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Meteor radar quasi two-day wave observations over 10 years at Collm (51.3° N, 13.0° E)

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Abstract

The quasi two-day wave (QTDW) at 82–97 km altitude over Collm (51° N, 13° E) has been observed using a VHF meteor radar. The long-term mean amplitudes calculated using data between September 2004 and August 2014 show a strong summer maximum and a much weaker winter maximum. In summer, the meridional amplitude is slightly larger than the zonal one with about 15 m s^{-1} at 91 km height. Phase differences are slightly greater than 90° on an average. The periods of the summer QTDW vary between 43 and 52 H during strong bursts, while in winter the periods tend to be more diffuse. On an average, the summer QTDW is amplified after a maximum of zonal wind shear which is connected with the summer mesospheric jet and there is a possible correlation of the summer mean amplitudes with the backgound wind shear. QTDW amplitudes exhibit considerable inter-annual variability, however, a clear relation between the 11 year solar cycle and the QTDW is not found.

1 Introduction

The quasi two-day wave (QTDW) is one of the most striking dynamical features in the mesosphere and lower thermosphere. The QTDW was first reported by Muller (1972) using a meteor wind radar at Sheffield, UK. He found significant oscillations with periods near 51 h from UK radar data. Even earlier, QTDWs have been discovered over Mogadishu (Babadshanov et al., 1973) near the equator. The QTDW at mid-latitudes is characterized by a clear maximum in summer, with one or several bursts of a duration of a few weeks each. At high latitudes the wave shows a different behavior compared to mid-latitudes, e.g. with maxima during winter (Muller and Nelson, 1978; Nozawa et al., 2003). The QTDW has been frequently observed by ground based (e.g., Muller, 1972; Babadshanov et al., 1973; Plumb et al., 1987; Jacobi et al., 1997; Gurubaran et al., 2001) and satellite instruments (Wu et al., 1996; Tunbridge et al., 2011). Additionally,

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several numerical studies simulated possible excitation processes (Salby, 1981a, b; Plumb, 1983; Palo et al., 1999; Salby and Callaghan, 2001).

Regarding possible forcing mechanisms, Salby (1981a, b) suggested the QTDW to be a manifestation of a Rossby gravity normal mode in an isothermal windless atmosphere with wave number 3, however, this mechanism could not explain its burst-like behavior. Applying a one-dimensional stability analysis Plumb (1983) introduced baroclinic instability as an excitation mechanism. Pfister (1985) supported this theory by using a two-dimensional quasi-geostrophic model and found a QTDW with wave numbers 2–4 and maxima at middle and high latitudes. However, this result did not resemble all the characteristics of the observed wave. Hence, Salby and Callaghan (2001) combined both mechanisms in numerical experiments and found a QTDW excitation in the winter hemisphere by planetary wave activity. Crossing the equator to the summer hemisphere the QTDW is then enhanced by baroclinic instability connected with the easterly mesospheric wind jet (Wu et al., 1996).

A hemispheric asymmetry has been observed (e.g., Tsuda et al., 1988; Tunbridge et al., 2011) with stronger amplitudes in the Southern Hemisphere (SH) compared to Northern Hemisphere (NH). The meridional component tends to be slightly larger than the zonal one at mid-latitudes (Pancheva et al., 2004) or of similar magnitude (Jacobi et al., 2001). The period of approximately 2 days varies between 43–56 h in the NH (Pancheva et al., 2004; Huang et al., 2013a). Generally, periods can be divided into three groups as suggested by Malinga and Ruohoniemi (2007), see also Pancheva et al. (2004) and Tunbridge et al. (2011). The dominating one has periods close to 48 h with wave numbers 2 and 3. The second group has much shorter periods of about 42–43 h. Different wave numbers are reported such as 2 and 3 or 4. The last group covers periods longer than 48 h and peaks at 52 h with wave numbers 2 and 3. In the SH these three groups could not be observed and periods are close to 48 h with wave number 3 (Wu et al., 1996; Walterscheid et al., 2015). Craig and Elford (1981) explored phase locking relative to the sun and suggested nonlinear interactions with diurnal tides. This is also supported by recent studies (e.g., Huang et al., 2013a; Moudden and Forbes,

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2014; Walterscheid et al., 2015). A possible correlation of QTDW amplitudes with the 11 year solar cycle has been found by Jacobi et al. (1997), who explained this finding by a stronger mesospheric wind shear during solar maximum.

In the following we present analyses of the QTDW from a meteor radar (MR) at Collm (51° N, 13° E) which has been started in 2004. Earlier, the low-frequency (LF) spaced receiver method has been applied at Collm since the late 1950 s until 2007. This was based on the reflection of commercial LF radio waves in the lower ionospheric E region. This led to regular daily gaps due to increased absorption during daylight hours, especially long in summer. These measurements had been used earlier to obtain a QTDW climatology over Collm (Jacobi et al., 1997). However, the limitations of the LF method may give rise to potential artifacts, namely uncertainties of the amplitude, and possible effects on the analyzed phases. Therefore, here the MR winds are analyzed and can be used to evaluate the earlier results. Collm MR wind data from 2004 to 2013 have already been analyzed with respect to the climatology of a 2 day oscillation by Lilienthal and Jacobi (2014), but their analyses based on a fixed period of 48 h. This may lead to different amplitudes and phases. In the present study, the true periods of the QTDW over Collm are calculated in order to improve their results. Further information about the mid-latitude QTDW can be provided with greater accuracy than the earlier LF measurements. Background shear obtained from the prevailing winds observed by the radar is used as a proxy for baroclinic instability.

2 Measurements and data analysis

A SKiYMET VHF MR is operated at Collm Observatory since late summer 2004 to measure mesopause region winds, replacing the earlier LF drift measurements (e.g., Jacobi et al., 1997). The MR operates at 36.2 MHz and has a pulse repetition frequency of 2144 Hz which is effectively reduced to 536 Hz due to a 4-point coherent integration. The power is 6 kW. The transmitting antenna is a 3-element Yagi with a sampling resolution of 1.87 ms and an angular and range resolution of about 2° and 2 km, respec-

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tively. The receiving interferometer consists of five 2-element Yagi antennas arranged as an asymmetric cross. This allows to calculate azimuth and elevation angle from phase comparisons of the individual receiver antenna pairs. Together with range measurements the meteor trail position is detected. The radar uses the Doppler shift of the reflected VHF radio wave from ionized meteor trails in order to measure the radial velocity along the line of sight of the radio wave. The radar and data collection procedure is described by Hocking et al. (2001).

The meteor trail reflection heights vary between 75 and 110 km with a maximum around 90 km (e.g., Stober et al., 2008). To analyse the wind field, the received meteors and corresponding radial winds are binned in six height gates centred at 82, 85, 88, 91 and 98 km. However, Jacobi (2012) showed that, owing to the vertical distribution of meteor count rates, nominal and mean heights are not necessarily the same. The uppermost height gate with a nominal height of 98 km refers to a mean height of about 97 km. The radar measurements deliver half-hourly mean horizontal wind values that are calculated by a least squares fit of the horizontal half-hourly wind components to the individual radial wind under the assumption that vertical winds are small (Hocking et al., 2001). An outlier rejection is added. The climatology of background winds and tides as measured by the Collm radar was presented by Jacobi (2012).

The periods of the QTDW are obtained from Lomb–Scargle periodogram analyses based on 11 days of meridional half-hourly wind data each. This method is chosen due to unevenly spaced data that mainly result from too few meteors during some half-hourly time intervals, especially at the upper and lower height gates during the afternoon. The period of maximum amplitude between 40 and 60 h was defined as the most probable period of the QTDW for the respective 11 day time interval. This period range is chosen in accordonce to the results of Huang et al. (2013a) who did not observe longer or shorter periods than these ones. The periodograms are calculated for the meridional component because the meridional QTDW amplitudes are observed to be larger than the zonal ones (Pancheva et al., 2004; Lilienthal and Jacobi, 2014). An example periodogram analysis is shown in Fig. 1, using data of a time interval centered on 25 July 2010. In this case, the amplitude maximum between 40 and 60 h is found at a period slightly larger than 40 h which represents the QTDW period for this date.

To obtain the amplitudes and phases of the QTDW a least-squares fit has been applied to the zonal and meridional horizontal half-hourly winds, which includes the prevailing wind, tidal oscillations of 24, 12 and 8 h, and the individual period of the QTDW as obtained from the periodogram analysis of the meridional wind. Each individual fit is again based on 11 days of half-hourly mean winds and the results are attributed to the center of this data window. For the example presented above the resulting amplitude of the QTDW is 27.6 $\mathrm{m\,s^{-1}}$ at a period of 40.5 h. The window was then shifted by one day. The least-squares fit was performed for both the zonal and the meridional wind component, and for each height gate separately. The following results are based on these data.

3 Results

3.1 Climatology

The upper and lower panel of Fig. 2 present the mean seasonal cycle of QTDW amplitudes. Here, we also present the total amplitudes A as a combination of zonal and meridional components A_z and A_m, respectively, as follows:

$$A = \sqrt{A_\mathrm{z} + A_\mathrm{m}}. \tag{1}$$

The lower panel of Fig. 2 refers to an altitude of 91 km (gate 4). It shows the total amplitudes of each year in light gray, starting in September 2004 and ending in August 2014. The black lines show the 10 year average for total (straight), meridional (dashed) and zonal (dotted) amplitudes and the red line shows 45 day adjacent averages of the 10 year mean total amplitude. As frequently reported in the literature, we find a strong summer and a weaker winter maximum. The first increase of the summer burst starts

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during May where the year 2006 even shows a strikingly strong burst. Maximum amplitudes are usually reached at the end of July and beginning of August. Then, the long-term average amplitudes exceed $15\,m\,s^{-1}$, but the maxima during the individual bursts can be larger, and in some years they reach up to $40\,m\,s^{-1}$. Note, however, that the amplitude values reported here depend on the length of the data window used for the least-squares fit, so that they would decrease if a longer window was chosen. The winter QTDW appears much weaker with average amplitudes between 5 to $10\,m\,s^{-1}$.

The vertical zonal wind shear, which has been calculated from the difference of the respective prevailing wind components at 94 and 88 km, is added as a blue line. On a long-time average, the QTDW amplitudes start to increase when the shear reaches its maximum. This can be understood to be a hint for baroclinic instability as a source of the QTDW. This will be further examined in Sect. 3.2. However, this relation is not observed in winter where the QTDW is assumed to appear due to instabilities of the polar night jet (e.g., Venne and Stanford, 1982; Hartmann, 1983; Sandford et al., 2008).

Generally, the meridional amplitude appears to be larger than the zonal one. Partly, this is due the fact that the period of the QTDW was determined as the one where the meridional amplitude maximizes but when using the zonal component to determine the period, the meridional QTDW amplitude is still larger than the zonal one (not shown here).

The upper panel of Fig. 2 combines the mean seasonal cycles of all six height gates in a contour plot where the respective heights of the gates are indicated by horizontal lines. The seasonal cycle is similar at the different height gates except for the uppermost one. The summer amplitudes maximize at about 88 km height. The winter maximum is strongest at higher altitudes in late winter where $10\,m\,s^{-1}$ can be exceeded, so that at the upper height gates, the amplitude difference between summer and winter decreases.

The distribution of meridional amplitudes during the years 2004 to 2014 as obtained from the Lomb–Scargle periodograms is shown in Fig. 3. Again, they refer to an altitude of 91 km. The black line denotes the period of maximum amplitude between 40 and

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60 h. Note that this curve determines the period that is taken as the real QTDW period for further analyses. Having a look at the summer season it is apparent that in certain years the QTDW appears in one single burst (such as 2007, 2010 or 2012) with typical seasonal maxima at the end of July or beginning of August. In other years, QTDW activity is split into two or more bursts (e.g., 2005, 2006, 2009). The largest amplitudes are usually found between June and August, however, in some years (e.g., 2006, 2009, 2014) significant amplitudes are observed in May, too. The running spectrum for 2006 is a typical example for a strong summer QTDW with two main bursts where the periods vary between more or less 40 and 52 h. At the onset of the summer wave in May and when it vanishes in August, the periods are longer than during the event. This feature from long periods to shorter ones and back to long ones is also seen in other years such as 2007 and 2012, but is weaker expressed in 2005 and 2009.

In each winter from 2005 to 2014 increased amplitudes of the QTDW can be seen. They are particularly large in 2006, 2012 and 2013. In some years (e.g., 2009, 2011, 2012) amplitudes also maximize in November or December. Periods appear to be very short in January with 44 h and less, and they increase until February where they often reach 52 h and more.

In the following we concentrate on the more intense summer QTDW, referring to the months May to August. In order to investigate the distribution of periods with respect to the amplitudes, Fig. 4 shows histograms of periods for different magnitudes of the amplitude where boundary periods (≤ 41 h or > 59 h) are omitted. Dark bars denote only larger amplitudes while white bars include days of all amplitudes. The histogram refers to an altitude of 91 km during summer (May–August). As a result, intervals with large QTDW amplitudes tend to exhibit shorter periods. This can be seen in the median which is slightly smaller if only regarding large amplitudes (47.9 h) compared to the median obtained for all amplitudes (49.3 h). For amplitudes larger than 15 m s^{-1}, the lower and upper quartiles are 45.8 and 52.7 h, respectively. For larger periods, smaller amplitudes dominate. Furthermore, three maxima are apparent at about 42–43, 47–48

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and 50–51 h, which is in accordance to the three groups presented by Malinga and Ruohoniemi (2007).

In the following we show summer QTDW data for amplitudes of at least $15\,\mathrm{m\,s^{-1}}$. Figure 5 shows the relative amplitude differences Δv between zonal and meridional QTDW amplitudes at 91 km altitude, given by:

$$\Delta v = 2\frac{v_\mathrm{z} - v_\mathrm{m}}{v_\mathrm{z} + v_\mathrm{m}} \cdot 100\,\%, \qquad (2)$$

where the index z refers to the zonal and the index m to the meridional component of the QTDW. Hence, positive (negative) Δv denote larger zonal (meridional) amplitudes. The mean and median of the summer data amount to −46.8 and −39.0 %, respectively. The 5 and 95 % percentiles are $P5 = -114.5\,\%$ and $P95 = 2.6\,\%$, respectively. Thus, the meridional component tends to be larger than the zonal one. Note, that the meridional amplitude also tends to be slightly larger due to the fact that the periods of the QTDW were chosen from the maximum meridional amplitude. However, this effect is small. If we calculate the relative amplitude differences using the periods at maximum zonal amplitude we obtain $P5 = -75.5\,\%$ and $P95 = 17.1\,\%$ which qualitatively leads to the same conclusion that the meridional amplitude is larger.

The phase differences between zonal and meridional QTDW components at 91 km altitude are shown in Fig. 6. The histogram includes the results for amplitudes larger than $15\,\mathrm{m\,s^{-1}}$ in black and white for summer (May–August) and the rest of the year, respectively. The small number of the latter shows that large amplitudes do mainly appear in summer. A Gaussian fit was applied to the summer histogram. As a typical feature of that distribution, mean (102.2°), median (101.1°) and mode (102.4°) are all of similar value. These values are only slightly larger than 90° and hence the zonal and meridional component are nearly in quadrature. Other height gates have Gaussian modes that are up to 10° larger compared to 91 km altitude.

Figure 7 (left panel) shows the means and SDs of the phase difference at all six height gates for amplitudes larger than $15\,\mathrm{m\,s^{-1}}$. The SD of the uppermost gate is almost twice as large as those of the gates below. Considering the lower gates the means are comparable to the one at 91 km, slightly higher than 90°. However, the SD of about 30° is large. The right panel of Fig. 7 shows the profile of the mean QTDW zonal and meridional amplitudes as well as their differences. At 82 km the meridional amplitude is only slightly larger than the zonal one. For greater altitudes, the difference is increasing up to a height of 91 km and almost constant above.

Vertical wavelengths λ_z were calculated for each interval if the amplitudes at 91 km altitude are larger than 15 $\mathrm{m\,s^{-1}}$ by:

$$\lambda_z = \frac{P}{\mathrm{d}T/\mathrm{d}z}, \tag{3}$$

by the ratio of the period P and the vertical gradient $\mathrm{d}/\mathrm{d}z$ of the phase T. In order to gain the same periods for all height gates, the least-squares fit has been run for all gates with the period obtained for 91 km altitude. The vertical phase gradients were calculated by applying linear fits of phase over height. The histogram in Fig. 8 shows all wavelengths retrieved with a value smaller than 400 km. Indeed, we obtain a few very large ("infinite") wavelengths that are not presented, when the phase does not significantly change with altitude, i.e. when the wave does not propagate vertically. This is true in about 12 % of all cases considered. For the values smaller than 400 km a Weibull fit is applied. The mode is 69 km whereas the median and mean of the data set < 400 km are much larger with 106 and 127 km, respectively.

3.2 Connection with background wind shear

Plumb (1983) introduced the idea that the origin of the QTDW is baroclinic instability of the easterly jet in the summer mesosphere. A necessary condition for that is that the northward gradient of quasi-geostrophic potential vorticity q_y must change sign somewhere in the flow domain to enable instability (Charney and Stern, 1962). This condition is given in the summer mesospheric jet in an altitude of about 70 km. Here, the vertical zonal wind profile has a minimum or, in other words, the easterly winds maximize. In order to investigate possible baroclinic instability by analyzing MR measurements from higher altitudes, a proxy needs to be determined because the wind maximum is outside the measurement range. We analyze the vertical wind shear of the zonal wind above the jet as a measure for its strength and hence for baroclinic instability.

We apply superposed epoch analyses in two ways: first, the key events are defined from the time series of the amplitude. When the low-pass filtered amplitudes show a maximum of at least 10 $m s^{-1}$, a time window from 20 days before the event until 10 days after the event is considered. Second, the key events are defined from the time series of the wind shear which was again low-pass filtered. Maxima of at least 3 $m s^{-1} km^{-1}$ are considered and the time window from −10 to +20 days is used. For each approach separately, the time windows are averaged over all key events in both variables, amplitude and wind shear. Note that the maximum of the key variable is not necessarily placed at day 0 since the maximum of the low pass filter was set to day 0 but not the real time series. The results for an altitude of 85 km are shown in Fig. 9. If the QTDW was amplified by baroclinic instability a maximum of the amplitudes would be expected to appear shortly after a maximum of wind shear as reported by Pendlebury (2012) or Ern et al. (2013). In Fig. 9, both ways of the epoch analysis show that the amplitude maximizes about 10 to 15 days after a maximum of wind shear. These results are consistent with the conclusion of Plumb et al. (1987): the QTDW is propagating eastward, opposite to the wind direction in the jet. With increasing amplitude it tends to act against its origin (Pendlebury, 2012; Ern et al., 2013) and diminishes the wind shear until amplification is too weak so that the amplitude decreases again. However, considering the large error bars in our data we can only speak about tendencies. The relation is not clear enough to prove the hypothesis of baroclinic instability as a forcing mechanism. Furthermore, the results shown here for 85 km altitude become less significant for higher altitudes.

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3.3 Inter-annual variability

A correlation of QTDW amplitudes to the 11 year solar cycle was found in Low Frequency Measurements by Jacobi et al. (1997) and recently by Huang et al. (2013b) using satellite measurements. Both report larger amplitudes during solar maximum. Due to the deep solar minimum in 2008 and 2009 an analysis of the inter-annual variability of the QTDW is of special interest. Figure 10 presents the F10.7 solar radio flux (black) and vertical zonal wind shear at 85 km (pink) in the upper part. The lower part shows the the total amplitudes at the four height gates between 85 and 94 km altitude. These parameters are given for summer (upper panel) and winter (lower panel). The seasonal mean data presented in the figure are shown each as a four-months average from May to August and from November to February while the year of the winter refers to the one of the respective January.

In summer, the amplitudes qualitatively show similar inter-annual variability at each altitude with a major maximum in 2006 and two minor maxima in 2009 and 2012. The correlation with the solar cycle is weak and insignificant. However, the correlation of the seasonal mean total amplitudes with the wind shear at 85 km altitude is stronger with correlation coefficients from $R = 0.4$ to 0.7. The zonal amplitude has a slightly larger correlation coefficient for all height gates; the meridional one is slightly smaller. However, either of them only differs by about 0.1. Jacobi and Ern (2013) report that gravity interactions reach to particularly high altitudes in 2008 and hence further increase the shear which is also visible in Fig. 10. However, this does not seem to affect the QTDW in summer.

In winter, amplitudes at different altitudes are not always as homogeneous as in summer. However, there is a clear peak in all altitudes during winter 2005/06 when a major stratospheric warming was observed. This is in good agreement to the general view that enhanced planetary wave activity can cause stratospheric warmings. The correlation between QTDW winter amplitudes and solar radio flux is in the lower height gates slightly higher than in summer but still not significant. Correlation coefficients vary between −0.4 and +0.4 where zonal amplitudes tend to have negative values and meridional ones tend to have positive values. The opposite holds for correlation with wind shear. Here, meridional amplitudes tend to be negatively correlated (up to $R = -0.7$) and zonal ones positively (up to $R = 0.7$). However, for different altitudes the values differ a lot and most correlations turn out to be insignificant. This is in accordance with the general view that the winter QTDW is a result of instability of the polar night jet, and thus originating from the lower atmosphere and not that much determined by mesospheric circulation.

As presented in the periodograms in Sect. 3.1 the appearance of the QTDW is not uniform in each year. This is why one might expect a seasonal mean not necessarily to be representative enough to describe the QTDW. Thus, we also compare different ways to describe seasonal mean QTDW activity during a season such as (1) the maximum total amplitude during a season, (2) the mean of the squared total amplitudes during a season as an estimate for energy and (3) the mean of amplitudes minus a threshold value of $6\,\mathrm{m\,s^{-1}}$, while negative values are set to zero. This latter value is taken from the "noise floor" visible in Fig. 2 during the equinoxes.

As a result, the estimates (2) and (3) behave behave very similar to the seasonal mean values concerning magnitudes and sign of the correlation coefficients for correlations with solar radio flux and vertical shear of the zonal wind.

Using the maximum as an estimate, the correlation with solar radio flux in summer turns out to be slightly positive for most altitudes with $R \approx 0.2$ in the lower height gates. However, this is still no clear correlation and thus the results more or less correspond with those obtained for other estimates. The same holds for summer, where positive values for zonal and negative values for meridional amplitudes dominate. The correlation between wind shear and seasonal maxima is mostly weaker than obtained for seasonal means by about 0.2.

To conclude, differences obtained with the four methods are not very large. Thus, the obtained relation between QTDW amplitudes and wind shear is robust and independent from the chosen method.

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4 Discussion and conclusion

The QTDW is analysed from Collm VHF meteor radar data. The considered time series begins after the installation of the radar in 2004 when it replaced earlier LF measurements (Jacobi et al., 1997) and reaches until 2014.

On a 10 year average, the QTDW has amplitudes of about 15 $m s^{-1}$ in summer when analyzed on an 11 day basis. In winter, a secondary maximum with amplitudes of 5 to 10 $m s^{-1}$ is observed. The periods of the QTDW tend to be longer in winter than in summer. Some years show a typical signature of periods during summer bursts that change in length from long to short and back to long while shorter periods are generally associated with larger amplitudes. Similar features were observed by Jacobi et al. (1997). This is in opposite to the results of Tsuda et al. (1988) and Williams and Avery (1992) who observed shortening periods or to those of Pendlebury (2012) who found continuously increasing periods during a burst.

Phase differences between the zonal and meridional component turn out to be slightly larger than 90° which indicates that the wave is nearly but not exactly circularly polarized. This value is a bit larger than the one reported by Jacobi et al. (1997). The zonal and meridional amplitudes are of comparable size at 82 km altitude but they change with height in a way that the meridional ones tend to be larger by about 50 %. This coincides with the results of Pancheva et al. (2004) but it could not be seen in the earlier LF measurements (Jacobi et al., 1997, 2001).

Vertical wavelengths were calculated from the vertical phase gradients. The mode of a fitted Weibull distribution is 69 km, while the median wavelength is 106 km. These values are comparable to those obtained by Thayaparan et al. (1997). Smaller values below 80 km are reported, e.g., by Gurubaran et al. (2001); Guharay et al. (2013) or Huang et al. (2013b). Even larger values are found by Craig and Elford (1981). What all studies have in common is the fact that very large, almost "infinite" values were occasionally obtained, so do we. This indicates that the wave does not propagate vertically in these cases.

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Furthermore, we find a connection between vertical zonal wind shear and QTDW amplitudes by applying superposed epoch analyses. They show a maximum of amplitudes about 10 days after a maximum of zonal wind shear at 85 km altitude. Also, a maximum of zonal wind shear is found about 10 to 15 days before the amplitude maximizes at 85 km. In the long-term mean annual cycle, zonal wind shear has a maximum when the QTDW starts to amplify. Also, in an inter-annual view, the correlation between zonal wind shear and amplitudes of the QTDW is high in summer but not in winter where the QTDW is assumed to be amplified by instability of the polar night jet. Since shear is taken here as a proxy for baroclinic instability we conclude that the QTDW over Collm is at least to a certain degree forced by instability of the summer mesospheric jet as reported by Ern et al. (2013) using satellite measurements, too. Also, Huang et al. (2013b) observed increasing QTDW amplitudes above regions of negative quasi-geostrophic potential vorticity.

Between QTDW amplitudes and the 11 year solar cycle a positive correlation is found in winter. In summer it is weaker and correlation coefficients tend to be negative. However, the correlation is not that clear. This can be explained by considering the results of Jacobi et al. (2011). They found a positive correlation of zonal wind shear and solar cycle except during solar minimum when correlation turns out to be negative. This may also hold for the QTDW due to the possible amplification by baroclinic instability. As the strong solar minimum in 2009 is centred in the analysed time series, longer observations are necessary to draw further conclusions.

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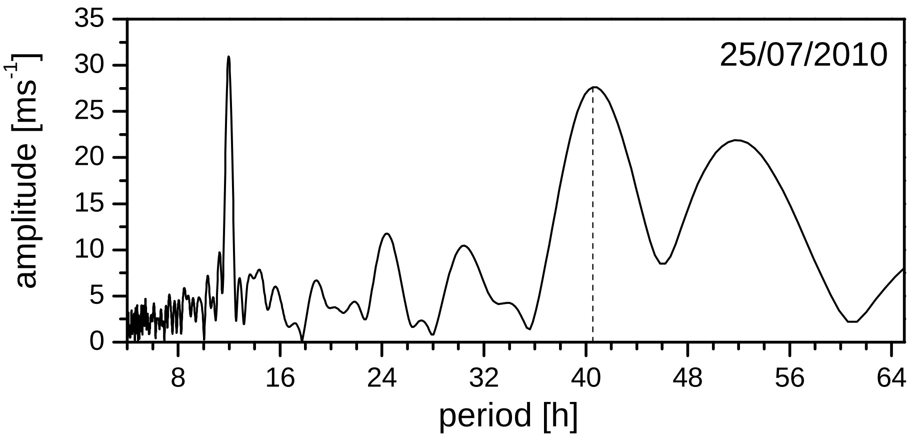

Figure 1. Lomb–Scargle periodogram of the meridional wind for a time interval of 11 days centered on 25 July 2010 (91 km altitude). The QTDW period for this day is set to the one with the maximum amplitude between 40 and 60 h, illustrated by the vertical dotted line.

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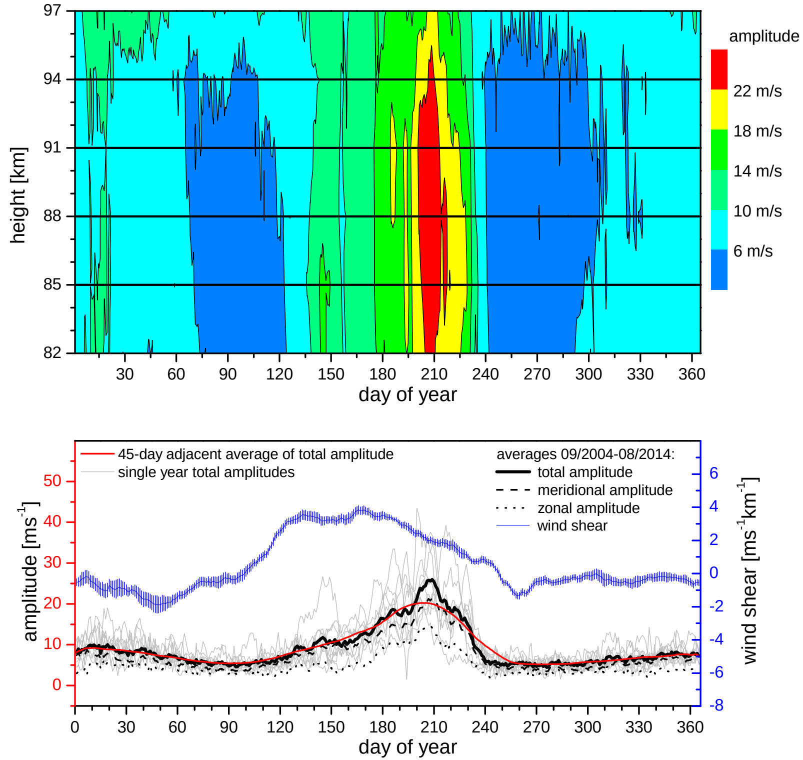

Figure 2. Upper panel: contour plot of the 10 year mean amplitudes over height in an annual cycle. The horizontal lines (black) mark the six height gates. Data are interpolated in between. Lower panel: total annual amplitudes between September 2004 and August 2014 (light gray). Average values of the years 2004–2014 in black for total (straight), meridional (dashed) and zonal (dotted) component. 45 day adjacent average for the total annual amplitude in red. The blue curve denotes the vertical shear of zonal wind including standard error. Data refer to an altitude of 91 km.

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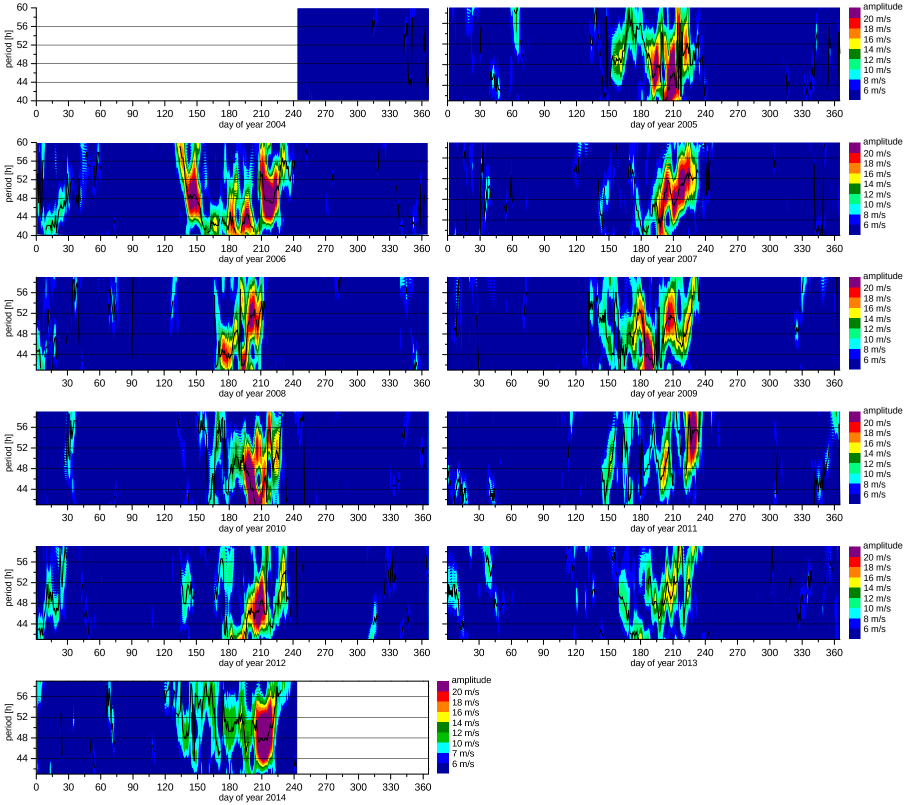

Figure 3. Periodograms of the meridional amplitude for the years 2004–2014 at 91 km altitude. Each day represents the center of an 11 day analysis of horizontal wind data. The black line follows the period of maximum amplitude between 40 and 60 h if amplitudes are larger than $6\,\mathrm{m\,s^{-1}}$.

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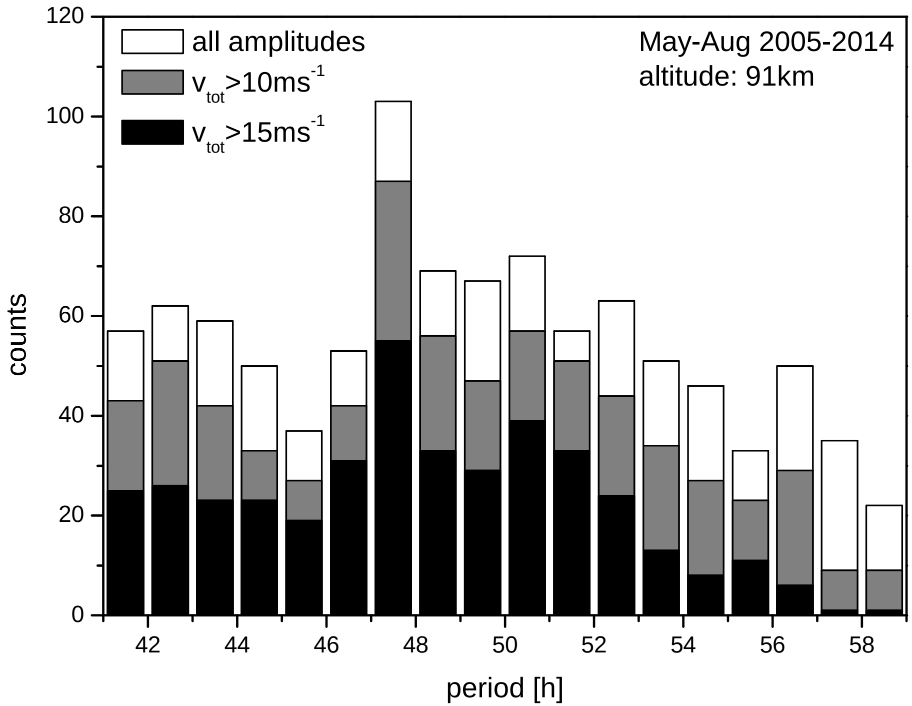

Figure 4. Distribution of QTDW periods in summer (May–August) for the years 2005–2014. Black: amplitudes larger 15 m s^{-1} only. Gray: amplitudes between 10 and 15 m s^{-1}. White: amplitudes smaller than 10 m s^{-1}.

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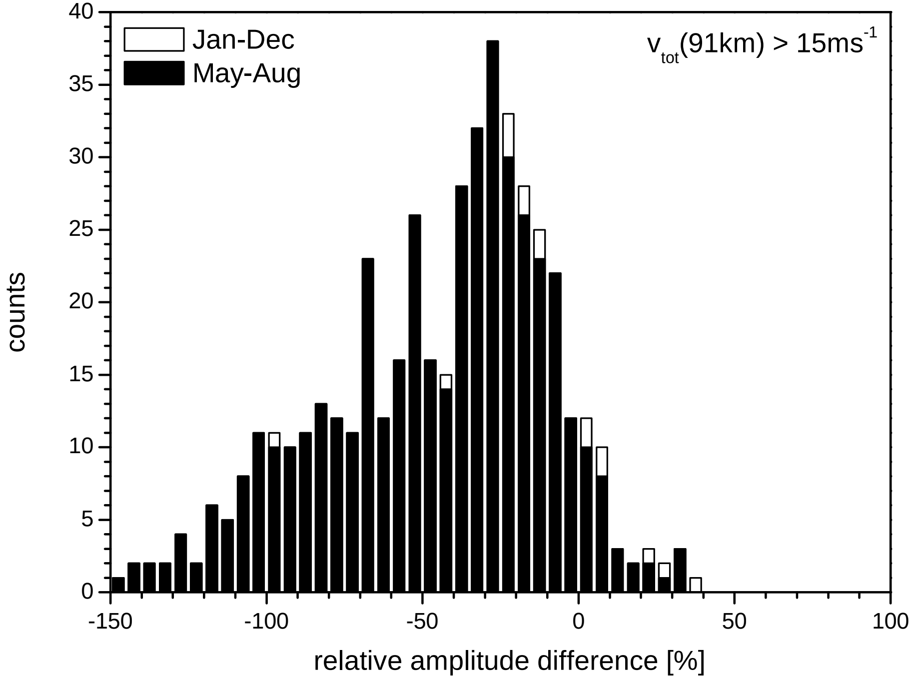

Figure 5. Histogram of the 91 km (gate 4) relative amplitude differences Δv of zonal and meridional component for amplitudes larger than 15 m s^{-1}. Black bars: summer (May–August) data, 460 days considered. White bars: rest of the year (January–April, September–December) data, 17 days considered. Positive values denote larger zonal than meridional amplitudes.

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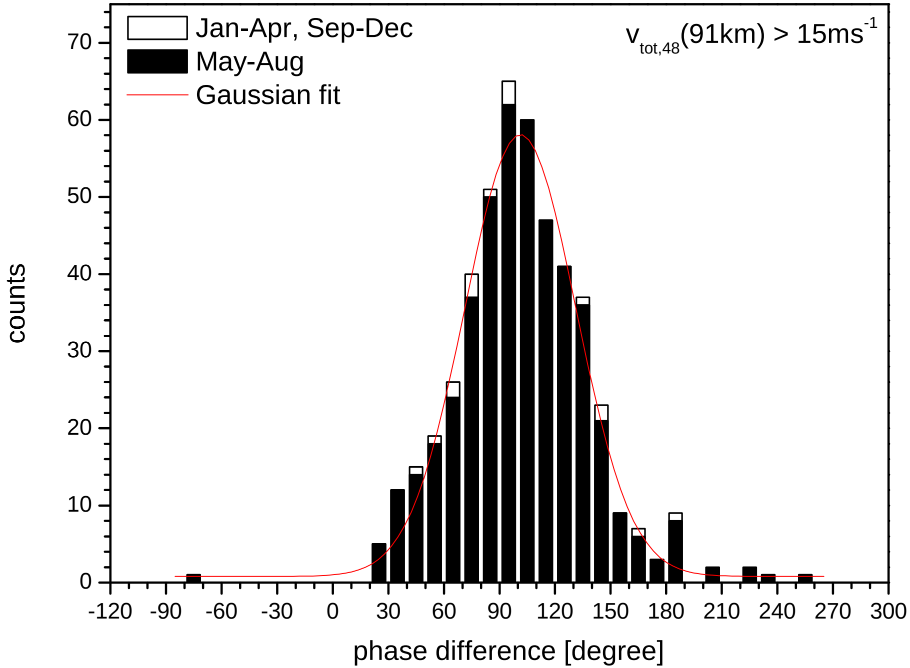

Figure 6. Histogram of the 91 km (gate 4) phase differences of zonal and meridional component for amplitudes larger than 15 m s^{-1}. Black bars: summer (May–August) data, 460 days considered. White bars: rest of the year (January–April, September–December) data, 17 days considered.

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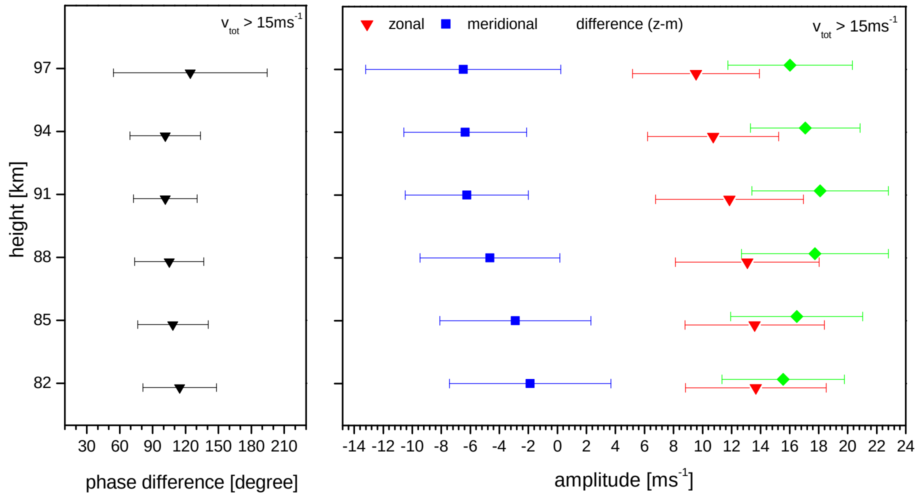

Figure 7. Left panel: mean phase difference (black) between zonal and meridional component 2004–2014 with SD. Right panel: zonal (red) and meridional (green) mean amplitude 2004–2014 with SD. Amplitude difference with SD in blue. For both panels only dates with total amplitude > 15 $m\,s^{-1}$ are used.

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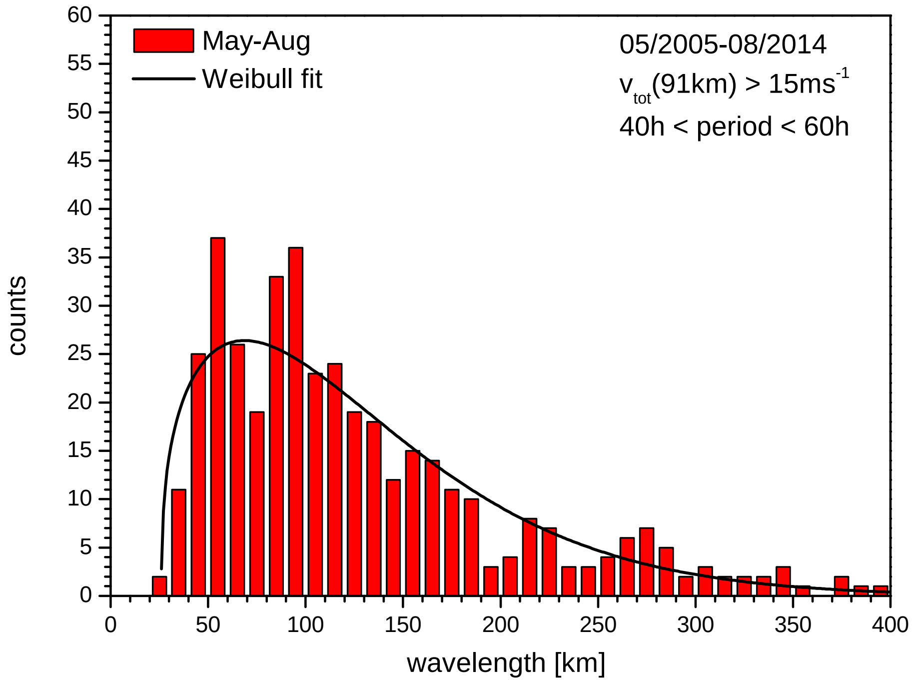

Figure 8. Histogram of daily vertical wavelengths during summer (May–August) for the time period from 2005 to 2014 (red bars) where only dates with total amplitude $> 15\,\mathrm{m\,s^{-1}}$ are used. Wavelengths longer than 400 km are not shown (refers to 56 days out of 460). Fit of a Weibull distribution in black.

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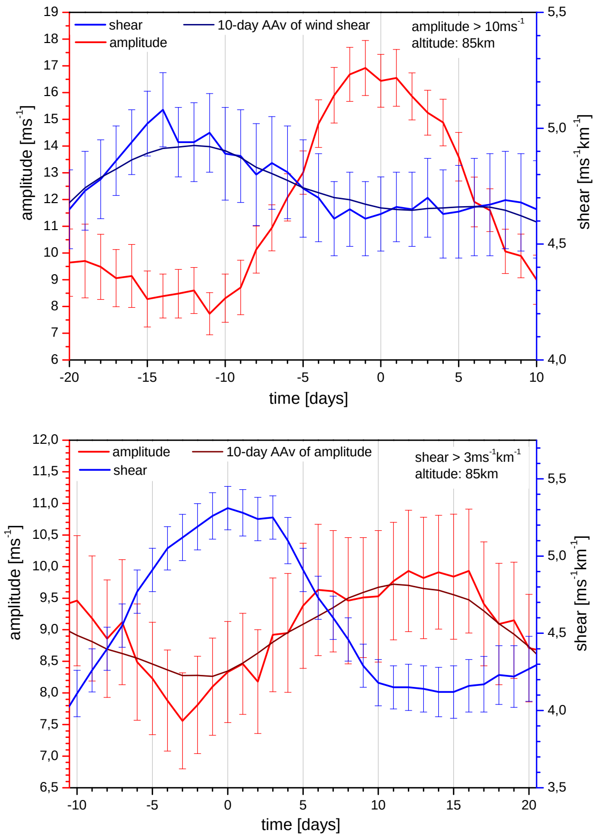

Figure 9. Superposed epoch analysis of vertical wind shear of the zonal prevailing wind (blue) and QTDW total amplitudes (red) at 85 km altitude, including standard error. 10 day adjacent averages of the amplitude (dark red) and wind shear (dark blue). Upper panel: maxima in wind shear > 3 $\mathrm{m\,s^{-1}\,km^{-1}}$ are considered as key events. Lower panel: maxima in QTDW amplitude > 10 $\mathrm{m\,s^{-1}}$ are considered as key events.

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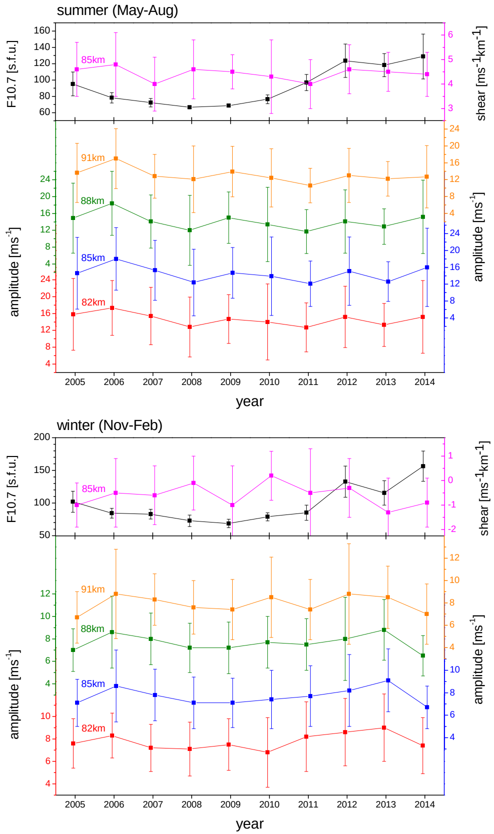

Figure 10. Seasonal mean QTDW total amplitudes for summer (May–August, upper panel) and winter (November–February, lower panel, the year refers to the one of the respective January) for different altitudes in orange, green, blue and red. Error bars denote the SD of the 11 day analyses during one season. Seasonal mean F10.7 solar radio fluxes (black) and zonal wind shear of the prevailing wind at 85 km (pink) are added.

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