Winds and Tides of the Antarctic Mesosphere and Lower Thermosphere: One Year of Meteor-Radar Observations Over Rothera (68°S, 68°W) and Comparisons with WACCM and eCMAM

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ARTICLE INFO

Keywords:
Atmospheric Tides
Meteor Radar Observations
WACCM
eCMAM

ABSTRACT

Atmospheric tides play a critical role in the dynamics and coupling of mesosphere and lower-thermosphere (MLT). Global Circulation Models (GCMs) that aim to span the lower, middle and upper atmosphere must therefore be capable of reproducing the tides and observations of tides are thus crucial to constrain the models. Here we present the first climatology of the 12- and 24-hour tides measured at heights of 80 - 100 km by a meteor radar over the Antarctic station of Rothera (68°S, 68°W). We use observations of tides from 2009 in the first test of two GCMs at these latitudes: the Whole Atmosphere Community Climate Model (WACCM) and the extended Canadian Middle Atmosphere Model (eCMAM, 24-hour tide only). Our radar observations reveal large-amplitude 12- and 24-hour tides which display a distinct seasonal variability. The 12-hour tide maximises around the equinoxes, reaching daily-mean amplitudes of about 40 ms⁻¹. The 24-hour tide is generally of smaller amplitude and maximises in summer. The observed 12-hour tide increases greatly in amplitude with increasing height over the range 80 - 100 km, whereas the 24-hour tide generally does not do so. Comparison with the models shows that, for the 12-hour tide, WACCM reproduces the observed amplitudes at heights near 80 km quite well, but does not reproduce either the strong observed increase with height or the equinoctial maxima. For the 24-hour tide, WACCM reproduces the observed small variation in amplitude with height, but suggests amplitudes somewhat larger than those observed whilst eCMAM generally reproduces the observed tidal amplitudes and the small variation of amplitude with height. The radar observations reveal great day-to-day variability in the amplitude of both tides, much of which is quasi periodic and occurs at periods similar to those of planetary waves, suggesting that it originates in non-linear tidal/planetary-wave coupling. The observed and model background winds display some notable differences, particularly in winter when eastward winds are observed at all heights but not reproduced in the models. We propose that these differences may arise from the lack of in-situ gravity-wave sources in the models and that this may also account for some of the differences apparent between the observed and modelled tides.

1. Introduction

The dynamics of the mesosphere and lower thermosphere (MLT) are dominated by atmospheric waves and tides of large amplitude (Smith, 2012; Becker, 2011). As the tides ascend towards the MLT, their amplitudes increase in response to the decreasing gas density and the tides reach amplitudes large enough to dominate the motion field of the MLT. Observations of tides in the MLT have revealed the dominant tides to be the 12-hour semi-diurnal tide at middle and high latitudes and the 24-hour diurnal tide at low latitudes (Mitchell et al., 2002; Davis et al., 2013).
The solar tides include both migrating and non-migrating components. The migrating modes are Sun-synchronous (i.e., Sun-following), propagate westward and have zonal wavenumbers equal to the number of cycles of the tide per day (Positive zonal referring to an eastward direction and positive meridional referring to northward). These tides are forced primarily in the lower atmosphere by solar heating of water vapour and ozone and the release of latent heat in deep tropospheric convection. In contrast, the non-migrating modes are not Sun-synchronous (i.e., not Sun-following), can propagate either eastwards or westwards and may have zonal wavenumbers not equal to the number of cycles of the tide per day. These non-migrating tides consequently include all modes that propagate eastwards and those westwards modes where the zonal wavenumber is not equal the number of cycles per day.

The non-migrating tides are believed to be forced primarily by the non-linear interactions that occur between tides and planetary waves generating so-called “secondary waves”, which include the non-migrating tidal modes (Teitelbaum and Vial, 1991; Beard et al., 1999; Palo et al., 2007; Gu and Du, 2018) and also by longitudinal departures from zonally-uniform forcing, such as land/sea differences in convective activity in the troposphere. Therefore, at any point in the atmosphere, the tides will be a superposition of both migrating and non-migrating modes.

The tides can have appreciable fluxes of energy and momentum and so have significant direct and indirect effects on the circulation and temperature of the MLT (Becker, 2017). Further, the tidal winds can act to filter the field of atmospheric gravity waves. This modulates the gravity-wave momentum fluxes and the consequent forcing of the global atmospheric circulation (Fritts and Alexander, 2003) and so may control the propagation of gravity waves to greater heights. In addition to perturbations in winds, the tides induce temperature perturbations that are believed to be an important driver of the variability of polar mesospheric clouds, because the tidal perturbations of temperature can modulate the cloud ice crystal population (Fiedler et al., 2005).

Tidal signatures propagate upwards from the MLT into the thermosphere where the divergence of tidal momentum and heat fluxes can drive zonal wind changes of more than 30 ms$^{-1}$ in the lower thermosphere and influence the transport of chemical species (Jones et al., 2014, 2019). Tides in the thermosphere also cause perturbations of neutral and plasma densities in the E and F regions of the ionosphere and so modulate the ionospheric wind dynamo (Oberheide et al., 2009; Yiğit and Medvedev, 2015; Liu, 2016). The winds, tides and waves of the MLT therefore form a strongly coupled system in which the tides greatly influence the structure and dynamics of the atmosphere and modulate the distribution and ionisation in the ionosphere.

A striking feature of atmospheric tides is their variability in amplitude and phase on a wide range of time scales, ranging from day-to-day fluctuations to long-term variability. Distinct seasonal variability has been reported at all latitudes (Mitchell et al., 2002; Davis et al., 2013). At high latitudes this seasonal variability is evident in a 12-hour tide that maximises in autumn and winter (Mitchell et al., 2002; Pancheva et al., 2020). The seasonal variability of the high-latitude 24-hour tide is less well determined by observations (partly because of its generally smaller amplitudes), but has been reported to include an extended summertime amplitude maximum at heights below about 90 km (Hibbins et al., 2007; Pancheva et al., 2020). The observed seasonal variability of tides has been proposed to result from phenomena including wave/mean-flow interactions and/or source variations and refraction/reflection of propagating tidal modes (McLandress, 2002; Riggin et al., 2003; Riggin and Lieberman, 2013).

Intra-seasonal variability has also been observed. For example, variability of Arctic 12-hour tides has been shown to be well correlated with the amplitude of planetary wavenumber 1 at Antarctic latitudes, indicating significant inter-hemispheric coupling (Smith et al., 2007) and there is also evidence of variability on the intra-seasonal time scales associated with the tropical Madden-Julian Oscillation (Yang et al., 2018). At inter-annual time scales, tidal amplitudes and phases have also been observed to vary in response to solar variability, the El Niño Southern Oscillation, sudden stratospheric warmings and the stratospheric Quasi-Biennial Oscillation (Kumari and Oberheide, 2020; Laskar et al., 2016).

At shorter time scales of less than 30 days, the tides are observed to exhibit great variability and their amplitudes are frequently observed to fluctuate from day to day by factors that can be as large as 400% or more (Beard et al., 1999). This variability has been termed “tidal weather” (Vitharana et al., 2019) and has been attributed to factors including:

1. variations in the background winds through which the tides must propagate (Vitharana et al., 2019)
2. variations in tidal forcing resulting from solar variability and/or fluctuations in the distribution of water vapour and stratospheric ozone (Pancheva et al., 2003; Lieberman et al., 2004)
3. non-linear interactions with planetary waves that generate secondary waves that then modulate with the primary tide, therefore modulating its amplitude (Teitelbaum and Vial, 1991; Beard et al., 1999).
The critical role of tides in coupling the lower/middle/upper atmosphere and the thermosphere-ionosphere system means that studies to determine tidal amplitudes, wavelengths and variability are essential in any attempt to understand the coupling of the MLT and other atmospheric layers. Further, such observations are also needed to constrain and guide the representation of tides in those GCMs that intend to span the MLT.

The large majority of observational studies of tides in the MLT have been made either by ground-based meteor and MF radars or by satellites. Satellite observations have generally focussed on the 24-hour tide where they can resolve the tidal spectrum into migrating and non-migrating components (Das et al., 2020). Satellite observations of the 12-hour tide are limited by the need for the satellite to precess through local time and so typically have time resolution of about 60 days. Satellite observations generally have very poor vertical resolution and their limited time resolution means that they are generally not able to investigate the tidal variability, “tidal weather”, that occurs on time scales shorter than the seasonal.

In contrast, while ground-based radars are unable to resolve the observed tidal spectrum into migrating and non-migrating components and are limited to the fixed location of the radar, they offer excellent height and time resolution. Such radar measurements are therefore able to determine tidal amplitudes, wavelengths and variability across all time scales and are so well suited to studies of short-term variability and the detailed vertical structure of the tides. However, there are known biases in some ground-based techniques that limit their ability to measure tides in the upper MLT. In particular, MF radars are known to systematically and significantly under-estimate wind speeds at heights above about 90 km (Wilhelm et al., 2017). In contrast, meteor radars are able to make measurements across a height range of ~ 80 - 100 km and so are ideally suited to measuring tides at these heights.

GCMs have been used to investigate the tides of the MLT and their coupling to levels above and below. The models used include eCMAM (the extended Canadian Middle Atmosphere Model , Ward et al. (2010)), WACCM-X (Whole Atmosphere Community Climate Model with thermosphere and ionosphere extension, Liu (2014)), GSWM (Global Scale Wave Model, Hagan et al. (1999)), the KMCM (Kühlungsborn Mechanistic General Circulation Model, Becker (2017)), UM (Met Office Extended Unified Model, Jackson et al. (2019)), WACCM-6 (Whole Atmosphere Community Climate Model Version 6, Gettelman et al. (2019)) and others.

Here we present observations of background winds and 12- and 24-hour tides at heights of 79 - 101 km made over the course of 2009 by a meteor radar located on the Antarctic Peninsula at Rothera (68°S, 68°W). We compare our results with the predictions of two models: the Whole Atmosphere Community Climate Model (WACCM-6, hereafter “WACCM”) in the case of the 12- and 24-hour tide and the extended Canadian Middle Atmosphere Model (eCMAM) for the 24-hour tide alone. In Section 2 we describe the radar, radar data used and introduce the two models used. In Section 3 we present measurements of the background zonal and meridional winds, a climatology of tidal amplitudes and phases as monthly-means and determine some properties of tidal variability on “tidal weather” timescales of less than a month. In each case we compare the observations with the predictions of WACCM and eCMAM. In Section 4 we consider how our results compare to other tidal studies and suggest causes of differences between the model predictions and observations. Finally in Section 5 we present our conclusions.

2. The Rothera Meteor Radar and the WACCM and eCMAM Models

In this study we use the hourly winds measured in the MLT throughout the full year of 2009 by a SKiYMET VHF meteor radar located at Rothera (68°S, 68°W) on Adelaide Island off the Antarctic Peninsula. The radar uses a solid-state transmitter of 6 kW peak power and during the course of these measurements it operated with a duty cycle of 15%, transmitted at a radio frequency of 32.5 MHz and had a pulse repetition frequency of 2144 Hz. The radar antenna receiver array had five elements used as an interferometer, allowing measurement of echo azimuth and zenith angles. In combination with range information, this enables the height of individual meteor echoes to be determined. Radial winds are measured by the Doppler method. From these measurements, hourly-mean horizontal winds are then calculated using the method described below. A more complete description of the SKiYMET meteor radar design is given in (Hocking et al., 2001).

The distribution of recorded meteors in height and time determines the resolution at which the radar can measure the winds. This is important in tidal studies because the diurnal cycle in meteor count rates may prevent wind measurements being made throughout each day. We illustrate the typical meteor distributions in the observations made by the Rothera radar in examples using data from the month of April 2009 and presented in Figure 1. The total number of meteors recorded in each hour of the day for the entire month is presented in Figure 1a. The figure reveals a distinct diurnal cycle in meteor count rates. The meteor count rates have a broad maximum at around 06:00 LT and a relatively
Figure 1: The distribution of meteors over a month shown as a composite day in (a) time and (b) height for April 2009 and (c) a day’s spatial distribution for 15 April 2009 at Rothera.

A narrow minimum at around 16:00 LT (The local time at Rothera is 4.53 hours prior to UTC). The ratio of maximum to minimum meteor count rates is $\sim 1.7$. This diurnal cycle in meteor count rates is typical of an all-sky system at polar latitudes and means that there are still adequate numbers of meteors recorded in the afternoon to enable calculation of MLT winds. Figure 1b presents the vertical distribution of meteors recorded for the entire month. The figure shows that meteor counts maximise at a height of $\sim 90$ km and have an approximately Gaussian distribution around this height with a full width at half maximum of $\sim 16$ km. This distribution is typical of VHF meteor radars. Younger et al. (2009) showed that the peak of the height distribution does indeed change over the year however, this is always close to 90 km. Figure 1c presents the distribution of meteors measured around the radar projected onto a horizontal plane for April 15, 2009 (one day only is presented for reasons of clarity in the figure). The figure shows that meteors are detected at all azimuths and that the distribution of meteors is such that the great majority of meteors are detected
within a circular volume centred on the radar with a diameter of $\sim 400$ km.

From the radial velocity measurements made for each individual meteor, hourly winds are calculated under the assumption that the flow is horizontal and uniform across the meteor collecting volume at any particular height. Here, we calculate the winds using the radial drift velocities measured for each meteor, subject to a Gaussian weighting in height and time around a given height and time. These Gaussian weightings are given full-width-half-maxima of 2 hours in time and 3 km in height. The centre of the Gaussian weighting is advanced through the data in steps of 1 hour in time and 1 km in height. By using this weighting, the meteors closer to the time and height in question are given more emphasis in the wind calculation than if the meteors each had equal weighting. The result is a time series of winds spaced by 1 hour in time and 1 km in height, with an effective time and height resolution of approximately 2 hours and 3 km, respectively. The vertical distribution of meteor counts allows us to then measure winds at heights from $\sim 79 - 101$ km using this method. The time series of winds at each height are resolved into zonal and meridional components.

In this study we will compare our radar observations with the output of two atmospheric models. These models are version 6 of the Whole Atmosphere Community Climate Model (WACCM6, hereafter WACCM) and the extended Canadian Middle Atmosphere Model (eCMAM). WACCM is the high-top atmospheric part of the Community Earth System Model (Hurrell et al., 2013; Marsh et al., 2013). It extends from the surface to a pressure level of $5.1 \times 10^{-6}$ hPa and has a horizontal resolution of 1.9 $^\circ$ in latitude and 2.5$^\circ$ in longitude. WACCM has 88 vertical levels with a vertical resolution ranging from 1.1 - 1.75 km in the troposphere and stratosphere to 3.5 km in the mesosphere and lower thermosphere (Pedatella et al., 2018). Here we use the Specified Dynamics version of WACCM which is nudged by reanalysis data from the troposphere and stratosphere but free running in the mesosphere and lower thermosphere.

The extended Canadian Middle Atmosphere Model (eCMAM) is a global circulation model which is based on the standard CMAM (Beagley et al., 2000) but with the upper boundary at a pressure level of $2 \times 10^{-7}$ mbar. It uses a triangular spectral truncation at wave number 32 and solves primary equations to a $6^\circ \times 6^\circ$ resolution to yield a 6-hourly wind output. There are 87 vertical levels on an irregular grid with a resolution of 150 m close to the surface, 2 km near to the tropopause and roughly 3 km in the middle atmosphere (Vitharana et al., 2019). eCMAM was developed to examine the nature of the physics and dynamical processes in the MLT without the artificial effects of a sponge layer, which can have the unfortunate effect of modifying the circulation in the model in an unrealistic fashion (Fomichev et al., 2002).

In the case of both models, the output used here consists of daily estimates of zonal and meridional wind and tidal amplitude and phase for the 12-hour tide (WACCM) and the 24-hour tide (WACCM and eCMAM) for 2009 from January 1 to December 31.

3. Methods and Results

In this Section we present the winds and tidal analysis as measured by the radar and compare these observations with the predictions of WACCM and eCMAM.

3.1. Hourly Winds in the Mesosphere and Lower Thermosphere over Rothera

Our radar observations of winds in the MLT reveal a wind field dominated by a large-amplitude 12-hour tide, superposed on the background winds and a variable field of planetary waves, gravity waves and other tidal components. As an example of these wind fields, Figure 2a and b present the hourly-mean winds measured over Rothera by the meteor radar for April 1 - 15 for the zonal and meridional components, respectively. There is no filtering applied to the wind data and so the winds include the background flow, tides, planetary waves and gravity waves.

In both components, the figure shows the motion field to be dominated by 12-hour tidal oscillations of large amplitude. The 24-hour tide is scarcely discernible against the much larger amplitude of the 12-hour tide. For the 12-hour tide, it can be seen that the tidal amplitudes generally increase with height to instantaneous values reaching as large as $\sim 50$ ms$^{-1}$ at heights near 100 km (e.g., the zonal winds at heights near 100 km on April 3). There is a readily apparent descent of the phase fronts with advancing time and the zonal tidal winds lead the meridional tidal winds by 3 hours, indicating that the tidal wind components are generally in phase quadrature and that the tidal wind vector rotates anticlockwise with time (seen from above). These features indicate an upwardly propagating tide. The figure also reveals conspicuous short-term variability in tidal amplitude. For example, at heights near 100 km, large amplitudes reaching $\sim 30$ ms$^{-1}$ are observed during April 9 – 12, but on April 13 the amplitudes at this height decrease to only $\sim 10$ ms$^{-1}$. This day-to-day variability is a distinct feature evident throughout the entire dataset.
Figure 2: This Figure shows the zonal (a) and meridional (b) hourly winds as a function of time and height over Rothera for April 1 to 15, 2009.

3.2. Monthly-Mean Zonal and Meridional Winds

The winds, tides and waves of the mesosphere are strongly coupled and the seasonal variation of these background winds can be measured by the radar. Figure 3 presents the monthly-mean winds measured over Rothera by the meteor radar for all of 2009. Also shown is the corresponding model output for WACCM and eCMAM.

Our radar measurements of the monthly-mean winds of the MLT are presented in Figure 3a and d. These winds have been calculated by creating a composite day for each month and then averaging the winds at each height over that composite day. Considering the zonal winds, a clear seasonal cycle is evident in which the winds are predominately eastward throughout the year with speeds of up to 30 ms\(^{-1}\) observed at the upper heights during January and February. Westward winds are only observed at the beginning and end of the year (January to March and October to December) and then only at height up to \(\sim 90\) km. These westward winds are at their strongest in December with zonal winds of \(-40\) ms\(^{-1}\) observed at heights near 80 km. This pattern of winds in the summer months is part of the strongly sheared zonal flow associated with the upper part of the middle atmosphere jet. In contrast, the wintertime flow consists of only eastward winds with speeds of 10 - 20 ms\(^{-1}\) at all heights during May to August. The strongest winds exceed 20 ms\(^{-1}\) at heights below about 87 km in June and July.

Figure 3b and c show the corresponding monthly-mean zonal winds from WACCM and eCMAM, respectively. These are produced by averaging the model daily wind values for each month. Considering WACCM, the summertime shear in the zonal winds is present as in the observations, although the winds at the upper heights near 100 km reach 40 ms\(^{-1}\) and are notably stronger than the observed values that are near 20 ms\(^{-1}\). The height of the wind reversal during these months agrees to within a few km with the observations. However, between March and September the winds in WACCM are consistently westward at heights above about 85 km. This is in distinct contrast to the radar observations. Considering eCMAM, the seasonal variation in winds is very similar to that seen in WACCM. Again the westward winds from March to October are in distinct contrast to the observed eastward winds.

Considering now the meridional winds, Figure 3d shows that the observed meridional winds are considerably weaker than the zonal. In summer the winds are generally northward with speeds > 10 ms\(^{-1}\) only seen in December. Southward winds are only observed from March to September at heights below about 85 km where southward flows reaching speeds of -10 ms\(^{-1}\) are observed.
Figure 3: Monthly-mean winds over Rothera from the meteor radar (a and d), WACCM (b and e) and eCMAM (c and f). The solid contours are positive values spaced every 10 ms\(^{-1}\) with the dashed lines negative values again spaced every 10 ms\(^{-1}\). Note that the scale on the meridional plots is different than that used on the zonal plots to allow for an easier comparison between the radar and models.

Figure 3e and f show the corresponding monthly-mean meridional winds from WACCM and eCMAM, respectively. Considering WACCM, it can be seen that the model has more extensive and stronger regions of southward flow. In particular, during summer the winds in WACCM are southward above the lower heights and there is a strong region of southward flow at all heights in October. During winter the meridional winds are somewhat stronger than those observed. Considering eCMAM, the seasonal cycle in the winds is similar to that seen in the radar observations. There is a more extensive region of southward flow in height of time than evident in the observations, although generally the flow velocities are of similar magnitudes.

The main difference between the observations and the models is consequently the presence in the observations of eastward winds throughout the winter at all heights, a feature not present in either of the models.

3.3. Composite Day

To investigate the seasonal variability of the tides we use a monthly tidal composite day analysis. This will allow us to investigate the average tidal amplitudes over height for each month individually. In this analysis, the composite days are formed for each individual month to yield a representative day for that month. However, this representative day will include, at each height, the background winds. Therefore, the mean at each height for the composite day is removed to reveal only the tidal perturbations.

Figure 4 presents the tidal composite days for the Rothera meteor radar data for each month in 2009. Figure 4a shows the zonal component of the tidal composite winds for each month. We see from the figure that throughout the year there is evidence of a large amplitude 12-hour tide with two cycles occurring over each 24 hour period and that
this tide generally has clear and coherent phase fronts. The 24-hour tide is also present, but at a smaller amplitude. It is noticeable however that in other months (e.g. January to March and November to December), the phase fronts are discontinuous with an abrupt change of phase typically occurring at heights near 90 km. A particularly clear example of this is in January, where at about 15:00 LT the tidal phase at heights near 92 km abruptly changes. The meridional tidal composite days essentially show the same behaviour as the zonal composites.

The tidal composite days do not allow for direct measurement of the amplitude of the individual tides (e.g. 24-hour, 12-hour, 8-hour etc.), because all tides are simultaneously present in a superposition. Therefore, in order to measure the amplitude and phase of each tide, a least-squares fit of a specified sinusoidal oscillation of period 24-, 12-, has 8- and 6-hours is made to the composite day wind time series at each height. The result of this analysis is the amplitude and phase of each tide at each height from 79 - 101 km. We will consider the results of this monthly composite day analysis later in the paper. Note that although our analysis measures the amplitudes and phases for all four tides, we will not consider the 8-hour and 6-hour tides any further in this study.
Figure 4: Background removed composite day for Rothera in 2009 in the zonal (a) and the Meridional (b). Positive winds are in red with negative winds in blue.
3.4. Seasonal Variability of the 12- and 24-Hour Tides

Figure 2 and Figure 4 indicate there is large variability of the tides on both short term and seasonal time scales, respectively. To investigate both the large scale and short timescale tidal variability concurrently, we use a 4 day composite day advanced through the data-set in steps of 1 day. This yields daily values of 4 day mean tidal amplitudes for each tide in both the zonal and meridional components. This is required as fitting to 1 days data would produce a poor tidal fit and therefore a poor representation of the true variability in the atmosphere. We then take this incremented composite day and use a 30 day running mean (incremented in steps of 1 day) to investigate seasonal variability. This allows us to not only see the changes of the tides on periods of months, but also gives a suggestion as to how the tide changes between this.

To highlight the seasonal and also short timescale variability, we present time series of the daily values from the 4 day composites at a height of 90 km in Figure 5a and b for the zonal and meridional respectively. In the case of the 12-hour tide, very dramatic short term amplitude variability is evident. For example, in May there is a dramatic change in amplitude from about 30 ms$^{-1}$ to less than 10 ms$^{-1}$ in the space of a few days - a change of more than a factor of three. This variability is a persistent feature of the tidal amplitude throughout the year. Further, much of this variability appears to be quasi-periodic in nature. For example, there is a regular pattern of repeating amplitude peaks from March to July with a period of about 10 days.

To determine the seasonal variation in the tidal amplitudes, a 30 day running mean amplitude was calculated from the four-day individual fits and this fit was incremented through the data in steps of one day. The results of this analysis are presented in Figure 5c and d for the 12-hour tide and in Figure 5e and f for the 24-hour tide. From the figures it is apparent that the 12-hour tide exhibits a large variation in amplitude over the course of the year. In particular, there is a strong semi-annual cycle in amplitude in both the zonal and meridional components. The maximum amplitudes are observed in the months around the equinoxes, from late March to June in the case of the autumnal equinox and from late August to mid-October in the case of the spring equinox. Minimum amplitudes are observed in the months around the solstices. There can also be a strong variation in tidal amplitude with height. In the months around the equinoxes tidal amplitudes increase from < 5 ms$^{-1}$ at heights near 80 km to > 35 ms$^{-1}$ at heights near 100 km. However, in the months around the summer solstice (i.e., December and January) the amplitudes actually show little variation with height and remain at about 10 ms$^{-1}$ at all heights observed.

In the case of the 24-hour tide, Figure 5e and f show that there is rather less variation in amplitude over the course of the year and the semiannual cycle evident for the 12-hour tide is not apparent. There is, however, a tendency for larger amplitudes to be observed in the summer months. For example, the meridional amplitudes at all heights are about 10 - 15 ms$^{-1}$ in January, February and December, but usually < 10 ms$^{-1}$ in the other months. Tidal amplitudes for the 24-hour tide remain < 10 ms$^{-1}$ throughout most of the year. Further, in contrast to the case for the 12-hour tide, the amplitudes of the 24-hour tide generally do not increase appreciably with increasing height.

These results confirm the impression gained from the composite days of Figure 4 that the 12-hour tides reach the largest amplitudes in the dataset and that the 24-hour tides are relatively small in comparison. We will now apply a similar analysis to the outputs from the WACCM and eCMAM models.
Figure 5: Tidal amplitudes of the 12- and 24-hour tides in 2009 for Rothera as a time series at 90 km (where the peak in the meteor distribution is) in the zonal (a) and the meridional (b). Time height contours of the 12-hour tide in (c) and (d) with the 24-hour tide in (e) and (f) for the zonal and meridional, respectively in both cases. Note the tick marks indicate the start of each month.

Figure 6 presents the results of an equivalent analysis to that applied to the radar data in Figure 5, but in this case applied to the WACCM output. Considering Figure 6a and b it is apparent that the amplitude of the 12-hour tide in WACCM at a height of 90 km is rather smaller than that observed by the radar. Further, the distinct quasi-periodic variability in tidal amplitude at time scales of several days observed by the radar is readily apparent in the WACCM results. The 10-day periodicity is also present albeit with smaller variations because of the smaller amplitudes in the 12-hour tide.

In the zonal wind, the running mean on the 24-hour tide is largest and is mostly around 20 ms$^{-1}$ for most of the year increasing at the end of the year. There is a lot of variability within the tide with large excursions from the baseline mean, especially in December where there are changes of around 30 ms$^{-1}$. Comparatively the 12-hour tide is small throughout the year with low variations from the baselines seen with values of around 5 - 10 ms$^{-1}$, much smaller than the 12-hour tide.

Figure 6c and d present time-height contours of the 12-hour tidal amplitudes in WACCM. The figures show there are generally larger amplitudes towards the upper height levels during summer and autumn in both the zonal and meridional components, with amplitudes reaching around 15 ms$^{-1}$. However, if we compare these results with the radar observations of Figure 5 it is notable that i) the strong semi-annual cycle in amplitude evident in the radar observations is not present in the WACCM results and ii) the dramatic increase in amplitude with increasing height evident in the radar observations is also not apparent.

Figure 6e and f present similar time-height contours for the 24-hour tidal amplitudes in WACCM. The figures show there is a generally similar seasonal cycle in the WACCM results to that of the radar observations. However, the
Mesospheric tides above the Antarctic

![WACCM 2009 TIDAL AMPLITUDES](image)

**Figure 6**: WACCM tidal amplitudes of the 12- and 24-hour tides as a time series at 90 km in the zonal (a) and the meridional (b). Time height contours of the 12-hour tide in (c) and (d) with the 24-hour tide in (e) and (f) for the zonal and meridional, respectively in both cases. Note the tick marks indicate the start of each month.

WACCM tides are generally of larger amplitude throughout the year. Typically the WACCM tidal amplitudes are in the range 10 - 20 ms$^{-1}$ compared to the radar observations of 5 - 10 ms$^{-1}$. We will discuss the seasonal variation in more detail later in the paper.

![Figure 7](image)

**Figure 7**: Presents the results of an equivalent analysis to that applied to the radar data in Figure 5, but in this case applied to the eCMAM output. As mentioned in Section 2, only 24-hour tidal fits were applied to eCMAM because of the time resolution of the outputs available from the model. Generally, the tidal amplitudes in eCMAM are 5 - 10 ms$^{-1}$ throughout the year, in very good agreement to the radar observations. As in the radar observations, the largest amplitudes occur in the summer months (January-February and December).
3.4.1. Amplitudes of the 12-hour Tide

To investigate this seasonal variation in more detail, we determined the monthly-mean profiles of amplitude and phase as a function of height for both the zonal and meridional components of the radar observations and the WACCM and eCMAM outputs for the 12- and 24-hour tides (with no 12-hour tide for eCMAM).

Figure 8a and b presents the vertical profile of the amplitude of the 12-hour tide in the zonal and meridional components, respectively. Note that in the figures, the shading surrounding the line representing the radar observations indicates the standard deviation of the sequence of incremented 4-day tidal fits to the data. It therefore indicates the range of variability of the tidal amplitude within a month rather than the error on the mean.

From the figures it can be seen that, generally, the observed amplitudes increase with increasing height. For example, this behaviour is very clear in April, May and September when the amplitudes increase from values of about 5 - 10 m s\(^{-1}\) at heights near 80 km to more than 30 m s\(^{-1}\) at heights near 100 km. However, in the summer months of January and December the amplitudes remain rather more constant and do not vary so much with height. In the summer and autumn months (January to May and December) the variability of the tidal amplitudes remains approximately constant with height. However, in the other months (June to November), the degree of variability increases markedly with height.

Also plotted are the amplitudes predicted by WACCM. These predicted amplitudes are generally in the range 10 - 20 m s\(^{-1}\), except in December when they rise to around 25 m s\(^{-1}\) at the upper heights. In most months, at the lower heights WACCM has similar amplitudes to those observed. Further in January to February and October to December, the WACCM results and the observations both display a gradual increase in amplitude with increasing height. For example, in October both WACCM and the observations suggest a tidal amplitude of \(\sim 8 - 10\) m s\(^{-1}\) at heights near 80 km, both rising to amplitudes of \(\sim 15\) m s\(^{-1}\) at heights near 100 km. In these months, WACCM and the observations generally agree well.

However, in March - May and August - September the observed amplitudes increase notably with height whereas the WACCM results display only very limited increase in amplitude. For example, in May, the observed zonal amplitudes increase from \(\sim 5\) m s\(^{-1}\) at heights near 80 km to more than \(30\) m s\(^{-1}\) at heights near 100 km, while the WACCM amplitudes increase only from \(\sim 10\) m s\(^{-1}\) to \(\sim 13\) m s\(^{-1}\) over this height range.
Mesospheric tides above the Antarctic

Figure 8: 12-hour tide monthly amplitudes as a function of height from Rothera, 2009 calculated using a monthly composite day analysis in the zonal (a) and meridional (b). The blue line represents the meteor radar and the blue shading represents the standard deviation of the values within the month at that height with WACCM plotted in an orange -. line.
3.4.2. Phases and Vertical Wavelengths of the 12-hour Tide

The least square fits which return the amplitude also return the phase, or the hour of first eastward maximum for the zonal and the first northward maximum in the meridional, of the tide. Figure 9a and b presents the corresponding tidal phases to the 12-hour tidal amplitudes shown in Figure 8 for the 12-hour tide above Rothera. Considering the radar observations plotted on the figures, it can be seen that in most months, the 12-hour tide displays fairly uniform phase progression with height. This is especially apparent from June through to September where phase is very well defined with a clear decrease in phase with increasing height, indicative of an upwardly propagating tide. These months with clear phase progression correspond to the months with large 12-hour tidal amplitudes in Figure 4.

Also plotted on the figures is the phase predicted by WACCM. In some of the months there is a good agreement between the gradient of the phases of the observations and the WACCM predictions. For example, this is especially clear in May to August. However, in other months the agreement is less good. For example, the phase gradients are notably different in February, March and September to November. In each of these months the phase gradient in WACCM is smaller than that observed - corresponding to longer vertical wavelengths (see below).

The phases were used to calculate the vertical wavelengths ($\lambda_z$) of the tide over the height range 80 - 100 km for both the radar observations and the WACCM results. Vertical wavelengths were only calculated where there is an approximately continuous phase progression with height. The phase was calculated using a linear fit to the phase data. A straight line was fitted to the vertical profile of phase with the gradient multiplied by the period to return the vertical wavelength. Table 1 presents the vertical wavelengths from the radar observations and for WACCM. For most of the year, the observed vertical wavelengths are about 16 - 45 km. The vertical wavelengths from WACCM are generally equal to or larger than those observed by the radar. In particular, the WACCM vertical wavelengths are notably longer in September, October and November.

<table>
<thead>
<tr>
<th>Month</th>
<th>Meteor Radar $\lambda_z$ (km)</th>
<th>WACCM $\lambda_z$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zonal Meridional</td>
<td>Zonal Meridional</td>
</tr>
<tr>
<td>January</td>
<td>15.6* 19.0</td>
<td>125.3 75.5</td>
</tr>
<tr>
<td>February</td>
<td>22.8* 14.1*</td>
<td>43.5 23.3</td>
</tr>
<tr>
<td>March</td>
<td>X X</td>
<td>54.8 60.4</td>
</tr>
<tr>
<td>April</td>
<td>25.2 15.2</td>
<td>54.3 38.7</td>
</tr>
<tr>
<td>May</td>
<td>27.5 19.6</td>
<td>28.7 37.8</td>
</tr>
<tr>
<td>June</td>
<td>28.9 44.1</td>
<td>41.9 40.1</td>
</tr>
<tr>
<td>July</td>
<td>28.6 29.7</td>
<td>28.1 37.5</td>
</tr>
<tr>
<td>August</td>
<td>39.0 24.7</td>
<td>41.1 37.1</td>
</tr>
<tr>
<td>September</td>
<td>23.9 20.1</td>
<td>44.6 34.6</td>
</tr>
<tr>
<td>October</td>
<td>19.1 16.5</td>
<td>47.7 28.0</td>
</tr>
<tr>
<td>November</td>
<td>21.1 37.0</td>
<td>101.2 53.8</td>
</tr>
<tr>
<td>December</td>
<td>31.3* 16.2*</td>
<td>44.8 33.9</td>
</tr>
</tbody>
</table>

Dempsey et al.: Preprint submitted to Elsevier
Figure 9: Monthly phase of the 12-hour tide as a function of height in local time at Rothera for 2009 in the zonal (a) and meridional (b). The meteor radar observations are plotted in blue with WACCM in orange. It can be seen that in most months, the 12-hour tide displays a fairly uniform phase progression with height.
3.4.3. Amplitudes of the 24-hour Tide

Figure 10a and b present the height profiles of amplitude of the 24-hour tide in the zonal and meridional components, respectively, plotted in the same way as Figure 8 again with the blue shading representing the variability (standard deviation) within the month. It can be seen that the amplitude of the 24-hour tide does not increase with increasing height, in contrast to the 12-hour tide. In fact, in most months the amplitudes are effectively constant across the height range observed with amplitudes typically being in the range 5 - 10 ms$^{-1}$, although in December the amplitudes do reach up to about 20 ms$^{-1}$. In all months, the zonal and meridional amplitudes are very similar.

Also plotted are the predictions of the WACCM and eCMAM models for the 24-hour tide. In the case of WACCM, for the majority of the year the amplitudes do not increase appreciably with height - generally in good agreement with the observations. However, the amplitudes predicted by WACCM are systematically larger than those observed. For example, in July in the observed zonal amplitudes are $\sim 5$ ms$^{-1}$ across the height range, whereas WACCM predicts $\sim 15$ ms$^{-1}$. In agreement with the observations, the zonal and meridional amplitudes are generally similar. In the case of eCMAM, the amplitudes predicted are generally very similar to those observed by the radar, with most months showing agreement to within 5 ms$^{-1}$ at most heights.
Figure 10: 24-hour tide monthly amplitudes as a function of height from Rothera, 2009 calculated from the composite day analysis for the zonal (a) and meridional (b). As before, the blue represents the meteor radar and the blue shading represents the standard deviation of the values within the month. Also plotted is WACCM as a red line and eCMAM as a green line.

(a) 24-hour tide zonal amplitudes for Rothera, 2009.

(b) 24-hour meridional amplitudes for Rothera, 2009.
3.4.4. Phases and Vertical Wavelengths of the 24-hour Tide

Figure 11a and b presents the corresponding tidal phases to the 24-hour tidal amplitudes of Figure 10. The figure presents both the radar observations and the results from WACCM and eCMAM. Considering the radar observations plotted on the figures, it can be seen that in most months, the 24-hour tide displays a smooth phase progression with height - although in June the zonal phases exhibit something of a discontinuity at a height of about 90 km. In most months the phase uniformly decreases with increasing height, indicating an upwardly propagating tide, although the phase gradients are substantially less than the case for the 12-hour tide. We draw attention to the unusual observed phases in the case of December. In this month, the phase gradients of the zonal and meridional components appear to have opposite signs - the phase of the zonal component decreases with increasing height whereas the meridional phase increases with increasing height (this will be discussed in Section 4).

Table 2 presents the vertical wavelengths for each month calculated from the phase gradients for the 24-hour tide from these observations. We see from the Table that the observed wavelengths are generally larger than those of the 12-hour tide and in most months are > 40 km.

Table 2 also presents the vertical wavelengths from both WACCM and eCMAM. In the case of WACCM, the vertical wavelengths predicted are either similar to or larger than those observed by the meteor radar. In some cases the wavelengths are very much larger, for example in January where the observed tides have a vertical wavelength of 48.0 km and WACCM predicts 343.2 km. In the case of eCMAM, absolute values of the vertical wavelengths are similar to those observed, especially in the months of June to August in the zonal. We see a range of vertical wavelengths from ~ 35 - 245 km, in agreement with the radar observations. However, the gradients predicted by eCMAM slope the opposite way to that observed, indicating a downward propagating tide.

Table 2
Table of the mean vertical wavelengths of the 24-hour tide over the height range of 79 - 101 km as observed by the meteor radar at Rothera and the values predicted by WACCM and eCMAM. Positive values indicate descending phase fronts indicative of upwardly propagating waves whereas negative values show the ascending phase fronts indicative of downward propagating waves.

<table>
<thead>
<tr>
<th>Month</th>
<th>Meteor Radar $\lambda_z$ (km)</th>
<th>WACCM $\lambda_z$ (km)</th>
<th>eCMAM $\lambda_z$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zonal</td>
<td>Meridional</td>
<td>Zonal</td>
</tr>
<tr>
<td>January</td>
<td>48.0</td>
<td>120.0</td>
<td>343.2</td>
</tr>
<tr>
<td>February</td>
<td>51.2</td>
<td>160.2</td>
<td>164.4</td>
</tr>
<tr>
<td>March</td>
<td>55.0</td>
<td>92.1</td>
<td>131.4</td>
</tr>
<tr>
<td>April</td>
<td>90.1</td>
<td>102.1</td>
<td>83.5</td>
</tr>
<tr>
<td>May</td>
<td>47.3</td>
<td>44.7</td>
<td>59.2</td>
</tr>
<tr>
<td>June</td>
<td>39.6</td>
<td>46.2</td>
<td>141.4</td>
</tr>
<tr>
<td>July</td>
<td>46.2</td>
<td>22.0</td>
<td>139.3</td>
</tr>
<tr>
<td>August</td>
<td>56.8</td>
<td>48.6</td>
<td>55.3</td>
</tr>
<tr>
<td>September</td>
<td>98.1</td>
<td>173.2</td>
<td>94.4</td>
</tr>
<tr>
<td>October</td>
<td>194.1</td>
<td>115.4</td>
<td>237.4</td>
</tr>
<tr>
<td>November</td>
<td>119.8</td>
<td>79.6</td>
<td>205.9</td>
</tr>
<tr>
<td>December</td>
<td>31.8</td>
<td>-140.7</td>
<td>84.7</td>
</tr>
</tbody>
</table>
Figure 11: Monthly phase of the 24-hour tide as a function of time and height in the zonal (a) and meridional (b). The radar observations are plotted in blue, WACCM in Orange and eCMAM in green.
3.5. Short-Term Variability of Tidal Amplitudes

Next we consider the short-term variability (2 - 24 days) of the 12- and 24-hour tidal amplitudes in both the radar observations and the WACCM output over Rothera. Note that because the output of eCMAM has a time step of 6 hours we will only use it to investigate the short term variability in the simulated wind.

To investigate the short-term variability of tidal amplitudes, a 1-day tidal fit was performed, which was advanced through the data-set in steps of 1 day. This provides us with daily tidal amplitudes for the zonal and meridional components of both the 12- and 24-hour tides. We select data from 90 km altitude for this analysis, due to the large number of meteors near this altitude which provides good confidence in our derived wind and tide measurements. In order to eliminate edge-effects near the start and end of the year, data for 2008 and 2010 are added at the beginning and end of our data for 2009, so that the whole 3-year timeseries is analysed.

To quantify the short-timescale variability of the daily tidal amplitudes, we use a sliding Lomb-Scargle analysis method (Lomb, 1976; Scargle, 1982). The Lomb-Scargle was selected due to its ability to analyse timeseries that contain occasional gaps in data, which makes it ideal for meteor radar timeseries. Other methods, such as the continuous wavelet transform (CWT), do not have this ability. On disadvantage of the Lomb-Scargle is that, in our implementation, discrete (fast) Fourier algorithms are used, which only analyse for periods that are integer fractions of the length of the windowed timeseries. In our analysis however, we overcome this limitation by using a range of window sizes to provide improved spectral resolution, described below.

In our sliding Lomb-Scargle (SLS) analysis method, a sliding time window is stepped through each timeseries of tidal amplitude in increments of one day. For each day, the localised Lomb-Scargle periodogram is computed within the specified time window. In order to analyse at an improved spectral resolution, a range of time window sizes for the Lomb-Scargle from 25 - 35 days is analysed for each day. These spectra were then combined and interpolated in frequency to provide the improved sampling. Note that this approach is different from oversampling a typical Lomb-Scargle spectrum, which does not provide additional information. By using a range of window sizes from 25 - 35 days, we can obtain localised periodograms at a higher spectral resolution. Here, this is particularly important for periods longer than around 10 days. The effective window size for our SLS analysis can be considered approximately 30 days.

Edge effects in the SLS analysis are minimal. Due to the sliding nature of the SLS analysis, periodic signals near the window edge will eventually be in the centre of a later window, where “cone-of-influence” effects are minimal, because the window is stepped along each day. Further, we only consider periods less than 24 days, which is shorter than the shortest window size considered in our SLS analysis (25 days).

This analysis provides the normalised power spectral density (PSD) of periodic variability of the 12- and 24-hour tidal amplitudes throughout 2009 over Rothera from meteor radar observations and WACCM output at 90 km altitude.

3.5.1. Observations of Short Term Tidal Variability

Figure 12 presents the results of this analysis of the tidal amplitudes observed over Rothera by the meteor radar. Figure 12a and b present time series of the daily amplitudes of the 12- and 24-hour tide at 90 km. The figures again reveal dramatic day-to-day variability in the amplitude of both tides. For example, both the 12- and 24-hour tidal amplitudes regularly vary by more than 200% from day to day throughout much of the year. There are also regular episodes where the variability has a quasi-periodic character, for example, in the case of the 12-hour tide, in May there is a distinct modulation of tidal amplitude by approx 15 ms$^{-1}$ with a period near 10 days. Similar episodes are apparent throughout the year and also in the case of the 24-hour tide.

The running Lomb-Scargle periodograms of Figure 12 reveal that the periodic variability generally occurs in “bursts” of a few months duration at most. In the case of the 12-hour tide (Figures 12c and d), during January and February in summer, there is relatively little periodic variation in the tidal amplitude. However, this changes in March where longer period modulations are seen with periods of roughly 12 to 24 days. This longer-period variability persists until the end of November with bursts of modulation taking place at periods ranging from 3 days to more than 15 days.

In the case of the 24-hour tide (Figures 12e and f) in the summer months of January and February, there is distinct variation in the tides of the shorter periods investigated. This may be suggestive of interactions with the quasi 2 day wave (Q2DW). This short period modulation is present through most of the year, albeit with varying strengths. Longer periods are particularly noticeable from August in the zonal and May in the meridional and in each case, persist for around 2 months and show periods of more than 16 days are present in both time series. In August in the zonal component there is also a large burst of 5 day modulation in the tidal amplitudes, however this is not apparent in the meridional component.

In addition to investigating the periods present in the amplitudes of the tides, we can also look at the periods present...
Mesospheric tides above the Antarctic

Figure 12: Observed short-term variability in the tidal amplitudes from Rothera, 2009. The zonal daily tidal amplitudes with a 30 day running mean are shown in (a) with the 12-hour tide in orange and 24-hour tide in blue with (b) showing the same for the meridional. Lomb-Scargle periodograms performed daily using 30 days of tidal amplitudes for the zonal 12-hour tide are shown in (c) and for the meridional 12-hour tide in (d). (e) and (f) show the same as (c) and (d) but for the 24-hour tide.

in the wind time series. Figure 13a and b present time series of MLT daily winds at 90 km above Rothera in both the zonal and meridional components and also presents a 30-day running mean advanced through the data set in steps of 1 day. From the figure it can be seen that in both components there is a clear day-to-day variability present throughout the year. Wind fluctuations can occur of up to about 40 ms\(^{-1}\) over a period of a few days. For example, the zonal winds change from 40 ms\(^{-1}\) to about 5 ms\(^{-1}\) in early September. Similar fluctuations are evident through much of the winter and spring months. There are also smaller fluctuations present around the autumnal equinox (March-April) and the summer solstice (January and December). The fluctuations seen here do not match periods associated with planetary waves.

Figure 13c and d present a running Lomb-Scargle periodogram analysis of these winds in an equivalent analysis to that of Figure 12. Periods of 5 to 10 days tend to be present in the zonal for much of the year except in March to April. Longer periods are also present, particularly in the winter months. Waves of period less than about 5 days tend to occur mostly in months away from the equinoxes. Both components show periods which could be related to planetary waves.
Mesospheric tides above the Antarctic

3.5.2. Short Term Variability in WACCM

The same analysis as that applied to the radar was also applied to the WACCM tidal amplitudes and is presented in Figure 14. Figure 14a and b present time series of the WACCM predicted amplitudes of the 12- and 24-hour tide at 90 km in the zonal and meridional components of the amplitudes, respectively. These figures reveal that there is large day-to-day variability predicted by WACCM in both tides, although somewhat smaller in magnitude than present in the radar observations of Figure 12.

In the case of the 12-hour tide in Figure 14c and d, there is a distinct difference between the summer months (January to February and December) and the remainder of the year. These summer months show variability in the WACCM tidal amplitudes across a range of periods from around 3 days, up to greater than 16 days. For example, December displays variability with large signals at periods of 5 days and January displays strong signals of variability at periods of > 10 days. However, for the remainder of the year, it is notable that there is less variability in either component.

In the case of the 24-hour tide, in Figure 14e and f variability persists for much of the year. Again, the summer months exhibit a larger degree of periodic variability compared to the rest of the year, with large-amplitude signal present at a range of periods in the months of January-February and November-December. In winter, there is also a notable signal present with a period near 16 days.

As with the radar observations, we will now investigate the periodicities present in the WACCM daily winds. Figure 15a and b present time series of the daily winds predicted by WACCM. Both the zonal and meridional winds display variability on the time scales associated with planetary waves. For example, deviations of ~ 40 ms^{-1} are seen

![Figure 13: Short term variability in the daily winds measured above Rothera during 2009. (a) Time series of the daily mean zonal wind, (b) Time series of the daily mean meridional wind. Thin line represents the daily data and bold line represents the 30 day running average of the data in both panels. (c) Lomb-Scargle periodogram of the daily mean zonal wind and (d) Lomb-Scargle periodogram of the daily mean meridional wind.](image-url)
in May in the zonal and similarly in October in the meridional.

Figure 15c and d present the periodograms of these WACCM daily winds, produced using the same method as the radar data. The figures shows a lack of variability at low periods for most of the year in both components. There are stronger features at periods between 5 and 10 days during October to November in both components. Both components also show large powers at periods of 16 days and larger.
3.5.3. Short Term Variability in eCMAM Winds

Although we have not considered the short term variability in eCMAM tidal amplitudes, we can still investigate wind variability. Figure 16a and b present time series of the daily winds predicted by eCMAM. Both the zonal and meridional components display bursts of variability with the largest deviations seen in January and February in the zonal and in November in the meridional. However, the variation in the zonal is not consistent throughout the year with some months displaying limited variation such as April where changes of $> 10 \text{ ms}^{-1}$ are regular. In contrast the meridional displays more consistent variability with regular changes of $\approx 20 \text{ ms}^{-1}$ are seen.

Figure 16c and d present the Lomb-Scargle periodograms of these eCMAM daily winds calculated as before with a 30-day window advanced through the dataset in steps of one day. Again, we see that, again, variability occurs in bursts. These are commonly seen at periods of 5 days and longer in both components, especially clear at $> 10$ days in October to December.
4. Discussion

This paper has presented a study of atmospheric tides measured in the Antarctic mesosphere and lower thermosphere above Rothera in 2009. The seasonal cycle of the 12- and 24-hour tides has been established and the results compared to two models: WACCM and eCMAM.

The hourly winds from Rothera were presented in Figure 2 and revealed a wind field dominated by the 12-hour tide, as seen in the Northern Hemisphere by Wilhelm et al. (2019) at Andenes (69.3°N, 16°E) and by Pancheva et al. (2020) at Tromsø (70°N, 19°E) and Svalbard (78°N, 16°E). Figure 3 showed the monthly-mean winds from observations plus WACCM and eCMAM. The observations showed that there is a clear annual cycle in the observed MLT winds above Rothera with summer months having westward wind below 85 km and winter months showing eastward flow at all heights. The seasonal cycle of the monthly-mean winds also agrees well with Hibbins et al. (2005) although does not match in amplitude. The large difference in amplitudes between the meteor radar and the medium frequency radar are not accounted for in the standard error and therefore standard deviation of the meteor radar tidal amplitudes (standard deviation being the standard error times the square root of the sample size). This may be in part due to the MF vs meteor radar bias, which will be discussed later.

The eastward wintertime flow observed is in contrast to that predicted by both models which both predicted westward wind during winter at all heights. This may be caused by gravity waves in the model only being produced at a surface level, not including any non-primary (or secondary) gravity waves (Vadas et al., 2003; Vadas and Becker, 2018; Becker and Vadas, 2018). Models which include these secondary waves, such as that in Becker and Vadas (2018) are shown to correctly predict a mesospheric wintertime eastward flow. These waves are not generally included in climate
models with gravity wave parameterisations, such as WACCM (Smith, 2012) and eCMAM (McLandress, 2002).

The background wind showing the westward winter zonal winds above 85 km in WACCM and eCMAM suggests: i) that the gravity wave drag in the models in winter is too strong and consequently causes a reversal of the winds from eastward to westward, ii) that these models do not include eastward flow caused by the non-primary gravity waves and iii) the gravity wave drag may also be acting to damp the tide with the wind reversal. These reasons may explain why tidal amplitudes generally do not grow much in winter in WACCM and eCMAM. Heale et al. (2020) suggest that tidal winds act as a filter for secondary waves entering the MLT. Comparatively Fritts et al. (2020) suggest that these secondary waves have influence on the tide and hence could also explain some differences in the tidal amplitudes.

Amplitudes profiles of both the 12-hour tide and the 24-hour tide were plotted in Figure 8 and Figure 10 respectively, including WACCM for the 12- and 24-hour tides and eCMAM for the 24-hour tide. For the 12-hour tide, the observations showed dramatic increase in amplitude with height, reaching amplitudes of 30 ms$^{-1}$ in some cases. In the case of WACCM, the lower heights compared had good agreement, with the values from the model regularly agreeing with the observed values. However, the observed vertical growth with height was not predicted by WACCM. This maybe because of the tuning of WACCM for the summer mesopause resulting in the model not performing well outside of this time period. The upper boundary location of WACCM (about 140 km) may also limit the amplitude and affect the phase structure of the simulated 12-hour tide, which has a long vertical wavelength (Table 1).

For the 24-hour tide, for the majority of the time, the models had the correct vertical structure. eCMAM performed particularly well matching a lot of the observed variation. This may however be a case of small numbers matching small numbers. The phases predicted by eCMAM also indicated downward propagating tides. This decrease of phase with increasing height was also seen by Du et al. (2007). These downward propagating tides in eCMAM could be reflection from the top of the model, however this is unlikely due due to the high top of eCMAM (220 km) meaning waves are unlikely to be reflected in the 79 - 101 km region we are studying. In the case of WACCM, the upper boundary is at 140 km with a substantial increase in wave damping (using a divergence damper with variable magnitude) as the boundary is approached. There is no previous evidence of reflection, especially at the 79 - 101 km region in height we are investigating. Ward et al. (2010) state that there is still work to be done on eCMAM for it to match observations despite it including realistic tidal forcing. The 24-hour tide from WACCM on the other hand is systematically larger than the radar in most months except for the summer months of December and January. The lack of growth in the 24-hour tide may be for a variety of reasons. For instance, the tide we observe is a superposition of many different tidal modes, each with different phase characteristics and each will maximise at varying heights. Combined with some in-situ generation of trapped tidal modes, as well as contributions from wave-tide interactions and other processes, the observed 24-hour tidal component may not change appreciably over the height range observed (Smith, 2012; Chang et al., 2011; Smith, 2003).

We can compare the tidal amplitudes from Rothera to that of a similar polar site. A meteor radar which can provide such a comparison is at Davis (69°S, 78°E) and Conte et al. (2017) measured the amplitude of the 12-hour tide in 2009, allowing for a direct comparison. Davis shows that there is some inter-annual variability in the 12-hour tide. They see a similar cycle in tidal amplitudes as presented in Figure 5 albeit with larger amplitudes. They observe a small increase of amplitude at 85 km of 30 ms$^{-1}$ in February, at Rothera 15 ms$^{-1}$ is observed in the the zonal 12-hour tide amplitude component. However, the overall behaviour is very similar which shows that similar latitudes are affected by comparable tides.

We have seen that both the tidal results from the radar and WACCM showed evidence of short term variability, both in periodic variations and also of episodic nature. In the case of the 12-hour tide, the radar observations show there is little periodic variation in summer, whereas the WACCM results show the largest variation in the summer months. In the case of the 24-hour tide both observations and the WACCM results show similar variation throughout the year, especially clear in the summer months. The short-term variability observed may link to non-linear interactions between the tides and planetary waves. In southern hemisphere summer, the quasi 2 day wave (Q2DW) achieves large amplitudes and may decrease the strength of the tides when present (Palo et al., 1999, 2007; Chang et al., 2011). This may explain why the 12-hour tide above Rothera in summer is diminished. There has been previous work showing evidence of planetary wave-tidal interactions in both the 12- and 24-hour tides (Pogoreltsev et al., 2007).

The 24-hour tide is around its largest value for the year in summer and hence may interact with the Q2DW. This non-linear interaction between the 24-hour tide and the Q2DW may yield resultant waves defined by the sum and difference of the zonal wavenumber and frequencies (Teitelbaum and Vial, 1991; Forbes and Moudden, 2012). Periods of around 3 days seen in Figure 12e and f may be indicative of a tidal-planetary wave interaction. Other planetary waves, such as the 10 day wave, have been linked to short term variability in the migrating 24-hour tide (Guharay et al., 2015).
as well as the 16 day wave (Huang et al., 2013). Although these interactions with planetary waves could account for tidal variability, it does not account for all the variability in the atmosphere, with other mechanisms possibly linking to this such as the variations in background winds (Angelats i Coll and Forbes, 2002) and changes in the sources of tidal sources (Pedatella et al., 2016).

Figure 14 showed WACCM lacked this variability, generally producing short-term variability in the winter months, but failed to generate any of the shorter period variability seen in the radar. Mayr et al. (2005) found that gravity waves are vital for the coupling process and hence, due to the models lacking secondary gravity waves, may provide a reason why the short-term variability predicted by the model does not match the radar observations.

More work is needed to constrain models effectively so they are able to correctly reproduce the observed atmosphere. However, simulations in models such as the Whole Atmosphere Model (WAM) by Akmaev et al. (2008) reveal the presence of tides modulated at planetary wave periods. But Liu (2016) propose that the day-to-day variability found in the MLT is a manifestation of the stochastic whole atmosphere system. This maybe a barrier for models aiming to replicate this unpredictable environment.

Satellite measurements of temperatures by SABER on the TIMED satellite have also been used to investigate MLT tides. SABER views to one side of the orbital track only and to maintain SABER on the satellite’s anti-sunward side, the satellite must thus cycle yaw angle every 60 days. Low and middle latitudes can therefore be observed regardless of yaw angle, but polar latitudes can be observed only in alternate yaw angles with repeated 60-day gaps in the observation. Because of this limitation, SABER has been used to resolve migrating and non-migrating tidal modes and to establish their global structures and seasonal/interannual variability for both the 12-hour and 24-hour tides at latitudes only up to about 50 degrees (e.g., Pancheva et al. (2009); Mukhtarov et al. (2009)). SABER is not generally able to measure tides at polar latitudes.

In contrast, the TIDI instrument on TIMED measures winds to both sides of the orbital track and so can make measurements at polar latitudes, albeit restricted by a need to observe for 60 days in order to determine tidal properties without problems caused by aliasing. Wu et al. (2011) used TIDI measurements of winds in the MLT to investigate the migrating 12-hour tide (W2) and the westward propagating zonal wavenumber 1 non-migrating 12-hour tide (W1). They found higher zonal wavenumbers were not of significant amplitude. Their observations included 2009 and so can be compared to those we report here, although we should note that to measure the tides they had to use a 60-day sliding window and a zonal mean. Making allowance for the inability of the TIDI analysis to capture variability on time scales of less than 60 days, the amplitudes measured by TIDI at a height of 95 km are generally similar to those observed by the radar. In particular, the two episode of large 12-hour tidal amplitudes evident at heights near 95 km in our radar observations of May - June and September – October (Figure 5) correspond well to times of large-amplitude W2 reported by Wu et al., but there is not a clear corresponding W1 feature. This suggests that the 12-hour tide we observe in the radar data during these times is primarily the W2 migrating mode. The study of Wu et al. also reveals a significant degree of interannual variability, an aspect of tidal behaviour that we cannot investigate here because of the single year of data considered.

In January 2009, the Northern Hemisphere experienced a Sudden Stratospheric Warming (SSW). This may have had an effect on the tidal variability we have measured with the meteor radar in the Southern hemisphere. Smith et al. (2007) found that the temporal variability of the 12-hour tide is well correlated with the amplitude of planetary wavenumber 1 indicating inter-hemispheric coupling. Koushik et al. (2020) find that planetary wave enhancements in the MLT are seen during SSW. However, in this paper we are only looking at one years worth of data and so it is difficult to say whether the SSW has increased the 12-hour tides variability in January.

The British Antarctic Survey’s Rothera base, where the meteor radar we have used is located, also has an MF radar that has been used to measure tides in the MLT. Hibbins et al. (2007) considered data recorded from 1997 to 2005 and estimated tidal amplitudes and phases. They report a 12-hour tide maximising in April and September, as is the case using the meteor radar at Rothera, and observe a 24-hour tide with amplitudes of around 8 ms⁻¹ and larger during January and February. A clear discrepancy between Hibbins et al. and the results from the meteor radar is the growth of amplitude with height. There are large increases in amplitude over 80 - 100 km in our results, something missing from the MF measurements which have fairly uniform amplitudes over all heights. Although in a different year and a different latitude, we can see that these results do not match those from Rothera meteor radar. The difference between the results of Hibbins et al. (2007) and those presented in our study may be due to a well-known speed bias between MF and meteor radar in the MLT where MF radars do not accurately represent the atmosphere above 80 km (Hines et al., 1993). This speed bias is demonstrated by Manson et al. (2004). Wilhelm et al. (2017) attribute the differences to two reasons. Firstly that, the measured centre of scatter of the MF beam is not necessarily the centre of the beam...
Mesospheric tides above the Antarctic

volume which, in most cases, weights the measurement to a lower zenith angle and therefore higher altitude. At high altitudes, above 92 km, this becomes important due to the broadening of the beam. Secondly, the scattering process itself leading to large differences between the main lobe of a vertical pointed narrow Doppler beam and the appropriate side lobes resulting in an unreliable radial velocity measurement above 92 km. Therefore MF radars are more suited to measuring the atmosphere at heights less than 80 km and so tidal analysis of the MLT is better suited to the capabilities of meteor radar.

Finally, we note that observations of 12- and 24-hour tides have also been made at Arctic latitudes in the Northern Hemisphere (Mitchell et al., 2002; Pancheva et al., 2020). The Mitchell et al. (2002) study used a meteor radar located at Esrange (68°N, 21°E) in the interval from August 1999 to July 2000. They observed a large 12-hour tide in both components in winter, with monthly mean amplitudes reaching 32 ms⁻¹, very similar to the amplitudes we have observed in winter at Rothera. In addition, the 24-hour tide observed at Esrange also agrees with that seen at Rothera having much smaller amplitudes than the 12-hour tide for the majority of the year, with the largest values seen in the summer. The recent study of Pancheva et al. (2020) included data from two meteor radars recorded over multiple years at Tromsø (70°N, 19°E) and Svalbard (78°N, 16°E). Their study revealed a generally similar seasonal behaviour to that reported here for the Antarctic but also noted unusual behaviour in the phase of the 24-hour tide in which at heights above about 90 km the phase gradients of the zonal and meridional components had opposite signs. This they interpreted as a transition from a trapped 24-hour tidal mode at heights below about 89-91 km transitioning to a vertically-propagating tide above these heights. Similar unusual behaviour is also apparent in our results, but is well defined in the case of December only. The occurrence of this unusual phase behaviour in two independent studies from opposite polar regions strongly suggests it is a persistent feature of tides in the MLT.

5. Conclusion

In this paper we have presented the first climatology of the 12- and 24-hour tides in the Antarctic MLT at heights of 80 to 100 km above Rothera (68°S, 68°W) measured using a meteor radar. We have investigated one complete year of observations from 2009 and used these observations to test two Global Circulation Models, WACCM and eCMAM. We have found that:

1. The observed monthly zonal mean winds display a striking eastward flow in winter that is not reproduced in the models. We propose that this is due to either, i) the models having been tuned to reproduce a realistic summer mesopause and thus being poorly constrained in winter, or ii) the models not including eastward propagating gravity waves that may be generated in situ in the stratosphere/mesosphere by the breaking of primary orographic waves.

2. The dynamics of the mesosphere and lower thermosphere over Rothera are dominated by 12- and 24-hour tides of large amplitude. The 12-hour tide can reach very large daily-mean amplitudes of about 40 ms⁻¹ and monthly-mean amplitudes as large as 30 ms⁻¹.

3. The 12-hour tide maximises around the equinoxes and amplitudes generally increase strongly with height such that the largest amplitudes are observed at heights of 95 - 100 km. The 24-hour tide maximises in the summer with little variation of amplitude with height.

4. The tidal amplitudes observed above 90 km are much larger than those observed by polar MF radars, including one located at the same site. We propose that this is a result of biases in MF radar observations.

5. In the case of the 12-hour tide, WACCM is generally in good agreement at heights below 90 km. However, at the upper heights the striking amplitude maxima observed in the radar data are not reproduced by the model. The vertical wavelengths predicted by WACCM tend to be somewhat larger than observed in most months.

6. In the case of the 24-hour tide, there is generally very good agreement in amplitudes between the observations and eCMAM. In some months eCMAM phases display positive gradients, indicating downward propagating tides. In the case of WACCM, the model amplitudes are systematically larger than observed and the vertical wavelengths are often equal to or larger than observed.

7. The observations reveal a very high degree of day-to-day variability in the amplitude of both the 12- and 24-hour tides - this is the variability identified as “tidal weather”. Much of this variability is quasi-periodic in nature and occurs at periods similar to that of planetary waves, suggesting that the non-linear coupling of tides and planetary waves explains much of this variability. This observed short-term variability is not well captured in WACCM.
The significance of these results is that they reveal the important contribution of the 12- and 24-hour tides to the dynamics of the Antarctic MLT and identify areas where the development of the GCMs should be focused to improve their ability to model a highly variable part of the atmosphere that is critical in the coupling of the lower, middle and upper atmosphere.

Acknowledgements

SMD is supported by a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council (NE/L002434/1) and is thankful for the support and additional training provided. NPH, TMG, CJW and NJM are supported by the UK Natural Environment Research Council (grant nos. NE/R001391/1 and NE/R001235/1).

The CESM project, of which WACCM is a component, is supported primarily by the National Science Foundation. The WACCM results are based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977. Computing and data storage resources, including the Cheyenne supercomputer (doi.org/10.5065/D6RX99HX), were provided by the Computational and Information Systems Laboratory (CISL) at NCAR.

Data Availability


CRedit authorship contribution statement


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Mesospheric tides above the Antarctic


