Long-term behaviour of E-region nighttime LF reflection heights – long-term trend, solar cycle, and the QBO

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Summary

The nighttime reflection height of low-frequency (LF) radio waves at oblique incidence is measured at Collm Observatory using 1.8 kHz sideband phase comparisons between the sky wave and the ground wave of a commercial 177 kHz LF transmitter. The measurements have been carried out continuously since September 1982, now allowing the analysis of trends and regular variations of the reflection height. In the time series is found a) a long-term negative trend and b) a solar cycle dependence, both confirming earlier measurements and theoretical estimations. Moreover, a significant oscillation of quasi-biennial period is visible in LF reflection heights, indicating a reaction of the midlatitude mesosphere/lower thermosphere region on the equatorial quasi-biennial oscillation.

Zusammenfassung

Am Observatorium Collm der Universität Leipzig werden die nächtlichen Reflexionshöhen von Langwellen auf 177 kHz unter Verwendung von Seitenbandinformationen in einem kleinen Bereich um 1.8 kHz gemessen. Die Messungen werden seit September 1982 durchgeführt und erlauben nunmehr Analysen von Langzeittrends und regulären Variationen der unteren Ionosphäre. Bei der Untersuchung der Zeitreihen fallen die folgenden Zusammenhänge auf: a) es existiert ein negativer Trend, welcher mit der Abkühlung der Stratosphäre in Zusammenhang steht, b) die Reflexionshöhe weist eine Modulation mit dem 11-Jährigen Sonnenfleckenzyklus auf und c) es ist eine deutliche quasi-zweijährige Schwingung sichtbar, die auf eine Kopplung der Mesosphäre und unteren Thermosphäre mit der äquatorialen Stratosphäre hinweist.

Introduction

It has been known for a long time that the middle atmosphere may serve as an indicator for climate variability. The connection between the lower and middle/upper atmosphere, besides chemical transport, is mainly performed through wave propagation and subsequent wave-mean flow interaction in the stratosphere and mesosphere. Owing to the low density of the upper middle atmosphere, the reaction and amplitude of trends may be very large compared to the original tropospheric signal. The same is the case for the middle atmosphere reaction on climate gas changes. It has been shown that in general the increase of greenhouse gases results in a cooling of the stratosphere (Ramaswamy et al., 2001) and mesosphere (Berger and Dameris, 1993; Akmaev and Formichev, 2000), although the trends in part of the mesopause region seems to be different from that, or obviously not existing (Lübken, 2000).

Among others, Berger and Dameris (1993), Akmaev and Formichev (2000), and Bremer and Berger (2002) have performed numerical model experiments of the middle atmosphere reaction on greenhouse gas changes. The results clearly show the cooling of the stratosphere/mesosphere. Considering the upper mesosphere/lower thermosphere (MLT) region, this leads to a descent of layers of constant pressure. This can be monitored using radio wave reflection heights, which are connected with altitudes of constant electron density that in turn are controlled by the pressure profile (Von Cossart and Taubenheim, 1990). Recently, Bremer and Berger (2002) successfully modelled this decrease and compared this to the measurement results.

It is known that the equatorial quasi-biennial oscillation (QBO) influences the winter mid- and high-latitude middle atmosphere as well (Holton and Tan, 1980), so that during QBO west phases the stratospheric vortex is deeper and colder than during QBO east phases. Labitzke (1987) showed that this dependence is modulated by the 11-year solar cycle. The QBO signal was also proven in Antarctic ozone depletion (Lait et al., 1989).

The influence of the QBO on the MLT region, however, is less clear. Jarvis (1997) found a QBO modulation of the semidiurnal tide expressed in ground geomagnetic variations. Sprenger et al. (1975) observed a quasi-biennial oscillation in annual mean MLT winds, but with significantly shorter period than the equatorial QBO. Jacobi et al. (1996), analysing Collm Central Europe MLT winds found that only the winter zonal prevailing winds are stronger during QBO west phase. This result is in accordance with the stratospheric behaviour described by Holton and Tan (1980). However, MLT wind measurements over Saskatoon, Canada, although revealing some biennial or quasi-biennial periodicity (Namboothiri et al., 1994), did not show a clear correspondence with the equatorial QBO, while a QBO effect on the mesospheric circulation over Japan (Namboothiri et al., 1999) basically affected the duration of the summer circulation. To conclude, the results on the QBO effect on the MLT region still appears to be inconclusive to a certain degree.

To investigate the long-term variability of the MLT region, we analysed nighttime low-frequency (LF) radio wave absolute reflection heights measured at Collm, Germany. When interpreting these data, however, it has to be taken into account that these height variations show the mixed signals of different processes. Firstly, a cooler mesosphere, which may be caused by both progressive cooling and periodic changes like a QBO, leads to a shrinking of the mesosphere and in the following to a decrease of constant pressure heights, which can broadly be attributed to layers of constant electron density in the lower ionospheric E-region. This means, the LF height variation is a measure for the integrated mesospheric temperature variation if a constant effective recombination coefficient is assumed. Secondly, increasing ionospheric electron content in the course of the solar cycle, for instance, causes that levels of constant electron density are found at lower heights. Since LF reflection heights broadly represent altitudes of fixed electron density, they necessarily need to decrease during solar maximum. However, it is known that the stratosphere and mesosphere exhibit a signal of the 11-year solar cycle (e.g., van Loon and Labitzke, 1990; Keckhut et al., 1995). This means, on time scales of solar variability using LF heights we cannot distinguish between the more direct solar effect through E-region ionisation, and a possible atmospheric response.

Description of the LF measurements and data analysis

Low frequency 177kHz radio waves from the Zehlendorf (near Berlin) commercial radio transmitter are registered at Collm Observatory east of Leipzig, Germany (distance to transmitter: 170 km). The virtual reflection heights h´ are estimated using measured travel time differences between the ground wave and the reflected sky wave by means of phase comparisons on sporadic oscillation bursts in a small modulation frequency range around 1.8 kHz of the amplitude modulated LF radio wave (Kürschner et al., 1987). The reflection height measurements have started in September 1982 and, as well as wind measurements (e.g., Jacobi et al., 1997), are carried out continuously since then. Generally, the height measurements are used to support the LF wind measurements in connection with calculating vertical wind profiles. For this purpose, above 95 km a factor regarding h´ is applied to correct the effect of group retardation in the ionosphere. However, because we are not primarily interested in exact quantitative analysis here, the original virtual heights are used. For most part of the measurements, the retardation effect is small, as has been found from wave field calculations.

During daylight hours, particularly in the summer months height measurements are not possible due to the strong D-region absorption then. Therefore, and because the radio wave reflection height exhibits a strong diurnal variation, it is disadvantageous to simply average over all measured height values of one day to derive daily mean heights. Therefore, a multiple regression analysis was applied to detect the nighttime mean height and a semidiurnal variation. These data have been compared with *average nighttime mean* h′, showing fundamental differences neither in the seasonal nor in the long-term behaviour. Each regression analysis was applied to 15 days of half-hourly mean h′ values, and the resulting mean nighttime height was attributed to the centre of the respective time window. The window then was shifted by one day, and the procedure was repeated.

The h′ data presented here differ from the phase-height measurements presented by Von Cossart and Taubenheim (1990) or Bremer and Berger (2002) in such a way, that we basically measure quasi continuously during the whole night the absolute reflection heights at the lower boundary of E-region above 90 km, while the indirect phase-height measurements are taken once a day and refer to heights in the D-region around 82 km to a constant zenith angle. Their transmitter distance was much longer (500-1500 km) and from the interference pattern of the recorded field strength of one transmitter it is only possible to derive relative changes of heights. Using two similar measuring paths, the ambiguity can be solved and absolute reflection heights are derived.

Results

In Figure 1 the 19-year averages of the 15-day mean reflection heights are shown in the left panel. The figure mainly shows the seasonal variation of h′. In the right panel annual mean reflection heights from 1983 to 2001 are displayed. The amplitude of the “error bars” here is mainly determined by the seasonal cycle of the reflection height. It can be seen from the figure that there is a sort of decadal variability in the long-term time series, with particularly high h′ values during solar minimum. This can easily be explained by the effect of varying ionisation between solar minimum and maximum.

In addition to the solar cycle dependence, an overall decrease of h′ during the period of observation is visible. This is in correspondence with results from other LF measurements presented by Taubenheim et al. (1990) and Bremer and Berger (2002) and can be explained by a progressive cooling of the mesosphere, which leads to a decrease of fixed pressure heights. However, the negative trend visible in the regression line in Figure 1 amounts to 90±40m/yr and is stronger than that one reported by other authors. This is probably partly due to (a) the limited length of the time series (19 years) available and (b) the different mean reflection heights. However, a multiple regression analysis (MRA) including the solar cycle and simultaneously a possible trend reveals the same value of annual height decrease. It may also be possible that there is an influence of a stepwise decrease in middle atmosphere temperatures due to volcanic influence. Volcanic eruptions lead to an increase of stratospheric temperatures (e.g. Angell, 1993). Superposition of this effect with a continuous cooling leads to stepwise changes in the middle atmosphere temperatures. Inspection of the stratospheric temperatures presented, e.g., by Pawson et al. (1998, their Figure 1), show that the El Chichon eruption

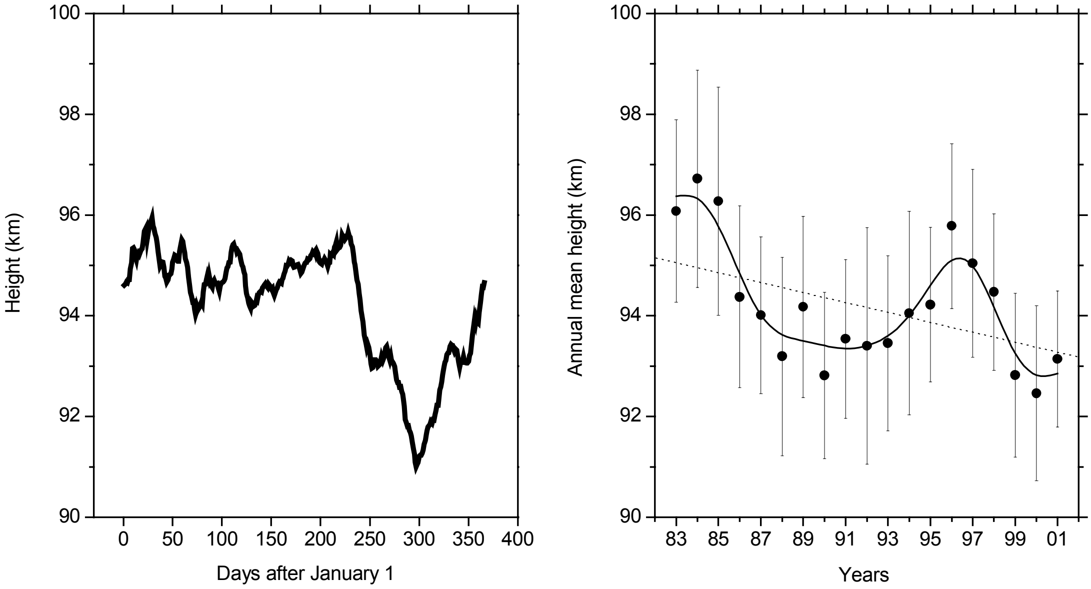

Figure 1: *Left panel: 15-day mean reflection heights 1/1983 – 12/2001, and 19-year averages (black line). Right panel: Annual mean reflection heights 1983 – 2001. The amplitude of the "error bars" is mainly determined by the seasonal cycle of the reflection height. The solid line shows smoothed annual mean values.*

leads to a warming in the early 1980s, which may be connected with the higher h′ in the first years of observations at Collm.

To show variations in the period range of several months to years, we applied transverse band-pass filters of order 2 – 6, depending on the problem. To give an impression of the filter characteristics, the transfer function of different filters is shown in Figure 2. Low pass (LP), high pass (HP) and combined BP (band pass) filters for 2nd (2), 4th (4) and 6th (6) order as examples for the used filter technique are shown for a resonant period of one year. LP (2) for an 11-year period is also added. From a power spectrum of the original time series (hatched columns in Figure 3) one may see that the main peaks are found for the semiannual and annual variation, a 2.2 year quasi-biennial peak, a 0.83 year peak, and the 11-year cycle. Band-pass filtering of the time series for these periods, and reconstruction of the time series delivers a spectrum that is reasonable close to the original spectrum (thick line in Figure 3), so that we may conclude that the filter technique provides a tool for investigating variations in the respective period ranges.

Results for the filtered time series are shown in Figure 4. The upper two panels show semiannual and annual oscillations. The time series exhibit modulation of their amplitudes. The quasi-biennial oscillation is shown in the middle panel. In this panel we also show results of a MRA including the QBO with simultaneous respect to the annual and semiannual period, applied to 3-year segments shifted by 30 days. It can be seen that both filter and regression techniques give similar results. The 4th panel presents the decadal variability. Here in particular the solar variability is visible. The amplitude amounts to 1 km, which is large compared to the results of other authors (Entzian, 1967, von Cossart and Taubenheim, 1987). One of the reasons may be the influence of the stepwise h′ decrease in the 1980s that will be misinterpreted as a solar modulation. Beyond that we have to take into consideration the differences of compositions of D-region and E-region and the different responses to solar variability. The low-

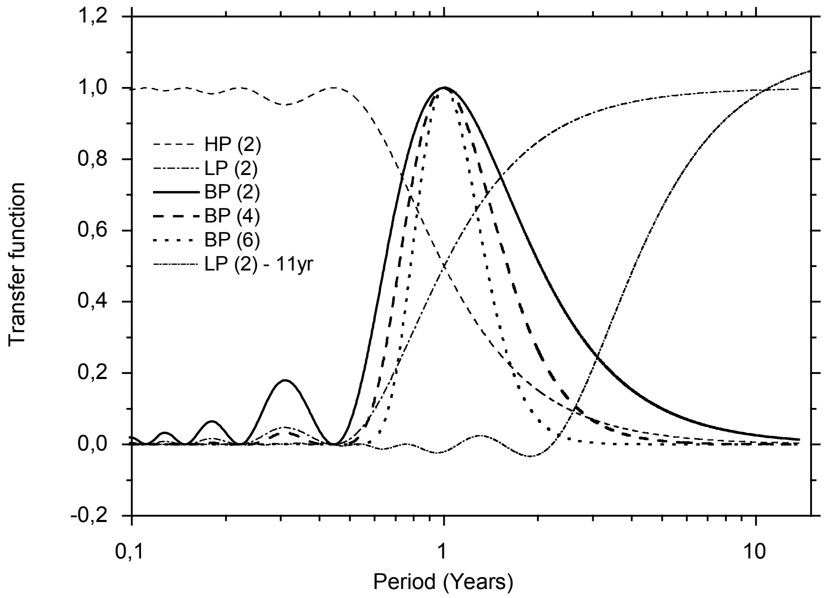

Figure 2: *Transverse filters LP (low pass), HP (high pass) and combined BP (band pass) for 2nd, 4th and 6th order (2), (4), (6) as examples for the used filter technique. Resonant period chosen is one year here. LP (2) for 11-year period is also added.*

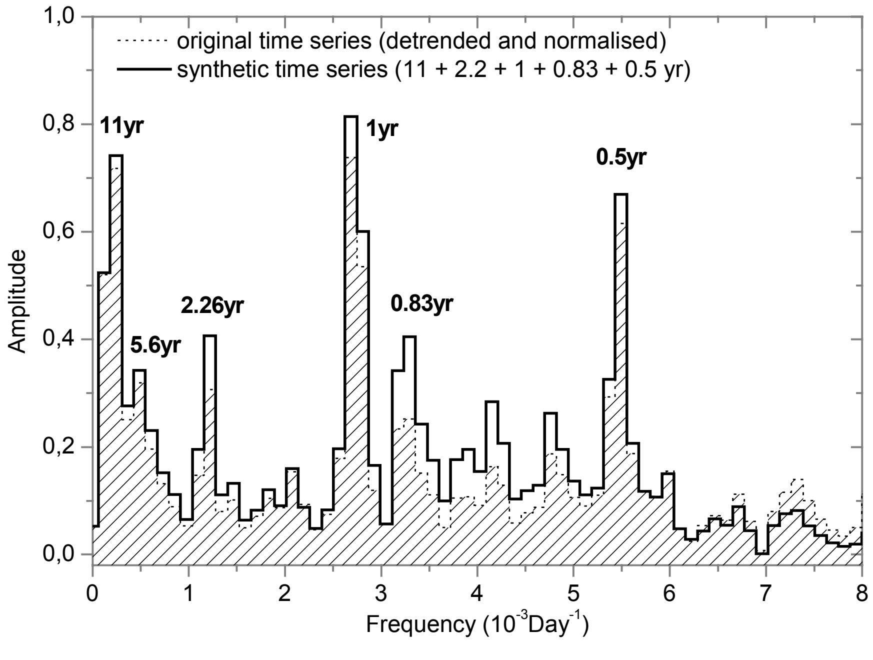

Figure 3: *Amplitude spectra of original (dotted line and columns) and synthetic (solid line) time series.*

ermost panel presents the total time series of the 15-day means, showing the long-term decrease of h´, which has already been presented in the right panel of Figure 1.

Apart from the annual and semiannual cycle, the 11-year variation and the QBO effect appear to be the prominent ones within the time series. To highlight the dependence, in Figure 5 the low-pass filtered h′ data are shown together with the annual mean sunspot numbers. Clearly, the reflection heights are lower during solar maximum than during solar minimum, which is

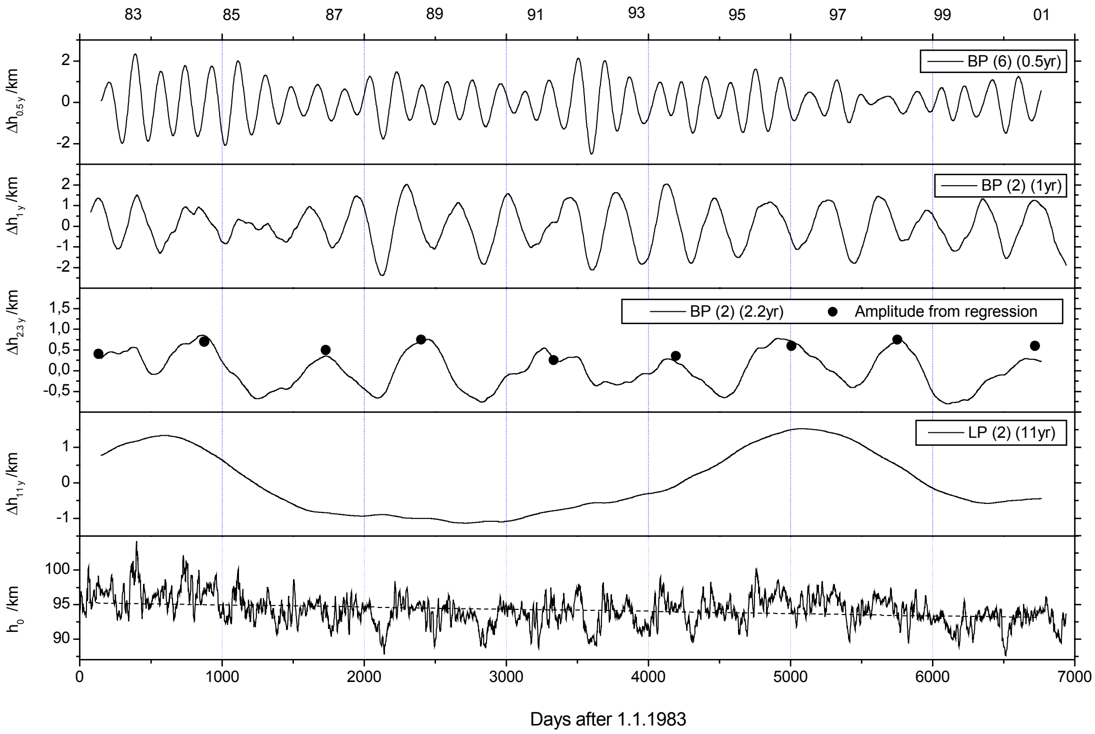

Figure 4: *Filtered time series using different band-pass filter windows: 0.5 yr (0.4 – 0.6 yr, uppermost panel), 1 yr (0.9 – 1.9 yr, second panel), 2.2 yr (1.5 – 3 yr, middle panel, also analyses from regression analysis including 0.5, 1, and 2.2 yr), 11 yr (high pass, 4 yr cut off, 4th panel), original time series with linear regression (lowermost panel).*

easily understandable from the stronger ionisation during times of high solar activity. The amplitude of the 11-year oscillation amounts to about 1 km, i.e. the difference between solar maximum and minimum is 2 km. This is more than has been reported in literature (Entzian, 1967), which can be attributed to a stepwise manner of the stratospheric progressive cooling (Pawson et al., 1998), partly due to the effect of volcanoes on the middle atmosphere. Comparing the h′ time series presented here with the phase-height measurements shown by Bremer and Berger (2002, their Figure 1), one can see that during the early 1980s particularly high h′ values were measured, an effect of non-solar origin. Because of the limited length of the time series in Figure 4, this stepwise change in our analysis contributes to an apparent solar effect. Another effect is that the middle atmosphere temperature is also dependent on solar activity (e.g., Keckhut et al., 1995). However, since the vertical distribution of this reaction is complicated – cooling in the upper stratosphere but heating in the mesosphere during solar maximum – it is unclear to what degree this effect contributes to the behaviour of constant pressure heights and subsequently reflection heights during solar maximum.

In Figure 6 the band-pass filtered reflection heights with a resonant frequency of 2.2 years are shown together with the equatorial 30 hPa winds. For comparison, the MRA results already presented in the middle panel of Figure 4 are also shown. It can be seen that for QBO west years in most cases the reflection heights are lower than during QBO east years. This would fit to the concept of a cooler middle atmosphere during QBO west years, which is in correspondence with the stratospheric behaviour during winter (Holton and Tan, 1980). However, we did not yet find any indication for a seasonal modulation of the signal. Further investigations of a possible QBO effect in different seasons are necessary.

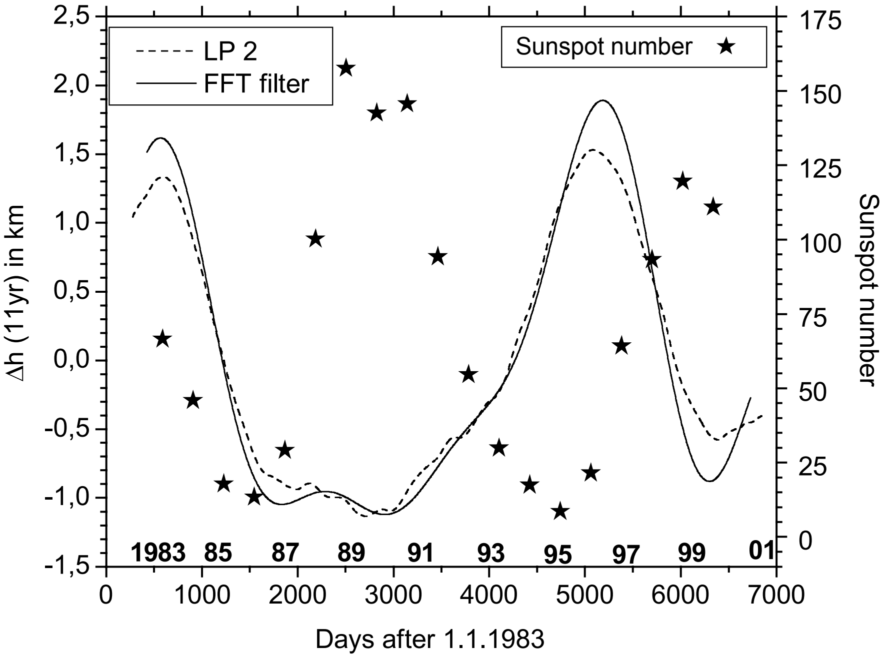

Figure 5: *Time series of low pass filtered reflection heights and annual mean sunspot numbers.*

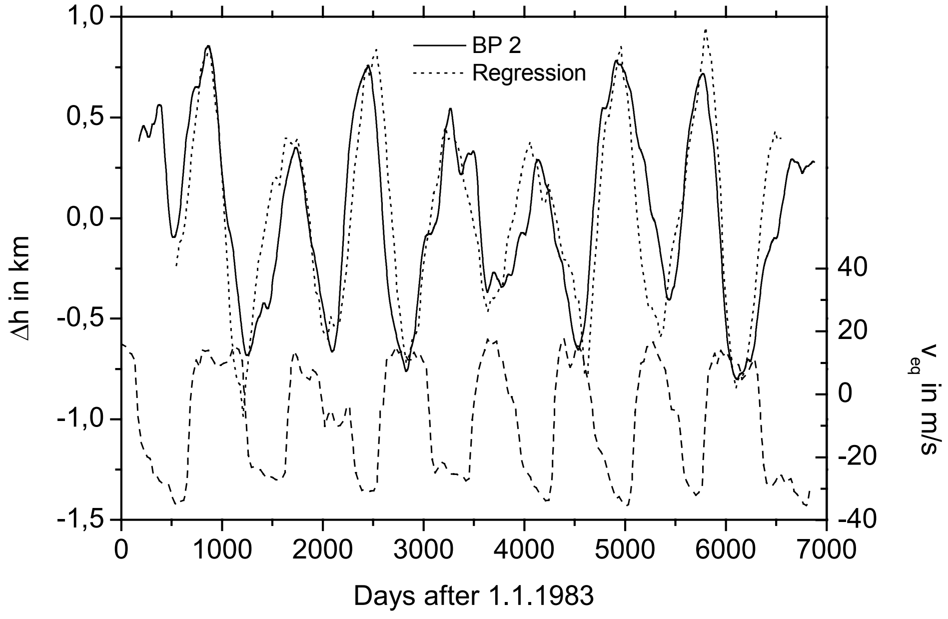

Figure 6: *Time series of band pass (2.2 years) filtered reflection heights (upper part of the figure, left axis), and equatorial winds at 30 hPa (lower part of the figure, right axis).*

Conclusions

Applying a filter technique to the 19-year time series of LF nighttime absolute ionospheric reflection heights measured at Collm between September 1982 and 2002 allows the identification of dominant trends and periodicities in the time series. Therefore we are able to analyse both atmospheric and solar possible effects on the lower E-region ionosphere. In particular, the time series of the mean reflection height show

- a possible negative long-term trend, which is broadly in correspondence with results from literature (e.g., Bremer and Berger, 2002), and
- a clear quasi-biennial oscillation, generally in phase with the stratospheric equatorial QBO at the 30 hPa level.

These characteristics indicate a response of the lower ionosphere region to the underlying neutral atmosphere. A negative trend may easily be explained by a long-term cooling of the middle atmosphere. However, the time series is still not long enough to allow a clear distinction between long-term trends and decadal variation.

The QBO effect is somewhat difficult to explain. It has been shown (Holton and Tan, 1980) that the winter stratospheric vortex is stronger during QBO west years and therefore lower heights, as shown in our study, could be explained from that fact if we attribute lower reflection heights to lower levels of constant pressure. However, a clear QBO effect on the MLT wind system over Collm has only been found in winter (Jacobi et al., 1996), so that it remains unclear why the QBO is visible in such a clear manner in the LF heights.

In addition to these probably neutral atmospheric effects on the E region, solar cycle dependence is also visible, which broadly corresponds to literature results (e.g. Entzian, 1967, von Cossart and Taubenheim, 1987). The amplitude of the solar cycle amounts to about 1 km, which is relatively large, compared with the values reported in literature, although these literature results generally were obtained at lower altitudes. However, taking into account a possible stepwise change in mesospheric temperatures, with a strong decrease in the middle 1980s, a part of the apparent solar cycle may be attributed to this kind of variability.

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