Inter-annual Variability of Nonlinear Wave Coupling in the Space-Atmosphere Interaction Region

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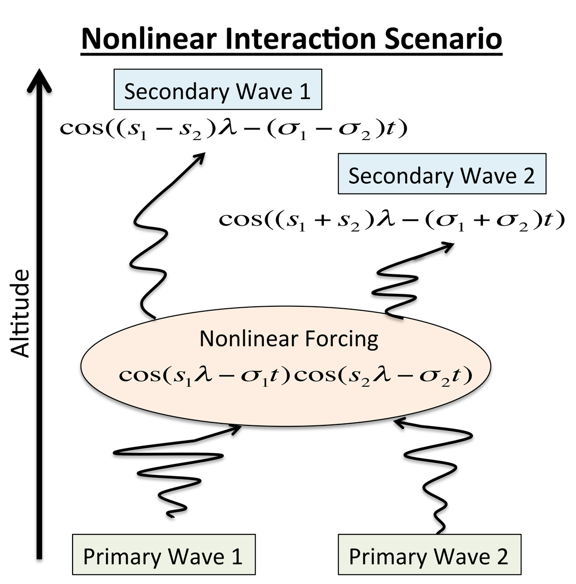
Introduction

Global scale wave-wave interactions

- Past research has primarily focused on atmospheric tides and planetary waves that are excited by solar-driven processes.
- However, theory and evidence suggests that waves may nonlinearly interact to produce secondary waves.

Impacts on the Space-Atmosphere Coupling

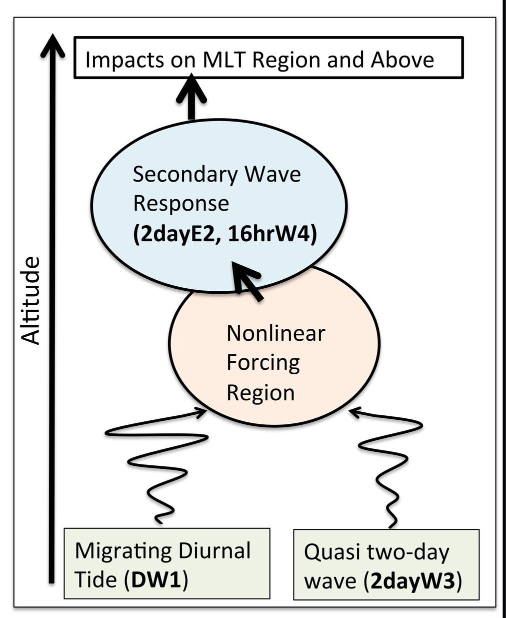
- Nonlinear interactions are a fundamental source of global scale variability in the atmosphere.
- Secondary waves may propagate vertically away from their forcing region and thus, couple space-atmosphere regions through currently unknown pathways.



Problem Statement

Although there has been evidence of secondary waves generated from wave-wave interaction in the atmosphere, the forcing and manifestation of these waves are poorly understood due to the difficulty of obtaining short term tidal/wave estimates on a global scale. This research focuses on the secondary waves arising from an interaction between the migrating diurnal tide (DW1) and quasi two-day wave (2dayW3), two of the largest waves in the MLT region. The fundamental questions to be answered in this study are:

- **Where in the atmosphere are DW1 and QTDW interacting to force secondary waves and where do significant responses occur?**
- **How does the nonlinear forcing region determine the secondary wave response?**



Methodology

Primary Wave Computation

Estimates for the DW1 and 2dayW3 in temperature and horizontal wind are extracted from the **NOGAPS-ALPHA** hourly model, which extends from the surface to about 95 km.

Nonlinear Forcing Computation

Secondary wave forcing arises from the nonlinear terms in the conservation equations, which contain products of primary waves in u, v and T (assuming w is small).

Zonal Forcing

$$\frac{\partial u}{\partial t} + \left\{\frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}\right\}u - \frac{uv\tan\phi}{a} + \frac{uw}{a} = F_{Cor,x} + F_{Pressgrad,x} + F_{fric,x} + F_{other,x}$$

Meridional Forcing

$$\frac{\partial v}{\partial t} + \left\{\frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}\right\}v + \frac{u^2\tan\phi}{a} + \frac{vw}{a} = F_{Cor,y} + F_{Pressgrad,y} + F_{fric,y} + F_{other,y}$$

Thermal Forcing

$$\rho c_v\left[\frac{\partial T}{\partial t} + \left\{\frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}\right\}T\right] = Work + Heat$$

Independent Var.:
Φ = latitude
λ = longitude
z = altitude
t = time

Field Variables:
u = zonal wind
v = meridional wind
w = vertical wind
T = temperature

Secondary Wave Response Computation

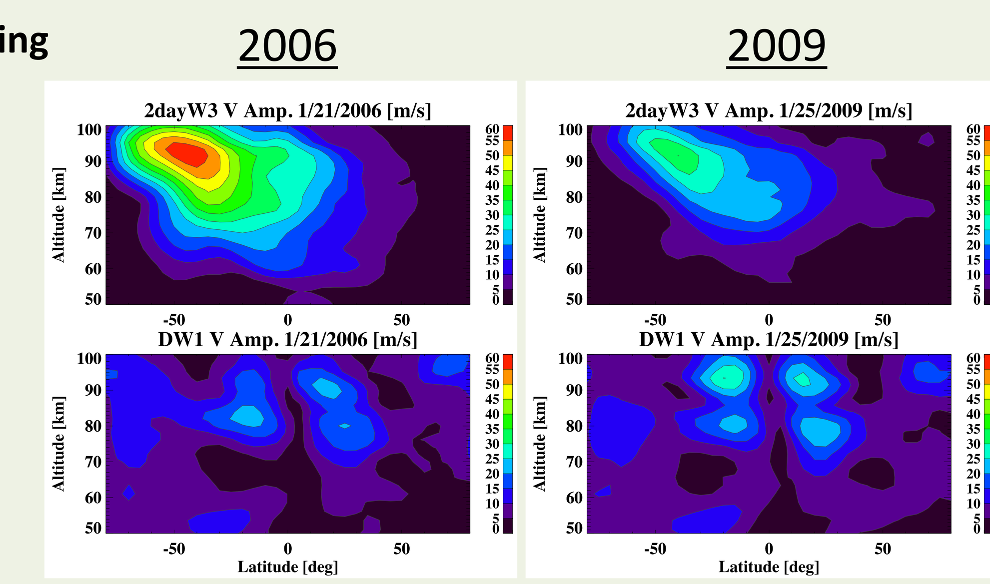
The nonlinear momentum and thermal forcing are input into a linearized tidal model derived from the **Global Scale Wave Model (GSWM)** to produce the 16hrW4 and 2dayE2 responses. Background temperatures and winds from NOGAPS-ALPHA are used.

Inter-annual Variability of 2dayW3-DW1 Nonlinear Interactions

1. Primary Waves

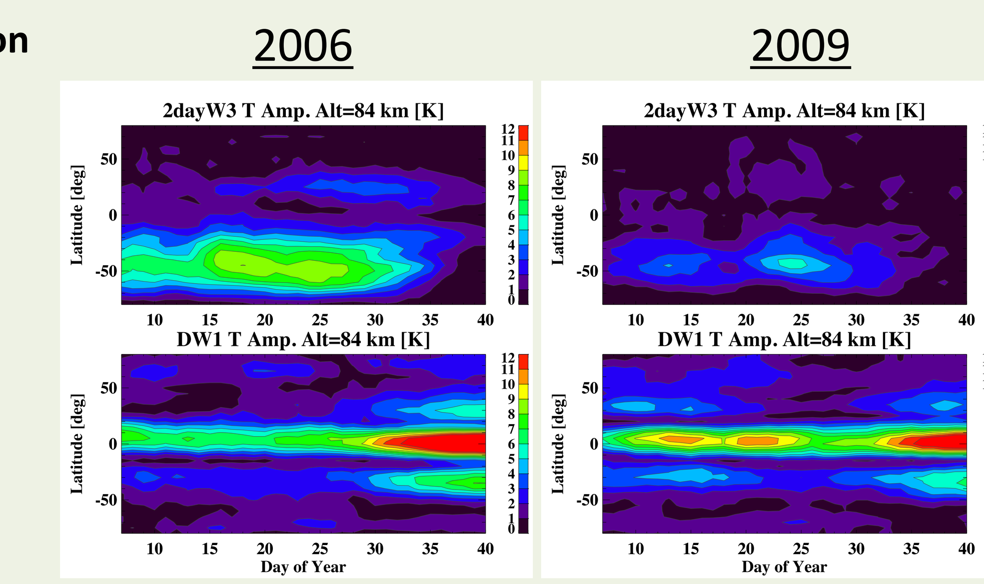
2dayW3-DW1 Vertical Coupling

- NOGAPS-ALPHA captures the majority of the 2dayW3 in the MLT region
- 2dayW3 is largest in the S. Hemisphere while DW1 is more dominant at low latitudes
- 2dayW3 peak in 2006 is twice as large in 2006 than in 2009



2dayW3-DW1 Time Evolution

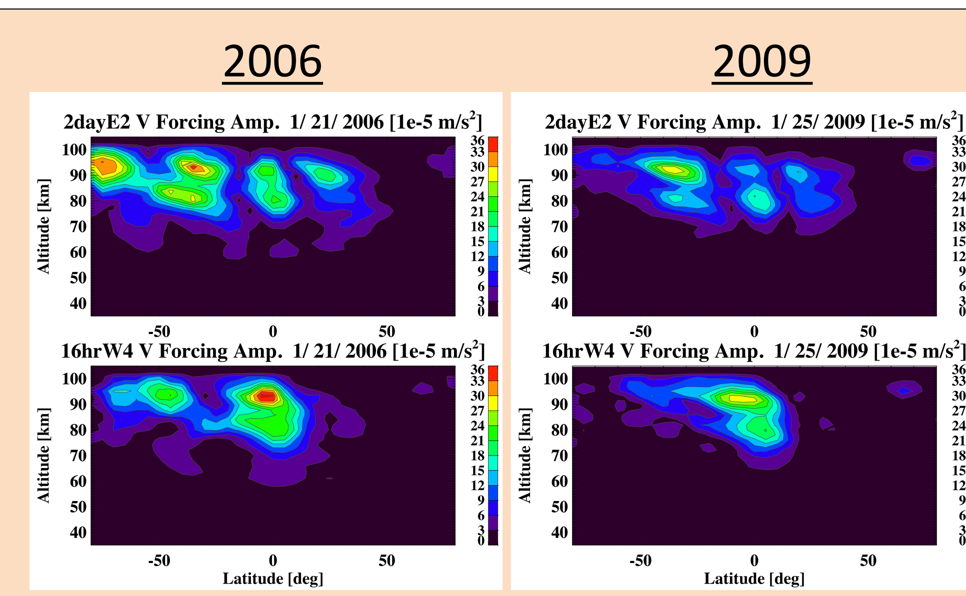
- 2dayW3 in 2006 lasts for about 25 days in 2006 while 2dayW3 in 2009 is brief
- Observed anti-correlation between 2dayW3 and DW1 amplitude explained by past studies



2. Nonlinear Forcing

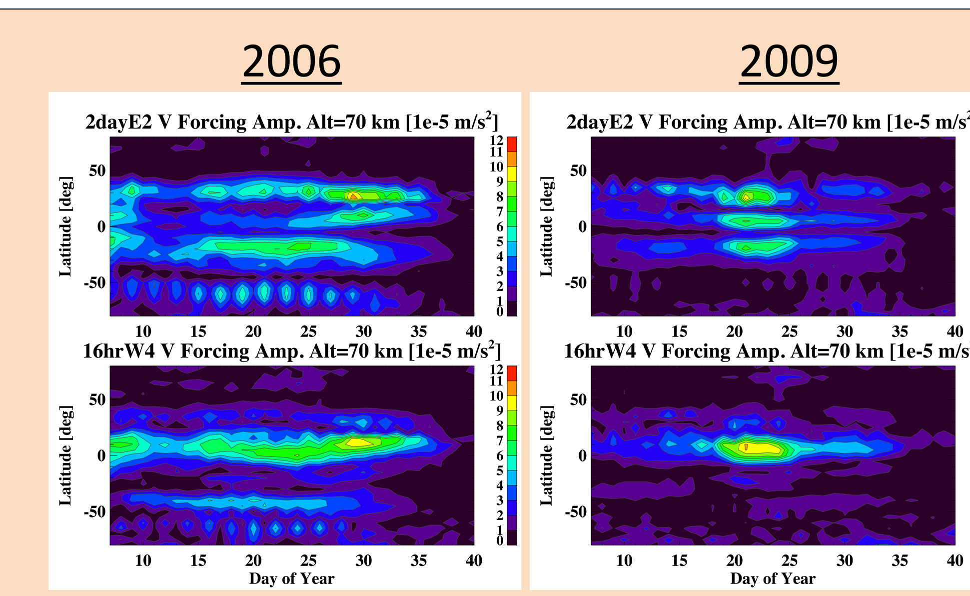
2dayE2-16hrW4 Latitudinal-Vertical Forcing Structure

- 2dayW3-DW1 interaction produces zonal momentum, meridional momentum and thermal forcing for secondary waves
- Peak forcing is located at 90km and larger in 2006
- Forcing is concentrated at lower latitudes for the 16hrW4



2dayE2-16hrW4 Temporal-Latitudinal Forcing Structure

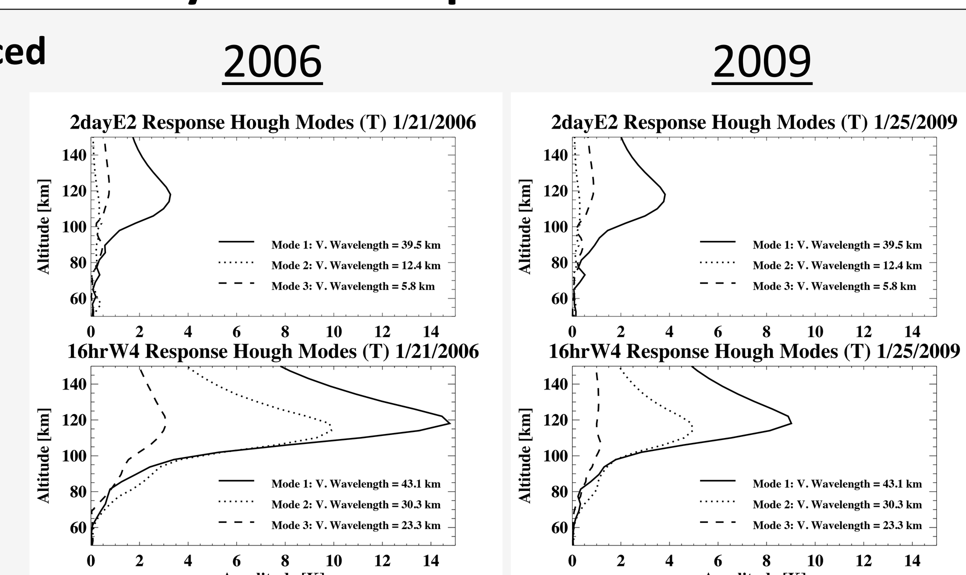
- Forcing is only significant at when the 2dayW3 large
- Peak day of forcing at 70 km is slightly offset from the 2dayW3 peak day
- Peak forcing at 70 km in each year is comparable



3. Factors Governing Secondary Wave Response

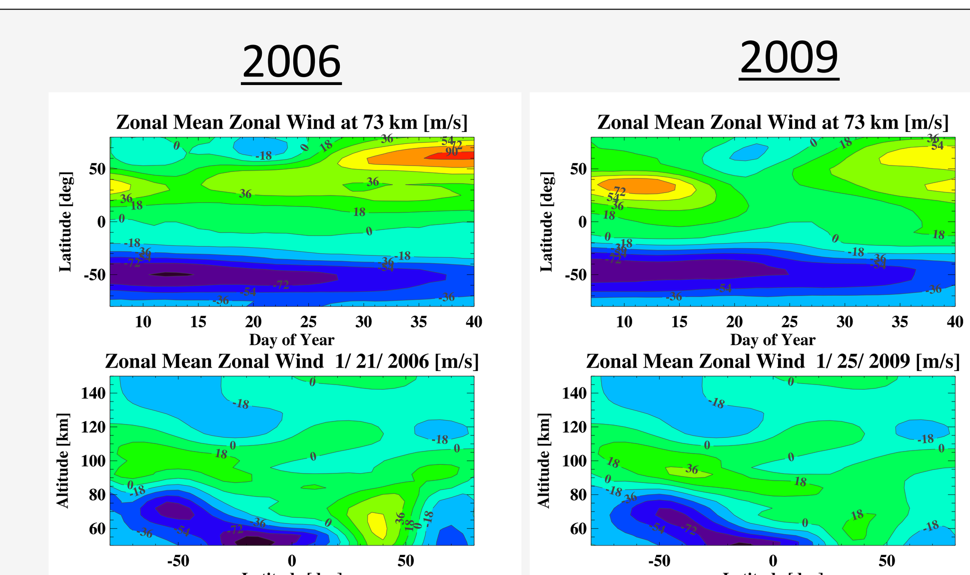
Secondary Hough Modes Forced (No Background Winds Case)

- Magnitude of secondary waves depends on:
  - Vertical wavelength
  - Frequency
  - Forcing projection onto lowest order Hough modes
- 16hrW4 is more effectively forced than 2dayE2



Background Wind Effects

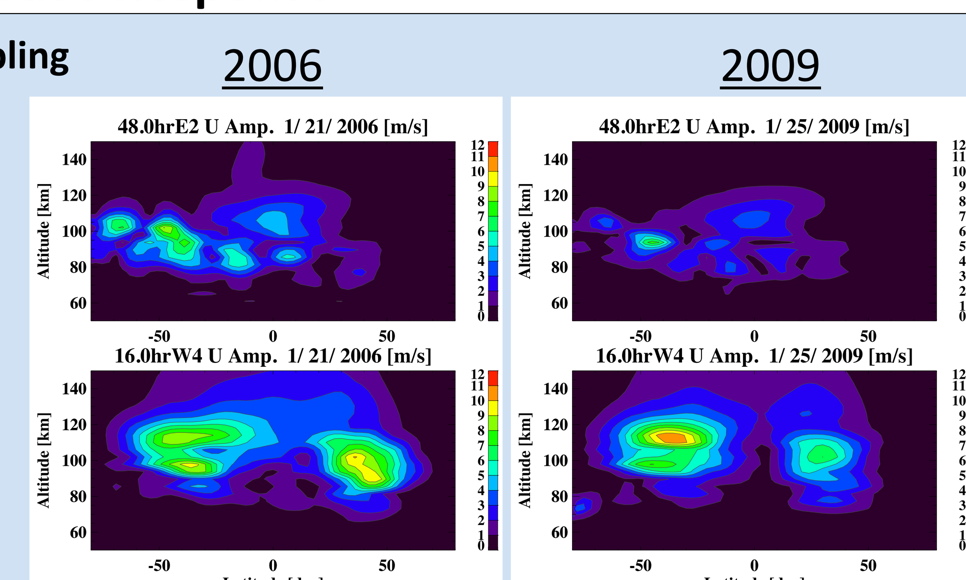
- Background winds determine the propagation conditions of secondary waves
- Eastward (westward) winds are more favorable for 16hrW4 (2dayE2) propagation



4. Overall Secondary Wave Response

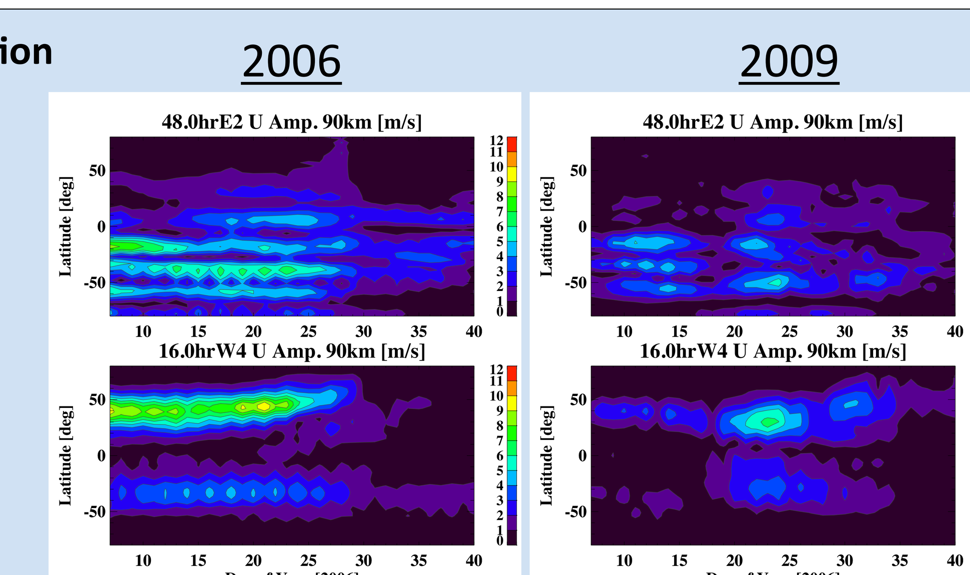
2dayE2-16hrW4 Vertical Coupling

- Secondary waves exist in years with strong and weak 2dayW3
- 16hrW4 is larger than 2dayE2 due to factors described above
- 16hrW4 penetrates into the lower E-region



2dayE2-16hrW4 Time Evolution

- 16hrW4 is largest in S. Hemisphere while 2dayE2 is largest in the N. Hemisphere at 90km due to background winds
- 16hrW4 secondary wave response tracks the evolution of the 2dayW3 in both years



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Conclusions

- Significant DW1-2dayW3 secondary wave activity is observed between 80 and 140 km.
- 16hrW4 and 2dayE2 secondary waves are predicted to maximize in the lower thermosphere.
- Largest secondary wave amplitudes are NOT coincident with the largest primary wave or nonlinear forcing amplitudes and highlight interhemispheric coupling
- 16hrW4 is larger than 2dayE2 response due to longer vertical wavelength, higher frequency and more effective forcing
- Background winds determine the latitudinal structure of the secondary wave response
- DW1-2dayW3 secondary waves may be generated even during weak 2dayW3 years