Short-Term Tidal Variability During Sudden Stratospheric Warming

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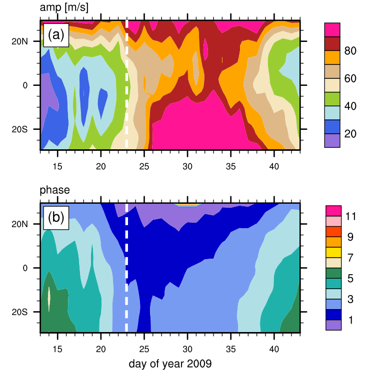
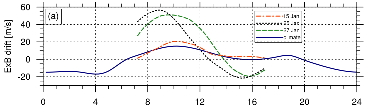
SW2 amplitude and phase changes during SSW 2009

(Wang et al., 2014)





Amplitude of zonal wind @ 115 km

$+$

Phase of zonal wind @ 115 km

$\Downarrow$

Plasma drift @ Jicamarca from GIP
GIP=Global Ionosphere Plasmasphere

What can cause SW2 amplitude and phase changes during SSW 2009?

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What can cause the short-term variability of tides?

The short-term variability of tides can be caused by (e.g., Vial 1993)

- Change in tidal forcing;
- Change in background propagation conditions;
- Introduction of energy near tidal frequencies by local or synoptic scale disturbances; and
- Non-linear interactions with atmospheric waves of different scales (and frequency, including modulation by planetary waves).

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What can cause tidal changes during SSW?

Several mechanisms have been proposed:

1. Stratospheric ozone change ⇒ heating changes (e.g., Goncharenko et al., 2012);
2. Reduction of north-south asymmetry of zonal background wind (Jin et al., 2012);
3. Nonlinear interactions between tides, and/or with planetary waves (e.g., Wang et al., 2012; Liu et al., 2010); and
4. Change in lunar tides (e.g., Fejer et al., 2010; Forbes and Zhang, 2012; Pedatella et al., 2014).

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Objective and methods

- To understand the short-term variability of tides during SSW; in particular the cause of SW2 amplitude and phase changes.

- To achieve this goal, we carry out a detailed analysis of WAM simulation of SSW 2009. In particular, we
  - Consider the first-order effects of the background wind and temperature;
  - Decompose the perturbation fields into Fourier modes in longitude-time and Hough modes in latitude; and
  - Solve the tidal vertical structure equation (VSE).

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The equations for perturbations

u-momentum
$$\frac{\partial u'}{\partial t} - fv' + \frac{1}{a\cos\phi}\frac{\partial \Phi'}{\partial \lambda} = R'_u, \tag{1a}$$

v-momentum
$$\frac{\partial v'}{\partial t} + fu' + \frac{1}{a}\frac{\partial \Phi'}{\partial \phi} = R'_v, \tag{1b}$$

thermodynamic
$$\frac{\partial \theta'}{\partial t} + \frac{\partial \bar{\theta}}{\partial z}w' = Q' + R'_\theta, \tag{1c}$$

where

$$R'_u \equiv -\frac{\bar{u}}{a\cos\phi}\frac{\partial u'}{\partial \lambda} - \frac{v'}{a\cos\phi}\frac{\partial \bar{u}\cos\phi}{\partial \phi} - \frac{\partial \bar{u}}{\partial z}w', \tag{2a}$$

$$R'_v \equiv -\frac{\bar{u}}{a\cos\phi}\frac{\partial v'}{\partial \lambda} - \frac{2\bar{u}\tan\phi}{a}u', \tag{2b}$$

$$R'_\theta \equiv -\frac{\bar{u}}{a\cos\phi}\frac{\partial \theta'}{\partial \lambda} - \frac{1}{a}\frac{\partial \bar{\theta}}{\partial \phi}v'. \tag{2c}$$

Fourier expansion in longitude and time

$$u'(\lambda, \phi, z, t) = \widetilde{u}(\phi, z) \exp[i(2\Omega\sigma t + s\lambda)], \tag{3}$$

$$\frac{\partial^2 \widetilde{w}}{\partial z^2} - \frac{1}{H}\frac{\partial \widetilde{w}}{\partial z} - \frac{N^2}{4a^2\Omega^2}\mathcal{F}(\widetilde{w}) = -\frac{1}{4a^2\Omega^2}\frac{R}{H}e^{-\kappa z/H}\mathcal{F}\left(\widetilde{Q} + \widetilde{R}_\theta\right) - \frac{\sigma}{2sa\Omega}\mathcal{F}_u\left(\frac{\partial \widetilde{R}_u}{\partial z}\right) + \frac{i\sigma}{2a\Omega}\mathcal{F}_v\left(\frac{\partial \widetilde{R}_v}{\partial z}\right),$$

$$\mathcal{F}(A) \equiv \frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sigma^2 - \sin^2\phi}\frac{\partial A}{\partial\phi}\right) - \frac{1}{\sigma^2 - \sin^2\phi}\left(\frac{s}{\sigma}\frac{\sigma^2 + \sin^2\phi}{\sigma^2 - \sin^2\phi} - \frac{s^2}{\cos^2\phi}A\right), \tag{4a}$$

$$\mathcal{F}_u(A) \equiv \frac{1}{\cos\phi}\left[\frac{\partial}{\partial\phi}\left(\frac{s}{\sigma}\frac{\cos\phi\sin\phi}{\sigma^2 - \sin^2\phi}A\right) + \frac{s^2}{\sigma^2 - \sin^2\phi}A\right], \tag{4b}$$

$$\mathcal{F}_v(A) \equiv \frac{1}{\cos\phi}\left[\frac{\partial}{\partial\phi}\left(\frac{\cos\phi}{\sigma^2 - \sin^2\phi}A\right) + \frac{s}{\sigma}\frac{\sin\phi}{\sigma^2 - \sin^2\phi}A\right]. \tag{4c}$$

Expansion in Hough modes

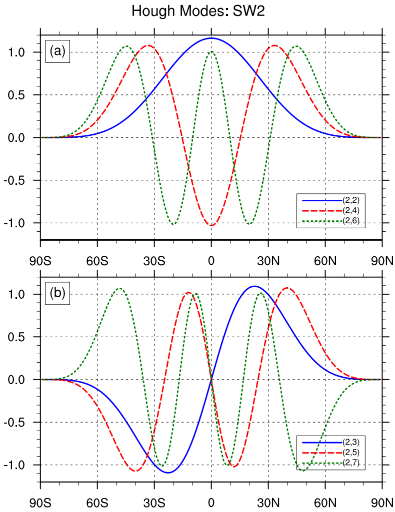
- Hough modes are eigenfunctons of Laplace tidal operator

$$\mathcal{F}(\Theta_n) + \gamma_n \Theta_n = 0.$$

- Expansion in Hough modes

$$\hat{w}_n(z) = \int_{-1}^{1} \hat{w}(\mu, z)\Theta_n(\mu) d\mu,$$

where $\mu = \sin\phi$ and the integration is done via Gauss quadrature rule.



The tidal VSE

We now have the tidal VSE in its final form (an ODE!)

$$\frac{d^2\hat{w}_n}{dz^2} + \left(\frac{\gamma_n \overline{N}^2}{4a^2\Omega^2} - \frac{1}{4H^2}\right)\hat{w}_n =$$

$$\frac{\gamma_n}{4a^2\Omega^2}\frac{R}{H}e^{-\kappa z/H}\hat{Q}_n - \frac{\sigma}{2sa\Omega}\hat{F}_n^u + \frac{i\sigma}{2a\Omega}\hat{F}_n^v + \frac{\gamma_n}{4a^2\Omega^2}\frac{R}{H}e^{-\kappa z/H}\hat{R}_{\theta n}, \tag{5}$$

where

$$\hat{F}_n^u \equiv \int_{-1}^{1}\mathcal{F}_u\left(\frac{\partial \hat{R}_u}{\partial z} + \frac{\hat{R}_u}{2H}\right)\Theta_n(\mu)d\mu, \tag{6a}$$

$$\hat{F}_n^v \equiv \int_{-1}^{1}\mathcal{F}_v\left(\frac{\partial \hat{R}_v}{\partial z} + \frac{\hat{R}_v}{2H}\right)\Theta_n(\mu)d\mu, \tag{6b}$$

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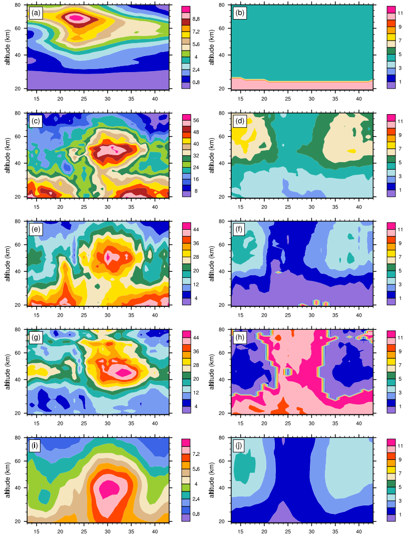
Hough analysis for (2,2) mode



$\hat{\bar{u}}_n$: symmetry of background wind

$\hat{u}_n$: large change in amp. & phase

$\hat{v}_n$: 90° phase shift from $\hat{u}_n$

$\hat{\theta}_n$: large change in amp. & phase

$\hat{w}_n$: large change in amp. & phase

Large consistent change in amp. & phase are shown in $\hat{u}_n$, $\hat{v}_n$, $\hat{w}_n$, & $\hat{\theta}_n$.

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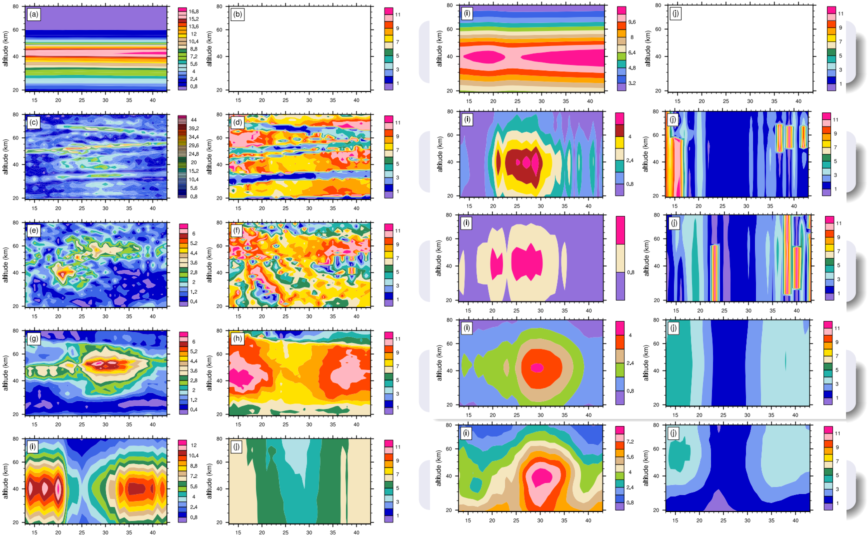
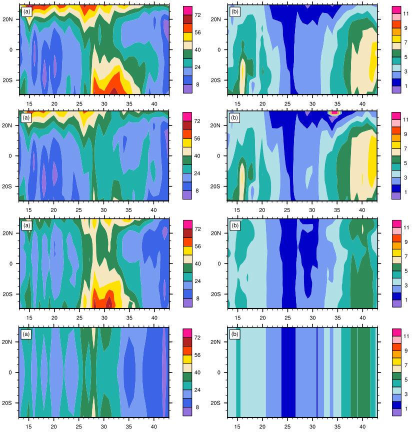
Solve the tidal VSE for (2,2) mode



Can the linear theory explain the full nonlinear model simulation?

Another way to solve the linear equations



All modes *with* background terms

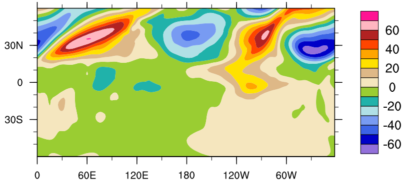
All modes *without* background

(2,2) mode *with* background

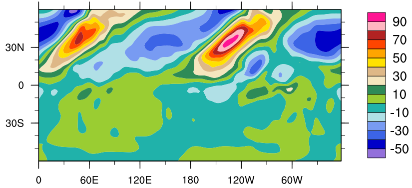
(2,2) mode *without* background

- The background terms contribute about 1/3 of the changes;
- The first symmetric (2,2) mode dominates.

Heuristic understanding of phase changes during SSW



u' at 2009011700 UTC



u' at 2009012300 UTC

- The change in the prevailing stratospheric background winds during the SSW can cause also the tidal wave phase change (Wang et al. 2014);
- It can be understood as the mass or wind anomaly being pushed/sheared more westward (or early local time) *materially*.

Summary and Conclusions

To understand causes of significant amplitude & phase changes in SW2 in WAM simulation of SSW 2009:

- A Hough function analysis shows large consistent amplitude & phase changes in SW2, mainly the first symmetric mode (2,2);
- The solution of the tidal vertical structure equation (VSE) with background wind and temperature shows:
    - The reduction of north-south asymmetry during SSW alone is not enough to explain the large amplitude & phase changes *after* the peak warming;
- The linear theory shed some lights on some features of tidal amplitude and phase change; but is not enough;
- Phase changes can be heuristically understood as the reversal of prevailing background wind "push"/shear the mass/wind anomaly more westward (or earlier local time) *materially*.