Variation with Height and Latitude of Radiosonde Temperature Trends in North America, 1975–94

JAMES K. ANGELL

Air Resources Laboratory, NOAA, Silver Spring, Maryland

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ABSTRACT

Based on the 120-station North American radiosonde network, temperature trends for 100–50-mb (low stratosphere), 300–100-mb (tropopause), and 850–300-mb (troposphere) layers, and Earth's surface, are evaluated for six 10° latitude bands extending from 20°–30°N to 70°–80°N for the 20-yr interval 1975–94. Confidence estimates are indicated by two standard errors of the least squares regression. In the average for the six latitude bands, the 100–50-mb annual temperature trend is -0.5°C decade^{-1} and the 850–300-mb trend is 0.2°C decade^{-1}. In spring at 70°–80°N, the 100–50-mb and 300–100-mb layers cool by almost 2°C decade^{-1}. The 300–100-mb layer cools by 0.7°C decade^{-1} relative to the 850–300-mb layer at 70°–80°N, but the two layers have the same warming trend at 20°–30°N, indicating the transition from the 300–100-mb layer being mostly in the stratosphere in polar regions to mostly in the troposphere in the northern subtropics. The surface warms much more than the troposphere at 70°–80°N (showing that surface temperature trends are not representative of tropospheric trends in polar regions) and slightly more at 20°–30°N, but surface warming is less than tropospheric warming in the 40°–70°N belt. At the surface at the radiosonde sites the 1200 UTC (morning) temperature cools relative to the 0000 UTC (evening) temperature by 0.05°C per decade on average, but the 850–300-mb temperature trends at 0000 UTC and 1200 UTC are essentially the same. The 0.7°C decade^{-1} cooling of low stratosphere relative to troposphere increases to 0.9°C decade^{-1} when adjustment is made for the stratospheric warming and tropospheric cooling following El Chichon and Pinatubo eruptions. The temperature trends obtained from 11 North American radiosonde stations in a 63-station global network agree well with the trends based on the entire 120-station network, and the latter are fairly representative of zonally averaged trends based on the 63-station network and microwave sounding unit data. Comparison with Canadian ozonesonde data shows that, in the low stratosphere and high troposphere during 1975–94, a decrease in temperature of 1°C decade^{-1} was associated with a decrease in ozone of about 10% decade^{-1}.

1. Introduction

About half the radiosonde stations in the 63-station global network used by Angell and Korshover (1983) have been affected by inhomogeneities in the temperature record (Gaffen 1994). This suggests that global temperature trends might best be estimated by first determining the trends for the most coherent radiosonde networks with the aim of obtaining kernels of reliable results, and then expanding the analysis into regions with less certain data. The logical network to start with in such an endeavor is the relatively homogeneous U.S.–Canadian network of 120 radiosonde stations.

In this paper, U.S. and Canadian temperature trends for 100–50-mb (low stratosphere), 300–100-mb (tropopause), and 850–300-mb (troposphere) layers, as well as the earth's surface, are evaluated for six 10° latitude bands extending from 20°–30°N to 70°–80°N for the 20-yr interval 1975–94, and shown as a function of height for the six latitude bands. Also evaluated are the differences in trend in these layers at 1200 UTC and 0000 UTC. The data record begins in 1975 because the first 2 yr of the Air Resources Laboratory radiosonde record, which separates 0000 UT and 1200 UTC observations (Ross et al. 1996) has too much missing data for this analysis. The record is terminated in 1994 because of the introduction of Vaisala sondes into the Canadian network.

The impact on low-stratospheric and tropospheric temperature trends of El Chichon and Pinatubo eruptions is estimated. Comparisons are made with temperature trends based on the 11 North American stations in the 63-station global network, as well as with zonally averaged trends based on this network and on MSU data obtained from NOAA satellites (Christy et al. 1995). Finally, in view of the interest in the possible development of an arctic ozone hole (Hansen et al. 1997), the temperature trends in northern latitudes are compared with ozone trends determined from Canadian ozonesondes. It is recognized that trends based on only

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Corresponding author address: Dr. J. K. Angell, OAR R/E/AR, 1315 East–West Highway, Silver Spring, MD 20910-3282.

TABLE 1. For the given latitude bands and layers, the standard deviation of individual radiosonde-station annual temperature anomalies (°C) averaged for the 20 yr 1975–94. At right is the number of radiosonde stations in each band, and the percentage of these stations that used Space Data Corporation sondes during 1989–94.

	100–50 mb	300–100 mb	850–300 mb	Surface	Number	Percent
70°–80°N	0.6	0.4	0.3	0.6	7	0
60°–70°N	0.6	0.4	0.5	0.8	15	20
50°–60°N	0.5	0.4	0.6	0.7	22	0
40°–50°N	0.4	0.3	0.4	0.7	31	13
30°–40°N	0.5	0.3	0.4	0.6	36	25
20°–30°N	0.3	0.2	0.2	0.3	9	11

20 yr of data may not be representative of longer-term trends, and the reader is cautioned accordingly. Note that as of the end of 1998, the MSU temperature record is also of 20-yr length.

2. Procedures

At each of the 120 United States and Canadian radiosonde stations with a data record from 1975 through 1994, the mean seasonal [December–February (DJF), etc.] temperature in low stratosphere, tropopause layer, and troposphere is determined at 0000 UTC and 1200 UTC from the difference in height (thickness) of, respectively, 100 and 50 mb, 300 and 100 mb, and 850 and 300 mb pressure surfaces by means of the hydrostatic equation (Angell and Korshover 1983). A mean seasonal surface temperature is also obtained at each of the radiosonde sites. These seasonal temperatures are then expressed as seasonal deviations from 1975–89 seasonal means, and an annual temperature deviation for each station obtained from the average of winter, spring, summer, and autumn temperature deviations. Note that the layer-mean temperature is a virtual temperature, that is, a function of atmospheric moisture content as well as temperature, so that in the following the tropospheric warming may be overestimated by as much as 10% because of concomitant increases in moisture (Elliott et al. 1994).

These seasonal and annual radiosonde-station temperature deviations (anomalies) are averaged for each of six 10° latitude bands extending from 20°–30°N to 70°–80°N. Alert, Canada (82°N) and San Juan, Puerto Rico (18°N) are included in 70°–80°N and 20°–30°N bands, respectively, because they are in the 63-station global network. The column second from right in Table 1 gives the number of radiosonde stations in each of the latitude bands. The subsequent analysis is based on latitude-band averages of 0000 UTC and 1200 UTC seasonal and annual temperature anomalies, except in section 6 where the difference in trend at the two times is considered.

Based on the average annual and seasonal temperature anomalies in each of the six latitude bands, temperature trends for these bands are determined for the 20-yr interval 1975–94 by means of least-squares regression. The significance of the trends is indicated by the value of two standard errors of estimate ($2\sigma_E$) of the linear regression, in the case of 20 data points:

$$2\sigma_E = \frac{\sigma}{1.3}(1 - r^2)^{1/2}, \qquad (1)$$

where σ is the standard deviation of the 20 yr of annual or seasonal temperature anomaly and r is the correlation with time of the 20 anomalies (Brooks and Carruthers 1953, p. 226).

3. Impact of a change in radiosonde

While the U.S.–Canadian radiosonde network is relatively homogeneous during 1975–94, the impact on temperature trend of the replacement of VIZ Manufacturing Company sondes by Space Data Corporation (SDC) sondes at 17 U.S. stations during 1989–94 has to be considered. The impact is estimated from the work of Baker et al. (1993), who compared radiosonde pressure heights at Bismark, ND (SDC station), and Rapid City, SD (VIZ station), with 6-h pressure-height forecasts made by the U.S. Navy's data assimilation system during 1990–92. Using the assimilation forecasts as a standard, pressure-height biases as a function of height were determined for the two sondes. It is deduced from these that in the annual average the SDC sondes indicate a 0.4°C warmer 100–50-mb and 300–100-mb layer than do the VIZ sondes, but a 0.2°C cooler 850–300-mb layer. Accordingly, the use of SDC sondes during 1989–94 has resulted, at an individual radiosonde station, in an apparent warming trend of 0.2°C decade^{-1} in 100–50-mb and 300–100-mb layers during 1975–94, but an apparent cooling trend of 0.1°C decade^{-1} in the 850–300-mb layer, that is, in an underestimate of the extent of stratospheric cooling relative to tropospheric warming. A referee points out that because the SDC sonde is more sensitive to solar angle variation than the VIZ sonde, the above biases would be slightly different at southwestern stations where most SDC sondes were located. Nevertheless, considering the percentage of SDC stations in the 10° latitude bands (right-hand column of Table 1), the introduction of SDC sondes into the United States network in 1989 alters the estimate of latitude-band temperature trend in this paper by less than 10%. Accordingly, no adjustment in trend has been made.

With regard to the introduction of Vaisala sondes (re-

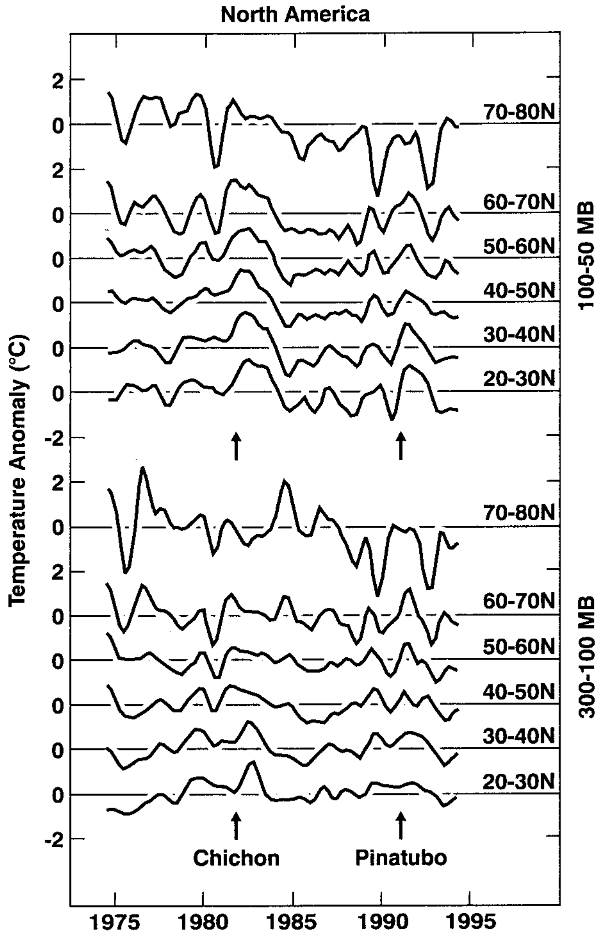

FIG. 1. Time variation in the average of radiosonde-station 100–50 mb (low stratosphere) and 300–100 mb (tropopause layer) seasonal temperature anomalies for North American 10° lat bends, 1975–1994. A binomial smoothing has been applied to the average seasonal anomalies for the six bands.

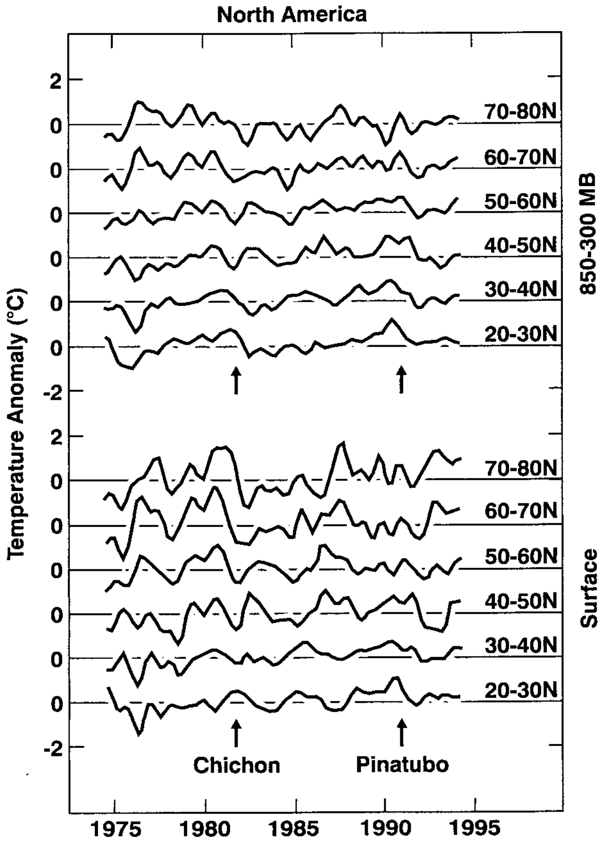

FIG. 2. As in Fig. 1 but for the 850–300-mb layer (troposphere) and the surface.

placing VIZ sondes) at 26 of the 33 Canadian stations during 1994, this referee also points out that for the 100–50-mb layer the Vaisala sondes would indicate cooler temperatures in daytime (0000 UTC) but warmer temperatures at night, so that in the average for the two times the impact of the change in instrumentation would be small (but perhaps not small when the trends at 0000 UTC are compared with the trends at 1200 UTC, see section 6).

A second referee points out that another reason for concern is that while VIZ has used the same thermistor since 1975, the housing and electronic hardware have changed, as has the National Weather Service data reduction system. It is beyond the scope of this paper to detail these matters, but the small difference in what are essentially daytime and nighttime temperature trends in section 6 suggests that the impact of these changes has not been large.

4. Background

Figure 1 shows the variation with time of North American 100–50 mb (low stratosphere) and 300–100 mb (tropopause layer) temperature anomalies, where a binomial smoothing (1, 4, 6, 4, 1 weighting of successive seasonal anomalies) has been applied. The traces parallel one another well except at 70°–80°N in both layers where there are large variations in temperature superimposed on relatively large temperature decreases. The cooling of the 100–50-mb layer is interrupted by warmings following the El Chichon (Mexico) eruption in the spring of 1982 and the Pinatubo (Philippines) eruption in the summer of 1991 (vertical arrows in Fig. 1). In the 300–100-mb layer the volcanic warming is mostly in lower latitudes following El Chichon but in higher latitudes following Pinatubo.

Figure 2 shows the variation of 850–300-mb (troposphere) and surface smoothed temperature anomalies. The warming in the troposphere and at the surface is more obviously interrupted by the Pinatubo eruption than the El Chichon eruption, partly because of the tropospheric warming associated with the powerful El Niño occurring near the time of the El Chichon eruption (Angell 1988). The volcanic impact on North American temperature in troposphere and low stratosphere is examined in more detail in section 7.

The standard deviation of the individual radiosonde-station annual temperature anomalies has been determined at 0000 UTC and 1200 UTC for each year and each 10° latitude band, and then averaged for the two times and the 20 yr in each of the three layers and the surface. The results are presented in the four left columns of Table 1. It is seen that the radiosonde stations in the North American network are quite consistent, the standard deviation of annual temperature anomaly hovering around 0.5°C.

The smaller standard deviation in the troposphere than at the surface shows the greater representativeness of the radiosonde observations. Even the 100–50-mb standard deviations never exceed the surface values in these latitude bands. The smallest standard deviation is often in the 300–100-mb layer. The standard deviation generally decreases with decrease in latitude but is particularly small at 20°–30°N because of the limited longitudinal extent of this band (Mexican stations not included in the analysis).

5. Variation of temperature trend with height

Based on least-squares regression, Fig. 3 shows the trend of North American annual temperature anomaly as a function of height in the six latitude bands; the trends plotted at the midpoints of 850–300-mb, 300–100-mb, and 100–50-mb layers; or at heights of 5.5, 12.5, and 18 km, respectively, as well as at the surface. The horizontal bars extend two standard errors of estimate each side of the trend values, as determined from Eq. (1). There is impressive evidence for a cooling of the 100–50-mb layer relative to the 850–300-mb layer above North America during 1975–94, the error bars for the respective layers not overlapping from 40°N to 60°N, and barely overlapping at 30°–40°N and 70°–80°N. Note also how the cooling of the 300–100-mb layer relative to the 850–300-mb layer becomes less with decreasing latitude, until at 20°–30°N the warming in the two layers is the same. This is in agreement with model estimates of the temperature change to be expected from the observed increase in greenhouse gases and sulfate aerosols, and decrease in low-stratospheric ozone (Tett et al. 1996, Fig. 2c). Another interesting feature of Fig. 3 is the systematic variation with latitude of the relation between surface and 850–300-mb temperature trend. The surface temperature warms much more than the 850–300-mb temperature at 70°–80°N, less than the 850–300-mb temperature between 40°N and 70°N, and more than the 850–300-mb temperature again at 20°–30°N. The much greater warming of surface than troposphere at 70°–80°N indicates that surface temperature trends are not representative of tropospheric trends in polar regions where there are strong temperature inversions near the surface (see also Kahl et al. 1993). The modeling results of Tett et al. also show warming of the surface relative to the troposphere in polar latitudes, but little evidence of a greater tropospheric warming than surface warming in midlatitudes (though they do in tropical latitudes).

Figure 4 shows the trend of seasonal temperature anomaly as a function of height in the six latitude bands. The anomalous annual cooling of 100–50 mb and 300–100 mb layers at 70°–80°N in Fig. 3 is seen from Fig. 4 to be mostly due to anomalous cooling in spring, a sensitive season from the viewpoint of development of

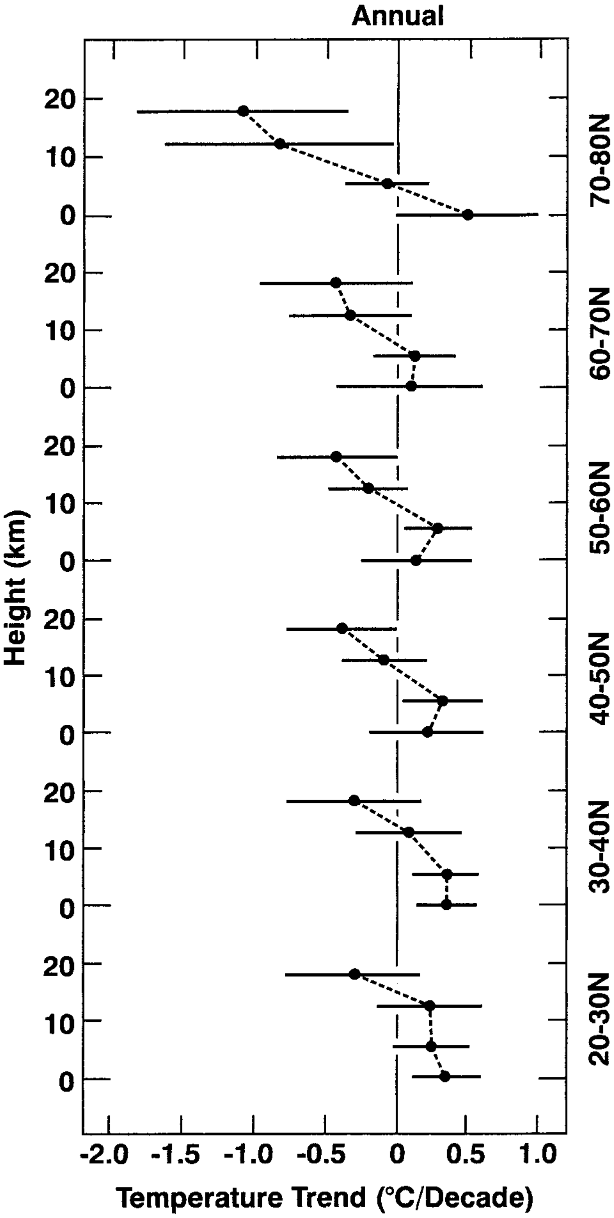

FIG. 3. North American annual temperature trends (°C decade^{-1}), and two-standard-error bars [see Eq. (1)], as a function of height in the six 10° lat bands, 1975–94. The trends are plotted at the midpoints of 100–50-mb, 300–100-mb, and 850–300-mb layers, as well as at the surface.

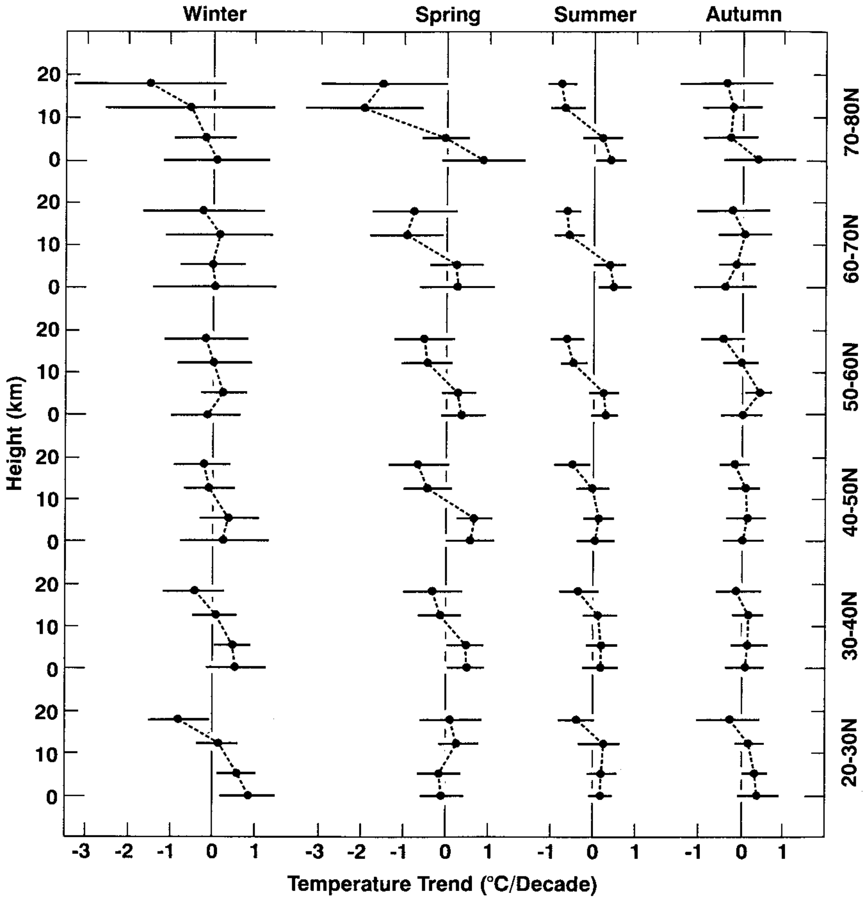

FIG. 4. As in Fig. 3 but for the seasons.

an arctic ozone hole (a comparison of temperature and ozone trends in northern latitudes is presented in section 9). In summer between 50° and 80°N there is a clear distinction (nonoverlapping error bars) between 100–50 mb and 300–100 mb cooling, and 850–300 mb and surface warming. This relation changes abruptly at 50°N, the latitude bands to the south showing similar warming of 300–100-mb and 850–300-mb layers and surface. Presumably, this reflects the change from the 300–100-mb layer being mostly in the stratosphere to the north of 50°N to mostly in the troposphere to the south of 50°N. Note that this change in temperature profile occurs at least 10° latitude farther south in spring. In winter, and especially autumn, there is much less change in temperature trend with height.

Table 2 summarizes Figs. 3 and 4 by presenting the averages of annual and seasonal temperature trends for the six latitude bands (not area weighted). In the annual average, the cooling in the 100–50-mb layer (trend of $-0.5°C$ decade^{-1}) is about twice the warming in the 850–300-mb layer and at the surface. The slightly greater surface warming than troposphere warming on an annual basis is due to greater surface warming in summer, and particularly spring, indicating a tendency for an increase in instability in these already convective seasons (perhaps in connection therewith, these are also the seasons in which the 300–100-mb layer cooled). Note from Table 2 how small the autumn trends are compared to the spring trends, indicating a basic difference in transition-season temperature trends.

6. Difference in 1200 UTC and 0000 UTC temperature trends

Karl et al. (1984, 1993) provide evidence that in North America, as well as other regions of the world, surface daily minimum temperatures have warmed at least twice as much as maximum temperatures between about 1940 and 1990. Even though the North American radiosonde observations at 1200 and 0000 UTC are usually not at the time of minimum or maximum temperature, it is of interest to see how temperature trends at 1200 and 0000 UTC differ. North American radiosonde observations at 1200 UTC span local times from 0200 to 0800 and at 0000 UTC from 1400 to 2000 LT so that on the basis of the Karl et al. results one would expect a greater surface warming at 1200 UTC (morning) than at 0000 UTC (evening).

TABLE 2. Average of the six latitude-band temperature trends (°C decade^{-1}) in each layer, and at the surface, in Figs. 3 and 4, 1975–94.

	Winter	Spring	Summer	Autumn	Annual
100–50 mb	−0.6	−0.6	−0.6	−0.3	−0.5
300–100 mb	0	−0.6	−0.2	0	−0.2
850–300 mb	0.3	0.3	0.2	0.1	0.2
Surface	0.3	0.5	0.3	0.1	0.3

Figure 5 shows the trends of 1200 minus 0000 UTC annual temperature anomalies as determined by least-squares regression. There is a striking difference between the results found for the surface and the 850–300-mb layer, both in regard to magnitude of trend and magnitude of error bar. In the 850–300-mb layer there is only limited evidence of a difference in trend at 1200 and 0000 UTC, and the small error bars signify little year-to-year variation in the 1200 minus 0000 UTC values. At the surface, however, there are relatively large differences in 1200 and 0000 UTC trend (and large error bars), culminating at 50°–60°N in the surface temperature cooling at 1200 UTC (morning) relative to 0000 UTC (evening) by 0.15°C decade^{-1}. Only at 20°–30°N is there the surface warming in morning relative to evening found by Karl et al. Table 3 shows that, in the average for the six latitude bands, the surface warming in evening relative to morning is a spring and summer phenomenon. These are the same seasons the surface warms relative to the troposphere (Table 2).

Unlike the 850–300-mb layer, Fig. 5 shows that in the 300–100-mb and 100–50-mb layers the 1200 minus 0000 UTC temperature trends vary considerably with latitude and the error bars are fairly large, suggesting greater uncertainty in the difference estimates. Even so, there is clearly an overall tendency for cooling at 1200 UTC relative to 0000 UTC and Table 3 indicates that this tendency is observed in all seasons in both layers except for the 100–50-mb layer in winter. Based on the work of Baker et al. (1993), the replacement of VIZ sondes by SDC sondes results in a 100–50-mb annual warming of 0.2°C at 1200 UTC compared to 0.6°C at 0000 UTC. This translates into a cooling at 1200 UTC relative to 0000 UTC of 0.05°C decade^{-1} in the 30°–40°N band (about half that observed at 100–50-mb in Fig. 5), so that an appreciable portion of the cooling at 1200 UTC relative to 0000 UTC in 100–50-mb and 300–100-mb layers of this band is due to replacement of VIZ sondes by SDC sondes. Note that north of 50°N where the change from VIZ sondes to Vaisala sondes in Canada during 1994 could have an impact on the difference in 100–50-mb trend between 1200 and 0000 UTC, the observed tendency for more cooling at 1200 than at 0000 UTC is the opposite of that expected from this change in instrumentation (see section 3).

Ross et al. (1996) determined the trend in evening (0000 UTC) minus morning (1200 UTC) temperatures at the surface and 850-, 700-, 500-, 400-, and 300-mb pressure surfaces at Canadian radiosonde stations south of 75°N for the interval 1973–93. They found a nonsignificant tendency for an annual surface warming of about 0.02°C decade^{-1} in the evening relative to morning, but at all five pressure surfaces a generally signif-

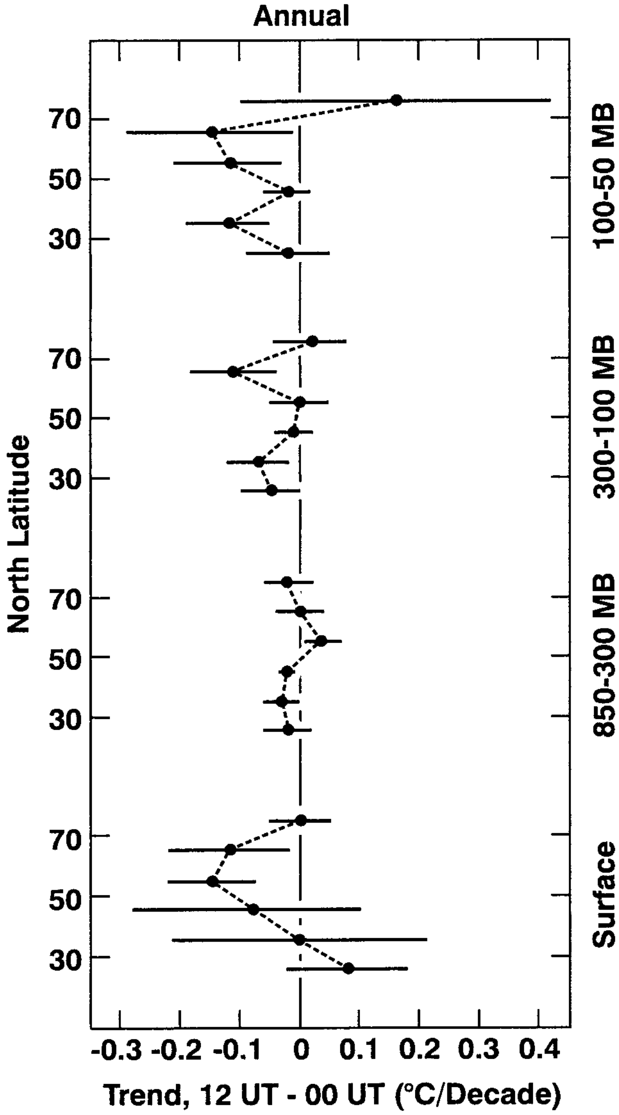

FIG. 5. North American trends of 1200 UT minus 0000 UT annual temperature anomaly (°C decade^{-1}), and two-standard-error bars, as a function of latitude for three layers and the surface, 1975–94.

TABLE 3. Average of the six latitude-band 1200 minus 0000 UTC annual temperature trends (°C decade^{-1}) in each layer, and at the surface, in Fig. 5, as well as seasonal averages, 1975–94.

	Winter	Spring	Summer	Autumn	Annual
100–50 mb	0.05	−0.03	−0.08	−0.11	−0.04
300–100 mb	−0.06	−0.04	−0.04	−0.02	−0.04
850–300 mb	−0.01	0.01	−0.02	0	−0.01
Surface	0.05	−0.15	−0.11	0.02	−0.05

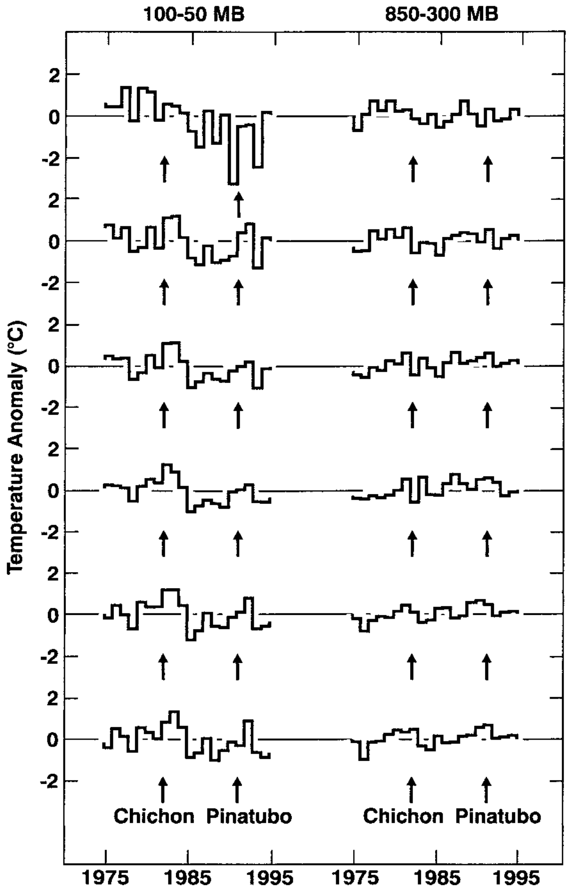

FIG. 6. North American 100–50-mb and 850–300-mb annual temperature anomalies (°C) in the six 10° lat bands, 1975–94.

icant annual warming in morning relative to evening of about 0.03°C decade^{-1}. These results are in qualitative, but not quantitative, agreement with the surface and 850–300-mb results shown in Fig. 5.

7. Impact of El Chichon and Pinatubo eruptions on temperature trend

Figure 6 shows the annual anomalies of temperature in 100–50-mb and 850–300-mb layers of the six North American latitude bands. El Chichon erupted in the spring of 1982, and the traces at left clearly indicate a warming of the 100–50-mb layer in 1982 and 1983 in all latitude bands except 70°–80°N. Pinatubo erupted in the summer of 1991, and although there is an obvious warming of the 100–50-mb layer in 1992 in all latitude bands except 70°–80°N, such a warming is not apparent in 1991 except at 60°–70°N. Although one has to be cautious because of the different seasons of the year in which the eruptions occurred, over North America the 100–50-mb warming following El Chichon appears to be greater than that following Pinatubo. However, because El Chichon erupted 7 yr after the beginning of the 1975–94 record whereas Pinatubo erupted only 3 yr before the end of the record, the 100–50-mb warmings following the two eruptions tend to cancel one another in the regression analysis so that the impact on 100–50-mb temperature trend is not large. The impact of the eruptions on stratospheric temperature trends is estimated here by replacing 1982 and 1983 temperature anomalies by the average of 1981 and 1984 anomalies, and 1991 and 1992 anomalies by the average of 1990 and 1993 anomalies.

The impact of the two eruptions on 850–300-mb temperature is not so clear cut. The traces at right in Fig. 6 show little 850–300-mb cooling in the year of the Pinatubo eruption (1991), but, with the exception of the 40°–50°N band, considerable cooling in 1992 followed by a slow warming. There is cooling in the year of the El Chichon eruption (1982) to the north of 40°N, but not to the south thereof. The powerful El Niño of 1982–83 had a strong warming influence on tropospheric temperature in low latitude (Angell 1988), and this is probably the main reason for this change in 1982 temperature anomaly with latitude. The impact of the eruptions on tropospheric temperature trends is estimated here by replacing the 850–300-mb temperature anomalies in 1983 and 1984 by the average of 1982 and 1985 anomalies, and the 1992 and 1993 anomalies by the average of 1991 and 1994 anomalies.

Figure 7 shows at top the annual unadjusted 100–50-mb and 850–300-mb North American temperature trends as a function of latitude, and at bottom the trends after replacement of the volcanic annual anomalies as indicated above. After adjustment the average difference between 100–50-mb and 850–300-mb annual temperature trends is 0.9°C decade^{-1} (compared to 0.7°C before adjustment), corresponding to an increase in lapse rate of about 0.014°C (100 m)$^{-1}$ between 1975 and 1994. The evidence for stratospheric cooling and tropospheric warming over North America during 1975–94 is even more impressive when the impact of El Chichon and Pinatubo eruptions on stratospheric and tropospheric temperature is considered.

8. Comparison with other trend estimates

An important aspect of this analysis is the comparison of temperature trends based on the 120-station North American radiosonde network with other temperature-trend estimates. These include the trend estimates obtained from 11 North American stations in the 63-station global network (indicating the representativeness of temperature trends based on a relatively small number of radiosonde stations), and two estimates of zonal-average temperature trends for northern latitudes (indicating the representativeness of the North American network with respect to a zonal-average network). The dots and accompanying error bars on both sides of Fig. 8 show the variation with latitude of 1975–94 temperature trends based on the entire 120-station North American radiosonde network. The crosses at left in Fig. 8 indicate

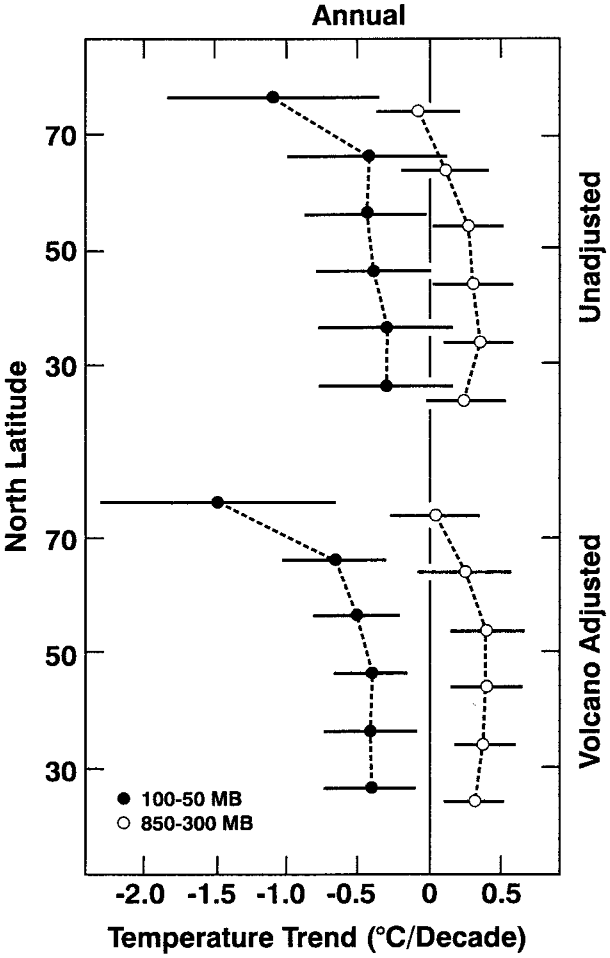

FIG. 7. North American annual temperature trends (°C decade^{-1}) in 100–50-mb (dot) and 850–300-mb (circle) layers, and two-standard-error bars, as a function of latitude, without (top) and with (bottom) adjustment for the impact of El Chichon and Pinatubo eruptions on the annual temperature in these layers, 1975–94.

1975–94 temperature trends as a function of latitude based on the 11 North American stations in the 63-station global radiosonde network. There is good agreement in trend in the 300–100-mb layer, the crosses always falling well within the 2-standard-error bars. This is also true in the 850–300-mb layer if the anomalous warming trend at Annette (A) is ignored. In the 100–50-mb layer the crosses fall within the error bars, but from 40° to 70°N the 11-station network indicates more cooling than does the full network. At the surface the agreement is poor south of 50°N. As expected, it is the surface estimates of temperature trend from a sparse network that are most problematic.

The circles and accompanying error bars at right in Fig. 8 indicate the 1975–94 temperature trends in north polar, temperate, and subtropic zones as estimated from the 63-station network. The agreement between the zonally averaged trend based on the 63-station network, and the trend based on the North American 120-station network, is excellent except in 100–50-mb and 300–100-mb layers of north subtropics (20°–30°N) where the 12 stations in the 63-station network show more cooling, or less warming, than do the 11 stations in the 120-station North American network. This points out the well-recognized problem that, because of changes in instrumentation and procedures at radiosonde stations outside of North America, the 63-station network probably shows too much upper-air cooling in the Tropics (Gaffen 1994). The temperature record from the microwave sounding unit (MSU) on National Oceanic and Atmospheric Administration satellites (Spencer and Christy 1993; Christy et al. 1995) begins in 1979, 4 yr after the beginning of the record in this paper. Accordingly, an exact comparison of the trends from the two records is not possible. To make the records of more nearly the same length, the MSU trends (M) for troposphere and low stratosphere of north polar and temperate zones are indicated at right in Fig. 8 for the interval 1979–96, as obtained from the seasonal issuances of John Christy of the Atmospheric Sciences Department of the University of Alabama at Huntsville. The agreement with MSU is good except in the low stratosphere of the north temperate zone where the zonally averaged MSU cooling trend is strongly influenced by the record cold 100–50-mb temperatures in 1995 and 1996.

9. Comparison of temperature and ozone trends

The springtime decrease in ozone above Antarctica (antarctic ozone hole) has been associated with a decrease in temperature (e.g., Angell 1986, his Fig. 1). Because of the possibility that an arctic ozone hole will develop (Taalas and Kyro 1994; Hansen et al. 1997), it is of interest to chart the relation between temperature and ozone trend also in northern latitudes (see also Randel and Cobb 1994). For that purpose, annual and seasonal ozone anomalies in 2–8-km, 8–16-km, and 16–24-km layers (Angell and Korshover 1979) are determined from ozonesonde data at the Canadian station of Resolute (75°N), and the average of the data at the Canadian stations of Edmonton (54°N) and Goose (53°N), and their trends compared to the seasonal and annual temperature trends as a function of height in 70°–80°N and 50°–60°N bands (see Figs. 3 and 4).

Figure 9 shows that in most cases the change in the two trends with height is in accord, an obvious exception being at 70°–80°N in winter above 10 km. Table 4 presents seasonal and annual averages of the temperature trends in 9–16- and 16–20-km layers, and of the ozone trends in 8–16 and 16–24-km layers. For the period 1975–94, a decrease in temperature of 1°C decade^{-1} is associated with a decrease in ozone of about 10% decade^{-1}. To the extent that temperature and ozone changes continue to mirror one another in this way (Ramaswamy et al. 1996), the monitoring of temperature in

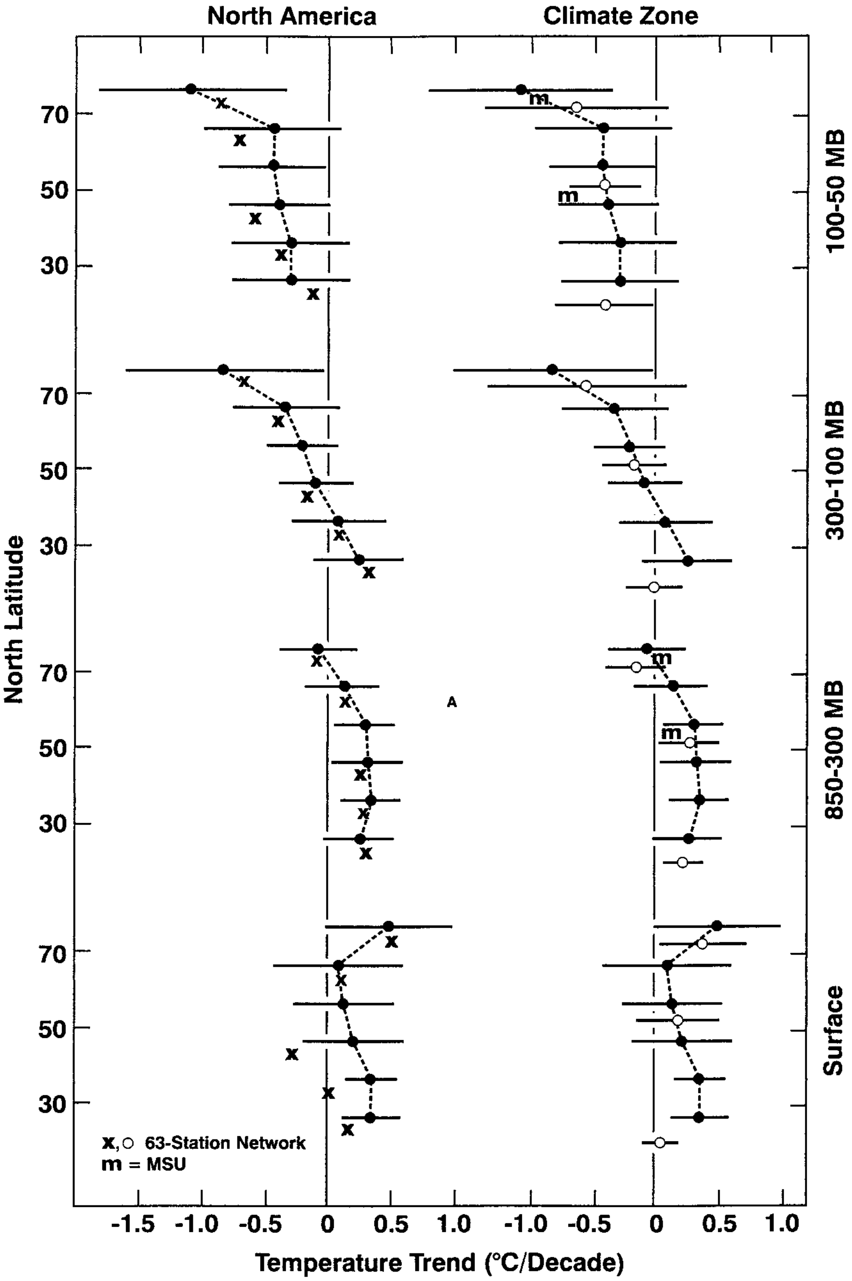

FIG. 8. The dots and connecting dashed lines show the variation with latitude of North American annual temperature trends, and two-standard-error bars, based on the 120-station radiosonde network, 1975–94. These are compared with trends based on the 11 North American stations (crosses at left with A the Annette trend) and the 32 stations (circles with error bars at right) of a 63-station global network. Microwave sounding unit (M) annual temperature trends for low stratosphere and troposphere, but for the interval 1979–96, are also shown at right.

the arctic provides a useful supplement to the monitoring of ozone.

10. Summary and conclusions

Based on the 120-station radiosonde network, the following are the main findings from this analysis of North American temperature trends in 100–50-mb (low stratosphere), 300–100-mb (tropopause), and 850–300-mb (troposphere) layers, and at the surface, for six 10° lat bands extending from 20°–30°N to 70°–80°N for the interval 1975–94. Unless otherwise stated, the findings below are for annual values and are averages for the six latitude bands.

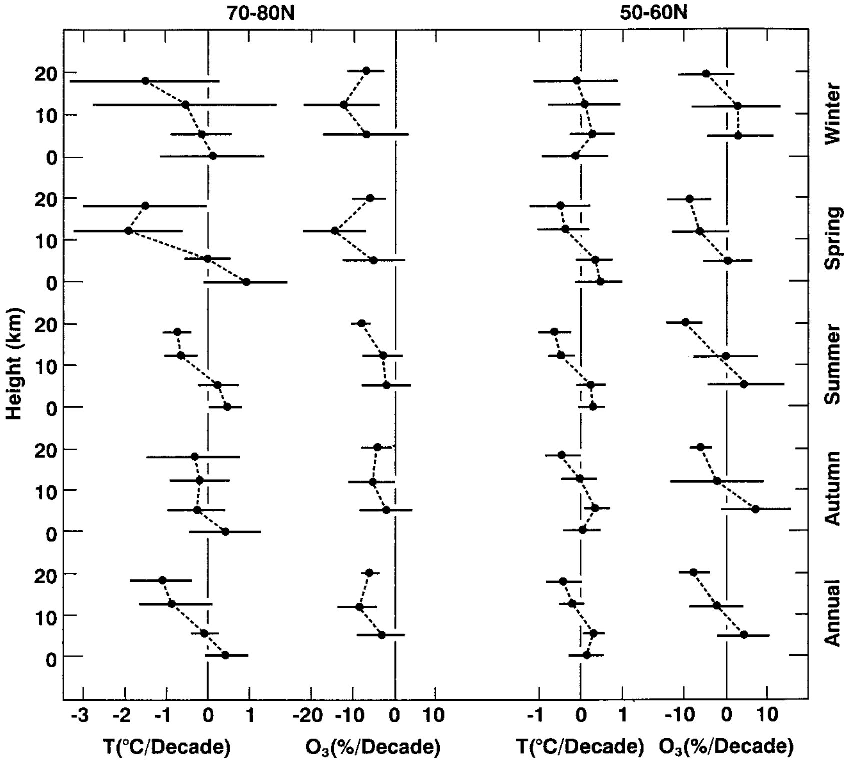

FIG. 9. North American annual and seasonal temperature trends (T in °C decade^{-1}) and ozone trends (0_3 in % decade^{-1}), and two-standard-error bars, as a function of height in 70°–80°N and 50°–60°N bands, 1975–94. Ozone trends are based on Resolute (75°N), and an average of Edmonton (54°N) and Goose (53°N), ozonesonde values.

1) The stratospheric 100–50-mb temperature trend is -0.5°C decade^{-1}, the tropospheric 850–300-mb trend is 0.2°C per decade. In the spring at 70°–80°N, the 100–50-mb and 300–100-mb layers cool by almost 2°C decade^{-1}.

2) There is a uniform progression from the 300–100-mb layer cooling by 0.7°C decade^{-1} relative to the 850–300-mb layer at 70°– 80°N to the two layers having the same warming trend at 20°–30°N. This reflects the change from the 300–100-mb layer being mostly in the stratosphere in northern climes to mostly in the troposphere in southern climes.

3) There is a systematic variation with latitude of the difference between surface and tropospheric warming, the surface warming much more than the tropospheric warming at 70°–80°N and slightly more at 20°–30°N, but less in the 40°–70°N belt. The much greater warming of surface temperature than troposphere temperature at 70°–80°N shows that surface temperature trends are not representative of tropospheric trends in the north polar region where there are strong temperature inversions near the surface.

TABLE 4. Average of the temperature trends (T in °C decade^{-1}) in 9–16- and 16–20-km layers, and ozone trends (0_3 in % decade^{-1}) in 8–16- and 16–24-km layers, of Fig. 9, 1975–94.

	Winter	Spring	Summer	Autumn	Annual
70°–80°N T	−1.1	−1.7	−0.7	−0.3	−1.0
0_3	−10	−11	−6	−5	−8
50°–60°N T	−0.1	−0.5	−0.6	−0.3	−0.4
0_3	−2	−8	−6	−4	−5

4) At the surface at the radiosonde sites, 1200 UTC (morning) temperature cools relative to 0000 UTC (evening) temperature by 0.05°C decade^{-1}, not the result found by others using the extensive surface–temperature network. The 850–300-mb temperature trends at 0000 and 1200 UTC are essentially the same. In 100–50-mb and 300–100-mb layers, the 1200 UTC temperature cools slightly relative to the 0000 UTC temperature, partly due to a change in sonde.

5) The 0.7°C decade^{-1} difference in trend between troposphere and low stratosphere increases to 0.9°C decade^{-1} when adjustment is made for the stratospheric warming and tropospheric cooling following El Chichon and Pinatubo eruptions. Over the 20-yr period, this corresponds to an increase in lapse rate of about 0.014°C $(100\ \mathrm{m})^{-1}$.

6) Except at the surface, the temperature trends based on the 11 North American radiosonde stations in a 63-station global network agree well with the trends based on the entire 120-station North American network, showing the representativeness of a small upper-air da-

taset. The trends based on the 120-station North American network agree fairly well with the zonal-average trends based on the 63-station global network and MSU.

7) Comparison with Canadian ozonesonde data shows that, between heights of about 8 km and 22 km during 1975–94, a decrease in temperature of 1°C decade^{-1} was associated with a decrease in ozone of about 10% decade^{-1}.

In conclusion, the extent to which the nearly 1°C decade^{-1} cooling of the low stratosphere relative to the troposphere over North America during 1975–94 represents evidence for an enhanced greenhouse effect is not completely clear since the low-stratospheric cooling may be partly related to ozone depletion. There is also the problem that the record is a relatively short one, the analysis is regional, and there is concern that inhomogeneities still lurk in the North American radiosonde data. It is planned to examine the latter possibility using advanced statistical techniques.

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