Tidal signatures in temperatures derived from daylight lidar soundings above Kühlungsborn (54°N, 12°E)
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ABSTRACT
We have developed a new Rayleigh–Mie–Raman (RMR) lidar at the mid-latitude station in Kühlungsborn (54°N, 12°E) for analyzing geophysical phenomena at day and night, e.g., temperature tides and Noctilucent Clouds. For this study we have used about 3100 h of data since April 2011 with additional data from summer 2010. The RMR lidar was in operation day and night in addition to the existing daylight-capable potassium resonance lidar. We show for the first time an overview of the altitude structure and seasonal variation of temperature tides, observed with lidars between 40 and 100 km altitude at a mid-latitude site. There is a gap around 80 km altitude due to a decreasing signal-to-noise ratio during the day. We derive mean tidal amplitudes and phases with 24-, 12-, and 8-h period. In most of the months, the diurnal component dominates the other tidal components with mean amplitudes of 1–2 K in the stratopause region (45–55 km altitude), where it is up to three times higher than semidiurnal and terdiurnal tidal amplitudes. The diurnal tide is damped at ~60 km altitude. In the mid-mesosphere (65–70 km) diurnal, semidiurnal, and terdiurnal tidal components have comparable mean amplitudes of about 1–1.5 K, except around the equinoxes. Around the mesopause the diurnal tide dominates again, with mean amplitudes of about 4 K, but with a large variability. The seasonal variation shows a conspicuous structure below ~65 km altitude with tidal amplitudes small in summer and large around the equinoxes. This structure vanishes above ~65 km. There, the amplitude increases in summer. The measured tidal amplitudes and phases are compared with the MERRA (Modern Era Retrospective analysis for Research and Applications) reanalysis data. Repeated soundings in subsequent years allow to examine the year-to-year variation. The data from March in both 2012 and 2013 show a prominent diurnal tide at around 45 km altitude with amplitudes about three times larger than in the other months. The short-term variability can be examined from continuous lidar operations during clear-sky periods. In a case study we show a large variability of the tidal amplitudes, especially the 8-h variation. This can only be examined due to a good temporal coverage of the lidar data.

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1. Introduction

Solar thermal tides have an enormous impact on dynamic processes of the mesosphere lower thermosphere (MLT) region and also for coupling mechanisms of different atmospheric layers. These atmospheric tides are global-scale waves inducing variations, e.g., in wind and temperature fields with diurnal, semidiurnal, and also higher periodic oscillations. Comparable to other waves, thermal tides propagate upwards with amplitudes growing with altitude. Thermal tides are classified into migrating tides (sun-synchronous and westward propagating) and non-migrating (not sun-synchronous) tides. Solar heating due to the absorption of solar radiation by trace gases (such as water vapor in the troposphere, ozone in the stratosphere and around the mesopause, as well as oxygen above 90 km altitude) is the main excitation mechanism of migrating thermal tides (e.g., Chapman and Lindzen, 1970; Forbes, 1984). Prominent processes for the excitation of non-migrating tides are longitudinal differences in tropospheric latent heat release and radiative heating (e.g., Hagan and Forbes, 2002; Zhang et al., 2010a), and also non-linear interactions between migrating tides and other waves (Oberheide et al., 2002). Theoretical numerical modeling of tides is performed by numerous modelers (e.g., McLandress, 2002; Achatz et al., 2008; Du and Ward, 2010; Zhang et al., 2010b). Tidal information from observations are mainly provided by satellite measurements (e.g., Taliaat and Lieberman, 1999; Oberheide et al., 2006; Huang et al., 2010; Pancheva et al., 2009) and by ground-based measurements, mainly from radars (e.g., Hoffmann et al., 2010; Lu et al., 2011; Jacob, 2012). Early studies focussed on diurnal and semidiurnal tides, while the terdiurnal tidal component attains interest in the literature and is increasingly being

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analyzed, e.g., by the help of ground-based wind radars (e.g., Teitelbaum et al., 1989; Beldon et al., 2006) or by satellite observations (e.g., Pancheva and Smith, 2013).

Only few publications deal with temperature variations derived by ground-based lidar observations. Daytime lidar soundings in the mesosphere are still technically challenging and only performed at a few stations worldwide (e.g., Chen et al., 1996; von Zahn et al., 2000; Chu et al., 2001; Klekociuk et al., 2003; Höfner and Lautenbach, 2009). Thus, observed tides being extracted from lidar temperatures are sparse. There are also few examples during polar nights. For example, Lübben et al. (2011) analyzed thermal tides in the summer mesopause region above Davis (69°S, 78°E). In another case, Fong et al. (2014) presented winter temperature tides between 30 and 110 km at McMurdo (78°S, 167°E).

At mid-latitudes (about 40°N) most observations of tides by daylight temperature lidars are performed between ~80 and 105 km (States and Gardner, 2000b; She et al., 2002; Fricke-Begemann and Höfner, 2005; Yuan et al., 2010). Gille et al. (1991) analyzed tidal components from daylight (nighttime) Rayleigh lidar measurements between 30 and 60 km (80 km) at Biscarrosse, France (44°N, 1°W) for two winter months. Nevertheless, the extraction of tidal waves from lidar temperatures with periods longer than 12-h is rare. Therefore, we have developed a new Rayleigh–Mie–Raman (RMR) lidar at the IAP in Kühlsprungborn (54°N, 12°E) for probing altitudes of ~40–75 km under full daylight conditions and high solar elevation angles of up to 60°. Routine soundings at day and night with the new RMR lidar started in April 2011, plus some initial soundings in summer 2010. As a consequence, about 3100 h of lidar soundings until October 2013 are considered in this publication. Additional soundings are performed with a daylight-capable potassium resonance lidar measuring temperatures between ~80 and 100 km altitude. Thus, a diurnal coverage is achieved over an altitude range of ~40–100 km. Admittedly, there is a gap in our measured data from both lidars at around 80 km due to a low signal-to-noise ratio during the day.

This paper is organized as follows: In Section 2 we describe the new lidar instrument as well as the available lidar data. Section 3 explains the method for deriving tidal parameters from our lidar data. In Section 4 we present the altitude structure of amplitudes and phases for October 2011, and for all available data from 2010 to 2013. We also show short-term variations for October 2011. Furthermore, we present an estimation of the seasonal variation of tidal parameters. The measured amplitudes and phases are compared with MERRA reanalysis data in Section 5. Finally, the main results will be discussed in Section 5 and summarized in Section 6.

2. Description of instruments and data

We have developed a new daylight-capable Rayleigh–Mie–Raman (RMR) lidar (Gerdung et al., 2010) in addition to the existing RMR lidar for nighttime temperature soundings (e.g., Alpers et al., 2004; Raute et al., 2006; Gerdung et al., 2008). An injection-seeded Nd:YAG laser is used as the transmitting power laser in the lidar system. The seeder is locked to an iodine absorption line to achieve high frequency stability needed for the narrow-band optical filters in the detector. A beam widening telescope is used to reduce the laser beam divergence down to about 60 μrad. The beam widening telescope actually enables only one-wavelength operation at 532 nm. The laser beam is transmitted co-axially into the atmosphere. Daylight observations require special filtering techniques that reduce the high background coming from the sun.

Spatial filtering by a small Field of View (FOV) and narrow-band spectral filtering with Fabry–Perot–Etalons (FPE) are applied. The new RMR lidar has a FOV of about 62 μrad compared to the power laser divergence, resulting in a lower background compared to typical (i.e. much larger) FOVs. Due to turbulence in the atmosphere, a fast real-time beam-stabilization has to be used to stabilize the laser beam within the small FOV (Eixmann et al., 2014). We adopted a technique first developed and implemented for the mobile IAP iron lidar (Höfner and Lautenbach, 2009). The remaining jitter of the beam axis is about 5 μrad during the day and less at night.

Spectral filtering for suppression of the solar background is achieved by applying a narrow-band interference filter (IF) and two Fabry–Perot–Etalons. The full-width-half-maximum (FWHM) of the IF is about 130 pm. Both etalons have similar optical properties with a free-spectral-range (FSR) of 120 pm (140 pm) and a FWHM of about 4 pm (4.5 pm) for the first (second) etalon, respectively. The FWHM of the etalon is in the range of the Doppler-broadening of the backscattered Rayleigh signal. Therefore, the transmission (T) of the etalons depends on the actual Doppler-broadening of backscattered light (T > 90% at 100 K and T < 80% at 350 K), i.e. on the atmospheric temperature profile. An altitude dependent transmission correction needs to be applied for absolute temperature calculation. This will be implemented in the near future. In this paper we mainly deal with temperature deviations from the mean profile. It can be shown that the systematic error for temperature deviations by ignoring the correction is about 5% of the temperature variation, i.e. the systematic error is much smaller than the statistical uncertainty. We report in detail about the effect of narrow-band FPE filters on temperature calculation in a prospective publication.

Soundings by RMR lidar are complemented by potassium resonance lidar measurements between 80 and 100 km altitude until September 2012. The potassium lidar uses a narrow-band alexandrite laser for scanning the Doppler broadened atomic potassium-D_{1} line at a wavelength of 770 nm (von Zahn and Höfner, 1998). The potassium lidar achieved daylight capability in 2002 due to the development of a Faraday-Anomalous-Dispersion-Optical-Filter (FADOF) (e.g. Fricke–Begemann et al., 2002; Höfner and Lautenbach, 2009). The temperature profiles with the combined lidars are calculated every 15 min with 2 h integration time and a vertical resolution of 1 km.

Fig. 1 shows a temperature profile from the daylight RMR lidar and the potassium lidar on 30 September 2011. The example shows a nearly continuous profile from ~38 to 96 km altitude. It demonstrates the capability of both lidars to operate at noon and at high solar elevation (~33°, integration time 09:30–11:30 Universal Time, UT). Measured data of both lidars show a strong wave structure with a temperature minimum around 83 km, even though there is still a small gap and no overlap of the profiles. The statistical uncertainty is less than 3 K below 70 km, and less than 10 K below 78 km as well as around 90 km altitude. For the other regions the uncertainty in this particular profile is larger than 10 K (and less than 20 K). In the subsequent tidal analysis, we omit all data with uncertainty larger than 10 K.

In Fig. 2, a time series of temperature variations from multiple daylight measurements (29 September to 3 October, 2011) is shown. Absolute temperatures (Fig. 2a) and temperature deviations from the daily mean (Fig. 2b) are calculated for the upper stratosphere and mesosphere at night and day. The temperature profiles of the RMR lidar reach up to 85 km during the night and up to 75 km during the day. They are complemented by data of the potassium lidar (~80–100 km at night, ~85–95 km at day). As shown in Fig. 2a, absolute temperatures in the mesopause region are as low as 160 K.

Wave structures with different periods are clearly visible in the whole altitude region (Fig. 2b). For this example the uncertainty of the temperatures is limited to 10 K, so the gap around 80 km is
larger than in the example above (Fig. 1). The data for this study are collected from routine soundings between April 2011 and October 2013, along with two months of summer data in 2010. Up to now, a good data coverage has been achieved for spring, summer, and autumn months (see Table 1). During winter, no data are available for November, December and February due to bad weather conditions in these months. For the monthly composites we only used periods of more than 90 h per month for the tidal analysis, except for the data of January and August 2012 (potassium lidar) with a slightly shorter total observation time than 90 h. Each observation lasted for at least 6 h. In total, 3100 h are available to derive tidal signatures from lidar measurements. In Section 3 we demonstrate the data analysis by using an example of October 2011.

3. Method of data analysis – tidal composite analysis of lidar data

It is obvious from Fig. 2 that the temperature variations show a superposition of various gravity and tidal waves. In the context of this paper we name all waves with periods of 24-, 12-, or 8-h as a tide, even if the particular modes of the waves cannot be identified from lidar data. We demonstrate our method of data analysis for October 2011 (i.e., 30 September–24 October). For this month, 182 h (within 9 days) of lidar soundings are used to perform a composite analysis. In this particular case, the lidar was in operation 84% of the time. The available temperature data are averaged for each particular local time and altitude. Non-Local-Solar-Time (non-LST) synchronous waves are largely removed by the averaging process. We subtracted the single daily mean profile to get temperature deviations. Temperature fluctuations of the individual days are averaged depending on LST (Fig. 3b), resulting in a time series with a resolution of 30 min for each altitude bin. Harmonic fits of a superposition of diurnal, semidiurnal, and terdiurnal tidal components are applied to these time series.

Figs. 3c and d show the temperature fluctuations and fits at 50 and 60 km for October 2011. The fitted variations with 24-, 12-, and 8-h period (blue lines) show good agreement to the observed variation (red lines with error bars) at both altitudes. The error bars combine statistical uncertainties, error of measurements, and natural variability. Fig. 3e shows the corresponding fitted temperature deviations for the whole altitude range, which nicely match the observed data.

Table 1

<table>
<thead>
<tr>
<th>Month</th>
<th>Year</th>
<th>Observation time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>2010</td>
<td>268 (259)</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td>176</td>
</tr>
<tr>
<td>April</td>
<td>2011</td>
<td>168 (184)</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td>146 (129)</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td>182 (126)</td>
</tr>
<tr>
<td>January</td>
<td>2012</td>
<td>108 (87)</td>
</tr>
<tr>
<td>March</td>
<td></td>
<td>157</td>
</tr>
<tr>
<td>May</td>
<td></td>
<td>171 (138)</td>
</tr>
<tr>
<td>June</td>
<td></td>
<td>105</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td>188 (108)</td>
</tr>
<tr>
<td>August</td>
<td></td>
<td>162 (89)</td>
</tr>
<tr>
<td>March</td>
<td>2013</td>
<td>130</td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>153</td>
</tr>
<tr>
<td>May</td>
<td></td>
<td>102</td>
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<td>June</td>
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<td>98</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td>115</td>
</tr>
</tbody>
</table>

Fig. 1. Temperature profiles on 30 September, 2011 for daylight RMR (blue) and potassium lidar (red) with an integration time of 2 h. The statistical uncertainty is marked as grey area. Solid lines mark regions with uncertainty less than 10 K, dashed lines mark regions with uncertainty between 10 and 20 K. The latter are ignored in further analysis. The black line is a temperature profile from COSPAR International Reference Atmosphere, CIRA-86, Fleming et al. (1990). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Fig. 2. Series of continuous lidar observations (about 84 h, 29 September–3 October, 2011). Absolute temperatures (a) and temperature deviations from the daily mean (b). The integration time is 2 h with a statistical uncertainty of maximal 10 K. Grey areas mark the nocturnal measurement time for a lidar without daylight capability. Times for this periods are given in Universal Time (UT). Times for tidal analysis given as Local-Solar-Time (LST).
reproduces the original deviation shown in Fig. 3b. Fig. 3f presents the residuals after subtraction of the fitted tidal components. No remaining dominant waves can be seen in the residual data. The results are omitted at around 80 km altitude due to an incomplete diurnal coverage. The method is also described by Lübken et al. (2011), analyzing thermal tides at polar latitudes.

4. Results of tidal analysis

In this section we present monthly mean amplitudes and phases for October 2011 in comparison with parameters obtained during different periods to study the variability of tidal amplitudes. Afterwards, we show mean tidal parameters for individual
months derived from all available data. Furthermore, the good data coverage allows an estimate of the seasonal variation of tidal amplitudes and phases for the selected heights.

Fig. 4 presents monthly mean tidal amplitudes (a) and phases (b) for the 24-, 12-, and 8-h components, calculated from all measurements of October 2011 (i.e. 30 September–24 October). The figure clearly shows a dominant diurnal tidal component at \( \sim 40-60 \) km altitude compared to the semi diurnal and ter diurnal components. Moreover, the 24-h component shows maximal amplitudes near the stratopause at \( \sim 48 \) km (3 K), and decreasing amplitudes above. Semi diurnal amplitudes are up to \( \sim 1.5 \) K, comparable to the ter diurnal amplitudes. The semi diurnal tide decreases between \( \sim 40 \) and \( 55 \) km, whereas the ter diurnal tide increases slightly in this altitude range. At altitudes between \( \sim 60 \) and \( 70 \) km, diurnal amplitudes vary between \( \sim 0.5 \) and \( 1.5 \) K, and are smaller than below. Semi diurnal and also ter diurnal amplitudes generally increase compared to altitudes below, and are both larger than the diurnal amplitudes. The semi diurnal component has two maxima (3 K) around 65 km and 73 km. Above 90 km, amplitudes of the diurnal and semi diurnal tide increase, e.g., up to \( \sim 8 \) K at 93 km (12-h). The ter diurnal component is also larger compared to lower heights, but generally decreases. The data is omitted above \( \sim 95 \) km due to a decreasing signal-to-noise ratio.

Regions of downward phase progression with altitude are found for all tidal components. For the diurnal tide the phase progression is in general downward up to 53 km altitude with a phase speed of about \( \sim 2.6 \) km/h (vertical wavelength of \( \sim 62 \) km) and downward above 90 km altitude (\( \sim 1.3 \) km/h, \( \sim 31 \) km). In between, the phase progression is to some extent disturbed and changes direction. Phase shifts are partly related to small amplitudes in the corresponding altitude range. The reader should note that small amplitudes will cause large uncertainty in the fitting algorithm, thus, making the associated phase values in these cases questionable. Semi diurnal and ter diurnal phases propagate downward over large altitude ranges (40–90 km). Regions of reverse phase progression (upward) are visible at 51–55 km (12-h), and 56–59 km (8-h). The 12-h phase speed is about \( \sim 1.4 \) km/h below 70 km with a corresponding vertical wavelength of \( \sim 17 \) km. Between \( \sim 86 \) and 95 km altitude, the 12-h phase propagates slower with altitude (\( \sim 1.1 \) km/h, vertical wavelength of 13 km) compared to altitudes below. The phase speed of the ter diurnal component is about \( \sim 2.2 \) km/h (vertical wavelength of \( \sim 18 \) km) below 70 km and similar between 85 and 90 km.

There is only limited knowledge about the short-term variability of tidal parameters (days to weeks), because, e.g., satellites typically average 1–2 months of data. To study the variability of tidal amplitudes with time we now separate the data set into two periods, namely 30 September–3 October (interval I), \( \sim 84 \) h of total sounding time) and 14–24 October (interval II, \( \sim 98 \) h of total sounding time), as shown in Fig. 5. The 24 h tidal component dominates at altitudes of 40–60 km. Amplitudes are similar for both time intervals up to \( \sim 50 \) km (Fig. 5a). Above, between 50 and 60 km, amplitudes of the 24-h component decrease, stronger for interval I and less for interval II. Between 60 and 70 km the 24-h amplitudes vary strongly with altitude (0.2–3 K). The 24-h component shows temporal phase shifts above 60 km (not illustrated here). Amplitudes in the separated intervals are larger than in the total interval. This can be explained by considering the phases during both intervals which change by about 9 h at 60 km altitude. This phase shift reduces mean tidal amplitudes compared to the short period data. Above 70 km a detailed analysis is no longer possible due to increasing errors (not shown, cf. Fig. 4), but in general, the 24-h tide seems to be larger in interval II compared to interval I. Amplitudes of the 12-h component show larger variations with time compared to the 24-h component at low altitudes.

Fig. 4. Measured tidal amplitudes (a) and phases (b) for the 24-h (blue), 12-h (red), and 8-h (green) components in October 2011. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Fig. 5. Short-term variability of measured tidal amplitudes and phases for the 24-h (a), 12-h (b), and 8-h (c) single components. The error bars are omitted for clarity, but plotted for the whole period in Fig. 4.
Between 62 and 65 km altitude, the amplitudes are similar in both intervals. Again, as found for the 24-h component, the 12-h component shows temporal phase shifts above 65 km (not illustrated here). Amplitudes in the separated intervals are larger than the total interval (phase shift during both intervals by about 4 h at 70 km altitude). This phase shift reduces mean tidal amplitudes compared to the short period data. Similar to the 12-h tide, the 8-h tide also shows a larger variation with time compared to the 24-h component in the lowest altitude range (40–50 km). In interval I the amplitudes are higher on average for the terdiurnal component compared to the amplitudes in interval II (~50–55 km, 60–75 km, and partly above 85 km altitude, Fig. 5c). Terdiurnal tidal amplitudes are enhanced in interval I (up to 2 K at 53 km) and reduced in interval II (~0.5 K). Above 60 km altitude, terdiurnal amplitudes increase in both periods with largest amplitudes in interval I. Obviously, the terdiurnal component is more prominent at the beginning of the period and vanishes at the end of the month. A general behavior concerning the different altitude ranges can be seen: the diurnal (semidiurnal) tidal component dominates at altitudes between 40 and 60 km (above 60–75 km). The 8-h component typically has

![Fig. 6. Altitudinal variation of monthly mean tidal amplitudes, 24-h (blue), 12-h (red), and 8-h (green). The particular years and observation hours are listed in Table 1. Error bars are mean values of the single fitted monthly uncertainties from 2010 to 2013. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)](image-url)
the smallest amplitudes, but gets important at some altitudes and intervals, e.g., in the first interval at 50–55 km and 60–75 km.

Beside these case studies on selected short intervals, our lidar data allow to examine the height variation of tidal parameters as a function of season. In the following, we describe monthly amplitudes and phases. Fig. 6 shows monthly mean amplitudes for all available data since April 2011 (plus some additional data from summer 2010). The weather conditions allow soundings mostly in spring, summer, and autumn. In general, below ~55 km altitude most months show higher amplitudes for the diurnal (~1–2 K) than for the semidiurnal (~0.5–1 K) and the terdiurnal (~0.5 K) component. March (~4.5 K) and October (~2.5 K) clearly show higher diurnal amplitudes than the other months at these altitudes. For the semidiurnal component, lowest amplitudes are observed in June (~0.5 K), whilst they are about three times higher in March/April and also in September/October. Amplitudes of the terdiurnal component are also low in summer (June, less than 0.2 K), and larger in spring (~0.5 K) and autumn (~1 K). Up to now, tidal amplitudes for winter can only be calculated for January 2012. The typical feature of a dominating diurnal tide at lower
altitudes (below ∼60 km) is not observed in January 2012. In this month, semidiurnal (diurnal) amplitudes are nearly constant (∼1 K) up to 50 km (60 km), terdiurnal amplitudes are vanishing at 45 km, but increase above. A pronounced maximum of the semidiurnal component, which does not appear in any other month, is found in January 2012 at ∼55 km altitude (∼4 K amplitude). The data from January may have been influenced by Sudden Stratospheric Warming (SSW) events, occurring in the measurement period of January 2012. In general, above 55 km and up to 65 km altitude, amplitudes of the diurnal component decrease in most of the months, showing lowest amplitudes in the late summer (July/August, ∼0.5 K), and maxima in January (∼5 K) and April (∼2.5 K). The maxima in autumn are less pronounced. Amplitudes of the semidiurnal tide generally increase with height, showing also a pronounced summer minimum with lowest amplitudes in the late summer (July/August, ∼0.5 K), and maxima in March/April, and September/October (up to 3 K). Terdiurnal amplitudes increase less with height, also revealing a minimum in summer (June–August), and maxima in autumn (up to 1 K). At these altitudes (55–65 km) January amplitudes show a stronger increase compared to other months as seen especially for the 24- and 8-h components (24-h maximum: ∼5 K, 8-h maximum: ∼4 K). Between 65 and 70 km altitude, amplitudes of all components typically increase again. Above 80 km (∼85–90 km), amplitudes of all components decrease in most cases, whereas above ∼90 km, amplitudes tend to increase, again. Error bars tend to be larger at these upper heights.

Fig. 7 shows the altitudinal variation of monthly mean phases for all available data. At low altitudes (∼40–60 km) the phase progression of the diurnal component is typically downward in all months. Above ∼60 km, there is a change of phase progression from downward to upward propagation in all months, but altitude

![Figure 7](image_url)
and strength of the phase shift vary between the months. The phase shift occurs in January at ∼55 km, between April and August and also in October at ∼65–70 km, and in March and September at ∼60 km. At altitudes above 85 km, phases are nearly constant in January, April, May, and August, and downward in June, July and to some extent in October. The semidiurnal tide shows a downward phase progression for all months at altitudes between ∼40 and 65 km, except for January where the downward phase progression is only up to 55 km. In some months the phase gradient changes above, showing, e.g., upward progression in January, April and June.

Between 85 and 95 km altitude the phase progression of the 12-h component is typically downward or nearly constant (June and July). In comparison to the semidiurnal component, the phase propagation of the terdiurnal component is more disturbed, partly due to the lower amplitudes of the terdiurnal component. This results in a larger uncertainty for the phase. At altitudes below ∼75 km, phases are nearly constant (March until June) or downward progressing (January, July until October). Between 85 and 95 km altitude, phases are roughly constant in January, April, and October, whilst they propagate downward in May until August.

Beside this height variation of tidal amplitudes and phases, Figs. 6 and 7 already show the seasonal variation of tides. This can be seen more clearly in Figs. 8 and 9. Different altitude ranges between 45 and 90 km are presented (mean values across 5 km vertical range). As already seen in Figs. 6 and 7, in the stratopause

![Fig. 9](image_url). Seasonal variation of monthly tidal phases for the 24-h (blue), 12-h (red), and 8-h (green) tidal components provided from RMR (a–e) and potassium (f) lidar. Monthly mean values from 2010 to 2013 are calculated for all data listed in Table 1. Error bars are mean values of the fitted monthly uncertainties from 2010 to 2013. At some altitudes data is partly missing. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)
The year-to-year persistency of our main results also implies that of tidal amplitudes and phases is beyond the scope of this paper. However, a detailed study of the year-to-year variability and 2013 is also observed in other months, although less pronounced. At some altitudes the data are in some extend divided into three altitude ranges (a) 44–55 km, (b) 51–57 km, and (c) 57–65 km. In general, the MERRA data show a dominating diurnal tide at altitudes below 60 km. The amplitudes are up to ∼2.2 K for the 24-h component, ∼0.6 K for the 12-h component, and small (∼0.3 K) for the 8-h component. Mean values of tidal amplitudes and also the phase progression agree roughly with our lidar observations. The diurnal variation is smaller than in our data, potentially due to the lower temporal resolution of MERRA. The monthly mean composites of MERRA do not reproduce the seasonal variation with smallest amplitudes in summer as found in our data. As seen in the lidar data the diurnal tide in MERRA typically decreases with altitude. The 12-h and 8-h components are roughly constant, i.e., do not show a significant increase with altitude, as observed by lidar especially at equinox.

Fig. 12 shows an altitude profile (October 2011) of MERRA amplitudes and phases for the 24-, 12-, and 8-h components between 40 and 65 km. In general, the height structure is similar to the lidar data (Fig. 4). The diurnal variation dominates the semi-diurnal and terdiurnal variation. As mentioned before, the largest amplitudes (up to ∼2.5 K) for the diurnal tide are observed at around 50 km. In agreement with the lidar data from October 2011 (Fig. 4), the tidal phases from MERRA show a downward progression for all components.

Overall for this time period between 2011 and 2013, the MERRA data do not show the general increase of amplitudes around equinoxes in the monthly mean composite and underestimates the terdiurnal tide, which is seen in our lidar data. Albeit, the dominating diurnal tide as well as the phase behavior is in agreement with our data.

5. Discussion

Temperature fluctuations can be measured by lidars with a high temporal and vertical resolution. Our new, daylight-independent lidar data set covering ∼3100 h gives an insight into the local tidal structure between 40 and 100 km altitude at Kühlungsborn (54°N, 12°E). Nevertheless, we cannot distinguish between migrating and non-migrating tides as well as local sun-synchronous waves in lidar data from a single location. In contrast, space-borne instruments like satellites provide global structures with a limited local time coverage. However, satellite’s tidal measurements need significant amount of sampling time to cover 24-h variations at one location and, thus, have great difficulties conducting tidal variability study. Thus, a combination of both, satellites and ground based techniques are desirable for analyzing tidal signatures. Ward et al. (2010) show good agreement between satellite and ground based tidal wind signatures in the CAWSES (Climate and Weather of the Sun-Earth System) tidal campaign. A comparison of our extensive temperature data set with other parameters (e.g., wind data) and also with satellite data is planned for the future.

For a direct comparison of our measurements with an independent data set we calculated mean amplitudes and phases from Modern Era Retrospective Analysis for Research and Applications (MERRA), cf. Rienecker et al. (2011). The MERRA data set delivers an un-interrupted three-hourly data set each day (at 00:00 UT, 03:00 UT, etc.) and is, in contrast to the lidar, not limited to clear-sky conditions. In this version, the horizontal grid resolution is 1.25° × 1.25° with a number of 42 pressure levels and a top level pressure of 0.1 hPa (∼65 km). See http://gmao.gsfc.nasa.gov/research/merra/intro.php for a description of the MERRA data and method. The altitudes are given in pressure units for MERRA. Thus, for a comparison with the lidar data, altitudes are converted in geometric altitudes via the approximated formula: \( Z = −H \ln(P/P_0) \), with the scale height \( H = 7 \) km, pressure \( P \), and reference pressure \( P_0 = 1013 \) hPa. We use the same months considered for the lidar observations, see Fig. 11. The MERRA data are divided into three altitude ranges (a) 44–51 km, (b) 51–57 km, and (c) 57–65 km. In general, the MERRA data show a dominating diurnal tide at altitudes below 60 km. The amplitudes are up to ∼2.2 K for the 24-h component, ∼0.6 K for the 12-h component, and small (∼0.3 K) for the 8-h component. Mean values of tidal amplitudes and also the phase progression agree roughly with our lidar observations. The diurnal variation is smaller than in our data, potentially due to the lower temporal resolution of MERRA. The monthly mean composites of MERRA do not reproduce the seasonal variation with smallest amplitudes in summer as found in our data. As seen in the lidar data the diurnal tide in MERRA typically decreases with altitude. The 12-h and 8-h components are roughly constant, i.e., do not show a significant increase with altitude, as observed by lidar especially at equinox.
At mid-latitudes, diurnal, semidiurnal, and terdiurnal tides have been observed before in wind data (e.g., Hoffmann et al., 2010; Lu et al., 2011) and in temperature data (e.g., States and...
Gardner, 2000b) of the mesosphere and lower thermosphere. Most of these data sets cover only a part of the region described here, or do not consider all tidal components. Precise temperature soundings in the mesosphere and lower thermosphere are rare, as they require regular daytime lidar soundings. They are extremely challenging and only performed at few stations. Most of the information derived from lidar temperatures are subject to the MLT region (e.g., Fricke-Begemann and Höfler, 2005; Yuan et al., 2010).

Fricke-Begemann and Höfler (2005) presented the 24-h, 12-h, and 8-h tidal wave perturbations in temperatures around the mesopause region (80–105 km) at two stations for one month each (Tenerife, 28′N, November 2000 and Kühlingborn, 54′N, February 2003). In this case study, Fricke-Begemann and Höfler (2005) found that the amplitude of the diurnal tide above Kühlingborn is in most altitudes less than half of the semidiurnal amplitude in winter. We have used the same potassium lidar for the mesopause region as Fricke-Begemann and Höfler (2005) have before, but we have widely extended the data base. States and Gardner (2000b) show the seasonal variation of tides observed by a sodium lidar from February 1996 to January 1998 at another mid-latitude station, Urbana, Illinois (40′N, 88′W). The seasonal variation of the tides is similar in spring, summer, and autumn. The 24-h variation is reduced in winter as also reported by Fricke-Begemann and Höfler (2005) and seen in our data set. Yuan et al. (2010) presented a study of diurnal tidal perturbations in temperatures by a sodium lidar (5000 h and TIMED/SABER observations above Fort Collins (41′N, 105′W). In contrast to States and Gardner (2000b), the tidal amplitudes show an annual variation with a maximum in February.

As mentioned above, Fricke-Begemann and Höfler (2005) found a lower diurnal than semidiurnal tide in winter, as well seen in our new lidar data (January). Furthermore, Yuan et al. (2010) reported a summer minimum (2–3 K), which is also seen in our lidar data. They found propagating diurnal tides observed with the lidar near equinox, and trapped modes during solstice. The SABER data in this study show maxima (6–7 K) in spring (March) and autumn (September), and minima in summer and winter (around solstices) as known from classical theory (Forbes, 1982a). As mentioned above, we found a similar seasonal behavior with maxima in April (14 K) and late summer (August, 6.5 K) in the new lidar data. We also see trapped modes in winter (January) with a maximum near 24 LST. The seasonal variation in the MLT region is mainly controlled by the combination of zonal mean winds and solar heating (McLandress, 2002). Hagan and Roble (2001) reported that the differences in phases between the infrared and ultraviolet forcing could have an impact on the seasonal variation of the tidal amplitudes. Furthermore, nonlinear interactions between the migrating diurnal tide and stationary planetary waves (SPW1) can produce trapped diurnal tidal modes. The maximum of SPW1 is found in winter and early spring in the northern hemisphere at middle latitudes, potentially initiating the large diurnal amplitudes in the MLT region. Forbes and Hagan (1988) presented differences in the diurnal tide propagation between solstice and equinox. Large atmospheric dissipation effects on the diurnal tide propagation during solstice could excite more evanescent modes due to mode coupling. Here, the dominant Hough mode (1, 1) couples into the first symmetric and asymmetric evanescent Hough modes (1, −2) and (1, −1). Thus the vertical wavelength increases (Yuan et al., 2010). This is also seen in our MLT data at winter solstice.

The semidiurnal tidal phase during summer near Fort Collins shows large vertical wavelengths in the mesopause region (Yuan et al., 2008), similar to our observations. During January and October we observe much shorter vertical wavelengths of the semidiurnal tide, which is also reported by Fricke-Begemann and Höfler (2005) for an earlier Kühlingborn data set, but not, e.g., by Yuan et al. (2008). This indicates that above our site the higher-order Hough modes (e.g., H2.10–H2.17) play a larger role compared to Fort Collins.

Very few studies cover the height range below 80 km. Gille et al. (1991) analyzed tidal components from Rayleigh lidar measurements between 30 and 80 km at Biscarrosse, France (44′N, 1′W) for winter (November 1988 and January 1989). For daylight conditions their lidar only covers heights below 60 km. Similar to our observations, they found constant amplitudes between 35 and 60 km (2–3 K) for the diurnal variation, but twice as large as in our data set. Vice versa, the semidiurnal variation has been found smaller in the Biscarrosse data (~2.5 K). The January tidal amplitudes in our data may have been influenced by sudden stratospheric warmings (SSWs) occurring in 2012. This result is consistent with WACCM (Whole Atmosphere Community Climate Model) simulations in the mesosphere and lower thermosphere region. Tidal amplitudes of the 12-h migrating solar tide are enhanced during SSWs due to changes in ozone forcing and nonlinear planetary wave interaction (Pedatella et al., 2012).

Dudhia et al. (1993) reported a local maximum of ~3 K (at 50 km) observed for the 24-h tide at mid-latitudes. They analyzed data from Improved Stratospheric And Mesospheric Sounder (ISAMS) on Upper Atmosphere Research Satellite (UARS) between 20 and 80 km in a winter period (December 5, 1991–January 13, 1992). Again, the amplitudes of diurnal variation in the stratosphere region are about twice as large as in our wintertime data. But also ISAMS data show a dominating semidiurnal tide, in good agreement to our observations, potentially again reflecting the influence of SSW.

Sakazaki et al. (2012) reported diurnal tides derived from SABER and MERRA reanalysis data. At mid-latitudes, double-maxima with 2–3 K in the upper stratosphere (near 50 km) occur in January. For the diurnal tide, amplitude maxima are found near the stratopause in all months (January, April, July, and October), as we see in our lidar data. A constant phase is obvious in this region at ~18 LT throughout the year, in good agreement with our results from lidar and MERRA data.

In most months, our lidar data set shows diurnal tides dominating up to ~60 km. But above, amplitudes of the diurnal tide decrease, perhaps due to the fact that the tides are trapped. Trapped tides are predicted poleward of 30° latitude and receive the strongest excitation by absorption of ozone at ~45 km altitude (e.g.,). The semidiurnal tide dominates compared to the diurnal tide and partly shows an exponential growth with height, e.g., in October. A vertical wavelength of about 62 km is derived for the diurnal component from phase progression of about ~2.6 km/h (Fig. 5). This vertical wavelength indicates negative Hough modes (only existing for diurnal tides) and is in agreement with theoretical expectations (e.g., Forbes and Garrett, 1978). Our observations are consistent with model results from Lindzen (1990), showing that most of the diurnal forcing goes into these negative, non-propagating modes.

Mukhtarov et al. (2009) reported the global (50°S–50°N) structure, seasonal, and inter-annual variability of the migrating diurnal tide derived from SABER/TIMED temperature measurements between 20 and 120 km (January 2002–December 2007). As discussed above, they also reported that below 70 km height the first symmetric trapped (1, −2) mode is dominating and amplifies around 50 km. Above this height mainly the symmetric propagating (1, 1) mode exists, as the trapped tidal mode (1, −2) decays beyond this altitude. The diurnal phase is constant during the considered six years and is in agreement with our data close to 16 LT. At mid-latitudes, diurnal amplitudes from SABER are between 4.5 and 5.5 K (near 40°). In the SABER data, the seasonal variation is dominated by a main annual variation (maximum
During summer) and a secondary semi-annual variation with equinoctial maxima. Our lidar data do not show a pronounced annual variation, but clearly a semi-annual variation. We have no reasonable explanation regarding the missing annual variation in our data at these altitudes. Perhaps this is because our lidar observations are performed at higher mid-latitudes (54°N). SABER samples up to maximal 50°N. Furthermore, only local variations can be derived from lidar measurements, but not the different modes of the tide. At higher altitudes (90 km) the semi-annual variability with maxima during equinoxes dominates, similar to our observations.

There are few publications dealing with the terdiurnal tidal component compared to the diurnal and semi-diurnal tidal component. Direct solar heating of the lower and also the middle atmosphere is mentioned as the source for the terdiurnal tide (Chapman and Lindzen, 1970). Further processes are described by Teitelbaum et al. (1989) like a non-linear interaction between the 24-h and 12-h tidal components, or an interaction between the 24-h component and gravity waves, or a combination of more than one mechanism. For example, Pancheva and Smith (2013) found a clear seasonal variability of the terdiurnal tide at mid-latitudes with maxima at equinoxes and winter from 8 years of SABER data (2002–2009). Our observation of the seasonal variation of the terdiurnal temperature tide also shows a maximum at equinoxes (esp. autumn). The observation is in general agreement with wind data from mid-latitudes. Similar to us, Beldon et al. (2006) as well as Smith (2000) observed largest amplitudes of the terdiurnal tide in autumn or around equinoxes, using radar or UARS satellite data, respectively.

6. Summary and conclusions

We have reported a first data set of temporal variations (24-, 12-, and 8-h periods) in temperatures from daylight lidar observations between 40 and 100 km. In this study local tides are analyzed using data between 2010 and 2013 at IAP in Kühlungsborn (54°N, 12°E). Soundings with the new daylight-capable Rayleigh–Mie–Raman lidar reach up to approximately 75 km during the day and up to 85 km during the night, complemented by a potassium resonance lidar above 80 km. Harmonic fits including diurnal and higher tidal components cover most of the observed total variation. The three tidal components (24-, 12-, and 8-h) are present during most months.

In general, the altitudinal variation shows a dominating diurnal tide in the stratosphere region (~1–2 K at 45–55 km). Above 55–60 km the diurnal tide is more or less damped. At ~65–70 km all tidal components have comparable amplitudes (~1–1.5 K). Larger mean amplitudes (~4 K for the dominating diurnal tide) as well as a greater variability are seen around 90 km.

Due to the good temporal coverage, continuous lidar soundings enable studying the short-term variability of the different tidal components. Short period tides (i.e., the 8- and 12-h) in October 2011 show differences (greater amplitudes) compared to the mean state. This is similar to the month-to-month variation, being as well greater for the 8- and 12-h than for the 24-h variation. Obviously, intermittent sources and propagation conditions play a larger role for the semi-diurnal and terdiurnal tide compared to the diurnal tide.

The seasonal variation of the diurnal and semi-diurnal (terdiurnal) tidal amplitudes shows maxima in spring and autumn (autumn) up to ~65 km. This is in agreement with theoretical expectations, mentioning direct heating by solar light absorption by ozone and water vapor. Equinox conditions create the best source for a semi-diurnal variation. This is shown by the roughly semi-annual variation of the 12-h component already in the stratosphere. Wind conditions around the stratosphere favor the propagation of the semi-diurnal tide in spring and autumn, while amplitudes remain constant in summer, indicating at least partial wave dumping. In the upper mesosphere/lower thermosphere (85–90 km), diurnal amplitudes increase again. A high seasonal variability of diurnal and terdiurnal amplitudes is obvious in the upper mesosphere indicating the relevance of (time-dependent) wind filtering for the propagation of tidal waves from the stratosphere to the mesopause region. Unfortunately, a detailed seasonal variation for this altitude region cannot be described due to the limited data set.

In most months upward propagating tides are found high up to the lower thermosphere. For October 2011, the diurnal component shows a downward phase progression with amplitude (~55 km) of about ~2.6 km/h, corresponding to a vertical wavelength of 62 km. In theoretical expectations this vertical wavelength indicates negative Hough modes. Semi-diurnal and terdiurnal phase progression is roughly downward over the whole altitude range, 40–90 km (12-h: ~1.4 km/h, 17 km, and 8-h: ~2.2 km/h, 18 km). In the upper mesosphere the 12-h phase progression is slightly slower (~1.1 km/h, 13 km) compared to lower altitudes.

The comparatively large amplitude of the semi-diurnal tide in the January stratopause region appears due to the influence of SSW. As described in literature, the enhanced amplitudes are maybe due to changes in ozone forcing and non-linear planetary wave interactions.

MERRA reproduces our observations of mean tidal amplitudes and phases below ~60 km altitude. Nevertheless, the seasonal variation is damped compared to our results in these two and a half years of data. The terdiurnal variation may be underestimated due to the limited temporal resolution of the MERRA data set.

The seasonal and altitudinal variation of tidal sources and propagation conditions cannot only be revealed by temperature data. In the future, the seasonal variation and short term variability should be further analyzed by means of additional data sets and the continuation of lidar studies.

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