Associations between the 11-Year Solar Cycle, the Quasi-Biennial Oscillation and the Atmosphere: A Summary of Recent Work [and Discussion]

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Associations between the 11-year solar cycle, the quasi-biennial oscillation and the atmosphere: a summary of recent work

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Atmospheric elements at all levels from the surface to the top of the middle atmosphere show a probable association with the 11-year solar cycle that can be observed only if the data are divided according to the phase of the quasi-biennial oscillation. In either phase the range between solar extremes is as large as the interannual variability of the given element; and the correlations are statistically meaningful when tested both by conventional and Monte Carlo techniques. The sign of the correlations changes spatially on the scale of planetary waves or teleconnections. As the correlations tend to be of opposite sign in the two phases of the quasi-biennial oscillation, correlating a full time series of an atmospheric element with the solar cycle nearly always yields negligible correlation coefficients.

1. The discovery of the solar signal in the middle atmosphere

We must first introduce two features in the atmosphere that were essential to the discovery of the association between the variability of the Sun and of the atmosphere: (i) the major midwinter warmings in the polar stratosphere, and (ii) the quasi-biennial oscillation (QBO) in the equatorial stratosphere.

(i) The QBO is a tendency for the wind in the equatorial stratosphere to change from east to west about every second year. Its phase propagates downward, and the oscillation disappears near the tropical tropopause (*ca.* 16 km; Naujokat 1986). Studies of the QBO in the extratropical stratosphere by Holton & Tan (1980) and Labitzke (1982) found it useful to group the data into winters with easterly or westerly winds in the equatorial QBO at 50 mbar† (*ca.* 21 km), because this division brings out marked differences in the general circulation of the entire stratosphere in the northern winter.

(ii) The polar cyclonic vortex in the normally cold stratosphere of the Northern Hemisphere in winter is a vigorous westerly current around a low in the Arctic. In certain years the vortex breaks down in the middle of winter, the Arctic becomes warmer than middle latitudes, and the west winds are replaced by easterlies. Such a major midwinter warming usually lasts about a month (Labitzke 1981). The warmings are unique to the Northern Hemisphere, and they are associated with amplification of the planetary waves in the troposphere and stratosphere. The effect of the major midwinter warmings extends horizontally to the tropics and vertically into the upper mesosphere.

The idea to search for a solar–terrestrial relation through the QBO stems from an observation by Labitzke (1982) that in the westerly phase of the QBO, major midwinter warmings tend to occur only in maxima of the 11-year solar cycle. Labitzke (1987*a*) confirmed this observation

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† 1 mbar = 10^2 Pa.

by plotting the 30 mbar (*ca.* 22 km) temperature at the North Pole in the west years of the QBO as a function of the sunspot number. We show an updated version of her diagram in figure 1, in which we substitute the 10.7 cm solar flux for the sunspots; the strength of this flux is closely related to the sunspot number, and it is a good, objective measure of the Sun's variability.

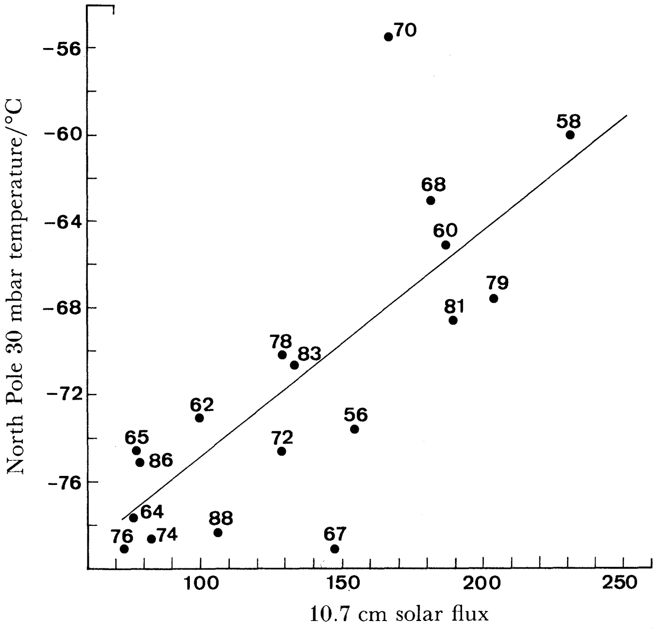

FIGURE 1. The 30 mbar (*ca.* 22 km) temperatures (degrees centigrade) at the North Pole in 18 winters (January–February) plotted against the 10.7 cm solar flux (units are 10^{-22} W m^{-2} Hz^{-1}) in the west years of the QBO. The line is the linear regression; the correlation is 0.77. In a bootstrap sample of 1000, 95% of the correlations lie between 0.54 and 0.91. The 99.9% confidence level for 16 degrees of freedom is 0.82.

The correlation between the two quantities in figure 1 is 0.77. Large correlation coefficients occur time and again in the following; we have tested their statistical significance both with conventional methods and with Monte Carlo methods, and they pass the tests without difficulty. The coefficient of 0.77, for instance, is significant between the 99% and 99.9% levels for 16 degrees of freedom. Even if one reduces the degrees of freedom to 10, considering that it takes four points to describe an 11-year solar cycle, the 0.77 remains well above the 95% confidence level. A Monte Carlo method called 'bootstrapping' tells us that the true correlation coefficient for our sample size is likely to lie between 0.54 and 0.91, and that it is almost certainly not zero. The statistical methods which we have applied are described in Labitzke & van Loon (1988) and van Loon & Labitzke (1988).

Our investigation has two obvious limitations: (1) we can use only slightly more than three solar cycles because the phase of the QBO cannot be defined before 1952; and (2) we cannot explain how the observed, comparatively small solar variability – $\frac{1}{10}\%$ of the total irradiance from solar maximum to solar minimum during the last solar cycle – can produce the often astonishingly large correlations with the atmospheric elements. It is therefore not certain that our results are universally valid. We must wait for confirmation, either through a physical explanation or through longer series of observations that can tell whether our statistics are stable.

The full series of 30 mbar temperature at the North Pole in January–February, 33 years, is

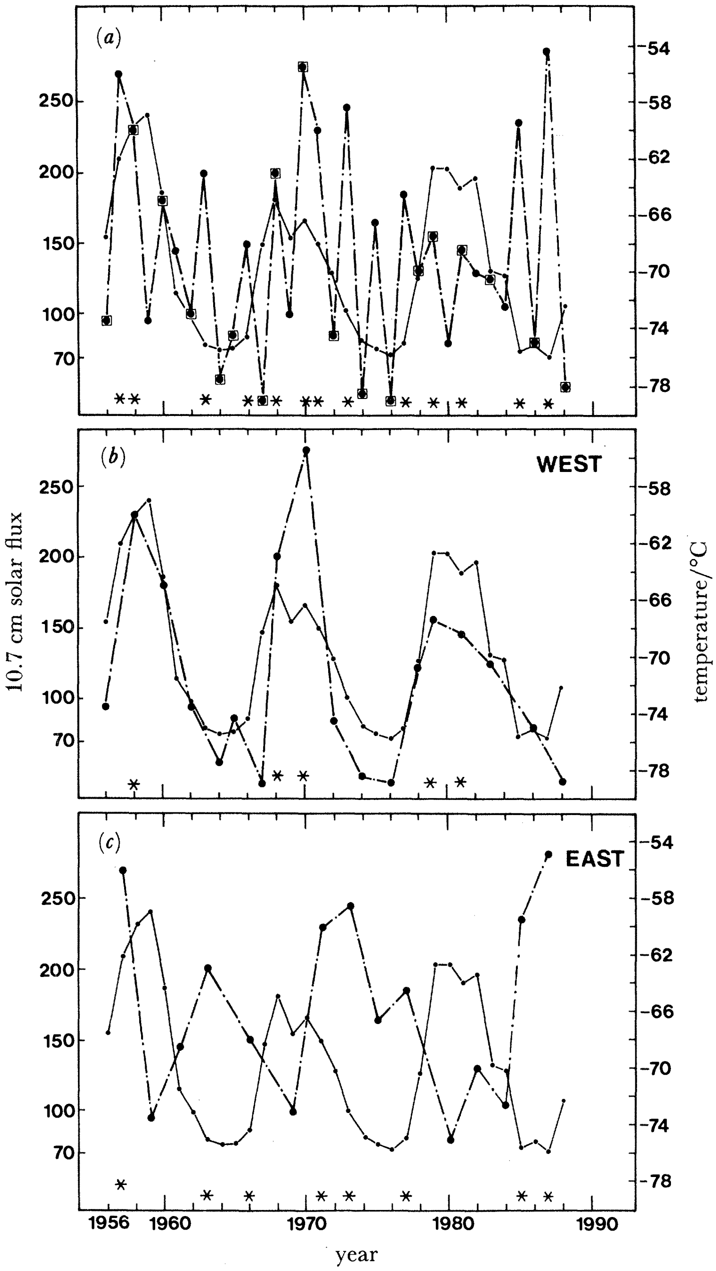

FIGURE 2. (*a*) Time series of the 10.7 cm solar flux and of the mean 30 mbar temperature (degrees centigrade) at the North Pole, January–February. Squares on the temperature curve denote winters in the west phase of the QBO. The asterisks are the years with major midwinter warmings: $n = 33$, $r = 0.13$ (1956–88). (*b*) The solar flux as in (*a*). The 30 mbar temperature curve is only for the winters in the west phase: $n = 18$, $r = 0.77$, 99% c.l. (confidence level) $= 0.65$. (*c*) As (*b*), but for winters in the east phase: $n = 15$, $r = -0.45$, 90% c.l. $= -0.44$. Update of figure 1 in Labitzke & van Loon (1988).

plotted in figure 2*a* together with the solar flux. The correlation between the two is only 0.13, but if the 33 years are divided into the 18 west and the 15 east years (figure 2*b*, *c*) the correlation is, as noted, 0.77 for the west and -0.45 for the east years. We examined how high is the probability for such a cross correlation with the solar flux to occur by accident if one divides a 33-year series into two with 18 years in one and 15 in the other. A Monte Carlo test showed that this would happen by chance only four times out of 1000. The details of the test are explained in Labitzke & van Loon (1988).

2. THE VERTICAL AND HORIZONTAL DISTRIBUTION IN THE MIDDLE ATMOSPHERE

The correlations in the east and west phase of the QBO at the North Pole in figure 2 have the same sign as high as about 35 km all over the Arctic. Labitzke & Chanin (1988) extended the correlations into the mesosphere by means of the rocketsonde observations from Heiss Island (81° N, 58° E) In the upper stratosphere, figure 3*a*, the correlations change sign so that here the west years are negative and the east years positive. Not until one reaches 60 km is the correlation of the same sign in both phases of the QBO. Consequently, there is a positive correlation in the mesosphere between the complete temperatures series and the Sun, whereas there is little or no relation between the complete series and the solar flux in the stratosphere where the east and west years offset each other.

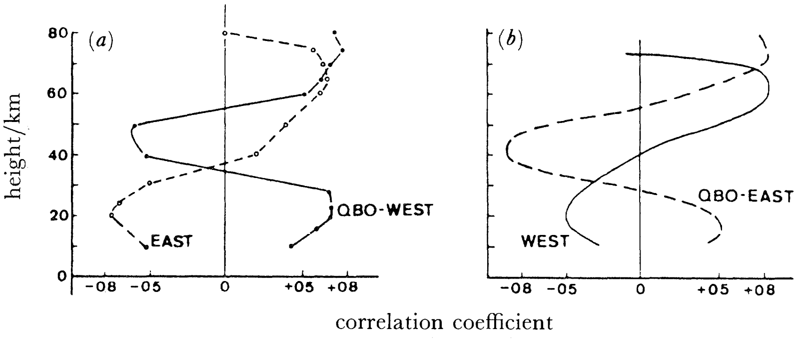

FIGURE 3. (*a*) Vertical distribution at Heiss Island (81° N, 58° E) of the correlation between the 10.7 cm solar flux and temperature in January–February in the east and in the west years of the QBO. (*b*) As (*a*), but for Haute Provence (44° N, 6° E). (Labitzke & Chanin 1988.)

The horizontal pattern of the correlations at the 30 mbar level is the same for the temperature and geopotential height. The latter is shown in figure 4. In the west years, figure 4*a*, the positive correlations in the Arctic are surrounded by negative correlations in middle and lower latitudes; in the east years (figure 4*b*) the distribution is the opposite. Translated into geostrophic wind, it means that in the west years the polar vortex tends to be weak in solar maximum and strong in solar minimum, and conversely in the east years.

The opposition in sign between the correlations in middle and high latitudes in figure 4 continues through the middle atmosphere. We illustrate this by means of the observations from a lidar station at Haute Provence (44° N, 6° E). The series of observations is short (Labitzke & Chanin 1988), but the fact that the vertical distribution is quite similar but opposite in phase to the one at Heiss Island fits the pattern in figure 4 and is worth emphasizing (figure 3*b*).

The difference between winters in the east and west phase is further illustrated by figure 5. We show (figure 5*a*) the mean difference of 30 mbar geopotential height between the two QBO phases in solar minima (i.e. solar flux below 90 units; see ordinate in figure 2). The largest difference in geopotential height is between the North Pole and the Aleutians and amounts to 1100 m. Where the gradient in this area is steepest it corresponds to a difference in geostrophic wind of 25 m s^{-1}. In other words, in solar minima the polar night jet stream in the west years

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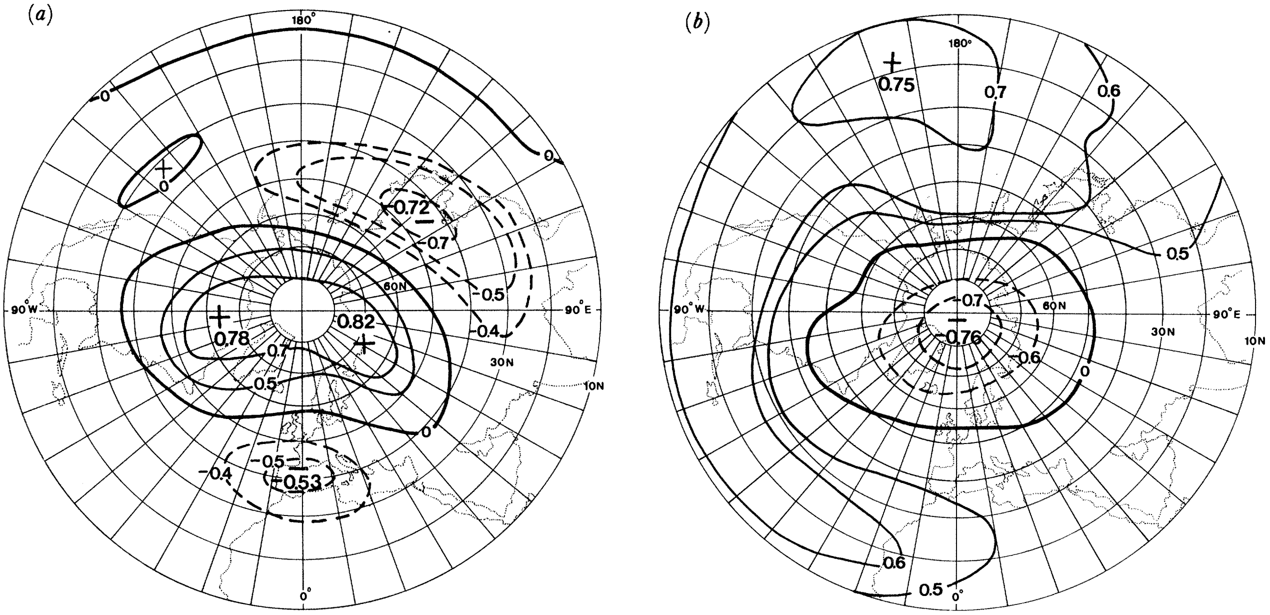

Figure 4. (*a*) Lines of equal correlation between 30 mbar geopotential height and 10.7 cm solar flux in January–February in the west phase of the QBO ($n = 15$). (*b*) As (*a*), but for the east years ($n = 12$). (Labitzke & van Loon 1988.)

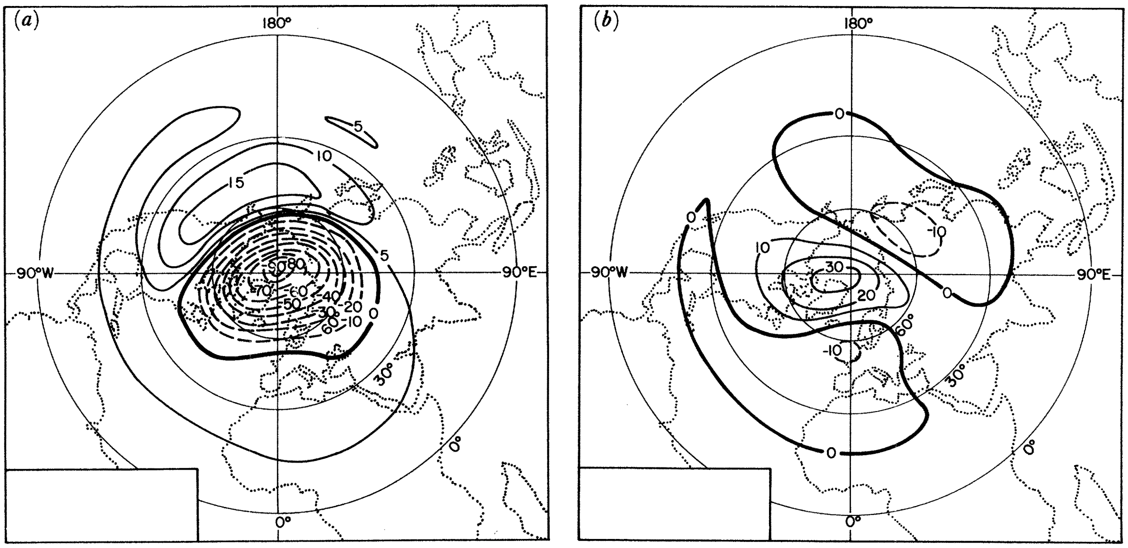

Figure 5. (*a*) The difference in 30 mbar heights (west minus east) in solar minima between January and February in west years (1964, 1965, 1974, 1976, 1986) and east years (1963, 1966, 1975, 1977, 1985); in geopotential dekameters. (*b*) As (*a*), but for solar maxima. West years: 1958, 1968, 1970, 1979, 1981. East years: 1959, 1969, 1971, 1980, 1982.

is here 25 m s^{-1} stronger than in the east years. The difference between the east and west years is not nearly so strong in the solar maxima, figure 5*b*, where it is only 40 % of that in the minima. One may interpret the difference between west and east years in solar maxima and solar minima as a difference in the influence of the QBO.

The response of the stratosphere on the Northern Hemisphere in winter to the 11-year solar cycle is then quite marked. As the following analysis indicates, the response to the cycle changes from winter to spring: figure 6 shows the correlation between the solar flux and the 30 mbar height in spring (March–April) in 16 west years of the QBO. The pattern is the opposite of that in winter (figure 4*a*). This change in pattern is associated with the well-known observation (Labitzke 1982, table 2) that winters during which a major midwinter warming has taken place tend to be followed by a late final (spring) warming, whereas a winter with a cold polar vortex tends to precede an early final warming. As noted above, the major midwinter warmings in the west years take place in the maxima of the 11-year solar cycle; the final warmings are then late, and the spring vortex is cold. In solar minima the vortex is cold in west years in midwinter, and the spring vortex is warm. The correlations are therefore negative in the Arctic in spring during west years.

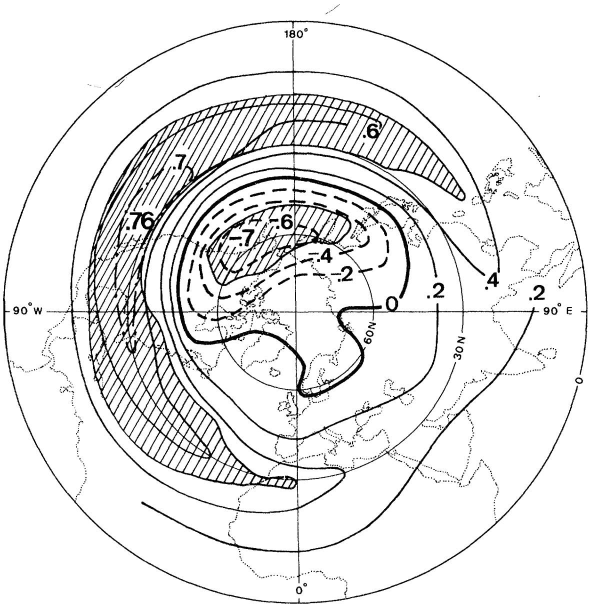

FIGURE 6. As figure 4*a*, but for March–April in west years of the QBO. The areas where the confidence level is above 95% are shaded. (Labitzke & van Loon 1989.)

It is also of interest to see if there is an association between the temperature variations in the stratosphere on the Southern Hemisphere and the 11-year solar cycle. Unfortunately, there are no long map series of the stratosphere on the Southern Hemisphere, and one must turn to station data to work with a reasonably long series. It is futile to search for a solar signal in the Antarctic stratosphere in midwinter because the vortex is then intense, cold and stable, and its interannual changes are small. The interannual standard deviation of the 50 mbar temperature in midwinter at the South Pole is, for instance, only 1 °C (Labitzke 1987*b*). We therefore use the month of October when the stratospheric polar vortex becomes unstable and the interannual standard deviation is five times larger than in winter. The highest level in the stratosphere with a fairly complete record at the South Pole is 50 mbar (*ca.* 18 km). The correlation between the solar flux and the 50 mbar temperature (figure 7*a*) is only 0.29; but if one divides the temperatures into the east and west years of the QBO, the correlation is 0.79 in the east years (figure 7*c*) and insignificantly small in the west years (figure 7*b*). Both

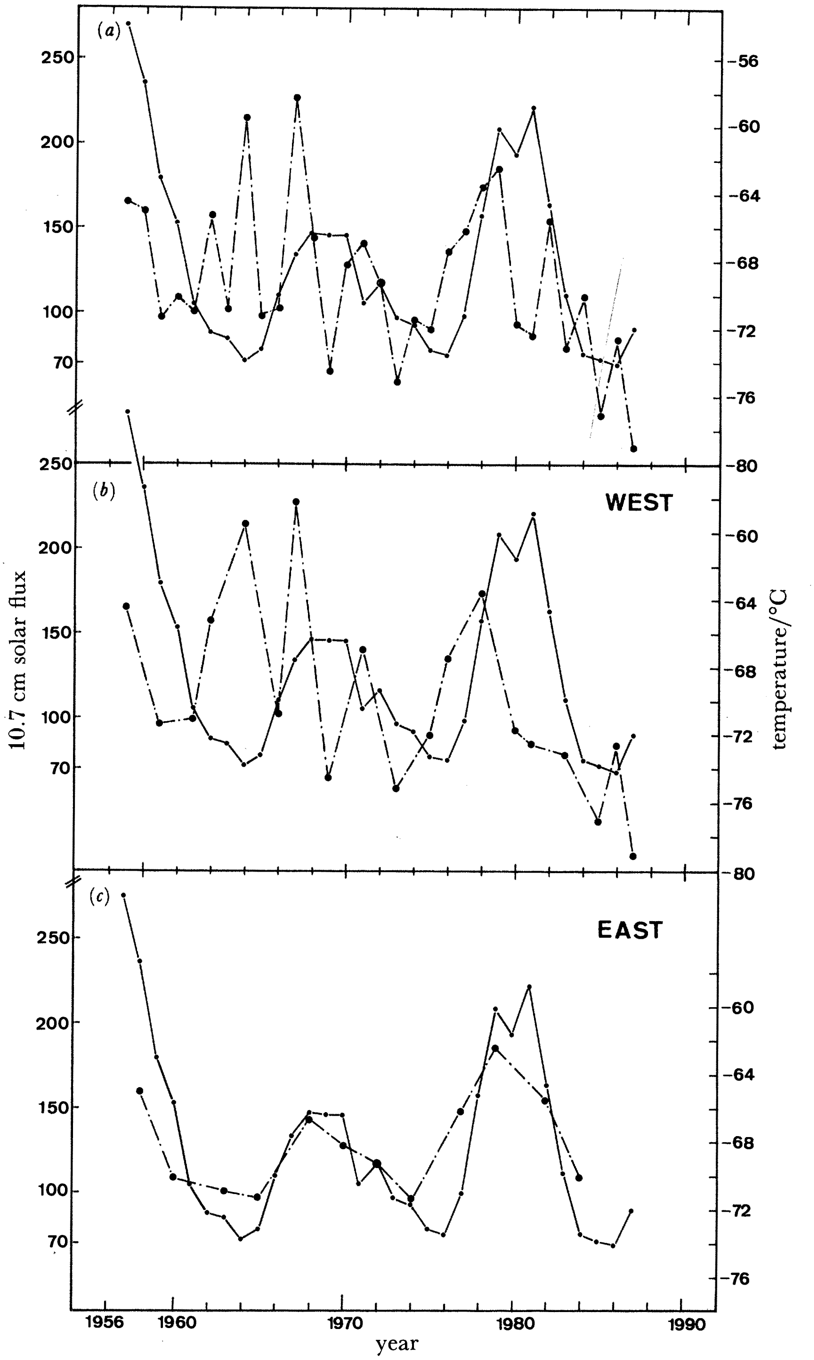

FIGURE 7. (*a*) Time series of the 10.7 cm solar flux, solid line, and the 50 mbar temperature at the South Pole in October ($r = 0.29$, $n = 31$). (*b*) As (*a*), but the temperatures are only in the west years of the QBO ($r = 0.15$, $n = 19$). (*c*) As (*a*), but the temperatures are only in the east years. East and west according to the equatorial wind at 50 mbar in September–October ($r = 0.79$, $n = 12$, 95% interval: 0.45–0.91). (Labitzke & van Loon 1989.)

conventional and Monte Carlo methods indicate that the correlation coefficient of 0.79 is unlikely to be accidental.

3. THE SOLAR SIGNAL IN THE TROPOSPHERE

The marked response to the solar flux in the stratosphere extends through the troposphere to the Earth's surface. In this section we show first the correlations between solar flux and sea level pressure in 19 winters in the west phase (figure 8*a*), and the correlations in 16 winters in the east phase (figure 8*b*). In the west phase the most distinct pattern is over North America and the Atlantic Ocean whereas in the east phase it is in the Pacific region. The two patterns resemble closely two well-known teleconnection patterns: the North Atlantic oscillation in the west years, and the North Pacific oscillation in the east years (Walker & Bliss 1932).

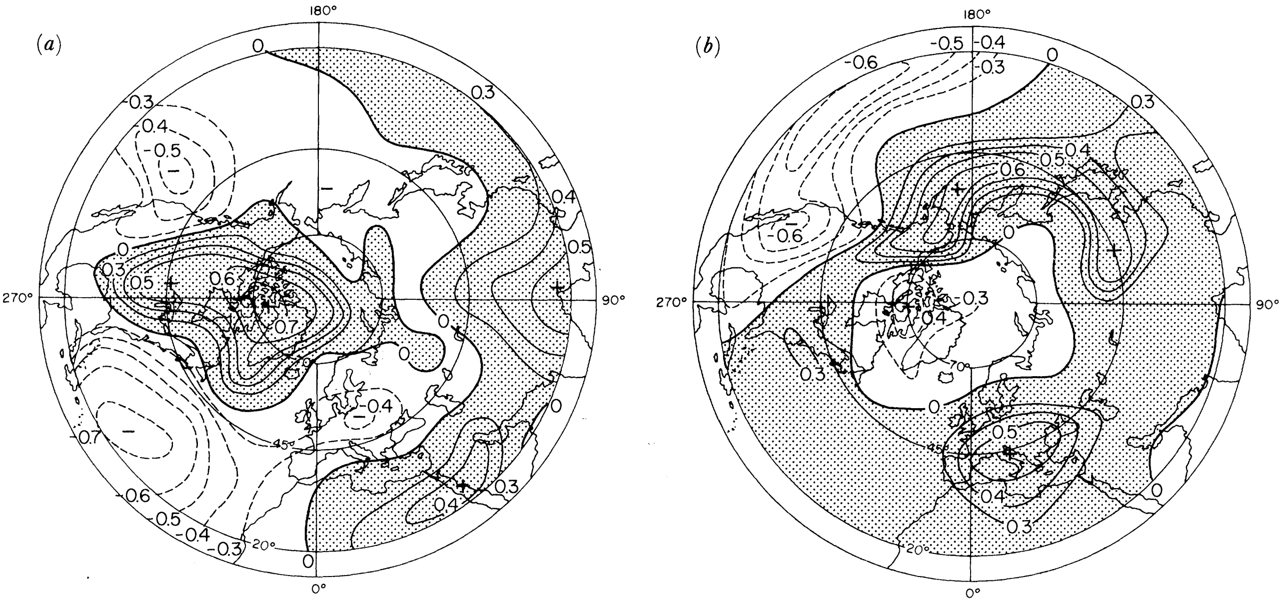

FIGURE 8. (*a*) Lines of equal correlation coefficient: sea level pressure in January–February at grid points correlated with the 10.7 cm solar flux for 19 winters when the QBO was westerly. (*b*) As (*a*), but for 16 winters when the QBO was easterly. Areas with positive correlations are shaded. (van Loon & Labitzke 1988.)

We have chosen three stations (figure 9) in the area of positive correlation over North America in the west phase to illustrate the relation between the solar flux and sea level pressure. Two of them, Des Moines and The Pas, lie where the correlation coefficient is between 0.5 and 0.6, and the third, Resolute, where the correlation is 0.7. In all three instances the association between the solar and pressure curves is conspicuous because the extremes of pressure tend to occur in extremes of the 11-year solar cycle. With a difference of 15 mbar between extremes at Resolute and The Pas and 9 mbar at Des Moines, the solar effect covers the whole range of interannual variability of the mean January–February sea level pressure. One finds the same large response in the atmospheric elements at all levels on both hemispheres. Other examples are the 30 mbar temperature in figure 2 and the curves in figure 10.

Because the correlations change sign on the scale of planetary waves, correlations between

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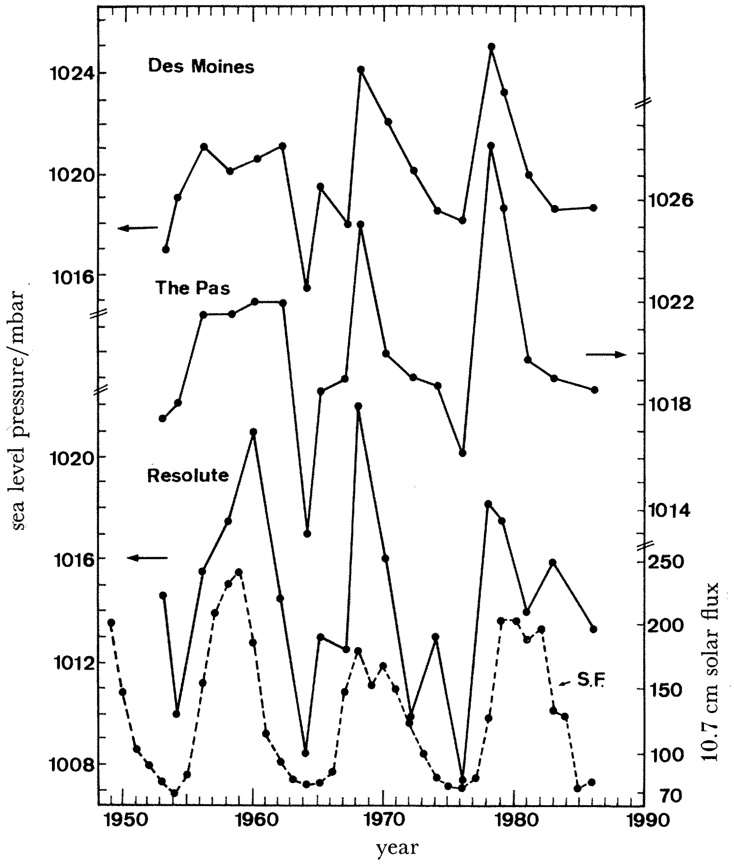

Figure 9. Time series of the 10.7 cm solar flux for all years (dashed line), and of sea level pressure at three North American stations for the years when the QBO was westerly in January–February. (van Loon & Labitzke 1988.)

the solar flux and zonal averages of pressure, or averages over large regions, mostly lead to insignificantly small numbers.

The correlation pattern in figure 8*a* indicates that there is a tendency for an anticyclonic anomalous circulation over North America in the west years in solar maxima that is flanked by anomalous cyclonic circulations, and conversely in solar minima. Therefore, there is a solar signal in the pressure difference between continent and ocean that is especially strong in the western Atlantic Ocean (figure 10*a*). Correlation between this pressure difference and the solar flux yields a coefficient of 0.77.

The change of geostrophic wind at sea level in winter from solar maximum to solar minimum in the west years can be deduced from the map in figure 8*a*. In solar maximum the anticyclonic anomalous circulation over North America is associated with northeasterly anomalous winds on its east side. In solar minima the circulation would be the opposite. Because the temperature level in winter is closely associated with the direction of the wind, the southeastern U.S. would thus tend to experience lower temperatures in solar maxima than in solar minima in the west years in the QBO. We illustrate this by the time series of surface air temperature at Charleston, South Carolina, in figure 10.

The correlation between solar flux and surface air temperature in winter over most of the Northern Hemisphere in the west years is shown in figure 11. If one compares this map with

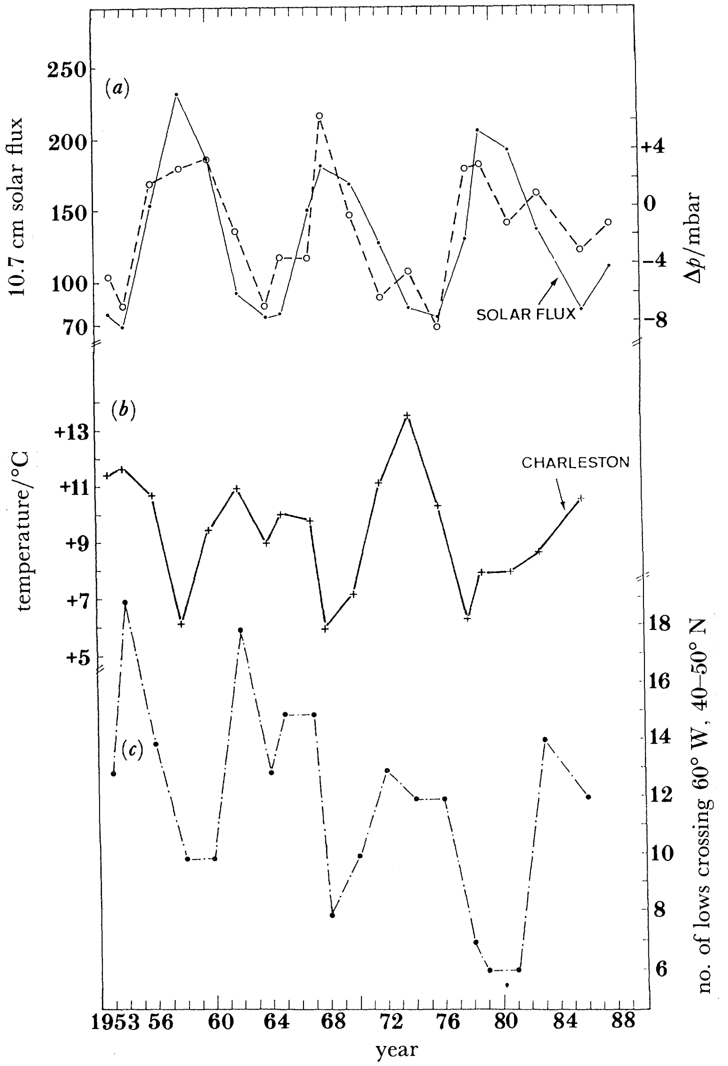

FIGURE 10. (*a*) Time series of 10.7 cm solar flux and of the pressure difference (70° N, 100° W) minus (20° N, 60° W) in the west years of the QBO, January–February. (*b*) Time series of the surface air temperature at Charleston, South Carolina, in January–February of the west years. (*c*) Times series of the number of lows crossing the 60th meridian west between the latitudes of 40° N and 50° N, in January–February of the west years.

the sea level pressure correlations in figure 8*a*, it is easy to see how well the two fit together if one considers the wind anomalies implicit in figure 8*a* and the temperature anomalies implicit in figure 11. To a large extent figure 11 also bears the impress of the North Atlantic Seesaw, which is a component of the North Atlantic oscillation. The Seesaw consists of a tendency for the temperature in northern Europe to be in-phase with the temperature in the central and eastern U.S., but out-of-phase with the temperature in southeastern Europe and Labrador–Greenland (van Loon & Rogers 1978).

The correlation between the 700 mbar height (*ca.* 3 km) and the 10.7 cm solar flux is shown in figure 12 for January–February in the 19 west years. The pattern implies that in these years the westerlies across North America and the adjacent ocean areas quite often must be appreciably weaker in solar maxima than in solar minima, whereas the opposite holds from North Africa to central Russia. The pattern in figure 12 resembles a well-known teleconnection pattern: we show as an example an update of a teleconnection map from Namias (1981) in figure 13; the 700 mbar height at 70° N, 90° W is here correlated with the heights everywhere else on the hemisphere in all 35 winters from 1952 to 1986. The pattern of the point correlations in figure 13 is nearly the same as that in figure 12 in which all points on the map are correlated with the solar flux in the 19 west years. Such similarities appear whenever a point that is highly correlated with the solar cycle is correlated with all other points.

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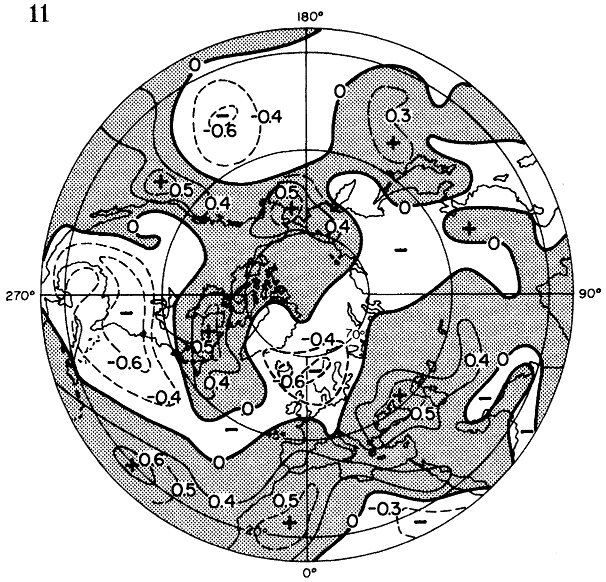

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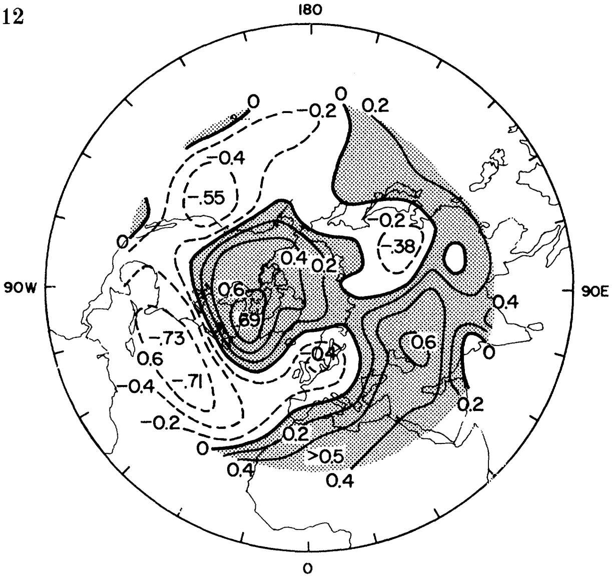

Figure 11. Lines of equal correlation coefficient: surface air temperature in January–February in west years at stations and in ocean blocks correlated with the 10.7 cm solar flux. Areas with positive correlations are shaded. (van Loon & Labitzke 1988.)

Figure 12. Lines of equal correlation between 700 mbar geopotential height at grid points and the 10.7 cm solar flux, in January–February and for years of westerly QBO. Areas with positive correlations are shaded. (van Loon & Labitzke 1988.)

The fact that a map of the correlations at all points with the solar flux is similar to a map of the correlations of one point with all other points may contain a key to how and where the solar variability affects the atmosphere, but it does not immediately lead to an explanation. Most likely, such a pattern is a property of the atmosphere's internal dynamics, a favoured mode that can be evoked within the atmosphere itself or by extraneous influences. Because the atmosphere responds so readily in the pattern, the forcing may not have to be large.

The correlations of solar flux with sea level pressure and 700 mbar height imply that pressure systems – lows and highs – are also affected by the solar variability. We show in the following an especially marked example of the changes in the frequency of low-pressure systems associated with the 11-year solar cycle.

We have counted the number of lows that crossed the meridian of 60° W between the latitudes of 40° N and 50° N, where the gradient of correlation is the steepest in the hemisphere (figure 12). The westerlies and the horizontal cyclonic shear in this area are weaker in the solar maxima in west years (above normal pressure to the north; below normal to the south) than in the solar minima (below normal pressure to the north; above normal pressure to the south). The number of lows crossing 60° W is therefore lower in the solar maxima than in the minima by about 40 %. The correlation between cyclone frequency and the solar flux in the 19 winters is −0.63.

Finally, we stress the strong vertical coherence of the solar signal, from the layers near the surface to the middle atmosphere. We pointed out in the discussion of figure 5*a*, which shows the difference in 30 mbar heights between west and east years in solar minima, that the circumpolar cyclonic vortex is by far stronger in the west years. The same difference appears in figure 14, but for the 700 mbar level, i.e. 20 km below the 30 mbar level. The two maps are very similar, allowing for more waves in the troposphere and slope with height.

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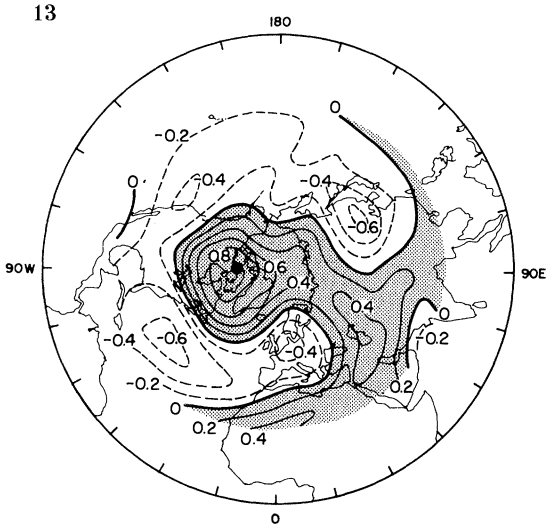

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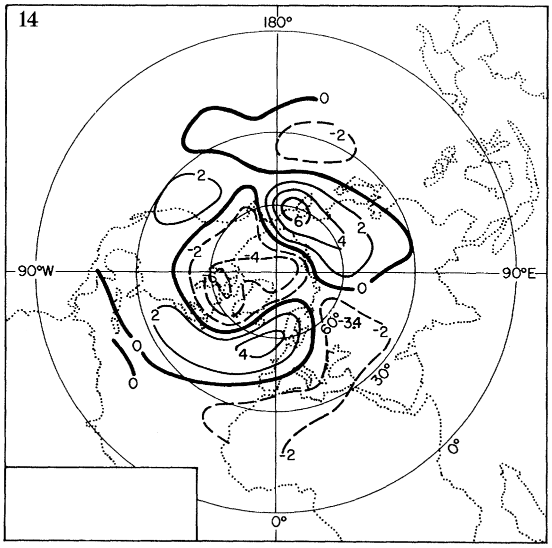

FIGURE 13. Lines of equal correlation between the 700 mbar geopotential height at 70° N, 90° W and the 700 mbar height elsewhere. For January–February and all years between 1952 and 1986. (van Loon & Labitzke 1988.)

FIGURE 14. As figure 5*a*, but for the 700 mbar level. The years in the west phase are: 1953, 1954, 1964, 1965, 1974, 1976, 1986; and the east years: 1952, 1966, 1973, 1977, 1987.

4. CONCLUSIONS

The observation (Labitzke 1982) that when the QBO is westerly, major midwinter warmings of the stratospheric cyclonic vortex on the Northern Hemisphere tend to occur only in maxima of the 11-year solar cycle, led to the discovery that one obtains statistically significant correlations between the solar variability and atmospheric elements when one groups the data according to the state of the QBO. As the correlations are often of opposite sign in the west and east phase of the QBO, the correlation coefficients are mostly small when one uses a full time series of an atmospheric element. The spatial patterns of the correlations resemble well-known teleconnection patterns that are inherent in the internal dynamics of the atmosphere and readily evoked within the atmosphere itself or by extraneous effects. The range of an atmospheric element between solar extremes covers the full interannual variability in both east and west years at all levels investigated.

We have tested the correlations both by conventional statistical methods and Monte Carlo techniques, and the tests suggest that our results are unlikely to have occurred by chance. We can, however, examine only three solar cycles for we do not know the state of the QBO before 1952. Added to this limitation is the fact that we cannot explain how the observed small solar variability could produce such large responses in the atmosphere. Therefore, one cannot yet exclude the possibility that the promising results stem from sample variations.

We have by now studied not only the Northern Hemisphere in winter, but also sea level pressure in the Southern Hemisphere in winter and in the Northern Hemisphere in summer. Our results are published in Labitzke & van Loon (1988); van Loon & Labitzke (1988); Labitzke & Chanin (1988) and Labitzke & van Loon (1989).

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Discussion

K. SHINE (*Department of Meteorology, University of Reading, U.K.*). I know that most of Professor Labitzke's work has been concerned with the Northern Hemisphere. However, there is much circumstantial evidence linking the QBO with the variability in the Antarctic ozone hole; I wonder if Professor Labitzke could comment on the possible role of solar variability in modulating the ozone hole?

KARIN LABITZKE. According to the data given in figure 7 and the current development of the QBO, the October 1989 will belong in the east years (figure 7*c*); as we will be in solar maximum, the correlation shows that it is probable that the temperature at 50 mbar in October 1989 will be above the mean for east years.