Surface Temperature Patterns Associated with the Southern Oscillation

MICHAEL S. HALPERT AND CHESTER F. ROPELEWSKI

Climate Analysis Center, NMC/NWS/NOAA, Washington, D.C.

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ABSTRACT

The "typical" global and large-scale regional temperature patterns associated with the low (warm) and high (cold) phases of the Southern Oscillation (SO) are investigated. A total of 12 separate regions were found to have consistent temperature patterns associated with low phase of the SO, while 11 areas were found to have temperature patterns associated with the high phase. Of these areas, 9 have expected temperature patterns during both phases of the SO. In the tropics, temperature anomalies are of the same sign as the SO-related sea surface temperature (SST) anomaly in all land regions except for one area in the west Pacific. Three extratropical responses to the low phase of the SO are found over North America and one is found in Japan. High SO-temperature patterns were found in the extratropics for Japan, western Europe, and northwestern North America. The identified temperature responses are more consistent in tropical regions than in the extratropics. The SO can influence the estimation of global surface temperature anomalies.

1. Introduction

A series of earlier studies by Ropelewski and Halpert (1986a, 1987, 1989) examined and documented large-scale precipitation patterns associated with the low (ENSO) and high phases of the Southern Oscillation (SO). In those studies, seasons and regions of SO-precipitation relationships were defined for several regions of the globe. This paper will provide a logical extension of prior work by exploring SO-temperature relationships using a similar methodology. The SO has been studied extensively, and it is now well known that the low phase of the SO (warm event) is associated with above-normal central Pacific sea surface temperatures (SSTs), while negative SST anomalies occur in conjunction with the high phase (cold event).

Much of the work relating the SO to surface parameters has focused on precipitation (e.g., Ropelewski and Halpert 1987, 1989; Shukla and Paolino 1983; Douglas and Englehart 1981). Walker and Bliss (1932) indicated SO-temperature relationships in some regions of the globe through a study of SO-temperature correlations. Berlage (1966) found some relationship between high-phase SO “relaxations” and northwest European cold winters. Newell and Weare (1976) first demonstrated that tropical temperature anomalies in the troposphere are in phase with SST anomalies in the equatorial Pacific. Others who examined relationships between tropospheric temperatures and equatorial Pacific SST anomalies included Angell (1981) and Pan and Oort (1983). These results were extended to surface temperatures and stratified into latitude bands by Bradley et al. (1987). Other work relating the SO and surface temperature variations has been performed by van Loon and Madden (1981), Ropelewski and Halpert (1986b), Kiladis and van Loon (1988), and more recently, Kiladis and Diaz (1989).

In this paper, we will present a comprehensive examination of the temperature patterns associated with the high and low extremes of the SO, extending the work of previous authors to encompass all relationships found to be associated with both phases of the SO. While other studies have examined SO-temperature relationships for predetermined seasons (e.g., Kiladis and van Loon 1988; Kiladis and Diaz 1989), this study lets the data determine the period of greatest SO-temperature response. Through harmonic analysis and compositing, the analysis identifies those regions with consistent SO-temperature relationships and also determines the seasonality of these relationships. Since precipitation relationships for a particular area were often found to mirror each other during both extremes, areas that are found to have an SO-temperature relationship for either extreme are also examined during the opposite phase. However, the harmonic analysis and ensuing compositing are done independently for each phase. Those areas having a statistically significant SO-temperature relationship will be identified and discussed, whenever possible, in terms of relevant circulation features.

2. Data

Global monthly mean temperature data for about 1200 stations were used for this study. Data for some
stations extend back to the 1880s, spanning a period of 25 ENSO episodes (Table 1) and 20 high SO periods (Table 2). Stations with less than 30 years of data were excluded from the analysis. A station's historical dataset must have included a minimum of 5 high or low SO events for it to have been included in the analysis. The primary source of these historical data is the World Monthly Surface Climatology provided by R. Jenne of the National Center for Atmospheric Research. Additional data were supplied by the Australian National Climate Center and some South and Central American data were supplied by Dr. Fred Wiernstadt of The Pennsylvania State University. Data for the 1980s were obtained mainly from CLIMAT reports received over the global telecommunications system at the National Meteorological Center. High SO years were defined as those years during which the Tahiti–Darwin SO index remains in the upper 25% of the distribution for 5 months or longer, while low SO years were defined as those years during which the SO index remains in the lower 25% (Ropelewski and Jones 1987). This definition of the low phase of the SO is different from the convention of Quinn et al. (1978) and Rasmusson and Carpenter (1982), which identified ENSO years according to the SST in the eastern Pacific. Deser and Wallace (1987) showed that SSTs in the eastern Pacific and the SO do not always act together. Since Horel and Wallace (1981) showed that extratropical teleconnections are related to SSTs in the central Pacific (and hence the SO), we have chosen the ENSO years according to the convention defined above.

3. Analysis

The analysis methods used here are similar to the methods used in Ropelewski and Halpert (1986a, 1987, 1989). Details can be obtained in Ropelewski and Halpert (1986a) and are outlined below. The monthly temperature means are represented as percentile ranks as suggested by Meisner (1976). Each calendar month of the entire record is ranked from 1 for the coldest month to n for the warmest month in an n year series. The ranks are then normalized by the number of years and multiplied by 100. This allows for comparisons between stations with different record lengths.

Twenty-four-month percentile rank composites are computed for each station, starting with the July preceding the event [designated Jul(−)], continuing through the June following the event year [Jun(+)], for both high and low phases of the SO. Composites are computed separately for each phase of the SO. The composite for each station is then fitted with the first harmonic of an idealized 24-month SO cycle (either high or low). This method assumes one temperature peak (or trough) during the duration of an SO event and also that the SO is phase locked to the annual cycle. If the relationship between the SO and temperature is not a simple one (i.e., more than one peak or trough during the event), or if the timing of the episode is inconsistent with the idealized event, this method will not clearly define it. A 24-month compositing period was chosen since this defines the period during which one phase of the SO goes through its entire cycle (Rasmusson and Carpenter 1982).

There are several difficulties associated with this compositing method. There are occasions throughout the record when high and low SO events occurred in consecutive years (i.e., 1972 and 1973). This produces the result that the year (−1) from one event can be the year (0) from the opposite event. Due to the apparent biennial nature of the SO (Meehl 1987; Kiladis and van Loon 1988; Rasmusson et al. 1990), these events can be thought of as one “complete” SO event. However, we performed the analyses as if the events are independent, since there are a number of high and low episodes that are not directly followed or preceded by an event of the opposite phase, and we also expect different responses during the two phases. There are also several instances where one phase of the SO spanned two years (i.e., 1970 and 1971). In these instances, only the first year of the event was used.

After the station composites are fit with a 24-month harmonic, the amplitude and phase of that harmonic is plotted as a vector for each station (Figs. 1a and 1b). In the analysis convention chosen here, the vector points toward the positive part of the cycle, that is, warmer-than-normal temperatures. It is only after examining the composites, described below, that the actual sign of the SO–temperature relationship can be determined. This study is concerned with large areas of the globe that exhibit strong SO–temperature relationships over periods of many months. Therefore, individual, or isolated, stations that show strong apparent relationships or areas that have short-time scale relationships are not considered for further study.

It is evident from Fig. 1 that potential SO–temperature relationships occur in the extratropics as well as in the tropics. This is evidenced by the many regions where neighboring vectors have a similar phase, such

<table>
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<th>Table 1. Years during which the Tahiti–Darwin Southern Oscillation index remained in the lower 25% of the distribution for 5 months or longer (after Ropelewski and Jones 1987).</th>
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<th>Table 2. Years during which the Tahiti–Darwin Southern Oscillation index remained in the upper 25% of the distribution for 5 months or longer (after Ropelewski and Jones 1987).</th>
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as in the northwestern part of North America. In high data density areas, only the vector based on the longest data record is plotted in each 4° latitude by 4° longitude subarea. However, these areas are only candidate regions for SO-temperature relationships. In order to better define the candidate areas, the “coherence” (see Ropelewski and Halpert 1986a) was computed and areas were modified so that the coherence for the candidate regions exceeded 0.85. The coherence is a measure of the consistency of the vector phases and is computed by calculating the ratio of the magnitude of the average harmonic vector for the region to the average of the individual vector magnitudes. The vector maps by themselves are not sufficient to establish the consistency of these relationships. Composites for these areas are needed to define the sign and season of the relationship, and then an examination of the time series is used to determine whether the relationship is statistically significant.

The temperature anomalies associated with the SO
appear to be of opposite sign for the two phases. This is illustrated in many areas throughout the tropics (Figs. 1a and 1b), including northern South America and the Caribbean, northern and central Australia, and Southeast Asia, which have vectors that point in opposite directions during the two phases. This implies that for a specific region, the sign of the potential anomaly will be opposite in the different SO phase or that the timing of the anomaly is 180° (one year) out of phase. Areas outside the tropics that have possible temperature relationships during both phases of the SO include southern Africa, central South America, and northwestern North America. From the harmonic vectors, it appears that Japan and the western Europe/northern Africa region have SO–temperature relationships only during the high phase, while the southeastern United States has a relationship only during the low phase.

Twenty-four-month standardized temperature composites centered on both the high and low phase of the SO were produced for all areas that had potential SO–temperature relationships during either phase. Since 8 warm event years follow cold episode years, it is possible that the harmonic vectors in areas with a strong signal for one phase might mask the signal in the other phase. Therefore, composites were produced and examined for both phases as long as one of the phases had a potential signal.

Southern Oscillation composites are used to subjectively identify “seasons” during which a consistent SO–temperature relationship might exist in the areas chosen from the analysis of the vector maps. These composites also give the sign of that relationship. Time series for these periods are then examined in order to determine the statistical significance of the SO–temperature relationship. The significance of the SO–temperature relationships is estimated through use of a hypergeometric distribution (Feller 1957). More details on the use of this distribution can be found in Ropelewski and Halpert (1987). All of the relationships examined here were significant at the 95% level, with the majority significant at the 99% level.

4. Regional temperature relationships

a. Global tropics

The global tropics is the area of the globe most directly affected by the Southern Oscillation. In the following discussion, the tropics include all areas located within 20° of the equator. The buildup of above-normal SSTs that accompanies the low phase of the SO results in above-normal land temperatures for many areas in the global tropics. Likewise, the below-normal SSTs found in conjunction with the high phase of the SO are associated with below-normal land temperatures throughout most of the tropics. The 24-month standardized temperature composite centered on the high phase of the SO (Fig. 2a) indicates that during cold events, temperatures in the global tropics are below normal during the Jul(0)–Jun(+) period. During warm events, the composite (Fig. 2b) implies that temperatures are above normal on average for the same period. A time series of standardized temperatures averaged over land stations in the global tropics (Fig. 3a) based on the Jul(0)–Jun(+) period shows the magnitude of the cooling during cold events. Of the 20 cold episodes that occurred between 1881 and 1988, only during the 1988 cold episode did tropical surface temperatures average above normal. In general, the magnitudes of the SO-related interannual temperature variability are much larger than the estimated recent trends in global surface temperature (Jones 1988; IPCC 1990). Nonetheless, the failure of the 1988 cold episode to be associated with colder-than-normal surface temperatures in the global tropics may be related to these longer-term trends. On the other hand, a time series of the zonally averaged 500-mb virtual temperature anomaly for the tropics (Fig. 4) shows that tropospheric temperatures during 1988 and 1989 were well below the 1979–88 mean. During the 25 warm events that occurred during the past 110 years, 21 were accompanied by above-normal temperatures. Both of the these relationships are significant at the 99% level based on the hypergeometric distribution.

Based upon the analyses described earlier, eight separate areas have been identified that have SO–temperature relationships and have at least 50% of their total area in the tropics. Of these regions, only the south-central and western Pacific area (an area between 10°S and 40°S, 160°E and 150°W) (Figs. 5a and 5b) has harmonic vectors that imply that the temperature anomalies are out of phase with the sea surface temperature anomalies in the central equatorial Pacific. The composites for this area of the Pacific (Figs. 2c and 2d) indicate that the temperature response to the Southern Oscillation is opposite for the two phases and occurs from Jan(0) through Nov(0). Cooler-than-normal conditions are found in 13 out of the 14 warm event years (Fig. 3b), consistent with the negative SST anomalies found in this region of the Pacific (Rasmusson and Carpenter 1982) during ENSO events. Conversely, warmer-than-normal conditions are found during all 10 cold event years. These reliable and early occurring relationships suggest that the western Pacific is important very early for both high and low phases of the SO. This is consistent with Meehl (1987), who concluded that the Indian–Pacific region is involved with producing SO-type signals in the ocean and the atmosphere, and with Trenberth and Shea (1987), who detailed the tendency for changes over the South Pacific to lead the SO.

The west coast of South America is another tropical region with very consistent SO–temperature relationships. This area is directly affected by the SST changes in the eastern Pacific. The map of harmonic analysis vectors (Figs. 6a and 6b) indicates strong relationships
during both phases of the SO for the coastal regions of Ecuador, Peru, Bolivia, and northern Chile. The strongest response in this region occurs during the May(0)–Apr(+) period (Figs. 2e and 2f), with above-normal temperatures occurring during warm events and below-normal temperatures during cold events. Although the historical record for stations in this region extends back only to the late 1940s, this period encompasses nine cold and nine warm event years. The May(0)–Apr(+) time series for this region (Fig. 3c) shows that all 9 warm event years are associated with above-normal temperatures, while below-normal temperatures occurred during every cold event year. The analysis expands on the SO–temperature correlation study presented by Aceituno (1988) by differentiating between the relationships for each SO phase separately and by
more clearly defining the "season" or time of the year with maximum SO-temperature response.

The harmonic vectors for South America (Figs. 6a and 6b) also indicate two other regions, Central America–Caribbean and central South America, which have potential SO-temperature relationships. These SO-temperature relationships are consistent with the correlation studies of Aceituno (1988). The Central America–Caribbean region appears to have strong temperature responses during both phases, as evidenced by the large, coherent area of vectors along northern South America, the Caribbean Islands, and Central America. The central South American region includes southern Brazil, Paraguay, the eastern half of Bolivia, and the northern part of Argentina for the low-phase years, while extending farther south during high-phase years to include central Argentina. Although the vectors in these two areas point in the same general direction, the areas are examined separately because of the sparsity of data throughout Brazil.

Below-normal temperatures from Jul(0) through Jun(+) in the Central American–Caribbean area are expected during cold event years (Fig. 2g) with above-normal temperatures for the same season during warm event years (Fig. 2h). The time series for the Jul(0)–Jun(+) period (Fig. 3d) shows that below-normal temperatures occurred during 10 of the 12 high-phase years in the record. The low SO-temperature relation-

**Fig. 3.** Temperature index (average standardized temperature) time series for (a) global tropics, Jul(0)–Jun(+) period; (b) south-central/west Pacific, Jan(0)–Nov(0) period; (c) west coast South America, May(0)–Apr(+) period; and (d) Central America–Caribbean, Jul(0)–Jun(+) period. The shaded bars represent few SO years and the arrows point at high SO years. (A downward pointing arrow indicates below normal temperatures.)

**Fig. 4.** Zonally averaged 500-mb temperature anomaly for the latitude band 20°N–20°S. The anomalies are calculated by subtracting the 1979–88 monthly mean temperatures for this latitude band from each of the monthly mean averaged temperatures. The x's indicated individual monthly values. The solid line is the 5-month running mean for the anomalies.
Fig. 5. Subjectively determined "core regions" of consistent (a) low or (b) high SO-temperature relationships: Eurasia, Africa, and Australia.
ship is also strong, with 15 out of the 18 low-phase years experiencing above-normal temperatures. Both of these relationships are significant at greater than the 99% level and are consistent with the general relationship in the tropics of above-normal temperatures during low-phase years and below-normal temperatures during high-phase years.

The 24-month temperature composites for the central South American region (Figs. 2i and 2j) indicate that the SO-temperature response is not as strong (coherent) as the relationship in the Central American-Caribbean region. The low-phase composite indicates above-normal temperatures from May (0) through Apr(+), while the composite based on the high-phase years indicates a period of below-normal temperatures that extends from Oct(0) through May(+). Both composites, however, show that December temperatures average near normal. Nevertheless, the time series for the Oct(0)–May(+) period (Fig. 7a) shows a very consistent signal with 13 of the 17 high-phase years having below-normal temperatures. Also, the five coldest Oct–May periods occurred in conjunction with the high phase of the SO. The time series for the May(0)–Apr(+) period (Fig. 7b) reveals that 15 out of the 20 low-phase years are associated with above-normal temperatures in this region. Given the total distribution of warm and cold years, this relationship is statistically significant at the 99% level. Also, 4 of the 7 warmest May–Apr periods are associated with the low phase of the SO, while none of the coldest May–Apr periods occurred in conjunction with a warm episode.

The harmonic vector maps (Figs. 5a and 5b) indicate that Africa has two potential areas of SO-temperature relationships. The area in western Africa, which stretches from just north of the equator to the northern edge of the Sahel, and the southeastern quarter of Africa, both have vectors that are consistent during both phases of the SO. However, the coherence for the western Africa region drops to below 0.90 during both phases of the SO. This indicates that the SO response throughout this region is not as strong and regular as the response in some of the other tropical regions.

Temperatures for the western Africa region are below normal during high-phase years for the Jul(0)–Jun(+) period (Fig. 8a) and above normal from Jul(0)–May(+) during low-phase years (Fig. 8b). The time series for the Jul(0)–Jun(+) period (Fig. 7c) extends through 9 high-index years and shows that this region experienced below-normal temperatures during all 9 years. The time series based on the Jul(0)–May(+) season for the low phase of the SO (Fig. 7d) is not as consistent as the time series for the high-phase years. Of the 11 low-index years in the record, only 8 experienced above-normal temperatures. Although five of the nine warmest July–May periods occurred during a low-phase year, the significance level of this relationship falls below the 95% level and thus is not statistically significant.

The cold event temperature composite for the
southeast Africa region (Fig. 8c) indicates a consistent signal with below-normal temperatures occurring from Aug(0) through Jun(+). A shorter period, beginning in Oct(0), is found in the composite based on the warm event years (Fig. 8d). The time series for these two periods support the idea that the SO-temperature relationship is very strong in this region. The Aug(0)–Jun(+) time series (Fig. 7e) shows that only 1 of the 17 high-phase years had above-normal temperatures. Likewise, the Oct(0)–Jun(+) period (Fig. 7d) also shows a very regular pattern with 20 out of the 23 low-phase years experiencing above-normal temperatures. This region includes an area that has been shown to experience drier-than-normal conditions from Nov(0) through May(+) during ENSO years (Ropelewski and Halpert 1987) and above-normal precipitation from Nov(0) through Apr(+) during the high phase of the SO (Ropelewski and Halpert 1989). The observed temperature patterns in this region are consistent with the increased (decreased) cloudiness and above-(below-) normal rainfall associated with cooler (warmer) temperatures.

Another tropical region with an apparent SO-temperature relationship is Southeast Asia, extending westward to India. The harmonic vectors for this region (Fig. 5a and 5b) point in the same general direction throughout this entire region. We examined the Indian area and the Southeast Asian area separately, but elected to combine the areas since the results for the individual areas were similar. Temperature anomalies for the whole region are below normal from Jul(0) through Jun(+) during high-phase years (Fig. 8e) and above normal for the Oct(0)–Jun(+) period during low-phase years (Fig. 8f).

The time series for the Jul(0)–Jun(+) period (Fig. 9a) shows that out of the 20 cold event years, only 2 were associated with above-normal temperatures, including 1988. In addition, most of the coldest years in the record occurred in conjunction with the high phase of the SO. The Oct(0)–Jun(+) time series (Fig. 9b) shows that 20 out of 25 low-phase years were warmer than normal, including 9 of the warmest 13. Both of these relationships are significant at the 99% level. This is consistent with results obtained by Kiladis and van Loon (1988), who found temperatures during the Nov(0)–Jan(+) period are above normal during the low phase and below normal during the high phase of the SO. The time series for the individual areas (not shown) are similar, with negative temperature anomalies occurring in 17 out of the 20 high-phase years in India and 17 out of 18 cold episode years experiencing colder-than-normal temperatures in Southeast Asia. For the low phase of the SO, 17 out of 23 Oct(0)–Jun(+) seasons had positive temperature anomalies.
in Southeast Asia, while India experienced above-normal temperatures during 19 out of 25 years.

The harmonic vectors for eastern Australia, based on the low-phase years (Fig. 5a), show two coherent areas, one in northeast Australia and another located to the south in subtropical central Australia. The high-phase vector map (Fig. 5b) indicates that the timing of the SO–temperature relationship in both regions is similar. Therefore, two areas for low SO–temperature relationships were analyzed separately but combined when examining the high phase of the cycle.

The low-phase composites for the northern and central regions (Figs. 8g and 8h, respectively) indicate that the central area experienced above-normal temperatures between Nov(0) and Jun(+), while the northern region has below-normal temperatures between May(0) and Oct(0) and positive temperature anomalies during the Dec(0)–Jun(+) period. The time series
(Figs. 9c–9e) for these regions support these relationships. In the northern region, 16 of the 20 warm event years were associated with above-normal temperatures during the Dec(0)–Jun(+) period, including 10 of the warmest 13. The relationship between negative temperature anomalies during the May(0)–Oct(0) period and the low phase of the SO is also very strong, with below-normal temperatures occurring in 18 out of the 21 low-phase years. The central region response is also statistically significant, with 14 warm Nov(0)–Jun(+) periods out of 20. The period of positive temperature anomalies is consistent with the timing of less-than-normal precipitation found during ENSO years (Ropelewski and Halpert 1987). However, this SO-temperature relationship is not as consistent as the response found in the northern region, probably because it is located outside the tropics and is influenced by other circulation features.

The temperature composite for the combined northern and central region in Australia centered on the high-phase years (Fig. 8i) is similar (although opposite) to the northern region low-phase composite in that there are two seasons of potential SO-temperature relationships identified. The composite indicates that the Apr(0)–Oct(0) period experiences above-normal temperatures, while the Nov(0)–Jun(+) period has temperatures that are below normal. The time series for the austral winter season (Fig. 9f) shows that 12 of the 17 cold event years had above-normal temperatures. Also, 5 of the 10 warmest seasons occurred in conjunction with the high phase. The Nov(0)–Jun(+) time series (Fig. 9g) shows that 14 of these 17 seasons experienced colder than normal temperatures. Both of these relationships are statistically significant at the 95% level. These results further refine the timing of the SO-temperature relationships of Kiladis and Diaz (1989), who found that temperatures during cold event years in this region are warmer than warm event tempera-
tures during the Jun(0)–Aug(0) season but that the reverse is true during the Dec(0)–Feb(+) and Mar(+)–May(+) seasons.

b. Extratropics

While most of the relationships between the Southern Oscillation and the temperatures in tropical regions can be associated with either shifts in convection or to the direct influence of the changes in the SSTs, SO–temperature patterns in the extratropics are probably related to shifts in the large-scale flow pattern (Rasmussen and Wallace 1983). The harmonic vectors (Figs. 1a and 1b) indicate that northern Europe, eastern Canada, northwestern North America, the southeastern United States, and Japan have possible temperature relationships with either the high or low phase of the SO. The low SO–temperature relationships in northwestern North America and the southeast United States were examined in Ropelewski and Halpert (1986a) and will not be discussed further here. These areas are, however, included in Table 3, with statistics based on the low-phase years that are used in this paper.

In addition to the areas in the southeastern United States and in the northwestern part of the continent, the harmonic vector map based on the low-phase years for North America (Fig. 6a) shows an area with a potential SO–temperature relationship located in eastern Canada. Ropelewski and Halpert (1986) originally found that the composite for eastern Canada did not support further analysis. However, we reexamined possible ENSO–temperature relationships in this area due to the acquisition of additional data. The standardized temperature composite (Fig. 10a) indicates that above-normal temperatures occur during the Dec(0)–May(+) period. The time series for the Dec(0)–May(+) season (Fig. 10b) shows that temperatures in 9 of the 12 ENSO years in the record were above normal. This result is significant at the 95% level.

The high-phase year harmonic vectors (Fig. 6b) indicate that potential relationships between temperature and cold events exist for the northwestern quarter of North America and in the eastern Great Lakes/southeastern Canada region. The temperature composite for the northwestern region (Fig. 10c) implies that this area experiences below-normal temperatures during the Nov(0)–Mar(+) period. No coherent period of above- or below-normal temperatures was found to exist in the eastern Great Lakes/southeastern Canada region. The time series for the Nov(0)–Mar(+) period (Fig. 10d) shows that 18 of the 20 high-phase years were accompanied by negative temperature departures in northwestern North America. This high SO–temperature relationship occurs in roughly the same season as the ENSO-related temperature relationship (Ropelewski and Halpert 1986a). The Pacific–North American (PNA) circulation pattern (i.e., trough in the Gulf of Alaska, ridge over northwestern North America, and trough in the Southeast) has been associated with the low phase of the SO (Horel and Wallace 1981). The high SO–temperature relationship in northwestern North America is consistent with a PNA pattern with opposite anomaly signs to what is seen during low-phase conditions.

The harmonic vector map based on the cold event years (Fig. 5b) indicates that relationships between the

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* From Ropelewski and Halpert 1986.
SO and temperature might exist for Japan, although the harmonic vectors for the warm event years (Fig. 5a) do not indicate a companion signal. The high-phase temperature composite (Fig. 11a) for this area implies that Japan experiences below-normal temperatures during the Nov(0)–May(+) season. The time series for the Nov(0)–May(+) season (Fig. 11b) shows that 16 out of the 20 high-phase years experienced temperatures that were below normal. However, during 3 out of the past 5 cold events, temperatures in Japan have been above normal, including 1988–89, which was the warmest Nov(0)–May(+) season in the record. Nev-
ertheless, the relationship between the high phase of the SO and below-normal temperatures in Japan is significant at the 95% level. It remains to be seen if the behavior of this SO–temperature relationship is stable or if the past five events are a statistical aberration. In fact, it is possible that other SO–temperature relationships discussed here are also statistical aberrations (Katz 1988), since there will always be some relationships that will be significant simply due to chance.

The temperature composite centered on low-phase years (Fig. 11c) indicates a period of above-normal temperatures from Oct(0) through Feb(+). The time series for the Oct(0)–Feb(+) season (Fig. 11d) shows that above-normal temperatures were found during only 11 out of the 25 ENSO events. However, temperatures were above normal during 8 out of the past 9 warm events. A closer examination of the time series reveals that a discontinuity occurs during the 1940s. Especially evident is the preponderance of negative temperature anomalies before 1947. A jump in mean seasonal air temperature is noted about 1950 (Yamamoto et al. 1985). Therefore, the Japanese dataset was split into two periods. A time series for the Oct(0)–Feb(+) period from 1881 to 1947 with anomalies from this base period (Fig. 11e) shows that 11 out of 16 low-phase years experienced above-normal temperatures. Similarly, a time series from 1948 to 1990 (Fig. 11f) shows that 7 out of the 9 ENSO years had positive temperature anomalies. Although neither of the relationships in these shorter time series is significant at the 95% level, the combined result, with 18 out of the 25 ENSO years having above-normal temperatures, is significant at the 95% level. Statistical results for the high-phase years based on the Nov(0)–May(+) period are unaffected by this discontinuity, although the magnitudes of the negative indices during high-phase years in the earlier part of the record are reduced.

The harmonic vectors for Europe (Fig. 5a and 5b) indicate a potential SO–temperature relationship during the low phase of the SO over northern Europe, and SO–temperature relationships during the high phase over western Europe/northern Africa and eastern Europe. The standardized temperature composites do not indicate a consistent period for a response over the eastern Europe region during high-phase years or over northern Europe during low-phase years. However, the cold event composite for the western Europe/northern Africa region (Fig. 12a) shows that the May(0)–Sep(0) period may experience above-normal temperatures with negative temperature anomalies during the Feb(+–May(+)) season. The time series for the May(0)–Sep(0) season indicates that this relationship is not statistically significant. However, the time series for the Feb(+–May(+)) season (Fig. 12b) shows that 17 out of the 20 cold event years had below-normal temperatures. This relationship is significant at the 99% level.

5. Discussion and summary

It is evident from the results presented here that Southern Oscillation–temperature relationships are global in nature. The 12 areas that have significant (9 at the 99% level) SO–temperature relationships during the low phase [including northwestern North America and the southeast United States, which were described in Ropelewski and Halpert (1986a)] are summarized in Table 3 and presented in schematic form in Fig. 13b. We have detailed 11 discrete regions that have statistically significant temperature relationships (8 at the 99% level) with the high phase of the SO. These results are summarized in Table 4 and presented in schematic form in Fig. 13a. Ten of these areas have temperature relationships during both phases of the SO that are opposite in sign.

As might be expected, the strongest SO–temperature relationships occur in the tropics. In general, surface air temperature anomalies are of the same sign as the local SST anomalies in the tropics. During warm episodes, surface temperatures are above normal in the eastern equatorial Pacific (west coast of South America). Conversely, surface temperatures in this region are below normal during cold events. In the southwest and western Pacific, air temperatures are anomalously cold during warm episodes and warm during cold episodes, as this region experiences SST anomalies out of phase with those in the central and eastern Pacific (e.g., see Rasmusson and Carpenter 1982). The general increase or decrease in surface temperatures throughout the global tropics is a delayed response to the warming or cooling of the equatorial SSTs, primarily in the Pacific. In some subtropical re-

![Fig. 12. (a) Composite temperature index for an idealized 24-month high SO cycle for western Europe/northern Africa. Dashed vertical lines indicate the extent of the period of the most significant SO–temperature relationship. (b) Temperature time series for western Europe/northern Africa for the Feb(+)–May(+) season. Shaded bars represent high SO years.](image-url)
regions, such as southeast Africa and Southeast Asia, the temperature relationships are probably influenced by variations in cloud cover. These areas were found to generally experience below-normal precipitation during warm events (Ropelewski and Halpert 1987) and above-normal precipitation during cold events (Ropelewski and Halpert 1989).

Outside of the tropics, relationships between the SO and temperature are not as reliable as the tropical responses and are most likely the result of tropical forcing of circulation patterns. The temperature anomalies over northwest North America are consistent with the presence of the PNA pattern, as are the below-normal temperatures in the southeastern United States. The absence of a temperature signal during the high phase of the SO in the Southeast is harder to explain, since precipitation is known to be below normal (Ropelewski and Halpert 1989). Temperature anomalies over Japan during cold events are similar to those that are experienced in northwest North America, with negative anomalies during the northern winter and spring. The observed relationship between Japan temperatures and
TABLE 4. Summary of high-SO-related temperature for selected regions of the globe. Significance levels are based on the hypergeometric distribution.

<table>
<thead>
<tr>
<th>Region</th>
<th>Season</th>
<th>Coherence</th>
<th>Total</th>
<th>Cold</th>
<th>Warm</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>North/South America</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central America–Caribbean</td>
<td>Jul (0)–Jun(+)</td>
<td>.91</td>
<td>12</td>
<td>10</td>
<td>2</td>
<td>.99</td>
</tr>
<tr>
<td>Central South America</td>
<td>Oct (0)–May(+)</td>
<td>.95</td>
<td>17</td>
<td>13</td>
<td>4</td>
<td>.95</td>
</tr>
<tr>
<td>West coast South America</td>
<td>May(0)–Apr(+)</td>
<td>.87</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>.99</td>
</tr>
<tr>
<td>Northwest North America</td>
<td>Nov(0)–Mar(+)</td>
<td>.97</td>
<td>20</td>
<td>18</td>
<td>2</td>
<td>.99</td>
</tr>
<tr>
<td>Europe/Asia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Europe/Northern Africa</td>
<td>Feb (+)–May(+)</td>
<td>.91</td>
<td>20</td>
<td>17</td>
<td>3</td>
<td>.99</td>
</tr>
<tr>
<td>Southeast Asia/India</td>
<td>Jul (0)–Jun(+)</td>
<td>.91</td>
<td>20</td>
<td>18</td>
<td>2</td>
<td>.99</td>
</tr>
<tr>
<td>Japan</td>
<td>Nov(0)–May(+)</td>
<td>.92</td>
<td>20</td>
<td>16</td>
<td>4</td>
<td>.95</td>
</tr>
<tr>
<td>Africa/Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Africa</td>
<td>Jul (0)–Jun(+)</td>
<td>.85</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>.99</td>
</tr>
<tr>
<td>Southeast Africa</td>
<td>Aug(0)–Jun(+)</td>
<td>.90</td>
<td>17</td>
<td>16</td>
<td>1</td>
<td>.99</td>
</tr>
<tr>
<td>Central/northern Australia</td>
<td>Apr(0)–Oct(0)</td>
<td>.93</td>
<td>17</td>
<td>12</td>
<td>5</td>
<td>.95</td>
</tr>
<tr>
<td>Central/northern Australia</td>
<td>Nov(0)–Jun(+)</td>
<td>.93</td>
<td>17</td>
<td>3</td>
<td>14</td>
<td>.95</td>
</tr>
<tr>
<td>South-central/western Pacific</td>
<td>Jan (0)–Nov(0)</td>
<td>.93</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>.99</td>
</tr>
</tbody>
</table>

ENSO shows that colder-than-normal conditions during the Oct(0)–Feb(+) period occurred in 18 out of the 25 ENSO years. Although this relationship is significant at the 95% level, there are no documented circulation changes or statistical circulation teleconnections that are known to influence Japan during this season. Therefore, the SO-temperature relationship in Japan during the low phase of the SO must be viewed with caution.

In comparing results for the high- and low-phase years, we find that all tropical areas have relationships during both phases of the SO. In some cases, the seasons of interest are the same (west coast of South America, Central America–Caribbean, south-central and western Pacific), but in some of the other regions, the temperature response during cold event years appears to begin earlier than the response during warm event years. This is true for southeast Africa and the Southeast Asia–India region. It is possible that the actual onset of the low SO-temperature relationship occurs earlier than the temperature composites imply because 8 of the 25 warm events follow cold event years.

While this paper has emphasized that the SO is associated with large surface temperature anomalies over many regions of the world, it should also be pointed out that the SO can have a profound influence on estimates of global surface temperature anomalies. Estimates of global temperatures are important in the monitoring and detection of global climate change. It is clear that many of the SO temperature relationships discussed here are in phase over large portions of the globe (e.g., Figs 1a and 1b). Further, it is also clear that the SO-temperature relationships tend to reach a maximum in the later phases of the SO cycle, and thus their influence tends to span the calendar year.

Time series of estimated Northern Hemisphere temperature anomalies for calendar years (Fig. 14a) shows no apparent relationship with the SO. A re-examination of Fig. 14a, however, shows that all but two of the calendar years following the nine warm episodes and all but one of the six cold episodes have relatively large temperature anomalies. This reflects the fact that the maximum SO-temperature responses in the Northern Hemisphere extratropics tend to occur in the

![Fig. 14](image-url)
year following the SO extreme (Pan and Oort 1983). Calendar-year temperature anomaly estimates arbitrarily split the SO–temperature relationship over two years and thus alias the SO signal.

Since most studies of global temperature trends are performed on anomaly time series that remove the annual cycle from the data, there is no technical or scientific reason to study these data averaged over the calendar year. This study suggests that the time series of the global and hemispheric temperature anomalies could be made more consistent with the known modes of climate variability associated with the SO. If 12-month anomalies are desirable, then Oct–Sep may be a more appropriate averaging period (e.g., Fig. 14b). The time series of Oct–Sep Northern Hemisphere temperature anomalies clearly identifies positive temperature anomalies with seven out of nine warm episodes. Since a relatively large pool of SO-related warm water persisted in the central Pacific through March 1988, a portion of the 1987–88 temperature anomaly can also be attributed to the previous warm episode. The high-index phase of the SO is associated with the negative anomalies of 1955, 1964, 1970, 1973, and 1975.

In summary, this paper has demonstrated that the SO influences surface temperatures on regional and global spatial scales. Although the effect of the SO is greatest in the tropics, some areas of the extratropics are influenced as well. It is clear that the effects of the SO cannot be ignored in attempts to monitor and detect global climate change and that the SO is related to a large part of interannual variability for several regions of the world.

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