VOL. 111, NO. 5 MONTHLY WEATHER REVIEW MAY 1983

Global Temperature Variations in the Troposphere and Stratosphere, 1958–1982

J. K. ANGELL AND J. KORSHOVER

Air Resources Laboratories, ERL, NOAA, Rockville, MD 20852

(Manuscript received 1 September 1982, in final form 18 January 1983)

ABSTRACT

A network of 63 well-distributed radiosonde stations has been used to estimate mean-annual temperature variations at the surface and for 85–30 kPa (850–300 mb), 30–10 kPa, 10–5 kPa, 10–3 kPa, and surface–10 kPa layers for five climatic zones, both hemispheres, and the world for the interval 1958–81. At the surface and in the 85–30 kPa layer there was global cooling of about 0.5°C between 1958 and about 1970, and global warming since, with 1980 and 1981 values approximately 0.1°C warmer than observed in 1958 and 1959. However, an update using seasonal data indicates appreciable cooling again between the northern springs of 1981 and 1982. In the 30–10 kPa layer there has been slight global cooling during most of the interval 1958–81, resulting in an increase in lapse rate in the 85–30 and 30–10 kPa layers during the last decade. In the middle and high stratosphere (26–55 km), Northern Hemisphere rocketsonde data suggest a 3–5°C cooling between 1970 and 1976, but little temperature change since.

There is evidence for an 0.3°C decrease in Northern Hemisphere surface temperature following the Agung eruption in 1963, as well as at least a 1.0°C temperature increase in the low stratosphere of the tropics, but no convincing evidence that the eruptions of Fuego in 1974 or St. Helens in 1980 affected either tropospheric or stratospheric temperatures. Between 1958 and 1981, the correlation between sea-surface temperature (SST) in the equatorial eastern Pacific, and global temperature for the surface–10 kPa layer, is a significant 0.58 at a lag of two seasons, SST leading. There is some indication that, in the tropics, this lag increases slightly with distance from the equator and height in the troposphere. During the past decade there has been a close (inverse) relation between the area of the 30 kPa (300 mb) north polar vortex and 85–30 kPa temperature. During 1958–81 the departure from the mean of the seasonal 85–30 kPa temperature in north temperate latitudes averaged −0.4°C three seasons after cool SST in the equatorial eastern Pacific when the quasi-biennial oscillation (QBO) at 5 kPa in the tropics was in the eastwind phase, and 0.2°C three seasons after warm SST when the QBO was in the westwind phase. Inasmuch as SST has warmed through 1982, and the QBO east wind maximum at 5 kPa occurred in mid 1982, this relation would imply a relatively warm north-temperate troposphere in 1983.

1. Introduction

This paper presents an update of global temperature changes in the troposphere (Angell and Korshover, 1978b) and low stratosphere (Angell and Korshover, 1978d), as well as the middle and high stratosphere of the Northern Hemisphere (Angell and Korshover, 1978c). While the discussion centers on variations in mean-annual temperature through 1981, consideration is given to seasonal temperature variations through the northern spring of 1982. The area of the 30 kPa (300 mb) north polar vortex (Angell and Korshover, 1978a) has also been updated through the spring of 1982, and its association with the Southern Oscillation (SO) and quasi-biennial oscillation (QBO) is examined. There is fairly impressive evidence of a relation between zonally-averaged tropospheric temperature in north temperate latitudes and the joint phases of the SO and QBO.

As shown by Fig. 1, we have used a relatively sparse network of 63 radiosonde stations to estimate global temperature. It was our view that by obtaining column-mean temperatures through the use of "thickness" analysis we would do away with the necessity of a dense observational network, and this was suggested to be so by the similarity in trend derived from two 6-station subsets in north temperate latitudes (Angell and Korshover, 1975). However, in view of the work of Barnett (1978), we did not expect the surface temperatures obtained at these scattered radiosonde stations to be particularly representative. In order to investigate this matter further, we here compare our Northern Hemisphere surface temperature (NHST) results with those of Jones, Wigley and Kelly (1982), who used gridded temperatures (mostly over land) based on surface observations at about 900 stations during the interval 1958–81.

The top diagram (and top abscissa scale) of Fig. 2 shows a 5-point binomial smoothing applied to the year-average NHST data of Jones, Wigley and Kelly (JWK), and Angell and Korshover (AK). This 1-4-6-4-1 weighting (divided by 16) of successive values is the same as a 1-2-1 weighting (divided by 4) applied twice, and this is the way we have actually done it, with a conservative 1-1 weighting applied twice at the end points. In the region of overlap the two temper-

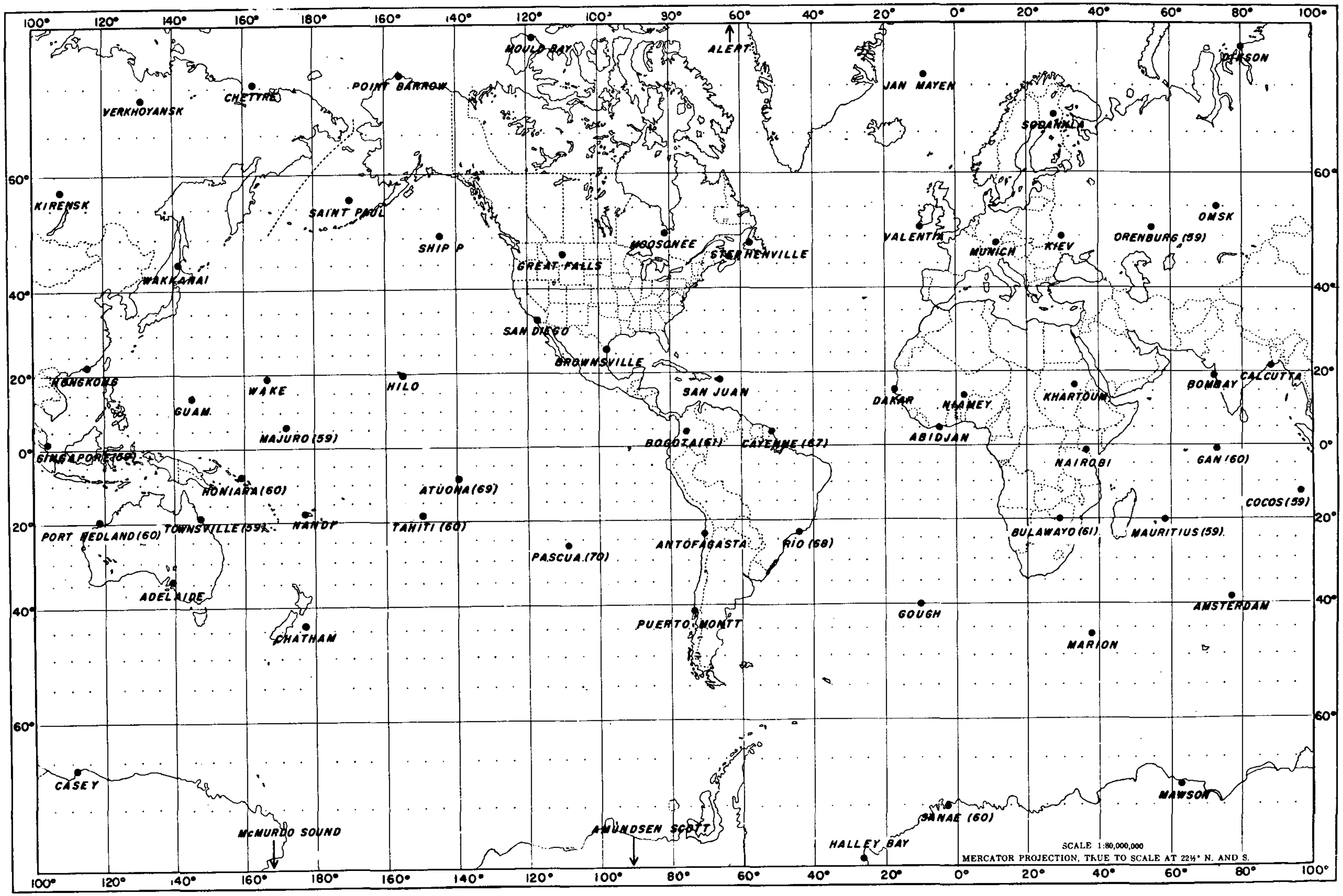

FIG. 1. Distribution of radiosonde stations used for the global temperature analysis. The numbers in parentheses show the year the temperature record began if it is other than 1958. In recent years Annette Island in the Alaskan panhandle (55°N, 132°N) has had to be substituted for *Ship P* (50°N, 145°N), and Trivandrum at the southern tip of India (9°N, 77°E) for Gan (1°S, 73°E).

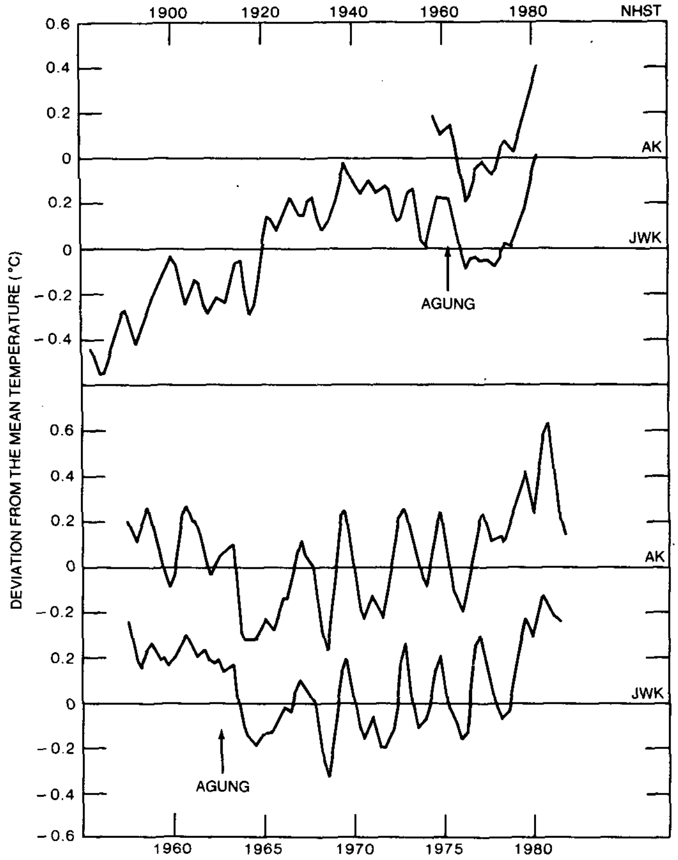

FIG. 2. Comparison of Northern Hemisphere surface temperature departures from the mean obtained by Jones, Wigley, and Kelly (JWK), and Angell and Korshover (AK). A 5-point binomial smoothing has been applied to mean-annual temperatures at top (abscissa scale at top), and to mean-seasonal temperatures at bottom (tick marks in summer of the given year). The Agung eruption is indicated.

ature traces are similar, and the correlation between the 24 unsmoothed yearly temperatures is 0.89. Note that the JWK data suggest that NHST in 1981 (the last point at top) was comparable to the warmest NHST previously observed in 1938. Also, both sets of data suggest a NHST decrease of about 0.3°C following the Agung (Indonesia) eruption in 1963, although the existence of cooling prior to the eruption (Barnett, 1978) confuses the estimation somewhat.

The bottom diagram (and bottom abscissa scale) of Fig. 2 shows a 5-point binomial smoothing of seasonal-average NHST. In both sets of data the seasonal values are obtained as deviations from long-term seasonal means, thereby eliminating the annual variation. The JWK data have been updated through the winter of 1982 in *Climate Monitor,* Vol. 11, published by the Climate Research Institute, University of East Anglia (AK data are plotted through the spring of 1982). The agreement between the two data sets is good except in 1960 and 1978, and the correlation between the 97 unsmoothed seasonal temperatures is 0.86. At least in the Northern Hemisphere, the sparse network seems to delineate surface temperature fluctuations quite well, i.e., the sparse network appears reasonably representative. The situation is not so clear-cut in the Southern Hemisphere, as discussed in Section 3.

2. Procedures

Most of the temperatures in this analysis are column-mean temperatures, obtained from the differences in height (thickness) between constant-pressure surfaces at individual radiosonde stations. This has the advantage of giving the mean temperature through a layer. The pressure-height data have been obtained from *Monthly Climatic Data for the World* (MCDW), a publication of the National Climatic Center, NOAA, except that the last two seasons of our record (northern winter and spring of 1982) are based on teletype data assembled at the National Meteorological Center, Suitland, MD. Parker (1980) has shown that gridpoint thicknesses determined from analyses by different meteorological agencies may be in considerable disagreement, particularly over the oceans and in subtropics, and has implied that temperature trends derived therefrom are unreliable. The use of station data avoids the subjectivity of the analysis procedure, and problems associated with changes in analysis procedure.

Inasmuch as 100 kPa (1000 mb) heights are not given in MCDW if the stations are much above sea level, we have chosen to examine separately the 85–30 kPa layer (1.5–9 km) which is within the troposphere at all latitudes, the 10–5 kPa (16–20 km) and 10–3 kPa (16–24 km) layers within the stratosphere at all latitudes, and the 30–10 kPa layer (9–16 km) within the troposphere in tropics, but stratosphere in polar regions. The reason for including two stratospheric layers is some recent decrease in the quantity of radiosonde data at 3 kPa. We also examine the surface–10 kPa layer (0–16 km) as a whole, which includes 90% of the atmospheric mass. The average (mass weighted) temperature for this layer has been obtained by letting the surface temperature represent the mean temperature in the surface–85 kPa layer (100–85 kPa layer), and then weighting the layer-mean temperature deviations by the pressure differences through the respective layers (15, 55 and 20 kPa).

The temperature data are evaluated as deviations from the mean, where, except in the south temperate stratosphere and Southern Hemisphere stratosphere, the mean is based on the 20-year interval 1958–77, that is, we have not changed the mean value with the addition of each year of new data. In south temperate and Southern Hemisphere stratospheres the mean is based on the interval 1964–77.

In subsequent diagrams the temperature data are usually presented as zonal averages for five climatic zones, i.e., two polar zones (60–90°), two temperate zones (30–60°) and a tropical zone (30°S–30°N), as well as both hemispheres and the world. The tropical average has been obtained from an equal weighting of north subtropical (10–30°N), equatorial (10°S–10°N) and south subtropical (10–30°S) zones since, at the earth's surface, these three areas are nearly equal. The hemispheric average has been obtained from a 1-2-2-1 weighting of averages for polar, temperate, subtropical and equatorial zones (crudely representing their respective areas), and the global average from an average of the two hemispheres.

In the diagram representing mean-annual values there are vertical bars which extend two standard deviations of the mean (standard deviations of the station departures from the mean divided by the square root of the number of stations) either side of the mean value. If the temperature deviations were normally distributed, and the station values independent in space and time, there would be only about a 5% chance that the true value of the annual mean lies outside the vertical extent of these bars. However, because the station spacing averages about 30° longitude, there are correlations between the station data which extend these confidence limits beyond their indicated values. It is estimated that the values for "two standard deviations of the mean" in the diagrams must be multiplied by about the square root of three (1.7) before they can be considered 95% confidence limits for the mean-annual values.

Table 1 presents average values of "two standard deviations of the mean" for the various pressure intervals and climatic zones, based on the period 1964–81. It was decided not to include in these averages the values for 1958–63 because, at higher levels, they were anomalously large due to the small quantity and poor quality of the data then. The smallest value in Table 1 (0.13°C) is found for the world average of the surface–10 kPa layer. Thus, if the departure from average of mean-annual global temperature in the surface–10 kPa layer exceeds 1.7 × 0.13°C = 0.22°C, then this departure from average would be considered significant at the 5% level. In general, the values of Table 1 increase with increasing height except that the value for the 85–30 kPa layer is always smaller than for the surface, suggesting that tropospheric temperatures are indeed more representative than surface temperatures.

3. Variations of mean-annual temperature in troposphere and low stratosphere

Fig. 3 shows the variation of mean-annual temperature from 1958 through 1981 at the surface (left)

TABLE 1. Average value of "two standard deviations of the mean" (°C), based on year-average temperature deviations from the mean at stations within the given regions during 1964–81. Because of the correlation between station data, these values must be multiplied by about 1.7 before they can represent average 95% confidence limits for the annual means.

	Surface	85–30 kPa	30–10 kPa	Sfc–10 kPa	10–5 kPa	10–3 kPa
North polar	0.62	0.39	0.52	0.32	0.76	0.85
North temperate	0.50	0.33	0.31	0.25	0.44	0.49
Tropics	0.21	0.19	0.33	0.18	0.41	0.52
South temperate	0.46	0.39	0.47	0.31	0.66	0.71
South polar	0.59	0.38	0.55	0.34	0.95	0.77
Northern Hemisphere	0.26	0.19	0.28	0.17	0.35	0.41
Southern Hemisphere	0.24	0.19	0.28	0.17	0.43	0.48
World	0.19	0.15	0.21	0.13	0.29	0.33

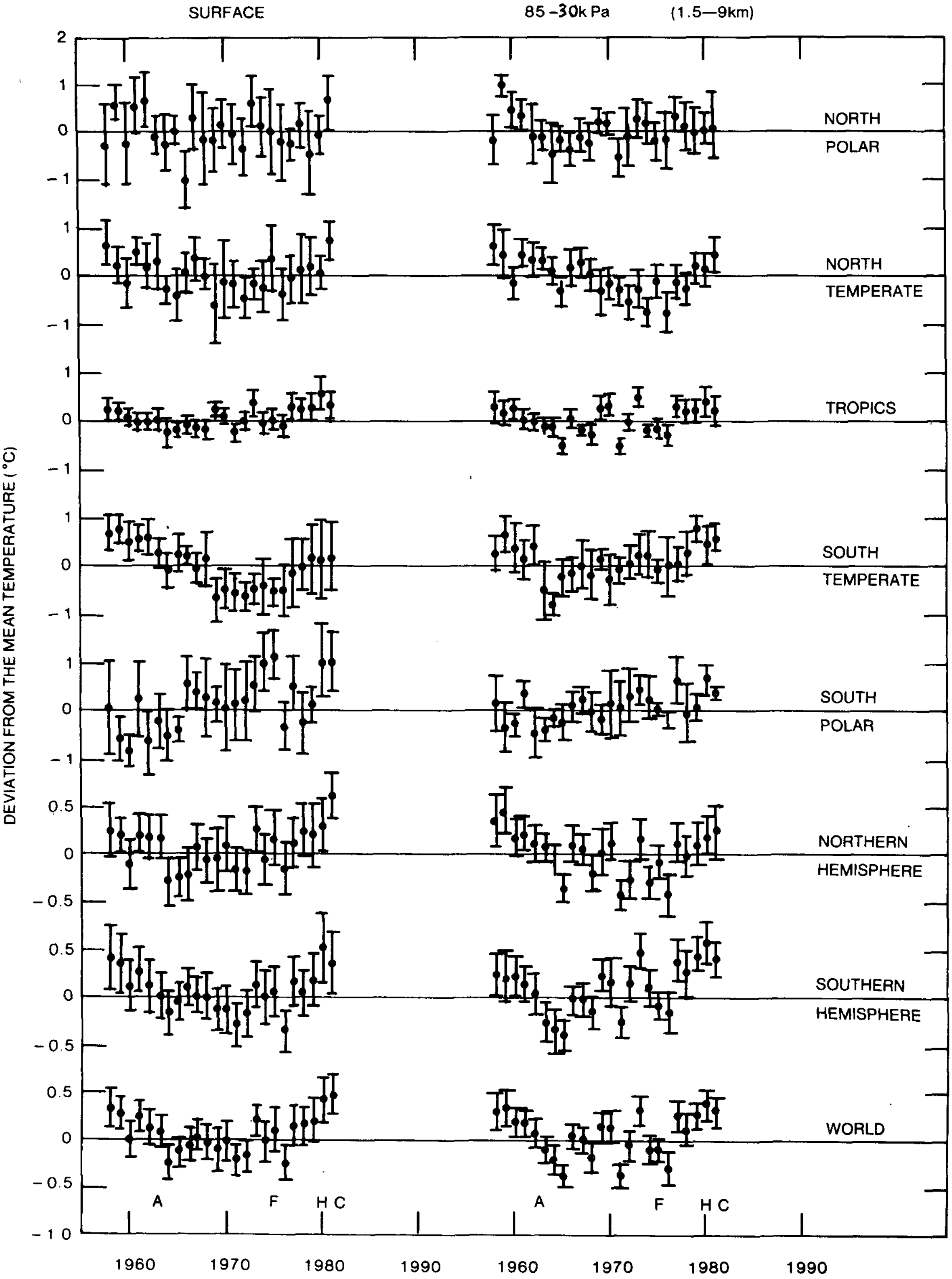

FIG. 3. Variation of mean-annual temperature from 1958 through 1981, at the surface and in the 85–30 kPa (850–300 mb) layer, expressed as a deviation from the mean for the interval 1958–77. The vertical bars extend two standard deviations of the mean either side of the mean-annual values, but because of the correlations between station data, the lengths of these bars must be multiplied by about 1.7 before they can be considered 95% confidence limits for the annual means. The volcanic eruptions of Agung (A), Fuego (F), St. Helens (H) and Chichon (C) are indicated at bottom. Note the change in ordinate scale.

and for the 85–30 kPa (850–300 mb) layer (right). Presented are zonal-mean values for the five climatic zones, both hemispheres, and the world. Because we also deal with seasonal values, the annual mean does not represent a mean for the calendar year but rather a mean for the period December through November.

There have been varied estimates of when the Northern Hemisphere cooling observed after 1940 (Fig. 2) ceased, and the recent warming began, hardly surprising in view of the precision of the trends. In general, those analyzing surface temperatures (e.g., Borzenkova *et al.*, 1976; Yamamoto and Hoshiai, 1979; Vinnikov *et al.*, 1980; Hansen *et al.*, 1981) have opted for an earlier time of temperature-trend reversal than those analyzing tropospheric or column-mean data (e.g. Dronia, 1974; Harley, 1978; Namias, 1980). The times of estimated temperature-trend reversal have ranged from shortly after the Agung eruption, say 1964 or 1965, to the cold year of 1976 and the cold winter of 1976–77. The JWK data in Fig. 2 indicate little surface temperature change over this interval.

The Northern Hemisphere traces in Fig. 3 show a surface warming beginning shortly after the Agung (A) eruption in 1963, but a tropospheric (85–30 kPa) cooling continuing until about 1976. There is the implication of an increase in Northern Hemisphere low-tropospheric lapse rate between 1964 and 1976 of about 0.01°C $(100\ \mathrm{m})^{-1}$, or one-hundredth the dry adiabatic lapse rate. In the Southern Hemisphere the opposite variation is indicated, with the tropospheric temperature warming after Agung and the surface temperature warming only in the mid 1970's, with the implication of a decrease in low-tropospheric lapse rate. Because of the alternating trends in the two hemispheres, the surface and 85–30 kPa trends for the world are similar in Fig. 3.

It is certainly debatable whether these subtle differences in trend between surface temperature and 85–30 kPa temperature are meaningful. The surface temperature changes derived from our sparse network in the Southern Hemisphere are especially questionable. The Southern Hemisphere sea-surface temperature (SST) data of Paltridge and Woodruff (1981) exhibit little change between 1958 and 1978, in contrast to the cooling and warming indicated in Fig. 3. Furthermore, the New Zealand surface temperature data of Salinger (1979) show a warming between 1965 and 1970, in contrast to the slight surface cooling in Fig. 3. There is, however, good agreement between the Southern Hemisphere 85–30 kPa traces in Fig. 3 and New Zealand surface temperature, both showing a cooling between 1958 and 1965, and a warming between 1965 and 1970. Considering the local nature of the New Zealand data, and the uncertainty regarding the compatibility of air temperature and SST variations, we conclude that the question of the representativeness of our Southern Hemisphere surface data remains to be resolved.

Fig. 3 also shows that, in 1981, the Northern Hemisphere surface temperature is indicated to be a significant 0.61°C above average (see also Table 2), the warmest temperature since the beginning of the record in 1958, and 0.31°C warmer than the 1980 value, in good agreement with Jones (1981). In the 85–30 kPa layer the 1981 temperature is not so extreme; though warmer than the 1980 temperature, it is not warmer than 1958 and 1959 temperatures for this layer, and is not significantly different from average. In the Southern Hemisphere both surface and 85–30 kPa temperatures are indicated to be slightly cooler in 1981 than 1980. As a consequence, the global 1980 and 1981 temperatures are comparable, a significant 0.3–0.5°C above average, or about 0.1°C warmer than observed in 1958–59.

With respect to the climatic zones, there is little evidence of an overall warming in north polar latitudes despite the warm surface temperature in 1981 (see Kelly *et al.*, 1982), but there is evidence of an overall warming in south polar latitudes (Antarctica). There also appears to have been an appreciable warming of the tropics during the last 20 years, though the 1981 temperature is about 0.2°C cooler than the 1980 temperature. This tropical warming is not particularly evident in the analysis of Hansen *et al.* (1981). However, Mitchell (1963) has shown that, over the interval 1880–1960, the variation in tropical surface temperature was similar to the variation in hemispheric and global temperature, as suggested for the last 20 years by the traces at left in Fig. 3.

TABLE 2. Deviation of mean-annual 1981 temperatures (°C) from the 1958–77 mean (1964–77 mean for south temperate and Southern Hemisphere 10–5 and 10–3 kPa layers).

	Surface	85–30 kPa	30–10 kPa	Sfc–10 kPa	10–5 kPa	10–3 kPa
North polar	0.67	0.10	−1.21	−0.09	−0.39	−0.28
North temperate	0.78	0.45	−0.37	0.32	0.29	0.36
Tropics	0.36	0.21	−0.54	0.08	−0.05	−0.24
South temperate	0.20	0.59	−0.38	0.28	−0.08	−0.51
South polar	1.05	0.39	0.54	0.54	0.10	0.19
Northern Hemisphere	0.61	0.24	−0.65	0.12	−0.09	−0.14
Southern Hemisphere	0.36	0.40	−0.25	0.24	0.06	−0.17
World	0.48	0.32	−0.45	0.18	−0.01	−0.15

Fig. 4 shows the variation in mean annual temperature for the 30–10 kPa layer (left) and the surface–10 kPa layer (right). The most interesting feature with respect to the 30–10 kPa layer is the absence (except perhaps in north temperate latitudes) of the cooling and warming trends observed at the surface and in the 85–30 kPa layer. Rather, in the global average there appears to have been, overall, a slight

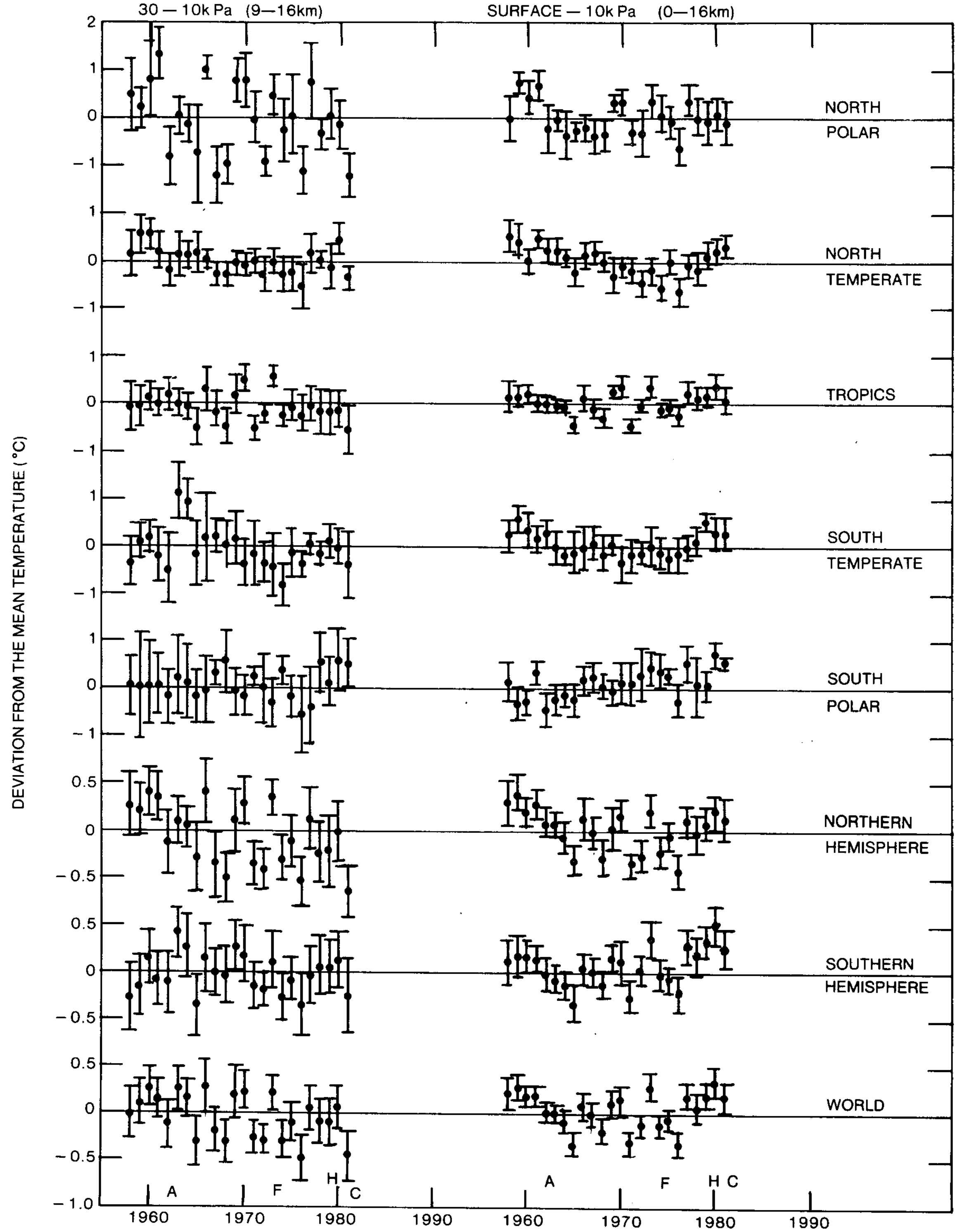

FIG. 4. As in Fig. 3, but for 30–10 kPa (300–100 mb) and surface–10 kPa (surface–100 mb) layers.

cooling of the 30–10 kPa layer, with the 1981 value nearly 0.5°C below average (see also Table 2). This evidence that the cooling and warming at the surface and in the 85–30 kPa layer does not generally extend to the 30–10 kPa layer may be an important finding of this study. In the interval 1965–81 there is the implication of a global increase in lapse rate of about 0.01°C $(100\ \text{m})^{-1}$ between 85–30 and 30–10 kPa layers.

In articles prior to this one we have considered the temperature variation in the surface–10 kPa layer as a whole as most representative of tropospheric temperature changes owing to the relatively small value for the standard deviation of the mean (see Table 1). However, because there has been little or no warming in the 30–10 kPa layer in recent years, use of the surface–10 kPa layer has resulted in a slight underestimate of recent tropospheric warming.

Fig. 5 shows the variation in mean annual temperature in the 10–5 kPa layer (left) and 10–3 kPa layer (right). Initially, we only tabulated data for the 10–3 kPa layer, wishing to extend the analysis as high into the stratosphere as possible. However, recently we have had reservations about the accuracy of such data on a global basis owing to the sparsity of observations at 3 kPa, and accordingly we now tabulate data for the 10–5 kPa layer as well.

In both these layers the significant warmth in the tropics in 1964 is at least partly due to the Agung (A) eruption in 1963 (Newell, 1970), although the phase of the quasi-biennial oscillation was such as to augment this warming (McInturff *et al.*, 1971). The anomalous coolness in the low stratosphere prior to Agung makes it difficult to estimate the amount of the warming in this layer due to Agung, but it would appear to exceed 1°C on the basis of Fig. 5. However, we find no convincing evidence of stratospheric warming as a result of either the Fuego (F) eruption in 1974 or the St. Helens (H) eruption in 1980. The global cooling since Agung is indicated to be greater in the 10–3 kPa layer than in the 10–5 kPa layer, but this is mostly due to differing trends in the Southern Hemisphere where the data are poor. The best high-level data are in north temperate latitudes, and here there has been essentially no low-stratospheric temperature change since 1961.

4. Temporal changes in lapse rate, meridional gradient and variability

Fig. 6 presents the temporal changes in meridional and vertical temperature gradients that may be inferred from Figs. 3–5, as well as estimates of the temporal changes in temperature variability in space and time. To obtain as conservative and representative an estimate as possible of these temporal changes, we have dealt with the full surface–10 kPa layer except when dealing with lapse rate changes.

The top traces of Fig. 6 show that, in both hemispheres, the year-to-year temperature change in the surface–10 kPa layer was small initially, and has been fairly small recently, but was relatively large from about 1965 to 1977. These large interannual changes between 1965 and 1977 mainly reflect the existence of a pronounced Southern Oscillation (e.g., Julian and Chervin, 1978) during this period which has strongly influenced the hemispheric temperature variations in this layer (Section 7). The spatial standard deviation of temperature (determined as the standard deviation of the departure of individual station years from individual station means) has increased slightly in both hemispheres in recent years, but the increase is so small that there is no convincing evidence of a trend in spatial variability.

The traces in the middle of Fig. 6 represent estimates of the temporal changes in lapse rate basically between troposphere and stratosphere (the difference in the temperature deviations from the mean in surface–10 kPa and 10–3 kPa layers), as well as basically in the troposphere (the difference in the temperature deviations from the mean in 85–30 kPa and 30–10 kPa layers). An upward trend to the right signifies an increase in lapse rate with time. There is evidence for a temporal increase in tropospheric lapse rate in both hemispheres, with the increase particularly large in the Southern Hemisphere following the pronounced minimum in lapse rate (coolness at low levels, warmth at high levels) apparently associated with the Agung eruption in 1963. In the Southern Hemisphere there is also evidence of an increase in lapse rate between troposphere and stratosphere, but not in the Northern Hemisphere where the data are best.

The temporal change in the surface–10 kPa meridional temperature gradient is considered from the point of view of change between tropics and temperate latitudes, and tropics and polar latitudes. Here an upward trend to the right signifies an increase in meridional temperature gradient with time. The meridional temperature gradient between tropics and temperate latitudes increased up to about 1970 in both hemispheres, and has decreased since, partly in response to the tropical air temperatures associated with the varying amplitudes of the Southern Oscillation (see Fig. 10), but there is little evidence of an overall change during the period of record. On the other hand, the meridional temperature difference between tropical and south polar latitudes has apparently decreased by at least 0.5°C during the past 20 years, although there is the suggestion that this decrease has ceased. There has been no noticeable change in meridional temperature gradient between tropics and north polar latitudes during the last 20 years.

The trace at lower left in Fig. 6 shows that, in the surface–10 kPa layer, there has been a consistent warming of the Southern Hemisphere relative to the

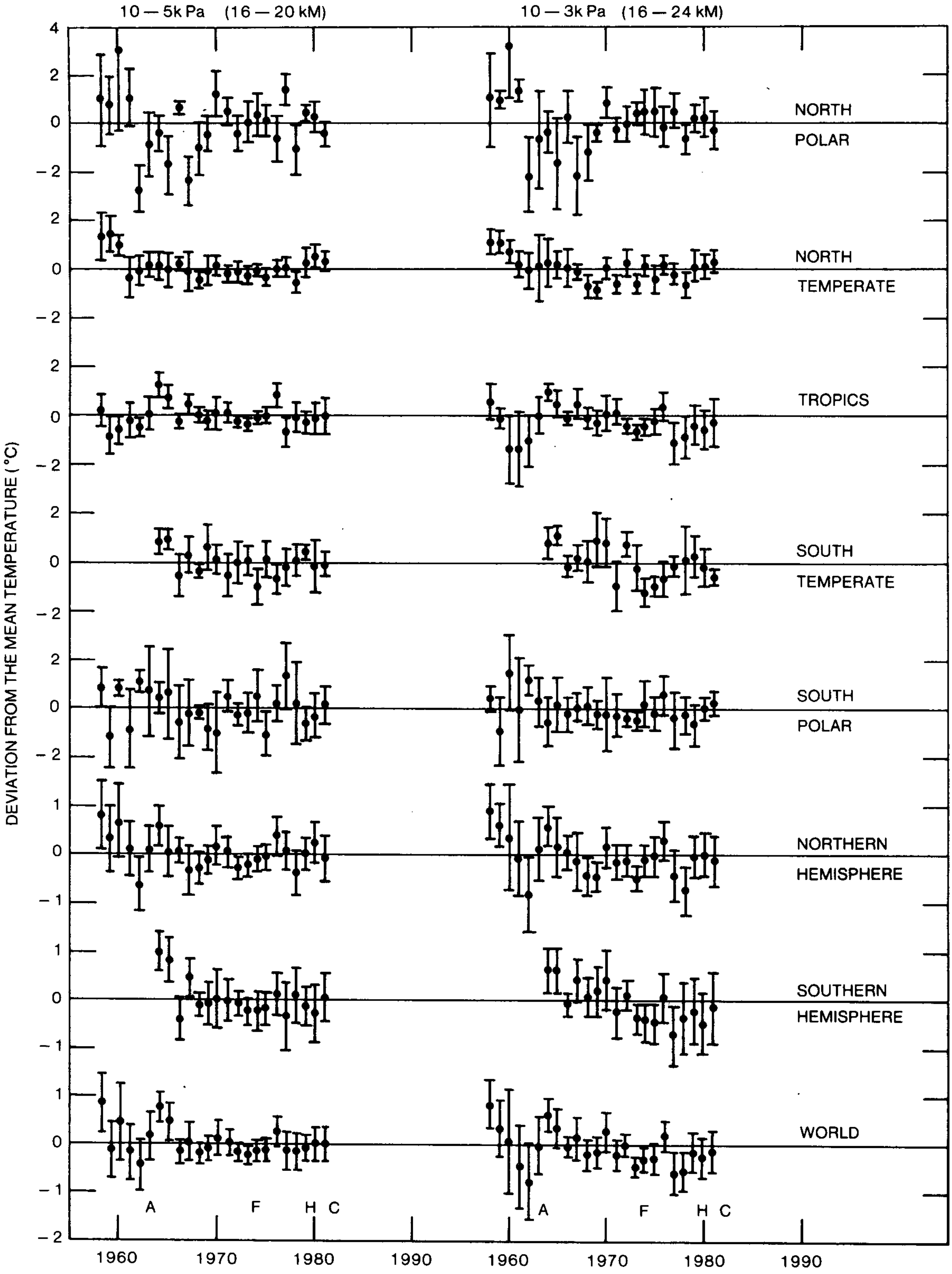

FIG. 5. As in Fig. 3, but for 10–5 kPa (100–50 mb) and 10–3 kPa (100–30 mb) layers. Note that for years 1958–1963 the "world" average is based on data only in north polar, north temperate, tropical and south polar climatic zones (1-2-6-1 weighting, respectively).

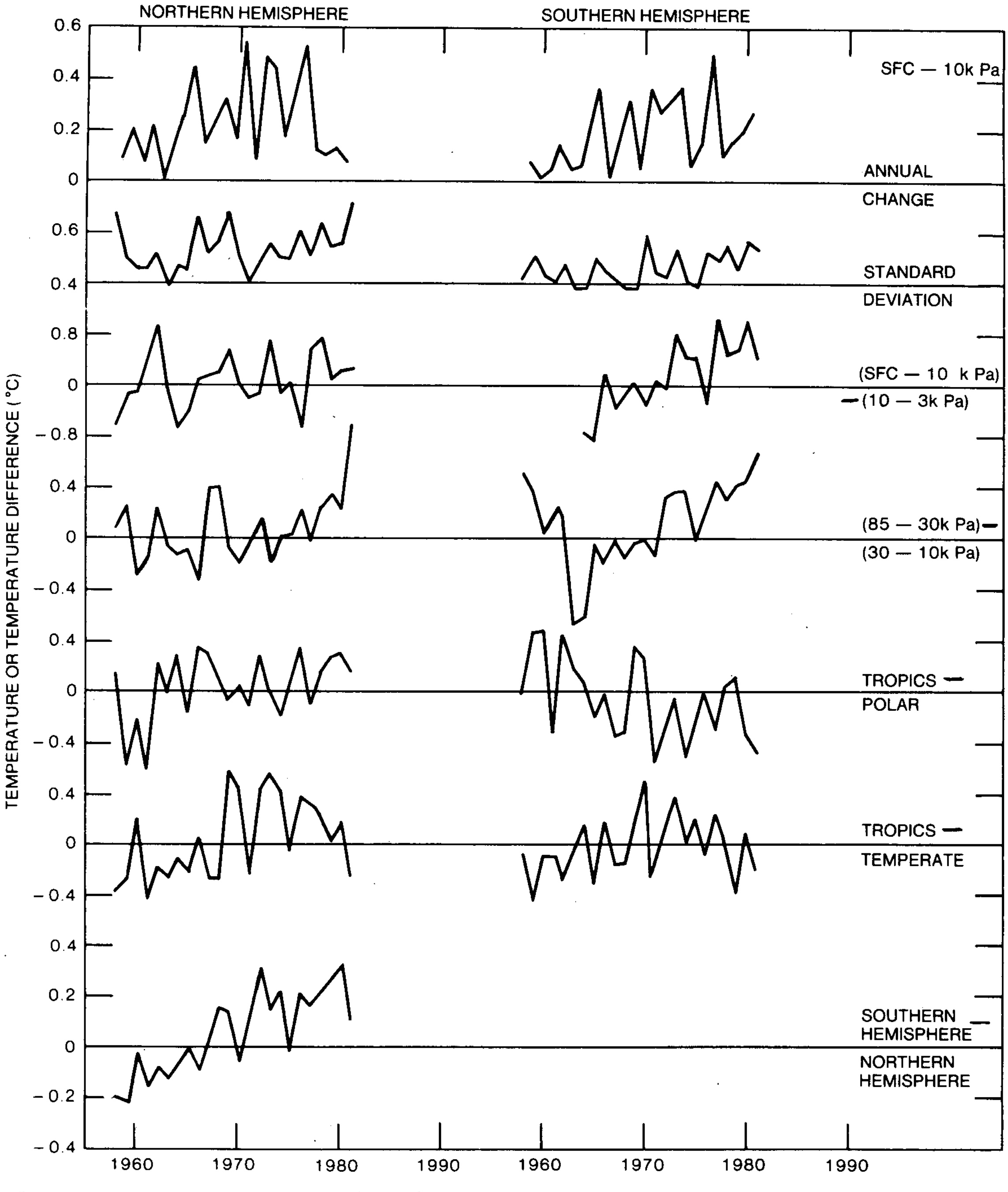

FIG. 6. The two top traces show the magnitude of the year-to-year temperature change and the temporal change in spatial standard deviation of temperature (station-year temperature relative to station mean) in the surface–10 kPa layer of the Northern and Southern Hemispheres; the two middle traces the temporal change in lapse rate as estimated from differences in the temperature deviations from the mean for given layers; and the bottom traces the temporal change in meridional temperature gradient as estimated from differences in the temperature deviations from the mean in the surface–10 kPa layer of given climatic zones, as well as the hemispheres. An upward trend to the right signifies a temporal increase in lapse rate, meridional temperature gradient, or Southern Hemisphere temperature relative to Northern Hemisphere temperature.

Northern Hemisphere during the past two decades. Thus, through the troposphere as a whole, the water hemisphere has warmed relative to the land hemisphere (or the land hemisphere has cooled relative to the water hemisphere).

5. Variation of mean-annual temperature in middle and high stratosphere

Atmospheric models predict that the temperature changes due to a CO_2 effect should be most apparent

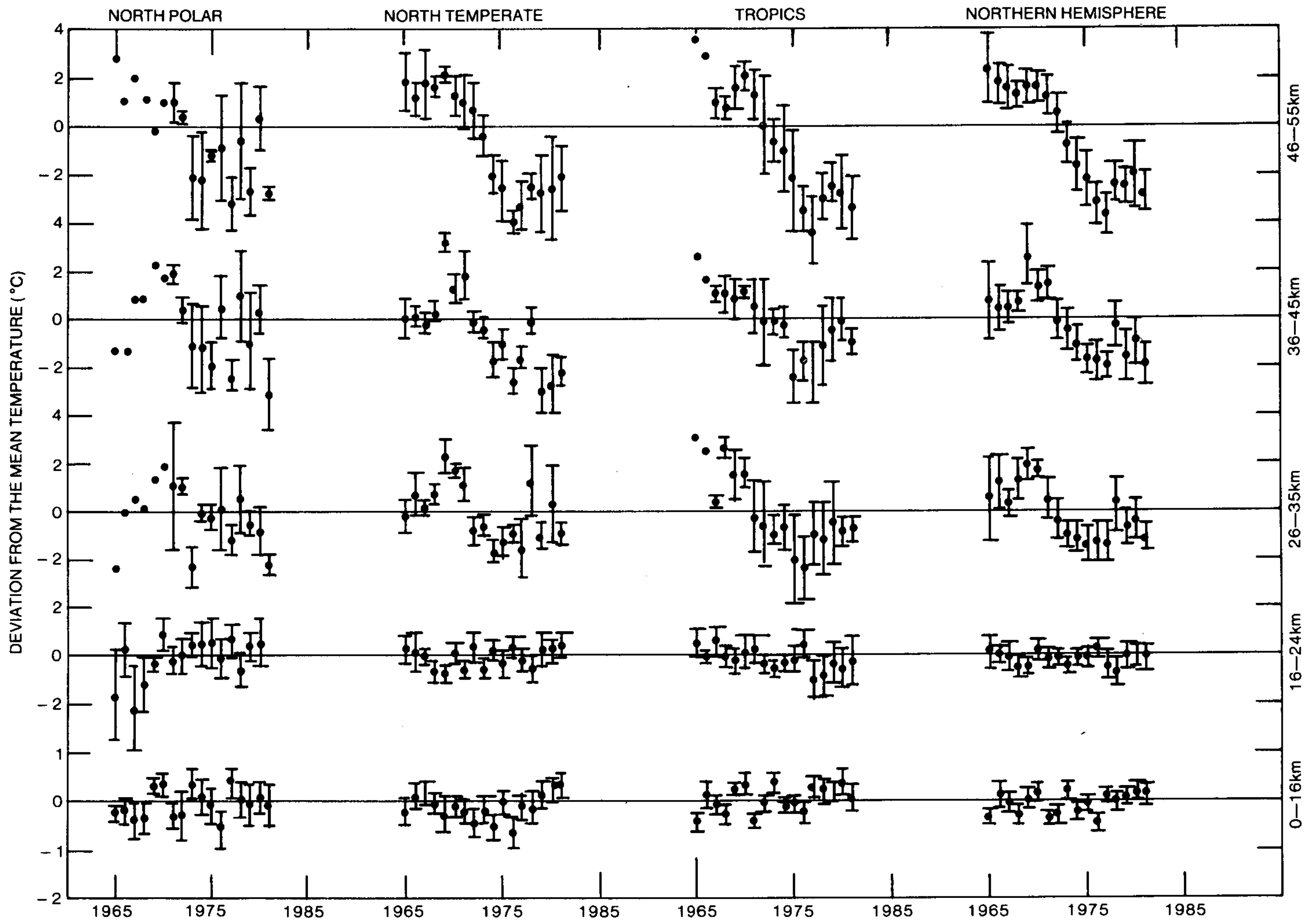

FIG. 7. Variation of mean-annual temperature from 1965 through 1981 for the height layers given at right. The three upper traces are based on rocketsonde data in the Western Hemisphere, and the two lower traces radiosonde data in both the Western and Eastern Hemispheres. The absence of vertical bars signifies that the annual mean is determined from only one station. Otherwise, see Fig. 3 legend.

in the middle and high stratosphere (25–50 km) where appreciable cooling would accompany the subtle warming at the surface (e.g., Manabe and Wetherald, 1975). Thus, as far as "first detection" of a CO_2 effect is concerned, the middle and high stratosphere would be the place to look if the "noise" levels were low and the temperature data comparable in quantity and quality to the data at the surface or in the troposphere. Unfortunately, they are not, mainly due to the limited number and distribution of rocketsonde stations.

The rocketsonde network is basically a United States network, and consequently most of the rocketsonde stations are in the Western Hemisphere. In addition, the rocketsonde network has recently undergone a reduction, and as of 1982 only two stations in polar latitudes (Shemya, Alaska and Primrose Lake, Canada), three tropical stations (Ascension, Kwajalein and Antigua) and four temperate-latitude stations (Wallops Island, Cape Kennedy, Point Mugu and Barking Sands, Hawaii) are in routine operation. Fig. 7 shows the variation in mean-annual temperature from 1965 through 1981 (expressed as a deviation from the mean for the interval 1965–77) in these climatic zones for height layers 26–35, 36–45 and 46–55 km, obtained by averaging temperatures at 1 km height intervals. The Northern Hemisphere average has been obtained from a 1-3-2 weighting of polar, temperate and tropical deviations, respectively. Shown at bottom for comparison are the temperature variations in 0–16 km (surface–10 kPa) and 16–24 km (10–3 kPa) layers obtained from the radiosonde data.

A striking feature of Fig. 7 is the large (3–5°C) rocketsonde-derived temperature decrease indicated for all three climatic zones, and the Northern Hemisphere as a whole, between about 1970 and 1976. Since there was a sunspot number maximum (106) in 1969, and a minimum (13) in 1976, some years ago it was hypothesized that there might be a direct relation between sunspot number and stratospheric temperature and ozone (Callis and Nealy, 1978; Penner and Chang, 1978). However, there is evidence for only a slight warming between 1976 and 1980 even though the sunspot number increased from 13 to 155 between these years. Thus, it is unlikely that the cooling between 1970 and 1976 was related to the decrease in sunspot number. The cooling was also much too large to be associated, in its entirety, with the observed increase in CO_2, but a small part of the cooling might be related to this increase.

TABLE 3. Comparison of the temperature change (°C) between 1970 and 1976 in the 16–24 km (10–3 kPa) layer of western and eastern hemispheres.

	Western Hemisphere	Eastern Hemisphere
North polar	−0.45	−1.57
North temperate	0.44	−0.21
Tropics	−0.70	1.02
Northern Hemisphere	−0.09	−0.03

The radiosonde-derived temperature data for the 16–24 km layer show almost no evidence of this cooling during the early 1970's. While it is true that the rocketsonde-derived temperature decrease during the early 1970's becomes smaller with decreasing height, the transition between rocketsonde trend and radiosonde trend still seems rather abrupt. There is always the possibility of instrumental problems with the rocketsonde data, though this is claimed not to be the case (Quiroz, 1979). Another possibility is that the discrepancy arises because the radiosonde data extend completely around the Northern Hemisphere, whereas the rocketsonde data are limited to the western quadrant of this hemisphere.

To investigate this latter possibility, Table 3 shows the temperature change between 1970 and 1976 in the 16–24 km (10–3 kPa) layer as deduced from equal numbers of radiosonde stations in the Western and Eastern Hemispheres. Although in the tropics there is indicated to have been much greater cooling between 1970 and 1976 in the Western Hemisphere than in the Eastern Hemisphere, in polar and temperate latitudes the opposite seems to have been the case. In the average for the Northern Hemisphere, then, the temperature change in the Western and Eastern Hemispheres is nearly the same, and accordingly, there is no convincing evidence that exclusion of the Eastern Hemisphere is the cause of the discrepancy between rocketsonde-derived and radiosonde-derived temperature trends. If the rocketsonde data do turn out to be valid, and representative of the hemisphere, then between 1970 and 1976 the average lapse rate between the surface and 50 km increased by about 0.01°C $(100\ \mathrm{m})^{-1}$ in the Northern Hemisphere, the same value obtained earlier for recent tropospheric lapse rate changes.

6. Variation of mean-seasonal temperature in the troposphere

In order to study phenomena such as the Southern Oscillation (SO) and quasi-biennial oscillation (QBO), as well as pinpoint the effects of volcanic eruptions and obtain up-to-date information concerning recent temperature fluctuations, it is necessary to analyze the temperature data at least by season. Fig. 8 shows temperature variations at the surface and in the 85–30 kPa layer (same format as Fig. 3), where a 5-point binomial smoothing has been applied to seasonal deviations from the long-term mean. The smoothed data in Fig. 8 extend through the northern spring of 1982, with the temperatures for winter and spring based on teletype data assembled by the National Meteorological Center.

Unlike the Northern Hemisphere, in the Southern Hemisphere there was no obvious surface tempera-

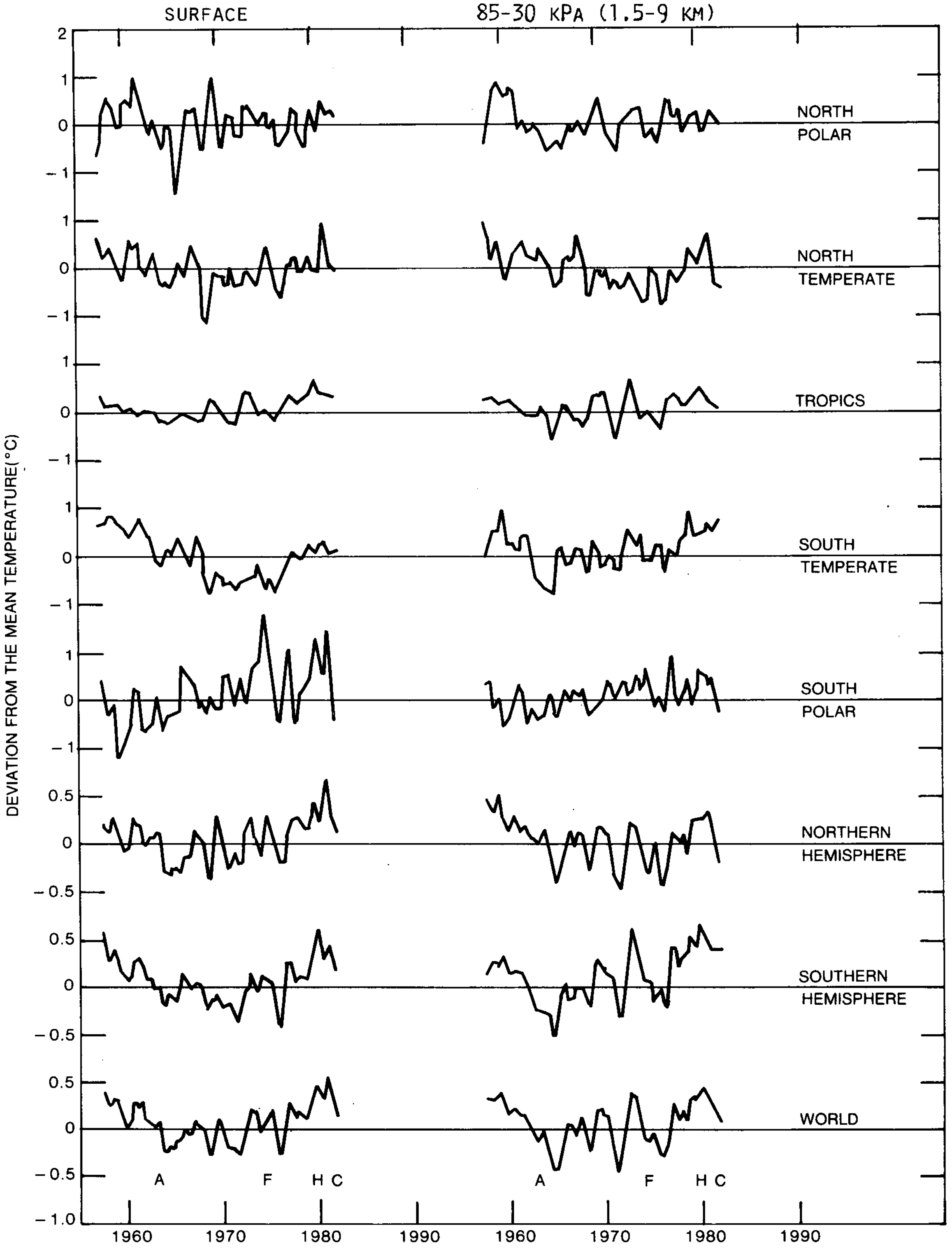

FIG. 8. Temperature variations through the northern spring of 1982 (1982 temperatures based on teletype data), at the surface and in the 85–30 kPa layer, as obtained from a 5-point binomial smoothing applied to successive seasonal values (tick marks in the northern summer). The major volcanic eruptions are indicated at bottom. Note the change in ordinate scale.

ture decrease associated with the Agung eruption in 1963, cooling occurring before the eruption, and continuing after the eruption. We also find no evidence, in any climatic zone, of anomalous cooling after the Fuego (F) eruption in 1974 or the St. Helens (H) eruption in 1980.

A noteworthy feature of Fig. 8 is the surface temperature peak in early 1981 in north temperate latitudes, with a smoothed value nearly 1°C above average. Since then the temperature is indicated to have decreased rapidly, so that by the spring of 1982 the surface temperature is average and the 85–30 kPa temperature below average. The 1°C decrease in north temperate latitudes was responsible for an 0.5°C decrease in Northern Hemisphere temperature and 0.25°C decrease in global temperature. This temperature decrease prior to the Chichon (C) eruption in the spring of 1982 may make it more difficult to detect the cooling effect of Chichon, as was apparently the case in the Southern Hemisphere with Agung. As this text was being prepared, Northern Hemisphere surface temperatures for the summer of 1982 became available, and they averaged 0.24°C warmer than the spring values, so that any surface cooling due to Chichon is not yet apparent on a hemispheric basis according to our analysis (stratospheric warming of 2–3°C *is* apparent at heights of 24 and 26 km at stations in the north subtropics, however, almost certainly attributable to Chichon).

Because of the great variability of winter temperatures, it has been suggested that, for purposes of trend detection, a better signal-to-noise ratio might be obtained from summer data (e.g., Wigley and Jones, 1981). Fig. 9 presents a comparison of winter (DJF) and summer (JJA) temperature variations for north polar and north temperate latitudes for various height intervals. The great interannual variability in winter temperature in north polar latitudes obviously makes trend detection difficult, and the relatively warm winter of 1980–81 at the surface certainly does not necessarily presage a long-term polar warming (note that this winter was not warm in the 85–30 kPa layer).

Examination of the summertime polar data shows that, while the interannual variability is indeed much less than in winter, the temperature trends in the various layers are not consistent, with slight cooling indicated for the surface and the 30–10 kPa layer, slight warming for the 85–30 kPa layer, and no change for the 10–3 kPa layer. In general, though, there is little evidence for north polar warming from the summer data either. Thus, the north polar region, where models indicate a CO_2-induced warming, should be most pronounced (Manabe and Wetherald, 1980), as yet shows almost no evidence of such warming according to this analysis.

The north temperate data show that the cooling and warming trends observed during the last 20 years at the surface and in the 85–30 kPa layer have been due mostly to changes in winter temperature, and very little to changes in summer temperature. If anything, there has been a slight overall cooling in summertime surface temperature in this climatic zone, in agreement with the polar zone.

7. Southern Oscillation

The Southern Oscillation phenomenon was first recognized as a 3–7 year alternation in pressure between eastern South Pacific and the Indonesian area (e.g., Troup, 1965; Trenberth, 1976, and references therein). More recently it has been found that this pressure alternation is intimately related to SST changes in the equatorial eastern Pacific. Thus, based on seasonal data from 1932 through 1981, there is a highly significant correlation of −0.64 between the SST in the specific region we have examined (0–10°S, 180–80°W) and a normalized pressure difference between Tahiti and Darwin (Angell, 1981). We find this relation to be almost exactly out of phase, with seasonal lag-1 correlations (backward and forward lagged) of −0.55 and −0.56.

The bottom trace of Fig. 10 shows the time variation of SST (5-point binomial smoothing) in this particular region of the equatorial eastern Pacific. It is apparent from Fig. 10 that the variation in zonally-averaged surface–10 kPa temperature in the tropics is remarkably similar to this SST variation, although the atmospheric temperature variation lags the SST variation somewhat. It is possible that any volcanic influence on tropical air temperature could be better delineated by separating out the SST signal from the air temperature signal (Newell and Weare, 1976). For example, around 1965, or after the Agung (A) eruption, the tropical surface–10 kPa trace in Fig. 10 appears relatively cool with respect to the SST trace (note the difference in ordinate scale). Isolation of the volcanic signal is obviously difficult, but we intend to pursue this matter making use of the Chichon eruption as well as the Agung eruption.

Fig. 10 shows that the similarity between SST variation and atmospheric temperature variation extends also to the Northern Hemisphere and the world as a whole. The left-hand diagrams of Fig. 11 show the lag correlations between our specific index of SST (0–10°S, 180–80°W) and zonally averaged surface–10 kPa temperatures in the tropics, Northern Hemisphere, and world. Here a correlation maximum to the right of the vertical dashed line signifies that the variation in air temperature follows the variation in SST by the indicated number of seasons. The short horizontal bars denote zero-lag correlations significant at the 5% level taking into account the considerable serial correlation of the data [for details of this evaluation see Angell (1981)].

Considering the relative magnitudes of the lagged correlations either side of the peak correlation (ad-

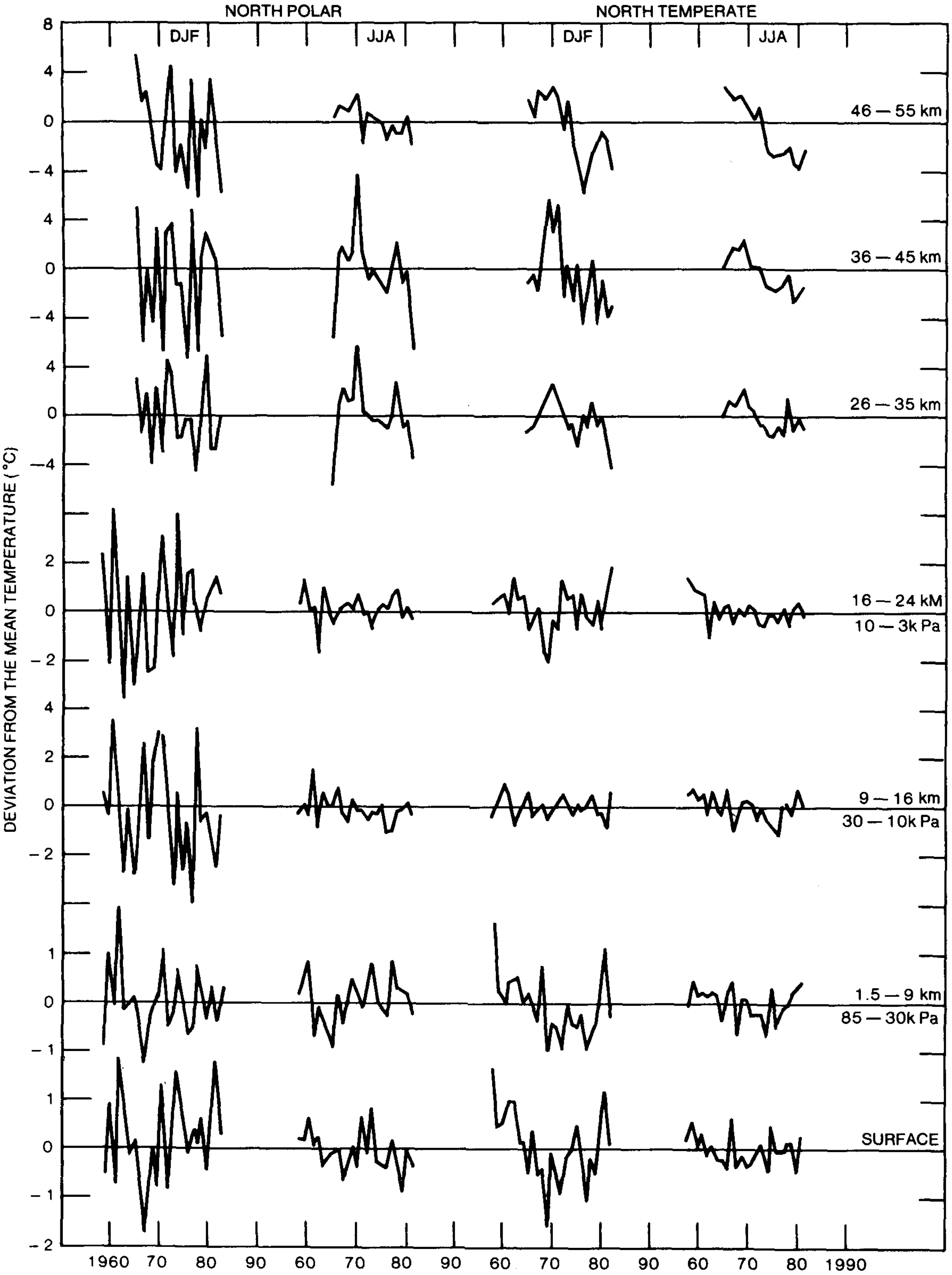

FIG. 9. Year-to-year variations in winter temperatures (DJF) and summer temperatures (JJA) in north polar and north temperate latitudes for the height intervals given at right. Note the change in ordinate scale.

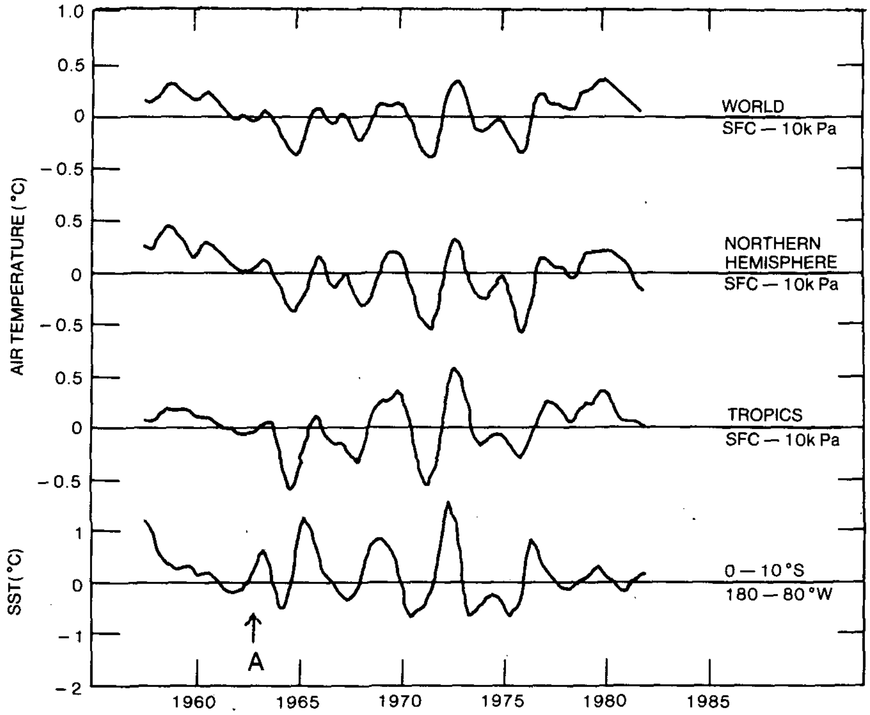

FIG. 10. Comparison between sea-surface temperature (SST) variations in the equatorial eastern Pacific, and temperature variations in the surface–10 kPa layer of the tropics, Northern Hemisphere and world, where a 5-point binomial smoothing has been applied to successive seasonal values. The tick marks are in the northern summer, and A denotes the Agung eruption. Note the change in ordinate scale.

mittedly an approximate procedure), it is seen that the tropical tropospheric temperature lags SST by just less than two seasons. The correlation maximum of 0.69 (based on seasonal data from 1958 through 1981) would be significant at better than the 1% level except that we are choosing the maximum correlation from a number of lagged correlations. The maximum correlation reduces to 0.60 for the Northern Hemisphere, and to 0.58 for the world as a whole, with the lag of maximum correlation slightly more than two seasons in both cases. Thus, when the Southern Oscillation is of large amplitude, as it generally was between 1958 and 1981, it has an impressive influence on surface–10 kPa temperature variations for hemisphere and world, and indeed provides an estimate of hemispheric and global temperatures in this layer two seasons in advance.

It should be made absolutely clear, however, that the relation between SST and Northern Hemisphere surface temperature (NHST) is not nearly so impressive as the relation between SST and Northern Hemisphere surface–10 kPa temperature. Thus, based on seasonal data for the interval 1958–81, the maximum correlation between SST and NHST is found at a lag of three seasons, with a value of 0.21 for the AK data and 0.30 for the JWK data (perhaps an indirect hint that the JWK data are more representative). Based on seasonal data for the 100-year interval 1882–1981, the maximum correlation between SST and NHST (JWK data) is 0.22 at a lag of two seasons. The smaller JWK correlation for the longer time period probably results both from the poorer quality of the early data, and the unusual strength of the Southern Oscillation during 1958–81.

While NHST is indicated to lag SST when dealing with seasonal data, when dealing with non-overlapping decadal data (10 values centered from 1885 to 1975) the maximum correlation of 0.9 occurs when SST lags NHST by 20 years, similar to the lag found by Paltridge and Woodruff (1981) when comparing long-term global SST data with the global surface temperature data of Mitchell (1963). A difference between relations on the short term and the long term is also found when comparing SST in equatorial eastern Pacific with Indian summer-monsoon rainfall (Parthasarathy and Mooley, 1978), the correlation being −0.6 for seasonal data extending from 1870 to 1980 (Angell, 1981), and 0.8 for non-overlapping decadal data (11 values centered from 1875 to 1975).

The middle diagrams of Fig. 11 show the lag correlation between SST and zonally-averaged temperature in the north subtropics, south subtropics, and the equatorial zone. The correlation is a maximum (and most significant) in the north subtropics but this may merely reflect the quality of the data in this zone. Again making use of the relative magnitudes of the

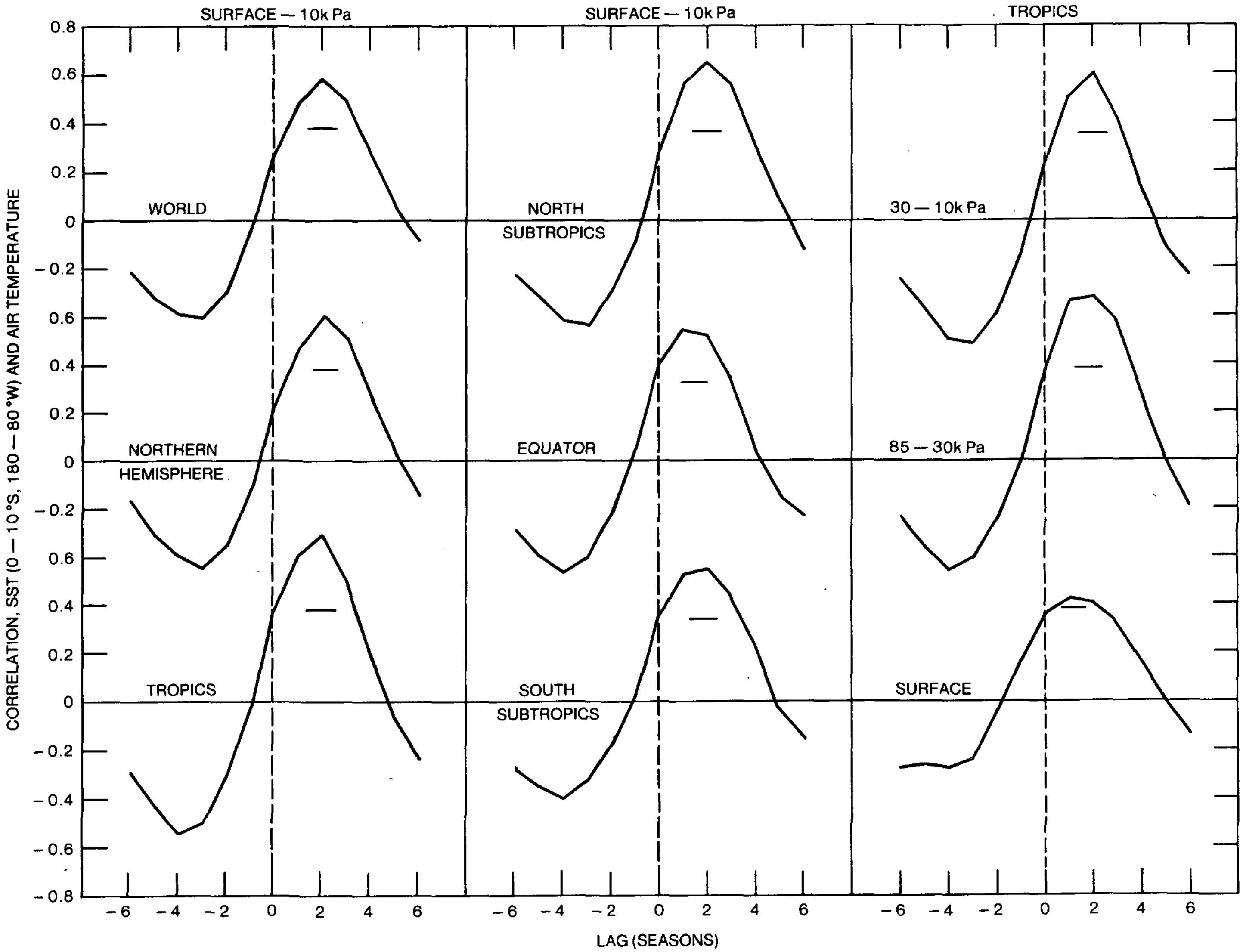

FIG. 11. Lag correlations between SST in the equatorial eastern Pacific and surface-10 kPa temperatures in various regions (left and center), as well as temperatures in various height layers of the tropics (right). A correlation maximum to the right of the dashed line signifies that zonally-averaged air temperature follows, in time, this SST. The short horizontal bars denote zero-lag correlations significant at the 5% level taking into account the serial correlation of the data.

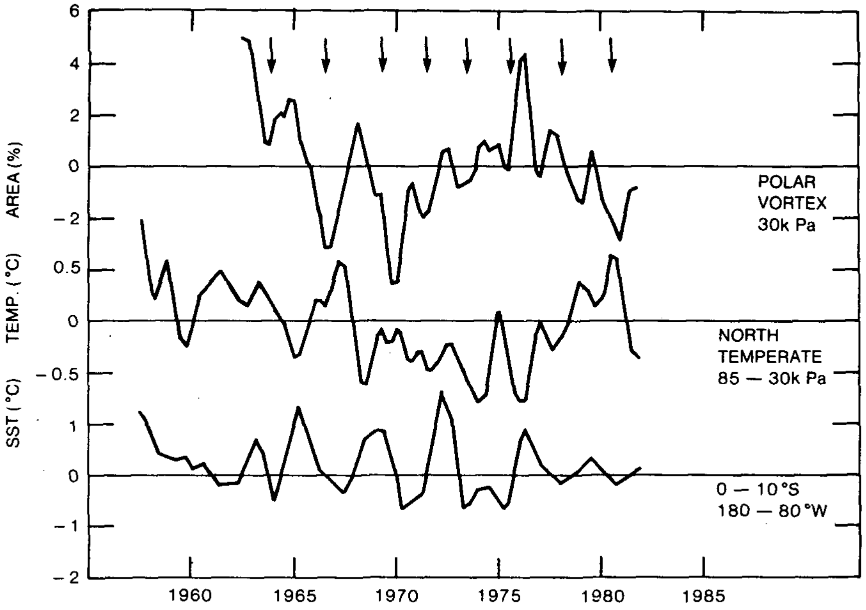

FIG. 12. Comparison between north-temperate temperatures in the 85–30 kPa layer, and the area of the 30 kPa (300 mb) north polar vortex (top trace), where a 5-point binomial smoothing has been applied to successive seasonal values (tick marks in summer). The trace at bottom shows the smoothed SST variation in equatorial eastern Pacific, the vertical arrows the time of quasi-biennial west wind maximum at 5 kPa in the tropics.

lagged correlations either side of the peak correlation, the lag between SST and tropospheric temperature is slightly more than one season at the equator, slightly less than two seasons in the south subtropics, and almost exactly two seasons in the north subtropics. Thus, there is some slight indication of a poleward progression of Southern Oscillation air temperature anomalies from a point on, or perhaps slightly south of, the equator.

The right-hand diagrams of Fig. 11 show the lag correlations between SST and tropical air temperature at the surface, and in 85–30 kPa and 30–10 kPa layers. At the surface the lag between the two is slightly more than one season, for the 85–30 kPa layer slightly less than two seasons, and about two seasons for the 30–10 kPa layer. Thus, there is some slight indication that Southern Oscillation air-temperature anomalies progress upward as well as poleward in the tropical troposphere.

8. Polar vortex

We have monitored the area of the 30 kPa (300 mb) north polar vortex since 1963 by planimetering the area poleward of contours in the main belt of westerlies on mean-monthly polar stereographic maps obtained from the Free University of Berlin (Angell and Korshover, 1978a). The top trace in Fig. 12 shows the seasonal variation in this vortex area (5-point binomial smoothing) expressed as a percentage deviation from the mean area. The variation in vortex area should be more or less inversely related to the variation in mean temperature in the 85–30 kPa layer because, if the 30 kPa height rises hydrostatically in accordance with increased column temperature in mid-latitudes, then a given contour might be expected to be found further north, "contracting" the polar vortex and resulting in a negative correlation between polar vortex area and the layer-mean temperature in mid-latitudes. The two top traces of Fig. 12 show that this has been the case for at least the last decade, with the variations out of phase both with respect to trend and shorter-period oscillations (for unknown reasons the trends were not out of phase during the early part of the record).

These areal variations provide useful confirmation of the tropospheric temperature trends derived from individual radiosonde stations in north temperature latitudes. In 1976 the 30 kPa polar vortex was indicated to be about 4% above-average size, and in 1981 about 3% below-average size. Note from Fig. 12 the very recent evidence for an increase in vortex size again, in agreement with the very recent cooling in north temperature latitudes.

The SST variations in the equatorial eastern Pacific are shown at the bottom in Fig. 12, and the vertical arrows at top show the time of quasi-biennial west wind maximum at 5 kPa (50 mb) in the tropics. There has been a tendency for the vortex to be contracted at the time of these arrows, or at time of quasi-biennial west-wind maximum (Angell and Korshover, 1978a; Holton and Tan, 1980), though the relation broke down badly in 1977–78, and the zero-lag correlation is only −0.20 based on years 1963–81 (the similarity in trend during the early part of the record reduces the magnitude of this negative correlation). In basic agreement with Fig. 11, the vortex has been most contracted three seasons after warmest SST in equatorial eastern Pacific, with the correlation of −0.32 at this lag just significant at the 5% level taking into account the serial correlation of the data. However, at zero lag the correlation is 0.23, showing that there has been a weak tendency for warm SST to be associated with an expanded vortex, in agreement with the findings of Horel and Wallace (1981) for the North Pacific area.

9. North-temperate tropospheric temperature in relation to SST and QBO

In view of the evidence from the preceding section of a relation between polar-vortex area at 30 kPa, and sea-surface temperature (SST) in the equatorial eastern Pacific as well as the phase of the quasi-biennial oscillation (QBO) at 5 kPa in the tropics, in this section we examine the relation between zonally-averaged temperature in the north temperate troposphere (85–30 kPa layer), and SST and QBO. It is apparent from Fig. 12 that, since about 1970, the phases of SST and QBO have tended to coincide (west-wind maximum near time of SST minimum), and this may have had some impact on the following results.

Table 4 shows the average seasonal temperature deviation from the mean in the 85–30 kPa layer of north temperate latitudes as a function of above-average (warm) and below-average (cool) SST, and the phase (west or east-wind) of the QBO based on the interval 1958–81. Since the lag of maximum correlation between SST and north-temperate temperature has been three seasons, whereas there has been a tendency for an in-phase relation between this temperature and the QBO, what is presented in Table 4 is the relation of the temperature to SST three seasons earlier, and to the QBO for the same season as the temperature. Appended to the average deviations are values of "two standard deviations of the mean" determined from individual seasonal values.

In Table 4 the top parentheses give the number of seasons when the north-temperate tropospheric temperature was warmer than average, and the bottom parentheses the number of seasons when this temperature was cooler than average. Application of the chi-squared technique to this contingency table (Hoel, 1947, p. 192) shows that the given distribution of positive and negative air temperature deviations is significant at nearly the 1% level. With respect to the individual categories, the average deviation of −0.4°C resulting when the east-wind phase of the QBO was preceded three seasons earlier by a relatively cool SST appears meaningful when compared with two standard deviations of the mean (0.2°C). The average deviation of 0.2°C resulting when the west wind phase of the QBO was preceded three seasons earlier by a relatively warm SST is not quite so impressive, since also in this case "two standard deviations of the mean" approaches 0.2°C. Comparison of the respective averages and totals in Table 4 shows that mid-latitude tropospheric temperatures have been somewhat more closely related to SST (with a three-season time lag) than to phase of the QBO, as was the case with the area of the polar vortex.

TABLE 4. Deviation from the mean of the average 85–30 kPa temperature (°C) in north temperate latitudes for warm and cool SST (0–10°S, 180–80°W), and west and east-wind phases of the quasi-biennial oscillation (QBO) at 5 kPa in the tropics, where seasonal SST has been compared with seasonal temperature and QBO three seasons later during the interval 1958–81. The appended values represent two standard deviations of the mean, and the number of seasons with positive and negative air temperature deviations from average is given within top and bottom parentheses, respectively.

	SST		
QBO	Warm	Cool	Average (total)
West-wind phase	0.20 ± 0.16 (22) (11)	−0.10 ± 0.23 (8) (10)	0.09 ± 0.13 (30) (21)
East-wind phase	0.08 ± 0.15 (13) (17)	−0.40 ± 0.20 (4) (14)	−0.14 ± 0.12 (17) (21)
Average (total)	0.15 ± 0.11 (35) (18)	−0.25 ± 0.15 (12) (24)	

These relations will continue to be monitored. SST has warmed through 1982, and the east-wind maximum of the QBO at 5 kPa occurred in mid 1982. On the basis of the relations in Table 4, these two events suggest a relatively warm north-temperate troposphere in 1983, other things being equal. Because of the Chichon eruption in the spring of 1982, other things are not equal, and in mid-latitudes a conflict may arise between the cooling due to Chichon and the warming often associated with the present and upcoming phases of SST and QBO.

10. Conclusions

The following are the main conclusions from this study:

1) At the surface and in the tropospheric 85–30 kPa (850–300 mb) layer, the hemispheric and global cooling during the first decade of the interval 1958–81 has been more than compensated by warming during the second decade, with the 1981 temperature about 0.1°C warmer than observed in 1958–59. While a seasonal update shows that the north-temperate temperature during the spring of 1982 was ~1°C cooler than during the spring of 1981, resulting in an 0.5°C cooler Northern Hemisphere and 0.25°C cooler world, this could be but a temporary perturbation on the warming trend.

2) In contrast to the long-term cooling and warming observed at the surface and in the 85–30 kPa layer, in the 30–10 kPa layer there has been gradual global cooling during most of the interval 1958–81. Accordingly, there is evidence of an increase in tropospheric lapse rate in the last decade. Southern Hemisphere data suggest a cooling of the low stratosphere (10–3 kPa layer) relative to the troposphere, but this is not apparent in the Northern Hemisphere where the data are good.

3) Northern Hemisphere rocketsonde data indicate that the 3–5°C cooling observed in the middle and high stratosphere (26–55 km) between 1970 and 1976 has not been compensated for by recent warming, with the temperature in 1980–81 almost the same as in 1976. Inasmuch as there was a sunspot maximum in 1980 as well as 1970, the early cooling is unlikely to be related to the decrease in sunspot number between 1970 and 1976. The cooling was also much too great to be associated, in its entirety, with the increase in CO_2, though a small part of the cooling could be related thereto.

4) There is evidence for an 0.3°C decrease in Northern Hemisphere surface temperature following the Agung eruption in 1963, but there was no obvious influence on Southern Hemisphere temperature, cooling occurring before the eruption and continuing after the eruption. The Agung eruption appeared to warm the low tropical stratosphere by at least 1°C. There is no convincing evidence that the eruptions of Fuego in 1974 or St. Helens in 1980 affected either tropospheric or stratospheric temperatures. Any surface cooling due to the Chichon eruption in 1982 may be difficult to detect because of the cooling occurring prior to this eruption.

5) Global temperature variations in the surface–10 kPa layer have been strongly influenced by the Southern Oscillation phenomenon during the interval 1958–81, with a correlation of nearly 0.6 between sea-surface temperature variations in equatorial eastern Pacific and global temperature variations in this layer two seasons later. Thus, these SST variations are a precursor of temperature variations through the bulk (by mass) of the atmosphere. There is some slight indication that, in the tropical troposphere, the air temperature anomalies associated with this SST propagate poleward and upward with time.

6) During the past decade the variation in area of the 30 kPa (300 mb) north polar vortex has been closely (inversely) related to the variation in 85–30 kPa temperature in north temperate latitudes, with the vortex 4% above-average size in 1976, 3% below-average size in 1981, and increasing in size again in 1982 in agreement with the very recent cooling in mid-latitudes.

7) There has been a fairly impressive tendency (during the interval 1958–81) for the 85–30 kPa temperature in north-temperate latitudes to be cool (averaging 0.4°C below the mean value) three seasons after cool SST in the equatorial eastern Pacific when the quasi-biennial oscillation (QBO) at 5 kPa in the tropics was in the east-wind phase. Not quite so impressive has been the tendency for this mid-latitude temperature to be warm (averaging 0.2°C above the mean value) three seasons after warm SST when the QBO was in the west-wind phase. Overall, the north-temperate temperature has been somewhat more closely related to SST (with a three-season time lag) than to phase of the QBO. Inasmuch as SST has warmed through 1982, and the QBO east-wind maximum at 5 kPa occurred in mid 1982, the present and upcoming phases of SST and QBO imply a warm north-temperate troposphere in 1983, other things being equal. Because of the Chichon eruption in the spring of 1982, other things are not equal, and there may be a conflict between the cooling due to Chichon and the warming often associated with the given phases of SST and QBO.

Nowadays, no temperature-trend paper is considered complete without presenting the evidence for, or against, a CO_2-induced temperature effect. Indeed, some papers have recently been written with the specific purpose of determining, by statistical means, whether a CO_2 effect has been observed, and if not, when it might be expected to be observed (e.g., Madden and Ramanathan, 1980; Epstein, 1982). The analysis in this paper yields mixed signals with respect to a possible CO_2 effect. On the one hand, the overall evidence for increasing lapse rates (i.e., the cooling of the 30–10 kPa layer relative to the 85–30 kPa layer and the surface, and the cooling of the middle and upper stratosphere relative to the low stratosphere) provides some support for a CO_2 effect. On the other hand, the spatial distribution of the recent warming has not followed model predictions of where the greatest CO_2 warming should take place; that is, we find little evidence for warming in north polar latitudes (though we do in south polar latitudes), but do find evidence for warming in the tropics. Even the hemispheric and global temperature variations as a whole are confusing with regard to a CO_2 effect, in that although the tropospheric warming in the last decade slightly exceeded the cooling in the previous decade, the 1981–82 data suggest a cooling again even before the Chichon eruption. Detection of an unambiguous CO_2 signal will be difficult, and will not be helped by volcanic eruptions (such as Chichon) which tend to cool the troposphere and warm the stratosphere, the opposite of the changes associated with a CO_2 increase.

Acknowledgments. We wish to thank Milton Smith and Dr. Albion Taylor of the Air Resources Laboratories for providing, on a routine basis, monthly-average radiosonde pressure-heights from teletype data assembled at the National Meteorological Center, and monthly-average rocketsonde temperatures from tapes prepared by the Analysis and Information Branch of the Climate Analysis Center. Partial support for this effort was provided by the Carbon Dioxide Research Division of the Department of Energy.

REFERENCES

Angell, J. K., 1981: Comparison of variations in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific. *Mon. Wea. Rev.*, **109**, 230–242.

——, and J. Korshover, 1975: Estimate of the global change in tropospheric temperature between 1958 and 1973. *Mon. Wea. Rev.*, **103**, 1007–1012.

——, and ——, 1978a: The expanded north-circumpolar vortex of 1976 and winter of 1976–77, and attendant vortex displacement. *Mon. Wea. Rev.*, **106**, 137–142.

——, and ——, 1978b: Global temperature variations, surface–100 mb: An update into 1977. *Mon. Wea. Rev.*, **106**, 755–770.

——, and ——, 1978c: Recent rocketsonde-derived temperature variations in the western hemisphere. *J. Atmos. Sci.*, **35**, 1758–1764.

——, and ——, 1978d: Estimate of global temperature variations in the 100–30 mb layer between 1958 and 1977. *Mon. Wea. Rev.*, **106**, 1422–1432.

Barnett, T. P., 1978: Estimating variability of surface air temperature in the Northern Hemisphere. *Mon. Wea. Rev.*, **106**, 1353–1367.

Borzenkova, I. I., K. Ya, Vinnikov, L. P. Spirina and D. I. Stekhovskii, 1976: Change in the air temperature of the Northern Hemisphere for the period 1881–1975. *Meteor. Gidrol.*, No. 7, 25–35.

Callis, L. B., and J. E. Nealy, 1978: Solar UV variability and its effect on stratospheric thermal structure and trace constituents. *Geophys. Res. Lett.*, **5**, 249–252.

Dronia, H., 1974: Uber temperaturanderungen der freien Atmosphare auf der Nordhalbkugel in den letzten 25 Jahren. *Meteor. Rundsch.*, **27**, 166–174.

Epstein, E. S., 1982: Detecting climate change. *J. Appl. Meteor.*, **21**, 1172–1182.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind and G. Russell, 1981: Climate impact of increasing atmospheric carbon dioxide. *Science*, **213**, 957–966.

Harley, W. S., 1978: Trends and variations of mean temperatures in the lower troposphere. *Mon. Wea. Rev.*, **106**, 413–416.

Hoel, P. G., 1947: *Introduction to Mathematical Statistics.* Wiley, 258 pp.

Holton, J. R., and H. C. Tan, 1980: The influence of the equatorial quasi-biennial oscillation on the global circulation at 50 mb. *J. Atmos. Sci.*, **37**, 2200–2208.

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

Jones, P. D., 1981: Summary of climatic events during 1981. *Climate Monitor,* **10**, 113–114.

——, T. M. L. Wigley and P. M. Kelly, 1982: Variations in surface air temperatures: Part 1. Northern Hemisphere, 1881–1980. *Mon. Wea. Rev.*, **110**, 59–70.

Julian, P. R., and M. Chervin, 1978: A study of the Southern Oscillation and Walker Circulation phenomena. *Mon. Wea. Rev.*, **106**, 1433–1451.

Kelly, P. M., P. D. Jones, C. B. Sear, B. S. G. Cherry and R. K. Tavakol, 1982: Variations in surface air temperatures: Part 2. Arctic regions, 1881–1980. *Mon. Wea. Rev.*, **110**, 71–83.

Madden, R. A., and V. Ramanathan, 1980: Detecting climate change due to increasing carbon dioxide. *Science,* **209**, 763–768.

Manabe, S., and R. T. Wetherald, 1975: The effects of doubling the CO_2 concentration on the climate of a general circulation model. *J. Atmos. Sci.*, **32**, 3–15.

——, and ——, 1980: On the distribution of climate change resulting from an increase in CO_2 content of the atmosphere. *J. Atmos. Sci.*, **37**, 99–118.

McInturff, R. M., A. J. Miller, J. K. Angell and J. Korshover, 1971: Possible effects on the stratosphere of the 1963 Mt. Agung eruption. *J. Atmos. Sci.*, **28**, 1304–1307.

Mitchell, J. M., 1963: On the world-wide pattern of secular temperature change. *Proc. UNESCO/WMO Symposium on Changes of Climate,* UNESCO Arid Zone Research Series, No. 20, UNESCO, 161–181.

Namias, J., 1980: Some concomitant regional anomalies associated with hemispherically averaged temperature variations. *J. Geophys. Res.*, **85**, 1585–1590.

Newell, R. E., 1970: Stratospheric temperature change from the Mt. Agung volcanic eruption of 1963. *J. Atmos. Sci.*, **27**, 977–978.

——, and B. C. Weare, 1976: Factors governing tropospheric mean temperature. *Science,* **194**, 1413–1414.

Paltridge, G., and S. Woodruff, 1981: Changes in global surface temperature from 1880 to 1977 derived from historical records of sea surface temperature. *Mon. Wea. Rev.*, **109**, 2427–2434.

Parker, D. E., 1980: Climatic change or analysts' artifice?—a study of grid-point upper-air data. *Meteor. Mag.*, **109**, 129–152.

Parthasarathy, B., and D. A. Mooley, 1978: Some features of a long homogeneous series of Indian summer monsoon rainfall. *Mon. Wea. Rev.*, **106**, 771–781.

Penner, J. E., and J. S. Chang, 1978: Possible variations in atmospheric ozone related to the eleven-year cycle. *Geophys. Res. Lett.*, **5**, 817–820.

Quiroz, R. S., 1979: Stratospheric temperatures during solar cycle 20. *J. Geophys. Res.*, **84**, 2415–2420.

Salinger, M. J., 1979: New Zealand climate: The temperature record, historical data and some agricultural implications. *Climatic Change,* **2**, 109–126.

Trenberth, K. E., 1976: Spatial and temporal variation of the Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **102**, 639–653.

Troup, A. J., 1965: The "southern oscillation". *Quart. J. Roy. Meteor. Soc.*, **91**, 490–506.

Vinnikov, K. Ya., G. V. Gruza, V. F. Zakharov, A. A. Kirillov, N. P. Kovyneva and E. Ya. Ran'kova, 1980: Present-day climatic changes in the Northern Hemisphere. *Meteor. Gidrol.*, No. 6, 5-17.

Wigley, T. M. L., and P. D. Jones, 1981: Detecting CO_2-induced climatic change. *Nature,* **292**, 205–208.

Yamamoto, R., and M. Hoshiai, 1979: Recent change of the Northern Hemisphere mean surface air temperature estimated by optimum interpolation. *Mon. Wea. Rev.*, **107**, 1239–1244.