Momentum Budget Analysis of the Migrating Diurnal Tide in WACCM4: Seasonal Variation

Xian Lu¹, Han-Li Liu², Alan Liu³, Jia Yue², Steven Franke¹
1. University of Illinois at Urbana-Champaign
2. HAO, NCAR
3. Embry-Riddle Aeronautical University
Mar 2, 2011
Outline

• The seasonal variation of the diurnal tide
  - Observations and WACCM4

• The momentum budget for the migrating diurnal tide
  - WACCM4

• The seasonal variation of the tidal heating and GW forcing
  - WACCM4

• Conclusions
Meteor Radar Observation (2002-2007)
Amplitude of the diurnal tide (Maui, HI, 21°N)

(a) Zonal Amplitude (m/s)

(b) Meridional Amplitude (m/s)
Semiannual Oscillation (SAO) of tidal amplitude (Maui, 21°N)
SAO of Tidal Amplitude
Cerro Pachon, Chile (30°S)

- SAO is most dominant for the seasonal variation of the tidal amplitude.
- The strongest diurnal tide occurs in March.
SAO of Tidal Amplitude (WACCM4)

- WACCM4 captures the seasonality of the diurnal tide
Amplitudes of the Migrating Diurnal Tide (March)

[Wu et al., 2008]

[Mukhtarov et al., 2009]
Momentum Budget Analysis

\[
\frac{\partial u}{\partial t} = f v - \frac{1}{a \cos \phi} \frac{\partial \Phi}{\partial \lambda} - \vec{V} \cdot \nabla u + \frac{u v}{a} \tan \phi + F_{GW,x} + F'
\]

Classical Tidal Theory

Advection
Curvature
Dissipation

[Chapman and Lindzen, 1970]

Advection Term:

\[
-\vec{V} \cdot \nabla u = -\left( \frac{u}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{v}{a} \frac{\partial u}{\partial \phi} + w \frac{\partial u}{\partial z} \right)
\]

Linear advection Term:

\[
\begin{align*}
\left\{ 
\begin{array}{l}
u = \bar{v} + v' \\
w = \bar{w} + w'
\end{array} \right. \Rightarrow F_{LinAd,x} &= -\left( \frac{v'}{a \partial \phi} + w' \frac{\partial u}{\partial z} \right) - \left( \frac{u}{a \cos \phi} \frac{\partial u'}{\partial \lambda} + \frac{v'}{a} \frac{\partial u'}{\partial \phi} + w' \frac{\partial u'}{\partial z} \right)
\end{align*}
\]
WACCM

Amplitude of Time Tendency (Zonal Wind)
Advection and GW forcing are two most important terms contributing to the momentum budget of the migrating diurnal tide.

For the zonal wind, they are comparable while for the meridional wind, advection term is more significant.
Which advection is more dominant?

- **Linear Zonal Advection Amplitude (m/s/day) W1**
- **Nonlinear Zonal Advection Amplitude (m/s/day) W1**
- **Linear Meridional Advection Amplitude (m/s/day) W1**
- **Nonlinear Meridional Advection Amplitude (m/s/day) W1**

- **Zonal**
- **Meridional**

> Because the zonal mean zonal wind is strong, linear advection is 3 times larger than nonlinear advection in the zonal wind.

> It is the opposite for the meridional wind.
GW sources
Frontogenesis > Convection > Orography

Total Zonal GW Forcing (m/s/day) W1 Mar

UTGWO (m/s/day) W1 Mar

UTGW SPEC (m/s/day) W1 Mar

Total

Convection

Front
Equivalent Rayleigh Friction
[Miyahara and Forbes, 1991]

\[
\frac{\partial u'}{\partial t} = F'
\]

\[
u' = \hat{u}(t)e^{i(\omega t - s\lambda)} = a(t)e^{i(-\varphi(t))} e^{i(\omega t - s\lambda)} = a(t)e^{i(\omega t - s\lambda - \varphi(t))}
\]

\[
F' = \hat{F}_u(t)e^{i(\omega t - s\lambda)}
\]

Define the Equivalent Rayleigh Friction as:

\[
ERF = -\frac{\hat{F}_u}{\hat{u}} = -\frac{\partial a(t)}{\partial t} - i(\omega - \frac{\partial \varphi(t)}{\partial t})
\]

Real Part of ERF determines the amplitude change and imaginary part determines the phase change.

\[\text{real}(ERF) > 0 : \text{Amplitude Decrease}\]
\[\text{imag}(ERF) < 0 : \text{Phase Advance}\]
- The structure of GW ERF is similar to that of the GSWM with strongest GW effect near 50°.

- But the magnitude in WACCM is one order in magnitude larger than the GSWM.

[Hagan et al., 1995]
GW drag is a most important term and it always damps the tide.

Vertical advection of the zonal mean zonal wind plays a role near the equator.

Contribution by nonlinear advection is relatively weak.
ERF Imaginary Part (Zonal Wind)

Gravity Wave

Linear Advection

- GW drag advances the phase.
- Linear advection is the most important term and it is largely determined by the meridional advection of zonal mean wind.
- Contribution by nonlinear advection is relatively weak.
ERF Real Part (Meridional Wind)

Gravity Wave

Linear Advection

Nonlinear Advection

Total
ERF Imaginary Part (Meridional Wind)

Gravity Wave

Linear Advection

Nonlinear Advection

Total

- The nonlinear advection is more important than GW forcing and linear advection for the meridional wind
Seasonal Variation of the GW Drag
Frontogenesis-GW drag to mean flow

[Graph showing seasonal variation with contour plots for each month from January to December.]
The GW drag to mean flow is stronger at solstice and weaker at equinox.
Seasonal Variation of the GW Drag
Frontogenesis-GW drag to the migrating diurnal tide

[Image of seasonal variation charts]

Altitude (km)

Latitude (Degree)
The GW drag to the migrating diurnal tide is stronger at equinox and weaker at solstice, which is different from the GW drag to mean flow.
The seasonality of the tidal heating due to the absorption of solar radiation by H$_2$O for Hough mode (1,1) is consistent with that of the temperature and horizontal winds.

The tidal heating is likely to cause the seasonal variation of the amplitude of the migrating diurnal tide.
Conclusions

• Advection and GW drag are two most important terms to account for the momentum budget of the migrating diurnal tide.

• GW drag always damps the tide and advances its phase.

• For the zonal wind, GW is responsible to change the amplitude and linear advection is to change the tidal phase.

• For the meridional wind, nonlinear advection is the most significant factor to change both amplitude and phase of the tide.

• The seasonal variation of GW forcing is more like a feedback to the tidal modulation, rather than a cause.

• Instead, tidal heating is likely to cause the seasonal variation of the tidal amplitude.
Thank you!