A Closer Look at the Effect of the 11-Year Solar Cycle and the Quasi-biennial Oscillation on Northern Hemisphere 700 mb Height and Extratropical North American Surface Temperature

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ABSTRACT

A recently discovered association between the 11-year solar cycle and the Northern Hemispheric low-frequency atmospheric circulation structure, which is most easily detectable when the two phases of the Quasi-biennial Oscillation (QBO) are considered individually, is described and subjected to global statistical significance tests.

Highly significant relationships are found during the January–February period. This is especially true for the west QBO phase, in which the solar flux is positively correlated with 700 mb heights and surface temperatures over central and northern Canada, and negatively correlated with heights in the western Atlantic along 30°N and with temperature in the southern and much of the eastern portions of the United States. The pattern of the flux-height correlation field resembles primarily the Tropical/Northern Hemisphere (TNH) long-wave circulation pattern and secondarily the North Atlantic Oscillation (NAO) pattern. For east QBO phase years a different structure is found, and for all years pooled a weaker but quite characterizable pattern emerges.

January–February correlations are studied for sensitivity to lead time in the QBO phase definition and for shorter period means for the west QBO phase. The latter inquiry reveals a concentration of the west phase relationship during the latter half of January.

The climate of the October–November period also appears to participate, to a lesser but significant degree, in a solar–QBO relationship for west phase QBO years.

For the west QBO phase, the January–February solar flux versus 700 mb height (and United States–Canada surface temperature) correlation pattern contains sufficient amplitude and field significance to be exploited for operational forecasting purposes at the Climate Analysis Center. However, in the absence of a verifiable physical basis of the solar–QBO–atmosphere association, and because the 45 mb stratospheric winds were selected to characterize the QBO in an a posteriori manner, the relationships are accepted with caution and will be regularly reevaluated.

1. Introduction

This study examines further a recently discovered association between the 11-year solar cycle and the atmosphere that is most easily detectable when the two phases of the Quasi-biennial Oscillation (QBO) are considered individually rather than pooled.

Documentation of a solar cycle–QBO–atmosphere relationship in Northern Hemisphere winter began for the stratosphere near the North Pole (Labitzke 1987) and was subsequently extended to cover the extratropical Northern Hemisphere for the lower stratosphere and middle troposphere (Labitzke and van Loon 1988),[1] and finally for the lower troposphere and the surface (van Loon and Labitzke 1988). The last paper reported statistically highly significant QBO-stratified solar cycle–atmosphere relationships at a number of locations; these involved surface air temperature, sea level pressure, and geopotential height. Further study indicated effects during other seasons and in the Southern Hemisphere (Labitzke and van Loon 1989).

The present study describes and examines the global (i.e., field) statistical significance of the overall spatial pattern of the solar–atmosphere relationship for the extratropical Northern Hemispheric 700 mb height and for the surface temperatures in the United States (including Alaska and Hawaii) and Canada. Three-, two-, and one-month mean relationships are considered at all times of the year, and still shorter averaging periods are tested during the part of the winter when the apparent effect is strongest. Further studies during this maximum effect period are designed to help define the form of the relationship in terms of previously established atmospheric circulation patterns. Lagged as well as simultaneous relationships are examined.

Knowledge of a relationship between the solar cycle,

[1] Sudden stratospheric warming is also discussed relative to the solar cycle and the QBO.

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the QBO, and the atmosphere is sought not only to better our understanding of atmospheric physics, but for the practical purpose of making possible more skillful short-term climate forecasts. The quasi-periodic behavior of the QBO and solar cycle provide possibilities for longer lead climate forecasting than that currently carried out at the Climate Analysis Center (CAC).

An examination of the statistical significance of solar–atmosphere relations is complicated by the cyclical character of the QBO and the solar flux. The QBO goes through one cycle in slightly longer than two years; the solar flux does so in about 11 years, resulting in an availability of about 3.5 solar cycles for the 38-year study. The long period of the solar cycle implies strong interannual autocorrelations for the flux. The number of truly independent time realizations is thus diminished, necessitating a stronger observed relationship to achieve a given statistical significance level, whether for a single location or over the study domain as a whole. This study uses appropriately designed Monte Carlo significance tests to assess van Loon and Labitzke's (1988) claim that the relationships are very unlikely due to chance, even in the current absence of an a priori physical explanation.

2. Data and analysis methods

a. Data

The data used in this study include the monthly mean u-component of the wind over the equator at 30 and 50 mb (leading to a dichotomous definition of the QBO phase—west or east), the monthly mean 10.7 cm solar flux, the monthly mean surface temperatures at 92 continental U.S. stations, 6 Alaskan, 3 Hawaiian and 25 Canadian stations, and monthly mean 700 mb geopotential height from 20°N northward. The data spanned from 1951–88, being limited by the beginning of the equatorial stratospheric wind records needed to define the QBO.

The monthly mean QBO phase was determined by the sign of the u-component of the monthly mean equatorial wind at 45 mb (a linear interpolation in p using the 50 and 30 mb winds), following the empirical determination of Labitzke and van Loon (1988) and van Loon and Labitzke (1988) that the 45 mb level maximizes the solar–atmosphere relationships when stratified by the QBO phase. The stations used for the QBO winds varied over time, but this is not harmful to the study because we find that the monthly wind measurements are correlated over 0.95 with one another for nearly all months of the year. For 1951–52, Balboa (located at 9.0°N, 79.6°W) was used; for 1953–63, Canton Island (2.8°S, 171.7°W) was used (from Fig. 1 in Naujokat 1986); and for 1964–88, Singapore (1.4°N, 103.9°E) was used. Although the complete (50 and 30 mb) wind data for Balboa go back only as early as July 1951, the 50 mb winds begin in January 1951 and extrapolation to several months earlier leaves little doubt that the 45 mb QBO wind was in the early or central portion of its west phase between December 1950 and February 1951.

When Canton Island or Singapore was used to derive the QBO phase, the sign of the u-component of the wind was the sole phase-determining element, because the stations that are very close to the equator have monthly mean zonal winds that are roughly symmetrically distributed about zero (see Fig. 2 in Naujokat 1986). Balboa, on the other hand, being 9 degrees north of the equator, has a marked skew toward easterly 45 mb winds. For the use of Balboa, a regression relationship between Balboa and Singapore was developed and the QBO phase was determined from the sign of the u-component of Singapore's well-predicted wind. The QBO wind data were obtained from the National Meteorological Center (NMC), archived by James Angell (personal communication), or from the graphical presentation in Naujokat (1986).

The monthly mean Ottawa observed (i.e., unadjusted for the varying earth–sun distance) solar flux at 10.7 cm (units 10^{-22} W m^{-2}) for 1951–88 were obtained from the NOAA/ERL Space Environment Laboratory in Boulder, Colorado.

Monthly mean surface temperatures for the same period at 101 U.S. stations (including 6 in Alaska and 3 in Hawaii) and 25 Canadian stations were obtained from the NMC from 1951–88. The station network is shown in Fig. 1. A paucity of reliable stations in Alaska and central and northern Canada necessitated the lower density there. Included in Hawaii are one leeward station (Honolulu) and two windward ones separated by 525 km (Hilo and Lihue).

The 700 mb geopotential height monthly mean data for 1951–88 on an approximately equal area 358-point grid for the Northern Hemisphere from 20°N northward were also obtained from the NMC.

One-, two-, and three-month means were computed for the 700 mb heights, surface temperatures, and solar fluxes. For the QBO phase, however, only 1-month means were used, the month being the first (second) of the months in a two (three)-month mean analysis of simultaneous relationships, but the second (third) of same in a lagged analysis where the QBO and solar flux preceded the lower atmospheric variables.

b. Analysis methods

The primary quantities to be described and evaluated statistically are the spatial fields of the correlation between the solar flux and the Northern Hemisphere 700 mb height, or between the solar flux and the U.S. and Canadian surface temperature, for each of the two stratifications of the QBO phase (west and east), for a given time of the year, a given averaging period, and possibly a given lag period. The primary Monte Carlo field significance test to be applied here assesses the probability that the observed west and east QBO phase

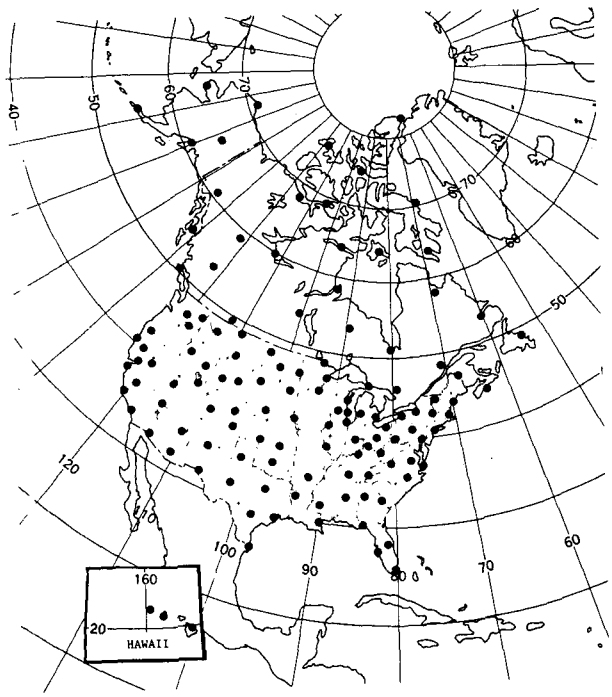

FIG. 1. The 126-station network for surface temperatures. The conterminous United States contains 92 stations, the entire United States 101, and Canada 25.

height-flux or temperature-flux correlation fields, as wholes, could be as strong as they are due to a random QBO phase assignment process, given the natural year-to-year variation in the atmosphere. The temporal autocorrelations of the flux and (to lesser degrees) of the other variables, as well as the spatial redundancy among neighboring grid points of height or temperature, are taken into account in this field significance test (Livezey and Chen 1983).

A suitable test statistic for the entire correlation field was devised to compare the observed fields with those resulting from many randomized QBO phase assignments. The basic test statistic used here is an integrated t-statistic, to be described now.

A t-statistic is calculated at each of the 358 grid points of Northern Hemisphere flux–height correlation coefficient (r) or at each of the 92 grid points of the conterminous U.S. flux-temperature correlation coefficient (or 126 grid points for total United States plus Canada). These local t-values are calculated as

$$t = [r^2(N-2)/(1-r^2)]^{1/2},$$

where N is the number of independent time points. Because the solar flux is strongly autocorrelated and the temperature and height are moderately correlated with the flux at some of the grid points, the number of independent time points at such points is less than the number of years in the sample. When this proved to be the case the sampling interval was increased to ensure that only independent samples were used to estimate t. This was done through estimation of the effective time between independent samplings using a modified version of a formula used in Davis (1976):

$$N = NY/(1 + 2 \sum_{L=1}^{NY-3} w\mathrm{CFF}_L\mathrm{CXX}_L). \quad (1)$$

Here NY is the unreduced temporal sample size (i.e., about 19 years for each QBO phase), L the lag in years, CFF_L and CXX_L the autocorrelations of the flux and of variable X (e.g., height or temperature) at lag L, and w is a weighting factor that damps results as a linear function of L. This reduces the effects of sampling errors at large L where fewer pairs of data are available to autocorrelate. The denominator is called the integral time scale, which exceeds 1 when the variables tend to have like-signed autocorrelations over the range of L.

When large integral time scales occur in regions of high flux-height (or flux-temperature) correlations, the values of t appropriately will be diminished greatly. Because east and west phase analyses already contain data from essentially every two years, only locations with integral time scales of greater than 2 are of concern. As an approximation to a more exact but unknown adjustment [given that (1) provides only rough estimates], locations with integral time scales of 3 or more were sampled only once for every two possible time points, resulting in one data point approximately every four years and a value of N reduced by one-half.

The field significance test statistic is the average of the t-values over all grid points of the map. Before averaging, however, the t-value at each grid point was converted to a z-value (i.e., the t-value for an infinitely large sample) having equivalent significance. (For example, a t-value of 2.306 for a correlation derived from 10 time points, or 8 degrees of freedom, would be converted to 1.960.) This was done so that equal t's would represent equal significances, given that N is only half as large at certain grid points as at most others. This average t field significance test statistic differs from that discussed in Livezey and Chen (1983) in that it represents an integrated significance level using the local t-values themselves rather than a count of how many of them exceed a given local significance threshold such as 0.05. The latter (Livezey and Chen 1983) procedure is perfectly suitable when the distribution of local significances is reasonably smooth. The average t, however, includes more information about the local significance levels (e.g., "near misses" or values that are minimally significant or extremely highly significant) and thus can more accurately evaluate irregularly shaped distributions of local significance. Since our data have considerable spatial dependence, Monte Carlo simulations rather than the binomial are required to define the random or "no effect" distributions. The integrated t-test statistic as well as a local significance

count were employed, though the former was used as the primary evaluative method in this study.

Monte Carlo simulations were carried out in which the QBO phase assignments were randomly shuffled with respect to year, keeping the observed number of cases in each phase. Two thousand iterations were run: 1000 for "odd" time points at locations having high integral time scales, and 1000 for "even" time points. (At the other locations, all time points were used in all cases.) The result using actual data was ranked among the random runs, and the fraction of random runs not exceeded (i.e., the field significance) was found. Field significances were computed for each QBO phase as well as for the joint result of the two separate corresponding phases considered as one set.

Another approach to the field significance tests was tried, in which, in lieu of the t-statistic, the correlation coefficients at all grid points were squared and summed, and comparison made with Monte Carlo simulations using random QBO phase assignments. This method was not complicated by explicit autocorrelational considerations. Several applications produced significance levels similar to those of the technique described above. This similarity, as well as that of the Livezey and Chen (1983) local significance counts, provided some assurance that results are not dramatically dependent on the details of the simulation method.

Because the January–February 2-month period produced the strongest apparent solar–atmosphere effect, several auxiliary analyses were carried out on that period. One such analysis is a Monte Carlo test using the integrated t-statistic, where instead of shuffling the QBO phase assignment to create the "no effect" distribution, the solar cycle phase was randomly assigned without destroying the general shape and autocorrelational properties of the cycle. Cycles containing realistically varying amplitudes, periods, and shapes were simulated based on the cycles over the last few centuries. Note that now the all-years, unstratified condition would be tested, which was impossible when shuffling the QBO phase assignments. The power of a cycle phase shuffle test would be expected to be somewhat less than that of a QBO phase shuffle test because the latter has more diverse permutations.

In another analysis designed to help define the morphology of the flux-700 mb height correlation pattern in January–February, significance tests were carried out for the correlation between the solar flux and the amplitudes of the ten leading January–February rotated principal component loading patterns. In a corroborating analysis (not shown but whose results are comfortingly similar to those of the flux-amplitude correlation), the significance of the projection of the height-flux correlation fields onto each of the ten leading rotated principal component loading patterns was calculated. A determination of which previously established atmospheric circulation patterns are most suggested by the solar–atmosphere correlation fields could help in the formation of a physical hypothesis regarding the fields.

3. Results

Table 1 contains results of the Monte Carlo field significance tests based on the integrated t-statistic described in section 2b, for 2000 random shufflings of the QBO phase assignment, for three averaging periods throughout the annual cycle. Field significances for the west QBO phase (W), the east phase (E), and jointly for the two separate phases as a unit (J) are shown for the correlation fields relating solar flux to Northern Hemisphere 700 mb height, surface temperatures over the conterminous United States (92 stations), and also, when an effect is suggested, those over the entire United States (including Alaska and Hawaii) and Canada (126 stations total). The p-values in Table 1 are given to three decimal places when significant at the 0.050 level or better. One should be aware of the multiplicity of tests performed, and the corresponding probability of occasional accidental field significances. Nonetheless, the table provides an overview of the times of the year meriting closer scrutiny.

When inspecting the cold season field significances to decide on the existence of a relationship, the primary requirement is for global significance in the Northern Hemisphere 700 mb height versus solar flux correlation field. This priority is based on the fact that the height field is the most global of those used in the study, and is of the scale on which winter effects were identified in van Loon and Labitzke (1988). Global significance in the temperature versus flux correlation field, while of interest and potentially more useful, is of relatively local scale and one should be cautious in accepting the reality of such in the absence of significance in the height field. On the other hand, if the height field is significant and the temperature field is not, individual stations in the temperature network achieving local significance may be accepted as exhibiting a real effect if they can be confidently related to one or more of the major "centers of action" in the height field; i.e., if there is an apparent physical connection. Failure of the temperature field to achieve significance in the presence of height field significance can occur when a line of zero temperature correlations lies across North America or when much of the strength in the height correlation field is not in central North America. The United States temperature field significance data are included to ascertain whether that portion of the Northern Hemisphere is affected when the hemisphere as a whole attains 700 mb height significance. The field significance of the enlarged temperature-flux correlation field (including Canada, Alaska, and Hawaii), while more global than that of the conterminous United States field, weights the conterminous United States portion most heavily because of the lower station density elsewhere. It is included mainly for heuristic interest and

TABLE 1. Field significances for QBO phase-stratified samples of correlations between solar flux and Northern Hemisphere 700 mb height (NH 700 mb), surface temperature in the conterminous United States (US92), and surface temperature in the entire United States and Canada (US126). One, two, and three-month mean periods are shown throughout the annual cycle. Underlining denotes p-values significant at the 0.05 level or better. W, E and J denote west, east and joint (not pooled; see text) QBO phase status.

1-month period		NH 700 mb	Temperature US92	Temperature US126	2-month period	NH 700 mb	Temperature US92	Temperature US126	3-month period	NH 700 mb	Temperature US92	Temperature US126
	W	.74	.24							.84	.30	
Aug	E	.29	.57						JAS	.48	.58	
	J	.50	.31			.83	.77			.71	.35	
					Aug–Sep	.62	.48					
	W	.68	.76			.79	.78			.21	.91	
Sep	E	.45	.69						ASO	.60	.49	
	J	.57	.92			.13	.18			.33	.81	
					Sep–Oct	.47	.13					
	W	.24	.023	.026		.18	.08			.07	.016	.015
Oct	E	.29	.41	.44					SON	.37	.17	.19
	J	.14	.022	.027		.11	.004	.005		.13	.023	.023
					Oct–Nov	.19	.28	.30				
	W	.15	.028	.010		.09	.004	.006		.41	.55	
Nov	E	.41	.24	.25					OND	.67	.57	
	J	.15	.030	.014		.83	.71			.55	.55	
					Nov–Dec	.70	.68					
	W	.53	.47			.84	.85			.66	.44	
Dec	E	.67	.33						NDJ	.31	.31	
	J	.61	.39			.36	.74			.47	.34	
					Dec–Jan	.39	.19					
	W	.010	.11	.038		.31	.37			.045	.48	.46
Jan	E	.26	.12	.16					DJF	.15	.15	.11
	J	.023	.06	.024		.003	.07	.07		.05	.19	.13
					Jan–Feb	.025	.41	.30				
	W	.29	.15	.16		.001	.033	.023		.006	.26	.15
Feb	E	.15	.91	.89					JFM	.22	.42	.38
	J	.15	.55	.55		.07	.42	.29		.009	.18	.08
					Feb–Mar	.59	.64	.63				
	W	.10	.58	.37		.14	.51	.41		.032	.38	.34
Mar	E	.96	.63	.78					FMA	.93	.68	.68
	J	.53	.72	.71		.050	.68	.59		.17	.53	.52
					Mar–Apr	.98	.72	.79				
	W	.55	.98			.44	.87	.89		.07	.041	
Apr	E	.98	.48						MAM	.99	.98	
	J	.99	.90			.13	.48			.60	.48	
					Apr–May	.94	.77					
	W	.11	.10			.63	.69			.15	.37	
May	E	.99	.91						AMJ	.97	.95	
	J	.78	.35			.07	.30			.72	.93	
					May–Jun	.75	.95					
	W	.37	.58			.22	.91			.11	.46	
Jun	E	.26	.47						MJJ	.31	.60	
	J	.20	.64			.40	.50			.07	.62	
					Jun–Jul	.11	.20					
	W	.55	.48			.10	.17			.44	.19	
Jul	E	.13	.12						JJA	.50	.06	
	J	.18	.20			.59	.21			.46	.05	
					Jul–Aug	.26	.47					
	W	.74	.24			.36	.27			.84	.30	
Aug	E	.29	.57							.48	.58	
	J	.50	.31							.71	.35	

as a rough vehicle for identification of situations in which Canada or Alaska might be affected more strongly than the lower 48 states.

There is one instance in which field significance in the U.S.–Canadian temperatures might be accepted in the absence of hemispheric height field significance. This is when the flux–height correlation pattern is strong and coherent on the planetary wave scale, but only over one-half (or more) of the hemisphere, and is reproduced for successive nonoverlapping (quasi-independent) periods. This situation could arise during the warm or transition seasons when full global re-

sponses are less prevalent and less likely due to the shorter length of the planetary waves and the weaker teleconnectivity among mutually distant locations (Namias 1981).

In order of apparent strength, the two times of the year when a relationship appears to exist are 1) midwinter, mostly for west QBO phase but also for east, and 2) midfall for west QBO phase. A third but more questionable relationship is found in late spring/early summer, first for the west phase (May–June) and then for the east (June–July). While several small but strong features are present in the correlation fields (primarily in the high latitude North Pacific), the field significance is marginal and we must wait perhaps one more solar cycle before reassessing the stability of the pattern. The July–August west and east phase correlation patterns discussed in Labitzke and van Loon (1989) were reproduced here but do not meet our criteria for field significance.

The details of the relationships at midwinter and midfall are now presented. Because the midwinter effect is by far the more prominent and consistent in character among the individual months of January, February, and March, special attention will be given to this period.

a. *Winter effect*

As indicated in Table 1, the 2-month mean period of January–February encompasses the major portion of the apparent winter effect: its significance value for the west QBO phase for the 700 mb height versus solar flux correlation field (0.003) is stronger than that of any other season or averaging period, and that for the east QBO phase (0.025) is the only significant east phase entry for 700 mb height in the table. The January–February mean (using January for the QBO phase) is the period most thoroughly examined in van Loon and Labitzke (1988), and the present work similarly will employ it in the greatest number of analyses.

1) JANUARY–FEBRUARY MEAN PERIOD RELATIONSHIPS

The January–February mean correlation fields for solar flux versus 700 mb height for west and east QBO phases are shown in Figs. 2 and 3, and those for flux versus surface temperature in Figs. 4 and 5. These are similar to those of van Loon and Labitzke (1988). Minor differences are attributable to the inclusion of 1951 and 1988 here. Correlation fields for the unstratified, 38-year datasets are considerably weaker than the phase-stratified fields, but more will be said about the 38-year flux–height correlation field below.

For the 38 years of January–February flux versus height data, the integral time scale is near one year over about two-thirds of the map, but peaks at approximately four years in three locations: 1) eastern Alaska–north-central Canada, just west of the highest west phase correlations, 2) the western Atlantic near 30°N, where west phase correlations are quite strongly negative, and 3) the eastern Pacific, where west phase correlations are moderately negative. The integral time scale for flux versus U.S. surface temperature is somewhat comparable, with an area in the eastern United States having peak values close to 4, corresponding to the strongest negative correlations of west phase flux versus temperature.

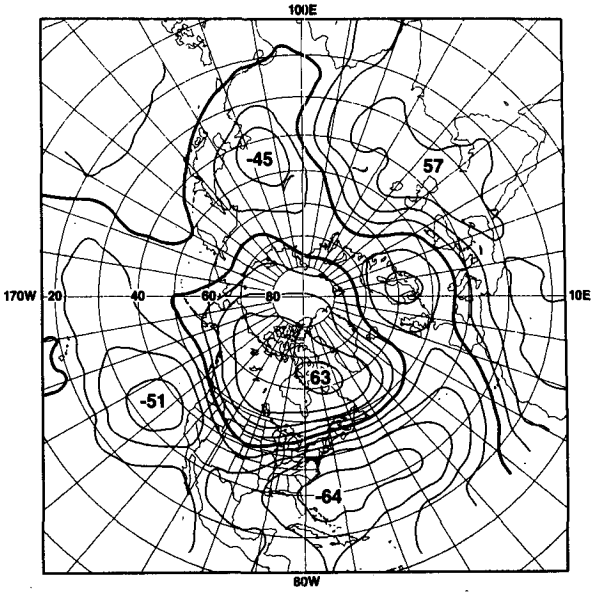

FIG. 2. Correlation (×100) between 10.7 cm solar flux and 700 mb height for the west QBO phase for the January–February period (21 years). Contour interval 15.

The highly significant west phase flux-height correlation map (Fig. 2) has several strong centers—highs over much of northern North America and southern/southwestern Asia, and lows over the subtropical western North Atlantic, off the California coast in the eastern North Pacific, and near Mongolia. This pattern is reminiscent of the Tropical/Northern Hemisphere (TNH) and North Atlantic Oscillation (NAO) patterns of low frequency (i.e., January–February mean) circulation variability as depicted using rotated principal component analysis (RPCA) in Barnston and Livezey (1987). The statistical significance of this resemblance will be discussed later in this section. The east phase flux–height correlation map (Fig. 3), also statistically significant, has noticeably strong centers defining a planetary wave circulation pattern (highs over the outer Aleutians, Mexico, and Europe; lows over Arabia and the central subtropical North Pacific).

The map of January–February correlation between flux and U.S.–Canadian surface temperature for the west QBO phase (Fig. 4) shows moderately strong negative correlations in much of the eastern, southern

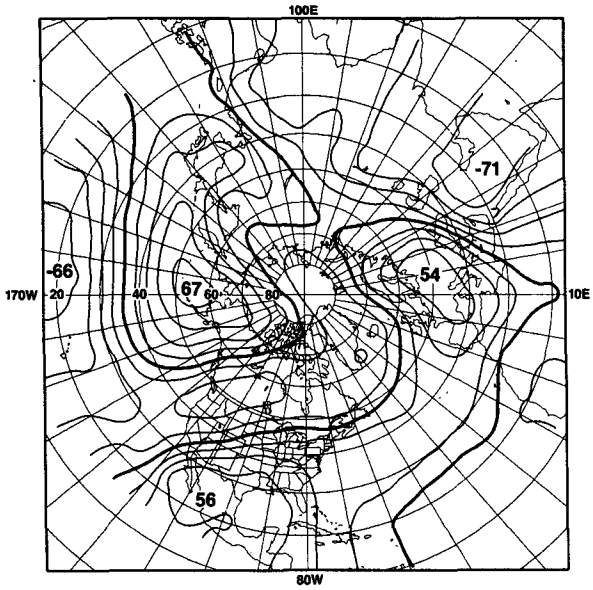

FIG. 3. As in Fig. 2 except for the east QBO phase (17 years).

midwestern, and southern central sectors of the United States; positive correlations are found over most of Canada. The east phase map (Fig. 5) reveals a weaker relationship pattern with a small area of moderately strong positive correlations in the southern Rockies. Although these two maps are not individually field significant ($P = 0.07$ and 0.30, respectively, for west and east QBO phase), the joint probability of the chance occurrence of the set of the two observed overall strengths is a significant 0.023. This lends more credence to the importance of stratifying by QBO phase, and more specifically, to the authenticity of the areas of locally strongest temperature–flux correlations. Additionally, the maps are supported by significant 700 mb height–flux correlation maps (see section 2b for an explanation for this method of reasoning), and areas of the temperature correlation maps can be associated with specific centers on the height correlation map. In the case of the west QBO phase, for example, negative temperature correlations in the eastern United States and positive correlations in northwestern Canada are unequivocally associated with the major low versus high 700 mb height correlation dipole over the same two general areas. For the east QBO phase, the authenticity of the high temperature correlations in the southern Rockies may be trusted to the extent that one believes that the height correlation center over Mexico is one of the major features contributing to the map's 0.025 field significance (and not a minor or random feature). A positive indication of field significance in the temperature maps from a different perspective is forthcoming in the context of the solar flux phase shuffle Monte Carlo significance tests, discussed later in this section.

2) ONE-MONTH MEAN RELATIONSHIPS

In the interest of pinpointing the time scale and the part of the winter during which the solar–QBO–atmosphere effect occurs, the 700 mb height versus solar flux correlation fields for the single months of January, February, and March are shown for the west QBO phase (Figs. 6, 7, and 8, respectively), followed by that for the 3-month period of January–February–March. The strong similarity among the three single month fields, with only the January field individually exhibiting global statistical significance, occurs despite the generally low monthly autocorrelation of 700 mb height (Van den Dool and Livezey 1984). This implies that, if the flux–height correlations reflect mainly linear (rather than asymmetric or outlier-dominated) relationships, the above-implied January–February mean climate pattern in and around the "centers of action" tends to recur or perhaps even persist during the January–February–March period when the flux level is high or low rather than near its mean value. The linearity of the relationships will be explored later in this section. Note that the March map (Fig. 8) has a similar configuration to that of January and February and bolsters the 3-month mean period correlation map (Fig. 9), with stronger values than those of February for the Canadian and Caribbean centers (and a stronger field significance level) but weaker for the southern Asian center. The December and April maps (not shown) do not exhibit the winter pattern.

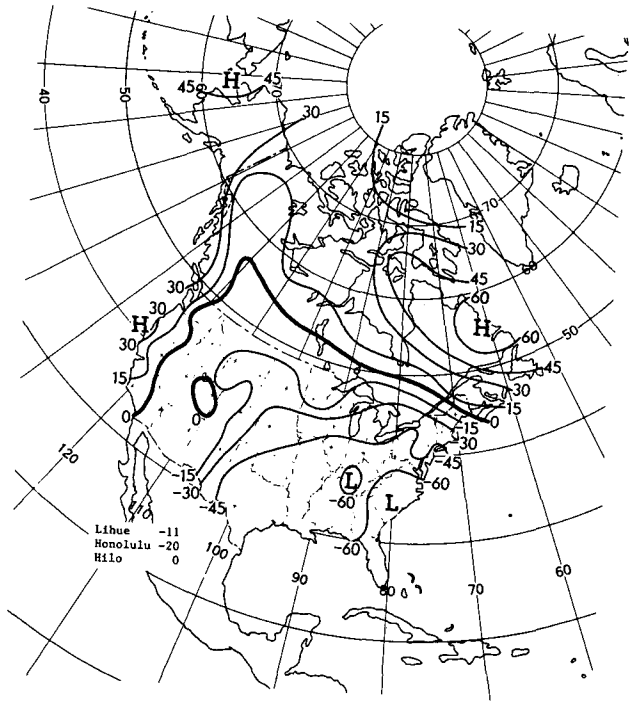

FIG. 4. Correlation (×100) between 10.7 cm solar flux and surface temperature for the west QBO phase for the January–February period (21 years). Contour interval 15.

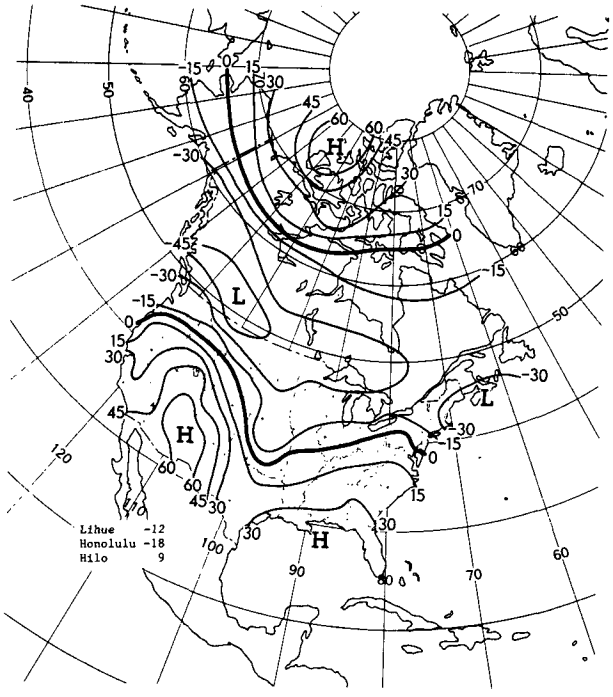

FIG. 5. As in Fig. 4 except for the east QBO phase (17 years).

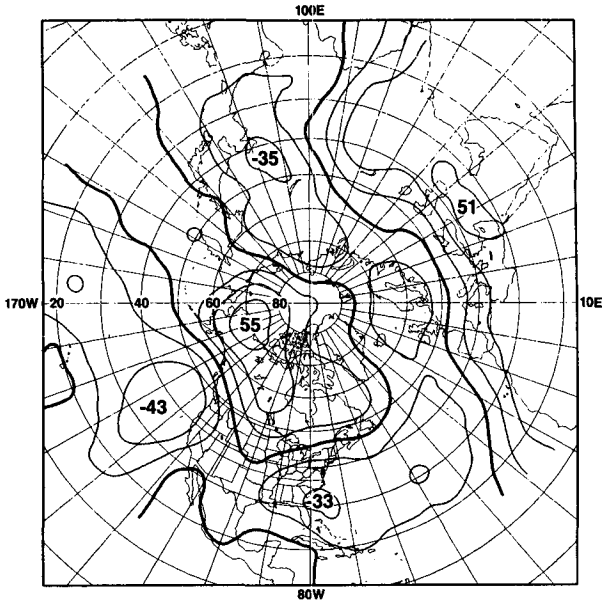

FIG. 7. As in Fig. 6 except for February.

The single-month United States–Canada west phase flux versus temperature correlation patterns for January and February (not shown) are generally similar to that of the January–February period except somewhat weaker (despite stronger positive correlations in eastern Canada in January), and March's pattern is weaker still. The January–February–March flux-temperature map (Fig. 10) has a slightly larger area of −0.60 and stronger correlations in the eastern United States, but is farther from attaining field significance (0.15 versus 0.07). However, the areas of strongest correlations may be considered genuine through association with major centers of the height correlation field (Fig. 9).

When the QBO is in its east phase the flux versus 700 mb height correlation fields are as shown in Figs. 11 and 12 for January and February, both of which

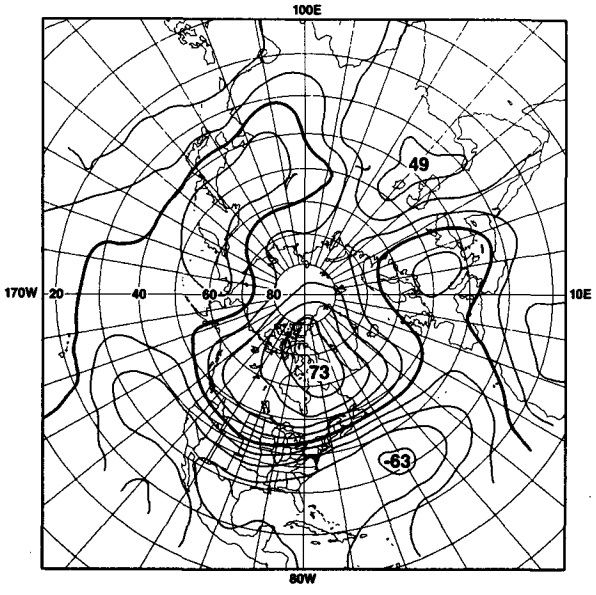

FIG. 6. Correlation (×100) between solar flux and 700 mb height for the west QBO phase for January.

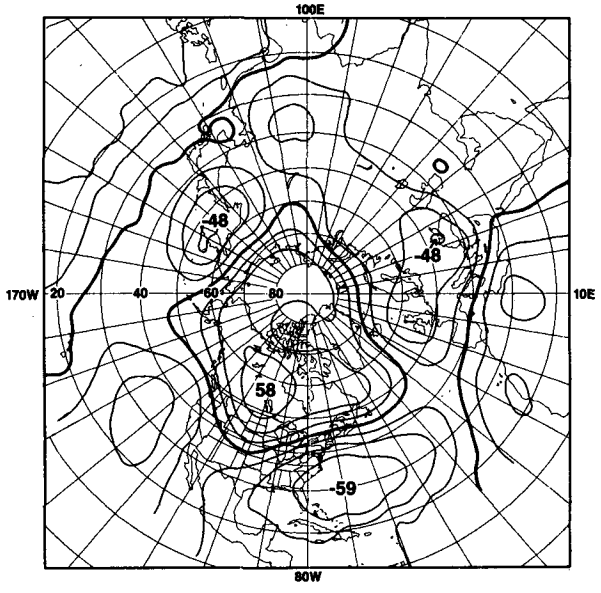

FIG. 8. As in Fig. 6 except for March.

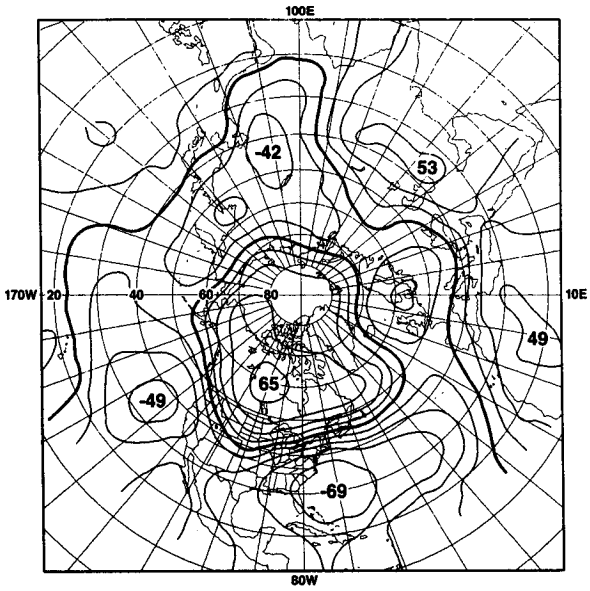

FIG. 9. As in Fig. 6 except for the January–February–March 3-month period.

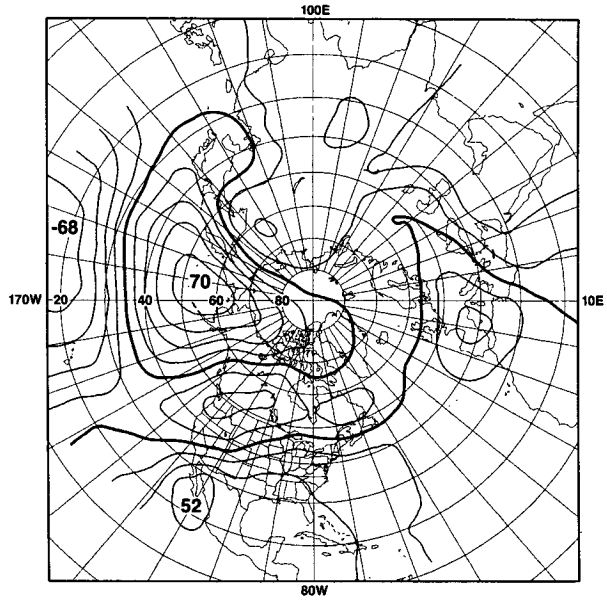

FIG. 11. Correlation (×100) between solar flux and 700 mb height for the east QBO phase for January.

resemble the field-significant 2-month January–February period field (Fig. 3) but fail to achieve significance because of the relative absence of filtering of the other sources of variability in the 1-month mean analysis. Although the flux–temperature correlations are not as impressively strong (or significant) for the east as for the west phase over the United States and Canada, Figs. 3, 11, and 12 indicate that the surface climate might be dramatically affected over northwestern Mexico, the eastern Soviet Union, western Europe and much of southern Asia; i.e., in regions of inferred mean anomalous warm or cold advection over meridionally extensive edges of correlation centers, as well as in regions directly under the centers.

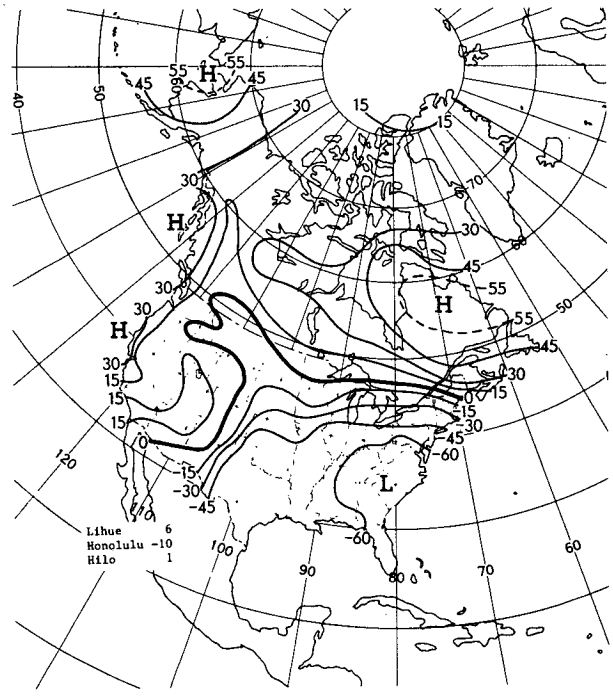

FIG. 10. Correlation (×100) between solar flux and surface temperature for the west QBO phase for the January–February–March 3-month period.

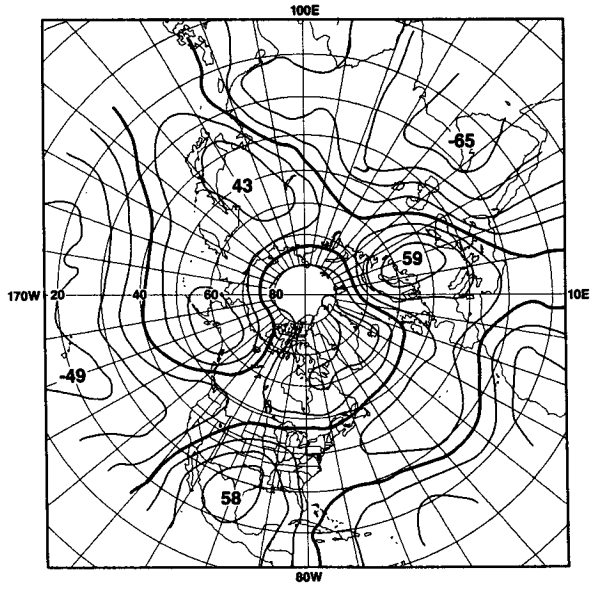

FIG. 12. As in Fig. 11 except for February.

3) ALTERNATE APPROACH TO MONTE CARLO FIELD SIGNIFICANCE TESTING

In a second set of Monte Carlo field significance tests designed to evaluate the significance from a different perspective, the phase of the solar cycle, rather than the QBO phase assignment, was shuffled 2000 times to form the random distribution of correlation fields and their integrated t-statistics, against which the t-statistic of the observed correlation field was ranked. Now, rather than evaluating the significance of the climate associated with the observed partitioning of east and west QBO phase years, we accept this partitioning as given and evaluate, within the set of years associated with one of the phases, the overall strength of the observed correlation field against those resulting from random choices of the phase and specific shape of the solar flux curve. Rather than randomly phasing the observed solar flux time series in this test, a 40 000-year solar flux series was modeled according to the observed characteristics (phase, amplitude, rise time, fall time, and year-to-year random variability) over the last few centuries. The observed autocorrelational properties of the flux were reproduced. The pooled, 38-year sample could now be tested also. Resulting p-values are shown in Table 2.

Interestingly, once the observed QBO phase partitioning is taken for granted, the west phase flux appears not to be optimally correlated with the 700 mb heights ($p = 0.12$). This does not invalidate the established field significance, however, because the flux phase shuffle test likely has less power than the QBO phase assignment shuffle test which has more numerous random permutations. What it does indicate is that although the west QBO phase flux-height correlation field can be exceeded by 12% of the randomly *modeled* flux cycles, less than 0.5% of other sets of 21 *observed* years from 1951 to 1988 randomly assigned as west phase years produce correlation fields stronger than that observed.

The remainder of the January–February phase-stratified flux shuffle results are significant except for the east phase temperature correlations over the contiguous United States, which come close (0.07) and clearly benefit when Canada, Alaska, and Hawaii are added to the domain. All joint (pairs of east–west results) p-values are significant.

The all-years (unstratified) condition unmistakably fails the significance test for both height and temperature, confirming the van Loon and Labitzke (1988) assertion that a relationship is only detectable for QBO phase-stratified data.

TABLE 2. Field significances for January–February correlation fields for solar flux versus 700 mb height or surface temperature, using a solar flux phase/shape shuffle Monte Carlo significance test.

QBO phase	Northern Hemisphere 700 mb height	Surface temperature: 92 Stations U.S. mainland	Surface temperature: 126 Stations all United States, Canada
West	.12	.018	.032
East	.019	.07	.026
Joint (E, W)	.017	.008	.002
All (no stratif)	.52	.26	.28

4) SUBMONTH PERIOD RELATIONSHIPS

In view of the west phase January 700 mb height–solar flux correlation map's field-significance without the benefit of the low-pass filtering of a longer averaging period, the possibility exists to define the time of the effect still further. To do this, a 31-day low-pass filter was applied to twice-daily 700 mb height observations with an amplitude response of 0.9 and 0.2 for signals with periods of 20 and 11.5 days, respectively (Blackmon 1976; O'Lenic and Livezey 1989). Although this filter removes most synoptic scale oscillations, it preserves considerably shorter fluctuations than does a 1-month mean filter. When QBO phase assignment shuffle Monte Carlo significance tests were applied to Northern Hemisphere height–flux correlation maps using the filtered daily height data centered on every fourth day from January through March, resulting p-values are as shown in Table 3. The west phase effect clearly belongs to the middle and latter portions of January, whose correlation fields (not shown) are highly similar to those of January (Fig. 6) and January–February (Fig. 2). This correlation pattern does not change until the beginning of February (when it also loses significance), and then is roughly restored (but not to field significant strength) in early to middle March. Although the differences in significance from period to period are subject to some uncertainty due to sampling considerations, the appearance of dramatically strong p-values in middle to late January provides the medium-range forecaster with a new predictive tool during that period if the QBO phase is westerly and the flux is far from its mean value.

The east phase effect is not significant during any single month nor in any filtered submonth period, but appears to be best defined in early January and mid-February.

5) LINEARITY

Although strong correlations require, by definition, a good linear fit between the variables in question, a closer look at the linearity of the height–flux relationships for the two QBO phases is in order. In units of standardized anomalies (times 100), a composite of the five highest flux years for the west QBO phase (1958, 1960, 1968, 1979, and 1981) is presented in Fig. 13a, while that for the five lowest years (1953, 1954, 1964, 1965, and 1976) is shown in Fig. 13b. Although notable exceptions are found in Europe,

TABLE 3. Field significances for submonth periods for solar flux versus 700 mb height correlation fields centered at given dates within January, February, and March.

	January								
	3	7	11	15	19	23	27	31	Jan as whole
West phase	.83	.83	.28	.000	.000	.002	.026	.035	.010
East phase	.16	.12	.50	.66	.52	.61	.92	.85	.26
Joint	.45	.34	.29	.013	.005	.014	.27	.19	.023
	February								
	4	8	12	16	20	24	28		Feb as whole
West phase	.10	.38	.28	.81	.67	.41	.46		.29
East phase	.54	.38	.29	.29	.52	.39	.34		.15
Joint	.18	.28	.18	.54	.63	.36	.35		.15
	March								
	4	8	12	16	20	24	28		Mar as whole
West phase	.23	.27	.23	.20	.16	.32	.66		.10
East phase	.76	.89	.90	.77	.64	.55	.21		.96
Joint	.50	.73	.69	.45	.28	.39	.34		.53

southeast Asia, and part of the subtropical Atlantic, the broader aspects of the patterns (e.g., the North American dipole) are roughly mirror images of one another. The low flux composite appears to emphasize low Alaskan–Canadian heights and low Asian heights, while the high flux composite is associated with high Canadian heights and low heights northeast of the Caribbean.

The composites of the four highest flux years for the east QBO phase (1957, 1959, 1980, and 1982) and the four lowest flux years (1963, 1975, 1985, and 1987) are given in Figs. 14a and 14b. In contrast to the west phase where a moderate degree of linearity is in evidence, the east phase flux extremes do not appear to induce opposite but structurally similar patterns other than in southern/southwestern Asia. The high flux composite has higher anomaly center values and much more closely resembles the east phase full sample correlation map (Fig. 3) than the low flux composite, suggesting that the low flux situation does not contribute to the relationship particularly well and thus may have little predictive value.

6) MORPHOLOGY

To help define the structure of the January–February flux-atmosphere correlation pattern for the two QBO phases, additional significance tests were carried out for the correlation between the solar flux and the amplitude of the ten leading January–February rotated principal component loading patterns derived from 1950–88 700 mb data. Table 4 lists these correlations and also shows the significant p-values for Monte Carlo significance tests where either the QBO phase assignment is shuffled to generate random flux-amplitude correlations (no asterisk), or the phase and shape of the solar flux is shuffled as described above (asterisk). Both types of Monte Carlo test were performed for each correlation coefficient.

Several noteworthy results are found. For the west QBO phase the Tropical/Northern Hemisphere (TNH) pattern principal component (Fig. 15) is correlated 0.47 with the flux (explaining 22% of the variance), significant at the 0.026 level; for the North Atlantic Oscillation (NAO; Fig. 16) the corresponding figures are 0.40 (16%) and 0.013. The Eurasian pattern No. 1 (EU1; Barnston and Livezey 1987) has a significant but low correlation. For the east QBO phase the principal component of an unclassified pattern involving the pole and parts of Eurasia correlates 0.56 with the flux (but falls short of significance), and the EU1 pattern shows a systematic relationship—this time in the opposite direction to that of the west QBO phase.

An interesting finding arises regarding the East Pacific (EP) pattern. Note that with all other patterns the correlation values are either of opposite sign for the west versus east QBO phase, or are of like sign with at least one of the coefficients close to zero. The East Pacific pattern, by contrast, has a moderately strong correlation of the same (negative) sign for both QBO phases. In this case the QBO phase assignment shuffle Monte Carlo test does not produce significant results because the east and west phases do not differ from one another sufficiently. When the flux phase (and shape) is shuffled, however, the observed case stands out significantly against the large set of random phase settings for both the east QBO phase, and, uniquely, for the no-stratification condition. This last finding suggests that the solar flux may impart a signal, as detected by the rotated principal component analysis fil-

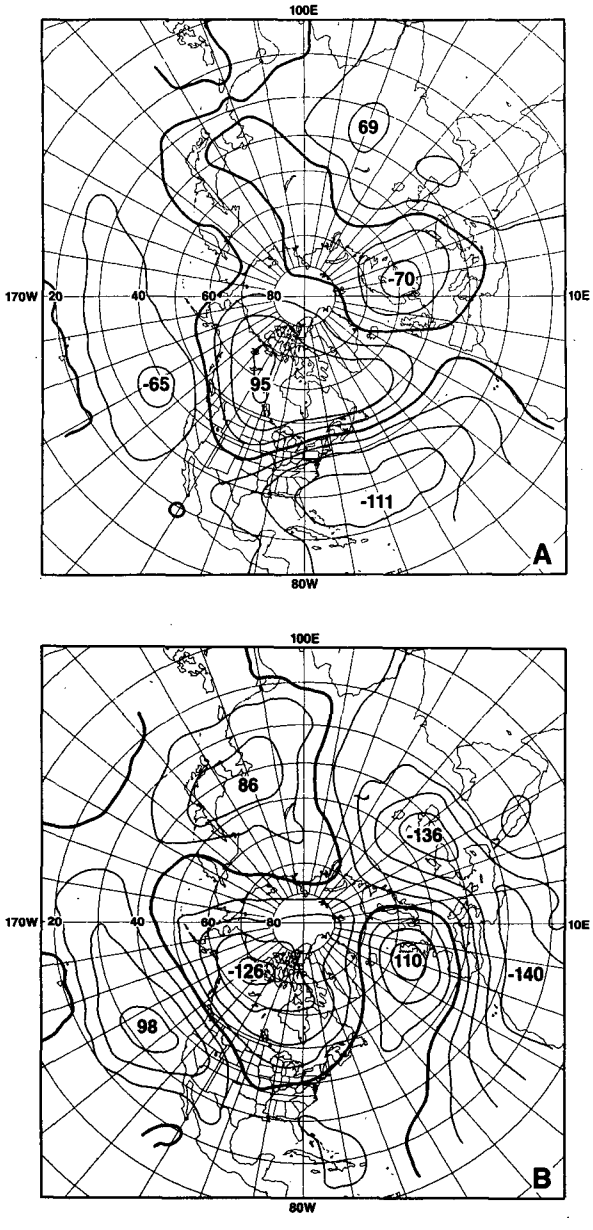

FIG. 13. Composite maps of 700 mb height anomaly (in standardized units times 100) for the 5 years having the (a) highest and (b) lowest solar flux values during west QBO phase years for the January–February period. Contour interval 30.

ter, to the Northern Hemisphere extratropical atmosphere that is not modulated by the QBO phase. The no-stratification flux–height correlation map is shown in Fig. 17, and the January–February East Pacific rotated principal component loading pattern in Fig. 18.

To supplement these structural findings, separate rotated principal component analyses were run for the 21 west QBO phase years and the 17 east phase years, both for the January–February period and for January alone. Eight modes were retained in the rotation, using the eigenvalue curves and the percentage of variance explained (80% to 86%) to make the truncation decision. Solutions were noisy and frequently mixed, emphasizing the need for adequate sample sizes in RPCA. Between the two sets of analyses, however, the TNH and EU1 patterns tended to appear as more leading modes in the west phase solutions, and the NAO and EP as more leading modes for the east phase. Although this does not necessarily coincide with expectations from Table 4, it suggests that the NAO pattern may be contained in the east phase height-flux correlation field in better form than in the west phase field, though

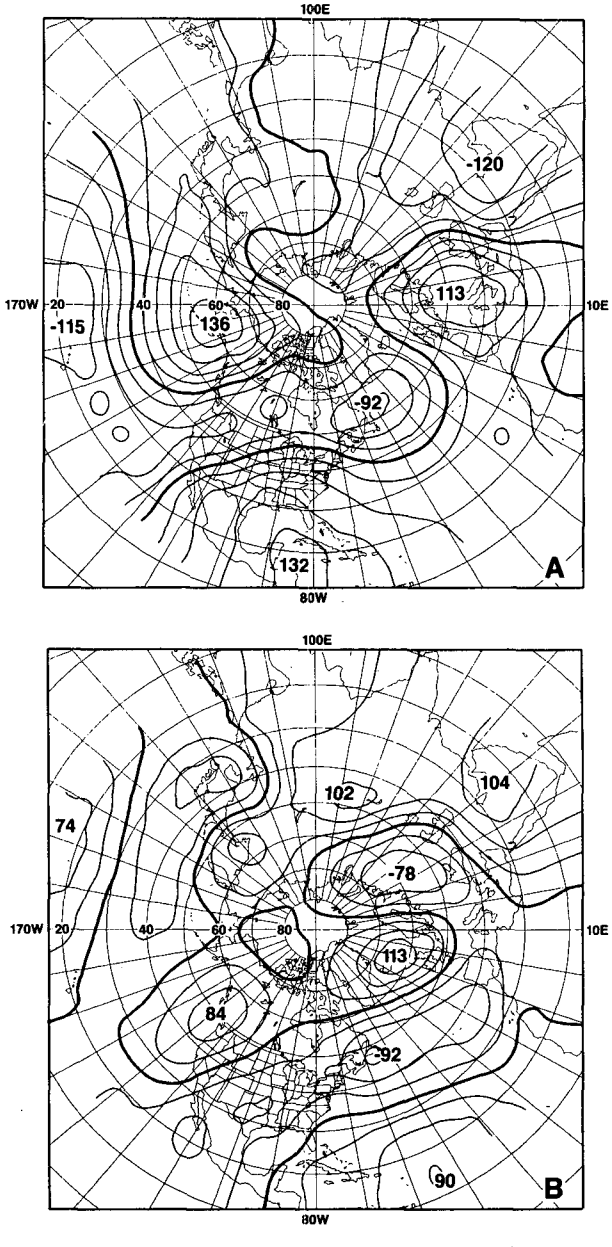

FIG. 14. As in Fig. 13 except for 4-year composites for the east QBO phase.

TABLE 4. Correlation between solar flux and the ten rotated principal component mode amplitude time series for January–February 700 mb height. Mode abbreviations as in Barnston and Livezey (1987). *P*-value follows correlation coefficient, in parentheses, if significant at 0.050 level or better. The QBO phase assignment is shuffled to generate random flux vs mode correlations (no asterisk), or the phase and the shape of the solar flux is shuffled (asterisk).

Mode	Percent variance	West QBO phase	East QBO phase	No stratification
1 PNA	11.8	−.11	.38	.13
2 NAO	10.3	.40 (.013)	−.28	.09
3 WPO	10.0	.02	−.00	.01
4 TNH	9.1	.47 (.026)	−.06	.23
5 —	7.7	.06	.56	.27
6 EA	7.5	.19	−.02	.08
7 EU1	7.0	.25 (.045)	−.33 (.027)	.01
8 NA	6.0	.04	.03	.03
9 EU2	6.0	.01	−.24	−.12
10 EP	5.9	−.48	−.68 (.014)*	−.58 (.035)*

it clearly comprises a lesser proportion of the total pattern in the former. The west phase correlation field may be somewhat better described as a TNH than an NAO pattern, considering the low latitude Atlantic center's location close to the Caribbean and the western center's location off the U.S. West Coast rather than inland.

The TNH versus NAO resemblance question is further illuminated when the leading unrotated principal component loading pattern, which combines the essential TNH and NAO characteristics (Fig. 19), is considered. The solar–atmospheric correlational statistics and attendant *p*-values for this hemispheric scale mode, shown in Table 5, indicate unreservedly that this is the favored mode to represent the January–February flux-height correlation pattern for the west QBO phase (Fig. 2), where a 0.65 flux-amplitude correlation is significant at less than the 0.001 level with a QBO phase assignment shuffle test and at the 0.032 level

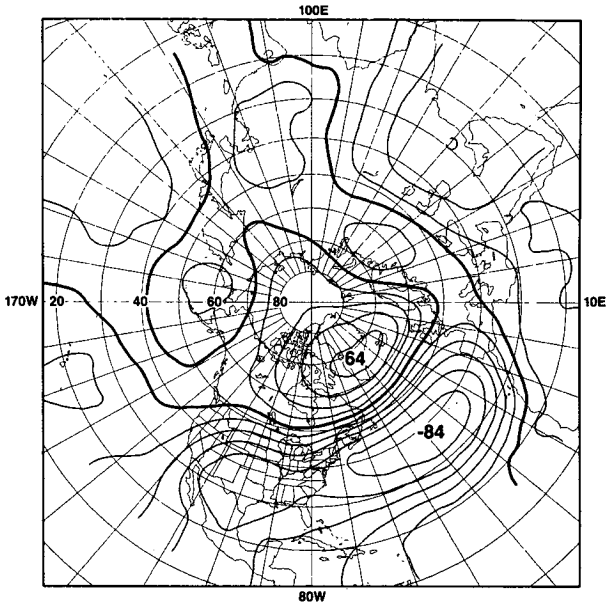

FIG. 16. As in Fig. 15 except for the North Atlantic Oscillation (NAO), mode number 2.

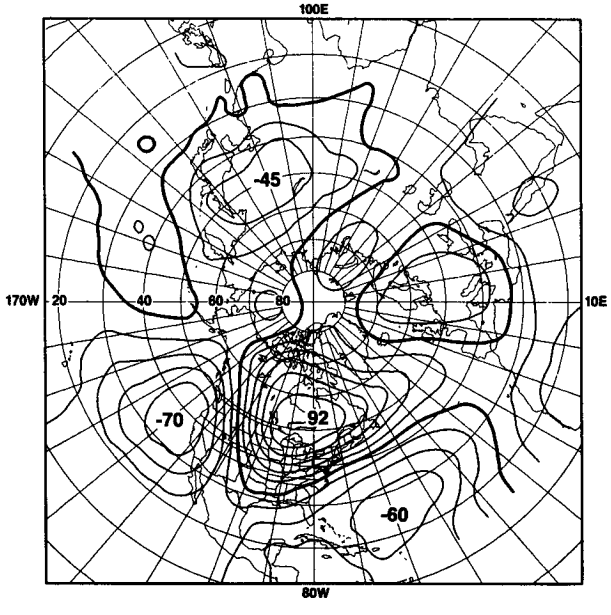

FIG. 15. The Tropical/Northern Hemisphere (TNH) low-frequency circulation pattern as depicted by mode number 4 of a rotated principal components analysis (RPCA) for all years of January–February mean 700 mb height for the 1950–88 period. Units are correlation coefficients (×100); contour interval 15.

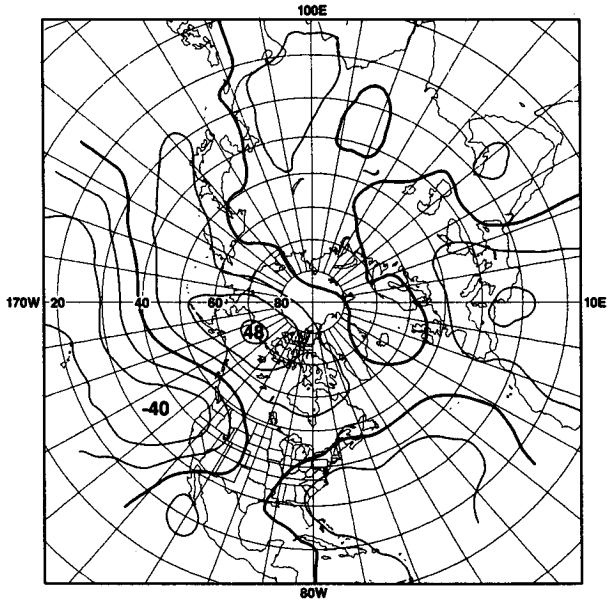

FIG. 17. Correlation (×100) between solar flux and 700 mb height for both west and east QBO phases pooled for the January–February period (38 years).

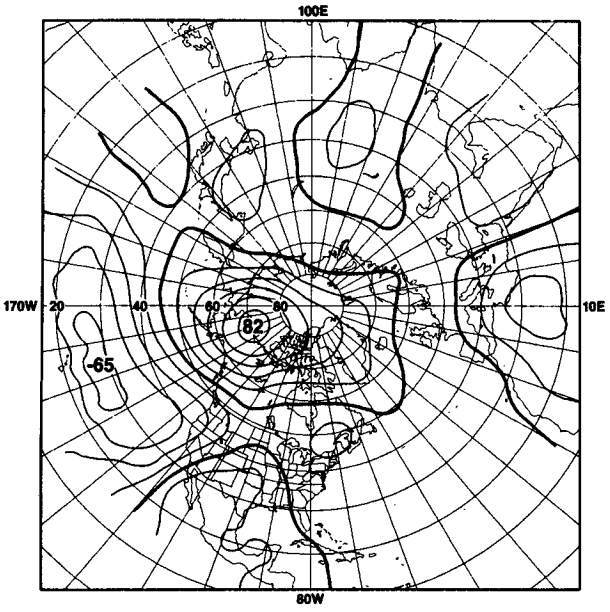

FIG. 18. As in Fig. 15 except for the East Pacific (EP) pattern, mode number 10.

with a flux phase/shape shuffle test. The mode explains 18.8 percent of the total 700 mb height variance, closely approximating the sum of the variances explained by the NAO and TNH rotated modes. The east phase flux–height correlation pattern (Fig. 3) is also moderately well (and statistically significantly) captured by the leading unrotated mode, especially in Eurasia.

None of the higher order unrotated components yield particularly revealing findings except for mode 7, which handles the unstratified flux–height correlation pattern somewhat similarly to the rotated mode 10 (i.e., the EP pattern).

The fact that an unrotated principal component may better delineate the solar–atmospheric phenomenon than the most representative rotated ones suggests that the phenomenon might be more of hemispheric than regional scale. While most of the low-frequency variations in atmospheric circulation are best portrayed and interpreted using the more regional rotated principal components (Horel 1981; Richman 1986; Barnston and Livezey 1987), perhaps certain conditionally extraterrestrially forced patterns are sufficiently global to be better depicted by an unrotated component.[2] The moderate resemblance to the more regional patterns such as the TNH and NAO raises the issue of possible interactions between QBO-conditional solar forcing and phenomena such as ENSO, which can affect the TNH pattern (Livezey and Mo 1987).

[2] However, O'Lenic and Livezey (1988) have shown that much of the over-regionalization of centers in RPCA results from inadequate prefiltering or rotation of too many modes, neither of which should be a problem here.

7) LAGGED RELATIONSHIPS

The winter period field significance tests for 700 mb height and surface temperature in the conterminous United States, using QBO phase assignment shuffling, were rerun for lagged relationships where the flux and QBO phase of a preceding period were used. The forecasting potential using different lead periods could then be evaluated. The outcome is depicted in Table 6, where the period of the climate variables (700 mb height, surface temperature) is indicated in the column on the left, and the four sets of columns to its right are for concurrent relationships (as in Table 1), periods of flux and QBO phase immediately preceding the target period, and periods ending 1 month and 2 months earlier than the beginning of the target period. The flux is always a 2-month mean and the QBO phase a 1-month mean for the second month of the flux period.

Results indicate some sensitivity to the lag length, but usually not enough to change the stability of the relationship substantially. Significant concurrent correlation fields generally remain significant, and exhibit nearly the same spatial pattern, with leading flux and QBO phase assignment. The periods of strongest concurrent relationships (January, January–February, and January–February–March) attain slightly stronger results for the "adjacent" lead time, still stronger ones for the 1-month lead, then slightly weaker ones for the 2-month lead. The February, February–March, and February–March–April relationships become noticeably stronger with the introduction of lags. On close examination, these changes can be attributed to changes in the QBO phase assignments of a small

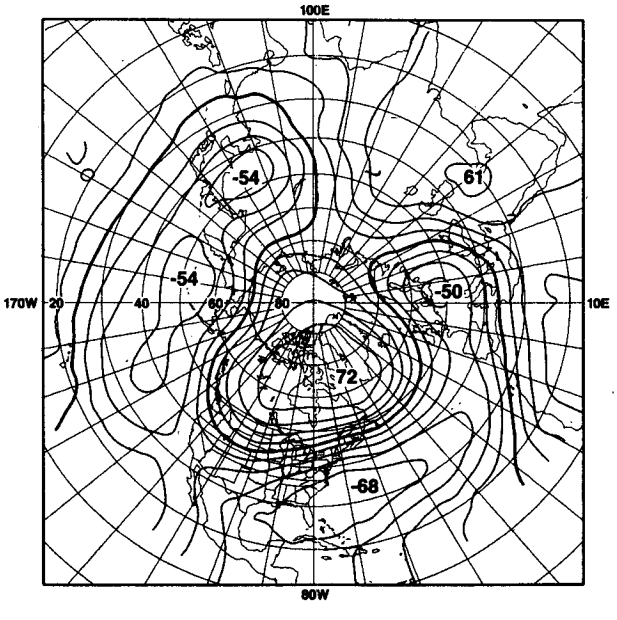

FIG. 19. The leading unrotated principal component for January–February mean 700 mb height for the 1950–88 period.

TABLE 5. As in Table 4 except for the leading unrotated principal component.

Mode	Percent variance	West QBO phase	East QBO phase	No stratification
1	18.8	.65 (.000), (.032)*	−.50 (.035)	.11

number of years, and not to flux differences that are relatively small. For example, when using December rather than January for QBO phase assignment, no changes in the membership of the west or east phase year sets occur (the strengthening in the significances for January, January–February, and January–February–March are thus due to different flux values). When November is used two years change phase membership, and when October is used two more years change. It is doubtful that meaningful conclusions can be reached on the basis of these small sample shifts using the dichotomous phase definition.

Because the flux has roughly five times as long a cycle as the QBO, additional tests were carried out for the January–February period in which only the flux led or lagged the other variables by one year. The result was a marked degradation of the strength and significance of the flux–height and flux–temperature correlation maps when the flux led by one year, and a very slight degradation when it followed by a year. Perhaps a source of imperfection in the concurrent flux–height correlations is not the overall phasing, but the month-

TABLE 6. *P*-values for January–February climate effects using the solar flux and QBO phase of three leading periods. First column contains concurrent relationships as in Table 1. Only conterminous United States surface temperature domain used.

				Lead time					
		Concurrent		Adjacent		1-Month		2-Month	
Period		NH 700 mb	US92 temp	NH 700 mb	US92 temp	NH 700 mb	US92 temp	NH 700 mb	US92 temp
	W	.53	.47	.69	.09	.71	.40	.98	.42
Dec	E	.67	.33	.75	.95	.27	.56	.60	.69
	J	.61	.39	.77	.42	.43	.42	.98	.59
	W	.010	.11	.003	.19	.000	.11	.006	.20
Jan	E	.26	.12	.09	.08	.036	.22	.13	.40
	J	.023	.06	.010	.09	.002	.10	.020	.25
	W	.29	.15	.015	.12	.016	.20	.007	.10
Feb	E	.15	.91	.07	.56	.06	.44	.007	.54
	J	.15	.58	.019	.13	.014	.20	.004	.12
	W	.10	.58	.10	.59	.05	.51	.030	.37
Mar	E	.96	.63	.99	.34	.98	.41	.99	.50
	J	.53	.71	.67	.46	.44	.41	.57	.37
	W	.36	.74	.19	.30	.32	.43	.59	.58
Dec–Jan	E	.39	.19	.15	.54	.12	.53	.15	.33
	J	.31	.37	.10	.32	.13	.44	.26	.40
	W	.003	.07	.001	.14	.000	.022	.002	.025
Jan–Feb	E	.025	.41	.003	.06	.000	.22	.003	.38
	J	.001	.034	.000	.027	.000	.014	.002	.026
	W	.07	.42	.003	.29	.000	.29	.001	.15
Feb–Mar	E	.59	.64	.73	.59	.64	.47	.54	.56
	J	.15	.56	.043	.34	.020	.26	.010	.14
	W	.050	.68	.035	.61	.030	.59	.017	.49
Mar–Apr	E	.98	.72	.95	.60	.96	.38	.99	.40
	J	.44	.91	.24	.78	.17	.48	.18	.39
	W	.045	.48	.005	.17	.017	.32	.12	.27
DJF	E	.15	.15	.005	.23	.020	.33	.018	.14
	J	.05	.19	.000	.13	.010	.27	.031	.13
	W	.006	.26	.000	.18	.000	.026	.001	.044
JFM	E	.22	.42	.09	.11	.08	.44	.15	.64
	J	.009	.19	.000	.031	.000	.018	.004	.12
	W	.032	.38	.001	.35	.001	.33	.000	.22
FMA	E	.93	.68	.74	.58	.69	.49	.66	.57
	J	.17	.53	.026	.38	.009	.33	.007	.25

to-month oscillations superimposed on the gradual cycling of the flux. When 5-month running mean fluxes were substituted for 1-month means, the January–February relationships remained essentially unchanged, suggesting at least that the shorter term variations (which can be nontrivial in some cases) do not play an important role in the January–February climate variability.

8) Individual west phase years

In an attempt to find relationships between the strength of the major north–south dipole in the west QBO phase 700 mb height versus solar flux correlation pattern and the phase and strength of the westerly QBO winds at 45 mb, the individual west phase years were examined more closely for the January–February period. In Fig. 20 the abscissa is the solar flux and the ordinate is the difference between the average 700 mb height at a cluster of grid points in the Hudson Bay–Hudson Strait region (in the center of high flux–height correlation; Fig. 2) and the average height at an elongated cluster of grid points near 30°N from 50° to 80°W (the center of low correlation). Within the figure each west phase year of January–February is plotted along with additional information about the January QBO. The negative correlation between the difference in heights and the flux is evident. The year is printed above the dot; below the dot are found first the zonal mean 45 mb equatorial wind (m s^{-1}), then the number of months the wind had been westerly, a slash, then the total number of months the wind would stay westerly in that particular west phase of the QBO cycle. Positive and negative departures from the regression line can be related to a west QBO phase of high or low intensity, one that had just begun, was nearing completion, or was to be short- or long-lived.

Inspection of the plot brings forth no clear relationships, leaving only a sense of an approximately concurrent relationship between the QBO and the flux–height correlation pattern. A dichotomous phase definition rather than a quantitative one appears to be appropriate, even for the phase and season that produce the strongest apparent relationships.

b. *Fall effect*

In Table 1 we note that a second period of the year appears to participate in the solar–atmosphere relationship when the QBO phase is westerly. While the

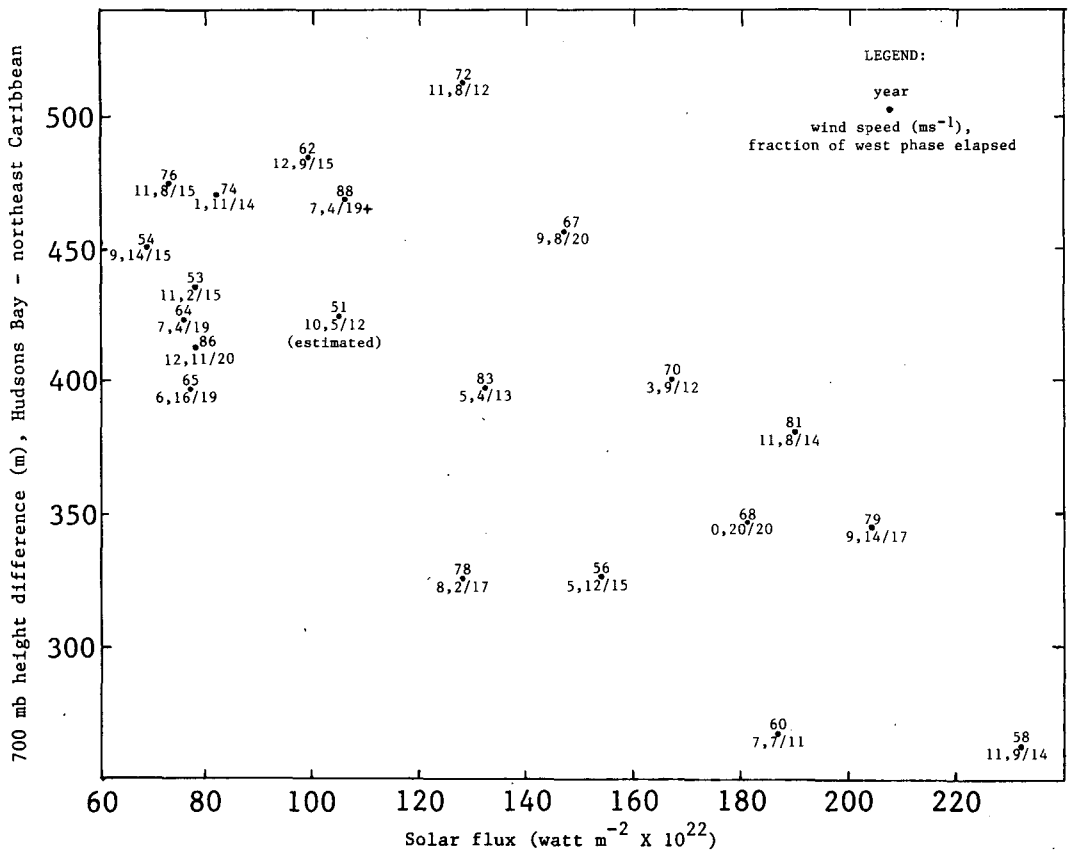

FIG. 20. Individual year plot for west QBO phase for the January–February period, depicting the effect of precise phase of QBO within the overall west phase on the relationship between solar flux and Hudson Bay–Caribbean 700 mb height difference. The correlation between flux and height difference is −0.71.

700 mb height versus solar flux correlation fields do not achieve significance (p = 0.24 in October, 0.15 in November, 0.11 in October–November, and 0.07 in September–October–November), the temperature-flux correlation fields for both the contiguous states alone and the expanded domain including Canada, Alaska, and Hawaii are quite highly significant for all four mean periods. The authenticity of the apparent effect may be estimated in this case by 1) evaluating the appearance of the height-flux correlation patterns for coherency, scale, and resemblance to previously recognized low-frequency atmospheric circulation patterns, and 2) comparing the October and November correlation patterns for similarity. The October and November west phase correlation patterns are presented in Figs. 21 and 22, respectively, the October–November correlation pattern is shown in Fig. 23, and the corresponding flux-temperature correlation pattern is given in Fig. 24.

The October and November height–flux correlation patterns are fairly coherent in the Pacific–North American (PNA) region and reminiscent of the small wavelength PNA pattern found at the beginning of the cold season (Barnston and Livezey 1987). The two patterns in this region are somewhat similar within sampling variability and yield an October–November pattern of comparable stature (limited still further to the PNA region) and an associated temperature-flux correlation pattern with a large area of −0.5 or stronger coefficients extending from west Texas to the Great Lakes–Middle Atlantic states, and equally strong positive coefficients in southeastern Alaska. While the fall west phase effect shows signs of being more than fortuitous sampling manifestations, its status is considerably less certain than that of the winter effect, requiring vigilance in the coming west phase years. The field-significant temperature–flux correlation patterns without corresponding 700 mb field significance may be accepted if the height pattern is regarded as sufficiently strong and coherent but allowably regional.

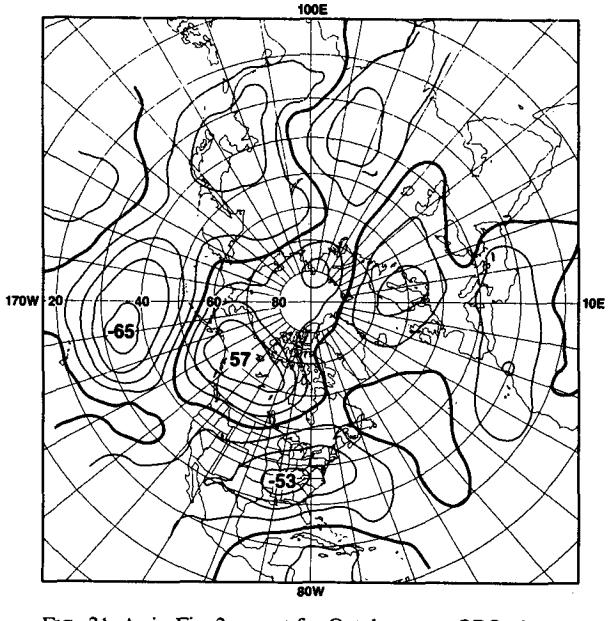

FIG. 21. As in Fig. 2 except for October, west QBO phase.

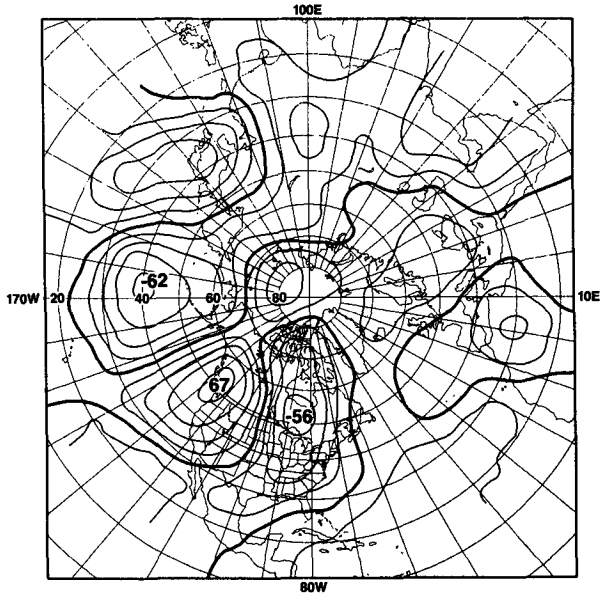

FIG. 22. As in Fig. 2 except for November, west QBO phase.

4. Discussion

Impressively strong field significances have been realized for the winter solar–atmosphere relationships for QBO phase-stratified samples, and passible significance levels have been found for fall relationships for the west QBO phase. The winter relationships are characterized by 1) p-values well beyond minimal expectations to be considered globally significant, and 2) replication of pattern among adjacent and embedded winter subperiods.

Despite these apparently compelling statistical results, however, some caution and reserve are in order in acceptance of the relationships. This is the case for two reasons:

1) The favorable results are contingent on the use of the 45 mb level for QBO phase-determining stratospheric winds. This was selected in an a posteriori manner, and Fig. 2 in van Loon and Labitzke (1988) indicates a marked sensitivity of the relationship to the level of the winds selected. Without a physical explanation for the favorability of the 45 mb level the question remains open as to whether chance could have played more than a minor role in the results.

2) There is no physical explanation for the overall relationship of solar flux, QBO phase, and the lower atmosphere. Tentative and partially applicable hy-

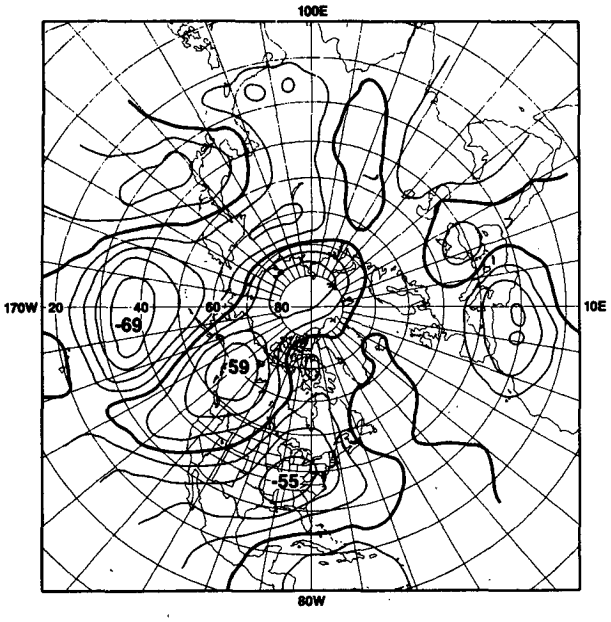

FIG. 23. As in Fig. 2 except for the October–November period, west QBO phase.

potheses have been offered (e.g., Barnett 1989) but independent confirmation of these has not been realized to date. The empirical status of the relationships and the absence of a credible physical argument, while not invalidating, warrant caution. Thus, the word "conclusions" does not appear in the name of this section.

Though caution is recommended in accepting the relationships described here, the statistical results are strong enough to justify their immediate use for operational forecasting purposes, subject to close surveillance of how well they continue to be obeyed over the coming years. At CAC the solar–QBO–atmosphere relationships will be used both in solo mode to make a United States temperature forecast, and also as part of a predictive analog forecast system that uses, additionally, numerous other climatic parameters to select similar or opposite past situations in the construction of the temperature forecast (Livezey and Barnston 1988; Barnston and Livezey 1989).

The solar–QBO–atmosphere relationships described here are one of at least two quasi-cyclical phenomena that affect United States temperature, the second being the El Niño–Southern Oscillation (ENSO). While ENSO effects on U.S. temperature have been shown to be relatively weak (Ropelewski and Halpert 1986), there are somewhat consistent indications (e.g., Chen 1981) in the 700 mb height as well as the attendant surface temperature anomaly structure. Specifically, a warm ENSO episode tends to produce negative temperature anomalies in the eastern states (especially the southeastern states, which receive the southerly displaced jet stream) and positive anomalies in the western states (especially the northern Rockies); a cold ENSO episode tends to produce the opposite pattern. The eastern United States, then, for example, is affected by the ENSO situation as well as the solar–QBO state. In January–February 1989, a cold ENSO episode took place, tending to force the southeastern states to be warm, while the solar–QBO state, with the flux above its mean and the QBO nearing the end of its west phase, inclined this same region toward cold temperature anomalies. The outcome was mostly in accordance with the ENSO forcing, which will tend to weaken the west phase solar–QBO relationships when 1989 is added to the analysis period. In January–February 1991 the QBO will very likely be in its west phase, the solar flux will still be well above its mean, and the ENSO will unlikely be in a cold phase and more likely in a neutral or warm phase. A long-lead forecast for the 2-month period in 1991, based on these features, would be for below normal temperatures in much of the eastern two-thirds of the United States, and normal to above normal temperatures in the western third as well as in much of Canada and Alaska. The authors are unofficially issuing this two-year lead climate forecast to underscore the advent of new possibilities in long-lead prediction as astronomical forcing factors begin to become part of our body of knowledge of short-term climate fluctuations.

Favorable verification of the above forecast will constitute another minor element of confirmation of the solar–QBO–atmosphere relationship put forth by van

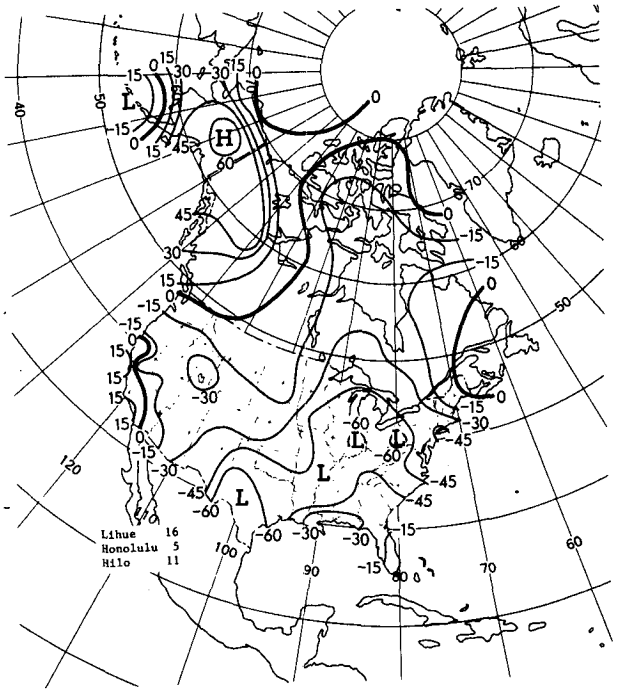

FIG. 24. As in Fig. 4 except for the October–November period, west QBO phase.

Loon and Labitzke (1988) and detailed further in this paper. One must wait longer than this, however, and progress toward discovery of the underlying physics, before unreservedly accepting the relationships so vividly demonstrated.

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