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# Connection between the troposphere and stratosphere on a decadal scale

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## ABSTRACT

A decadal oscillation of the geopotential heights in the lower stratosphere, which is well-correlated with the 11-year solar cycle, is closely linked to changes of the temperature on the same time scale in the middle and upper troposphere, the temperature being higher on an average in the maxima than in the minima of the 11-year solar cycle. It appears likely that these changes in the tropospheric temperature are associated with changes in the Hadley circulation. It is well established that the decadal oscillation in the stratosphere is modulated by the Quasi-Biennial Oscillation in winter. We point out that the QBO also modulates the decadal oscillation at other times of the year, but that the effect of the modulation is then weaker because of the different wind regime in the stratosphere.

## 1. Introduction

In addition to the two well-known non-cyclical oscillations in the atmosphere, the Quasi-Biennial Oscillation (QBO) and the Southern Oscillation (SO), a third one has been discovered lately which has an *average* period of 10 to 12 years (Labitzke, 1987; Van Loon and Labitzke, 1990; and Labitzke and Van Loon, 1992a). It has been described as taking place mainly in the stratosphere, but recent work has shown that it is visible in the tropospheric temperature of the regions where its presence is notable in the stratosphere. In this paper, we expand the description of the vertical structure of the 10-to-12-year oscillation, abbreviated as TTO, to try to find an association with atmospheric circulation systems. Its average period during the four decades available is close to that of the 11-year sunspot cycle, and as its phase appears to be the same as that of the solar cycle, the two are well correlated. This does not necessarily mean that the atmospheric oscillation is caused by variations on the sun; nevertheless, we shall describe the TTO mainly by its correlations with the 10.7 cm solar radio flux (the unit is $10^{-22}$ Wm$^{-2}$ Hz$^{-1}$) which is a good indicator of the 11-year sunspot cycle.

Our data are derived from the daily historical maps analyzed in the Stratospheric Research Group at the Freie Universität Berlin, and from tropospheric temperature analyses by the U.S. National Meteorological Center. The vertical profiles are from radiosonde stations listed in the NOAA publication "Monthly Climatic Data of the World", and more recently compiled at NCAR.

## 2. The TTO in the horizontal and vertical

### 2.1. *Horizontal distribution*

The TTO in the lower and middle stratosphere is plain to see through the pattern of correlation between the 30 hPa height and the 10.7 cm solar flux (Fig. 1): the shape of the pattern changes little from one season to another since throughout the year the highest correlations are found near 30° N, with the largest values over the western

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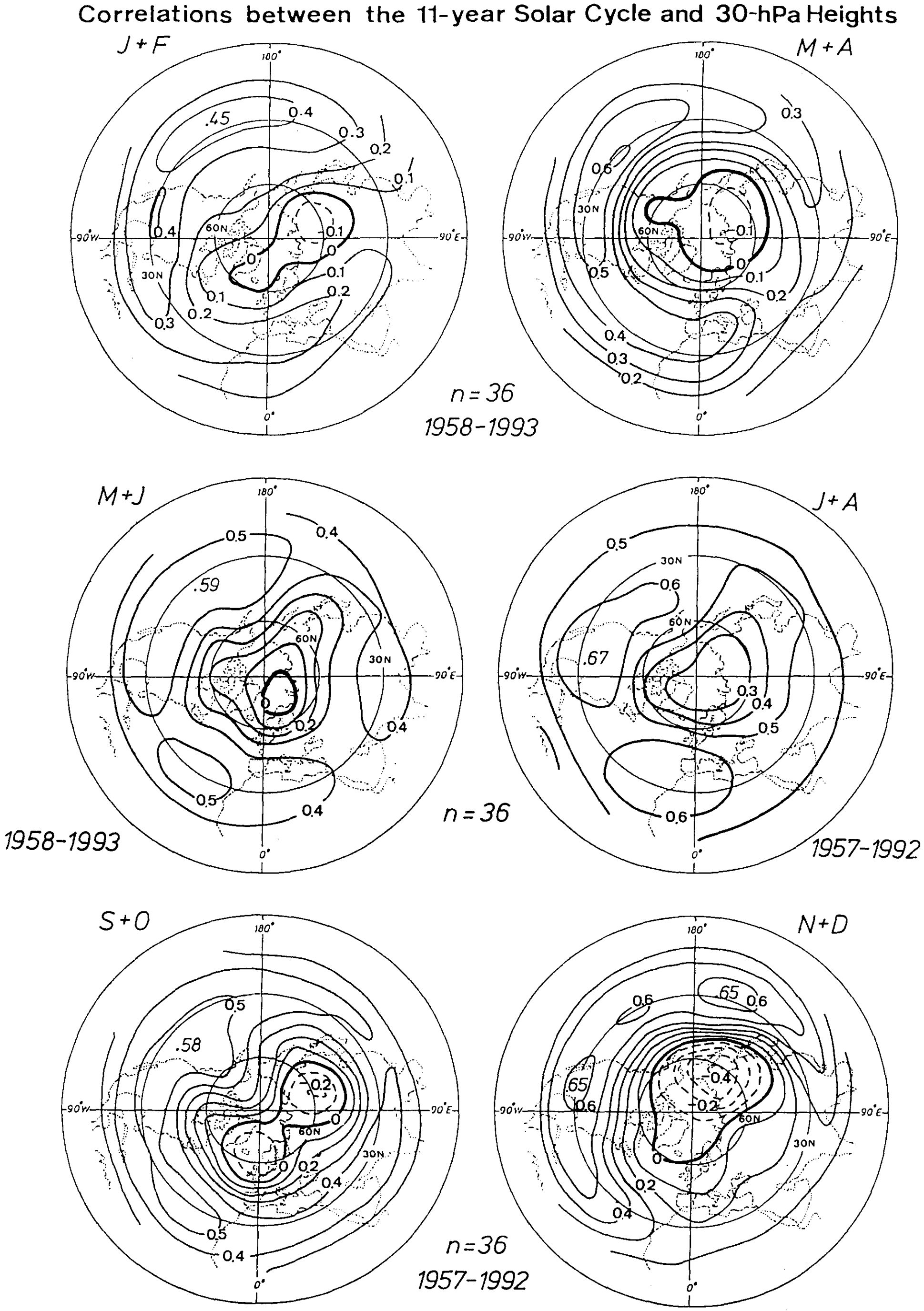

*Fig. 1.* Correlations between 10.7 cm solar flux (unit is $10^{-22}$ $Wm^{-2}$ $Hz^{-1}$) and the 30 hPa height, for 2-month mean values of the 30 hPa height; $n = 36$. Updated from Van Loon and Labitzke (1990).

hemisphere. The largest area with high correlations is found in July–August, and the smallest in January–February. The correlation between the annual mean 30 hPa height and the solar cycle (Fig. 2, upper panel) shows, not surprisingly, the same pattern as the maps in Fig. 1. We have shaded the areas where the local significance is high to draw attention to the characteristic pattern which is found in every season (cf., Fig. 1), but it is clear that the degrees of freedom are reduced by temporal and spatial dependence in the data. It is doubtful, in any event, if one should pay much attention to statistical significance in such comparatively short series which are unlikely to be stationary. Note that neither the pattern nor size of the correlation coefficients has changed as more years have been added to the record.

The time series of the 30 hPa height at 30° N–150° W gives an idea of how many realizations of the TTO are included in the period covered by the maps in Figs. 1 and 2. The effect of El Chichon's eruption in 1982, an unusual warming of the lower tropical and subtropical stratosphere, is evident in that and the following year. At the 30 hPa level the monthly mean radiosonde observations published in "Monthly Climatic Data of the World", which is our source station data, didn't become available until 1964. This, incidentally, is why the 30 hPa time series at Charleston in Fig. 10 does not begin till that year.

### 2.2. *Vertical distribution*

Local variations in the 30 hPa height are largely linked to variations in the temperature of the air column below, which can be seen in Fig. 3a: the curves in this figure show the temperature difference between three maxima and three minima in the 11-year solar cycle at four tropical stations with annual correlations coefficients of 0.5 to 0.7. At all 4 stations the troposphere is, on an average, warmer at solar maximum than at solar minimum. At the levels near the tropopause they are colder at solar maximum; and at the two southernmost stations, Koror and Truk, the stratosphere is warmer in solar maxima, as in the troposphere. Two tropical-subtropical stations farther east in the region of high correlations, San Diego in California and San Juan in Puerto Rico (Fig. 3b), also have a higher average tropospheric temperature in the solar maxima. It is clear from these vertical profiles of the temperature difference between solar cycle extremes that the high positive correlations between the 30 hPa height and the 10.7 cm solar flux in Fig. 2 to a great extent must be due to variations in the temperature of the middle and upper troposphere.

### 2.3. *Possible association with the Hadley circulation*

The shape of the vertical profiles of the difference between solar extremes is the same throughout the year, but at Hawaii (Fig. 4a) the difference is largest in winter and spring and smallest in autumn, and at Truk (Fig. 4b) the difference is largest from May to October and smallest from November to February. The shape of the profiles and the position of the stations (a) in the vicinity of the Intertropical Convergence Zone (ITCZ): Koror and Truk, and (b) in the outer-tropical and subtropical zone of subsidence: Hawaii, San Juan, and San Diego, suggest that the temperature difference between peaks and valleys in the TTO is associated with a difference in the strength of the Hadley circulation. If that is so, the warmer troposphere at the northern stations would be owing to stronger subsidence at the peaks than in the valleys of the TTO, and the warmer troposphere at the southern stations would be associated with more convection and release of latent heat near the ITCZ in a stronger Hadley circulation at the TTO peaks.

The vertical profiles of the mean temperature difference between solar extremes at a station between the ITCZ and the sinking branch of the Hadley circulation, Guam at 14° N–145° E, lends credibility to this hypothesis. The island has a dry period in winter, when the ITCZ lies to the south of it, and a wet season in summer when the ITCZ is near: the combined rainfall of January and February is 200 mm, and in July–August it is 740 mm. The temperature difference in the troposphere between solar extremes is about 0.2°C in winter (Fig. 5), but in summer it is three to five times higher in the upper half of the troposphere where the release of latent heat would be most noticeable.

The idea of a stronger Hadley circulation at the peaks of the TTO is tested in a preliminary way in the following. We compare a year with intense convection in the ITCZ in the Pacific Ocean, 1983, a warm event in the Southern Oscillation, with a period, 1985, when the low-latitude convection in the Pacific was weaker. In a warm event, the

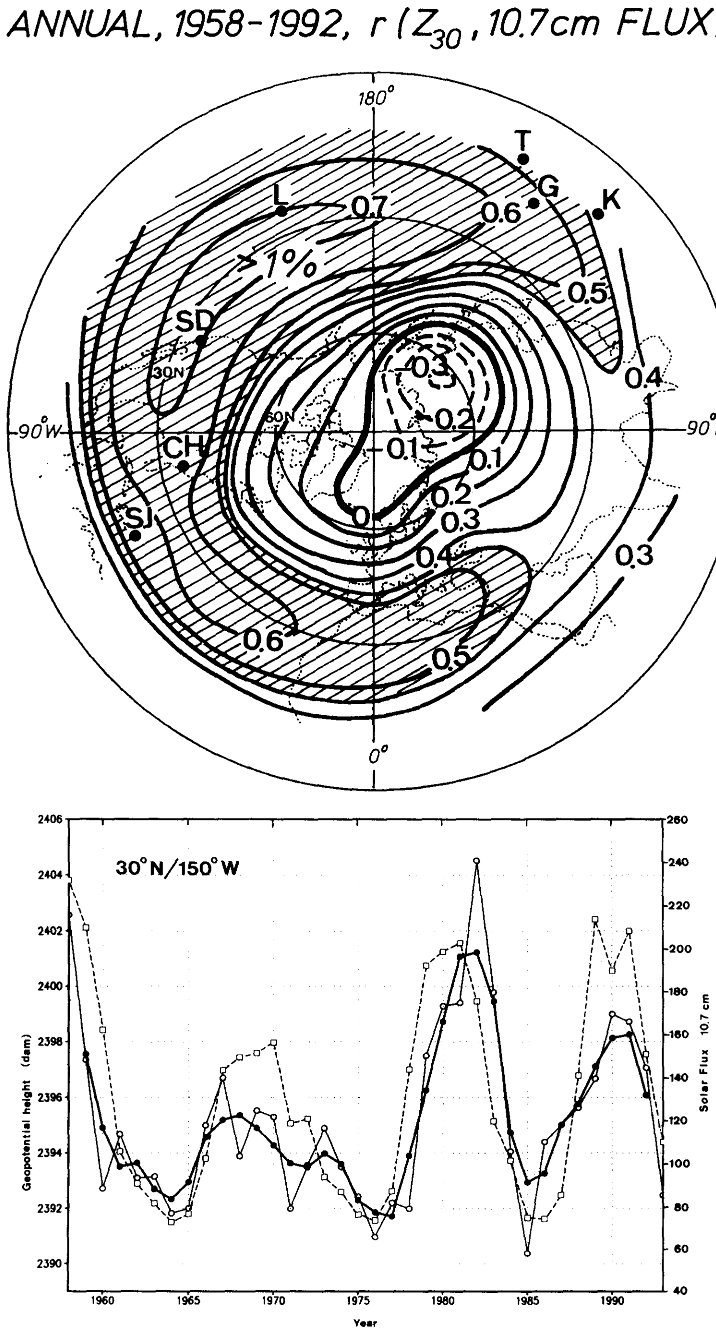

*Fig. 2.* (Upper panel) The same as Fig. 1, but for the mean annual values of the 30 hPa height, $n = 35$. The area where the local statistical significance is above the 1% level is hatched. The dots are positions of stations: SD San Diego, CH Charleston, SJ San Juan, L Lihue, T Truk, K Koror, G Guam. Updated from Van Loon and Labitzke, 1990. (Lower panel) Time series of the annual mean 30 hPa height at 30° N–150° W (thin continuous line); the unit is geopotential dekameter. From the analyses in the Stratospheric Research Group, Berlin. The thin dashed line is the 10.7 cm solar flux, and the heavy line is a three-year running mean of the annual mean 30 hPa height at the point.

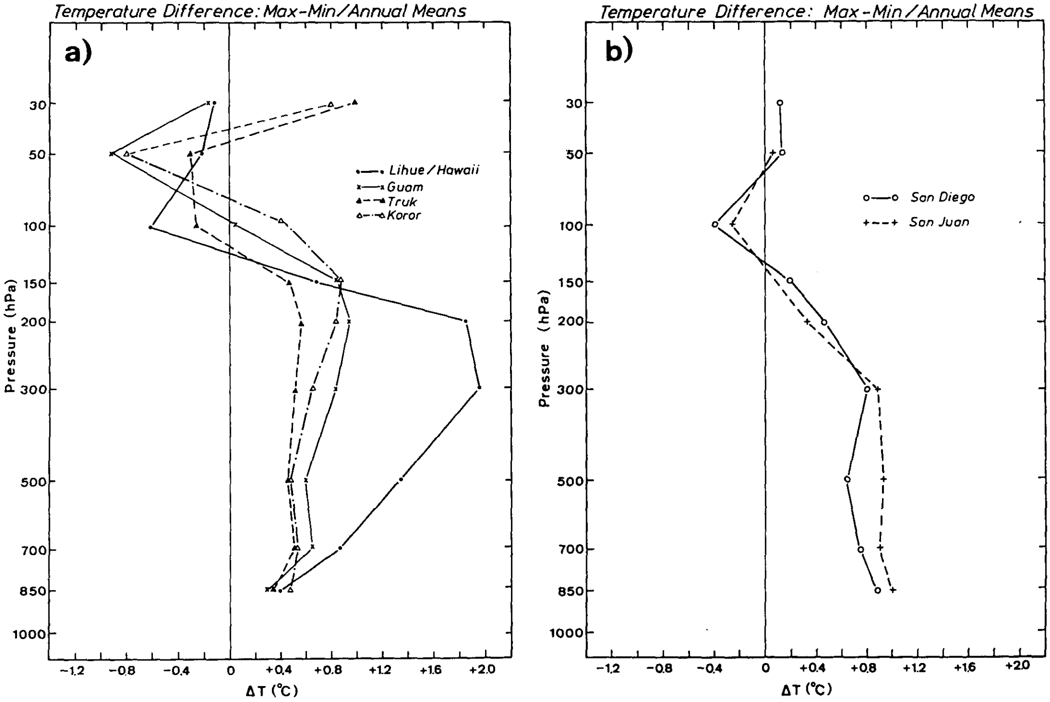

*Fig. 3.* (a) The temperature difference between maxima and minima in the 11-year solar cycle at four tropical islands. The unit is °C. (b) The average temperature difference between maxima and minima in the solar cycle at San Diego, California, and San Juan, Puerto Rico; the unit is °C.

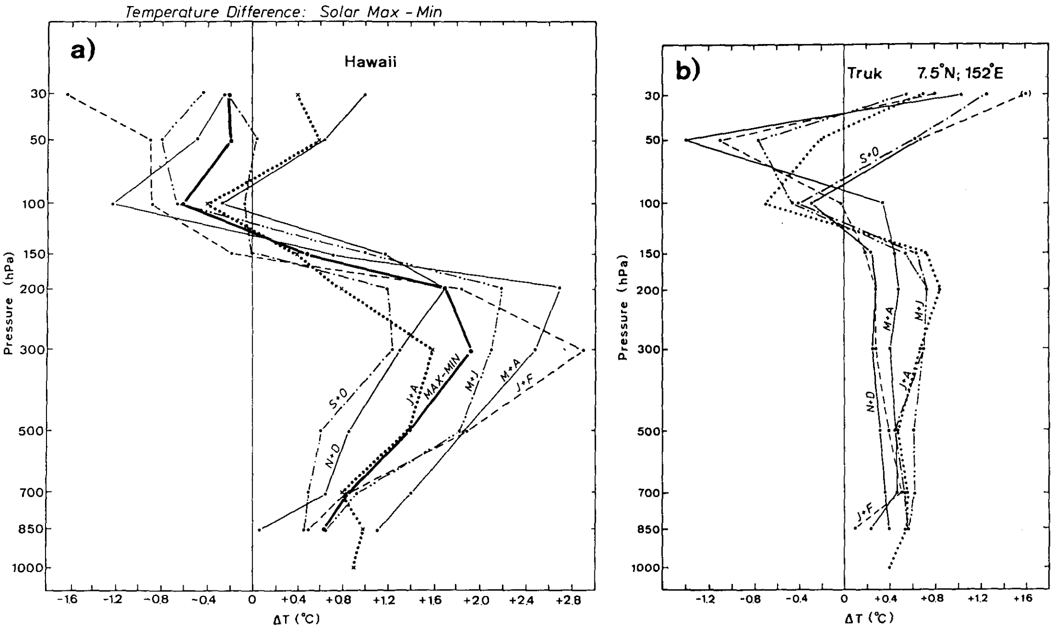

*Fig. 4.* (a) 2-month average temperature difference between maxima and minima in the 11-year solar cycle at Hawaii, the heavy solid line is the annual mean; the unit is °C. (b) The same for Truk.

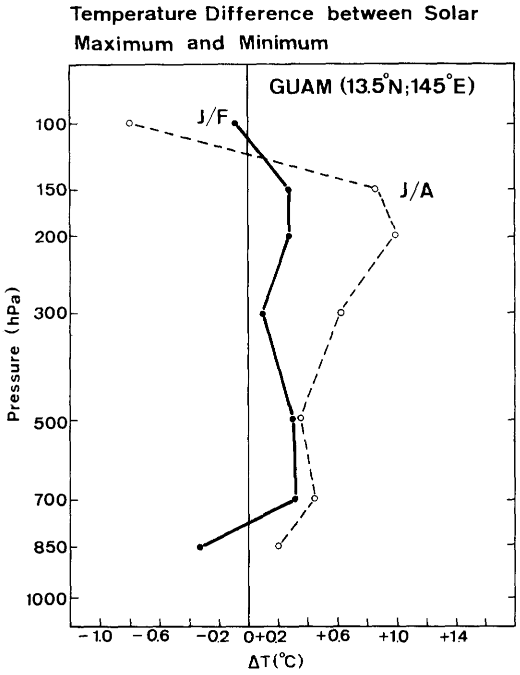

*Fig. 5.* The mean temperature difference (°C) between three solar maxima and minima at Guam in January/February (solid) and July/August (dashed).

latitudes of Hawaii are prone to drought because of stronger than normal subsidence on the poleward side of the Hadley circulation (Ropelewski and Halpern, 1987, their Figs. 2, 3).

The vertical profile of the temperature difference between the winters of 1983 and 1985 at Hawaii (Fig. 6a) shows that the middle and upper troposphere in the winter with strong tropical convection, 1983, was as much as 4°C warmer than in 1985. The shape of the profile is the same as that of the mean difference between the extremes of the TTO shown in the same figure. At Truk in summer, Fig. 6b, the year with the stronger convection also has the warmer troposphere, as have the years at the peaks of the TTO. One can thus accept as a working hypothesis that the mechanism of the TTO includes a variation of the Hadley circulation on a decadal scale. This hypothesis will be the basis of further diagnosis and numerical experiment.

## 3. An effect of the QBO

The influence of the QBO on the circulation in the extratropical stratosphere in winter has often been studied (e.g., Labitzke, 1965; Holton

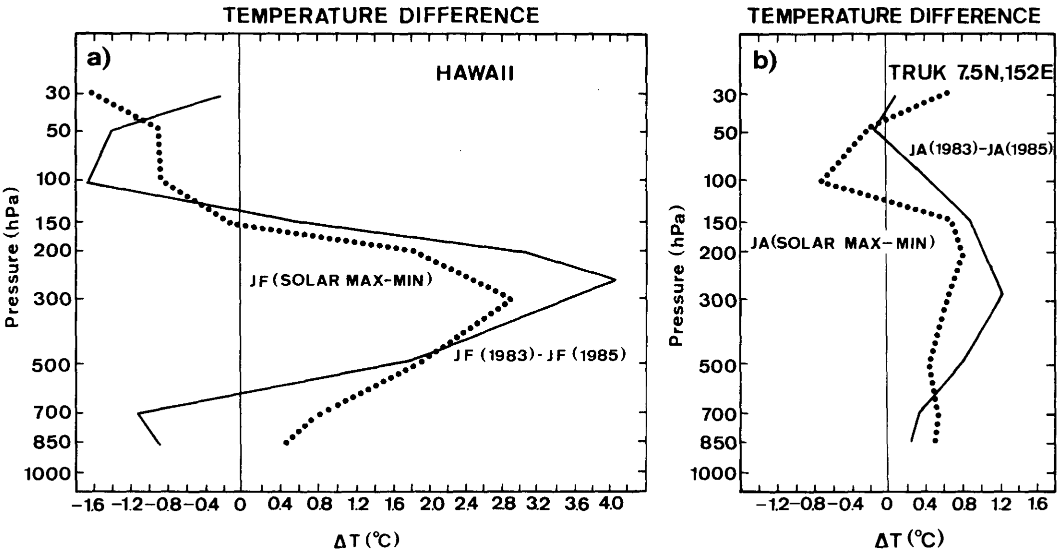

*Fig. 6.* (a) Dotted line: the mean temperature difference between three solar maxima and minima at Lihue, Hawaii, in January–February. Solid line: the mean temperature difference (the mean at four gridpoints about Hawaii) between January–February 1983 and 1985. The unit is °C. (b) The same as (a), but for Truk in July–August.

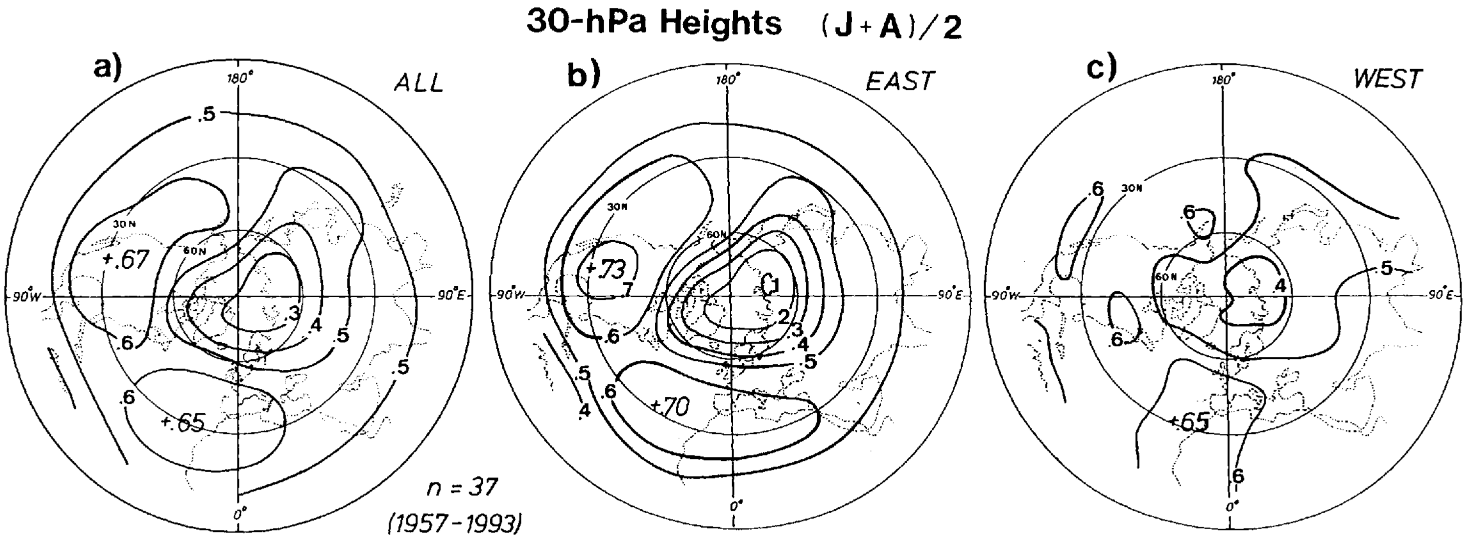

*Fig. 7.* (a) The 30 hPa height in July–August correlated with the 10.7 cm solar flux; $n = 37$. (b) The same for the east years in the QBO ($n = 18$), and (c) for the west years ($n = 19$). Updated from Labitzke and Van Loon (1989).

and Tan, 1980, 1982; Wallace and Chang, 1982; Labitzke, 1982; Van Loon and Labitzke, 1987); but it was not possible to obtain an unambiguous description of the extratropical signal until it was found that the influence of the QBO is affected by a decadal wave (for instance, Labitzke, 1987; Labitzke and Van Loon, 1992b; Kodera, 1993). Holton (1994) suggests that the winter stratosphere on the Northern Hemisphere has two basic climate regimes: one in which the eddy motions are strong and polar temperatures high, and a second in which the eddy motions are weak and the polar temperatures are low. The equatorial QBO influences the extratropics in winter, according to Holton "through the mechanism of changing the probability that the winter stratosphere lies in either the strong or weak eddy regime. This influence appears to undergo a quasi-decadal variation [our TTO], which may or may not be related to the solar cycle". Holton speculates that if the TTO is "related to solar forcing, the mechanism is one in which the net effect of weak solar cycle forcing alters the probability density function of the climate regimes in such a way that the strong eddy regime becomes more probable in the westerly QBO phase during sunspot maximum than during sunspot minimum".

The influence of the QBO on the stratospheric winter circulation was inherent in the original description of the TTO (Labitzke, 1987) and has been elaborated on in several of our papers. In the following, we show that an influence by the QBO is not limited to the winter months but can be detected in other seasons as well, although it is then smaller than in winter and different because of the different wind regimes in the stratosphere. In the correlation map for July–August (Fig. 7a), 37 years are represented, from 1957 till 1993; the map is field significant at the 1 % level in a Monte Carlo test (Van Loon and Labitzke, 1990). The correlations in the east years (Fig. 7b) are not only somewhat higher than in the west years (Fig. 7c) in the crescent-shaped area where the largest correlations are always found (Figs. 1, 2), but they also largely define the shape of the crescent in the correlations of *all* the summers with the solar flux (Fig. 7a).

We mentioned in Subsection 2.2 that the large positive correlations in the tropics and subtropics between the 11-year solar cycle and the 30 hPa height to a great extent are associated with the temperature in the middle and upper troposphere, which is higher in solar maxima than in the minima; in the levels near the tropopause the temperature in the solar maxima are lower than those in the solar minima, as seen for example in Fig. 4b. In the stratosphere the 50 hPa level in the tropics is within the layer which is affected by changes in the tropopause. The temperature difference between solar maximum and minimum is therefore most often negative at 50 hPa in the vertical profiles which are located in the area with the highest correlations between 30 hPa height and the solar flux. But the conditions differ according to whether it is an east or a west year of the QBO: in Fig. 8a the 50 hPa temperature in the west years in July–August are correlated with the 10.7 cm flux; the correlation coefficients are small and their sign is mainly negative in the tropics and subtropics. In the east years, however, the sign in the crescent is positive and the values are appreciably higher (Fig. 8b). Thus, the 50 hPa level contributes nothing in the west years to the large positive correlations between the sun and the 30 hPa heights, whereas in the east years the 50 hPa level does make a contribution. The same relationship between temperature and sun in the QBO west and east years exists at 30 hPa in Figs. 8c and d: there are few positive values in the west years and all are small, but in the east years the correlations are positive and large. It is thus clear that the tropical-subtropical association between the 30 hPa height and the solar cycle (Fig. 7a; the correlation map for 50 hPa is similar, Fig. 9) stems mainly from the troposphere in the west years and from both the troposphere and stratosphere in the east years.

## 4. Conclusion

During the past 4 decades, the heights of the stratospheric constant pressure levels have varied on a decadal scale. Data from before that period are not available in the stratosphere. We demonstrate that the decadal variation in the stratosphere, in the large areas where the decadal variation is pronounced (south of about 45° N, and especially over the western hemisphere), is closely linked to changes in the middle and upper troposphere on the same time scale. The fact that the tropospheric column is warmer in the maxima

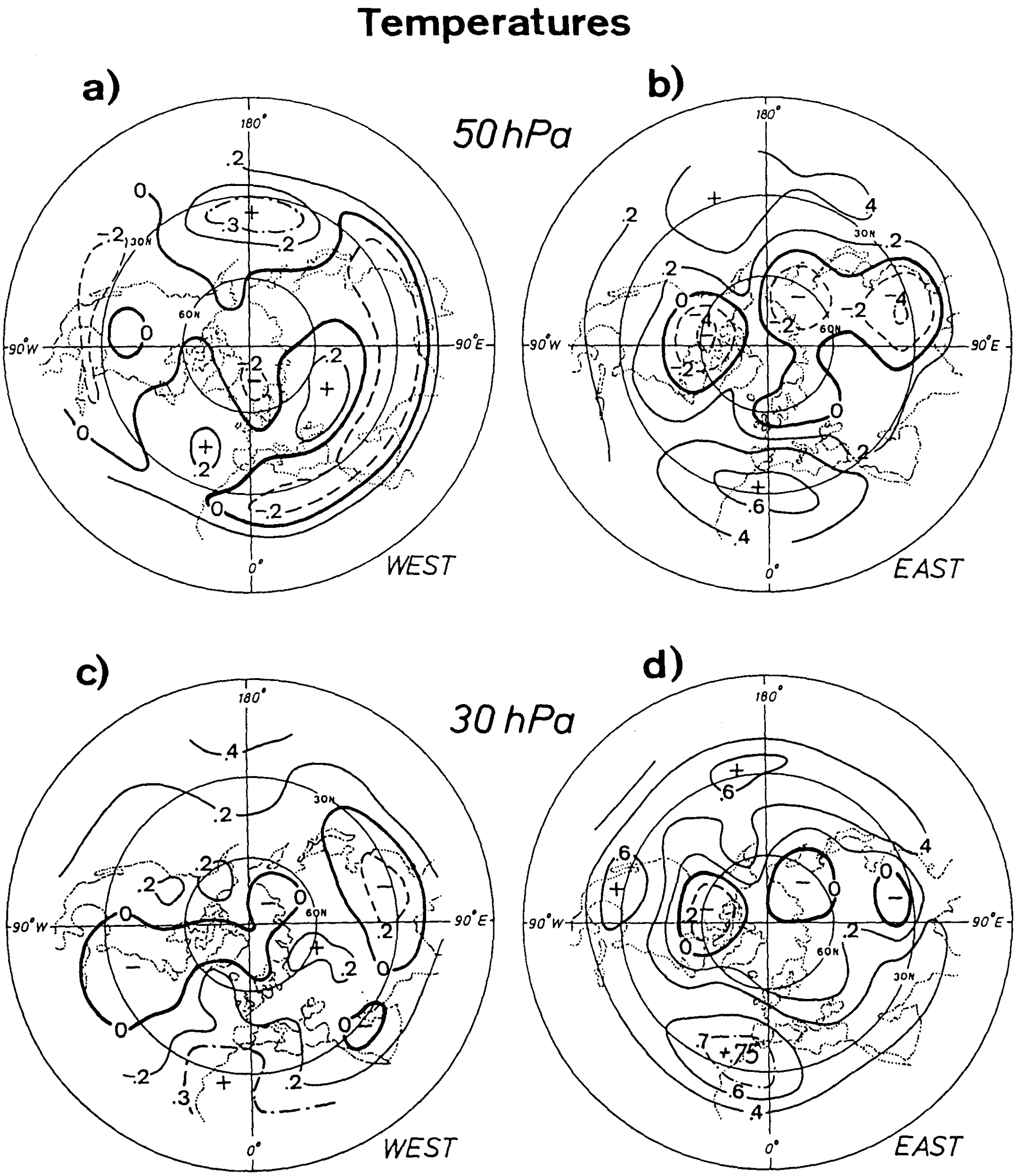

*Fig. 8.* Correlation between temperature and 10.7 cm solar flux in July–August: (a) 50 hPa, west years, (b) 50 hPa east years, (c) 30 hPa west years, (d) 30 hPa east years.

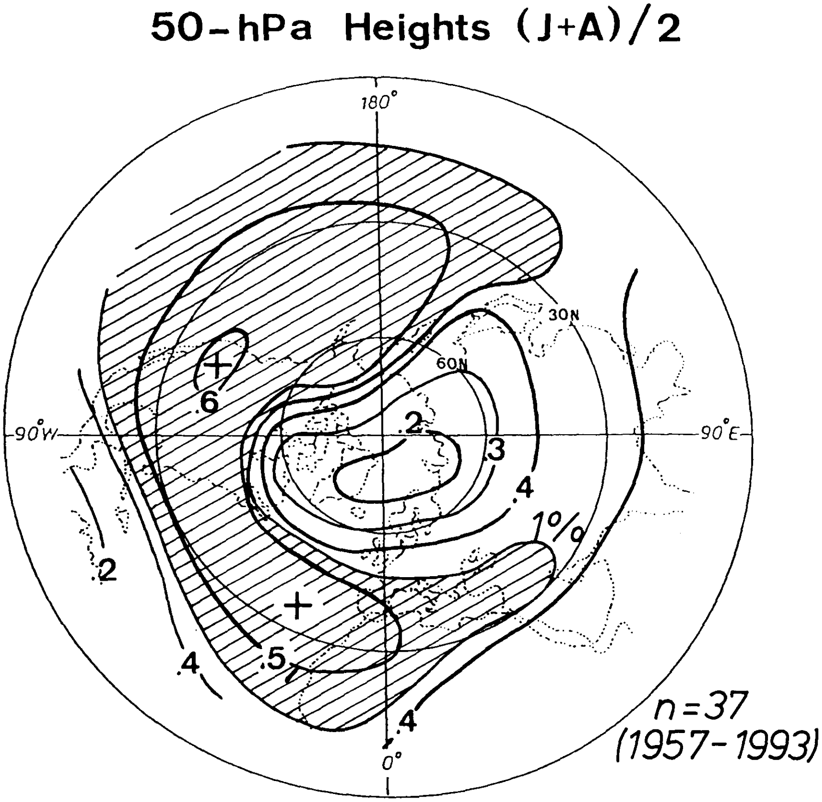

*Fig. 9.* Correlation between 50 hPa height and the 10.7 cm solar flux in July–August, $n = 37$.

of the 11-year solar cycle than in its minima at stations which lie in the inner tropics and in the subtropics suggests that the warmer column in the solar maxima is associated with an enhanced Hadley circulation. If so, the troposphere at stations near the Intertropical Convergence Zone is warmed more by the release of latent heat at the solar maxima than in the minima. The two-monthly vertical profiles at Truk, Fig. 4b, lend support to this idea: it is noteworthy that in the seasons when the ITCZ is farthest away from the island, the temperature difference between the solar extremes is smallest, and that when the ITCZ is closest (May to October) the temperature difference is largest. In addition, in the levels about the tropopause, 100 hPa–50 hPa, the temperature is lower in the solar maxima, a trait that one would expect if the convection is stronger in the solar maxima and the tropopause levels therefore are lifted and cooled dry-adiabatically more than in the solar minima. In analogy: a stronger Hadley circulation in the solar maxima would produce a warmer troposphere at the subtropical stations through stronger subsidence, such as observed at, for instance, Lihue in the Hawaiian Islands (Fig. 4a). A comparison of the vertical profiles of the temperature differences between solar extremes with the profiles of the differences between a period with strong and one with weak Hadley circulation shows that the vertical distribution of the temperature differences has the same shape and sign in both, and it is therefore possible that the TTO is associated with changes in the Hadley circulation on a decadal scale.

Finally, we should like to stress that apart from the winter months, when the Quasi-Biennial-Oscillation modulates the TTO, the *undivided* time series of the atmospheric elements run parallel to the 11-year sunspot cycle. The 30 hPa and 100 hPa heights and the 200 hPa temperature at

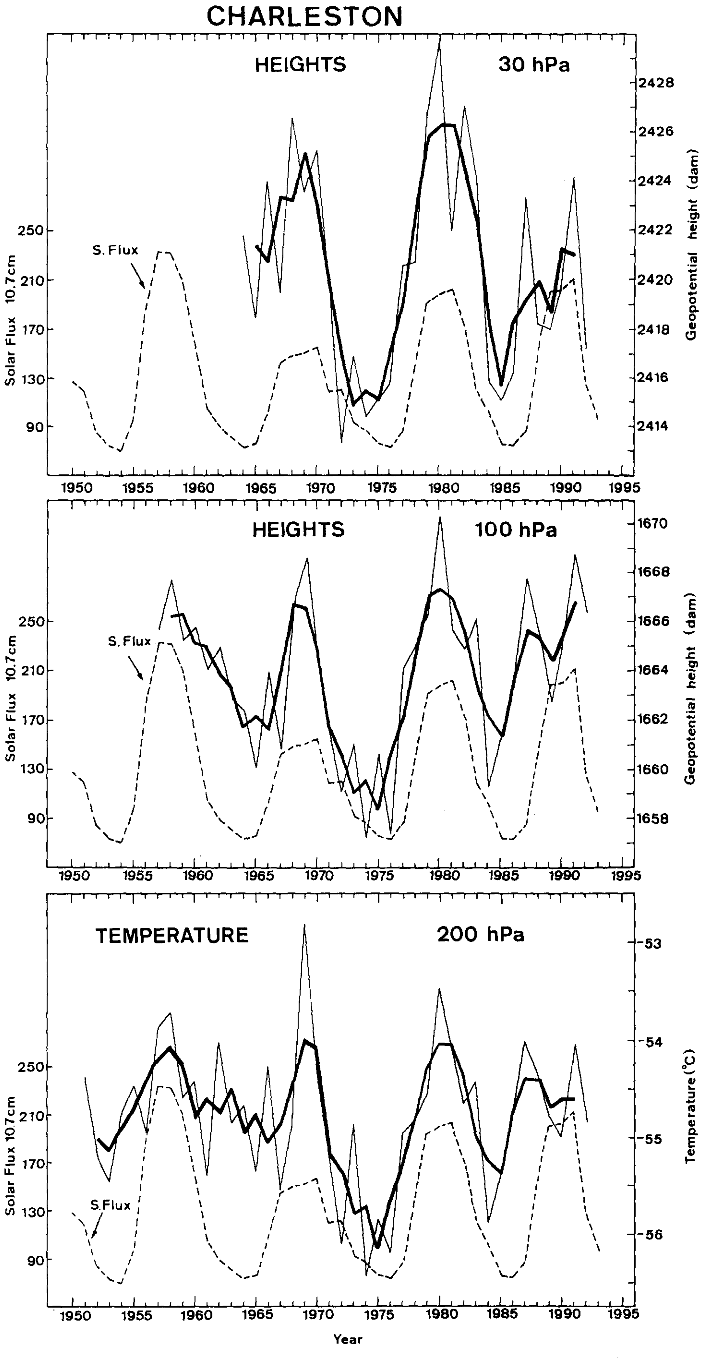

*Fig. 10.* Time series of the 10.7 cm solar flux and of the 100 hPa and 30 hPa height and the 200 hPa temperature at Charleston, South Carolina, in July–August. The heavy solid lines are three-year running averages. Updated from Labitzke and Van Loon (1992a).

Charleston (South Carolina) in Fig. 10 are an example of this, and further examples can be seen in Van Loon and Labitzke (1990, their Fig. 11). We mention this because both proponents and antagonists of the idea that the TTO may be caused by solar variations have focused their attention on the effect of the QBO on the TTO in winter. It seems more logical that one should first try to explain or disprove a solar effect in the months when the TTO is not strongly modulated by the QBO and the connection thus would be less complex.

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