latitude
Longitude
HWM07
NEUTRAL MERIDIONAL WIND (+NORTH) (m/s)
UT= 0.00 ZP= 2.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL MERIDIONAL WIND (+NORTH) (m/s)
UT= 0.00 ZP= -4.00
Latitude
Longitude
TGCM (tiegcm1-82)
NEUTRAL MERIDIONAL WIND (+NORTH) (m/s)
UT= 0.00 ZP= 2.00
Latitude
Longitude

Migrating Diurnal Tide: Temperature



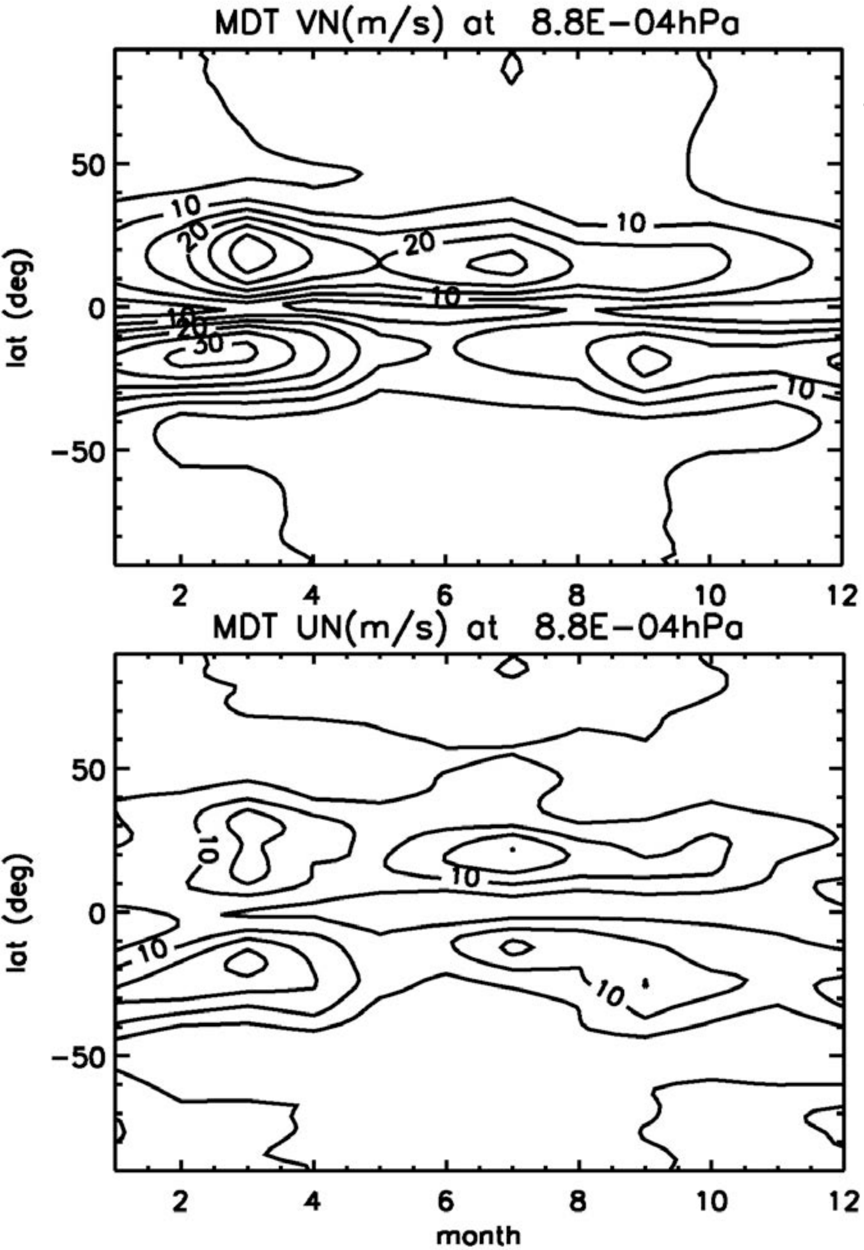




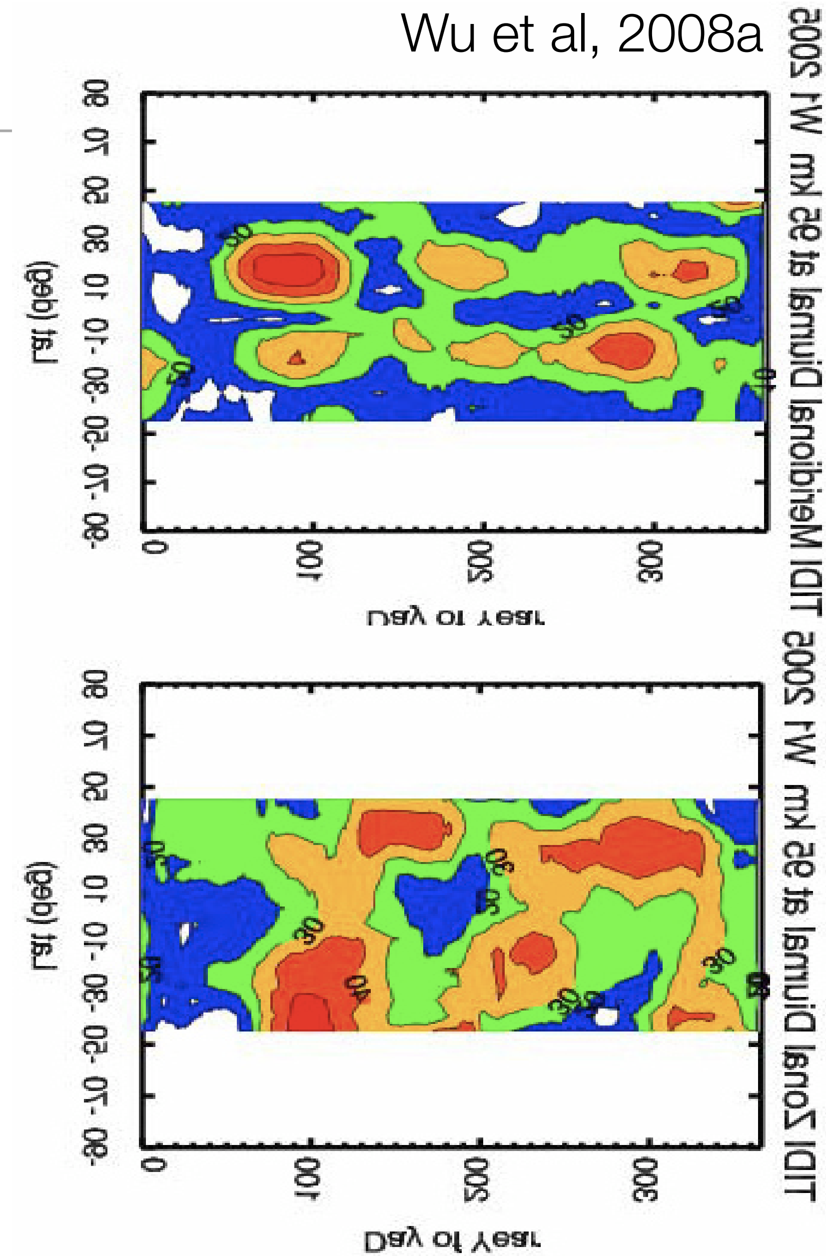


Garcia and Lieberman, 2007

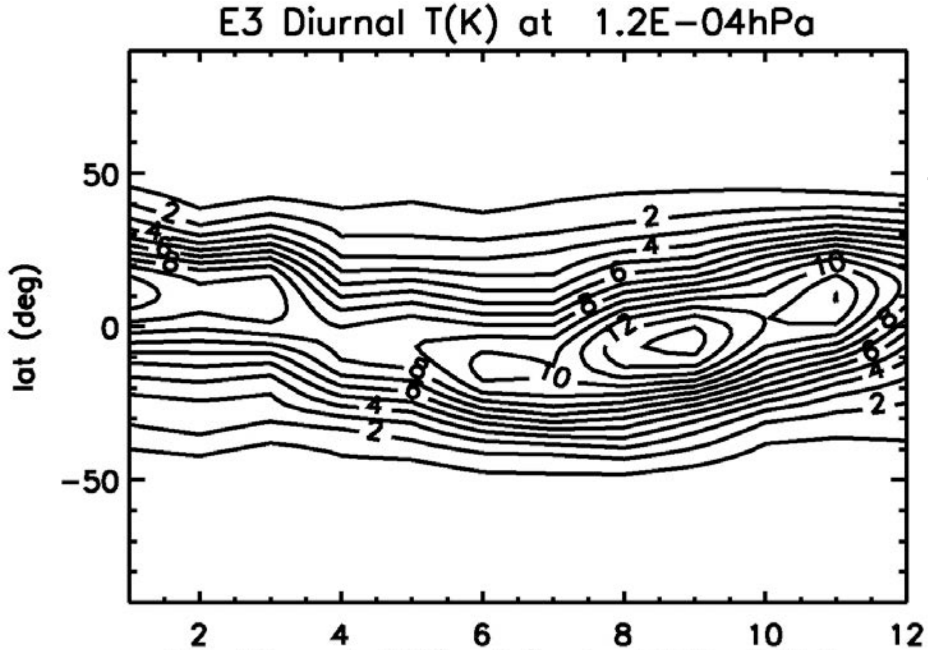
Migrating Diurnal Tide: Horizontal Winds

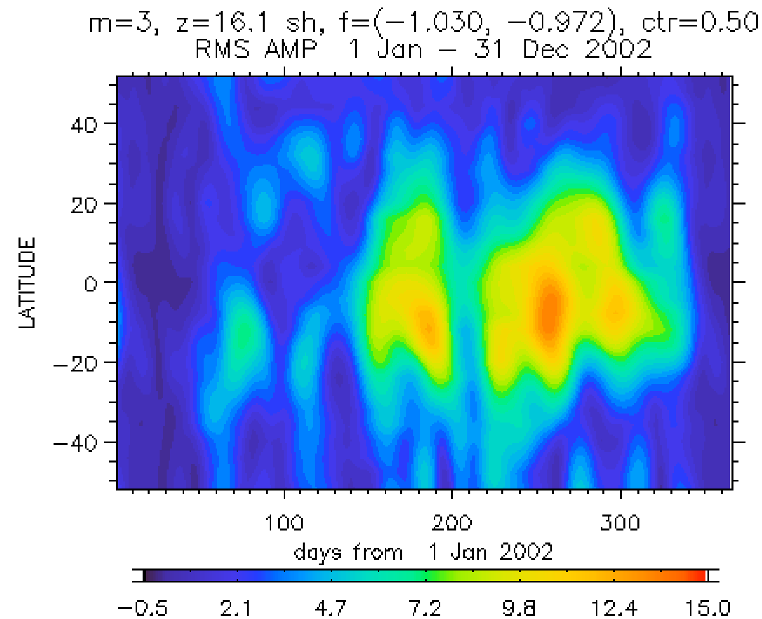


Wu et al, 2008a

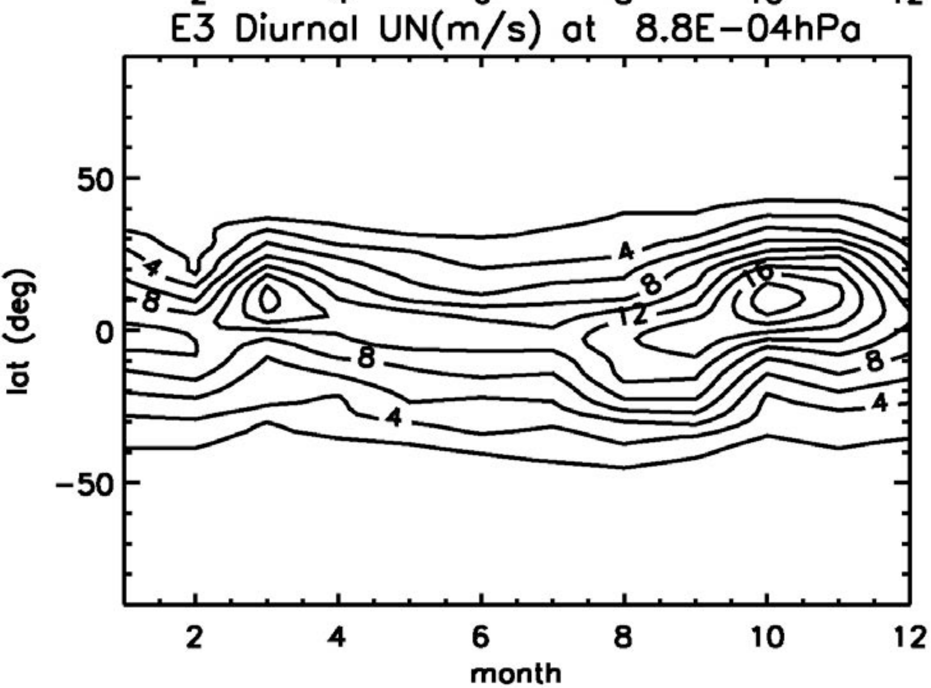


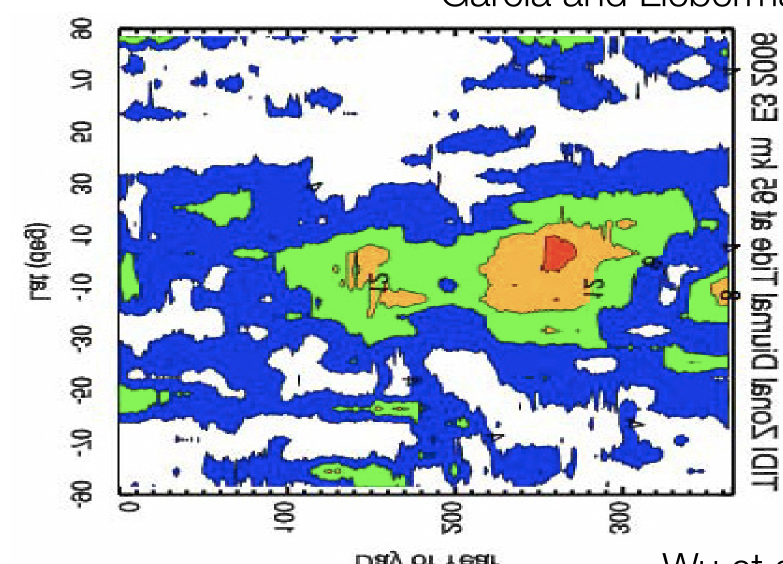
Nonmigrating: Diurnal E3





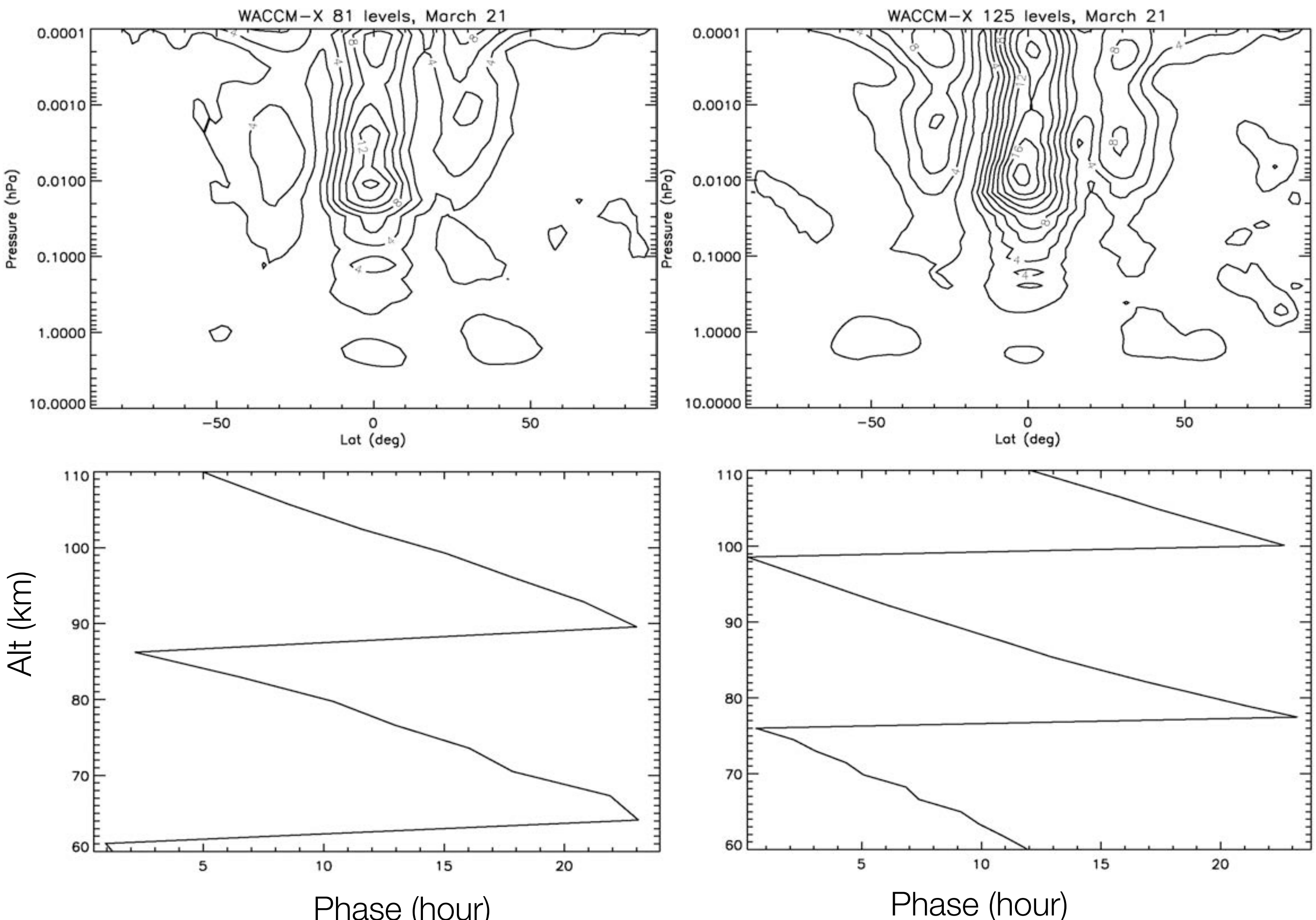
Garcia and Lieberman, 2007





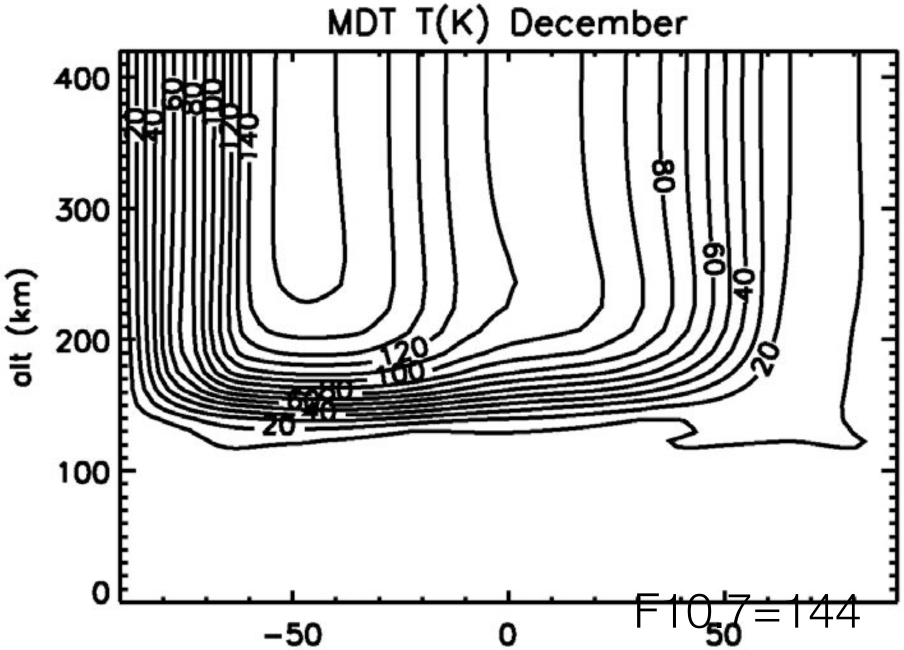
Wu et al, 2008b

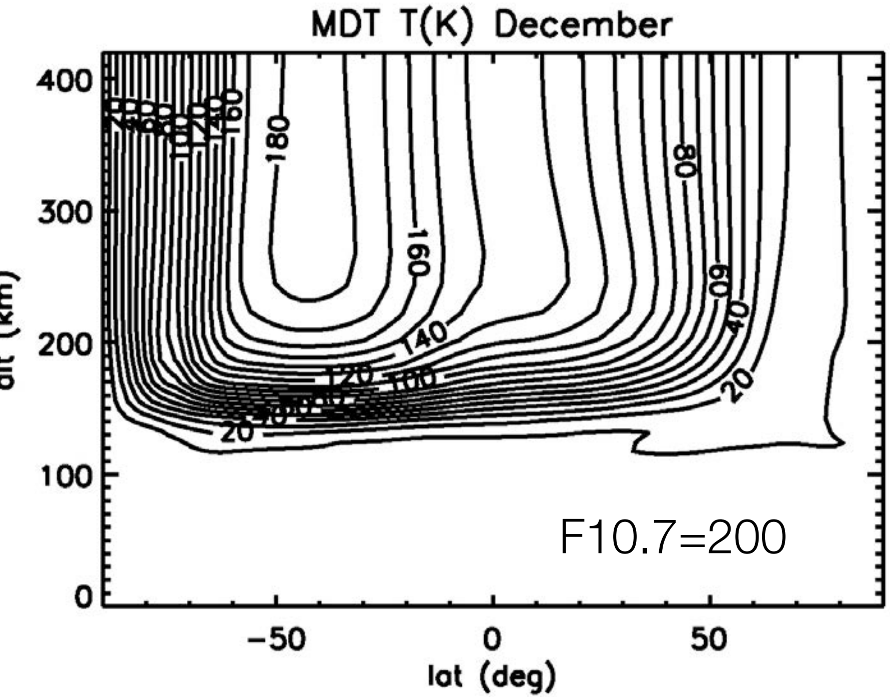
81 vs. 125 levels

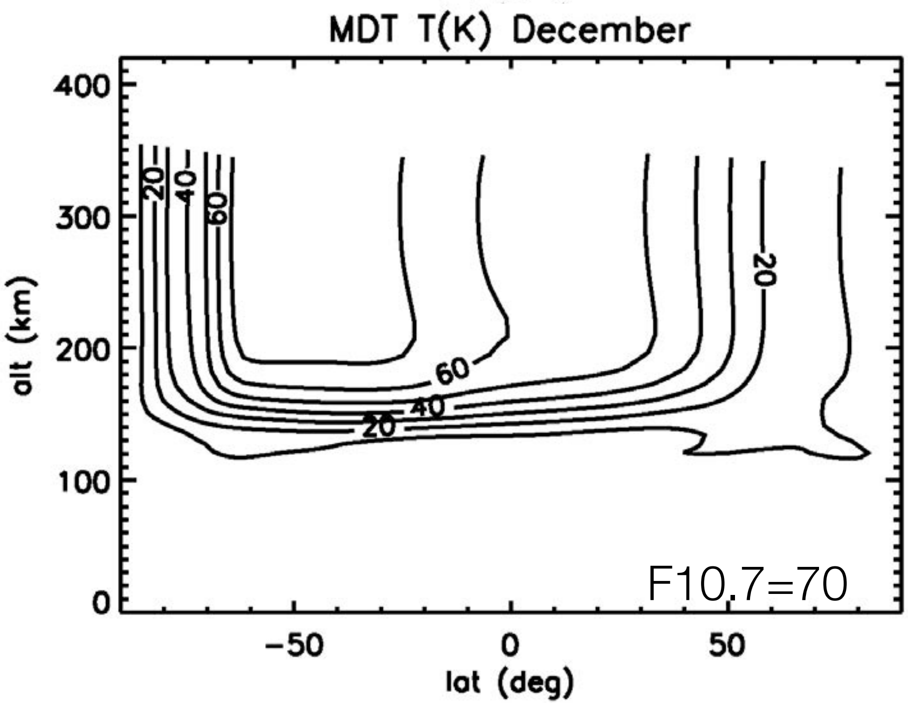


CEDAR, 2009

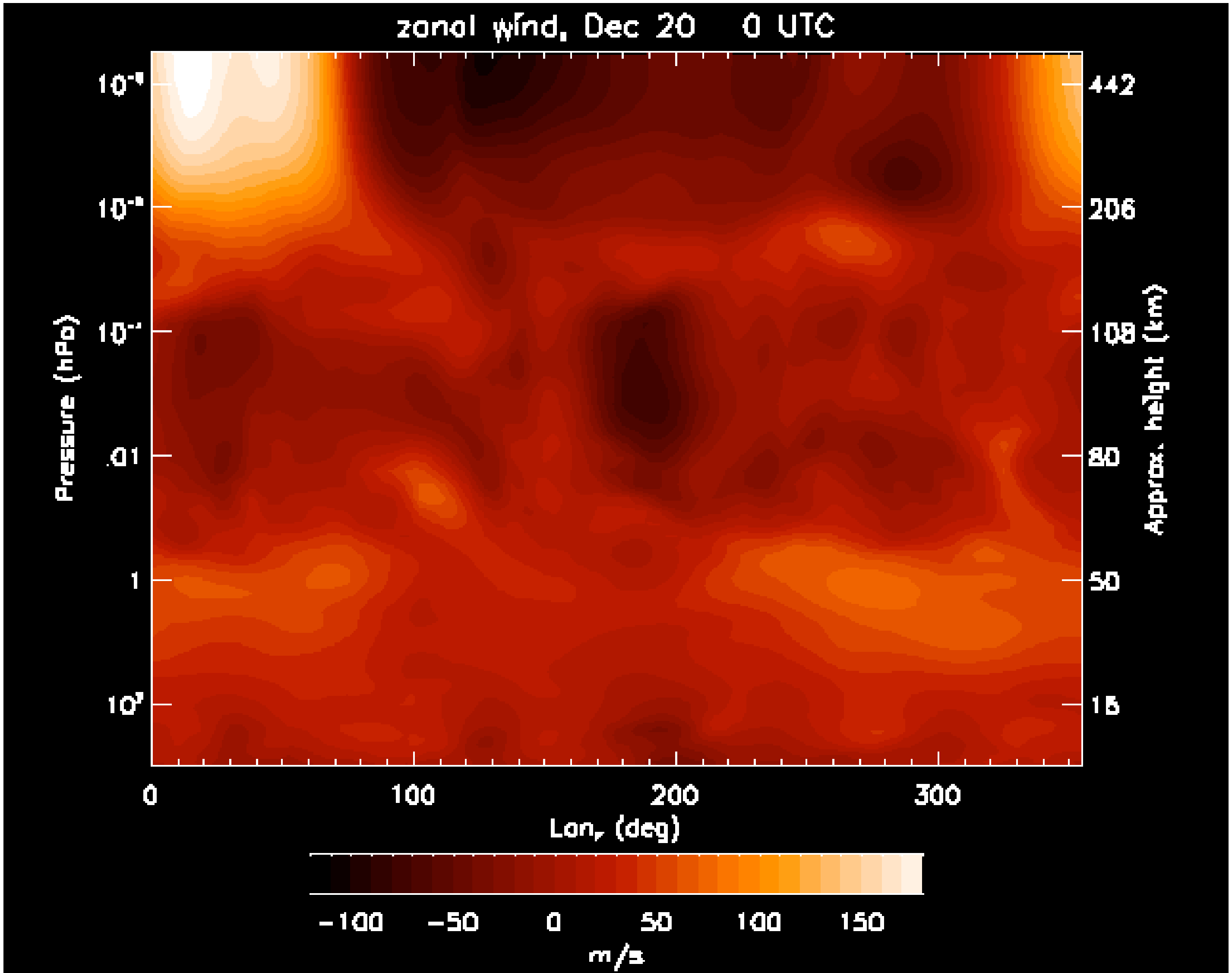
Thermospheric migrating diurnal tide







Short-term Variability



Polar mesospheric clouds

with A. Merkel

CEDAR, 2009

PMCs are water ice clouds near the mesopause (~83 km)

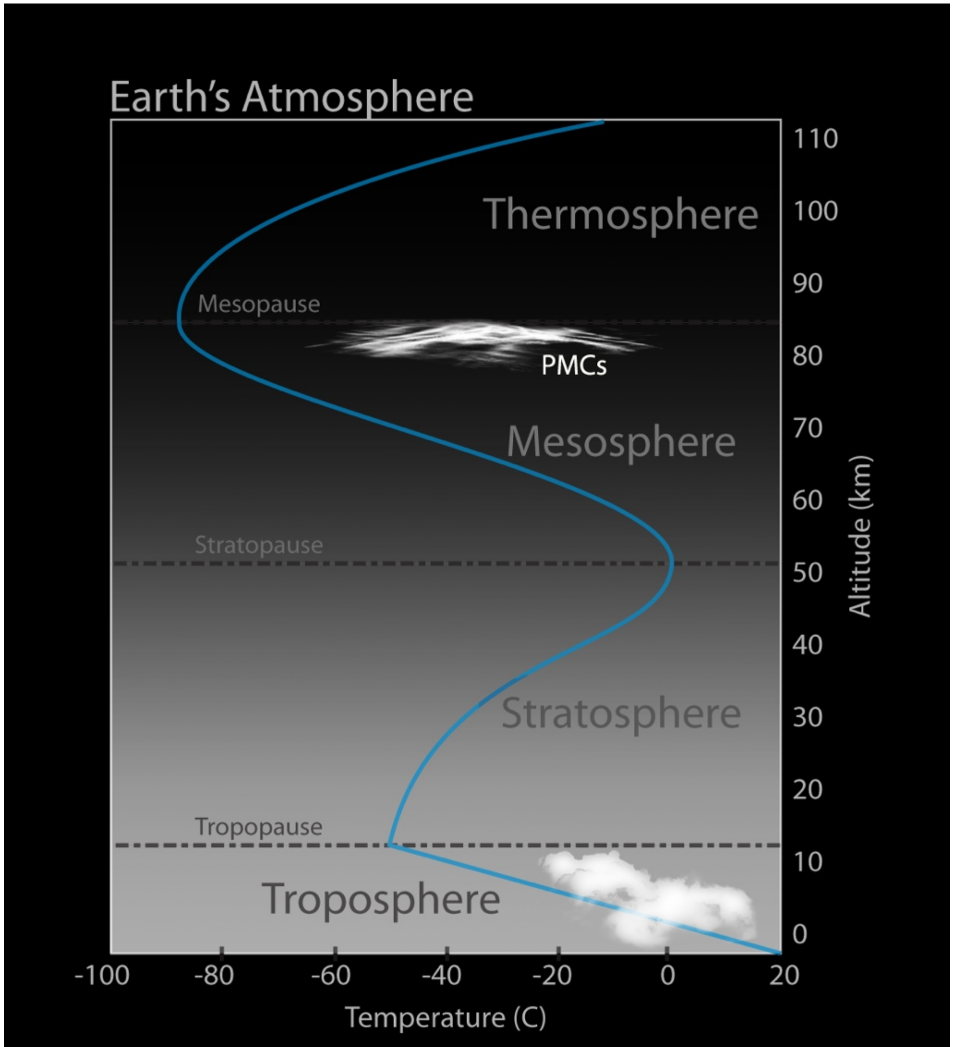
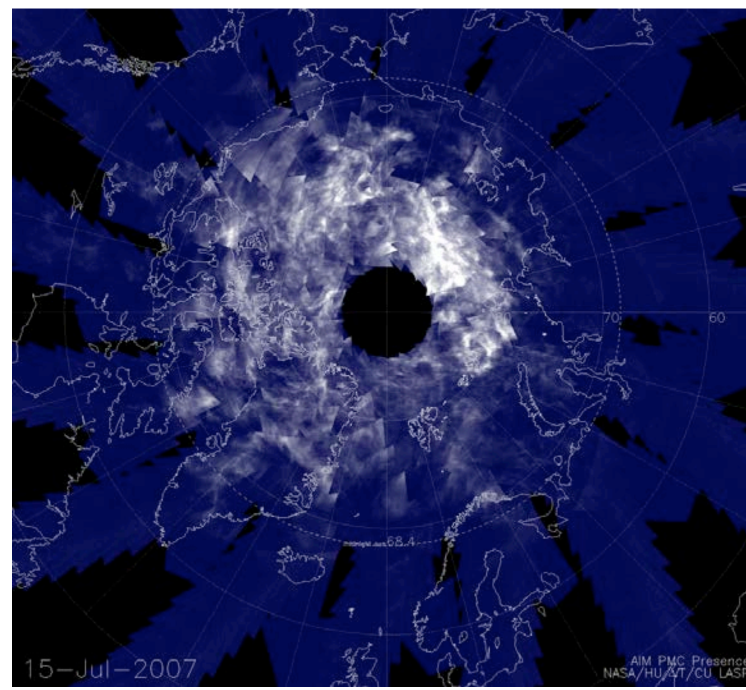
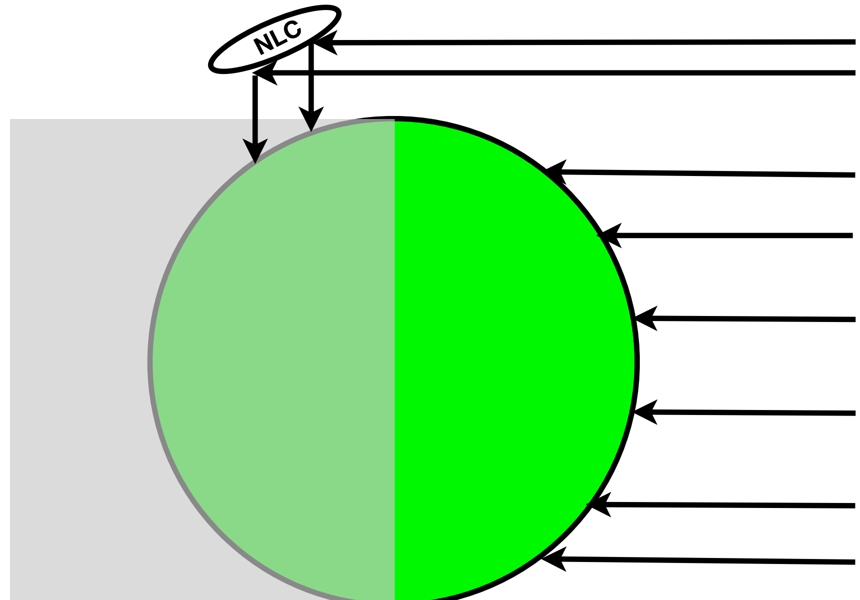


Image Credit: Emily Hill Design

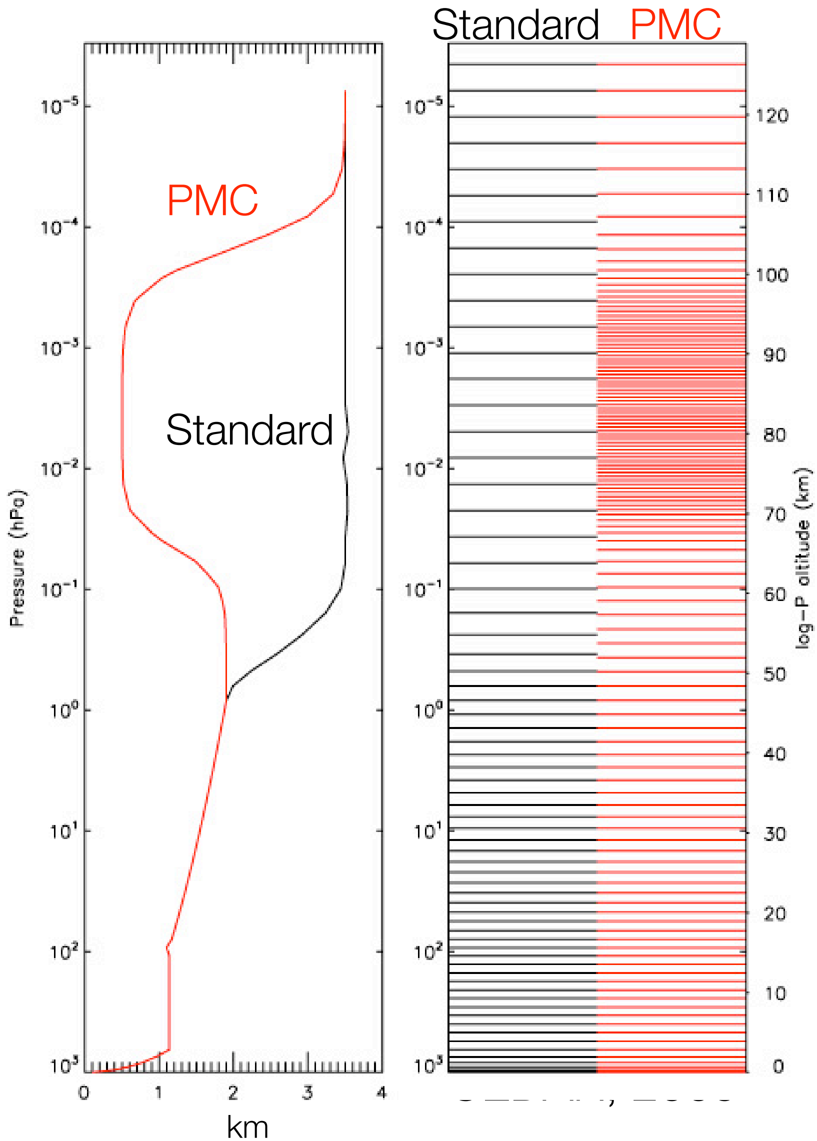


Notilucent clouds (NLC) when viewed from the ground

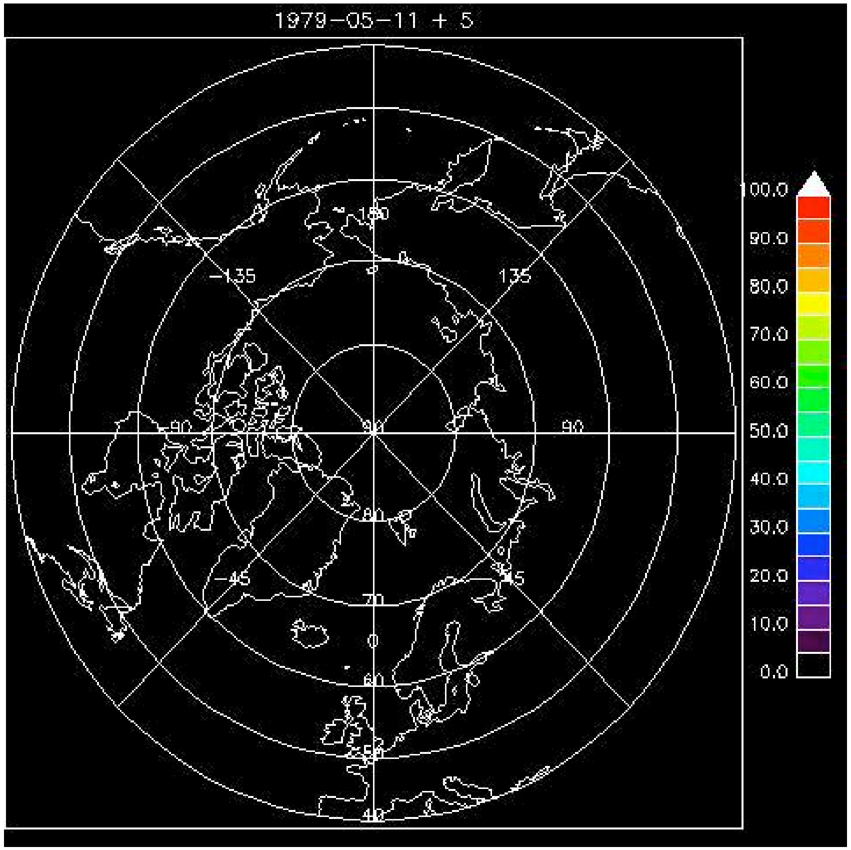


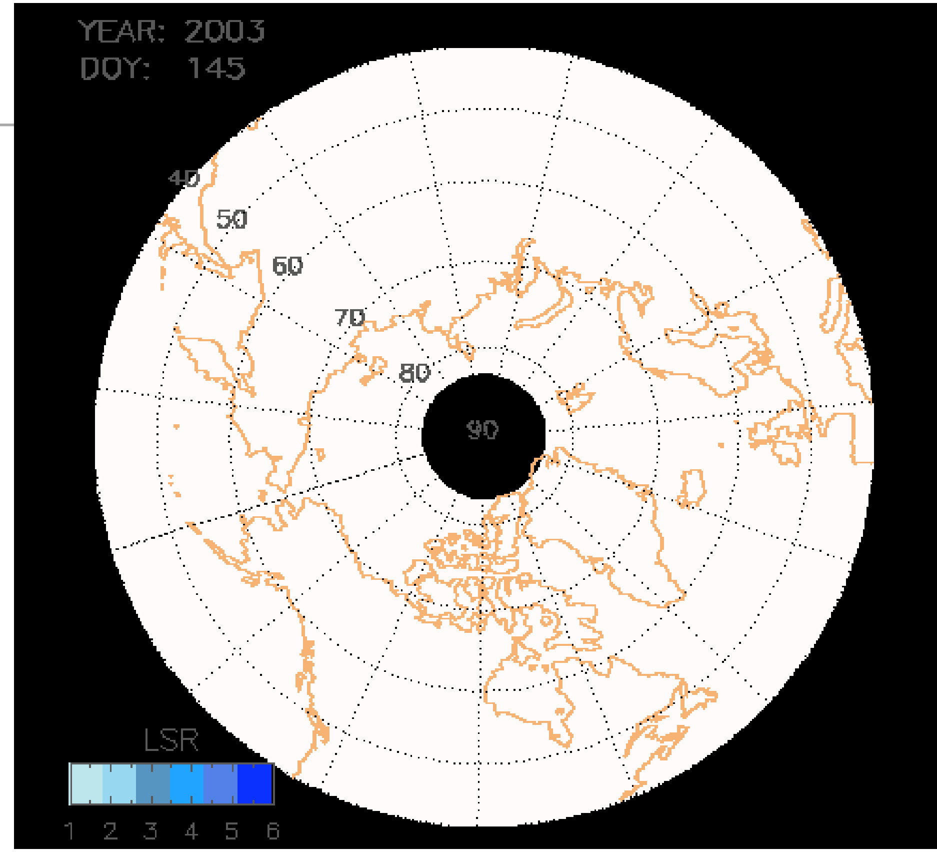
WACCM-3 with PMC parameterization

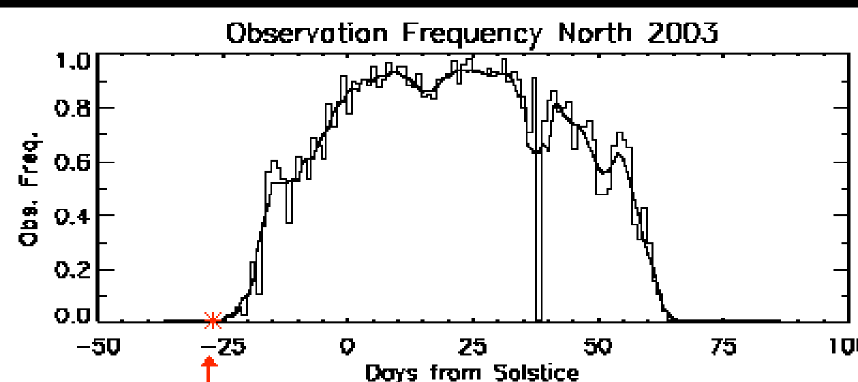
- 124 levels with 0.5 km resolution near the mesopause
- macroscale PMC parameterization of ice nucleation, growth, and sublimation
- Ice diffused, advected and sedimented
- Intended for long integrations (solar cycle, trends, etc.)
- Depends on local parameters (i.e. not particle-following)
- ~16 wall clock hrs. / year on 192 processors



WACCM & SNOE albedo

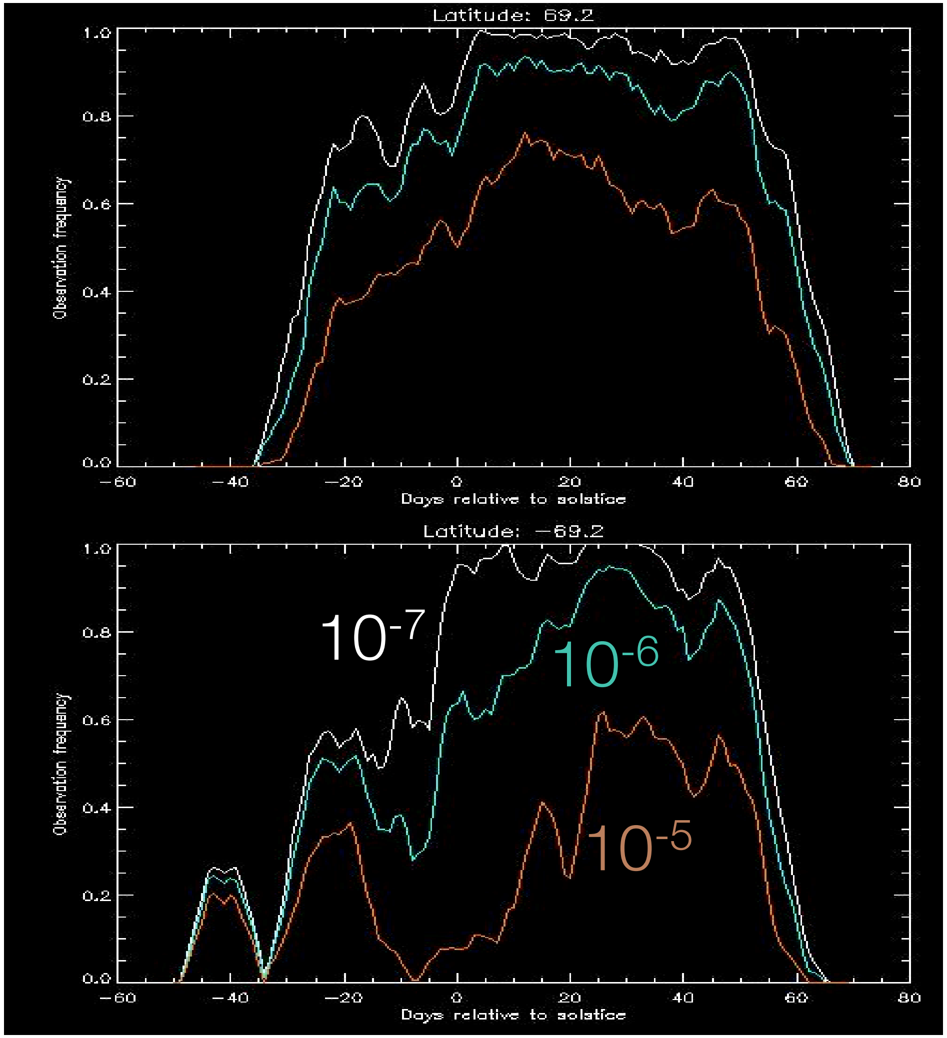


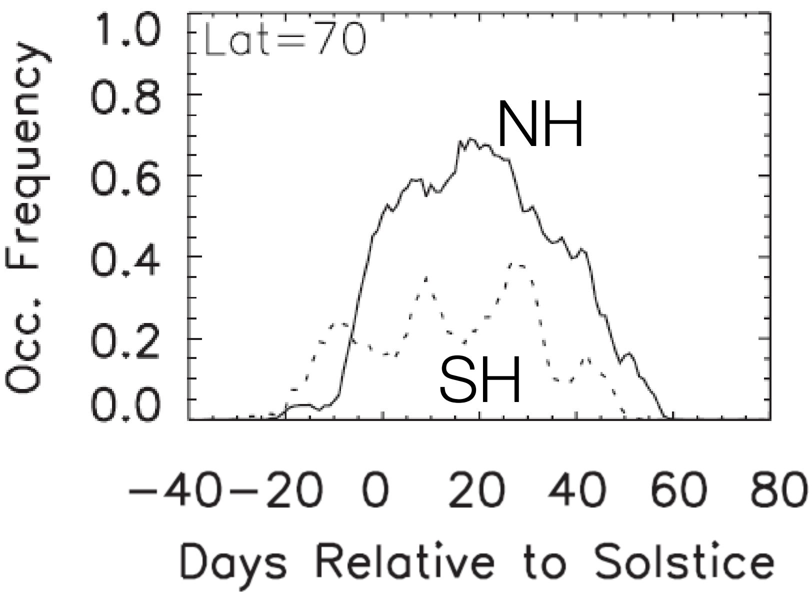




- Assume Gaussian distrib. width of 13 nm
- Backscatter ratio calculated for 90°

Occurrence frequency at 70˚



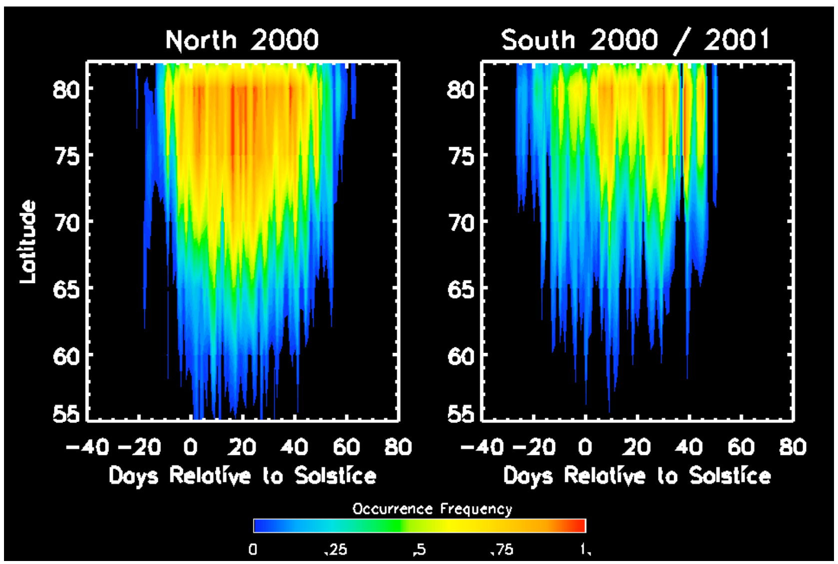


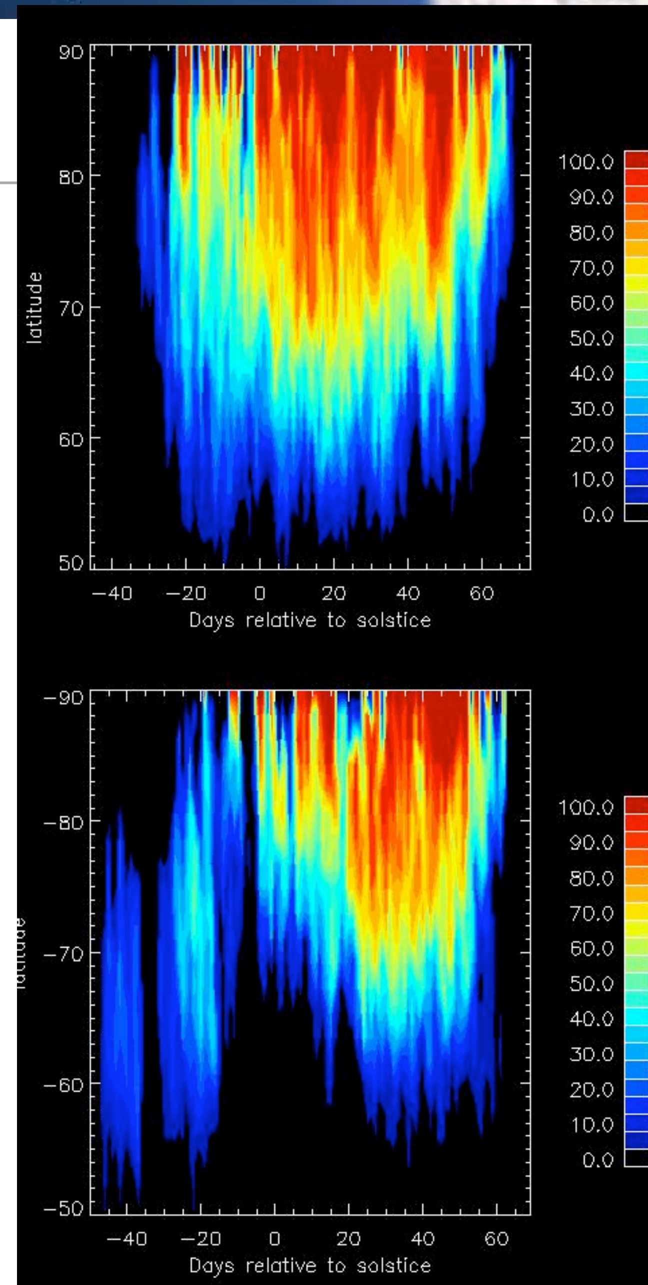
Bailey et al., 2007

CEDAR, 2009

PMC observation frequency

SNOE



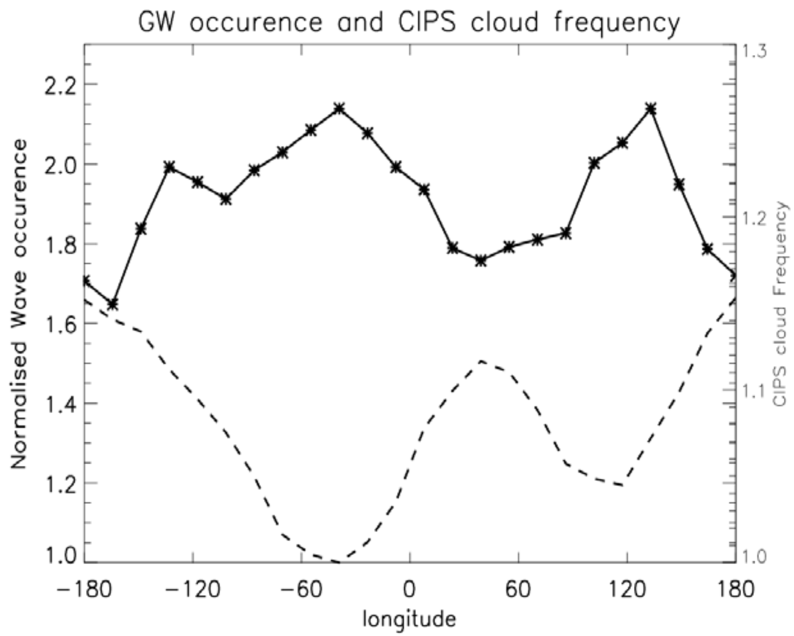


albedo > 10^{-5}

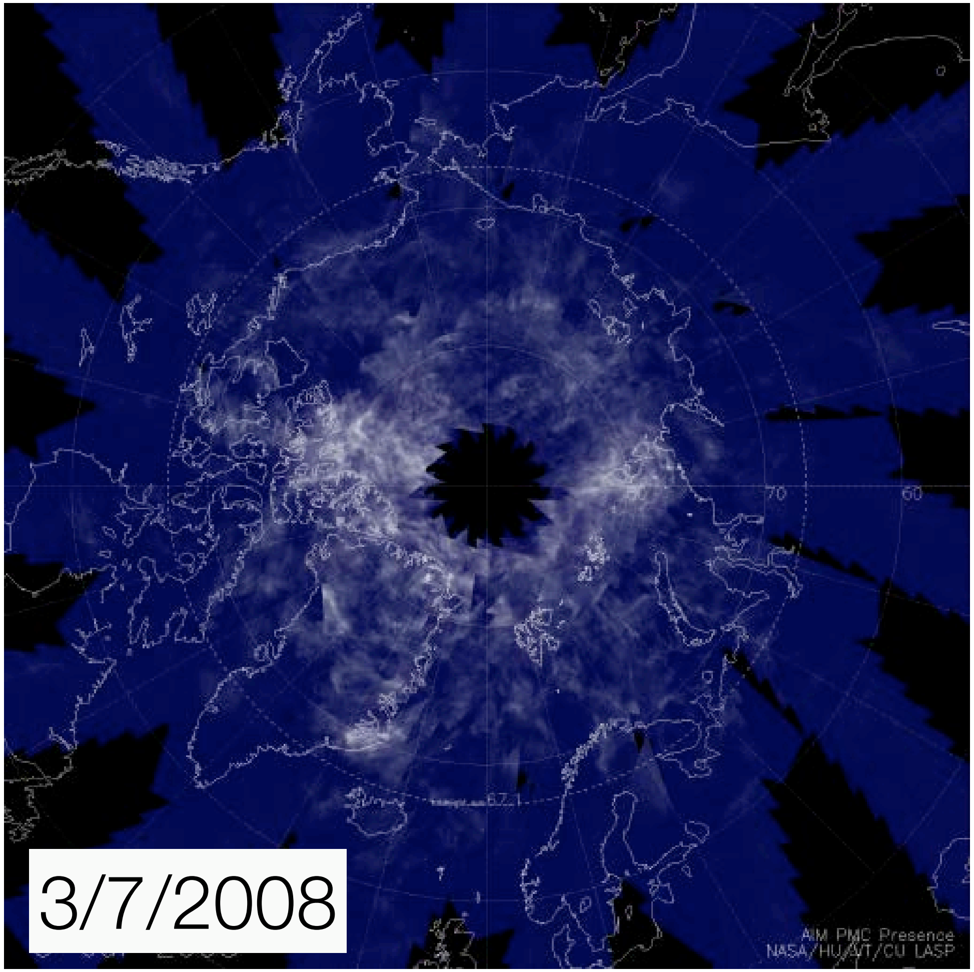
Can solar tides produce zonal asymmetry?

CIPS cloud frequency

NH Days 172-195, 70-80 N

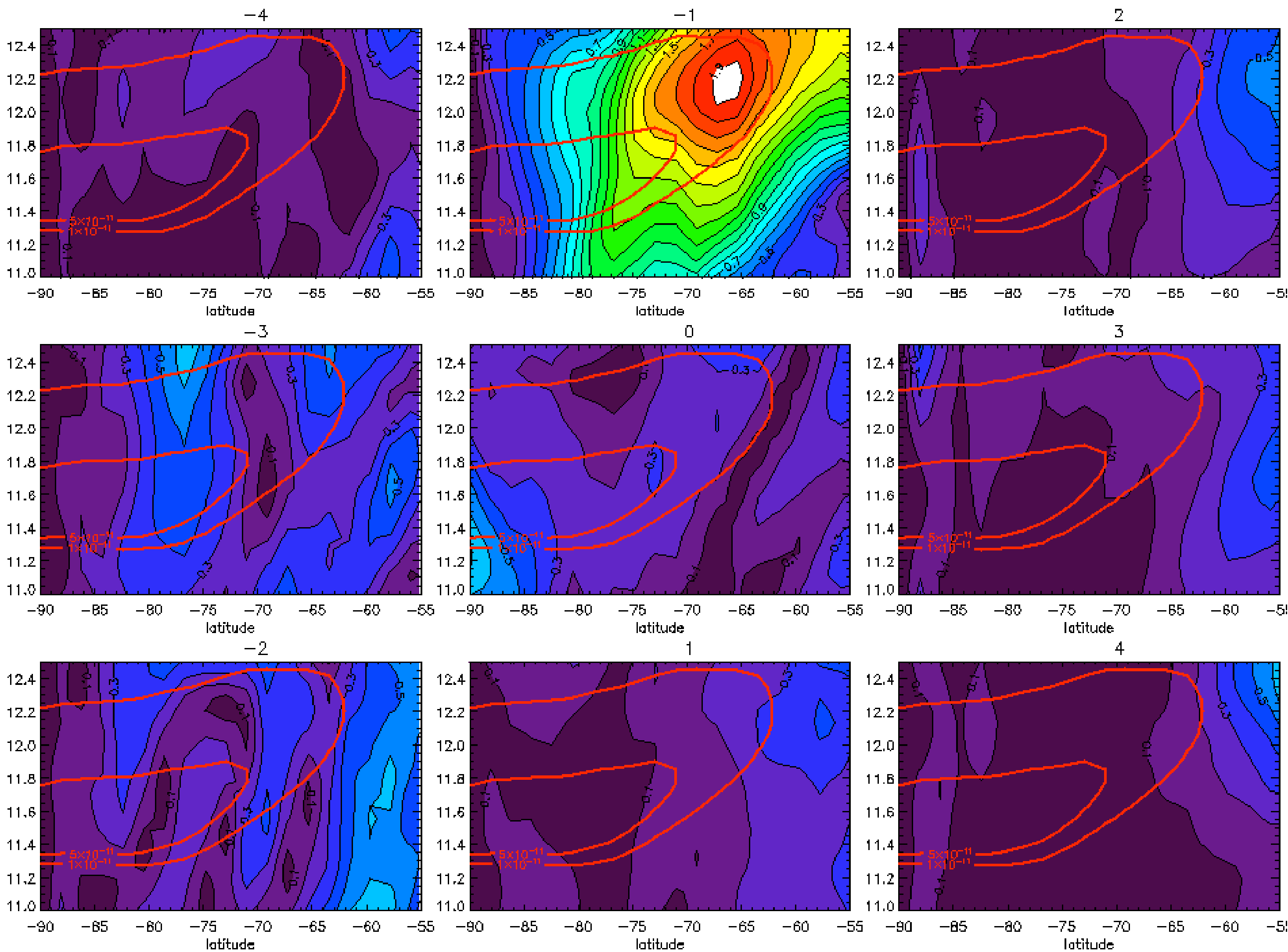


Analysis by Amal Chandran, CU/LASP

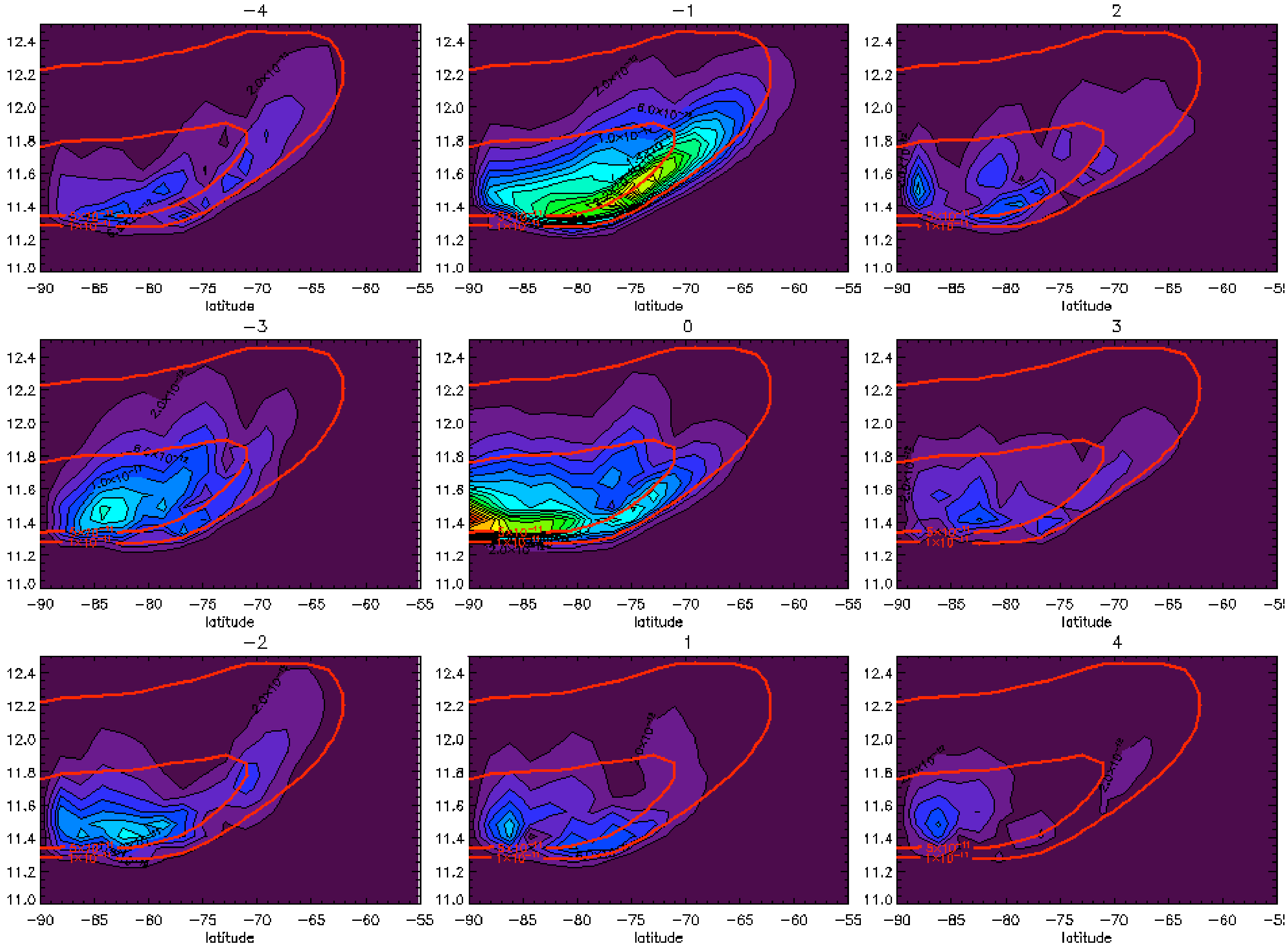


CEDAR, 2009

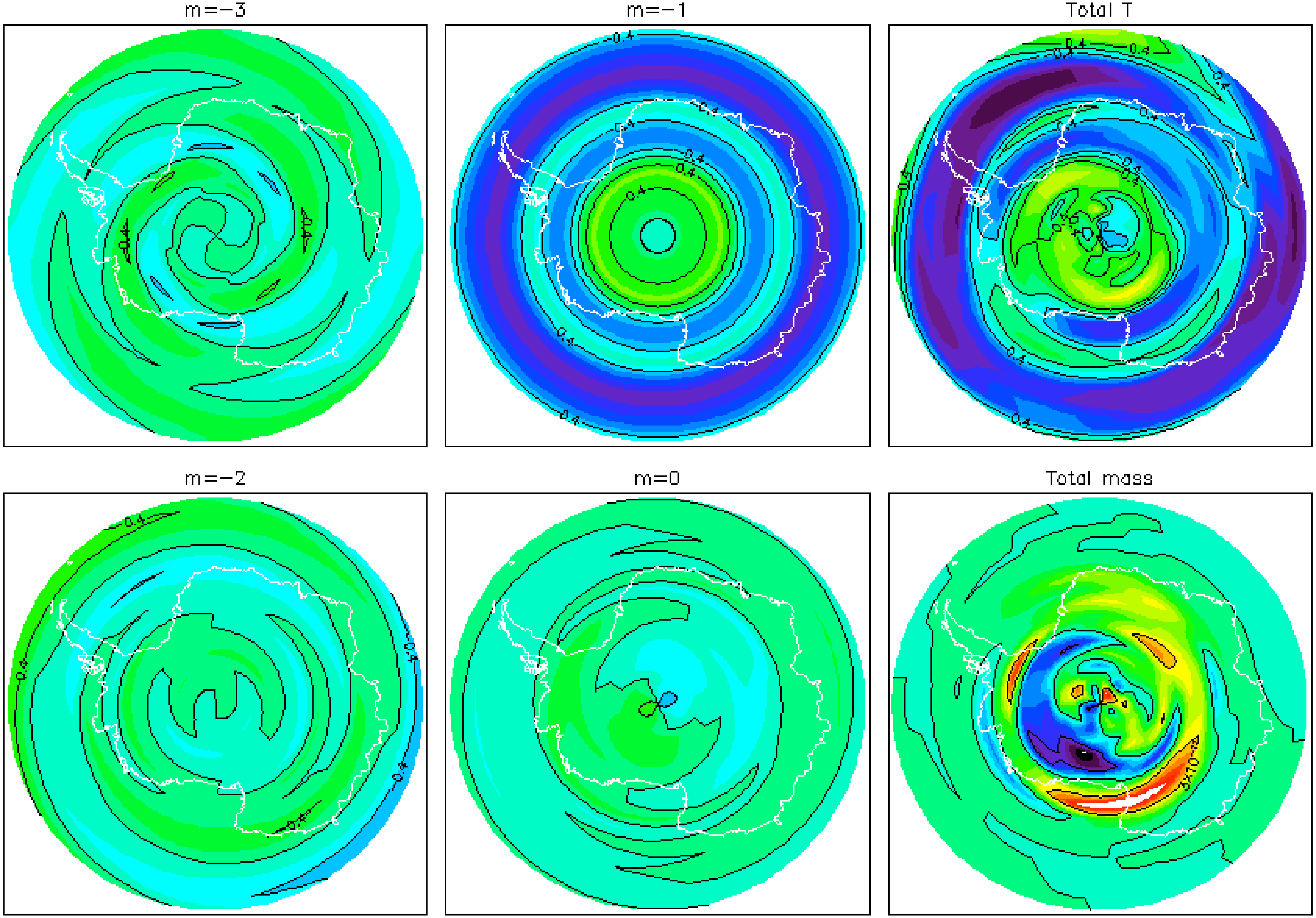
WACCM T tidal amplitudes & mean ice mass



WACCM ice mass tidal amplitudes & mean



Souther hemisphere tidal temperature viewed from sun-synchronous satellite at 12:00 hrs. local time



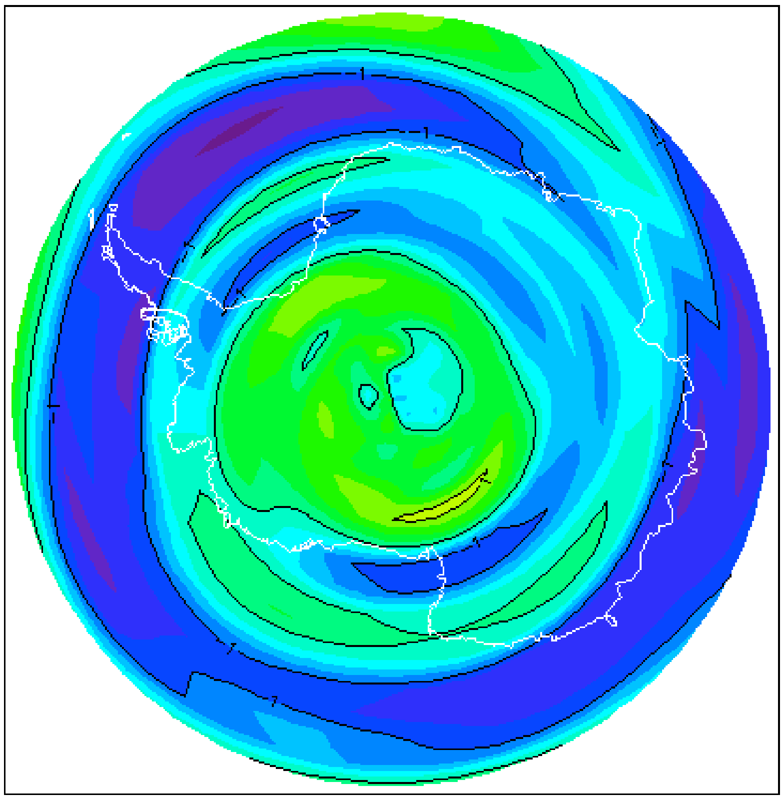
@11.5 ScaleHts. ~81km

Ice mass

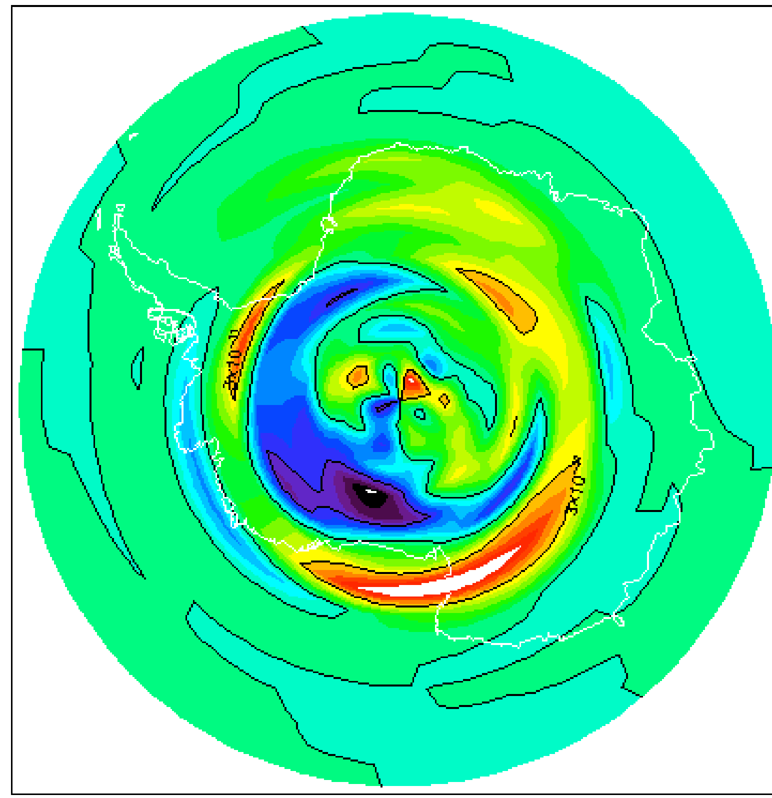
8 x 5-day mean sequence of T and ice mass

Tidal amplitudes
Southern Hemisphere Jan 11-15 @ 11.5 scale hts.

Temperature

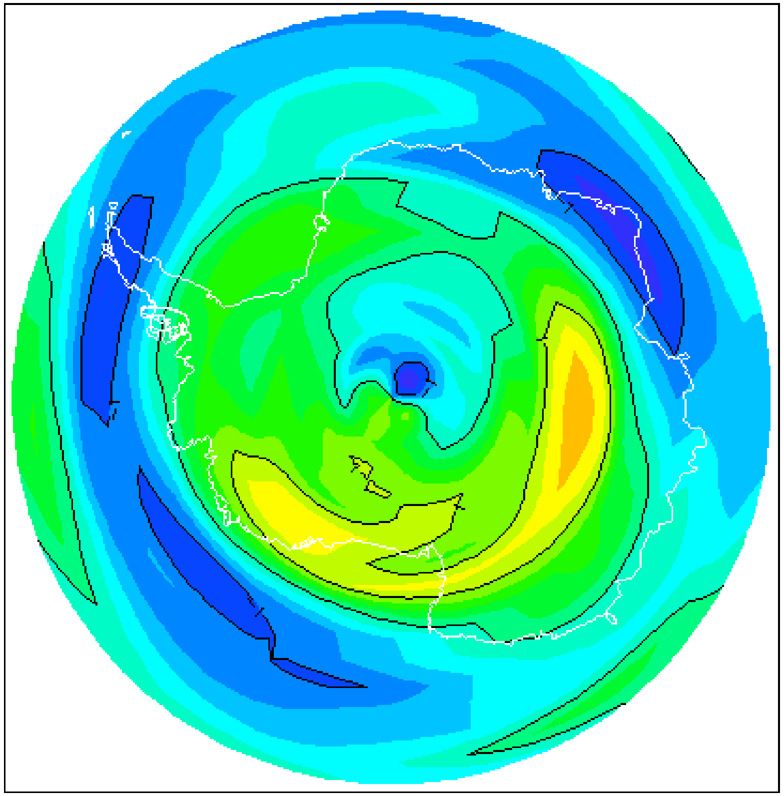


Ice Mass

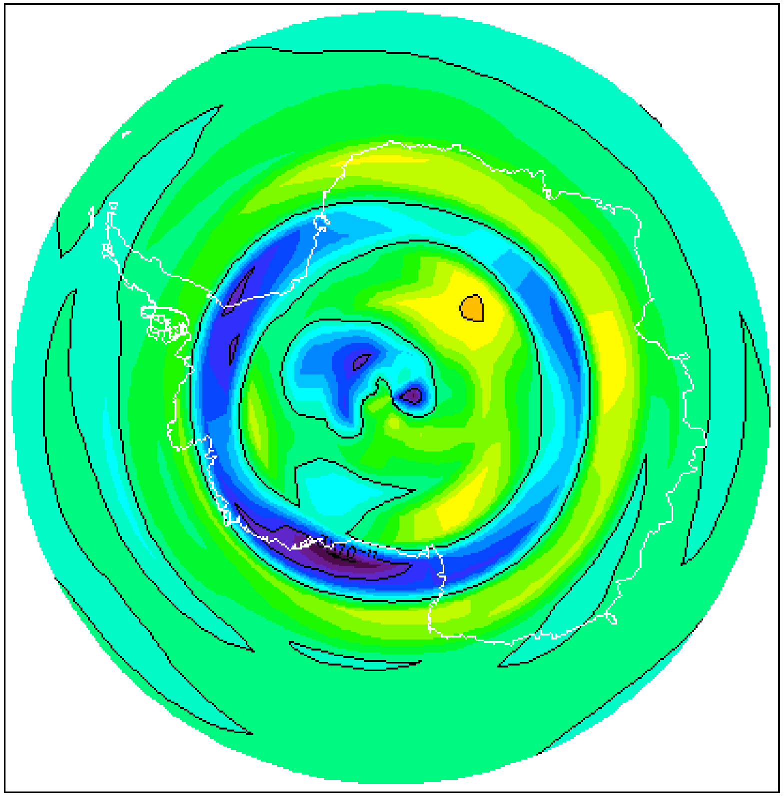


Tidal amplitudes
Southern Hemisphere Jan 16-20 @ 11.5 scale hts.

Temperature

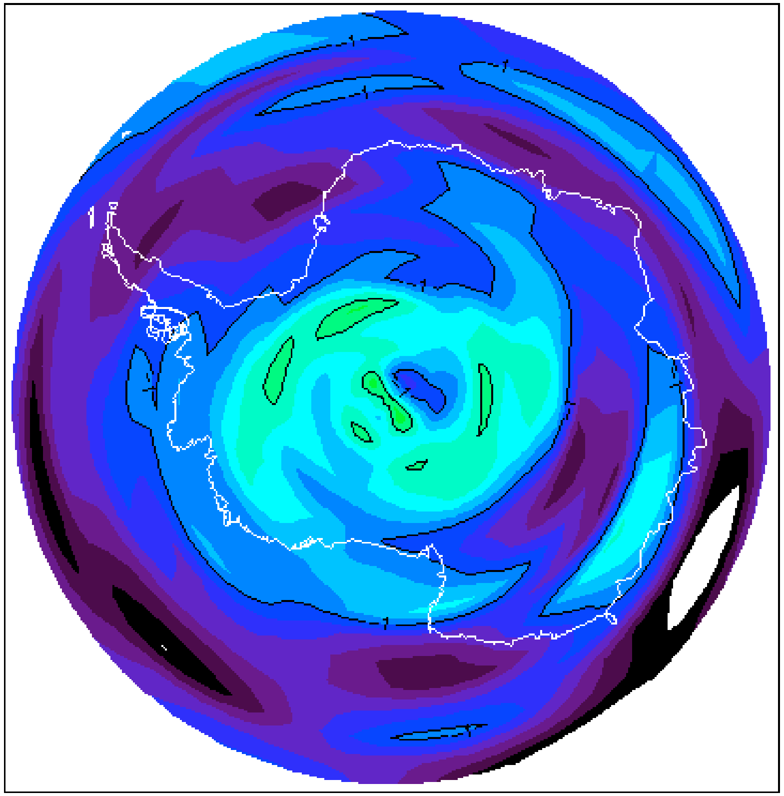


Ice Mass

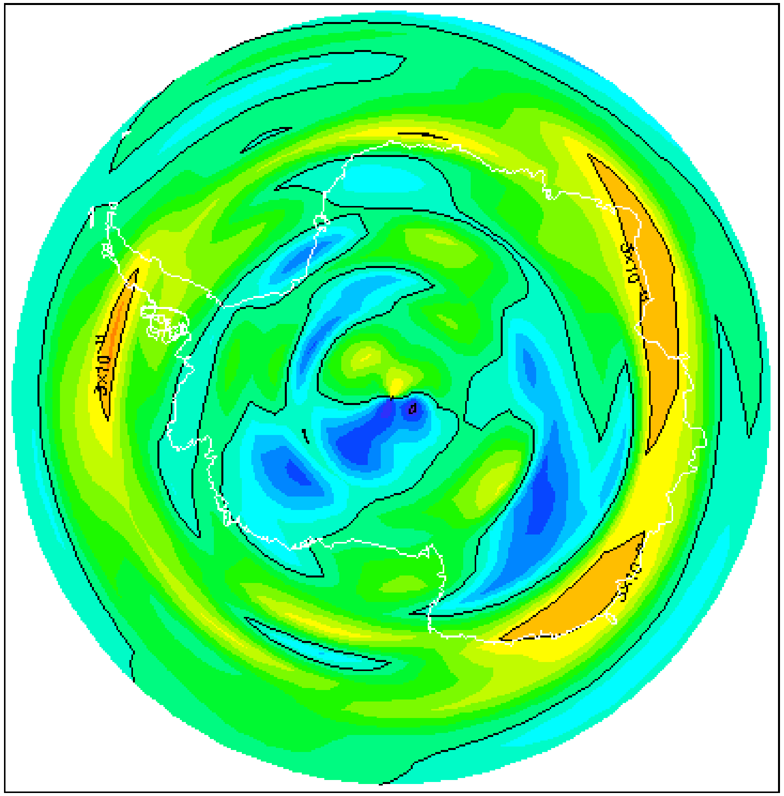


Tidal amplitudes
Southern Hemisphere Jan 21-25 @ 11.5 scale hts.

Temperature

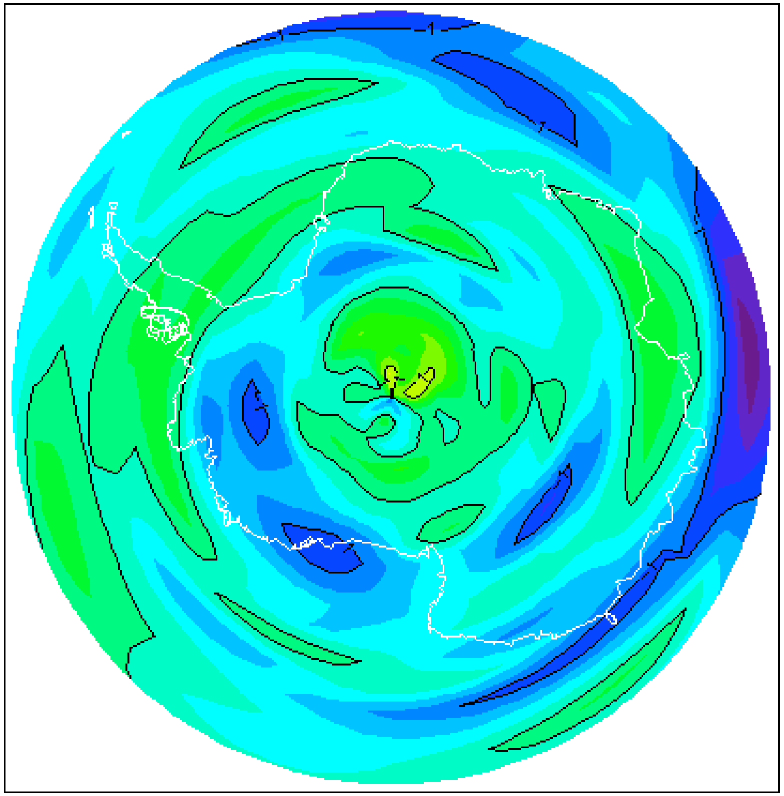


Ice Mass

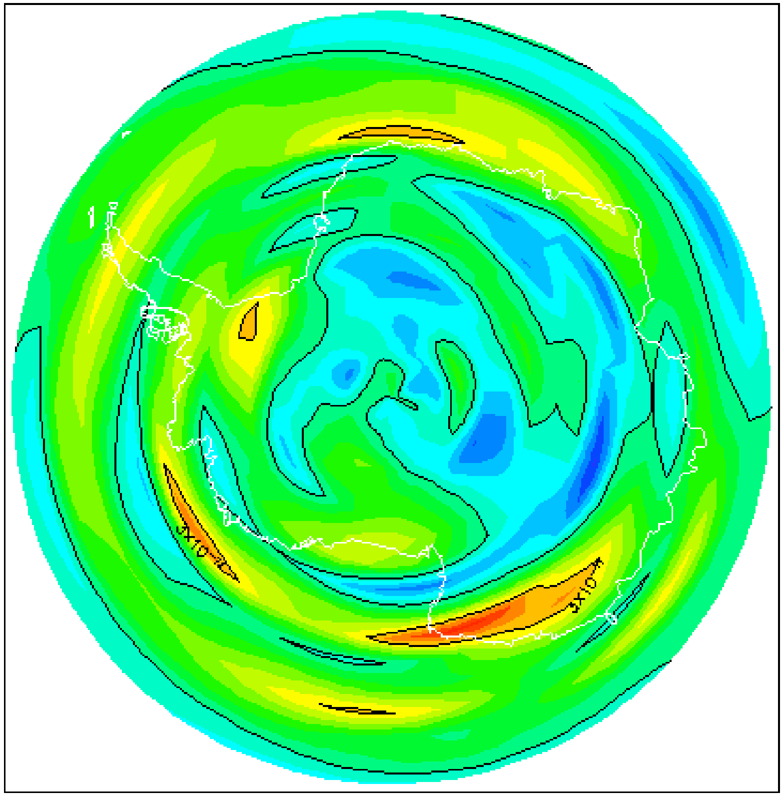


Tidal amplitudes
Southern Hemisphere Jan 26-30 @ 11.5 scale hts.

Temperature

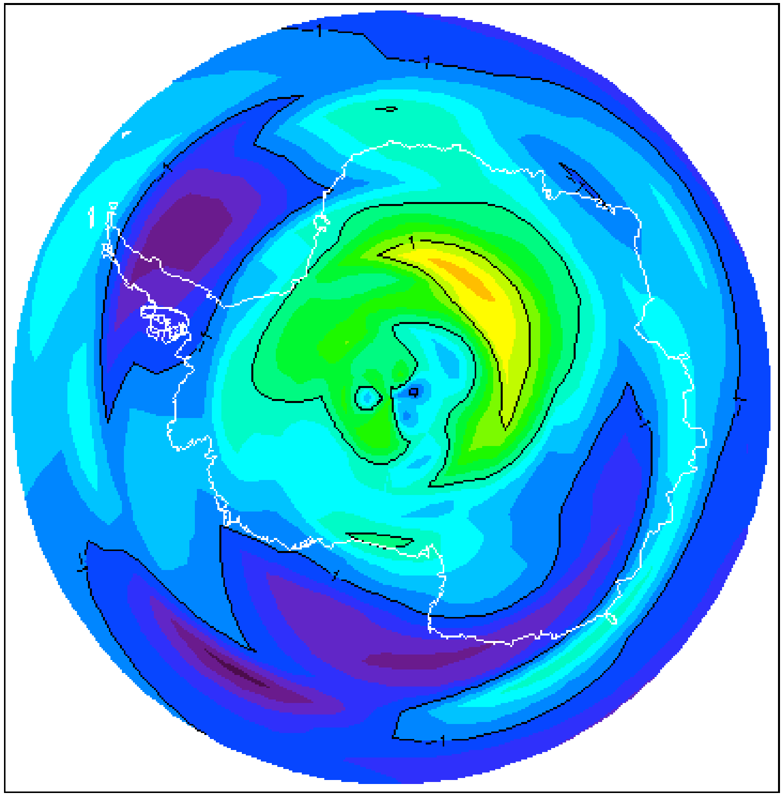


Ice Mass

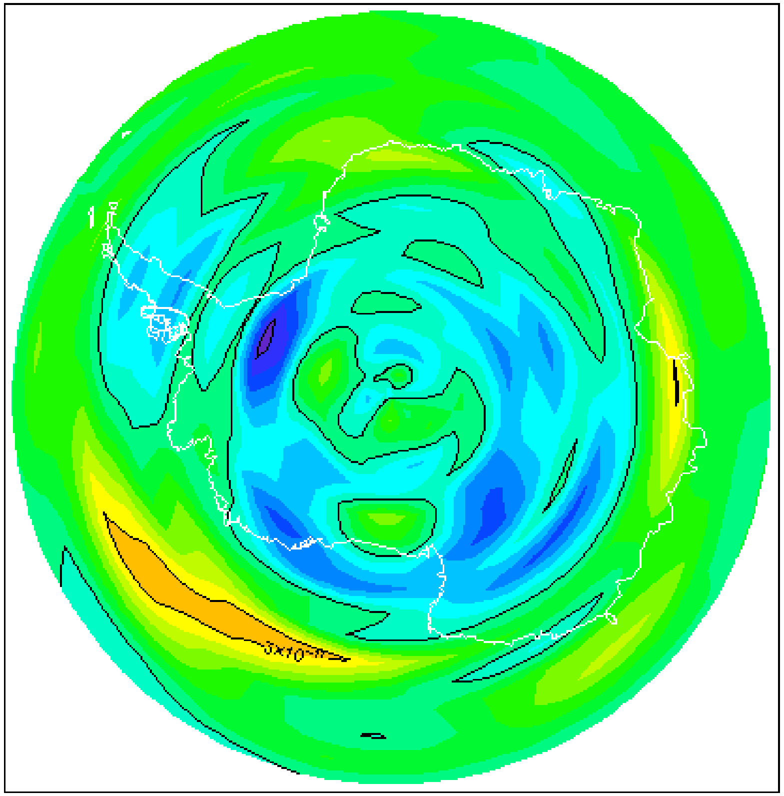


Tidal amplitudes
Southern Hemisphere J31- F04 @ 11.5 scale hts.

Temperature

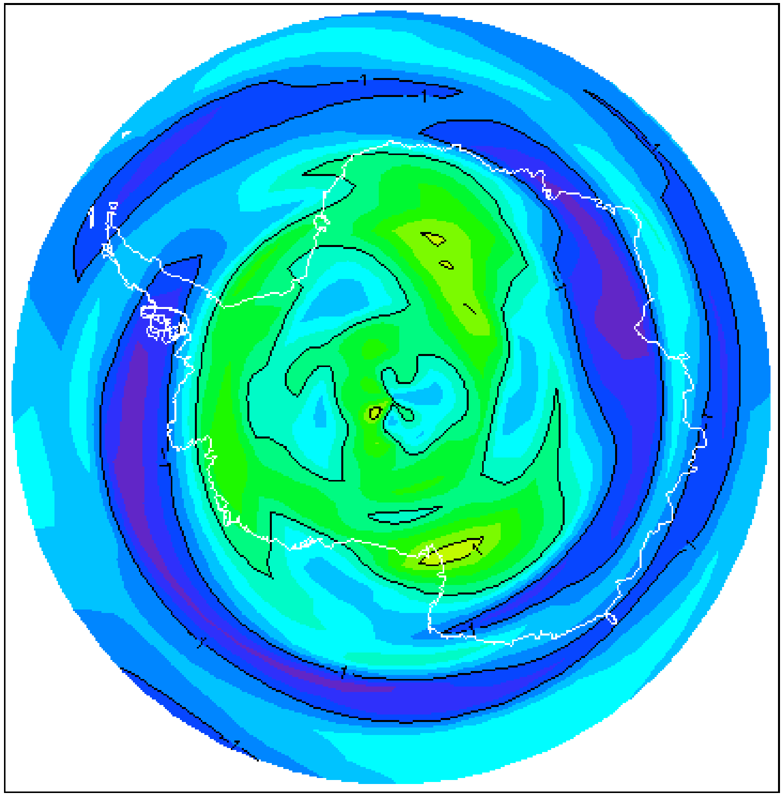


Ice Mass

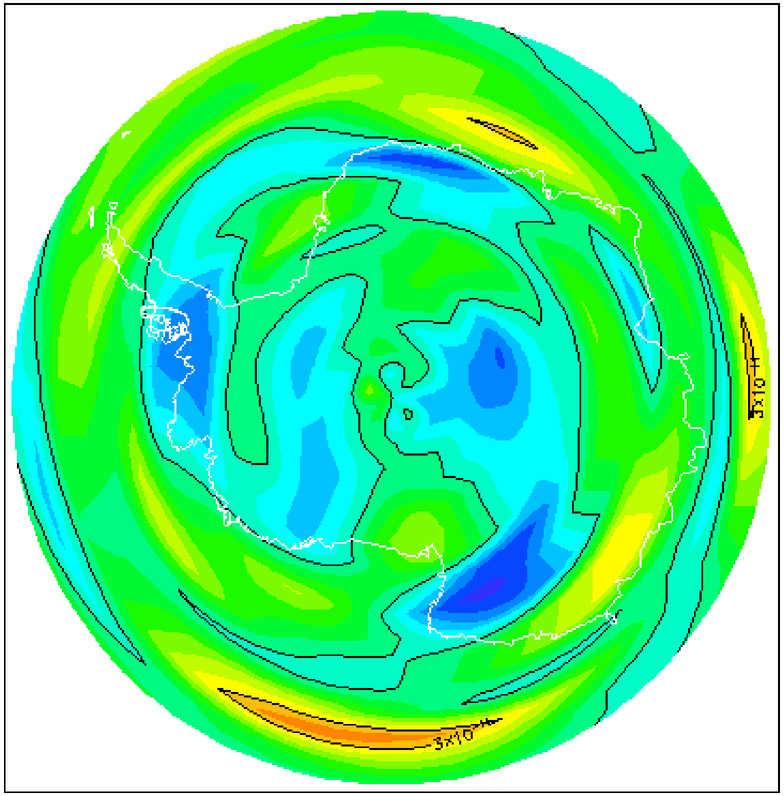


Tidal amplitudes
Southern Hemisphere Feb 05-09 @ 11.5 scale hts.

Temperature

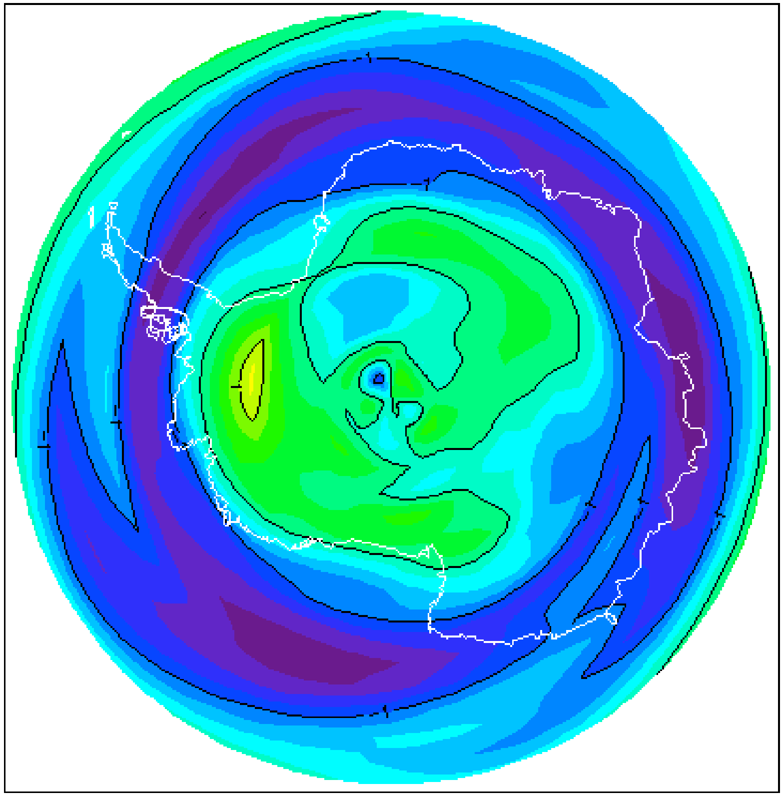


Ice Mass

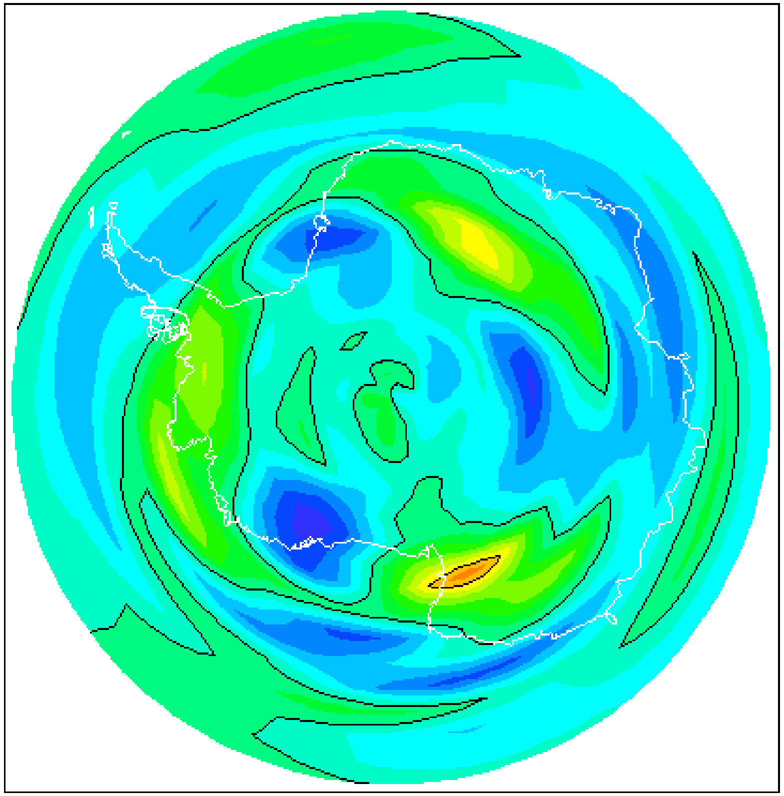


Tidal amplitudes
Southern Hemisphere Feb 10-14 @ 11.5 scale hts.

Temperature

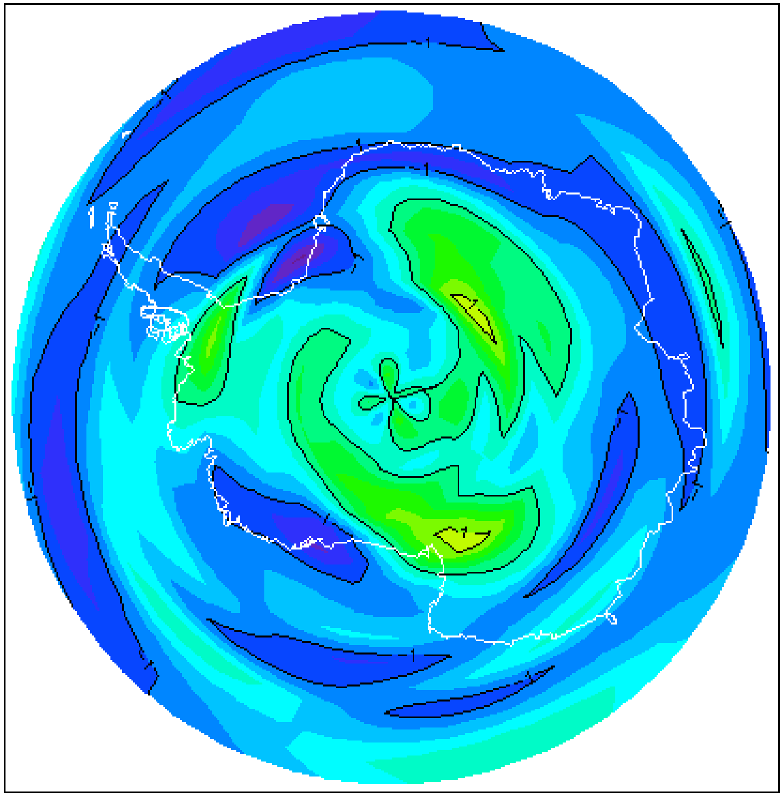


Ice Mass

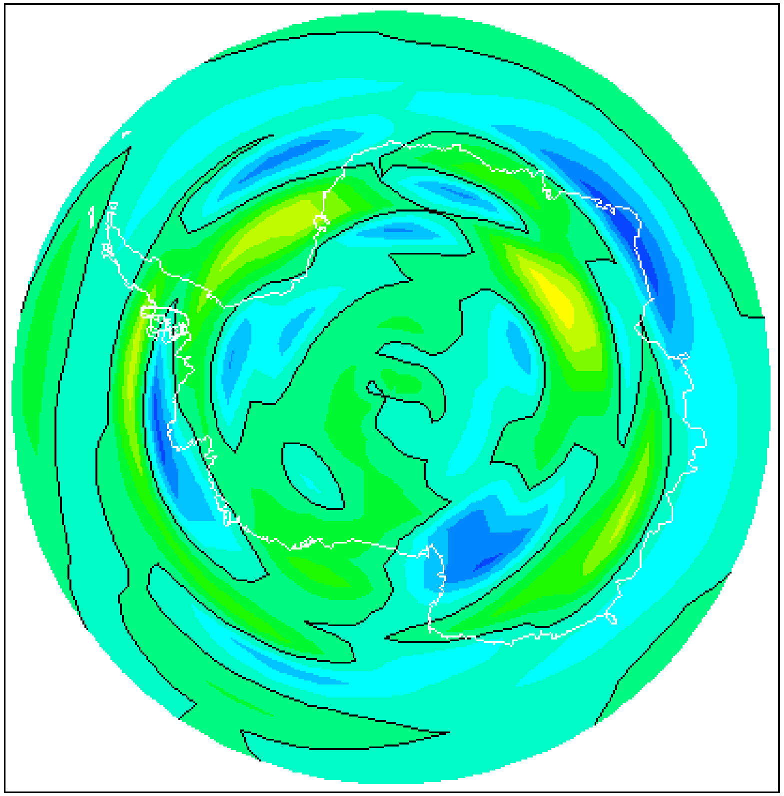


Tidal amplitudes
Southern Hemisphere Feb 15-19 @ 11.5 scale hts.

Temperature

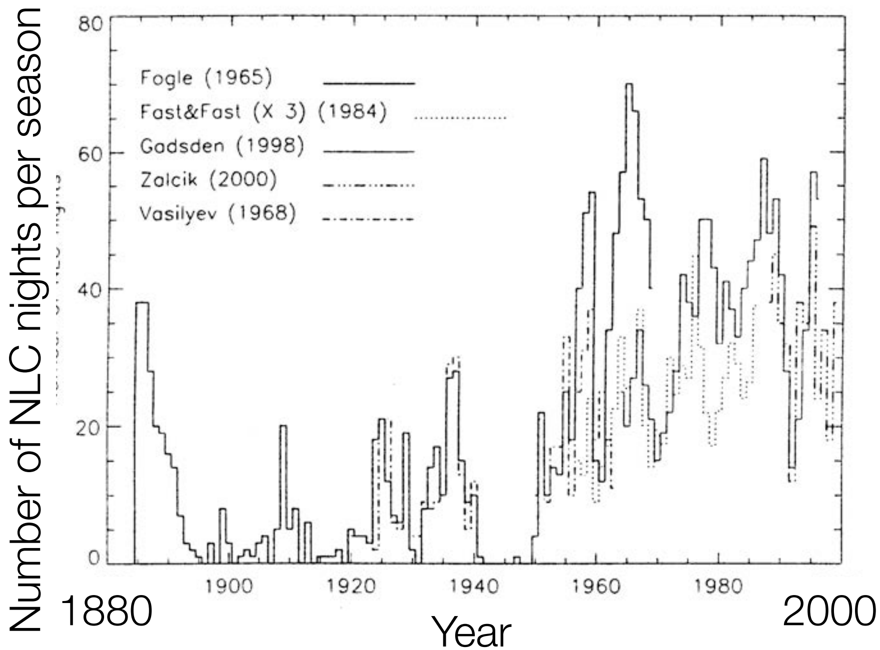


Ice Mass

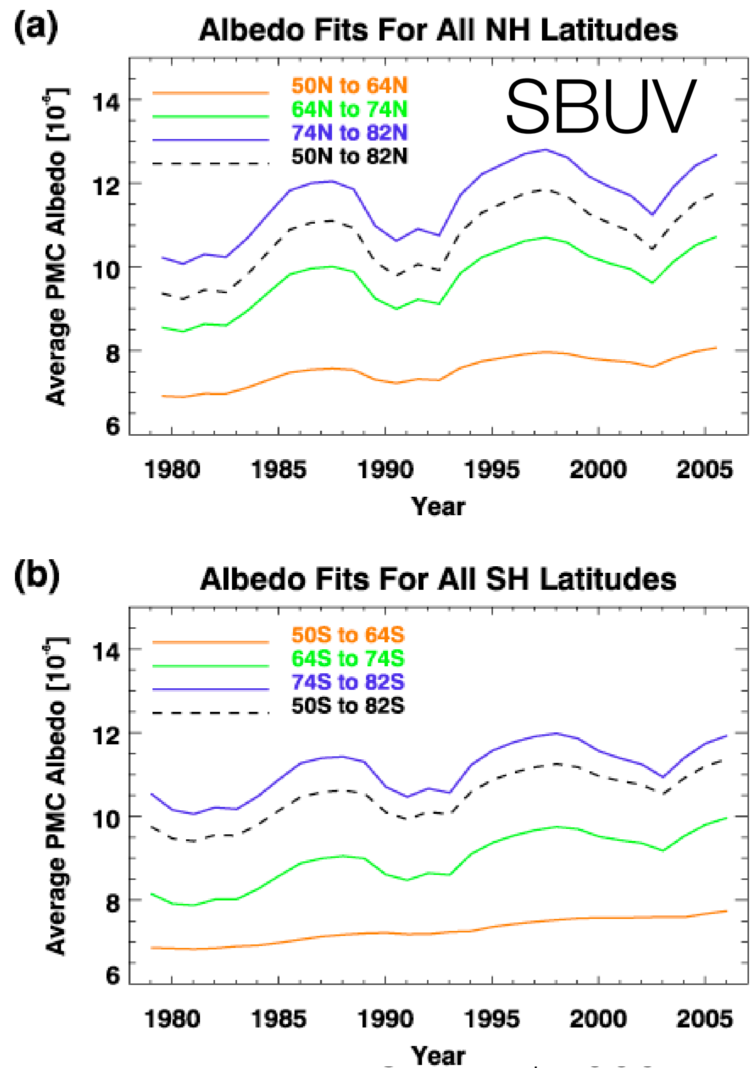


PMC frequency & brightness are increasing

Ground based observations



Thomas and Olivero, 2001



DeLand et al., 2007

WACCM albedo calculations

- Albedo calculated at 252 nm a 120° scattering angle
- Albedo above detectable threshold calculated over each season
- Season defined as SBUV: -30 to +70 DFS.
- Threshold dependent on latitude (DeLand):

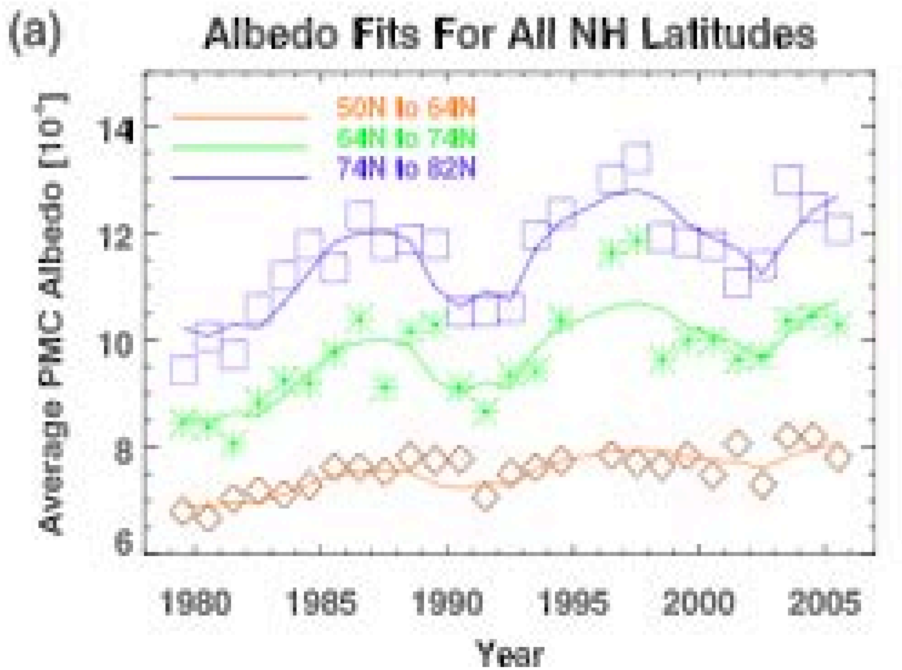
  50N to 64N = 5.5G Threshold

  64N to 74N = 6.5G threshold

  74N to 82N = 7.5G threshold

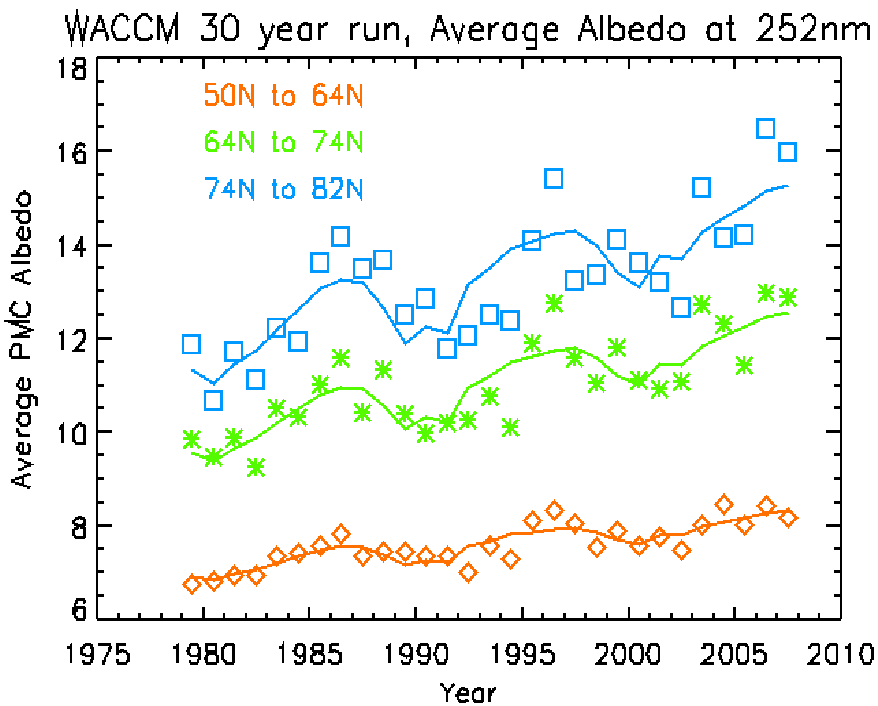
Northern hemisphere

SBUV



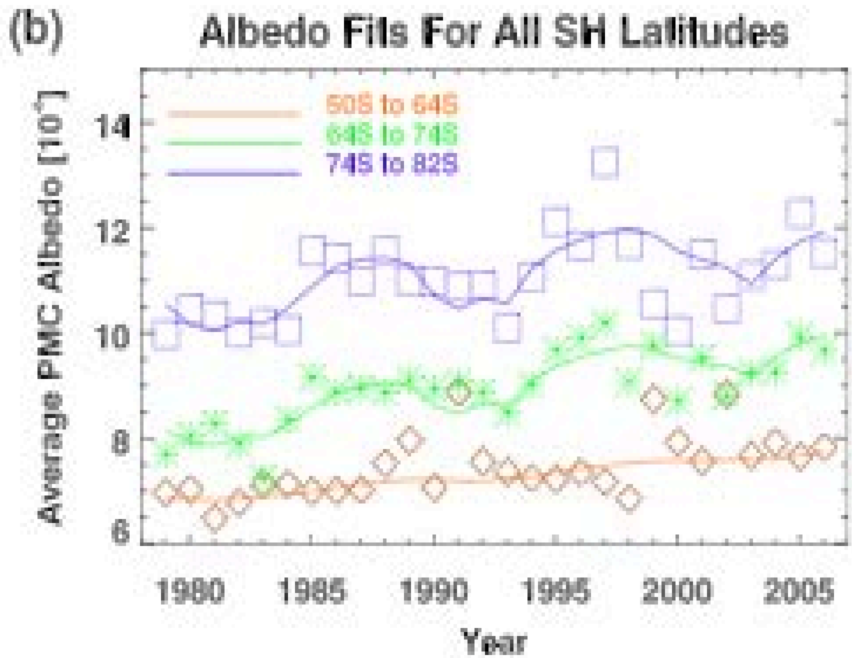
DeLand et al. 2007

WACCM



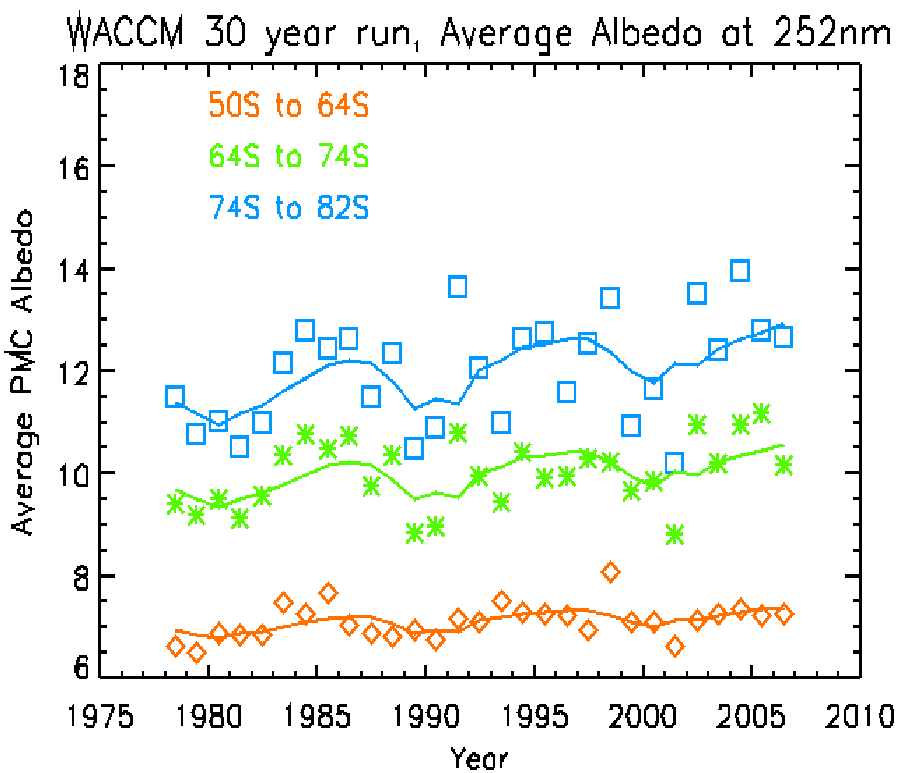
Southern hemisphere

SBUV



DeLand et al. 2007

WACCM

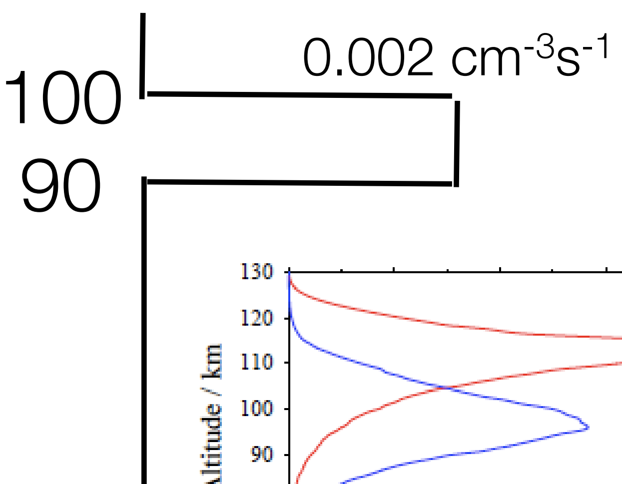


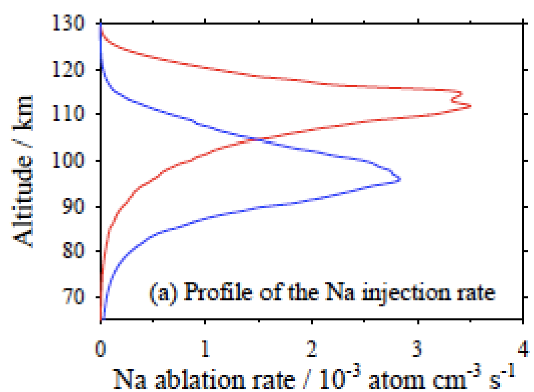
Meteoric sodium

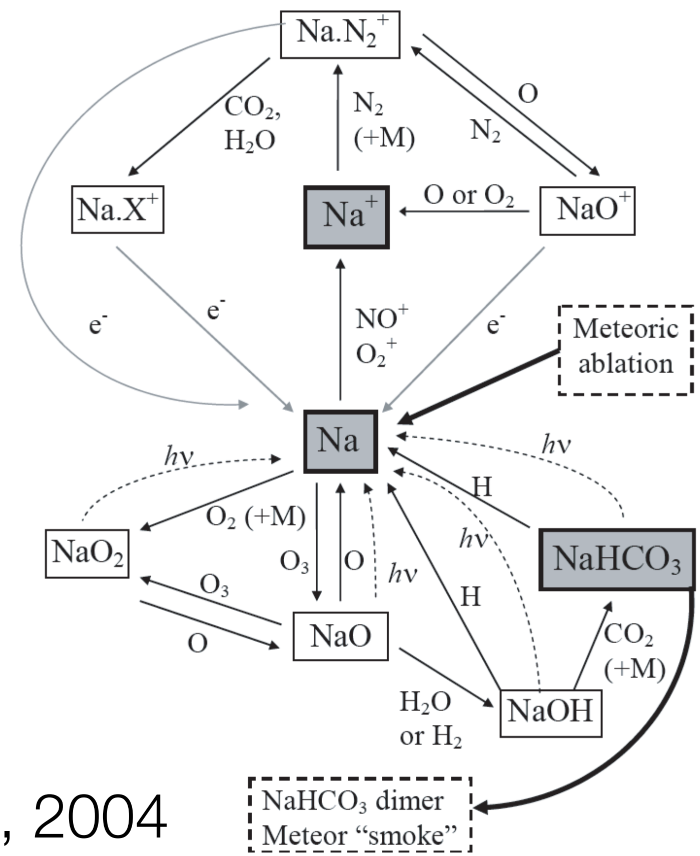
WACCM sodium chemistry model

Chemistry follows Plane [2004]

- 26 Na chemical reactions
- 5 photolysis reactions
- *very* simplified constant meteor input function:



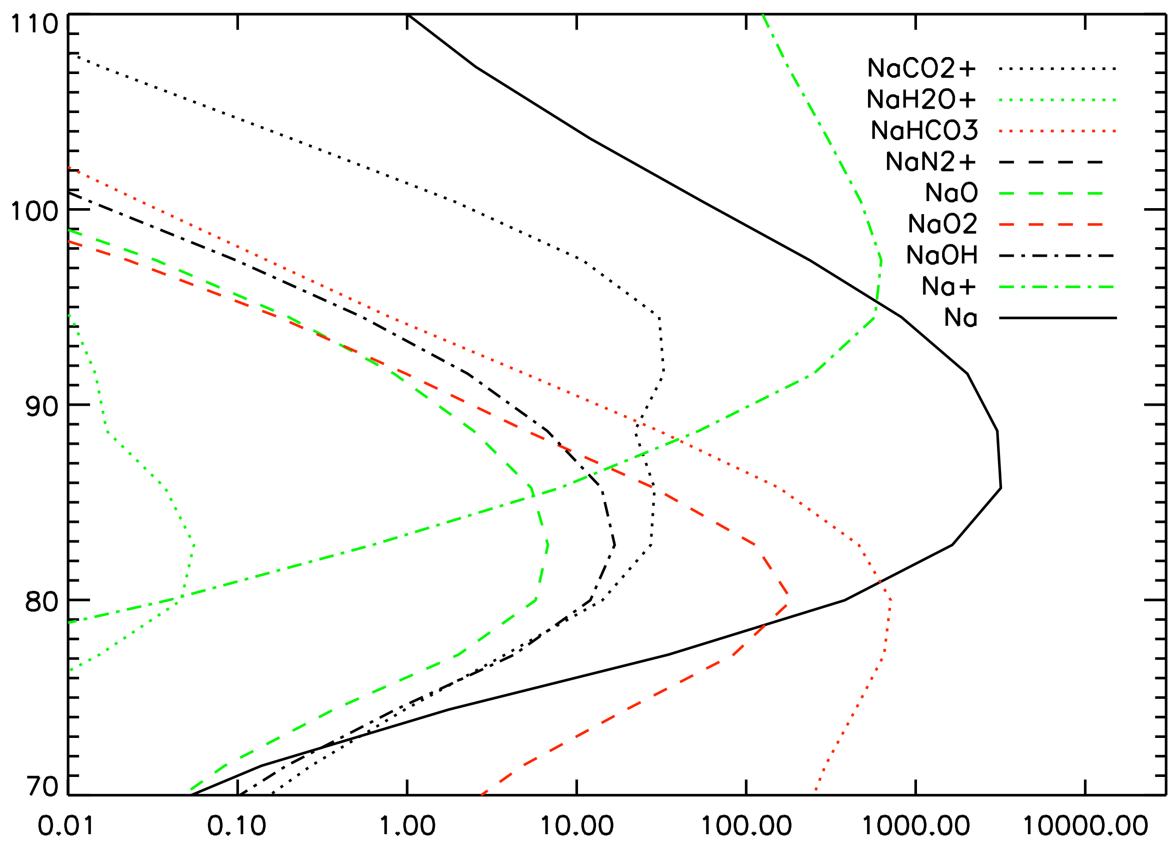


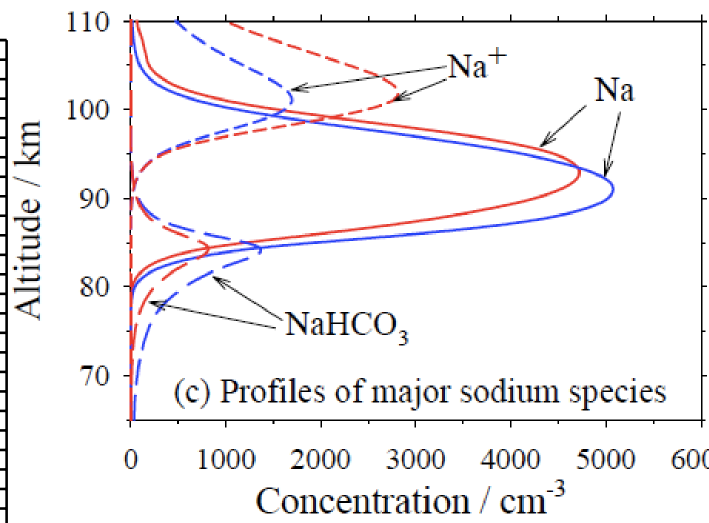


Plane, 2004

CEDAR, 2009

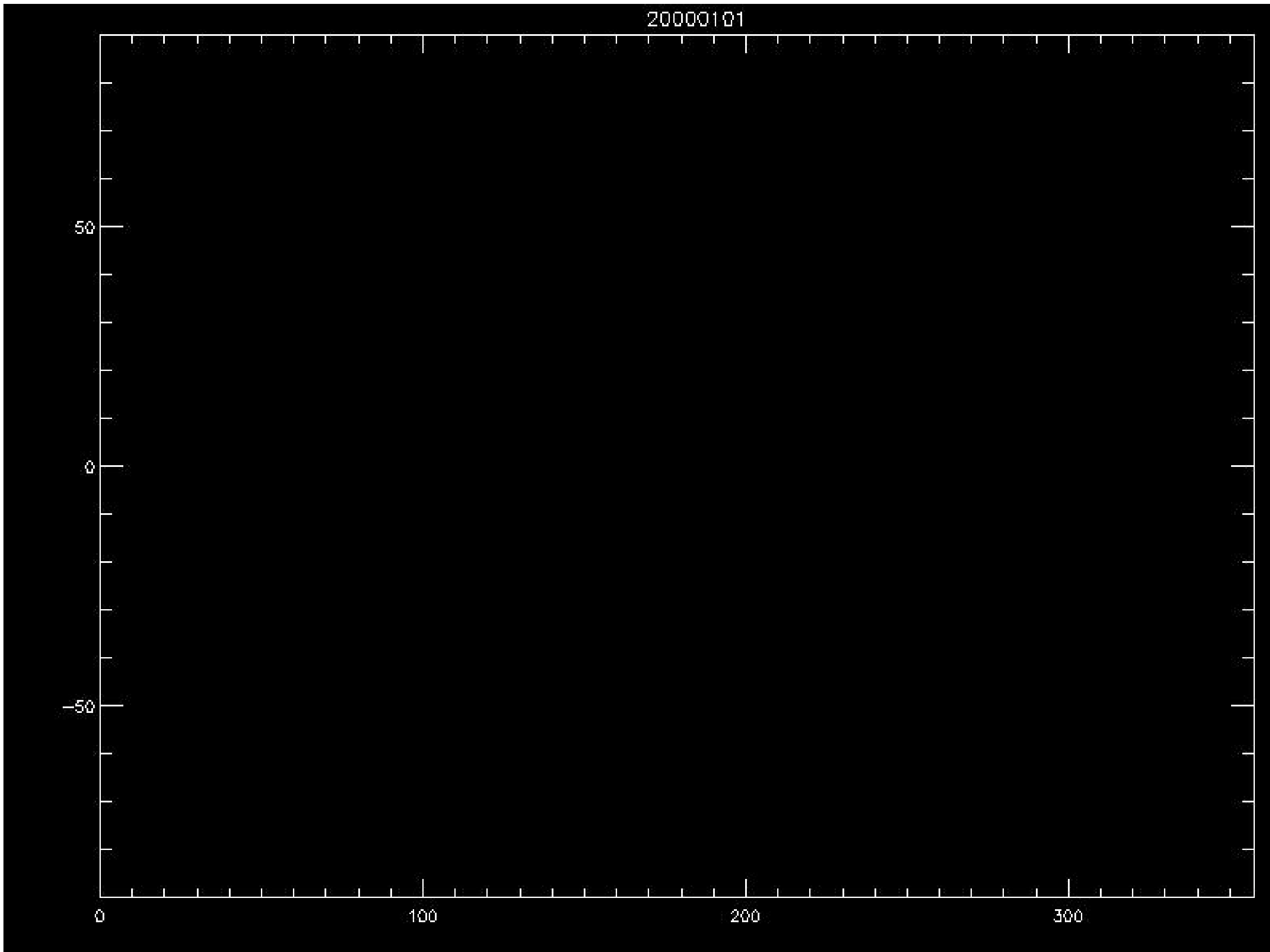
Global mean constituent profiles





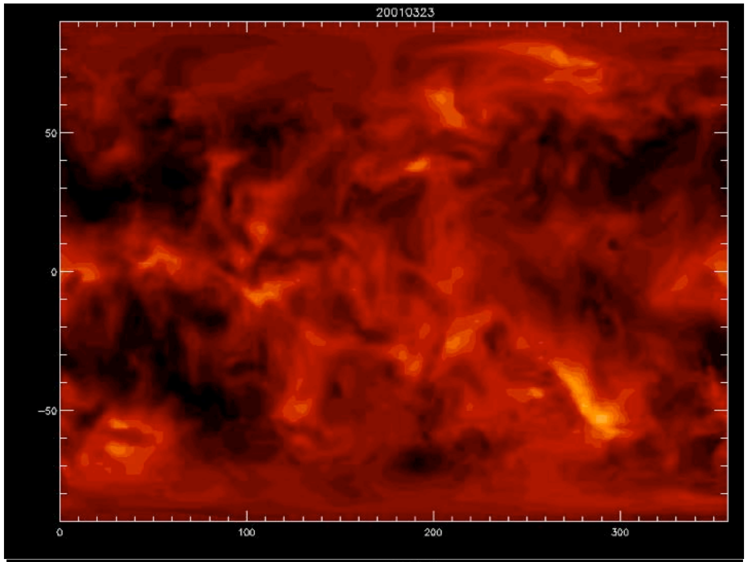
Plane, 2004

Daily ‘snapshots’ of sodium ~90km / UT00

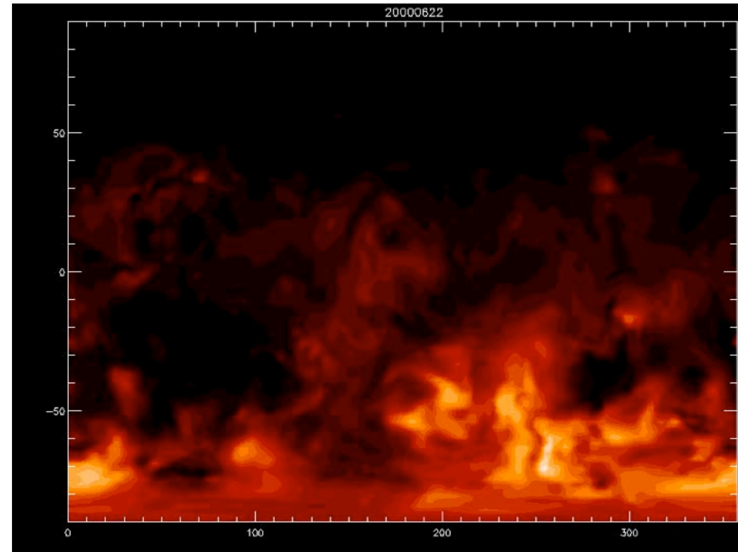


Sodium density at ~90 km

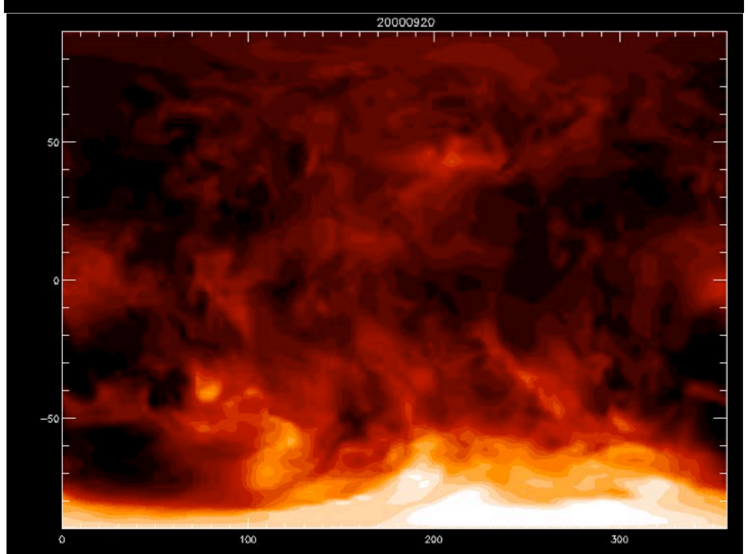
3/23



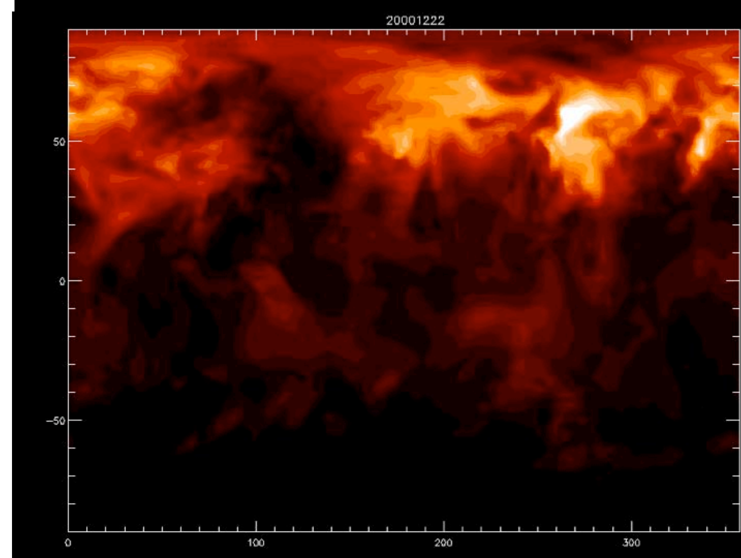
6/22



9/20

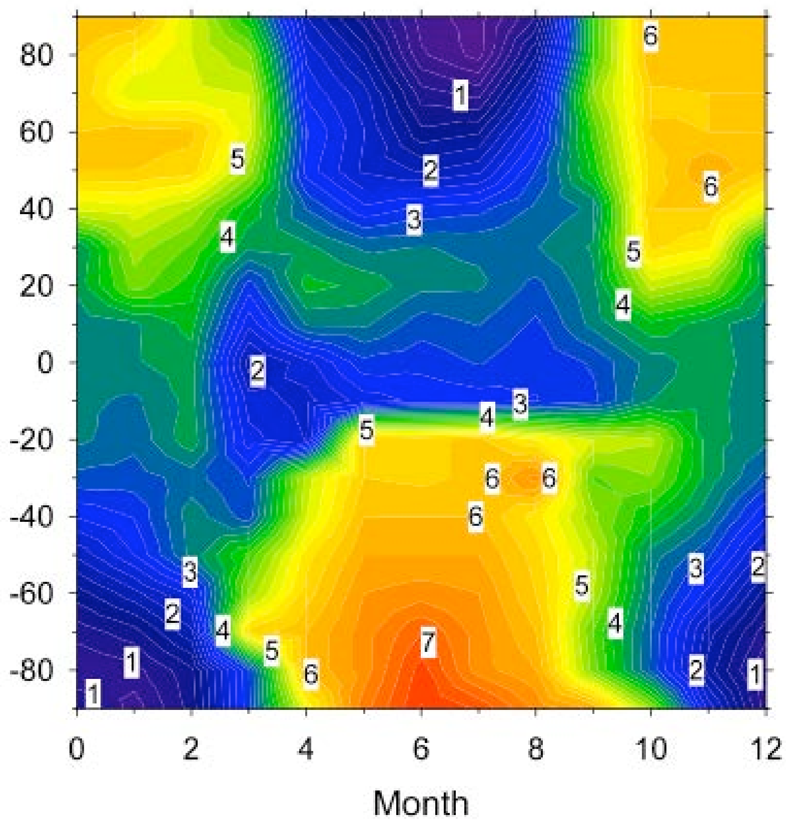


12/22



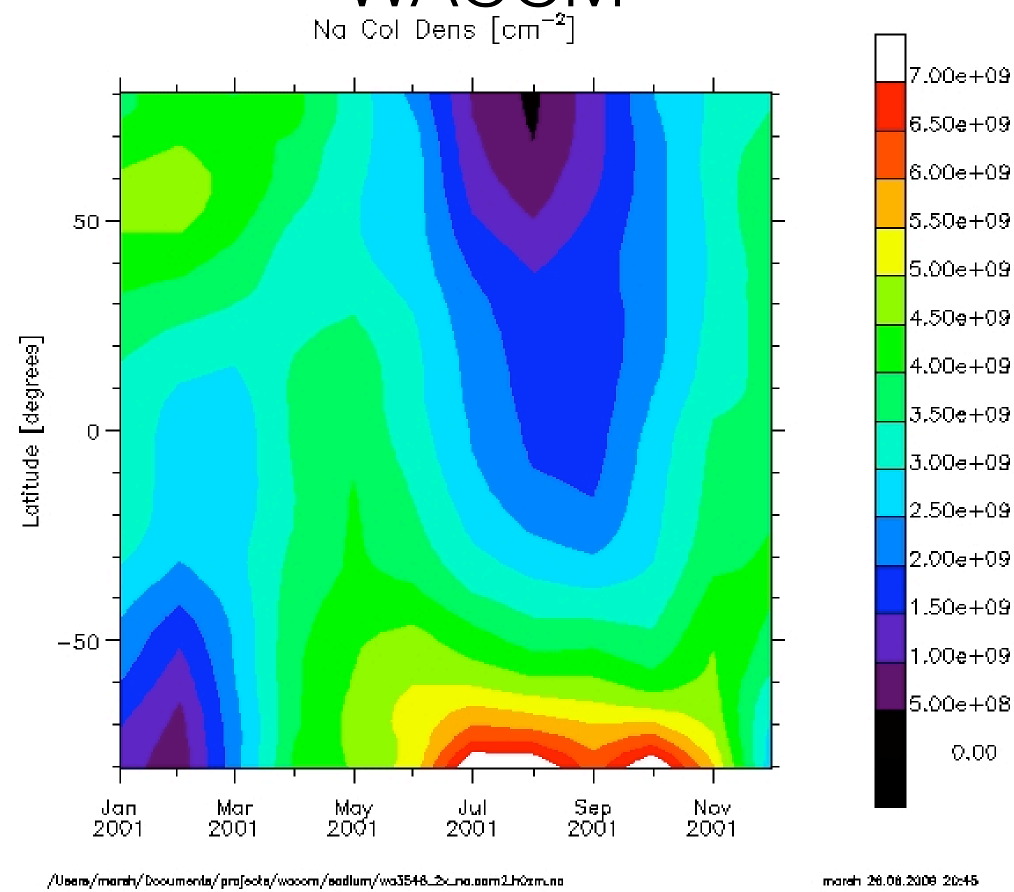
Seasonal variation of sodium column density

Osiris



Plane, 2009

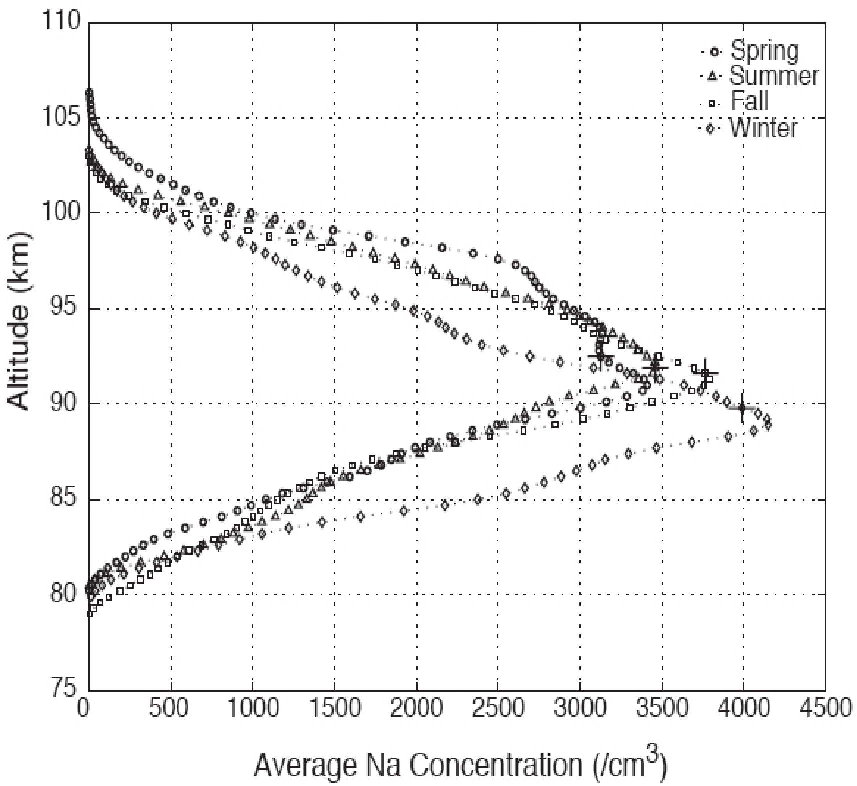
WACCM



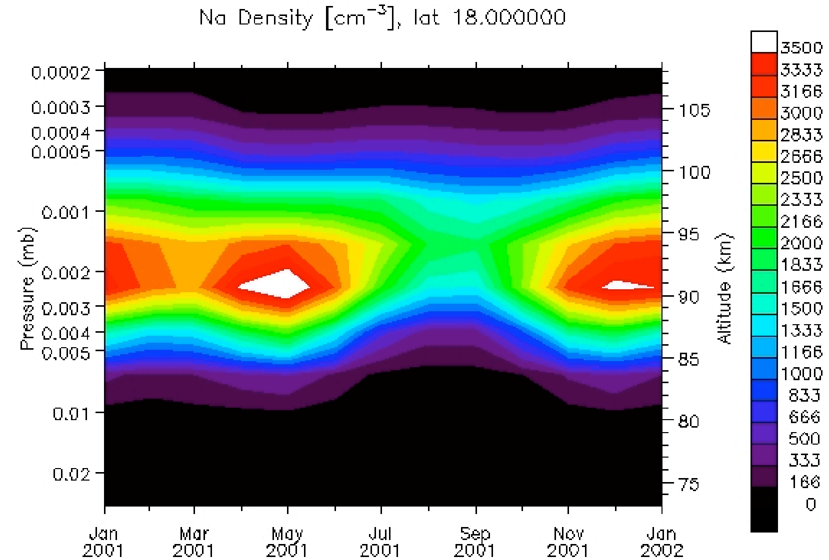
CEDAR, 2009

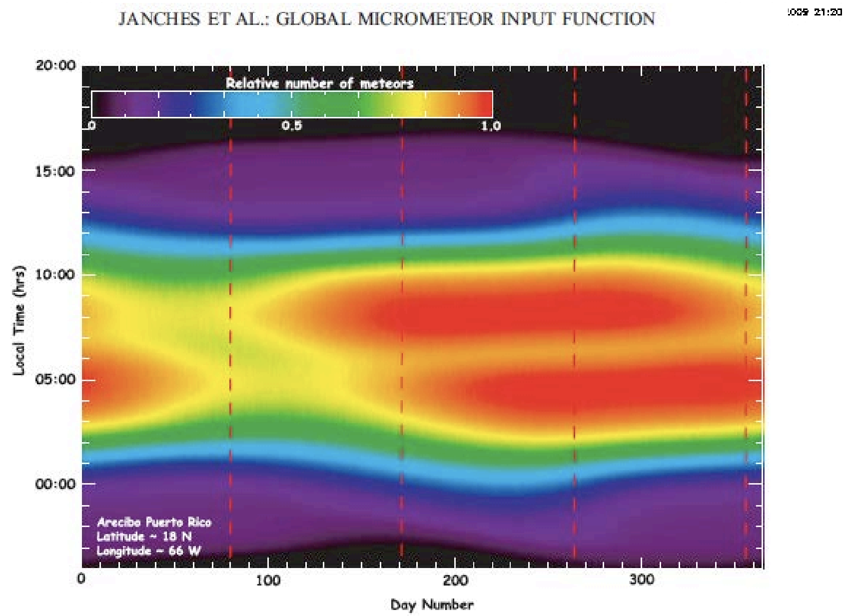
WACCM

Whole Atmosphere Community Climate Model



Arecibo ISR
Zhou, 2005



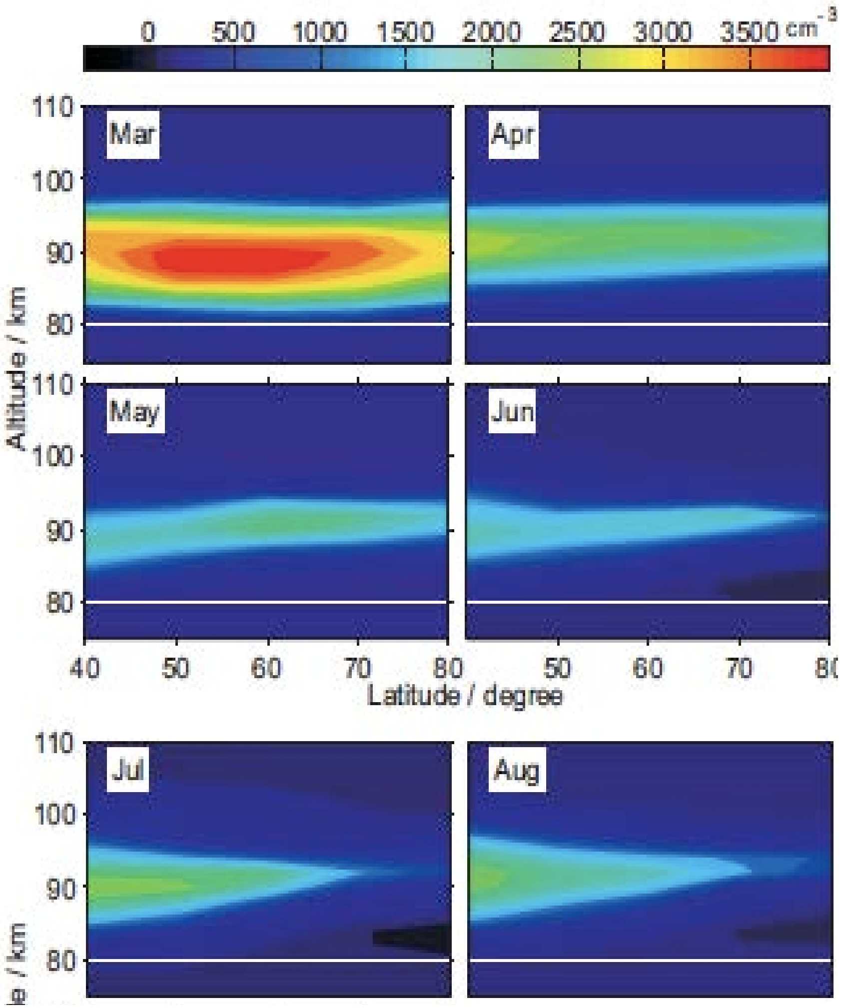


CEDAR, 2009

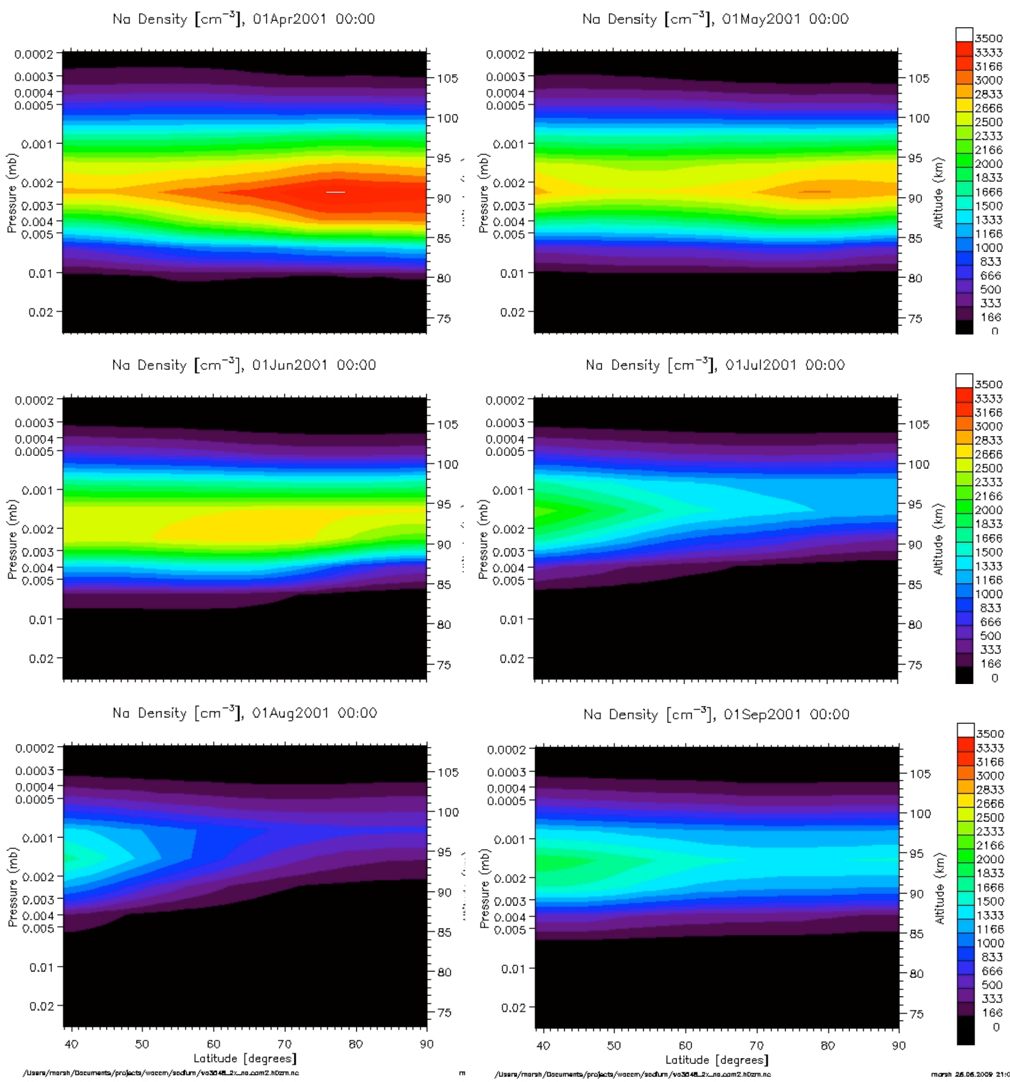
WACCM Whole Atmosphere Community Climate Model

NCAR

OSIRIS seasonality



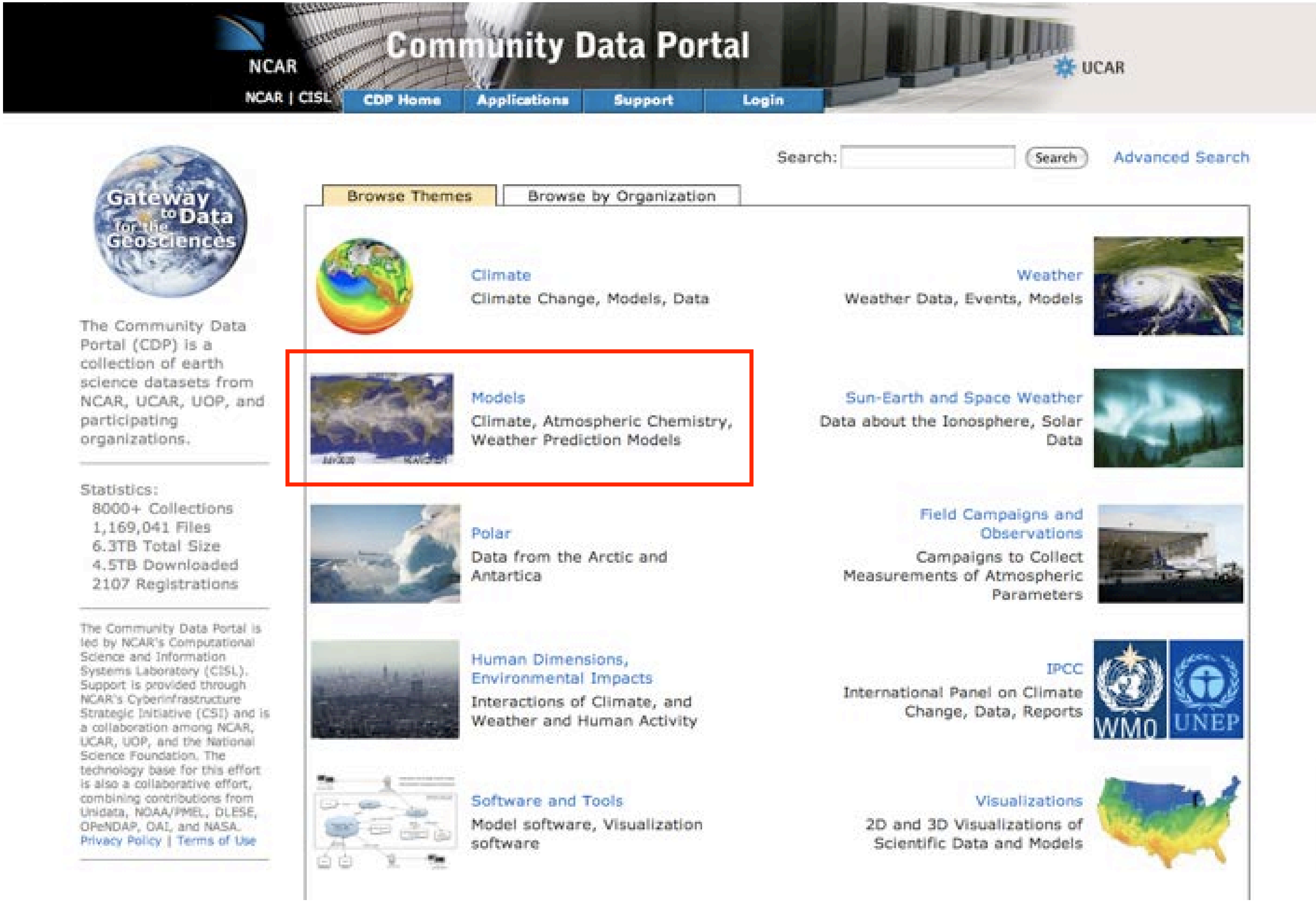
Fan et al., 2007



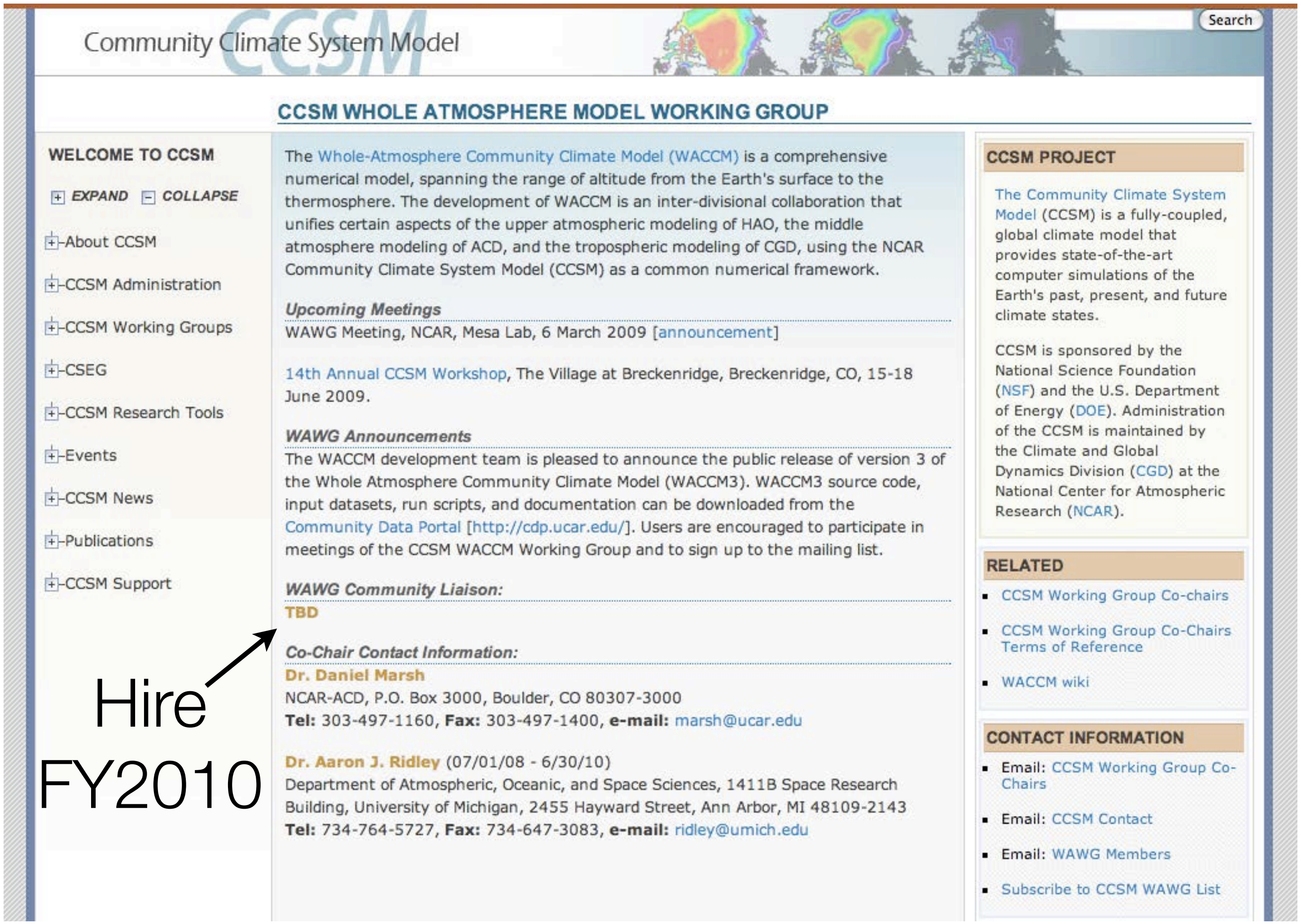
WACCM is available to the scientific community ...

NCAR WACCM Whole Atmosphere Community Climate Model

http://cdp.ucar.edu/



Webpage http://www.ccsm.ucar.edu/working_groups/



Community Climate System Model

Search

CCSM WHOLE ATMOSPHERE MODEL WORKING GROUP

WELCOME TO CCSM

EXPAND *COLLAPSE*

- About CCSM
- CCSM Administration
- CCSM Working Groups
- CSEG
- CCSM Research Tools
- Events
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- Publications
- CCSM Support

The Whole-Atmosphere Community Climate Model (WACCM) is a comprehensive numerical model, spanning the range of altitude from the Earth's surface to the thermosphere. The development of WACCM is an inter-divisional collaboration that unifies certain aspects of the upper atmospheric modeling of HAO, the middle atmosphere modeling of ACD, and the tropospheric modeling of CGD, using the NCAR Community Climate System Model (CCSM) as a common numerical framework.

Upcoming Meetings

WAWG Meeting, NCAR, Mesa Lab, 6 March 2009 [announcement]

14th Annual CCSM Workshop, The Village at Breckenridge, Breckenridge, CO, 15-18 June 2009.

WAWG Announcements

The WACCM development team is pleased to announce the public release of version 3 of the Whole Atmosphere Community Climate Model (WACCM3). WACCM3 source code, input datasets, run scripts, and documentation can be downloaded from the Community Data Portal [http://cdp.ucar.edu/]. Users are encouraged to participate in meetings of the CCSM WACCM Working Group and to sign up to the mailing list.

WAWG Community Liaison:

TBD

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Tel: 734-764-5727, **Fax:** 734-647-3083, **e-mail:** ridley@umich.edu

CCSM PROJECT

The Community Climate System Model (CCSM) is a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.

CCSM is sponsored by the National Science Foundation (NSF) and the U.S. Department of Energy (DOE). Administration of the CCSM is maintained by the Climate and Global Dynamics Division (CGD) at the National Center for Atmospheric Research (NCAR).

RELATED

- CCSM Working Group Co-chairs
- CCSM Working Group Co-Chairs Terms of Reference
- WACCM wiki

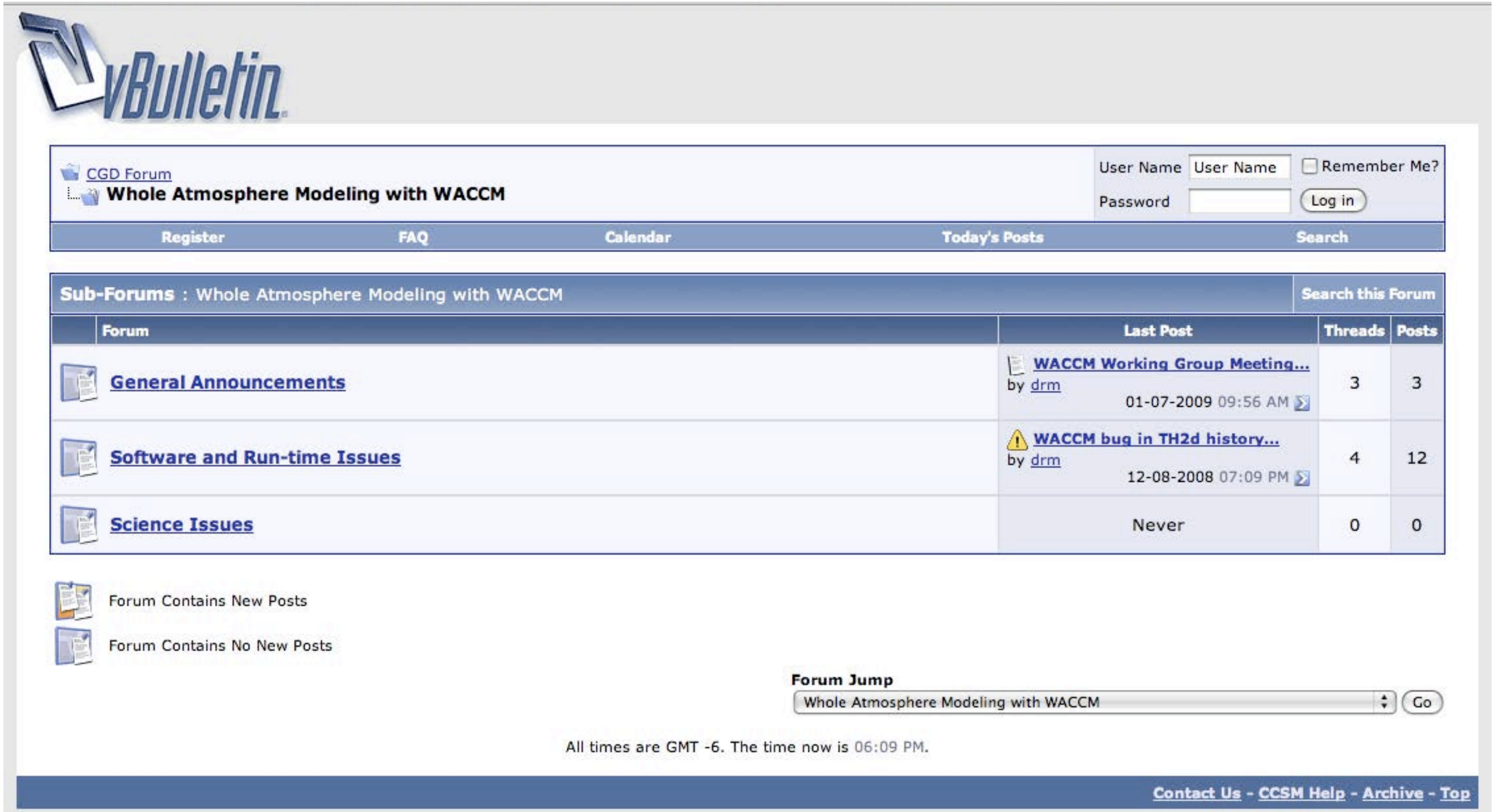
CONTACT INFORMATION

- Email: CCSM Working Group Co-Chairs
- Email: CCSM Contact
- Email: WAWG Members
- Subscribe to CCSM WAWG List

Hire FY2010

WACCM forum on CCSM Bulletin Board

http://bb.cgd.ucar.edu/



Summary I

- Tides
  - WACCM produces diurnal/semi-diurnal migrating and non-migrating tides in general agreement with observations
  - Tidal amplitudes usually lower than observed (~factor 2)
  - Seasonal and inter-annual variability is well-simulated including QBO modulation
- WACCM-X
  - Thermospheric extension of WACCM reproduces reasonable composition, temperatures and winds (inc. tides) up to 500km
  - Ionospheric electrodynamics under development

Summary II

- PMCs
  - Macroscale parameterization of PMCs incorporated into WACCM reproduces observed seasonal and latitudinal variations ice mass, albedo, frequency
  - WACCM analysis indicates significant variability induced by tides
  - Long-term SBUV record well-simulated by WACCM
- WACCM with sodium chemistry
  - Plane (2004) chemistry implemented with simplified MIF
  - Significant variability caused by dynamics
  - Seasonality not as observed - need more realistic MIF

Future activities

- Continued WACCM-X development
- IPCC AR5 simulations using WACCM/CCSM4 with fully-interactive ocean -- investigate "high-top" vs. "low-top" (first with ionosphere?)
- Internally generated QBO
- Couple meteoric metal input function to Na chemistry and compare to LIDAR observations. Extend chemistry to Fe.
- Use metal chemistry model to estimate 'smoke' CCN concentrations fed into PMC model

Thank you