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A new perspective on the longitudinal variability of the semidiurnal tide

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[1] The longitudinal variability of the semidiurnal tide in the Antarctic upper mesosphere is investigated by comparison of observations from two radars at approximately opposite sides of Antarctica. Under the assumption that the tide is composed of an S = 2 (migrating) and S = 1 (westward-propagating, non-migrating) component only, the relative phases of the components are shown to vary with season such that the waves are typically in constructive interference during the winter (summer) months at longitudes around 0°E (180°E). We show that this has profound effects on the seasonal behaviour of the semidiurnal tide around 78°S dependent on the longitude, and that no single-station observations at this latitude can be considered representative of a "zonal mean". The superposition of these two waves is used to interpret differences in previously-published ground-based climatologies of the tide. **Citation:** Hibbins, R. E., O. J. Marsh, A. J. McDonald, and M. J. Jarvis (2010), A new perspective on the longitudinal variability of the semidiurnal tide, *Geophys. Res. Lett.*, *37*, L14804, doi:10.1029/2010GL044015.

1. Introduction

[2] Numerous studies have identified and characterised the nature of non-migrating tidal components in the atmosphere, in particular the different modes of the semidiurnal tide in the high-latitude southern-hemisphere mesosphere and lower-thermosphere (MLT) region using optical data [e.g., *Hernandez et al.*, 1993], radar winds [e.g., *Forbes et al.*, 1995; *Riggin et al.*, 1999; *Murphy et al.*, 2003, 2006; *Baumgaertner et al.*, 2006; *Hibbins et al.*, 2010] and satellite data [e.g., *Iimura et al.*, 2009]. In the most extensive study to date *Murphy et al.* [2006] used composite days of monthly-mean horizontal winds, generated from data recorded over multiple years at eight different ground-based stations located across Antarctica, to extract all semidiurnal tidal oscillations with zonal wavenumbers from 0 to 3 (S = 0 to 3) normalised to a latitude of 69°S. Their results showed that during winter the migrating S = 2 component was dominant, but during the summer months a strong S = 1 westward-propagating component developed, first observed over South Pole [*Hernandez et al.*, 1993; *Forbes et al.*, 1995]. This work demonstrated that the S = 1 12-hour wave was still a significant component in the summertime semidiurnal tide field as far north as 69°S. In addition to the S = 1 and S = 2 components *Murphy et al.* [2006] demonstrated that at times S = 0 and S = 3 components significantly contributed to the semidiurnal tide. During December the strength of the S = 1 component caused significant non-zero semidiurnal tidal amplitudes at South Pole and a high degree of longitudinal asymmetry with the strongest semidiurnal tide predicted at longitudes around 180°E. These results were also supported by *Iimura et al.* [2009] who used TIDI data from the TIMED satellite and presented climatologies of only the non-migrating eastward- and westward-propagating components of the semidiurnal tide in the high southern latitude MLT. At 90km altitude, the westward-propagating S = 1 component was found to dominate, with summer time amplitudes up to 16 ms^{-1} at high latitudes, with smaller contributions from the S = 0 (up to ~4ms^{-1} amplitude in summer) and S = 3 (up to ~3ms^{-1} amplitude in winter) components.

[3] *Baumgaertner et al.* [2006] extracted semidiurnal tide data from 10-day composites of the horizontal winds in the upper mesosphere recorded by the Halley (76°S, 333°E) imaging Doppler interferometer (IDI) and the Scott Base (78°S, 167°E) MF radar. Under the assumption that the total semidiurnal tide field at each location was composed of the vector sum of an S = 2 sun-synchronous and S = 1 westward-propagating components only, time series of the amplitude and phase of each of these two components were derived over a four year period between 1998 and 2001. They observed the summer time dominance of the S = 1 component over the S = 2, and by comparing the relative phase of each component over a 50−day period in early winter 2000, found that there was a preferred longitude for constructive interference between the two waves. During this period the waves were found to be in phase (constructively interfering) around Scott Base longitudes and out of phase (destructively interfering) around Halley longitudes.

[4] *Hibbins et al.* [2010] used a similar approach to that of *Baumgaertner et al.* [2006] to look for evidence of quasi-biennial variability of the semidiurnal tide in the MLT at high southern latitudes [*Hibbins et al.*, 2007a]. In this instance they used meteor wind data from the Halley SuperDARN radar for comparison with the Scott Base MF radar. The observations offered the excellent long-term uninterrupted data coverage required to extract small signals associated with interannual variability. By comparing horizontal wind data recorded simultaneously from these two radars situated at approximately opposite sides of the Antarctic, and assuming that the tidal field is composed of S = 2 and S = 1 components only, a 12-year time series of the two components of the semidiurnal tide was derived. In agreement with the results of *Baumgaertner et al.* [2006] it was found that throughout the 12 years of observations the tide is a complex mixture of the two components with the S = 1 component typically larger (smaller) than the S = 2 component during the summer (winter) months.

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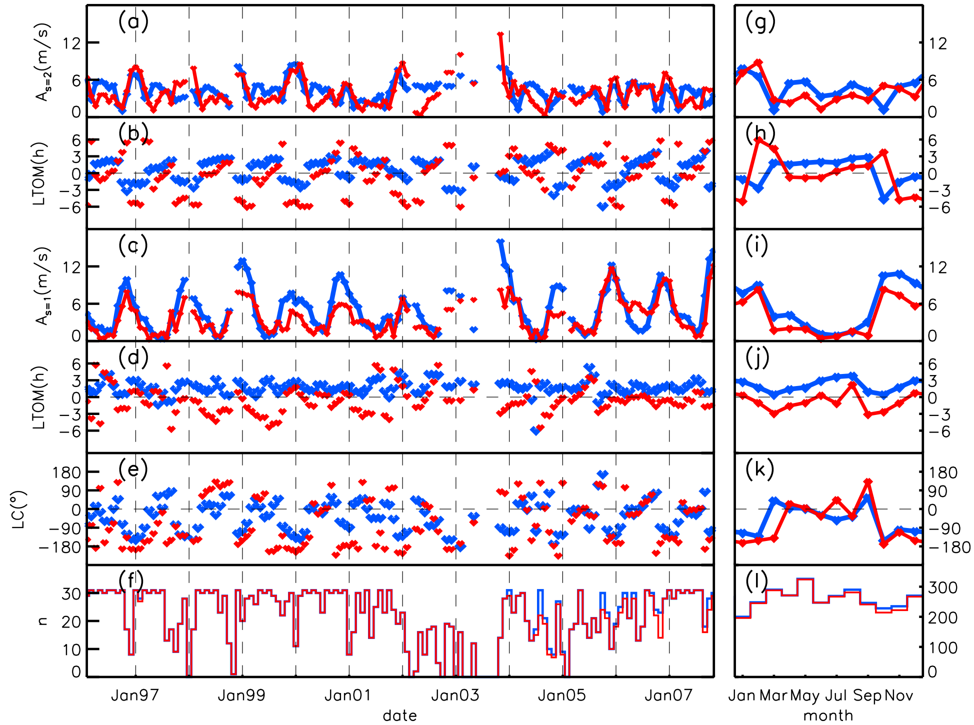

Figure 1. Zonal (red) and meridional (blue) semidiurnal tide data at 78°S and 90km altitude: (a) monthly mean amplitude and (b) time of maximum at 0° longitude for the migrating S = 2 component; (c and d) similarly, for the non-migrating westwards S = 1 component; (e) longitude east of Greenwich at which the two components are in constructive interference; (f) number of individual days' data recorded in each month; (g–k) vector averaged monthly mean climatologies generated from the data presented in Figures 1a–1e, respectively; (l) total number of individual days' data recorded in each calendar month.

[5] Attempts to quantify the longitudinal variability of atmospheric parameters are motivated in part by studies of wave/wave interactions, but also as a prerequisite to global studies of latitudinal variability [e.g., *Pancheva et al.*, 2002]. In the case of the semidiurnal tide several studies have investigated the longitudinal variability in narrow bands of latitude from both multi-instrument ground-based radars [e.g., *Jacobi et al.*, 1999; *Merzlyakov et al.*, 2001; *Pancheva et al.*, 2002] and, more recently, satellite observations [e.g., *Cierpik et al.*, 2003; *Friedman et al.*, 2009]. Longitudinal variations in the tide have been variously ascribed to zonally-asymmetric gravity wave forcing, non-linear interactions with planetary waves and interactions between migrating and non-migrating components to the tidal field.

[6] In this paper we take a different approach, and use the time series of S = 1 and S = 2 tidal components presented by *Hibbins et al.* [2010] to investigate the longitudinal dependence of the amplitude and phase of the semidiurnal tide in the Antarctic MLT. We use these data to reconstruct the semidiurnal tide field from the vector sum of the two components. We demonstrate that large differences between the seasonal behaviour of the semidiurnal tide at different observational longitudes arise solely from the interactions between these two components, and use this approach to interpret some of the differences observed in previously-published climatologies of the Antarctic semidiurnal tide.

2. Data

[7] Time series of the components of the semidiurnal tide at an altitude of ~90km and a latitude of 78°S were generated from 12 years of data recorded between January 1996 and December 2007. The technique used to extract the components was identical to that presented by *Hibbins et al.* [2010]. Briefly, composite days of hourly mean zonal and meridional winds recorded from the Halley SuperDARN radar [*Greenwald et al.*, 1985, 1995] meteor echoes [*Hall et al.*, 1997; *Yukimatu and Tsutsumi*, 2002; *Hibbins and Jarvis*, 2008], and the Scott Base MF radar [*Fraser*, 1984, 1989; *Baumgaertner et al.*, 2005] were simultaneously fitted to a functional form representative of the westward-propagating migrating (S = 2) and non-migrating (S = 1) semidiurnal tide and the migrating diurnal tide only. The derived tidal components were then vector averaged into monthly means. These data, together with the vector averaged monthly mean climatologies are reproduced in Figures 1a–1d and 1g–1j, respectively. Figure 1 shows that the S = 1 component is of a similar amplitude or stronger than the S = 2 component during the summer months of October to February and a smaller amplitude, though still present, during the months of March to September. The phase of the S = 1 component is remarkably stable throughout the 12 year period used in this analysis with a time of northwards maximum around 2–3 UT at 0° longitude during winter and summer and a little earlier during the equinoxes. The time of eastwards maximum of the S = 1 component in the zonal wind is almost exactly 3 hours earlier than the meridional component, showing circular polarisation throughout the year. The S = 2 component has a similar phase at 0° longitude to the S = 1 component during the winter months of April to September. By contrast during the summer months the phase of the S = 2 component lags

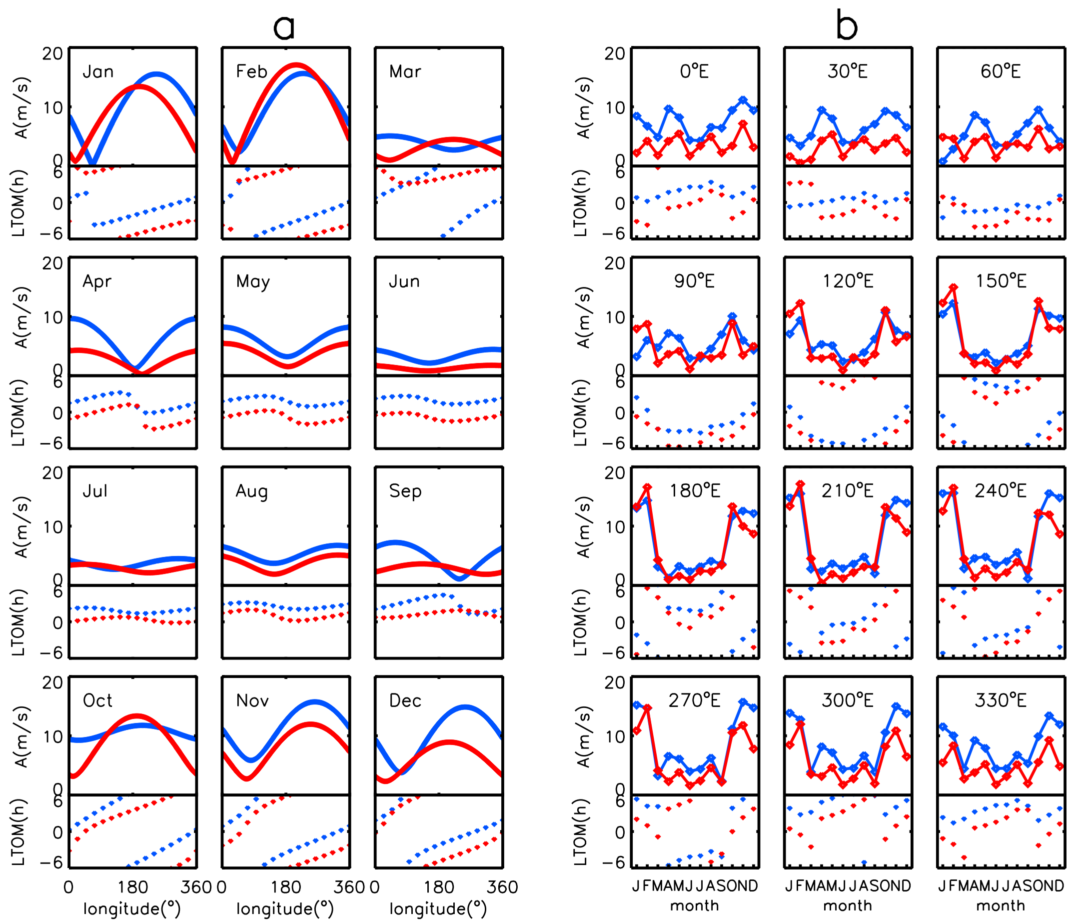

Figure 2. (a) Amplitude (top of each plot) and phase (bottom of each plot) of the vector sum of the S = 1 and S = 2 components of the semidiurnal tide at 78°S and 90km altitude for each month plotted as a function of longitude. (b) climatologies of the amplitude (top of each plot) and phase (bottom of each plot) of the vector sum of the S = 1 and S = 2 components of the semidiurnal tide plotted for all longitudes at 30° intervals. Zonal component: red; meridional component: blue.

that of the S = 1 component at 0° longitude by around 5 hours.

[8] As the S = 2 component has a westward-propagating zonal phase speed exactly half that of the S = 1 component, then the longitude (east of Greenwich) at which these two waves are in phase is given by *Baumgaertner et al.* [2006] as $L_c = (t_2 - t_1)/12*360°$ where t_2 and t_1 are the times of maximum in UT of the S = 2 and S = 1 components of the tide at the Greenwich meridian respectively. Conversely, at L_c-180° the two waves are exactly out of phase, so at L_c (L_c-180°) they interfere constructively (destructively), increasing (reducing) the amplitude of the unresolved tide observed at that longitude. Figures 1e and 1k show L_c for each month for the tides observed in both the zonal and meridional winds. The two waves are approximately in phase (out of phase) at 0° longitude during the winter (summer) months. As discussed above this implies that at the opposite side of the Antarctic (180°E) the two waves are approximately out of phase (in phase) during the winter (summer) months. Therefore during winter we would expect to see constructive (destructive) interference between the two components around 0° (180°) longitude and the opposite effect in the summer months. The equinoxes are a transition period during which the longitude of coincidence between the two waves switches from the summer to winter states, with L_c around 45°E. *Murphy et al.* [2006] and *Baumgaertner et al.* [2006] have both previously indicated that during December the semidiurnal tide in the MLT at high Southern latitudes is larger at longitudes around 180°E. This study confirms that during December the preferred longitude for constructive interference between the two tides is ~180°. In addition we are able to demonstrate that this remains fairly constant throughout the summer months of October to February in both the zonal and meridional components of the wind, switching to a markedly different state in winter, primarily driven by the changing phase of the migrating semidiurnal tide.

[9] Knowing the seasonal behaviour of the amplitude and phase of the two strongest (westward-propagating) components, and under the assumption that these two components are the only components of the tide at 78°S and 90 km altitude [*Baumgaertner et al.*, 2006], it is now possible to derive the amplitude and phase of the vector sum of these two components at any given longitude given by [e.g., *Murphy et al.*, 2006] $A_{S=1}\cos(2\Omega t + \lambda - \varphi_{S=1}) + A_{S=2}\cos(2\Omega t + 2\lambda - \varphi_{S=2})$, where A and φ are the amplitude and phase in radians (TOM.2π/12) of the individual components of the tide, and where t and λ are universal time and longitude (east of Greenwich) respectively. Figure 2a shows how the amplitude and phase (in this case converted into the

local, longitude dependent, time of maximum northwards or eastwards) of the total semidiurnal tide varies as a function of longitude.

[10] Figure 2a shows the consequences of the longitudinal and seasonal dependence of constructive and destructive interference between the two components of the tide on the total unresolved amplitude. In common with the studies of *Pancheva et al.* [2002] and *Jacobi et al.* [1999] an S1-like wave structure in the tidal amplitudes is observed. This is most pronounced during the summer months of November through to February where the semidiurnal tidal amplitude around 225°E is up to 15 ms^{-1} stronger than at 45°E. The location of this maximum in amplitude shifts to around 0°E during the winter months of April through to August, and the amplitude variability with longitude reduces as the S = 1 component of the tide becomes weak relative to the S = 2 mode (Figure 1i). In addition Figure 2a shows the phases of the tide measured in local time. During the winter months, when the sun-synchronous S = 2 tide is largest, the phase is largely constant across all longitudes, varying by around ±1 hour LT between May and August. However, outside this time the influence of the non-migrating S = 1 tide dominates the phases, which vary by a complete cycle during the months of October to December.

[11] An alternative (and potentially more instructive) way to view these data is to derive climatologies for a series of longitudes around a circle of latitude (78°S in this case). These results are presented in Figure 2b which shows the seasonality of the semidiurnal tide at 90 km and 78°S at 30° intervals of longitude. Here, the full effects of the seasonal and longitudinal variability can clearly be seen. Between 0°E and 90°E the amplitude of the semidiurnal tide is characterised by equinoctial maxima and solstice minima, particularly evident in the meridional component of the tide. Eastwards of this, the two tidal components come into constructive interference in summer time and dominate the winter amplitudes between 120°E and 270°E, peaking around 210°E at nearly 20 ms^{-1} in February. Between longitudes 120°E and 210°E the phases of the tides vary with the local time of maximum up to 8 hours later in summer than winter in the semidiurnal tide measured in both the zonal and meridional winds, whereas closer to the Greenwich meridian the tidal phases are seen to vary less with season.

3. Discussion

[12] *Murphy* [2002] invoked the concept of a two-component 12 hour tide to interpret observations of the semidiurnal tide made during the austral winter of 1996/7. It was suggested that rapid changes in the amplitude and phase of the tide observed in the MLT above Davis station could be explained by the assumption that the wave was composed of an invariant and a rapidly varying component. In this study we have specifically derived the amplitude and phase of the semidiurnal tidal components over a 12 year period to show how at different longitudes and seasons these components can interact either constructively or destructively to give markedly different seasonal behaviour dependent on the longitude of the observations. What is clear from these results is that in the circumstance where a migrating and non-migrating component of comparable magnitude contribute to the total semidiurnal tidal field, then any individual station observations cannot be considered representative of a "zonal mean" as the separate components of the tide cannot be resolved. This is especially important if attempting to draw conclusions on the latitudinal structure of tides, for example from ground-based data from globally distributed observation sites.

[13] While the derived climatologies presented in Figure 2b are obviously a good match for climatologies generated from the individual sites at Halley [e.g., *Hibbins and Jarvis*, 2008] and Scott Base [e.g., *Baumgaertner et al.*, 2005] (see discussion by *Hibbins et al.* [2010]), it is interesting to look for evidence of similar seasonal behaviour from previously-published climatologies of the semidiurnal tide in the high latitude southern hemisphere MLT. Perhaps the most striking feature of Figure 2b is the equinoctial enhancements seen in the amplitudes generated at longitudes between approximately 30°E and 90°E in contrast to the strong summer time amplitudes present between 150°E and 270°E and the "flatter", less strongly-seasonal climatology between 300°E and 0°E. Although ground-based observations at latitudes around 78°S are limited to Scott Base and Halley only, several studies have focussed on the seasonal behaviour of the semidiurnal tide from lower latitude Antarctic sites. *Portnyagin et al.* [1993] and *Avery et al.* [1989] have presented climatologies of the semidiurnal tide in the Antarctic lower thermosphere recorded from Scott Base, Mawson (68°S, 63°E) and Molodezhnaya (68°S, 46°E). Over Mawson and Molodezhnaya strong equinoctial maxima were observed in the semidiurnal tidal amplitudes in contrast to the summer time maxima observed from Scott Base. Figure 2b shows similar equinoctial enhancements in the semidiurnal tide at longitudes around 30°E and 60°E as those seen in the Mawson and Molodezhnaya climatologies. Although these bases are at substantially lower latitude than the derived climatologies in Figure 2b, the observation of equinoctial maxima over Mawson and Molodezhnaya are entirely consistent with the conclusion that during the equinoxes the longitude of constructive interference between the S = 1 and S = 2 components of the tide drifts to around 45°E (Figure 1k). Similarly the Davis (69°S, 78°E), Syowa (69°S, 40°E) and Rothera (68°S, 292°E) semidiurnal tide climatologies presented by *Riggin et al.* [2003], *Murphy et al.* [2003], and *Hibbins et al.* [2007b] show strong equinoctial enhancements in the semidiurnal tidal amplitudes over Davis and Syowa which are absent over Rothera.

[14] Hence, our analysis suggests that at this altitude it is not necessary to invoke complex processes such as zonally-asymmetric gravity wave forcing to explain the variability of the semidiurnal tide climatologies; rather a simple summation of the observed S = 1 and S = 2 components provides good agreement with observations.

4. Summary

[15] The relative phases of the S = 1 and S = 2 components of the semidiurnal tide in the Antarctic upper mesosphere have been shown to vary with season, leading to longitudes where the two components are either in constructive or destructive interference depending on the time of year. A superposition of these two components changes as a function of longitude and season to generate markedly different climatological behaviour of the semidiurnal tide dependent on the observational longitude. This analysis

demonstrates the important point that it is not possible to interpret the observations from any individual station at these high latitudes as representative of a zonal mean, and provides a perspective which can explain some of the large longitudinal differences between previously-published high latitude southern hemisphere climatologies of the semidiurnal tide in the upper mesosphere. In particular, the tendency for an equinoctial enhancement of the semidiurnal tide observed at sites with longitudes around 30°–90°E and the absence of this feature at other longitudes can readily be interpreted from the data derived entirely from Halley and Scott Base. An investigation of the consequences of this longitudinal asymmetry, and a similar study to compare the longitudinal behaviour of the tides in the high-latitude northern hemisphere will be the subject of a future paper.

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