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Article

The global signal of the 11-year sunspot cycle in the stratosphere: Differences between solar maxima and minima

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Abstract

Based on the data of 4 solar cycles, the global structure of the signal of the 11-year sunspot cycle (SSC) in the stratosphere and troposphere was examined in earlier studies, using correlations between the solar cycle and heights and temperatures at different pressure levels. Here, this work is expanded to show the differences of geopotential heights and temperatures between maxima and minima of the SSC. The global solar signal is shown and the differences between the hemispheres are stressed. It is pointed out that during the northern winter (January/February) the QBO modulates the *global* solar signal. This study puts the earlier work on a firmer ground and gives the community of modellers, who simulate the solar signal with GCMs, quantitative values for comparison.

Zusammenfassung

Bisher haben wir die globale Struktur des Signals des 11-jährigen Sonnenfleckenzyklus (SFZ) in der Stratosphäre und Troposphäre an Hand von Korrelationen zwischen dem SFZ und Höhen oder Temperaturen in verschiedenen Druckniveaus untersucht. Dazu hatten wir Daten von 4 Zyklen des SFZ zur Verfügung, 1958–1998. Hier wird diese Untersuchung ausgedehnt, indem die Differenzen der geopotentiellen Höhen zwischen den Maxima und Minima im SFZ berechnet werden. Es werden das globale Signal gezeigt, die Unterschiede zwischen den Hemisphären betont, und es wird besonders darauf hingewiesen, dass während des Nordwinters (Januar/Februar) das *globale* solare Signal in der unteren Stratosphäre von der QBO moduliert wird. Diese Untersuchung liefert quantitative Werte des solaren Signals im 11-jährigen Zyklus, die für Vergleiche mit Modellergebnissen benötigt werden.

1 Introduction

The search for a signal of the 11-year sunspot cycle (SSC) in the heights and temperatures of the lower stratosphere was previously successfully conducted for the Northern Hemisphere with a data set from the Freie Universität Berlin (FUB), covering four solar cycles. The historic analyses from the FUB start with the IGY (International Geophysical Year) in July 1957 when new radiosonde stations were established and existing ones were improved. The analyses were always carried out as a research project with continuity in time and space and there is general agreement that this data set is very reliable also during the early years in the series.

This work has been extended to the whole globe by means of the NCEP/NCAR re-analyses (KALNAY et al., 1996) for the period 1958–1998. Correlations based on the re-analyses show that the solar signal exists in the Southern Hemisphere too, and that it is of nearly the same size and shape as on the Northern Hemisphere (VAN LOON and LABITZKE, 1998, 1999).

It is the purpose of this paper to show the size of the changes of the stratospheric heights and temperatures which can be attributed to the SSC. The period of 1968–1998 is used for the *global* studies as the re-analyses are less reliable in the early part of the period, before 1968, mainly because of the lack of radiosonde stations over the Southern Hemisphere, the lack of high reaching balloons in the early years and the scarce satellite information before 1979.

2 Data and methods

As a measure of the SSC the monthly mean values of the 10.7 cm solar flux are used. This is an objectively measured radiowave, highly and positively correlated with the SSC. No causal relationship is implied by the use of this parameter.

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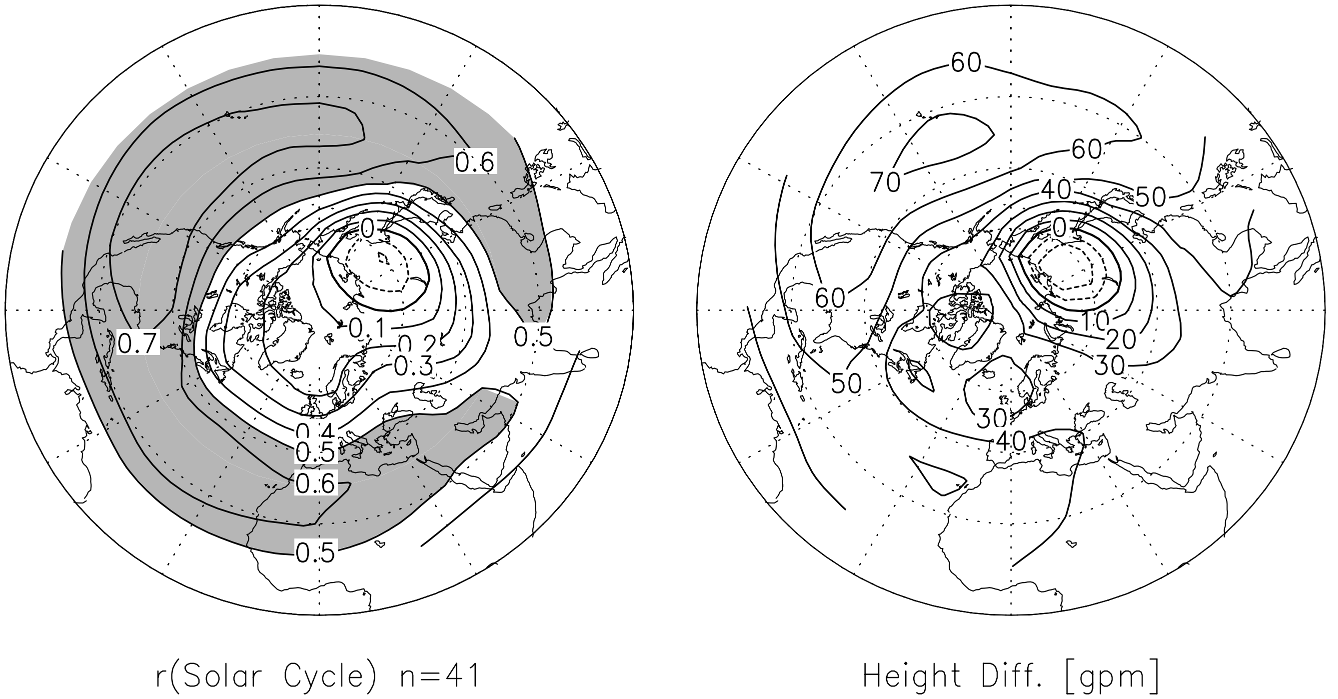

Figure 1: Left: Correlations between the 10.7 cm solar flux (the 11-year solar cycle) and the annual mean 30-hPa heights, 1958–1998 (FUB data); shaded for emphasis where the correlations are above 0.5. Right: Height differences (geopot. m) between solar maxima and minima.

For the *range* of the SSC the mean difference of the 10.7 cm solar flux between solar minima (about 70 units) and solar maxima (about 200 units) is used, i.e. 130 units. Any linear correlation can be represented also by a regression line with $y = a + bx$, where x in this case is the 10.7 cm solar flux and b is the slope. This slope is used here, multiplied by 130, in order to get the differences between solar minima and maxima, as presented in this paper.

For the analysis of the solar signal over the Northern Hemisphere, the FUB 30-hPa height data are used for the period 1958–1998. To show the solar signal on a *global* scale, the NCEP/NCAR re-analyses are used for the period 1968-1998, because of the scarce data before this date, particularly over the Southern Hemisphere.

Linear correlations and the calculated differences of stratospheric elements show *directly* the synoptic structure of the global solar signal. Except for the northern winters it is not necessary to involve other influences like the QBO and the SO, as can be judged from Fig.2.

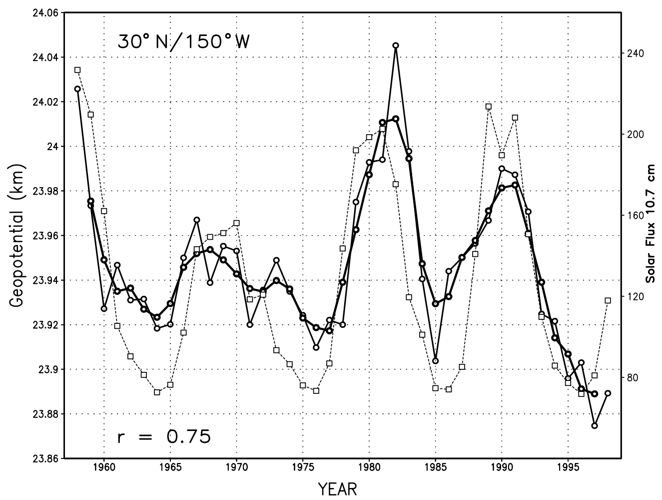

Figure 2: Time series of the 10.7 cm solar flux (dashed line) and of the annual mean 30-hPa heights (thin solid line) and their three-year running means (heavy solid line) in geopot. km for the gridpoint 30N/150W. (FUB data)

3 The solar signal in the annual mean

3.1 Northern hemisphere 30-hPa heights

Figure 1 shows on the left hand side the correlations between the 10.7 cm solar flux and the annual means of the 30-hPa heights for the period from 1958 to 1998, for the Northern Hemisphere (FUB data). The areas with correlations larger than 0.5 are shaded for emphasis. (The statistical significance of the correlations cannot be determined because we have only 4 solar cycles and the degrees of freedom are therefore limited). Clearly, there are large areas with correlations higher than 0.5, and the axis of highest correlations is at about 30N. Over the polar region and into middle latitudes the correlations are weak in the annual average.

The differences of the annual mean 30-hPa heights between solar maxima and minima are shown on the right hand side of Fig. 1. In the areas of highest correlations the annual mean 30-hPa heights are about 70 geopotential meters higher in the maxima than in the minima of the 11-year solar cycle.

Figure 2 shows the time series of the 10.7 cm solar flux and of the annual mean 30-hPa heights (and their

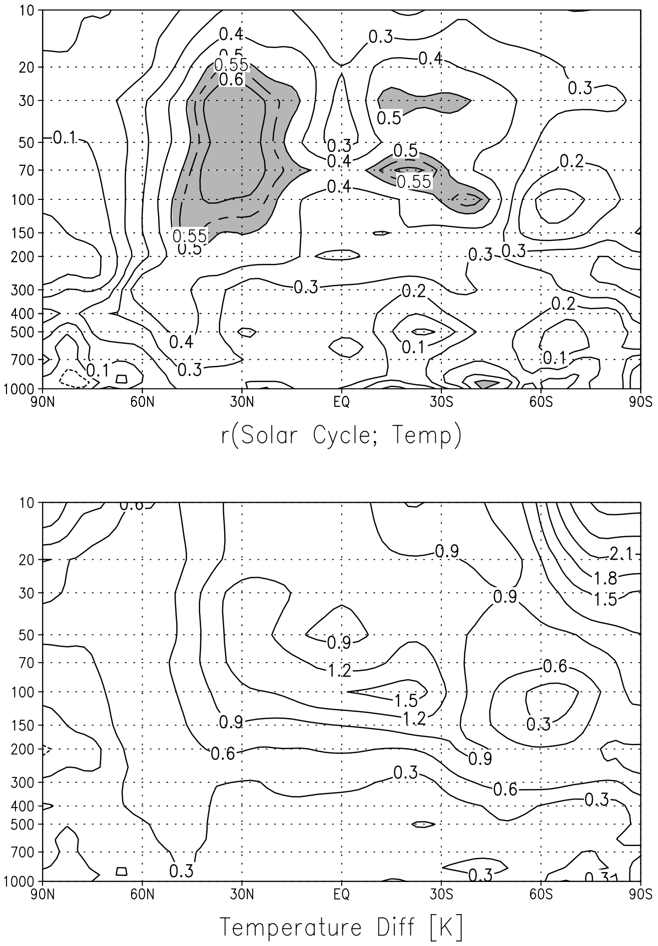

Figure 3: Vertical meridional sections for the period 1968–1998 of (top): the correlations between the zonally averaged annual mean temperatures and the 11-year solar cycle (shaded for emphasis where the correlations are above 0.5); (bottom): the zonally averaged temperature differences (K) between solar maxima and minima of the annual means. (NCEP/NCAR data)

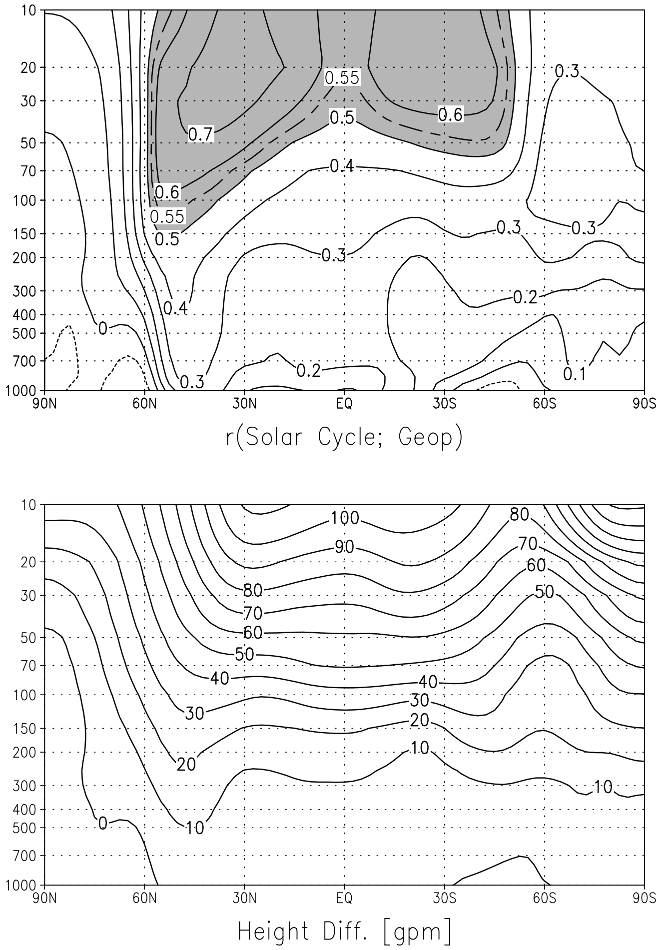

Figure 4: Vertical meridional sections for the period 1968–1998 of (top): the correlations between the zonally averaged annual mean heights and the 11-year solar cycle (shaded for emphasis where the correlations are larger than 0.5); (bottom): the zonally averaged height differences (geopot.m) between solar maxima and minima of the annual means. (NCEP/NCAR data)

three-year running means) at a gridpoint near Hawaii (30N, 150W) where the correlations exceed 0.7; that is, where half the interannual variance of the heights is associated with the solar cycle. Obviously, this signal is larger than any other influence controlling the interannual variability in the subtropics.

3.2 Zonal mean temperatures

The NCEP/NCAR re-analyses of the stratosphere are less reliable in the early part of the period because of the lack of radiosonde stations, especially over the Southern Hemisphere, the lack of high reaching balloons in the early years, and the scarce satellite information before 1979. Therefore, the shorter period from 1968 till 1998 is used here to analyze the *global solar signal*.

The vertical structure of the correlations of the zonal mean temperatures from 1000 to 10 hPa is shown in Fig. 3, together with the respective temperature differences between solar maxima and minima. Again, correlations larger than 0.5 are shaded. The largest correlations (up to 0.6) and the largest temperature differences (up to 1.5 K) are confined to the height regime between 200 and 20 hPa, and to the latitude range from 45N to 45S (*r* above 0.4).

3.3 Zonal mean geopotential heights

From hydrostatic considerations the temperature differences (Fig. 3) must lead to height differences further up, and these differences as well as the correlations are shown in Fig. 4. Correlations larger than 0.5 start at 150 hPa/50N (Fig. 4, upper part), grow with height to more than 0.7 around 20 hPa/30N, and above 50 hPa the correlations larger than 0.5 reach from 60N to 50S. The zonal mean height differences between solar maxima and minima (Fig. 4, lower part) grow to values larger than 100 geopot.m near 10 hPa.

3.4 Global 70-hPa temperatures

The 70-hPa level is chosen here for the analysis of the horizontal structure of the temperature signal, because the signal starts to be well pronounced at this level over

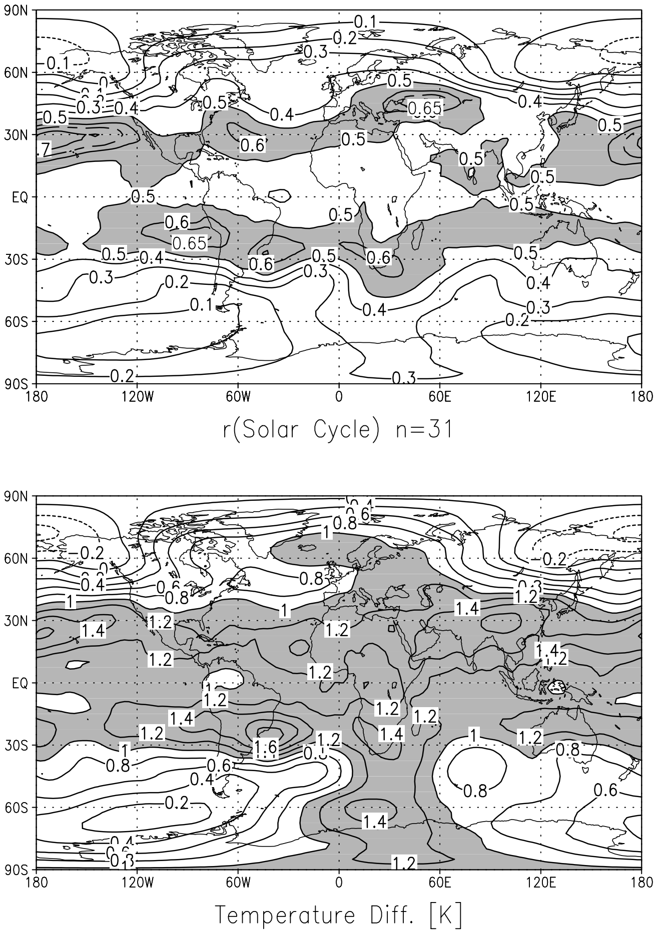

Figure 5: Top: Correlations between the 10.7 cm solar flux and the annual mean 70-hPa temperatures, 1968–1998; shaded for emphasis where the correlations are above 0.5; (bottom): temperature differences (K) between solar maxima and minima; shaded where the differences are above 1 K. (NCEP/NCAR data)

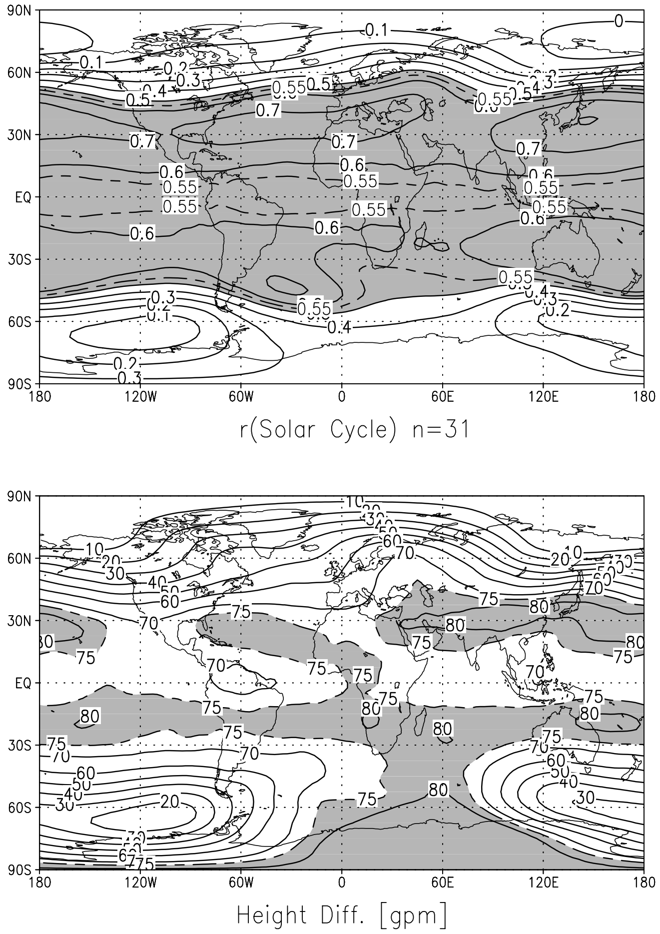

Figure 6: Same as Fig. 5, but for the 30-hPa heights; upper part: correlations; lower part: height differences; shaded where the differences are above 75 geopot. m.)

both hemispheres, cf. Fig. 3. The horizontal distributions of the correlations with the solar cycle and of the temperature differences between solar maxima and minima are shown in Fig. 5 for the 70-hPa level. The banded structure of the correlations (Fig. 5, upper panel) with clear maxima (up to 0.7), centered near 30N and 20S, respectively, is similar to results shown earlier for the 30-hPa heights (e.g. VAN LOON and LABITZKE, 1998, 1999). In the annual mean the temperature differences are above 1 K from about 40N to 30S, reaching 1.8 K in the areas of largest correlations, Fig. 5, lower panel.

3.5 Global 30-hPa heights

The horizontal structure of the correlations between the annual mean 30-hPa heights and the 10.7 cm solar flux is shown in Fig. 6, together with the height differences between solar maxima and minima. The extensive belts with high correlations over both hemispheres stand out clearly (upper panel), as well as the maxima of the height differences. On this projection the *global* range of the solar signal is easily recognized: from about 50N to about 45S, where the correlations are above 0.5, the stratospheric heights are between 60 and 80 meters higher in maxima than in minima of the solar cycle. The belts of maxima (up to 80 m) lie at about 30N and 20S, and there is a clear minimum over the equator (about 70m). This implies an anomalous eastwind in the annual mean over the tropics during solar maxima (and *vice versa in minima*) and points to an influence of the SSC on the QBO, as discussed by SALBY and CALLAGHAN (2000).

4 March of the solar signal through the year

4.1 At the 70-hPa level

In addition to the results in the annual mean it is of interest to follow the solar signal through the year. This is shown in Fig. 7 with the correlations and with the differences between solar maxima and minima of the monthly mean zonal mean 70-hPa temperatures. Most impressive are the very consistent positive temperature differences at the 70-hPa level: temperature differences of about 1K are observed through the year from about 40N to 40S, with maxima over the tropics (up to 1.5 K between 30N

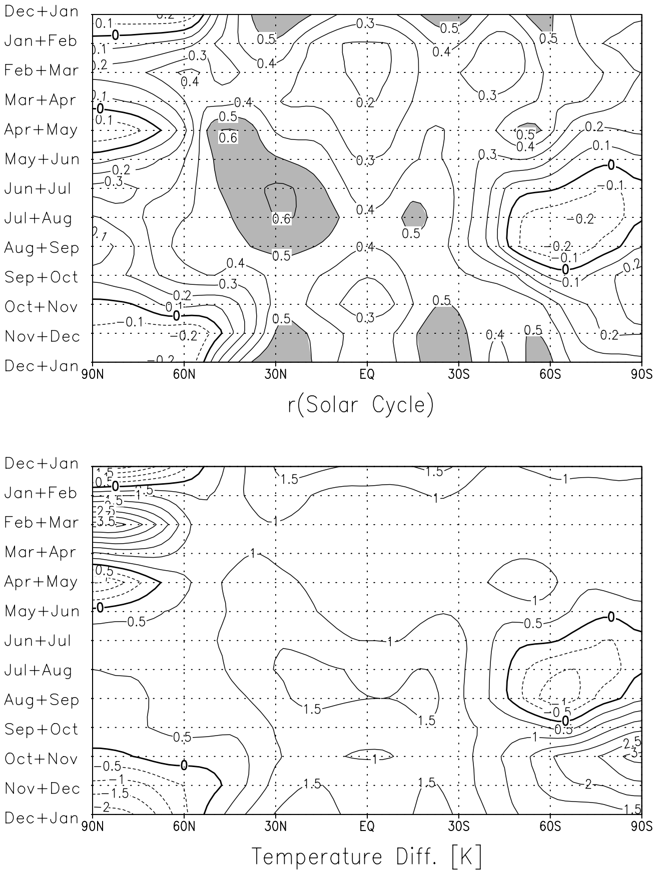

Figure 7: Two-monthly running (top): correlations between the 10.7 cm solar flux and the zonal mean 70-hPa temperatures; (bottom): temperature differences (K) between solar maxima and minima. (NCEP/NCAR data, 1968–1998)

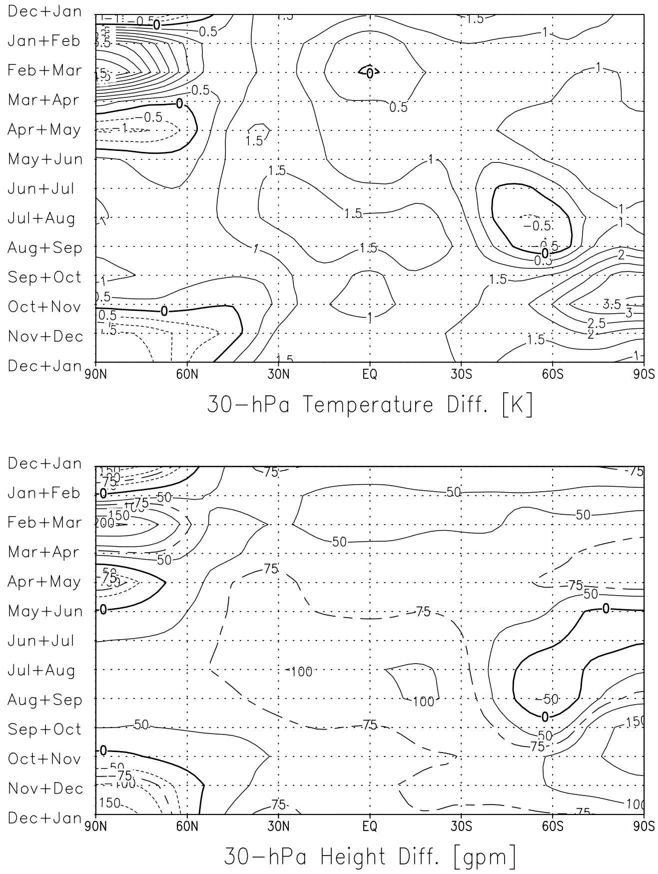

Figure 8: Two-monthly running (top): 30-hPa temperature differences (K) and (bottom): 30-hPa height differences (geopot. m) between solar maxima and minima. (NCEP/NCAR data, 1968–1998)

and 30S) during the northern (May through September) as well as the southern (November through January) summers. As in our earlier results, there exists always a symmetry around the equator and a second maximum (in the correlations or height/temperature differences) is found over the other hemisphere, respectively. This hints to a connection to the two branches of the Hadley circulation (LABITZKE and VAN LOON, 1995). Over both polar regions correlations are weak and therefore the temperature differences are not discussed here.

4.2 At the 30-hPa level

The temperature differences at the 30-hPa level (Fig. 8, upper panel) are very similar to the differences at the 70-hPa level. That means that throughout the year between about 40N and 40S and from about 100 hPa up to 20 hPa the whole lower stratosphere is warmer (between 1 and 2 K) during maxima than minima of the SSC. Such a value of temperature change (1 to 2 K) has been required by SALBY and CALLAGHAN (2000) to explain their results. The strong signal in the temperatures at the 30-hPa level implies a continuation of the solar signal in the heights further up in the middle stratosphere, above the 10-hPa level which is the highest level available from the NCEP/NCAR re-analyses.

The structure of the differences of the zonal mean 30-hPa heights between solar maxima and minima, Fig. 8 (lower panel) is also very clear: except for the polar regions where the correlations (not shown) are weak, the heights are always higher during maxima of the solar cycle. Between 60N and 40S the zonal mean 30-hPa heights are practically 75 to 100 geopot. meters higher during the maxima, except for the late northern winter when the dynamics of the arctic polar vortex are disturbing the solar signal from the northern subtropics to the Antarctic (LABITZKE and VAN LOON, 2000), Section 5.

The temperature (Fig. 7) and height differences (Fig. 8) over the subtropics agree with our earlier work using radiosonde stations (LABITZKE and VAN LOON, 1995). We showed that an increase in the *temperatures* from minimum to maximum in the 11-year solar cycle is found already in the upper troposphere and that the height increases observed in the stratosphere must follow from the hydrostatic relationship. We suggested that the positive temperature differences could be explained to some extend by an intensified Hadley circulation, i.e. intensified downward motion in the upper troposphere

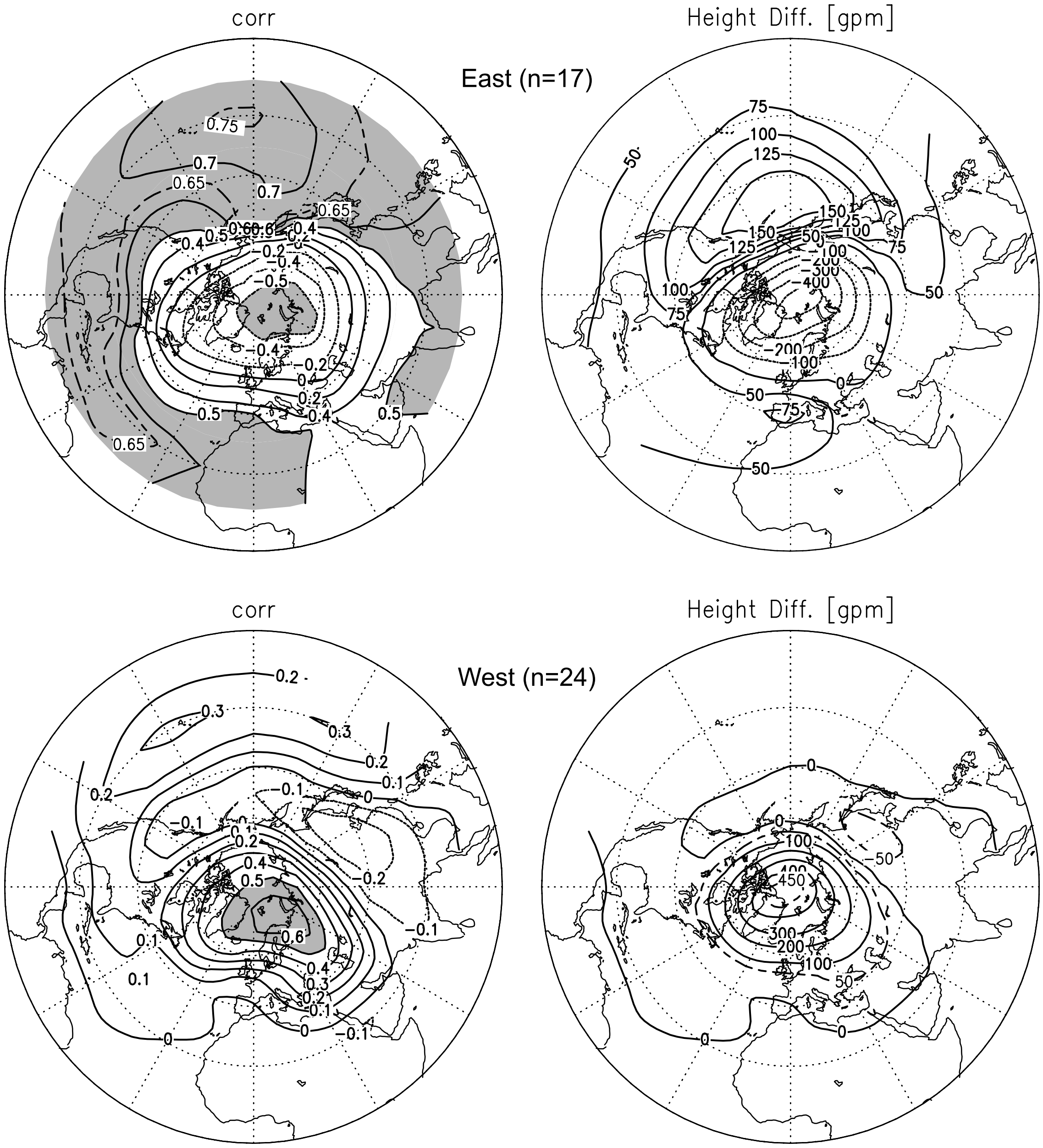

Figure 9: Same as Fig. 1, but for [(January+February)/2] and grouped into the years in the east phase of the QBO, upper two panels, and the years in the west phase of the QBO, lower two panels. No shading is applied here for the height differences. (FUB data, 1958–1998)

during solar maxima in the ring of largest positive correlations.

The concurrent correlations and height differences over the Southern Hemisphere agree with this idea, as there are always two cells (downward branches) of the Hadley circulation, moving meridionally as the sun with the seasons.

5 Northern hemisphere winters

5.1 Northern hemisphere

We have shown several times that during the northern winters the solar signal is weak if one uses a full series of stratospheric heights for correlation with the 11-year solar cycle (LABITZKE, 1987; LABITZKE and VAN LOON, 1988; VAN LOON and LABITZKE, 1994). The QBO modulates the solar signal and it is necessary to group the data into years when the QBO in the lower stratosphere (about 45 hPa) was in its west phase and years when it was in its east phase.

Figure 9 displays the correlations for the Northern Hemisphere winters (FUB data), grouped into the east and west phases of the QBO (left hand panels). During the east phase (upper left) the correlations are similar to those of the annual mean (Fig. 1) and of the northern summer (not shown). Over the Aleutian Islands the height differences between maxima and minima of the solar cycle for the northern winters in the east phase (upper right hand panel) are larger than 150m. This suggests a dynamical response which during solar maxima leads

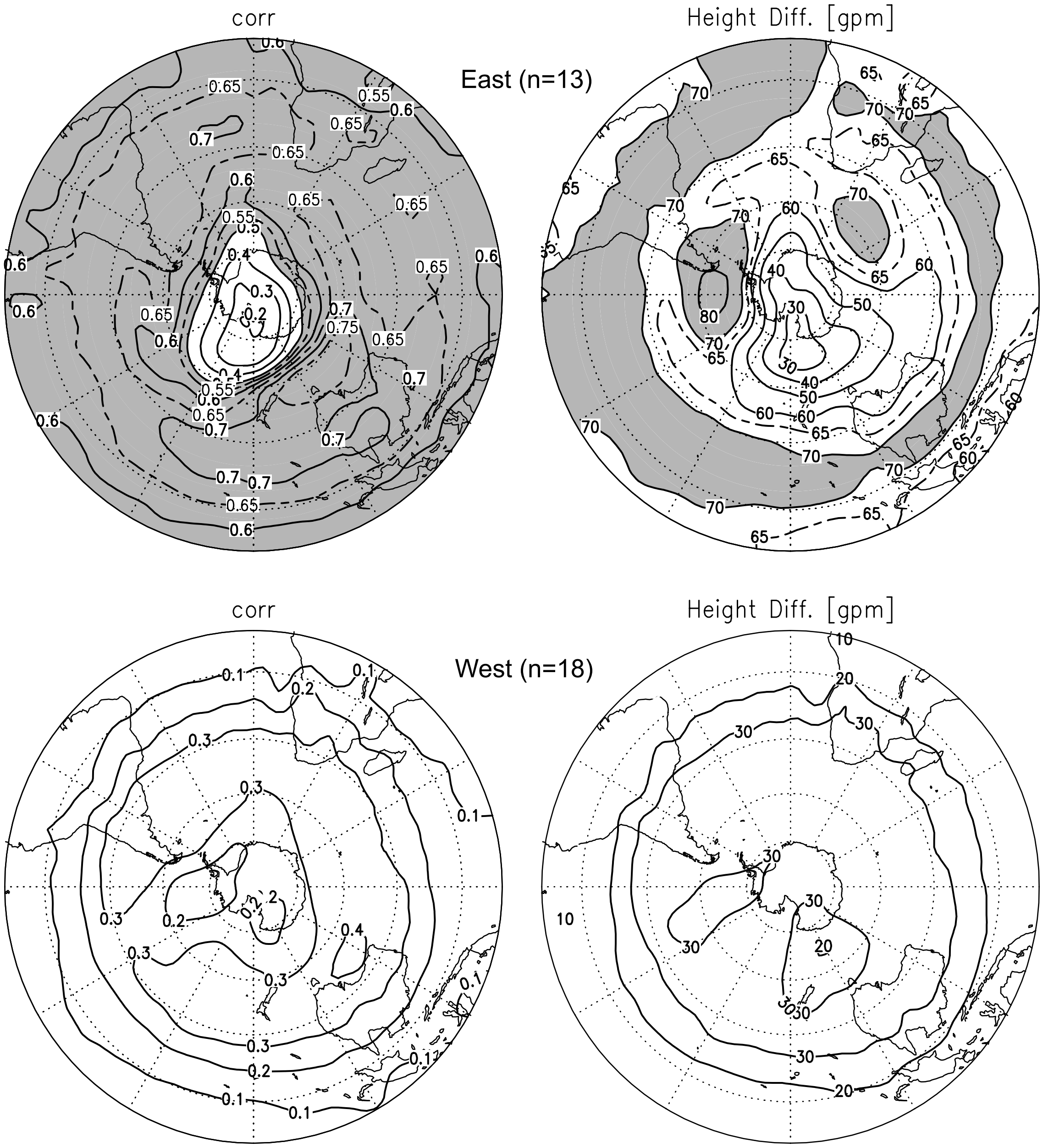

Figure 10: Same as Fig. 9, but for the Southern Hemisphere; shaded where the differences are above 70 geopot. m. (NCEP/NCAR data, 1968–1998)

to an intensification of the stratospheric Aleutian high, i.e. the planetary height wave 1.

The Aleutian high, on the other hand results from warming through sinking motions on the poleward side of the strong Asian tropospheric jet stream. Therefore, one may speculate that this jet stream is also influenced by the solar cycle.

Over the rest of the hemisphere a belt of positive anomalies is found around 30N, similar to the pattern in the maps discussed before. The positive height anomalies intensify the polar night jet during solar maxima.

An intensification of the Aleutian high is connected with an intensification of the polar vortex through teleconnections (SHEA et al., 1992), therefore the negative correlations and the negative differences over the Arctic can be understood in this context. The negative differences over the north polar region are also associated with an intensification of the stratospheric polar night jet during solar maxima, as far as the winters during the east phase of the QBO are concerned. LABITZKE and VAN LOON (2000) showed that this effect is most pronounced in the latter part of the winter, namely in February.

During the west phase of the QBO, the correlations are positive and the height differences large, up to +450 geopot. m., over the Arctic in January/February, due to the fact that in this phase of the QBO major stratospheric warmings tend to take place during solar maxima (Fig. 9, lower panels). These strong stratospheric warmings over the Arctic are connected with widespread downward motion over the Arctic and middle high latitudes. At the same time upward motion and cooling takes place outside the high latitudes over the rest of the Northern Hemisphere and far into the Southern Hemisphere, as observed first by FRITZ and SOULES (1970). This cooling acts against the usual warming (positive correlations, e.g., Fig. 1) during solar maxima and therefore the correlations are weak and the differences are small outside the high northern latitudes.

5.2 Southern hemisphere

The differences between east and west phase in the QBO are also seen over the Southern Hemisphere, although it is summer there, Fig. 10. During the east phase of the QBO the pattern of the solar signal is similar to that of the northern summer, (not shown). Correlations larger than 0.5 cover most of the Southern Hemisphere, with the largest correlations in a belt between 10 and 30S, (Fig. 10, upper left panel). From Australia into the Pacific and from South America across the Atlantic, there are large areas with correlation coefficients higher than 0.7.

During the east phase the height differences over the Southern Hemisphere in summer, Fig. 10 (upper right panel), are of the same magnitude as over the northern summer hemisphere, (not shown).

As discussed already above, during the west phase of the QBO (Fig. 10, lower panels), the solar signal has nearly disappeared in the Southern Hemisphere, as the dynamic interaction from the Northern (winter) Hemisphere counteracts the solar signal over the Southern (summer) Hemisphere during this phase of the QBO.

6 Summary and outlook

For the annual mean the magnitude of the solar signal is analyzed on the time-scale of 11-years. Differences between solar maxima and minima are calculated and it is shown that over a large vertical and latitudinal range the heights and temperatures in the stratosphere are higher during solar maxima than during solar minima.

In most months (and in the annual mean) the signal is larger over the Northern Hemisphere, where it extends farther poleward und also farther down into the upper troposphere. We suggest that the solar effect influences the diabatic meridional circulation over the tropics and subtropics, and particularly the Hadley circulation in the sense that the solar signal intensifies the Hadley circulation in the maximum phase of the solar cycle.

During the northern winters the QBO modulates the *global* solar signal.

These results support our earlier work and give the community of modellers who are simulating the solar signal with GCMs quantitative values for comparison (e.g., HAIGH, 1996; BALACHANDRAN et al., 1999; SHINDELL et al., 1999).

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