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Source regions for Antarctic MLT non-migrating semidiurnal tides

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[1] Source regions for the westward propagating zonal wavenumber one and three components of the semidiurnal tide observed in the summer mesosphere and lower thermosphere over Antarctica are identified by correlating local tidal variations with global planetary wave one activity in the stratosphere and lower mesosphere. The advantages of using zonal wavenumber resolved tidal amplitudes for such a study are described. The results support the prediction of a source region in the northern hemisphere.
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1. Introduction

[2] Variations in the wind at harmonics of the solar day have long been observed in the mesosphere and lower thermosphere (MLT). A theoretical framework to explain these variations has been constructed by considering the response of a shallow stationary isothermal atmosphere to gravitational (lunar) and thermal (solar) forcing [*Chapman and Lindzen*, 1970], and is summarized by *Forbes* [1995]. These tides were thought to be dominated by zonal wavenumber components that were sun-synchronous (termed migrating tides) because of the efficiency of their forcing by insolation of water vapour and ozone.

[3] Meteor radar observations made from the South Pole have shown the existence of a non-sun-synchronous (non-migrating) zonal wavenumber-one component of the semidiurnal tide [*Forbes et al.*, 1995; *Portnyagin et al.*, 1998; *Lau et al.*, 2006]. Investigations of possible source mechanisms have included non-linear interactions with planetary waves [*Teitelbaum and Vial*, 1991] and zonally asymmetric thermal forcing [*Hagan and Forbes*, 2003]. In the latter, tropospheric latent heat release due to deep convective activity was used to force non-migrating components of the tide in a linear wave model. However, the response in the MLT region was found to be weak. This was not the case in non-linear interaction modeling studies where a source region for the summertime semidiurnal zonal wavenumber one tidal component was identified in the vicinity of the wintertime stratosphere [*Yamashita et al.*, 2002; *Angelats i Coll and Forbes*, 2002].

[4] The relatively low frequency of planetary waves (when compared to the semidiurnal tide's frequency) enables the non-linear interactions noted above to produce sum and difference zonal wavenumber pairs whose periods remain approximately semidiurnal. *Teitelbaum and Vial* [1991] modeled such interactions and showed that, for a constant amplitude traveling planetary wave, the tidal amplitude was modulated at the planetary wave frequency. Two aspects of their results are important in the context of this study: their results portray the tidal amplitudes that would be observed at a single station, which is the sum of multiple zonal wavenumber components; and a single planetary wave is used in their model. Thus a constant amplitude planetary wave produces a time-varying tide amplitude if the wavenumbers cannot be separated. A result of this is that real-atmosphere characteristics such as the presence of multiple planetary waves whose amplitudes are not constant will yield a planetary wave-tide relationship more complex than that identified by *Teitelbaum and Vial* [1991].

[5] A recent study by *Smith et al.* [2007] correlated northern MLT combined-wavenumber semidiurnal tide observations from Esrange (68°N, 21°E) with zonal wavenumber one planetary wave activity over the latitude-height range observable from the TIMED/SABER satellite. Their correlations show a linkage to the southern stratosphere but not in all years of the study. In the light of the previous paragraph, the presence of any correlation may be surprising. However, *Smith et al.* [2007] note that the dominance of the non-migrating component of the tide could explain their positive correlations. The ability to separate zonal wavenumbers would clearly be of advantage.

[6] Wavenumber-one tides are observed from the South Pole because of their dominance at that latitude [*Forbes et al.*, 1995; *Portnyagin et al.*, 1998; *Lau et al.*, 2006]. *Riggin et al.* [1999] and *Baumgaertner et al.* [2006] assumed semidiurnal wavenumbers one and two at two radar sites near 78°S to extract spatial structure. Poleward of approximately 60° latitude, assumptions about the linearity of the latitudinal variation in tidal amplitudes make it simple to extract zonal wavenumber components from multi-station observations [*Murphy et al.*, 2006]. A group of four concurrently operating Antarctic MF radars has made it possible to extend the technique used by *Murphy et al.* [2006] to produce time series of wavenumber resolved tidal amplitudes. In this paper, a correlation analysis applied to wavenumber resolved data is described and the results for

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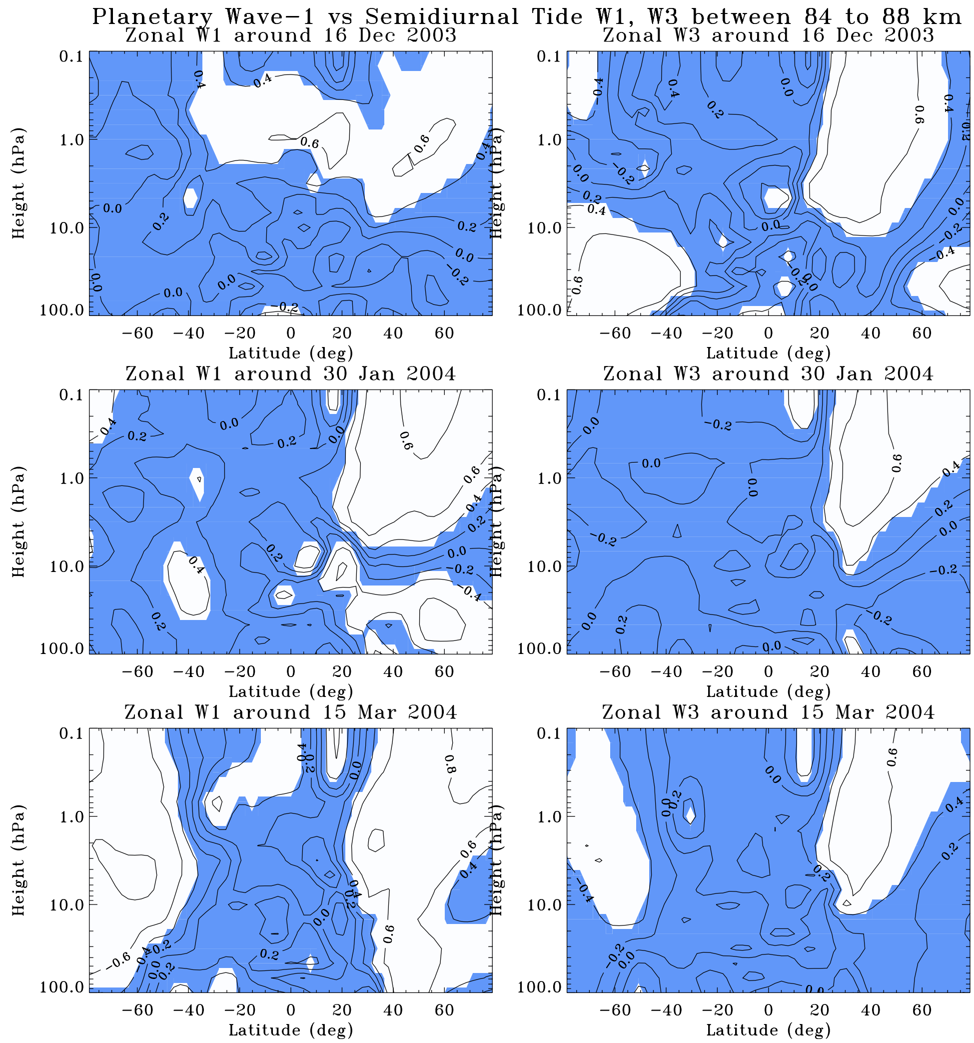

Figure 1. Cross-sections of the correlation between the zonal (left) W1 and (right) W3 semidiurnal tide at 68.6°S and 84–88 km, and the global geopotential height wave-one planetary wave amplitudes from Nov 2003 to April 2004. Blue shading indicates a significance of less than 90%.

the interval November 2003 to April 2004 are presented and discussed.

2. Data

[7] Winds in the MLT used in this study are provided by MF radars operating at Davis (68.6°S, 78.0°E), Rothera (67.6°S, 68.1°W), Scott (77.9°S, 166.7°E) and Syowa (69.0°S, 39.6°E) stations in Antarctica. The analysis technique described by *Murphy et al.* [2006] is applied between 78 and 94 km altitude, but using a 4-day running window with a 1-day step. The 4-day window was chosen as a compromise between the spectral resolution of the tidal fit and the temporal resolution required in the resulting time series. Data must be available for at least 75% of local times and 50% of the window at all four stations for the analysis to proceed. As a result, some approximately one week gaps in the data set are present but these do not adversely affect the analysis. The resulting data product is a time series of daily estimates of the amplitude and phase of the standing and westward propagating zonal wavenumbers 1–3 (W1–W3) of the diurnal and semidiurnal tide (interpolated to the latitude of Davis).

[8] Planetary waves in the global stratosphere and lower mesosphere are identified by fitting zonal wavenumbers to geopotential height data from the UKMO assimilated data set [*Swinbank et al.*, 2006] between pressure levels of 100 and 0.1 hPa and latitudes between ±78.75°. The amplitude and longitude of maximum are obtained at each height and 2.5° latitude step resolved by the data using a running 4-day window with a 1-day step (as for the tides).

3. Correlation Analysis and Its Justification

[9] The correlation analysis used in this study is similar to that used by *Smith et al.* [2007]. 90-day time series of the height-averaged amplitude of the semidiurnal tide at each wavenumber are correlated with time series of the global planetary wave-one amplitude. Latitude-height cross sections of the Pearson correlation coefficient are then overlaid on the correlation significance to produce results such as those in Figure 1. The significance of the correlation is calculated using a decreased number of degrees of

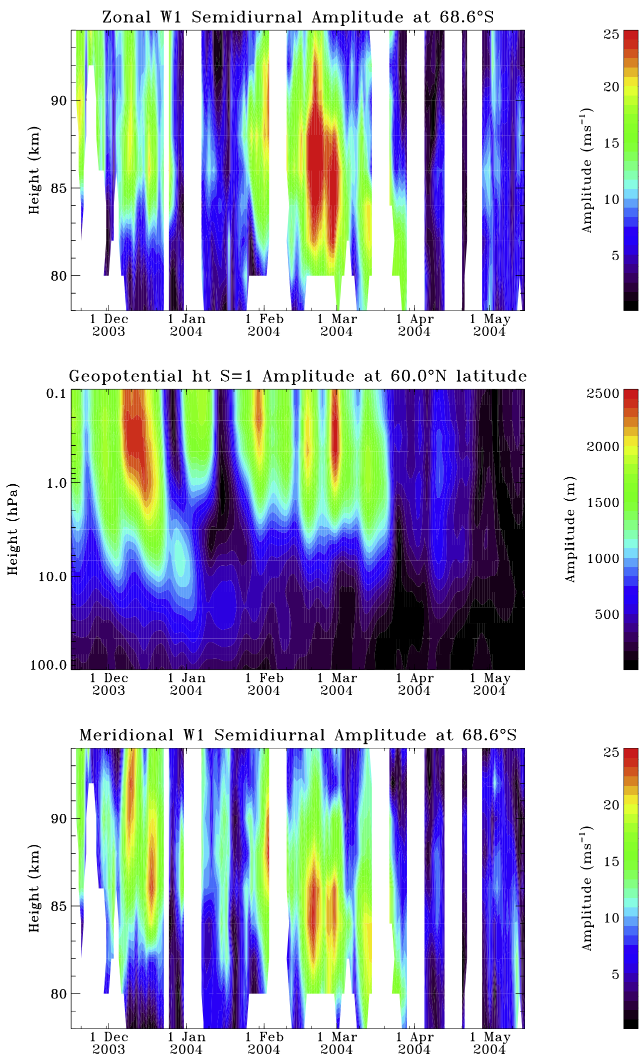

Figure 2. Amplitudes of the (top) zonal and (bottom) meridional W1 semidiurnal tide at 68.6°S with (middle) the assimilated planetary wave-one amplitude at 60°N between 100 and 0.1 hPa.

freedom to account for the 4-times oversampling associated with the window and step lengths used. The correlation maps presented in Figure 1 traverse the data interval in 45-day steps (such that there is 45 days of overlap in adjacent plots).

[10] The quadratic terms associated with interactions between tidal and planetary wave variations of the form $A\cos(\omega t + s\lambda - \varphi)$ are $A_T A_P \cos((\omega_T - \omega_P)t + (s_T - s_P)\lambda - (\varphi_T - \varphi_P))$ and $A_T A_P \cos((\omega_T + \omega_P)t + (s_T + s_P)\lambda - (\varphi_T + \varphi_P))$ where ω, s and φ are the wave frequencies, zonal wavenumbers and phases, t is time and λ is longitude (in radians) and the subscript denotes the wave type [e.g., *Angelats i Coll and Forbes*, 2002]. The interaction invoked to explain the semidiurnal W1 component observed in the high-latitude summer combines the migrating (W2) semidiurnal tide ($\omega = 2\pi/12$ h, $s = 2$) with a quasi-stationary wave-one planetary wave ($\omega = 0$, $s = 1$) [*Forbes et al.*, 1995; *Yamashita et al.*, 2002]. The above equations predict ($\omega = 2\pi/12$ h, $s = 1$) and ($\omega = 2\pi/12$ h, $s = 3$) components of amplitude proportional to $A_T A_P$. Variations in the planetary wave amplitude in the source region should be detectable in the observed tidal products.

[11] A physical picture of the interactions described above is as follows: the migrating component of the semidiurnal tide propagates around the earth and interacts with the planetary wave structures present in the stratosphere and lower mesosphere. These interactions yield tidal products that also propagate upward and are observed in the Antarctic MLT region [*Aso*, 2007]. For most planetary waves, the longitude of maximum changes little in the time the tide takes to complete one circuit of the earth so the planetary wave appears stationary to the tide. The vertical wavelength of the semidiurnal tide [e.g., *Forbes*, 1995] is such that it propagates from the source region to the MLT within a few tidal periods. Thus temporal changes in the planetary wave amplitude will propagate to the MLT region with a lag of less than 1–2 days. The exact lag will depend on the vertical wavelength of the tidal modes excited by the interaction. Changes in a traveling planetary wave's longitude of maximum will change the time of maximum of the resulting non-migrating tides but not their amplitude. Thus, temporal variations in the amplitude of stratospheric planetary waves will yield corresponding variations in the non-migrating tidal amplitudes at close to zero lag times, and correlations between these two amplitudes should allow source regions of the non-migrating tides to be identified.

4. Discussion

[12] The correlations depicted in Figure 1 (left) are for three windows of 90-day length between early November 2003 to late April 2004. Tidal amplitudes of the zonal winds for the W1 component at the latitude of Davis (68.6°S) were averaged over the height interval 84–88 km before the correlation coefficients were calculated; this height interval captures the strong tidal variations that occur through the data set. The zonal wind results show that regions of significant positive correlation exist in the northern mid- to high-latitudes that span between half and all of the height range represented (100–0.1 hPa or approximately 16 to 64 km). The meridional wind results are very similar and are not shown.

[13] These regions of high correlation indicate coherent behaviour of the tide and planetary wave and suggest likely source regions for the W1 tidal component near 60°N. In Figure 2, height versus time images of the W1 component of the tide and the S = 1 component of the assimilated geopotential height data at 60.0°N are compared. It can be seen that the planetary wave amplitude maximizes in the upper stratosphere and lower mesosphere, and that there is considerable variation in this amplitude with time. These temporal variations are also present in the tidal amplitudes (verifying the high measured correlations).

[14] The region of larger planetary wave amplitudes apparent in Figure 2 defines a suitable altitude range over which the planetary wave amplitudes can be averaged for comparison with tidal amplitudes. Figure 3 presents a time series of the average planetary wave one amplitude between 2.2 and 0.1 hPa along with the concurrent semidiurnal W1 zonal wind amplitude averaged between 84 and 88 km (Figure 3, top). The high correlation between these two time series provides strong support for the hypothesis that the

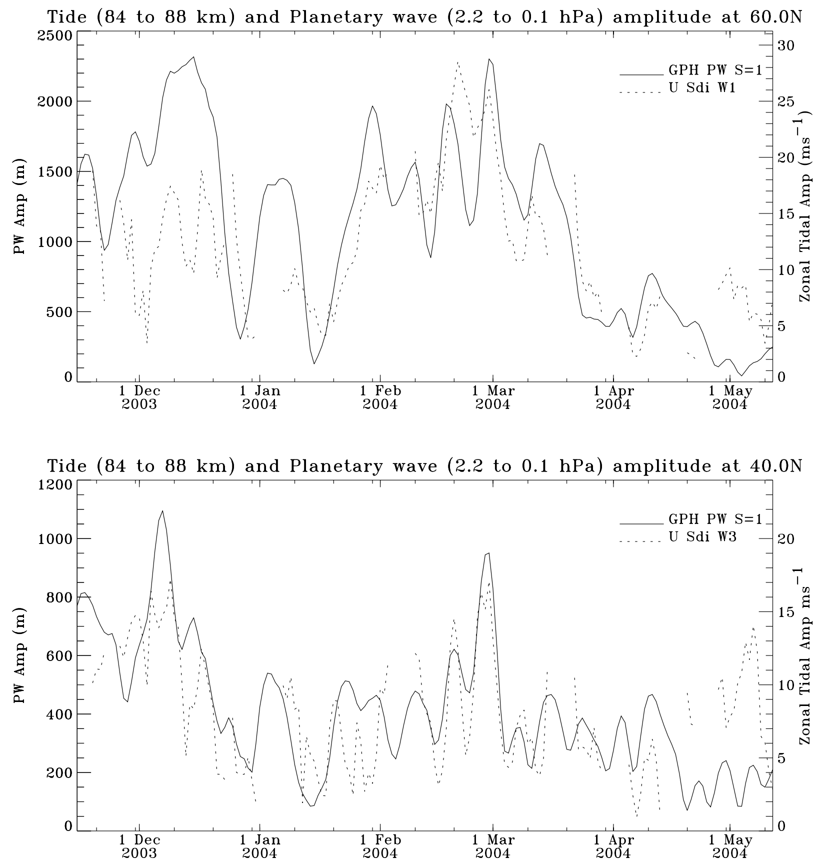

Figure 3. Time series of the 84–88 km zonal tidal amplitude at 68.6°S and the planetary wave one amplitude in the region of maximum correlation for the (top) W1 and (bottom) W3 semidiurnal tidal components.

source of this non-migrating semidiurnal component is near 60°N. It also is noted that the correlation persists at small amplitudes indicating the creation of W1 tidal components at moderate as well as large planetary wave amplitudes.

[15] Inspection of the W1 results in Figure 1 show regions of significant but negative correlation (30 Jan 2004: northern hemisphere <20 hPa; 15 March 2004: high southern latitudes). Investigation of these correlations has shown that they correspond to regions where the planetary wave activity is weak (see Figure 2). No correlation cross-sections were found where only negative correlations were significant. It is concluded that negative correlations are either fortuitous or reflect some weak planetary wave variations in concert with stronger activity elsewhere, and that the regions of positive correlation are dominant.

[16] The theory of non-linear interactions described above predicts that a W3 semidiurnal tide should accompany the W1. Latitude-height cross-sections of the correlation of the zonal wind W3 tidal component with the same planetary wave one component considered above are presented in Figure 1 (right). Northern hemisphere peaks in the correlation are apparent but they occur at lower latitudes to the concurrent W1 component. Using the same height averaging bounds as for W1 but planetary wave amplitudes at 40°N, the results in Figure 3 (bottom) were compiled. The planetary wave amplitudes are less at this latitude but the strong correlation apparent in Figure 3 (bottom) is evidence for the production of both a W1 and W3 tide. Note also that the W3 amplitudes are smaller than those of the W1.

[17] In order to explain the difference in the latitude at which the W1 and W3 maximum correlations occur, it is noted that the cosine product ideas presented above do not consider the vertical and horizontal structure of the waves and their products. For each zonal wavenumber, the tidal products will be representable (to a good approximation) as combinations of the modes within sets of Hough or velocity expansion functions [e.g., *Forbes*, 1995]. For a product wave to be excited, the vertical scale of the interaction region will need to be roughly half the vertical wavelength of a mode so that energy is transferred efficiently into that mode. The horizontal structure of the interaction region will also need to map onto modes that can propagate to the MLT region.

[18] It was noted by *Murphy et al.* [2006] that the W1 semidiurnal tidal wind component can be non-zero in the vicinity of the pole. This is true of the planetary wave one amplitude as well. As a result, interactions producing a W1 tide can map onto tidal expansion functions over much of the high-latitude region. The W3 tidal component, however, cannot exist at the pole and must decay in amplitude from mid- to high-latitudes. This difference in the velocity expansion function latitudinal structures can explain the occurrence of the W3 correlation peak at lower latitudes: the interaction region for this combination cannot extend as far poleward.

[19] Finally, although the term 'non-linear interactions' is used to describe the production of sum and difference wavenumber-frequency pairs, linear processes may also be

responsible [*Merzlyakov et al.*, 2001]: a description of the effect of sinusoidal variations of the background insolation absorption is presented by *Chapman and Lindzen* [1970]. The small tidal amplitudes present in the stratosphere and lower mesosphere may not support a non-linear interaction. Figure 3 showed that non-migrating tidal products were modulated at low planetary wave amplitudes. Mechanisms associated with particle fluxes and thermospheric Joule heating have also been suggested [*Riggin et al.*, 1999; *Baumgaertner et al.*, 2006]. Thus, the details of the mechanism for creating non-migrating tidal components is an open question.

5. Conclusions

[20] In this study, the correlation analysis used by *Smith et al.* [2007] has been applied to tidal variations separated into zonal wavenumbers. Concurrent variations in Antarctic MLT tides and in northern hemisphere planetary wave amplitudes have provided observational support for the prediction that the W1 semidiurnal tide first observed at South Pole has the northern stratosphere and lower mesosphere as its source region. Similar observations of its companion W3 semidiurnal product further support this prediction and highlight the role played by the horizontal and vertical structure of the tides and planetary waves in creating non-migrating tides.

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