The Quasi 16-day Wave in the Summer Midlatitude Mesopause Region and its Dependence on the Equatorial Quasi-Biennial Oscillation

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Zusammenfassung:

Aus täglichen Analysen des sommerlichen zonalen Grundwindes im Mesopausenbereich, der am Observatorium Collm der Universität Leipzig gemessen wurde, werden niederfrequente Variationen im Zeitbereich planetarer Wellen (10 - 20 Tage) bestimmt. Obwohl die direkte Ausbreitung derartiger Wellen durch die stratosphärischen und mesosphärischen Ostwinde verhindert wird, werden in manchen Jahren trotzdem Oszillationen gemessen, die mit planetaren Wellen im Zusammenhang stehen können. Dies unterstützt die Theorie, daß sich planetare Wellen von der Winterhalbkugel entlang der Zonen schwachen Windes bis in die Mesopausenregion mittlerer und polarer Breiten ausbreiten. Betrachtet man die interanuelle Variabilität dieser Wellen, fällt eine Abhängigkeit von der äquatorialen quasi 2-jährigen Schwingung (QBO) auf, wobei während der Ostphase der QBO die Wellenaktivität gering ist, während sie in der Westphase der QBO stärker sein kann. Der Einfluß der QBO auf die sommerliche Wellenaktivität wird vom 11-jährigen Sonnenfleckenzyklus moduliert, wobei während des solaren Maximums stärkere Aktivität zu verzeichnen ist.

Summary:

From daily estimates of the summer mesopause region zonal prevailing wind measured at the Collm Observatory of the University of Leipzig long-term variations in the period range of planetary waves (10-20 days) are detected. Although the direct propagation of these waves from lower layers into the mesosphere is not possible because of the wave filtering in the summer stratospheric and mesospheric easterlies, in some years oscillations are found that can be connected with planetary waves, supporting the theory of the propagation of these waves from the equatorial region to the midlatitude and polar upper mesosphere along the zero wind line. The interannual variability of these waves shows a dependence on the equatorial quasi-biennial oscillation (QBO), so that in general during the east phase of the QBO the planetary wave activity is small, while during the QBO west phase it can be larger. The influence of the QBO on the planetary wave activity is modulated by the 11-year solar cycle, so that the strongest signal is found during solar maximum.

1. Introduction

In the past there has been several attempts to investigate the influence of the equatorial stratospheric quasi-biennial oscillation (QBO) on the midlatitude middle atmosphere. Sprenger and Schminder (1967) have found a 26-month oscillation in the mesospheric circulation, while Sprenger et al. (1975) found a 22-month oscillation from ionospheric drift measurements. More recently a quasi-biennial oscillation in Saskatoon medium-frequency radar wind data was found by Namboothiri et al. (1994), but there was no clear connection of the phase of the equatorial QBO to the mesopause prevailing wind oscillation with the phase of the QBO. The connection between QBO, solar activity and winter midlatitude stratospheric circulation (e.g. Labitzke and van Loon, 1992, 1996) is well known, but the reaction of the mesosphere on sudden stratospheric warmings is strongly variable, so that the QBO signal as it is to be seen in the winter mesopause is rather weak. Jacobi et al., (1996a) found a dependence of the winter zonal prevailing wind on the equatorial QBO, but this was statistically significant only for the December data, when generally stratwarm events appear more rarely than in January and February. In summer, no statistically significant influence of the equatorial QBO on the midlatitude mesopause region could be found. This annual variability of the QBO-influence on the mean mesopause dynamics leads to secondary oscillations, which were found by Tung and Yang (1994) in stratospheric ozone. Jacobi et al. (1996a) pointed out, that secondary oscillations are also present in the midlatitude mesopause region dynamics.

Recently, however, Espy et al. (1997) found an influence of the equatorial QBO on the summer polar mesosphere that can be seen in the interannual variability of the quasi 16-day wave, which was identified as the 2nd symmetric mode of zonal wavenumber 1. They also referred to measurements of Williams and Avery (1992), who have found a 16-day wave event in summer 1984 radar measurements in Alaska. Generally, westward travelling planetary wave are filtered out by the stratospheric and mesospheric easterlies and therefore cannot propagate up to the summer upper middle atmosphere, although the 5-day wave, being the 1st symmetric mode of zonal wavenumber 1 (e.g. Rodgers, 1976), due to its high phase speed sometimes is able to propagate up to the summer mesosphere (Grollmann, 1992), and therefore can be observed in all seasons (Salby and Roper, 1980). The slower 16-day wave, however, should not be able to propagate through the stratospheric easterlies. However, some measurements have shown that in some summers the 16-day wave can be present in the mesosphere as well (Tsuda et al., 1988; Jacobi et al., 1996b).

Two mechanisms have been suggested to explain the propagation of the 16-day wave into the mesosphere. The first one is, that the wave is generated in the winter hemisphere and guided along the zero wind line to the summer mesosphere (Dickinson et al., 1968; Miyahara et al., 1991; Forbes et al., 1995). A second, or rather additional explanation is, that planetary waves are generated by oscillatory breaking of gravity waves, which are modulated in the troposphere and lower stratosphere of the summer hemisphere (Holton, 1984; Williams and Avery, 1992; Forbes et al., 1995). However, Espy et al. (1997) have shown that there is evidence for a QBO influence on the 16-day wave activity in summer, so that the former explanation is supported by their measurements. They suggest that during the easterly phase of the QBO, the waves propagation is blocked through the equatorial stratospheric easterly winds so that then the planetary wave activity in the polar mesosphere is strongly reduced.

The dataset that was used by Espy et al. (1997) contained only 4 years, and although the summer 1984 wind measurements of Williams and Avery (1992) were included into the investigation, the conclusions were based on a rather small database. Thus, to investigate a possible QBO-dependence of planetary waves on a long-term data base, in the following midlatitude mesopause region wind data of the years 1981 through 1996 are used, which were measured at the Collm Observatory of the University of Leipzig.

2. Measurements and data evaluation

The wind field of the mesopause region over Central Europe is continuously observed at the Collm Observatory of the University of Leipzig by daily total reflection (D1) nighttime radio wind measurements in the low-frequency (LF) range. The ionospherically reflected sky wave of three commercial radio transmitters on 177, 225, and 270 kHz is used (Kürschner and Schminder, 1986; Schminder and Kürschner, 1988, 1992, 1994; Jacobi et al., 1997a). The data are automatically interpreted using a modified form of the similar fade method (Kürschner, 1975) and combined to half-hourly mean values of the three measuring paths, referring to a mean reflection point at about 52°N, 15°E.

Since 1983 the reference height h is measured on 177 kHz using travel time differences between the ground wave and the reflected sky wave in a modulation frequency range near 1.8 kHz (Kürschner et al., 1987). Since this height is varying during the day and in summer due to large absorption in the daytime D-region generally no measurements are possible then, a multiple regression analysis with height dependent coefficients is used to determine monthly mean profiles of the prevailing wind and the semidiurnal tide as well as other wind oscillations:

$$\begin{aligned} v_z &= \sum_{k=0}^{q} h^k a_{0k_z} + \sum_{j=1}^{p}\left(\sum_{k=0}^{q} b_{jk_z} h^k \sin\omega_j t + \sum_{k=0}^{q} c_{jk_z} h^k \cos\omega_j t\right) + \varepsilon \ , \\ v_m &= \sum_{k=0}^{q} h^k a_{0k_m} + \sum_{j=1}^{p}\left(\sum_{k=0}^{q} b_{jk_m} h^k \sin\omega_j t + \sum_{k=0}^{q} c_{jk_m} h^k \cos\omega_j t\right) + \varepsilon \ , \end{aligned} \tag{1}$$

where v_z and v_m are the measured horizontal wind data and ω_j the angular frequencies of the respective oscillations. The spectral selectivity of the separation of prevailing and tidal wind is improved through fitting the measured values for the horizontal semidiurnal tidal wind components as vector (Kürschner, 1991), which requires the assumption of clockwise circularly polarised tidal wind components:

$$b_{1k_m} = -c_{1k_z} \quad \text{and} \quad c_{1k_m} = b_{1k_z} \ . \tag{2}$$

The tidal winds, however, are not further regarded in this investigation. The diurnal tidal components are not considered in Eq. (1), because the regularly distributed daily data gaps would lead to a large error in the calculation of these. Thus an error of the prevailing wind can occur when only nighttime measurements are performed. However, at midlatitudes the diurnal tide is a much less dominant feature than the semidiurnal tide (e.g. Manson et al., 1989), and comparison of calculations of the zonal prevailing wind calculated with and without including the diurnal tide into the regression analysis (not shown here) led to an error of less than 4 ms^{-1} in the mean values of the prevailing wind in each month that is due to omitting the diurnal period in Eq. (1). Additionally, in this investigation we are interested in the variations of the prevailing wind, which are not affected if the prevailing winds should contain a bias. The zonal and meridional prevailing wind is calculated after:

$$v_{oz}(h) = \sum_{k=0}^{q} h^k a_{0k,z} \qquad \text{and} \qquad v_{om}(h) = \sum_{k=0}^{q} h^k a_{0k,m} \ . \tag{3}$$

with an uncertainty of 5 ms^{-1}. In addition to this, also daily estimates of the prevailing wind can be obtained by applying Eq. (1) with $k = 0$ (e.g. Jacobi et al., 1996b, 1997b). In this case reflection height variations are not taken into account, therefore only those nighttime wind values are used in Eq. (2) when the reflection height is found to be near its mean nighttime value and varies only slightly. In summer this mean nighttime reference height is found between 95 and 100 km.

3. Results

3.1 14-year mean periodograms

A 14-year mean periodogram of the zonal and meridional prevailing wind amplitude for July and August is shown in the upper panel of Figure 1. In the lower panel the zonal components are shown for July and August separately. The data are calculated using a regression analysis after Eq. (1) with $k = 2$ and $j = 2$, including the angular frequency $\omega_1 = 2\pi/12\text{h}$ and varying the second period $P_2 = 2\pi/\omega_2$ from 2 to 30 days, with a step rate of 6 hours. The strongest signal

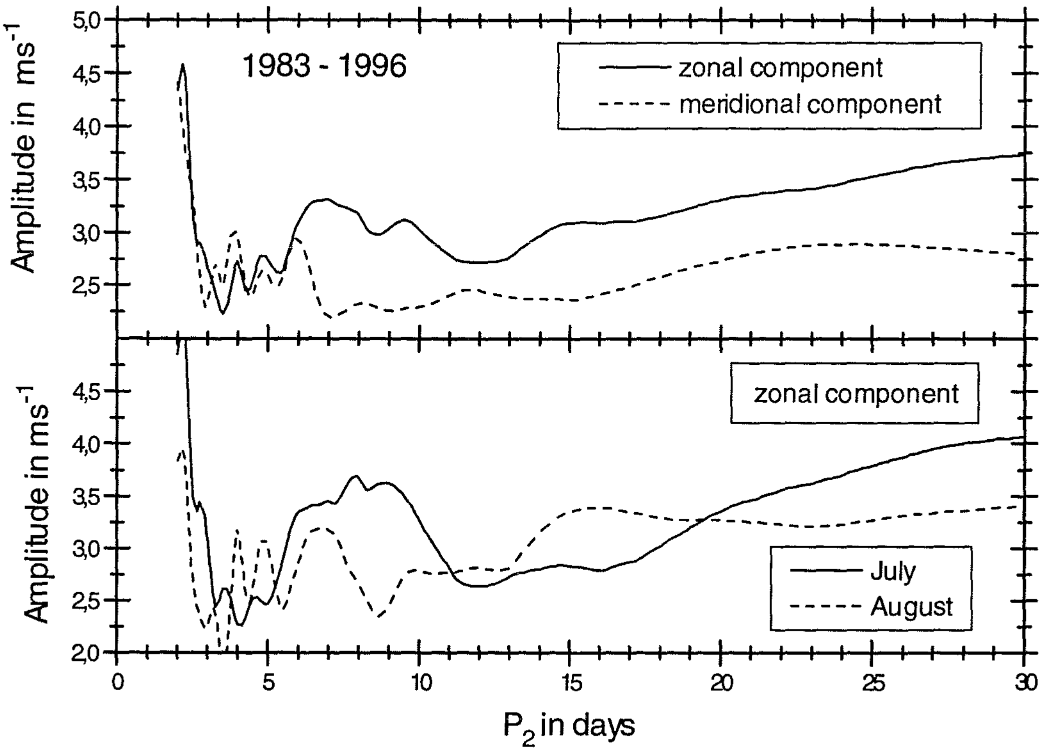

Figure 1: Amplitude spectrum of the zonal prevailing wind, calculated for each month using a regression analysis after Eq. (1) with $k = 2$ and $j = 2$, with $\omega_1 = 2\pi/12h$ and varying the second period $P_2 = 2\pi/\omega_2$ from 2 to 30 days, with a step rate of 6 hours. The data are 1983 - 1996 mean values. Upper panel: July/August means of the zonal and meridional component. Lower panel: zonal component for July and August separately.

that can be seen in Figure 1 belongs to the quasi 2-day wave. This is a well known feature in the summer mesosphere and lower thermosphere (Muller and Nelson, 1978; Clark et al., 1994; Meek et al., 1996; Jacobi et al., 1997c, and many others), which was first detected by Muller (1972). Salby (1981a,b) identified this phenomenon as a westward travelling planetary wave with wavenumber 3. In contrast to the 5- or 16-day wave, however, the 2-day wave is an in-situ effect of the mesosphere, originating from a resonant amplification of the antisymmetric (3,3)-normal mode (Salby, 1981a,b) or baroclinic instability near the summer stratospheric wind jet (Plumb, 1983; Pfister, 1985). Thus a dependence of the 2-day wave on the QBO is not to be expected. A detailed analysis of the quasi 2-day wave as measured at Collm is given by Jacobi et al. (1997c).

A large peak is found in Figure 1 at periods between 6 and 10 days. As it can be seen especially from comparison of the zonal and meridional component and from the lower panel, too, this peak obviously consists of several maximum values. The short-period one (6-7 days) possibly can be regarded as a Doppler shifted 5-day wave, which is a regular feature in the midlatitude mesosphere. In summer the mean nighttime reference heights are found above the mesospheric easterlies, and the zonal prevailing mean winds amount to more than 15 ms^{-1} there. This is shown in Figure 2, where, depending on the mean monthly variability of the wind field, mean monthly or half-monthly zonal prevailing winds for the 1983 - 1996 period are shown. The data are updates of those presented by Jacobi et al. (1997a). It can be seen that the maximum zonal prevailing winds in summer at 95 km height reach 15 ms^{-1} in August and are even stronger at higher altitudes. This means that the prevailing winds are strong enough to influence the period even of the relatively fast 5-day wave. However, as it was pointed out in the introduction, the 5-day wave due to its high phase speed partially can propagate through the mesospheric easterlies, and thus an influence of the equatorial QBO on the summer 5-day wave is not to be expected, because the existence of this wave in the midlatitude summer mesosphere is not dependent on its propagation through the equatorial region. Lastovicka (1993) showed from ionospheric absorption measurements, that there is no evidence for an effect of the equatorial QBO on planetary waves with periods shorter than 10 days. Additionally, Jacobi et al. (1996a) could not find any QBO signal in the summer mesospheric mean winds, and numerical simulations performed by Dameris (1988) and Dameris and Ebel (1990) do not indicate an influence of the equatorial QBO on the mean summer midlatitude dynamics. Thus a possible interannual variation of the 5-day wave through the variation of the mean wind field is not likely, too. This was proved from the Collm data by comparing summer mean standard deviation calculated from daily 6 - 8 days period bandpass filtered zonal wind data with the equatorial stratospheric winds. A 75% probability for no correlation between the QBO and the planetary waves in the period window given was found.

In Figure 1 additional maximum zonal amplitudes are found at 8 and 9 days. Possibly the 8-day peak could be the result of a 16-day wave that has gone through a quadratic system. An 8-day oscillation has been reported by Salby and Roper (1980). Tsuda et al. (1988) have also found 6 - 8 day oscillations in the summer mesosphere. Salby et al. (1984) and Vincent (1993a,b) has reported 3 - 10 day oscillations in the equatorial mesosphere that are due to Kelvin waves that are only present in the zonal component, however these are restricted to near equatorial latitudes and it is doubtful that they are visible in midlatitude measurements.

In the upper panel of Figure 1 the 16-day wave is only found as a plateau in the spectrum of the zonal component, and there is some variability at larger periods that, however, is due to the general variability of the wind field of the mesopause region. In the lower panel, for August relative maximum amplitudes are found near periods of 15 - 16 days, but this peak is smeared in the summer means in the upper panel. These peaks can be regarded as the signal of the 16-day wave. Thus in the following section the interannual behaviour of this oscillation will be considered in detail.

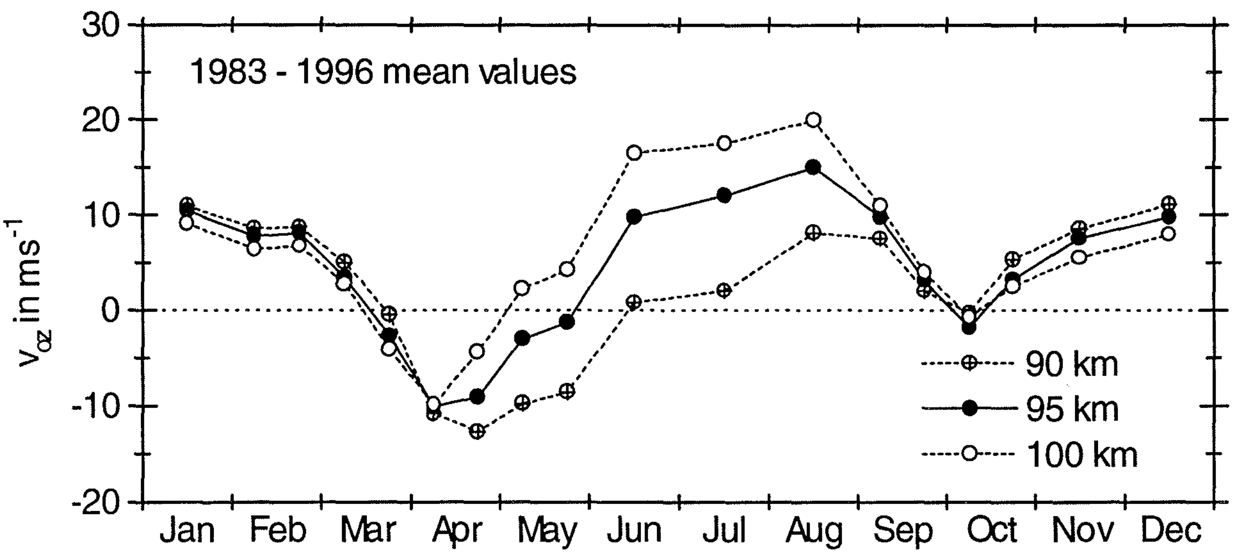

Figure 2: 1983 - 1996 mean monthly or half-monthly mean values of the zonal prevailing wind measured at Collm for three heights. The data are updates from Jacobi et al. (1997a).

3.2. Interannual variability of the 16-day wave

As an example for the interannual variability in Figure 3 the 12 - 20 day bandpass filtered time series of the zonal prevailing wind, calculated from daily analyses after Eq. (1) with k = 0, is shown for the summers of 1987 (QBO east) and 1988 (QBO west). It can be seen that generally the variation is low with amplitudes of 2 ms^{-1} and less, and only in July 1988 enhanced amplitudes are found that form a sort of burst of an oscillation with a period of about 16 days. Thus in total the 16-day wave activity is larger in 1988, although the appearance of the wave is only intermittent.

To investigate the wave activity on a long-term base and to take into account the intermittence of the planetary wave, in Figure 4 the mean standard deviation σ for July and August is shown for every year of the period 1981 - 1996, after a bandpass filter with the period windows 14 - 18 or 12 - 20 days, respectively, was applied to the time series of the daily zonal prevailing wind values. This procedure was described by Jacobi et al. (1996b, 1997b), who investigated the long-term variability of planetary wave activity on an annual base. From their monthly mean spectra they concluded that the variance or standard deviation can be considered as a signal for the planetary wave activity, thus subsequently we also refer to σ using the term „planetary wave activity". The equatorial stratospheric zonal wind v_{eq} is added to Figure 4, as well as the 13-monthly smoothed sunspot number. Considering the curve of the wave activity in the 14 - 18 day period window, its interannual variation in most of the years follows the QBO signal, so that the wave activity is reduced when the equatorial winds come from the east or conversely high planetary wave activity is only possible during periods of large v_{eq}, i.e. during QBO west years. However, this correlation is not straightforward; there are 2 years, 1983 and 1985, when despite of westerly equatorial winds the midlatitude planetary wave activity is low. This means, that the western phase of the QBO is a requirement for large planetary wave activity in the mesopause region, but not in all cases these waves are really found, while in QBO east years the propagation of planetary waves into the midlatitude mesopause is generally impossible or strongly reduced, respectively, due to the blocking mechanism of the equatorial stratospheric easterlies that was described above.

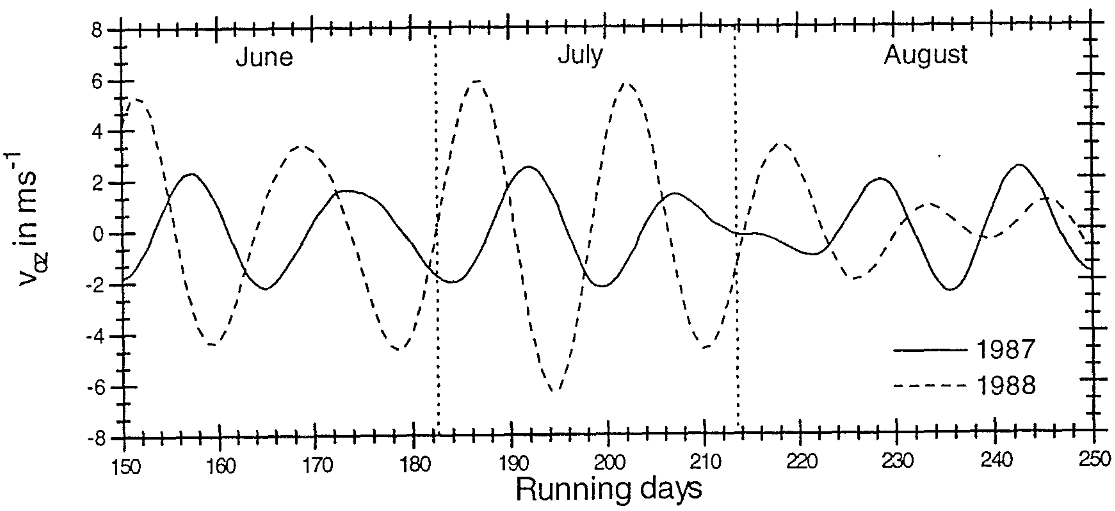

Figure 3: Two examples for the long-period variability of the mesopause region wind field in the summer mesosphere. The data are daily estimates of the zonal prevailing wind that are bandpass filtered using a Lanczos filter with 100 weights and a period window of 12 - 20 days.

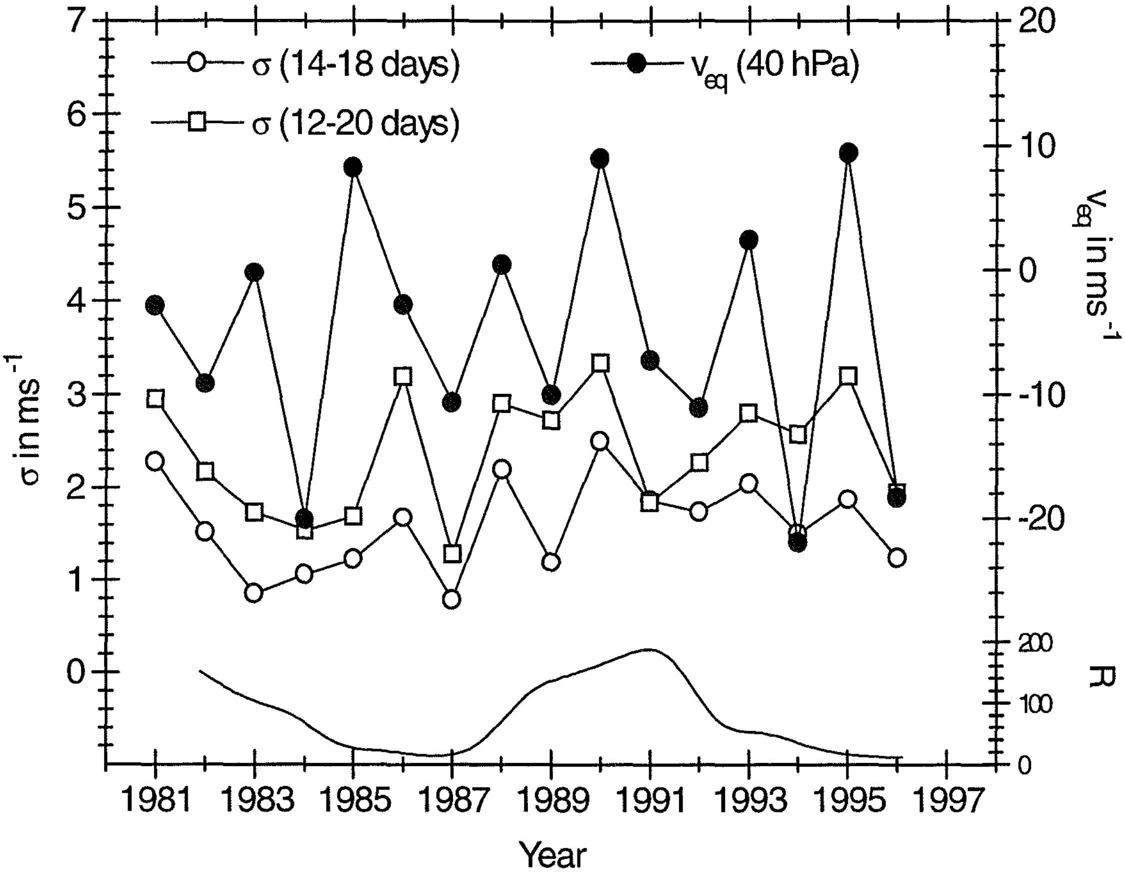

Figure 4: Summer (July/August) mean planetary wave activity, represented by the standard deviation σ of the zonal prevailing wind v_{oz}, taken from time series of daily estimates of v_{oz} that were bandpass filtered in the period windows indicated in the legend. The equatorial zonal stratospheric wind (for 40 hPa, taken as mean value of 30 and 50 hPa) is also given. In the lower part of the figure the 13-monthly smoothed sunspot number is added.

Considering a larger period window, i.e. 12 - 20 days, the general pattern is still found, although in some years (1989, 1991, 1992) the planetary wave activity curve doesn't follow the v_{eq} curve so closely. In Figure 5 the standard deviation values $\sigma_{14\text{-}18}$ and $\sigma_{12\text{-}20}$ are plotted in dependence of each other. They are, with some few exceptions, closely related to each other so that the 14 - 18 day period window may be considered as sufficient for the description of the 16-day wave activity.

3.3. Solar cycle dependence

In Figure 4 the 13-monthly smoothed sunspot number is added. During solar maximum, i.e. in the late 80s and early 90s a tendency for an enhancement of the planetary wave activity is visible, which possibly modulates the QBO-dependence of the wave activity. To investigate the time series of the planetary wave activity with respect to a possible solar influence, the monthly means of $\sigma_{14\text{-}18}$ of the years 1981 - 1996 that were normalised by their 16-year mean, were analysed using a multiple regression analysis:

$$\sigma_{14-18} = a + b \bullet \text{year} + c \bullet R. \quad (4)$$

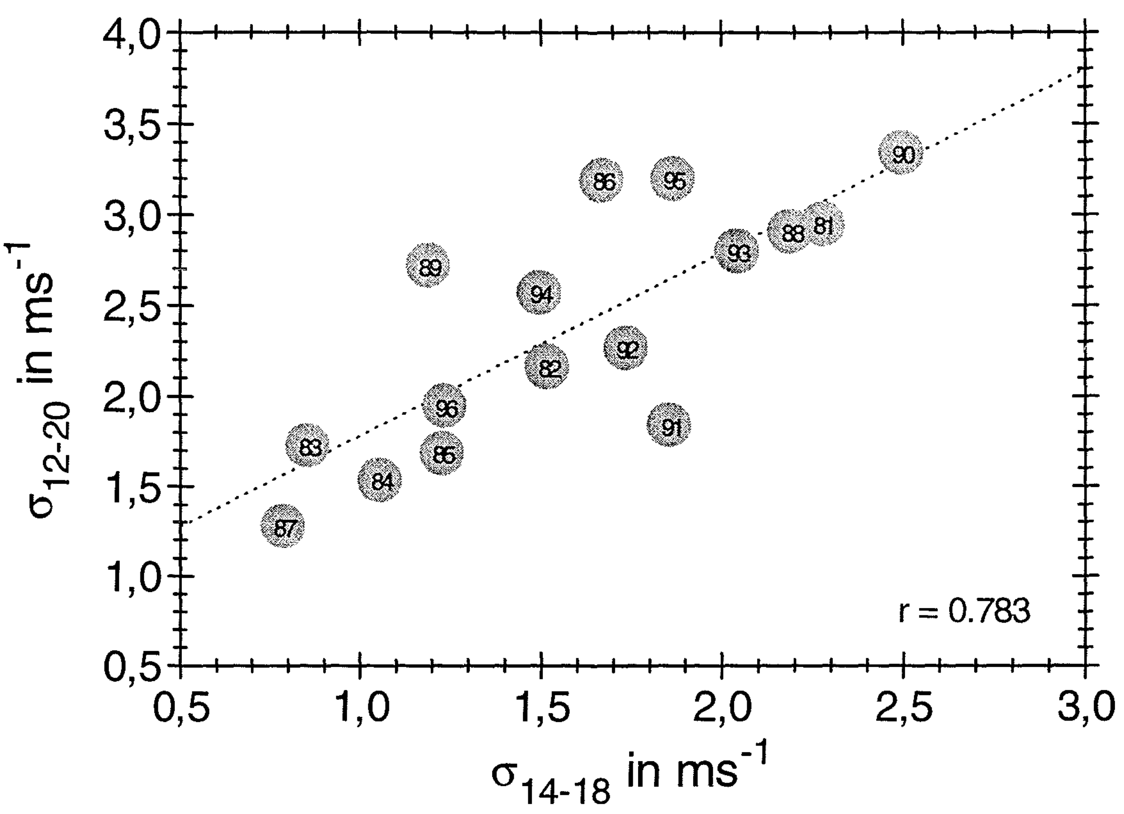

Figure 5: Standard deviation, taken from the time series of daily estimates of the zonal prevailing wind that was bandpass filtered in the period window 12 - 20 days, in dependence of the 14 - 18 days period window bandpass filtered zonal prevailing wind.

The results are shown in Figure 6. The coefficients b and c are given for each month of the year, the arrow, pointing at the July value of c in the lower panel denote a significant dependence on the 95%-level (t-test). It can be seen that no significant trend can be detected, although a weak general tendency for increasing planetary wave activity can be inferred. This coincides with the general positive long-term trend in planetary wave activity that was found by Jacobi et al. (1996b, 1997b) or Bittner et al. (1997). Considering the solar cycle dependence c, the summer values exhibit a positive correlation, as it is already suggested by Figure 4. This shows, that the planetary wave activity is variable from year to year, and thus a direct correlation with the QBO cannot be expected.

Thus the dependence of the planetary wave activity on the equatorial QBO cannot be considered as a close connection, but rather a modulation of the QBO signal on the long-term variability of σ in the course of the years. Therefore the correlation between σ and v_{eq} is relatively weak; this can be seen in Figure 7, where σ_{14-18} is shown in dependence of the equatorial zonal wind v_{eq}. The correlation coefficient amounts to 0.472 only, although a trend is visible. If we consider the solar cycle dependence of the summer planetary wave activity, a stronger correlation, however, can be expected if the data are grouped by the solar activity, since during solar minimum the planetary wave activity is low at any rate and thus its modulation by the equatorial QBO should be less effective. Therefore in Figure 7 the data are grouped by the July/August mean of the 13-monthly smoothed sunspot number R. Now it is clearly visible that for low solar activity ($R < 50$) no significant dependence of the planetary wave on the

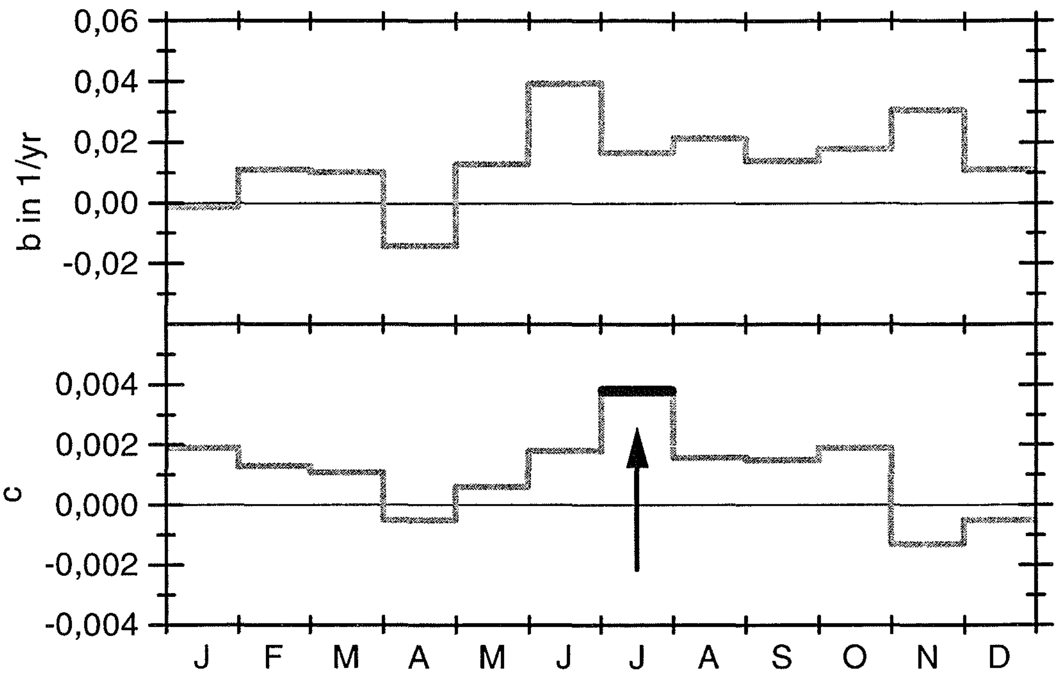

Figure 6: Coefficients b (trend) and c (solar cycle dependence), calculated after Eq. 4 for each month of the year, from normalised monthly values of $\sigma_{14\text{-}18}$.

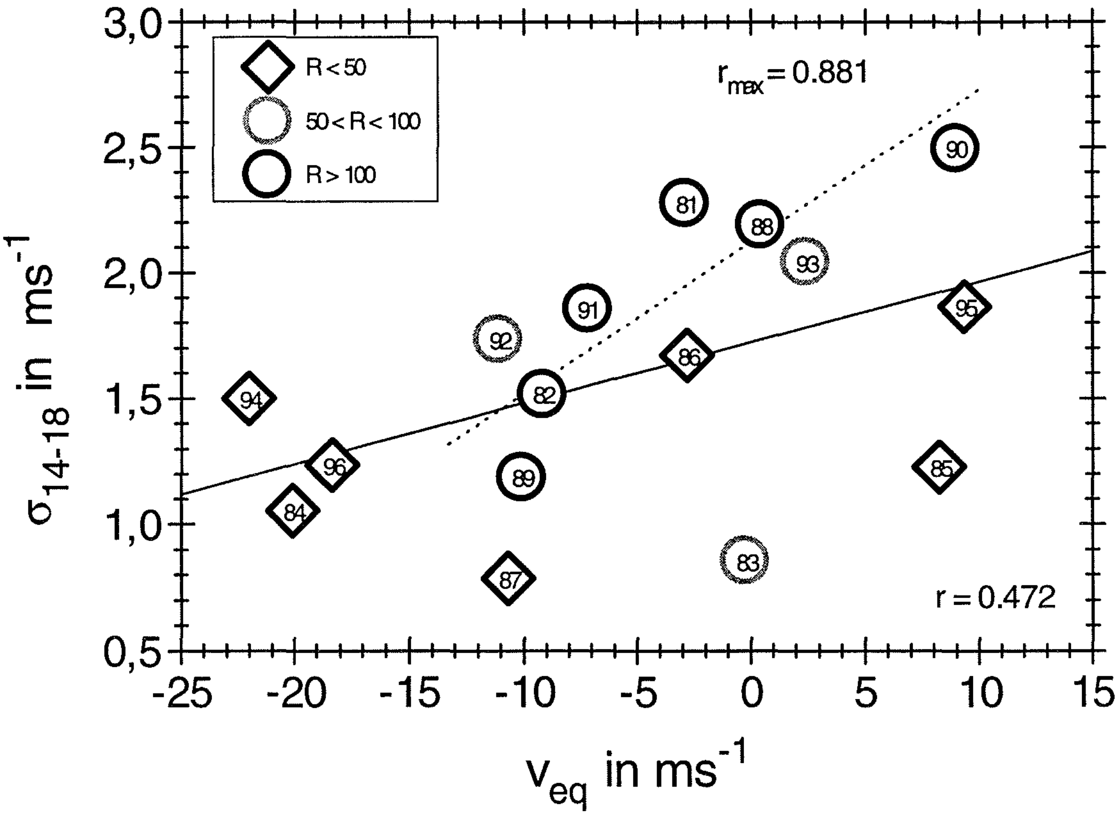

Figure 7: July/August standard deviation σ *of the zonal prevailing wind* v_{oz}, *taken from the bandpass filtered (14 - 18 days period window) time series of daily estimates of* v_{oz}. *in dependence of the equatorial zonal stratospheric wind (for 40 hPa, taken as mean value of 30 and 50 hPa). The values are classified in high, moderate and low solar activity, as indicated by the ranges of July/August mean of the 13-monthly smoothed sunspot number R in the legend.*

QBO is found, while for high solar activity (R > 100) the dependence is much stronger, as shown by the dotted regression line, and the correlation coefficient amounts to $r_{max} = 0.881$. This dependence is significant on the 95%-level, however, the database only consists of 6 years in this case and thus conclusions should be drawn with care.

4. Discussion and conclusions

Regarding the summer midlatitude upper mesosphere/lower thermosphere, planetary wave activity at time scales of more than 10 days is found in some years, despite the fact that the strong summer mesospheric easterlies generally prohibit the direct propagation of slowly westward travelling long-period planetary waves from the summer troposphere to the mesosphere. The Collm measurements presented here support results from literature (Tsuda et al., 1988; Williams and Avery, 1992; Espy et al., 1997), although the data do not necessarily correspond to each other when single years are regarded. The 15-day wave that was found, for instance, by Tsuda et al. (1985) in August 1985 as well as the July 1984 event presented by Williams and Avery (1992) could not be confirmed by the Collm measurements.

Espy et al. (1997) have proposed a QBO dependence of the planetary wave activity in the polar mesopause region and confirmed this by comparing their data with the 10 hPa Singapore winds. They pointed out that these results confirm the theory of a propagation of planetary waves, which are generated in the winter hemisphere, to the polar summer mesopause region, since a modulation of these waves can only take place in the equatorial stratosphere. From the Collm winds a QBO dependence of the 16-day wave is clearly to be seen, so that large amplitudes of the 16-day wave are only found when westerly winds are found in the equatorial stratosphere. In addition, however, this signal is modulated by the long-term variability of the planetary wave activity. Especially a solar cycle dependence is found, so that a strong influence of the QBO is found during solar maximum, while for solar minimum the influence is small.

The 40 hPa equatorial QBO signal used here, however, have a time lag of about 10 months against the 10 hPa winds (Naujokat, 1986; Jacobi et al., 1996a) that are used by Espy et al. (1997), and thus the results found here for the Collm winds are just contradicting those of Espy et al. (1997). However, as it can be seen from Figure 4, the interannual variability of the Collm $\sigma_{14\text{-}18}$ generally is not very large in the first half of the 1990s and the QBO effect seen there is relatively small, compared to the period of 1987 - 1990. It also has to be kept in mind that the definition of the QBO phase is difficult in some cases. So, for example, in the summers of 1984 and 1994 the QBO at 10 hPa had just reached the westerly phase (Naujokat, 1986; Naujokat et al., 1995) and the equatorial stratospheric winds below were still clearly in the easterly phase.

However, independently from the definition of the QBO phase, the differences in mesopause wave activity that are found between midlatitudes and polar latitudes are unexplained so far. A possible influence could be given by the different heights referred to. Espy et al. (1997) used nightglow data referring to a mean height of about 87 km, and also the 16-day wave amplitude found by Williams and Avery (1992) for July 1984 maximises at around 85 km and decreases with height. The maximum measuring density of the Collm summer wind data, in contrast to that, is found at heights between 95 and 100 km. It is, however, not quite clear why the different measuring heights should lead to a completely different dependence of the planetary wave activity on the QBO. The numerical calculations of Forbes at al. (1995) show that the region of enhanced summer 16-day wave activity is limited to a relatively small height region, and the absolute height of this region as also depending on the background wind field, so that it is conceivable that during different QBO phases the height of this region changes and thus the 16-day wave is seen by the different measuring systems at different phases of the QBO. On the other hand, numerical results presented by Dameris (1988) and Dameris and Ebel (1990) indicate that the summer hemisphere midlatitude and polar dynamics is not much influenced by the QBO, and the results of Jacobi et al. (1996a) also show that the July and August mean mesopause zonal winds at Collm do not depend on the equatorial QBO. Thus the cause of the differences that arises between the polar and midlatitude planetary wave activity is still unclear. Latitudinal effects could play a role, but the model results of Forbes et al. (1995) show that for cases with enhanced leakage of planetary wave energy from the winter to the summer hemisphere the region of larger wave amplitudes is spread over a relatively wide latitude range and thus the effect of the latitudinal difference should not be dominant. Further theoretical and experimental effort seems to be necessary to explain the differences found in polar and midlatitude measurements.

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