Arch. Met. Geoph. Biocl., Ser. A 34, 111–130 (1985)

ARCHIVES
FOR METEOROLOGY,
GEOPHYSICS, AND
BIOCLIMATOLOGY

551.526.6:551.577.35

Department of Atmospheric Science, Colorado State University,
Fort Collins, Colorado, U.S.A.

Influence of Pacific Sea Surface Temperatures on Seasonal Precipitation over the Western Plateau of the United States

J. D. Sheaffer and **E. R. Reiter**

With 11 Figures

Received January 17, 1985

Summary

Analysis of the long-term variability of interseasonal correlations between various climatological data for the western United States indicates that the transient aspects of these correlations are linked to trends in Sea Surface Temperatures (SST) in the Pacific Ocean. Stratifying climatological data by the dominant modes of Pacific SST anomalies seems to enhance interseasonal correlations between various climate parameters for the western plateau area. For example, when warm SSTs occur in the equatorial eastern Pacific, summer precipitation anomalies in peripheral areas of the plateau are highly correlated with thermal and precipitation anomalies over the plateau during the prior spring. When we selectively examine portions of the data set representing extreme SST anomaly conditions, the inferred associations become systematically stronger. The observations suggest that much of the variance typically encountered in computing interseasonal correlation statistics for climatological data may be due to variable influences associated with ocean temperature anomalies in remote locations. Although no comprehensive explanation is offered for the observations, there is a general consistency with prior studies of the relationships between various SST anomalies and weather trends in western North America. With additional refinement and extended scope these results may provide the basis for improved forecasts of seasonal weather trends, both in the western United States and elsewhere.

Zusammenfassung

Der Einfluß von Oberflächentemperaturen des Pazifiks auf die jahreszeitlichen Niederschläge über dem westlichen Plateau der Vereinigten Staaten

Die Analyse der allmählichen Veränderlichkeit der Korrelationen zwischen meteorologischen Daten aus verschiedenen Jahreszeiten zeigen über den westlichen Vereinigten Staaten, daß ein Zusammenhang zwischen diesen Änderungen und den Tendenzen in den Meeresoberflächentemperaturen im Pazifik besteht. Wenn klimatologische Daten je nach den dominierenden Feldern der Meerestemperaturen eingeordnet werden, verbessern sich die Korrelationen, welche verschiedene Jahreszeiten überspannen. So sind zum Beispiel bei warmen Meerestemperaturanomalien im äquatorialen Ostpazifik die sommerlichen Niederschlagsanomalien in der Umgebung des Plateaus stark mit den Temperatur- und Niederschlagsanomalien über dem Plateau im vorhergehenden Frühling korreliert. Wird jene Untergruppe der Daten untersucht, welche extremen Meerestemperaturanomalien entspricht, so werden die entsprechenden Korrelationsbeziehungen noch stärker. Diese Beobachtungen deuten an, daß ein Großteil der Varianz, die für gewöhnlich in Korrelationen klimatologischer Daten zwischen verschiedenen Jahreszeiten auftritt, auf Einflüsse von Meerestemperaturanomalien in entfernten Gebieten zurückgeführt werden kann. Obzwar keine umfassende Erklärung für diese Beobachtungstatsache angeboten wird, besteht eine allgemeine Konsistenz mit früheren Studien in den Zusammenhängen zwischen Meerestemperaturanomalien und Witterungstendenzen im westlichen Nordamerika. Verbesserte und erweiterte Studien dieser Art können die Basis für die Langfristprognose jahreszeitlicher Witterungstendenzen in den Vereinigten Staaten und anderswo bilden.

1. Introduction

This note describes preliminary work with empirical procedures for forecasting seasonal precipitation anomalies in the Western Plateau region of the United States. In developing empirical relationships for long-range weather forecasting it is prudent to study situations wherein reasonable forcing mechanisms can be identified, *a priori*, to account for any strong statistical associations that might be obtained. One typical situation involves the monsoon circulations of the Northern Hemisphere. Recently Tang and Reiter [1] and Reiter and Tang [2] have described the effects of thermal forcing over elevated terrain for a variety of monsoon flow regimes in and around the Tibetan and Rocky Mountain Plateau regions. Because the influence of plateau-induced forcing is now reasonably well-defined we can anticipate the probable influence of anomalous thermal or moisture conditions on subsequent weather. The apparent association between anomalous Eurasian snow cover and the intensity of the summer monsoon in India, described by Hahn and Shukla [4] and Dickson [3] is cited as an example of prior work in this area.
The lack of long-term stability for interseasonal correlations between various weather elements is a well-known problem in long-range weather forecasting. Nicholls [5] has shown that optimum seasonal forecasts for spring precipitation in Australia are obtained when the empirical data base for these forecasts is limited to the 15-year period preceding the year for which the forecast is made. When either longer or shorter records were used the quality of the precipitation forecasts tended to deteriorate. This result is a notable improvement over many correlation studies wherein apparently strong

associations are observed in limited data but simply fail when a longer period of record is examined.
Many researchers have argued that anomalous Sea Surface Temperatures (SST) in the Pacific ocean exert an important influence on atmospheric circulation over North America on seasonal time scales [6–9]. Because SST anomalies tend to be relatively stable in time, one way of incorporating slowly varying anomalies of large-scale circulations into the analysis of climatological data is to stratify the data by the dominant modes of SST variations. The simplest approach is to group climatological data according to the sign of broad scale SST anomalies and compare the interseasonal correlations obtained for each subset.

2. Data and Methods

With the assistance of Dr. Roy Jenne of the National Center of Atmospheric Research we obtained a 40-year (1941–1980) record of monthly air temperatures and precipitation for many stations in the continental United States. This data set is limited to those stations which had not undergone a significant change of location during this 40-year interval. These data were further screened to remove stations for which more than three percent of the monthly reports were characterized as either "estimated" or "missing". The remaining stations in a seven-state study area are shown in Fig. 1. The data included more than 450 precipitation stations and more than 300 air temperature stations.
Seasonal anomalies relative to the 40-year means were computed for temperature and precipitation for each station. Seasons were defined as December, January and February for winter; March, April and May for spring, and so forth. No attempt was made to remove any long-term trends in the data. The anomalies for each season at each station were then ranked from one to forty wherein the driest (coolest) season was given the value "one" and the wettest (warmest) season given the value "forty". The ranked values for each season were also summed for 10 to 15 stations within the smaller regions shown in Fig. 1. These regional sums of ranks were then reranked from one to forty, as described above, to obtain spatially averaged indices of seasonal anomalies for each area.
We initially examined somewhat smaller spatial and temporal domains. Working with 20 years of data (1961–1980) we computed the correlation between the combined seasonal precipitation at 25 high elevation stations in the upper Colorado River Basin (see Fig. 1) and temperature and precipitation data in the nearby area for various seasonal lags. A surprisingly strong correlation was observed between winter precipitation in the upper Colorado Basin and air temperatures during the preceding autumns in

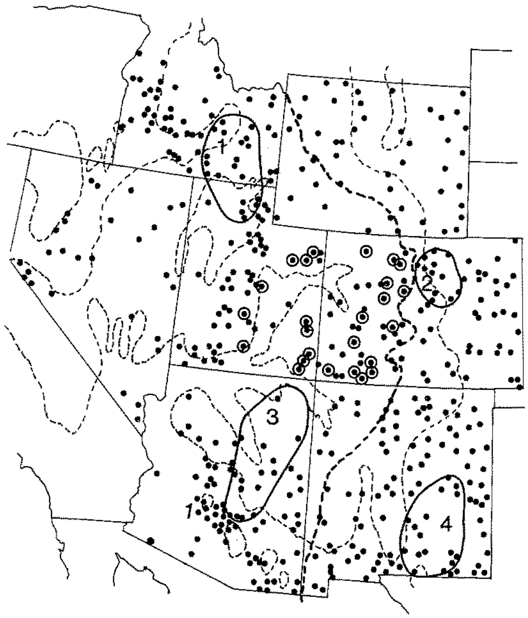

Fig. 1. Study area and precipitation stations. Temperature data were obtained for approximately 75 percent of these locations. Spatially averaged anomaly indices were obtained for each of the four smaller regions. The circled dots represent stations above 2000 meters elevation that comprised the upper Colorado River Basin index (see text). The thin dashed lines bound areas above 2000 meters elevation and the heavy dashed line represents the continental divide between Pacific and Atlantic drainages

northeastern Arizona. This finding prompted us to construct area averaged temperature and precipitation indices for area 3, so as to allow closer examination of this relationship. Composite temperature and precipitation indices for areas 1, 2 and 4 were also constructed at the same time. Areas 1 and 4 were in the extreme northwestern and southeastern corners of the original data set. Area 2 was near the northeastern corner of the region and included the site of Colorado State University. With the exception of area 2 a deliberate effort was made to have the area indices span at least two major drainages so as to avoid dominance by very localized effects. The data set was later expanded to include 40 years of data for the somewhat larger domain shown in Fig. 1.

Only large-scale variations of SSTs were used to stratify the land area climatological data. For this we have relied entirely on published analyses of SST anomalies which are referenced below.

As we were seeking only to examine the strength and stability of simple interseasonal correlations between the various area and station anomaly indices, only elementary statistical methods have been applied. Testing for correlations (Spearman's Rank Correlation Test) at various seasonal lags (0 to 4) has been done for most combinations of temperature and precipitation indices for the four areas shown in Fig. 1. To examine the temporal variability of these correlations, we have computed 5-, 10- and 15-year running correlations for each combination of indices at each lag. In addition, for most cases we have also computed lagged correlations between the area indices of temperature and precipitation and anomalies at each individual station within the region.

3. Results

The running correlation tests between the various area averaged indices yielded a large number of correlation time series, most of which revealed rather substantial temporal variability in the strength of the interseasonal associations. Several recurrent patterns of variation were observed in many of the time series, one of which is illustrated in Fig. 2. Inspection of the anomaly time series in Fig. 2B reveals that, although these two indices tend to track one another most of the time, the sequence is interspersed with brief periods where the two series are notably out of phase. Comparing the in phase and out of phase periods of these anomaly time series with the widely reported trends of SSTs in the equatorial eastern Pacific (Fig. 2B) revealed a rather close correspondence. In particular, when SSTs in the equatorial eastern Pacific were warmer than normal, the time series in Fig. 2B tend to be in phase; when cold anomalies occurred in the equatorial eastern Pacific, the series are frequently out of phase.

We examined this apparent connection by splitting the 40 years of data into two 20-year sets representing comparatively positive and negative SST anomalies in the equatorial eastern Pacific during the spring of each year. The spring period was considered so that seasonal forecasts for summer precipitation might be made from the resulting data sets. For convenience we will refer to the condition in which comparatively warm SSTs occur in the eastern Pacific as the Negative Southern Oscillation (NSO), as it tends to coincide with negative surface pressure anomalies at Tahiti. The cold water, or Positive Southern Oscillation phase will be referred to as the PSO. In lieu of a suitable SST data set of our own for this distinction, various published data were examined [10–18]. The resulting NSO and PSO years, listed in Table 1, represent our subjective evaluation of these and other sources. In general these designations reflect the broad scale trend in the SST anomalies along the equator from 180° eastward. Many of the SO phase designations in Table 1 were based on rather close visual examination of plotted data. In addition, the SST data for the 1940s are notably poorer

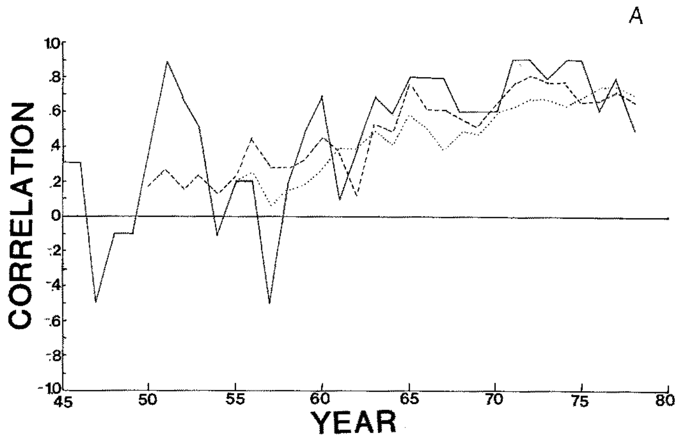

Fig. 2A. Running correlation coefficients (ordinate) between spring temperature anomalies in area 3 and summer precipitation in area 4 for 5- (solid line), 10- (dahsed line) and 15- (dotted line) year periods. The abscissa represents the last year of data entering each respective correlation value. Hence, the first 15-year correlation value, representing 1941–55, is plotted for 1955

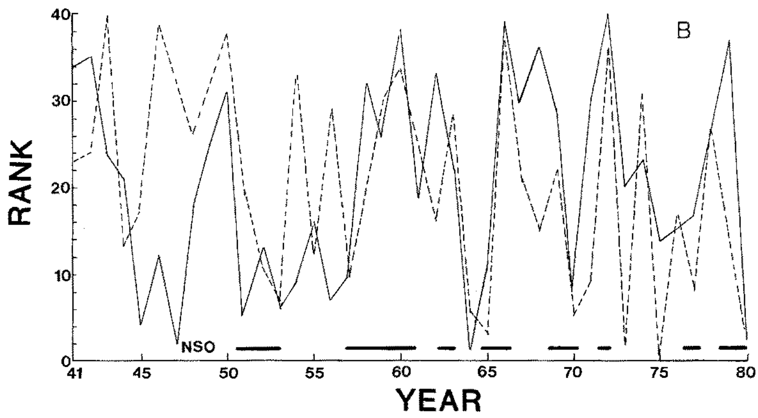

Fig. 2B. Forty-year (1941–1980) ranked time series of spring air temperature anomalies in area 3 (dashed) and summer precipitation anomalies in area 4 (solid). Ordinate gives the rank (1 . . . 40). The intermittent line just above the abscissa represents those years (after 1949) when relatively warm SST conditions occurred during spring in the Equatorial Eastern Pacific and less representative than those available for the rest of the period and only two sources of temporally detailed data were located for the period 1941 through 1948 [12, 14]. Because of the lack of intercomparability and because the available data were limited to values representative of areas

Table 1. *Years (1941–1980) when Spring Sea Surface Temperatures were Comparatively Warm (NSO) and Comparatively Cool (PSO) in the Equatorial Eastern Pacific Ocean*

NSO:	1941, 42, 44, 48, 51, 52, 53, 57, 58, 59, 60, 63, 65, 66, 69, 70, 72, 76, 77, 80
PSO:	1943, 44, 45, 47, 49, 50, 54, 55, 56, 61, 62, 64, 67, 68, 71, 73, 74, 75, 78, 79

Table 2. *Years with the Ten Warmest (NSO) and Ten Coolest (PSO) Spring Sea Surface Temperatures in the Equatorial Eastern Pacific Ocean During the Years 1950–1980*

NSO:	1952, 53, 57, 58, 59, 65, 66, 69, 72, 80
PSO:	1950, 54, 55, 56, 62, 64, 68, 71, 74, 75

Table 3. *Years (1950–79) when the Sign of the First Eigenvector of Spring Pacific Sea Surface Temperatures was Positive (NSO) and Negative PSO).* Following Fig. 1 in Horel and Wallace [16] and Fig. 4 in Hsiung and Newell [18]

NSO:	1952, 53, 57, 58, 59, 60, 61, 65, 66, 69, 70, 72, 76, 77, 79 (15 years)
PSO:	1950, 51, 54, 55, 56, 62, 63, 64, 67, 68, 71, 73, 74, 75, 78 (15 years)

totally south of the equator, we treated this eight-year period as a separate data set which was divided into four warm and four cool SST years. To check the results for the two 20-year periods, we then selected ten years each with the warmest and coldest equatorial Pacific SST values in the period between 1950 and 1980. These years are listed in Table 2. Because the SO is a Pacific basin-wide phenomenon, we also separated the years according to the sign of the first eigenvector of SST anomalies in the eastern equatorial and north Pacific Ocean during the spring of each year (Table 3). This stratification is based on data for the 30-year period between 1950 and 1979, originally computed by Weare et al. [17], and extended by Horel and Wallace [16] and Hsiung and Newell [18].

Whereas the 40-year rank correlation between spring air temperature in area 3 and summer precipitation in area 4 was found to be 0.390, the 20-year values were 0.800 and −0.185 for the negative and positive phases of the SO, respectively. For the 10-year extreme case correlation tests, the values were 0.830 for the NSO and −0.079 for the PSO. Results for the 15-year correlations using the first eigenvector of eastern Pacific SST's were 0.886 for the NSO and 0.156 for the PSO. The direct implication of these findings is that during the negative phase of the SO a large portion of the variance of summer precipitation in eastern New Mexico (area 4) is explained by spring air temperature anomalies in area 3. However, correlations obtained in this way must be interpreted with caution. The opportunity for chance assocations in tests of this sort is fairly high and cannot be precisely defined. Nevertheless, for reference we note that the critical correlation values for the 1% significance level for 40, 20 and 15 temporal degrees of freedom are 0.394, 0.534 and 0.623, respectively.

Although this relationship has not been objectively tested with independent data, the associations between spring temperature in area 3 and summer precipitation anomalies in area 4 (published routinely in the Weekly Weather and Crop Bulletin) for 1981 through 1984 are qualitatively correct. Also, the extreme case results described previously and other random tests for subsets of the NSO data show good internal consistency for the rather strong interseasonal correlations.

The summer precipitation index for area 4 was also correlated with spring air temperature anomalies at each station in the entire study region for all 40 years. Results of this test, shown in Fig. 3A, are consistent with Fig. 2 but suggest that an even stronger association exists between summer precipitation in area 4 and spring air temperatures in northeastern Wyoming. Similar analyses are shown in Figs. 3B and 3C except that the data have been separated according to the SO breakdown given in Table 1. This simple decomposition yields a much different perspective. The NSO correlation field in Fig. 3B has a southwest to northeast orientation and is much stronger, especially in southwestern Utah. During the PSO years (Fig. 3C) the correlation field is generally negative and appears to be oriented from north to south.

This spatial decomposition was repeated for the eigenvector stratification given in Table 3. In this case (not shown) similar patterns were obtained for the correlation fields but correlations exceeding 0.75 were obtained for most of the area enclosed by the 0.6 isopleth in Fig. 3B. The corresponding PSO correlation values in Fig. 3C increased slightly (i.e., became less negative) and hence were insignificant everywhere.

Since relatively warm (cool) springs in the study region also tend to be relatively dry (wet) [19], we tested to see whether a similar spatial distribution of correlations, but of the opposite sign, existed between spring precipitation over the region and summer precipitation in eastern New Mexico. Results of this test for both phases of the SO are shown in Fig. 4. Once again the strength of the correlation is greatly diminished during the PSO phase and the strongest correlations during the NSO are centered in Utah, most notably over the Wasatch Mountains.

Methods for estimating the effective degrees of freedom and hence of the

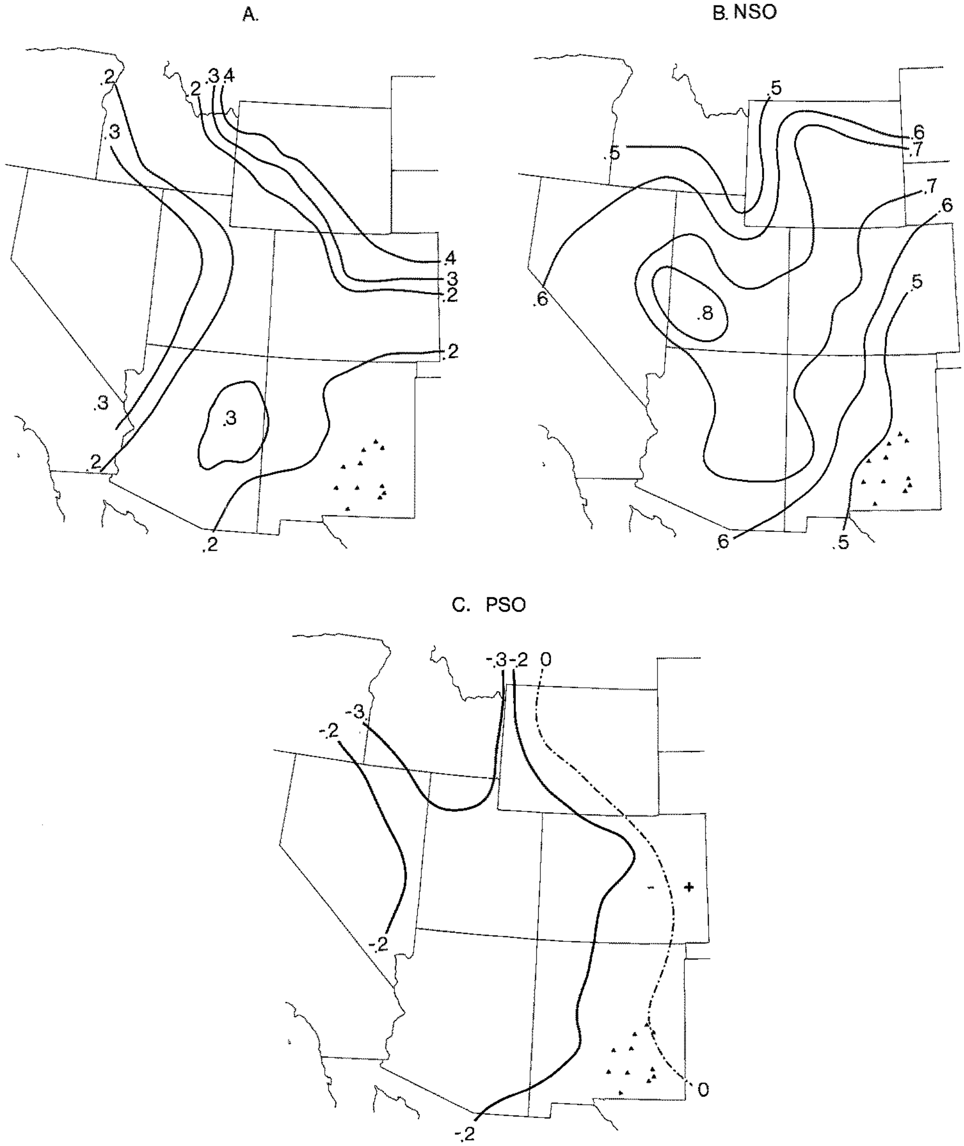

Fig. 3. (A) Analysis of 40-year rank correlations between spring air temperature anomalies at each station and subsequent summer precipitation anomalies in area 4. The cluster of small triangular symbols represents the locations of stations included in the area 4 index. The analysis shows those areas within which most of the station correlations, (e.g., the median correlations) exceeded the values shown. (B) and (C) as in Fig. 3A, except that the data have been separated into 20-year sets according to the negative (NSO) or positive (PSO) phase of the Southern Oscillation during the prior spring. The negative and positive years are listed in Table 1 and the basis for the SO designations is described in the text

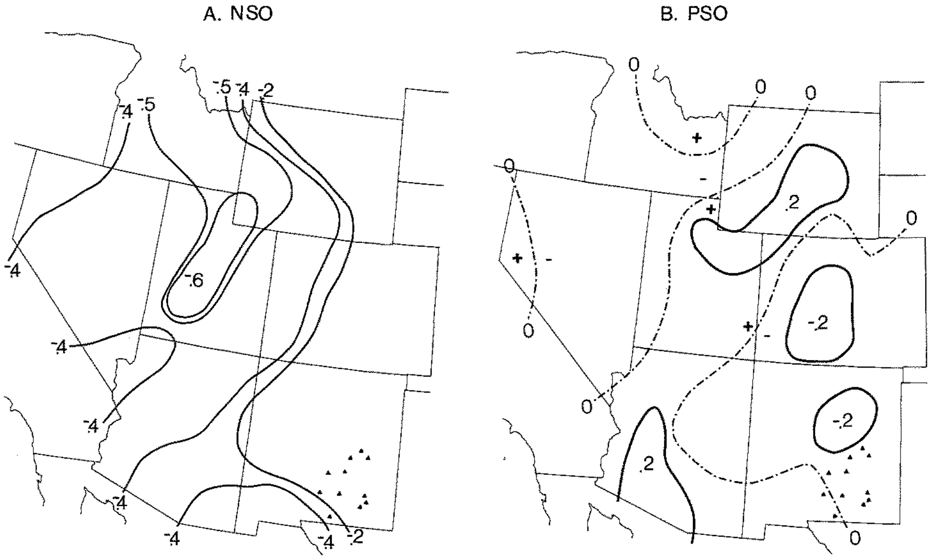

Fig. 4. As in Fig. 3B and C, except for spring precipitation at each station in relation to summer precipitation in area 4

statistical significance in data fields such as those in Figs. 3 and 4 have been described by Davis [20] and Livezey and Chen [21]. Monte Carlo tests of this sort require a comparatively large commitment of resources and were not systematically applied in these preliminary studies. However, limited testing with random data yielded notably weaker correlations than those shown in Figs. 3A, 3B, and 4A.

Another characteristic behavior observed in the running correlation time series, but for cold season precipitation, is illustrated in Fig. 5. A distinct change in phase relationship between the anomaly time series in Fig. 5B occurred in the early to mid-1960s. This out of phase to in phase switch is reflected in the gradual reversal of the sign of the running correlation time series. The timing of this phase reversal is similar to that of a notable change in the second eigenvector of global SSTs which, as reported by Weare et al. [17] and, Hsiung and Newell [18] reflects a long-term cooling trend in the North Pacific Ocean. The time series of the amplitude for this SST eigenvector is consistently positive prior to 1964 and, with the exception of a brief period in 1967, is consistently negative thereafter.

With this temporal scale in mind we divided the climatological data for the plateau area into two periods, fall 1949 to winter 1964 and fall 1964 to winter 1980, and obtained the results shown in Fig. 6. These analyses represent the correlations between regional air temperatures in fall and

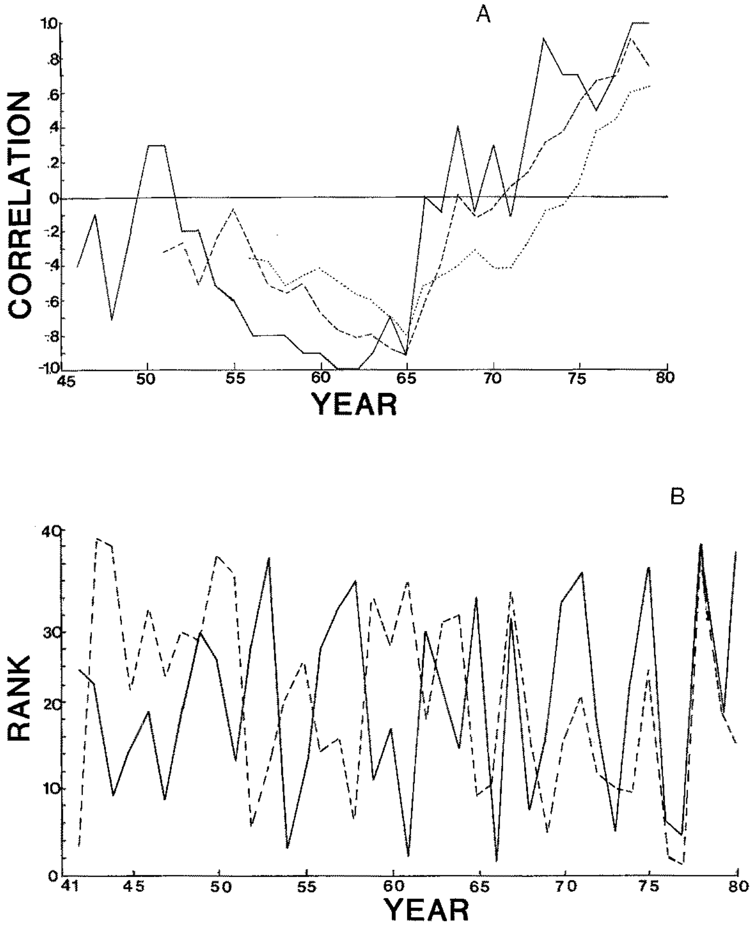

Fig. 5. (A) As in Fig. 2A, except for fall air temperature in area 3 and winter plus spring precipitation in area 1. (B) As in Fig. 2B, except for fall air temperature in area 3 (dashed line) and winter plus spring precipitation in area 1 (solid line)

the combined cold season (winter and spring) precipitation at the highland stations in the upper Colorado River Basin (these high elevation stations are shown in Fig. 1). The results in Fig. 6 also reflect the change in the interseasonal relationship between the two periods that are observed in Fig. 5.

We repeated the analysis shown in Fig. 6 for two 10-year periods; 1954 to 1963 when Hsiung's and Newell's second SST eigenvector was consistently positive and, 1971 to 1980, when it was consistently negative. The 1954

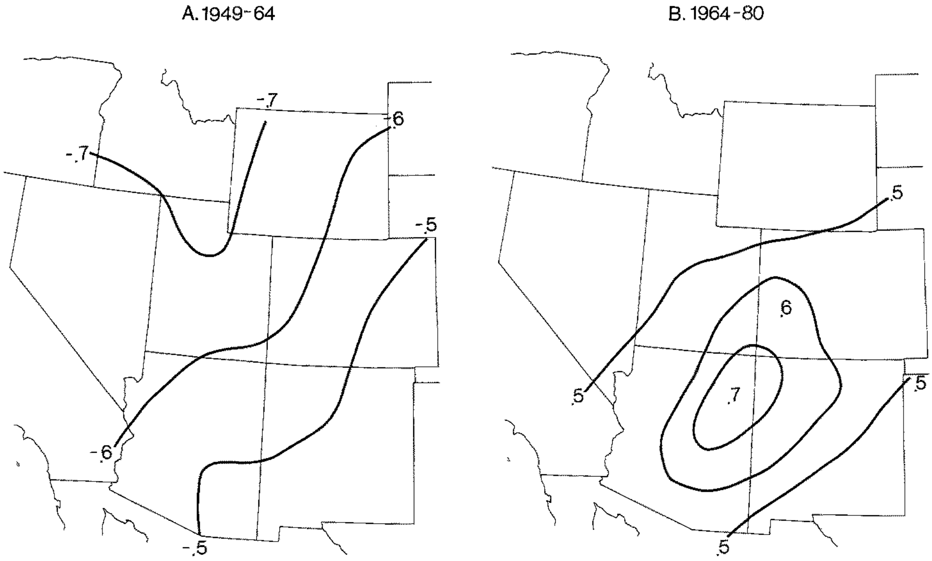

Fig. 6. Correlations between fall air temperatures at each station and cold season (winter plus spring) precipitation in the upper Colorado River Basin for 1949–64 (15 years) and 1964–80 (16 years). The stations included in the upper Colorado index are shown in Fig. 1

to 1963 correlations were found to be essentially the same as those in Fig. 6A. The pattern of the correlation fields for the 1971 to 1980 period was similar to that in Fig. 6B but was stronger such that most of the area within the 0.6 isopleth in Fig. 6B had correlation values exceeding 0.8. The latter results lend additional credibility to the suggested association between trends in North Pacific SSTs and the correlation between fall air temperatures and cold season precipitation over the plateau.

Several other large-scale climate parameters have been reported to undergo abrupt shifts or transitions at the same time as those represented in Figs. 5 and 6. In addition to North Pacific SSTs these include: the frequency of cyclogenesis over North America (see [22]), eigenvectors of Northern Hemisphere sea level pressure (see [23]), and empirical climate state vectors proposed by Barnett and Preisendorfer [7] and Baker-Blocker and Bouwer [24]. Also, it can be observed in Fig. 2A that after about 1963 consistently positive correlations occur between spring air temperature in area 3 and summer precipitation in area 4, even though the frequency of NSO and PSO years during this period is approximately equal. Hence, the abrupt changes in the correlations shown in Figs. 5 and 6 have multiple parallels in other climate data and therefore seem unlikely to be due entirely to chance.

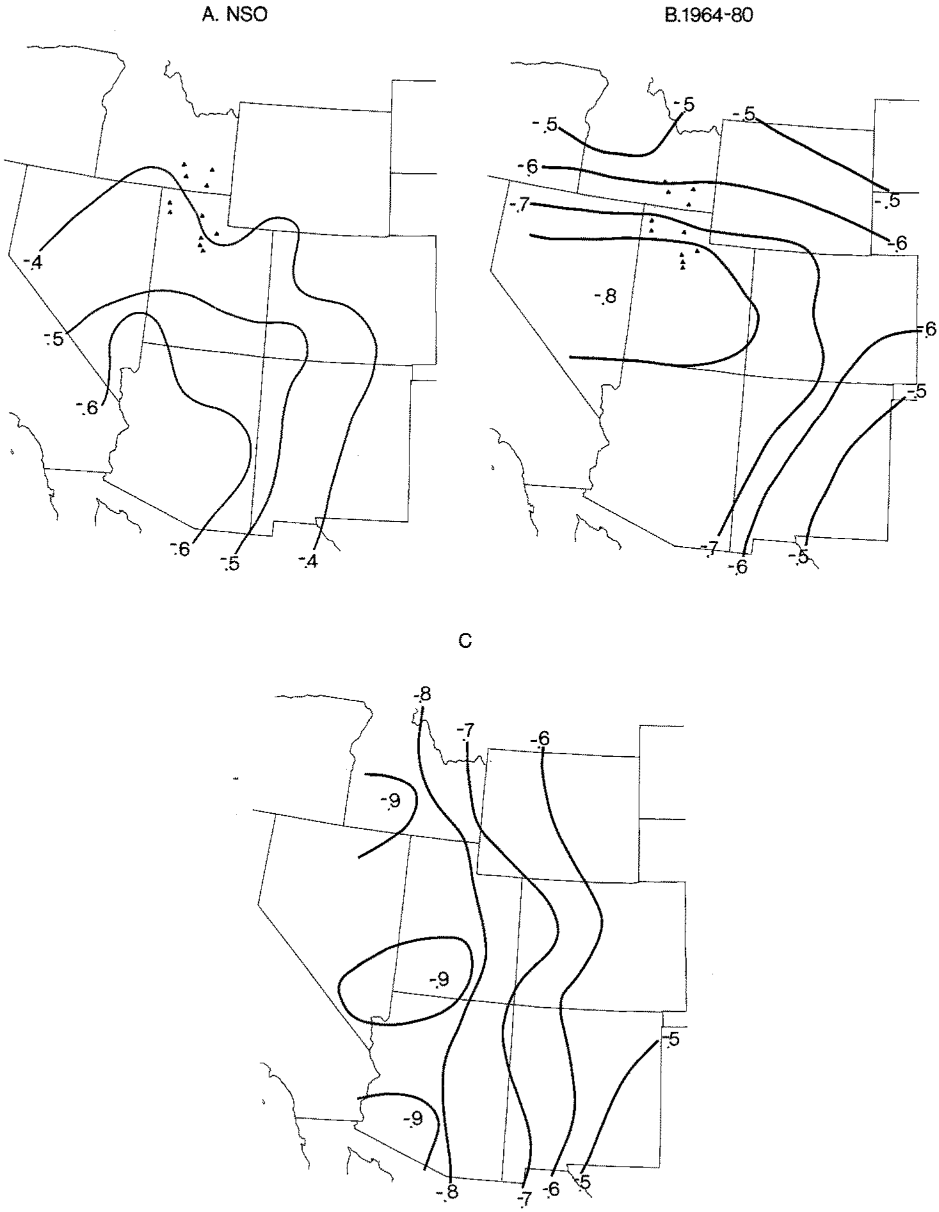

Fig. 7. (A) Correlations between regional spring air temperatures and summer precipitation in area 1 for the NSO stratification (20 years), (B) for the North Pacific cooling trend from 1964 to 1980 (16 years). The years for the NSO analysis are given in Table 1. In (C), the five strongest PSO years (68, 71, 74, 75, 78) have been removed from the data for (B)

Previous research has shown that good spatial coherence exists between the large-scale variations of SSTs throughout the northern and the equatorial regions of the Pacific Ocean [6, 17, 18, 25]. Therefore, it would be overly simplistic to assume that the influence of SST variability in only one region of the Pacific completely governs any of the interseasonal associations described previously. This consideration is illustrated in Fig. 7 wherein correlations are stratified according to both the equatorial SST anomalies and the North Pacific cooling trend. Each of the analyses in Fig. 7 shows strong correlations between regional spring air temperature anomalies and warm season (summer plus fall) precipitation in area 1. However, in contrast with the findings for area 4 (Figs. 3 and 4), the strongest correlations in this case (Fig. 7B) appear to be linked to the cooling trend in the North Pacific.

Correlations obtained for data stratified according to a combined index of both the SO and the North Pacific cooling trend are shown in Fig. 7C and in Fig. 8. In each case very strong correlations are obtained, though for a somewhat diminished data base. The previously noted trend in Fig. 2A, after 1963, is apparently a reflection of the same associations observed in Fig. 7C, but of the opposite sign relative to spring air temperatures. The results in Fig. 8 show the relationship between fall air temperatures and cold season precipitation in the upper Colorado basin when Pacific SST anomalies are characterized by; (A) warm water in *both* the eastern equatorial areas as well as the northeast and northwest Pacific and; (B) cold surface water in these same areas.

From Figs. 2 through 8 and related results we find that, in general, interseasonal relationships like those discussed above for the northwestern portion of the region (e.g., area 1) appear to be dominated by SST anomalies in the North Pacific. However, for most of the region, influences can be ascribed to both the North Pacific and equatorial Pacific SST fields, with a tendency for stronger correlations in relation to equatorial Pacific SST anomalies, especially for warm season precipitation anomalies.

4. Discussion

The results in the previous section summarize our preliminary analyses of two recurrent patterns in the long-term variations of interseasonal correlations between climate data for the western plateau of the United States. Several additional patterns of long-term variation were observed for other combinations of area indices and seasonal lags but these have not yet been examined in detail. The significance of the results is compromised by the limited spatial domain and lack of rigorous statistical testing. Nevertheless, to establish the direction for additional work it is useful to explore some of the implications of these initial results.

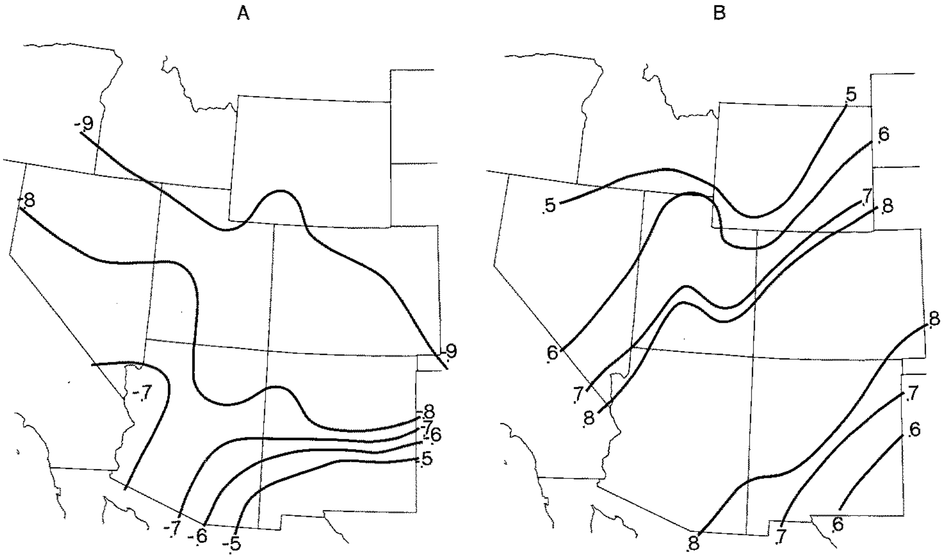

Fig. 8. (A) Ten-year correlations between fall air temperatures and cold season precipitation in the upper Colorado basin for fall 1949 through winter 1964 with the five strongest PSO years (1949, 50, 54, 55, 56) removed. (B) As in A but for fall 1964 through winter 1980 with the six strongest NSO years (1965, 68, 69, 72, 76, 79) removed

It can be argued that the NSO and PSO correlations shown in Figs. 3 and 4 may be a manifestation of the same circulation anomalies that lead to extended droughts in the Great Plains. Chen [26] has shown that when the SO is negative during Northern Hemisphere springs, 700 mb height fields over North America in the following summers tend to assume a pattern similar to that which Namias [27] and Erickson [28] have linked to droughts in the south central United States. This so-called "three wave" pattern consists of anomalously high 700 mb heights centered over the eastern North Pacific, the southern Great Plains and the central North Atlantic. These highs are separated by low centers over the northeastern and southwestern United States. This anomaly pattern tends to be reversed during summers following PSO springs. Composite summer height fields for both phases of the SO also show these same anomaly patterns (Figs. 14 and 15 in [26]). The development of an upper level anticyclone over the southern Great Plains is a normal feature of the annual spring-to-summer transition period. Therefore, relatively wet and cool conditions over the western plateau in spring present a favorable phase association for the timely enhancement of this Great Plains high as part of the preferred three wave pattern of NSO

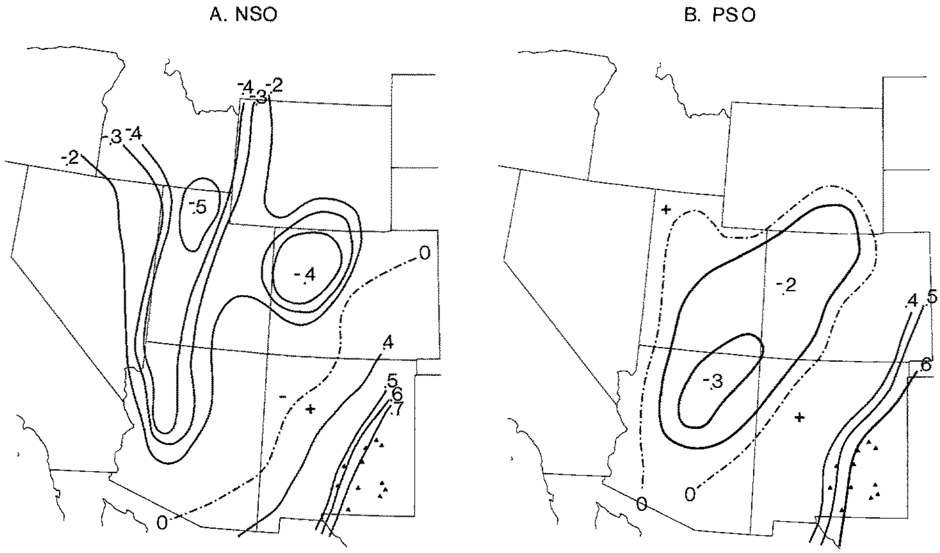

Fig. 9. Correlations between summer precipitation at each station and summer precipitation in area 4 for both phases of the southern oscillation (20 years)

summers. Allowing that enhanced and presistent high pressure over the southern Great Plains tends to suppress convective precipitation in eastern New Mexico, dry summers in area 4 are then systematically linked to wet, cool NSO springs over the plateau as shown in Figs. 3A and 4A. Conversely, dry and warm spring conditions over the plateau will oppose the development of the characteristic three wave pattern of the NSO. Consequently, in this case a diminished or displaced Great Plains high will allow greater than normal summer precipitation in area 4.

This interpretation of Figs. 3A and 4A suggests that summer precipitation anomalies over the plains of eastern New Mexico should be inversely related to summer precipitation over the plateau during NSO years. This conjecture is verified by the results shown in Figs. 9 and 10 which, however, also indicate a similar inverse association during PSO years.

The PSO correlations in Figs. 3B and 4B require a related but somewhat different interpretation. The correlations between summer PSO precipitation in areas 3 and 4 and regional precipitation during the prior winter are shown in Fig. 11. The analyses in Fig. 11 reflect the same general trend that is obtained when regional spring precipitation is correlated with PSO summer precipitation in each of the areas, but the winter to summer correlations are notably stronger as can be seen by comparing Fig. 10B with Fig. 4B. Patterns of correlations similar to, but weaker than, those in Fig. 11 were

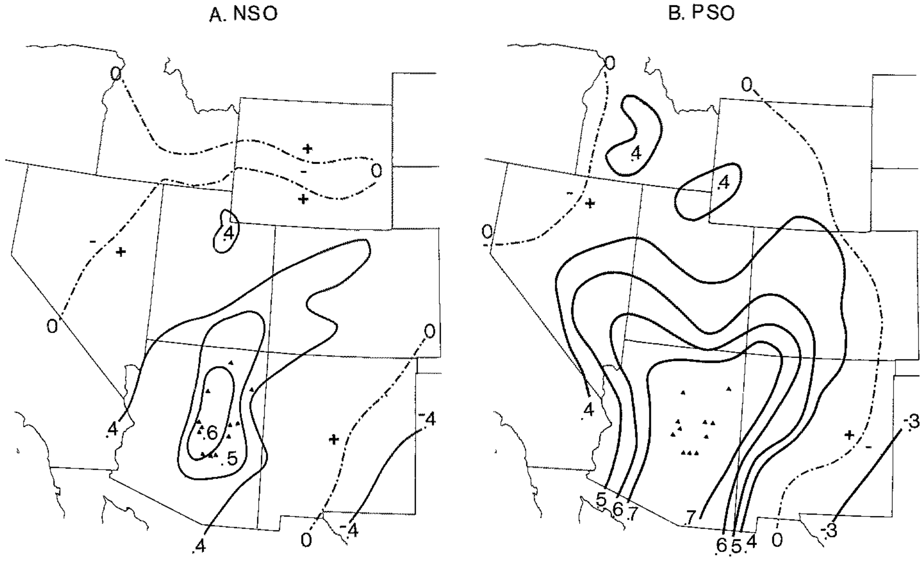

Fig. 10. Correlations between summer precipitation at each station and summer precipitation in area 3 for both phases of the southern oscillation (20 years)

also obtained when combined winter and spring precipitation anomalies were correlated with summer precipitation in areas 3 and 4. The reasons for the latter observation are not clear but may be related to the timing of the onset of the wet seasons in these areas. (The relationships in Fig. 11 also become much stronger when data are further stratified as in Figs. 7C and 8.)

As indicated previously, Chen's study [26] shows a tendency for the occurrence of greater than normal summer 700 mb heights over the western and northern portion of the plateau during PSO summers. Hence, the negative correlations in Fig. 10A suggest that above normal summer precipitation occurs in area 3 when dry conditions and anomalous thermal forcing over the plateau are sufficient to generate low-level advection of moisture into area 3 from the south in opposition to the preferred PSO circulation. This logic can be extended to make inferences for inverse effects during wet PSO springs over the plateau and, for the downwind influence of anomalous plateau conditions on circulation anomalies over the Great Plains and hence, for summer PSO precipitation trends in area 4.

Following the work of Chen [26] and Namias [6], similar arguments can be advanced for mechanisms linking the influence of the SO and North Pacific SST anomalies to the correlations shown in Figs. 6, 7 and 8. However, both these and the previous arguments are speculative in view of the limited scope of the present study.

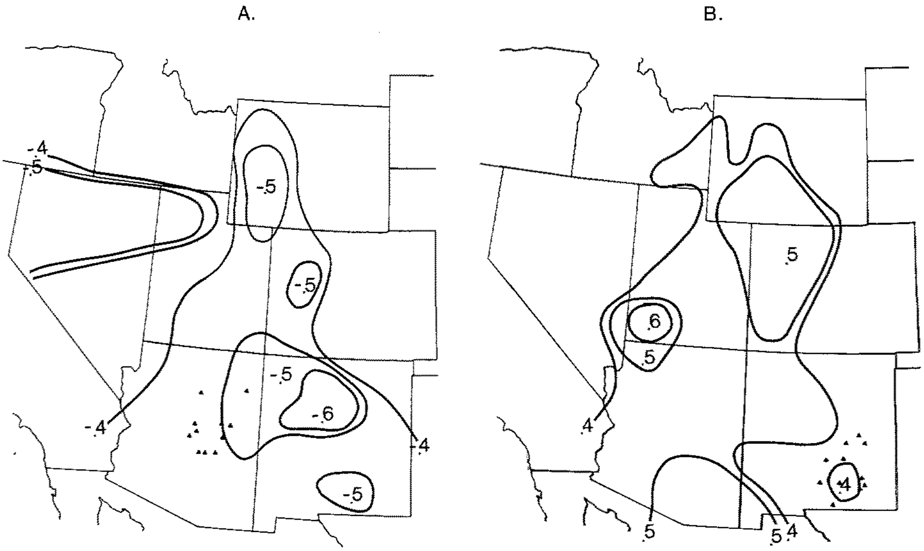

Fig. 11. Correlations between winter precipitation at each station and subsequent summer precipitation in area 3 (A) and area 4 (B) during the PSO

Summary and Conclusions

The long-term trends of SSTs in the equatorial and North Pacific Ocean have been used as indices for separating climatological data for the western plateau of the United States. The resulting data subsets exhibit substantially stonger interseasonal correlations than were obtained either for the entire data period or for limited tests with randomly selected data. When data are grouped according to the sign of SST anomalies in the equatorial eastern Pacific, strong correlations are observed between spring temperatures and precipitation and subsequent summer precipitation, especially in the southern and eastern portions of the Western Plateau. When data are grouped according to the long-term trends of SSTs in the North Pacific, strong associations are observed between fall air temperatures and winter precipitation, especially in the western and northern portions of the study region. Additional systematic stratifications for extreme case SST anomalies and for combinations of both SST anomaly modes consistently lead to even stronger interseasonal correlations. In accord with prior analyses and modeling studies, the results also suggest that certain combinations of anomalous land and sea surface conditions may promote the development of the rather stable circulation patterns associated with notable climatic anomalies.

From these results we conclude that the same climatological factors which govern the long-term variability of broad-scale SST anomalies in the Pacific Ocean also can be observed as slowly varying trends in the interseasonal correlations between various climate data in the western United States. If this apparent linkage can be verified with more rigorous methods, simple climate data should then be useful for making improved seasonal weather forecasts, both for the western United States and presumably elsewhere.

Acknowledgement

The research reported in this paper was supported by the U.S. Department of Energy, Contract DE-AC02-76EV01340.

References

1. Tang, M., Reiter, E. R.: Plateau Monsoons of the Northern Hemisphere: A Comparison Between North America and Tibet. Mon. Weath. Rev. *112*, 617–637 (1984).
2. Reiter, E. R., Tang, M.: Plateau Effects on Diurnal Circulation Patterns. Mon. Weath. Rev. *112*, 638–651 (1984).
3. Dickson, R. R.: Eurasian Snow Cover Versus Indian Monsoon Rainfall – An Extension of the Hahn-Shukla Results. J. Climate Appl. Met. *23*, 171–173 (1984).
4. Hahn, D. G., Shukla, J.: An Apparent Relationship Between Eurasian Snow Cover and Indian Monsoon Rainfall. J. Atmos. Sci. *33*, 2461–2462 (1976).
5. Nicholls, N.: The Stability of Empirical Long-Range Forecast Techniques: A Case Study. J. Climate Appl. Met. *23*, 143–147 (1984).
6. Namias, J.: Multiple Causes of the North American Abnormal Winter 1976–77. Mon. Weath. Rev. *106*, 279–295 (1978).
7. Barnett, T. P., Preisendorfer, R. W.: Multifield Analog Prediction of Short-Term Climate Fluctuations Using a Climate State Vector. J. Atmos. Sci. *35*, 1771–1787 (1978).
8. Wallace, J. M., Gutzler, D. S.: Teleconnections in the Geopotential Height Field During the Northern Hemisphere Winter. Mon. Weath. Rev. *109*, 784–812 (1981).
9. Reiter, E. R.: Teleconnections with Tropical Precipitation Surges. J. Atmos. Sci. *40*, 1631–1647 (1983).
10. Julian, P. R., Chervin, R. M.: A Study of the Southern Oscillation and Walker Circulation Phenomenon. J. Atmos. Sci. *106*, 1433–1451 (1978).
11. Rasmusson, E. M., Carpenter, T. H.: Variations in Tropical Sea Surface Temperature and Surface Wind Fields Associated with the Southern Oscillation/El Niño. Mon. Weath. Rev. *110*, 354–384 (1982).
12. Angell, J. K.: Comparison of Variations in Atmospheric Quantities with Sea Surface Temperature Variations in the Equatorial Eastern Pacific. Mon. Weath. Rev. *109*, 230–243 (1981).
13. Pan, Y. H., Oort, A. H.: Global Climate Variations Connected with Sea Surface Temperature Anomalies in the Eastern Equatorial Pacific Ocean for the 1958–73 Period. Mon. Weath. Rev. *111*, 1244–1258 (1983).

14. Rasmusson, E. M.: El Niño: The Ocean/Atmosphere Connection. Oceanus *27*, 5–12 (1984).
15. Rasmusson, E. M., Wallace, J. M.: Meteorological Aspects of the El Niño/Southern Oscillation. Science *222*, 1195–1202 (1983).
16. Horel, J. D., Wallace, J. M.: Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation. Mon. Weath. Rev. *109*, 813–829 (1981).
17. Weare, B. C., Navato, A. R., Newell, R. E.: Empirical Orthogonal Analysis of Pacific Ocean Surface Temperatures. J. Phys. Oceanogr. *6*, 671–678 (1976).
18. Hsiung, J., Newell, R. E.: The Principal Nonseasonal Modes of Variation of Global Sea Surface Temperature. J. Phys. Oceanogr. *13*, 1957–1967 (1983).
19. Namias, J.: Persistence of U.S. Seasonal Temperatures up to One Year. Mon. Weath. Rev. *106*, 1557–1567 (1978).
20. Davis, R. E.: Predictability of Sea-Surface Temperatures and Sea-Level Pressure Anomalies over the North Pacific Ocean. J. Phys. Oceanogr. *6*, 249–266 (1976).
21. Livezey, R. E., Chen, W. Y.: Statistical Field Significance and Its Determination by Monte Carlo Techniques. Mon. Weath. Rev. *111*, 46–50 (1983).
22. Whittaker, L. M., Horn, L. H.: Geographical and Seasonal Distribution of North American Cyclogenesis (1958–1977). Mon. Weath. Rev. *109*, 2312–2322 (1981).
23. Rodgers, J. C.: Spatial Variability of Seasonal Sea Level Pressures and 500 mb Height Anomalies. Mon. Weath. Rev. *109*, 2093–2106 (1981).
24. Baker-Blocker, A., Bouwer, S. D.: El Niño: Evidence for Climatic Nondeterminism? Accepted for Publication in Arch. Met. Geoph. Biokl., Ser. B (1985).
25. Middleton, J. W.: A Cross-Spectral Study of the Spatial Relationships in the North Pacific Sea Surface Temperature Anomaly Field. Environmental Research Paper No. 23. Colorado State University, Fort Collins, CO (1980).
26. Chen, W. Y.: Fluctuations in Northern Hemisphere 700 mb Height Field Associated with the Southern Oscillation. Mon. Weath. Rev. *110*, 808–823 (1982).
27. Namias, J.: Anatomy of Great Plains Protracted Heat Waves (especially the 1980 U.S. summer drought). Mon. Weath. Rev. *110*, 839–851 (1982).
28. Erickson, C. O.: Hemispheric Anomalies of 700 mb Height and Sea Level Pressure Related to Mean Summer Temperatures Over the United States. Mon. Weath. Rev. *111*, 545–561 (1983).

Authors' addresses: Mr. John D. Sheaffer and Dr. Elmar R. Reiter, Department of Atmospheric Science, Solar House 3, Colorado State University, Ft. Collins, CO 80523, U.S.A.

Verleger: Springer-Verlag KG, Mölkerbastei 5, A-1010 Wien. – Herausgeber: Prof. Dr. Elmar R. Reiter, Colorado State University, Ft. Collins, CO 80523, U.S.A. – Redaktion: Gregor Mendel-Straße 33, A-1180 Wien. – Hersteller: IBM-Composersatz Springer-Verlag Wien. – Reproduktion und Offsetdruck: Adolf Holzhausens Nachfolger, Kandlgasse 19-21, A-1070 Wien. – Verlagsort: Wien. – Herstellungsort: Wien. – Printed in Austria.