XIII. GLOBAL ATMOSPHERIC SAMPLING PROGRAM

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The Global Atmospheric Sampling Program (GASP) is a program to measure the levels of minor atmospheric constituents. It is a long-term effort to obtain baseline data and to monitor key atmospheric constituents associated with emissions of aircraft engines in order to determine, if possible, if aircraft are contributing to pollution of the upper atmosphere. This assessment can aid in determining the extent to which combustor emissions must be reduced.

Automated instruments have been installed on commercial B-747 aircraft. Data thus acquired on a global basis over the commercial air routes for 5 to 10 years will be analyzed by the Lewis Research Center.

During the initial GASP development, concerns over the effects of aircraft emissions on stratospheric ozone led to the Climatic Impact Assessment Program (CIAP). This program began in 1971 and concluded with its Report of Findings in 1975 (ref. 1). This program was primarily directed to emissions of oxides of nitrogen from high-altitude aircraft. More recently, a new threat to the ozone layer from photodissociation of the chlorofluoromethanes (CFM's) was proposed (ref. 2). A report late last year by the National Academy of Sciences arrived at the tentative conclusions that the chlorofluoromethanes present a threat to the ozone layer but that an immediate ban was not required, thus allowing some time for further study (ref. 3). Recently, a timetable for rulemaking procedures banning manufacture and use of chlorofluoromethanes was announced by the regulatory agencies. In addition to the problem of ozone depletion, a longer range problem due to man-made pollutants is the possible modification of climate since increased concentration of infrared gaseous absorbers or aerosol scatters of radiation could effect the Earth's thermal balance. For example,

there has been some speculation that carbon nuclei and sulfur dioxide in aircraft engine emissions could act as precursors for locally increased aerosol formation.

As part of the NASA FY 1976 Authorization Act, NASA was instructed by Congress to develop and implement a comprehensive program to provide an understanding of the chemical and physical integrity of the Earth's upper atmosphere. The long-term goal of the NASA program is directed toward the scientific objective of a better understanding of the upper atmosphere. The short-term goals involve assessments of current threats to the ozone layer, including the impact of chlorofluoromethanes and space shuttle and aircraft exhaust on the ozone layer.

The assessment report on chlorofluoromethane impact is in preparation. The space shuttle assessment has been completed, with essentially a finding of negligible effects. NASA will conduct an assessment in the near future of the effects of aircraft emissions on ozone as a followup to the CIAP studies. The baseline data from GASP as well as from other NASA programs studying the impact of aircraft, such as the measurements from the high-altitude U-2 aircraft, will be used to improve models of the atmosphere for refining the aircraft assessment. Baseline data and the assessment report will be made available to the Federal Aviation Administration (FAA) and the Environmental Protection Agency (EPA) to aid them in their own assessments.

The constituents measured in GASP are related to the long-term objectives and the assessments of the effect of aircraft exhaust on ozone. The correctness of stratospheric and tropospheric models for predicting long-range trends will depend to a large extent on the input data in the form of boundary conditions and transport coefficients. The one-dimensional models that have been used to predict effects of aircraft and chlorofluoromethanes make use of assumed eddy diffusion coefficients to parameterize transport. These models may fit the existing data set reasonably well, but the diffusion coefficients bear little relation to actual transport mechanisms since there is sufficient evidence that most of the transport takes place through large-scale interchange of tropospheric and stratospheric air masses. A better characterization of the distribution of the minor atmospheric constitutents in space and time can provide some insight into their sources, sinks, and interrelations.

Since ozone has a wide range of variability, the data must be treated statistically over a reasonably long time to establish some order. We must first determine ozone's global distribution - how it is transported from the middle and upper stratosphere (where it is formed by photochemistry) to the troposphere and ultimately to the surface, where it is destroyed. Its residual variance after accounting for periodic variations has to be determined and compared with measurement accuracy to assess whether the small long-term changes predicted by atmospheric modeling can be identified.

Measurements of oxides of nitrogen (NO_x), carbon monoxide (CO), and aerosols were initially chosen because aircraft engine exhaust can be a source of these constituents, though not necessarily a significant one. By better characterizing their distribution globally and their natural variation, we can more accurately define the most significant sources and sinks. For example, lower stratospheric or upper tropospheric photochemistry involving the hydroxyl radical may be a significant loss mechanism for NO_x and CO and for formation of the sulfate aerosol.

The GASP program has been in operation for $2\frac{1}{2}$ years. Although some of the more important measurements have just begun or are scheduled to begin within the next few months, some very significant results are emerging and are covered in this presentation.

GASP DATA COVERAGE

The airlines that are presently participating in GASP in this global study are shown in figure XIII-1. This figure shows 747's of United Airlines, Pan Am, Qantas Airways of Australia, another Pan Am (a new long range, higher altitude special performance (SP) version of the 747), and the NASA Convair-990 flying laboratory, which is also equipped with a GASP system. The CV-990 is used to survey off-airline routes. These airlines were chosen to provide coverage of the major global air routes, as shown in figure XIII-2.

United Airlines collects data over the United States, coast to coast and to Hawaii. Pan Am flies around the world and to South America. Qantas, based in Sydney, flies frequently to Europe and to the West Coast of the United States.

The majority of data have been and are being taken in the Northern Hemisphere, as shown in figure XIII-3. The distribution of data is shown in 5^{o} increments of latitude north and south of the equator. The fraction of total data received from the Northern Hemisphere peaks in the 40^{o} North latitude range. Airlines with mainly Northern Hemisphere air routes were chosen to frequently cover the more industrialized and heavy airlane traffic areas. The Southern Hemisphere is covered to a lesser extent in order to evaluate and compare this less polluted area.

The distribution of GASP data by flight altitude is shown in figure XIII-4. The fraction of total data for each flight altitude between 21 000 and 45 000 feet peaks at flight levels of 35 000, 37 000, and 39 000 feet. The 747 SP generally flies higher and will contribute more to the data between 39 000 and 45 000 feet. It had been in service only a relatively short time when data in this figure were assembled.

GASP air constituent measurements and supplemental data are listed in table XIII-1. Ozone, water vapor, NO_x, and CO are measured with in-situ instruments, and chlorofluoromethanes are measured from bottle samples. The number density of particles greater than 0.3 micrometer is measured with a light-scattering instrument, and smaller particles called condensation nuclei are measured with a cloud-chamber instrument. Mass concentrations of sulfates and nitrates are determined from laboratory analysis of filter paper samples exposed in flight.

At the time of each air constituent measurement, certain supplemental data are recorded. Time and position of the aircraft and its altitude, speed, and direction pinpoint each air constituent measurement. Data related to meteorology are also taken. Air temperature, wind direction and velocity, and an indication of turbulence as measured by the vertical acceleration are recorded. The light-scattering instrument for measuring the larger particle sizes also indicates the presence of clouds in the flightpath.

Each GASP-equipped aircraft flies about 10 hours per day, for a total of about 5400 miles each day or about 8 million miles per year for the four 747's. A data set is recorded every 5 minutes or about every 45 miles.

GASP SYSTEM

Location of the GASP equipment in the 747's is shown in figure XIII-5. The installation is near the nose below the passenger deck. Two air sample inlets mounted in a single strut (fig. XIII-6) sample both gases and particulates outside the boundary layer very near the nose. One of the inlets is designed for isokinetic sampling for measuring particle number density. Both inlets are capped below 20 000 feet (as photographed in fig. XIII-6) to prevent possible contamination of the air sample ducting.

Air flows from the inlet in a 1-inch-diameter tube aft to the measuring instruments. A rack mounted to the airframe holds most of the GASP instruments, as shown in figure XIII-7. The instruments are packaged in standard airline avionics cases. Considerable plumbing is required, as shown in figure XIII-7 to duct the air sample around and to measure various pressures associated with the instruments. Air is also ducted in a 3-inch-diameter tube from the inlet to the other side of the aircraft, where a mechanism is located for exposing the particle filter papers. This mechanism is similar to a slide projector and holds eight filters that are exposed in sequence.

Total weight of the installed system is about 850 pounds. All equipment meets FAA certification requirements, and the entire installed system was flight tested during a special flight following which a supplemental type certificate of airworthiness was issued for the GASP system. Operation is completely automatic, requiring no attention by the flight crews.

GASP system control and data acquisition are performed by the three units shown in figure XIII-8. Automatic control of all system operations and management of all data are functions of the data management and control unit. This unit contains a small special-purpose computer preprogrammed to provide the automation. Most of the data are acquired by a conventional airline flight data acquisition unit. Data from the GASP instruments and other parts of the system, as well as from the aircraft systems, flow to this unit. Position and wind data come from the aircraft's inertial navigation system. All data are recorded on a digital airborne recorder. The tape cassettes are replaced about every 2 weeks.

GASP INSTRUMENTS

Measurement Requirements

Table XIII-2 lists the species of interest to GASP and their expected concentrations. Ozone and water vapor do not pose a great measurement problem, but carbon monoxide at less than 1/4 part per million (ppm) and nitric oxide at less than 0.3 part per billion (ppb) represent a challenge because of the high sensitivity required.

Particles with diameters greater than 0.3 micrometer range from about 0.01 to 10 particles per cubic centimeter, and the condensation nuclei range from perhaps 30 to 3000 nuclei per cubic centimeter. Fluorocarbon 11 is in the fractional ppb range and is measured by laboratory analysis of captured air samples. The sulfates and nitrates are measured by laboratory analysis of material captured on filters.

The following discussion is limited to the in-situ measurements, which are all but the last three in table XIII-2. For comparison with these concentrations, table XIII-3 lists the GASP instruments and their ranges. The two measurements where range is of particular concern are the CO and NO measurements. The CO instrument has a full-scale range of 1 ppm and can detect changes in concentration of 0.02 ppm. The NO instrument has a full-scale range of 10 ppb and should be able to detect changes in concentration of 0.05 ppb. In both cases, these are the best instruments available that could meet the GASP operational requirements.

In general, the GASP instruments are modifications of laboratory instruments. The modifications are aimed at two fundamental requirements: operation in a totally automated system, and operation in a commercial airline environment. This last requirement imposes not only the physical environment of flight and certain safety precautions, but also a high use factor and limited accessibility for servicing.

Ozone

Ozone is measured with an ultraviolet absorption photometer with a range of 3 ppb to 20 ppm. Figure XIII-9 is a block diagram of this instru-

ment. The instrument has an ultraviolet source, an absorption tube through which the sample flows, an ultraviolet detector, and an electronic signal conditioner. This instrument works on the principle that ozone in the air sample absorbs some of the ultraviolet light passing through the sample. Thus, it is necessary to accurately measure small changes in the ultraviolet light coming out of the absorption tube. The instrument does this by alternating between measurements of ozone-free air and the sample. The ozone-free air is obtained by routing the sample through the ozone scrubber during half of the cycle.

Certain in-flight tests are made to ensure the integrity of the measurements. For the ozone instrument these tests include an overall zero measurement and a measurement of two electronic signals that indicate the condition of the ultraviolet source and the presence of excessive contamination on the absorption tube windows. For the zero measurement the sample is routed through a charcoal filter upstream of the instrument.

The accuracy of the ozone measurements depends on a number of factors. The calibration standard has an estimated uncertainty of ± 7 percent, the instruments have a long-term repeatability within ± 2 percent, and the data are corrected for ozone destruction in the pressurization system. This correction is 13 ± 5 percent of the indicated ozone concentration.

Water Vapor

Water vapor is measured with a cooled-mirror hygrometer shown schematically in figure XIII-10. With this instrument, a cooled mirror is exposed to the sample flow such that a thin layer of dew or frost is formed. An optical system senses mirror reflectance and operates a thermoelectric cooler to maintain the mirror temperature at the dewfrost point.

Carbon Monoxide

Carbon monoxide is measured with an infrared absorption analyzer that uses fluorescence from two oxygen isotopes of CO as the source of infrared energy. This technique, in combination with a long-path multireflection

absorption cell, gives the high sensitivity and stability needed for a 1-ppm full-scale instrument. Figure XIII-11 is a block diagram of this instrument.

The CO analyzers are calibrated in the laboratory with a mixture of CO in nitrogen. The estimated uncertainty of this calibration is ± 2 percent at 1 ppm concentration.

Nitric Oxide

The nitric oxide analyzer to be used in GASP is a chemiluminescent analyzer, shown schematically in figure XIII-12. In this instrument, nitric oxide in the sample reacts with ozone, and photons are emitted. The photons are detected and counted as individual events. The very high sensitivity is achieved, in part, by using a high sample flow rate and a special technique for in-flight zero measurement. Also, an in-flight span measurement will be made using calibration gas carried with the instrument.

Nitric oxide instruments are not yet being flown on the 747 aircraft; the first instrument is scheduled for installation in the fall of 1977.

Aerosol Particles

Aerosol particles are a class of particles in the size range from tenths of a micrometer to tens of micrometers. These particles are measured by light-scattering techniques.

Condensation Nuclei

Condensation nuclei are very small airborne particles, from tenths to thousandths of a micrometer, that act as nucleation sites for the condensation of vapor. These particles are measured with a cloud chamber instrument. The instrument has a built-in pressurization system designed to concentrate the sample. This design gives high sensitivity so that measurements at concentrations as low as 30 nuclei per cubic centimeter can be made.

RESULTS

Data Preparation

The data preparation begins with the routine service check of the aircraft and the removal of the tape cassette. The information on the cassette is transcribed onto computer-compatible tape by United Airlines in San Francisco. NASA Lewis then does the data reduction and preliminary analysis. Any malfunctioning instrument not found in the routine service check is identified and scheduled for replacement.

Electronic instrument identification codes, recorded with the data, are used during data reduction to select the proper laboratory calibration curves. The tropopause pressure fields from the National Meteorological Center and the results of the whole air sample and filter sample analyses are added to the data tape at this time.

While the final tape is being prepared at NASA, a report is written describing the availability of the data and some of their selected highlights. As a last step, the prepared tape and availability report are sent to the National Climatic Center for archiving and to NOAA and NASA contractors for detailed analysis.

Atmosphere Structure

As an aid in understanding the GASP atmospheric data, the basic structure of the aircraft-traveled portion of the upper atmosphere is shown in figure XIII-13. The troposphere and the stratosphere are the atmospheric regions of interest. The boundary between these two regions, called the tropopause, varies in altitude with season, latitude, and local meteorological conditions. The troposphere is characterized by decreasing air temperature for increasing altitude. The airflow tends to be turbulent and to have low values of ozone. The region retains air pollutants for just days before they wash out in the rains. The stratosphere on the other hand is characterized by increasing air temperature. Its airflow tends to be stable and to have ozone values as much as 100 times greater than those in the troposphere. Pollutants remain for long periods, often years.

The GASP-equipped aircraft obtain data in both regions. The altitude of the local tropopause determines if the aircraft operates well into the troposphere, near the boundary, or well into the stratosphere.

GASP Atmospheric Data

A typical case study showing GASP data for a single flight from Los Angeles to Tokyo last September is presented in figure XIII-14. The flight levels and local tropopause heights and ozone and static air temperatures are shown plotted versus longitude. The local tropopause was obtained from space and time interpolations of the pressure fields supplied by the National Meteorological Center (NMC).

These local, but simultaneously acquired, data illustrate several important points of interest to GASP data users. First, the relative values of the various constituents are a very reliable indicator of either stratospheric or tropospheric air. And, second, the distance between the tropopause height and the aircraft flight level varies greatly, even during one flight.

In figure XIII-14, the increased ozone, up to 400 ppb by volume, and the warming static air temperatures, after an initial colder temperature, are indicative of flight in stratospheric air. Another indicator of stratospheric air, independent from GASP data, is when the NMC tropopause height is below the aircraft flight level. The distance between the tropopause height and the flight level is usually expressed as a pressure interval, in terms of millibars above or below the tropopause. For a constant flight level of 39 000 feet, the aircraft is initially in the troposphere at a flight level of 200 mbars and the tropopause is at 180 mbars, or 20 mbars above the flight level. The aircraft then enters the stratosphere as the tropopause drops to 285 mbars, or 85 mbars below the flight level.

Atmospheric Ozone

Figure XIII-15 shows data taken on March 20 during a flight from New York to San Francisco. The flightpath is given in figure XIII-16. As

the aircraft took off and climbed, the air temperature decreased. At 31 000 feet, the temperature began to increase, as did the local ozone. These increasing values are two characteristics of stratospheric air and indicate that the height of the tropopause was much lower than its average expected height of about 34 000 feet for this latitude and season.

Cabin Ozone

The high ozone levels shown in figure XIII-15 are interesting to the atmospheric scientist, but are also of concern to the airlines. Ever since high-altitude flight began with jet aircraft, the airlines have been concerned with high ozone and its possible presence in the aircraft cabin. The extreme winter of 1976-77 made it a problem.

During this winter, the airlines received a number of complaints from passengers and crew members about physical discomfort experienced during flight. Initial reports came from long-distance nonstop flights on the 747 SP and then from the regular 747's and other types of aircraft. Possible causes were thought to be low cabin humidity, fatigue, or high levels of cabin ozone. The primary cause, cabin ozone, was positively identified for the first time when a GASP system measured high levels of outside ozone in good correlation with reports of discomfort.

The data of figure XIII-15 show that ozone levels of 900 ppbv were encountered for 2 hours. In response to reports of discomfort made during this flight, the captain lowered the aircraft flight level by 4000 feet. However, as the data show, the ozone level had already decreased before the change was made.

Having identified the cause, NASA and the airlines equipped two 747's with a second ozone instrument to obtain a simultaneous measurement of cabin ozone with atmospheric ozone. Ozone data were obtained during March and April, the peak ozone months at the middle latitudes. The atmospheric ozone levels in figure XIII-17 are from two flights heading from New York to Los Angeles, on March 31 and April 3. Neither flight exceeded 39 000 feet. The data correlate well over the entire range of atmospheric ozone values. The solid curve is arbitrary, drawn to show that, on the average, 40 percent of the atmospheric ozone was measured in the cabin.

In 1962-63, the FAA sponsored a study (ref. 4) to measure cabin ozone levels in all of the then-current commercial jet aircraft. The three data points represented here by triangles are from that study. These data points are only approximate since the atmospheric data were obtained from nearby, but not simultaneous, Air Force ozonesonde vertical profiles. The study found no differences in ozone destruction efficiency among the various jet aircraft types. If the FAA-sponsored study and the GASP data do indeed follow a similar correlation, then the FAA study, which measured cabin ozone levels as high as 400 ppbv, shows that aircraft also experienced atmospheric levels up to 1000 ppbv in 1962-63. The GASP data for the winter of 1976-77 will be analysed to determine if the average atmospheric ozone level, and hence the cabin ozone level, was higher than previous years' levels.

While more comparison data are needed to completely define the ozone destruction correlation, prior and future GASP atmospheric ozone data can be used to define the frequency, location, and seasonal aspects of the cabin ozone problem. Even with what is known to date, though, the airlines and airframe companies are investigating the effectiveness and practicality of several corrective actions. NASA, for its part, will use the GASP system to continue collecting atmospheric ozone data that the airlines can use to evaluate the effectiveness of their investigations.

Condensation Nuclei

Condensation nuclei data in figure XIII-18 were obtained from GASP in early March 1977. The data were obtained every 5 to 10 minutes over a flight of several hours. Most of the data indicate concentrations below 300 particles per cubic centimeter. Other data recorded continuously over a 5-minute period revealed a finer structure than is shown here, however. These small particles act as nucleation centers for the growth of the larger aerosol particles in the visible size range. Aerosol particles scatter sunlight, thereby affecting the radiation balance between the Sun and the Earth, with possible effects on climate.

Various experimenters have measured condensation nuclei in the troposphere between 100 and 1000 particles per cubic centimeter and stratospheric values between 10 and 100 particles per cubic centimeter. Some experimenters suggest that the high concentrations in the upper troposphere are caused by jet aircraft operations. These comments are summarized in reference 5. While this has not been proven, experimenters onboard the NASA Convair 990 research aircraft have measured these high concentrations while passing through a jet wake. Figure XIII-18 shows ozone data taken simultaneously with the nuclei data. The distribution of ozone suggests an inverse relation with the condensation nuclei data. More ozone and nuclei data will be needed, however, before this relation can be established.

Filter Collection of Aerosols

A filter collection technique is used in the GASP program to determine the aerosol chemical composition. The F106 aircraft, shown in figure XII-19, was used to develop the filter collection procedures. The air inlet tube ducts air to filter collection systems built into the pod on each wing. Data from the F106 are shown in figure XIII-20. The 747 data exhibit similar levels.

These data show that the sulfate concentrations in the lower stratosphere are 2.5 to 3 times higher than the upper troposphere concentrations. The data indicate a local secondary peak in sulfates in the lower stratosphere. The presence of this peak is good evidence of a sulfate source either at the tropopause or in the lower stratosphere. This source may be sulfur dioxide, which is transported into the stratosphere and then oxidized in a set of reactions to produce the sulfuric acid or ammonium sulfate material collected in the filter samples.

These filters have also been analyzed for nitrates. The measured concentrations are similar to those measured for the sulfates.

NASA will provide sufficient coverage with the GASP filter samplers to conclusively identify the sulfate source regions and to characterize the nitrate and other constituent concentrations in the vicinity of the tropopause. These filter data and the condensation nuclei and aerosol particle data will be used in existing computer models in the overall NASA program to verify

aerosol formation theories and to predict effects, if any, of aircraft exhaust emissions on the aerosol layers.

DATA ANALYSIS

Figure XIII-21 is a composite of data from all GASP flights in 1975. This figure shows ozone as a function of pressure intervals from the tropopause. The mean values are given by the solid curve, and ± 1 standard deviation from the mean is shown by the shaded area. Since altitude varies nonlinearly with pressure, the distance from the aircraft to the tropopause depends on both the pressure interval and the tropopause pressure. For reference, the first 40-mbar interval above the tropopause corresponds to about 4000 feet.

In the troposphere the ozone levels are low and nearly constant. Ozone begins to increase in the vicinity of the tropopause and exhibits a rather steep gradient in the lower stratosphere. This profile agrees favorably with the ozone distribution from the 1976 U.S. standard atmosphere, shown as the dashed curve. The mean flight altitude corresponding to the stratospheric GASP observations is about 38 000 feet; the mean altitude for the tropospheric observations in about 36 000 feet. This would not create much of a vertical profile if the tropopause remained at a nearly constant altitude. However, as can be seen in figure XIII-14, the height of the tropopause can vary substantially. This variation is a primary factor in whether GASP data are obtained in the troposphere or stratosphere.

Monthly mean values of the tropopause height show an annual cycle that causes seasonal variations in the mean ozone levels at any given altitude. In figure XIII-22, the bimonthly averages of data for latitudes from 37.5° to 47.5° North are represented by the solid curve. Mean ozone levels are highest in the spring and lowest in the fall. As on the previous figure ± 1 standard deviation is shown by the shaded area. Measurements from the North American ozonesonde network, operated by the Air Force Cambridge Research Laboratory (AFCRL) from 1963 to 1971, provide a historical data base for comparison with the GASP data. The long-dashed line on this figure shows the average of data from two United States stations for 1963-64 (ref. 6). The short-dashed line is the average of data gridded at 40° and

45° North for 1963-71 (ref. 7). Both curves agree favorably with the GASP mean and are well within 1 standard deviation.

In addition to the seasonal variation, mean ozone levels are also dependent on latitude, in response to the general decrease in the height of the tropopause from the equator toward the poles. An example of the variation of ozone with latitude is shown in figure XIII-23. The solid curve is the mean ozone level from the March 1975 and March 1976 GASP data. As before, data from the North American ozonesonde network are shown as dashed lines for comparison with the GASP data. An interesting feature here is the local maximums at mid-latitudes that are evident in both the GASP data and the 1963-64 data (ref. 6). These are a result of the active downward transport of ozone that occurs predominantly at the mid-latitudes in the spring.

The absence of this feature in the 8-year average (ref. 7) is probably due to variations in the mean location of the jet stream that have averaged it out over the longer time interval. The GASP data in both figures are distributed longitudinally around the globe; the ozonesonde data are from only the North American sector.

Figure XIII-21 to -23 are plotted from a data analysis performed at Lewis. To extend our capabilities in meteorological analyses of GASP data, Lewis is currently supporting scientific research studies with the Atmospheric Sciences Research Center (ASRC) at the University at Albany and with the Research Division of Control Data Corporation (CDC).

A primary task in the analyses being conducted at Albany is the examination of new measurements for spatial, temporal, and historical consistency. These analyses include both gaseous and aerosol species and their interrelations. This effort is closely tied to data reduction at Lewis so that we can be assured that GASP data are consistent with previous measurements and that they are sufficiently accurate to be of value to the scientific community.

Other analytical efforts at ASRC will be aimed primarily at the analysis of data in the high-density airlanes. If any long-term trends in constituent levels are occurring, they should become apparent in these corridors first, primarily because of the comparatively high rate of data acquisition. In this effort, ASRC will attempt to establish corridor baseline levels and to estimate the minimum measurement period that would be necessary to detect any trends. Because of the frequency of data across the contiguous

United States, and the availability of independent meteorological data, this corridor is particularly well suited for studying stratospheric-tropospheric transport.

Figure XIII-24 provides an example of a specific analysis of several GASP flights that gives some insight into where vertical transport is occurring. These curves show mean ozone levels as a function of pressure intervals from the tropopause, separated according to the curvature of the wind field. In the Northern Hemisphere, cyclonic curvature (counterclockwise wind rotation) occurs in low-pressure systems, and anticyclonic curvature (clockwise wind rotation) occurs in high-pressure systems. In this figure the ozone distribution for cyclonic curvature is shown by the solid line, and the distribution for anticyclonic curvature is shown by the dashed line. The shaded area indicates ± 1 standard deviation and is shown for each curve. Although there is some overlap, the difference in the mean ozone levels between these curves from 40 mbar below to 40 mbar above the tropopause is entirely unambiguous and shows that stratospheric ozone is injected into the troposphere in large-scale cyclonic systems. The initial analyses of the effects of wind curvature on the ozone distribution and the scheme used for calculating curvature from the GASP data are presented in reference 8.

Our other contract program is with the Research Division of Control Data Corporation (CDC). A continuing task in this program is the accumulation of gridded statistical data, by month, for intervals in latitude, longitude, and altitude. CDC's analysis of these global statistical data include correlations with meteorological parameters.

Figure XIII-25, adapted from reference 9, shows an example of the correlation of GASP ozone data with a parameter derived from archived meteorological data fields. The solid curves are contours of constant mean ozone as a function of latitude and altitude for combined March 1975 and March 1976 data. These contours indicate the general increase in ozone with increasing latitude and increasing altitude. The new feature here is the inclusion of contours of constant potential vorticity, which are shown by the short-dashed lines. This parameter is a measure of the absolute angular momentum of an air parcel and is conserved in adiabatic transport. Thus, potential vorticity provides a useful tracer for atmospheric motions. The similarity of these contours to the ozone contours shows clearly that the ozone distribution is

transport dominated in this altitude range. The long-dashed line on this figure is the mean location of the tropopause. The bulges in the ozone and potential vorticity contours that extended below the tropopause at about 40^{o} North are apparent intrusions of stratospheric air into the troposphere.

Analyses similar to this have yielded estimates of the north-south transport of ozone due to transient eddy motions, and the first direct estimates of ozone transport across the tropopause (ref. 9). Although these estimates are preliminary, they agree favorably with estimates made by other researchers based on ground-level observations.

CDC's transport estimates to date have demonstrated the unique capability of the GASP data to provide this type of information. CDC will also be performing semiannual to quasi-biannual trend analyses to establish the natural periodic variation in constituent levels. These natural variations must be known and accounted for in analyzing emissions-related perturbations or trends in the data. Although the results of statistical analyses presented here have all concerned ozone distributions, similar analyses will be performed for other species as sufficient data are acquired.

CONCLUDING REMARKS

Data taken during the first 2 years of GASP operations have expanded the coverage of local ozone measurements in the 29 000- to 45 000-foot altitude range over what has been available from ozonesondes. Comparisons with the historical data base from the North American network have been good, showing little change from data taken 12 years ago. Only a few ozonesonde stations are now regularly reporting data, so that GASP has filled a gap. Analysis of the GASP data has shown that ozone correlates well with height above the tropopause, illustrating its stratospheric source. The correlations with wind curvature and potential vorticity indicate its nature as a transport-dominated species that is moved downward through large-scale low-pressure weather systems at mid-latitudes. Direct estimates of the downward flux of ozone through the tropopause are in good agreement with estimates based on flux at ground level. A better understanding of the transport mechanism and the flux distribution with latitude and longitude can

be used to improve models for predicting ozone depletion due to stratospheric aircraft emissions. Aside from the objectives of the measurements program, the GASP ozone measurements confirmed a problem of high ozone levels inside the aircraft cabin that had resulted in complaints of respiratory problems by passengers and crew.

Limited aerosol composition measurements from filter samples show low levels of sulfates and nitrates in the upper troposphere. Higher values above the tropopause measured by GASP and by others indicate a stratospheric source for these constituents, which are in the form of sulfuric acid or ammonium sulfate and nitric acid. The acids act as sinks for the oxides of sulfur and nitrogen in the stratosphere and are removed by rain in the troposphere. A tropospheric source for the oxide precursors cannot be ruled out, however. An expected, greater return of filter samples and correlation of these data with condensation nuclei and larger-particle-size data should further our understanding of aerosol formation and its global distribution.

Recently installed instruments for measuring carbon monoxide and condensation nuclei are beginning to return data. These can be expected to provide the type of information on transport of these species and their sources and sinks that is now emerging from the ozone data base. Measurements of nitric oxide from a new instrument and an expected greater return of filter samples for measurement of nitric acid will yield the baseline data on the oxides of nitrogen and their variation that are needed as inputs to physically real models of the atmosphere.

A long-term measurement effort with the GASP-equipped 747 aircraft is continuing, in order to provide the large data base required for a definitive assessment of aircraft effects on the upper atmosphere. Results of the program to date have expanded knowledge of transport processes and hence are contributing to the long-range objectives of the NASA program. It is only through a better understanding of the chemical and physical integrity and transport processes in the upper atmosphere that we can predict with confidence the effects of perturbations caused by man.

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8. Falconer, P. D.; Holdeman, J. D.; and Taylor, A. D.: Atmospheric Ozone Measurements Made from B-747 Airliners: Spring 1975. NASA TM X-73675, 1977.

9. Nastrom, G. D.: Variability and Transport of Ozone at the Tropopause from the First Year of GASP Data. (RR-4, Control Data Corp.; NAS 2-7807.) NASA CR-135176, 1977.

AIR CONSTITUENT MEASUREMENTS

- GASES
  - OZONE
  - WATER VAPOR
  - OXIDES OF NITROGEN
  - CARBON MONOXIDE
  - CHLOROFLUOROMETHANES
- PARTICULATES
  - NO. DENSITY (>0.3 μm DIAM)
  - CONDENSATION NUCLEI
  - MASS CONCENTRATION OF
    - SULFATES
    - NITRATES

SUPPLEMENTAL DATA

- FLIGHT DATA
  - TIME & DATE
  - LATITUDE
  - LONGITUDE
  - ALTITUDE
  - AIR SPEED
  - HEADING
- METEOROLOGICAL DATA
  - OUTSIDE AIR TEMP
  - WIND DIRECTION
  - WIND VELOCITY
  - TURBULENCE (VERTICAL ACCEL)
  - CLOUD ENCOUNTERS

Table XIII-1. CS-77-362

GASP MEASURING INSTRUMENTS

OZONE	ULTRAVIOLET ABSORPTION PHOTOMETER RANGE 3 ppb TO 20 ppm
WATER VAPOR	COOLED MIRROR HYGROMETER DEW-FROST POINT RANGE -80^{0} TO $+20^{0}$ C
CARBON MONOXIDE	INFRARED ABSORPTION ANALYZER RANGE 0.02 TO 1 ppm
NITRIC OXIDE	CHEMILUMINESCENT ANALYZER RANGE 0.05 TO 10 ppb
PARTICLES (D > 0.3 μm)	LIGHT SCATTERING SENSOR
CONDENSATION NUCLEI	CLOUD CHAMBER MIN. CONCENTRATION 30/cm^3

CS-77-406

Table XIII-2.

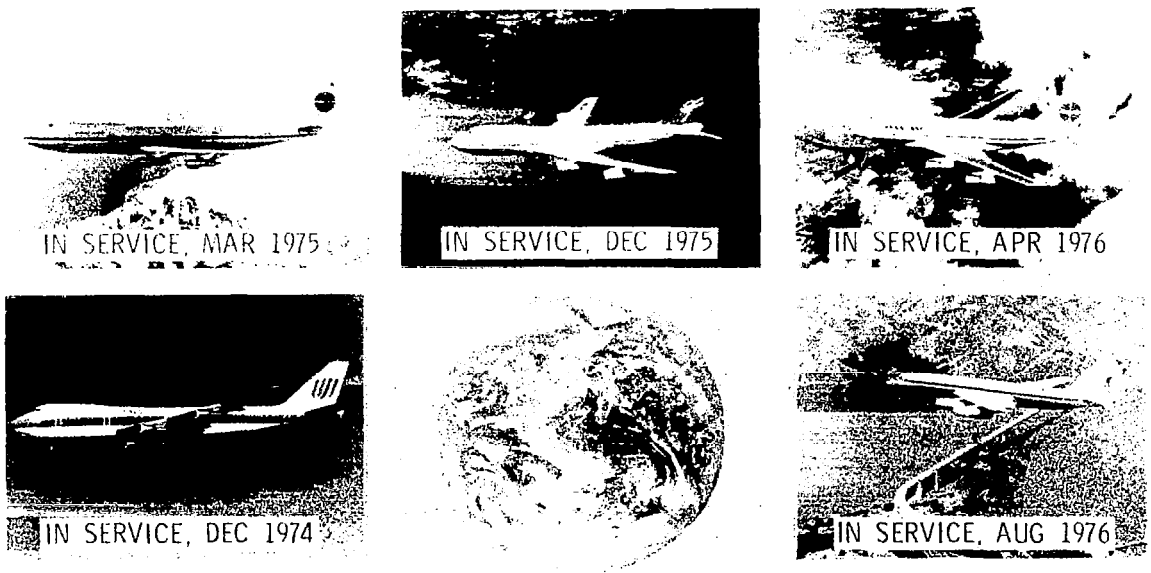
SPECIES CONCENTRATIONS
ALTITUDE: 30 TO 45 THOUSAND ft

SPECIES	EXPECTED RANGE
OZONE	0.03-1.2 ppm
WATER VAPOR	-80^{0} - -20^{0} C DEW-FROST POINT
CARBON MONOXIDE	0.04-0.25 ppm
NITRIC OXIDE	0.02-0.3 ppb
PARTICLES (D > 0.3 μm)	0.01-10/cm^3
CONDENSATION NUCLEI	30-3000/cm^3
FLUOROCARBON 11	0.06-0.15 ppb
SULFATES	0.02-0.3 μg-m^{-3}
NITRATES	0.02-0.3 μg-m^{-3}

CS-77-405

Table XIII-3.

GASP PARTICIPATING AIRLINES



CS-77-421

Figure XIII-1.

GASP ROUTE STRUCTURE

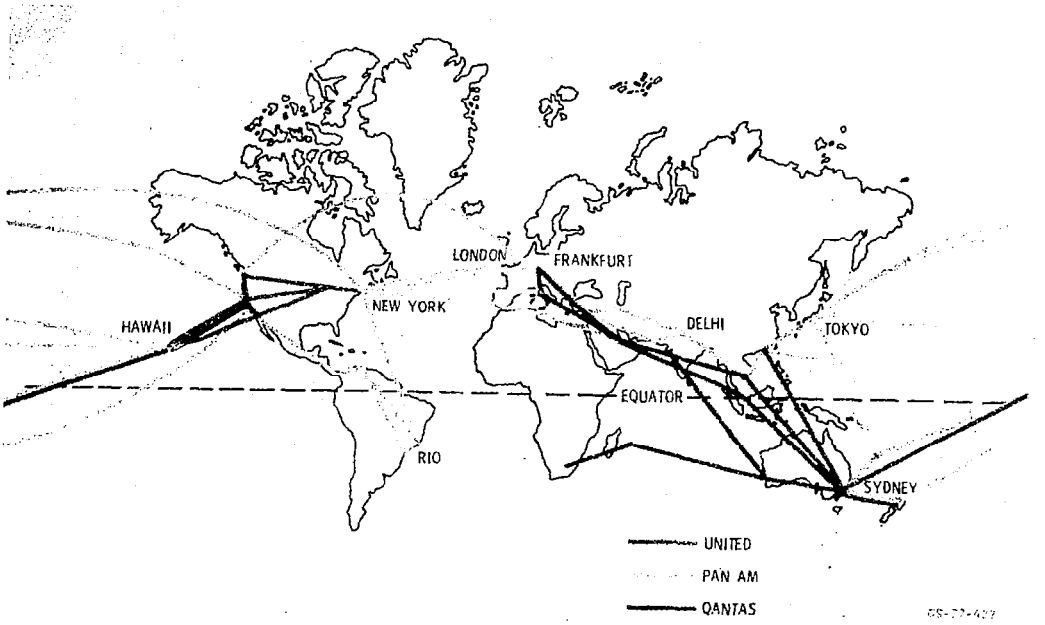


Figure XIII-2.

DISTRIBUTION OF GASP DATA BY LATITUDE

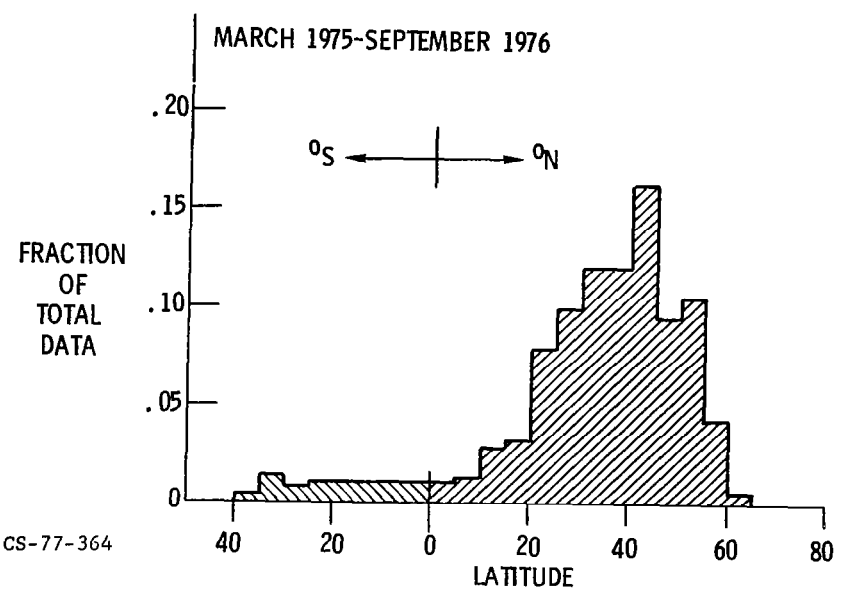


Figure XIII-3.

DISTRIBUTION OF GASP DATA BY FLIGHT ALTITUDE

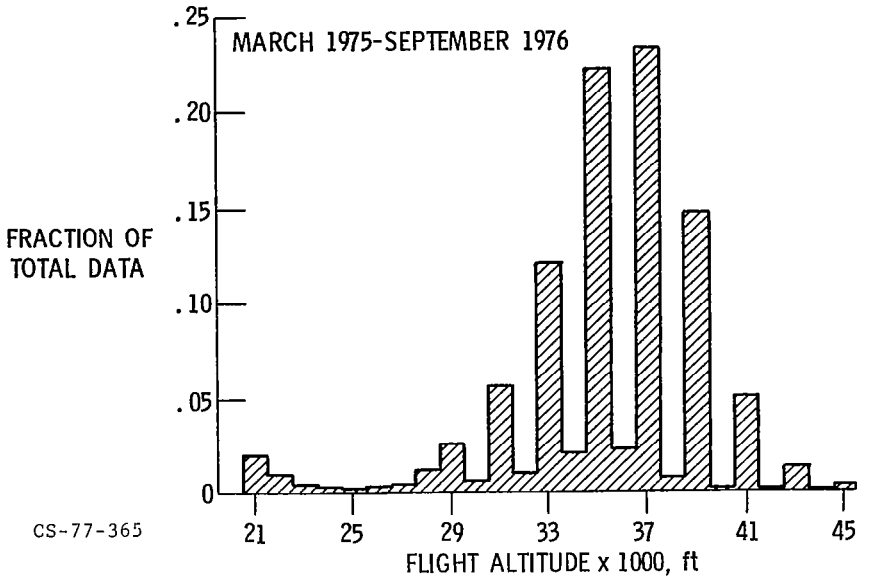


Figure XIII-4.

GASP SYSTEM INSTALLATION

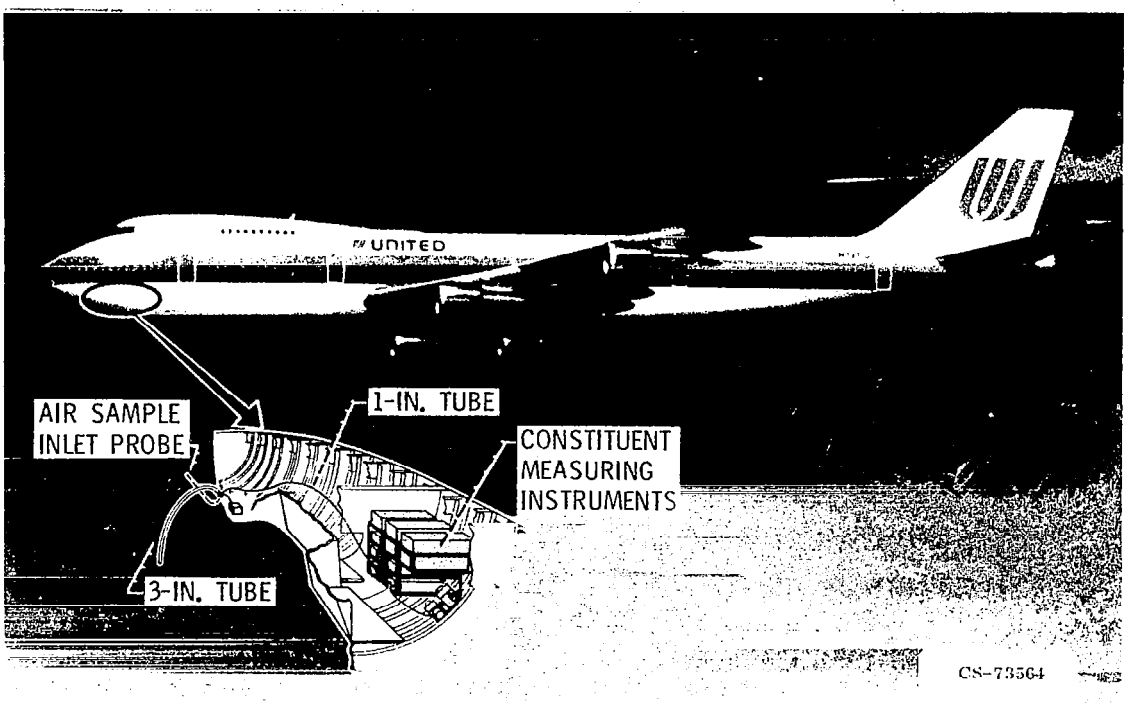


Figure XIII-5.

PROBE DETAIL

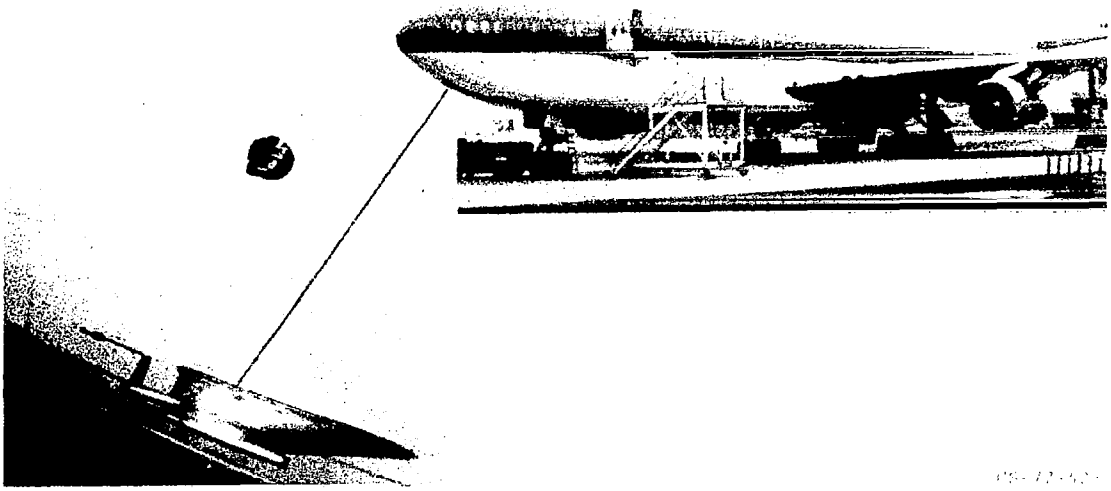


Figure XIII-6.

EQUIPMENT IN AIRCRAFT

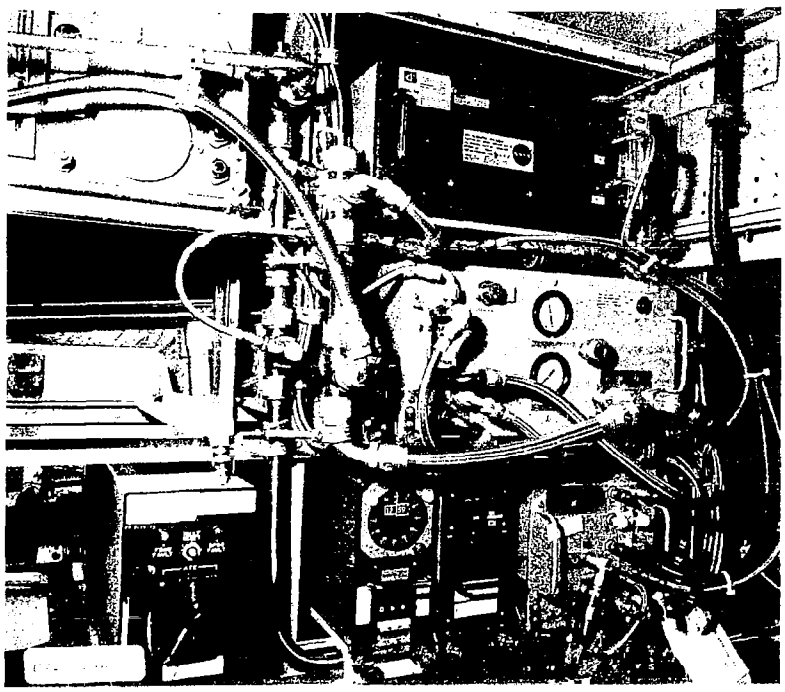


Figure XIII-7.

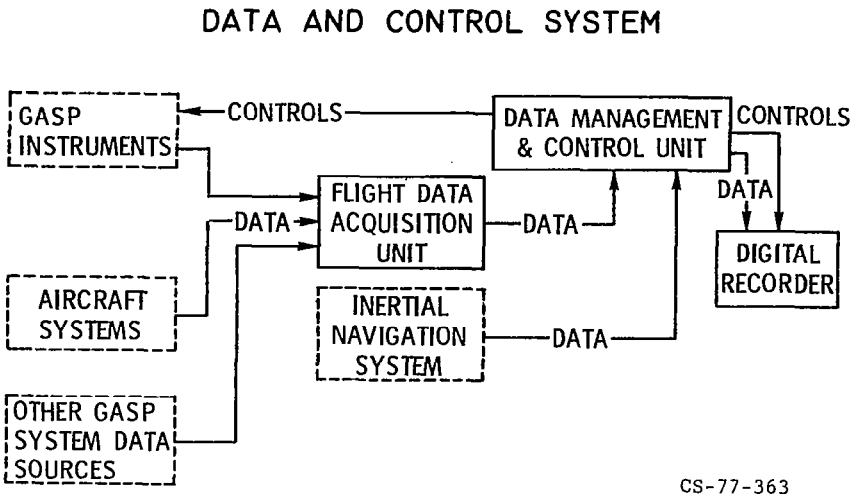


Figure XIII-8.

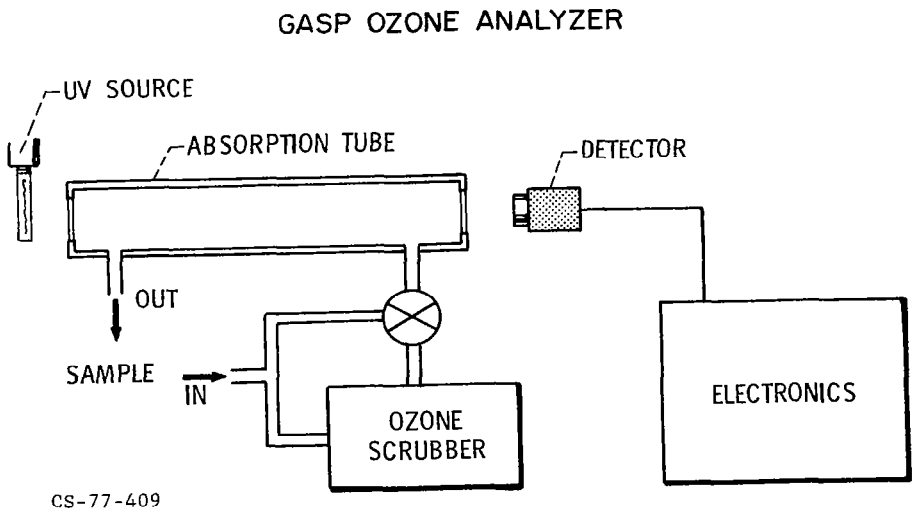


Figure XIII-9.

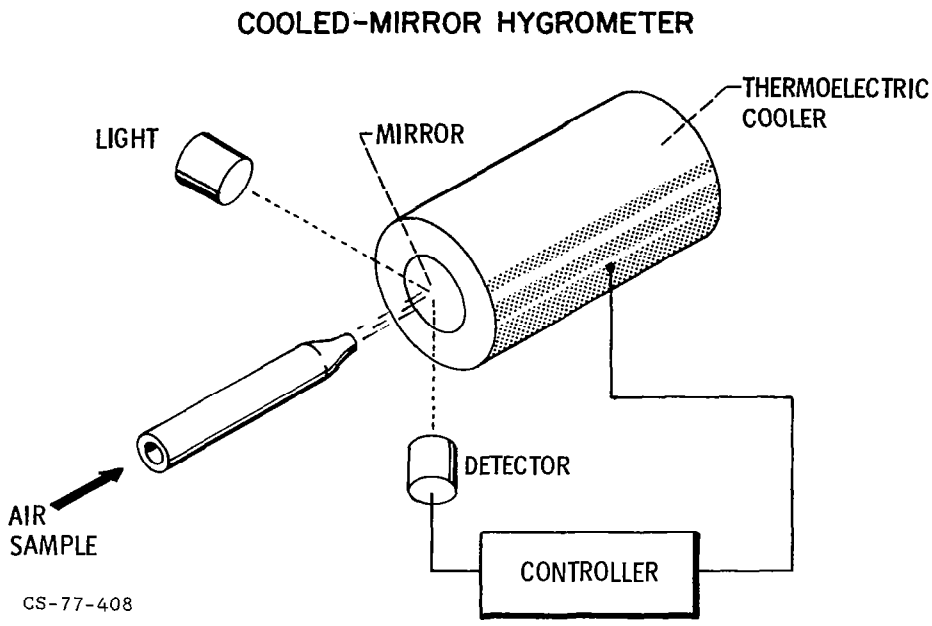


Figure XIII-10.

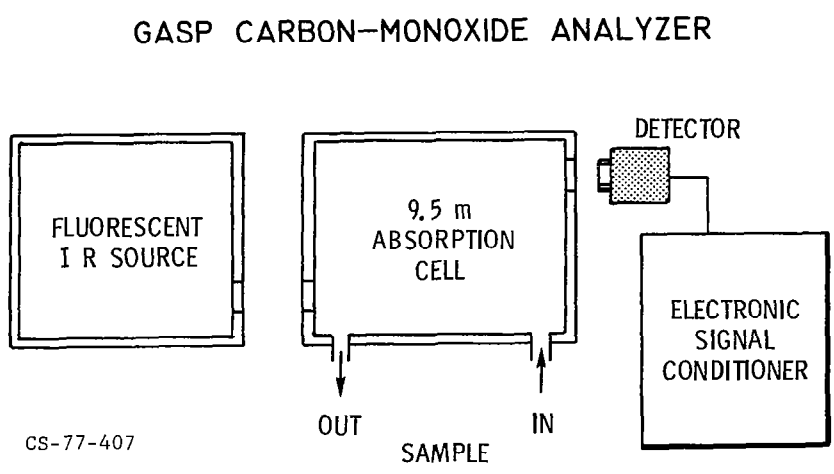


Figure XIII-11.

GASP NITRIC OXIDE ANALYZER

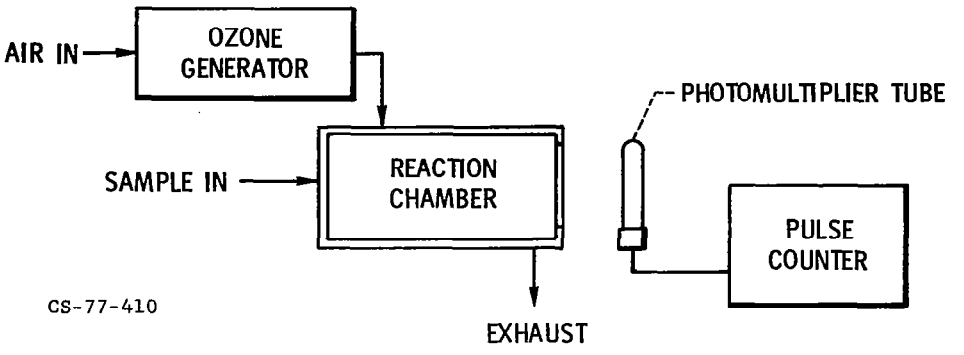


Figure XIII-12.

BASIC ATMOSPHERIC STRUCTURE

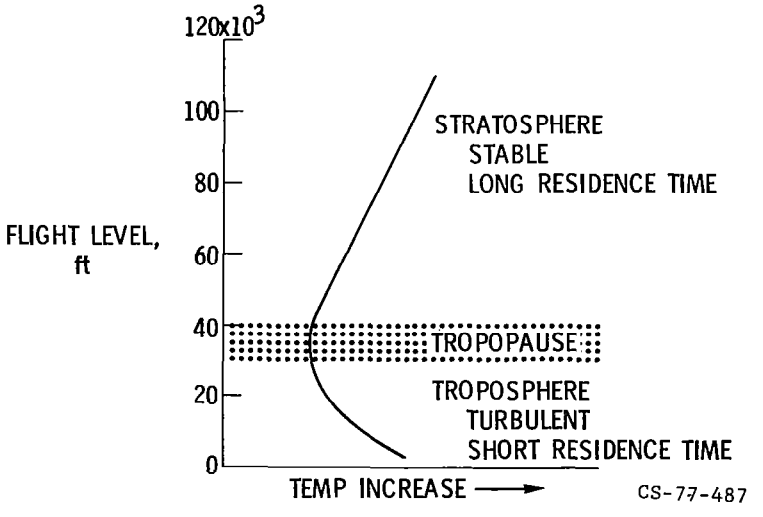


Figure XIII-13.

CASE STUDY FOR ATMOSPHERIC DATA FOR SEPTEMBER 2–3, 1976

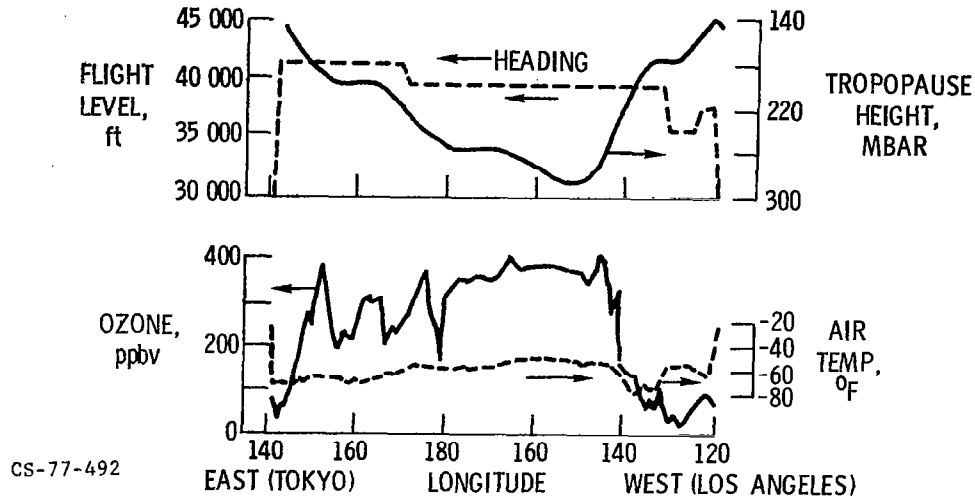


Figure XIII-14.

ATMOSPHERIC OZONE FOR MARCH 20, 1977

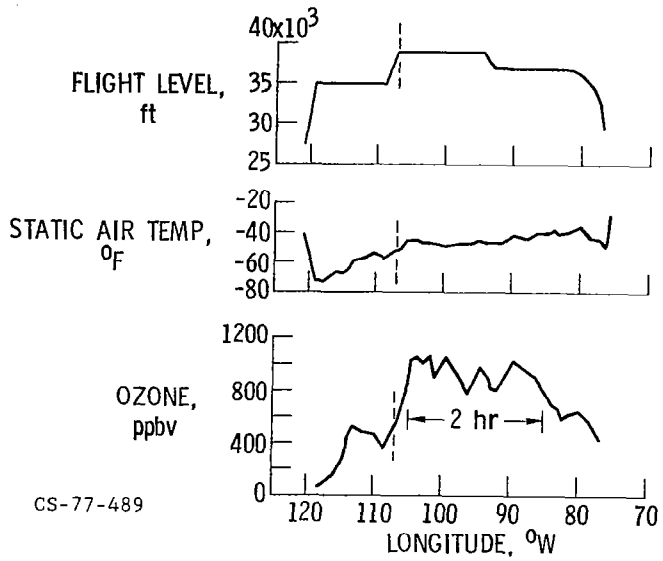


Figure XIII-15.

FLIGHT PATH BETWEEN NEW YORK AND SAN FRANCISCO

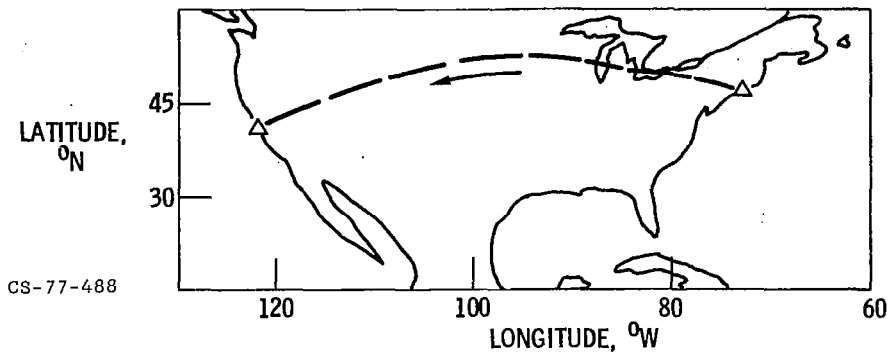


Figure XIII-16.

CORRELATION OF CABIN OZONE
WITH ATMOSPHERIC OZONE LEVELS

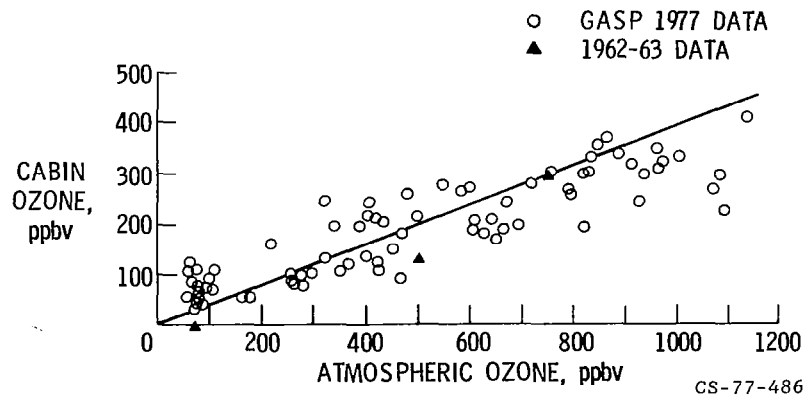


Figure XIII-17.

CONDENSATION NUCLEI AND OZONE

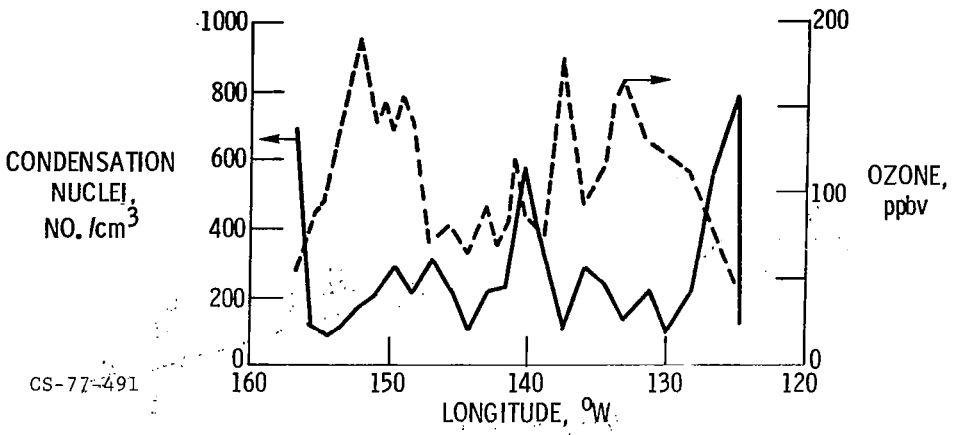


Figure XIII-18.

NASA
C-74-1669

UPPER ATMOSPHERE PARTICULATE SAMPLING WITH F106

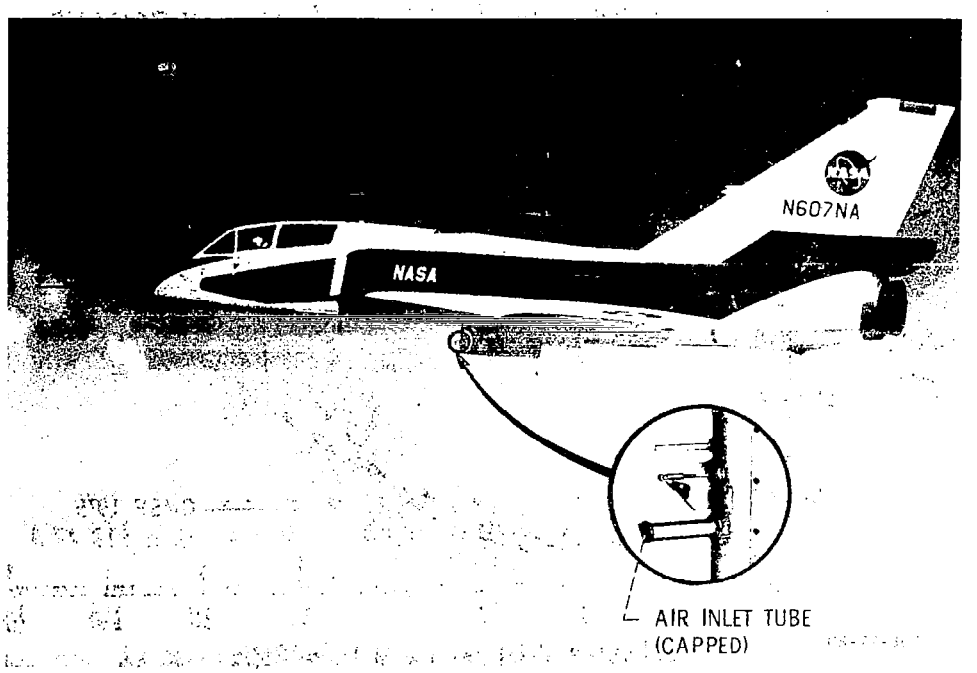


Figure XIII-19.

VARIATION IN SULFATE CONCENTRATION
BETWEEN STRATOSPHERE AND TROPOSPHERE

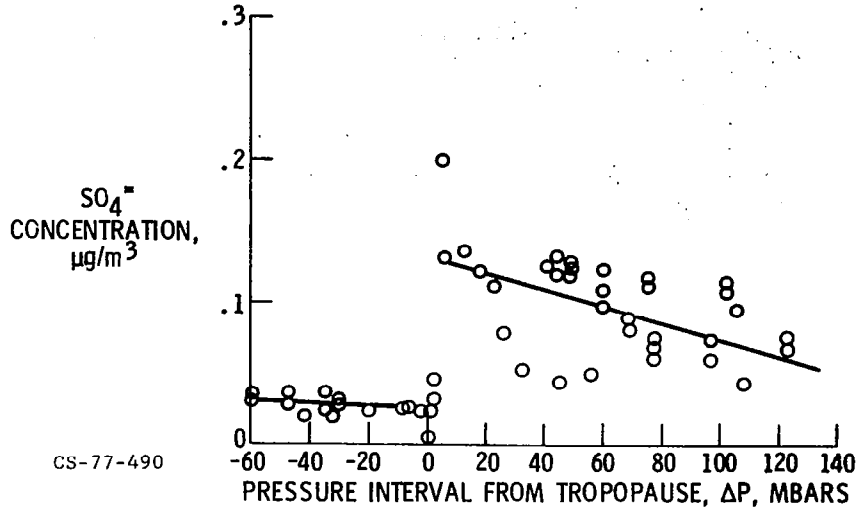


Figure XIII-20.

DISTRIBUTION OF OZONE WITH RESPECT TO TROPOPAUSE

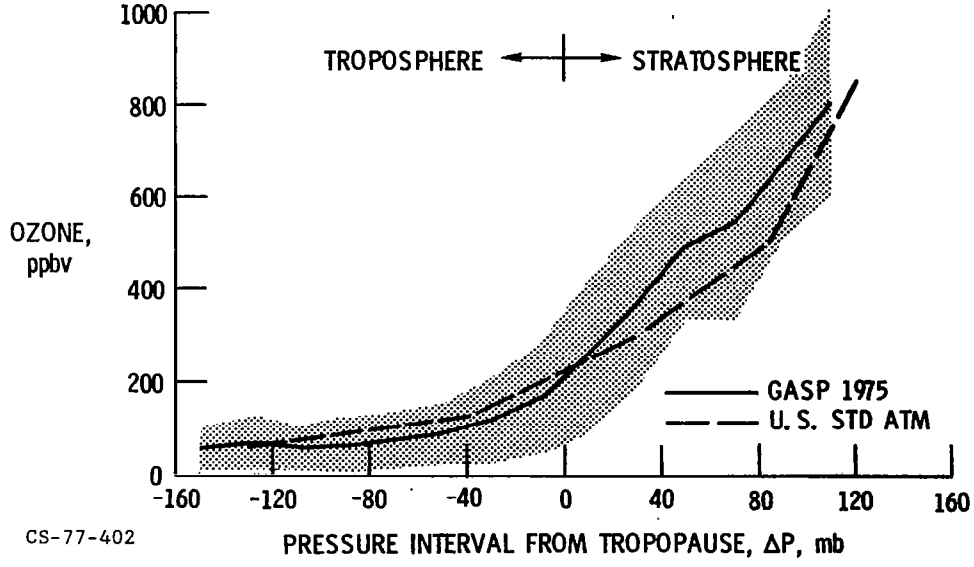


Figure XIII-21.

BIMONTHLY OZONE DISTRIBUTION FOR 37.5–47.5N LATITUDE

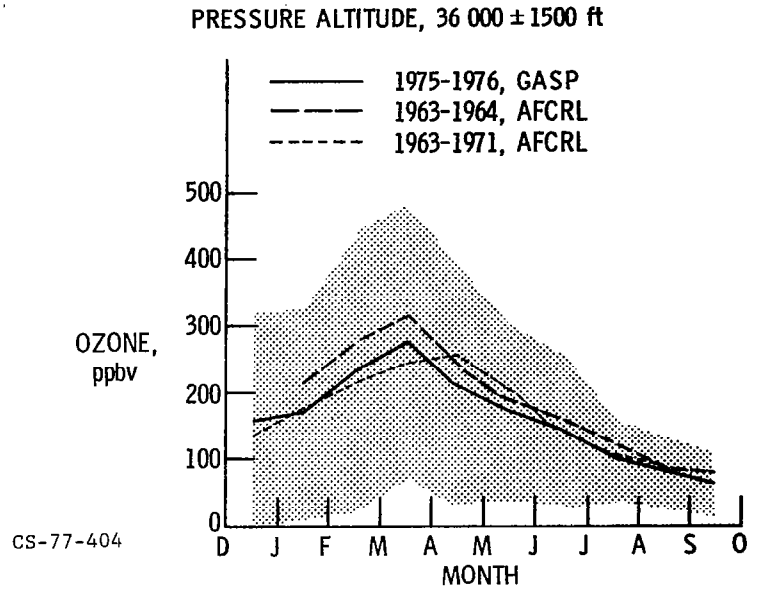


Figure XIII-22.

LATITUDINAL OZONE DISTRIBUTION FOR MARCH

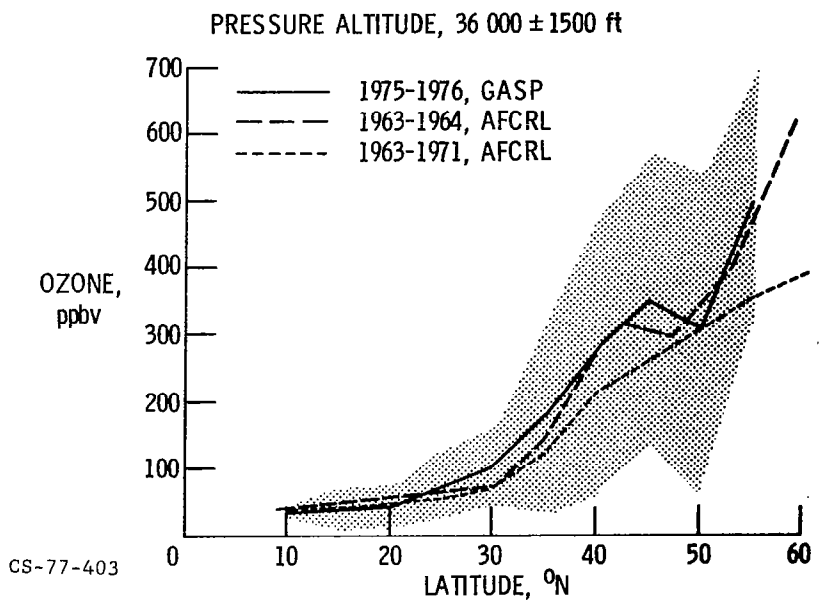


Figure XIII-23.

EFFECT OF WIND CURVATURE ON OZONE DISTRIBUTION

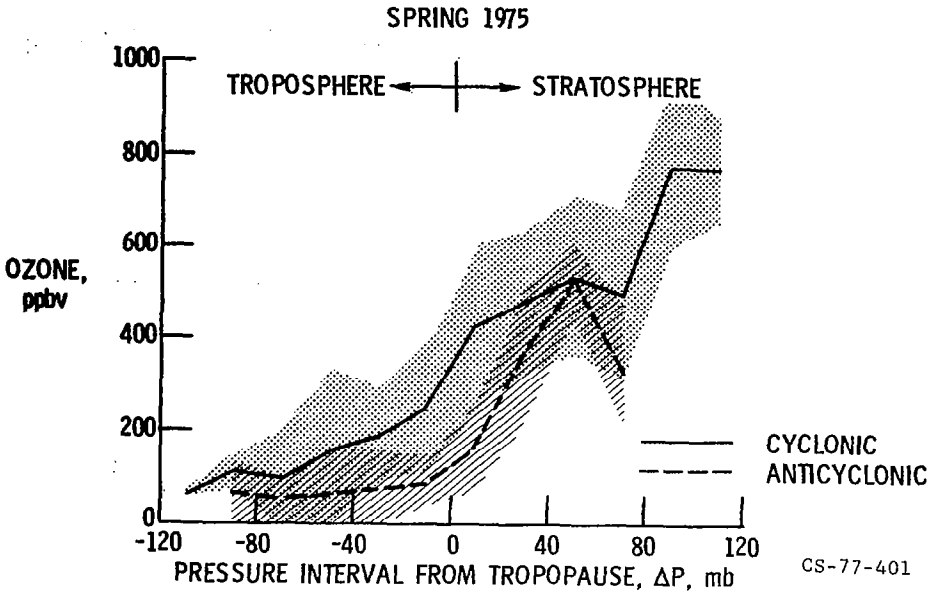


Figure XIII-24.

CORRELATION OF OZONE WITH POTENTIAL VORTICITY

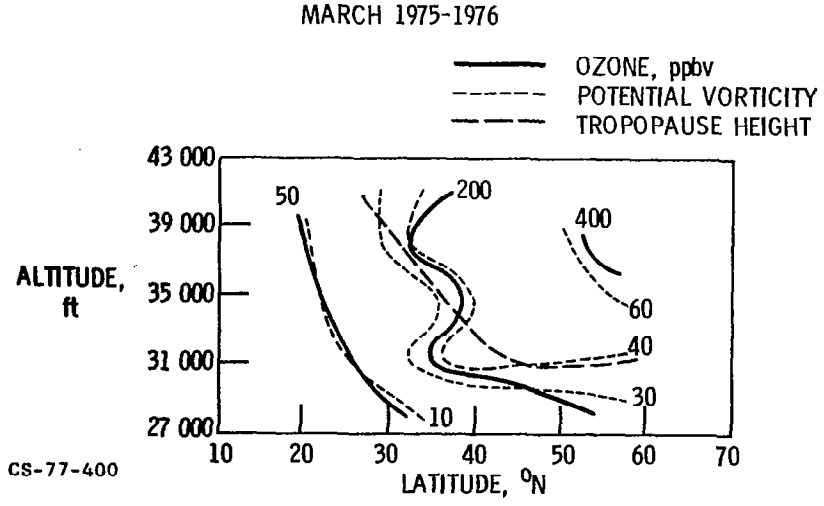


Figure XIII-25.