Lecture #1
Tidal Models

Charles McLandress (Banff Summer School 7-13 May 2005)

Outline of Lecture

1. Introduction
2. Brief description of tides
3. Observations of tides
4. Simulating tides using a general circulation model (GCM)
5. Interpreting the GCM results using a mechanistic tidal model
6. Summary

Part 1: Introduction

- Tides are the dominant disturbances in the mesosphere and lower thermosphere.
  - horizontal wind speeds up to 100 m/s.
  - any instrument measuring the region of the atmosphere above 80 km will see a strong tidal signal.
- Tides are to a good first approximation linear and their sources are known:
  - GCMs should therefore be able to simulate the overall qualitative features of tides.
- If the GCM is able to simulate features that are not understood then we can use the GCM to learn something about the real atmosphere.

Part 2: Brief description of tides

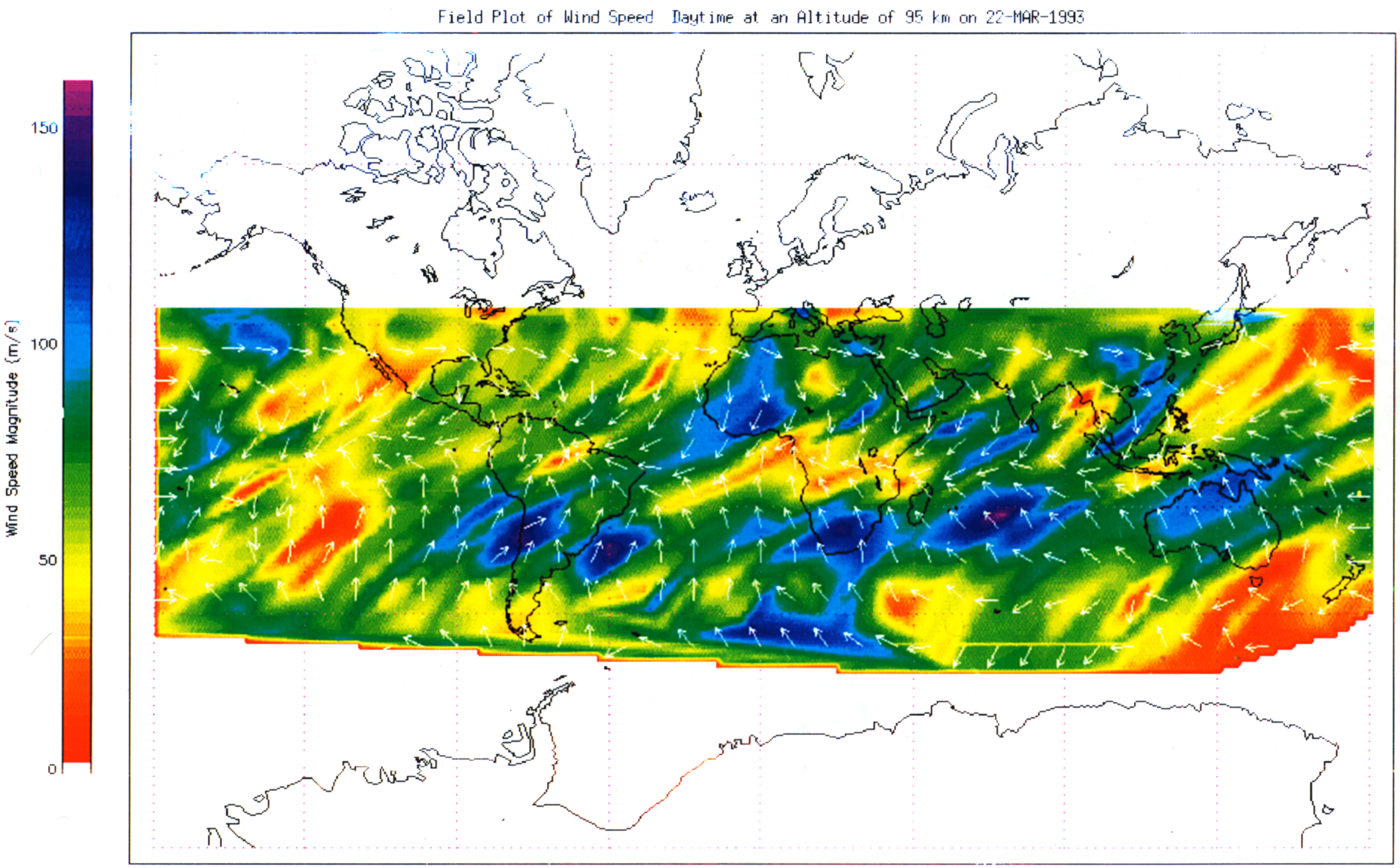
- Tides are global-scale waves that are forced primarily by solar radiation and can propagate upward over great heights.
  - periods are subharmonics of a day - diurnal, semidiurnal, etc,
  - propagate westward following the apparent motion of the Sun (so-called “migrating” tides).
- The diurnal tide is dominant at low latitudes
  - generated in the troposphere,
  - propagates up to lower thermosphere (100 km) where it is dissipated.
- In this lecture we discuss only the **migrating diurnal tide.**

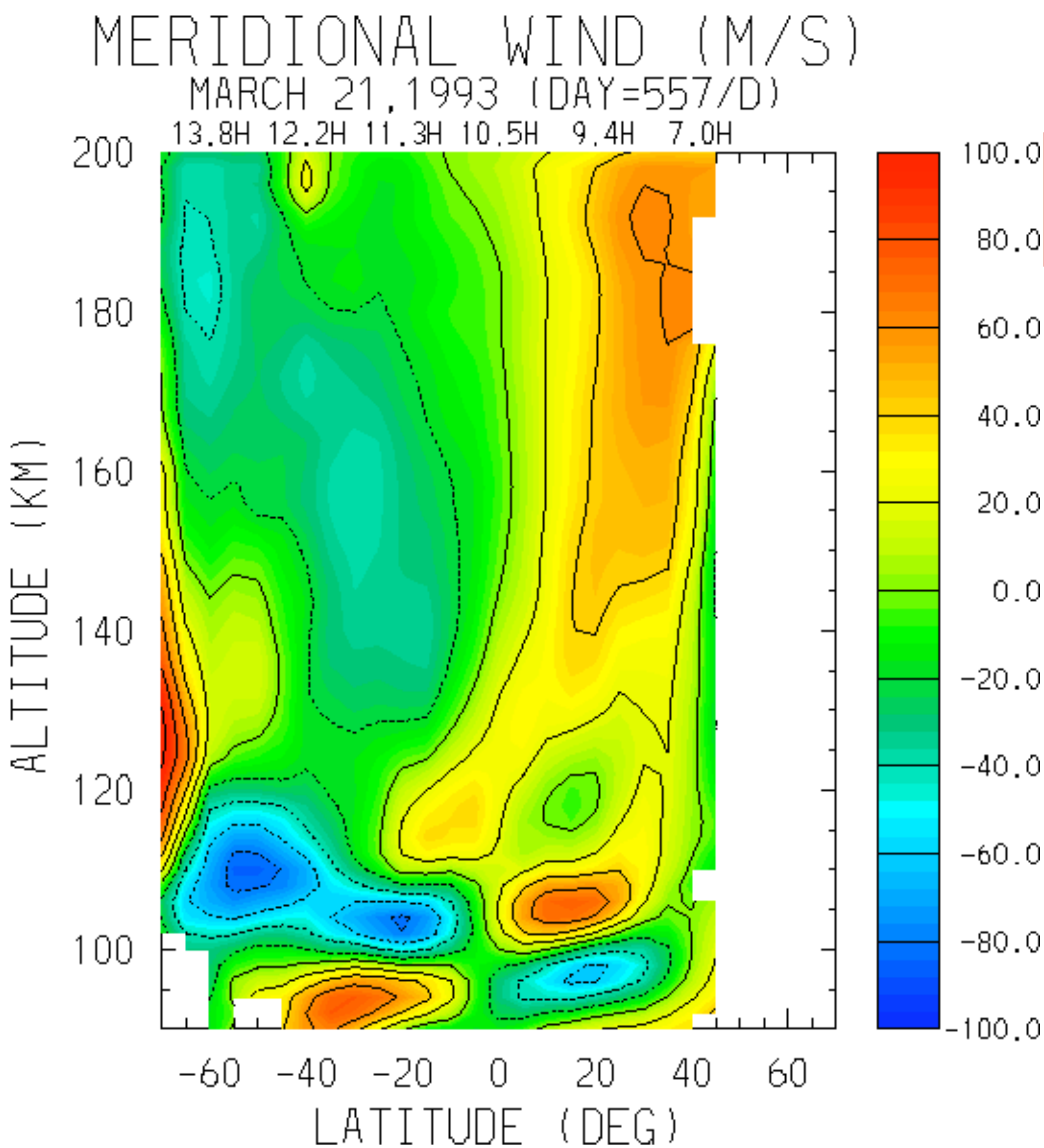
Part 3: Observations

- Upper Atmosphere Research Satellite (UARS)
- Ground-based radar winds

Observations from WINDII on UARS

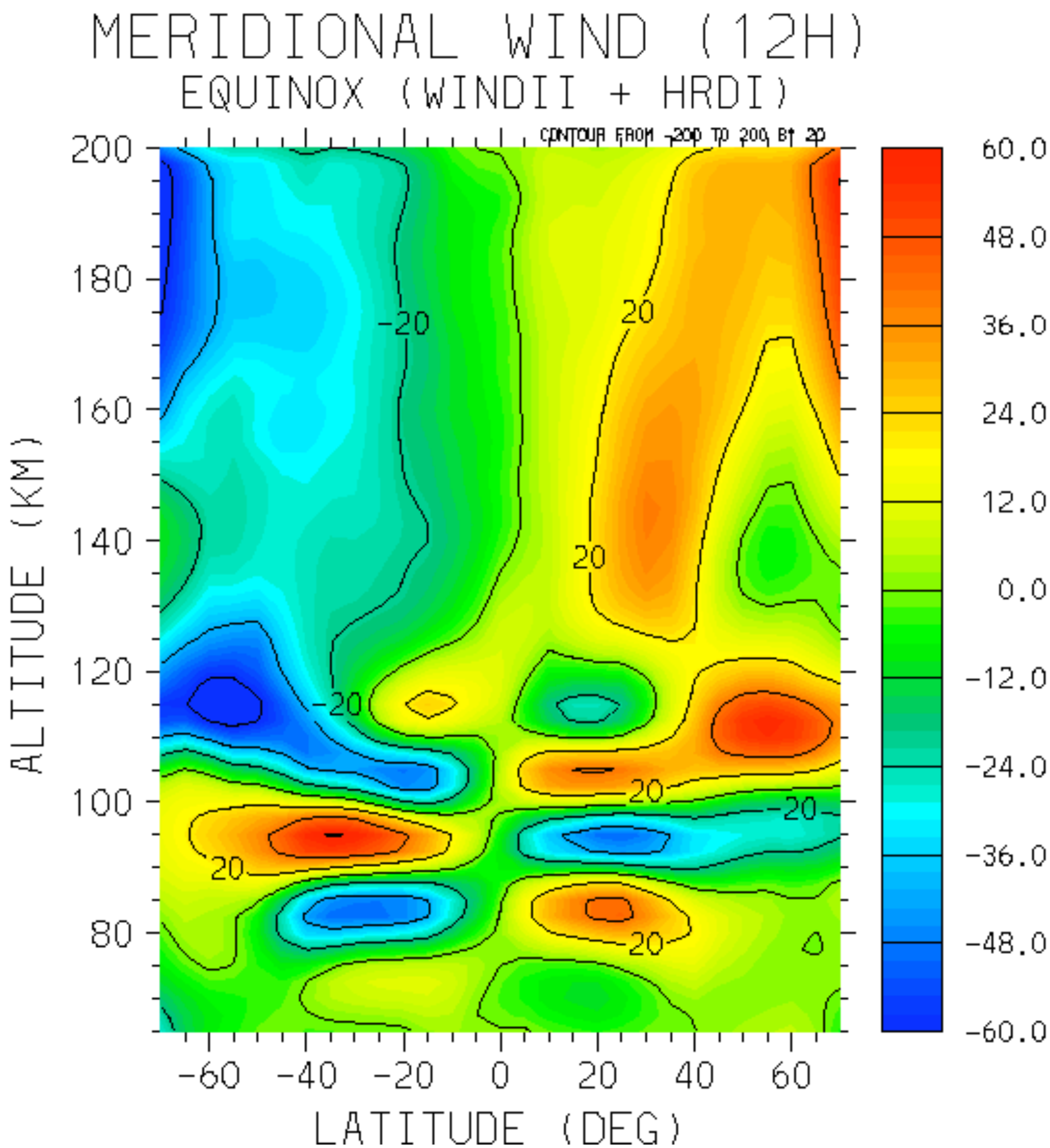
(horizontal winds at 95 km for a single day)





WINDII Observations

- single day
- zonal average of descending orbits
- cell-like structure below 120 km at low latitudes is the diurnal tide



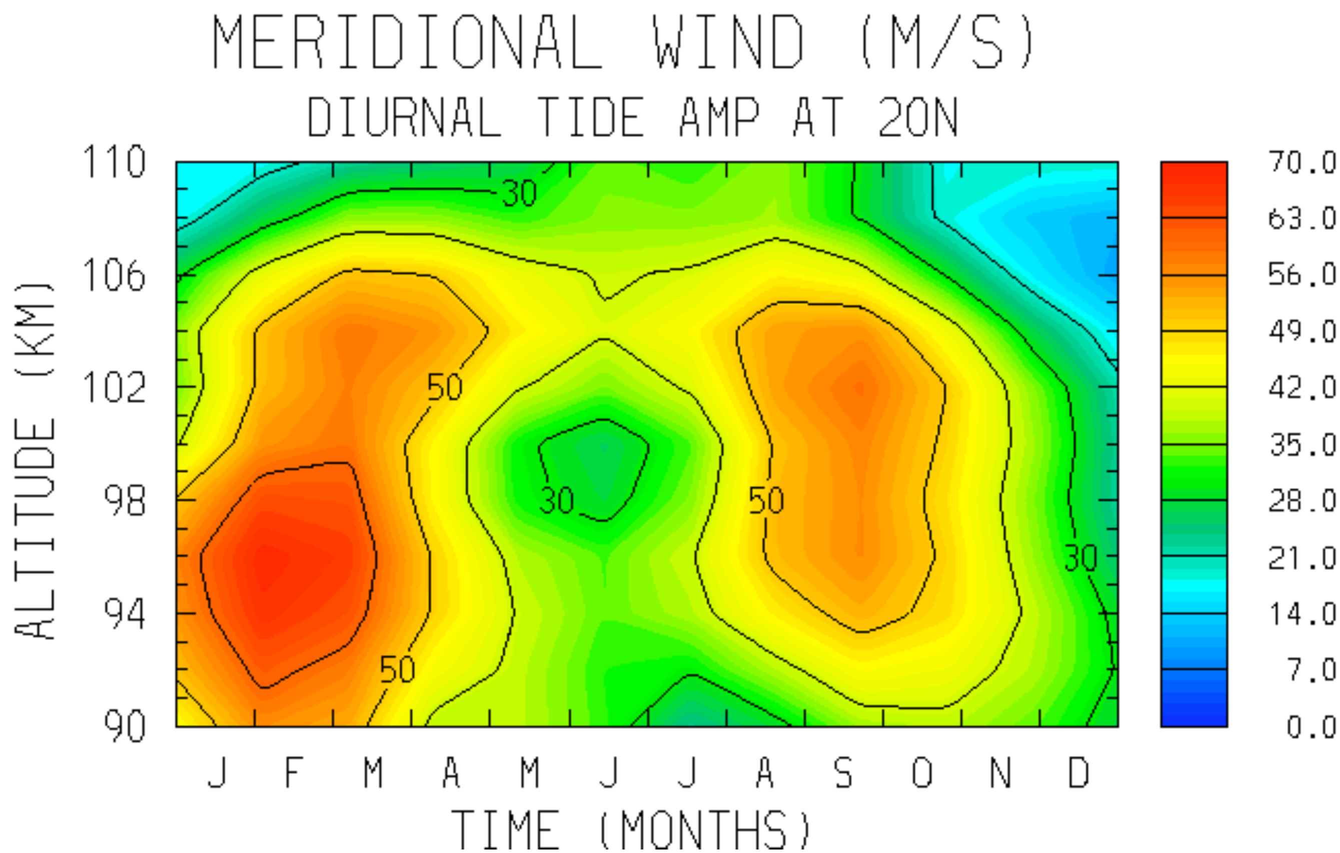
McLandress et al. (JGR, 1996)

Combined WINDII and HRDI Observations

- at 12h local time
- seasonal average

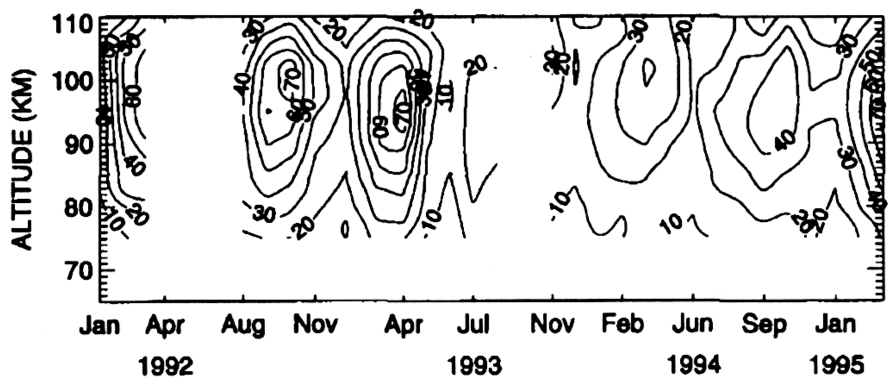
WINDII Observations

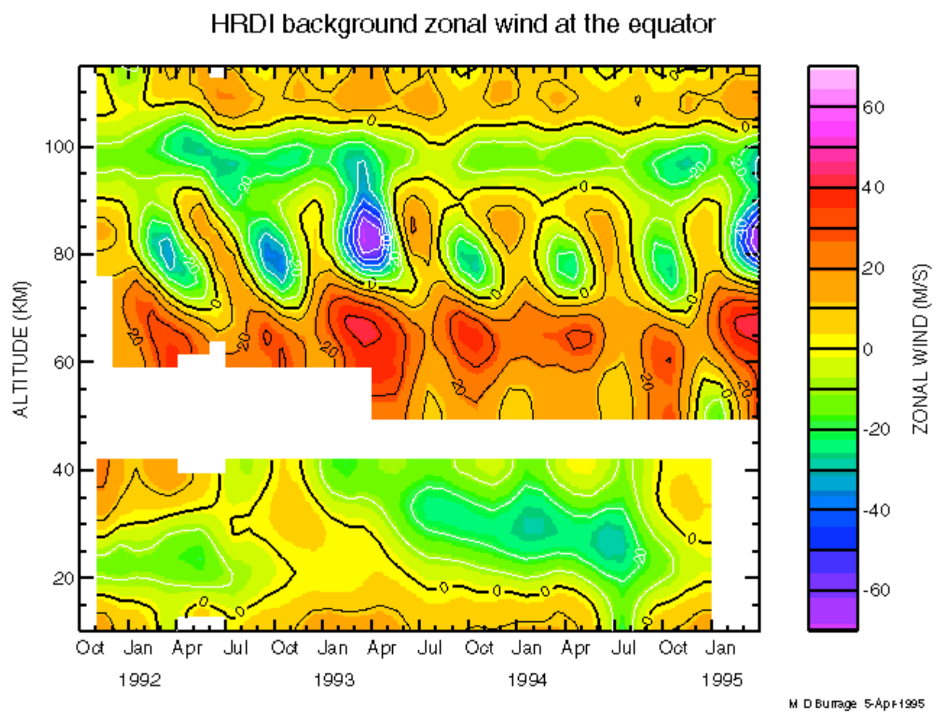
- note semi-annual variation of amplitude



McLandress et al (JGR, 1996)

HRDI Observations



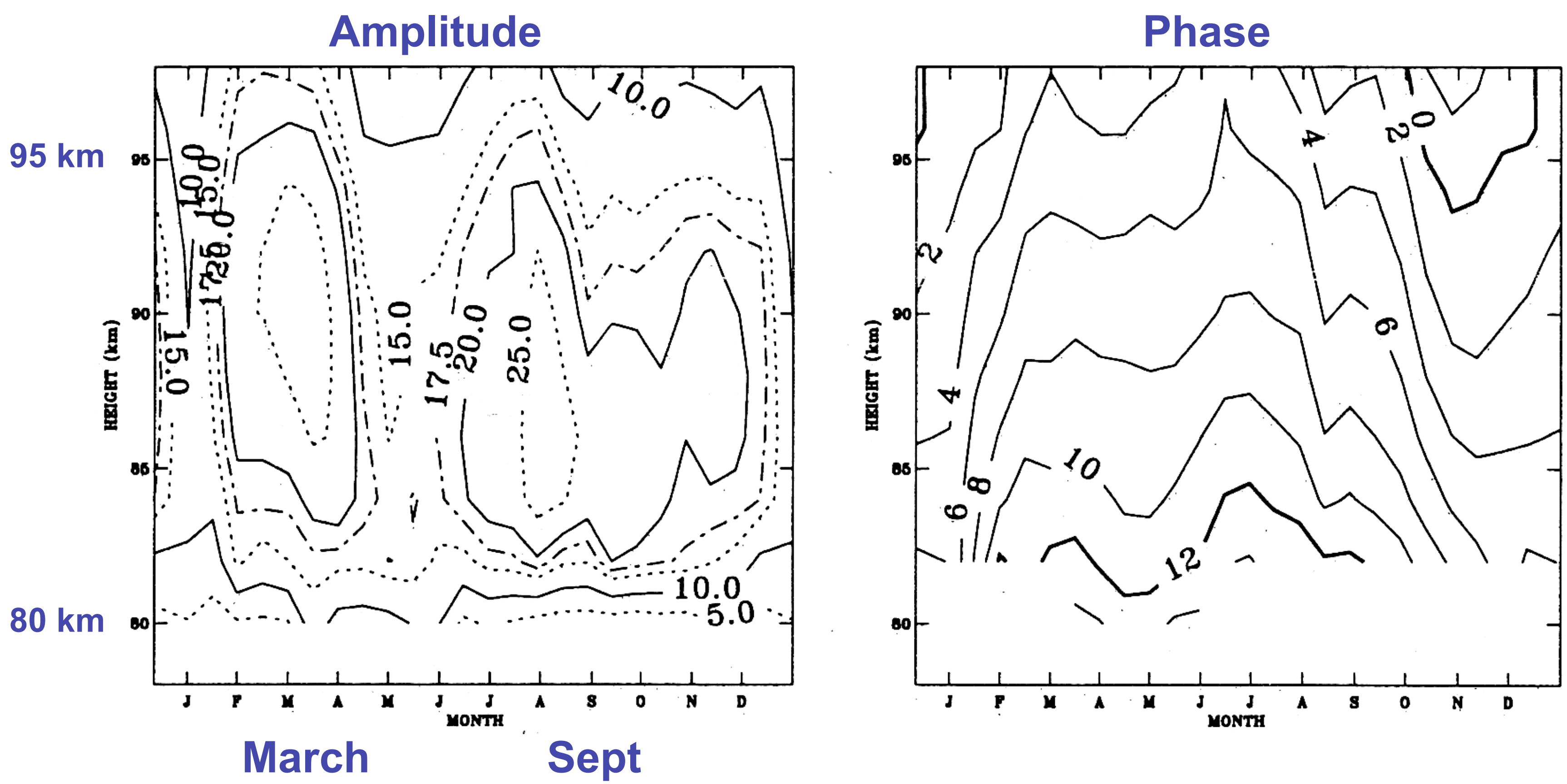


Interannual variation of tidal amplitude (strong in 1992 & 93 weak in 1994 & 95) - is it related to the stratospheric zonal wind QBO?

Lieberman (JATP 1997, top)

Burrage et al. (JGR 1996, bottom)

Radar observations at Hawaii



Vincent et al (JGR, 1998)

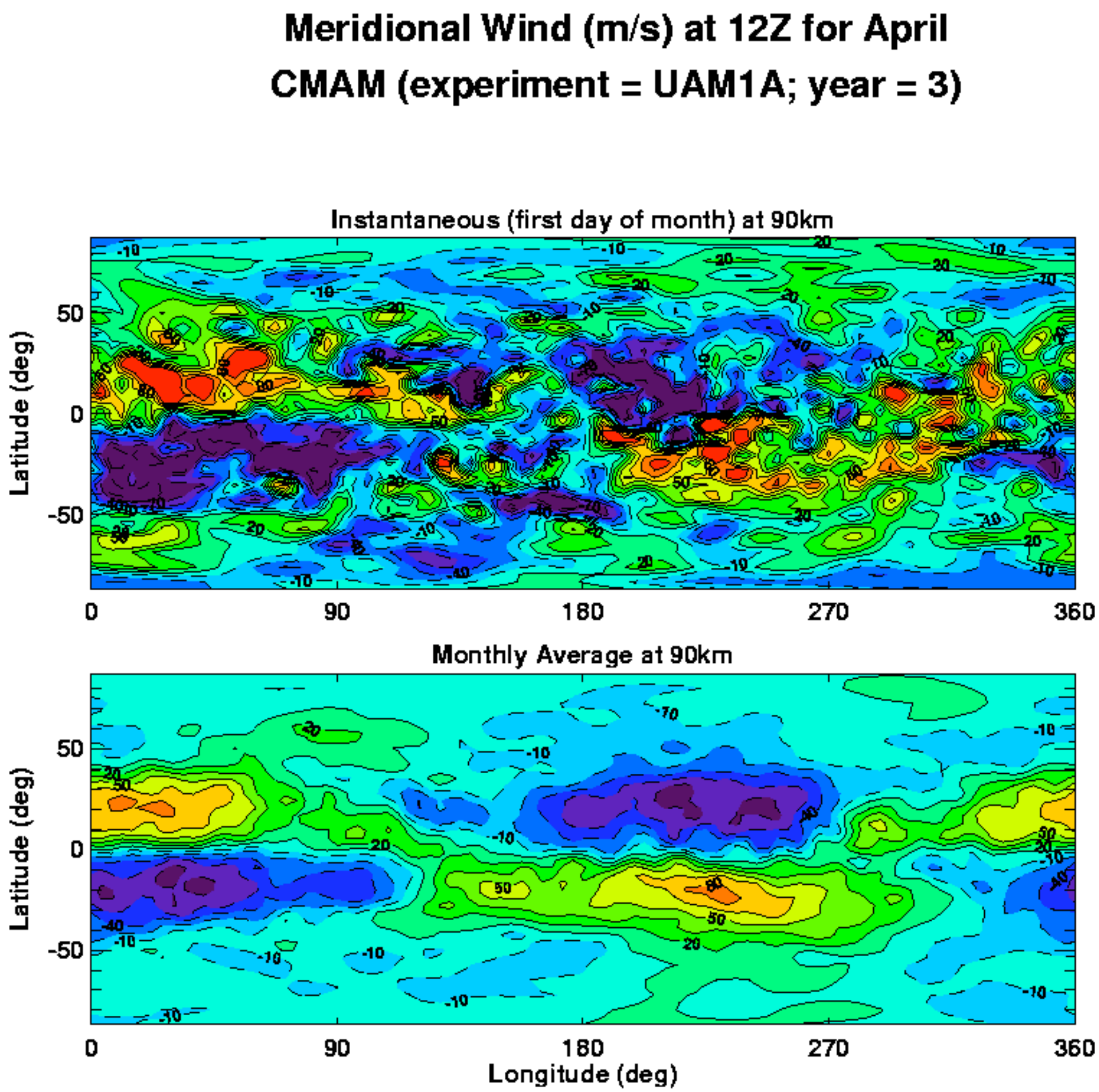
Two Basic Questions

1. What causes the observed seasonal variation of the diurnal tide?
   – heating?
   – dissipation by small-scale gravity waves?
   – background atmosphere?
2. Can models be used to address this question?

Part 3: Simulating tides using a general circulation model (GCM)

Canadian Middle Atmosphere Model

- Extended version with top at 200 km.
- T32 horizontal resolution (6 x 6 deg).
- Physical parameterizations relevant to the troposphere up to the lower thermosphere (e.g., solar heating, latent heat release by convection, gravity wave drag).
- Gory details given in Fomichev et al (2002 JGR).



CMAM simulation

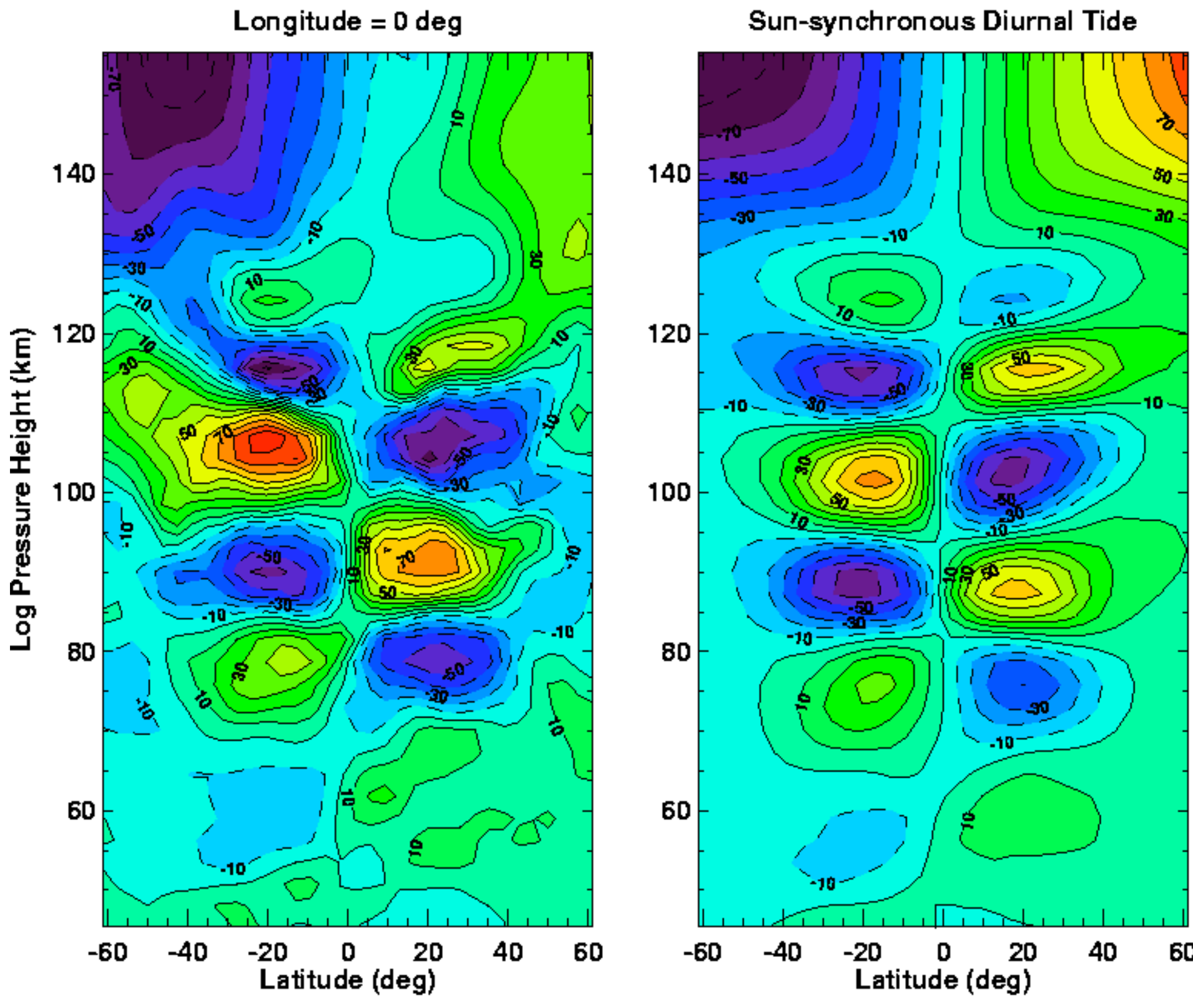
instantaneous

(Note the small-scale structure)

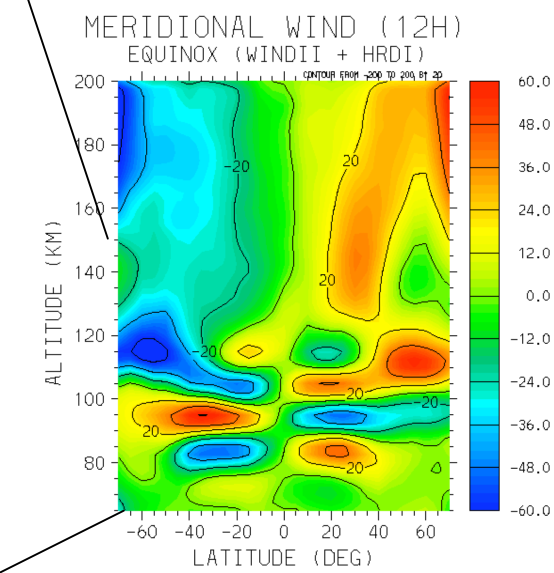
monthly average

CMAM Simulation

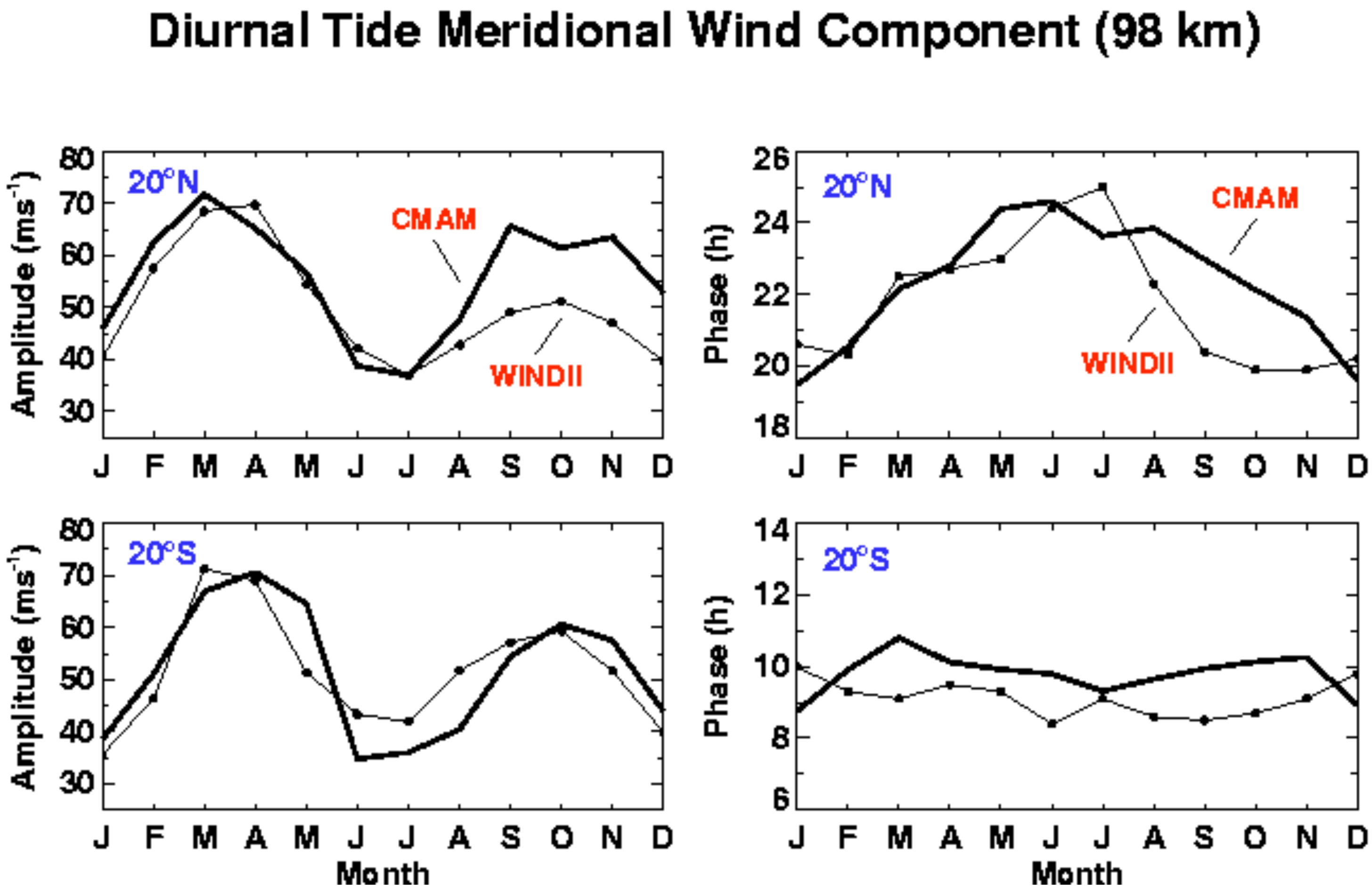
Meridional Wind (m/s) at 12Z for April (monthly average)
CMAM (experiment = UAM1A; year = 3)



Satellite observations

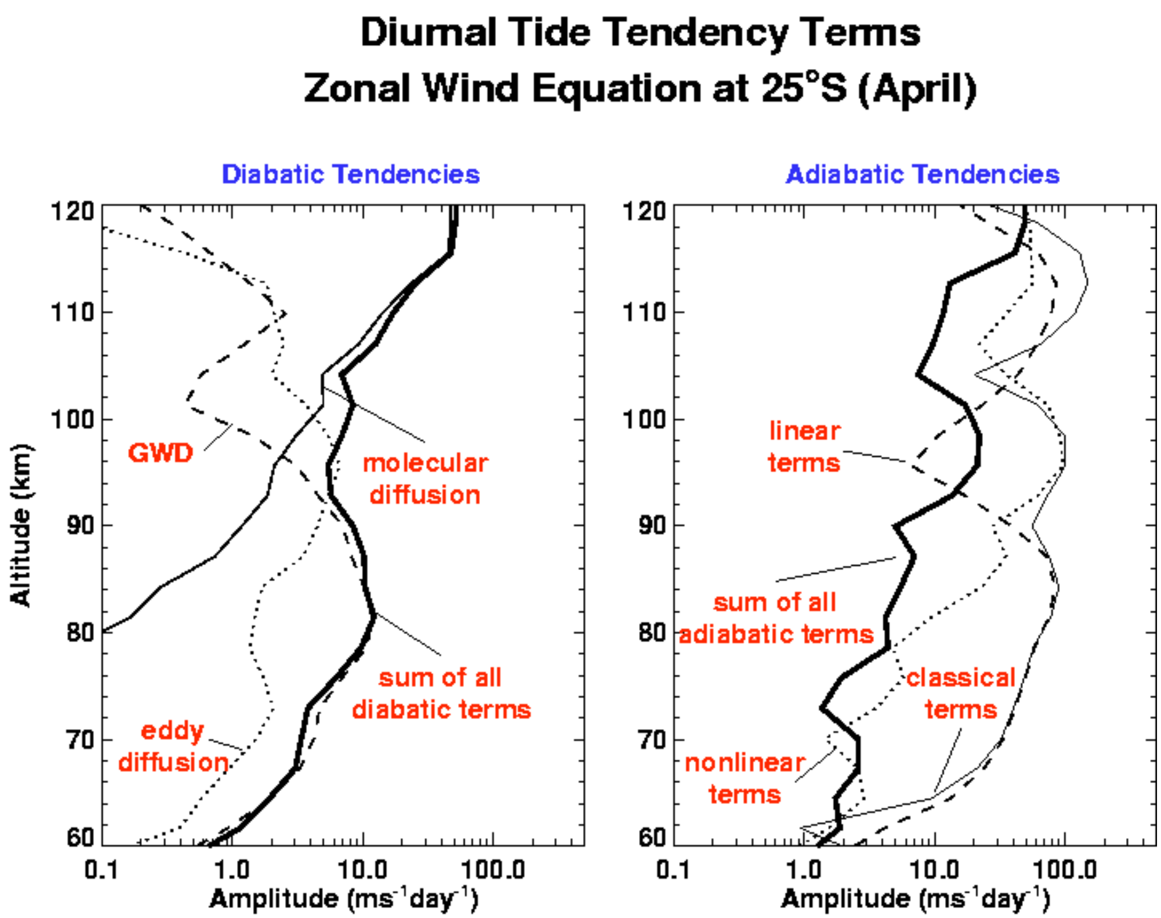


CMAM simulation versus WINDII observations



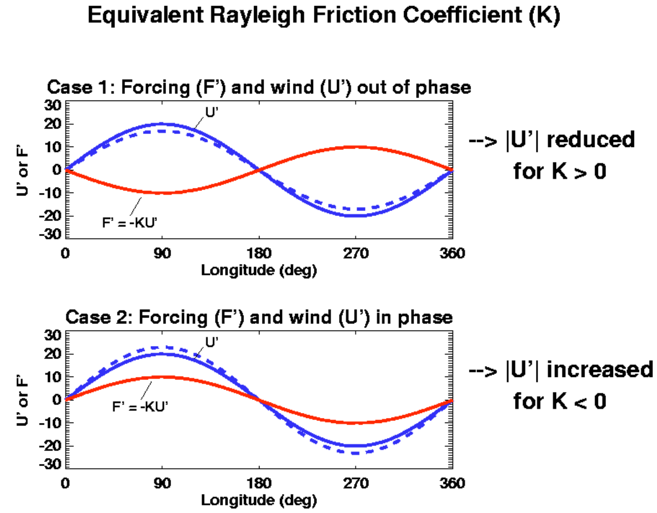
McLandress (JAS, 2002, Part I)

Terms in the zonal wind equation of the tide (diagnosed from the CMAM results)

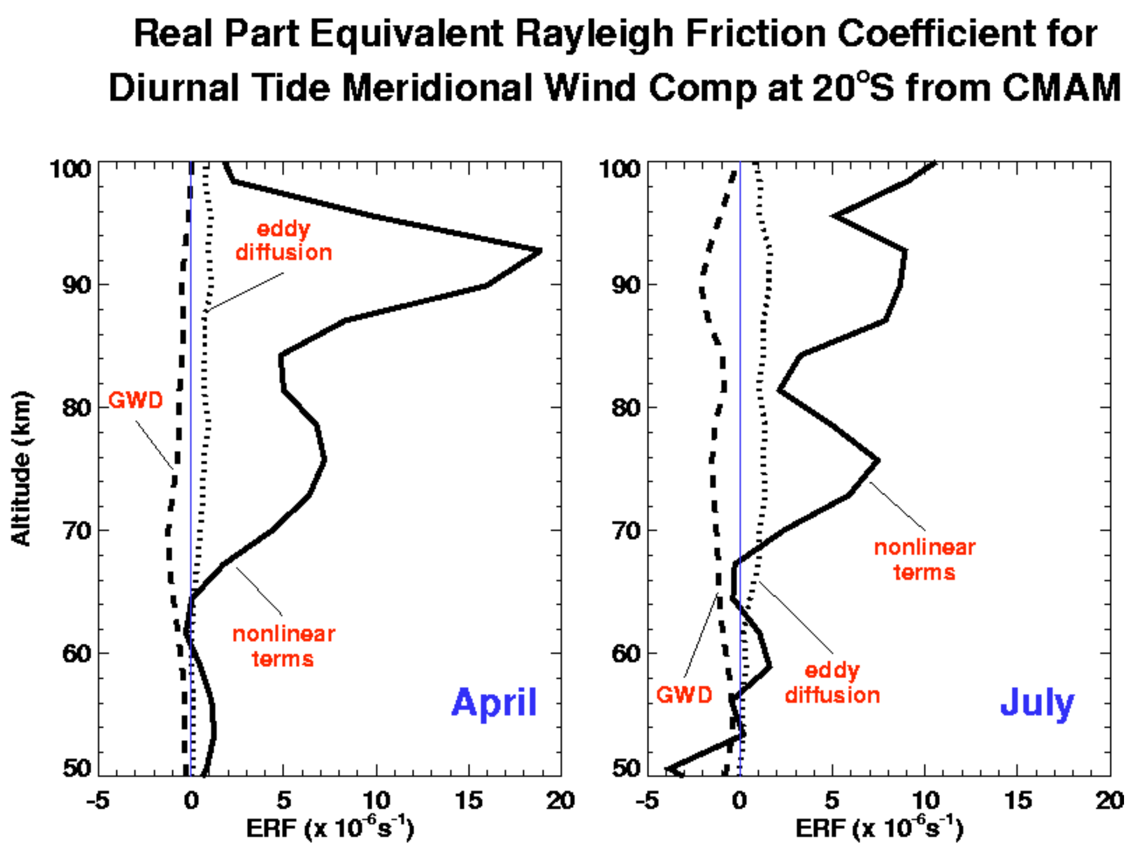


- Diabatic tendencies like gravity wave drag are much weaker than advection terms
- Linear advection terms appear to be the most important advection terms in the zonal wind equation.

Interpreting the CMAM tidal tendencies using an "equivalent Rayleigh friction" formulation



Terms in meridional wind equation



- For the meridional wind component the nonlinear terms are the dominant damping mechanism.
- The nonlinear damping for April is stronger than in July.
- Clearly nonlinearity is not the cause of the semiannual amplitude variation since it is strongest when the tide is strongest.

Part 4: Interpreting the GCM results using a mechanistic tidal model

- The CMAM results are difficult to interpret because of the very complicated nature of the model.
  - Identifying the precise causes of the seasonal variation of the tide in the CMAM is not possible.
- To make any progress we need to construct a simpler model.

Choice of Model

- Linear since cause and effect can be isolated.
- Spherical geometry since the tide is of planetary scale (curvature terms are important).
- Use tidal heating terms from the CMAM to generate the tide.
- Use monthly zonal mean U and T from the CMAM as the background state.
- Must prescribe extra dissipation in mesosphere to roughly account for the missing nonlinear terms.
- Details given in McLandress (JAS, 2002, Part II).

Linearized Primitive Equations on the Sphere

$$\frac{\bar{D}u'}{\bar{D}t} - \left(f - \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(\bar{u}\cos\phi)\right)v' + \frac{\partial\bar{u}}{\partial z}w' + \frac{1}{a\cos\phi}\frac{\partial\Phi'}{\partial\lambda} = F'_u$$

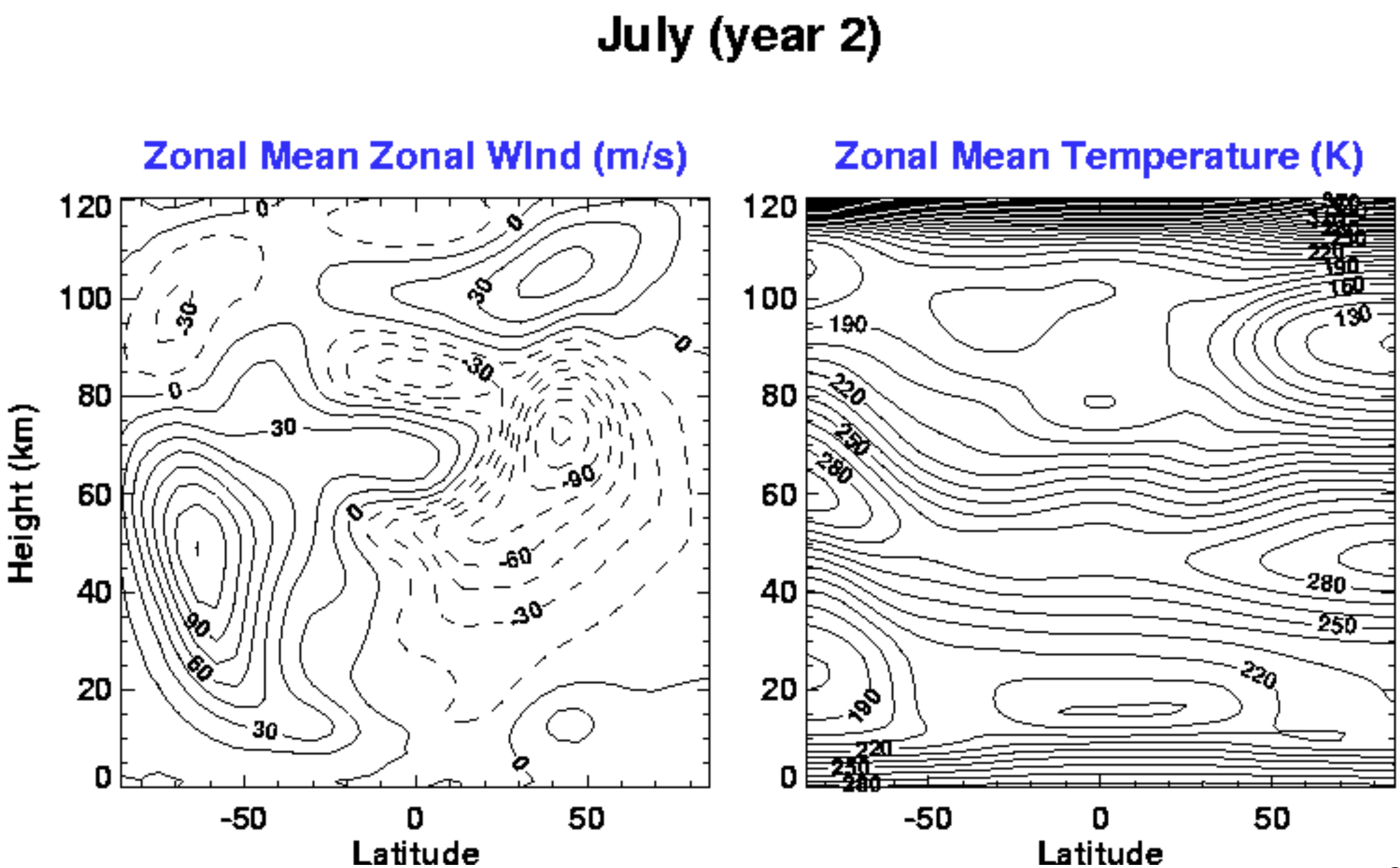
$$\frac{\bar{D}v'}{\bar{D}t} + \left(f + \frac{2\bar{u}\tan\phi}{a}\right)u' + \frac{1}{a}\frac{\partial\Phi'}{\partial\phi} = F'_v$$

$$\frac{\bar{D}}{\bar{D}t}\left(\frac{\partial\Phi'}{\partial z}\right) + \frac{R}{aH}\frac{\partial\bar{T}}{\partial\phi}v' + N^2w' = \frac{\kappa J'}{H} + F'_T$$

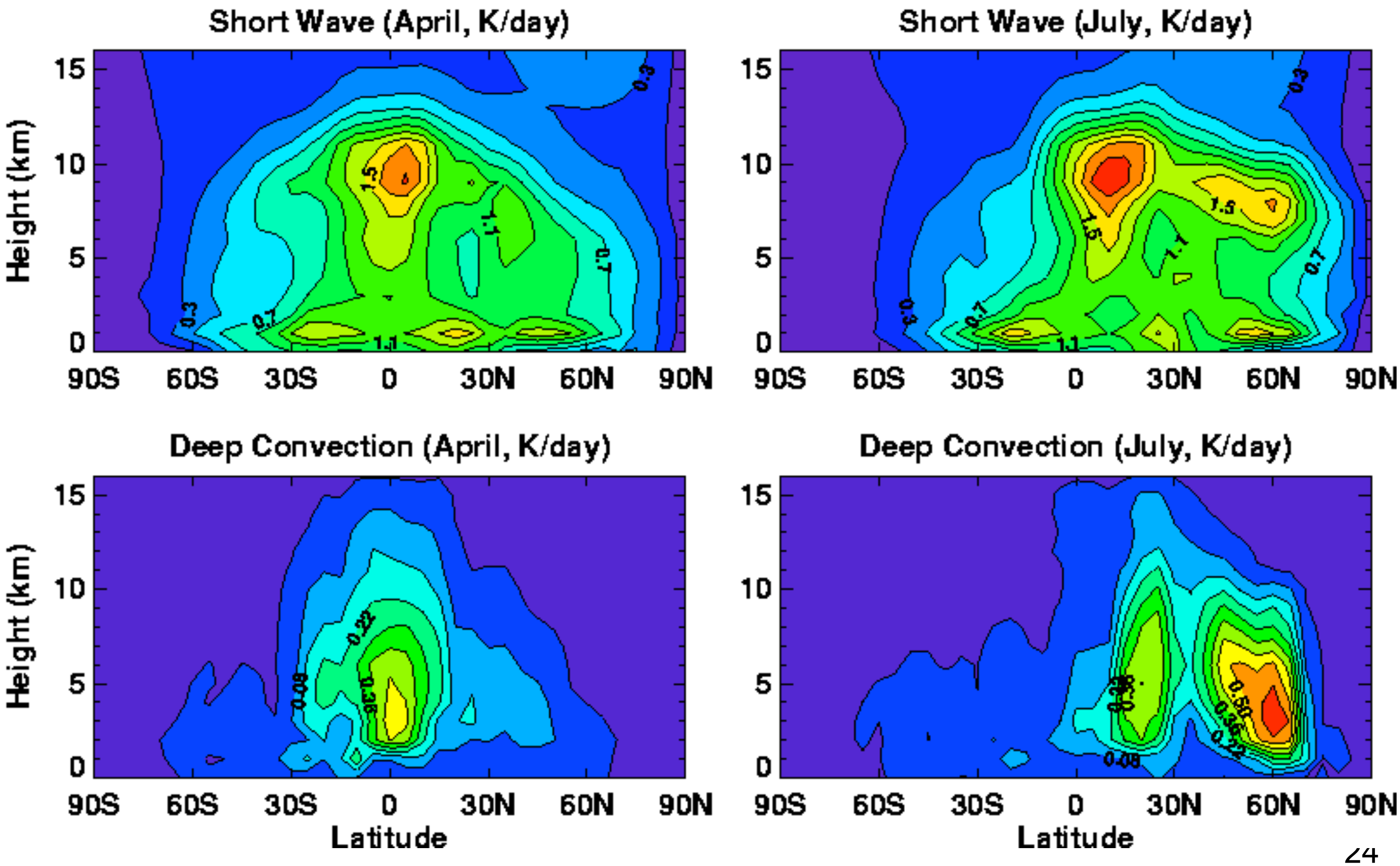
$$\frac{1}{a\cos\phi}\left[\frac{\partial u'}{\partial\lambda} + \frac{\partial}{\partial\phi}(v'\cos\phi)\right] + \frac{1}{p}\frac{\partial}{\partial z}(pw') = 0$$

where $$\frac{\bar{D}}{\bar{D}t} \equiv \frac{\partial}{\partial t} + \frac{\bar{u}}{a\cos\phi}\frac{\partial}{\partial\lambda}$$

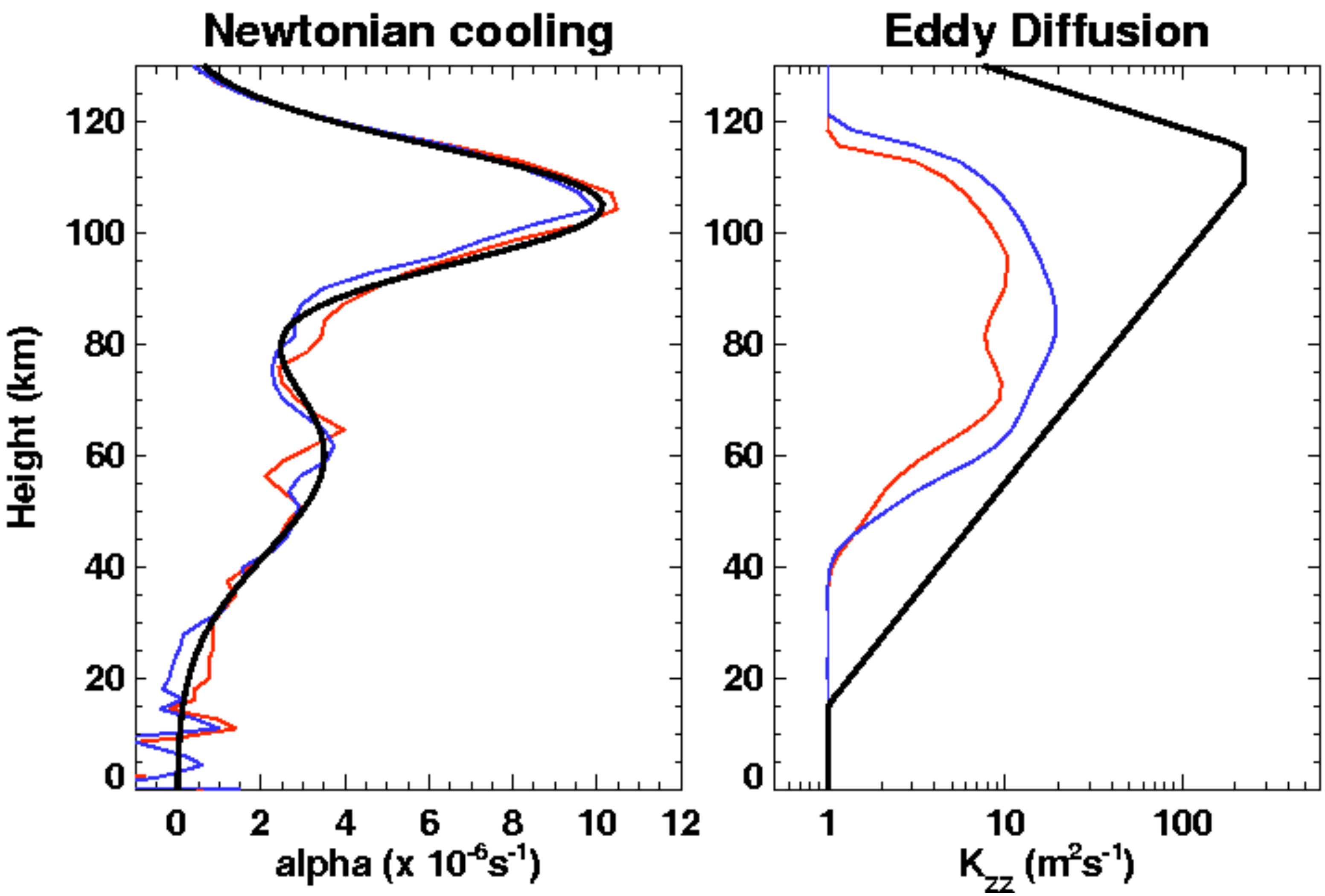
Monthly zonal mean zonal winds and temperatures are used for the background state of the linear model



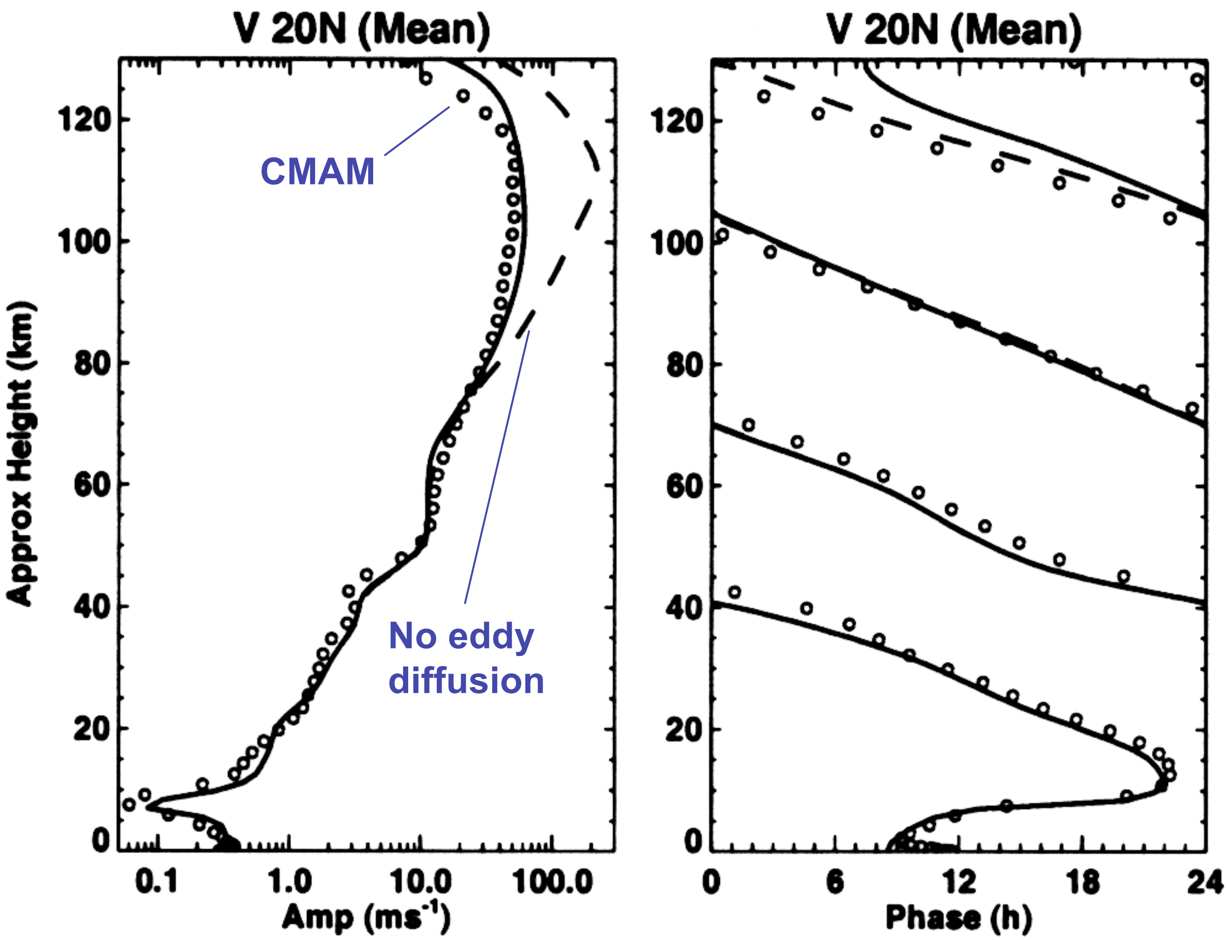
Migrating Diurnal Tide Heating (CMAM)



Damping terms for Linear Model



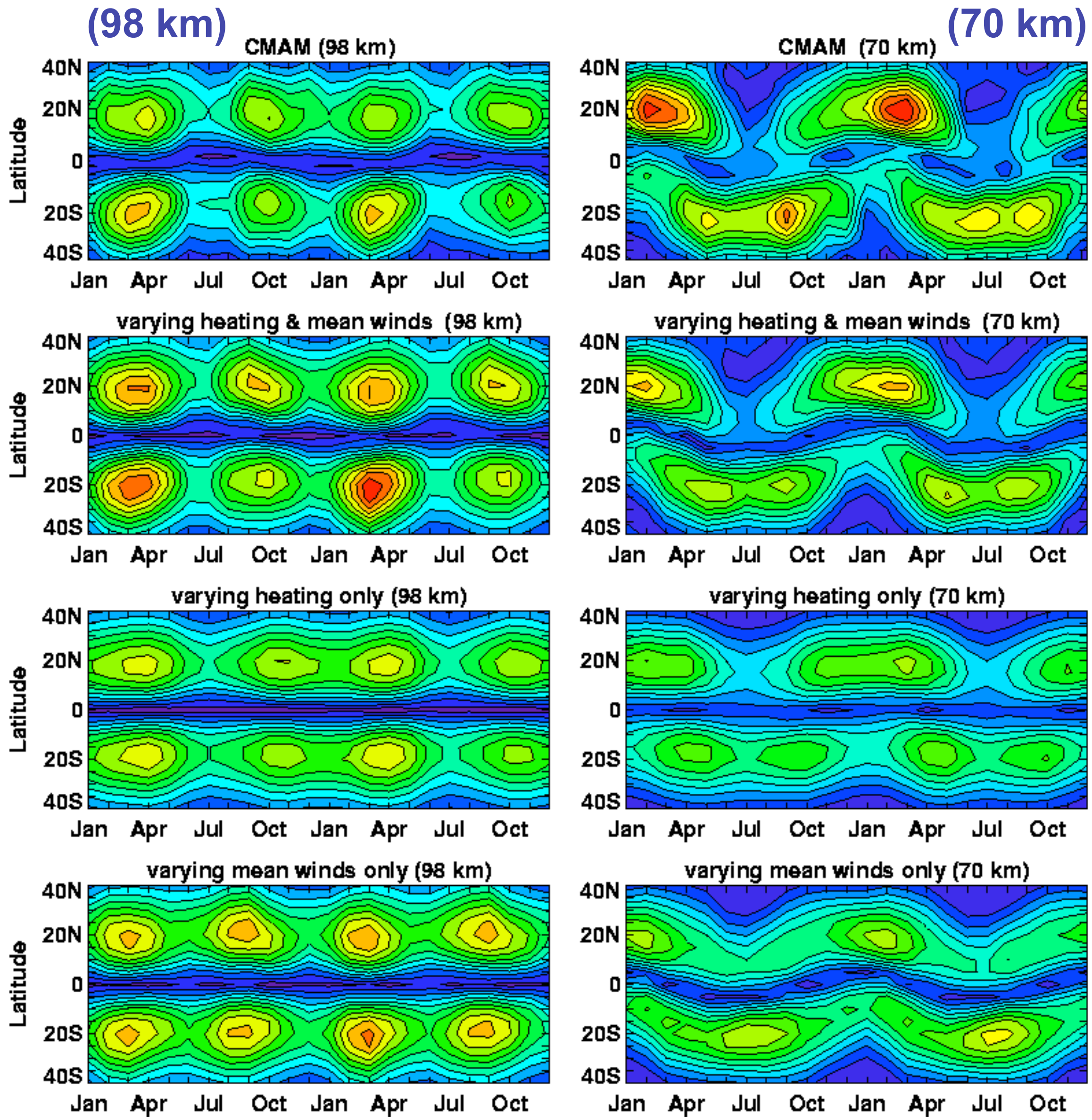
Validation of linear tidal model



- Linear model results using the enhanced vertical diffusion best matches CMAM.
- Eddy diffusion (or some other form of dissipation) is needed to mimic the effects of nonlinearity in the GCM.

Diurnal Tide Meridional Wind Amplitude

CMAM versus Linear Model



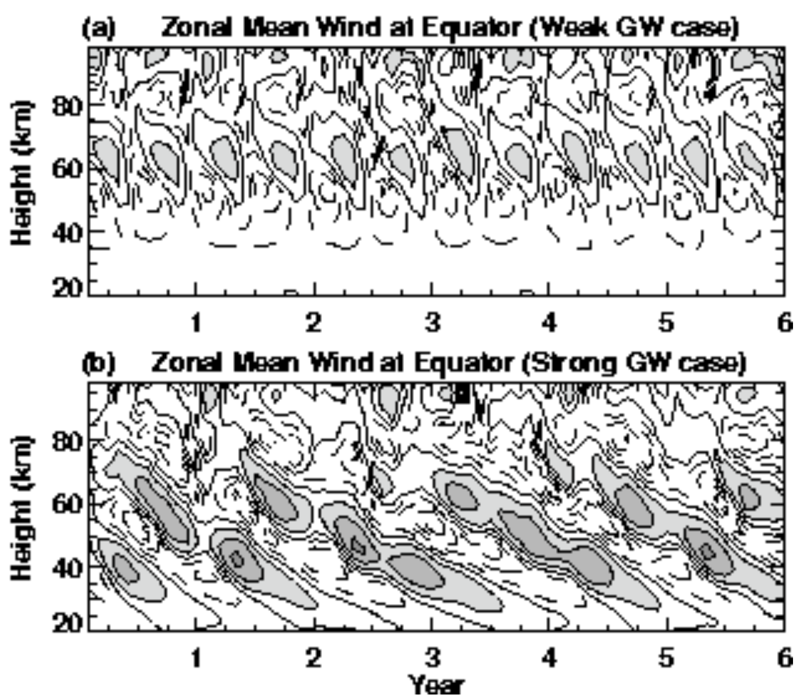
CMAM simulation

Linear model (varying mean winds & heating)

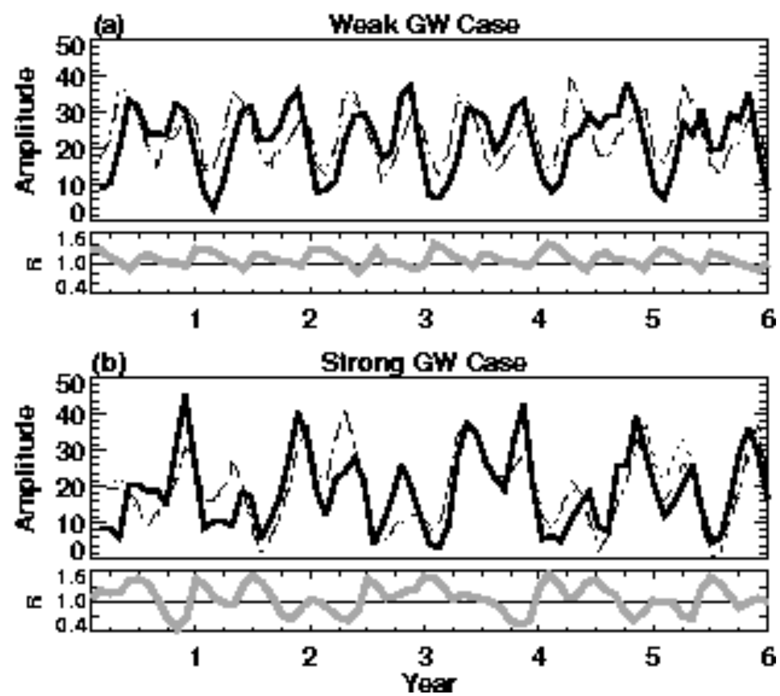
Linear model (varying heating only)

Linear model (varying mean winds only)

Use of GCM and linear model to investigate inter-annual variations of tidal amplitude due to QBO-like oscillation in zonal mean wind



mean winds at equator from CMAM



tidal amplitudes from CMAM and linear model

from McLandress (GRL, 2002)

Summary of Lecture

- “migrating” diurnal tide is the dominant disturbance in the equatorial atmosphere in the 80 to 110 km region.
  - propagates westward with the apparent motion of the sun with a period of 24 hours.
  - forced mainly in troposphere by solar heating.
- ground-based and satellite observations show that the tidal amplitude undergoes a strong seasonal variation with a six-month period (semi-annual) that peaks near the equinoxes.

- The following atmospheric models were used to understand this semiannual variation:
  1. a GCM that simulates the atmosphere from the ground to the lower thermosphere (e.g., the extended version of the CMAM).
  2. a linear model that has the same spatial domain of the GCM but without the complicated physical parameterizations.
     - this model is constrained with the tidal heating terms and background zonal mean winds and temperatures from the GCM.
     - care must be taken to take into account processes that are not captured in the linear model, such as
       - nonlinear effects which tend to reduce the exponential growth with height of the vertically propagating tide (use an eddy diffusion formulation)
       - non-LTE radiative transfer which also acts to damp the tide (use a Newtonian cooling formulation).

- What did these 2 models tell us about the semiannual variation of the tide?
  - The GCM (CMAM) told us that it was not due to small-scale GWs or resolved disturbances.
  - The linear model told us that it was due to seasonal variations of both the tropospheric heating and mean winds:
    - Heating is strongest at equator near equinox when sun is overhead -- this spatial pattern is able to more strongly force the propagating tide.
    - Mean winds affect tide through its latitudinal gradient which is strongest near solstice -- stronger shears tend to suppress tidal amplitude although the exact reason for this is unclear

The End