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Trends and climatic shifts in mesosphere/lower thermosphere planetary waves Collm (52°N, 15°E)

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Abstract

Long-period oscillations in the period range between 2-30 days, interpreted as planetary wave (PW) signatures, have been analysed using daily upper mesosphere/lower thermosphere wind measurements near 90 km over Collm (52°N, 15°E) in the time interval 1980-2005. Strong interannual and interdecadal variability of PW are found. Since the 1990s, a tendency for larger zonal amplitudes compared to meridional ones, has been observed, thus long-term trends are visible, which are positive in the zonal component, but negative in the meridional component. The change appears in a stepwise manner, so that a sudden change of the mean is visible rather than a linear trend. The behaviour of the upper middle atmosphere winds is similar to analysed wave changes in the stratosphere, indicating a coupling of the atmospheric layers through planetary waves.

Zusammenfassung

Mit Hilfe von täglichen Windmessungen im Mesopausenbereich bei 90 km werden langperiodische Schwankungen im Zeitbereich von 2-30 Tagen untersucht, die als das Signal planetarer Wellen gelten. Im Zeitraum 1980-2005 werden deutliche Schwankungen von Jahr zu Jahr als auch langfristige Trends gefunden. Einer Zunahme der zonalen Komponente der Schwankungen seit 1990 steht eine Abnahme der meridionalen Komponente gegenüber. Diese Änderung erfolgt in rascher Form, so dass sich die Änderung der Zirkulation im Mesopausenbereich als klimatische Verschiebung, und weniger als Trend darstellt. Das Verhalten der Dynamik im Mesopausenbereich korrespondiert mit möglichen Änderungen klimatischer Parameter in anderen Schichten der Atmosphäre und weist auf eine Kopplung atmosphärischer Schichten untereinander hin.

Introduction

Wind oscillations at planetary wave (PW) periods (2, 5, 10, 16 days) in the mesosphere/lower thermosphere (MLT) region, which has 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. 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 in atmospheric layers below the MLT region. Some indication is given 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.

To date there are only few measurements of PW available, which cover a sufficiently long time interval to draw conclusions on PW trends in the MLT region. 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., 1997a). Lastovicka and Krizan (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. Assuming that this ozone behaviour is dynamically forced, they compared this behaviour with MLT winds presented by Bremer et al. (1997). Recently, Portnyagin et al. (2006) have presented mean MLT winds at Northern Hemisphere midlatitude stations and found that there is a structural change in MLT prevailing wind and semidiurnal tidal amplitude trends around 1990. Considering the stratosphere, Baumgaertner et al. (2005, their Figure 16) showed PW 1 amplitudes from NCEP/NCAR data at 78°S, which exhibited a clear increase around 1990.

Here, estimates of PW activity from the mesopause wind measurements at Collm, Germany, will be presented and analysed with respect to long-term trends. For this purpose, the measured oscillations of the 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 of Jacobi et al. (1998), but here we include 13 years of additional data, i.e. the time interval 1996-2005 (and January 2006 also, but this data is only used to present time series), and reanalysed data from 1980-1982. This means a doubling of the length of the time series compared to the one in Jacobi et al. (1998), which now allows the detection of long-term trends rather than tendencies only, an investigation of a possible solar cycle effect, and the construction of a more reliable long-term mean climatology. Note that the measurement principle has kept constant during the entire time interval 1980-2005, which allows the detection of trends with little danger of artefacts contaminating these.

One has to keep in mind that the wave parameters itself (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, 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.

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 and meridional 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 daylight hours 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 most time of the winter the measurements are possible during the whole day. The reflection height is measured on 177 kHz using travel time differences between the ground wave and the ionospherically reflected sky wave. The differences are obtained using side-band phase comparisons of both wave components in the modulation frequency range near 1.8 kHz (Kürschner et al., 1987).

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 for the horizontal wind components as a vector, assuming clockwise circularly polarized tidal wind components (Kürschner, 1991):

$$v_z = u + b\ \sin(\omega t) + c\ \cos(\omega t) + \varepsilon\ ,\quad v_m = v + b\ \cos(\omega t) - c\ \sin(\omega t) + \varepsilon\ , \qquad (1)$$

and minimising ε, while u and v are the daily zonal and meridional prevailing wind values, and $\omega = 2\pi/12h$ 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 cases only leads to an additionally offset error of the prevailing wind components which will be filtered out for the most part if long-period variations are considered. The semidiurnal tidal amplitudes and phases can be taken from the regression analyses results (coefficients b, c), but they are not regarded in this investigation.

Note that the reflection height is not directly used here. The virtual reflection height h´ ranges roughly between 85 and 105 km on a monthly average. After sunrise h´ decreases rapidly due to increase in E- and D-region ionisation. Since absorption during the day is large, partially no measurements are possible then. In the late afternoon h´ rises slowly to its nighttime values. Additionally, in winter after midnight some times very high values of h´ are found as a result of the split of the reflected sky wave into the ordinary and the extraordinary magnetoionic component due to the earth magnetic field. 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 and in winter months large vertical gradients of semidiurnal tidal wind amplitude and phase would influence the results of the analysis due to apparent wind variations while the reflection height changes. Therefore only those half-hourly mean wind values are included, when the mean monthly virtual reflection height has values that are sufficiently close to the mean nighttime value of about 95 km. Further details may be found in Jacobi et al. (1998). Note that the real height h is lower than the virtual height due to the travel time retardation of sky waves near the reflection range in the ionosphere. The differences amounts to about 5 km at h = 90 km (h´ = 95 km) so that our daily winds refer to an approximate altitude of 90 km.

An example of daily zonal and meridional prevailing winds in the year 2005 is given in Figure 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. In this case, the long-term mean seasonal cycle, with northerly winds in summer, and small (mainly southerly) winds in winter (e.g. Portnyagin, 1986; Middleton et al., 2002), is not so well expressed here as in other years .

The time series of daily prevailing winds include, besides the seasonal variation, much 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. A part of this variability, however, is owing to PWs. To investigate this, we applied a Lanczos filter with 100 weights to the time series of daily zonal prevailing winds, using different period bands of 0-3, 3-7, 7-12, 12-30, and 0-30 days, to analyse the variability of the wind field in these period intervals. Note that the data base consists in daily prevailing wind values, so that a period band of 0-3 days in reality means variability at periods between 2 and 3 days, however, including some additional spectral energy coming from shorter periods through aliasing.

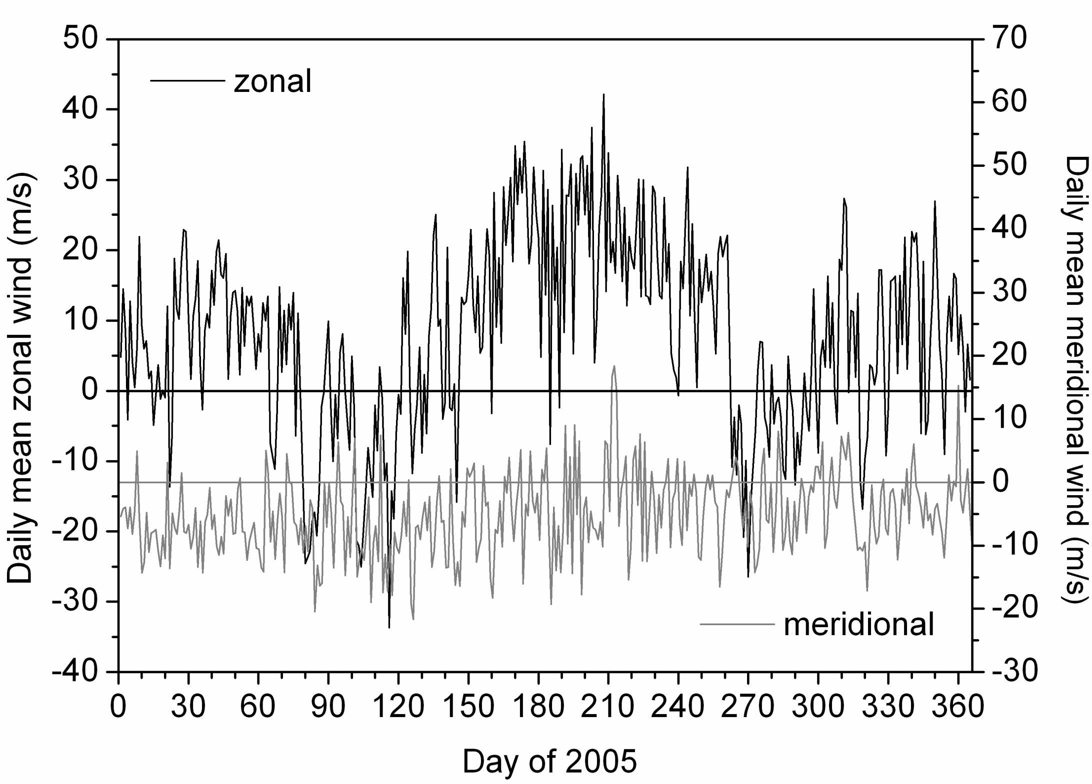

Figure 1: *Examples of time series of daily zonal (positive eastward) and meridional (positive northward) prevailing winds during 2005.*

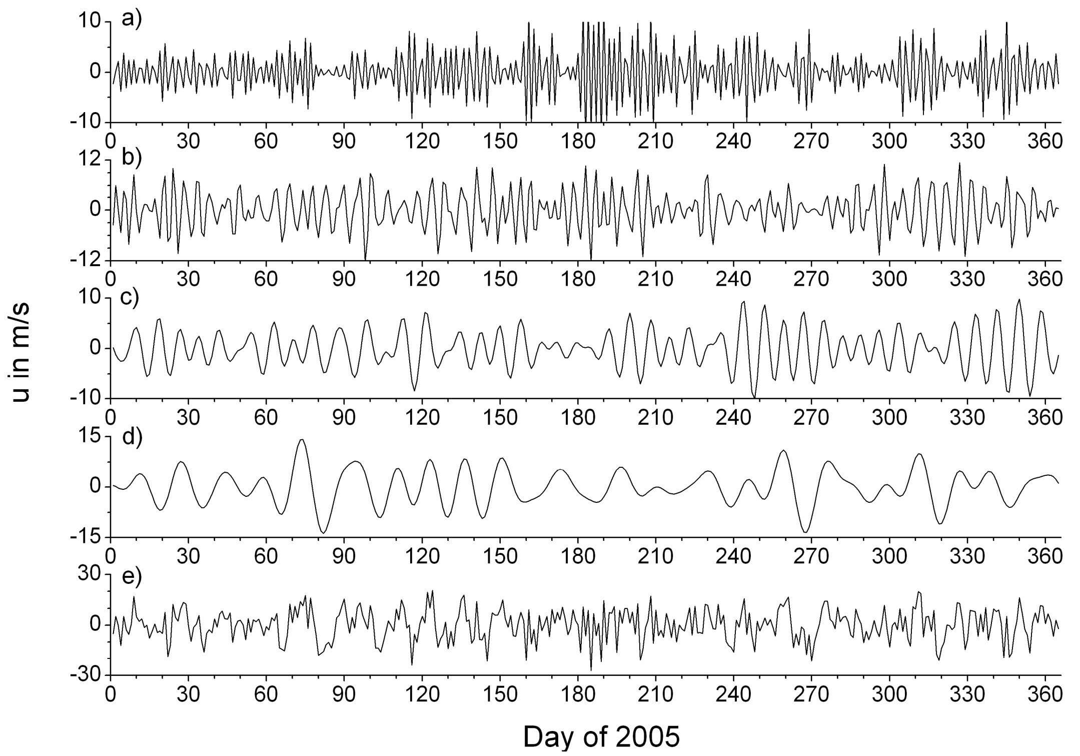

Figure 2: *Time series of filtered daily zonal winds in 2005 using different period bands a) 2-3 days, b) 3-7 days, c) 7-12 days, d) 12-30 days, e) 2-30 days.*

Examples of filtered time series of the zonal wind, again for the year 2005, are shown in Figure 2. There is a tendency that the short-period waves (2-3 days period range, Figure 2a) maximise in summer at midlatitudes, which is a hint that this is really a signature of the quasi-2-day wave (QTDW), which is mainly a summer phenomenon (Muller and Nelson, 1978). 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 the estimated amplitude is too small. There is, however, indication that the QTDW phase is, to a certain degree, phase locked (Clark et al., 1994; Jacobi et al., 1997b), so that the filtering of the QTDW through the use of daily prevailing winds is not very variable and the year-to-year variability of our resulting variance thus reflects QTDW variability. Of course, the results concerning the QTDW can be considered as qualitative only. At medium periods (3-7 days, Figure 2b), potentially including the quasi 5-day wave, the seasonal variability appears less strongly expressed, while the long-period variations (7-12 days and 12-30 days, which serve as proxies for the quasi 10- and 16-day wave) show a tendency towards larger amplitudes in winter. This behaviour is typical for PWs, 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 these filtered time series daily values of the standard deviation σ are calculated using a 48-day time interval each, and the respective value is attributed to the centre of the interval. From these data monthly and annual means are calculated. The procedure is similar to that described in Jacobi et al. (1998), but slightly different period ranges are used here with the filtering of the time series.

Long-term mean wave activity and interannual variability

Figure 2 only gives an example of the seasonal behaviour of wind variability in the long-period range. The long-term mean variability of the total standard deviation, being the square root of the sum of the variances of zonal and meridional winds in the respective period windows, are given in Figure 3 for each month of the year. Values are monthly means averaged over the years 1980-2005. Note that a monthly mean here is constructed from daily means that in turn are taken from a 48-day data window, so that in fact the data of the preceding and following months are to a certain degree included in the respective monthly mean. This provides some additional smoothing of the seasonal cycles shown in Figure 3. The expected variability of the long-period variations in the respective period windows is well visible in Figure 3. The signature of the QTDW maximises during summer months and the 5-day wave shows a slight tendency to peak there also. The long-period waves maximise in winter, but are nevertheless visible during summer, too.

Time series of the zonal, meridional and total variance in the different period intervals are shown in Figure 4. The variance instead of the standard deviation is used here to aim at a more clearly expression concerning the year-to-year variations. The left and right hand panels show the data for January and July, respective, being characteristic for winter and summer conditions. A striking feature is the strong interannual variability. Several panels show a quasi decadal variation with maximum values around 1990. Particularly impressively this variation is visible at the summer 3-7 days period range. Some time series, in particular for the long-period waves (10-day wave, 16-day wave) at times show a clear year-to-year variability. Comparison with the equatorial quasi-biennial oscillation (QBO), however, did not show an unambiguous correlation. A clear long-term trend of the total variance (the solid symbols) is not visible.

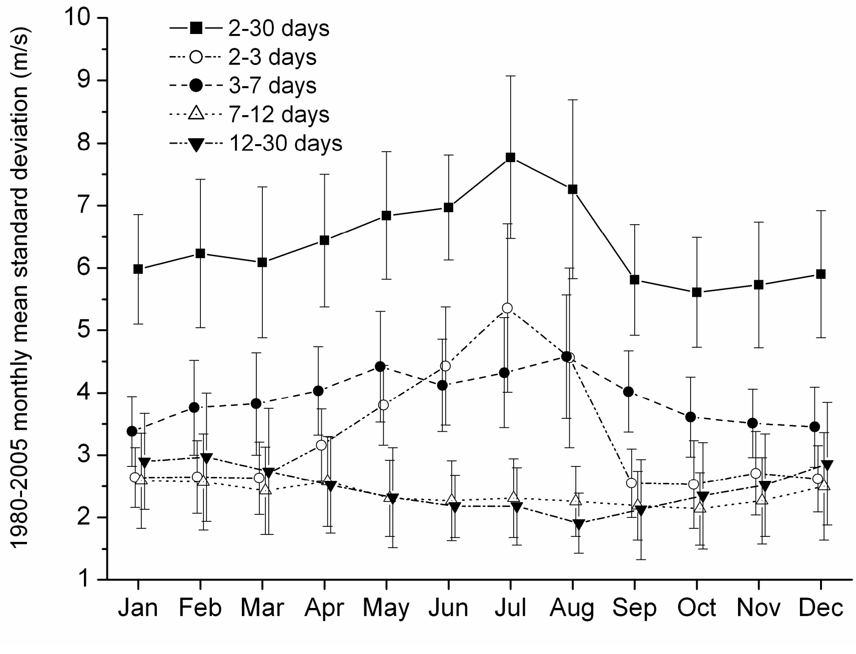

Figure 3: *1980-2005 mean monthly mean standard deviation of daily winds at different period bands.*

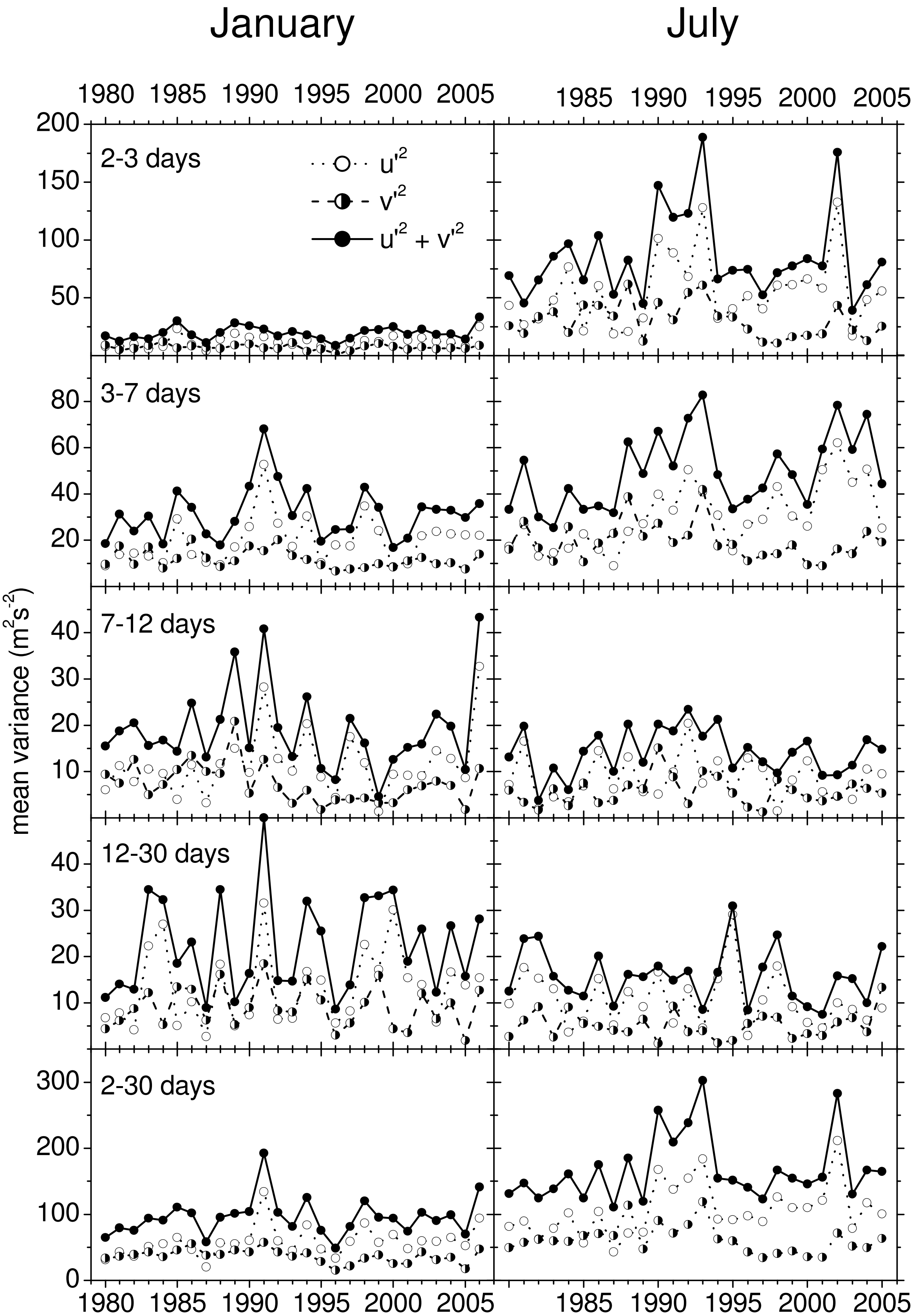

Figure 4: *Time series of zonal (u'²), meridional (v'²) and total (u'+v'²) wind variance for winter (left panels) and summer (right panels), for different period bands. Note the different scaling of the ordinate in the respective panels.*

Figure 4 also shows that, on average, the zonal wind variability is stronger than the meridional one. This is true for each period window considered here, however, there is some indication that, more expressed at short periods, this difference is larger for the later years (since about the 1990s) than for the early years of the measurements, particularly visible as dominating phenomenon in the period range 2-30 days in the bottom left-hand and right-hand panels of Figure 4, too. Taking into account that there is no clear trend for the total variance, this means that during the last 2-3 decades the zonal wind component of PW increased, while the meridional ones decreased. In the following section this behaviour will be analysed in more detail.

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

From some of the time series in Figure 4 a maximum of wind variance around 1990 is visible, which roughly coincides with the maximum of solar cycle 22. To analyse, whether this maximum of the variance around 1990 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 monthly mean variances

$$\sigma^2 = \sigma_0^2 + \mathrm{A} \cdot \mathrm{year} + \mathrm{B} \cdot \mathrm{F10.7}\ , \qquad (2)$$

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. Eq. (2) was applied to the zonal, meridional and total variance. The coefficients A and B are shown in Figure 5 for each month of the year separately. Solid symbols denote statistically significant correlation according to a t-test.

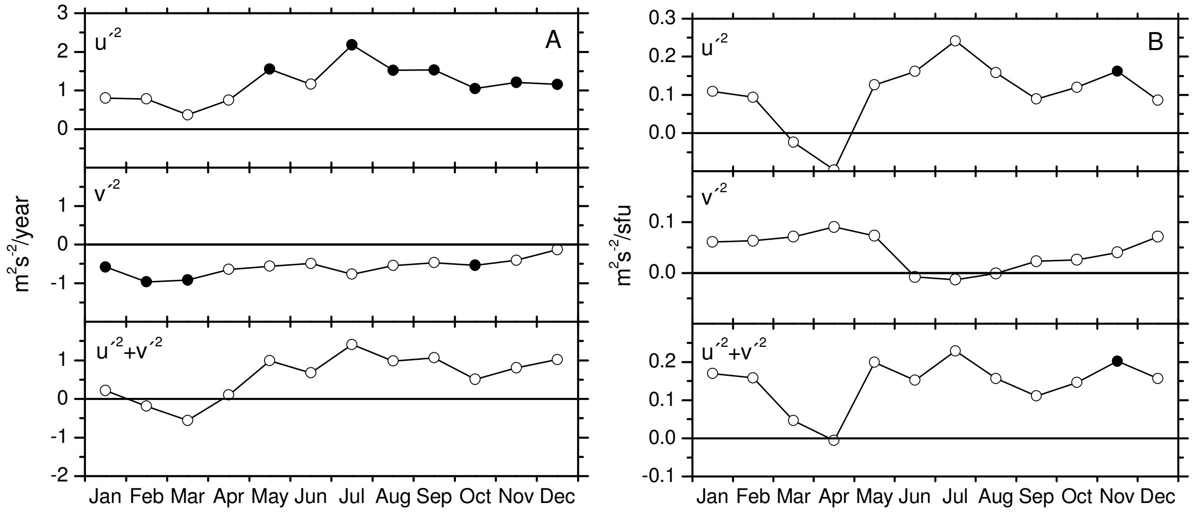

Figure 5: *Trend coefficient A (left panel) and solar cycle dependence coefficient B (right panel) of Eq. (2) for variance in the 2-30 days period interval, derived from a multiple regression analysis.*

The left panel of Figure 5 shows the behaviour expected from the visual inspection of Figure 4, while the zonal variance increases for each month of the year, the meridional variance decreases. This results, for the total variance, in weak trends, or inconclusive behaviour over the year, with insignificant positive and negative trends for different months.

The right panel of Figure 5 shows the PW dependence on solar activity. The correlation is not significant except for one month; although for the zonal component the coefficients are quite large in summer, the strong interannual variability does not allow conclusions on a possible influence of the solar cycle on MLT wave activity. The mean winds (Jacobi and Kürschner, 2006) do show an influence of the solar activity, but the variability of winds, which is a more indirect parameter since wave propagation is dependent on the mean flow and therefore a solar effect on PW would be a secondary phenomenon, does not exhibit this clear behaviour.

Figure 4 and the left panel of Figure 5 indicate that, while the long-term average total variance does not change, the horizontal components do show a long-term trend in opposite directions, so that the difference between zonal and meridional variability might provide a clear signal of potential long-term variations. As an example, in Figure 6 we present the annual mean differences of the zonal and meridional standard deviations $\Delta\sigma = \sigma_{zon}-\sigma_{mer}$ in the period interval 2-30 days, calculated from the monthly means. A linear fit

$$\Delta\sigma = a + b \times \text{year} \ , \qquad (3)$$

gives an increase of $b = 0.12 \pm 0.02 \ ms^{-1}$, with a correlation coefficient of $r = 0.83$. This increase is visible for each period band selected. The results of the linear fits are presented in the first three columns of Table 1.

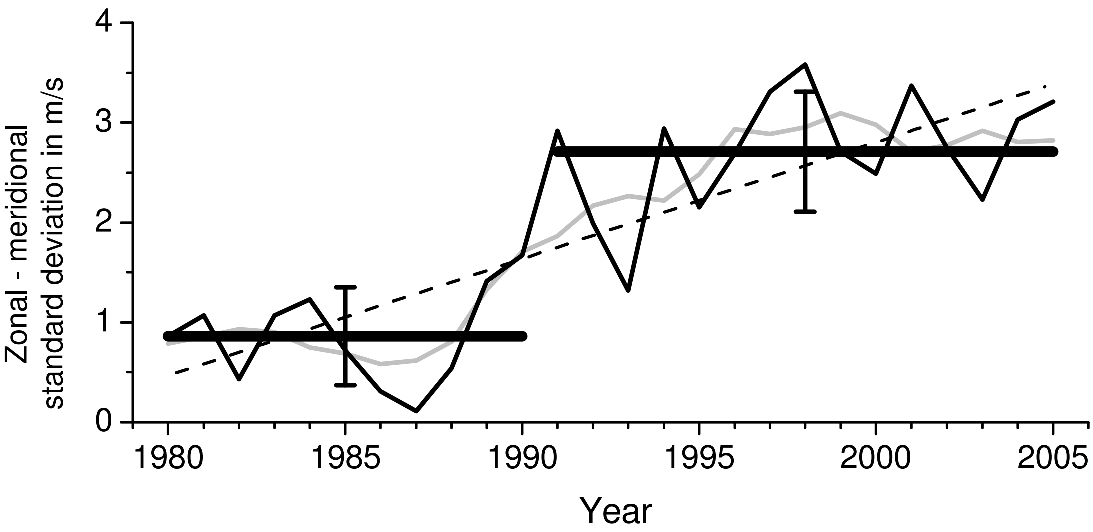

Figure 6: *Annual mean differences of zonal–meridional standard deviation $\Delta\sigma$ of filtered (2-30 days) MLT winds. A linear fit curve is added. The grey line represents a 3-year running mean of the data. Mean values and their standard deviations are also shown for the time intervals 1980-1990 and 1991-2005.*

Period interval	b ($ms^{-1}yr^{-1}$)	r	$\Delta\sigma_{80\text{-}90}$ (ms^{-1})	$s_{80\text{-}90}$ (ms^{-1})	$\Delta\sigma_{91\text{-}05}$ (ms^{-1})	$s_{91\text{-}05}$ (ms^{-1})	$\Delta\Delta\sigma$ (ms^{-1})
2-3 days	0.066	0.74	0.34	0.45	1.43	0.38	1.09
3-7 days	0.073	0.74	0.23	0.48	1.38	0.52	1.15
7-12 days	0.040	0.65	0.42	0.24	1.07	0.40	0.65
12-30 days	0.040	0.55	0.68	0.44	1.30	0.49	0.62
2-30 days	0.117	0.83	0.86	0.49	2.71	0.60	1.86

Table 1: *Linear trend parameter b from Eq. (3) for annual mean zonal–meridional standard deviations of MLT winds together with the correlation coefficient r. Also given are mean annual mean $\Delta\sigma_{80\text{-}90}$ and $\Delta\sigma_{91\text{-}05}$ until 1990 and after 1990, with standard deviations s, and the difference $\Delta\Delta\sigma = \Delta\sigma_{91\text{-}05} - \Delta\sigma_{80\text{-}90}$, for different period bands. Residuals between the difference of the 4th and 6th column and the last column are due to rounding errors.*

Analysis of a possible climatic shift around 1990

Figure 6 is an example of the long-term behaviour of $\Delta\sigma$ and shows a clear increase of the difference between zonal and meridional long-period wind variations. However, as can be seen from the figure, in particular from the slightly smoothed data, the increase of this difference is probably not linear, but rather shows a stepwise behaviour, with a climatic shift around a certain time, and small trends before and after that time. From visual inspection we assume that this shift appears around 1990, and in the following we compare the $\Delta\sigma$ data from 1980-1990 with those from 1991-2005. Long-term mean of annual mean standard deviations and the standard deviations of these means are also shown in Figure 6. A significant difference is visible. Again, this stepwise change around 1990 is evident for each period window analysed here (see the last 5 columns in Table 1).

PWs 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 the case especially with the quasi two-day wave. This raises the question whether some climatic change around 1990 is visible in tropospheric or lower stratospheric parameters, too. Baumgaertner et al. (2005, their Figure 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.

Stratospheric analyses

For analysis of stratospheric PW activity and the detection of possible similar climatic shifts, NCEP/NCAR horizontal winds at 30 hPa are used. We used the phase-difference method for analysing PW in space-time from global gridded meteorological fields through observation of the longitudinal phase change for separation (Pogoreltsev et al., 2002). The zonal harmonic decomposition for one latitude circle (52.5°N) is done using singular value decomposition, resulting in time-dependent coefficients for the cosine and sine term for each mode (zonal wavenumber m=1,2,3). Calculating the amplitude and phase from the coefficients two eastward propagating waves can be generated describing the behaviour of the field at longitudes 0°W and 90°W for m=1 and 0°W and 45°W for m=2. The phase difference of both waves at these points gives an image of the eastward and westward travelling part. An applied Fourier analysis shows the spectral behaviour for each component resulting a characteristic compositions of waves isolated from the atmospheric signals during a time segment of 48-days. The amplitude and phase of the stationary part are calculated from the two coefficients which are constant for both waves during the selected time interval. This procedure is repeated by shifting the window by one day, providing time dependent images of wave activity during selected time intervals.

Annual mean zonal and meridional stratospheric SPW1 amplitudes are shown in the upper panel of Figure 7. The curves show, as the MLT wind data does, a tendency for an increase after 1990, which is in correspondence with literature results (Baumgaertner et al., 2005). Moreover, the interannual behaviour especially of the zonal component shows, at least for the second part of the time series, e.g. after about 1990, a hint to a solar cycle connection, with, on average, weaker wave activity during solar maximum.

Note that the meridional component, in contrast to the behaviour of the MLT amplitudes, also shows an increase after 1990. A clear trend is not visible; there are several years with large amplitudes in the 1980s and few years of weak amplitudes around 2000. Thus, when calculating the difference of zonal and meridional amplitude to compare the data with Collm MLT wind ones, the possible trend or climatic shift even decreases. Zonal-meridional amplitude differences are presented in the lower panel of Figure 7. Mean values and their standard deviations are shown for the time intervals 1980-1990 and 1991-2005. Although visually the change around 1990 is noticeable, the mean values before and after 1990 differ only slightly, and this difference is not significant. Note that there is a tendency for stronger interannual variability after 1990. The grey line in the lower panel of Figure 7 represents a linear curve fit for the years 1980-1990 (correlation coefficient $r = 0.67$). The corresponding fit for the time after 1990 reveals a zero trend ($r < 0.01$). Although the linear trends are not significant at the 95% level, it indicates a possible change after 1990 also in the stratosphere.

Note that the Collm analysis, derived from one single ground-based measurement, does not include any information on SPW. However, travelling PW interact with the SPW and therefore in the MLT region may carry the signature of SPW1 variability. The corresponding change of the trend or mean level, respectively, of wave activity in the stratosphere and MLT thus indicates a possible interaction of PW in the stratosphere that leads to a coupling of middle atmosphere layers.

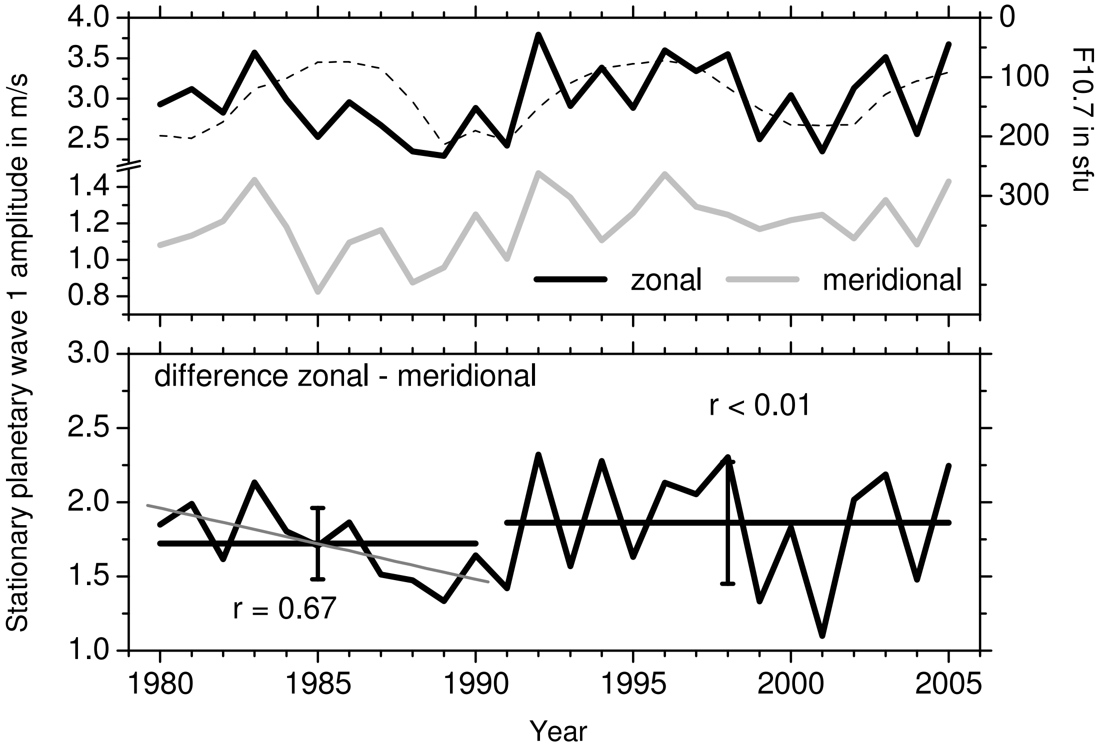

Figure 7: *Upper panel: Annual mean SPW1 amplitudes at 30 hPa, 52.5°N. Note the different scaling before and after the axis break. The F10.7 radio flux is added as a dashed line. Note that the axis orientation is reversed. Lower panel: Differences of zonal–meridional SPW1 amplitudes. Mean values and their standard deviations are also shown for the time intervals 1980-1990 and 1991-2005. The grey line represents a linear curve fit for the years 1980-1990. The corresponding fit for the time after 1990 reveals a zero trend. The correlation coefficients for the fits are also given.*

Conclusions

Analysing 26 years of long-period MLT 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 the zonal wind fluctuations increase, while the meridional wind fluctuations decrease. Analysing the PW activity in detail shows that the trend is non-linear, while before and after about 1990 weak trends are visible; a climatic shift appears between these two time intervals.

This shift occurring around 1990 corresponds with changes of other MLT parameters at that time. Relatively early it was shown that there are changes in the observed long-term trends of mean winds and tides over Collm (Jacobi et al., 1997a). Recently it could be shown that these changes are of hemispheric scale (Portnyagin et al., 2006). Of specific interest in this connection 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 magnetometer measurements presented by Jarvis (2005).

We may conclude that there are structural changes of long-term trends in some MLT parameters, which may together represent a signature of changes of trends of the global circulation.

There are other atmospheric parameters that also show a change in long-term trends. This is a tendency towards a recovery of the ozone layer (visible in the total ozone content as well as in upper stratospheric ozone) which possibly began around 1996 (Newchurch, et al., 2003; Reinsel et al., 2005). 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 in trends in stratospheric dynamics (for example, the midlatitude winter heat flux at 100 hPa increases since mid-1990s) and in a decrease of chlorine loading (Dhomse et al., 2005; 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 in reconcilable with changes in cloudiness and atmospheric transmission, and may also influence global circulation.

Baumgaertner et al. (2005, their Figure 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 Krizan, 2006) indicate that there is a change in stratospheric PW activity that may be connected with the MLT wave activity. Our own analysis in Figure 1 also indicates a change in stratospheric wave activity around 1990. This suggests that MLT PW activity is connected with stratospheric PW.

In conclusion, we have shown that the midlatitude MLT and planetary wave activity shows a structural trend change around 1990. This change is in correspondence with changes of the lower and middle atmosphere, which may indicate that the MLT dynamics are forced by global atmospheric changes. Note, however, that the structure of these changes may differ, so that some parameters show a sequence of decreasing and increasing, as ozone or solar radiation, while MLT PW activity variations indicate a climatic shift with distinct non-linear behaviour. Therefore the interpretation of the MLT trends has to be made with special care. This is also the case since the time series available are still comparatively short, and it is not clear whether detected changes or trends will continue for the next decades. More research on these trends and the connection between lower/middle atmosphere and MLT is necessary to clarify these points.

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