Association between the 11-Yr Solar Cycle, the QBO, and the Atmosphere. Part III: Aspects of the Association

KARIN LABITZKE

Institut für Meteorologie, Freie Universität Berlin, Federal Republic of Germany

HARRY VAN LOON*

*National Center for Atmospheric Research,** Boulder, Colorado*

(Manuscript received 7 June 1988, in final form 17 November 1988)

ABSTRACT

The probable association in the northern winter between the atmosphere and the 11-yr solar cycle extends to the frequency of lows in the North American east coast trough and thus adds a synoptic aspect to the previously described atmospheric variability on the 11-yr time scale. Statistically significant correlations of sea level pressure, 700-mb height, and surface air temperature on the Northern Hemisphere in July–August with the 11-yr solar cycle are found primarily over the oceans. The few years for which data of sea level pressure at grid points are available on the Southern Hemisphere yield coherent correlation patterns in summer and winter which are especially marked in the East years of the QBO. The temperature in the lower stratosphere over the South Pole in spring is well correlated with the solar activity in the East and hardly at all in the West years of the QBO. On the Northern Hemisphere the West years in spring are as strongly correlated with the solar cycle in the stratosphere as they are in winter. The pattern of positive and negative correlations is, however, the opposite of that in winter, which we interpret as being related to the different time of occurrence of the final warming in years with or without major midwinter warmings.

1. Introduction

We described a probable association between the 11-yr solar cycle and changes in the atmosphere in winter on the Northern Hemisphere in Labitzke and van Loon (1988) and van Loon and Labitzke (1988) (hereafter referred to as LvL and vLL, respectively). As this association is evident only when the data are separated according to the state of the Quasi-Biennial Oscillation (QBO), we can work with only a little more than three solar cycles because the direction of the wind in the QBO is not known before 1952. Statistical tests of the relationship, by conventional methods and by Monte Carlo techniques, suggest that our results probably did not occur by chance. However, owing to the short sample and to the fact that there is as yet no way in which our large correlation coefficients can be explained by the observed, small solar variability, one cannot be certain that our results are universally valid.

The data which we use are listed in the two previous papers, where we also explain the statistical methods as well as our definition of the phase of the QBO. In this paper we use, in addition, gridded sea level pressures from the Southern Hemisphere, derived from South African historical analyses for 1951–1958 and from Australian analyses after May 1972. The QBO winds, which are from stations near the equator (Naujokat 1986) and the values of the 10.7 cm solar flux can be obtained from the first author. All values of the elements used in this study are as observed, with no smoothing in time.

2. Synoptic aspects

a. Frequency of lows

The map in Fig. 1 shows the correlation between 700-mb geopotential height in January–February and the 10.7 cm solar flux for 19 winters in the West phase of the QBO. A discussion of the pattern appears in vLL together with the statistical tests. We note that the correlation pattern implies that the westerlies across North America and well into the North Atlantic Ocean are likely to be weaker in solar maxima than in minima in the westerly QBO years. Presumably, the mean horizontal cyclonic shear in this area is therefore also af-

---

* Visiting scientist, Freie Universität Berlin.

** The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Corresponding author address: Dr. Karen Labitzke, Institute of Meteorology, FUB, Dietrich-Schafer-Weg 6-10, 1000 Berlin 41, Federal Republic of Germany.

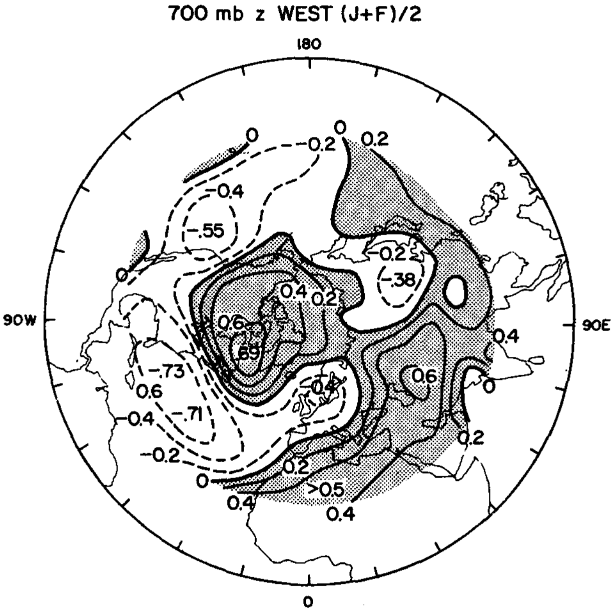

FIG. 1. Lines of equal correlation between 700-mb geopotential heights at grid points and the 10.7 cm solar flux. January–February, 19 yr in westerly QBO. From van Loon and Labitzke (1988).

fected by the solar cycle, as well as the speed of movement and frequency of lows. We shall show an especially marked example of the effect on the frequency of low-pressure systems by the solar cycle in the following.

The information about the lows was obtained from the *Mariners Weather Log* in which maps of "Tracks of Centers of Cyclones at Sea Level" over the North Pacific and North Atlantic Oceans appear bimonthly. Before 1957 the tracks were published in the *Monthly Weather Review.* We tabulated the number of tracks crossing the chosen meridian, 60°W, in intervals of 5 deg lat in the same manner as in a study of the connection between trends of pressure and storm tracks in van Loon and Williams (1977). In the southwestern North Atlantic the gradient of correlation is the steepest in the hemisphere (Fig. 1), and here, as Fig. 2 shows, the number of lows between 40° and 50°N is considerably lower in the solar maxima than in the minima when the westerlies tend to be stronger in the area. The correlation between the number of lows and the solar flux in the 19 winters in Fig. 2 is −0.63, with the 95% bootstrap interval between −0.47 and −0.79.

In the following we refer often to the "95% bootstrap interval," outside which lie only 5% of the correlations in the bootstrap sample. Half of the width of this interval may be interpreted as the bootstrap estimate of the average distance between the observed correlation for a random sample and the true correlation for such a sample size. The true value of r is likely to lie within the bootstrap interval. We have described the method in detail in vLL.

Brown and John (1979) found a solar-cycle dependence in the latitude of storm tracks over the northeast Atlantic. They note that, "The average track crossing the region at latitudes north of 50°N is some 2.5 degrees of latitude further south at sunspot maximum than at sunspot minimum." In the West phase our correlation with the solar flux is negative at 700 mb (Fig. 1) and sea level (vLL, our Fig. 3a) in the region mentioned by Brown and John, with positive correlations northwest of Iceland. The distribution of sign means that the westerlies north of 50°N in this area would be weaker and south of 50°N stronger in solar maximum than in solar minimum. One should therefore expect Brown and John's results to be enhanced in the West years. When Tinsley (1988) grouped Brown and John's data between 1952 and 1976 according to our scheme of East and West years, he found that their signal of 2.5° lat stems from the West years, and that when one considers those years alone the displacement of the tracks increases to 6 deg lat between solar maximum and minimum. As Brown and John's signal extends back through three solar cycles before 1952, their work thus suggests that our results may also be applicable to the period before 1952.

b. Pressure gradients in the North Atlantic Ocean

In the North Atlantic Ocean the West years of the QBO dominate the solar relationship with the atmospheric circulation at the surface (vLL, Fig. 3a). A time series for *all* years of anomalies in the difference of sea level pressure between 70°N, 90°W and 20°N, 60°W is shown in Fig. 3a. If one correlates the West years in this series with the solar flux one obtains a statistically significant correlation of 0.77 (95% bootstrap interval: 0.60–0.86; see also Fig. 6 in vLL), whereas the correlation in the East years is a negative, but not significant −0.36. We show the distribution of the pressure-difference anomalies in the West years as a function of the solar flux in Fig. 3b: At low solar flux (<100) all 8 yr show negative anomalies; and at high solar flux (>130) eight out of nine values are positive.

The effect on the surface air temperature of the pressure differences (geostrophic wind) at low and high solar activity emerges from a comparison between Figs. 3b and 4a. The latter shows the temperature deviations at Charleston, South Carolina, in single years, grouped according to the QBO and the solar flux. Seven of the eight West years at low solar flux have positive temperature anomalies, and the year with a negative anomaly is less than 0.5°C below the normal. In this situation the pressure is above normal in the southwest Atlantic (Fig. 3b) and below over northern Canada.

With high solar flux values (>130 units) in the West years, the anomalies are the reverse of those described

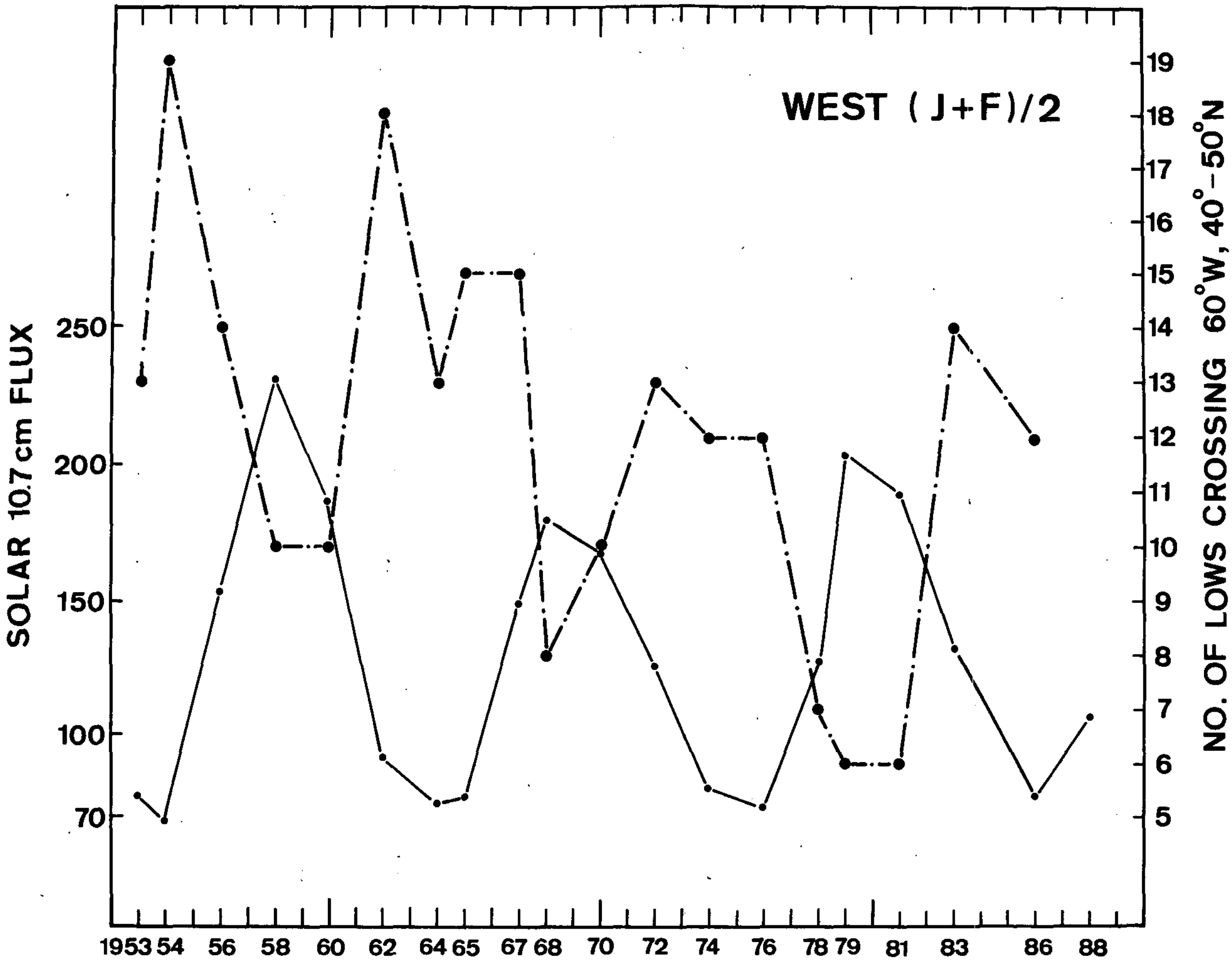

FIG. 2. Solid line: time series of the 10.7 cm solar flux. Broken line: time series of the number of low centers crossing 60°W between 40°N and 50°N. January–February for 19 yr of westerly QBO.

above (cf. Figs. 3b and 4a). The weaker and opposite relationship in the East years can be seen from a comparison between Figs. 3c and 4b.

To sum up: In the years when the QBO is West and the solar activity is high the tropospheric westerlies tend to be weak in the southwestern North Atlantic, with a weak Bermuda high and few lows in middle latitudes, and the surface air temperatures over the southeastern U.S. and the adjacent ocean are low. The opposite happens in minima of the solar cycle. In the years with an easterly QBO, the relationship of temperature and pressure with the solar cycle is the reverse, but it is much weaker than in the West years.

A similar example can be given from the area between Scandinavia and the Denmark Strait where the surface air temperature is also negatively correlated with the 11-yr solar cycle in the West years (vLL, our Fig. 8). In this instance one should use the sea level pressure difference between northwest Greenland and Central Europe to show the change in the geostrophic surface wind between solar maximum and minimum (vLL, our Fig. 3a). The distribution of surface air temperature in the two phases of the QBO, arranged according to the level of solar flux, is shown for Akureyri in Iceland (Fig. 4c, d), where the correlation of the temperature with the 11-yr cycle is large in the West years (−0.72, vLL). The distribution in these years of the temperature anomalies in low and high solar flux resembles the one at Charleston. In the East years the correlation with the solar cycle is close to zero at Akureyri. These circumstances fit the study of the storm tracks by Brown and John as extended by Tinsley.

c. North Pacific Ocean

In winter, the solar-SLP correlations in the East years of the QBO are by far strongest over the North Pacific Ocean (vLL, our Fig. 3b). We would like to point out

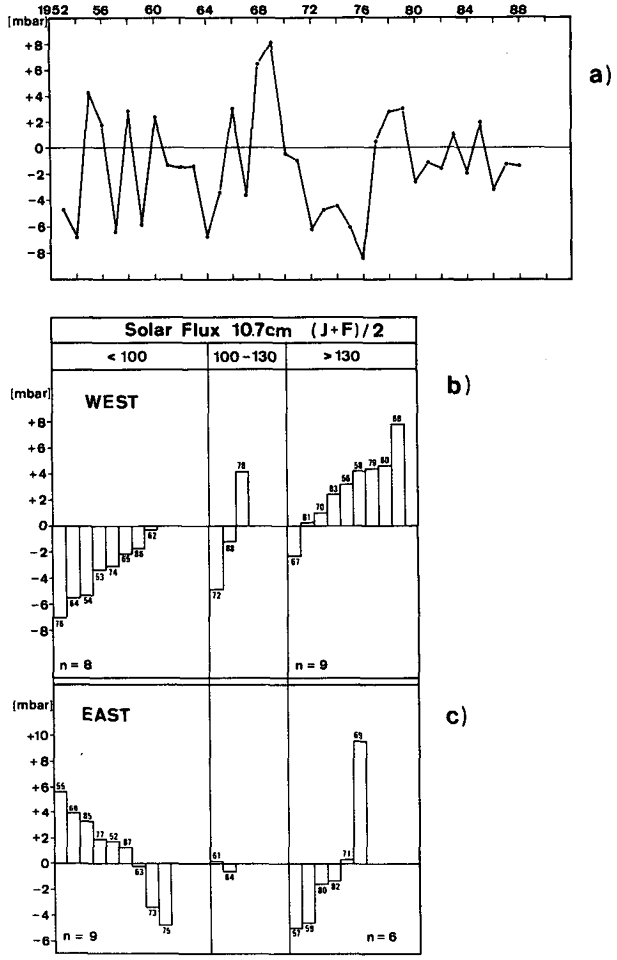

FIG. 3. (a) Time series of anomalies of the SLP difference (70°N, 100°W)–(20°N/60°W) in January–February. (b) The anomalies from (a) in the West years of the QBO, distributed according to the level of solar flux: below 100 units, between 100 and 130 units, and above 130 units. The year is shown at each anomaly. (c) Same as (b) but for the East years.

one observation which may be important. In January–February during the period 1952–87 there were 10 Warm Events of the Southern Oscillation at the mature (final) stage, as defined by Rasmusson and Carpenter (1982). The distribution of the events according to solar cycle and QBO is shown in Table 1. One half of them occurred in the West years where they are evenly distributed between solar maximum and minimum. The other half of the mature stages, those in the East

TABLE 1. Number of mature stages of warm events (January–February) arranged according to the state of the QBO and the 11-yr solar cycle.

	West QBO	East QBO
Solar max	3	0
Solar min	2	5

TABLE 2. Direction of the zonal wind at 50–40 mb above the equator in July–August. The underlined years are the ones with pressures at grid points on the Southern Hemisphere.

East	West
1954	1953
1956	1955
1958	1957
1960	1959
1962	1961
1963	1964
1965	1966
1968	1967
1970	1969
1972	1971
1974	1973
1977	1975
1979	1976
1981	1978
1982	1980
1984	1983
	1985
	1986
$n = 16$	$n = 18$

years, all occurred in solar minima. The sample is, however, too small to lend itself to statistical testing. One should also consider that we are dealing with the final stage of a Warm Event and that if the solar cycle should affect the atmosphere in such a way that no Mature Stage occurs in solar maxima in the East phase of the QBO, the solar effect must have begun long before, as the precursors of an extreme in the Southern Oscillation begin early (Rasmusson and Carpenter 1982; van Loon and Shea 1987).

TABLE 3. Bootstrap test of sea level pressure in July–August. The column on the right shows the interval with 95% of the correlations in the bootstrap sample. The procedure is explained in van Loon and Labitzke (1988).

Position	Name	n	r	95% Interval
		West		
72.0°N 102.5°E	Hatanga	17	0.67	0.19–0.84
62.9°N 152.4°E	Sejmcan	18	0.53	0.14–0.78
36.6°N 136.7°E	Kanazawa	18	−0.63	−0.36–−0.80
82.5°N 62.3°W	Alert	18	0.49	0.10–0.72
50.8°N 150.9°W	COADS	14	0.61	0.14–0.84
42.9°N 149.0°E	COADS	14	−0.63	−0.30–−0.86
34.9°N 178.9°E	COADS	14	−0.71	−0.37–−0.87
21.2°N 157.1°W	COADS	14	−0.72	−0.46–−0.90
18.8°N 125.0°W	COADS	14	−0.66	−0.30–−0.87
		East		
58.7°N 156.7°W	King Salmon	16	−0.74	−0.45–−0.91
52.9°N 162.9°W	COADS	13	−0.72	−0.27–−0.90
46.8°N 40.9°W	COADS	13	−0.73	−0.25–−0.91
20.8°N 175.0°E	COADS	13	0.70	0.28–0.68
20.9°N 18.7°W	COADS	12	0.70	0.40–0.86

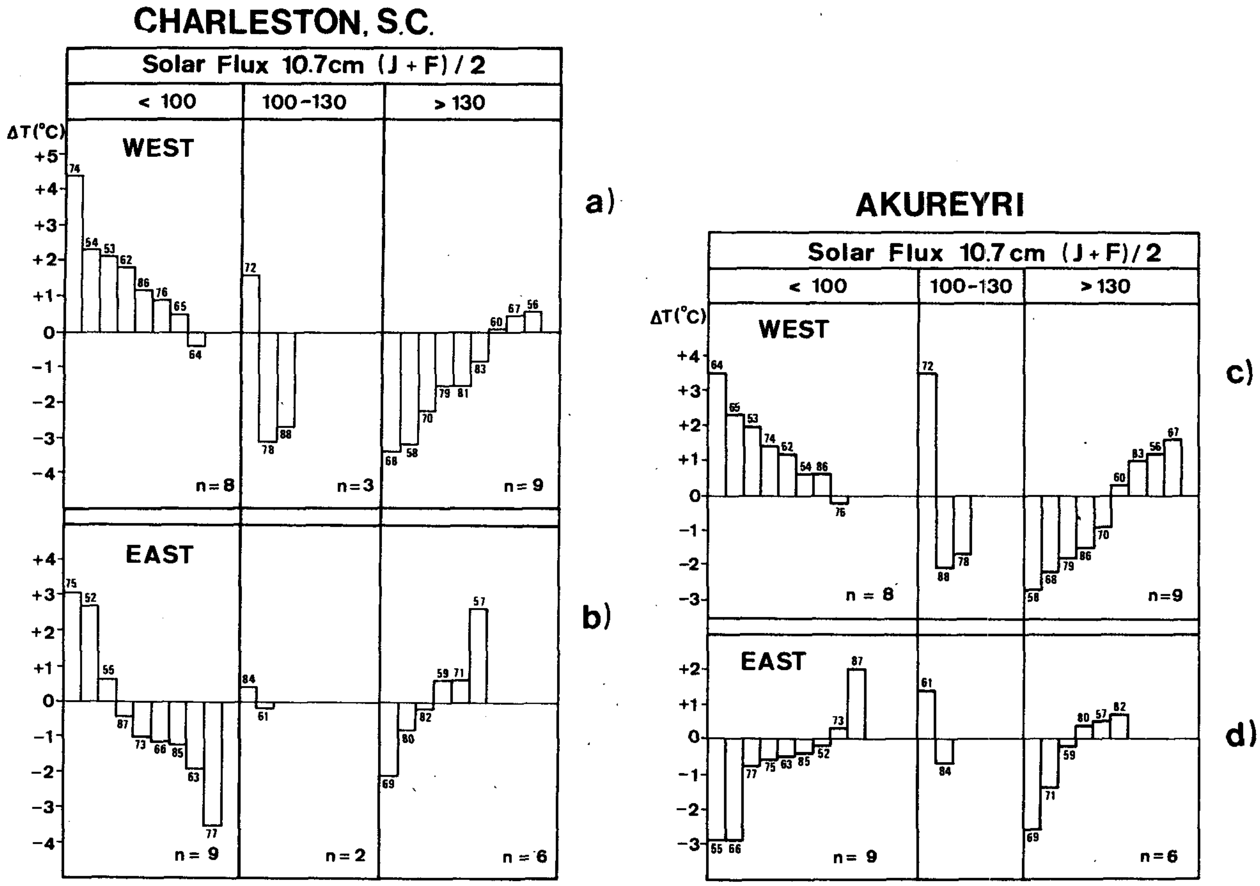

FIG. 4. (a) The surface air temperature anomalies at Charleston (32.9°N, 80°W) in the West years of the QBO, distributed according to the level of solar flux; below 100 units, between 100 and 130 units, and above 130 units. The year is shown at each anomaly. (b) Same as (a) but for the East years. (c) and (d) the same as (a) and (b), respectively, but for Akureyri (65.7°N, 18.1°W).

3. Summer, Northern Hemisphere

Climate signals are more conspicuous in winter, when the planetary waves are large, than in summer. We have correlated SLP, 700-mb height, and surface air temperature in July–August with the solar flux, and although the patterns of correlation are not so impressive as those we obtained for the winter months in vLL, they contain interesting features. The correlations between solar flux and sea level pressure and 700-mb height are shown in Fig. 5, and the years of East and West winds at 50–40 mb according to which the data are grouped are listed in Table 2 for July–August. The response of the lower atmosphere in summer to the solar cycle is strongest in the Pacific in both East and West years. The bootstrap tests in Tables 3 and 4 show that the centers of the positive and negative correlation patterns are statistically significant, with no values crossing zero. The patterns are more wavy in the East than in the West years, and the correlations are larger at 700 mb than at sea level.

TABLE 4. Bootstrap test of 700-mb height in July–August. The column on the right shows the interval with 95% of the correlations in the bootstrap sample. The procedure is explained in van Loon and Labitzke (1988).

Position	*r*	95% Interval
	West (18 yr)	
35°N 65°E	0.67	0.33–0.82
35°N 175°E	−0.70	−0.41–−0.88
60°N 170°E	0.65	0.22–0.80
70°N 95°E	0.60	0.15–0.80
80°N 85°W	0.62	0.21–0.81
	East (16 yr)	
20°N 65°W	0.59	0.30–0.78
20°N 25°W	0.72	0.47–0.87
20°N 155°W	0.56	0.20–0.76
20°N 5°E	0.60	0.15–0.83
35°N 130°W	0.80	0.58–0.90
35°N 175°E	0.67	0.43–0.84
60°N 155°W	−0.60	−0.25–−0.82

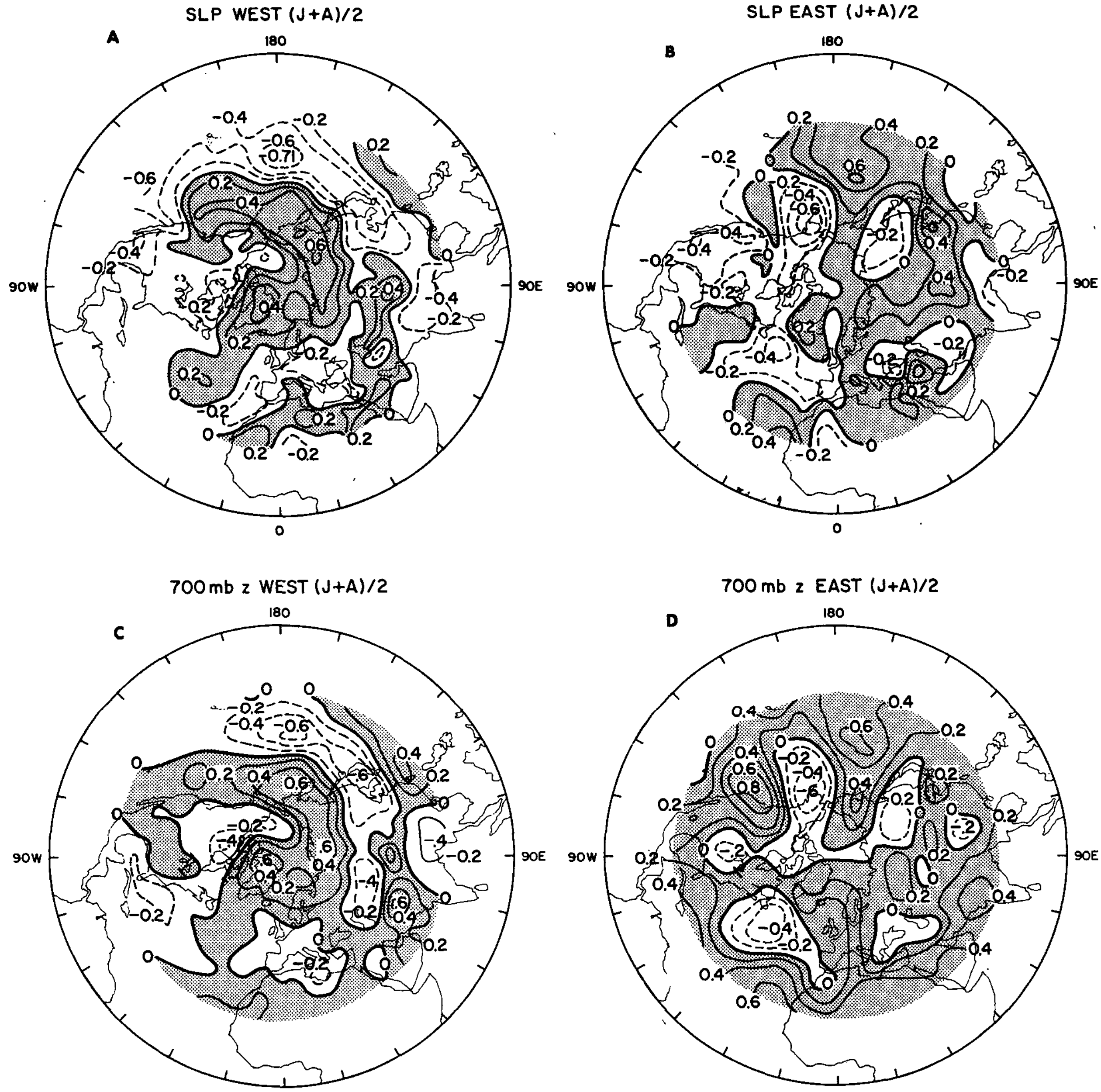

FIG. 5. (a) Lines of equal correlation between sea level pressure at grid points and the 10.7 cm solar flux. July–August, 18 yr in westerly QBO. (b) Same as (a) but for 17 yr in easterly QBO. (c) Same as (a), but for 700-mb geopotential height. (d) Same as (b), but for 700-mb geopotential height. Statistical tests in Tables 3 and 4.

The correlations above 0.6 between the surface air temperature in July–August and the solar flux (Figs. 6a, b) are consistent with those in the pressure but are limited to the oceans. Advection of air apparently does not play as dominant a role in determining temperature level in summer as it does in winter: The design of the temperature correlations in the West years (Fig. 6a), suggests that both the effect of the wind on the ocean's mixed layer and perhaps cloudiness decide the response of the temperature since the positive correlations coincide with the circumference of the Pacific high and the negative patch with the center or axis of the ridge. There is even a suggestion that the upwelling along the North American coast may be affected by the solar cycle in this phase, with positive temperature correlations along the coast.

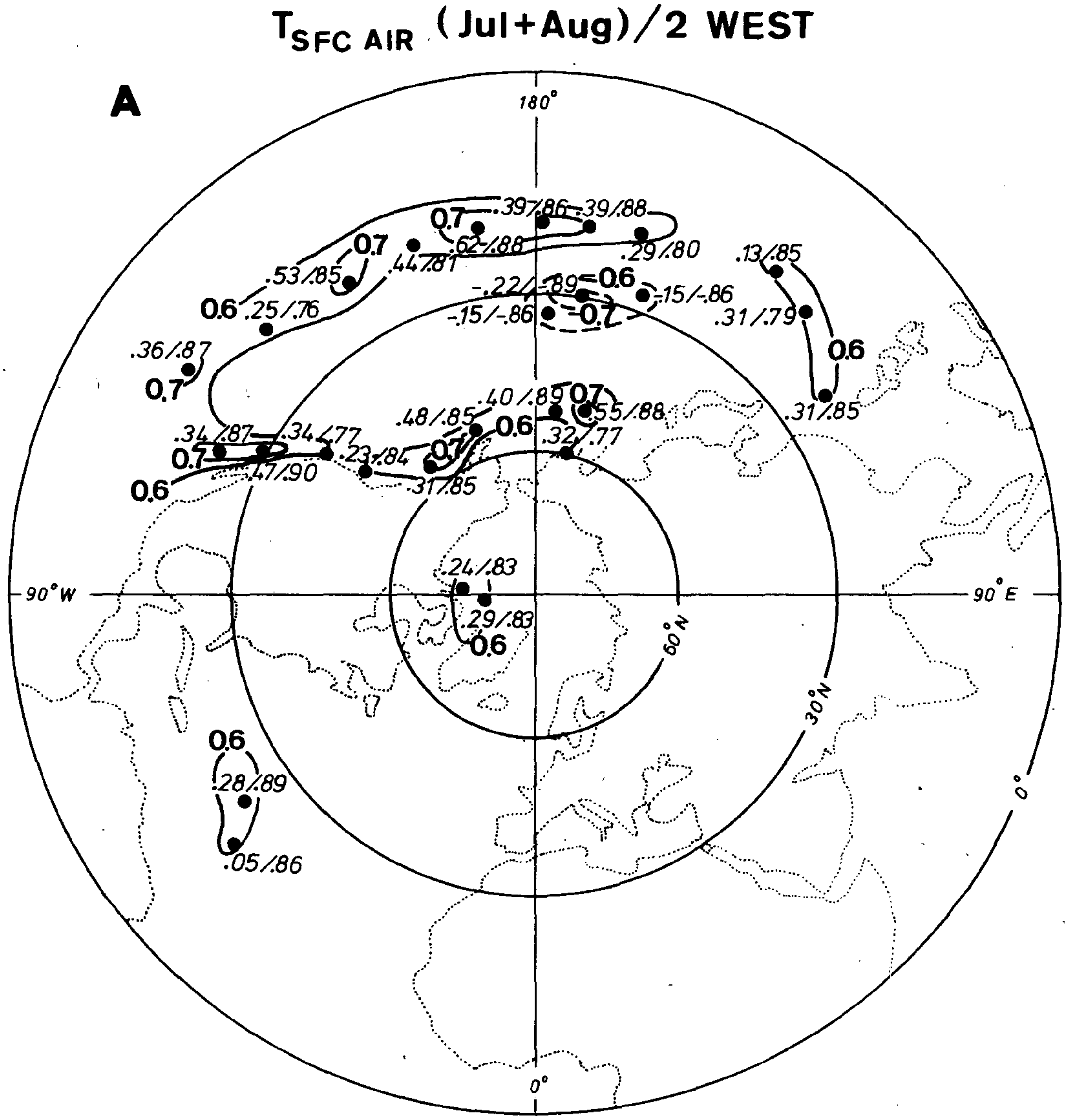

FIG. 6. (a) Correlations between the 10.7 cm solar flux and surface air temperature at stations and ocean blocks from the Comprehensive Ocean Atmosphere Data Set (COADS). The numbers refer to a bootstrap test: 0.36/0.87 thus means that 95% of the correlations in a bootstrap sample of 1000 fell between 0.36 and 0.87. For July–August in West years, n for stations = 18, for COADS 14. (b) Same as (a) but for East years; n for stations = 14, for COADS 13.

In both East and West years the air temperature correlations in summer reach statistical significance over the ocean.

4. Winter and spring, Southern Hemisphere

There are few points of observations over the vast southern oceans and comparatively few years with analysis of sea level pressure over the whole hemisphere. Because of the sparse network of stations, these analyses are not reliable everywhere, the least reliable parts being over the South Pacific Ocean south of the subtropical high. In contrast with the Northern Hemisphere, the correlations with the solar activity seem to be higher in the East years of the QBO in both summer and winter. We show only the winter correlations in the East years, owing to the small sample and flawed data. The correlation between sea level pressure and solar flux for the available 10 years, underlined in Table 2, appears in Fig. 7. The analyses of SLP which we use consist of one series from 1951 to 1958 from the South African Weather Bureau, and another from the Australian Bureau of Meteorology which begins in 1972. The years 1959–71 are thus not part of Fig. 7.

The negative correlations over the antarctic are sur-

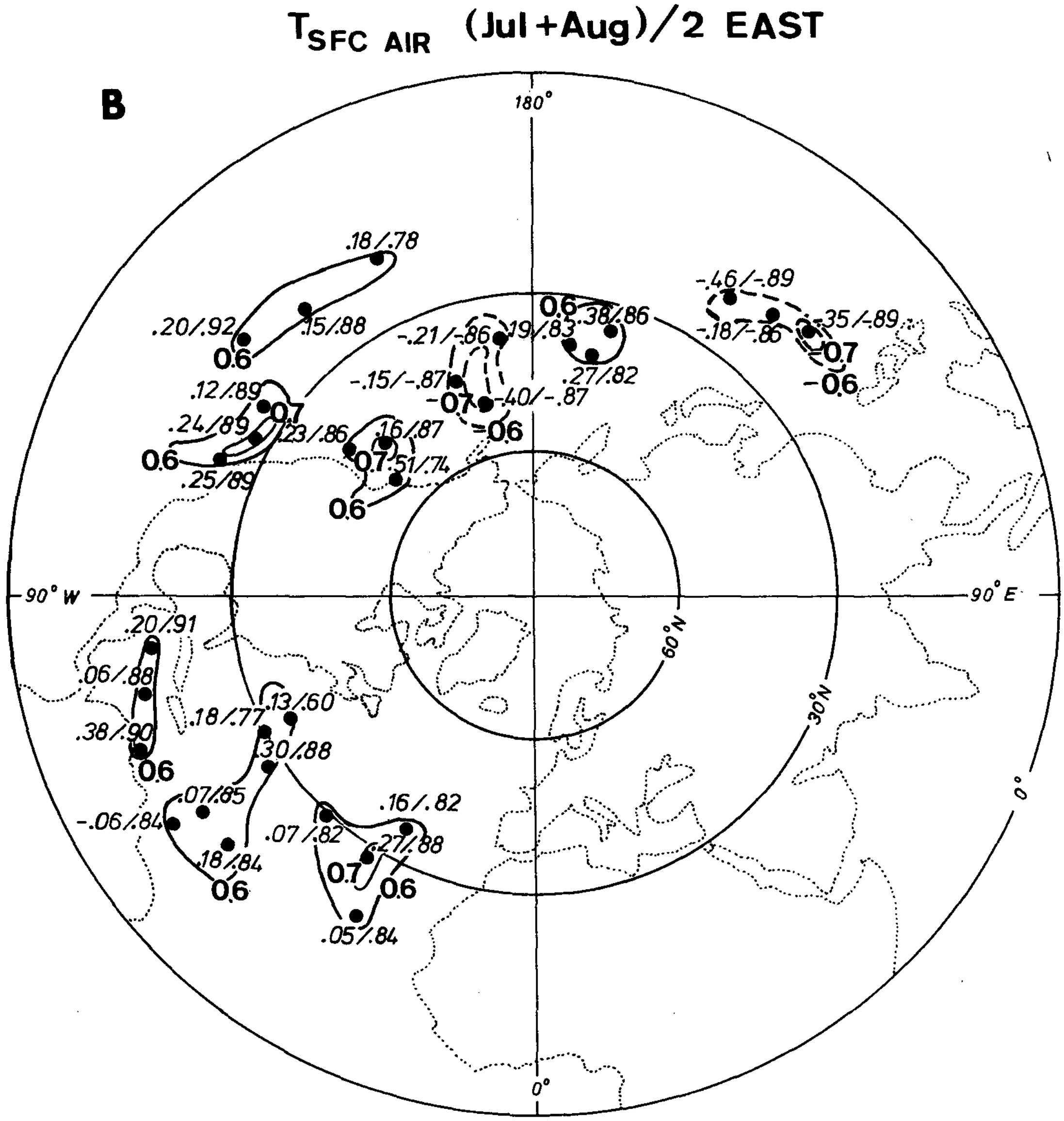

FIG. 6. (*Continued*)

rounded by positive correlations in the belt of westerlies with the highest correlation in the zone where the westerlies are strongest: the Indian and Atlantic oceans. The correlation pattern resembles eigenvector one in SLP (Rogers and van Loon 1982) and contains the well-known distribution of wave one (van Loon and Jenne 1972; Trenberth 1980). In terms of geostrophic wind, the pattern shows an inclination for the westerlies to strengthen south of 45°S in solar maxima, such as happened in the FGGE winter of 1979 and the IGY winter of 1958, while weakening to the north, and conversely in solar minima.

The time series of station data in Fig. 8, which also cover the years 1959–71 when no grid point data are available, illustrate the opposite variation of SLP in middle and high latitudes in the East years. Observations began in 1956 on Gough Island (40.4°S, 9.9°W), and in 1957 at SANAE (South African National Antarctic Expedition, 70.3°S, 2.4°W). In Fig. 7 the correlation of the gridpoint nearest Gough Island is about 0.45. In the time series, Fig. 8a, the six additional East years fit well and improve the correlation ($r = 0.61$ for $n = 15$, the 95% bootstrap interval is 0.35–0.80). At SANAE (Fig. 8b) where $r = -0.61$ for 14 years, the 95% bootstrap interval is −0.29–−0.81. Here, too, the additional years fit well.

The difference in SLP between the two stations (Fig. 8c) varies between 18 mb and 35 mb over the 30 deg of latitudes. It is positively correlated with the 11-yr solar cycle in the East years with $r = 0.70$ for $n = 14$,

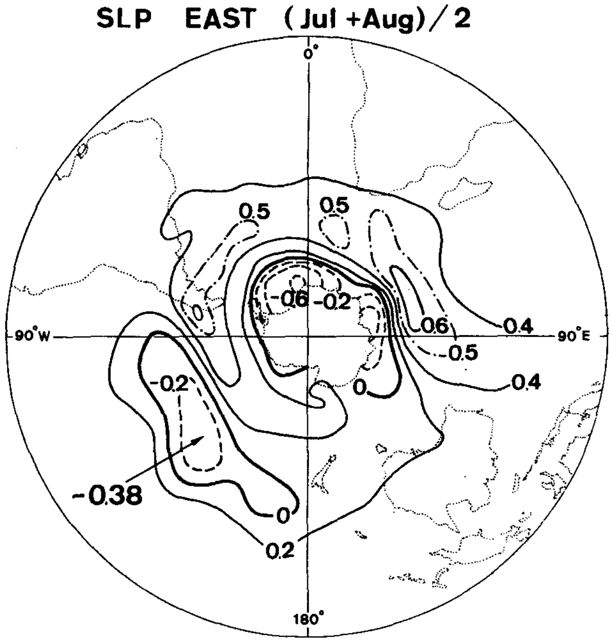

FIG. 7. Correlations between sea level pressure on the Southern Hemisphere in July–August in East years and the 10.7 cm solar flux, for the years 1954, 1956, 1958, 1972, 1974, 1977, 1979, 1981, 1982, 1984.

and a 95% bootstrap interval of 0.45 to 0.84. The fact that the 6 yr which lack in the gridded data fit into the 11-yr solar cycle is reason for cautious optimism about the reliability of the correlation pattern and the possibility that we may be dealing with a solar effect.

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-yr solar cycle such as the one we showed in LvL for the Northern Hemisphere. Unfortunately, there is no long series of maps of stratospheric temperature for the Southern Hemisphere and one must instead turn to station data. The very low temperatures in the antarctic winter stratosphere (see, e.g., Labitzke and van Loon 1972) frequently cause the sounding balloons to burst in the upper troposphere–lower stratosphere. This is responsible not only for an uneven record but also for some bias in the mean temperature toward days when the balloons reach higher levels. Although there appears to be a solar signal in the troposphere in July–August (Figs. 7 and 8), it is futile to search for a solar signal in the stratosphere in the midwinter months because the vortex is then cold and stable and the interannual variability is small: the interannual standard deviation of the 50-mb temperature in midwinter is only 1°C at the South Pole (Labitzke 1987). We have therefore

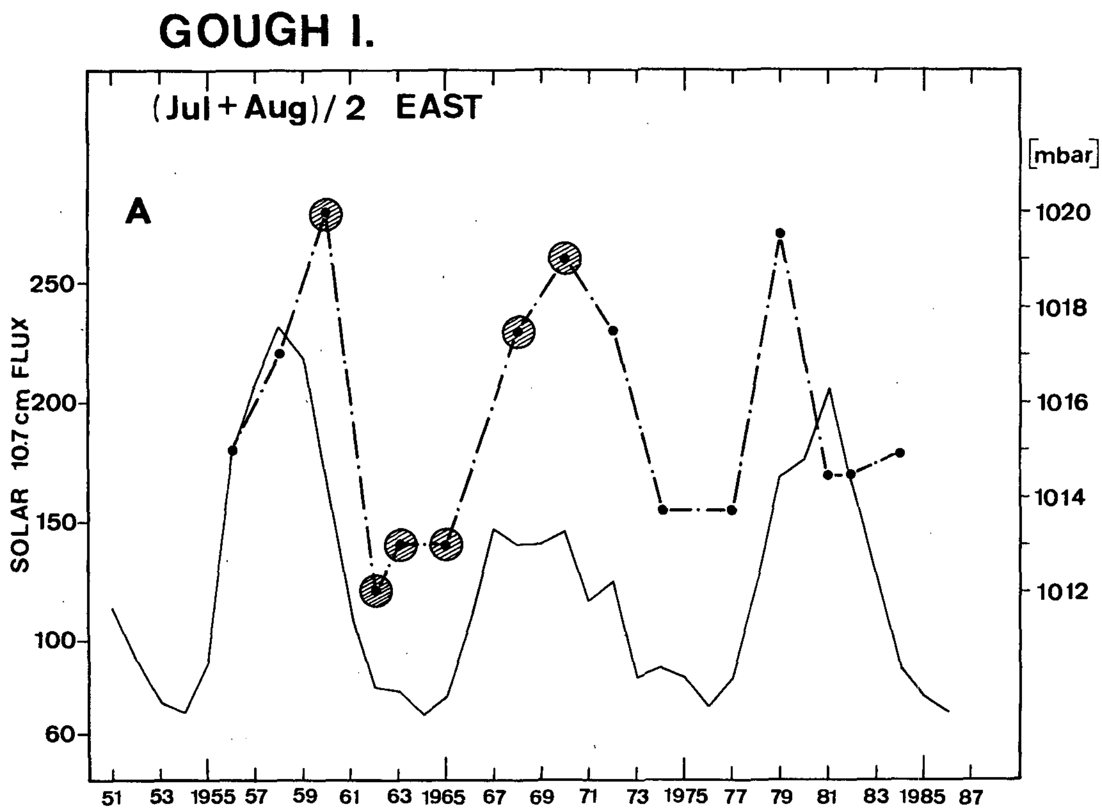

FIG. 8. (a) Times series of 10.7 cm solar flux (solid line) and of sea level pressure in East years, July–August, at Gough Island (40.4°S, 9.9°W). The years with emphasis are not part of the correlations in Fig. 7. (b) Time series in East years of sea level pressure at SANAE (70.3°S, 2.4°W). (c) The difference Gough-SANAE.

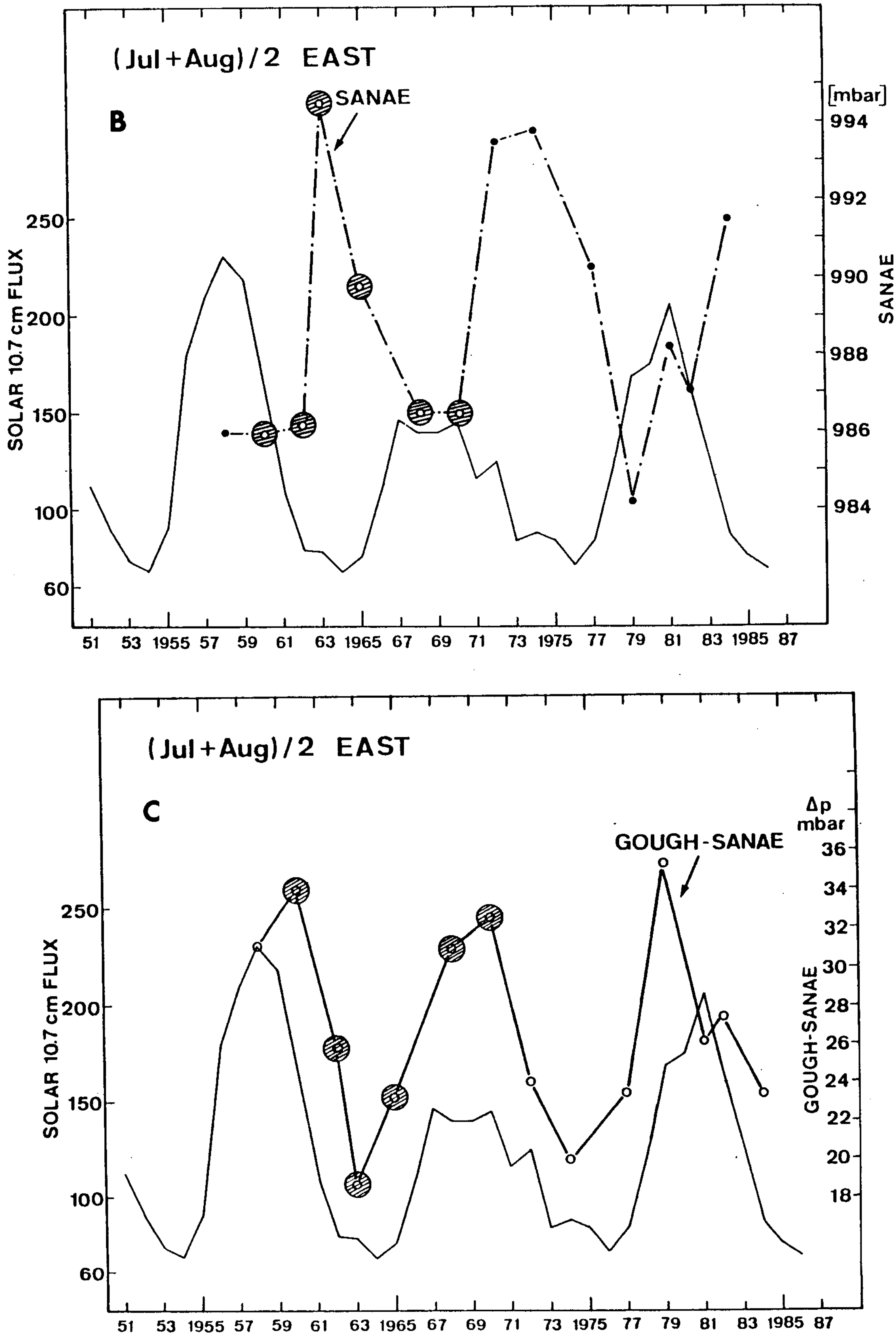

FIG. 8. (*Continued*)

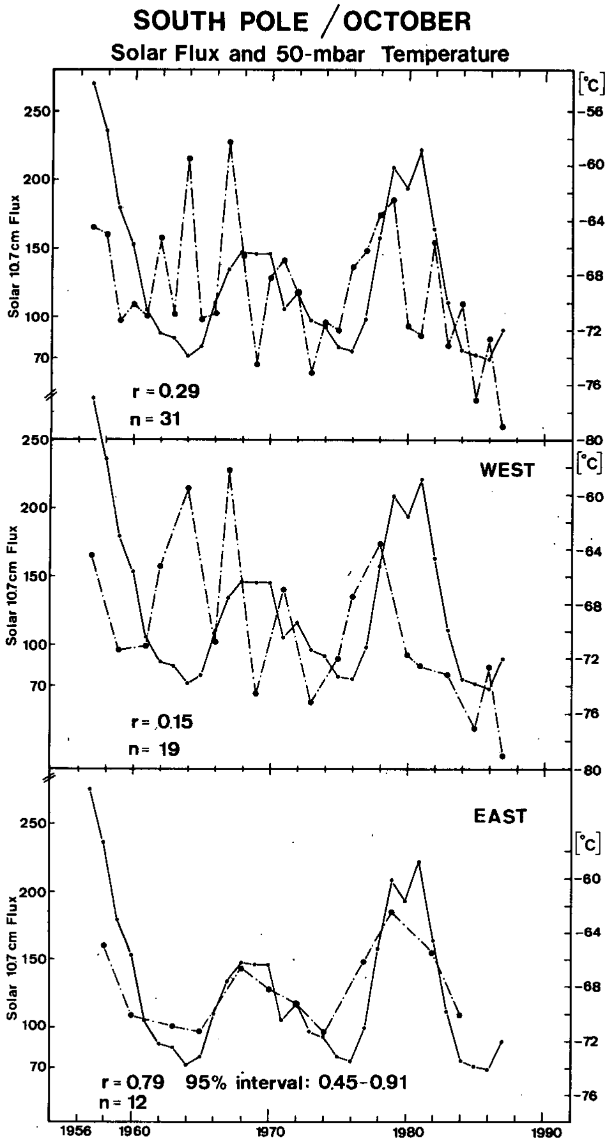

FIG. 9. (a) Time series of the 10.7 cm solar flux, solid line, and the temperature at 50 mb at the South Pole in October, broken line. (b) Same as (a) but only in the West years for the temperature. (c) Same as (a) but only in the East years for the temperature. The 0.45–0.91 is the interval within which lie 95% of the correlations in the bootstrap sample of 1000. East and West according to the equatorial zonal wind at 50 mb in September–October.

used 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 stratospheric level with a fairly complete record at the South Pole in October is 50 mb. Figure 9 presents a time series of 50-mb temperature and of the 10.7 cm solar flux. The correlation between the two is a not-significant 0.29. If, however, one divides the temperatures into East and West years according to the QBO at 50 mb on the equator in September–October, the correlation coefficient is small in the West years (Fig. 9b, 0.15) but rises to 0.79 for the East years (Fig. 9c). This number is near the 99% confidence level in a standard test; and in a bootstrap test 95% of the correlations in the bootstrap sample of 1000 fall within the interval 0.45–0.91. It is not unlikely that the temperature at the South Pole is affected by the solar cycle in the East years of the QBO at the end of winter/beginning of spring. In this instance we have used the equatorial winds at 50 mb only, because the correlation reaches a peak at this level in September–October, whereas it is about the same at 50 and 40 mb in January–February (see vLL, Fig. 2 and accompanying text).

5. Northern spring

The response of the stratosphere on the Northern Hemisphere in winter to the 11-yr solar cycle is quite marked, as was shown in LvL. In the West years the arctic temperatures and heights are positively correlated with the cycle while those in middle and low latitudes are negatively correlated; the converse holds for the East years. As the following analysis indicates, these conditions change from winter to spring. Figure 10 shows the correlation between the solar flux and 30-mb geopotential height in spring (March–April) in West years of the QBO (n = 16). The pattern is the opposite of that in the West years for January–February (LvL, our Fig. 5a), with negative correlations in the arctic surrounded by positive correlations in March–April. This change in pattern is probably associated with the well-known observation (Labitzke 1982, her Table 2) that winters during which a major midwinter warming has taken place tend to be followed by a late final warming, whereas a winter with a cold polar vortex

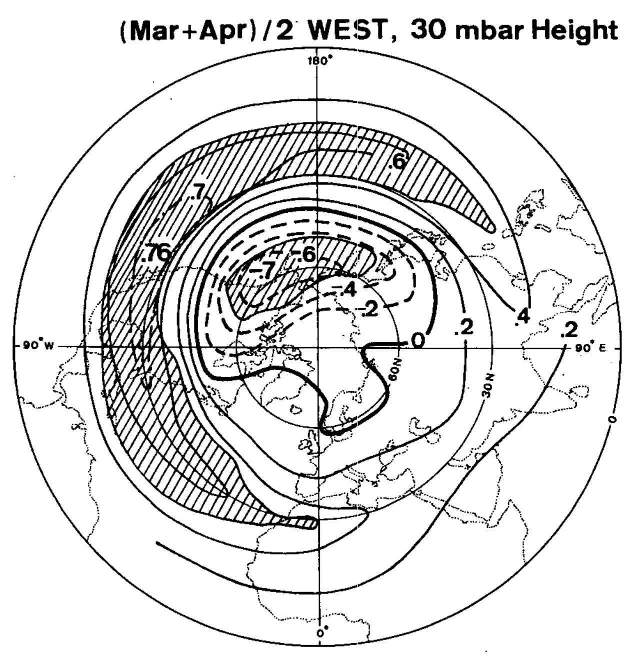

FIG. 10. Correlation between the 10.7 cm solar flux and 30-mb geopotential height in March–April for 16 West yr. In the hatched areas the correlation exceeds the 95% confidence level of 0.52 for n − 2 degrees of freedom.

tends to precede an early final warming. The major midwinter warmings in the West years take place in the peaks of the solar cycle; the final warmings are then late, the spring vortex cold, and the correlations in March and April are thus negative in the arctic (Fig. 10). This circumstance, as well as our other analyses, imply that we are not dealing primarily with direct radiative effects but that dynamics play an important role in the relationship between the atmosphere and the solar variability. We also stress the importance of not including March with the winter months because the correlation patterns in January–February and March–April are opposite.

6. Conclusion

We have added a number of examples to our general description in Parts I and II to show other aspects of the possible association between the 11-yr solar cycle and the atmosphere. Some follow directly from the analyses in LvL and vLL, such as the variations in the frequency of lows in the Atlantic Ocean and the associated changes in horizontal pressure differences and surface air temperature in winter. The correlations in these instances lie between 0.6 and 0.8 for sample sizes of 19, and they are statistically highly significant. Others are from the summer season; in this season statistically significant correlations between solar flux and SLP and 700-mb geopotential height are found principally over the North Pacific Ocean. Although the correlation coefficients in the centers of the negative and positive areas are as high as 0.6–0.8 and are statistically quite significant, the patterns are less obvious than those in winter when the statistically significant areas are well distributed within the familiar teleconnections of the North Atlantic and North Pacific Oscillations.

The signal, if such it is, of the 11-yr cycle in surface air temperature in summer appears only over water, r being 0.6–0.7 over wide ocean regions. It is clearly associated with the variability in pressure, but unlike winter, when changes in advection primarily determine the changes in temperature, the pressure correlation patterns in summer suggest that the dominant influence may be the effect of the wind on the well-mixed layer and of changes in cloudiness.

Despite the poor coverage of observations and the short series of values at grid points on the Southern Hemisphere, correlations of SLP in winter with the solar cycle for 10 winters in East years, distributed over two different periods, yield a coherent pattern. The pattern is that of the first eigenvector in SLP and indicates that the westerlies tend to strengthen south of about 45°S in solar maximum and weaken to the north, especially in the South Atlantic and Indian oceans, and conversely in solar minimum. Time series of SLP at stations show that the 6 missing East yr in the grid point data between 1959 and 1971 not only fit into the pattern but enhance the correlation coefficients.

At the South Pole the temperature at 50 mb in spring is well correlated with the solar flux in the East years of the QBO ($r = 0.79$ for $n = 12$) and hardly at all in the West years ($r = 0.15$ for $n = 19$).

In spring (March and April) on the Northern Hemisphere the West years in the stratosphere are remarkably well correlated with the solar cycle with more than 35% of the area above the 95% confidence level, but the pattern of correlation is almost the opposite of that of the West years in winter. We suggest that this opposition is due to the fact that when a major midwinter warming has occurred in a given year, the final warming in spring tends to be later than usual. As major midwinter warmings in the west years so far have been observed only in solar maxima, these maxima are thus associated with late final warmings and a cold spring vortex; and the correlation therefore is negative over the Gulf of Alaska–Bering Sea in Fig. 10.

Acknowledgments. We are grateful for the invaluable and indispensable help which we have received from D. J. Shea with respect to computation and statistical testing.

REFERENCES

Brown, G. M., and J. T. John, 1979: Solar cycle influences in tropospheric circulation. *J. Atmos. Terr. Phys.*, **41**, 43–52.

Labitzke, K., 1982: On the interannual variability of the middle stratosphere during northern winters. *J. Meteor. Soc. Jpn.*, **60**, 124–139.

——, 1987: The lower stratosphere over the polar regions in winter and spring: Relation between meteorological parameters and total ozone. *Ann. Geophys.*, **5A**, 95–102.

——, and H. van Loon, 1972: The stratosphere in the Southern Hemisphere. *Meteorology of the Southern Hemisphere*, C. W. Newton, Ed., *Meteor. Monogr.*, **13(35)**, 113–138.

——, and ——, 1988: Associations between the 11-year solar cycle, the QBO, and the atmosphere. Part I: The troposphere and stratosphere in the Northern Hemisphere in winter. *J. Atmos. Terr. Phys.*, **50**, 197–206.

Naujokat, B., 1986: An update of the observed Quasi-Biennial Oscillation of the stratospheric winds over the tropics. *J. Atmos. Sci.*, **43**, 1873–1877.

Rasmusson, E. M., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354–384.

Rogers, J. C., and H. van Loon, 1982: Spatial variability of sea level pressure and 500 mb height anomalies over the Southern Hemisphere. *Mon. Wea. Rev.*, **110**, 1375–1392.

Tinsley, B. A., 1988: Latitude variation of storm tracks in the North Atlantic; the solar cycle and the QBO influences. *Geophys. Res. Lett.*, **15**, 409–412.

Trenberth, K. E., 1980: Planetary waves at 500 mb in the Southern Hemisphere. *Mon. Wea. Rev.*, **108**, 1378–1379.

van Loon, H., and R. L. Jenne, 1972: The zonal harmonic standing waves in the Southern Hemisphere. *J. Geophys. Res.*, **77**, 992–1003.

——, and J. Williams, 1977: The connection between trends of mean temperature and circulation at the surface. Part IV: Comparison of the surface in the Northern Hemisphere with the upper air and with the Antarctic in winter. *Mon. Wea. Rev.*, **105**, 636–647.

——, and D. J. Shea, 1987: The Southern Oscillation. Part VI: Anomalies of sea level pressure on the Southern Hemisphere and of Pacific sea surface temperature during the development of a Warm Event. *Mon. Wea. Rev.*, **115**, 370–379.

——, and K. Labitzke, 1988: Association between the 11-year solar cycle, the QBO, and the atmosphere. Part II: Surface and 700 mb on the Northern Hemisphere in winter. *J. Climate*, **1**, 905–920.