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Variability in the stratosphere: The sun and the QBO

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Large effects of solar variability related to the 11-year sunspot cycle (SSC) are seen in the stratosphere, but only if the data are grouped according to the phase of the QBO (Quasi-Biennial Oscillation). New results based on an extended, 66-year long data set fully confirm earlier findings and suggest a significant effect of the SSC on the occurrence of the Major Midwinter Warmings (MMWs) over the Arctic as well as on the strength of the stratospheric polar vortex and on the mean meridional circulation. By means of teleconnections the dynamical interaction between the Arctic and the Tropics in the stratosphere and in the troposphere is shown for the whole data set and compared with the anomalies of single events. The results suggest strongly that during the northern winter the teleconnections between the Arctic and the Tropics were determined by the MMWs and the undisturbed, cold winters, respectively. These events in the stratosphere depend, however, on the 11-year SSC and on the QBO. The stratosphere is least disturbed during the northern summer when the interannual variability is small. And if the different phases of the QBO are introduced, a large solar signal is found in the eastphase of the QBO (more than two standard deviations). It is shown that the QBO not only modulates the solar signal on the decadal scale, but that the QBO is itself modulated by the solar variability.

1 Introduction

The large interannual variability of the Arctic winters in the stratosphere depends on the development of Major Midwinter Warmings (MMWs), but as well on the frequently occurring very cold winters which are connected with a very strong polar vortex (e.g., Labitzke, 1982). As discussed before (Labitzke, 1987; Labitzke and van Loon, 1988; van Loon and Labitzke, 2000; Crooks and Gray, 2005), these events depend strongly on the SSC and on the respective phase of the QBO (Quasi-Biennial Oscillation).

By means of teleconnections the dynamical interaction between the Arctic and the Tropics in the stratosphere and in the troposphere is shown for the whole data set and compared with the anomalies of single events. The results suggest strongly that during the northern winter the teleconnections between the Arctic and the Tropics were determined by the MMWs and the COLD winters, respectively. These events in the stratosphere depend, however, on the 11-year SSC and on the QBO.

The stratosphere is dynamically least disturbed during the northern summer and the interannual variability is low, Fig. 1. And if the different phases of the QBO are

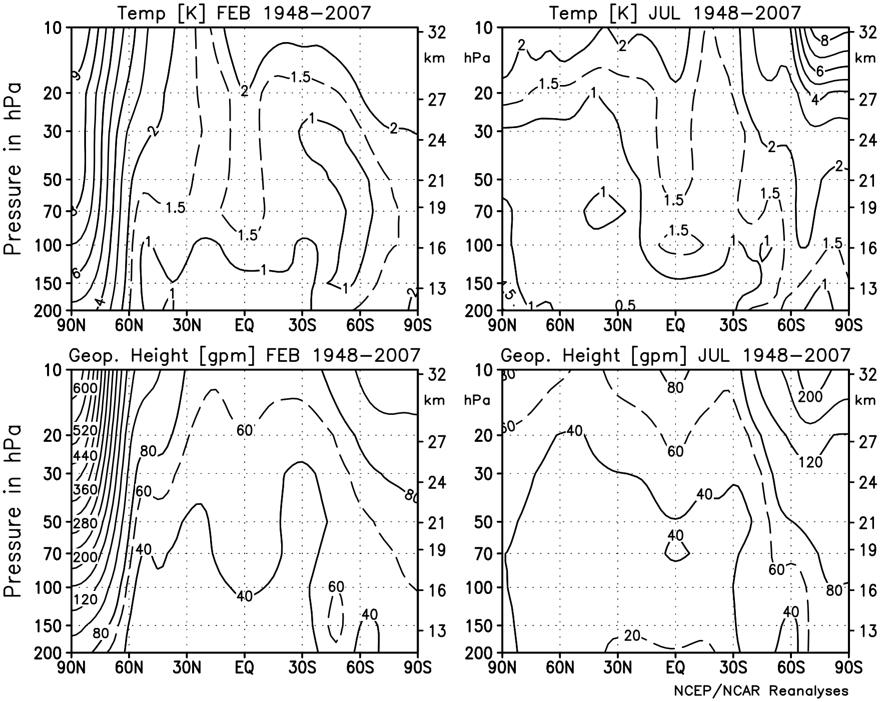

Fig. 1. Vertical meridional sections of the standard deviations for February (left) and July (right) of the zonal mean monthly mean temperatures (K), upper panels, and of the zonal mean monthly mean geopotential heights (geopot.m), lower panels, for the period 1948–2007, n (number of years) = 60 (NCEP/NCAR re-analyses) (Labitzke *et al.*, 2006, updated).

introduced, a large solar signal is found also in summer.

2 Data and Methods

For this study, some data are available for the period 1942–2007 (n = number of years = 66), as decribed in Labitzke *et al.* (2006). These are mainly the NCEP/NCAR re-analyses 1948 till 2007 (Kalnay *et al.*, 1996) and the statistically reconstructed 30-hPa heights at the North Pole (1942 till 1947) from Brönnimann *et al.* (2005). 29 MMWs occurred in Dec., Jan., or Feb., i.e. during 44% of all winters (Labitzke *et al.*, 2006). The QBO is an oscillation in the atmosphere which is best observed with radiosonde data in the stratosphere above the equator, where the zonal winds change between east and west with time. The period of the QBO varies in space and time, with an average value near 28 months at all levels, see reviews by Naujokat (1986) and Baldwin *et al.* (2001).

Because the QBO modulates the solar signal in the stratosphere, and in turn is modulated by the sun (e.g., Soukharev and Hood, 2001; Labitzke, 2005), it is necessary to stratify the data into years for which the equatorial QBO in the lower stratosphere (at about 45 hPa, e.g., Holton and Tan, 1980) was in its westerly or easterly phase (QBO data set (starting 1953) in: Labitzke and Collaborators, 2002).

Information on the phase of the QBO before 1953 was extended back to 1942 based on historical pilot balloon wind data (Labitzke *et al.*, 2006). Note that this extension is only tentative as the historical upper-level wind data are very sparse and of uncertain quality. But meanwhile Brönnimann *et al.* (2007) confirmed our QBO analysis.

Monthly mean values of the 10.7 cm solar flux are used as a proxy for variations through the SSC. The flux values are expressed in solar flux units: 1 s.f.u. $= 10^{-22}$ W m^{-2} Hz^{-1}. This is an objectively measured radio wave intensity, highly and positively correlated with the 11-year SSC and particularly with the UV part of the solar spectrum (Hood, 2003).

For the earliest years, before the regular measurements of the 10.7 cm solar flux became available in 1947, we derived the solar flux from a regression between the sunspot numbers and the flux (see Labitzke *et al.*, 2006).

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 (Labitzke, 2003).

The significance of our results depends on the number of solar cycles available. We have reached 6.5 solar cycles and we can now safely say that the results for the northern winters, especially in the west phase of the QBO, with r reaching 0.7, are highly significant; ($r = 0.5 \sim 95\%$; $r = 0.66 \sim 99\%$).

3 Variability of the Stratospheric Winters

3.1 Standard deviations for February and July

The Arctic stratosphere reaches its highest variability in winter. Figure 1 gives an example of the variability of the stratosphere during the northern winter (February) and summer (July). It is remarkable that in the lower and middle stratosphere the standard deviations in the Arctic winter are three to four times larger than those in the Antarctic winter. This is due to the fact that Major Mid-Winter Warmings which create the large variability of the Arctic, do usually not penetrate to the lower stratosphere over the Antarctic. But the variability is large in the upper stratosphere over the Antarctic, where so-called Minor Mid-Winter Warmings occur frequently (Labitzke and van Loon, 1972).

When the Antarctic westerly vortex breaks down in spring (September–November), the middle stratosphere varies so much from one spring to another that the standard deviation at the South Pole in October (Labitzke and van Loon, 1999, their figure 2.11) approaches that at the North Pole in January and February. In summer the variability is low in both hemispheres. A relative maximum of variability is observed on the equator due to the QBO.

3.2 Time series over the Arctic

To give an impression of the large interannual variability of the Arctic stratosphere in winter, time series over the North Pole of the 30-hPa temperatures (°C) in January and of the 30-hPa heights (geopot.dam) in February are given in Fig. 2(a) and 2(b), respectively. The variability is largest during this part of the winter, with standard deviations (sigma) of 8.5 K in January and 45.5 gpdam in February.

It is of great interest to note that the overall trend of the 30-hPa temperatures in January is slightly positive, 0.8 K per decade (84% significance) and that of the 30-hPa heights in February is practically zero (0.23 geopot.dam per decade)—(see, e.g., discussions about temperature trends in the Arctic by Pawson and Naujokat (1999) and Labitzke and Kunze (2005)).

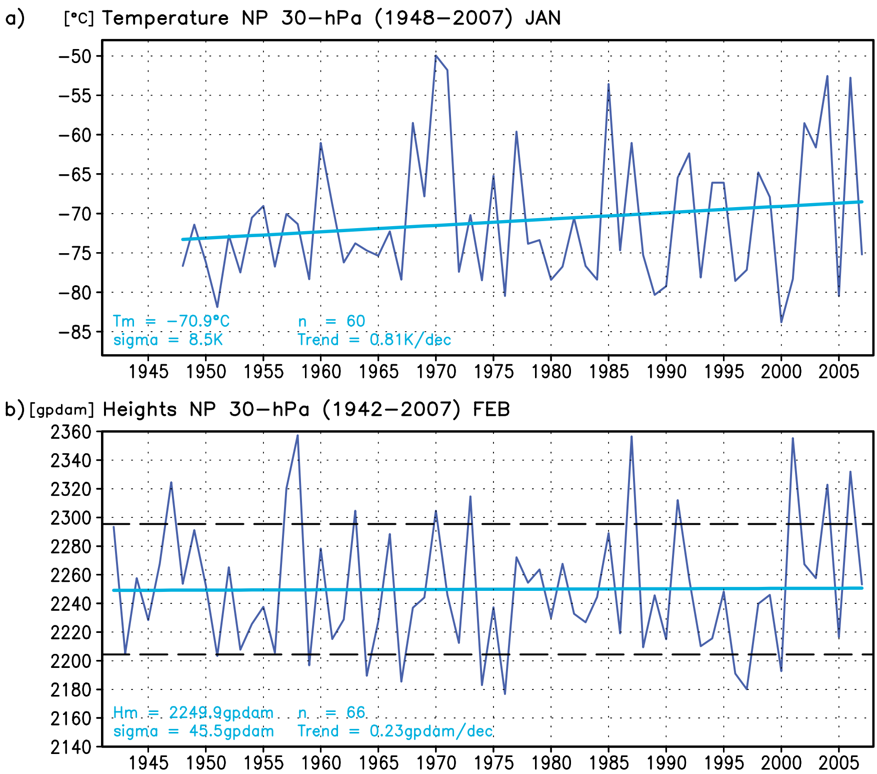

Fig. 2. (a) Time series of the monthly mean 30-hPa temperatures (°C) over the North Pole in January, 1948 through 2007. A trend line is given for the whole period (NCEP/NCAR re-analyses). (b) Time series of the monthly mean 30-hPa heights (geopot.dam) over the North Pole in February, 1942 through 2007, with a trend line and the + and −1 sigma lines (dashed). n = number of years. (NCEP/NCAR re-analyses and reconstructions, see Labitzke *et al.*, 2006.)

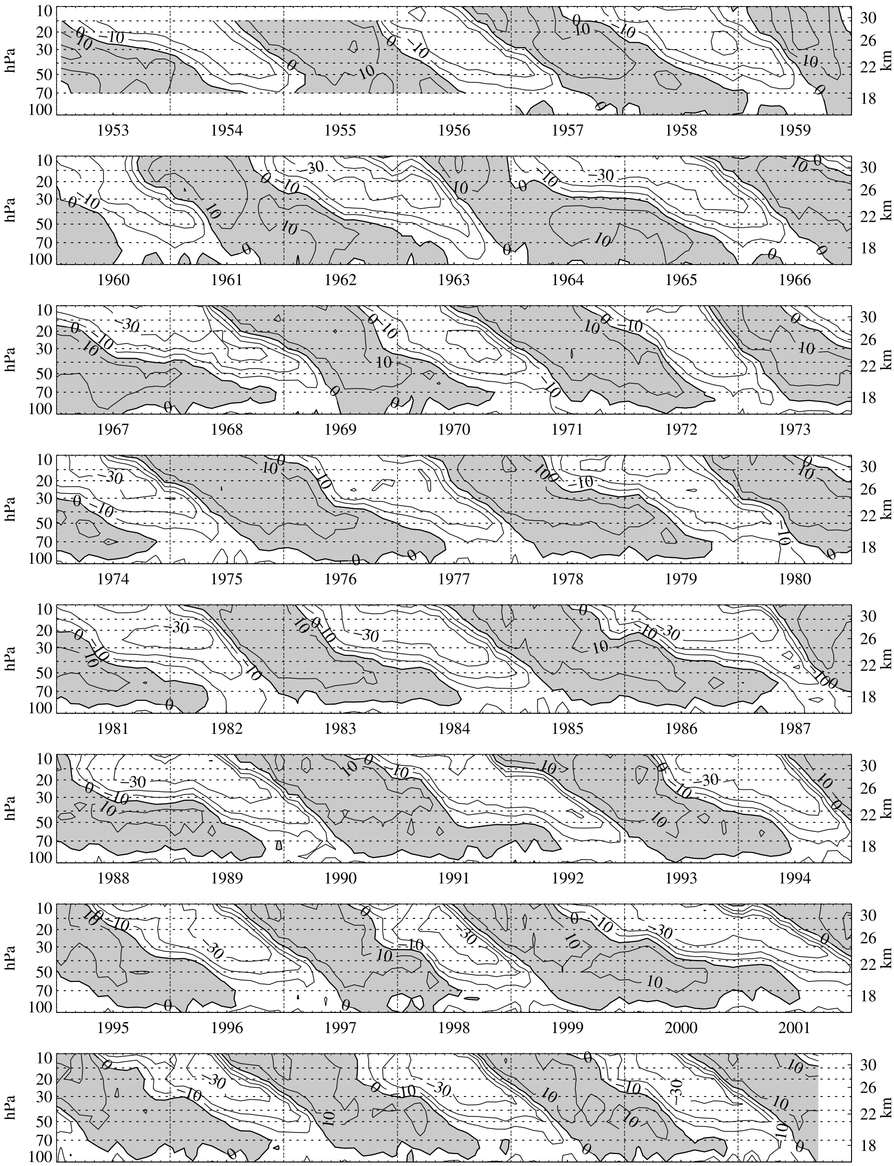

Fig. 3. Time height section of monthly mean zonal winds (m/s) at equatorial stations: Canton Island, 3°S/172°W (Jan 1953–Aug 1967), Gan/Maledive Islands, 1°S/73°E (Sep 1967–Dec 1975) and Singapore, 1°N/104°E (since Jan 1976). Isopleths are at 10 m/sec intervals; winds from the west are grey, updated from Naujokat (1986).

3.3 Factors responsible for the variability

The state of the Arctic westerly vortex in northern winter is influenced by several factors (van Loon and Labitzke, 1993):

- The QBO, Fig. 3, consists of downward propagating west and east winds in the stratosphere with an average period of about 28 month; this pattern is centered on the equator. A historical review and the present explanation of the QBO can be found in Labitzke and van Loon (1999). The QBO modulates the Arctic and also the Antarctic polar vortex (Labitzke, 2004a), but this modulation changes sign depending on the phase in the solar cycle, see Section 3.4.

- Another quantity whose effect is felt in the stratosphere is the Southern Oscillation. The SO is defined as a "see-saw" in atmospheric mass (evidenced by sea-level pressure) between the Pacific Ocean and the Australian-Indian region, (see, e.g., Labitzke and van Loon, 1999). Its influence is global and reaches into the stratosphere. The anomalies in the lower stratosphere associated with extremes of the SO are described in van Loon and Labitzke (1987), where they are discussed in terms of other influences such as the QBO and volcanic eruptions. In the warm extremes (WE) of the SO (i.e., El Ninos) the stratospheric temperatures and heights at Arctic latitudes are most of the time well above normal (about 1 standard deviation), and conversely in the cold extremes (CE).

- The stratosphere is also influenced by different types of waves which penetrate under certain conditions from the troposphere to the stratosphere. These are the very large scale planetary waves. Further, different types of the so-called gravity waves reach the stratosphere where they deposit their momentum, depending on the vertical profiles of the zonal winds.

- Tides are very important for the dynamics in the upper stratosphere and mesosphere. They develop in these regions mainly through thermal forcing of the rotating earth's atmosphere by the sun.

- Yet another influence on the stratosphere is the solar variability which until recently received little attention. The influence of the 11-year SSC will be discussed in the next section.

3.4 Connections between the Arctic stratosphere, the sun and the QBO during winter

Based on results published in 1982, Labitzke (1987) found that a signal of the 11-year SSC emerged when the Arctic stratospheric temperatures and geopotential heights were grouped into two categories determined by the direction of the equatorial wind in the stratosphere (QBO). Figure 4 shows in two scatter diagrams the correlations between the 30-hPa heights over the North Pole in February (i.e., the data of Fig. 2(b)) and the SSC, with the data grouped according to the QBO. The data span 6.5 solar cycles, see Fig. 5.

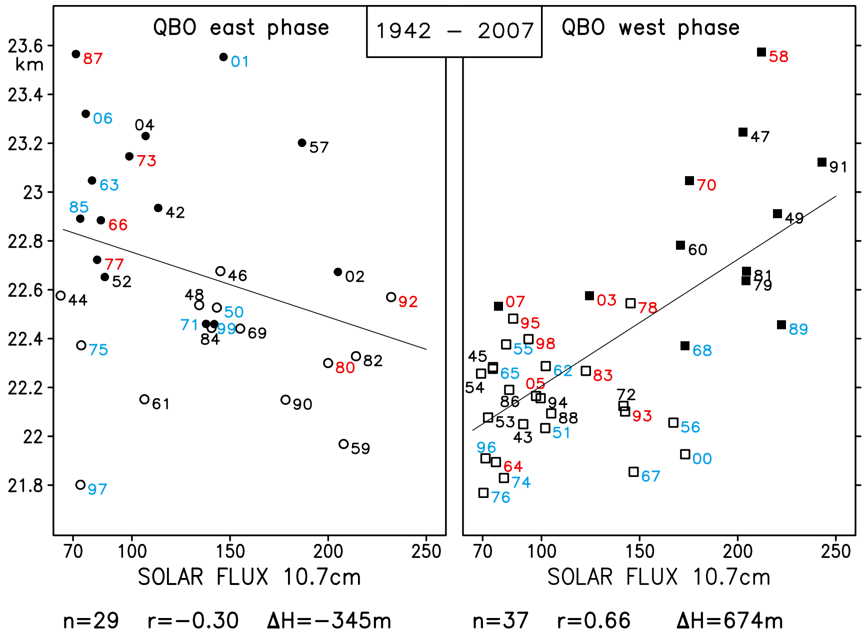

Fig. 4. Scatter diagrams of the monthly mean 30-hPa geopotential heights (geopot.km) in February at the North Pole (1942 till 2007), plotted against the 10.7 cm solar flux. Left: Circles: years in the east phase of the QBO ($n = 29$). Right: Squares: years in the west phase ($n = 37$). The numbers indicate the respective years, with WE in red and CE in blue. Filled symbols denote MMWs. r = correlation coefficient; ΔH gives the mean difference of the heights (geopot.m) between solar maxima (200 s.flux units) and solar minima (70 s.flux units). (Reconstructions: 1942 till 1947; NCEP/NCAR re-analyses: 1948 till 2007.) (van Loon and Labitzke (1994), updated.)

It is obvious (Fig. 4) that the correlations are opposite in the two different phases of the QBO: while they are significantly positive in the QBO-west group ($r = 0.66$, significance about 99%), they are negative in the QBO-east group. The filled symbols indicate the occurrence of MMWs, which took place preferably during solar maxima in the west phase and during solar minima in the east phase. There is a tendency for warm events to occur together with MMWs in solar maximum/west phase, but in solar minimum with the east phase.

The average height difference (ΔH in Fig. 4) between solar maxima and minima is very large in the west phase winters, reaching 67.4 geopot.dam which is 1.5 standard deviations of the interannual variability (cf. Fig. 2(b)).

Figure 5 presents the SSC based on the 10.7 cm solar flux in January and February for the period 1942–2007. It is indicated whether a winter (January/February) belonged to the west (squares) or east (circles) phase of the QBO. Large filled symbols indicate the occurrence of the 27 MMWs in January and February. n = number of years.

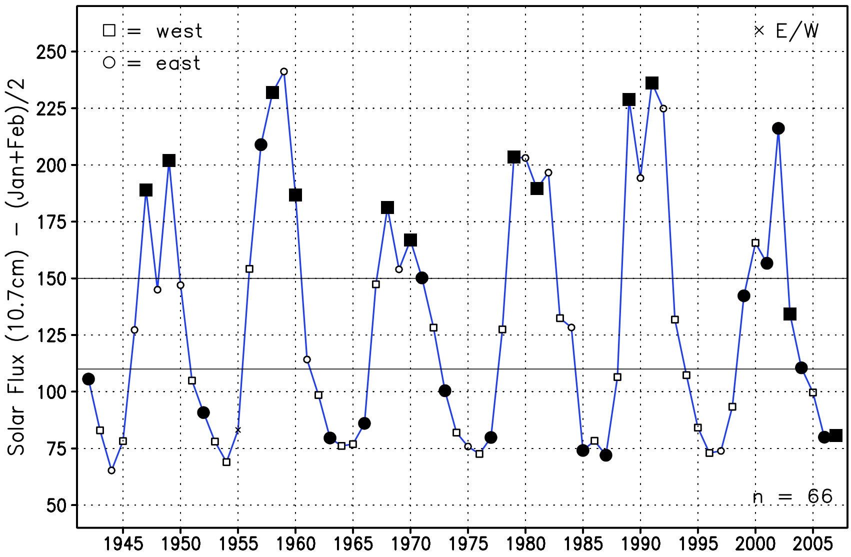

Fig. 5. Time series of the 10.7 cm solar flux, 1942 through 2007, (January+February)/2. Squares denote winters in the west phase of the QBO, circles winters in the east phase. For the classification, the QBO-winds in January and February are used at the 40 and 50 hPa levels, divided by 4. Large filled symbols indicate the occurrence of Major Midwinter Warmings (MMWs) (Labitzke and van Loon, 1990, updated).

While the data shown in Fig. 4 are only for the lower stratosphere (30 hPa) above the North Pole, Fig. 6 shows on the left hand side the correlations of the 30-hPa heights for the whole Northern Hemisphere, with the winters in the east phase of the QBO in the upper part of the figure, and the winters in the west phase of the QBO in the lower part. Again, the pattern of correlations is clearly very different in the two groups, with negative correlations over the Arctic in the east phase and large positive correlations there in the west phase. Outside of the Arctic the correlations are positive and strong in the east phase, but very weak in the west phase.

The respective height differences between solar maxima and minima are given on the right hand side of Fig. 6. In the east phase of the QBO the heights tend to be below normal over the Arctic in solar maxima (about one standard deviation, see Fig. 1); they are above normal towards the equator, indicating an intensification of the Aleutian High. In the west phase, the Arctic heights tend to be well above normal (about 1.5 standard deviations) in solar maxima; there are only very small height differences outside the Arctic.

Figure 7 shows on the left hand side vertical meridional sections of the correlations between the solar 10.7 cm flux and zonally averaged temperatures, and on the right hand side the corresponding temperature differences between solar maxima and minima. When all years are used in February, the correlations and the corresponding

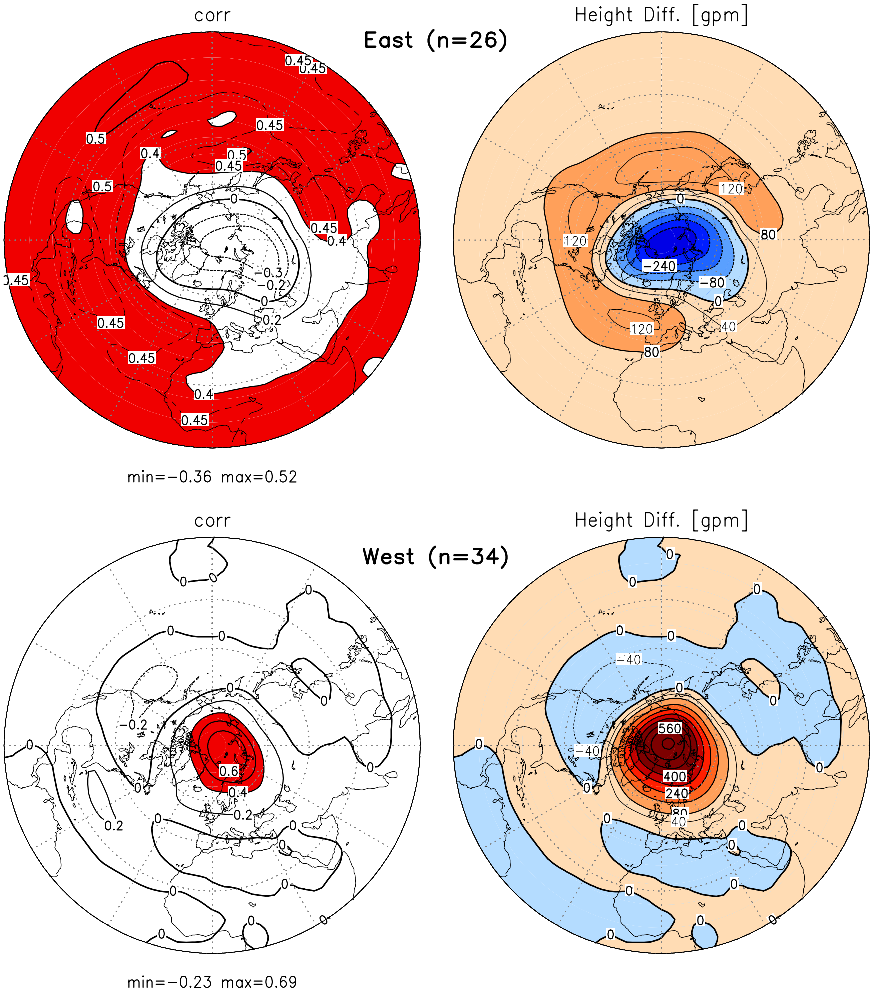

Fig. 6. Left: Correlations between the 10.7 cm solar flux (the 11-year solar cycle) and 30-hPa heights in February, shaded for emphasis where the correlations are above 0.4: upper panel: years in the east phase of the QBO; lower panel: years in the west phase of the QBO. Right: Respectively, height differences (geopot.m) between solar maxima and minima. NCEP/NCAR re-analyses, period: 1948–2007, $n = 60$); (Labitzke, 2002, updated).

temperature differences (top left and right, respectively) are very small. But, in the east phase of the QBO, the correlations of the zonally averaged temperatures with the solar cycle are positive from 60°N to the South Pole in the summer hemisphere, and negative north of 60°N, in the winter hemisphere. On the right hand side in the middle panel are the zonally averaged temperature differences between solar maxima and

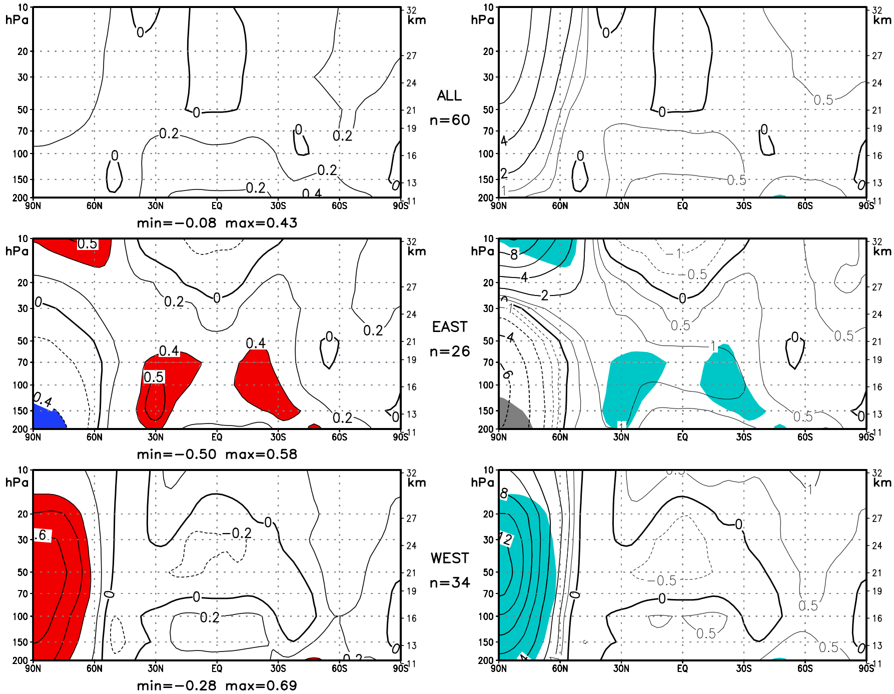

Fig. 7. Vertical meridional sections between 200 and 10 hPa of, on the left, the correlations between the detrended zonally averaged temperatures for February and the 10.7 cm solar flux (shaded for emphasis where the correlations are larger than 0.4), and, on the right, the respective temperature differences (K) between solar maxima and minima, shaded where the corresponding correlations on the left hand side are above 0.4. The upper panels show all years, the middle panels only years in the east phase of the QBO, and the lower panels only years in the west phase of the QBO (NCEP/NCAR re-analyses, 1948–2007) (Labitzke, 2002, updated).

minima in the east phase of the QBO which correspond to the correlations on the left side; the shading is the same as that in the correlations where it denotes correlations above 0.4.

In the west phase of the QBO (Fig. 7, bottom), the correlations with the 10.7 cm solar flux are highly positive over the Arctic ($r = 0.7$) and near zero or weakly negative elsewhere. The large positive correlations are associated with the frequent MMWs which occur when the QBO is in the west phase at solar maxima (e.g., van Loon and Labitzke, 2000). The Arctic temperatures and heights in the stratosphere are then determined by strong subsidence. Outside the Arctic the lower latitudes are expected to warm at solar maximum but, because of the subsidence and warming in the Arctic, the warming to the south is dynamically counter-balanced by a rising motion and cooling, well into the southern (summer) hemisphere.

The height and temperature changes shown in Figs. 6 and 7 indicate that the solar cycle influences the "Mean Meridional Circulation (MMC)", also called "Brewer-Dobson Circulation (BDC)". Forced by planetary waves the MMC regulates winter-time polar temperatures through downwelling and adiabatic warming (e.g., Kodera and Kuroda, 2002; Kuroda and Kodera, 2002; Hood and Soukharev, 2003; Labitzke, 2003; Hood, 2004; Salby and Callaghan, 2004, 2006; Matthes *et al.*, 2006).

During the west phase of the QBO the MMC is intensified during solar maxima (and *vice versa* during solar minima), with large positive anomalies over the Arctic (intensified downwelling and warming), and concurrent weak anomalies (anomalous upwelling/adiabatic cooling) over the Tropics and Subtropics, as shown in the lower maps in Fig. 6 and the lowest panels in Fig. 7. During the east phase the MMC is weakened in solar maxima, with reduced downwelling (anomalous upwelling/cooling) and negative anomalies over the Arctic in solar maxima, and concurrent anomalous downwelling with positive anomalies over the Tropics and Subtropics.

4 Teleconnections in Winter

The strong signal of the SSC in combination with the QBO provokes the question whether there are related signals outside the Arctic and maybe also in the troposphere. One way to investigate this question is using teleconnections (here: correlations) which showed interesting results (e.g., Shea *et al.*, 1991; van Loon and Labitzke, 1998). The opposite temperature changes between high and low latitudes during stratospheric warmings were already shown with early rocket and satellite data (Labitzke, 1972; Labitzke and Barnett, 1973).

4.1 North pole versus equator

To look for the connections in the lower stratosphere itself, we correlated in (Jan+Feb)/2 the 70-hPa temperatures at the North Pole with the zonal mean 70-hPa temperatures over the equator, for the period 1948 till 2007, Fig. 8. (The tropical tropopause is near 70 hPa.) The correlation is negative, as expected, because warming in the Arctic stratosphere is accompanied by cooling over the Tropics and Subtropics, and *vice versa*. But the correlation of -0.65 is very high, and considering the large number of years ($n = 60$), this correlation is very significant (better than 99.9%), as it is independent from the solar cycle and the QBO. This figure shows nicely the direct connection between high and low latitudes.

The variability of the temperatures over the equator is dominated by the QBO, and the east phase is generally colder than the mean and the west phase warmer. The lowest temperatures over the equator (Fig. 8) occurred with MMWs in the east phase, e.g., in 1966, 1973, 2004 and 2006. Three eruptions of tropical volcanoes lead to significant warming of the tropical stratosphere, marked here with A for Agung (April 1963), CH for Chichon (April 1982) and P for Pinatubo (June 1991). While Agung and Chichon belong to the west phase of the QBO and the temperatures should already be higher than the mean, Pinatubo belongs to the east phase and temperatures should be lower than the mean. Therefore the warming after Pinatubo in Jan/Feb 1992 is as strong as that after the two other volcanoes (e.g., Labitzke and van Loon, 1996). And after the QBO changed to west (Jan/Feb 1993 (P + 1)) the warming due

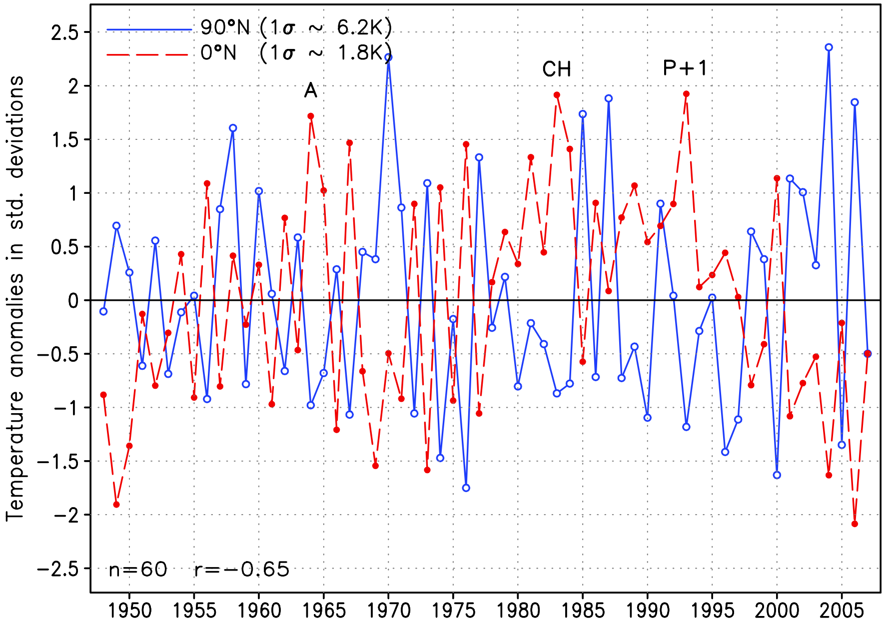

Fig. 8. Time series of the anomalies (in standard deviations) in (Jan+Feb)/2 of the 70-hPa temperatures over the North Pole (solid line) and around the equator (dashed line), 1948–2007; A, CH and P indicate the eruptions of three tropical volcanoes. $n = 60$; correlation $r = -0.65$ (NCEP/NCAR re-analyses).

to Pinatubo is fully comparable to that of the other volcanoes.

4.2 Teleconnections versus the five strongest Major Midwinter Warmings and the five coldest winters

4.2.1 The 5 strongest Major Midwinter Warmings

Figure 9(a) shows the global distribution of the correlations (i.e., the teleconnections) between the 70-hPa temperatures at the North Pole and the whole map, in (Jan+Feb)/2.

Clearly, the region south of about 60°N is negatively correlated with the Arctic. This is consistent with the idea of an intensification of the Mean Meridional Circulation (MMC) over the Arctic, when a MMW with anomalous warming, connected with downwelling, governs the Arctic and anomalous cooling (upwelling) is observed south of the polar region, far into the southern hemisphere (Kodera and Kuroda, 2002; Kuroda and Kodera, 2002; Labitzke, 2003; Salby and Callaghan, 2004, 2006; Kodera, 2006). (The difference of the correlations between the two different phases of the QBO is small, not shown).

Figure 9(b) gives for the 5 strongest MMWs the deviations of the 70-hPa temperatures in (Jan+Feb)/2 from the long-term mean 1968–2007. We choose MMWs of the QBO east/solar min group: 1977; 1985; 1987; 2004; 2006. But the anomalies of

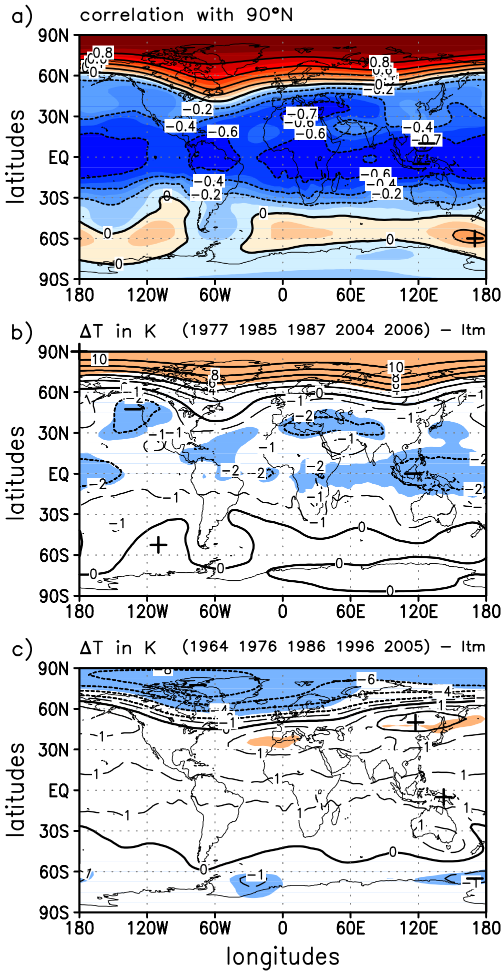

Fig. 9. (a) Teleconnections (i.e. correlations) at the 70-hPa level between the North Pole and the rest of the map for the temperatures in (Jan+Feb)/2. (NCEP/NCAR re-analyses, 1948–2007; $n = 60$). (b) Deviations of the 70-hPa temperatures (K) in (Jan+Feb)/2 of the five strongest MMWs (in solar min/east) from the long-term mean (ltm) (1968 through 2007). Shaded are anomalies larger than 1 standard deviation. (NCEP/NCAR re-analyses.) (c) As (b), but for the five coldest winters (in solar min/west).

the QBO west/solar max group are very similar (not shown).

The pattern of the anomalies can be directly compared with the correlations in Fig. 9(a) and shows the strong interaction between high and low latitudes connected with the MMWs. The influence of the northern winters reaches as far as 40°S, as observed already with early satellite data (Fritz and Soules, 1970; Labitzke and Barnett,

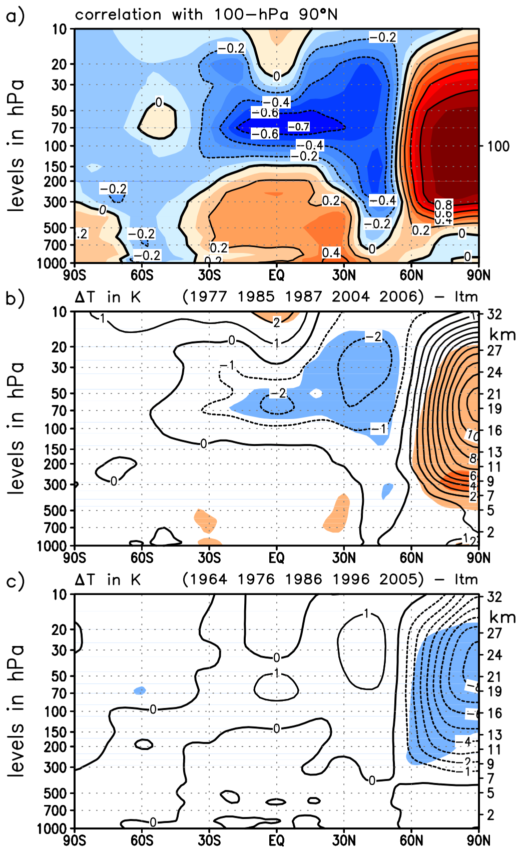

Fig. 10. (a) Vertical meridional section from 1000 to 10 hPa of the teleconnections (i.e., correlations) between the 100-hPa temperature at the North Pole and the rest of the globe in (Jan+Feb)/2. (NCEP/NCAR re-analyses, period 1968–2007). (b) Vertical meridional section from 1000 to 10 hPa of the deviations of the zonal mean temperatures (K) in (Jan+Feb)/2 of the five strongest MMWs from the long-term mean (1968 through 2007). Light shading: anomalies larger than 1 standard deviation, heavy shading: anomalies larger than 2 standard deviations. (c) As (b), but for the five coldest winters. (NCEP/NCAR re-analyses.)

1973).

Considering the large signals of the MMWs and the interaction between high and low latitudes, it is of great interest to see if this signal penetrates to the troposphere. Figure 10(a) shows a vertical meridional section of the teleconnections between the 100-hPa level over the Arctic and the rest of the atmosphere from the ground to 10 hPa. The interaction between high and low latitudes is very clearly visible with a maximum of the negative correlation over the equator at the 70-hPa level which is the tropopause region here, (cf. Fig. 8). And over the Arctic the positive cor-

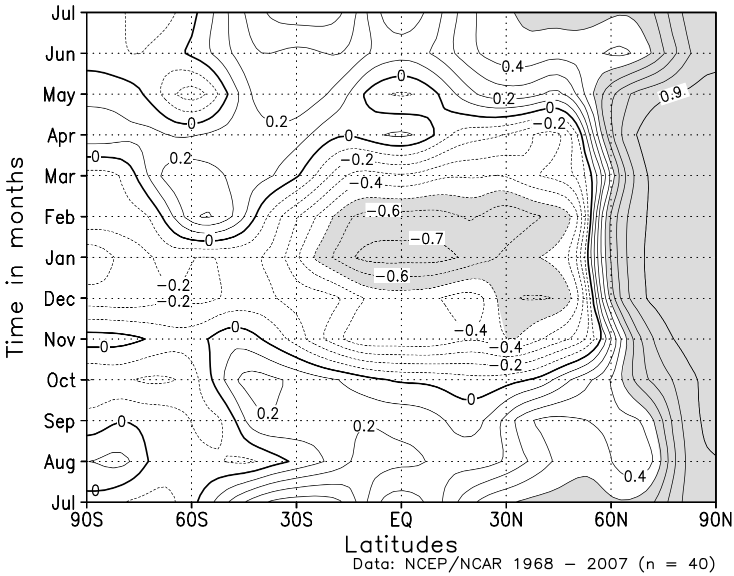

Fig. 11. Teleconnections (i.e., correlations) between the 100-hPa temperature at the North Pole and the zonal mean 70-hPa temperature (90°N–90°S) throughout the year. Shaded are correlations of more/less than +0.5/−0.5 (NCEP/NCAR re-analyses, period 1968–2007).

relations reach deep into the troposphere. Of great interest is the positive correlation in the tropical troposphere below the negative correlation in the tropopause region which appears to be a result from the warming over the Arctic.

This can be compared with the 5 strongest MMWs, Fig. 10(b). Here we are again dealing with the temperature anomalies, like in Fig. 9(b). The strong MMWs dominate the polar region not only in the stratosphere, but also in the troposphere where the positive anomalies reach to the ground, with more than 2 standard deviations in the upper troposphere over the Arctic. And outside the Arctic, south of about 60°N, the anomalies are significantly negative in the stratosphere over the Tropics and Subtropics. The structure of the anomalies indicates clearly a downward propagation of the stratospheric warming over the Arctic (e.g., Baldwin and Dunkerton, 2001).

In the stratosphere, the cooling outside the Arctic was to be expected from the teleconnections, see Fig. 10(a). The concurrent warming in the troposphere (most prominently over 30°S) is also consistent as regards the teleconnections (Salby and Callaghan, 2006).

4.2.2 The 5 coldest winters

These winters (1964, 1976, 1986, 1996, 2005) belong to the west phase winters in solar minimum and are among the coldest winters in the Arctic stratosphere since 1942, see Figs. 2 and 8. Accordingly, the deviations of the 70-hPa temperatures in (Jan+Feb)/2 from the long-term mean, Fig. 9(c), are negative in the Arctic stratosphere (more than one standard deviation) and positive from about 60°N till 40°S. The vertical section of the anomalies (Fig. 10(c)) is very similar to Fig. 10(b), but, ofcourse, with opposite sign.

4.2.3 Structure of the teleconnections through the year

In Fig. 10(a) we showed for (Jan+Feb)/2 a vertical meridional section of the teleconnections between the 100-hPa level over the Arctic and the rest of the atmosphere from the ground to 10 hPa. Here the link between high and low latitudes is strongest at the 70-hPa level. Therefore, we show in Fig. 11 the development of this link through the year. And the period with the strongest correlations coincides clearly with the period of the northern winter, when planetary scale waves are strongest.

5 Connections between the Stratosphere, the sun and the QBO during Summer

The stratosphere is dynamically least disturbed during the northern summer (Labitzke and van Loon, 1999) and the interannual variability is small, cf. Fig. 1. And if the different phases of the QBO are introduced a large solar signal is found. Figure 12 gives on the left the correlations of the 30-hPa temperatures with the 11-year SSC, with all data on top, the east phase data in the middle and the west phase data at the bottom.

The division into these two groups yields very clear results: the correlations for all years are a result of the strong correlations in the east phase, and the west phase contributes only very little. The very homogeneous pattern of the high correlations in the east phase is striking and convincing, as many different regions with different data problems give the same results. Accordingly, the temperature differences (on the right, middle panel) between solar max and min are over large areas higher than 2 standard deviations, see Fig. 1. To illustrate this strong correlation in summer, the time series of the monthly mean 30-hPa temperatures of July are given for a gridpoint near Nagasaki/Japan, Fig. 13. Again, the figure shows all data on top, the east phase in the middle and the west phase data at the bottom. The correlation of $r = 0.84$ (in the east phase) is clearly supported by the data of the single years. Only in July 1982 is the temperature a bit higher compared to the other solar maxima; but this is a response to the eruption of the Mexican volcanoe El Chichon (CH) in March/April 1982.

The correlations on the left of Fig. 14 show for July the vertical distribution of the relationship between the solar variability and the temperature, from the troposphere to the middle stratosphere. Again, the data are grouped in all years and in the east and west phases of the QBO. The corresponding temperature differences are given in the middle of the diagram, and the standardized temperature differences are on the right. Originally we made this division according to the phase of the QBO only in the northern winter data (Labitzke and van Loon, 1988); but it turns out that it is also a valid approach throughout the year (Labitzke, 2003, 2004a, b, 2005).

The results for the east phase (Fig. 14) are most striking: two centers with correlations above 0.7 are found over the Subtropics between 20 and 30 hPa. Further down, the double maximum in the east phase changes into one maximum, centered on the equatorial tropopause (Labitzke, 2003). The temperature differences between

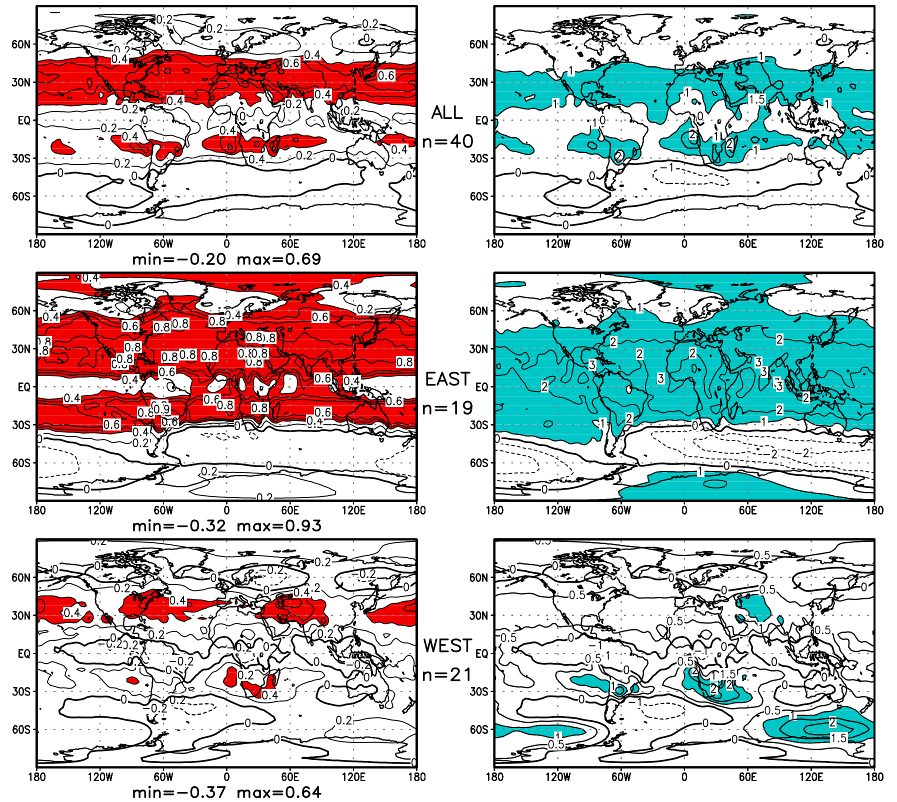

Fig. 12. Left: Correlations between the 10.7 cm solar flux and the detrended 30-hPa temperatures in July; shaded for emphasis where the correlations are above 0.4. Right: The respective temperature differences (K) between solar maxima and minima; shaded where the differences are above 1 K. Upper panels: all years; middle panels: only years in the east phase of the QBO; lower panels: only years in the west phase of the QBO. (NCEP/NCAR re-analyses, 1968–2007 (Labitzke, 2003, updated).)

solar maxima and minima are large, more than two standard deviations in some regions. This warming, i.e., positive anomalies, can only be explained by anomalous downwelling (i.e., reduced upwelling) over the Subtropics and Tropics (Kodera and Kuroda, 2002; Shepherd, 2002) which—in other words—means a weakening of the BDC for solar maxima/east phase of the QBO, as discussed above already for the northern winter.

In northern summer the solar variability signal is much weaker in the west phase years than in the east phase years and restricted to the northern hemisphere (lower panels in Fig. 14).

Figure 15 shows for the east and west phases of the QBO maps of the height differences (between solar maxima and minima) over the Subtropics and Tropics in

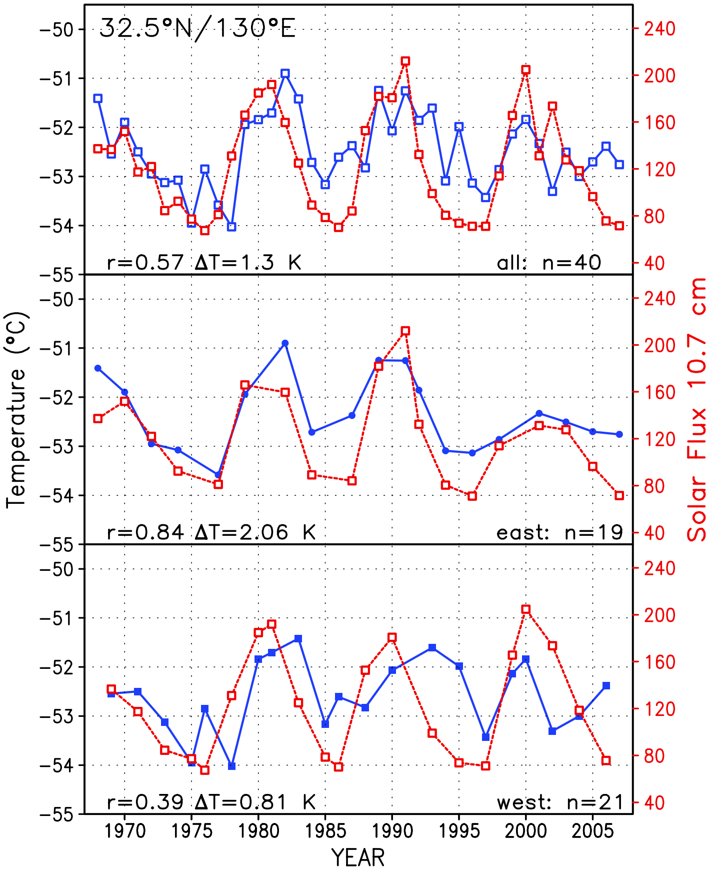

Fig. 13. Time series of monthly mean values of the 10.7 cm solar flux (dashed lines) and detrended 30-hPa temperatures in July at the grid point 32.5°N/130°E, (near Nagasaki/Japan). The upper panel shows all years ($n = 40$), the middle panel only years in the east phase of the QBO ($n = 19$), and the lower panel only years in the west phase of the QBO ($n = 21$). r = correlation coefficients; ΔT = temperature difference (K) between solar maxima and minima (NCEP/NCAR re-analyses, 1968–2007).

July for the 30-hPa level (about 24 km): again, the east phase dominates the solar signal (upper part of Fig. 15). In addition, the anomalous zonal (west-east) wind in the equatorial belt is affected by the solar variability on the decadal scale. At the top of the figure anomalously high values (more than two standard deviations, Fig. 1) are centered over the equator. This means that an anomalous ridge is centered on the equator in the solar maximum east years, connected with anomalous winds from the west. Therefore, during solar maxima in QBO/east years the low-latitude east wind is weakened, and conversely in the solar minimum years.

In the west phase of the QBO (bottom of Fig. 15), the pattern of the anomalies of

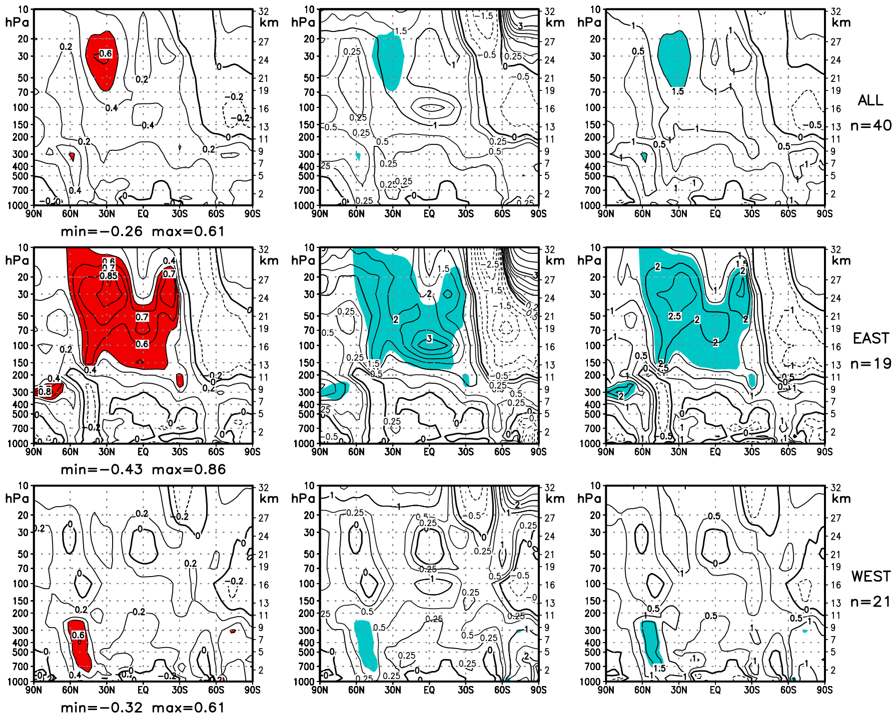

Fig. 14. Left: Vertical meridional sections of the correlations between the 10.7 cm solar flux and the detrended zonal mean temperatures in July; shaded for emphasis where correlations are above 0.5. Middle: The respective temperature differences (K) between solar maxima and minima, shaded where the corresponding correlations on the left hand side are above 0.5. Right: As for the middle row but standardized with the standard deviations. Upper panels: all years; middle panels: only years in the east phase of the QBO; lower panels: only years in the west phase of the QBO. (NCEP/NCAR re-analyses, 1968–2007.) (Labitzke (2003), updated.)

the geopotential heights is completely opposite, with the lowest values on the equator in solar maxima. The anomalous winds are from the east and the QBO is again weaker in solar maxima. The QBO thus not only modulates the solar signal on the decadal scale, but is itself modulated by the solar variability (Salby and Callaghan, 2000; Gray *et al.*, 2001; Soukharev and Hood, 2001; Labitzke, 2003, 2004b).

6 Summary

During solar minima the so-called "Holton-Tan Relationship" is valid for both phases of the QBO: In the QBO-eastphase the Arctic is relatively warm, with frequent MMWs, while during the westphase cold polar vortices dominate. However, during solar maxima the situation is reversed, especially during the westphase of the QBO.

New results based on an extended, 66-year long data set fully confirm our earlier

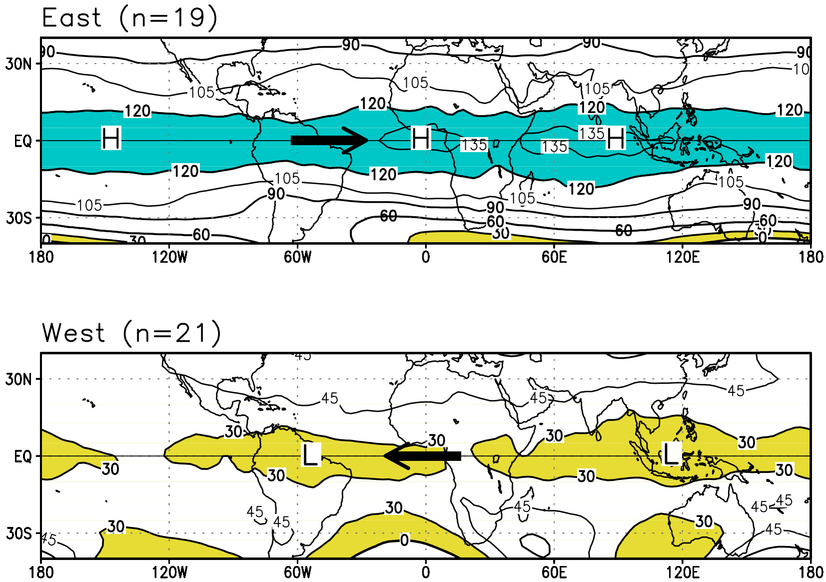

Fig. 15. Maps of the 30-hPa height differences (geopot.m) in July between solar maxima and minima. The upper map is for years in the east phase of the QBO, and the lower map for years in the west phase of the QBO. Arrows indicate the direction of the anomalous winds. (NCEP/NCAR re-analyses, 1968–2007.) (Labitzke (2003), adopted from her figure 5.)

findings and suggest a significant effect of the SSC on the occurrence of the Major Midwinter Warmings (MMWs) as well as on the strenght of the stratospheric polar vortex and on the mean meridional circulation.

Teleconnections show the dynamical interaction between the Arctic and the Tropics, and between the stratosphere and the troposphere. Their structure is very similar to the structure of the anomalies during strong MMWs in the stratosphere and of the anomalies during very cold stratospheric polar winters, respectively.

The results shown here suggest strongly that for the period from 1942–2007 ($n = 66$) the teleconnections between the Arctic and the Tropics and Subtropics during the northern winters were determined (in the stratosphere and in the troposphere) by the events in the stratosphere over the Arctic: i.e. by 27 stratospheric MMWs in January or February (44% of all winters) and by 29 COLD winters (about 50% of all). And these events are coupled to the 11-year SSC and to the QBO, as described above.

Outside the northern winter the eastphase of the QBO dominates with strong positive correlations over the Tropics and Subtropics, with the largest signal of the 11-year SSC (more than 2 standard deviations) during the northern summer.

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