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Trends in MLT region winds and planetary waves, Collm (52° N, 15° E)

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Abstract. Long-period oscillations in the period range 2–30 days, interpreted as planetary wave (PW) signatures, have been analysed using daily mesosphere/lower thermosphere wind measurements near 90 km over Collm (52° N, 15° E) in the time interval 1980–2005. Interannual and interdecadal variability of PW are found. Since the 1990s, a tendency for larger zonal amplitudes compared to meridional ones has been observed, i.e. some long-term trends are visible, which are positive in the zonal component, but negative in the meridional component. There is a tendency of the trend to be non-linear for waves with periods lower than 7 days, so that a climatic transition appears around 1990, with smaller changes before and after that time. A solar cycle effect on PW is weak, but there is a tendency for a positive correlation between solar flux and wave activity, if a time lag of PW activity with respect to the solar flux of about 2 years is taken into consideration.

Keywords. Meteorology and atmospheric dynamics (General circulation; Middle atmosphere dynamics; Waves and tides)

1 Introduction

Wind oscillations at planetary wave (PW) periods (2, 5, 10, 16 days) in the mesosphere/lower thermosphere (MLT) region, which have been frequently described in literature, are generally interpreted as the signal of PW. During recent years, the question of the interannual variability of these waves has been discussed, e.g. with respect of a possible influence of the equatorial quasi-biennial oscillation (QBO) on MLT PW activity (Espy et al., 1997). In particular it is of interest whether there is a long-term trend in wave parameters which may indicate a possible coupling with climatic trends or shifts. Some evidence exists that long-term trends may be present in PW activity (Lastovicka et al., 1994; Jacobi et al., 1998), although a clear direction of these trends is not given, and there is an indication that these trends are intermittent.

Until today there are very few measurements of PW available, which cover a sufficiently long time interval to draw conclusions on PW trends in the MLT. In addition, results have indicated that these trends may be intermittent, or change direction, which has also been shown for other MLT parameters (e.g. Jacobi et al., 1997). Lastovicka and Krisan (2006) presented a change of trend in total ozone content (TOC) and ozone laminae, the latter being the signature of ozone streamers in the vertical and thus it may be an indication for PW (breaking) activity in the stratosphere. They found, that a decrease of TOC and ozone content within laminae before 1995 was followed by an increase after that time. Assuming that this ozone behaviour is dynamically forced, they compared this behaviour with MLT winds presented by Bremer et al. (1997). More recently, Portnyagin et al. (2006) have presented mean MLT winds at Northern Hemisphere midlatitude stations and found that there is indeed a trend change in MLT wind parameters (prevailing winds and semidiurnal tidal amplitudes) around 1990. Considering the stratosphere, Baumgaertner et al. (2005, their Fig. 16) showed PW 1 amplitudes at 78° S, which increased around 1990.

To obtain a more comprehensive picture of middle atmosphere trends and their possible changes, further studies especially of the long-term variability of PW are required. To this end, estimates of PW activity from the mesopause wind measurements at Collm, Germany (52° N, 15° E), will be presented here with a focus on long-term trends. For this purpose, the measured oscillations of daily wind data are interpreted as the signal of PW activity after removal of the semidiurnal tidal wind. The paper represents, to a certain degree, an update of the results presented by Jacobi et al. (1998), but here we include 10 years of additional data.

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One has to keep in mind that the wave parameters (such as the wavenumber or phase speed, for instance) cannot be determined from single point measurements and therefore strictly speaking only the term "oscillations" could be used. However, as has been shown, the accordance of the results with PW estimations known from literature generally is good enough to establish a correlation between the measured oscillations and PW activity. Therefore the term 'waves' is used even if these cannot really be identified from the measurements used here.

2 Data base and analysis

Daily D1 radio wind measurements in the LF range use the ionospherically reflected sky waves of commercial radio transmitters on three measuring paths (177, 225 and 270 kHz). The measurements are carried out according to the closely-spaced receiver technique. An algorithmic and automated form of the similar-fade method is used to interpret the sky wave field strength measurements as a consequence of wind (see e.g. Schminder and Kürschner, 1994). The data are combined to half-hourly zonal (v_z) and meridional (v_m) mean wind values on each frequency. Including the results of the individual measurements on each of the three frequencies, combined with a weighting function based on an estimate of the "chaotic velocity" (Sprenger and Schminder, 1969), mean values are calculated that refer to a reflection point at 52° N, 15° E. Since during the day the absorption of the sky wave in the ionospheric D-region is too large, the daily measuring period is restricted to night and twilight hours in summer, while in the winter the measurements are possible during the whole day. Since late 1982 the reflection height is measured at 177 kHz using travel time differences between the ground wave and the ionospherically reflected sky wave. The differences are obtained using sideband phase comparisons of both wave components in the modulation frequency range near 1.8 kHz (Kürschner et al., 1987).

Since the measurements are inhomogeneously distributed in time and altitude, a multiple regression analysis is used to determine estimates of the daily prevailing wind as well as the tidal wind field components from the half-hourly mean values v_z and v_m of the measured zonal and meridional wind components. The spectral selectivity of the separation of prevailing and tidal wind was improved through fitting the measured values v_z and v_m for the horizontal wind components as a vector, assuming clockwise circularly polarized tidal wind components (Kürschner, 1991):

$$v_z = u + a \cdot \sin(\omega t) + b \cdot \cos(\omega t) + \varepsilon \quad ,$$
$$v_m = v + a \cdot \cos(\omega t) - b \cdot \sin(\omega t) + \varepsilon, \tag{1}$$

and minimising ε, while u and v are the daily zonal and meridional prevailing wind values, and ω=2π/12 h is the angular frequency of the semidiurnal tide. The diurnal tidal components are not taken into account, because the daily, quasi-regularly distributed data gaps would lead to a large error. On the other hand, at midlatitudes the diurnal tide is, except for spring, a much less dominant feature than the semidiurnal tide. Additionally, the error resulting from neglecting the diurnal oscillation for the most part only leads to an offset of the prevailing wind components. This offset will be filtered out if long-period variations are considered, although a modulation of the diurnal tide at PW periods might produce an observable effect, which we cannot distinguish from the original PW. The semidiurnal tidal amplitudes and phases can be taken from the coefficients a and b of the regression analyses in Eq. (1), but they are not regarded in this investigation.

Note that the reflection height is not directly used here. Since the total reflection height measurements of sky waves provide wind values only at one height at a time (which is varying through the course of one day) a direct estimation of daily wind profiles is not possible in a certain way. However, if the measured half-hourly wind components of several days are combined in one analysis, a mean wind profile can be calculated using a modified form of a Eq. (1) with height-dependent coefficients (e.g. Kürschner and Jacobi, 2005, and references therein).

The virtual reflection height h' ranges roughly between 85 and 105 km on a monthly average. After sunrise h' decreases rapidly due to ionisation in the D-region. Since absorption during daylight hours is large, practically no measurements are possible then in summer. In the late afternoon h' rises slowly to its nighttime values. As a consequence of these diurnal reflection height variations not all of the half-hourly measurements can be used for the regression analysis after Eq. (1), since especially in summer large gradients of the zonal prevailing wind would influence the results of the analysis due to apparent wind variations while the reflection height changes. Therefore only nighttime half-hourly mean wind values are included into the analysis, when the long-term mean virtual reflection height has values that are sufficiently close to the mean nighttime value of about 95 km. The data windows for each month of the year differ and are longer during winter than during summer. Further details may be found in Jacobi et al. (1998). Note that the real height h is lower than the virtual height and the differences amount to about 5 km at h=90 km (h'=95 km) so that our daily winds refer to an approximate altitude of 90 km.

Owing to increased ionisation during the solar maximum compared to solar minimum, there is a negative correlation of the reflection height and the 11-year solar cycle. Moreover, cooling of the mesosphere during the last decades lead to a shrinking of the mesospheric layers and a decrease of the reflection height of LF waves, too (e.g. Bremer and Berger, 2002). The question, whether long-term or solar variations of h influence the MLT wind system as measured with the LF method has been discussed on several occasions (Jacobi, 1998; Jacobi et al., 2005; Jacobi and Kürschner, 2006). In

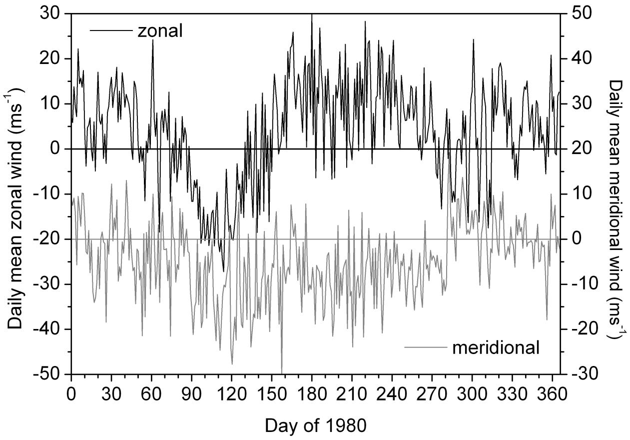

Fig. 1. Examples of time series of daily zonal (positive eastward) and meridional (positive northward) winds during 1980.

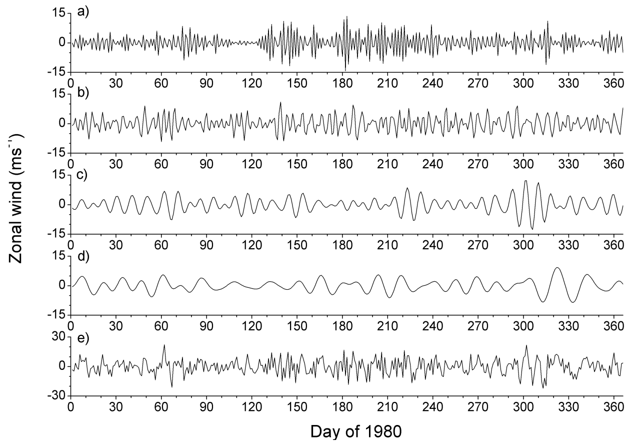

Fig. 2. Time series of filtered zonal winds in 1980 using different period bands **(a)** 2–3 days, **(b)** 3–7 days, **(c)** 7–12 days, **(d)** 12–30 days, **(e)** 2–30 days.

brief, a shrinking of the mesosphere should generally lead to a decrease of the height levels of the wind systems also, so that the effect on the measured trends is small. This argument of course does not hold for a possible solar cycle effect, but Jacobi (1998) has shown that the measured signal of MLT mean wind dependence on the solar flux is still retained if the solar cycle reflection height changes are taken into account.

An example of daily zonal (positive eastward) and meridional (positive northward) prevailing winds in the year 1980 is given in Fig. 1. The zonal winds show the well-known seasonal variations at midlatitudes, with westerly winds in winter and summer, and easterlies around the equinoxes. The meridional wind is weaker. The meridional wind jet is directed from the summer to the winter pole, leading to southward winds in summer (e.g. Portnyagin, 1986; Middleton et al., 2002). Since the jet decreases in height from the summer to the winter pole, the winter northward maximum is actually found below 90 km. At 90 km the winds are only weakly positive on a seasonal average. Since there is a decrease of the strength of the meridional wind jet both in summer and (less significant) in winter (e.g. Jacobi and Kürschner, 2006), in some recent years at 90 km the signature of the meridional wind jet is not as clearly expressed any more.

The daily prevailing winds, which refer to an altitude around 90 km show, besides the seasonal variation, significant variability on the day-to-day time scale. This may partly be due to uncertainties in the daily wind analysis, and also to a possible impact of mean nighttime height changes from day to day. Part of this variability, however, may be due to PW. To investigate this, we applied a Lanczos filter (Duchon, 1979) with 100 weights to the time series of daily zonal and meridional prevailing winds, using different period bands of 2–3, 3–7, 7–12, 12–30, and 2–30 days, to analyse the variability of the wind field in these period intervals. The procedure is described in Jacobi et al. (1998), but different period ranges are used here.

Note that the data base consists of daily prevailing wind values, so that a period band of 2–3 days includes some additional spectral energy coming from shorter periods through aliasing. Examples of filtered time series of the zonal wind, again for the year 1980, are shown in Fig. 2. There is a tendency that the short-period waves (Fig. 2a) maximise in summer at midlatitudes, which is a hint that this is really a signature of the quasi-2-day wave (QTDW), which near 90 km is mainly a summer phenomenon (Muller and Nelson, 1978; Chshyolkova et al., 2005) and which is the dominating dynamical feature in the summer MLT (e.g. Jacobi et al., 1998) with amplitudes of up to 50 ms^{-1} in the Southern Hemisphere (Craig et al., 1980). However, since the data base consists in daily zonal prevailing winds, the QTDW is partly invisible in these data depending on its phase position and in all cases the estimated amplitude is too small. There is, however, some indication that the QTDW is, to a certain degree, phase locked (Clark et al., 1994; Harris, 1994), so that the degree of filtering of the QTDW through the use of daily winds is not very variable and the year-to-year variability of our resulting variance does reflect the real QTDW variability. Nevertheless, the results concerning the QTDW presented in the following can be considered as qualitative only. At medium periods (Fig. 2b), potentially including the quasi 5-day wave, the seasonal variability appears less strongly expressed, which is owing to the high phase speed of the quasi 5-day wave which partly allows propagation through the summer hemisphere. The long-period variations show the expected tendency towards larger amplitudes in winter (e.g. Luo et al., 2000). This behaviour is typical for PW in the MLT, so that we may conclude that at least a considerable part of the variance in the respective period windows is owing to PW activity.

From the filtered time series of the zonal and meridional wind monthly and 3-monthly mean values of the standard

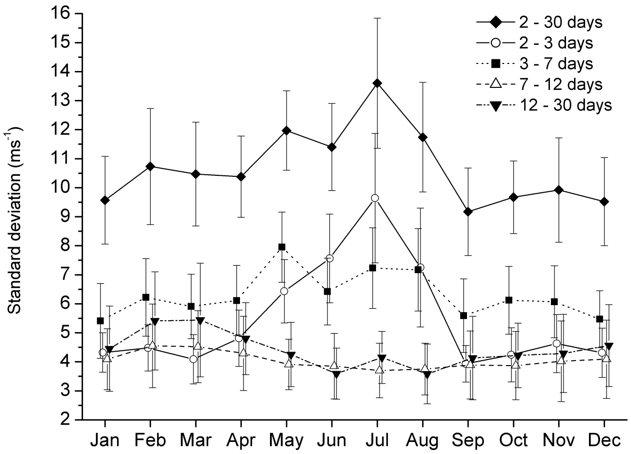

Fig. 3. 1980–2005 mean monthly mean standard deviations σ_h of daily winds at different period bands.

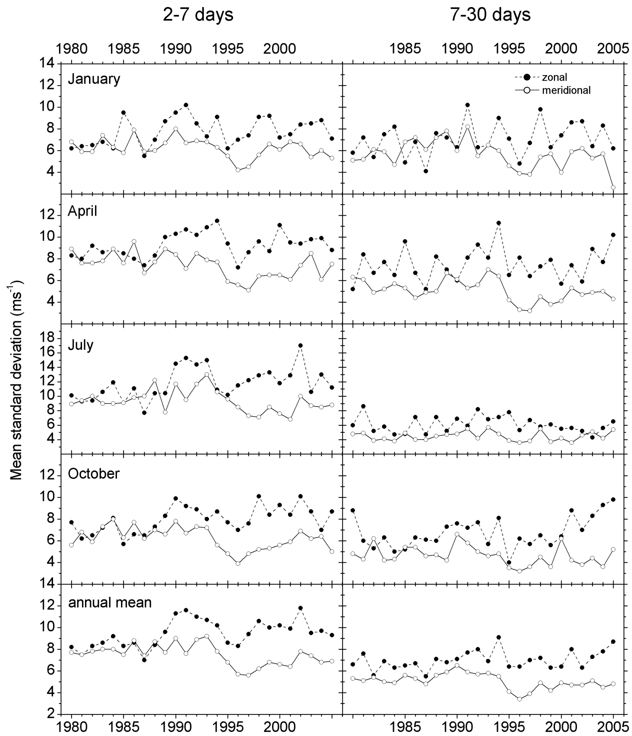

Fig. 4. Time series of zonal (solid symbols) and meridional (open symbols) wind standard deviation for four seasons (3-monthly means centred at the month indicated in the panels) and the annual mean, for the period bands 2–7 days (left panels) and 7–30 days (right panels). Note the different scaling of the ordinate for July.

deviations σ_u (zonal) σ_v (meridional) are calculated, and the respective value is attributed to the centre of the interval. The total standard deviation $\sigma_h=\sqrt{\sigma_u^2+\sigma_v^2}$ was calculated as the square root of the sum of the variances of zonal and meridional winds in the respective period windows.

3 Results

3.1 Long-term mean wave activity, and interannual variability

Figure 2 only represents an example of the seasonal behaviour of wind variability in the long-period range. The 26-year means of the monthly total standard deviation, averaged over the years 1980–2005, are shown in Fig. 3. The expected variability of the long-period variations in the respective period windows in well visible. While the signature of the QTDW clearly peaks during summer months, and the 5-day wave shows a slight tendency to peak during summer also, the long-period waves maximise in late winter, but are nevertheless visible during summer, too. Note that the relative amplitudes of the different waves in Fig. 3 are difficult to compare, because they depend on the width of the respective filter windows.

Time series of the zonal and meridional standard deviations in two different period intervals are shown in Fig. 4 for different seasons and for the annual mean. The left and right hand panels show the data for period windows 2–7 days and 7–30 days, respectively. A striking feature is the strong interannual variability. Several panels show a quasi decadal variation with maximum values shortly after 1990. Some time series, in particular for the long-period waves (10-day wave, 16-day wave) at times show a strong year-to-year variability. Comparison with the equatorial QBO, however, did not show an unambiguous correlation.

Figure 4 also shows that, on an average, the zonal wind variability σ_u is stronger than the meridional component σ_v. This is true for each period window and season considered. There is also some indication that, more expressed at short periods than in the long periods, this difference is larger for the later years (since about 1988–1990) than for the early years of the measurements. This is e.g. visible as a dominating phenomenon in the annual mean standard deviation in the 2–7 days period range (bottom left-hand panel of Fig. 4). In the following section this behaviour will be analysed in more detail.

3.2 Long-term trends and solar influence on long-period oscillations

From some of the time series in Fig. 4 a maximum of σ shortly after 1990 is visible, which roughly coincides with the maximum of solar cycle 22. To analyse whether this maximum is owing to a possible influence of solar variability similar to the response of the mean circulation on the 11-year solar cycle (Jacobi and Kürschner, 2006), we analyse the possible long-term trends together with the potential solar cycle influence, and applied a multiple regression analysis to the

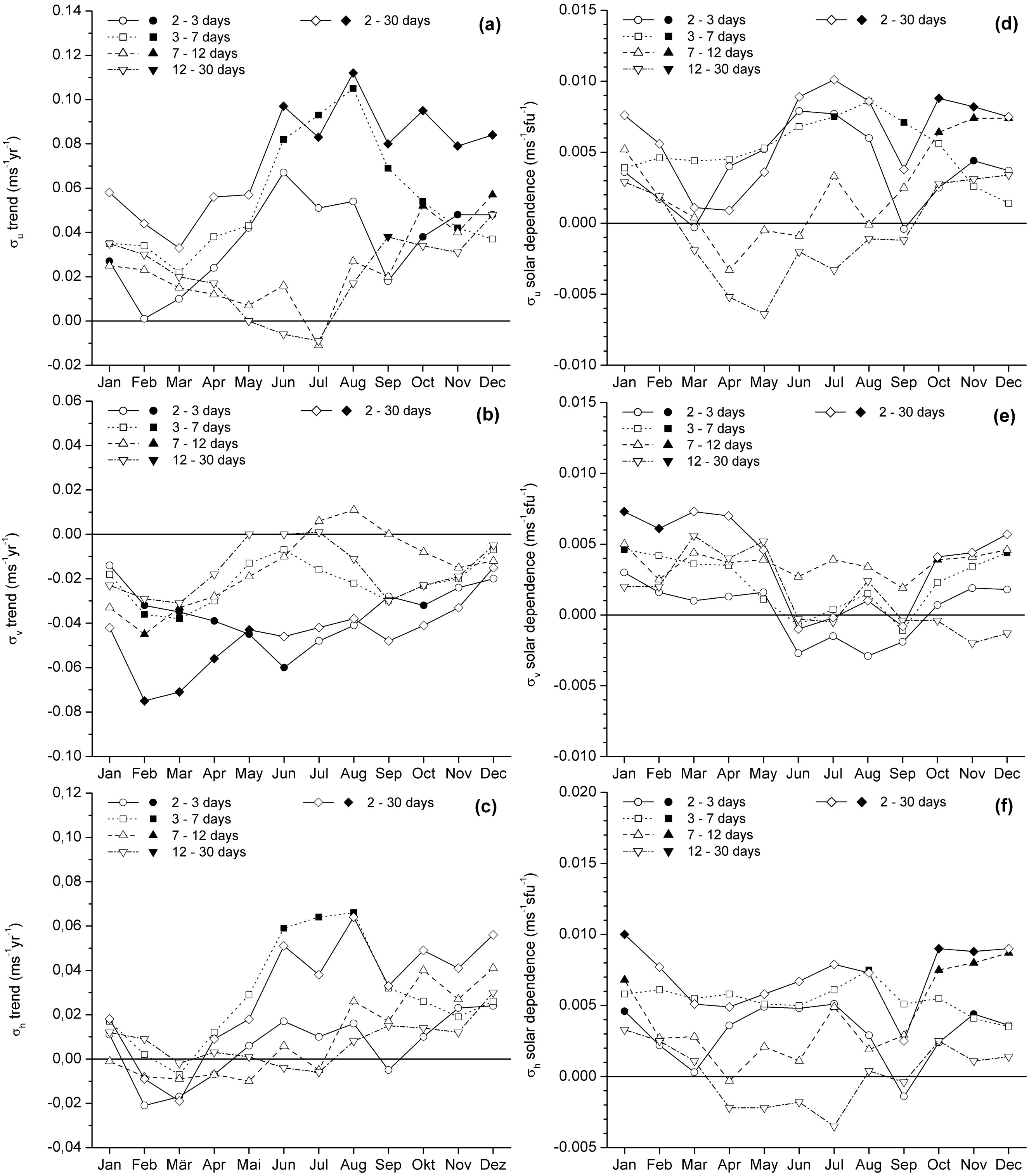

Fig. 5. Trend (left panels) and solar cycle dependence (right panels) coefficients (*A* and *B* from Eq. 2) for the standard deviation of the zonal (upper panels), meridional (middle panels) and total (lower panels) daily mean winds filtered in different period interval, derived from a multiple regression analysis. Solid symbols denote statistically significant correlation according to a t-test.

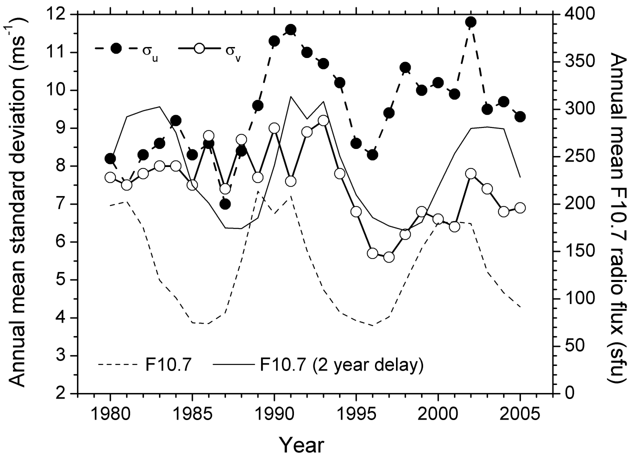

Fig. 6. Time series of annual mean σ_u and σ_v in the period range 2–7 days, together with the annual mean F10.7 solar radio flux (dashed line). The solar flux, which was shifted by 2 years and 100 sfu is also added as solid line.

monthly mean standard deviations

$$\sigma = \sigma_0 + A \cdot \mathrm{yr} + B \cdot \mathrm{F10.7}, \tag{2}$$

with F10.7 as the solar radio flux, and σ being the monthly mean standard deviation of the time series filtered in the 2–30 days period interval. Equation (2) was applied to the zonal, meridional and total standard deviation. The coefficients A and B are shown in Fig. 5 for each month of the year separately. Note, however, that the respective months denote the centre of a 3-monthly time interval, so that the results for consecutive months are not independent from each other. Solid symbols denote statistically significant correlation according to a t-test.

The left panels of Fig. 5 shows the behaviour expected from the visual inspection of Fig. 4. While the zonal amplitudes increase for nearly each month of the year and each period interval, the meridional variance decreases in general. An exception are the long-period waves in summer, where no trend is visible neither in σ_u nor in σ_v. The different trends in zonal and meridional amplitudes result in weaker trends in the total standard deviation. An exception is a strong positive trend in σ_u in the 3–7 days period range, and the σ_h trend is also positive then.

The right panels of Fig. 5 show the PW dependence on solar activity. The correlation is, for some winter months, significant for some period intervals. The long-period oscillations with periods of more than 7 days show weak coefficients in summer, which is understandable since the corresponding PW generally show small amplitudes then. Partly positive correlation is found in winter. The zonal component of the 2–3 and 3–7 days period PW show generally positive correlation, with large values especially in summer. But these summer correlations are, with one month as an exception, not significant. Visual inspection of Fig. 4 indicates that the maximum amplitudes are not found during solar maximum, but few years later, which is especially the case with the 2–7 days period interval PW. We again show annual mean σ_u and σ_v in Fig. 6, together with the F10.7 solar radio flux and the same radio flux, which was shifted by 2 years. Visually, the σ_u and σ_v curves fit better to the shifted flux than to the original flux. Applying Eq. (2) to the standard deviation time series but allowing for a delay with respect to the solar cycle, we obtain strongest and most significant solar cycle dependence when a delay between 1 and 3 years is taken into account. This is shown in Fig. 7. For the period range 2–7 days (left panels) taking into account a one or two year delay gives nearly the same response in the zonal component, while for the meridional component a 3-years delay would result in an even stronger correlation in summer. In the case of the longer-period PW (right panels) the results are less conclusive. The zonal component (Fig. 7c), with a delay of 3 years, gives a good correlation in late winter/spring. But a delay of 1 or 2 years also give significant correlation in one month each. In the meridional component no clear effect of a shift by one year is visible, and the correlation especially in winter decreases when a longer delay is considered. We may conclude that in summer there is an indication for a delayed response of the short-period (2–7 days) wave activity to the solar cycle. A physical reason for such a delay (if there is one, and the effect is not only due to the relative shortness of the time series) is unclear. Note, however, that von Zahn and Berger (2006) indicated a similar delay in noctilucent cloud variability in the summer mesopause region.

3.3 Long-term trends of the differences of horizontal standard deviations

Figure 4 and the left panel of Fig. 5 indicate that, while the long-term average total variance does not change very much, the horizontal components do often show a long-term trend in opposite directions, so that the difference between zonal and meridional variability might provide an even clearer signal of potential long-term variations. This is suggested especially by the lowermost left panel in Fig. 4 and from Fig. 5a, b for the period range 2–7 days. There is a decadal variability of both σ_u and σ_v, lagging the solar cycle by about 2 years with the same sign for the zonal and the meridional component. Therefore, considering the difference $\Delta\sigma = \sigma_u - \sigma_v$ will at least partly take out the decadal variation, and may more clearly show the long-term behaviour. As an example, in Fig. 8 we present the seasonal and annual mean differences of the zonal and meridional standard deviations in the period intervals 2–7 and 7–30 days, calculated from the monthly means. A linear fit

$$\Delta\sigma = c + d \times \mathrm{yr} \quad , \tag{3}$$

gives an increase of d=0.15±0.02 ms^{-1} yr^{-1} and d=0.08±0.02 ms^{-1} yr^{-1} for the annual mean $\Delta\sigma$ in the period bands 2–7 and 7–30 days, respectively, with correlation

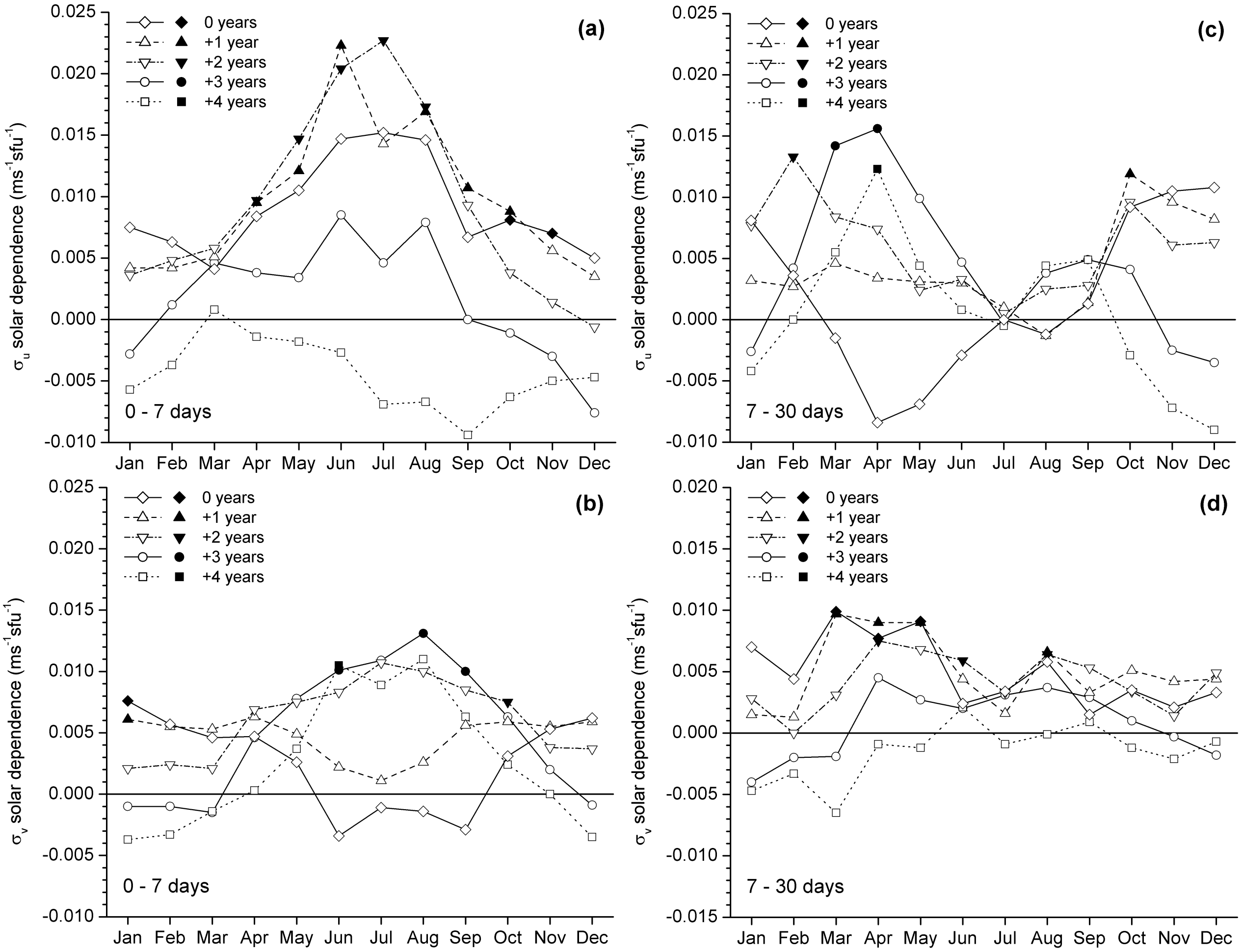

Fig. 7. Solar cycle dependence (coefficients B from Eq. 2) for the standard deviations of the zonal (upper panels) and meridional (lower panels) daily mean wind filtered in the 2–7 (left panels) and 7–30 (right panels) period intervals. The F10.7 time series has been shifted with respect to the winds by 0–4 years, i.e. a shift of one year means that the 1990 F10.7 value is compared with the winds in 1991 etc. Solid symbols denote statistically significant correlation according to a t-test.

coefficients r=0.77 and r=0.63. This increase is, for the 2–7 day period window, visible for each season (d=0.10, 0.13, 0.19, 0.14 ms^{-1} yr^{-1} for December–February (DJF), March–May (MAM), June–August (JJA), September–November (SON), each of these values is significant at the 95% level according to a t-test). For the longer periods (7–30 day, Fig. 8b) there is not such a clear trend (d=0.11, 0.09, $-$0.02, 0.11 ms^{-1} yr^{-1} for DJF, MAM, JJA, SON) especially in summer, see also Fig. 5a, b, but the DJF and SON trends are positive and significant. This again is connected with the weak PW activity in summer.

Considering especially the seasonal and annual mean values of the 2–7 period band PW in Fig. 8a, visual inspection indicates a sort of climatic shift around 1990, and small trends before and after that time. Figure 8 also shows fits of a ramp function (RAMPFIT, Mudelsee, 2000) to the annual and seasonal $\Delta\sigma$ time series, which allows the determination of starting and end point of a transition. RAMPFIT allows checking the validity of the ramp function fit through analysis of the weighted residuals, and provides uncertainties through bootstrap resampling. The results in Fig. 8a indicate that there is a transition starting around 1987/1988 in each season. Note, however, that for winter (DJF) the validity of the ramp function is questionable, however, generally in winter the amplitudes are smaller than in summer. The duration of this transition differs. In some cases the fit indicates a relatively quick transition (MAM and annual mean). But in summer and autumn the transition is very smooth, and the uncertainty of the starting and end point is 4 and 3 years, respectively, so that actually no clear conclusion on the real form of the change can be drawn. Note also that the quick transition of the annual average is mainly due to the 1991 $\Delta\sigma$ value, which again is dominated by the large amplitudes of the QTDW in this year (e.g. Jacobi, 1998). Removing

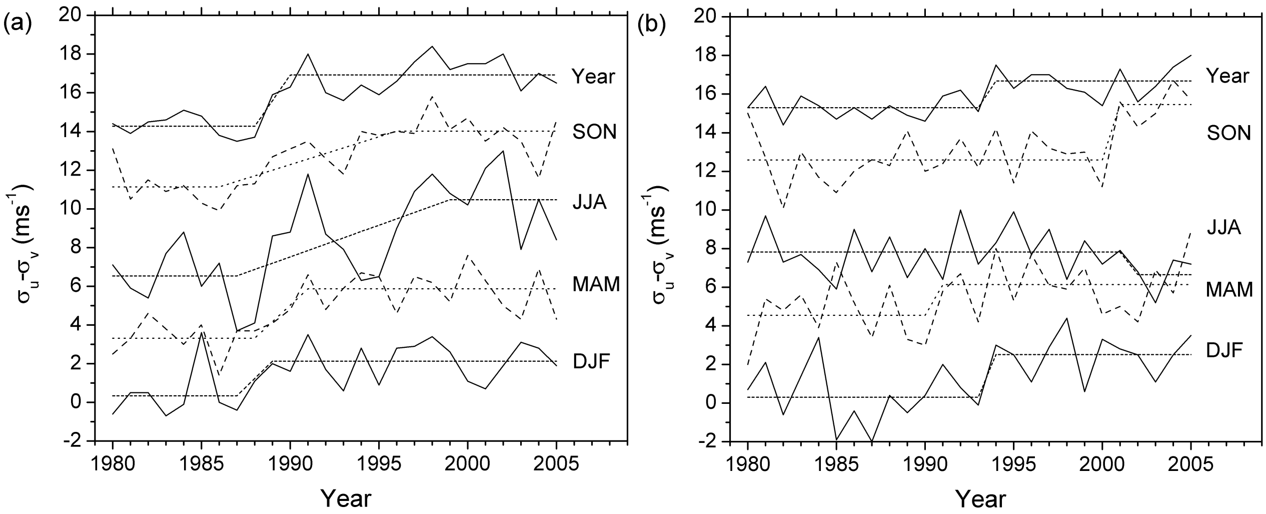

Fig. 8. Seasonal mean differences of zonal-meridional standard deviation $\Delta\sigma=\sigma_u-\sigma_v$ of filtered MLT winds **(a)** 2–7 days window, **(b)** 7–30 days window. The time series have been shifted with respect to each other by adding $3\,\mathrm{ms}^{-1}$ (MAM), $6\,\mathrm{ms}^{-1}$ (JJA), $11\,\mathrm{ms}^{-1}$ (SON) and $14\,\mathrm{ms}^{-1}$ (annual mean). Results of a ramp function regression after Mudelsee (2000) are added.

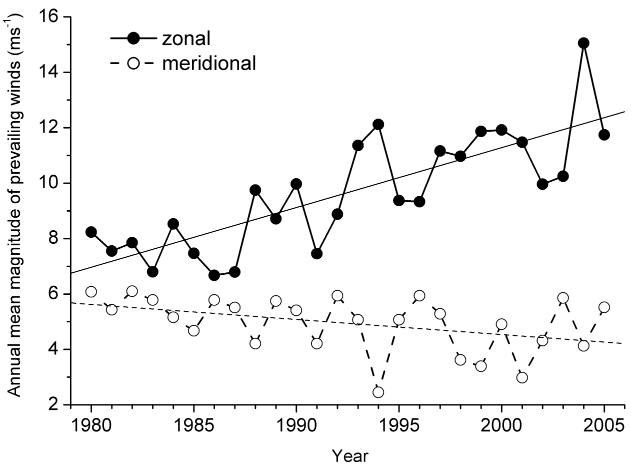

Fig. 9. Annual mean magnitudes of zonal and meridional prevailing winds over Collm.

of this data point would lead to a fit with a much slower transition that lasted until 2000, although the starting point of the transition (1988) remains the same. Thus, we may only conclude that there is an indication for a change in PW amplitudes, which probably began after the middle 1980s, but cannot draw final conclusions about the progress of this change in the following years.

For the longer periods (Fig. 8b) the results differ between summer and winter, and the changes are generally not so well expressed. In summer the tendency is even negative and the change is not significant. In winter and spring there is an uncertainty of the begin/end of the transition of 3/1 and 6/4 years, respectively, so that, taking into account the weak overall change, we cannot draw conclusions on nature of a change. This is also the case with autumn, a fitting procedure suggests a change for the last years of the time series, but we cannot see the real form of this change. Note that, on an annual average, there is a positive linear trend for the 7–30 day period range PW also, however, we cannot clearly identify whether this is a linear trend or whether there is a time interval when a stronger transition occurs.

PW in the mesosphere are generally assumed to be propagating upwards from the lower atmosphere or are the result of instability of the mesospheric jets, the latter is especially the case with the quasi two-day wave. This raises the question whether some climatic change around between the 1980s and later years is visible in tropospheric or stratospheric parameters, too. Baumgaertner et al. (2005, their Fig. 16) showed PW 1 amplitudes from NCEP/NCAR data at 78° S, which exhibited a clear increase around 1990. Also, the change of trends in ozone laminae (Lastovicka and Krisan, 2006) indicate that there is a change in stratospheric PW activity that may be connected with the MLT wave activity.

3.4 Connection with mean wind trends and potential artefacts

Earlier analyses of Collm MLT winds have shown a long-term increase of the zonal prevailing wind more or less throughout the year and a decrease of the magnitude of the meridional prevailing wind both in summer and winter (Bremer at al., 1997; Jacobi and Kürschner, 2006), which is in correspondence with results from other midlatitude stations (e.g. Middleton et al., 2002). To demonstrate the trend, in Fig. 9 we present annual mean zonal and meridional

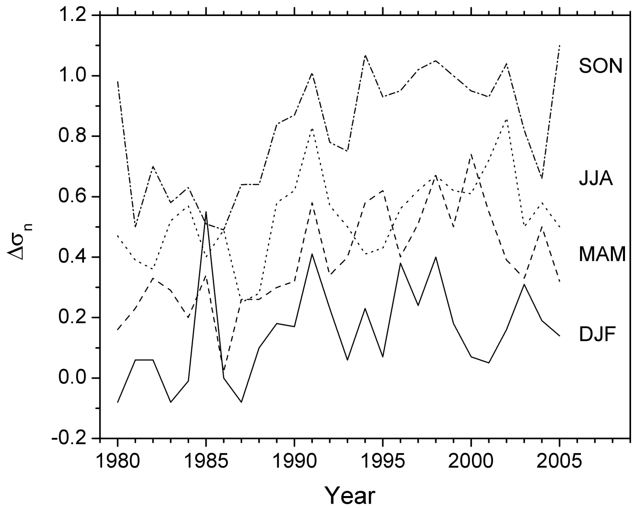

Fig. 10. Time series of 3-monthly mean differences of zonalmeridional standard deviations of MLT winds, divided by the magnitudes of the 3-monthly mean prevailing horizontal winds.

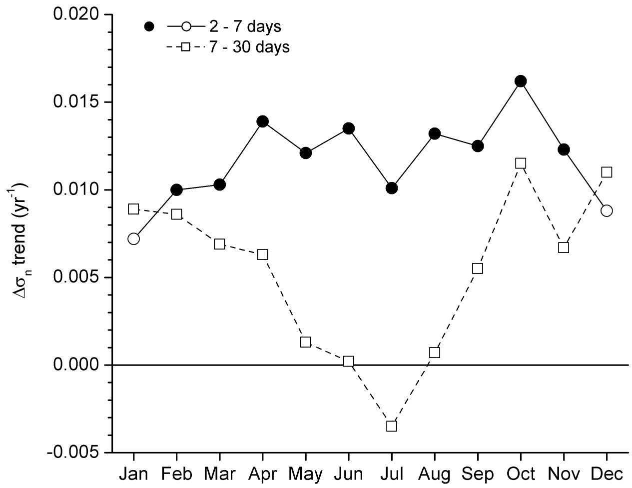

Fig. 11. Long term trend coefficients (B from Eq. 2) for the zonal-meridional standard deviation difference, which was divided by the magnitude of the prevailing wind, for each month of the year, and for 2 different period intervals.

prevailing wind speeds that are based on the monthly mean zonal (v_{oz}) and meridional (v_{om}) prevailing winds, which have been calculated using Eq. (1) on the basis of the monthly median half-hourly mean winds, i.e. using a composite day for each month as in Jacobi and Kürschner (2006). The annual means have been calculated from the monthly absolute values:

$$\overline{v}_{oz} = \frac{1}{12}\sum_{i=1}^{12}\left|v_{oz,i}\right|, \quad \overline{v}_{om} = \frac{1}{12}\sum_{i=1}^{12}\left|v_{om,i}\right| \quad , \tag{4}$$

with index i indicating the respective month. In Fig. 9 these annual mean magnitudes of the zonal and meridional prevailing winds are shown as time series. There is a long-term increase of the zonal component (d=0.22±0.03 ms^{-1} yr^{-1}, r=0.80) and a somewhat weaker decrease of the meridional wind magnitude (d=−0.05±0.02 ms^{-1} yr^{-1}, r=0.41). Jacobi and Kürschner (2006) also showed monthly and seasonal trends. The trends shown in Fig. 9 point in the same direction than the standard deviation trends do. This raises the question whether the change in absolute values of the prevailing wind may be responsible for the variance trends, i.e. whether the presented results on PW trends may be contaminated by artefacts if the uncertainty of the daily mean winds, which contributes to the variance, is dependent on the absolute wind value itself.

We have calculated the variance, as an expression of PW activity, from the daily mean wind values. Generally, the error in estimating winds using the similar fade method is, among others, dependent on the accuracy of determining the time differences between corresponding fading extreme values at the 3 receivers. This accuracy on the one hand decreases with increasing wind velocity, because the velocity and the time differences are reciprocal and the accuracy of measured time differences (0.25 s) is assumed constant. On the other hand high values of velocity are mostly connected with higher fading frequency and therefore more individual measuring points referred to the measuring interval (30 min). These two effects show a kind of compensation. Thus it appears reasonable to assume that the accuracy is, as a first approximation, independent on the wind velocity itself, which means that independently on the daily mean wind we may expect errors in analysing these wind values that are of similar order of magnitude and we do not expect that the detected PW trends are artefacts. To test this, we scaled the monthly $\Delta\sigma$ values with the magnitude of the monthly mean winds

$$\Delta\sigma_n = \frac{\sigma_u - \sigma_v}{\sqrt{(v_{oz})^2 + (v_{om})^2}}. \tag{5}$$

If the trends are preserved in $\Delta\sigma_n$, this is an indication that they are not dependent on the mean wind and thus are not the result of artefacts. Examples for seasonal $\Delta\sigma_n$ (2–30 days period) are shown in Fig. 10. Although the interannual variability has increased in some cases (which is understandable, because the prevailing wind is small in some months), in each season there still remains a positive trend. Note that the trends in this overall (over the entire period range 2–30 days) standard deviation are dominated by the shorter periods in summer and the longer periods in winter, so that the results for the 7–30 days period PW in summer, which point in a different direction, are not visible in Fig. 10. The trend coefficients A after Eq. (2) are shown in Fig. 11 for each month (again representing 3-monthly means each) for the two period intervals 2–7 and 7–30 days. The results from the analysis of the unscaled standard deviations in Fig. 8 are preserved. While the short-period PW show a positive $\Delta\sigma$

and $\Delta\sigma_n$ trend in each month, the long-period waves show a positive trend in winter, and a weak or negative one in summer. Note that the results for the long-period waves are not significant (open symbols). We may conclude that the long-term trends in monthly mean winds do not seriously affect the PW analysis results, and we can, at least qualitatively, consider the data trends presented in Fig. 8 as realistic and not as a result of artefacts.

4 Conclusions

Analysing 26 years of long-period wind variations over Collm, which may be interpreted as the signal of PW, we found a signal of long-term trends during the last 2–3 decades, which is in opposite direction when the two horizontal components are considered, namely in general the zonal wind fluctuations increase while the meridional wind fluctuations decrease in amplitude, so that their differences increase. These trends are accompanied by corresponding trends of the absolute values of the mean winds. Analysing the PW activity in detail indicates that the trends may be non-linear, with a transition to larger amplitude differences starting in the late 1980s. This is relatively well visible in the shorter periods (up to 7 days), while the winter PW with longer periods (7–30 days) do not show such a behaviour, and the summer long-period PW amplitudes are even weakly decreasing. However, the quasi 10-day and 16-day waves are not able to propagate directly from the lower atmosphere to the summer MLT, but only through the equatorial waveguide or from the winter to the summer MLT, so that their amplitudes then are small. Thus on an annual average we have an increase of PW activity in each period range considered.

Already relatively early it was shown that obviously there are trends of MLT parameters (Bremer et al., 1997), and also changes in long-term trends of mean winds and tides over Collm have been reported (Jacobi et al., 1997). Recently it could be shown that these changes are of hemispheric scale, since they are seen in different long-term MLT wind time series concomitantly (Portnyagin et al., 2006). Of specific interest has been the long-term decrease of the semidiurnal tidal amplitudes since the beginning of the MLT wind measurements. The more recent data show that this decrease has levelled off, or even turned to an increase. This is in correspondence with recent literature results from the Southern Hemisphere (Baumgaertner et al., 2005) and also with magnetometer measurements presented by Jarvis (2005). We may conclude that there are probably structural changes of long-term trends in some MLT parameters, which may together represent a signature of changes in trends of the global circulation and which may affect the PW at time scales of the quasi 2- and 5-day wave.

There are several other atmospheric parameters that also display changes in the long-term trend. For example, there is a tendency towards a slowdown of ozone decrease or a recovery of the ozone layer (visible in the total ozone content as well as in upper stratospheric ozone) which possibly began around 1996 (Reinsel et al., 2002, 2005; Newchurch, et al., 2003). The total ozone and ozone laminae trend patterns indicate a corresponding change in the sign of trends in the mid-1990s, its origin being probably changes of the trends in stratospheric dynamics (for example, the midlatitude winter heat flux at 100 hPa increases since the mid-1990s) and in a decrease of chlorine loading (Dhomse et al., 2006; Krizan and Lastovicka, 2005). Wild et al. (2005) reported that global dimming, i.e. the decline in solar radiation has changed to a solar brightening after 1990, which is consistent with changes in cloudiness and atmospheric transmission, and may also influence global the circulation. Stratospheric planetary wave activity also show a change in the 1990s (Baumgaertner et al., 2005) and Randel et al. (2006) reported an increased Brewer-Dobson circulation beginning in 2001.

However, at present we may only speculate here about the physical reason for the MLT wave behavior and whether this is connected with changes in the lower atmosphere. It may be possible that there is a meridional shift in the PW waveguide, which may alter the meridional structure of the PW so that we obtain a change in the ratio of meridional and zonal amplitudes. This may be superposed by long-term changes in wave forcing and propagation conditions that affect the registered amplitudes. To get more insight into possible processes would require modeling of the middle atmosphere, and assimilating the typical tropospheric and stratospheric conditions, which, e.g. expressed through the NAO and AO indices, also show changes, or changes in trends. There is an indication that the MLT circulation in winter is correlated with the NAO (Jacobi and Beckmann, 1999), therefore modeling of the MLT response to tropospheric circulation changes an interesting task for further research.

To conclude, we have shown that the midlatitude MLT PW activity as seen from LF D1 wind measurements over Collm shows a trend, with an indication for a transition around after the late 1980s for waves with periods shorter than 7 days, i.e. mainly for the quasi 2- and 5-day wave. Long-period waves also show long-term trends, which are weaker, so we could not draw conclusions whether these trends are linear or not.

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