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Aerosol exchange in the remote troposphere

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ABSTRACT

A series of meteorological research flights were conducted over the Pacific Ocean, Antarctica, and the Antarctic seas, during the months of October, November and December, 1977, 1978 and 1980. The route of these flights was generally along an axis most distant from the temperate continents.

Relatively high ozone mixing ratios were found over many oceanic areas, in agreement with GAMETAG observations. A minimum of tropospheric ozone was observed near the ITCZ, but ozone appeared to be advected into the tropical troposphere near the 500 mb level. The cumulus of the intertropical convergence zone are effective conveyors of aerosol, carrying enhanced aerosol concentrations to above the 200 mb level. The enhanced aerosol concentrations of the ITCZ were found to be transported into the adjacent tropical troposphere.

The greatest aerosol concentrations were found in and near the high cumulus of the ITCZ, beneath the Southern Subtropical jet, and near stratiform clouds in the southern hemisphere. The aerosol concentration diminished steadily with increasing latitude south of the southern subtropical jet, in dry air.

Uniform aerosol concentrations were observed in the Antarctic troposphere, except in the vicinity of cirrus layers aloft, and in moist or cloudy layers near the surface. Enhanced ozone mixing ratios were found in troughs about the periphery of Antarctica, and in slightly turbulent layers near mountains. Ozone and aerosol concentrations sometimes co-varied with respect to time but, no systematic variation could be shown among ozone concentration, aerosol concentration and meteorological parameters.

Ozone and aerosol concentrations observed over a wide geographic area of Antarctica were stratified into two altitude classes, and the results mapped. Ozone concentrations in the mid troposphere (550 to 400 mb levels) were small and nearly invariant over the interior of Antarctica. Ozone concentrations in the upper tropospheric (400 – 300 mb) layers varied greatly, and became quite large over troughs and about the periphery of Antarctica, and in the vicinity of high mountains. Ozone exchange appears quite vigorous in the upper troposphere and frequent aerosol exchange occurs in the lower troposphere, but the stability of the middle troposphere inhibits mixing among these levels, in agreement with the hypothesis of Oltmanns and Komhyr.

Vertical profiles of aerosol concentration indicate an aerosol decrease of 25 particles cm^{-3} Km^{-1} in clear air over Antarctica. Moist and/or cloudy air over and near the Ross and Weddell Seas is enhanced with aerosol, relative to this dry profile. Moist layers over the interior of Antarctica are also enhanced in aerosol concentration in comparison with dry Antarctic air.

1. Introduction

Particulate matter is constantly generated over most of the Earth's surface, forming an aerosol in the mixing layer. This aerosol consists primarily of sea salts over the oceans, soil dusts and organic materials over the continents, and combustion products over inhabited areas. Occasionally, intense surface heating may cause these particles to be carried to great heights immediately over the source, but more generally, meteorological processes gradually exchange the particulate ma-

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terial through the troposphere. It would be ideal to simultaneously measure many physical and chemical properties of the tropospheric aerosol, at several latitudes and altitudes to determine the transport and distribution of these physical and chemical properties in the atmosphere. Realistically, we might hope to be able to measure some bulk properties of the aerosol, at many altitudes and latitudes a few times, and identify regions of aerosol stratification, and places of vigorous aerosol exchange. This knowledge could then facilitate more extensive study of specific physical and chemical properties of the aerosol in defined exchange regions, and aid in understanding the long range meteorological transport of some materials to the polar regions.

Aitken (1923) pioneered in the study of aerosol exchange by making measurements atop hills and mountains in Scotland and the Alps. The research vessels Galilee and Carnegie (Waite, 1946), conducted aerosol studies over the world ocean, which were compiled into a map, showing the distribution of oceanic aerosols by Shiratori (1934). Landsberg (1938) extensively employed the Scholz (1932) counter to determine the aerosol concentration over the seas, as well as over extensive continental areas. Weigand appears to be the first to have reported a decrease in aerosol concentration with increasing height in the troposphere, according to Weickmann (1957). Twomey (1955) and Weickmann (1957) used aircraft to examine the variation in aerosol concentration above land, and in the vicinity of convective activity. Woodcock and Spencer (1957) used an airborne aerosol photometer to investigate the exchange and transport of sea salt nuclei, and Vonnegut (1950) first reported the development of a "continuous" (several expansions per second) nucleus counter which was capable of resolving changes in total aerosol concentration in real time, while airborne.

A great increase in the number of oceanographic ships and cruises during the 1960's expanded the opportunity for study of air/sea and continental/marine aerosol exchange. Cobb and Wells (1970) reported the first global aerosol survey since that of the Carnegie, and Elliott et al. (1974) were able to obtain multi-day records from a large number of oceanic points from Glomar Challenger. Dedicated aerosol research cruises were completed by FS Meteor (Jaenicke et al., 1971) and USNS Hayes (Hoppel et al., 1977).

Some aircraft sampling of lower tropospheric aerosol over the Pacific was accomplished by the author, as a guest of the US Naval Research Laboratory in 1970 and a major research effort was accomplished by the GAME TAG (Danielsen, 1980) program over the central Pacific. Aerosol data was collected in the upper troposphere by the NASA Global Air Sampling Program (Falconer et al. 1983) via aircraft of opportunity. This paper describes aerosol measurements in the remote troposphere conducted on three TransPacific flights, followed by three Antarctic surveys, as part of an Antarctic Meteorological Research flight series, sponsored by the US Antarctic Research Program.

The instrumentation of this aircraft and the flight protocols generally used in the experiments are given in Hogan (1979), Robinson et al., (1983), Schoenhals and Hutchins (1977), and Renard and Foster (1978). The meteorological sensors were installed by Kaman Aircraft, duplicating those of the Air Force and NOAA C130 research aircraft; the ozone instruments are duplicate Dasibi ozone analyzers, and the aerosol instrumentation used to obtain the values reported in the following sections is a photoelectric nucleus counter with diffusion battery, as decribed in Hogan et al. (1975). This aerosol instrumentation measures Aitken nuclei (AN), as the analog of total aerosol number (Vali, 1985), mean diffusion coefficient, and number of charged particles. Experimental evidence indicates that such an Aitken nucleus measurement is a good surrogate measurement of bulk aerosol properties, in the remote troposphere and over Antarctica (Hogan et al. 1984).

2. Geographic characteristics of the research area

The distribution of aerosol (AN) concentration near the surface of the seas, and over the Antarctic, is shown in Fig. 1, on Spilhaus (1942) projection. The heavy lines separate the major concentration classes. Those areas designated "I" have a mean concentration of less than 300/cm^3, and those designated "II" a mean concentration of 500/cm^3 or less. The areas between the class II

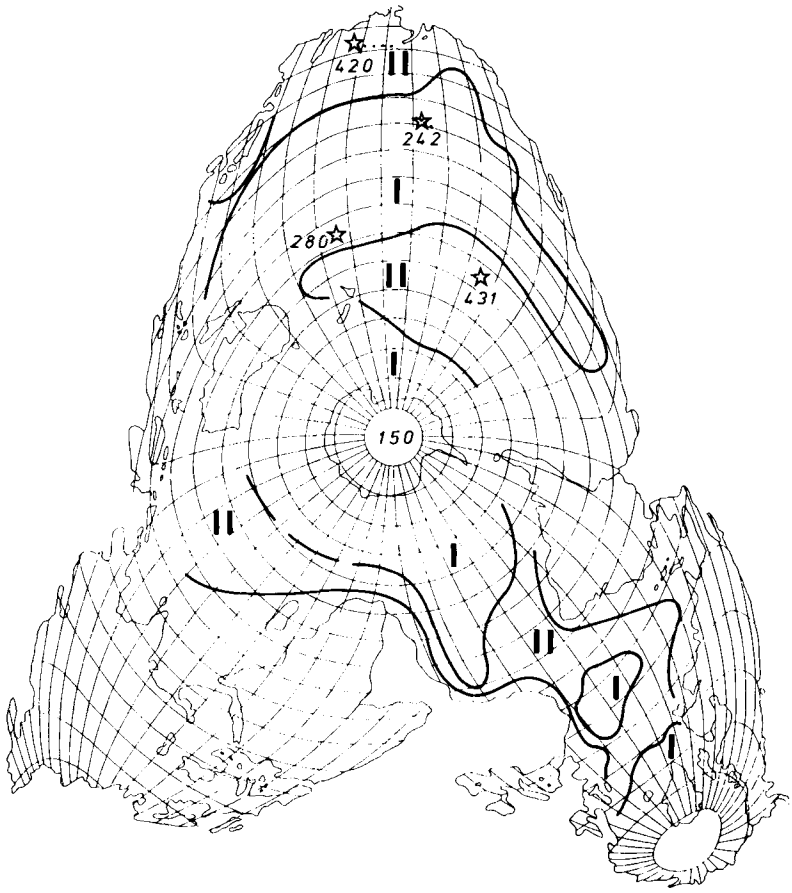

Fig. 1. Mean Aitken nucleus concentration over the seas, from Hogan (1977) on Spilhaus projection. Concentrations of less than 300/cm^3 are designated by (I), less than 500/cm^3 by (II). The stars show island locations with one year or more of data, and the adjacent number of the mean concentration measured at the island.

isopleth, and the continental outline, frequently receive continental aerosol on offshore winds and have average concentrations of 500/cm^3 to 2000/cm^3.

The starred locations designate island stations where one year or more of observations were obtained. The mean concentration, in number per cm^3, is noted at each location. The mean value of 150/cm^3 noted over Antarctica, is a summer season average, for comparison with the flight data to be reported.

The plotted isoplethes in Fig. 1 were transferred from Hogan (1977) and are essentially in agreement with a similar presentation given by Podzimek (1980). Examining these isoplethes, with knowledge that the Spilhaus projection is an equal area projection, shows that "maritime" (AN) concentrations of less than 500/cm^3 are dominant over the surface of the earth. The tracks of the several research flight missions reported in this paper are shown in Fig. 2, which represents 46% of the earth's area. These tracks cross the major features of the global circulation system (Hadley cells, intertropical convergence, subtropical jet, polar front jet) at great distances from the continents.

3. Transects of the Hadley cells

The TransPacific flight routes used to reach Antarctica during October and November of 1977, 1978 and 1980, began at Pt. Mugu, CA, and followed great circles to Oahu (HNL), American

Samoa (PGO), Christchurch, New Zealand (ZCH), and McMurdo, Antarctica (ZCM), as shown in Fig. 2. The meteorological conditions, aerosol concentration, and ozone concentrations observed in and about the Hadley cells on one flight during October 1980, are shown in Fig. 3. The temperatures shown are potential temperatures and the plotted line is broken at each altitude change. Flight altitude varied from 5 to 8 km over these tropical legs of the route, and was always in the troposphere. Aerosol (AN) concentrations are expressed as though pressure corrected to the 1000 mb level; ozone concentrations are in ppm volume mixing ratio. This allows comparison of temperature, aerosol, and ozone concentration measurements made at several altitudes.

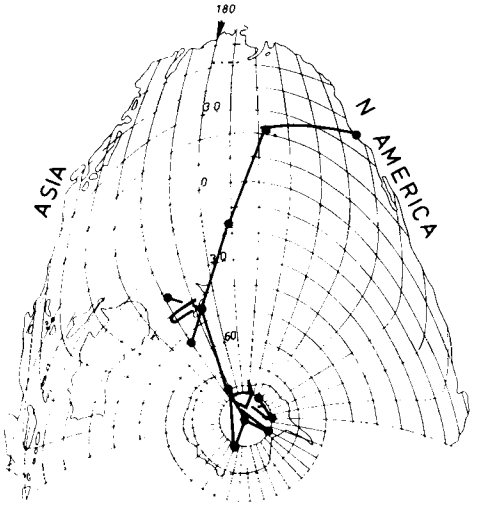

Fig. 2. The Pacific Basin and Antarctica on Spilhaus projection. Routes of research flights are shown by the heavy lines.

The wind flags shown are derived from the airplane's air data computer. A pennant represents 25 m s^{-1}, each full wind barb 5 m s^{-1} and half barbs 2.5 m s^{-1}. The flight pressure level in millibars of each leg is shown above the wind flags. Large cumulus turrets were encountered near the ITCZ, and heavy clouds were near a weak front at 15S. Measurements made in cloud are noted by circles about the temperature trace.

Easterly (off shore) winds were encountered for

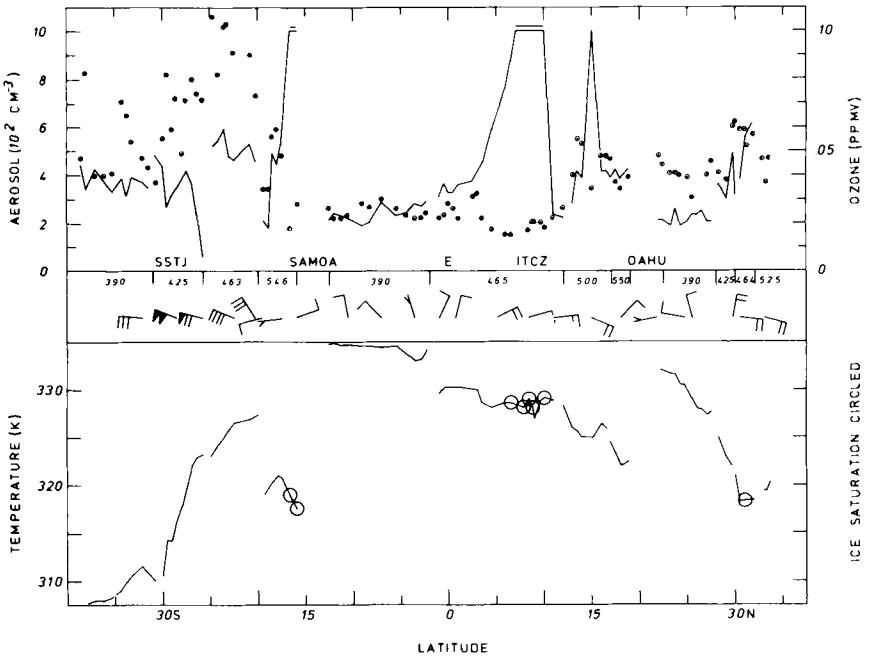

Fig. 3. A transect of the Hadley cells obtained during October 1980. Potential temperature at flight altitude is shown in the lower panel. Aerosol concentration is plotted, ozone concentration shown as points in the upper panel. Breaks in the plotted lines indicate altitude changes. Observations made in cloud, or in ice saturated air, are circled on the temperature plot.

a few hundred km off the coast of North America. Upon crossing the 30N parallel, potential temperature increased with decreasing latitude on entering the dry air and weak tropospheric winds of the Hadley circulation. The aerosol (AN) concentrations measured are comparable to the mean surface aerosol concentrations shown in Fig. 1, and with those measured above the trade inversion in the vicinity of Mauna Loa (Hogan, 1976).

About 16 hours elapsed between landing and take-off at Oahu, beginning a southerly course for Samoa. Somewhat greater aerosol concentrations were encountered above convective cells north of the ITCZ, and AN concentrations in excess of 2000/cm^3 accompanied towering cumulus and cumulonimbus near the ITCZ. These particles were carried into drier air south of the ITCZ by the northerly winds at flight altitude. The aerosol and ozone concentrations appear to have an out of phase relationship near the ITCZ.

A similar out of phase relation was found between ozone and aerosol (AN) concentrations while exiting the Hadley cell north of the southern subtropical jet (SSTJ). Temperature and ozone concentration varied considerably near the SSTJ, but aerosol concentration remained fairly constant, at values comparable to those at the surface as shown in Fig. 1. This may indicate that Austral spring exchange processes disperse near surface aerosol through the troposphere above the seas.

The general trends in ozone and aerosol concentration indicate a weak advection of ozone into the Hadley cell region from the north, at about the 500 mb level. A sharp transition in aerosol and ozone concentrations above a front, equatorward of the southern subtropical jet was also found in October 1977. This evidence suggests that the SSTJ might define an aerosol and ozone boundary during southern hemisphere spring.

4. Transects of the southern hemisphere Ferrel cell and Polar Front Jet

Results of a transect of the Southern Polar Front Jet, from this flight series were presented by Hogan (1981a). A reanalysis of the wind, temperature and ozone observations of the 12 Nov 77 transect of the jet is shown in Fig. 4. These results are very similar to those of Danielsen and Mohnen (1977), obtained during a jet transect in northern hemisphere spring. The latitudinal variation of wind speed, potential temperature, and ozone mixing ratio from Hogan (1981a), are shown in the lower panel of Fig. 4. The maximum wind speed was encountered at 59°S, and all strong winds were from NNW direction. The data were separated and ozone mixing ratios are plotted against concurrently measured potential temperatures, for observations made (cold side) poleward of the jet maximum, in the upper left panel of Fig. 4. Ozone mixing ratios are similarly plotted against potential temperature for observations equatorward (warm side) of the jet maximum in the upper right panel of Fig. 4.

The ozone concentration and potential temperature seem linearly related in the left panel on Fig. 4. Such a linear relationship among potential temperature and ozone might exist if two adjacent atmospheric layers, differing in ozone concentration and potential temperature, were being mixed without diabatic heating or cooling processes. Perfect linearity in the relation would indicate conservative mixing of the two layers.

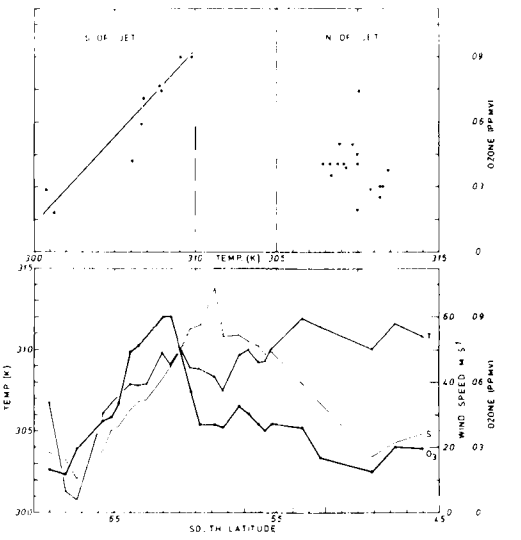

Fig. 4. Jet stream transect of Hogan (1981a) in lower panel. Upper panels show relation of ozone and potential temperature poleward of jet on the left side and equatorward of jet on the right side. *T* denotes potential temperature, *S* wind speed and *O* ozone concentration.

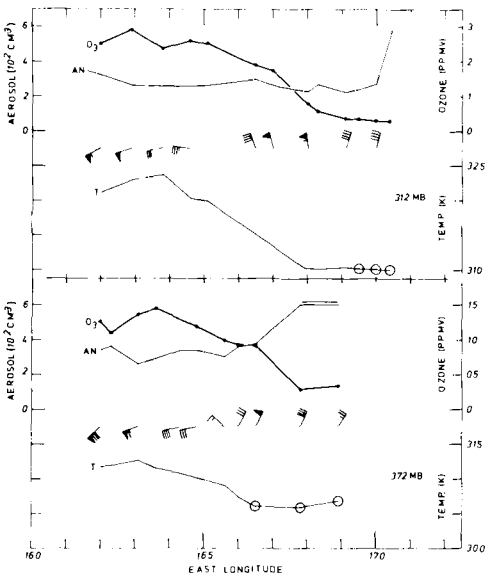

Fig. 5. An east-west profile beneath a jet, over the Tasman Sea, 18 October 1980. Observations made in stratiform cloud or ice saturated air are circled. The double line indicates aerosol concentration (AN) greater than full scale on the sensitive detector used.

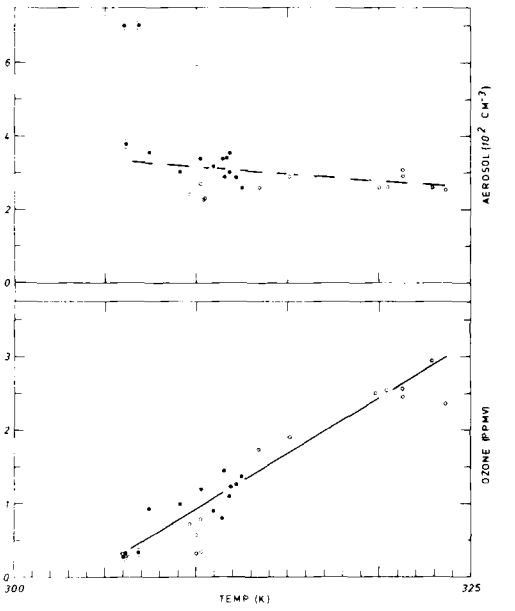

Fig. 6. Aerosol concentration and ozone mixing ratio from Fig. 5, plotted as a function of potential temperature. Observations in cloud or ice saturated air are again circled.

An east-west transect of the southern polar front jet was conducted on 18 Oct 1980, along the 42S parallel. The techniques of Danielsen and Hipskind (1980) were used to predict the location of descending stratospheric air in this area. The aircraft flew westward at a pressure level of 372 mb crossing a maximum ozone concentration of 0.50 ppmv at 164E. The aircraft climbed to the 312 mb pressure level at 162 E where an ozone mixing ratio of 0.30 ppmv was encountered.

The data from this east-west transect are shown in Figs. 5 and 6. The circled temperatures in Fig. 5 indicate observations made in As clouds at 372 mb, and Cs clouds at 312 mb, at the east end of the transect. The maximum aerosol concentration is found in the cloudy area at both altitudes. The trend in ozone concentration with respect to potential temperature seems similar at both altitudes in Fig. 5. Ozone mixing ratio and aerosol (AN) concentration are plotted against concurrently observed potential temperatures from these transects in Fig. 6. Points observed at 312 mb are shown as open circles, and those observed at 372 mb are shown by solid circles, with points observed while in cloud enclosed by a larger circle. There is a fairly linear relation among the several observations of ozone mixing ratio and potential temperature. There is little change in aerosol (AN) concentration with respect to altitude or potential temperature change.

Several similar experiments were conducted over the Tasman Sea in Austral spring 1977, 1978 and 1980, where Danielsen's techniques were used to forecast intrusion of stratospheric air into the troposphere. It was possible to isolate areas of similar linear relation between ozone concentration and potential temperature in these experiments as well. This indicates that, over the marine hemisphere, where little continental interference occurs, there are frequent events where adjacent atmospheric layers exchange quantitatively and conservatively with respect to ozone and potential temperature. The small variation in aerosol (AN) concentration concurrently observed is evidence for an extremely homogeneous aerosol population throughout the troposphere and lower stratosphere in this geographic area.

5. Transects of Antarctica from 75–90°S

Antarctica acts as a large, ice covered, aerosol sourceless object, over which air is advected, and

aged, to reach an endpoint with respect to temperature, and aerosol concentration. While not perfect, Antarctica probably presents the most ideal area available on this planet, to test meteorological (Lettau, 1971) and atmospheric aerosol theories, with a minimum of possible contamination of the experiment.

These flight experiments were based at the U.S. Antarctic station, at McMurdo Sound. Meteorological data, forecasts, and satellite information was available through the Meteorological Office of the Naval Force Antarctica. Many members of the Meteorological Detachment cooperated in these experiments (Renard and Foster, 1978), and general flight protocols were given in Hogan (1979).

The initial goals of this meteorological research program were to determine the vertical profile of atmospheric structure, aerosol and trace gases over the Antarctic seas, the ice shelf, and the polar plateau, and to measure the gradients in any of these quantities at several altitudes over the Antarctic ice mass. Antarctica is divided into a high polar plateau, and a lower plateau and ice shelf by the TransAntarctic Mountains (locations of these stations and features are given in Fig. 12). The initial (Hogan, 1979) series of Antarctic research flights obtained profiles from the ice shelf near McMurdo across the TransAntarctic Mountains and the plateau to South Pole. Another profile was obtained along 80°S latitude over a tropospheric trough seaward of the Mountains. During the second (1978) series of experiments, vertical profiles were made over sea, shelf and plateau and long transects were made across the plateau and lower ice. The initial goals were achieved, and additional exchange features were observed through serendipity (Robinson et al. 1983).

A transect along 165°E longitude from the vicinity of McMurdo Station at 75°S to South Pole at 90°S begins over sea ice or open water, crosses permanent shelf ice of similar elevation, and then crosses the TransAntarctic Mountains and the Polar Plateau. There are about 5 degrees of latitude of each surface condition below the flight path.

There is no meteorological station along the route, but upper air soundings are regularly taken at South Pole (NPX) and McMurdo (ZCM) near each end of the route. Wind and temperature observations from the aircraft enroute can then be used to construct an isentropic cross section over the transect, as shown in the center panels of Fig. 7, which illustrates a typical flight profile, obtained 8 November 1977.

The southbound leg was conducted at 450 mb and the northbound leg at 390 mb. Although winds are generally light, and the air quite cold all along the flight route there is a wind shift indicative of a weak front near 82°S latitude. This "front" is often marked by gentle turbulence, noticeable in flight. A chronology of navigators' reports from this route during 1980 showed a wind shift in this area on over 50% of occasions (M. S. Foster, personal communication), indicating a persistent boundary between interior Antarctic air, and slightly warmer air.

The latitudinal variation of frost point depression (T) aerosol concentration (A) and ozone mixing ratio (O) are shown for 450 mb in the lower panel and for 390 mb in the upper panel of

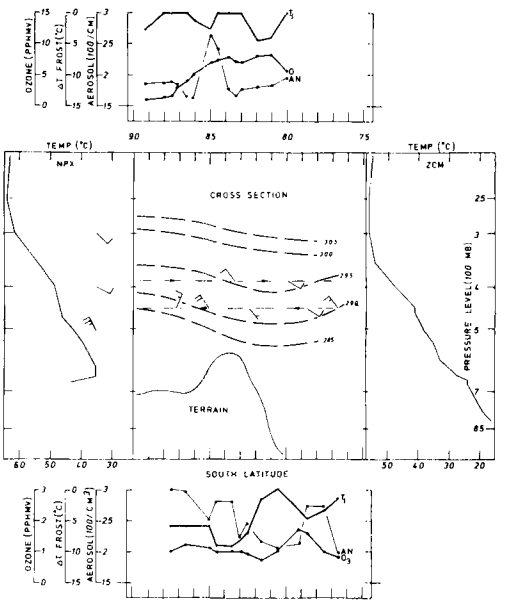

Fig. 7. Transects from near McMurdo (75°S) to South Pole and return, 8 November 1977. Approximate terrain height is shown beneath the flight paths and concurrent soundings are shown in the left and right panels. Isentropes and wind along the flight route are shown in the center panel. *T* denotes potential temperature, *O*, ozone concentration, and *A*, aerosol concentration. This figure illustrates the meteorological analysis applied to the Antarctic data.

Fig. 7. This figure illustrates the meteorological analysis used to prepare the data presented in subsequent sections.

The aerosol and ozone concentrations observed at the flight levels above 400 mb on three similar flights are plotted against the concurrently measured potential temperature in Fig. 8. Also shown are data from a flight at similar altitude, over a trough at a constant 80S latitude over the Ross Ice Shelf on 11 Nov 1977 (Hogan, 1979). The linear relation among ozone concentration and potential temperature found over the Ross Ice Shelf trough is similar to that found over the Tasman Sea 18 Oct 1980, shown in Figs. 5 and 6. The small concurrent variation in aerosol concentration is also similar to that observed over the Tasman Sea.

It is a reasonable hypothesis that quantitative and conservative mixing may have been occurring between two layers on 10 and 11 November. The mixing and exchange of 7 and 8 November seems more complicated, involving several layers. This may have been locally forced mixing, induced by the TransAntarctic Mountains. The wide range of aerosol and ozone concentrations observed on 7 and 8 November are evidence that

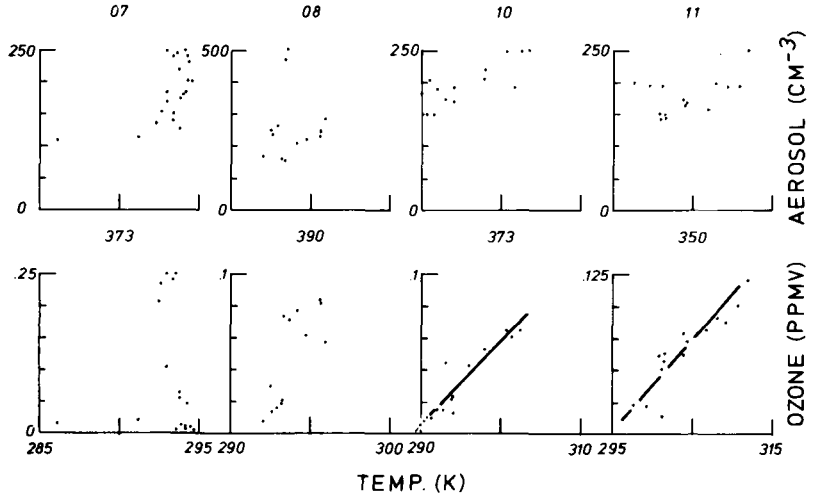

Fig. 8. Aerosol concentration and ozone mixing ratio versus potential temperature over 75 to 90°S, 7 to 11 Nov 1977. The flight of 11 November was above a trough over the Ross Ice Shelf, along 80°S latitude. Pressure levels are centrally noted.

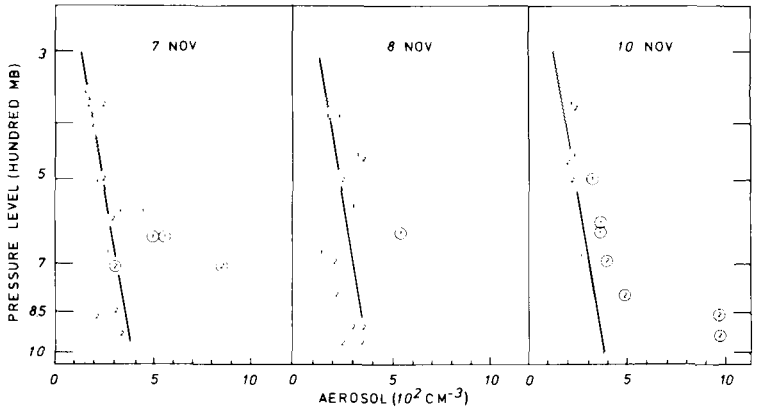

Fig. 9. Vertical profiles of aerosol concentration over the South Pole (1) and McMurdo Sound (2). Circled values were obtained in cloud or ice saturated air. the slopes of the plotted lines are $-25/cm^3/Km$.

fairly vigorous exchange was occurring, even though the lapse rates obtained from the NPX and ZCM soundings indicated stability in the layers near the flight level.

The flights of 7, 8 and 10 November 1977 were terminated by vertical profiles over McMurdo Sound and the polar plateau. The vertical variation of aerosol (AN) concentration on these days is shown in Fig. 9. Data points obtained over the polar plateau are noted by 1 and data points obtained over McMurdo Sound are noted by 2. Observations made while in cloud (usually ice crystals at South Pole, and stratus or strato cumulus at McMurdo Sound) are circled. The aerosol concentration observed at each pressure level is quite similar on each day, unless a cloud layer is present.

All aerosol concentrations are expressed as equivalent 1000 mb concentrations as previously explained. The slope of the plotted line is -25 cm^{-3} Km^{-1} indicative of a steady decrease in concentration with increasing distance above the surface. The circled values are generally greater than the uncircled values, indicating humid air is richer in aerosol (AN) than dry.

The general trend in these observations indicates a rather homogeneous distribution of aerosol material through the dry Antarctic troposphere. The aerosol concentration most generally increases concurrently with the presence of moist or cloudy air.

6. Additional aerosol soundings over Antarctica

Vertical profiles of meteorological parameters, ozone, and aerosol (AN) concentration, were measured over the open water of the Ross Sea, and directly south of that point over the Ross Ice Shelf, at the foot of the TransAntarctic Mountains, in November 1978. The data from these profiles is shown in Fig. 10. The surface wind over the Ross Sea was relatively light, and the surface was roughened by swells but not breaking waves. Stratus and strato cumulus were present in a layer 0.45 to 1.0 km above the surface, and thin Cs (a visible ice crystal layer) was present above 8 km. The winds were northly at all altitudes over the open sea, carrying this air over the ice shelf.

Aerosol concentrations were quite variable at

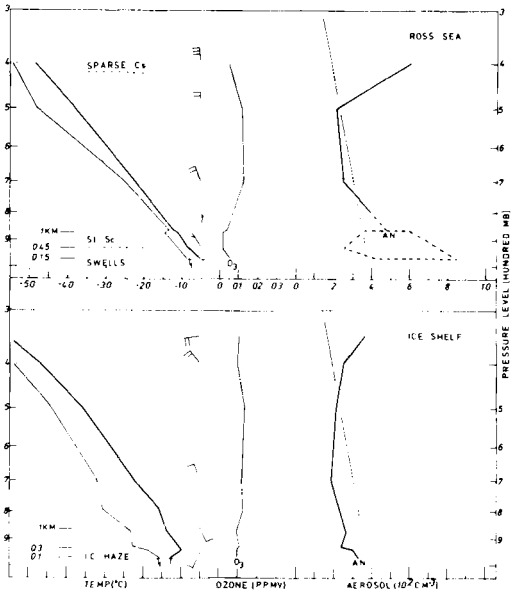

Fig. 10. Vertical profiles of aerosol (AN) ozone concentration, temperature, dew point temperature and wind, over the Ross Sea, and 500 km downwind, over the Ross ice shelf, November 1978. The dashed lines enclose the range of concentrations found near the sea surface. The bars at 0.15, 0.45, and 1 km denote geometric height above the sea surface.

0.15 Km above the surface and at cloud base, 0.45 Km above the surface, similar to later findings (Hogan et al., 1984) at similar latitude over a steaming lead in the Arctic. An aerosol concentration of 400 to 600/cm^3 was found at cloud top level, 1 km above the sea surface. The range of observations is enclosed by broken lines in the upper panel of Fig. 10. The aerosol concentration rapidly decreases above the marine mixing layer, and approximates the tropospheric concentrations shown in Fig. 9, in the 700 mb to 500 mb layer. The aerosol concentration increased just beneath, and in, sparse Cs at the 400 mb level.

Aerosol (AN) concentration decreased with increasing latitude at the 400 mb level, and was one half of the initial concentration when a descending vertical profile was begun over the Ross Ice Shelf. The aerosol concentration diminished, with decreasing altitude to the 700 mb level. Aerosol concentrations below 700 mb, and above an ice crystal haze at 0.1 Km approximate those of Fig. 9.

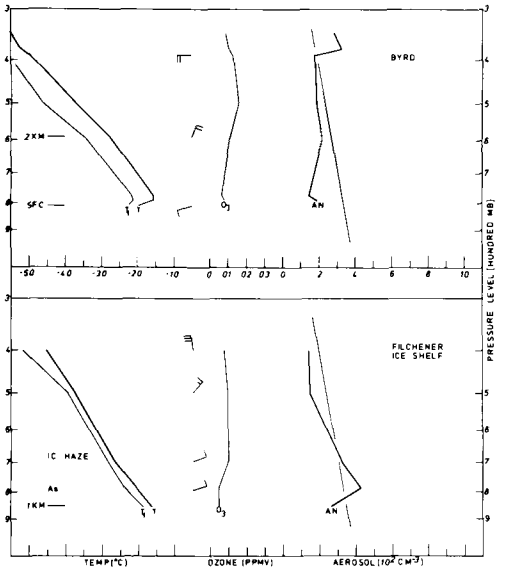

Fig. 11. Vertical profiles of Byrd Station, December 3, 1978 and the Filchener Ice Shelf, November 1978, as in Fig. 10. The surface at Byrd Station coincides with the 810 mb level. The descent ceased at 1 km above the surface over the Filchener ice shelf.

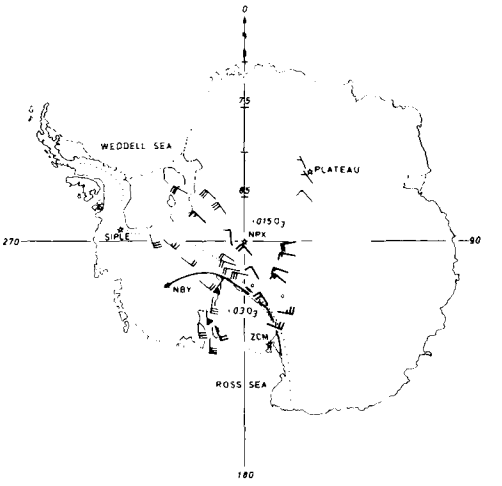

Fig. 12. Winds and maximum ozone concentrations in ppm volume observed over Antarctica, below the 400 mb level. The location of the observation coincides with the base of the wind flag. The dots indicate alignment of the TransAntarctic Mountains.

It would appear that aerosol was advected from the Ross Sea to the base of the TransAntarctic Mountains, over the Ross Ice Shelf. The former cirrus layer subsided and dried while passing over the ice shelf, enhancing the aerosol concentration in the mid to upper troposphere.

Additional vertical profiles shown in Fig. 11 were obtained over Byrd station in East Antarctica on 3 December 1978 and over the Filchener Ice Shelf, poleward of the Weddell Sea, in November 1978. The Byrd station aerosol concentration approximates those in Fig. 9 below the 400 mb level. The sounding obtained on a relatively clear day over the Filchener ice shelf again shows evidence of an enhanced aerosol concentration in relatively moist air, below the 500 mb level.

7. A compilation of Antarctic aerosol data

Nearly 250 hours of meteorological research flights were completed, over Antarctica during late October 1977, November 1977, November 1978, and early December 1978. The surface of the polar plateau is generally above the 700 mb level, and transcontinental transects were flown at pressure levels above 541 mb (5 km in the standard atmosphere). The highest transect segment was conducted at the 285 mb level (9.5 km).

The data from the transects were stratified, separating those in the mid troposphere (541 mb to 410 mb) from those in the upper troposphere (410 to 306 mb) and the meteorological and ozone data were compiled in map form. Aerosol (AN) concentrations were very consistent, and are not plotted on the maps. Fig. 12 shows the winds and maximum ozone mixing ratios observed over Antarctica at flight levels below 410 mb. The flight routes can be reconstructed by connecting the bases of the wind flags.

It is apparent from Fig. 12 that the mid tropospheric winds, over the Antarctic plateau, interior of the TransAntarctic Mountains were of relatively uniform speed and direction over the duration of these experiments. Stronger and more variable winds were observed exterior of the Mountains over the Ross Ice Shelf and Marie Byrd Island.

The arrow in Fig. 12 defines "Grid North" as the Greenwich Meridian. The mid tropospheric wind over the Antarctic plateau is then a "north westerly," flowing from the Weddell-Sea — Atlantic sector across Antarctica towards Australia. Low pressure systems frequently intrude over the Ross Sea and Marie Byrd Island, bringing stron-

ger winds of variable direction. The persistence of winds from NW, in the middle troposphere over the interior is in agreement with the climatology of south pole winds prepared by Samson (1983).

Fig. 13. Winds and maximum ozone concentrations in ppm volume observed over Antarctica between the 400 mb and 300 mb level, in the same format as Fig. 12. Duplicate observations are not plotted in either figure.

The maximum ozone mixing ratio observed over the interior of Antarctica at these flight levels was 0.015 ppmv. Ozone mixing ratios of 0.015–0.030 ppmv were found over troughs and near the TransAntarctic Mountains. The heavy line plotted in Fig. 12 separates these two classes of ozone concentration.

Winds and maximum ozone concentrations measured at flight levels above 410 mb are shown in Fig. 13. The northwest quadrant shows minimal ozone mixing ratios of <0.015 ppmv; the eastern polar plateau is also characterized by relatively small ozone concentrations of <0.030 ppmv. Relatively high ozone mixing ratios of 0.090 ppmv were found over the Ellsworth Mountains (Robinson et al. 1983) over a trough above the Ross Ice Shelf, and over the TransAntarctic Mountains adjacent to the Ross Ice Shelf.

All of the aerosol and ozone measurements made above the Antarctic ice in 1977 and 1978 were stratified by pressure altitude, and are plotted at 0.2 km increments in Fig. 14. The number of observations at each pressure level is noted at the level. The horizontal bars correspond to the range of aerosol concentration and ozone

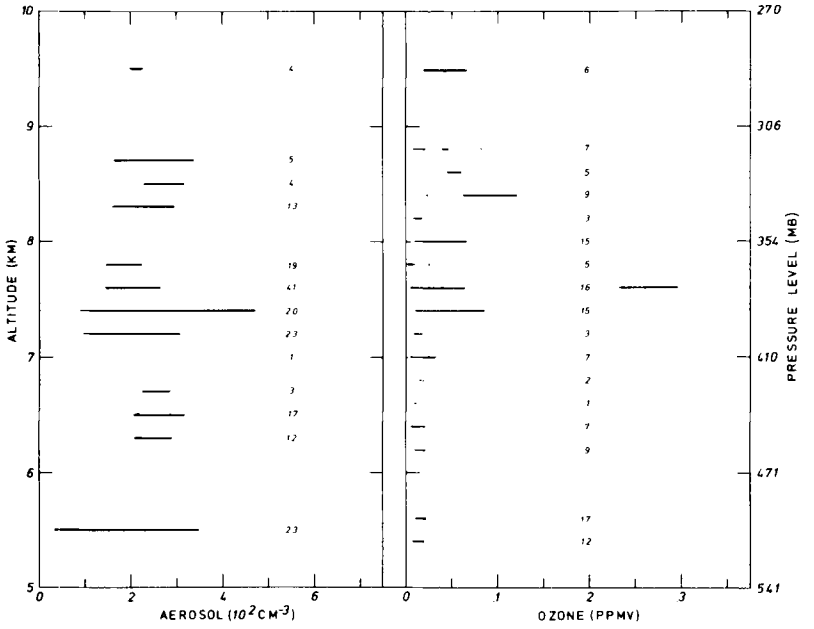

Fig. 14. Range of aerosol and ozone concentrations in ppm volume observed over Antarctica, plotted at the level observed. All data collected south of 75° latitude during 1977 and 1978 are shown. The narrow range of aerosol and ozone concentrations observed in the 6 to 7 km layer indicates that this stable layer isolates the more vigorously exchanging layers above and below it.

mixing ratio observed over several flights and/or at several points along a constant level transect. Single observations are shown as points as in the 7 km level aerosol data; scattered data is shown as line segments and points as in the 8.8 km ozone data. Different data recording techniques allowed stratification of the 5 to 6 km ozone data obtained above and below 500 mb, but forced pooling of 5 to 6 km aerosol data. The aerosol (AN) data is again expressed as equivalent concentration at the 1000 mb pressure level.

Examining Fig. 14 indicates a wide range of aerosol concentration in the 5 to 6 km layer, and a similarly wide range of values in the 7 to 8 km layer. There is little variation in ozone or aerosol concentration in the 6 to 7 km layer. This indicates that deep exchange is inhibited by the stability of the troposphere in the 6 to 7 km layer.

8. Latitude and altitude variation of aerosol concentrations

The data obtained during the TransPacific and Antarctic flight experiments at several latitudes and altitudes has been compiled to complete the survey of aerosol exchange in the several circulation regimes. Each leg of the TransPacific flights of this series are normally of 8 or more hours duration for the LC130R aircraft used. As this flight time approaches the endurance of the aircraft, most flight levels over the Pacific were selected on the basis of fuel economy, which confined measurements to 5 to 8 km above the surface between 30°N and 30°S latitude. Research flights over the Tasman Sea, and Antarctica, were flown at many altitudes, from the surface to the aircraft's ceiling of about 10 km. The flight level coinciding with an air temperature of −54°C was the limiting altitude in all cases.

The flight observations of October 1977, November 1978, and October 1980, along the flight paths of Fig. 2, were first stratified by pressure level, into 1 km thick altitude bands. The clear air observations (not in cloud, humidity less than ice saturated) were then segregated into 5 degree latitude increments and the mean aerosol concentration in each 1 km layer was, calculated. The mean and extreme values of aerosol concentra-

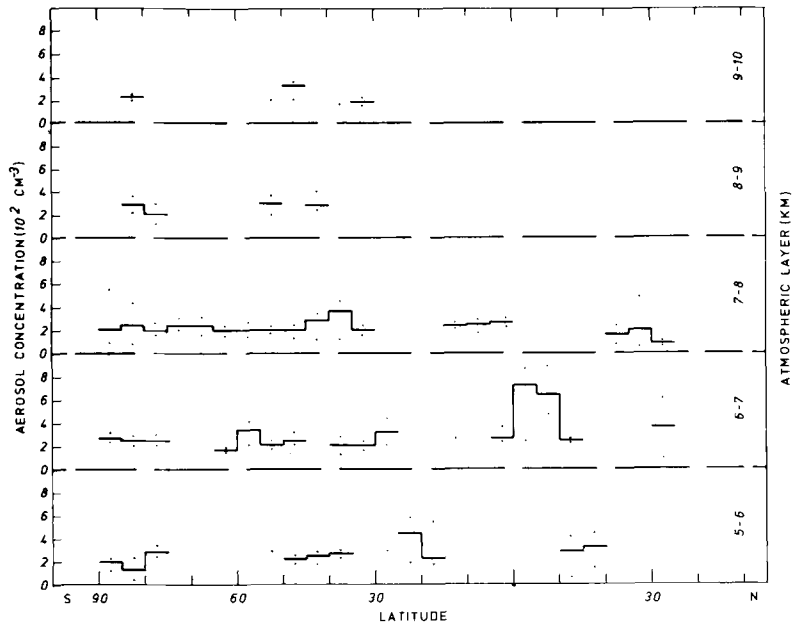

Fig. 15. Clear air aerosol concentrations, stratified by flight level and latitude, from the flights of 1977, 1978 and 1980. All data were collected above the trade inversion and below the tropopause.

tion in each altitude/latitude category are plotted in Fig. 15. These data are limited to the clear, dry air, observations, and as such represent a homogeneous condition for a cross section of the many meteorological regimes.

Some interesting features of this figure are the maximum mean aerosol concentration observed at 6–7 km over the ITCZ, a less pronounced maximum in the layers from 5 to 8 km near the southern subtropical jet at 25–30°S latitude, and the gradual decrease in mean aerosol concentration with increasing south latitude in the 5–6 km layer. It would appear from this figure that aerosol enters the troposphere in the vicinity of the intertropical convergence, and around fronts near the southern subtropical jet at the limit of the Hadley cell, and then spreads through the troposphere. There was also a great amount of exchange about the polar front jet in the Ferrel cell. The geographic homogeneity of the southern hemisphere, and the frequency of Ferrel cell mixing events generates a continuum of aerosol concentration which exhibits little change in concentration when adjacent air masses or layers are mixed.

All of the dry air flight data in Fig. 15 were combined, and the tropospheric mean aerosol concentration for all flight levels between 5 and 10 km was calculated. The mean value is plotted against latitude in the upper panel of Fig. 16. The combination of flight levels yields a slightly broader data base, and generally smooths trends in aerosol concentration with respect to latitude. The plotted line in the lower panel is extracted from the same data base as Fig. 1, with additional data from Hogan (1981b) south of 45°S. The Antarctic values, given for Vanda (78°S) and South Pole (90°S) are summer averages, to be comparable with the season of the flight data in the panel above, and with the Dec–Jan data from USCGC Northwind in Hogan (1981b).

The ascending cumulus turrets of the ITCZ appear to be a very active conveyor of aerosol to the tropical troposphere, where the mean concentration exceeds that measured at the surface. While the mid latitude oceans are persistent sources of particles, the exchange of these particles into the mid troposphere seems limited in these observed cases. There is an interesting, near linear, decrease in mean tropospheric aerosol concentration, south of the Hadley cell circulation in the Southern Hemisphere. This may be an indicator of mean latitudinal exchange, but much more data is needed to verify or reject this idea.

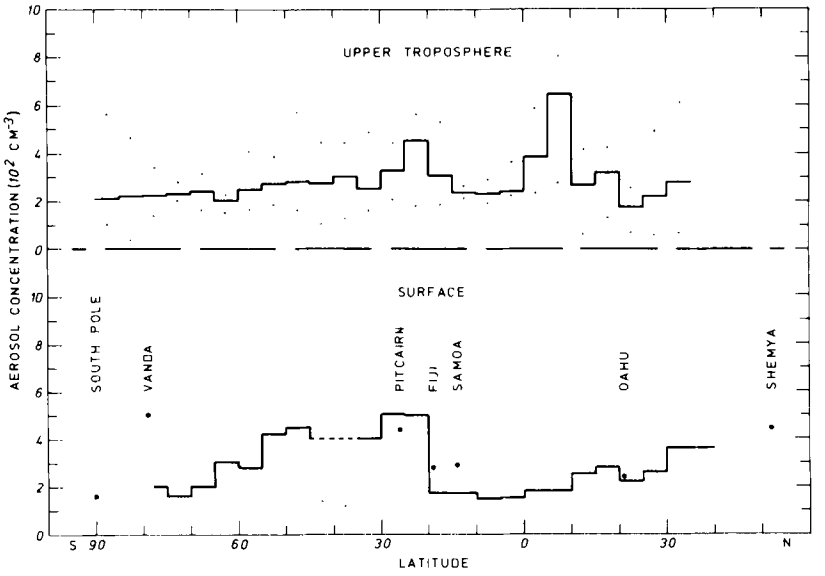

Fig. 16. The upper panel shows the mean clear air aerosol concentrations observed along the routes shown in Fig. 2, for the years 1977, 1978 and 1980. The lower panel shows mean surface aerosol concentrations, extracted from Fig. 1, and from Hogan (1981b).

9. Discussion

A series of flight experiments has found a relatively uniform concentration of aerosol (AN) in the cloudless troposphere over the marine hemisphere as predicted many times by Junge. The aerosol concentration increases by several fold near cumulus turrets in the tropics (Fig. 3) and around As and Cs in the higher latitudes of the southern hemisphere. Aerosol carried to the mid and upper troposphere in the cloud production process is mixed through these layers as the clouds dissipate. When only dry air aerosol observations are considered as in Figs. 15, 16, the regions of aerosol introduction, in cloud regions around the intertropical convergence and the southern subtropical jet, are still apparent.

Examining individual meteorological features, such as the transect of the polar front jet in Figs. 4 and 5 shows area of aerosol exchange at the edge of stratiform layers adjacent to upper level fronts. Ozone measurements indicate that stratosphere-troposphere exchange occurs beneath the jet, near the stratiform clouds. A first examination of Fig. 5 indicates an out-of-phase relation of aerosol and ozone concentration in this exchange layer, as reported by Shapiro (1980).

More detailed analysis, as in Fig. 6, shows that, in a case where ozone exchange seems predictable and regular, no systematic variation occurs in aerosol concentration. This might be explained by the presence of a steady decrease in aerosol concentration as distance above the surface increases and by the homogeneity in aerosol concentration between adjacent air masses in the southern hemisphere. Mixing of two such layers as air masses exchange would produce no apparent change in aerosol concentration. This hypothesis cannot be tested with the available data, because the layers above 300 mb which were apparently the source of increased ozone concentration, could not be reached with the airplane.

Several of the figures show aerosol (AN) concentrations in and near stratiform (As, Cs) clouds which exceed typical surface aerosol concentrations found over the sea at those latitudes. The same phenomena is observed at the surface of the polar plateau, where aerosol (AN) concentrations of more than 500/cm^3 are observed in the company of low stratiform clouds and warm air, apparently advected to the station from oceanic sectors. These concentrations, measured at the 680 mb (3 km) level exceed typical surface concentrations measured over the south Atlantic Ocean and Weddell Sea by Meszaros and Vissy (1974).

Observation of enhanced aerosol concentrations in moist (or stratiform cloudy) tropospheric air is a frequent occurrence. It is not possible to determine, from available data, if cloud forming (or decaying) processes generate this aerosol, or if the enhanced aerosol concentration is produced by stormy sea surfaces, which escape measurement by surface observers.

A wide range of aerosol concentrations was found in the 5–6 km layer, over Antarctica (Fig. 14) in correspondence with a narrow range of small ozone concentrations. The vertical profiles of aerosol concentration shown in Figs. 9 and 10 show higher aerosol concentrations in moist cloudy air over McMurdo Sound. The aerosol and ozone profiles obtained over the Ross Sea, Ross Ice Shelf and Filchener Ice Shelf show maximum aerosol concentration corresponding with minimum ozone concentration, and moist air in the lower levels.

A narrow range of both aerosol and ozone concentrations is observed in the 6–7 km layer over Antarctica. A very smooth linear decrease in aerosol concentration with height is found over this altitude range in the vertical profiles of Figs. 9, 10 and 11. The 7 to 8 km layer shows greatest variation and greatest concentration of both aerosol and ozone; the layers above this show considerable range of ozone concentration, but a narrow range of aerosol concentration. These considerations can be combined to produce a preliminary hypothesis of Antarctic aerosol exchange.

Aerosol and moisture originate in the surface layers over the seas surrounding Antarctica. Both particles and water vapor are carried aloft in the vicinity of low pressure systems, forming clouds. As low pressure systems move over the ice, heat is lost from the system causing subsidence and drying. This moisture and aerosol is generally confined to the air over the lower terrain of Antarctica.

If such a system enters the Filchener ice shelf area, some of the aerosol laden air will be carried up the shallow slope of the ice by the persistent NW tropospheric winds, and be carried over the Polar Plateau in the layers just above the surface.

This air is ozone poor from its recent surface history, and when mixed through the lower troposphere will cause increases in aerosol concentration and little change in ozone concentration. The upper mixing limit of this marine aerosol seems to be near the 500 mb level.

Relatively ozone rich air is advected over Antarctica at higher altitudes. The air exchanges with upper tropospheric air in the layers above 400 mb. The exchange seems most frequent in troughs over low lying Antarctica, and in the vicinity of mountains. There was no evidence of deep exchange found over polar plateau, but the number of observations is small.

Quite vigorous aerosol exchange occurred below the 500 mb level over Antarctica, but it was not accompanied by ozone exchange. Vigorous ozone exchange occurred above the 400 mb level, but only sporadic aerosol differences accompanied larger ozone concentration differences. Extreme stability in the 400 to 500 mb layer prevented these two actively exchanging layers from exchanging with each other. Surface evidence for this isolation is found in the frequent excursions in surface aerosol concentration which accompany warm advection and cloudiness on the polar plateau (Hogan et al., 1982; Hogan et al., 1984), and the rarity of excursions in ozone concentration there (Oltmanns and Komhyr, 1975).

10. Conclusions

A series of meteorological research flights over the central Pacific showed the aerosol concentration in the mid to upper troposphere to be related to major features of global circulation. The ITCZ was an active conveyor of aerosol to the tropical troposphere, and the fronts near the limit of the Hadley circulation and the southern subtropical jet were also active in aerosol transfer.

Relatively uniform aerosol concentrations were found in the dry troposphere south of 30°S latitude. This uniformity is hypothesized to be a result of homogeneity of aerosol production over the Southern Ocean, similarity of aerosol concentration in adjacent air masses, frequent mixing events in the southern Ferrel cell, and a steady decrease in aerosol concentration with increasing altitude, extending from the mid troposphere through the lower stratosphere. This apparent "one for one" exchange of aerosol (AN) was measured in bulk form. It will require a large, sophisticated experiment to determine the variation in chemical properties of particles as these exchanges occur.

Typical aerosol concentrations in the dry Antarctic troposphere are only slightly less than those in the marine troposphere over the South Pacific, concurrent with Junge's hypothesis. There is a near linear decrease in aerosol concentration with increasing altitude in the dry Antarctic troposphere. This "aerosol lapse rate" reflects a surface aerosol source, in the same manner in which a temperature lapse reflects a surface source of heat. Greater aerosol concentrations are found in moist or cloudy tropospheric layers, when compared with dry air in the same layer.

Surface aerosol is carried aloft about low pressure systems and with cloudiness over lower Antarctic terrain. A slow lifting of the surface aerosol layer also occurs as the persistent northwesterly (grid direction) tropospheric wind carries air of recent maritime residence over the Filchener ice shelf and up the ice slope to the polar plateau. The increased aerosol concentrations found in moist and cloudy air over the Ross Sea and Filchener ice shelf are comparable to stormy air values observed at the surface at South Pole.

Over Antarctica, relatively vigorous exchange of ozone was found in the layers above 400 mb, in troughs about the periphery of the continent and over mountains. Small variation in bulk aerosol properties often coincided with wide variation in ozone concentration. This vigorous ozone exchange was confined to layers above 400 mb by the stability of the 400–500 mb layer, and was not observed near the surface.

A major question persists relative to the source of enhanced aerosol concentrations found in moist air near Antarctic stratiform clouds, and near tropical cumulus towers. Are these particles transported from the sea surface, dispersed in cloud forming and dissipating processes, or formed in situ through photo chemical in other processes? These experiments measured only bulk properties of the aerosol, and cannot determine what chemical changes occurred concurrently. The experiments have defined the meteorological regimes in which more sophisticated experiments could be productively attempted.

There is a continuum of aerosol concentrations which shows a uniform decrease with increasing latitude or altitude in the dry remote troposphere. Aerosol inputs to this reservoir generally occur concurrently with inputs of water vapor, in the vicinity of well defined meteorological features.

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