An Examination of El Niño–La Niña-Related Precipitation and Temperature Anomalies across the Northern Plains

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ABSTRACT

Monthly total precipitation and mean temperature data records extending from the late nineteenth century to 1990 were collected for 147 stations in South Dakota, North Dakota, and portions of adjacent states and provinces. This region, defined as the Northern Plains region (NPR), was examined for patterns associated with the warm phase (ENSO) and the cold phase (LNSO) of the Southern Oscillation to elucidate some of the debate concerning a signal in this area. Based on a correlation analysis, the NPR was treated as having one spatial degree of freedom.

Using Monte Carlo simulations of the Student's t-test statistic, four seasons with significant changes in mean precipitation or temperature during either ENSO or LNSO were identified. A highly significant signal was evident during the ENSO April to October season for precipitation, where the mean precipitation increased 7.21 cm for the 23 events studied. Here 20 of these 23 ENSO events exhibited precipitation above the median value, and 14 of the 23 events were in the upper quartile. In contrast, a strong signal for decreased LNSO precipitation was noted where May to August precipitation averaged 3.91 cm lower during the 17 events, with similar significance values. Complementing the enhanced ENSO warm season precipitation, the August to October temperature decreased by 2.17°C, with a significant number of events in both the lowest half and lowest quartile. Finally, temperature averaged 4.67°C cooler during LNSO winters. These results will be useful for limited-season prediction of precipitation and temperature tendencies across the NPR.

It is interesting to note that the initial ENSO years did not reveal a significant temperature increase during the NPR winter, which is in contrast to similar studies. However, by slightly modifying the years that were classified as ENSO years, a significant winter temperature response was indicated. This suggests that there is a tendency for warmer NPR winters during ENSO; however, this was not statistically significant.

1. Introduction

Drought, and more recently, persistent heavy rains, have been a major concern over the grain-producing areas of the Northern Plains, especially during the 1980s and 1990s. Many plausible explanations for these dynamic climate fluctuations exist. Among these are El Niño–Southern Oscillation (ENSO), La Niña–Southern Oscillation (LNSO),[1] variations in stratospheric volcanic debris and anthropogenic aerosols, and possibly solar and lunar cycles (e.g., Sellers 1965; Trenberth et al. 1988; Philander 1990; Peixoto and Oort 1992). The Southern Oscillation (SO) (pioneering work provided by Walker and Bliss 1932), and more specifically ENSO (which is a manifestation of the seesaw in sea surface temperatures (SSTs) and pressure patterns between the western and southeastern tropical Pacific Ocean), has been shown to account for a significant portion of the climatic variability across parts of the Northern and Southern Hemispheres (Chen 1981; Rasmusson and Carpenter 1982, 1983; Ropelewski and Halpert 1986, hereafter referred to as RH86, 1987; Kiladis and Diaz 1989; Halpert and Ropelewski 1992). The Climate Prediction Center (CPC) has recently made tangible some of these results (as well as

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[1] The terms El Niño, El Niño–Southern Oscillation (ENSO), warm event, cold event, and La Niña have caused much confusion and ambiguity in the literature during the 1980s as the study of these phenomena intensified (Aceituno 1992). In this study we use the nomenclature suggested by Aceituno (1992), and in addition, LNSO (La Niña–Southern Oscillation) is used to refer to unusually cold waters appearing in the eastern Pacific with the associated weather patterns over the Pacific Ocean opposite those of the ENSO.

modeling results) by improving the long-lead forecasting process (Barnston et al. 1994).

During the mature phase of an ENSO event (typically in winter), the midlevel circulation patterns across the Northern Hemisphere are generally dominated by the Pacific–North American (PNA), Tropical Northern Hemisphere (TNH), and West Pacific Oscillation (WPO) patterns (Horel and Wallace 1981; Wallace and Gutzler 1981; Barnston and Livezey 1987; Livezey and Mo 1987; Barnston et al. 1991). These patterns are often realized by strong troughing in the Gulf of Alaska, anomalously high heights across western North America, and below-average heights with an enhanced subtropical jet stream across the southeastern United States (Rasmusson and Wallace 1983). RH86 have performed analyses using North American monthly mean temperature and total precipitation records, and their results concur with the above circulation patterns. More specifically, part of the Northern Plains region (NPR), defined here as the area generally bounded by 1° in both latitude and longitude surrounding the Dakotas, was discovered to have a weak to moderate ENSO-related precipitation signal (essentially South Dakota south through the Texas panhandle). A more significant ENSO-related temperature signal was found along the northern periphery of the NPR, covering much of northwestern North America.

Barnston et al. (1991) have shown that winter surface temperature patterns in the United States are substantially affected by the TNH (Fig. 1a) and PNA (Fig. 1b) patterns, and furthermore that these patterns are favored by the east and west phases of the quasi-biennial oscillation (QBO) respectively (Barnston and Livezey 1991). A positive (negative) projection of TNH pattern facilitates above- (below-) average January–February temperatures in the Great Lakes and western Midwest, whereas a positive (negative) PNA projection emphasizes warmth (cold) in the western third of the country and cold (warmth) in the southeast (Barnston et al. 1991). A given positive projection of either pattern is generally favored during ENSO years, whereas a given negative projection is favored during LNSO years, depending on the QBO phase. Considering this and Fig. 1, the NPR may be located favorably for above-average temperatures during an ENSO winter and below-average temperatures for an LNSO winter.

The objective of this study is to further examine the NPR for climatic responses associated with the SO extremes using various statistical testing techniques—along the lines of the work presented by RH86. This work was performed especially because there still is some debate about the SO forcing on climate in this region and also because of the availability of data from a companion study (Bunkers et al. 1995). This study differs from similar studies in that 1) several statistical tests are utilized to determine the significance of the results, and 2) the study is regional in scope (i.e., just the NPR). The data and methods are discussed in section 2, the results are presented in section 3, and the summary and conclusions are given in section 4.

2. Data and methods

a. Data

Monthly climatic data consisting of total precipitation and average temperature were collected for 174 stations in South Dakota, North Dakota, and the area bounded by 1° in both latitude and longitude surrounding the Dakotas (defined as the NPR). The data were obtained in digitized format from the respective state climatologists and the Canadian Atmospheric Environment Service. After screening for missing data, 147 stations were retained. It was required that stations have less than five years of missing data for 1931–1990. Prior to 1931, station density decreased but remained adequate to spatially represent the NPR beginning at 1880. Additionally, little data were missing during the pre-1931 period for those stations that were retained. Further discussion of the dataset is provided by Bunkers et al. (1995). These 147 stations were then composited into one time series representing the NPR for 1880–1990, spanning 23 ENSO events and 17 LNSO events.

Using the data subset for 1931–1990, separate spatial correlation analyses were performed for both average annual temperature and total precipitation across the NPR (Figs. 2a,b). This was achieved by selecting the first-order weather station closest to the center of the domain (Bismarck, North Dakota) and correlating it with the other 146 stations. Most of the correlation values for temperature are >0.8, with the smallest values (still >0.50) near the periphery (Fig. 2a). All but one value in the southwestern part of the NPR were >0.65. Additionally, a correlation analysis was performed using January–February temperature (not shown), with much the same results. A weaker spatial correlation is apparent for precipitation (Fig. 2b); however, a large area of >0.50 covers most of the Dakotas. All but two values were greater than 0.20, and all but ten values were greater than 0.30. Figure 2 suggests that the NPR has one degree of spatial freedom (at the most two) and therefore will be treated as such. This is consistent with the spatial scale of ENSO (~1000 km), as well as other studies of the United States climatological variability (Karl and Koscielny 1982; Karl and Riebsame 1984).

b. Methods

Initially, ENSO (LNSO) years were defined with the intention that only moderate to strong events would be identified (Tables 1a,b), mainly because results suggest that routine prediction of these events is feasible (e.g., Barnett et al. 1988). Although the determination of the ENSO (LNSO) years required some subjectivity,

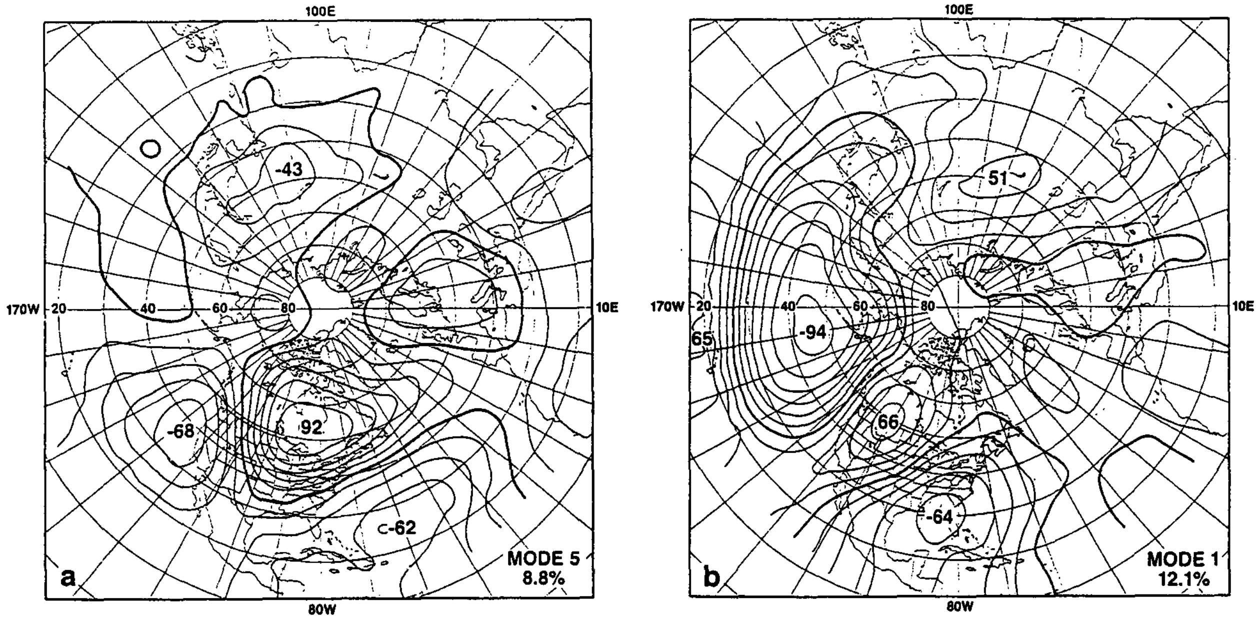

FIG. 1. Phases of January–February 700-mb circulation using varimax-rotated principal component loading patterns of 1950–1989 geopotential height data, scaled as correlation coefficients. The mode number and percent variance explained are given in the lower right corner. The given correlations correspond to negative Southern Oscillation Index (SOI) values (described further by Barnston and Livezey 1987). (a) Tropical–Northern Hemisphere (TNH) pattern, and (b) Pacific–North American (PNA) pattern. Figures reproduced from Barnston et al. (1991).

two criteria were used to eliminate weak events. All ENSO (LNSO) events were required to exhibit values of the Southern Oscillation Index (SOI), as calculated by the Climate Prediction Center, below (above) one standard deviation for a period of at least five months during a calendar year [the five-month criterion is analogous to Ropelewski and Halpert (1989)]. This procedure was generally applied to the post-1935 data because the pre-1935 SOI data are slightly less reliable (Ropelewski and Jones 1987). For the pre-1935 data, a more subjective approach using various sources was taken. For example, the year 1887 was included as an ENSO year rather than 1888, based on Rasmusson and Carpenter's (1983) identification of 1887 as a warm episode. Also, 1885 was identified as an ENSO year because there were five values of the SOI below one standard deviation. The 1939–1941 low SOI period has been identified as two events; one at the onset (1939) and one at the end (1941). This was based primarily on previous studies (Rasmusson and Carpenter 1983).

The LNSO years used in this study are the same as those identified by Ropelewski and Jones (1987), with the exception of 1892 and 1909. The year 1909 was excluded because SOI data indicate that values were less than 0.8 for the last five months of the year. Additionally, van Loon and Madden (1981) did not list this year as an LNSO episode. Here 1893 was chosen instead of 1892 because the sea level pressure (SLP) anomaly at Darwin, Australia, was predominantly negative for 1892.

An ENSO (LNSO) year was defined as the year leading into the winter in which the mature event took place. For example, the year 1968 was included in Table 1a as an ENSO year rather than 1969, which was listed by other authors. Rasmusson and Carpenter (1982) indicated that this warm episode was underway by the July–September period of 1968, as shown by the westerly wind anomalies. Thus, 1968 was chosen, instead of 1969, as the onset of the ENSO event. One will find minor discrepancies between the years used herein with those of other studies (van Loon and Madden 1981; Rasmusson and Carpenter 1982, 1983; Rasmusson and Wallace 1983; Ropelewski and Jones 1987). To address this issue further, a series of sensitivity tests in which years were slightly altered was conducted (section 3c).

After the SO-extreme years were established, time periods (or "seasons") that contained potential climate signals were identified by developing four (2 year long) composites. The 2-yr period started with January of the ENSO (LNSO) year, designated as January(0). Using monthly precipitation and temperature, respectively, averages were developed for the non-ENSO (non-LNSO) years and then subtracted from the average values for ENSO (LNSO) years. This same procedure was repeated for the non-ENSO(+) and non-LNSO(+) years, where the plus sign denotes the

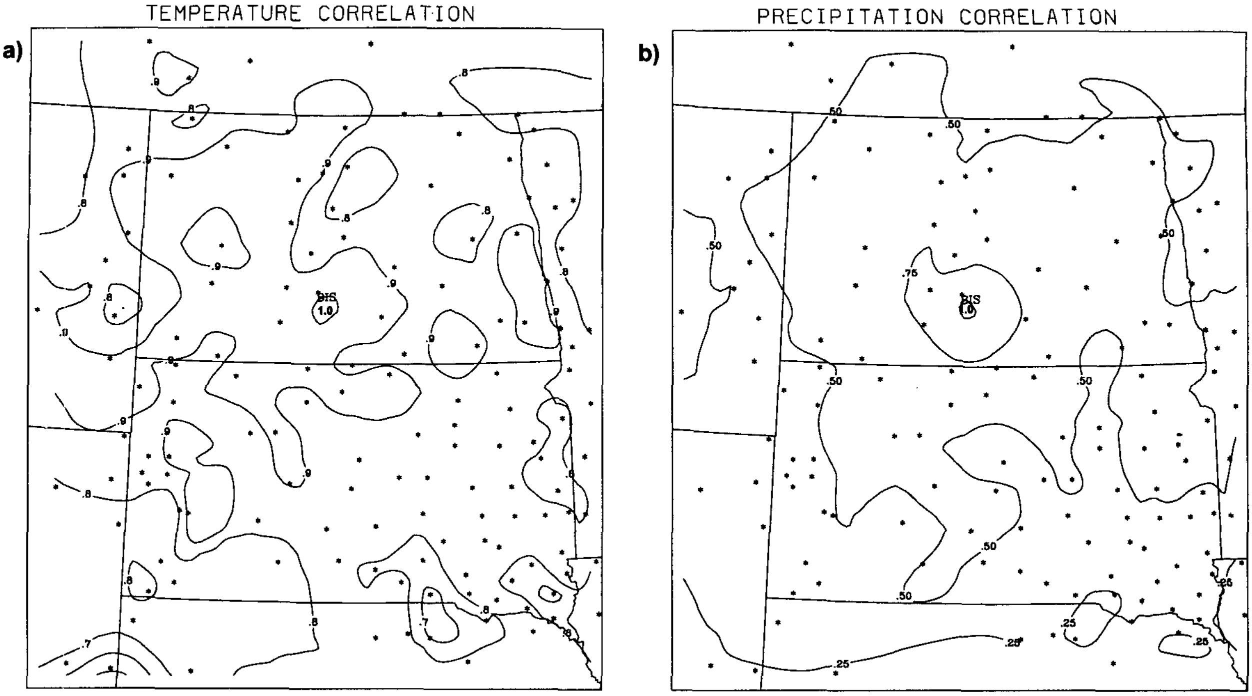

FIG. 2. Northern Plains spatial correlation analyses using Bismarck, North Dakota, as a base point for annual: (a) average temperature and (b) total precipitation. Bismarck is denoted as "BIS." The other 146 stations are denoted with an asterisk (*).

year following the SO extreme. Non-ENSO years included LNSO years for the compositing procedure, and vice versa.

After the calculations were performed, the mean monthly temperature and precipitation differences throughout the 2-yr SO-extreme composite could be assessed for each of the four responses. Similar to RH86, the 24 consecutive monthly departures were then examined for "seasons" where significant departures from the mean non-SO-extreme temperature or precipitation occurred for a period of three to several months. For example, an April(0) to October(0) ENSO season was defined if the NPR exhibited significant temperature or precipitation departures during the months extending from April to October during the ENSO year. The lower criterion of three months was selected because 1) ENSO and LNSO act on a relatively long timescale, and unrelated variability (such as that which comes with individual weather events) can mask their signal on timescales of shorter than three months; 2) significant results for individual months may occur by chance (in fact 5% of them should be); and 3) this lower limit corresponds to that used by RH86. It should be noted that other authors have correlated the SOI with U.S. temperature for only a 2-month period (e.g., Barnston et al. 1991).

The seasons that contained potential climate signals were tested for significance using three methods: 1) a second Student's t-test, 2) the Wilcoxon rank-sum test, and 3) the Kruskal–Wallis test. These three tests were employed to determine if there was a statistically significant difference in the mean (or median) temperature or precipitation between the defined seasons and the long-term (non-SO-extreme) average. The test statistic for comparing the means between two independent samples drawn from a normal distribution given by Milton and Arnold (1990),

$$T = \frac{\bar{X}_1 - \bar{X}_2}{\left(\dfrac{S_1^2}{n_1} + \dfrac{S_2^2}{n_2}\right)^{1/2}}, \qquad (1)$$

was used to test the null hypothesis H_0: $\mu_1 = \mu_2$. Subscript one corresponds to SO-extreme years and subscript two corresponds to non-SO-extreme years. The alternative hypothesis, H_1, is either right-tailed ($\mu_1 > \mu_2$) or left-tailed ($\mu_1 < \mu_2$), depending on what is being tested. These tests were determined based on a priori knowledge from Ropelewski and Halpert (1987) and Halpert and Ropelewski (1992). A critical value of $\alpha = 0.05$ was set as the criterion for committing a Type I error.

Since temperature and especially precipitation data usually do not satisfy the assumptions of independence and normality, the significance of T could not be determined by using a standard T-distribution table. (It should be noted that the central limit theorem often allows monthly means to be treated as Gaussian, de-

TABLE 1. (a) List of the 23 moderate to strong ENSO years used in this study. Years were determined using data from van Loon and Madden (1981), Rasmusson and Carpenter (1982, 1983), Ropelewski and Jones (1987), and data from the Climate Prediction Center. (b) List of the 17 moderate to strong LNSO years used in this study. Years were determined using data from van Loon and Madden (1981), Ropelewski and Jones (1987), and data from the Climate Prediction Center.

a) ENSO

Years	1880	1885	1887	1896	1900	1905	1911	1914	1918	1923	1926
1939	1941	1946	1951	1953	1957	1965	1968	1972	1977	1982	1986

b) LNSO

Years	1886	1889	1893	1904	1910	1916	1917	1924	1928	1938	1950
	1955	1956	1971	1973	1975	1988					

spite a clear deviation from normality on the part of the constituent daily data. For precipitation, the chances for satisfaction are less than for temperature.) More rigorous Monte Carlo simulations were used to randomize each temperature or precipitation time series 10 000 times, allowing an empirically derived random distribution of t statistics to be formed (i.e., an empirical counterpart to a theoretical distribution). The original t statistic was compared to the empirically derived random distribution to assess its statistical significance. This test was performed both with and without replacement.

Because of potential shortcomings of the Monte Carlo procedure noted by Zwiers (1987), Wilcoxon rank-sum and Kruskal–Wallis tests were performed to determine if the median values were significantly different. Although these two nonparametric test statistics have the advantage of being applied to any distribution, parametric testing methods are more rigorous than nonparametric methods (Panofsky and Brier 1968). Since Monte Carlo simulation of the t statistic has been used to evaluate its statistical significance with acceptable results (e.g., Karl et al. 1987), the Wilcoxon rank-sum and Kruskal–Wallis tests were used only to reinforce the results. Furthermore, the values for all autocorrelation coefficients at lag $t + 1$ were between 0.15 and 0.18. Since little autocorrelation was present, the Monte Carlo simulation was robust (Zwiers 1987). The net effect of using three different statistical tests is to "lower" the alpha value, making the results more credible.

If the three statistical tests indicated that the temperature or precipitation departures from the non-ENSO (non-LNSO) mean were significant ($\alpha = 0.05$), the standardized time series were evaluated to determine if there were a disproportionately large number of values: 1) above the median and above the 75th percentile, *or* 2) below the median and below the 25th percentile. The binomial probability function (BPF) (Milton and Arnold 1990) was used to ascertain this significance based on an a priori critical level of $\alpha = 0.05$. This test assumes that data are independent. The BPF was also used by Karl et al. (1987) to test for analogous disproportionalities. A *strong signal* was defined when both of the median and quartile tests were significant. A *weak signal* was defined when only one of these two tests was significant.

3. Results

a. El Niño–Southern Oscillation (ENSO) patterns

An increase in the spring through early autumn precipitation was generally noted during ENSO years across the NPR (Fig. 3). Most monthly departures averaged from around 1 cm or higher for April(0) through October(0) when the ENSO years were compared to the non-ENSO years. An exception was the increase of approximately 0.5 cm during July, which is still significant. This season corresponds to that defined by RH86 for the High Plains (HP), which again is the area roughly from north Texas to South Dakota. Precipitation tended to be deficient during April(+) and May(+), although this period is not considered to be significant since it fails to meet the three consecutive month criterion.

Based on the t test, precipitation was significantly greater during the April(0) through October(0) ENSO period, with an average increase of 7.21 cm (Fig. 4). The change in mean precipitation was highly significant based both on a Monte Carlo resampling of the t statistic without replacement ($p < 0.0001$) and 100 000 simulations with replacement ($p = 0.0005$). Similar highly significant levels were obtained from the Wilcoxon rank-sum and Kruskal–Wallis tests ($p = 0.0001$). Figure 4 indicates that 20 of the 23 years (87%) were associated with above median precipitation, with $p = 0.0002$ based on the BPF. Not only were most of the years above median, but a disproportionately large number of ENSO years were also in the upper quartile of the distribution (61%). Therefore, a strong signal is apparent, indicating the propensity for precipitation to be anomalously high during the April(0) through October(0) ENSO season in the NPR. Another noteworthy feature is that precipitation has been above median during each ENSO season since 1941.

A comparison of Fig. 4 with RH86's Fig. 7 indicates that the three negative departures during ENSO years (1918, 1925, 1939) were also negative in the HP. In five other instances, negative values are found for the HP that correspond to positive values in the NPR. However, one of these values would not be positive when using the ENSO year (1976 in lieu of 1977) given by RH86. Using the same ENSO years as RH86, the results are still highly significant. Clearly the ENSO-related precipitation signal that RH86 identified in the HP extends farther north into the NPR as well. Isolation of the geographic region in which such a signal is the

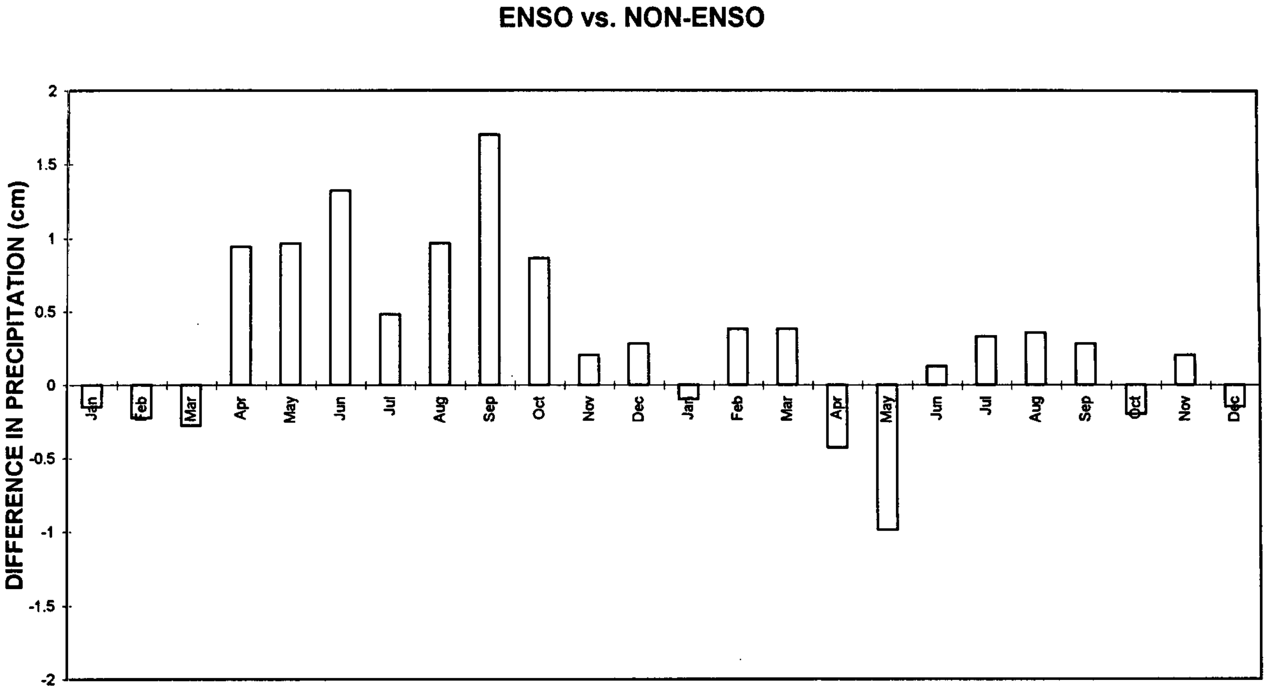

FIG. 3. Monthly average difference in precipitation (cm) between ENSO (23) and non-ENSO (88) years for the 2-yr period beginning January(0) of the ENSO year. Positive (negative) values denote an increase (a decrease) in the mean monthly precipitation for ENSO.

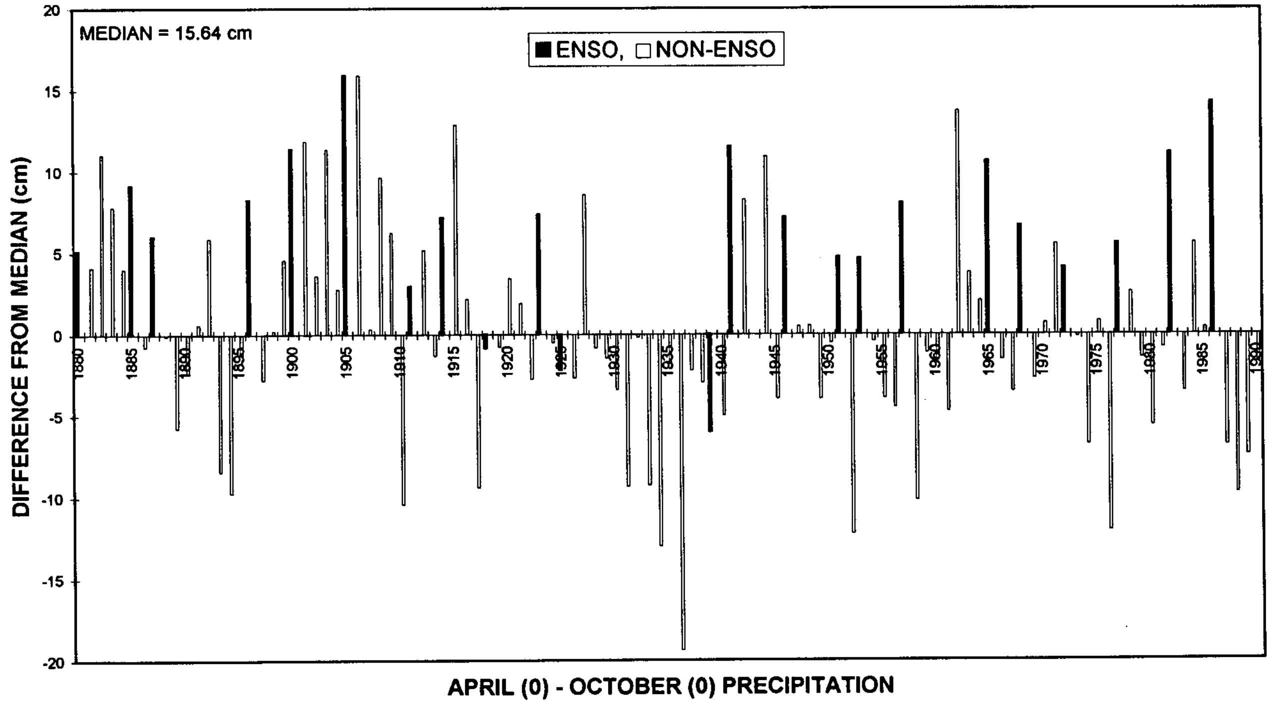

FIG. 4. ENSO April(0) to October(0) precipitation composite for the NPR. Solid bars represent ENSO years (Δmean = 7.21 cm, $T = 5.70$, $p < 0.0001$; 87% > median, $p = 0.0002$; 61% in upper quartile, $p = 0.0003$).

strongest (statistically) is not possible based on this or RH86's study and is not warranted since climatic responses to phenomena such as ENSO tend to manifest themselves over broad rather than isolated regions. The NPR was most likely omitted from RH86's study due to the strong temporal smoothing effect of their harmonic number one fit.

There is no support for a statistically significant ENSO-related winter (December–February) temperature response in the NPR (Figs. 5, 7). Although temperature averaged between 1° and 2°C warmer for December(0) and February(+) of a mature ENSO, the mean temperature difference was below the median for January(+) when compared to non-ENSO years (Fig. 5). However, a significant decrease in August(0) to October(0) temperature is noted with values around 0.75°C cooler (Fig. 5), complementing the increase in ENSO precipitation (Fig. 3). Other months were locally significant [i.e. March(0), May(0), and March(+)] but not representative of large-scale ENSO-related temperature forcings.

The fact that the NPR lacks a significant ENSO-related winter temperature response is not surprising. RH86 identified northwestern North America as having above-average ENSO-related winter temperature, but this included only the northern periphery of the NPR (generally central North Dakota northward). Additionally, Winston (1983) found difficulty in specifying a relationship between U.S. mean surface temperature and ENSO. The fact that positive projections on the PNA, TNH, and WPO patterns are all highly probable during certain strong ENSO winters, with the tendency for negative TNH and positive PNA and WPO projections during other ENSO winters (Livezey and Mo 1987), also supports this inconsistency.

During the ENSO August(0) to October(0) period, temperature averaged 2.93°C cooler when contrasted with non-ENSO years. This was significant with $p = 0.002$ based on 10 000 resamplings of the t statistic without replacement and significant with $p = 0.006$ based on 100 000 resamplings with replacement. Again, favorable results were obtained from the Wilcoxon rank-sum and Kruskal–Wallis tests ($p = 0.0001$). Based on Fig. 6, a strong signal was noted since 17 of the 23 ENSO years (74%) were associated with below median temperature ($p = 0.02$), while 13 of the 23 years (56%) portray values in the lowest quartile ($p = 0.001$). This signal is physically consistent with the enhanced ENSO precipitation, since summer temperature and precipitation tend to be negatively correlated (Chang and Wallace 1987).

Although not significant, a composite was developed for the December(0) through February(+) temperature for illustrative purposes (Fig. 7). Only 56% of the ENSO winters were associated with above median temperature, with an average increase of 2.92°C ($p = 0.08$). Upon comparison of PNA and TNH time series (1950–1984) in appendix F of Barnston and Livezey (1987) with Fig. 7, two patterns may be inferred (albeit further study is necessary to make any generalizations). For example, three ENSO winter seasons associated with above median temperature (1957–

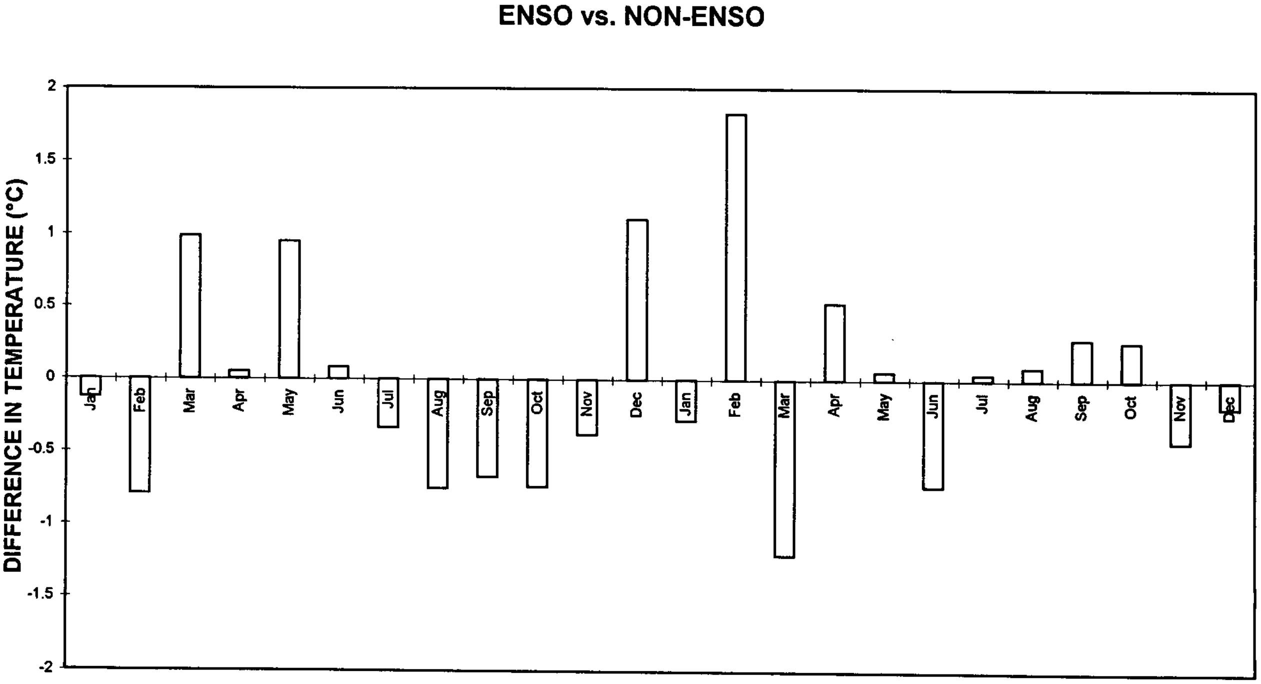

FIG. 5. Same as Fig. 3 except for temperature (°C).

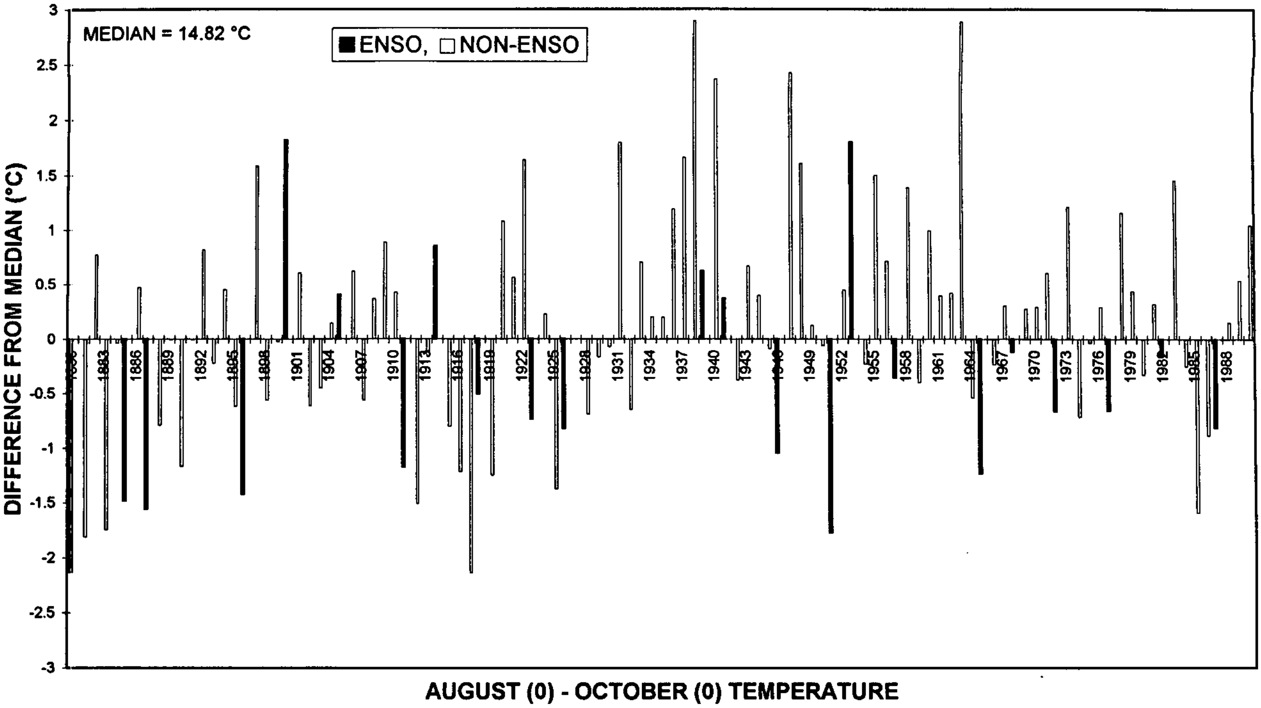

FIG. 6. Same as Fig. 4 except for August(0) to October(0) temperature (Δmean = −2.17°C, $T = -2.93$, $p = 0.002$; 74% < median, $p = 0.02$; 56% in lower quartile, $p = 0.001$).

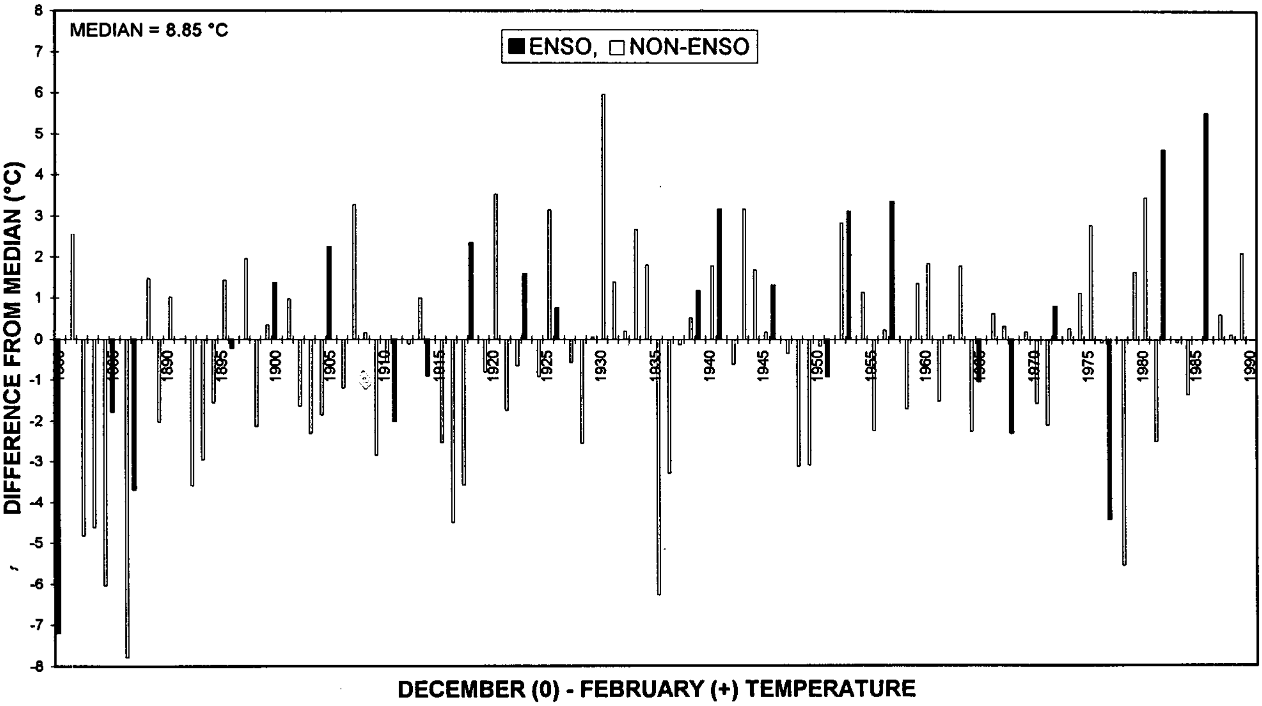

FIG. 7. Same as Fig. 4 except for December(0) to February(+) temperature (Δmean = 2.92°C, $T = 1.39$, $p = 0.08$; 56% > median, $p = 0.34$; 35% in upper quartile, $p = 0.20$).

1958, 1972–1973, 1982–1983) were also characterized generally by positive PNA and negative TNH projections. (However, similar projections were associated with the below-average 1977–1978 winter temperature.) Three other ENSO winters with negative temperature anomalies (1951/1952, 1965/1966, 1968/1969) were associated with negative projections for both the PNA and TNH patterns, while the warmer 1953–1954 winter exhibited negative projections as well (albeit weaker for the TNH). Perhaps positive PNA and negative TNH patterns manifest themselves in warmer winter temperature in the NPR and negative projections on both lead to below-average winter temperatures. The anomalously warm 1991/1992 ENSO winter was also accompanied by a combination of positive PNA and negative TNH projections, resulting in above-normal heights over the western and north-central United States, with below-average heights in the vicinity of the Hudson Bay (Le Comte 1993).

b. La Niña–Southern Oscillation (LNSO) patterns

Opposite to ENSO (although for a slightly shorter season), a significant decrease in the May(0) to August(0) precipitation was noted during LNSO years (Fig. 8). Monthly departures were generally from 0.5 to 1 cm less than the median when LNSO years were compared to non-LNSO years. A weaker two-month signal was also noted for June(+) to July(+) but may be a reflection of two instances were the LNSO years were consecutive. The May(0) to August(0) signal is consistent with the findings of Ropelewski and Halpert (1989), who found that (a) LNSO precipitation anomaly relationships are opposite in sign to the ENSO responses, (b) precipitation relationships held for more than 70% of the LNSO years, and (c) in 13 of the 15 regions studied, the LNSO precipitation relationships occurred in almost the identical seasons to those associated with ENSO.

The composited time series for May(0) to August(0) precipitation exemplifies the tendency for precipitation to be below median during LNSO years (Fig. 9). The average difference in LNSO precipitation from the median was −3.91 cm ($p = 0.0009$). The significance level was still quite high when resampling with replacement ($p = 0.004$). As with the earlier responses, the Wilcoxon rank-sum and Kruskal–Wallis tests were highly significant ($p = 0.0001$). Although the significance is high, the statistical values are slightly less than that for the ENSO counterpart. Figure 9 indicates that 13 of the 17 LNSO years (76%) experienced below-median precipitation in the NPR ($p = 0.02$). Eight of the 17 years (47%) were also in the lowest quartile of the distribution ($p = 0.04$). Therefore, a strong LNSO-related signal is apparent in the NPR, based on the statistical analyses. Although the results are somewhat weaker than those for ENSO, possibly due to the smaller sample size (six fewer LNSO events), the results are still highly significant.

In contrast to ENSO temperature, a significant signal is evident in LNSO winter temperatures. Departures ranged from 1° to 2°C below the median for December(0) to February(+) when LNSO years were compared to non-LNSO years (Fig. 10). Another noteworthy feature is the decrease in January(0) to February(0) temperature, which again may partially be a reflection of two instances where LNSO years occurred consecutively. Once again, this occurrence is generally opposite to that of ENSO winter temperature, consistent with Halpert and Ropelewski (1992).

The December(0) to February(+) composited time series for temperature illustrates the tendency for LNSO-related temperature to be below median across the NPR (Fig. 11). On the average, temperature was 4.67°C below the median for the 17 LNSO events ($p = 0.01$). Results were similarly significant for the Monte Carlo resampling of the t statistic when resampling was done with replacement ($p = 0.02$). Further support was gained from the Wilcoxon rank sum and Kruskal–Wallis tests ($0.01 < p < 0.02$). Based on the BPF, only a weak signal was apparent (Fig. 11). Only 12 of the 17 LNSO years (71%) were associated with below median temperature ($p = 0.07$); however, 8 of the 17 years (47%) were associated with temperature in the lower quartile of the distribution ($p = 0.04$). This stronger response for LNSO winter temperature versus ENSO winter temperature across the NPR is also suggested by Halpert and Ropelewski (1992).

Although only 12 of the 17 LNSO years (specific to this study) were less than the median temperature, use of the LNSO years used by Halpert and Ropelewski (1992) yields more significant results. By including 1909, 1964, and 1970, the BPF results are highly significant: 15 of 20 years below median (75%, $p = 0.02$) and 10 of 20 years in lowest quartile (50%, $p = 0.01$). The other three statistical test results are additionally more robust. Examination of the time series in appendix F of Barnston and Livezey (1987) shows that five of six LNSO events were concurrent with a negative projection of the PNA. In one instance (1975–1976), the projections were positive for both the PNA and TNH patterns. In this case, only a small negative departure from the median temperature was noted.

c. Sensitivity tests to the ENSO/LNSO years

As indicated earlier, there are minor discrepancies in the ENSO/LNSO years used in this study, as compared to previous studies. In order to examine the difference on the outcome of the t test, Monte Carlo simulations were performed by varying the ENSO/LNSO years for a specific response. In the case of ENSO events, 1977 was changed to 1976 and 1968 was changed to 1969. Additionally, the weaker years of 1930 and 1932 were included, with 25 ENSO years represented. For LNSO years, 1909, 1964, and 1970 were included, giving a total of 20 events. The choice of these years was based

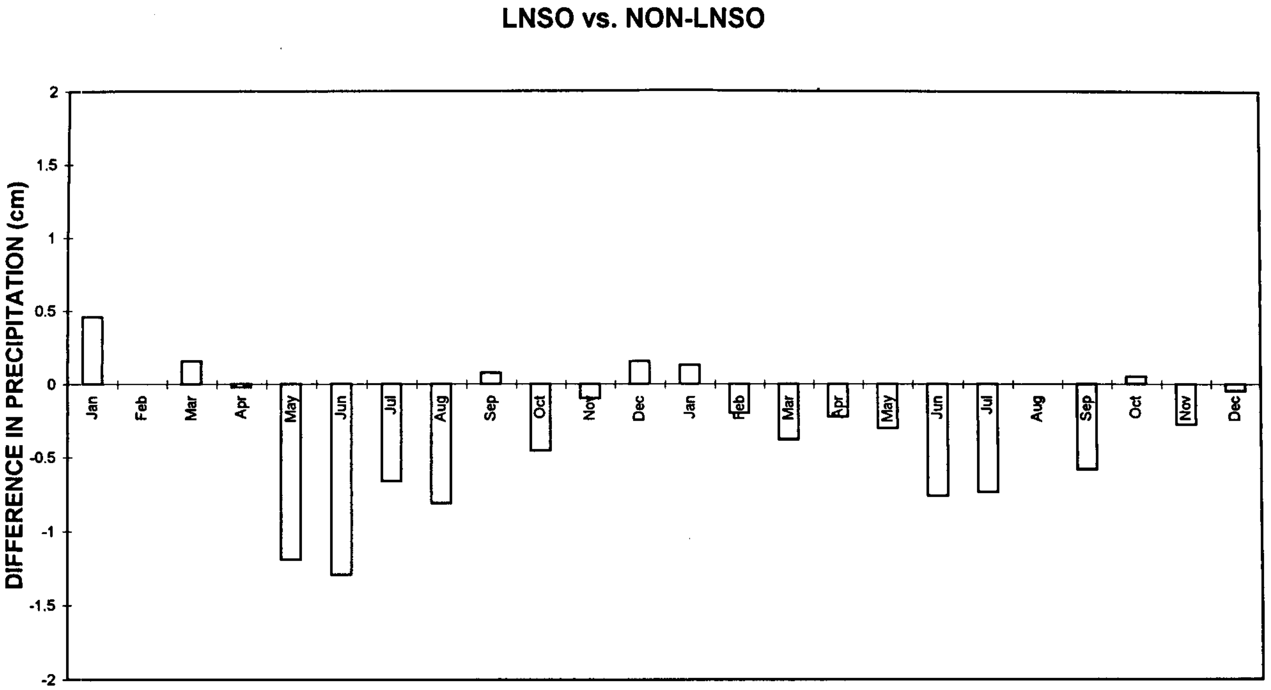

FIG. 8. Monthly average difference in precipitation (cm) between LNSO (17) and non-LNSO (94) years for the 2-yr period beginning January(0) of the LNSO year. Positive (negative) values denote an increase (a decrease) in the mean monthly precipitation for LNSO.

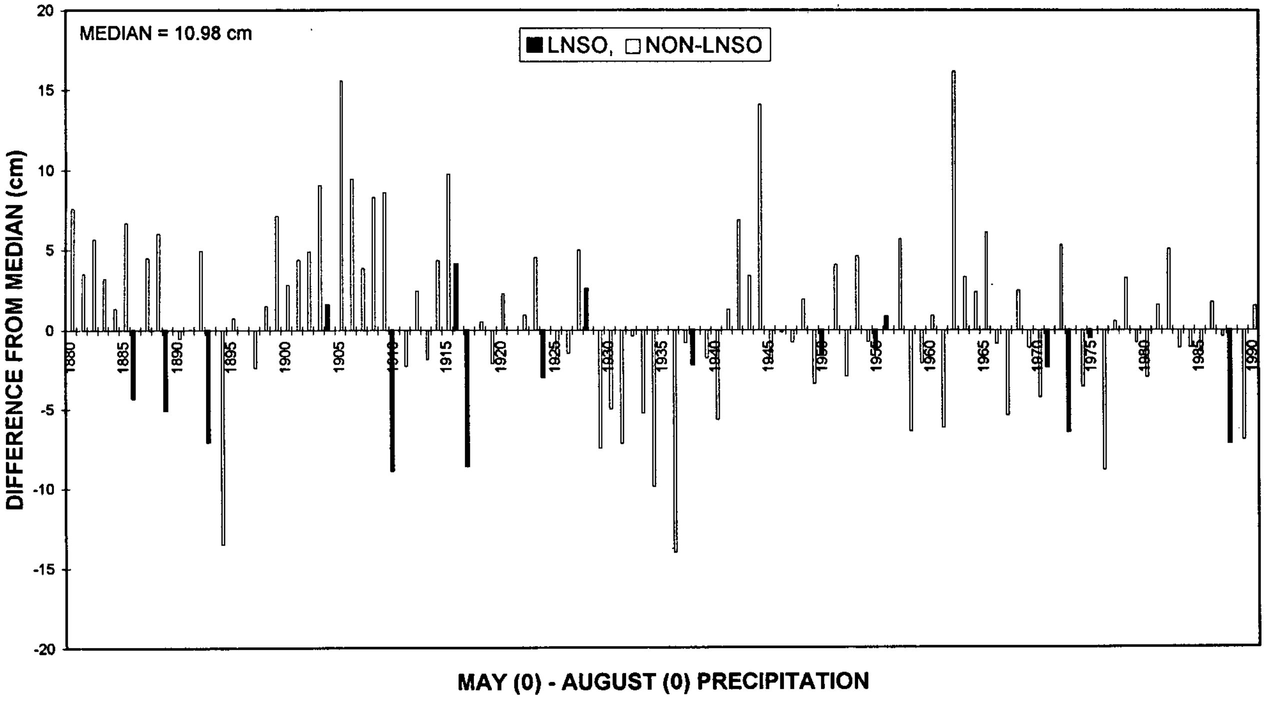

FIG. 9. LNSO May(0) to August(0) precipitation composite for the NPR. Solid bars represent LNSO years (Δmean = -3.91 cm, $T = -3.55$, $p = 0.0009$; 76% < median, $p = 0.02$; 47% in lower quartile, $p = 0.04$).

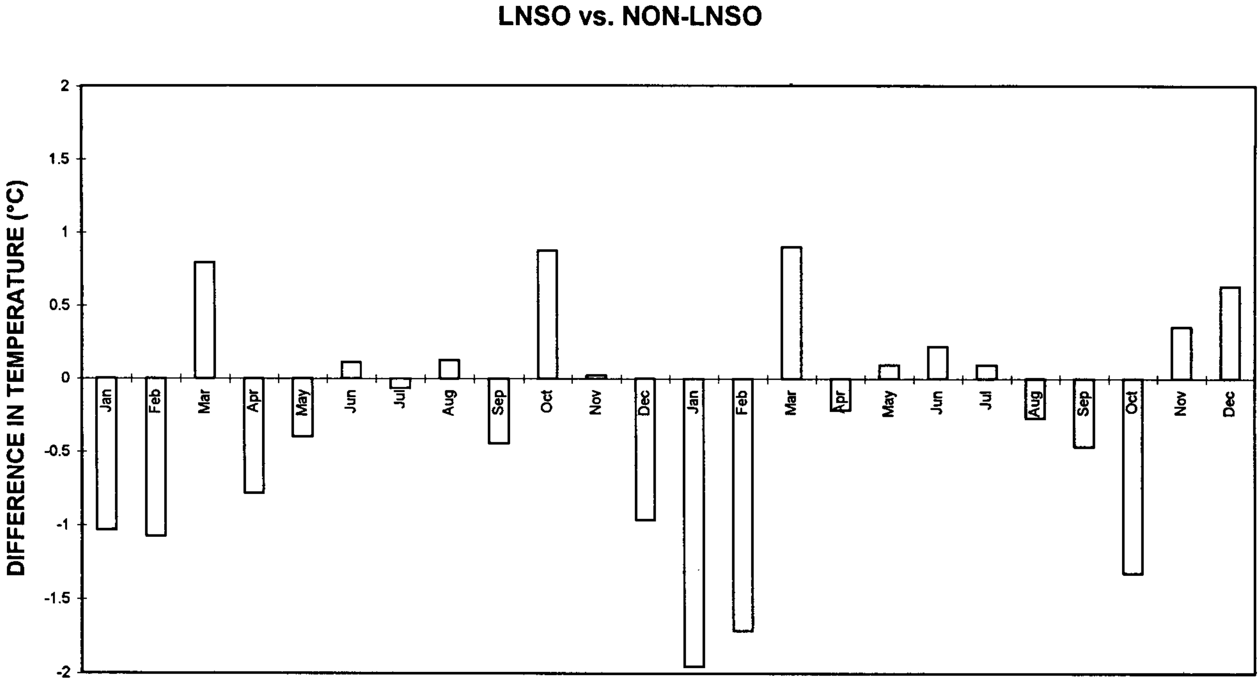

FIG. 10. Same as Fig. 8 except for temperature (°C).

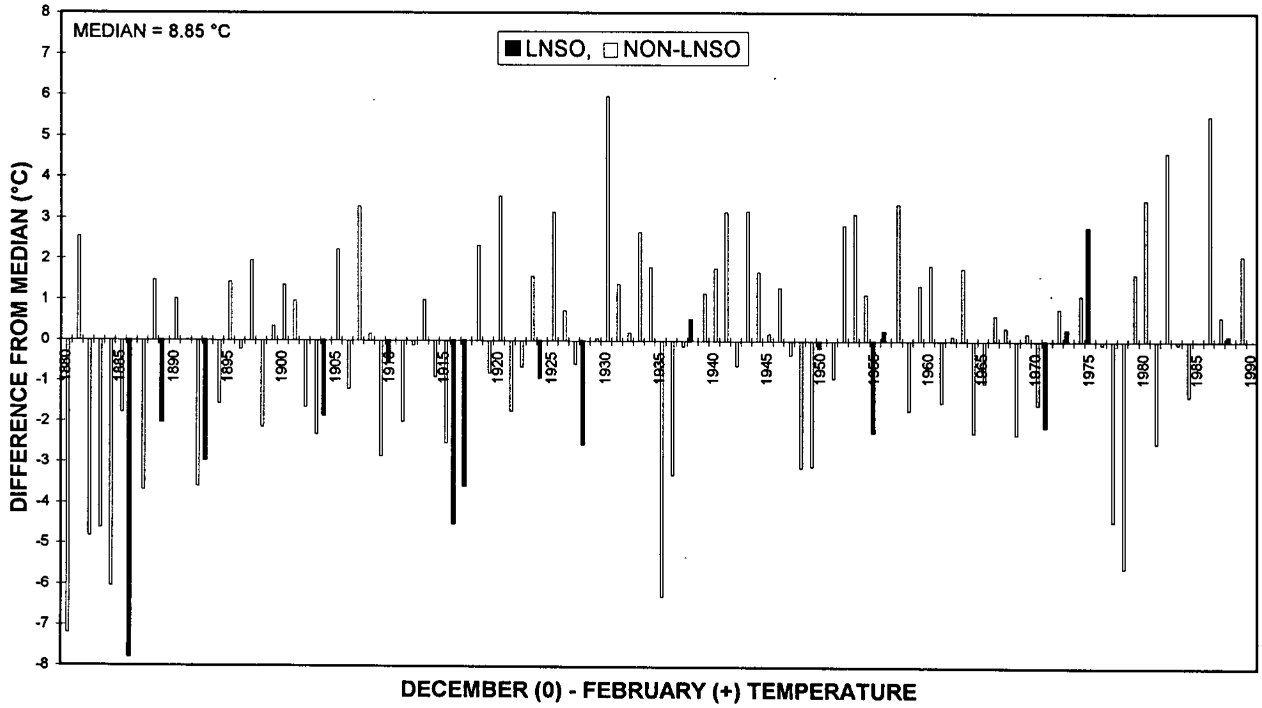

FIG. 11. Same as Fig. 9 except for December(0) to February(+) temperature (Δmean = -4.67°C, $T = -2.44$, $p = 0.01$; 71% $<$ median, $p = 0.07$; 47% in lower quartile, $p = 0.04$).

on some of the discrepancies found in RH86 and Ropelewski and Jones (1987).

The results remained unchanged for each of the four significant responses, and, in addition, a significant response for ENSO winter temperature became apparent. For ENSO April(0) to October(0) precipitation, a strong signal is still apparent with *p* values ranging from 0.0006 to 0.004 for the *t* test and from 0.01 to 0.02 for the BPF test (compare with Table 2). The *t* test results for the LNSO May(0) to August(0) precipitation were significant at the 0.006 to 0.01 level, with BPF results significant at the 0.04 to 0.05 level. Results remained nearly the same for the ENSO August(0) to October(0) temperature response. ENSO winter temperature was now significantly different from the non-ENSO counterpart at the 0.01 to 0.02 level; however, with BPF results still remaining insignificant. The LNSO winter temperature response strengthened, with Monte Carlo simulations indicating significance at the 0.04 to 0.01 level and BPF results at the 0.01 to 0.02 level. Therefore, the results are stable and indicative of significant SO-related climate forcing in the NPR.

4. Summary and conclusions

The NPR, generally encompassing the Dakotas, was evaluated for ENSO- and LNSO-related precipitation and temperature responses. Current results suggest that significant ENSO- and LNSO-related precipitation signals are evident across this region. The strongest signal across the NPR is for increased precipitation during the ENSO April(0) to October(0) season. RH86 identified the same season for the HP area (which overlaps the southern NPR) but deemed their results to be inconclusive. A strongly significant, albeit slightly weaker, response also occurs for the LNSO May(0) to August(0) season when precipitation tends to be diminished over the NPR. This response is opposite in sign to the ENSO-related precipitation response and occurs in roughly the same season, which is again consistent with Ropelewski and Halpert (1989). Temperature is significantly decreased during the ENSO August(0) to October(0) season and may partially be a result of the enhanced ENSO April(0) to October(0) precipitation. Finally, a moderately significant response was apparent for decreased LNSO winter temperature, with insignificant results for ENSO winter temperature. In addition, sensitivity tests confirm the results, with highly significant results still achieved for the above responses based on minor modifications to the classification of ENSO/LNSO years. Table 2 summarizes the results for the SO-extreme years used herein.

There may be several reasons why RH86 did not suggest the ENSO-related April(0) to October(0) precipitation signal in the NPR was significant. In their analysis, RH86 used the first harmonic vector of individual stations to objectively outline areas of North America that may possess a climate signal. The strong temporal smoothing may have masked a signal in the NPR. Also, a considerable amount of variation in evolution and teleconnection patterns occurs from one ENSO episode to the next, especially far from the tropical Pacific (Ropelewski, personal communication, 1993). It is not believed that use of ENSO years adopted in this study would have made their results significant.

It is difficult to find a physical mechanism that is responsible for the enhanced (diminished) warm season precipitation during ENSO (LNSO). The authors speculate that the strong SO-related precipitation signals across the NPR may be partly caused by the westward migration of the Bermuda high and its interaction with the subtropical jet stream (Stahle and Cleaveland 1992). An investigation of the ENSO April(0) to October(0) precipitation patterns across the southeastern United States may provide insight to anomalies associated with this NPR wet period. In addition, a composite 700- or 500-mb pattern for the April(0) to Oc-

TABLE 2. Statistical results for the SO-related responses of precipitation and temperature across the NPR. The *t* test and *p* value columns refer to the Monte Carlo simulations (10 000) of the *t* statistic and their significance (resampling without replacement). The Δmean column refers to the change in mean precipitation or temperature between SO and non-SO extreme years. The first value in the median column refers the percent of SO extreme years with values either: (a) above the median if the *t* test is positive or (b) below the median if the *t* test is negative. The second value in the median column refers to the *p* value (%) associated with the first using the BPF. The quartile column is the same as the median column except values are with respect to the upper or lower quartile, instead of the median.

Response	*t* test	Δmean	*p* value	Median	Quartile
ENSO pcp Apr–Oct	5.70	7.21 cm	<0.0001	87%/0.02%	61%/0.03%
ENSO tmp Aug–Oct	−2.93	−2.17°C	0.002	74%/1.73%	56%/0.12%
ENSO tmp Dec–Feb	1.39	2.92°C	0.08	56%/33.9%	35%/19.6%
LNSO pcp May–Aug	−3.55	−3.91 cm	0.0009	76%/2.45%	47%/4.02%
LNSO tmp Dec–Feb	−2.44	−4.67°C	0.01	71%/7.17%	47%/4.02%

tober(0) ENSO and non-ENSO seasons may help to elucidate the seasonal migration of the Bermuda high. This may also help to explain the "stronger" signal in the NPR versus the HP. Below-normal precipitation in the southeastern United States is consistent with the hypothesized westward displacement of the Bermuda high (Stahle and Cleaveland 1992).

Note that although RH86 identified enhanced precipitation during the ENSO October(0) to March(+) season across the southeastern United States, a weaker signal for a dry spring and summer may go undetected because their harmonic analysis identified the stronger winter response. In a 2-yr harmonic analysis, such as that performed by RH86, different anomaly tendencies only one-half a year apart cannot be distinguished using only the first harmonic.

Finally, it is interesting to note that the initial ENSO years did not reveal a significant temperature increase during the NPR winter, in contrast to similar studies (e.g., RH86). However, by slightly modifying the years that were classified as ENSO years, a significant increase in mean ENSO winter temperature was indicated by the *t* test. (Albeit, the BPF results still remained insignificant.) It is possible that the sensitivity results are a reflection of some phenomenon that was opposing the "ENSO warming" during the altered years, thus masking a signal. The inclusion of 1932 as an ENSO year (which was 6°C above median) indicates that weaker, less predictable events may contribute to warmer winters as well. Furthermore, the northern NPR has a stronger ENSO-related winter temperature response than the southern NPR, perhaps because of its proximity to significant TNH and PNA "centers of actions" (see Figs. 1, 2; and Fig. 1 of Barnston et al. 1991). These results suggest that there is a tendency for warmer NPR winters during ENSO; however, this was not discovered to be statistically significant.

The climate patterns associated with ENSO and LNSO should be monitored to determine the usefulness of this study's results. The results herein suggest strong warm season precipitation and weaker winter temperature responses (nonsignificant for ENSO) across the NPR, having potential forecast application. However, Madden and Shea (1978) suggest, due to natural variability, that time-averaged temperature is largely unpredictable; this places constraints on long-range forecasting. They show that for winter temperature, the ratio of actual interannual variability to the estimated natural variability is slightly greater than unity across the NPR. As another caveat, volcanic effects, such as those from the violent June 1991 Mt. Pinatubo eruption, may alter the SOI evolution and modify world climate patterns in confounding ways. Although the above SO-related results are encouraging, other factors also govern climate, and thus there is no assurance that any given SO-related phenomenon will result in the "expected" precipitation and temperature patterns across the NPR.

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REFERENCES

Aceituno, P., 1992: El Niño, the Southern Oscillation, and ENSO: Confusing names for a complex ocean–atmosphere interaction. *Bull. Amer. Meteor. Soc.,* **73,** 483–485.

Barnett, T., N. Graham, M. Cane, S. Zebiak, S. Dolan, J. O'Brien, and D. Legler, 1988: On the prediction of the El Niño of 1986–87. *Science,* **241,** 192–196.

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality, and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev.,* **115,** 1083–1126.

——, and ——, 1991: Statistical prediction of January–February mean Northern Hemisphere climate from the 11-yr solar cycle and the Southern Oscillation for west and east QBO phases. *J. Climate,* **4,** 249–262.

——, ——, and M. S. Halpert, 1991: Modulation of Southern Oscillation–Northern Hemisphere mid-winter climate relationships by the QBO. *J. Climate,* **4,** 203–217.

——, and Coauthors, 1994: Long-lead seasonal forecasts—Where do we stand? *Bull. Amer. Meteor. Soc.,* **75,** 2097–2114.

Bunkers, M. J., J. R. Miller Jr., and A. T. DeGaetano, 1996: Definition of climate regions in the Northern Plains using an objective cluster modification technique. *J. Climate,* **9,** 130–146.

Chang, F. C., and J. M. Wallace, 1987: Meteorological conditions during heat waves and droughts in the United States Great Plains. *Mon. Wea. Rev.,* **115,** 1253–1269.

Chen, W. Y., 1982: Fluctuations in Northern Hemisphere 700-mb height field associated with the Southern Oscillation. *Mon. Wea. Rev.,* **110,** 808–823.

Halpert, M. S., and C. F. Ropelewski, 1992: Surface temperature patterns associated with the Southern Oscillation. *J. Climate,* **5,** 577–593.

Horel, J. D., and J. M. Wallace, 1981: Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.,* **109,** 813–829.

Karl, T. R., and A. J. Koscielny, 1982: Drought in the United States: 1895–1981. *J. Climatol.,* **2,** 313–329.

——, and W. E. Riebsame, 1984: The identification of 10–20-yr temperature and precipitation fluctuations in the contiguous United States. *J. Climate Appl. Meteor.,* **23,** 950–966.

——, G. Kukla, and J. Gavin, 1987: Recent temperature changes during overcast and clear skies in the United States. *J. Climate Appl. Meteor.*, **26,** 698–711.

Kiladis, G. N., and H. F. Diaz, 1989: Global climate anomalies associated with extremes in the Southern Oscillation. *J. Climate,* **2,** 1069–1090.

Le Comte, D., 1993: Highlights in the United States. *Weatherwise,* **46,** 8–13.

Livezey, R. E., and K. C. Mo, 1987: Tropical–extratropical teleconnections during the Northern Hemisphere winter. Part II: Relationships between monthly mean Northern Hemisphere circulation patterns and proxies for tropical convection. *Mon. Wea. Rev.,* **115,** 3115–3132.

Madden, R. A., and D. J. Shea, 1978: Estimates of the natural variability of time-averaged temperatures over the United States. *Mon. Wea. Rev.,* **106,** 1695–1703.

Milton, J. S., and J. C. Arnold, 1990: *Introduction to Probability and Statistics: Principles and Applications for Engineering and the Computing Sciences.* McGraw Hill, 700 pp.

Panofsky, H. A., and G. W. Brier, 1968: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University, 224 pp.

Peixoto, J. P., and A. H. Oort, 1992: *Physics of Climate.* American Institute of Physics, 520 pp.

Philander, S. G., 1990: *El Niño, La Niña, and the Southern Oscillation.* Academic Press, 293 pp.

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

——, and ——, 1983: The relationship between eastern equatorial pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Wea. Rev.,* **111,** 517–528.

——, and J. M. Wallace, 1983: Meteorological aspects of the El Niño/Southern Oscillation. *Science,* **222,** 1195–1202.

Ropelewski, C. F., and M. S. Halpert, 1986: North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev.,* **114,** 2352–2362.

——, and ——, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.,* **115,** 1606–1626.

——, and P. D. Jones, 1987: An extension of the Tahiti–Darwin Southern Oscillation index. *Mon. Wea. Rev.,* **115,** 2161–2165.

——, and M. S. Halpert, 1989: Precipitation patterns associated with the high index phase of the Southern Oscillation. *J. Climate,* **2,** 268–284.

Sellers, W. D., 1965: *Physical Climatology.* University of Chicago, 272 pp.

Stahle, D. W., and M. K. Cleaveland, 1992: Reconstruction and analysis of spring rainfall over the southeastern United States for the past 1000 years. *Bull. Amer. Meteor. Soc.,* **73,** 1947–1961.

Trenberth, K. E., G. W. Branstator, and P. A. Arkin, 1988: Origins of the 1988 North American drought. *Science,* **242,** 1640–1645.

van Loon, H., and R. A. Madden, 1981: The Southern Oscillation. Part I: Global associations with pressure and temperature in northern winter. *Mon. Wea. Rev.,* **109,** 1150–1162.

Walker, G. T., and E. W. Bliss, 1932: World Weather V. *Mem. Roy. Meteor. Soc.,* **4,** 54–84.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.

Winston, J. S., 1983: Major developments in zonal and regional climate anomalies over the tropics and subtropics in spring and summer 1982. *Proc. Seventh Annual Climate Diagnostics Workshop,* Boulder, CO, United States Department of Commerce, 45–59.

Zwiers, F. W., 1987: Statistical considerations for climate experiments. Part II: Multivariate tests. *J. Climate Appl. Meteor.,* **26,** 477–487.