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## Amplification of the quasi-two day wave through nonlinear interaction with the migrating diurnal tide

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[1] We present a case study of the non-linear interaction between the quasi-two day wave (Q2DW) and the migrating diurnal tide based on global synoptic meridional wind fields for January 2006 and January 2008 from a high-altitude data assimilation/forecast system. We find large quasi-two day wave amplitudes, small diurnal tide amplitudes, and phase locking of the Q2DW with the diurnal cycle during January 2006. In January 2008 the amplitudes of the Q2DW were much smaller, with no evidence of phase locking, while the tidal amplitudes were larger than in the 2006 case. Space-time spectral analysis reveals an enhancement in a diurnal zonal wavenumber 6 feature in the January 2006 case, which can be attributed to a non-linear interaction between the Q2DW and migrating diurnal tide. The relatively strong summer easterly jet in the extratropical upper mesosphere during early January 2006 appears to have created conditions favoring this interaction. **Citation:** McCormack, J. P., S. D. Eckermann, K. W. Hoppel, and R. A. Vincent (2010), Amplification of the quasi-two day wave through nonlinear interaction with the migrating diurnal tide, *Geophys. Res. Lett.*, *37*, L16810, doi:10.1029/2010GL043906.

### 1. Introduction

[2] The quasi-two day wave (Q2DW) is a westward-propagating Rossby normal mode of zonal wavenumber 3 [Salby, 1981] that appears recurrently in the mesosphere and can dominate local dynamics. It has been extensively documented in observations from both the ground [e.g., Muller and Nelson, 1978; Harris and Vincent, 1993; Lima et al., 2004] and from satellites [e.g., Rodgers and Prata, 1981; Garcia et al., 2005; Limpasuvan and Wu, 2009]. In the extratropics, the Q2DW is found mainly 2–4 weeks after summer solstice, with the Southern Hemisphere Q2DW in January typically having much larger amplitude than its Northern Hemisphere counterpart in July. This study focuses on the behavior of the Q2DW in the Southern Hemisphere summer mesosphere.

[3] The temporal variability of the Q2DW is related to baroclinic or barotropic instability [Plumb, 1983; Lieberman, 1999], which tends to occur along the equatorward flank of the summertime mesospheric easterly jet. Consequently, the amplitude of the extratropical Q2DW can vary substantially

throughout the course of a season, and from one year to the next, depending on the vertical shear characteristics of the background zonal winds. To illustrate this point, the black curves in Figure 1 show time series of meridional winds at 88 km obtained from ground-based radar measurements over Adelaide, Australia for January 2006 and January 2008, when the Q2DW typically peaks in amplitude [Harris, 1994]. As Figure 1 shows, the amplitude of the Q2DW was much larger in January 2006 than in January 2008.

[4] A characteristic feature of the Q2DW in the Southern Hemisphere summer mesosphere is that it often amplifies rapidly in early January when its period is close to 48 hours, with maximum northward winds occurring shortly after local noon [Harris, 1994]. More recently, the study of the MF radar winds at 88 km over Adelaide by Hecht et al. [2010] shows that this rapid amplification of the Q2DW occurs more generally when its period is at or slightly less than 48 hours. Figure 1a shows that from January 7–11 2006, when the Q2DW amplitude rapidly increases, the peak northward MF radar wind value occurs near local noon every two days (as indicated by the vertical lines in Figure 1). Soon thereafter, the wind peak tends to occur progressively earlier. This behavior is consistent with the study of Hecht et al. [2010], who report Q2DW periods of 42–44 hours over this same period. Ground-based observations often show that the rapid growth of the Q2DW with a period near 48 hours occurs simultaneously with a decrease in the amplitude of the diurnal tide [see, e.g., Harris, 1994; Lima et al., 2004; Pancheva, 2006].

[5] A model proposed by Walterscheid and Vincent [1996] can account for the observed sudden amplification and phase locking of the Q2DW as well as its anticorrelation with the diurnal tide. The model explains these features via a two-step process initiated by interaction of the Q2DW with the migrating diurnal and semi-diurnal tides, ultimately producing a diurnal zonal wavenumber 6 feature. Some confirmation of this process was documented in the modeling study of Palo et al. [1999].

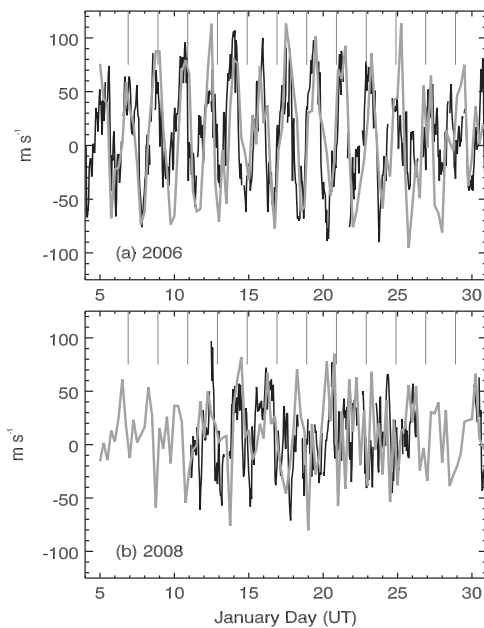
[6] Observational evidence of the interaction proposed by Walterscheid and Vincent [1996] is difficult to obtain, since single-location ground-based measurements of mesospheric winds (e.g., Figure 1) are unlikely to discriminate among waves of similar periods but different zonal wavenumbers, such as the diurnal wavenumber 6 feature and the diurnal tide. In addition, reconstructions of asynoptic measurements from a single satellite instrument, which have been used in the past to analyze the Q2DW, cannot unambiguously resolve wave motions with periods of ~1 day or less.

[7] This study examines Q2DW-tide interactions using global synoptic meteorological analyses produced every 6 hours from the surface to ~90 km altitude by assimilating satellite observations with an advanced-level physics high-

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**Figure 1.** Time series of meridional winds over Adelaide, Australia ( $35^{\circ}\text{S}$ ,  $138^{\circ}\text{E}$ ) during (a) January 2006 and (b) January 2008. Black curve represents ground-based MF radar observations at 88 km. Gray curve represents NOGAPS-ALPHA meteorological analyses at the 0.0036 hPa level ( $\sim 88$  km in log-pressure altitude). Vertical lines are drawn every two days at local noon.

altitude (ALPHA) version of the Navy Operational Global Atmospheric Prediction System (NOGAPS). Space-time spectral analysis of NOGAPS-ALPHA winds can discriminate among the diurnal wavenumber 1, the phase-locked wavenumber 3 2-day wave, and the diurnal wavenumber 6 feature proposed by *Walterscheid and Vincent* [1996]. We find that this diurnal wavenumber 6 feature appears in early January 2006 when the Q2DW exhibits rapid amplification, but it does not appear in January 2008, when the Q2DW amplitudes were much weaker than in the 2006 case.

## 2. Data and Analysis

[8] NOGAPS-ALPHA data assimilation couples the three-dimensional variational (3DVAR) algorithm of *Daley and Barker* [2001] with the NOGAPS-ALPHA spectral forecast model [see *Hoppel et al.*, 2008, and references therein]. It assimilates standard low-level meteorological observations along with stratospheric and mesospheric temperatures from both the Aura Microwave Limb Sounder (MLS) and from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. The forecast model employs a triangular truncation at wavenumber 79 (T79) with 68 model levels (T79L68) extending to 0.0005 hPa. The intrinsic grid point resolution of these analysis fields is  $\sim 2^{\circ}$  horizontally and  $\sim 2$  km vertically in the stratosphere and mesosphere. This configuration has been used to generate 6-hourly global  $1^{\circ} \times 1^{\circ}$  NOGAPS-ALPHA analyses on reference pressure levels from July 2007 to September 2009, and from

January to February 2006. For further details, see *Eckermann et al.* [2009] and *McCormack et al.* [2009].

[9] To assess the usefulness of analyzed winds for Q2DW research, Figure 1 compares analyzed meridional winds at 0.0036 hPa (pressure height  $\sim 88$  km) over Adelaide ( $35^{\circ}\text{S}$ ,  $138^{\circ}\text{E}$ ) during January 2006 and 2008 with corresponding meridional winds at 88 km measured by the Adelaide MF radar using spaced-antenna drifts, a technique used to continuously observe and study mesospheric Q2DW dynamics at this location for over 40 years [*Harris*, 1994]. Figure 1 reveals good overall agreement in the amplitude and phase of the analyzed Q2DW meridional winds. In particular, the analyzed winds capture the rapid amplification of the Q2DW in early January 2006 and the much weaker Q2DW in January 2008.

[10] We perform two-dimensional space-time spectral analysis of NOGAPS-ALPHA meridional winds as in the work by *McCormack et al.* [2009]. Despite preliminary evidence that the analyzed mesospheric semidiurnal winds are reliable [*Eckermann et al.*, 2009; *Stevens et al.*, 2010], the 6-hourly sampling rate (Nyquist frequency of 2 cpd) raises the possibility that semi-diurnal tidal features in the spectral results could be subject to aliasing from shorter time scales. Consequently, we limit our focus on the role of the diurnal tide in the present study.

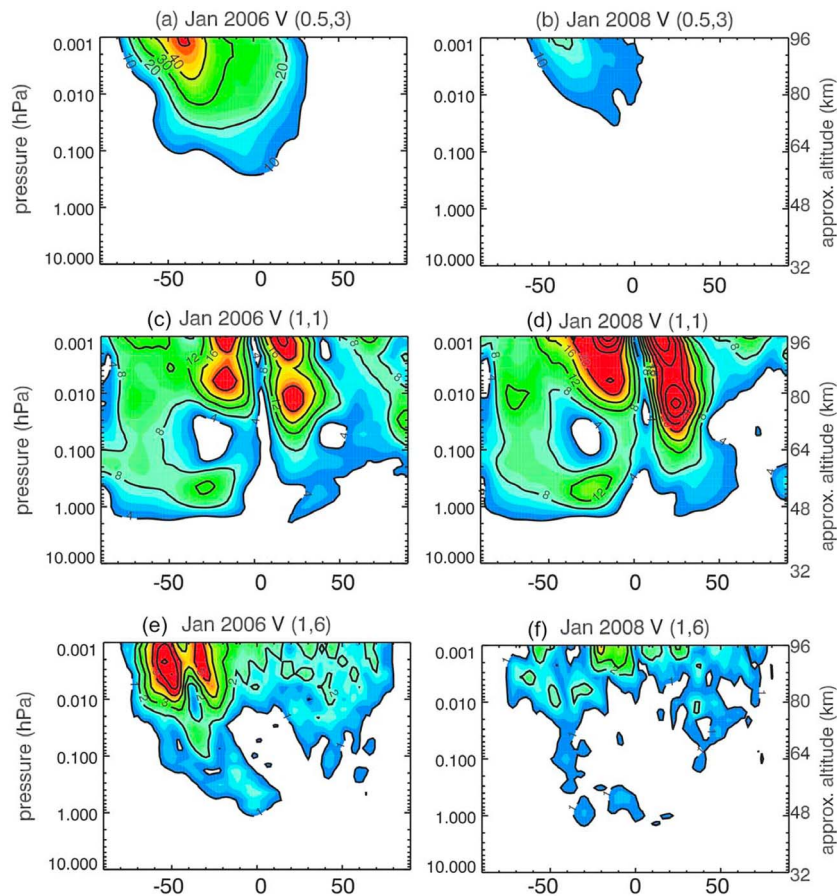
## 3. Results

[11] Space-time power spectra of NOGAPS-ALPHA meridional winds during January 2006 averaged between  $30^{\circ}$ – $50^{\circ}\text{S}$  latitude at the 0.0036 hPa level (not shown) reveal a dominant spectral peak related to the Q2DW near 0.5 cpd westward at zonal wavenumber 3, hereafter referred to as [0.5,3]. Additional peaks associated with the migrating diurnal tide (or [1,1]) and diurnal wavenumber 6 (or [1,6]) were also found. No significant peaks were found to be associated with eastward traveling waves for this level and latitude band.

[12] Based on this result, we applied the inverse Fourier transform with a band-pass filter to the NOGAPS-ALPHA meridional wind fields for both January 2006 and January 2008 cases in order to examine the differences in the global structure of these waves. Specifically, we isolated wind fluctuations associated with the [0.5,3], [1,1], and [1,6] features by selecting pass bands at zonal wavenumber 3 and 0.4–0.6 cpd, zonal wavenumber 1 and 0.95–1.05 cpd, and zonal wavenumber 6 at 0.99–1.16 cpd, respectively. Values of the root-mean-square (RMS) zonal wave amplitudes were computed from the resulting time series at each analysis time (i.e., every 6 hours).

[13] Figure 2 plots the monthly average values of the RMS amplitudes for each of these three features for January 2006 and 2008. Overall, the spatial structure of the Q2DW, diurnal tide, and diurnal wavenumber 6 features derived from the NOGAPS-ALPHA meridional wind analyses agree well with model simulations [e.g., *Palo et al.*, 1999].

[14] A comparison of the mean RMS amplitudes of the Q2DW between 2006 and 2008 (Figures 2a and 2b) shows much larger amplitudes in 2006, consistent with the ground-based observations in Figure 1. The RMS amplitudes of the diurnal tide (Figures 2c and 2d), on the other hand, are larger during 2008 than in 2006. The [1,6] amplitudes (Figures 2e and 2f) are larger in 2006 than in 2008, similar



**Figure 2.** Height-latitude variations in the monthly mean amplitudes of the quasi-two day wave [0.5,3], migrating diurnal tide [1,1], and westward [1,6] obtained from NOGAPS-ALPHA meridional winds for January 2006 (left column) and January 2008 (right column). Contour intervals are every (a, b)  $10 \text{ m s}^{-1}$ , (c, d)  $4 \text{ m s}^{-1}$ , and (e, f)  $1 \text{ m s}^{-1}$ .

to the behavior of the Q2DW. The prominent diurnal wavenumber 6 feature in the January 2006 case (Figure 2e) suggests that the non-linear parametric Q2DW-tidal interaction proposed by *Walterscheid and Vincent* [1996] can explain the rapid growth of the Q2DW during this time.

[15] Additional support for this mechanism can be seen from the time behavior of the [0.5,3], [1,1], and [1,6] components throughout the month of January obtained from the band-pass filtered winds. Figure 3 plots time series of the RMS amplitudes for each of these three components at 0.0036 hPa and  $35^\circ\text{S}$  for the January 2006 and January 2008 cases. In the January 2006 case (Figure 3a), we find a strong positive correlation between the time behavior of the [0.5,3] and [1,6] mode amplitudes from 5–15 January, when the rapid amplification of the Q2DW was observed over Adelaide (Figure 1a). In the January 2008 case (Figure 3b), there is no apparent coupling between the [0.5,3] and [1,6] components.

[16] As noted in the introduction, the behavior of the Q2DW can be highly sensitive to the background zonal wind distribution. The primary feature of the zonal winds in the extratropical Southern Hemisphere summer mesosphere is the easterly jet located near  $45^\circ\text{S}$ . Regions of baroclinic instability along the equatorward flank of this jet are the primary source regions for the Q2DW in January 2006 [*McCormack et al.*, 2009]. Examining the differences in the

easterly zonal wind jet between the January 2006 and 2008 cases may help explain why the non-linear interaction between the Q2DW and the diurnal tide led to the rapid growth of the Q2DW in 2006. Figure 4 plots time series of NOGAPS-ALPHA zonal mean zonal winds at  $45^\circ\text{S}$  and 0.01 hPa during January 2006 and 2008. We find that the easterly jet was stronger in 2006 than in 2008 throughout most of the month. In particular, from days 9–14 the zonal mean easterly wind speed was near  $60 \text{ m s}^{-1}$  in 2006.

[17] The study by *Walterscheid and Vincent* [1996] found that nonlinear excitation of the [1,6] component is, in general, rather limited until the speed of the background easterly flow reaches or exceeds  $58 \text{ m s}^{-1}$ . This suggests that the comparatively strong easterly jet in the extratropical summer mesosphere during January 2006 produced conditions favoring excitation of the [1,6] mode component, which subsequently led to the reduced period and rapid amplification of the Q2DW. We are currently extending the NOGAPS-ALPHA meteorological analyses to include the years 2005–2009 in order to better understand the relationship between interannual variability in the background zonal winds and the behavior of the Q2DW.

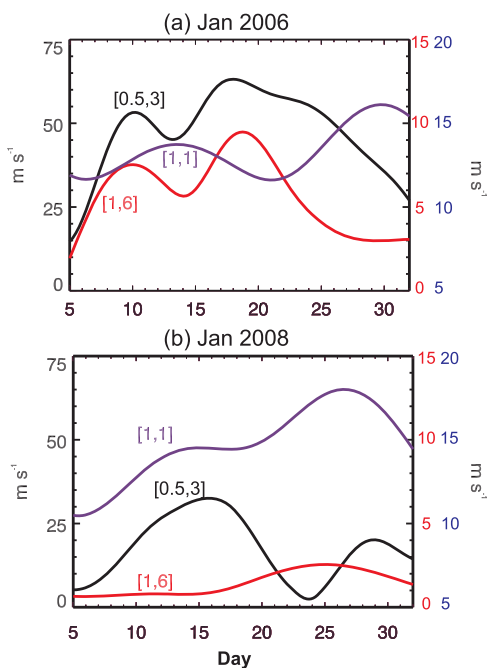
#### 4. Summary and Discussion

[18] Space-time spectral analysis of NOGAPS-ALPHA meridional winds reveals evidence for the non-linear inter-

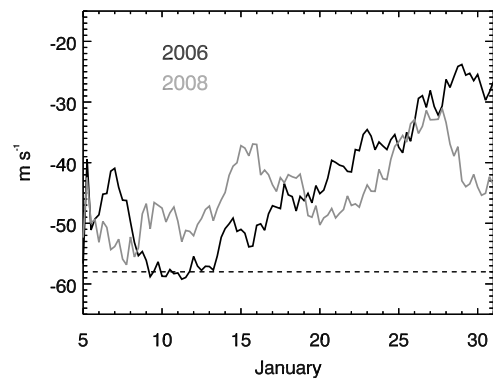
action between the Q2DW and the diurnal tide via a diurnal zonal wavenumber 6 feature, which can explain the rapid amplification of the Q2DW in January 2006, when the summer easterly jet was particularly strong. The presence of this interaction in the January 2006 case, but not in the January 2008 case (when the summer easterly jet was comparatively weaker), may help to explain why not all modeling studies of the Q2DW can reproduce this interaction.

[19] It should be noted that the [1,6] feature is not the only indicator of the proposed non-linear interaction. Other secondary waves such as the [1.5,4] (i.e., 16-hour period) or the [2.5,5] (9.6 hour period) components are also possible from non-linear interaction of the Q2DW and tides, which can then produce the [1,6] mode through subsequent interactions. The [1.5,4] and [2.5,5] waves are not found in our space-time analysis because the  $\pm 3$  hour 3DVAR analysis window in NOGAPS-ALPHA does not offer the necessary temporal resolution.

[20] Finally, a recent study by *Limpasuvan and Wu* [2009] also examined the behavior of the Q2DW during January 2006 using satellite-based line-of-sight mesospheric winds from MLS. They reported an anomalous westward two-day zonal wavenumber 2 feature at 91–92 km that appeared in early January, coincident with the rapid growth of the westward wavenumber 3 feature usually associated with the Q2DW. Our spectral analysis finds no such wavenumber 2 feature at any Southern extratropical latitudes during January 2006, up to 90 km. Future direct



**Figure 3.** Time series of RMS amplitudes of the quasi-two day wave (black curve), migrating diurnal tide (blue curve), and diurnal wavenumber 6 (red curve) components determined from band-pass filtered NOGAPS-ALPHA meridional wind (in  $\text{m s}^{-1}$ ) at 0.0036 hPa and  $35^\circ\text{S}$  for (a) January 2006 and (b) January 2008. Values on the left and right vertical axes range from 0–75  $\text{m s}^{-1}$ , 5–20  $\text{m s}^{-1}$ , and 0–15  $\text{m s}^{-1}$  for the [0.5,3], [1,1], and [1,6] components, respectively.



**Figure 4.** Time series of NOGAPS-ALPHA zonal mean zonal wind at 0.01 hPa and  $45^\circ\text{S}$  during January 2006 (black curve) and January 2008 (gray curve). Dashed line at  $58 \text{ m s}^{-1}$  indicates threshold value for growth of the [1,6] component.

comparisons of the NOGAPS-ALPHA analyzed winds with such line-of-sight wind estimates may clarify the reasons for this discrepancy.

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