Global Temperature Variation, Surface–100 mb: An Update into 1977

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ABSTRACT

Based on a network of 63 well-spaced radiosonde stations around the world, the global temperature within the surface to 100 mb layer was lower in 1976 than in any year since commencement of the record in 1958, and the 1976 surface temperature equaled the global record for the lowest temperature set in 1964; but even so the trend in global temperature since 1965 has been small compared to the 0.5°C decrease during 1960–65. Between 1958 and 1976 the surface to 100 mb temperature in north extratropics decreased by about 1°C, with the decrease twice as great in winter as in summer, and in 1976 this region was 0.2°C lower than in any previous year of record. During the northern winter of 1976–77, both temperate zones were very cold but the polar and tropical zones were quite warm, so that in the hemispheric or global average the season was not anomalous. In the Eastern Hemisphere of the northern extratropics there has been considerable surface warming during the past decade (although a cooling aloft), and this may explain the Soviet concern with warming related to carbon dioxide emissions. There has been a slight overall increase in temperature in the tropics since 1965, mostly in the Western Hemisphere, on which have been superimposed large and significant temperature variations of about a three-year period. These variations, probably related to the Southern Oscillation (and recently not so pronounced), extend in obvious fashion also into north extratropics, and should be taken into account for diagnoses and prognoses in northern latitudes. The rate of increase of carbon dioxide at Mauna Loa and the South Pole is augmented in the warm phase of the tropical oscillation, presumably because of a relation between atmospheric and oceanic temperature. There is evidence for a consistent quasi-biennial variation in temperature at all latitudes, with the temperature approximately 0.1°C higher than average about six months prior to the quasi-biennial west wind maximum at 50 mb in the tropics. The spatial and temporal variability in temperature have tended to increase over the period of record, in accord with the increase in meridional temperature gradient in both hemispheres and the indicated increase in lapse rate in the Northern Hemisphere.

1. Introduction

In a recent paper (Angell and Korshover, 1977) the year-average variation in global temperature between the surface and 100 mb was presented for the period 1958–75. In view of the ever-increasing interest in climatic variation in general, and temperature variation in particular [see the discussion by Mitchell (1976)], it was thought desirable to obtain more detail in the analysis by computing seasonal as well as annual means of temperature. This allows for the delineation of quasi-biennial variations, permits much more precision in trend comparison between, for example, temperature and carbon dioxide, and most obvious of all, makes possible the determination of the temperature trend by season. In recognition of the considerable publicity attending the severe winter of 1976–77 in eastern North America, this paper was delayed until global data for that season could be analyzed, although this involves terminating the data series at a known extremum. Work has also been completed on a paper dealing with temperature trends in the low stratosphere (100–30 mb), to be published at a later date. Tabulations of both sets of data could be made available to interested parties.

2. Procedures

A map showing the location of the 63 radiosonde stations used in the analysis was presented in the earlier paper. In brief, the analysis is based on eight evenly spaced radiosonde stations in North Polar regions (north of 60°N), 12 stations in the north temperate zone (30–60°N), 12 stations in north subtropics (10–30°N), nine stations near the equator (10°N–10°S), ten stations in south subtropics (10–30°S), six stations in the south temperate zone (30–60°S) and six stations in south polar regions (Antarctica). Mean monthly values of the height of the 850, 300 and 100 mb surfaces, as well as surface temperature, were obtained from the publication *Monthly Climatic Data for the World* issued by the Environmental Data Service of the U.S. Department of Commerce, and the "thicknesses" between these pressure surfaces were averaged by season (winter is December, January, February, etc.) and converted

to mean temperature. In the following, for simplicity, we present only temperature trends for the surface and the surface to 100 mb layer, where the latter has been obtained by weighting the temperature by the pressure interval of the layers used (550 and 200 mb), and assuming that the surface temperature applies to the layer 1000–850 mb (150 mb weighting). Thus, the surface temperature contributes 17% to the layer-mean temperature. Because of our limited data sample, the surface to 100 mb data should be much more representative than the surface data alone, owing both to the integration in the vertical and the larger scales of temperature variations aloft.

To eliminate the large annual fluctuations in temperature, the deviation from the record mean at each station has been determined for each season for each year, and the seasonal deviations placed back in calendar order. The station values have then been averaged for each climatic zone, and a standard deviation determined for that zone based on the individual station values. Confidence limits for the mean values have been estimated by evaluation of two standard deviations of the mean, that is, two standard deviations divided by the square root of the number of stations in the climatic zone, and are represented by vertical bars in the following diagrams. If it is assumed that the station values are essentially independent, which should be so considering their separation distance, there is only about a 5% chance that the true value of the climatic-zone mean lies outside the vertical extent of these bars. Finally, both the seasonal mean values and the attendant standard deviations of the mean have been smoothed by application of a 1–2–1 weighting (divided by 4) twice to the successive seasonal values (1–1 at beginning and end of record). While such a smoothing has undesirable features, including the obvious one that with every update the last two values have to be altered, it was felt necessary in order that the trends be clearly delineated and the "forest not be lost for the trees." Such a smoothing reduces the amplitude of any quasi-biennial fluctuation by about 30%.

Average values for north and south extratropics have been obtained by a 1–2 weighting of polar and temperate-zone means, respectively (very roughly approximating the areas of the earth's surface the zones represent), and for the tropics by an equal weighting of north and south subtropic and equatorial-zone means. The hemispheric means were obtained from a 1–2–2–1 weighting of polar, temperate, subtropical and equatorial-zone means, respectively, and the global mean from a 1–2–2–2–2–2–1 weighting of north polar, north temperate, north subtropical, equatorial, south subtropical, south temperate and south polar-zone means, respectively. Note that the equatorial mean is applied to both hemispheres, so that the hemispheric means are not completely independent (by a factor of 1 in 6 or 17%).

The confidence limits for tropics, extratropics, hemisphere and world have been obtained by applying the appropriate climatic-zone weighting to the climatic-zone variances, adding in the (weighted) variance of the climatic-zone means about the derived mean for tropics, extratropics, hemisphere or world, and finding the square root or standard deviation. The standard deviation of the mean is then evaluated based on the number of stations in the expanded areas.

3. Temperature variation in tropics and extratropics

Fig. 1 shows the derived temperature variation in the north extratropics (north of 30°N), tropics and south extratropics for the surface and surface to 100 mb layer. Although evaluated, confidence limits are not shown for the former because they are at least half again as large as the confidence limits for the layer and result in an awkward diagram. In this and subsequent diagrams the tick marks are in summer of the given year. Noteworthy features of Fig. 1 include the following:

1) The general temperature decrease in the north extratropics between 1958 and 1976, amounting to about 1°C for the surface to 100 mb layer. This is similar to the decrease obtained by Dronia (1974) using 1000–500 mb grid-point thicknesses in the north extratropics. At the surface the temperature decrease is slightly less (the two traces converge), implying a subtle increase in lapse rate. Since the vertical bars at the beginning and end of the record do not overlap, the temperature decrease in the surface to 100 mb layer is presumed significant at the 95% level. With the given smoothing, the lowest temperatures of the 19-year record were observed in the surface to 100 mb layer in 1976 (0.5°C below the mean), but at the surface the winter of 1968–69 is indicated to have been colder than the winter of 1976–77, even though the latter was 0.7°C below the mean.

2) The uniform, but slight, decrease in temperature of the tropics between 1958 and the approximate time of the eruption of Mt. Agung, Bali (spring of 1963), and the large significant temperature oscillations of about three-year period and 0.3°C amplitude thereafter. It has not escaped our notice that these three-year oscillations show up also in the surface to 100 mb trace for the north extratropics with a little lag (shown more clearly in Fig. 11), so that these tropical oscillations should be taken into account for diagnoses and prognoses in northern latitudes (this will be investigated carefully). If anything, there has been a slight overall rise in temperature in the tropics during the time of these oscillations, and accordingly over the period of record the meridional temperature gradient between tropics and north extratropics has increased by at least 0.5°C (convergence of the two pairs of traces). van Loon and Williams (1977) provide evidence for an increase in this gradient between 1949 and 1972, as well

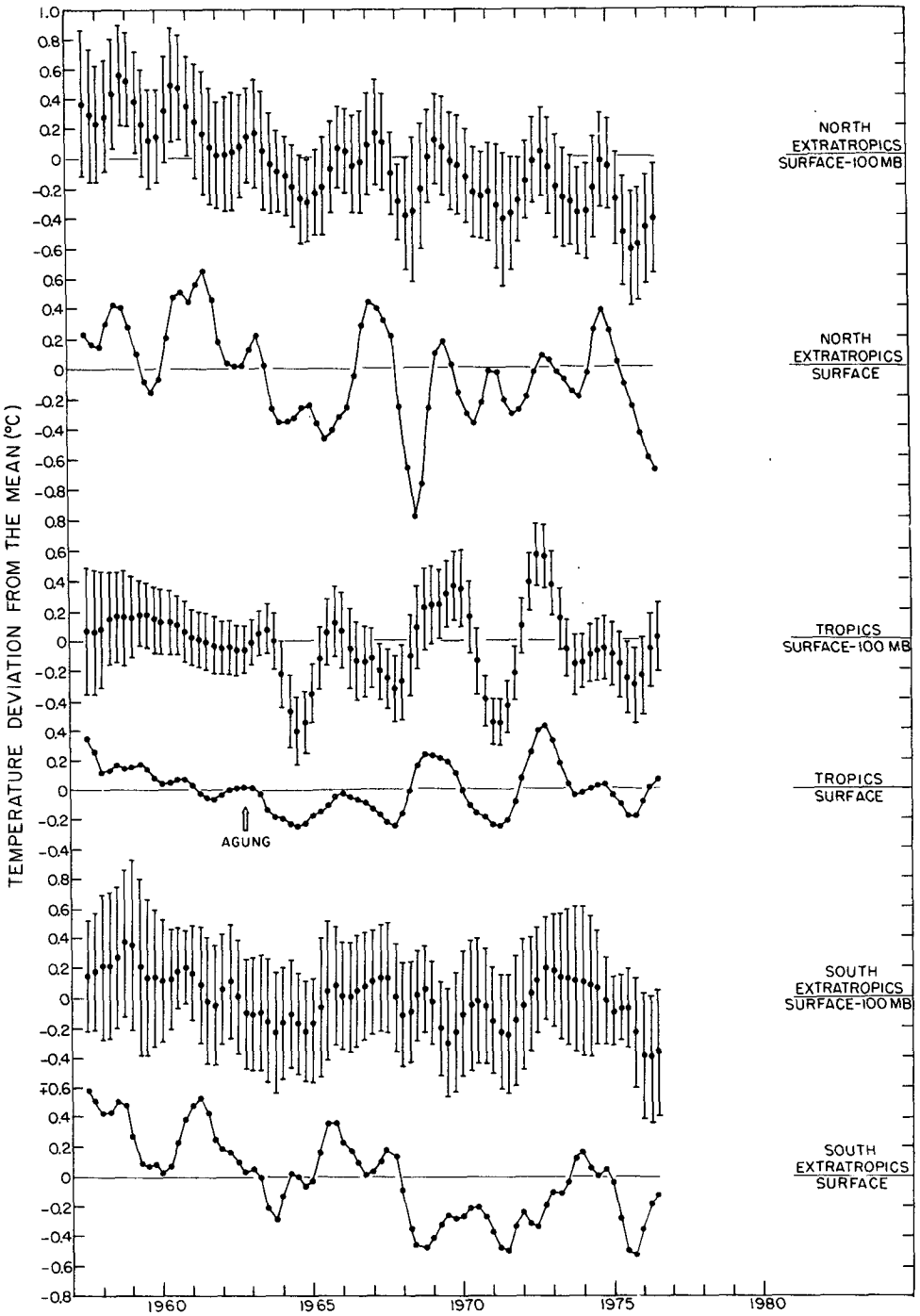

FIG. 1. Temperature variation (°C) in the tropics and north and south extratropics, for the surface and surface to 100 mb layer. A 1–2–1 smoothing (1–1 at beginning and end of record) has been applied twice to the successive seasonal-mean values, and to the confidence limits for the surface to 100 mb layer, where the confidence limits (vertical bars) extend two standard deviations of the mean either side of the mean. The tick marks are in summer of the given year, and the eruption of Mt. Agung (Bali) is indicated at center.

as for a decrease in atmospheric stability in north extratropics during this time.

3) The decreasing temperature in the south extratropics, amounting to about 0.8°C at the surface between 1958 and 1976 but less in the surface to 100 mb layer (the two traces diverge), implying a subtle de-

crease in lapse rate. The temperature decrease in the surface to 100 mb layer is not indicated to be significant, partly because of the relatively small data sample in south extratropics. With the given smoothing, the lowest temperatures of record were observed in 1976 at both the surface and in the surface to 100 mb layer, and the meridional temperature gradient between the tropics and the south extratropics also increased by nearly 0.5°C over the period of record.

4. Variations within climatic zones

With Fig. 1 as background, we examine the temperature variations in the various climatic zones. Fig. 2 presents the temperature variations within the tropics, i.e., in the north and south subtropics and at the equator. The three-year temperature oscillations for all three (independent) regions are almost identical, and generally significant, so there can be little doubt concerning the reality of these oscillations, which tend to increase in amplitude with height (surface to 100 mb amplitude larger than surface amplitude). One obvious difference in the traces is that at the equator there is no temperature decrease during the period 1958–65, whereas in both subtropics there is impressive evidence for such a decrease, pointing up again the increase in meridional temperature gradient which has occurred. Note that the pronounced three-year oscillation has become disorganized in recent years, with a temperature minimum in 1975–76 or at a time when there would have been a temperature maximum if the three-year periodicity per se had persisted. Thus, there is the circumstance, perhaps coincidental, that the three-year oscillation in the tropics began shortly after the eruption of Agung, and appears to have partly broken down at about the time of the Fuego (Guatemala) eruption in the autumn of 1974.

These three-year temperature oscillations in the tropical troposphere are seemingly of too long a period to be associated *directly* with the well-known quasi-biennial oscillation of temperature and wind in the tropical stratosphere (although this will be examined more closely as our stratospheric analysis proceeds), but rather probably represent or reflect what has come to be known as the Southern Oscillation (Trenberth, 1976). Thus, the times of maximum temperature in Fig. 2 correspond well with the times of maximum sea surface temperature in the tropical Pacific (Newell and Weare, 1976), and in particular with the El Niño occurrences (an invasion of warm water off the west coast of northern South America) in 1965–66, 1969–70, 1972–73 and possibly 1975 (Quinn, 1976; Machta *et al.*, 1977). These relations will be considered again in Section 11 in connection with the variation in rate of increase of atmospheric CO_2.

Fig. 3 shows that the derived temperature variations are similar in north and south temperate latitudes, with a gradual cooling during most of the period and, with the given smoothing, record low temperatures in 1976 in the surface to 100 mb layer (~0.8° and 0.5°C below the mean, respectively). In both cases the temperature decreases in the surface to 100 mb layer are significant, although barely so in the case of south temperate latitudes. Note that the sudden surface cooling in the winter of 1968–69 in north temperate latitudes was accomplished by a similar sharp cooling in south temperate latitudes, but that in the latter case the temperature remained low.

The temperature variations in polar regions are of particular interest because any temperature increase resulting from CO_2 emissions should be a maximum there (Manabe and Wetherald, 1975). Unfortunately, the temporal and spatial variability in temperature is also largest in polar regions, making trend determination unusually difficult. Fig. 3 points up the dissimilarity in the two polar trends. In the south polar region (Antarctica) there was at least a 1°C warming between 1960 and 1975, significant in the surface to 100 mb layer, followed by an abrupt cooling to near-average values in 1976, the latter bringing into question the concept that the warming in high latitudes of the Southern Hemisphere is a harbinger of global warming due perhaps to a CO_2 effect (Damon and Kunen, 1976). In north polar regions, however, there was a significant cooling in the surface to 100 mb layer between 1960 and 1965, but no really significant or systematic change thereafter, although some surface warming is apparent (see also Dickson *et al.*, 1975). The winter of 1976–77 was characterized by the presence of a warm north-polar anticyclone, yielding relatively warm temperatures in the surface to 100 mb layer but not at the surface. The temperatures in Antarctica were also relatively warm during this season.

5. Variations for hemisphere and world

Fig. 4 presents the temperature variations for Northern and Southern Hemisphere and for the world. The large three-year tropical oscillations dominate the hemispheric and global means, making detection of subtle long-term trends rather difficult, but it is apparent that following a significant global temperature decrease of about 0.5°C between 1960 and 1965, there has been little systematic temperature change since. The similarity in temperature decrease in both hemispheres during 1960–65, approximately 0.6°C in the Northern Hemisphere (see also Starr and Oort, 1973) and 0.4°C in the Southern Hemisphere, emphasizes that the temperature variations in the two hemispheres can be in concert, as does the absence of an appreciable temperature change after 1965 in the Northern (Brinkmann, 1976) or Southern Hemispheres. There is close agreement between Fig. 4 and the hemispheric and global surface temperature variations (between 1957 and 1972) deduced by Yamamoto *et al.* (1975, 1977) from a network of 600 stations, and the agreement

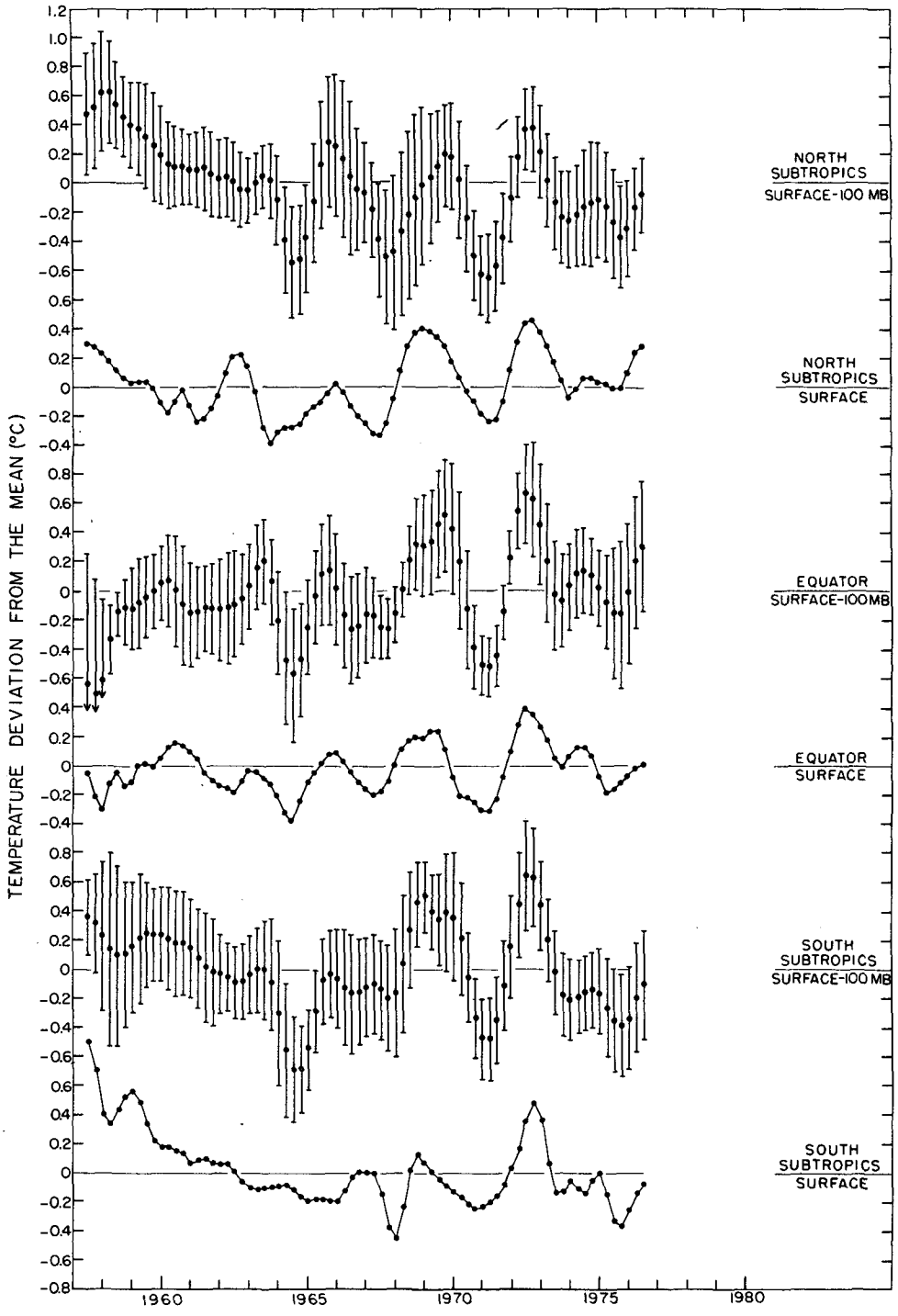

FIG. 2. Temperature variation within the tropics, or in the north and south subtropics and at the equator. Otherwise, see Fig. 1 legend.

remains good for an update into 1976 (Kukla *et al.*, 1977). Note that the tendency for an increase in lapse rate in the Northern Hemisphere [amounting to ~0.3°C (500 mb)$^{-1}$ or 0.05°C km^{-1}] has been nearly balanced by a tendency for a decrease in lapse rate in the Southern Hemisphere, so that in the global average there is little evidence for a change in stability over the period of record despite the increase in meridional temperature gradient. It is possible that a small part of the alleged increase in lapse rate in the Northern Hemi-

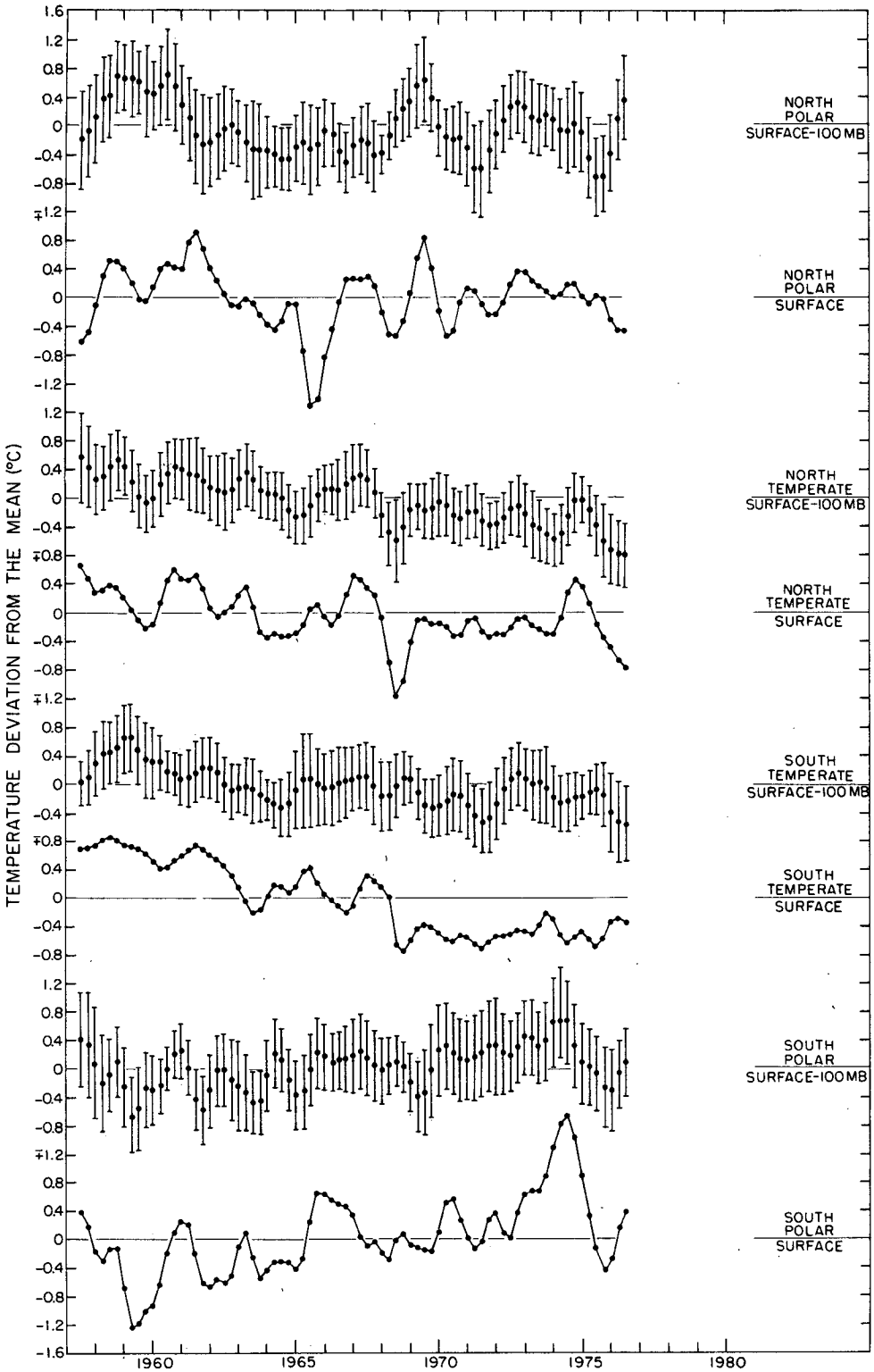

FIG. 3. Temperature variation within the north and south extratropics, or in the north and south polar and temperate zones. Because of the large temperature variability in these zones, the ordinate scale is double that of other similar diagrams. Otherwise, see Fig. 1 legend.

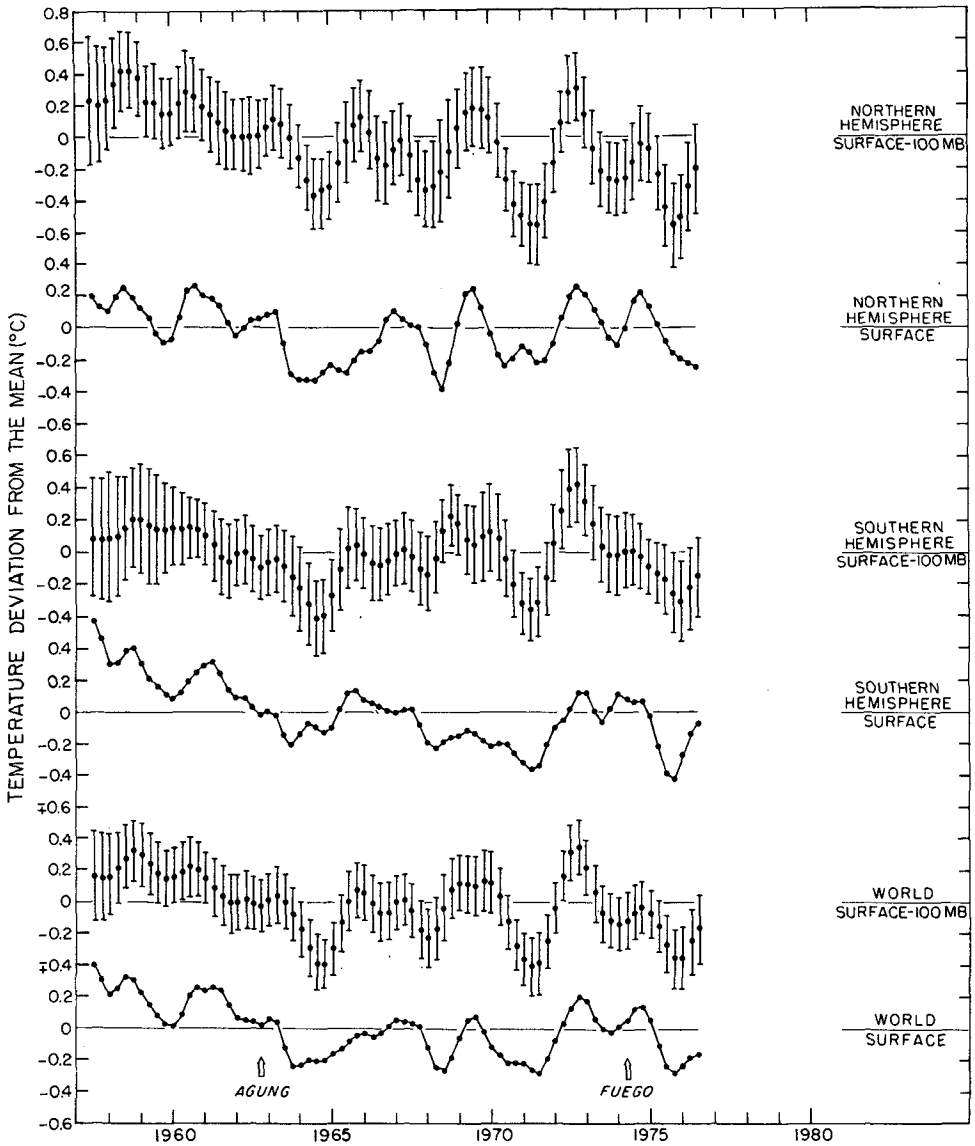

FIG. 4. Temperature variation for the Northern and Southern Hemispheres, and for the world as a whole. The eruptions of Mt. Agung and volcano Fuego (Guatemala) are indicated at bottom. Otherwise, see Fig. 1 legend.

sphere is fictitious and due to anthropogenic heating affecting surface temperatures at some station locations.

The arrows at the bottom of Fig. 4 denote the eruptions of Agung and Fuego. In both cases a global temperature decrease exceeding 0.3°C at the surface and in the surface to 100 mb layer began about six months after the eruption, but in neither case was the decrease really anomalously large or abrupt. What makes these two temperature decreases somewhat unique is that they are not so obviously related to a cessation of the El Niño phenomenon. Yamamoto *et al.* (1975) would like to associate all the large global temperature decreases with volcanic eruptions, but we do not feel this is reasonable. The hemispheric surface traces show that the Agung eruption was associated with a larger temperature decrease in the Northern (0.4°C) than Southern (0.2°C) Hemisphere, despite the fact that Agung is at 8°S, and this has caused some controversy (Ellsaesser, 1977), but it is possible, even probable, that the greater thermal inertia of the oceanic hemisphere would produce this result.

Figs. 1 and 11 show that at the surface in the tropics a temperature decrease totaling 0.3°C began three months after the Agung eruption, with a temperature minimum 21 months after the eruption, not out of line with the delay time promulgated by Oliver (1976) for large volcanic eruptions. In the surface to 100 mb layer, however, the trend was different, with a warming during

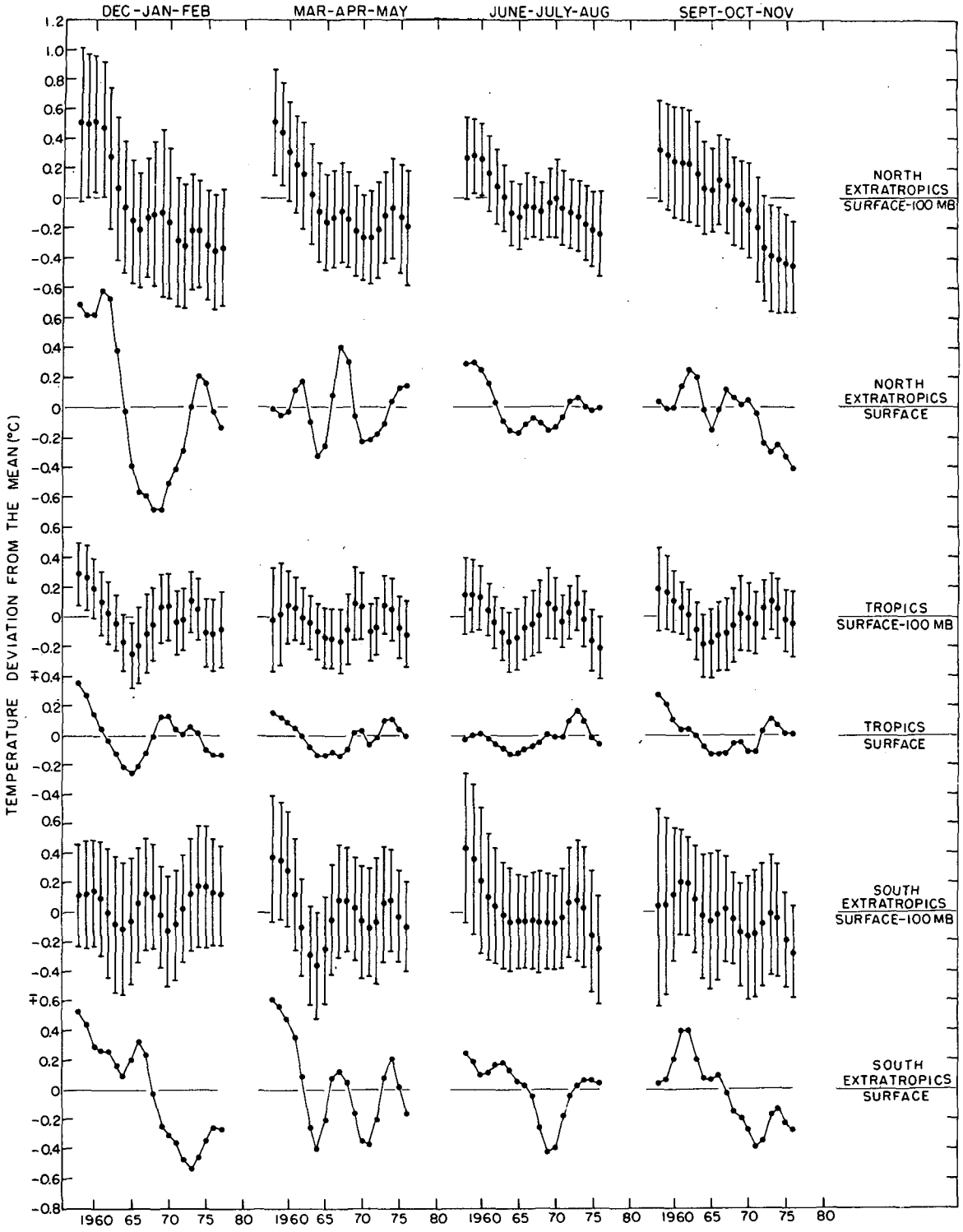

FIG. 5. Temperature variation by season in tropics and north and south extratropics. A 1–2–1 smoothing (1–1 at beginning and end of record) has been applied twice to the successive annual values, and to the confidence limits, which again extend two standard deviations of the mean either side of the mean.

the nine months subsequent to the eruption and an abrupt cooling thereafter. Thus, there is indicated to have been a surface cooling at the same time there was a warming aloft, perhaps reflecting the radiation interplay brought about by volcanic aerosols (Newell, 1970). Another large volcanic eruption may be necessary

before it will be possible to state with assurance the effect of such an eruption on atmospheric temperature.

6. Variation by season

One of the advantages of the present technique for eliminating the annual oscillation (as opposed to the use of 12-month running means, for example) is that the temperature data are available by season, and hence it is a simple task to determine how different seasons contribute to the observed trends. While companion pieces to Figs. 1–4 have been compiled illustrating the temperature trends by season for climatic zone, hemisphere and world, for brevity we here present as Fig. 5 only the diagram illustrating the trend by "season" in the north and south extratropics and tropics (December, January, February of 1961–62 is listed as 1962). Note that because of the smoothing (a 1–2–1 smoothing applied twice to successive yearly values, except 1–1 at beginning and end of record), the average of the overall temperature change for the four seasons does not equal the long-term temperature change derived from Fig. 1.

Fig. 5 shows that with the given smoothing, during the period 1958–76 the surface to 100 mb temperature in north extratropics decreased by about 0.9°C in winter, 0.8°C in autumn, 0.7°C in spring and 0.5°C in summer. Thus, though the temperature decreases are significant in all four seasons, as anticipated they are larger in winter than in summer. The surface temperature changes are more chaotic and exhibit very large differences between winter and summer. As expected, in the tropics the "seasonal" temperature trends are similar, although the 1960–65 temperature decrease is largest in winter. Based on the surface to 100 mb data, in the south extratropics there is again evidence for a larger decrease in temperature in winter than in summer (the latter season exhibiting no decrease in temperature at all), but the differences between the surface and surface to 100 mb trends are large, particularly in summer. It would appear that in regions with few observations the derived trends by season may be unrepresentative, especially in the case of surface data.

7. Trend in the Eastern and Western Hemispheres

With the limited number of stations in the data sample, it is not possible to go into much detail concerning the contribution of various longitude bands to the observed trends, and accordingly we here confine ourselves to the trends for the Eastern and Western Hemispheres. Fig. 6 presents a comparison of the temperature trends in the Western (solid line) and Eastern (dashed line) Hemispheres for tropics and extratropics, using a heavy smoothing (1–2–1 smoothing applied twice to three-year block-average values, except 1–1 at beginning and end of record) because we are interested only in the large-scale variations.

In the north extratropics, the Western Hemisphere

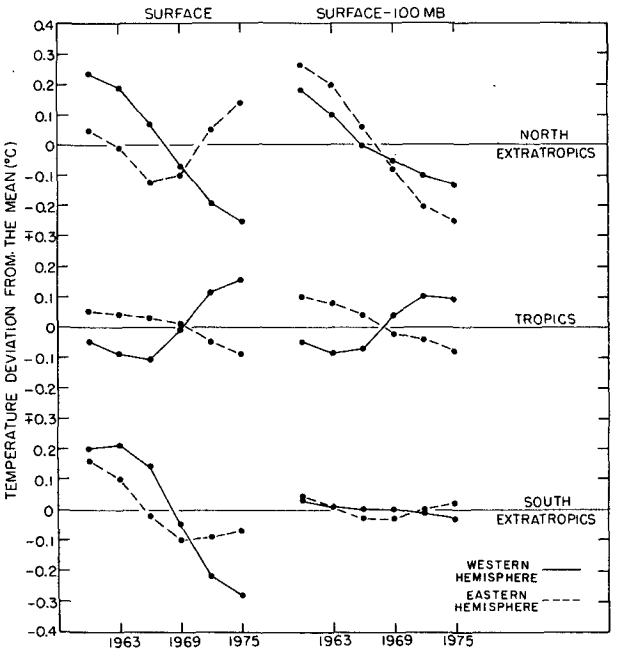

FIG. 6. Comparison of the temperature trends in the Western (solid lines) and Eastern (dashed lines) Hemispheres for the tropics and extratropics. A 1–2–1 smoothing (1–1 at beginning and end of each record) has been applied twice to successive three-year block-average values of the temperature at the surface and in the surface to 100 mb layer.

temperature decrease over the period of record is similar at the surface and in the surface to 100 mb layer, but in the Eastern Hemisphere there is a quite amazing difference after 1969, with warming indicated for the surface but continued cooling for the surface to 100 mb layer. We suggest that it is this large surface warming in the Eastern Hemisphere that has prompted several publications by Russian climatologists (Budyko and Vinnikov, 1976; Borzenkova, *et al.*, 1976; Budyko, 1977) concerning the possible effects on atmospheric temperature of increasing amounts of CO_2. There is the implication here of a considerable increase in lapse rate in the Soviet area. The greater cooling indicated for Eastern than Western hemisphere in the surface to 100 mb layer would be in accord with the gradual overall movement of the 300 mb polar vortex into the Eastern Hemisphere (Angell and Korshover, 1978).

In the tropics the surface and surface to 100 mb data are consistent in showing that the warming in this region has been confined to the western hemisphere. Analysis of the three-year oscillation indicates that, while the oscillations are exactly in phase in both hemispheres, the amplitude of the oscillation is slightly (10–20%) larger in the Western Hemisphere, perhaps illustrating the influence of sea surface temperatures in the eastern tropical Pacific.

In the south extratropics there has been considerable surface cooling in both hemispheres, but little cooling in the surface to 100 mb layer, again implying a decrease

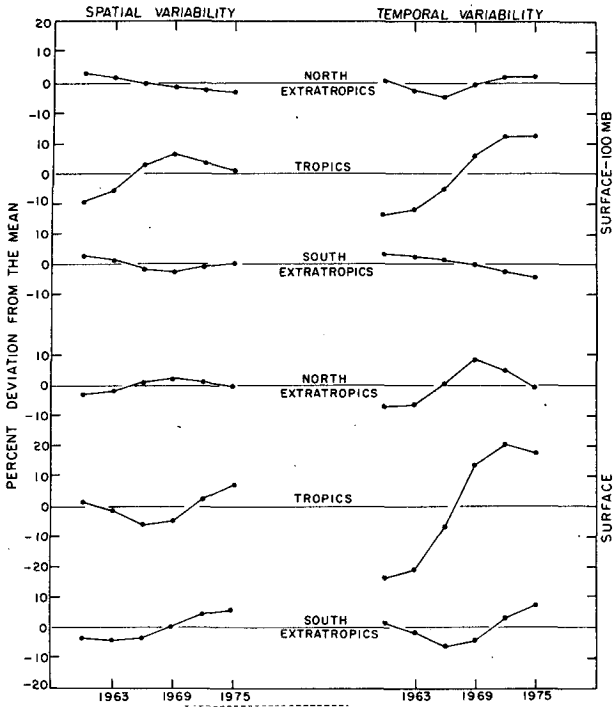

FIG. 7. Trend in the spatial and temporal variability of surface (bottom) and surface to 100 mb (top) temperature, where the spatial variability is determined from the standard deviation of the individual station values, and the temporal variability from the season-to-season change in the temperature deviation from the mean. Smoothing as in Fig. 6.

in lapse rate. The difference between the surface temperature trend in the Eastern and Western Hemispheres in the south extratropics bears some resemblance to the (larger) difference in trend in the north extratropics, providing support for the reality of the diverse surface trends in the Eastern and Western Hemispheres in the north extratropics.

8. Trend in spatial and temporal variability

The spatial variability has been estimated from the standard deviation of simultaneous temperature values at individual stations. Thus, if the temperature deviations at all the stations were the same, the spatial variability would be zero, but when the stations are inconsistent and exhibit both positive and negative deviations, the spatial variability becomes large. A large spatial variability would be expected in the case of strong and persistent meridional flows (low-index pattern). There is a problem that the standard deviation is also a function of the accuracy and consistency of the data. This may not be of concern with surface data, but presumably the radiosonde data have improved through the years and hence one would expect a decrease in standard deviation for the surface to 100 mb layer, other things being equal.

The temporal variability has first been examined from the point of view of season-to-season changes in the temperature deviation from the mean. That is, if the four seasons of the year had a similar temperature deviation from the mean, the temporal variation is small, but if winter and summer are cold, and spring and autumn warm, the temporal variation is large.

Fig. 7 shows the trend in spatial and temporal variability so obtained, expressed as a percentage deviation from the mean variability, where the severe smoothing of Fig. 6 has again been applied. At the surface, both the spatial and temporal variability in the tropics and extratropics have increased from beginning to end of record, although in the north extratropics the variability was a maximum about 1969 followed by a slight decrease thereafter. When one considers the surface to 100 mb layer, however, the increase in variability is not particularly obvious (except of course in the tropics), perhaps because the actual increase in variability is being counteracted by a decrease in variability associated with an improvement of radiosonde instruments and data-reduction procedures.

The temporal trend in variability may also be examined (and perhaps more logically) from the point of view of year-to-year or interannual changes in temperature rather than season-to-season changes. Table 1 shows the average interannual variation in temperature at the surface and in the surface to 100 mb layer for successive three-year segments of the record. Note the following:

1) In the north extratropics in the surface to 100 mb layer the interannual variation during the period 1973–76 averaged 0.38°C, the largest value over the length of record, but relatively large values were observed also during 1958–64.

2) In the tropics the interannual variability increased fivefold at the surface and tenfold in the surface to 100 mb layer between 1958–61 and 1970–73, but has recently decreased somewhat with the partial breakdown of the three-year oscillation.

3) In the south extratropics (oceanic hemisphere) the interannual variability is only about half that observed in the north extratropics (continental hemisphere), but again there has been an increase in variability in the surface to 100 mb layer over the period of record.

Thus, the available evidence suggests that, on the average, both the spatial and temporal variability of temperature *have* become greater in recent years, in keeping with the increase in meridional temperature gradient and, at least in the Northern Hemisphere, the increase in lapse rate.

9. Relation of recent data to data of previous years

To place the most recent data into perspective, Fig. 8 presents the temperature deviation from the mean in 1976 (crosses) in comparison with the deviations from the mean in the other 18 years since 1958

TABLE 1. Average year-to-year variation in mean temperature (°C) for successive three-year segments of the record at the surface and in the surface to 100 mb layer.

	North extratropics		Tropics		South extratropics	
	Surface	Surface to 100 mb	Surface	Surface to 100 mb	Surface	Surface to 100 mb
1958–61	0.44	0.33	0.07	0.06	0.27	0.11
1961–64	0.29	0.29	0.15	0.04	0.23	0.13
1964–67	0.36	0.12	0.09	0.38	0.28	0.11
1967–70	0.53	0.10	0.21	0.26	0.19	0.16
1970–73	0.31	0.27	0.28	0.59	0.09	0.15
1973–76	0.41	0.38	0.19	0.30	0.20	0.15

(circles), for climatic zones, tropics and extratropics, hemisphere and world. Future updates may basically involve diagrams of this type. In the average for the world we find that 1976 was the coldest year of record in the surface to 100 mb layer (0.37°C below the mean) and tied with 1964 for the coldest year of record at the surface (0.25°C below the mean). The surface to 100 mb layer in north extratropics averaged more than 0.6°C

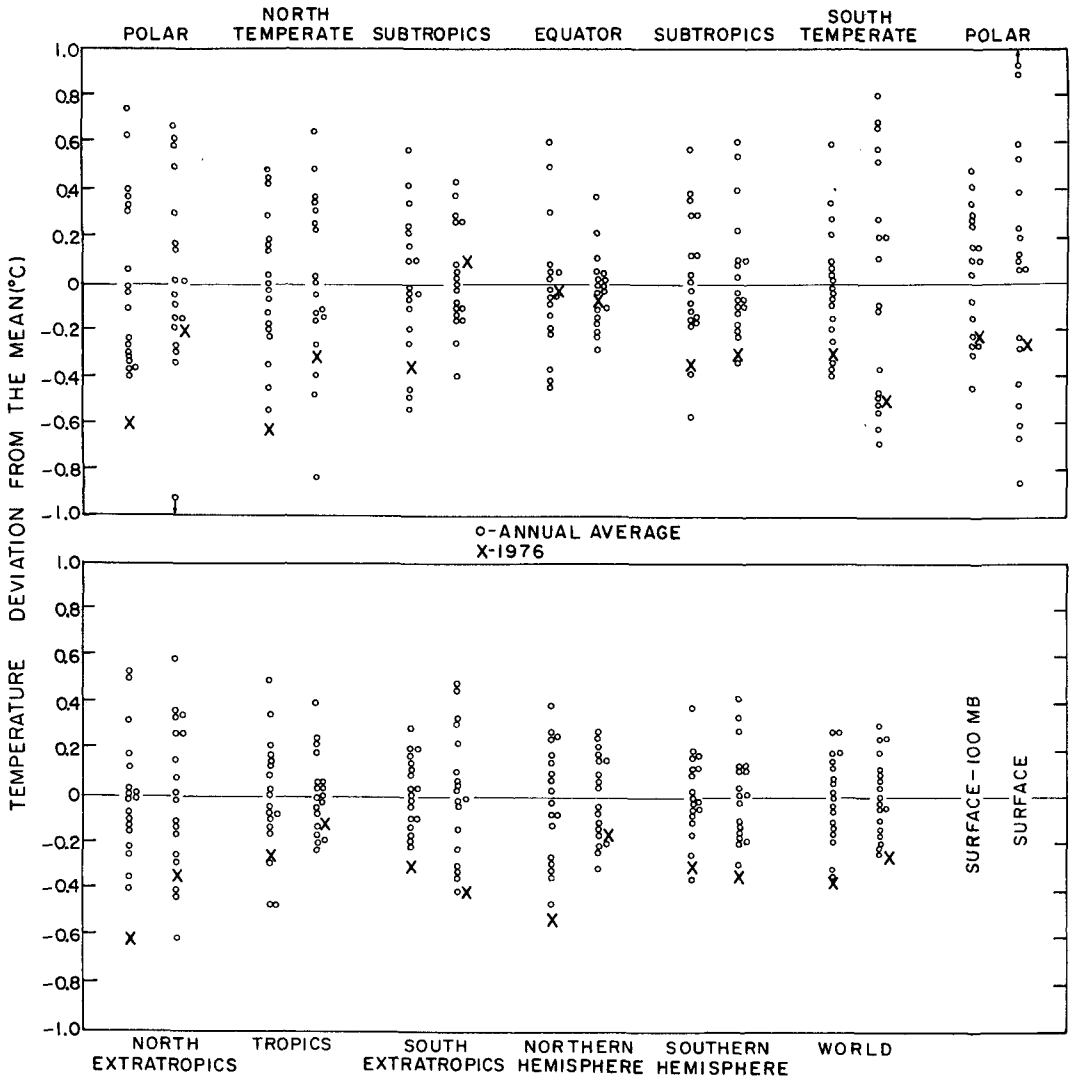

FIG. 8. Comparison of the temperature in 1976 (crosses) with the mean annual temperature for the 18 prior years (circles), for climatic zones, tropics and extratropics, hemisphere and world. For each region, the left-hand distribution represents the surface to 100 mb temperature, the right-hand distribution the surface temperature.

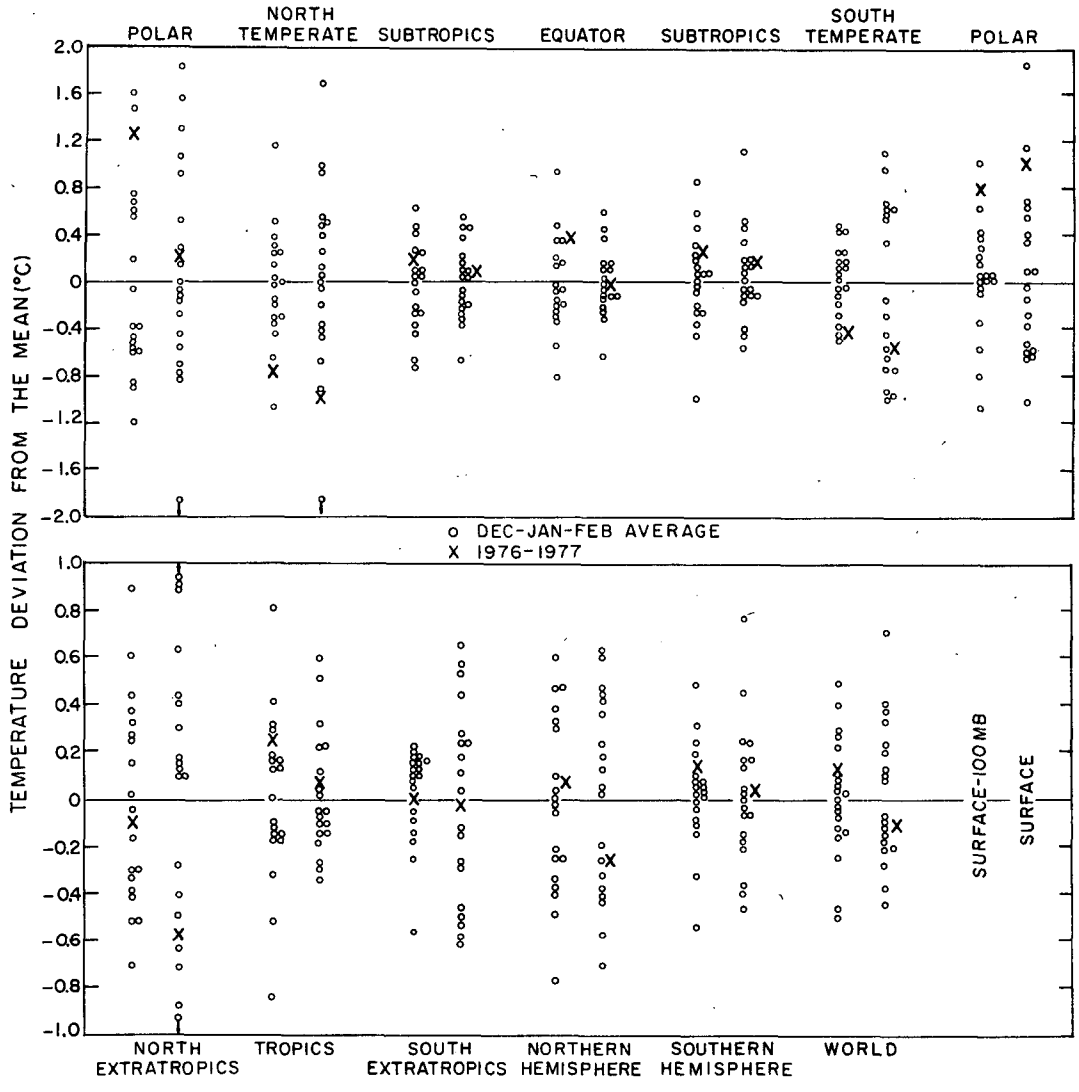

FIG. 9. Comparison of the northern winter of 1976–77 (crosses) with the 19 prior northern winters (circles). Otherwise, see Fig. 8 legend.

below the mean in 1976, exceeding by 0.2°C the previous yearly low set in 1972. Dronia (Kukla *et al.*, 1977) also found the years 1976 and 1972 to be the coldest of record (back to 1949) in the north extratropics based on 1000–500 mb thicknesses, and there is agreement here as well with the findings of Angell and Korshover (1978) that the 300 mb north circumpolar vortex was more expanded in 1976 than in any year since 1963 (beginning of the vortex record), with 1972 the second most expanded year. Note that in the Northern Hemisphere the (negative) deviation from the mean in the surface to 100 mb layer always exceeded the value at the surface, pointing up the relatively large lapse rate existing in this hemisphere in 1976. In the Southern Hemisphere, on the other hand, the temperature deviations were nearly the same at the surface and in the surface to 100 mb layer.

Fig. 9 presents a similar diagram for the last three months of record, namely, December, January and February of 1976–77. This was a cold period in both temperate latitudes, only the winter of 1969–70 being colder in northern temperate latitudes (there is a discrepancy here with the vortex-area results, which showed the 300 mb vortex most expanded in the winter of 1976–77, not 1969–70). However, both polar regions were warm (recall the intense north-polar anticyclone during this winter) and the tropics were also relatively warm, so that in the average for the hemisphere and world the temperature was near the mean. Thus, perhaps contrary to expectation, the year 1976 was the anomaly on a global basis, not the Northern Hemisphere winter of 1976–77.

10. The quasi-biennial oscillation in temperature

In order to look for some relation between the surface or surface to 100 mb temperature and the quasi-biennial

oscillation of the tropical stratosphere, we have averaged the unsmoothed seasonal data in the various climatic zones using the season of quasi-biennial west wind maximum at 50 mb in the tropics as the origin (superposed epoch method). Based on nine such quasi-biennial cycles, Fig. 10 shows that there is evidence, particularly consistent in the surface to 100 mb layer, for the temperature to be about 0.1°C above average six months or so prior to the tropical quasi-biennial west wind maximum at 50 mb, and about 0.1°C below average six months or so after this west wind maximum. While this is not a large range, it is certainly not negligible either. The consistency in phase among the different climatic zones is somewhat surprising because often there is an alternation in phase of the quasi-biennial variation between tropics and extratropics, as in the case of total ozone for example.

The above phase relation between temperature and tropical west wind maximum has held up well during the past few years, inasmuch as the last quasi-biennial west wind maximum at 50 mb in the tropics was in the northern winter of 1975–76, and we have already seen that 1976 was a cold year. With the assumption of a 24-month quasi-biennial period, the next tropical west wind maximum would be in the winter of 1977–78, implying a relatively warm 1977, other things being equal, and a preliminary look at the most recent data indicates that this is so. Whether the contribution from this "quasi-biennial warmth" will extend through the winter of 1977–78 depends to some extent on the length of the quasi-biennial period. In view of the aforementioned evidence that the three-year tropical oscillation (Southern Oscillation) extends into the north extratropics (Figs. 1 and 11), and the evidence in this section for a quasi-biennial variation in temperature in the north extratropics, it would appear that temperature variations in northern latitudes are closely related to temperature variations in the tropics. Obviously, such relations deserve detailed study (see also Wright, 1977) in the context of long-range predictions for temperate latitudes.

There is some discrepancy between the quasi-biennial results above and the results derived from the size of the 300 mb north circumpolar vortex (Angell and Korshover, 1978). In the latter paper it is shown that there has been an impressive tendency for the vortex to be most contracted at the time of quasi-biennial west wind maximum at 50 mb in the tropics, and this implies warmest temperatures at this time in north temperate latitudes, rather than 3–6 months earlier as shown by the surface to 100 mb trace for north temperate latitudes in Fig. 10. The discrepancy could be due to the different periods of record (only 1963–76 in the case of the vortex) or an appreciable variation in surface pressure (which also affects vortex size), but more likely simply reflects the inconsistencies which result when dealing with relatively short periods of record.

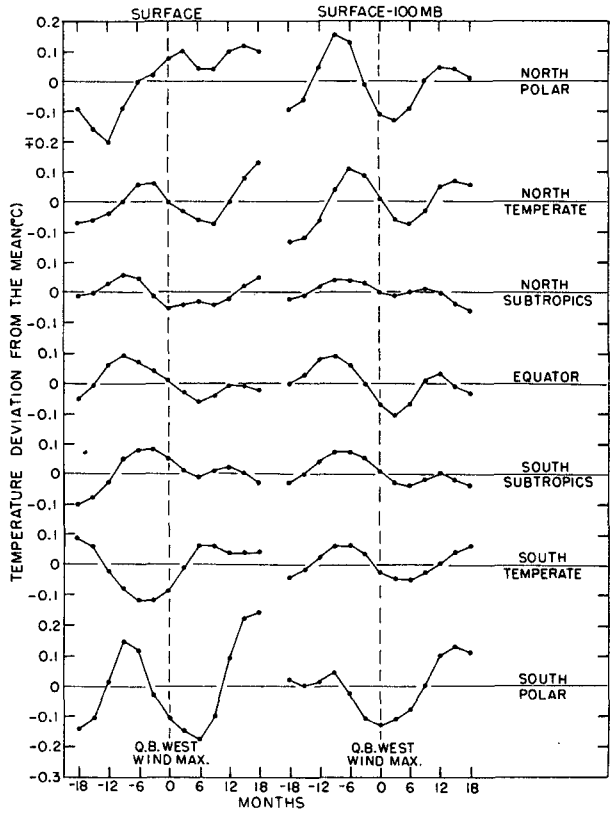

FIG. 10. Variation of climatic-zone temperature at the surface (left) and in the surface to 100 mb layer (right) with respect to the season of quasi-biennial west wind maximum at 50 mb in the tropics (negative abscissa values signify that the temperature precedes the west wind maximum), as obtained by the superposed epoch method applied to nine cycles of the quasi-biennial oscillation. A 1–2–1 smoothing has been applied twice to successive seasonal lags.

11. Comparison of carbon dioxide and temperature variations

Fig. 11 illustrates the trend in CO_2 at Mauna Loa, Hawaii and at the South Pole station of Amundsen Scott, obtained in the same manner as the temperature trends, i.e., a 1–2–1 smoothing applied twice to successive seasonal values with the annual variation eliminated in the same way. The vertical dashed lines show that in most cases the rate of increase of CO_2 has been relatively large at, or slightly preceding, the time of atmospheric temperature maximum in the tropics (and north extratropics). This may reflect the existence of a close relation between atmospheric and oceanic temperature in the tropics, since it has been shown by Bacastow (1976) and Newell and Weare (1977) that there is a good correlation between sea surface temperature in the tropical Pacific and rate of increase of CO_2, presumably because more CO_2 is released from the oceans when they are relatively warm. There are the peculiarities in Fig. 3, however, of no augmentation in the rate of CO_2 increase at Mauna Loa during the temperature

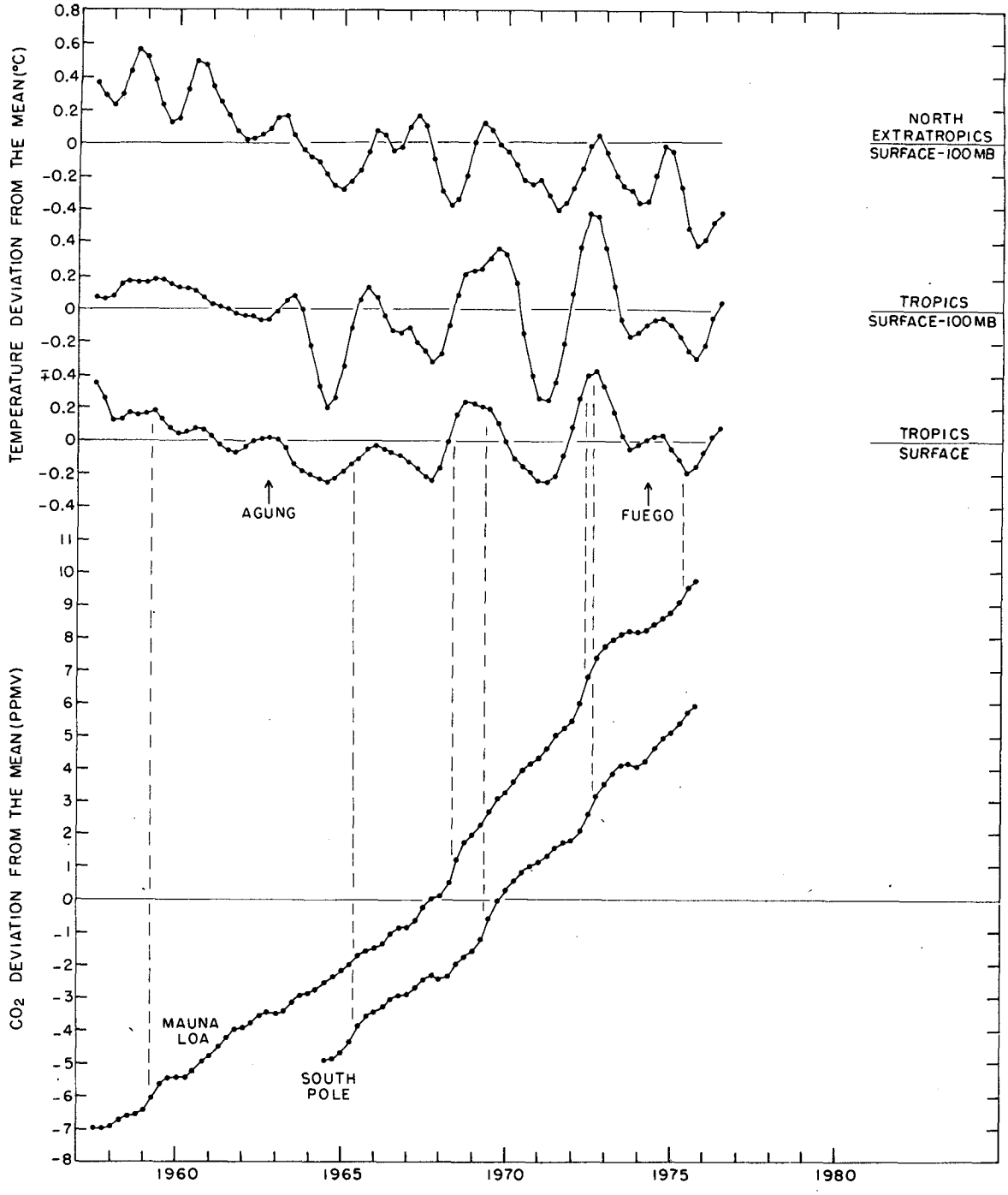

FIG. 11. Comparison of the rate of increase of CO_2, at Mauna Loa, Hawaii, and at the South Pole Station of Amundsen-Scott, with temperature variations in tropics and north extratropics. The CO_2 data have been analyzed and smoothed in the same way as the temperature data (see Fig. 1 legend), and again the eruptions of Agung and Fuego are indicated at center and the tick marks are in summer of the given year.

maximum of 1965–66, and the different intervals between the respective CO_2 augmentations at Mauna Loa and South Pole during the temperature maxima of 1969–70 and 1972–73. Furthermore, in late 1975 there was a fairly rapid increase of CO_2 at Mauna Loa which did not show up at the South Pole and which also is not related to a tropical temperature maximum.

One other attribute of the CO_2 trend should be emphasized. Between 1958 and 1968 the rate of increase of CO_2 at Mauna Loa averaged about 0.7 ppm year^{-1},

whereas between 1968 and 1973 the increase averaged about 1.4 ppm year^{-1}, and even between the periods of augmentation 1.2 ppm year^{-1}. In contrast to this near doubling of the rate of increase of CO_2, the CO_2 input into the atmosphere only increased by about 30% between the periods 1961–67 and 1967–74 (Baes *et al.*, 1976), so that factors other than emission rates appear to be involved in the overall CO_2 growth rate. There is evidence from Fig. 11 for a slowing down of this growth rate after 1973, recognized also by Peterson *et al.* (1977), and this would be in keeping with the reduced emissions of recent years indicated by Baes *et al.* It is apparent that the South Pole measurements are more conservative than the Mauna Loa measurements, that is, they yield a more consistent increase of CO_2 with time, undoubtedly a result of the more remote location.

12. Conclusions

Following are 10 of the more important points from this update of global temperature data into 1977:

1) On a global basis, the mean temperature in the surface to 100 mb layer was lower in 1976 than in any year since commencement of the record in 1958, and the 1976 surface temperature equaled the previous record low set in 1964, but even so the global temperature trend since 1965 has been small compared to the 0.5°C decrease in temperature between 1960 and 1965.

2) The winter of 1976–77 in north temperate latitudes was the next coldest of record, and this season was relatively cold also in south temperate latitudes, but because of relatively warm tropical and (especially) polar regions, the hemispheric and global-mean temperatures were not anomalous.

3) The mean temperature in the surface to 100 mb layer decreased by a significant 1°C in the north extratropics between 1958 and 1976, with the latter year 0.6°C below the mean or 0.2°C colder than any previous year. Because of the slight warming in the tropics after 1965, the meridional temperature gradient in the Northern Hemisphere is indicated to have increased by at least 0.5°C over the period of record, and by somewhat less in the Southern Hemisphere.

4) In the north extratropics the long-term temperature decrease during winter has been twice that during summer, though both decreases are significant.

5) There is evidence for an increase in lapse rate in the Northern Hemisphere and a nearly equal decrease in lapse rate in the Southern Hemisphere over the period of record.

6) The three-year variation in tropical temperature which began about 1964 (shortly after the Agung eruption), and which presumably is related to the Southern Oscillation, became less pronounced after 1975. There has been a clear tendency for the rate of increase of CO_2 at Mauna Loa and the South Pole to be augmented at the time of the temperature maxima associated with this oscillation.

7) The three-year oscillations in tropical temperature extend in obvious fashion into the north extratropics, and consideration should be given to these oscillations when dealing with diagnoses or prognoses in northern latitudes.

8) The year-to-year variation in surface to 100 mb temperature in the north extratropics was the largest of record during 1973–76, and in addition to the very large increase in interannual variability in the tropics associated with the advent of the three-year oscillation, there has also been an increase in interannual temperature variability in the south extratropics. An overall increase in spatial temperature variability is indicated for the tropics and extratropics at the surface, but only for the tropics in the surface to 100 mb layer, perhaps because of an improvement in radiosonde accuracy.

9) There is evidence for a quasi-biennial variation in temperature, basically in phase at all latitudes in the surface to 100 mb layer, with the temperature about 0.1°C warmer than average approximately six months prior to the quasi-biennial west wind maximum at 50 mb in the tropics.

10) Surface temperatures in the Eastern Hemisphere of the north extratropics warmed considerably during the past decade even though the surface to 100 mb temperature continued cooling, implying a considerable increase in lapse rate. Presumably, it is this surface warming that led to Russian concern regarding the greenhouse effect of enhanced CO_2 releases, but the indicated cooling aloft raises the question of surface-temperature representativeness and pertinence.

It is planned to update these temperature data seasonally and to contribute updates to the literature when appropriate.

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