

1 Source regions for Antarctic MLT non-migrating 2 semidiurnal tides

D. J. Murphy,¹ T. Aso,² D. C. Fritts,³ R. E. Hibbins,⁴ A. J. McDonald,⁵ D.

M. Riggin,³, M. Tsutsumi² and R. A. Vincent⁶

D. J. Murphy, Australian Antarctic Division, Department of the Environment, Water, Heritage and the Arts, 203 Channel Highway, Kingston, TAS 7050, Australia (damian.murphy@aad.gov.au)

T. Aso and M. Tsutsumi, National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo, Japan (e-mail: t-aso@nipr.ac.jp; tutumi@uap.nipr.ac.jp)

A. J. McDonald, Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand (e-mail: adrian.mcdonald@canterbury.ac.nz)

R. E. Hibbins, Physical Sciences Division, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, United Kingdom (e-mail: rehi@bas.ac.uk)

D. C. Fritts and D. M. Riggin, Colorado Research Associates/NWRA, 3380 Mitchell Lane, Boulder, CO 80301, USA (email:dave@cora.nwra.com; riggin@cora.nwra.com)

R. A. Vincent, Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, 5005, Australia (e-mail: robert.vincent@adelaide.edu.au)

¹Australian Antarctic Division, Kingston,

3 Source regions for the westward propagating zonal wavenumber one and
4 three components of the semidiurnal tide observed in the summer mesosphere
5 and lower thermosphere over Antarctica are identified by correlating local
6 tidal variations with global planetary wave one activity in the stratosphere
7 and lower mesosphere. The advantages of using zonal wavenumber resolved
8 tidal amplitudes for such a study are described. The results support the pre-
9 diction of a source region in the northern hemisphere.

¹Tasmania, Australia

²National Institute of Polar Research,
Tokyo, Japan

³Colorado Research Associates/NWRA,
Boulder, USA

⁴Physical Sciences Division, British
Antarctic Survey, Cambridge, UK

⁵University of Canterbury, Christchurch,
New Zealand

⁶University of Adelaide, Adelaide, South
Australia, Australia

1. Introduction

10 Variations in the wind at harmonics of the solar day have long been observed in the
11 mesosphere and lower thermosphere (MLT). A theoretical framework to explain these vari-
12 ations has been constructed by considering the response of a shallow stationary isothermal
13 atmosphere to gravitational (lunar) and thermal (solar) forcing [*Chapman and Lindzen,*
14 1970], and is summarized in *Forbes* [1995]. These tides were thought to be dominated
15 by zonal wavenumber components that were sun-synchronous (termed migrating tides)
16 because of the efficiency of their forcing by insolation of water vapour and ozone.

17 Meteor radar observations made from the South Pole have shown the existence of a non-
18 sun-synchronous (non-migrating) zonal wavenumber-one component of the semidiurnal
19 tide [*Forbes et al., 1995; Portnyagin et al., 1998; Lau et al., 2006*]. Investigations of
20 possible source mechanisms have included non-linear interactions with planetary waves
21 [*Teitelbaum and Vial, 1991*] and zonally asymmetric thermal forcing [*Hagan and Forbes,*
22 2003]. In the latter, tropospheric latent heat release due to deep convective activity was
23 used to force non-migrating components of the tide in a linear wave model. However,
24 the response in the MLT region was found to be weak. This was not the case in non-
25 linear interaction modeling studies where a source region for the summertime semidiurnal
26 zonal wavenumber one tidal component was identified in the vicinity of the wintertime
27 stratosphere [*Yamashita et al., 2002; Angelats i Coll et al., 2002*].

28 The relatively low frequency of planetary waves (when compared to the semidiurnal
29 tide's frequency) enables the non-linear interactions noted above to produce sum and dif-
30 ference zonal wavenumber pairs whose periods remain approximately semidiurnal. *Teitel-*

31 *baum and Vial* [1991] modeled such interactions and showed that, for a constant amplitude
32 traveling planetary wave, the tidal amplitude was modulated at the planetary wave fre-
33 quency. Two aspects of their results are important in the context of this study: their
34 results portray the tidal amplitudes that would be observed at a single station, which is
35 the sum of multiple zonal wavenumber components; and a single planetary wave is used in
36 their model. Thus a constant amplitude planetary wave produces a time-varying tide am-
37 plitude if the wavenumbers cannot be separated. A result of this is that real-atmosphere
38 characteristics such as the presence of multiple planetary waves whose amplitudes are not
39 constant will yield a planetary wave-tide relationship more complex than that identified
40 by *Teitelbaum and Vial* [1991].

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

49 Wavenumber-one tides are observed **from** the South Pole [**by ground-based radars**
50 deleted] because of their dominance at that latitude [*Forbes et al.*, 1995; *Portnyagin et*
51 *al.*, 1998; *Lau et al.*, 2006]. *Riggin et al.*, [1999] and *Baumgaertner et al.*, 2006] assumed
52 semidiurnal wavenumbers one and two at two radar sites near 78°S to extract spatial

53 structure. Poleward of approximately 60° latitude, assumptions about the **linearity of**
54 **the** [inserted] latitudinal variation in tidal amplitudes make it simple to extract zonal
55 wavenumber components from multi-station observations [Murphy et al., 2006]. A group
56 of four concurrently operating Antarctic MF radars has made it possible to extend the
57 technique used by Murphy et al. [2006] to produce time series of wavenumber resolved tidal
58 amplitudes. In this paper, a correlation analysis applied to wavenumber resolved data is
59 described and the results for the interval November 2003 to April 2004 are presented and
60 discussed.

2. The Data [Was Data and Analysis]

61 Winds in the MLT used in this study are provided by MF radars operating at Davis
62 (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 ,
63 39.6°E) stations in Antarctica. The analysis technique described in Murphy et al. [2006]
64 is applied between 78 and 94 km altitude, but using a 4-day running window with a 1-day
65 step. The 4-day window was chosen as a compromise between the spectral resolution
66 of the tidal fit and the temporal resolution required in the resulting time series. Data
67 must be available for at least 75% of local times and 50% of the window at all four
68 stations for the analysis to proceed. As a result, some approximately one week gaps in
69 the data set are present but these do not adversely affect the analysis. The resulting data
70 product is a time series of daily estimates of the amplitude and phase of the standing and
71 westward propagating zonal wavenumbers 1–3 (W1–W3) of the diurnal and semidiurnal
72 tide ([deleted **scaled** and replaced with **interpolated**] to the latitude of Davis).

73 Planetary waves in the global stratosphere and lower mesosphere are identified by fitting
 74 zonal wavenumbers to geopotential height data from the UKMO assimilated data set
 75 [Swinbank *et al.*, 2006] between pressure levels of 100 and 0.1 hPa and latitudes between
 76 $\pm 78.75^\circ$. The amplitude and longitude of maximum are obtained at each height and 2.5°
 77 latitude step resolved by the data using a running 4-day window with a 1-day step (as for
 78 the tides).

3. Correlation analysis and its justification [was a subsection]

79 The correlation analysis used in this study is similar to that used by *Smith et al.*
 80 [2007]. 90-day time series of the height-averaged amplitude of the semidiurnal tide at each
 81 wavenumber are correlated with time series of the global planetary wave-one amplitude.
 82 Latitude-height cross sections of the Pearson correlation coefficient are then overlaid on
 83 the correlation significance to produce results such as those in Figure 1. The significance
 84 of the correlation is calculated using a decreased number of degrees of freedom to account
 85 for the 4-times oversampling associated with the window and step lengths used. The
 86 correlation maps presented in Figure 1 traverse the data interval in 45-day steps (such
 87 that there is 45 days of overlap in adjacent panels).

88 The quadratic terms associated with interactions between tidal and planetary wave vari-
 89 ations of the form $A \cos(\omega t + s\lambda - \varphi)$ are $A_T A_P \cos((\omega_T - \omega_P)t + (s_T - s_P)\lambda - (\varphi_T - \varphi_P))$
 90 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 fre-
 91 quencies, zonal wavenumbers and phases, t is time and λ is longitude (in radians) and the
 92 subscript denotes the wave type [e.g. *Angelats i Coll et al.*, 2002]. The interaction invoked
 93 to explain the semidiurnal W1 component observed in the high-latitude summer combines

Figure 1

94 the migrating (W2) semidiurnal tide ($\omega = 2\pi/12$ h, $s = 2$) with a quasi-stationary wave-
95 one planetary wave ($\omega = 0$, $s = 1$) [*Forbes et al.*, 1995; *Yamashita et al.*, 2002]. The
96 above equations predict ($\omega = 2\pi/12$ h, $s = 1$) and ($\omega = 2\pi/12$ h, $s = 3$) components
97 of amplitude proportional to $A_T A_P$. Variations in the planetary wave amplitude in the
98 source region should be detectable in the observed tidal products.

99 A physical picture of the interactions described above is as follows: the migrating compo-
100 nent of the semidiurnal tide propagates around the earth and interacts with the planetary
101 wave structures present in the stratosphere and lower mesosphere. These interactions
102 yield tidal products that also propagate upward and are observed in the Antarctic MLT
103 region [*Aso*, 2007]. For most planetary waves, the longitude of maximum changes little
104 in the time the tide takes to complete one circuit of the earth so the planetary wave ap-
105 pears stationary to the tide. The vertical wavelength of the semidiurnal tide [e.g. *Forbes*,
106 1995] is such that it propagates from the source region to the MLT within a few tidal
107 periods. Thus temporal changes in the planetary wave amplitude will propagate to the
108 MLT region with [insert **a lag of less than 1-2 days**; delete ‘little lag’].[insert **The**
109 **exact lag will depend on the vertical wavelength of the tidal modes excited**
110 **by the interaction.**] Changes in a traveling planetary wave’s longitude of maximum
111 will change the time of maximum of the resulting non-migrating tides but not their am-
112 plitude. Thus, temporal variations in the amplitude of stratospheric planetary waves will
113 yield corresponding variations in the non-migrating tidal amplitudes at close to zero lag
114 times, and correlations between these two amplitudes should allow source regions of the
115 non-migrating tides to be identified.

4. Discussion [was ‘Results and Discussion’]

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

125 These regions of high correlation indicate coherent behaviour of the tide and planetary
126 wave and suggest likely source regions for the W1 tidal component near 60°N. In Figure
127 2, height vs. time images of the W1 component of the tide and the S=1 component of
128 the assimilated geopotential height data at 60.0°N are compared. It can be seen that the
129 planetary wave amplitude maximizes in the upper stratosphere and lower mesosphere, and
130 that there is considerable variation in this amplitude with time. These temporal variations
131 are also present in the tidal amplitudes (verifying the high measured correlations).

132 The region of larger planetary wave amplitudes apparent in Figure 2 defines a suitable
133 altitude range over which the planetary wave amplitudes can be averaged for comparison
134 with tidal amplitudes. Figure 3 presents a time series of the average planetary wave one
135 amplitude between 2.2 and 0.1 hPa along with the concurrent semidiurnal W1 zonal wind
136 amplitude averaged between 84 and 88 km (upper panel). The high correlation between

Figure 2**Figure 3**

137 these two time series provides strong support for the hypothesis that the source of this
138 non-migrating semidiurnal component is near 60°N. It also is noted that the correlation
139 persists at small amplitudes indicating the creation of W1 tidal components at moderate
140 as well as large planetary wave amplitudes.

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

149 The theory of non-linear interactions described above predicts that a W3 semidiurnal
150 tide should accompany the W1. Latitude-height cross-sections of the correlation of the
151 zonal wind W3 tidal component with the same planetary wave one component considered
152 above are presented in the right hand column of Figure 1. Northern hemisphere peaks
153 in the correlation are apparent but they occur at lower latitudes to the concurrent W1
154 component. Using the same height averaging bounds as for W1 but planetary wave am-
155 plitudes at 40°N, the results in the lower panel of Figure 3 were compiled. The planetary
156 wave amplitudes are less at this latitude but the strong correlation apparent in this fig-
157 ure is evidence for the production of both a W1 and W3 tide. Note also that the W3
158 amplitudes are smaller than those of the W1.

159 In order to explain the difference in the latitude at which the W1 and W3 maximum
160 correlations occur, it is noted that the cosine product ideas presented above do not con-
161 sider the vertical and horizontal structure of the waves and their products. For each zonal
162 wavenumber, the tidal products will be representable (to a good approximation) as com-
163 binations of the modes within sets of Hough or velocity expansion functions [e.g. *Forbes*,
164 1995]. For a product wave to be excited, the vertical scale of the interaction region will
165 need to be roughly half the vertical wavelength of a mode so that energy is transferred
166 efficiently into that mode. The horizontal structure of the interaction region will also need
167 to map onto modes that can propagate to the MLT region.

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

176 Finally, although the term ‘non-linear interactions’ is used to describe the production
177 of sum and difference wavenumber-frequency pairs, linear processes may also be respon-
178 sible [*Merzlyakov et al.*, 2001]: a description of the effect of sinusoidal variations of the
179 background insolation absorption is presented in *Chapman and Lindzen* [1970]. The small
180 tidal amplitudes present in the stratosphere and lower mesosphere may not support a non-

181 linear interaction. Figure 3 showed that non-migrating tidal products were modulated at
182 low planetary wave amplitudes. Mechanisms associated with particle fluxes and thermo-
183 spheric Joule heating have also been suggested [*Riggin et al.*, 1999; *Baumgaertner et al.*,
184 2006]. Thus, the details of the mechanism for creating non-migrating tidal components is
185 an open question.

5. Conclusions

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

194 **Acknowledgments.** The Davis MF radar is supported by Australian Antarctic Sci-
195 ence Advisory Committee grant number 674 and Australian Research Council grant
196 DP0346394. This research has been supported by a Grant-in Aid for Scientific Research
197 (14740287) from Japan Society for the Promotion of Science (JSPS). The Ministry of
198 Education, Culture, Sports, Science and Technology supports the MF radar system. The
199 40th-45th Japanese Antarctic Research Expeditions (JAREs) have carried out the MF
200 radar operation at Syowa. The Rothera MF radar was jointly supported by National
201 Science Foundation grant OPP-0438777 and by the UK Natural Environment Research

202 Council. The Scott Base radar is supported by the University of Canterbury and Antarc-
203 tica New Zealand. Communications between DJM and Evgeny Merzlyakov were greatly
204 appreciated.

References

- 205 Angelats i Coll, M., and J. M. Forbes (2002), Nonlinear interactions in the upper atmo-
206 sphere: The s=1 and s=3 nonmigrating semidiurnal tides, *J. Geophys. Res.*, *107*, A8,
207 10.1029/2001JA900179.
- 208 Aso, T. (2007), A note on the semidiurnal non-migrating tide at polar latitudes, *Earth*
209 *Plan. Spac.*, *59* e21-e24.
- 210 Baumgaertner, A.J.G., M.J. Jarvis, A.J. McDonald and G.J. Fraser (2006), Observations
211 of the wavenumber 1 and 2 components of the semi-diurnal tide over Antarctica *J.*
212 *Atmos. Sol. Terr. Phys.*, *68* 1195-1214.
- 213 Chapman, S. and R. S. Lindzen (1970), *Atmospheric Tides*, D. Reidel, Hingham, MA.
- 214 Forbes, J. M. (1995), Tidal and planetary waves. In R. M. Johnson and T. L. Killeen,
215 editors, *The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and*
216 *Theory*, 67–87. American Geophysical Union.
- 217 Forbes, J. M., N. A. Makarov and Yu. I. Portnyagin (1995), First results from the meteor
218 radar at south pole: A large 12-hour oscillation with zonal wavenumber one, *Geophys.*
219 *Res. Lett.*, *22*, (23), 3247–3250.
- 220 Hagan, M. E., and J. M. Forbes (2003), Migrating and nonmigrating semidiurnal tides
221 in the upper atmosphere excited by tropospheric latent heat release, *J. Geophys. Res.*,
222 *108*, 1062, doi:10.1029/2002JA009466.

- 223 Lau, E. M., S. K. Avery, J. P. Avery, S. E. Palo, and N. A. Makarov (2006), Tidal analysis
224 of meridional winds at the South Pole using a VHF interferometric meteor radar, *J.*
225 *Geophys. Res.*, *111*, D16108, doi:10.1029/2005JD006734.
- 226 Merzlyakov, E. G., Yu. I. Portnyagin, C. Jacobi, N. J. Mitchell, H. G. Muller, A. H.
227 Manson, A. N. Fachrutdinova, W. Singer and P. Hoffmann (2001), On the longitudinal
228 structure of the transient day-to-day variation of the semidiurnal tide in the mid-latitude
229 lower thermosphere I. Winter season, *Ann. Geophys.*, *19*, 542–562.
- 230 Murphy, D. J., J. M. Forbes, R. L. Walterscheid, M. E. Hagan, S. K. Avery, T. Aso, G.
231 J. Fraser, D. C. Fritts, M. J. Jarvis, A. J. McDonald, D. M. Riggini, M. Tsutsumi and
232 R. A. Vincent (2006), A climatology of tides in the Antarctic mesosphere and lower
233 thermosphere, *J. Geophys. Res.*, *111*, D23104, doi:10.1029/2005JD006803.
- 234 Portnyagin, Y. I., J. M. Forbes, N. A. Makarov, E. G. Merzlyakov and S. Palo (1998),
235 The summertime 12-h wind oscillation with zonal wavenumber $s=1$ in the lower ther-
236 mosphere over the South Pole, *Ann. Geophys.*, *16*, 828–837.
- 237 Riggini, D. M., D. C. Fritts, M. J. Jarvis and G. O. L. Jones (1999), Spatial structure
238 of the 12-hour wave in the Antarctic as observed by radar. *Earth, Plan. Spac.*, *51*,
239 621–628.
- 240 Smith, A. K., D. V. Pancheva, N. J. Mitchell, D. R. Marsh, J. M. Russell III
241 and M. G. Mlynczak (2007), A link between variability of the semidiurnal tide
242 and planetary waves in the opposite hemisphere, *Geophys. Res. Lett.*, *34*, L07809,
243 doi:10.1029/2006GL028929.

- 244 Swinbank, R., A. O'Neill, A. C. Lorenc, S. P. Ballard, R. S. Bell, N. B. Ingleby, P. L.
245 F. Andrews, D. M. Barker, J. R. Bray, A. M. Clayton, T. Dalby, D. Li, T.J. Payne,
246 F.W. Saunders, B. Macpherson, M.J.P. Cullen, T. Davies and M.H. Mawson (2006),
247 Stratospheric Assimilated Data, [internet] British Atmospheric Data Centre. Available
248 from <http://badc.nerc.ac.uk/data/assim/>
- 249 Teitelbaum, H., and F. Vial (1991), On tidal variability induced by nonlinear interaction
250 with planetary waves, *J. Geophys. Res.*, *96*, (A8), 14,169–14,178.
- 251 Yamashita, K., S. Miyahara, Y. Miyoshi, K. Kawano, and J. Ninomiya (2002), Seasonal
252 variation of non-migrating semidiurnal tide in the polar MLT region in a general circu-
253 lation model, *J. Atmos. Sol. Terr. Phys.*, *64*, (8–11), 1083–1094.

Figure 1. Cross-sections of the correlation between the zonal W1 and 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%.

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

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 W1 and W3 semidiurnal tidal components.