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GLOBAL MEASUREMENTS OF GASEOUS AND AEROSOL TRACE SPECIES IN THE UPPER TROPOSPHERE AND LOWER STRATOSPHERE FROM DAILY FLIGHTS OF 747 AIRLINERS

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Abstract

An extensive amount of atmospheric constituent data is collected by four airline-operated 747 aircraft equipped by NASA with special instrumentation. Data from areas not covered by the airlines are obtained less frequently using an instrumented NASA aircraft. Extensive measurements include ozone, carbon monoxide, water vapor, and aerosol and condensation nuclei number density. Less extensive measurements include chlorofluoromethanes (F-11), sulfates and nitrates. Certain meteorological and flight information are also recorded at the time of these measurements. World routes range in latitude from about 60° N near North America to about 40° S over Australia and 23° S over South America. Typical data show significant changes in ozone, carbon monoxide, and water vapor when crossing the tropopause either during changes in altitude or at cruise altitude. These gases as well as light scattering particles and condensation nuclei exhibit considerable variability along a flight route. Data tapes containing several of the measured constituents are available to researchers at the NOAA National Climatic Center.

Introduction

This report briefly describes the NASA Global Atmospheric Sampling Program (GASP) including the on-board system which collects atmospheric data automatically, the extensive atmospheric measurement capability, and the data handling and distribution procedures. Typical data and some examples of data selected from specific flights are also presented. These include ozone, carbon monoxide, water vapor, chlorofluoromethanes (F-11), and aerosols.

The GASP project utilizes 747 commercial airliners as instrumented flight platforms. This approach using four airliners operated by different airlines gives frequent and extensive global coverage of the upper troposphere and lower stratosphere. NASA aircraft (CV-990 and F-106) are also used to obtain data in off-route areas and in specialized tests.

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Data Acquisition and System Control

All major components of the data acquisition and system control are airborne units used by many airlines in normal flight data recording systems. The preprogramed processor for automatic system control is a modified Data Management Unit. This unit also provides certain data acquisition functions. Additional data acquisition is handled by a standard Flight Data Acquisition Unit. All data are recorded on a digital cassette recorder which is the same type Digital Aids Recorder (DAR) used by airlines for flight data recording. The GASP system is autonomous having dedicated units for all data acquisition and system control.

Automatic control of all system operations is provided by the small 8 K memory special purpose computer. Instruments are turned on during aircraft preflight. The computer or processor takes over control just prior to takeoff. A standby condition is held until a signal is received by the processor from the altimeter to set up the system for sampling. A basic 60-minute sampling cycle is constructed by alternating 5-minute air sampling and 5-minute calibration modes. Thus, there are six sample readings and six different calibrations taken each cycle. All data are recorded during a 16-second period at the end of each 5-minute air sampling and calibration modes. All instruments do not require the full six calibrations each hour. Where calibration data are not needed, air sample readings are taken. Before landing the system is returned to a standby condition.

Atmospheric Measurement Capability

Atmospheric constituents that are measured from the GASP equipped airlines are listed in Table I. Gases and particulates are shown separately. To date, the 747 airliners have been equipped to measure all constituents except oxides of nitrogen and condensation nuclei. However, airline qualified instrumentation to measure these two constituents is being acquired and some data have been taken with flight-type instruments on the NASA CV-990 aircraft. These instruments will be added to the 747 airliners in the near future.

The NASA Ames Research Center CV-990 has been used to flight test all of the instruments used on the 747's and, at the same time, has acquired atmospheric data. Dedicated flights are made to sample specific areas, to compare with other measuring techniques and to determine vertical profiles. An automated system similar to that on the 747's is installed on the CV-990 to obtain data from global areas not covered by the airline routes.

In addition to the air sample measurements, related data are also recorded. These include both flight and meteorological data listed in Table I. Flight data pinpoint precisely the time and location of each air sample data point. Data related to meteorology are also taken to describe conditions under which the atmospheric constituents are measured.

Gases

Ozone, water vapor, carbon monoxide, and oxides of nitrogen are real-time, in-situ measurements. Chlorofluoromethanes are measured by laboratory analysis of whole air samples periodically collected in stainless steel cylinders (grab-sampling).

Ozone. A continuous reading (update every 20 seconds) ultraviolet absorption photometer is used to measure ozone. The range is from 3 to 20,000 ppbv (parts per billion by volume) with a sensitivity of 3 ppbv. Calibration at NASA is made with a laboratory-type ozone generator over a range from 0 to 1,000 ppbv. The generator is periodically calibrated by the 1 percent neutral buffered potassium iodide method with an estimated accuracy of 7 percent. In-flight measurement of instrument zero is made by flowing the air sample through a charcoal filter external to the instrument.

A concern in the ozone measurement is the destruction of ozone in the lines from the inlet probe to the instrument, and in the sample pump that raises the sample pressure to 1 atm. The lines are teflon, and the pump is a teflon coated diaphragm pump. Ozone destruction through the aircraft installed system has been measured under conditions simulating operation in flight. Ozone destruction is approximately 16 percent of the concentration at the probe inlet. The ozone destruction data are used as a correction in the data reduction.

Water Vapor This instrument consists of a sensing element and a separate electronics unit. The sensing element is located in an externally mounted probe. An aluminum oxide sensor has been used up to this point in the program. Excessive time response to changes in temperature and humidity along with occasional contamination problems have limited the amount of valid data obtained from this instrument. A cooled-mirror frost point hygrometer is being acquired as a replacement to obtain better data.

The aluminum oxide sensors are calibrated by NASA over a range of dew-frost points from 0^{o} to -70^{o} C. Mixtures of dry nitrogen and air are used to vary the dew - frost point over this range. A laboratory-type cooled-mirror hygrometer is used as a reference measurement for calibrating the aluminum oxide sensors. Calibrations are made at room temperature, -20^{o}C and -40^{o}C. Sensors are periodically removed from the aircraft for NASA laboratory recalibration, and the data discarded if they do not agree within the uncertainty of the calibration system ($\pm$ 2^{o}C).

Carbon Monoxide. A non-dispersive infrared analyzer, using a dual-isotope fluorescence principle is used to measure carbon monoxide. Modifications of a commercial 0 to 20 ppm full-scale analyzer to a lower range of 0 to 1 ppm were made to achieve a sensitivity to 20 ppb. A prototype instrument having this low range sensitivity has been successfully flight tested on the CV-990 and is being installed on the 747's.

The instrument is calibrated at NASA using a commercially prepared gas mixture of approximately 18 ppm CO in N_2 combined with a dilution process.

In-flight tests on this instrument include a zero test produced by passing the air sample through a Hopkalite filter and a test to measure the gain of the electronic circuit.

Chlorofluoromethanes (F-11). This measurement is not made on a real-time basis. Instead, a unit mounted in the GASP equipment rack, consists of four 1-liter stainless steel bottles in which whole air "grab" samples are collected. The bottles and associated seal-off valves and plumbing are contained in a standard aircraft case. The entire case is replaced after all four bottles are filled with the desired whole air samples. The exposed bottles are returned to NASA for analysis using gas chromatography with an electron capture detector.

Oxide of Nitrogen. The chemiluminescence technique is used to measure nitric oxide. This instrument has been developed to measure very low concentrations of NO with an airborne unit. The limit of detectability is 0.05 ppbv. Instrument range is 0 to 2 ppbv.

The ozone needed for the chemiluminescent reaction with NO is generated within the instrument. In-flight calibrations are made with gas having less than 0.05 ppbv NO ("zero" point) and gas having about 1.0 ppb concentration of NO ("Span" point).

This instrument has been operated on the NASA aircraft and is to be installed on the airline 747's when repackaging to airline specifications is completed.

Particulates

Particle Number Density. This instrument utilizes the light scattering principle to measure the number density of airborne particles above about 0.5 microns diameter. It consists of two units; 1) a sensing unit mounted near the inlet probe, which contains the light source and optics; and 2) an electronics package mounted in the equipment rack, which contains the counting circuits.

The instrument accumulates a count of the number of particles in the air sample flow for a fixed period of time, normally 1 minute. The sample flow rate through the sensing unit (30 liters/min.) is measured using a choked venturi flowmeter.

Flight test experience with this instrument indicated that flight through a cloud resulted in a particle size distribution that is significantly different from that of a clear air sample, mainly in the total count of the largest size particles. A simple cloud detector is, therefore, obtained by observing the counting rate of the largest size particles. A modification of the particle counter instrument to provide a count rate that is related to cloud density gives cloud detector capability for the GASP systems.

Sulfate and Nitrate Concentrations. These measurements are made by laboratory analysis of filter elements exposed earlier in flight and returned to NASA. A filter element is inserted into a 76mm diameter air sampling duct for two hours and retracted into a cartridge by an actuator assembly developed at NASA. Airflow through the filter is measured by a venturi unit. Each filter (IPC cellulose fiber) is enclosed within a clean room assembled cartridge to prevent contamination.

Condensation Nuclei. The concentration per unit volume of condensation nuclei greater than 0.002 microns diameter is measured by condensing water on these small particles to form a visible cloud inside a tube. Light attenuation through the resulting fog is a function of the number of particles or enlarged nuclei in the enclosed volume. Condensation of water on the nuclei is produced by adding water to the air sample and suddenly reducing the pressure inside the air sample tube. The particles grow to about 20 microns diameter before the light attenuation measurement is made. Concentrations are measured once per second.

Pressurization of the air sample taken at altitude to nearly 1 atmosphere is necessary before entering the instrument. This is required for the proper expansion process in the sample tube. In order not to change the volumetric concentration of particles in the sample tube, the sample is pressurized by introducing pressurized cabin air in which all small particles have been filtered out.

Concentration range is 30 to 30,000 particles/cc. Calibration is determined by a Pollack counter which has been established as a reference.

Related Information

Flight Data. Aircraft data are recorded at the time data are read from the air constituent instruments. Position (latitude, longitude), altitude, headings, and airspeed are obtained from the inertial navigation system (INS) and central air data computer (CADC) that are on the aircraft. A separate clock-calendar unit is provided as part of the GASP system to give time and date (GMT).

Meteorological Data. Meteorological conditions existing at the time air constituent data are taken are somewhat limited to those measurements that are readily available. Outside air temperature and wind direction and velocity are easily obtained from the aircraft CADC and INS systems. Vertical acceleration (an indication of turbulence) is taken from the aircraft flight recording system. Cloud encounter are obtained from the large size range (greater than 3 microns) of the particle counter.

Vertical acceleration is always recorded as part of the normal data and in case of encountering significant turbulence, which is presently set at less than 0.8G or more than 1.2G, a special recording is taken. Normal sequences of data acquisition will be interrupted when these acceleration limits occur to take these special data. All data which has been stored in a memory eight seconds prior to the turbulence encounter will be recorded along with the real-time data. Thus, information shortly before the acceleration limits are encountered is obtained. The special recording will continue for 60 seconds after the acceleration limits have ceased. The acceleration is sampled at eight times per second. Thus, a fast response, time-amplitude trace of the acceleration variability can be made from the recorded digital data.

Information on cloud encounters from the particle counter is used to evaluate cloud density, time in clouds, and the number of cloud encounters. The counting rate indicates cloud density. Time in clouds is recorded as the number of seconds preset threshold values of counting rate are continuously exceeded. The threshold value has been determined from visual observations in flight to be a very light wispy type of cloud through which the aircraft is passing. Visibility remains good in this condition.

Tropopause pressures are independently obtained from the National Meteorological Center (NMC). Gridded data archives from NMC are space interpolated for each location of a GASP data point at the nearest time of observation.

Routes of GASP Equipped Aircraft

Air routes flown by the four 747 airliners equipped with GASP systems are shown in Figure 2a. Worldwide coverage is provided by the combined routes of Pan American, Qantas, and United Airlines. The route structure of United Airlines within the United States and to Hawaii is shown in more detail in Figure 2b.

World routes extend to about 60°N latitude near the North American Continent and to about 40°S latitude over Australia. Equatorial regions that are sampled are over the Pacific Ocean, Indian Ocean, India and South America. An around-the-world orbit with the same aircraft in about 45 hours is made at a random frequency by the Pan American aircraft. Directions are both eastbound and westbound. A long range Pan Am 747SP (Special Performance) aircraft equipped with a GASP system has been flying non-stop between New York and Tokyo and between Los Angeles and Tokyo. Qantas Airways provides measurements in the Southern Hemisphere over Australia and through the tropical regions to the Middle East and Europe and to the West Coast of the United States.

Routes over the contiguous United States and to Hawaii flown by United Airlines are between northeast coast cities (Boston and New York) and west coast cities (Seattle, San Francisco, Los Angeles). Routes between west coast cities and Chicago, Cleveland and Pittsburgh are also surveyed. Hawaiian flights operate from San Francisco, Los Angeles, Las Vegas and Chicago.

Data Acquisition Capability

Each GASP equipped aircraft flies about 10 hours per day giving coverage of 8600 Km (5400 miles) every day or about 13,000,000 Km (8,000,000 miles) per year for the four airline aircraft. A data set recorded every five minutes about (72 Km apart) in flight above 6Km (20,000 ft.) provides 12 data sets per hour per aircraft. Four aircraft provide 480 data sets per day. Each data set includes about 80 variables in three categories; air sample data, system operation information, and flight data including data related to meteorology. As an example, after removing calibration data, the 480 data sets provide 320 readings of ozone concentrations per day along the aircraft routes.

Data Dissemination

GASP data from the 747 airliners and the NASA aircraft follow the processing shown in the flow diagram of Figure 3. All data are received at the NASA, Lewis Research Center Computing Center where initial data tapes are processed. This procedure consists of compacting (deleting information taken for data validity and no longer needed) and formating for permanent records and future analysis.

Data Storage

Permanent data tapes consisting of several flights on each tape are sent to the NOAA storage center at Asheville, North Carolina (National Climatic Center). A flight is as customarily defined between the cities of departure and destination. A NASA publication is issued for each data tape sent to the data storage center.[6, 7] This report describes the data available on the tape and certain interesting aspects of the data. Processing procedures and tape specifications are also included in the report. The purpose of data storage at Asheville is to provide convenient access of all data by other atmospheric researchers on request.

Analysis

The major objectives are to measure and analyze those constituents of the atmosphere related to aircraft engine emissions. The analyses are directed toward defining baseline values of those constituents and detecting long term adverse changes, if any, in atmospheric quality. Other pollutants not related to aircraft engine emissions but of special interest to air quality and climatology such as the chlorofluoromethanes are measured and directed toward similar analyses.

The data are currently being analyzed with the assistance of other organizations. Relevant meteorological data (including the tropopause pressure) are obtained from NOAA. Case studies are performed related to meteorology.[8]

NASA-Lewis is maintaining complete documentation of all data that are obtained. Also, some specialized analyses of interesting flight records are performed at NASA and reported.

Typical GASP Flight Data

One example of GASP atmospheric data gathering capability is shown in figure 4. This set of data was obtained on the NASA GASP equipped aircraft. These data illustrate the real-time measurements that are normally taken every 5-minutes. Whole air (grab) samples and filter paper exposures are taken much less frequently and are analyzed at a later date. A "grab" sample can be taken every third day on each aircraft. A filter exposure can be recovered about once every two weeks from each aircraft. A multifilter modification to the existing single filter units planned for the near future will increase filter exposures to every third day.

Real-Time Measurements

The data plotted in figure 4 recorded every 5-minutes include:

1. Mixing ratios of ozone and carbon monoxide.
2. Number densities of condensation nuclei and light scattering particles above 0.25 microns radius.

3. Meteorological data consisting of wind speed and direction, air and frost point temperatures.

4. Aircraft altitude.

These data show that this flight passed through the tropopause on climb to 10.5 Km at about 1945 GMT and again on descent from 10.5 Km at about 2100 GMT. Penetration of the stratosphere is characterized by a sharp increase in ozone from less than 100 ppbv to nearly 400 ppbv. Concentrations of carbon monoxide dropped from about 150 ppbv to around 50 ppbv. The normal increase in air temperature is also seen. Dry stratospheric air is evident by the measurement of decreasing frost points although the sensor appears slow to respond.

Upon descent, entrance into the troposphere is characterized by a rapid drop of ozone and a return of carbon monoxide and water vapor to tropospheric values. Condensation nuclei number density varied about 2 orders of magnitude with the variability and measured values not showing differences between the troposphere and stratosphere. Particle concentrations varied less than 2 orders of magnitude between the troposphere and stratosphere. An increase in particle concentrations within the stratosphere appeared to be more closely associated with a shift in wind direction. More extensive data have shown particle concentrations to have generally less variability in the stratosphere than in the troposphere.

From the above data, crossing of the tropopause is evident by significant changes in ozone, carbon monoxide, water vapor, and the normal increase/decrease of air temperature. It should be noted that passage through the tropopause is commonly seen at constant flight altitude as well as in changes in altitude as illustrated in Figure 4. Thus, changes in tropopause height along the flight route are frequently observed. This can be seen in Figure 5 where ozone, air temperature, flight altitude and tropopause pressure are plotted along a westbound global flight route of a GASP equipped aircraft from San Francisco to Frankfurt, West Germany. Tropopause pressures were provided by the National Meteorological Center (NMC) data archives. Generally good correlation is seen between significant changes in ozone mixing ratios and crossing of the independently determined tropopause. A slight exception to this was a flight indication of penetrating the stratosphere (sharp increase in ozone) over the Middle East at a flight altitude below the NMC determined tropopause pressure. This was in an area of discontinuity in the derived tropopause pressure which could account for the lack of correlation.

Flight in the troposphere is experienced much of the time along the GASP flight routes. Flight time in the lower stratosphere is a function of altitude, season, and geographical location. Flights in the tropical regions are entirely within the troposphere whereas flights in more northern latitudes can be almost entirely in the lower stratosphere at cruise altitudes. An example of this was a nonstop flight from New Yrok to Tokyo on April 26, 1976 when the GASP equipped aircraft was in the stratosphere at cruise altitude for the entire flight of over 13 hours. A typical GASP flight entirely in the troposphere as determined by ozone measurements is shown in Figure 6. This was a flight from New York to Los Angeles on September 5, 1975 in which ozone mixing ratio varied between 30 ppbv and 90 ppbv. Although ozone mixing ratios are typically below 100 ppbv in the troposphere, values greater than 150 ppbv are occasionally measured below the tropopause derived from the NMC data archives. For an ozone measurement as shown in Figure 6, two values are recorded; the reading at the time the data were recorded (local reading), and an average (ave. reading) of six measurements taken during the 2-minutes previous to the time of the data record. The six instrument readouts are stored and averaged in the on-board computer.

Whole-Air Sample and Filter Measurements

Whole-air samples taken in flight and returned to NASA-Lewis are presently analyzed for CF Cl_3 (F-11). These samples can be analyzed for other constituents when desired. An example of CF Cl_3 from air samples taken in the troposphere on August 17, 1976 is:

$CFCl_3$ (pptv)	Altitude (Km)	Location
140	9.4	Southeastern Calif.
137	1.8	Near San Francisco
132	0.18	Over Pacific Ocean about 500 Km off north coast Calif.

The above samples were taken on the NASA CV-990 aircraft over a wide range of altitudes indicating in this case a rather uniform vertical distribution within the troposphere.

Filter elements exposed in flight and returned to NASA-Lewis are presently analyzed for sulfate ($SO_4^=$) and nitrate (NO_3^-) contained in the atmospheric aerosols collected on the filters. An example of values from filters exposed during March 1976 on scheduled airline flights at altitudes between 11 and 12 Km is:

Sulfate (micro-grams/m^3)	Nitrate (micro-grams/m^3)	Flights
.15	.08	London to New York
.03	.06	New York to San Fran.
.18	.10	Los Angeles to Chicago
.06	.07	San Francisco to Tokyo

The above filter samples were exposed for 2 hours during each flight. Detection limit is about .03 micro-grams/m^3.

Concluding Remarks

The NASA Global Atmospheric Sampling Program (GASP) is presently acquiring world-wide measurements of trace constituents in the troposphere and lower stratosphere. The unique approach of equipping 747 airliners with special instrumentation provides an extensive amount of data along commercial air routes. Four GASP equipped 747's operated by three different airlines sample the atmosphere along many of the airlines of the world on a random basis in that flight times and specific routes are not controlled. Data from areas not covered by these air routes are obtained on a less frequent basis from instrumented NASA aircraft.

Gaseous and aerosol trace species being measured include ozone, carbon monoxide, water vapor, chlorofluoromethanes (F-11), sulfates, nitrates, and aerosol and condensation nuclei number density. In addition to these measurements, data related to meteorology including air temperature, wind direction and velocity, and the presence of clouds in the flight path; and flight data including time, position (latitude, longitude, and altitude) and acceleration are recorded each time the trace species are measured.

World routes range in latitude from about 60°N near North America to about 40°S over Australia and 23°S over South America. Routes over the contiguous United States are between northeast coast cities and west coast cities. An air route between Hawaii, west coast cities, or Chicago is flown almost daily. The four instrumented aircraft average over 34,000 Km (21,000 miles) per day along various sections of these routes. Data are recorded every five minutes or at points about 72 Km apart at altitudes between 6 and 13.7 Km.

Convenient access to the data is provided to interested researchers. Data tapes are stored at the NOAA National Climatic Center in Asheville, North Carolina following processing at NASA. Notice of data availability is through NASA reports describing the information on the data tapes.

Typical GASP data show significant changes in ozone, carbon monoxide, and water vapor when crossing the tropopause. Tropospheric values of ozone generally less than 100 ppbv increase greatly when penetrating the stratosphere. Non-urban tropospheric values of carbon monoxide in the order of 150 ppbv decrease to about 50 ppbv in the lower stratosphere. These gases as well as light scattering particles and condensation nuclei exhibit considerable variability. Particle and condensation nuclei number densities vary over several orders of magnitude along a flight route. An example of sulfate and nitrate concentrations collected on filter elements in flight on different air routes range up to about 0.20 micrograms/m^3 for sulfates and 0.10 micrograms/m^3 for nitrates. An analysis of three whole air samples taken in flight over and near California showed tropospheric $CF\ Cl_3$ (F-11) to be about 140 pptv.

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TABLE I. - GASP MEASUREMENTS

Particulates	Gases
Number density (> 0.5 μm dia.)	Ozone
Condensation nuclei	Water vapor
Mass concentration of	Oxides of nitrogen
Sulfates	Carbon monoxide
Nitrates	Chlorofluoromethanes
Chlorides	

Related information

Flight data	Meteorological data
Time and date	Outside air temperature
Latitude	Wind direction
Longitude	Wind velocity
Altitude	Turbulence (vertical accel.)
Air speed	Cloud encounters
Heading	Tropopause pressure (from NMC)

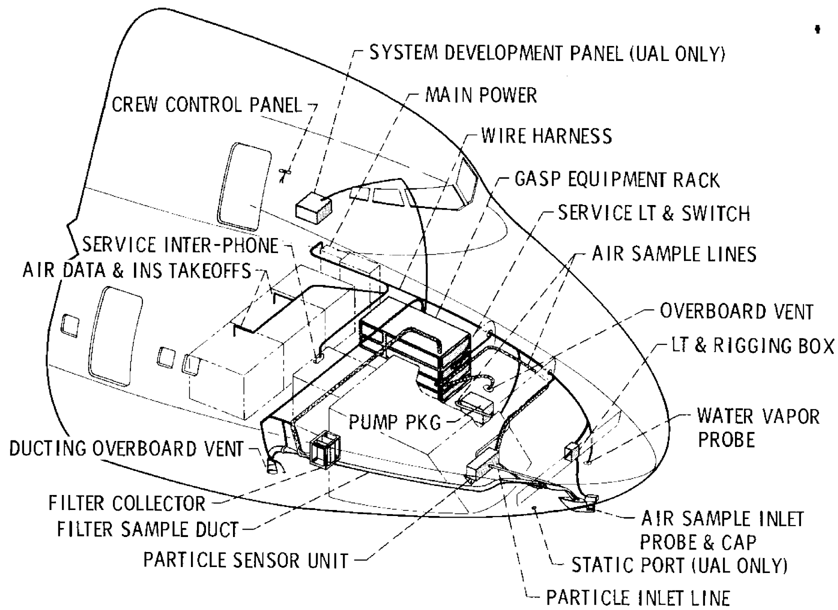

Figure 1. - GASP system installation on 747.

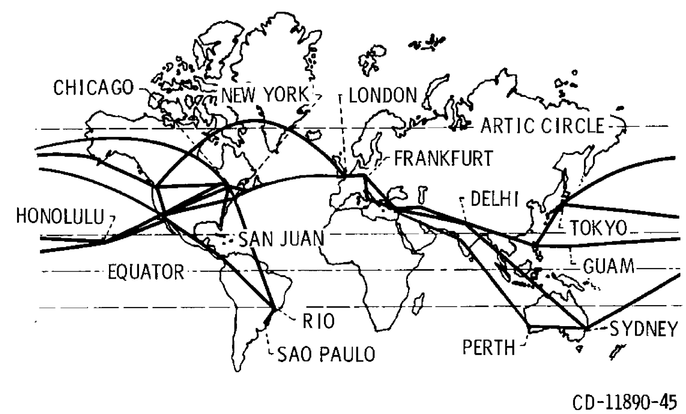

Figure 2a. - GASP global route structure.

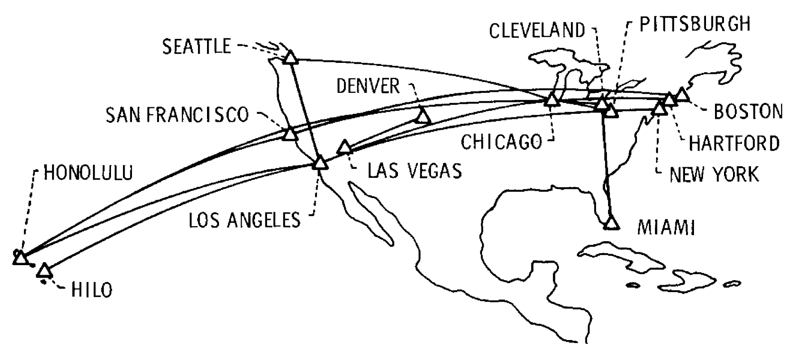

Figure 2b. - GASP route structure within the United States.

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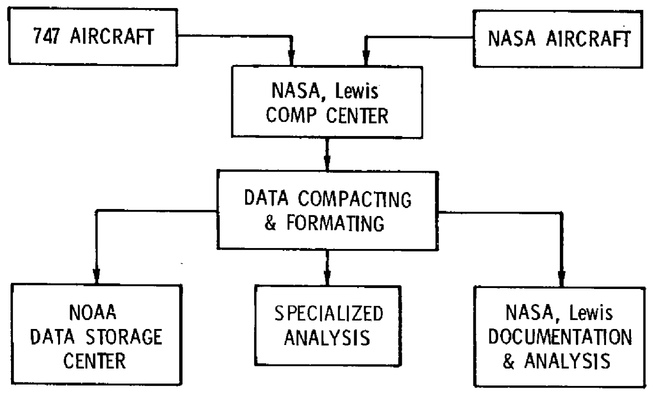

Figure 3. - GASP data flow diagram.

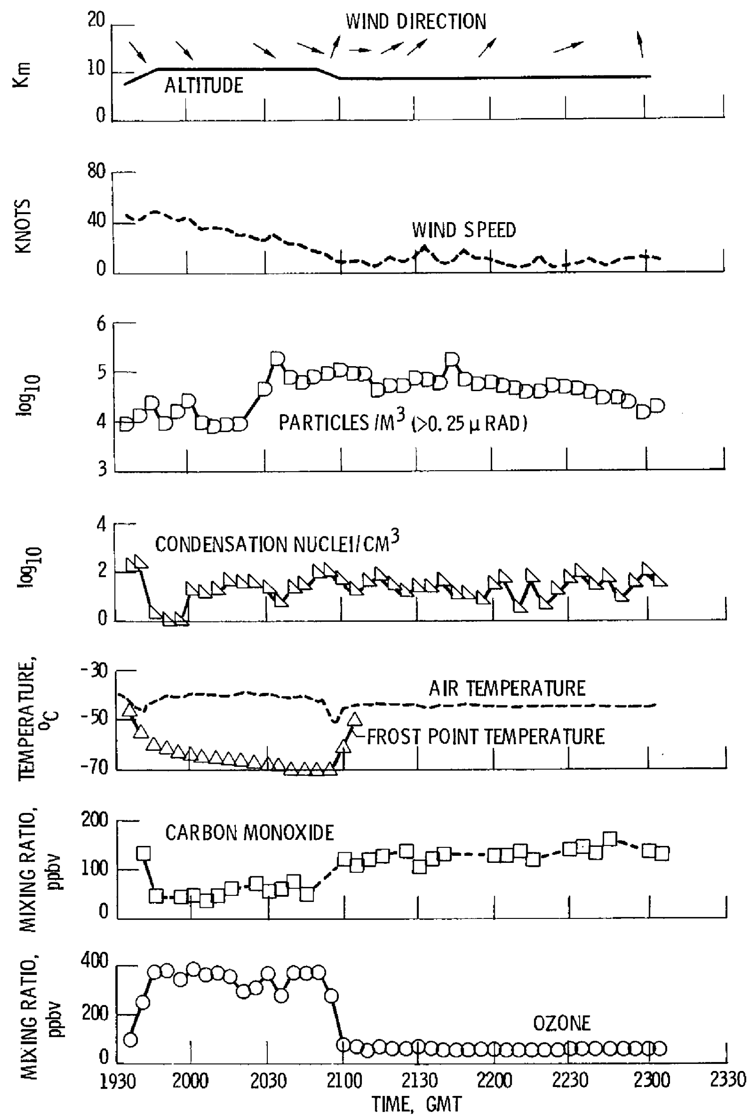

Figure 4. - Typical GASP flight data. The example taken on NASA CV-990 on August 27, 1975 at approximately 75° N - 143° W.

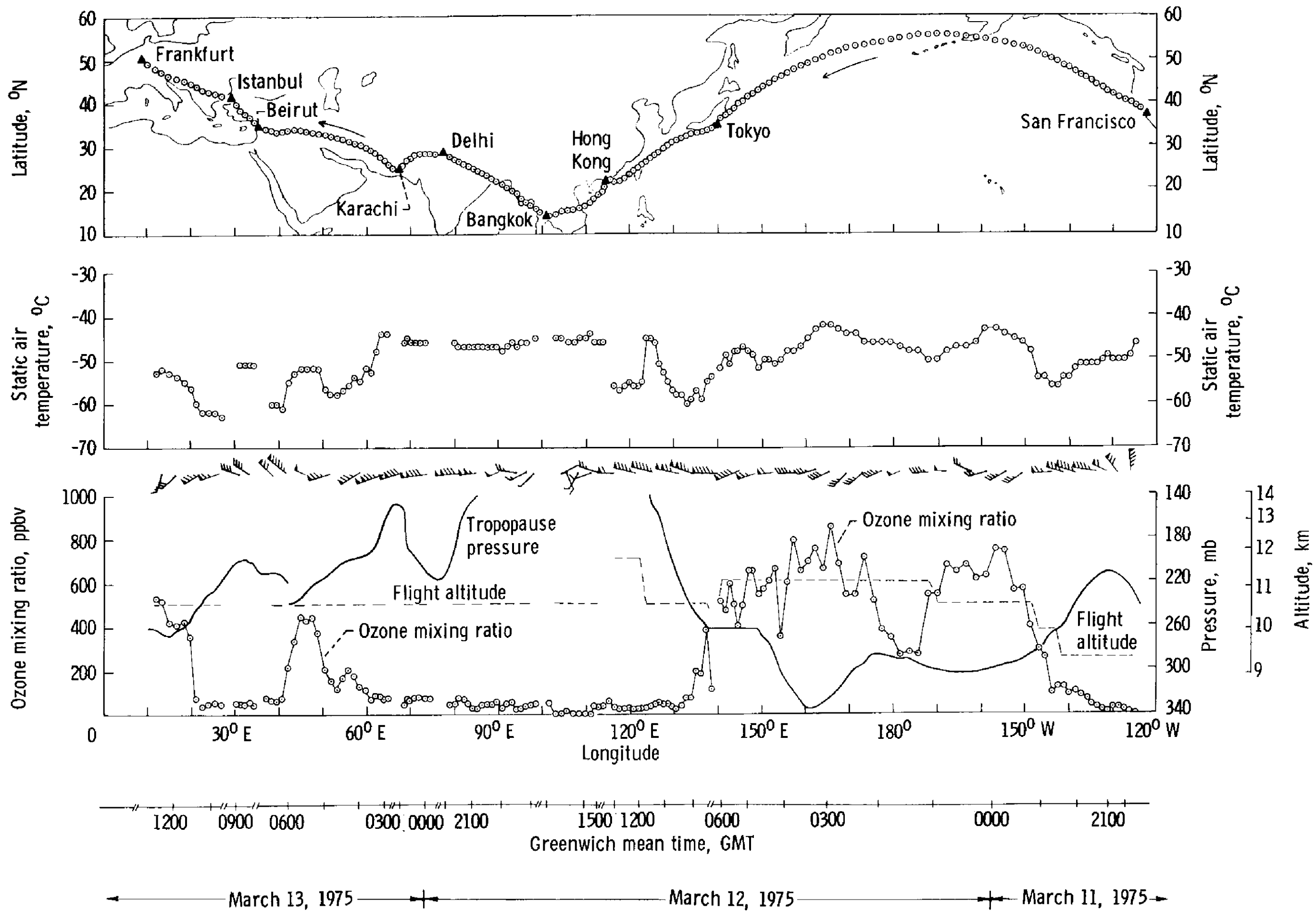

Figure 5. - Typical GASP flight data and independently derived tropopause pressure for a global flight of a Pan American 747.

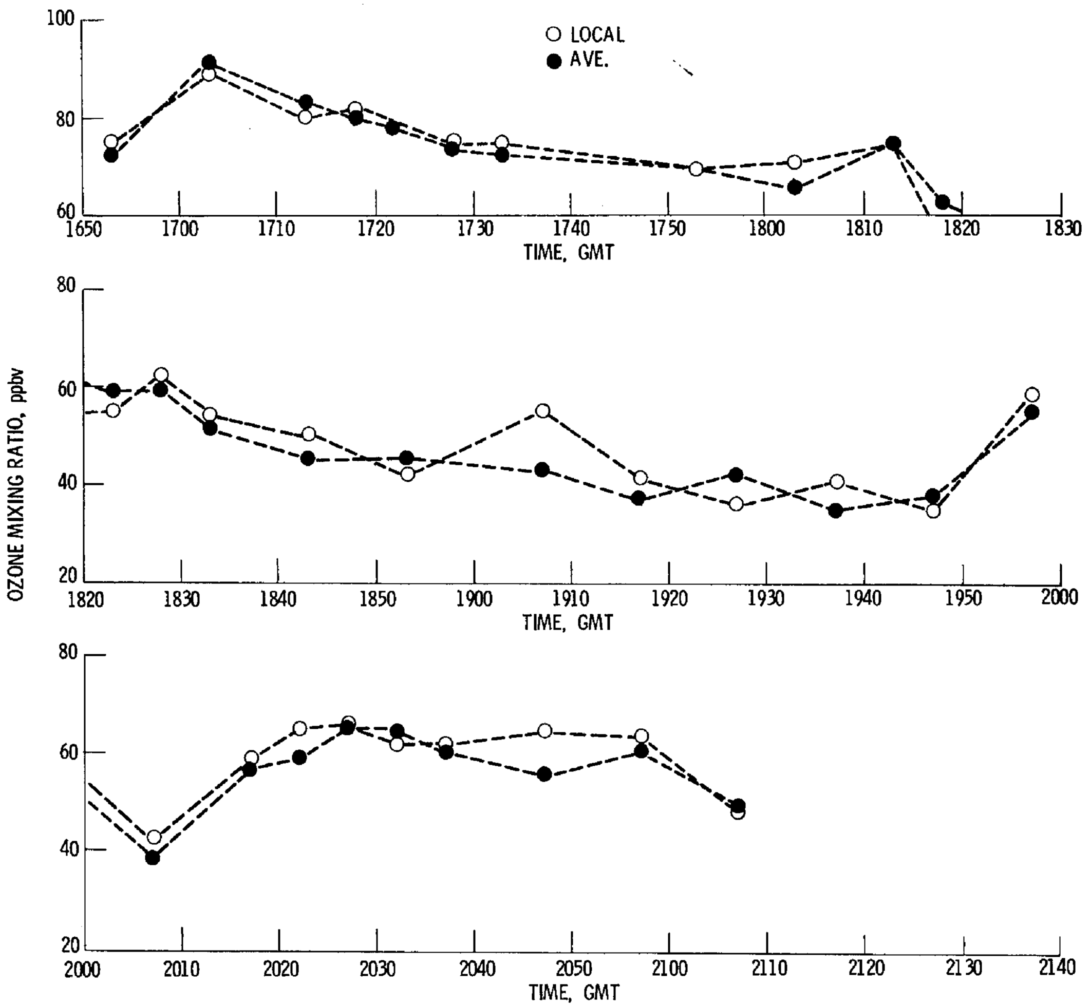

Figure 6. - Typical GASP ozone measurements in the troposphere. This example taken on United Airlines 747 on September 5, 1975 between New York and Los Angeles.

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