Pacific Sea Surface Temperature Associations with Southwestern United States Summer Rainfall and Atmospheric Circulation

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ABSTRACT: Pacific sea surface temperatures (SSTs) are examined for their associations with (1) summer rainfall, and (2) the latitude location of the mid-tropospheric subtropical high pressure ridge (STR) in the southwestern United States during 1945 to 1986. Extreme northward (southward) displacements of STR are associated with wet (dry) summers over Arizona and an enhanced (weakened) gradient of SST off the California and Baja coasts. These tend to follow winters marked by positive (negative) phases of the PNA, Pacific/North America, teleconnection pattern. Recent decadal variations of Arizona summer rainfall (1950s wet; 1970s dry) appear similarily related to southwestern United States synoptic circulation and eastern Pacific SSTs.

INTRODUCTION

Air/sea interaction is a continuing concern in climatic dynamics. SST variations have been implicated in the shorter-term (seasonal, interannual) variations of rainfall and temperature in both tropics and extratropics (e.g., Namias and Cayan, 1981). These often comprise the dominant mode of SST variability in the equatorial and North Pacific known as El Niño Southern Oscillation (ENSO) and its teleconnections (Chiu and Newell, 1983; Ropelewski and Halpert, 1987).

The southwest United States (principally Arizona) experiences a bimodal (winter, mid-summer) precipitation distribution. The summer rainfall singularity (or *monsoon*) dominates the months of July and August and stands in stark contrast to the aridity of the preceding months (Bryson and Lowry, 1955). Strong changes in mid-tropospheric circulation are associated with the arrival of subtropical moisture from the Gulf of California/eastern Pacific (Hales, 1974) and comprise a northward and westward shift of the STR. Within-season and interannual fluctuations in latitude location of STR have been correlated with changes in satellite-observed cloud cover over the southwestern United States (Carleton, 1985) and, accordingly, Arizona precipitation anomalies (Carleton, 1987).

A typing scheme of daily 500mb height patterns associated with southwestern U.S. summer cloud cover variations (Carleton, 1986) has been used to subjectively classify daily maps for summers 1945 through 1987. Figure 1 shows summer mean values of an index of the STR. It is in ratio form and is given as the number of days of northward-displaced STR over the southwest (Four Corners High)/number of days of southward-displaced STR.

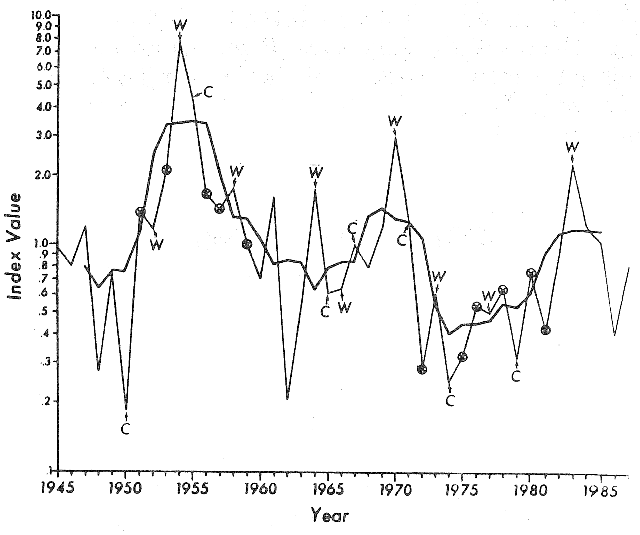

Figure 1. Individual and 5-summer moving averages of the circulation index STR (= n of days anticyclonic north ÷ n of days anticyclonic south) for the southwestern United States, 1945-1987. Note the logarithmic scale on the vertical axis. Summers indicated "W" ("C") follow peak warm (cold) events of ENSO. Other summers (circled "X") are used in the *undisturbed decadal* composites of SST for the 1950s and 1970s (e.g., see Figure 7).

The STR index is significantly correlated with Arizona statewide summer rainfall over a 40-year period, especially for August ($r = 0.698$; $r^2 = 49\%$). Further, STR was consistently farther north in summers of the 1950s and farther south for much of the 1970s (Figure 1). The *persistence* (runs of days) of the anticyclonic types is similarly highly correlated with Arizona rainfall and also with the STR latitude index (Carleton, 1987).

This study examines the associations of Pacific SSTs with both Arizona summer rainfall variations and the STR index for the 1945-1987 period.

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SUMMER STR / ARIZONA RAINFALL ASSOCIATIONS

Table 1 shows the selection of summers used for the composite analysis of Arizona rainfall and Pacific SST. In (a), wet (dry) summers are selected on the basis of at least 45% of Arizona rainfall stations having standardized summer rainfall departures equal to or exceeding + (-) 0.6 standard deviations from the long-term (1951-1980) means for July 1 to September 15 (Weser, 1985).

This results in 8 wet and 8 dry summers, a few of which repeat in Table 1(b). Composite (average) maps of rainfall departures were then derived. In Table 1(b), similar composite rainfall departure maps were derived, only in this case for summers of extreme northward: index values > 2.0 (southward: values < 0.4) STR (refer to Figure 1). The resulting composites (Figure 2) strongly resemble the maps derived using the years in Table 1(a) (not shown). They confirm the role of STR for Arizona summer rainfall variations.

Table 1. Stratification of extreme Arizona summer rainfall and circulation.

(a) 8 Wet and 8 Dry Summers, 1951-1980[a]		*(b)* 5 STR(North) and 7 STR(South) Summers, 1945-1987[b]	
Wet Summers	Dry Summers	STR (North)	STR (South)
1951	1952	1953	1948
1954	1956	1954	1950
1955	1962*	1955	1962
1963	1972*	1970	1972
1964	1973	1983	1974
1966	1978		1975
1967	1979*		1979
1970	1980		

[a] Where at least 45% of stations exceed + (-) 0.60 standard deviations from the 30-year station means.

[b] Where circulation index anticyclonic north/a-c south is greater (less) than 2.0 (0.4).

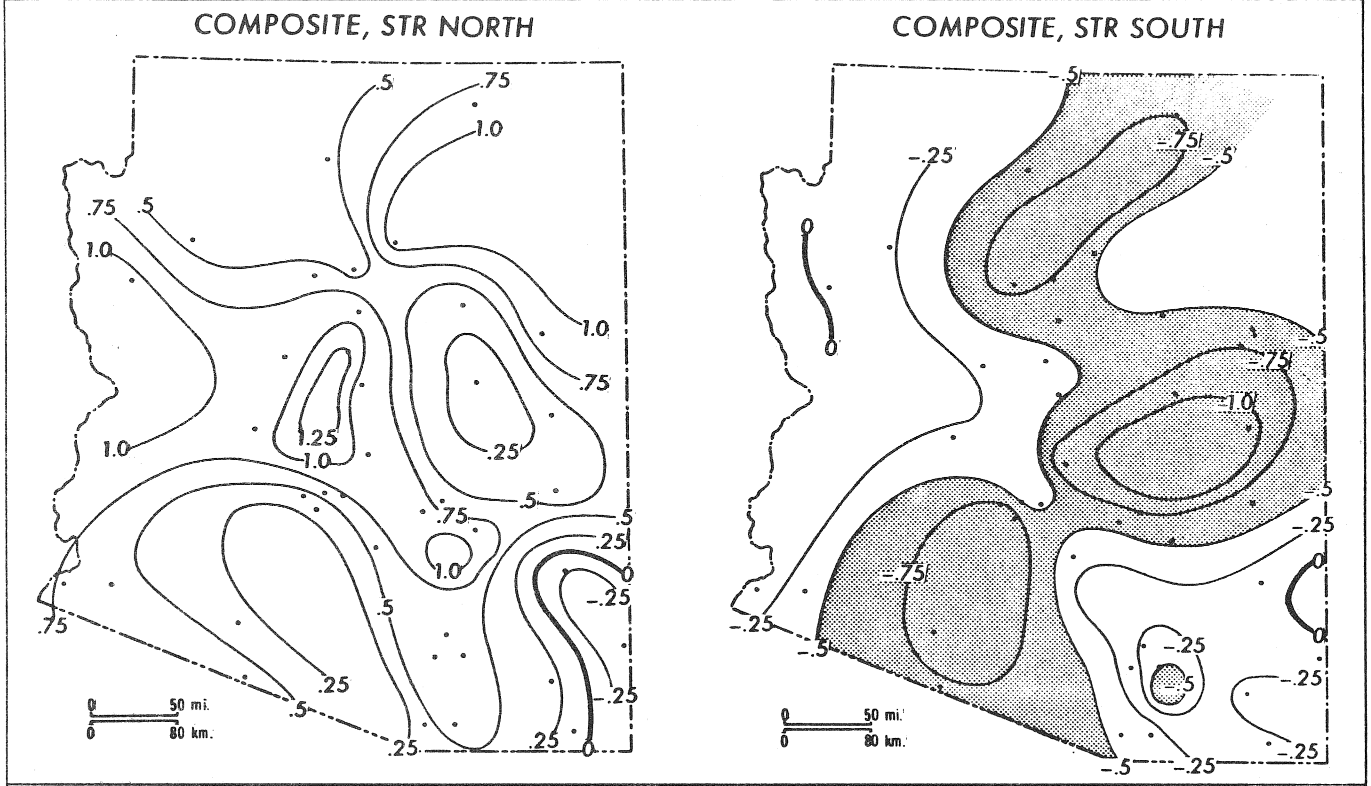


Figure 2. Composite normalized rainfall departure patterns for Arizona (standard deviation units) for summers of extreme northward STR *(5 years: 1953, 1954, 1955, 1970, 1983)* and extreme southward STR *(7 years: 1948, 1950, 1962, 1972, 1974, 1975, 1979)*. The patterns appear very similar to those derived by compositing extreme rainfall summers in the 1951-1980 period (Table 1(a)).

PACIFIC SST / ARIZONA SUMMER RAINFALL ASSOCIATIONS

The Gulf of California and eastern Pacific are important for both intraseasonal variations *(bursts, breaks)* of Arizona summer rainfall (Hales, 1974) and the interannual variations of southwestern United States climate related to ENSO (Sheaffer and Reiter, 1985; Carleton, 1987; Andrade and Sellers, 1988). Thus, an examination of Pacific SST / Arizona rainfall / southwest U.S. circulation relationships is appropriate. Figure 3 shows the area covered by the COADS (*Cooperative Ocean-Atmosphere Data Set*, 10° lat./long. grids) and NODC (*National Oceanic Data Center*, 5° lat./long. grids) SST data of interest in this study. The NODC data are used to identify SST associations with Arizona summer rainfall for the years listed in Table 1(a), and the COADS is used for corroboration and also to identify broad-scale teleconnection patterns of SST that might be related to STR.

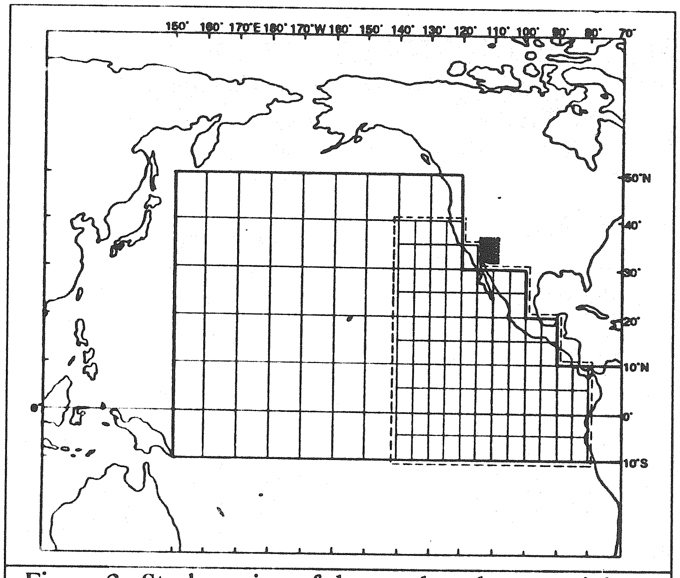


Figure 3. Study region of the north and equatorial Pacific Ocean covered by the COADS (10°x10° lat./long. boxes) and NOCD (5°x5° lat./long. boxes). Arizona is shown shaded.

Compositing the NODC SST data separately for wet and dry summers, subtracting one composite from the other, and performing difference-of-means tests on the cell values reveals the pattern shown in Figure 4 (JJA only). The pattern is somewhat difficult to interpret, because of insufficient numbers of observations in near-equatorial cells and lack of significant differences in others.

However, the general appearance is one of lower SSTs in wet years in cells for which significant differences occur. This resembles broadly the composite difference map for MAM (not shown).

If one correlates the stratified (wet, dry summer) SSTs for six grid cells having acceptable numbers of observations with Arizona statewide rainfall, the results are as shown in Figure 5. Rainfall in the wet summer composite is significantly negatively correlated with SSTs along the California/northern Baja coasts. SSTs in the Gulf of California are weakly positive. The enhanced longitudinal SST gradient in wet summers may favor a low-level wind anomaly from the southwest that facilitates transport of subtropical moisture into the desert southwest.

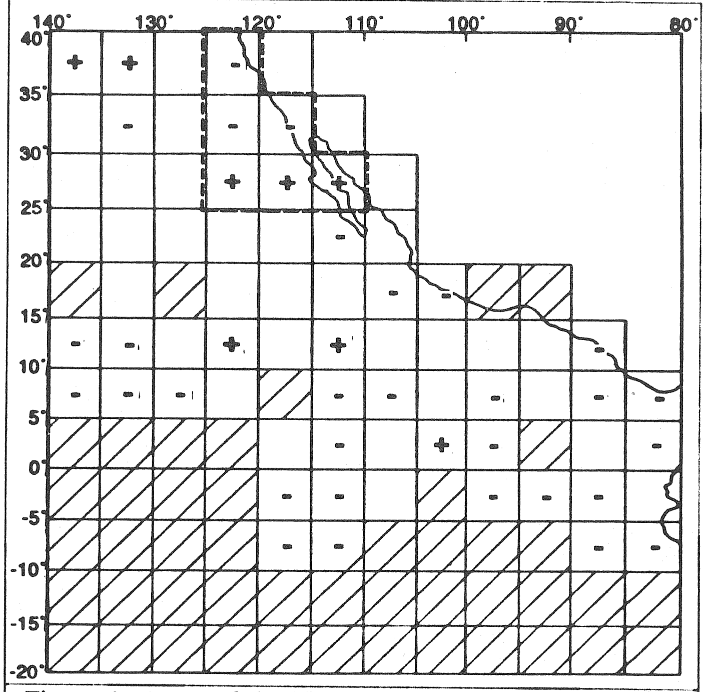


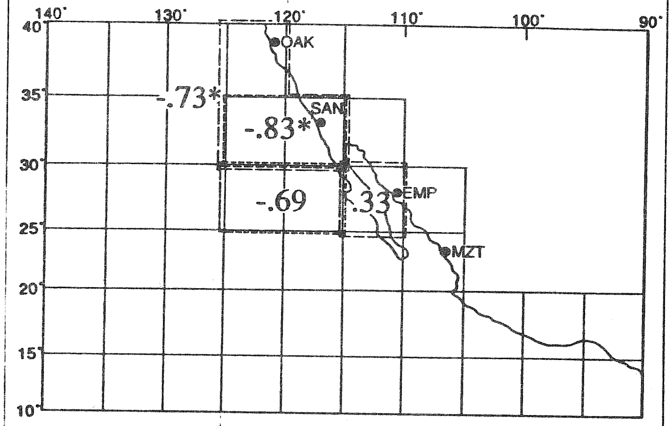
Figure 4. Areas of significant difference in sea surface temperatures between wet and dry composites (Table 1a) for JJA (5% significance level). + = higher SSTs in wet years; – = higher SSTs in dry years; blank = no significant difference. Shaded cells indicate insufficient numbers of observations.

The lack of significant SST/Arizona rainfall correlations in dry summers and absence of a strong longitudinal SST gradient for this region may imply a weakened low-level wind that helps limit the northward penetration of moisture from the eastern Pacific/Gulf of California. This postulated link between the SSTs and wind fields of this region is being investigated.

PACIFIC SST / SUMMER STR ASSOCIATIONS

In an effort to compare the foregoing SST / rainfall results with the association between Pacific SSTs and the circulation (STR), seasonal composite difference maps of COADS SST were computed for summers of STR-north minus STR-south. Possible lead associations of SST over Arizona summer rainfall are considered by computing seasonal difference maps for spring-1 and winter-1. Broadscale summer (i.e., contemporaneous) SST difference patterns are generally weakly defined (not shown); those for winter and spring are more strongly defined. The difference pattern for winter (Figure 6) resembles EOF number 1 of the nonseasonal

a) Wet Summers



b) Dry Summers

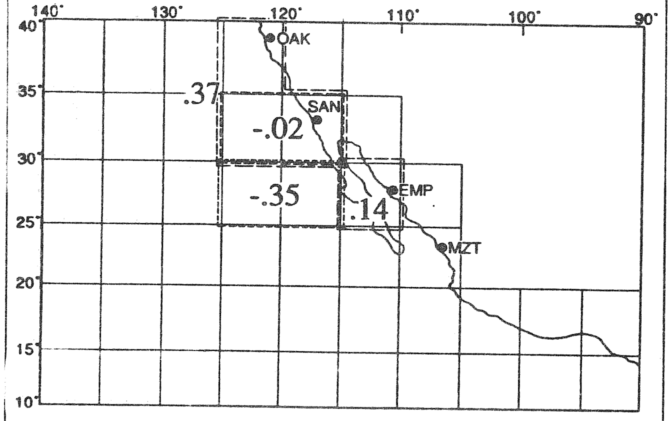


Figure 5. Correlation coefficients between SST and Arizona rainfall stratified according to occurrence in wet versus dry summers (Table 1a). Coefficients are for combinations of six grid cells for which sufficient numbers of observations are available for the years studied (other cells generally have few observations).

SST that is associated with ENSO (e.g., Chiu and Newell, 1983).

Such a pattern may favor (although not exclusively) the positive high amplitude phase of the PNA (Pacific-North America) teleconnection pattern. The role of antecedent winter PNA for the summer circulation and rainfall of the southwestern United States is demonstrated in Table 2. A significant difference exists in PNA winter values that precede extreme STR summers, and is such that a positive, high amplitude (negative, zonal) phase tends to precede STR-north (STR-south). A similar, although slightly weaker, relationship exists for summers composited on the basis of Arizona rainfall departures (Table 2a).

Since high amplitude PNA may occur in the absence of a negative extreme, or El Niño, of the Southern Oscillation Index, SOI (e.g., Hamilton, 1988), there are no significant differences found in the antecedent seasonal

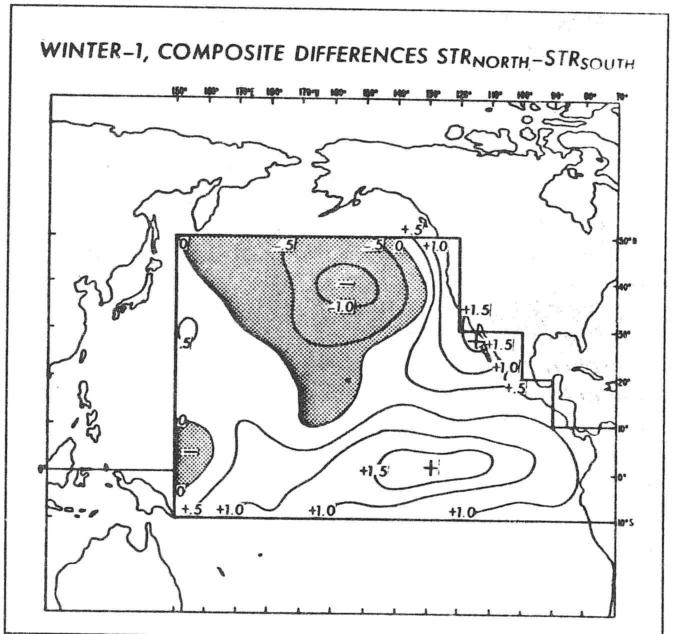


Figure 6. Composite differences of SST (°C) for winters preceding summers of extreme STR-north minus STR-south (Table 1b). Isotherm interval is 0.5°C. Negative differences are shaded.

Table 2. Composite means and significance levels for circulation indices stratified according to extremes of Arizona summer rainfall.

(a) *Wet* vs. *Dry* Summers, 1951-1980

	STR	PI	PNA^{+}	$\mathrm{SOI}_{\mathrm{DJF}}^{*}$	$\mathrm{SOI}_{\mathrm{MAM}}^{*}$
Wet	2.48	1.99	0.28	4.53	2.71
Dry	0.71	0.95	-0.25	4.07	2.59
U-Stat.	12	9	16	27	23
Signif.	0.019	0.007	0.052	-.-	-.-

(b) STR-North vs. STR-South Summers, 1945-1987

	PI	PNA^{+}	$\mathrm{SOI}_{\mathrm{DJF}}^{*}$	$\mathrm{SOI}_{\mathrm{MAM}}^{*}$
STR-North	2.38	0.39	2.80	2.47
STR-South	0.55	-0.49	5.65	3.43
U-Stat.	0	4	3	9
Signif.	0.002	0.026	0.015	0.165

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[*] Based on the non-normalized seasonal values of Parker (1983).

[+] Based on the winter season values (DJF) provided

SOI and Arizona summer rainfall (Table 1a). This compares with the summer season results of Andrade and Sellers (1988). However, a significant difference is observed for winter SOIs and summer STR (Table 1b). Note also the consistent and significant differences in STR between summers of opposing Arizona rainfall anomalies (Table 1a).

DECADAL CHANGES IN PACIFIC SST/STR/ARIZONA RAINFALL

The foregoing results suggest strongly that wetter (drier) summers in Arizona are marked by generally northward (southward) displaced STR over the southwestern United States and an enhanced (weakened) SST gradient between the California/Baja coasts and Gulf of California. In addition, wetter (drier) summers seem to follow positive (negative) phases of PNA and associated broadscale SST patterns. Examination of Figure 1 reveals runs of summers in the 1950s (1970s) that were characterized by northward (southward) displaced STR. Similarily, a tendency toward decreasing summer rainfall in Arizona during the 1960s and 1970s has been noted elsewhere (e.g., Johnson, 1978). The question arises as to the possible changes in Pacific SST between the 1950s and 1970s that may have been, at least partly, responsible for these rainfall/circulation variations.

Difference patterns of the composite SSTs for summers of the 1950s (1951-1959) minus the 1970s (1972-1981) are spatially inhomogeneous (not shown). These arise, in part, from the presence of ENSO extremes in those decades (Figure 1). Removing these years and computing *undisturbed decadal* SST composites and difference fields for the remaining years of the 1950s and 1970s reveals more spatially homogeneous patterns. The difference pattern for summer, which is broadly similar to that for spring-1, is shown in Figure 7. Figure 7 suggests that the runs of wetter (drier) summers and northward- (southward-) displaced STR in the 1950s (1970s) were associated with an enhanced longitudinal gradient of SST between the Gulf of California and California/Baja coasts. This may have influenced the transport of subtropical moisture at lower levels into the desert southwest in a similar way to that suggested for the multi-year cross-decadal composites computed earlier. Future studies hope to examine in more detail these decadal variations in SST and their impact on the atmospheric circulation of the southwestern United States.

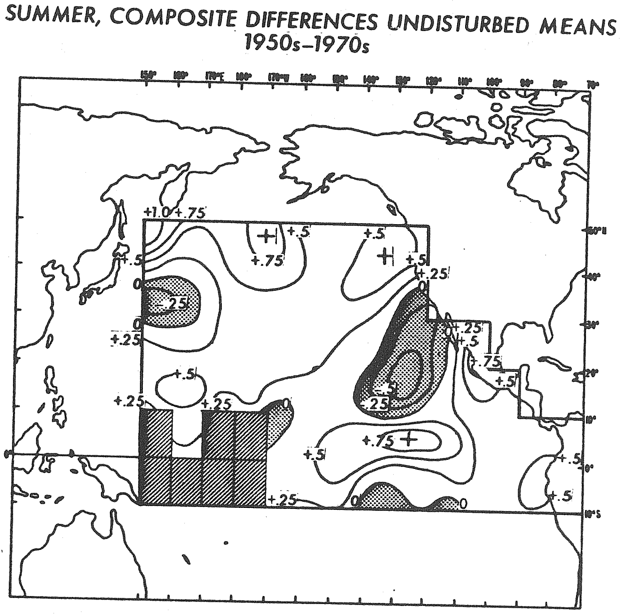

Figure 7. Similar to Figure 6, except in summer and for composite *undisturbed decadal* differences, 1950s minus 1970s (refer to Figure 1). Shaded cells indicate absence of data in one or more years. Note the change in the isotherm interval to 0.25°C compared with Figure 6.

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