Stratospheric Aerosol Measurements II: The Worldwide Distribution

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ABSTRACT

Global surveys of stratospheric and upper tropospheric aerosols have been made using balloon-borne photoelectric particle counters. The natural variability observed at each flight station was small enough so that typical profiles could be identified. Data are presented in the form of latitude cross sections showing lines of constant aerosol mixing ratio. The stratospheric aerosol layer is clearly delineated as well as small transient layers in the troposphere and lower stratosphere. At high and low latitudes the aerosol mixing ratio profile apparently experiences a simple shift in altitude corresponding to the change in local tropopause height.

1. Introduction

In the spring of 1972 the University of Wyoming's Atmospheric Physics Group began a world survey of stratospheric aerosols. The program involved regular balloon soundings from several stations in the Northern Hemisphere and somewhat less frequent soundings made from a few stations in the Southern Hemisphere. In February of 1974 the field research was brought to an end with a total of nine hemispheric latitude surveys completed including two in the Southern Hemisphere. Data from this program provide benchmark information concerning the stratospheric aerosol during the time period associated with the observations. In addition, several new aspects of the 20 km aerosol layer are now apparent that have not previously been appreciated or known. In a companion paper (Hofmann *et al.*, 1975; referred to as Part I) the instrumentation was discussed in detail and results of extensive northern midlatitude measurements were presented. It is the purpose of this paper to present and discuss some of the major features of the latitude surveys.

2. Instrumentation

The balloon-borne data acquisition system employed in this program consists primarily of an aerosol detector supplemented by ozone, temperature and pressure sensors. Past experience has shown that the measurement of several atmospheric parameters is frequently helpful for correctly interpreting the aerosol profiles. The aerosol detector is a photoelectric particle counter designed for high-altitude operation. It was first employed by one of the authors in 1963 (Rosen, 1964) to measure the vertical distribution of fine particles from ground level to 30 km, and since that time has undergone several modifications to permit easy operation in the field. The counter responds to particles in two size ranges: those having diameters greater than 0.3 μm and those greater than 0.5 μm. A more complete description of the instrument, its operation and calibration are given in Part I. The ozone detector and the temperature and pressure sensors are commercially available equipment.

3. Data acquisition sites

Seven different stations in the Northern Hemisphere and four in the Southern Hemisphere have been utilized during this program. Table 1 lists these stations and their geographic coordinates. Only a few of these sites were employed on a frequent basis. Soundings from the Ice Island T-3, McMurdo, and the South Pole stations

TABLE 1. Stratospheric aerosol stations.

Station	Latitude	Longitude
Ice Island T-3	~85°N	~105°W
Barrow, Alaska	71.3°N	156°W
Ft. McMurray, Alberta	57.4°N	114.0°W
Duluth, Minnesota	46.7°N	92°W
Laramie, Wyoming	41.2°N	105°W
Palestine, Texas	31.8°N	95°W
Albrook AFB, Panama	9°N	80°W
Longreach, Australia	23.5°S	144°E
Mildura, Australia	34.2°S	141°E
McMurdo Station, Antarctica	77.2°S	167°E
South Pole Station, Antarctica	90°S	

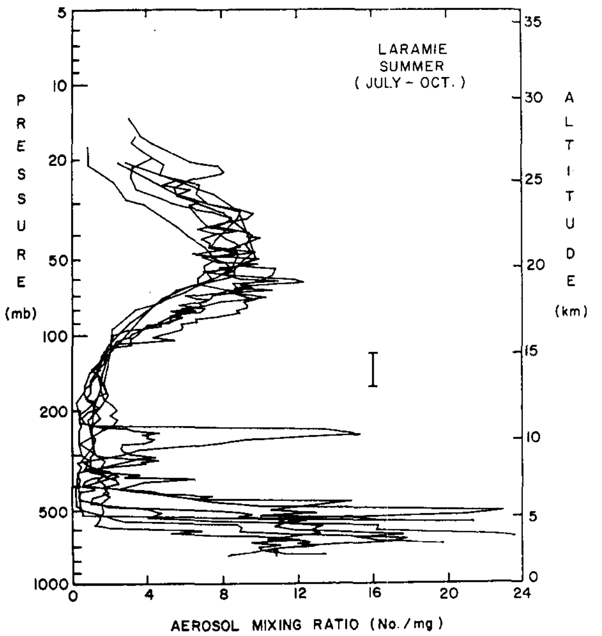

FIG. 1. Mixing ratio profiles over Laramie during the summers of 1972 and 1973. The vertical bar represents the range of tropopause heights.

were made at yearly intervals. Bimonthly soundings were conducted from Barrow, Alaska; Ft. McMurray, Canada; Duluth, Minn.; Palestine, Tex.; and Panama. One of these stations (Duluth) was only utilized for a short time, and the Ft. McMurray station was dropped after a year. Soundings at irregular intervals have been made at Longreach and Mildura, Australia. The most frequent soundings were made from Laramie at a rate of about one per month.

4. Results

Data from individual soundings have been presented in progress reports in the form of charts and tabulations (Hofmann *et al.*, 1972–73). Latitude surveys derived from individual soundings have also been reported (Hofmann *et al.*, GM 19) but without discussion.

A major first step in the interpretation of survey data is the identification of unusual or non-typical profiles. Only after some recognizable pattern is obtained can typical data be identified. The Laramie flights provide the most information for this type of study. Typical seasonal profiles have been identified and presented for the Wyoming site (Part I). For the convenience of easy reference and comparison, a composite of summertime soundings from Laramie is shown in Fig. 1. The spring soundings show a wide amount of variation near the tropopause level, whereas the summer profiles are all very similar. This is what might be expected since spring represents a time of year when atmospheric conditions are changing rapidly and are in a somewhat disturbed state. On the other hand, summer is a time of relatively stationary conditions. The fall and winter soundings also tend to show larger variations than the summer soundings, probably because the fall season is a time of rapidly changing conditions and in the winter season the atmosphere fails to reach any kind of quasi-stationary state, perhaps owing to the large latitude gradient in temperature. We have thus come to the conclusion that, for the present, summer is probably the best season to compare soundings from a large range of latitudes because the stratospheric aerosol layer appears to be in a relatively stable and uniform configuration. For this season it is apparently not necessary to conduct soundings simultaneously from all stations and there is a very high probability that any one sounding will correctly represent the average conditions for the respective site.

Soundings from high or low latitudes seem to show a lesser degree of variability than the midlatitude soundings. An identifiable typical profile emerged after only a few soundings at Barrow and Panama, whereas it took a much longer time for a consistent picture to become evident for the Laramie soundings. Fig. 2 illustrates the consistency between four soundings made at Barrow at different times of the year. These profiles of mixing ratio have been normalized to the same value at 60 mb and shifted in height slightly so that the maximum of each occurs at about 60 mb. The normalization was required due to a general decrease in stratospheric aerosol (Part I) over the period of the soundings,

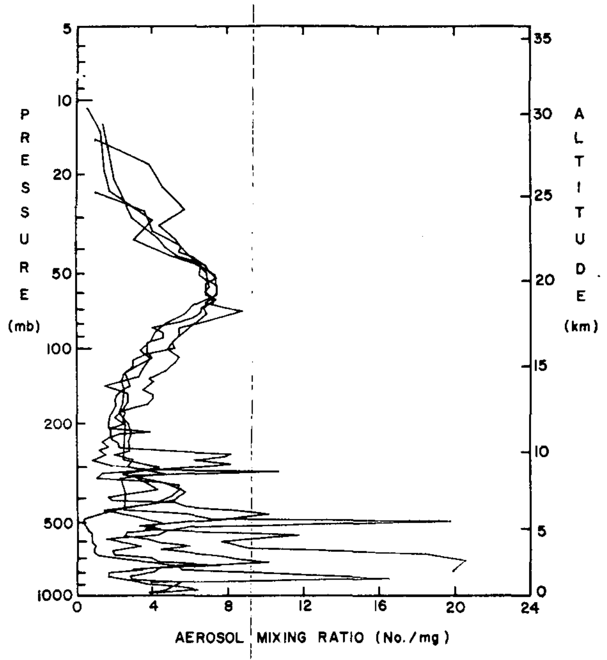

FIG. 2. Mixing ratio profiles obtained over Barrow, Alaska, covering the months of June through November. A slight normalization has been applied so that all soundings have the same value at 60 mb. In addition, the profiles have been shifted slightly so that the maximum mixing ratio occurs at 60 mb.

with the first one about 20% higher than the last. The amount of vertical shift required corresponds very closely to the difference in apparent tropopause heights. The correlation coefficient between the tropopause height and the amount of shift is 0.84. One additional Barrow sounding available is not shown in Fig. 2 because the profile is quite different and considered nontypical.

The Panama soundings have been treated in a similar manner. As in the case of the Barrow soundings, the individual profiles taken during different times of the year were shifted in altitude and normalized in concentration until a best fit was obtained. The result of this procedure is shown in Fig. 3. (One of the available profiles for this site has been left out because we consider it somewhat nontypical.) The correlation between the amount of vertical shift for the best fit and the local tropopause height is 0.82. It should be noted that a similar behavior is not apparent in the aerosol profile over Laramie, where relatively large variations in the local tropopause height may be observed during one season with no apparent corresponding shift in the aerosol profile (Part I).

Similar attempts to find typical profiles over Ft. McMurray and Palestine have been made. These stations seem to be under the influence of relatively strong seasonal variations as is the Laramie station and the amount of data available does not allow us to decisively identify typical seasonal profiles. In addition the Texas station sometimes behaves as a tropical site and sometimes as a midlatitude site.

Once typical profiles can be recognized for each site, a latitude profile can be constructed with confidence that it represents an average condition for the season in which the soundings were made. Aerosol profiles are first plotted for a particular series and then compared with typical soundings and with each other, as illustrated in Fig. 4. Individual profiles are then smoothed by hand, eliminating obvious cloud layers and the finestructure that is not present in adjacent profiles. Mixing ratio values are transferred to a latitude cross-

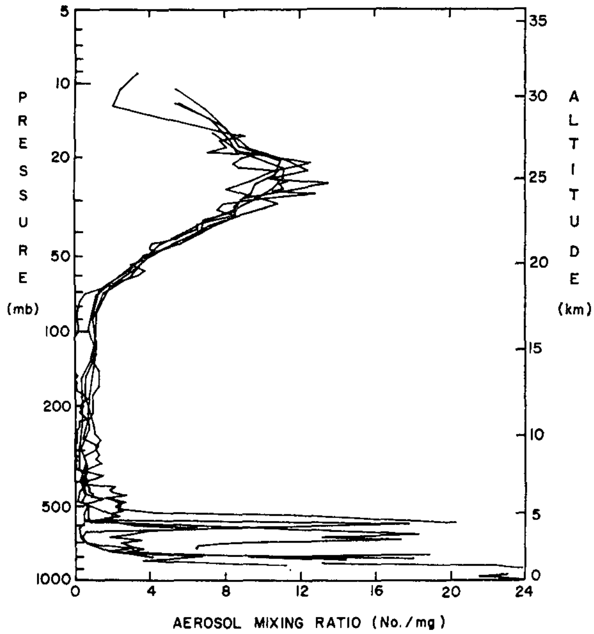

Fig. 3. Mixing ratio profiles obtained over Panama during the months of September 1972, March 1973, April 1973, June 1973 and November 1973. A slight normalization has been applied so that all soundings have the same value at the maximum. In addition, the profiles have been shifted slightly so that the maximum mixing ratio occurs at the same altitude.

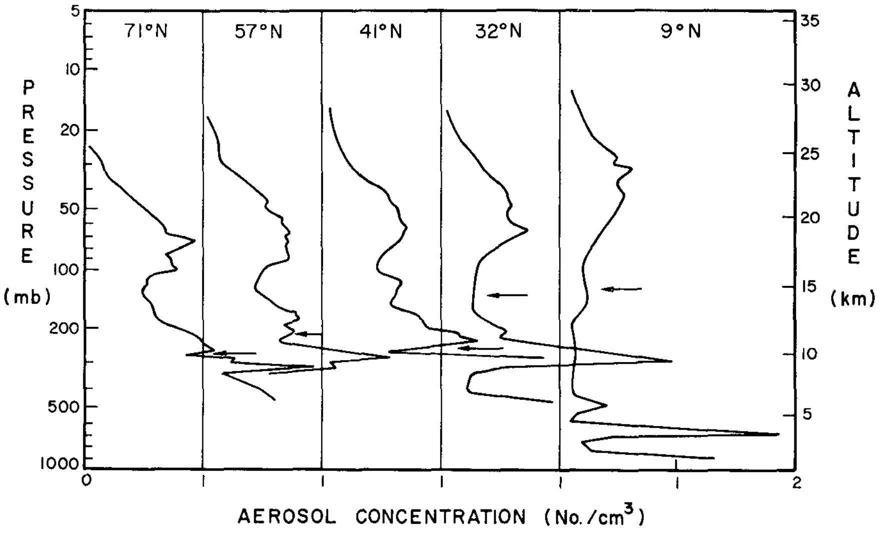

Fig. 4. A comparison of five Northern Hemisphere soundings made in June of 1973. Reading from left to right the dates of the soundings are as follows: 27 June, 19 June, 19 June, 19 June and 27 June. The arrows mark the observed position of the tropopause.

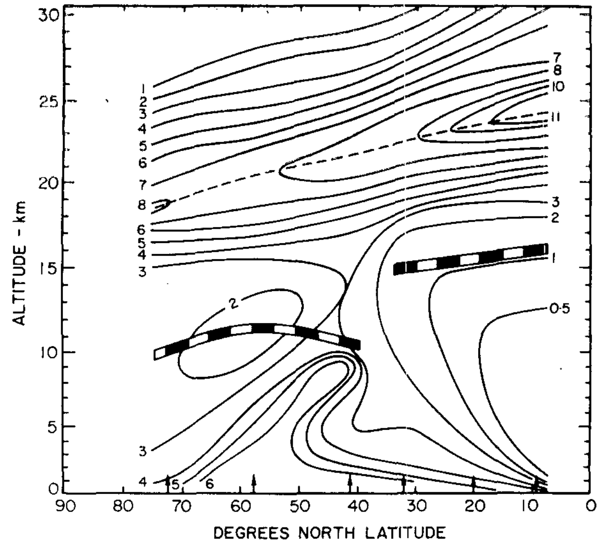

FIG. 5. An aerosol cross section made from the data presented in Fig. 4. The arrows along the bottom mark the sounding sites and the heavy broken lines represent the tropopause. The constant mixing ratio isopleths are in units of number of aerosol particles per milligram of air. The dashed line represents the maximum of the stratospheric aerosol layer.

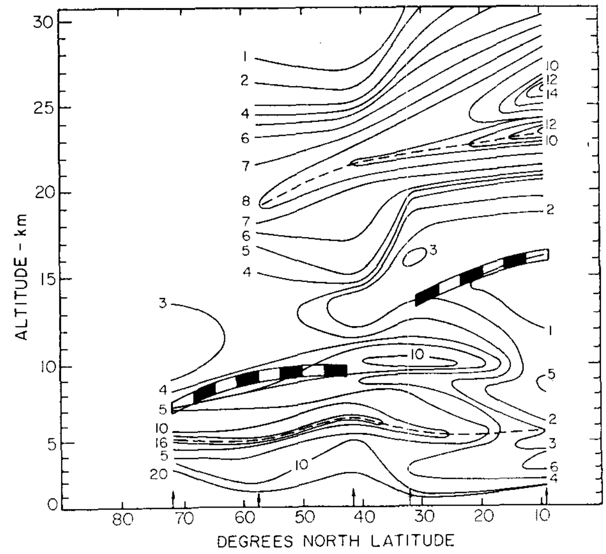

FIG. 6. An aerosol cross section for April 1973.

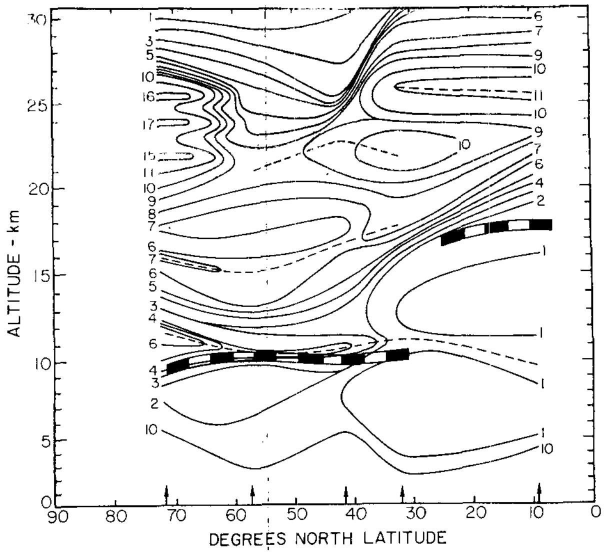

FIG. 7. An aerosol cross section for February–March 1973.

section chart and smooth curves are hand-drawn through the points, as illustrated in Fig. 5. Although these aerosol surveys also cover the troposphere, a good deal of caution must be exercised in their correct interpretation at low altitude, especially below 5 km. In this region a considerable amount of structure may be present in the original aerosol profile that is lost by the smoothing process. In some cases where adjacent profiles were similar, an effort was made to preserve the finestructure, but the resulting latitude survey should be considered somewhat speculative for the troposphere. Similar latitude cross sections are also constructed for the corresponding ozone mixing ratio and potential temperature following a similar procedure.

Mixing ratio rather than concentration is used in our analysis for several reasons. It is this quantity that is conserved in transport processes that do not involve mixing, and it is the gradient of this quantity that is important in transport by diffusion or mixing. Furthermore, in polar and equatorial regions it is the mixing ratio profile that apparently experiences a simple shift in altitude with varying tropopause height.

The amount of latitude resolution needed to obtain representative structure can be estimated from the latitude surveys themselves. If the structure size is larger than the distance between sounding sites, then adequate resolution has probably been obtained. In some cases, especially in spring, the latitude profiles show structures on the order of the site spacing indicating that the resolution may not be adequate. Unfortunately, the number of sites could not be increased under the existing constraints of the sampling program.

5. Discussion

Although the latitude survey profiles presently available are crude and perhaps somewhat inadequate, they do nevertheless suggest and illustrate some important aspects of the global distribution of aerosols. In view of the uncertainty of the lower altitude data, the discussion here will be limited to the upper troposphere and stratosphere.

Fig. 5 is believed to represent a typical summer distribution of stratospheric aerosol. Even the April survey shown in Fig. 6 is similar to this one except for the unusual double layer over Panama. In fact, all of the latitude surveys are roughly similar to the one shown in Fig. 5 except for the February–March cross section shown in Fig. 7 and the November 1974 cross section (Fig. 8). The individual soundings used to produce Fig. 7 are probably not representative because they were obtained in the early spring when the atmosphere was apparently undergoing considerable change and large latitude gradients existed. This conclusion is also supported by the fact that much of the structure has dimensions similar to the latitude spacing of the individual profiles indicating that not enough horizontal resolution is available in the basic data. In addition, the Barrow sounding was highly unusual above 15 km showing the presence of three distinct aerosol layers of relatively high mixing ratio.

The latitude surveys that are considered typical show a maximum in the mixing ratio over the equator at about 24 km decreasing to about 17 km over the poles. In addition, there is a significant latitude gradient in the value of the mixing ratio at the maximum with the higher mixing ratios being over the equator. This observation is consistent with an equatorial source but does not necessarily eliminate the possibility of other smaller supplementary source regions.

Extensive aerosol layers apparently have been observed on several occasions in the Northern Hemisphere. They usually occurred in the lower stratosphere and upper troposphere and in some cases seemed to cover a latitude range from Barrow, Alaska, to Panama (see for instance Figs. 6 and 7). The layers appear to be continuous, but more latitude coverage would be necessary to prove this beyond doubt. From individual soundings it is apparent that in the lower stratosphere an ozone layer generally appears with an aerosol layer, whereas in the troposphere there does not seem to be any recognizable structure in the ozone profile that can be associated with the existing aerosol layer. This suggests a different mechanism for the creation of tropospheric layers since they cannot simply be stratospheric-type layers that have moved to lower altitudes.

On one occasion layers at the 25 km level were observed over Barrow (see Fig. 7). It has been suggested that these could be associated with nacreous clouds but lack of supporting structure in the temperature, water vapor and ozone data and lack of repeated occurrences render these data relatively uninterpretable.

One possible source of the tropospheric aerosol layers is volcanic eruptions. In early summer of 1972, a Japanese volcano erupted, injecting a smoke cloud up to an altitude of about 9 km or approximately to the level of the tropopause. Extensive dust layers throughout the troposphere were observed that summer but no unusual increase in the concentration of stratospheric aerosols was noted. These data have been reported elsewhere (Rosen *et al.*, 1972). The layer between 5 and 6 km in Fig. 6 is probably also of volcanic origin but it is difficult to associate it with a specific eruption or volcano. An ash cloud was reported over Helgefell in Iceland on 25 January 1973, extending to an altitude of 6 or 7 km (Smithsonian, 1973a). The numerous eruptions of Asama in Japan during February, March and April 1973 produced clouds rising to 4 or 5 km (Smithsonian, 1973b).

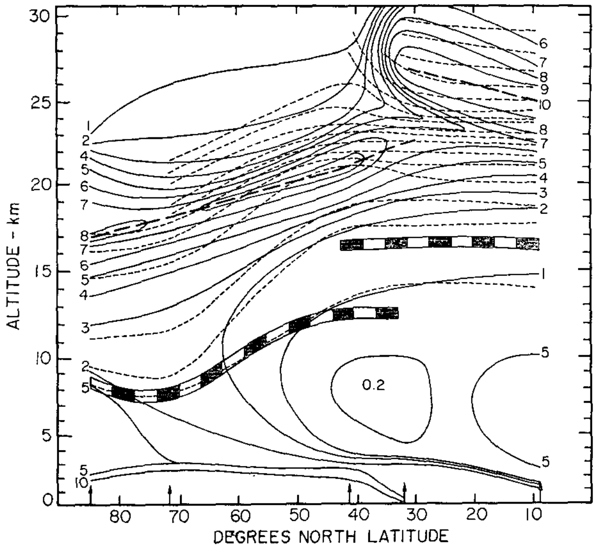

Fig. 8. A comparison of aerosol (solid lines) and ozone (dashed lines) cross sections for November 1973. The constant ozone mixing ratio isopleths were derived from data obtained simultaneously with the aerosol data.

It is believed that volcanic eruptions can go unnoticed in many parts of the world and thus give rise to tropospheric dust layers that cannot be associated with any known volcanic activity. We do not believe a large enough eruption has occurred during this measurement period to enable us to fully assess the influence of volcanic activity on the stratospheric aerosol layer.

In an effort to examine the transport of stratospheric aerosols, potential temperature and constant ozone mixing ratio charts have been made along with each aerosol cross-section survey. In regions where these three constituents are conservative, their structures should be similar or show complimentary features. However, there appears to be very little correlation between the structures of these quantities on a global scale except at times near the level of the tropopause. It should be noted that individual soundings show a great deal of similarity in ozone and aerosol finestructure in the first few kilometers above the tropopause (Rosen, 1968).

Fig. 8 is a superposition of an aerosol and ozone cross section and suggests a somewhat similar structure of these two constituents in the very lower stratosphere. At higher altitudes, however, there are regions where the ozone mixing ratio isopleths cross those of the aerosol mixing ratio at relatively large angles. In addition, constant aerosol mixing ratio isopleths are observed to be steeper than the almost horizontal isopleths of potential temperature (not shown), indicating that at least one of these quantities cannot be con-

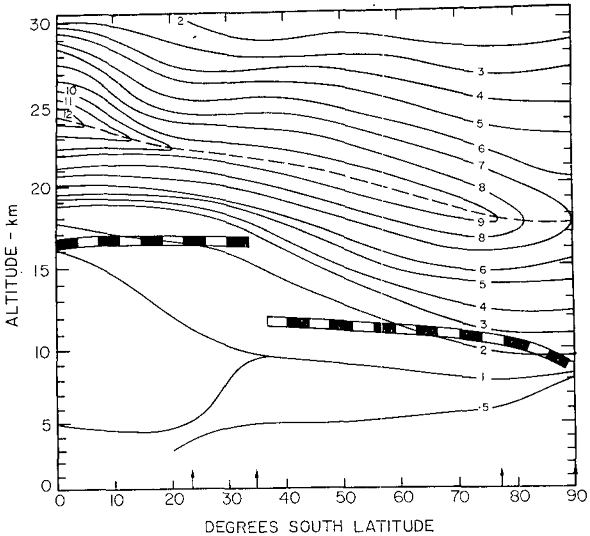

FIG. 9. An aerosol cross section obtained in the Southern Hemisphere during the 1972–73 austral summer.

sidered a good tracer for stratospheric motions. In view of the general lack of similarity in structure on a global scale of aerosol, ozone and potential temperature, we feel the usefulness of these quantities as tracers for large-scale and long-term stratospheric motions is questionable.

A latitude survey was conducted in the Southern Hemisphere during the austral summer. The soundings were made from Australia and the Antarctic and a model of the Panama soundings was used to generate an equatorial profile. The results shown in Fig. 9 indicate that there is no major difference between the Northern and Southern Hemisphere stratospheric aerosol layer. This observation may provide fairly restrictive constraints for proposed models of the stratospheric aerosol source.

6. Summary

A relatively stable configuration of the stratospheric aerosol layer apparently exists during the Northern Hemisphere summer. There is a remarkable similarity between the aerosol cross section in both hemispheres during their respective summers. The observed decrease in the maximum mixing ratio from equatorial regions to polar regions is consistent with an equatorial source of stratospheric aerosols. The tropopause height apparently plays an important role in vertical shifts in the mixing ratio profile, especially in equatorial regions. Extensive dust layers have been observed, some of which are associated with stratospheric-tropospheric exchange phenomena and others in the troposphere associated with volcanic activity.

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