Comparison of Variations in Atmospheric Quantities with Sea Surface Temperature Variations in the Equatorial Eastern Pacific

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ABSTRACT

Sea surface temperature (SST) variations in the equatorial eastern Pacific (0–10°S, 180–90°W) are compared with variations in atmospheric temperature, circulation, rainfall and trace-constituent amount. Significant at the 99.9% level (taking into account the serial correlation in the seasonal data) is the zero-lag correlation of −0.62 between this SST and the Southern Oscillation Index (normalized pressure difference between Tahiti and Darwin) during 1932–79, the correlation of 0.72 between this SST and the zonally averaged temperature in the tropical troposphere two seasons later during 1958–79, and the correlation of −0.62 between this SST and Indian summer monsoon rainfall 1–2 seasons earlier during 1868–1977. Significant at the 99% level is the correlation of 0.67 between this SST and rate of increase of CO_2 at the South Pole 2–3 seasons later during 1965–76, and significant at the 95% level the correlation of 0.37 between this SST and rate of increase of CO_2 at Mauna Loa one season later during 1958–78. Also significant at nearly the 99% level is the negative zero-lag correlation between this SST and rainfall in eastern Australia. Correlations of marginal significance (95% level) have been obtained between this SST and the Northern Hemisphere, temperate-latitude and United States temperatures, north circumpolar vortex area at 10 km and vortex displacement, latitude of the subpolar low and subtropical high, and total ozone, stratospheric water vapor and sunshine duration in the North American region. Implied relationships include enhanced Hadley circulation near time of warmest SST, minimum Indian summer monsoon rainfall and United States sunshine duration at time of expanded polar vortex and equatorward displacement of subpolar low and subtropical high, and cold winter temperature in the United States at time of warm SST, or at the time both of expanded polar vortex and displacement of the vortex toward 90°W.

1. Introduction

In his search for precursors to the Indian monsoon rainfall, Walker (1923, 1924, 1928a,b, 1937) uncovered a tendency, particularly south of the equator, for a variation in pressure between eastern and western Pacific over a period of years, an alternation he called the Southern Oscillation. Bjerknes (1966, 1969, 1972) showed that this alternation in surface pressure was related to variations in rainfall and sea surface temperature (SST) in equatorial eastern Pacific and, in particular, to the anomalously warm SST off the coast of Peru known as El Niño. With his customary modesty, Bjerknes introduced the term Walker Circulation to denote the tendency for a direct atmospheric circulation in the zonal plane with strength dependent on the magnitude of the SST gradient between the western and eastern Pacific (weak Walker Circulation at the time of El Niño). Wyrtki (1973, 1974, 1975) pointed out the close association between the Southern Oscillation and strength of equatorial ocean currents, as well as trade winds, and Reiter (1978, 1979) has shown recently that variations in trade wind convergence are an integral part of the Southern Oscillation phenomenon.

A useful summary of early knowledge concerning the Southern Oscillation has been presented by Troup (1965), with the work of Berlage (1966) emphasizing apparent global aspects of the phenomenon. That there is a rapidly increasing interest in the Southern Oscillation can be seen from the output of important papers during recent years (e.g., Krueger and Winston, 1975; Kidson, 1975; Trenberth, 1976; Wright, 1977; Julian and Chervin, 1978; Khandekar, 1979; Rowntree, 1979). The purpose of this paper is to examine more closely the relation between SST in the equatorial eastern Pacific and atmospheric variables, with emphasis on the longer periods of record and attention to the significance of derived relations.

The basic data set for comparison with atmospheric variables consists of seasonally averaged sea surface temperatures in the region 0–10°S, 180–90°W, as compiled by the Environmental Research Laboratories of NOAA at Boulder, Colorado, for years 1860–1976, and updated into 1979 from data provided in *Fishing Information* issued monthly by the NOAA Southwest Fisheries Center, La Jolla, California. These SST data, derived from

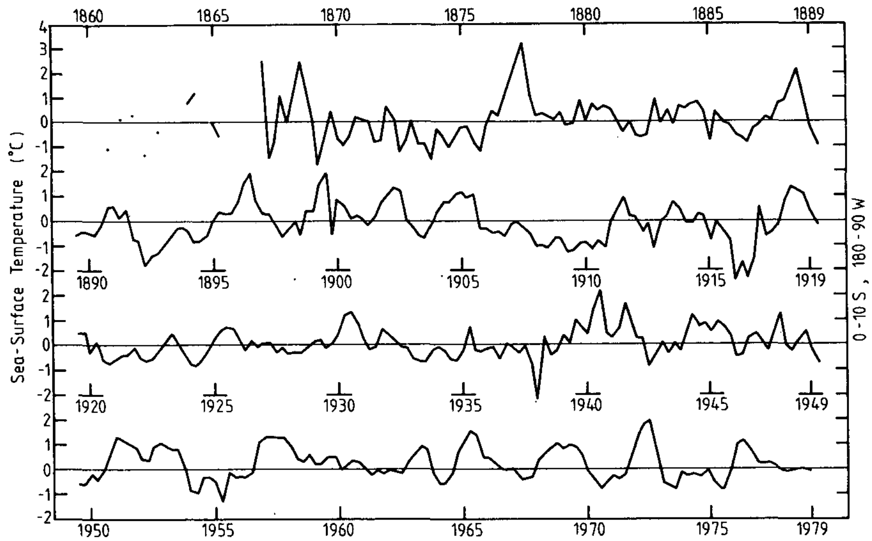

FIG. 1. Time variation in seasonal sea surface temperature in the region 0–10°S, 180–90°W (SST*) for years 1860–1979. The tick marks represent June-July-August of the given year. In this and subsequent diagrams the annual variation has been eliminated by use of deviations from long-term seasonal means.

careful summarizations of extensive ship reports, are believed to be as accurate and representative as can reasonably be hoped for, although the possibility of a seasonal bias and a long-term trend in sample location cannot be denied. The annual variation in SST has been removed from these data through evaluation of deviations from long-term seasonal means, and where appropriate the same procedure has been applied to the other data of this paper. Warm temperatures in this equatorial region are usually associated with El Niño events.

Fig. 1 shows the SST variation in the region 0–10°S, 180–90°W between 1860 and 1979. Hereafter the SST in this region will be denoted as SST*. There has been an intermittent tendency for SST* variations of 3–5 years period, with the tendency unusually clearcut after 1965. The autocorrelation trace based on the total record crosses the zero axis at a lag of 4.5 three-month seasons, implying a quasi-periodicity of about 4.5 years (see also Wright, 1977). In the following these SST* variations will be compared with variations in atmospheric temperature, circulation, rainfall and trace-constituent amount.

2. Procedures

In order to quantify the relations between SST* and atmospheric variables, lagged correlations have been calculated up to six seasons either side of the zero-lag correlation. In subsequent diagrams a correlation maximum to the right of the vertical dashed line (zero-lag line) signifies that variations in the given atmospheric quantity tend to follow variations in SST* by the indicated number of seasons. There was concern that the lag correlations so obtained might be unrepresentative because the data had not been normalized so that each season represents the same amount of variance, and therefore seasons with large interannual variations (such as SST* in December–February) might dominate the lag relation. Accordingly, a number of quantities (including SST*) were normalized by the standard deviation of the seasonal values, and new lag correlations evaluated. In all cases the difference between normalized and unnormalized lag correlations was negligible. The correlations presented herein are based on unnormalized data.

The question arises as to the significance of lagged correlations, particularly when the series are quite highly autocorrelated (serially correlated) as is frequently the case here. It is shown by Quenouille (1952, p. 168) that a good estimate of the effective number of independent observations entering into the calculation of cross correlation coefficients is given by

$$N/(1 + 2r_1r_1' + 2r_2r_2' + \cdots), \qquad (1)$$

where N is the number of data points in each of the two series, r_1 and r_1' are the lag-one autocorrelations of the two series, r_2 and r_2' the lag-two autocorrelations of the two series, etc. The calculation has been terminated at lag four because the correlation products become negligible thereafter. The significance of the correlation has then been estimated by using the effective number of independent observations so determined in Fisher's Z test.

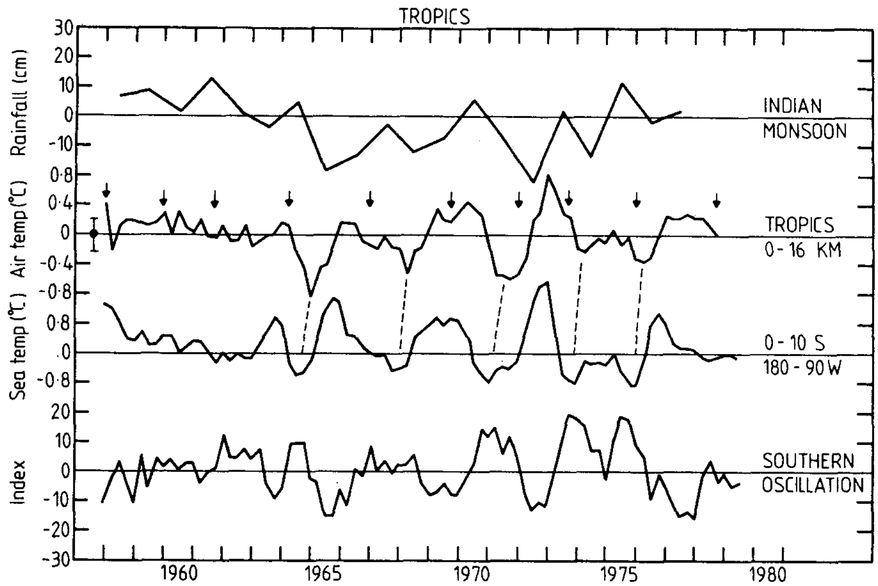

FIG. 2. Comparison of time variations in Southern Oscillation Index (normalized pressure difference between Tahiti and Darwin), SST*, zonally averaged tropospheric temperature in the tropics, and Indian summer monsoon rainfall. Vertical arrows denote time of quasi-biennial west wind maximum at a height of 20 km in the tropics. There is about a 5% chance that the true mean value of seasonal air temperature lies outside the extent of the vertical bar at left.

In subsequent diagrams short horizontal bars represent correlations significant at the 95% (two standard deviation) level. It is recognized that a correlation exceeding the 95% confidence limit might well occur by chance when 13 lag correlations are evaluated. However, lag correlations significant at the 99% (three standard deviation) level are probably meaningful, and lag correlations significant at the 99.9% (four standard deviation) level are undoubtedly meaningful.

3. Comparison with tropical quantities

Fig. 2 shows the variation, since 1958, of SST*, zonally averaged tropospheric temperature in the tropics between 30°N and 30°S (Angell and Korshover, 1978a), average summer monsoon (June–September) rainfall for India (Parthasarathy and Mooley, 1978), and a normalized Southern Oscillation Index (SOI*), where normalization was achieved by dividing the departure from average of the mean monthly pressure difference between Tahiti and Darwin by the standard deviation of the values for that month (Troup, 1967). The data are plotted by season, with the annual variation eliminated through the use of deviations from long-term seasonal means.

a. Southern Oscillation Index

Fig. 2 shows that between 1958 and 1979 there has been an almost exact out-of-phase relation between SST* and SOI*; i.e., warm SST* has been associated with relatively high pressure at Darwin and/or low pressure at Tahiti (see, also, Weare *et al.*, 1976; Julian and Chervin, 1978). Calculations show (two bottom curves of lagged correlations in Fig. 3) that the inverse relation between SST* and SOI* is significant at the 99.9% level based on years 1958–79, and significant at the six standard deviation level based on years 1932–79. However, Table 1 shows that when lag correlations are evaluated as a function of season (of SST*), the variation in SOI* is indicated to follow the variation in SST* by about one season in June-July-August (JJA), but precede it by about one season in December-January-February (DJF). Thus, as shown by Wright (1977), in the case of seasonal lag correlations it does make some difference whether one refers to equatorial SST or a SOI.

b. Temperature

Fig. 2 also shows a close relation between SST* and zonally averaged tropospheric (0–16 km) temperature in the tropics, and therefore Fig. 1 probably provides an estimate of year-to-year tropical air temperature variations back to at least 1880. The dashed lines in Fig. 2 point up the tendency during 1958–78 for tropical tropospheric temperature to follow SST*. In recent years there has also been a slight tendency for tropospheric temperatures in the tropics to be relatively cool near times of quasi-biennial west wind maxima at the height of 20 km in the tropics (vertical arrows).

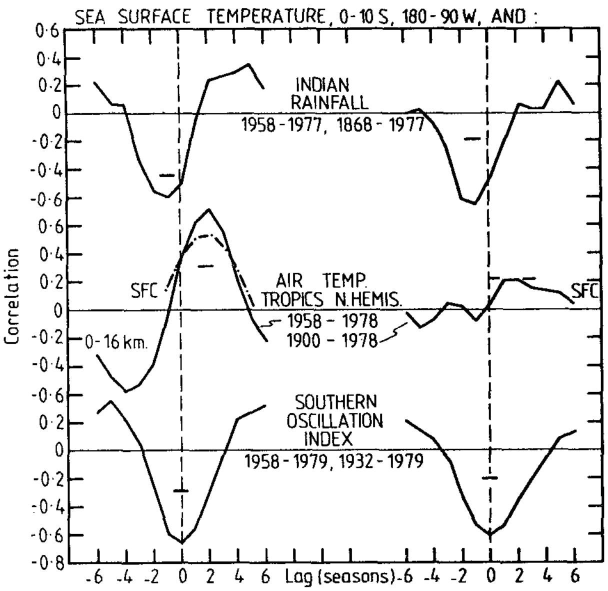

FIG. 3. Lag correlations between SST* and the quantities of Fig. 2 for given years of record, as well as tropical and Northern Hemisphere surface temperature. A correlation maximum to the right of the dashed (zero-lag) line signifies that the variations in that quantity follow the variations in SST* by the indicated number of seasons. The horizontal bars represent correlations significant at the 95% level taking into account the serial correlation in the data.

The solid curve at middle left in Fig. 3 indicates that, between 1958 and 1978, the maximum correlation of 0.72 between SST* and zonally averaged tropical-tropospheric temperature occurred when the latter lagged the former by two seasons (see also Newell and Weare, 1976). Such a correlation is significant at the 99.9% level. Table 1 suggests that this lag increases uniformly from one season in DJF to three seasons in JJA. Thus, the lag of maximum correlation between SOI* and tropical tropospheric temperature is about two seasons for all seasons.

The dash-dot line at middle left in Fig. 3 represents a portion of the lagged correlation curve using surface air temperature rather than temperature for the 0–16 km layer (same stations). Surface air temperature also lags SST* by almost two seasons, so that mixing between surface and troposphere as a whole does not appear a major factor in the time delay. There has also been no appreciable time delay between tropospheric temperature variations near the equator and in subtropics (Angell and Korshover, 1978a). Consequently, there can be little doubt that, during 1958–78, SST variations in the region 0–10°S, 180–90°W preceded zonally averaged air temperature variations near the equator. Newell (1979) has considered some of the implications of this lag relationship for forecasting climatic changes several months ahead.

To see if this lag between SST* and air temperature extended further back in time, yearly Northern Hemisphere surface temperatures were obtained for the period 1900–57 (Mitchell, 1961). Inasmuch as between 1958 and 1978 the correlation between SST* and 0–16 km Northern Hemisphere temperature was 0.60 at a lag of two seasons (compared to 0.72 for tropical temperature), hemispheric temperatures should be suitable for such a study [the tropical temperatures for 1900–60 plotted in Mitchell (1963) are 5-year averages]. However, since

TABLE 1. Variation with season of maximum or minimum lagged correlation (r) between SST (0–10°S, 180–90°W) and given variables. A positive lag signifies that the SST variations occurred the given number of seasons earlier. In the case of the Index, tropical temperature, and rate of CO_2 increase, the season is that of the SST; otherwise that of the other variable.

Variable	DJF		MAM		JJA		SON		95% significance level
	r	lag	r	lag	r	lag	r	lag	
Southern Oscillation Index	−0.68	−1	−0.57	0	−0.67	1	−0.75	0	−0.32
0–16 km mean temperature									
Tropics	0.74	1	0.58	2	0.80	3	0.80	2	0.48
North temperate	0.19	3	0.42	3	0.54	4	0.32	5	0.48
South temperate	0.42	4	0.40	3	0.45	2	0.34	2	0.48
Australian rainfall									
Queensland	−0.36	−1	−0.33	0	−0.34	1	−0.33	0	−0.37
New South Wales	−0.25	−1	−0.12	0	−0.42	1	−0.35	0	−0.37
Rate of CO_2 increase									
Mauna Loa	0.49	0	0.23	0	0.46	2	0.52	1	0.48
South Pole	0.72	1	0.41	2	0.59	3	0.71	2	0.60
Stratospheric water vapor									
Washington, DC	0.36	1	0.08	2	0.24	1	0.30	1	0.57
Sunshine duration									
United States	−0.20	−2	−0.27	0	−0.39	−1	−0.40	0	−0.39

TABLE 2. Variation with approximate 20-year interval of maximum or minimum lagged correlation (r) between SST (0–10°S, 180–90°W) and given variables. A positive lag signifies that the SST variations occurred the given number of seasons earlier.

Variable	Interval	r	lag	95% significance level
Northern Hemisphere surface temperature	1900–1919	0.31	1	0.43
	1920–1939	0.23	2	0.43
	1940–1959	0.21	1	0.43
	1960–1978	0.37	2	0.45
Indian summer monsoon rainfall	1868–1889	−0.63	−2	−0.44
	1890–1911	−0.74	−1	−0.44
	1912–1933	−0.62	−1	−0.44
	1934–1955	−0.51	−1	−0.44
	1956–1977	−0.67	−1	−0.44
Estimated latitude				
Subpolar low	1900–1919	−0.07	0	−0.43
	1920–1939	−0.34	1	−0.43
	1940–1959	−0.44	−1	−0.43
	1960–1972	−0.51	1	−0.57
Subtropical high	1900–1919	−0.32	0	−0.43
	1920–1939	−0.28	2	−0.43
	1940–1959	−0.63	−2	−0.43
	1960–1972	−0.30	−2	−0.57

even these hemispheric temperatures were not available by season, the lag correlation can only be approximate (the SST* for each season has been lag-correlated against year-average hemispheric temperature). The curve at middle right in Fig. 3 shows that for the total period of record (1900–78), Northern Hemisphere surface temperatures did tend to be warm 1–2 seasons after warm SST*, but the maximum correlation of 0.21 is only significant at the 95% level.

Table 2 presents the correlation and lag for 20-year intervals. The correlation was greatest between 1960 and 1978, but even this correlation of 0.37 is not significant at the 95% level, and is much reduced from the correlation of 0.60 found from 0–16 km hemispheric temperatures. It is apparent that the relation between SST* and hemispheric temperature is much poorer when surface temperatures are used than when tropospheric temperatures are used. At this time it cannot be stated categorically that the lag between SST* and tropical air temperature, so obvious during 1958–78, has prevailed over the longer time period.

c. Indian summer-monsoon rainfall

The curve of Indian summer-monsoon (June–September) rainfall appears related to the other curves of Fig. 2. The relation can be expressed as either relatively small rainfall amounts slightly preceding warm SST*, or as relatively large rainfall amounts slightly following warm tropospheric temperatures in the tropics. The first relation will be shown shortly to be highly significant over the long term, and the second relation may simply derive from it owing to the tendency for a quasi-periodicity of 3–4 years during this time. Nevertheless, one cannot ignore the observation that in 17 of the 20 years between 1958 and 1977 Indian summer-monsoon rainfall was either above average two seasons after warm temperatures in the tropical troposphere, or below average two seasons after cool temperatures, and that this same relation also held in 1978 (a wet monsoon year). This relation should continue to be monitored in the future to determine the extent to which it persists when SST* variations become less pronounced and more irregular (1979 should be an average summer-monsoon year according to this relation).

The two top curves in Fig. 3 show the lag correlation between SST* and Indian summer–monsoon rainfall. For years 1958–77 the minimum correlation of −0.60 occurs at a lag of minus one season, but is significant at only the 2.5 standard deviation level owing to the limited data sample. However, the correlation is even slightly greater for the entire period 1868–1977, resulting in significance at the six standard deviation level (this high significance results in part from the fact that there is no serial correlation in yearly values of Indian monsoon rainfall). Table 2 presents the correlation and lag for 22-year intervals. During all five intervals the correlation is significant at better than the 95% level. The correlation is lowest (−0.51) for the interval which includes World War II.

Fig. 4 shows a scattergram of yearly comparisons between Indian summer-monsoon rainfall and SST* two seasons later (the El Niño season). In more than two-thirds of the years above-average SST* followed below-average monsoon rainfall and vice versa. The relatively high correlation of −0.62 results mainly from the relation between below-average monsoon rainfall and above-average SST*. Thus, there have been 20 years since 1868 in which SST* was more than 0.8°C above average during the El Niño season (DJF), and in each of these years Indian monsoon rainfall was below average during the preceding summer. Accordingly, a necessary condition for a major El Niño may be below-average Indian summer-monsoon rainfall two seasons earlier, although obviously the observation of below-average rainfall does not guarantee even a weak El Niño. The ability to foresee a major El Niño would certainly be of importance to the fishing industry in particular, and the public in general (Quinn, 1974; Barnett and Hasselmann, 1979).

It appears that Walker recognized the possibility that Indian monsoon rainfall might be the precursor

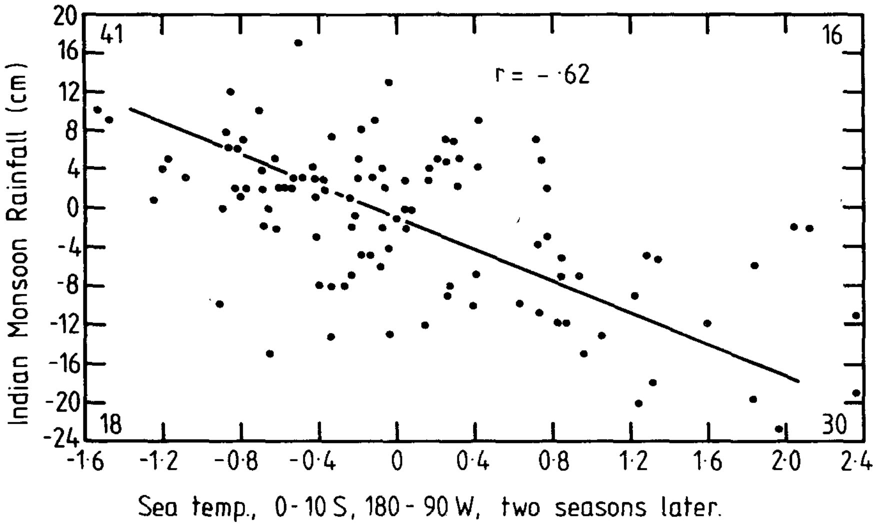

FIG. 4. Comparison between Indian summer monsoon rainfall, and SST* two seasons later, for years 1868–1977. The quadrant count is indicated at the corners, while the solid line denotes the regression line associated with the correlation of −0.62.

to subsequent events because Sir Charles Normand stated (1953, p. 469) in his eulogy of Walker during a presidential address to the Royal Meteorological Society, ". . . *Indian monsoon rainfall has its connections with later rather than earlier events. The Indian monsoon therefore stands out as an active, not a passive feature in world weather, more efficient as a forecasting tool than as an event to be* forecast".

4. Comparison with temperate latitude quantities

The possibility of a relation between SST in the North Pacific and North American weather has been discussed by Namias in a series of papers (e.g., 1970, 1973, 1978). However, on the basis of results from the NCAR general circulation model, Julian and Chervin (1978) state, ". . . it is possible that the general circulation of the atmosphere is rather more sensitive to changes in tropical oceanic surface temperatures than to changes in midlatitude oceanic temperatures . . ." The possibility of a lag relation between the Southern Oscillation and temperate latitude quantities has been touched upon as well by Quinn and Burt (1972), Rowntree (1972), Pittock (1073), Wright (1977) and others. Fig. 5 shows the variation, since 1958, of SST*, zonally averaged temperature in 0–16 km layers of north and south temperate latitudes (Angell and Korshover, 1978a), and north polar vortex area at a height of 10 km (Angell and Korshover, 1978b). This section considers the evidence for a lag relation between SST* and these temperate latitude quantities, as well as United States temperature and Australian rainfall.

a. Temperate latitude temperatures

The dashed lines in Fig. 5 point up the tendency for temperate latitude temperature minima following SST* minima, although the relation is not nearly so impressive as in the case of tropical temperature. For example, the cold year of 1976 in north temperate latitudes may be related to the relatively cool SST* year of 1975. Alternately, one could consider that warm temperatures in temperate latitudes have tended to precede cool SST*. The lagged correlations at lower and middle left in Fig. 6 show that the 0–16 km temperatures in north and south temperate latitudes tended to lag SST* by 2–3 seasons during 1958–78, but in each case the significance is marginal at the 95% level.

Table 1 presents the correlation between SST* and temperate latitude temperature according to temperate latitude season. In south temperate latitudes there has been little variation in the correlation by season, although the lag is indicated to be greater in summer (DJF) than in winter. In north temperate latitudes, however, the correlation is much greater in summer (JJA) than in winter. Thus, based on years 1958–78, there is the suggestion that SST* is a more useful precursor to summer temperatures than to winter temperatures in north temperate latitudes.

b. Polar-vortex area and latitude of subpolar low and subtropical high

The top curve in Fig. 5 shows that an expanded north circumpolar vortex, as determined from mean-monthly polar stereographic maps by the area lying

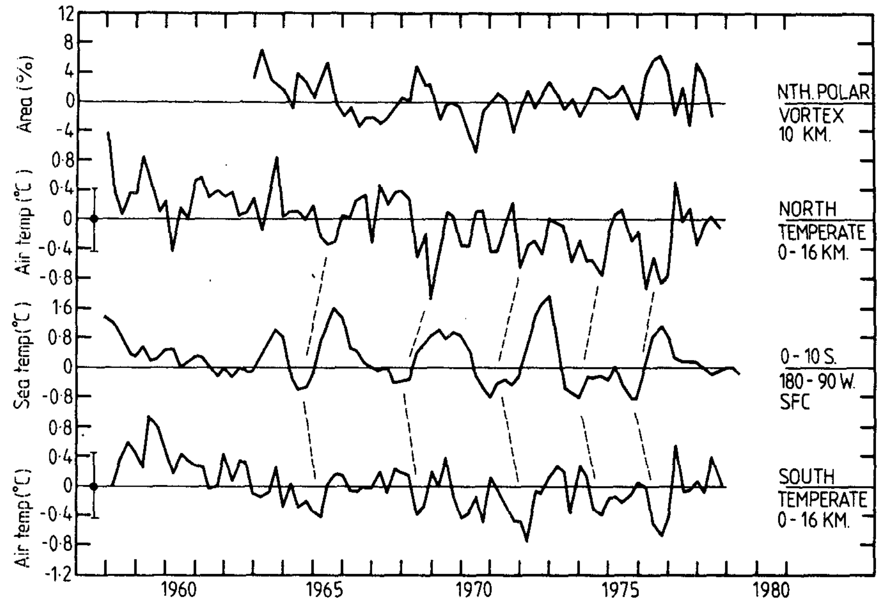

FIG. 5. Comparison of time variations in SST*, zonally averaged temperature in the 0–16 km layer of north and south temperate latitudes, and area of the north circumpolar vortex at a height of 10 km. There is about a 5% chance that the true mean value of seasonal air temperature lies outside the extent of the vertical bars at left.

within 300 mb contour values in the main belt of westerlies, has been generally associated with cool temperatures in the 0–16 km layer of north temperate latitudes, and vice versa, with the relation particularly good in recent years. Thus, the polar-vortex area provides a useful check on the 0–16 km temperatures derived from individual stations in north temperate latitudes. The lagged correlations at upper left in Fig. 6 show that, during 1963–78, the north polar vortex tended to be most contracted 2–3 seasons after warmest SST*, in good agreement with the results obtained for 0–16 km temperature in north temperate latitudes, but most expanded only one season before warmest SST*, not exactly in agreement with this temperature. At both times the correlation is marginally significant at the 95% level.

In an attempt to obtain a longer data record which might be related to polar-vortex area, the yearly latitude of subpolar low and subtropical high has been estimated from zonally averaged surface pressure differences between 60 and 65°N, and 30 and 35°N, respectively. Inasmuch as the central latitudes of subpolar low and subtropical high usually lie within these latitude bands for the year as a whole, a poleward displacement of the subtropical high usually involves a rise in pressure at 35°N relative to 30°N, and a poleward displacement of the subpolar low a rise in pressure at 60°N relative to 65°N. Thus, the pressure difference between the two latitudes should be crudely proportional to latitude of the low or high.

The data series used in this evaluation (the Northern Hemisphere Historical Weather Map Series) has many omissions, errors and inconsistencies over the period 1900–72 (e.g., Madden, 1976; Williams and van Loon, 1976), and the data since 1972 are partly in error and have not been used in this analysis (R. Jenne, personal communication). Nonetheless, the right-hand traces of Fig. 6 show basic agreement with the vortex-area results for the shorter time period; i.e., equatorward displacement of subpolar low and subtropical high (and expanded polar vortex) near time of warmest SST*. Again, however, the correlations are only marginally significant at the 95% level. If there is any validity to these lagged correlations, as well as those obtained previously for Northern Hemisphere surface temperature (repeated at bottom of Fig. 6 for convenience), then subpolar low and subtropical high tend to be displaced furthest equatorward several seasons after the time of coolest hemispheric temperature.

Table 2 represents the correlation and lag between SST* and estimated latitude of subpolar low and subtropical high for 20-year intervals. The correlation is indicated to have increased with time in the case of the subpolar low, but not in the case of the subtropical high. Only two of the correlations are significant at the 95% level. During 1960–72 the estimated latitude of the subtropical high was a minimum two seasons before warmest SST*, whereas the estimated latitude of subpolar low was a minimum one season after warmest SST*, bracketing the observation of an expanded polar vortex one season before warmest SST* during 1963–78 (Fig. 6). The

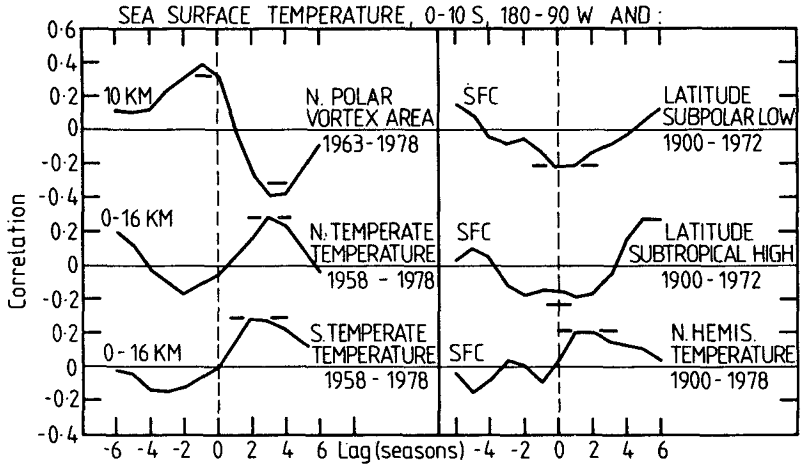

FIG. 6. Lag correlation between SST* and the quantities of Fig. 5 (left), as well as estimated latitude of subpolar low and subtropical high (right) for given years of record. The horizontal bars represent correlations significant at the 95% level taking into account the serial correlation in the data.

finding of an expanded polar vortex, and equatorward displacement of subpolar low and subtropical high, near time of warmest SST* is in agreement with the hypothesis (Pittock, 1973) that a relatively intense Hadley circulation (warm equatorial SST) should be associated with a Hadley circulation more confined to tropical latitudes (equatorward displacement of subtropical high) because the induced baroclinic instability leads to breakdown of the meridional circulation into eddies at lower latitude.

c. Displacement of polar-vortex centroid

Fig. 7 shows, at right, the lagged correlations between SST* and the polar vortex displacement from its mean location, as determined from the quadrant

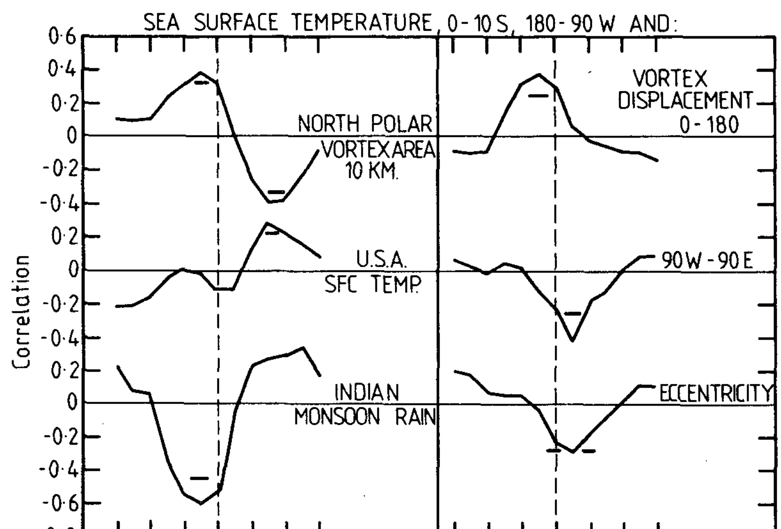

FIG. 7. Lag correlations between SST* and displacement of the 10 km north circumpolar vortex along given meridians during 1963–78 [right], as well as polar vortex area (1963–78), United States surface temperature (1958–78), and Indian summer-monsoon rainfall (1958–77) [left]. Positive lag correlations at right signify displacement toward 90°E, 180°, and greater vortex distance from the North pole. The horizontal bars represent correlations significant at the 95% level taking into acount the serial correlation in the data.

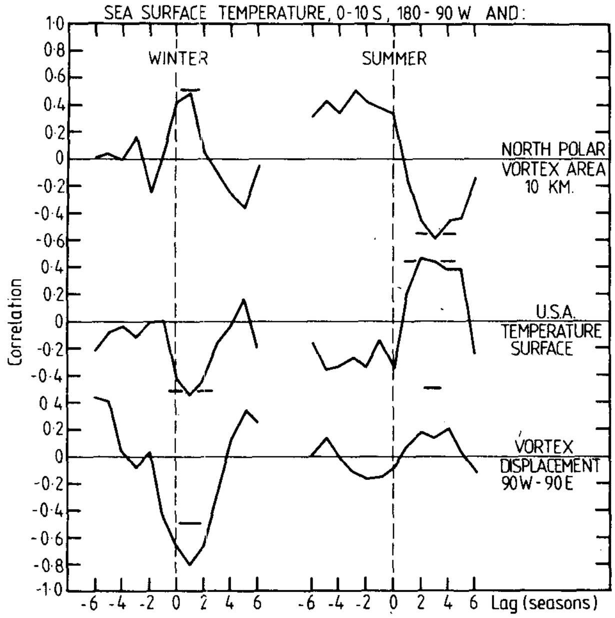

FIG. 8. Lag correlations between SST* and winter and summer values of polar-vortex area, United States surface temperature, and vortex displacement along meridians 90°W–90°E. The record extends from 1963–78 for the vortex data, 1958–78 for the temperature data. The horizontal bars represent correlations significant at the 95% level taking into account the serial correlation in the data.

areas lying within 300 mb contour values in the main belt of westerlies. During 1963–78 the polar vortex has tended to be displaced furthest toward 90°W (North America) one season after warmest SST*, and furthest toward the 180th meridian (North Pacific) one season before warmest SST*, although in both cases the significance only slightly exceeds the 95% level. Thus, the tendency has been for displacement of the polar vortex toward the region 180–90°W at times of warm water there, or El Niño occurrences, in agreement with the model findings of Rowntree (1972) and Julian and Chervin (1978). Vortex eccentricity (distance from the North Pole) has been mainly a function of displacement along meridians 90°W–90°E.

d. United States temperature

The left-hand curves of Fig. 7 show that Indian summer monsoon rainfall has tended to be a minimum when the polar vortex was most expanded (as expected), and United States surface temperatures (36 station network) warmest when the vortex was most contracted, though the significance in the latter case is marginal. The question arises as to whether regional variations are associated more with expansion and contraction of the polar vortex as a whole, or with displacement of the vortex in a certain direction.

As an example of a preliminary look at this question, Fig. 8 shows for winter and summer the lagged correlations between SST* and north-polar vortex area, vortex displacement along meridians 90°W–90°E, and United States surface temperature. At least during 1958–78 there has been a tendency for winter temperatures in the United States to be cold if the winter season occurred at the time of, or shortly after, a period of warm SST* (see, also, Wright, 1977; Henricksen, 1979), and this is the same time the winter polar vortex had tended to be most expanded and displaced furthest toward 90°W. Thus, United States winter temperatures appear related both to vortex size and vortex displacement. In summer, on the other hand, United States temperatures have been related mainly to vortex size, there having been negligible correlation between SST* and vortex displacement. Longer data records will have to be examined before these relations can be considered definitive.

e. Australian rainfall

Pittock (1975) found correlations exceeding 0.5 (significant at the 99% level) between SOI* and annual rainfall in temperate latitudes of eastern Australia during 1941–70. Using the coherent set of seasonal rainfall data for the eastern Australian regions of southern Queensland (25°S) and northern New South Wales (30°S) compiled by E. Webb for 1950–1979, we find the zero lag correlation of −0.32 between Queensland rainfall and SST* significant at the 99.9% level, whereas the zero-lag correlation of −0.24 between New South Wales rainfall and SST* is significant at only slightly more than the 95% level. Thus, both the correlation, and significance of the correlation, increase with approach to the equator. Even so, the correlations do not attain the values obtained by Pittock, presumably mostly because the use of annual values results in a more uniform data set.

Table 1 presents the correlation according to season of rainfall value. In the southern summer (DJF) the variation in rainfall has preceded the variation of SST* by one season, as was the case with Indian summer-monsoon rainfall, but in the southern winter (JJA) the rainfall variation has followed the SST* variation by one season. Therefore, Australian rainfall has been in phase with the SOI* in all seasons, as has Indian monsoon rainfall in summer.

5. Comparison with carbon dioxide and other trace species

a. Carbon dioxide

The reason for the observed interannual variability in rate of increase of atmospheric carbon dioxide (CO_2) has been somewhat of a question for many

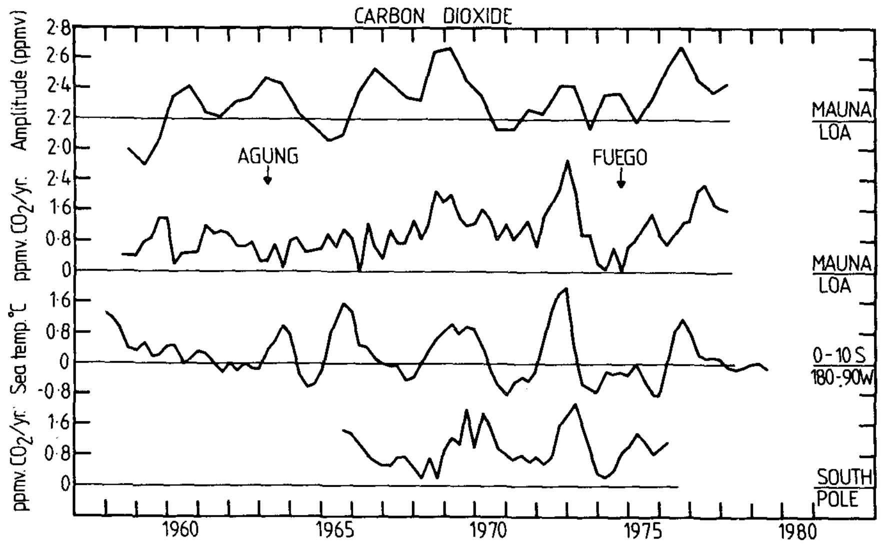

FIG. 9. Comparison of the time variations in SST*, *rate of increase* of atmospheric CO_2 at South Pole and Mauna Loa, Hawaii and annual amplitude of the CO_2 variation at Mauna Loa. The eruptions of Agung (Bali) and Fuego (Guatemala) are indicated at center.

years (e.g., Pearman, 1978). Fig. 9 illustrates the comparison between SST* and yearly increase in atmospheric CO_2 (winter to winter, spring to spring, etc., with values plotted in summer and autumn, etc.) at Mauna Loa, Hawaii (20°N) and at the South Pole. At both stations the *rate of increase* of CO_2 has usually been a maximum shortly after warmest SST* (see, also, Bacastow, 1976). An exception is the period around 1965 at Mauna Loa. There is also the impression that the rate of CO_2 increase at Mauna Loa has been lagging the SST* more during recent years. The rate of CO_2 increase at Mauna Loa and South Pole was a minimum before the Fuego (Guatemala) eruption of 1974, so there is unlikely to be a causal relation. The generally large rate of CO_2 increase at Mauna Loa between 1967 and 1973 does not appear related to SST*, and this enhanced increase is also not apparent in the South Pole curve.

The top curve in Fig. 9 represents the amplitude of the yearly CO_2 variation at Mauna Loa, obtained as the difference between autumn values and the average spring values either side thereof, and spring values and the average autumn values either side thereof. There has been a slight increase in this amplitude during the period of record, with shorter period variations perhaps related to SST*.

The solid curves at lower and middle left in Fig. 10 illustrate the lag correlations between SST* and rate of increase of CO_2 at South Pole and Mauna Loa. The dash-dot lines represent portions of the lag-correlation curves for the relatively short CO_2 records from southern Australia (40°S) and Weather Ship P at 50°N (G. Pearman, private communication). At the South Pole the rate of CO_2 increase has been a maximum about 7 months after warmest SST*, and the correlation of 0.67 at this lag is significant at the 99% level. Over Southern Australia the maximum correlation of 0.72 occurs at a lag of about 4 months, but the correlation is only significant at slightly better than the 95% level owing to the limited length of record (1972–78). Because of the difference of 3 months or so in the maximum rate of CO_2 increase at 40 and 90°S, care is required when considering the meaning of CO_2 gradients between the two areas.

At Mauna Loa the rate of CO_2 increase has been a maximum about 2 months after warmest SST*, but the correlation of 0.37 at this lag is only significant at the 95% level (the lack of agreement in the traces around 1965 is the main reason for the absence of a more significant correlation in this case). The maximum correlation at Weather Ship P occurs at the surprisingly large lag of 10 months, or 3 months larger than found for the South Pole. Despite the indication of a marginally significant correlation, the results from Weather Ship P should be accepted with caution. The top trace at left in Fig. 10 shows that the tendency for the annual amplitude of CO_2 variations at Mauna Loa to be in phase with SST* is not yet significant, though an interesting relation worth monitoring in future.

Table 1 presents the correlation and lag between SST* and rate of CO_2 increase at Mauna Loa and South Pole as a function of season of SST value. At Mauna Loa there is indicated to be no lag between SST* and rate of CO_2 increase in winter and spring. At both stations the correlation is relatively small in March-April-May (MAM), suggesting that SST* during this season has less impact on rate of CO_2 increase. Once again, it is apparent that if the lag

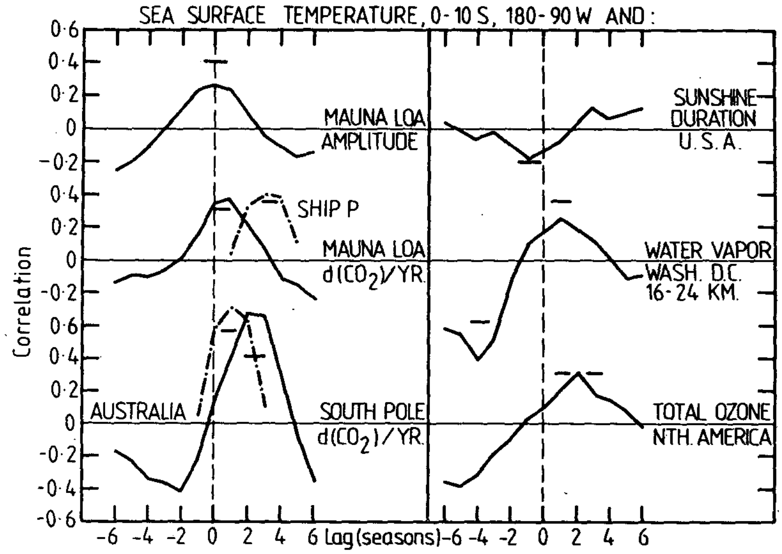

FIG. 10. Lag correlations between SST*, *rate of increase* of atmospheric CO_2 at Mauna Loa and South Pole (solid curves at middle and lower left), and at Weather Ship P (50°N, 140°W) and over southern Australia (dash-dot curves at middle and lower left). The record extends from 1958 to 1978 at Mauna Loa, 1965–76 at South Pole, 1972–78 over Australia, and 1969–78 at Ship P. The relation with annual amplitude of the CO_2 variation at Mauna Loa is given in upper left. At right are shown SST* relations with respect to North American values of total ozone (1961–78), water vapor amount in the low stratosphere at Washington, DC (1964–76) and sunshine duration for the contiguous United States (1950–78). The horizontal bars represent correlations significant at the 95% level taking into account the serial correlation in the data.

were computed with respect to SOI* there would be little seasonal variation in the lag.

In summary, there can be little doubt but that much of the year-to-year variation in rate of CO_2 increase is associated with SST variations in the equatorial eastern Pacific, and this removes a question mark of long standing.

b. *Water vapor and sunshine duration*

Fig. 11 shows the comparison between SST* and water vapor amount in the low stratosphere (16–24 km) at Washington, DC (Mastenbrook, 1974), temperature at 100 mb (16 km) near the equator, and sunshine duration over the contiguous United States (Angell and Korshover, 1978c). There is some evidence that water vapor variations in the low stratosphere at Washington are related to SST*, as shown by the dashed lines. With the questionable assumption that the 16 km temperature is a reasonable approximation to the tropopause temperature, then the tropopause temperature is governed mainly by the quasi-biennial oscillation (vertical arrows), and the relation to water vapor amount in midlatitudes is good only during the early part of the record. The question of whether the water vapor amount in the low stratosphere of temperate latitudes is more closely related to equatorial SST (Southern Oscillation) or to quasi-biennial oscillation is an interesting one, to be answered only through extension of the water vapor records.

The trend in water vapor amount in the low stratosphere at Washington has not been at all related to the trend in SST*, but weakly related to the trend in 16 km temperature and United States sunshine duration (minimum sunshine duration, or maximum cloudiness, near time of maximal water vapor amount). The tendency for a slight overall decrease in water vapor amount in the low stratosphere at Washington during recent years is in agreement with recently acquired data from Mildura, Australia (Hyson, 1978).

The lag correlation between SST* and water vapor in the low stratosphere at Washington is given at middle right in Fig. 10. Between 1964 and 1977 water vapor amount has tended to be a maximum one season after warmest SST*, though the correlation is only marginally significant at the 95% level (taking into account also the minimum correlation prior to warmest SST*). Inasmuch as the water vapor amount at Washington should be at least partly dependent on transport from equatorial regions, there is the implication that warm SST*, indeed, is associated with an intensification of the Hadley circulation, as suggested by Bjerknes (1966), Reiter (1978) and others. This, in turn, would imply that a strong Hadley circulation is associated with a weak Walker cir-

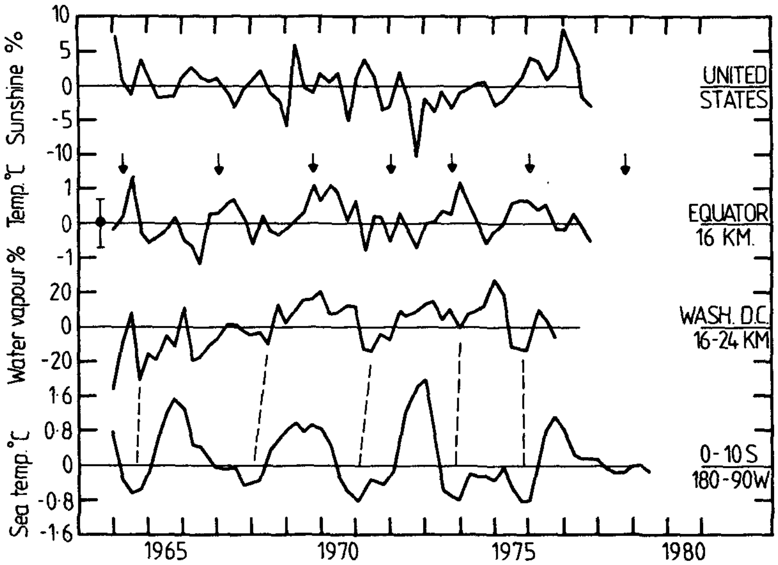

FIG. 11. Comparison of time variations in SST*, water vapor variation in the low stratosphere (16–24 km) at Washington, DC, 100 mb (16 km) temperature at the equator, and sunshine duration over the contiguous United States. Vertical arrows denote time of quasi-biennial west wind maximum at 20 km in the tropics. There is about a 5% chance that the true mean value of seasonal 16 km temperature lies outside the extent of the vertical bar at left.

culation, and vice versa. However, the situation is not clearcut since one may argue that an enhanced Hadley circulation should be associated with a lower tropopause temperature in the tropics and therefore with a smaller water vapor flux into the tropical stratosphere based on the "cold trap" theory.

The minimum in sunshine duration (maximum in cloudiness) over the United States has tended to occur one season before warmest SST* (upper right trace in Fig. 10), and thus appears more closely related to an expanded north circumpolar vortex (Fig. 7) than to large water vapor amounts in the low stratosphere of north temperate latitudes.

Table 1 presents the correlation and lag between SST* and water vapor by season. The positive correlation between SST* and water vapor in the low stratosphere at Washington, DC is largest in the northern winter (water vapor amount lagging SST* by one season), but even this correlation of 0.36 is not significant at the 95% level. The negative correlations between SST* and sunshine duration are significant at the 95% level in northern summer and autumn.

c. *Ozone*

The lag correlation between SST* and total ozone over North America is given at lower right in Fig. 10. In basic agreement with the water vapor results at Washington, the total O_3 over North America has tended to be a maximum two seasons after warmest SST* during 1961–78, with the maximum correlation again marginally significant at the 95% level. Inasmuch as the ozone amount in extratropics partly depends on the ozone transport from the tropics, there is again the implication of an enhanced Hadley circulation (extending into the stratosphere) at time of warm equatorial SST (see, also, Pittock, 1973).

6. Summary

A warm sea surface temperature (SST) in the equatorial eastern Pacific (0–10°S, 180–90°W), hereafter known as SST*, has been related to the following at the 99.9% significance level (years of record in parenthesis):

1) A negative value of the Southern Oscillation index, or normalized pressure difference between Tahiti and Darwin (1932–79).

2) Warm temperature in the tropical troposphere two seasons later (1958–78).

3) Small values of Indian summer monsoon rainfall 1–2 seasons earlier (1866–77). There have been 20 years in which SST* was at least 0.8°C above average during the El Niño season (DJF), and during each of these years the summer monsoon rainfall in India two seasons earlier was below average. In 17 of the 20 years between 1958 and 1977, above-average monsoon rainfall has followed (by about two seasons) warm tropospheric temperatures in the tropics, and below-average rainfall has followed cool temperatures.

A warm SST* has been related to the following at the 99% significance level:

1) Decrease in rainfall in eastern Australia (1950–79).
2) Enhanced rate of increase of atmospheric CO_2 at the South Pole 2–3 seasons later (1965–76). At other CO_2 stations significance exceeds the 95% level, with lag time depending on distance of the CO_2 measurement from the equator.

A warm SST* has been related to the following at the marginal 95% significance level:

1) Warm temperatures in the 0–16 km layer of north and south temperate latitudes, and at the surface in the United States, 2–3 seasons later (1958–78).
2) Warm Northern Hemisphere surface temperature 1–2 seasons later (1900–78).
3) A contracted north circumpolar vortex area about three seasons later, or an expanded vortex about one season earlier (1963–78).
4) Equatorward displacement of subpolar low and subtropical high (1900–72).
5) Displacement of the polar vortex toward the region 180–90°W (1963–78).
6) Increased ozone over North America and increased water vapor in the low stratosphere at Washington, DC 1–2 seasons later (early 1960's to late 1970's).
7) Cold winter temperatures in the United States (1958–78).

The relationship of greatest interest is probably that between Indian summer-monsoon rainfall and SST*, in general, because it implies that the intensity of the Indian monsoon may be a key to subsequent events, and in particular because it may lead to better forecasting of the El Niño phenomenon. The relationship of next greatest interest is probably that between SST* and zonally averaged tropical-tropospheric temperature two seasons later, seemingly allowing for estimates of equatorial and subtropical air temperatures two seasons in advance. The apparent extension of these relations to higher latitudes (cold United States winters near time of warm SST*) should be monitored further with a view toward inclusion in seasonal forecasting techniques. It is pleasing to see that an expanded polar vortex is associated with relatively small rainfall amounts during the Indian summer monsoon, as would be expected. Furthermore, the temperate latitude variations in water vapor amount in the low stratosphere, and in total ozone, seem to be in agreement with the concept of an enhanced Hadley circulation accompanying warm SST*. Continued monitoring of these relations should firm-up these findings, and perhaps uncover new ones.

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