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COMPARISON OF OZONE MEASUREMENT TECHNIQUES USING AIRCRAFT, BALLOON, AND GROUND-BASED MEASUREMENTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1977

1. Report No. NASA TM X-3520	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPARISON OF OZONE MEASUREMENT TECHNIQUES USING AIRCRAFT, BALLOON, AND GROUND-BASED MEASUREMENTS		5. Report Date April 1977
		6. Performing Organization Code
7. Author(s) Daniel Briehl and Gregory M. Reck		8. Performing Organization Report No. E-8951
		10. Work Unit No. 197-10
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

In order to verify the ultraviolet absorption technique used in the Global Atmospheric Sampling Program, two flight experiments were conducted employing several techniques, both in situ and remote, for measuring atmospheric ozone. The first experiment used the NASA CV-990 equipped with an ultraviolet absorption ozone monitor and an ultraviolet spectrophotometer, a balloon ozonesonde, and a Dobson station for determining and comparing the ozone concentration data. A second experiment compared ozone data from an automated sampling system aboard a B-747 with data from a manned system installed on the NASA CV-990 during a cross-country flight with both aircraft following the same flight path separated by 32 kilometers.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Global Air Sampling Program; Air pollution; Atmospheric composition; Air quality; Gas analysis; Ozonometry	Unclassified - unlimited STAR Category 45

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	17	A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

COMPARISON OF OZONE MEASUREMENT TECHNIQUES USING AIRCRAFT, BALLOON, AND GROUND-BASED MEASUREMENTS

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SUMMARY

Two flight experiments were conducted employing several techniques for measuring the atmospheric ozone so that the ultraviolet absorption technique used in the Global Atmospheric Sampling Program (GASP) could be verified. In the first experiment, an in situ ultraviolet absorption monitor and an ultraviolet spectrophotometer on board the CV-990, a balloon ozonesonde, and a Dobson spectrophotometer were compared when the CV-990 overflew Wallops Island, Virginia, at six different altitudes on December 2, 1975. In the second experiment, a B-747 equipped with an automated sampling system and the CV-990 equipped with a manned system made a cross-country flight at the same altitude with the CV-990 32 kilometers behind the B-747 to compare the in situ ozone monitors on board each aircraft. Results of these tests showed that the in situ ultraviolet absorption ozone monitors used by GASP compared favorably with the other ozone measurement techniques, and an ultraviolet spectrophotometer appeared promising as a technique for obtaining overburden measurements.

INTRODUCTION

This report presents the results of a flight experiment conducted to compare several different ozone measurement techniques, including a balloon ozonesonde and a Dobson station, so that the in situ ozone measurements now being obtained routinely as part of the Global Atmospheric Sampling Program (GASP) (ref. 1) could be verified. In addition, flight measurements from in situ ozone monitors employing the same measurement technique installed in an automated B-747 system and a manned system on board the NASA CV-990 are compared to demonstrate that the two aircraft flying the same route would yield comparable ozone data. Finally, an ultraviolet spectrophotometer is examined for possible use on B-747 aircraft equipped with automated sampling systems.

The need for obtaining reliable data on the concentrations of a number of minor atmospheric constituents including ozone arises from the continuing concern regarding the effects of aircraft exhaust emissions on the troposphere and lower stratosphere. In its "Report of Findings," the Climatic Impact Assessment Program (ref. 2) emphasizes the urgent need for detailed measurements of the natural composition of the upper atmosphere as well as ongoing research and monitoring programs to obtain additional knowledge of the atmosphere, to detect changes in atmospheric quality, and to provide inputs for atmospheric models. Reference 2 suggests several constituents of importance in atmospheric investigation, including ozone.

The NASA Global Atmospheric Sampling Program (GASP) is currently underway at the Lewis Research Center using four commercial Boeing 747 airliners equipped with automated instrument systems to routinely collect in situ measurements of several minor atmospheric constituents including ozone (refs. 3 and 4). The NASA CV-990 research aircraft is used to evaluate sampling instruments and systems in flight as well as to confirm measurement methods (refs. 5 to 7). Reference 5 contains comparisons of two in situ ozone measurement techniques, the ultraviolet absorption technique and the electrochemical concentration cell (ECC) technique, which was used on the ozonesonde. Agreement between the two instruments in the reference was within 20 parts per billion by volume (ppbv) for the range of ambient concentrations encountered.

DESCRIPTION OF INSTRUMENTS

In Situ Ozone Monitor

The B-747 and the CV-990 were equipped with a self-contained ultraviolet absorption photometer, which is described in reference 8. In addition, the CV-990 was equipped with an electrochemical cell ozone monitor (ref. 9) as a backup in the event of a failure of the ultraviolet absorption photometer. On the CV-990 the sample inlet and discharge probes were installed in a passenger window frame in the forward part of the aircraft. Isolation ball valves and a bypass line permitted purging the inlet probe with ambient air when measurements were not being taken. On the B-747 the sample inlet probe was located near the nose of the aircraft. The probe was closed at altitudes below 6 kilometers. On both aircraft, the sample air is pressurized to 1.013×10^5 newtons per square meter (1 atm) with a single-stage diaphragm pump.

The ultraviolet absorption photometer alternately passed the sample air and ozone-free sample air (obtained by passing the air through an ozone destruction catalyst) through a 71-centimeter-long tube and measured the difference in intensity of an ultraviolet beam traversing the same path length. The difference was converted into the ozone mixing ratio. The instrument employs a reference system which compensates for variations in the optical components, interfering gases, and variations in the ultraviolet source. The ultraviolet absorption and the electrochemical concentration cell ozone instruments were checked in the laboratory over the range of 0 to 1000 ppbv against an ozone generator calibrated by the 1-percent neutral buffered potassium iodide (KI) method. The estimated accuracy of the KI procedure is 7 percent.

Ozone results reported herein were corrected for ozone destruction in the inlet tubing and pressurization system. Tests indicated that the ozone destruction was a linear function of inlet concentration over the range of 45 to 975 ppbv and was 12 percent for the CV-990 and 22 percent for the B-747. The tests were made on both aircraft a few days before the flight experiments.

Ultraviolet Spectrophotometer

The CV-990 was equipped with an ultraviolet spectrophotometer (UVS) for evaluation as a possible future instrument on GASP-equipped B-747 airliners. The total ozone overburden was calculated from measurements of downward ultraviolet radiation from 400 to 200 nanometers. Ultraviolet flux was measured omnidirectionally (throughout the optical acceptance angle) by a diffuser, a movable wheel containing bandpass filters, and an ultraviolet photomultiplier. The instrument is described in detail in reference 10.

The UVS was originally designed for another aircraft with the instrument optics protruding through the aircraft skin, thus giving the instrument an unobstructed view angle. However, due to the mounting modifications necessary on the CV-990, the optical acceptance half-angle was reduced from 75° to 59° from the vertical. The instrument was installed below a zenith port equipped with an ultraviolet grade quartz window. The instrument was cooled with thermoelectric coolers, and conditioned air was circulated across the quartz window to prevent condensation of water vapor. As a result of the reduction of the acceptance half-angle, it was impossible to view the Sun directly because of the solar declination in December when the measurements were made. Only the Rayleigh scattered ultraviolet component could be measured; however, the analysis procedure used still gives a value for the total ozone above the flight level, but this value becomes less accurate at altitudes above about 10 kilometers where most of the Rayleigh scattering takes place in the ozone layer. In future installations reductions in the acceptance half-angle could be eliminated by mounting the UVS flush with the aircraft skin.

Balloon Ozonesonde

The balloon ozonesonde used an in situ electrochemical concentration cell. Cell output and static air temperature were telemetered from the ozonesonde up to 33.8 kilometers, the burst altitude.

Dobson Spectrophotometer

The Dobson spectrophotometer (DS) was located at the NASA Wallops Flight Center, Wallops Island, Virginia. The DS is a specialized double beam monochrometer used for determining atmospheric total ozone overburden by measuring the ratio of the intensities of two selected wavelengths of ultraviolet light in the solar spectrum (ref. 11).

RESULTS AND DISCUSSION

Wallops Overflight

The CV-990 equipped with an in situ ultraviolet absorption photometer and an ultraviolet spectrophotometer overflew NASA Wallops Flight Center, Wallops Island, Virginia six times on December 2, 1975, between 1650 and 1935 GMT. The flight path of the CV-990 are shown in figure 1. Flight altitudes were 4.4, 6.1, 7.6, 9.5, 10.7, and 12.2 kilometers. Flight time at each altitude was at least 15 minutes with each pass centered over Wallops Flight Center. The flight pattern was an approach to Wallops from the south at 4.4 kilometers for the first leg, a 180° turn, and then a climb to 6.1 kilometers for the next leg along the same flight path. This pattern continued until the altitude survey was completed. Figure 2 shows variation in ozone concentration as measured by the in situ ozone monitor, flight altitude, wind speed and direction, and static air temperature as a function of GMT. Data in figure 2 are plotted at 5-minute intervals, although data from the in situ ozone monitor were available at 20-second intervals.

At altitudes of 4.4, 6.1, and 7.6 kilometers, ozone concentrations were below 70 ppbv. Also, little change in concentration occurred as the aircraft climbed from 4.4 to 6.1 kilometers and from 6.1 to 7.6 kilometers, thus indicating fairly uniform ozone distribution at the lower altitudes. The ozone concentration increased slightly over the levels for the 7.6-kilometer run during the 9.5-kilometer run; the average ozone concentration at 9.5 kilometers was 81 ppbv. The largest increase in ozone concentration was observed during the climb from 9.5 to 10.7 kilometers; the average ozone concentration at this altitude was 145 ppbv. Only a small increase in ozone concentration was observed during the final climb to 12.2 kilometers; however, after reaching this altitude, the ozone concentration began to increase over a 10-minute period to a maximum value of 210 ppbv, and the average concentration at this altitude was 185 ppbv.

The ozonesonde was launched at 1904 GMT from Wallops Island as the CV-990 was starting its final altitude run. The ozonesonde flight path is included in figure 1. Table I shows the temporal and spatial separation of the ozonesonde and the CV-990 during the survey. Wind direction measured from the CV-990 closely paralleled the balloon track indicating that the two platforms probably sampled the same air mass.

The static air temperature profiles as measured from the CV-990 and the ozonesonde are compared in figure 3. The temperature profiles agree well, particularly above 7 kilometers where agreement is within 2 C^{o}. The tropopause began at approximately 10.5 kilometers where the National Climatic Center definition of a lapse rate of less than 2.5 C^{o} per kilometer is taken to define the tropopause. Thus, the final altitude run at 12.2 kilometers was above the tropopause. These data compare favorably with the National Weather Service (NWS) tropopause data for 0000 GMT on December 3, 1975, which shows a tropopause altitude of 264 hectopascals (mb) and a tropopause temperature of -51^{o} C over the Wallops Flight Center. However, during the period from 1200 GMT on December 2, 1975, to 0000 GMT on December 3, 1975, the NWS data showed a change in tropopause height over Wallops from 200 to 264 hectopascals. Thus, tropopause conditions were changing considerably during the period of the flight experiment. Note that the ozonesonde static air temperature profile indicates a "double tropopause," the second occurring at 16.2 kilometers where there is a definite increase in temperature with altitude.

Vertical ozone profiles as measured by the ozonesonde and the in situ ultraviolet absorption instrument are compared in figure 4. Ozonesonde data are plotted only up to 13.6 kilometers in figure 4; however, ozonesonde data up to burst altitude (33.8 km) are given in table II. Bars through the CV-990 ozone data in figure 4 indicate the spread in data at each altitude. Agreement is quite good except for the data point at 9.5 kilometers where the slope of the CV-990 profile is considerably less than the slope of the ozonesonde profile and the measurements differ by 36 ppbv. The average difference between the remaining ultraviolet absorption data points and the interpolated ozonesonde profile is 10.5 ppbv. The difference in ozone concentrations measured at the 9.5-kilometer altitude near the observed tropopause is not surprising in view of the time separation of the measurements (from table II) and the variations in tropopause height during the experiment.

In addition to the in situ ozone monitor, the ultraviolet spectrophotometer (UVS) was operating during the Wallops overflights. The total ozone values calculated from the UVS data are compared with the integrated ozonesonde profile in table III. The UVS and the ozonesonde measurements are in good agreement at 9.5 and 10.7 kilometers even though the UVS has an uncertainty of about 5 percent. The UVS measurement at 12.2 kilometers indicates about 20 percent less ozone than the integrated ozonesonde value.

This difference is to be expected in the Rayleigh scattered component. On future installations on the B-747's automated GASP sampling system, the UVS will be mounted flush with the aircraft skin so that there will be no installation-imposed limitation on the acceptance angle of the instrument.

Table III also lists the results of three DS readings taken on the day of the ozonesonde launch and the CV-990 overflights. The DS was located at the NASA Wallops Flight Center. All the readings are in excellent agreement with the integrated ozonesonde value. The DS reading closest to the time of the ozonesonde launch was 5 percent lower than the integrated ozonesonde value. Thus, both the in situ measurements, the ozonesonde, and the CV-990 ultraviolet absorption photometer, were in good agreement with the integrated measurements from the DS and the UVS.

CV-990/B-747 Ozone Measurement Comparison

In order to verify the in situ ozone ultraviolet absorption measurement technique employed on the B-747's automated GASP system, a chase flight was arranged in which the CV-990 followed a GASP-equipped B-747 on a cross-country flight for 2.88 hours on November 28, 1975. The CV-990 flight path, including a 30-minute loiter over Nevada and the rendezvous, is shown in figure 5. The B-747 aircraft was on a regularly scheduled flight from San Francisco to Boston. The CV-990 flight originated from Moffett Field, California, broke off from the chase at 2350 GMT over Carleton, Michigan, and terminated at Selfridge AFB, Michigan. The two aircraft rendezvoused at a 11.3-kilometer altitude at 2057 GMT with the CV-990 retaining a 32-kilometer separation from the B-747 during the chase.

An observer on board the B-747 was equipped with a portable panel which was used to check the GASP system operational status as well as manually extract data. Communications were maintained between the observer on the B-747 and the personnel on the CV-990 as the chase progressed. Two failures militated against complete success on this experiment. The first failure was the digital tape recorder on board the B-747. This failure necessitated obtaining all data manually with the portable panel. The second failure occurred when a leak developed in the in situ ultraviolet absorption ozone monitor on board the CV-990 at 2200 GMT. Fortunately, the leak had no effect on the backup electrochemical concentration cell ozone monitor on the CV-990 which provided in situ ozone data for the balance of the flight.

The results of the flight are shown in figure 6. With the exception of a single data point at 2115 GMT, the agreement between the ozone measurements on both aircraft was good. Table IV summarizes the available data from the ultraviolet absorption ozone monitor on the B-747 and compares these data with data from the CV-990. Agreement was within 27 ppbv on the average. It should be noted that the comparisons are made on the basis of data taken at the same GMT and not the same position. At the average speeds of the two aircraft, the 32-kilometer separation corresponded to over a 2-minute delay before the CV-990 reached the same sampling position as the B-747. This effect may have contributed to the difference in ozone concentration observed at 2115 GMT when the ozone concentration was changing rapidly.

The ozone concentration data indicate that both aircraft encountered high ozone concentrations during the initial portion of the flight and an ozone peak at approximately 2125 GMT. Figure 5 includes a tropopause pressure analysis derived from data supplied by the NWS for 0000 GMT on November 29, 1975 (approximately the end of the rendezvous). The data indicate a steep gradient in tropopause pressure over western Nevada and the ozone peak is nearly coincident with the region of maximum pressure indicating a stratospheric penetration. An earlier tropopause analysis at 1200 GMT on November 28, 1975, showed a tropopause pressure of 360 hectopascals over most of western Nevada and at least 300 hectopascals over central and northern California. Thus, the high ozone concentrations observed during the CV-990 loitering maneuvers prior to 2057 GMT were also obtained in stratospheric air. The location of the peak ozone concentration agrees with the observation of reference 12 of ozone maxima in the lower stratosphere associated with the shift in wind direction from northwesterly to southwesterly near a trough. The drop in CV-990 static air temperature data at approximately 2200 GMP coincided with the upward sloping tropopause shown in figure 5 over Colorado; the remainder of the flight was close to the tropopause.

SUMMARY OF RESULTS

Two separate flight experiments were performed to verify the ultraviolet absorption ozone measurement technique employed in the Global Atmospheric Sampling Program and to evaluate a UVS for ozone overburden measurements. In the first experiment, the CV-990 overflew Wallops Island, Virginia, at six different altitudes; the measurements were made with the in situ ultraviolet absorption ozone monitor and compared to data taken by an ozonesonde launched from Wallops during the overflight. Also, the integrated ozone data from the ozonesonde were compared with total ozone data from both an ultraviolet ozone spectrophotometer on board the CV-990 and a Dobson spectrophotometer located at Wallops. In the second experiment, data taken from in situ ozone monitors on board the CV-990 and a GASP-equipped B-747 were compared for a flight in which the CV-990 chased the B-747 on a 2.88-hour cross-country flight. Results are as follows:

1. The ozone altitude profile obtained by the in situ ultraviolet absorption monitor on board the CV-990 compared well with the ozone profile obtained from the ozonesonde. The maximum difference of 36 ppbv occurred at the tropopause altitude (9.5 km). The

average difference between the remaining ultraviolet absorption data points and the interpolated ozonesonde profile was 10.5 ppbv.

2. Total ozone as measured by the UVS compared favorably with total ozone from the integrated ozonesonde data except at 12.2 kilometers where the UVS has a 20 percent inherent uncertainty. The ultraviolet spectrophotometer therefore proved to be a good candidate for installation in GASP-equipped B-747's provided it is mounted flush with the aircraft skin so that there is no reduction in the acceptance angle.

3. Three Dobson spectrophotometer total ozone readings were in excellent agreement with the integrated ozonesonde total ozone measurements.

4. Both the in situ measurements, the ozonesonde, and the CV-990 ultraviolet absorption photometer were in good agreement with the integrated ozone measurements from the DS and the UVS.

5. During the CV-990/B-747 chase flight the ozone monitors on board the CV-990 agreed with the ultraviolet absorption monitor on board the B-747 to within 27 ppbv on the average.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 30, 1976,
197-10.

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TABLE I. - POSITION DATA FOR CV-990 AND OZONESONDE

Altitude, km	Start, GMT	Finish, GMT	Heading, deg	Separation,[a] km	Separation,[a] hr:min
4.4	1650	1717	21	56.5	2:16
6.4	1720	1751	215	20.5	1:50
7.6	1755	1813	21	37.2	1:27
9.5	1816	1841	215	63.5	1:08
10.7	1846	1904	21	31.3	0:48
12.2	1908	1934	215	74.0	0:27

[a]Computed at Wallops Island, Virginia.

TABLE II. - OZONESONDE DATA

GMT	Ambient temperature, °C	Position				Altitude, m	Ozone concentration, ppbv
		West longitude,		North latitude,			
		deg	min	deg	min		
19:04:11	7.8	75	29.0	37	50.5	3	25
19:04:21	6.5	75	28.6	37	50.7	153	23
19:09:41	.3	75	28.3	37	51.1	1 477	35
19:15:31	-8.0	75	25.7	37	51.0	3 013	37
19:24:21	-24.0	75	17.9	37	51.1	5 550	50
19:29:31	-36.2	74	59.8	37	51.6	7 140	48
19:36:51	-45.6	74	59.0	37	53.9	9 088	120
19:41:11	-48.7	74	52.0	37	55.9	10 283	144
19:46:41	-50.0	74	42.1	37	59.7	11 737	165
19:54:11	-52.5	74	28.4	38	2.4	13 591	327
20:05:01	-59.3	74	13.6	38	3.5	16 174	360
20:13:51	-58.2	74	7.1	38	4.3	18 403	1 540
20:18:11	-57.2	74	4.5	38	4.7	19 480	1 470
20:22:31	-58.0	74	2.6	38	6.0	20 517	2 060
20:26:41	-54.6	73	.3	38	6.4	23 080	5 040
20:34:51	-55.4	73	53.6	38	7.6	23 760	5 040
20:44:01	-48.6	73	46.4	38	10.0	26 310	6 350
20:59:11	-37.4	73	30.6	38	20.5	30 932	9 000
-------	-33.2	--	----	--	----	33 424	9 450
-------	-32.8	--	----	--	----	33 850	10 150

TABLE III. - COMPARISON OF UVS, OZONESONDE, AND DOBSON DATA

GMT	Altitude, km	Solar zenith angle, deg	UVS Ozone, atm-cm	Integrated sonde ozone, atm-cm	$\left(\frac{\text{UVS } O_3}{\text{Sonde } O_3}\right)$	Dobson ozone, atm-cm	$\left(\frac{\text{Sonde } O_3}{\text{Dobson } O_3}\right)$
1822	9.5	64.0	0.312	0.312	1.000	-----	-----
1836	9.5	63.7	.310	.312	.994	-----	-----
1853	10.7	66.3	.319	.307	1.039	-----	-----
1917	12.2	69.3	.250	.301	.831	-----	-----
1926	12.2	69.3	.233	.301	.774	-----	-----
1523	----	----	-----	.340	-----	0.322	1.056
1728	----	----	-----	.340	-----	.327	1.040
1920	----	----	-----	.340	-----	.323	1.053

TABLE IV. - COMPARISON OF OZONE DATA FROM

CV-990 AND B-747 TAKEN DURING CHASE FLIGHT

GMT	B-747 ultraviolet absorption ozone, ppbv	CV-990 ultraviolet absorption or electrochemical concentration cell ozone, ppbv	Difference, ppbv
2115	293	160	+133
2123	359	285	+74
2123	339	285	+54
2143	122	90	+32
2143	107	90	+17
2143	96	90	+6
2155	83	82	+1
2200	49	40	+9
2207	89	---	----
2215	71	89	-18
2223	73	89	-16
2235	92	85	+7
2255	126	117	+9
2305	127	88	+39
2313	135	89	+46
2321	129	78	+51
2331	104	82	+22
2341	53	59	-6

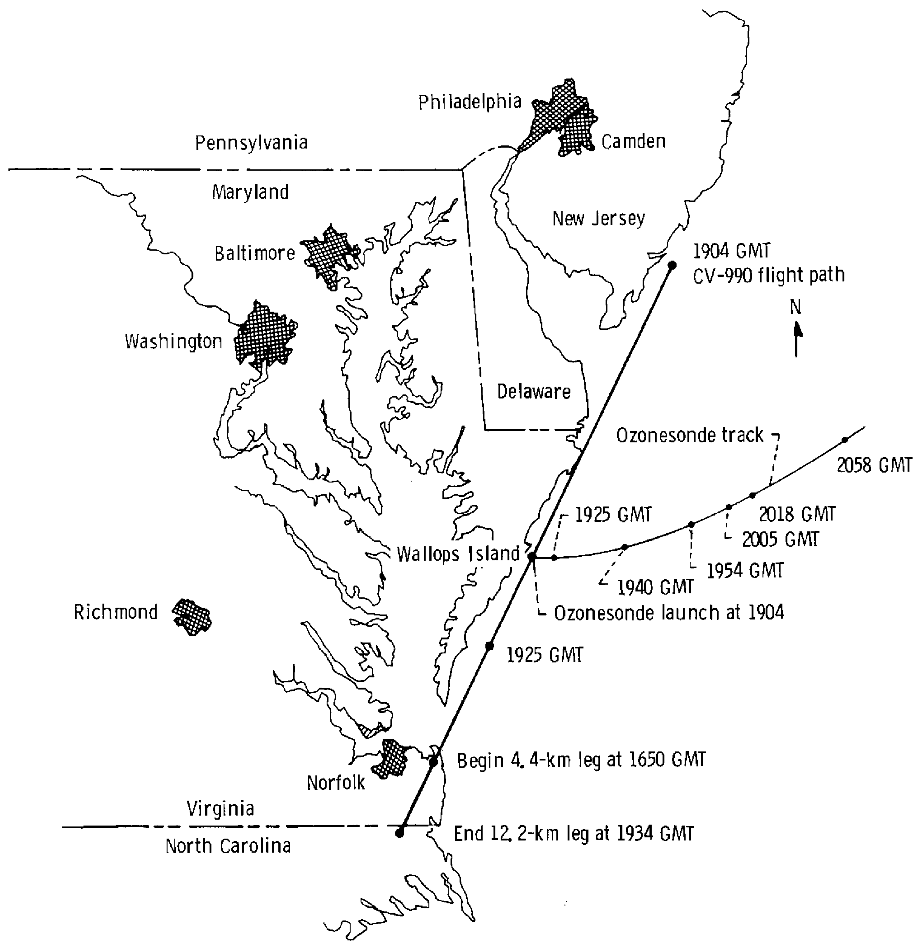

Figure 1. - CV-990 flight path and balloon ozonesonde track.

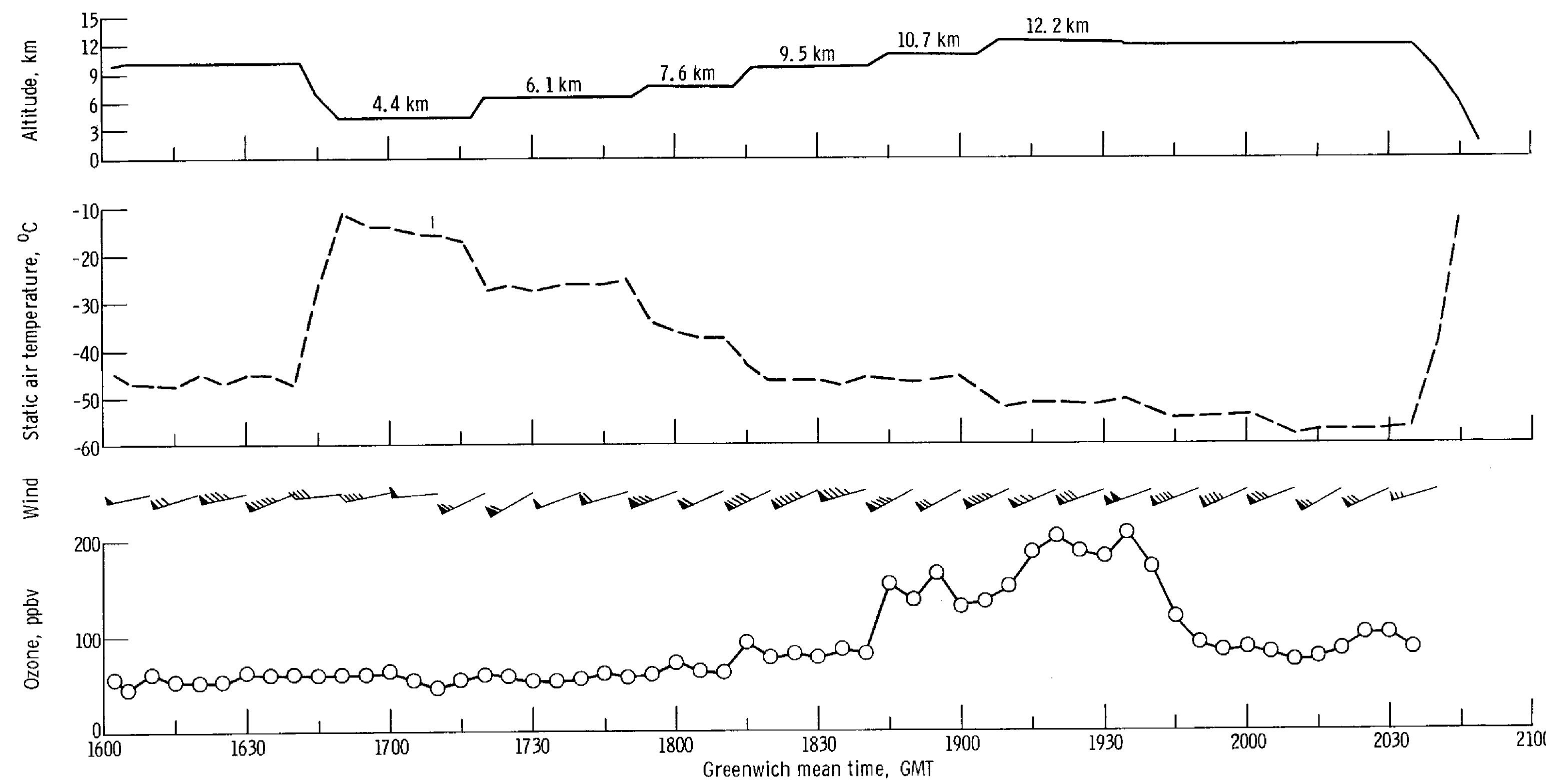

Figure 2. - Altitude, static air temperature, wind, and in situ ozone data from CV-990 Wallops overflight, December 2, 1975. Wind barbs follow National Weather Service conventions.

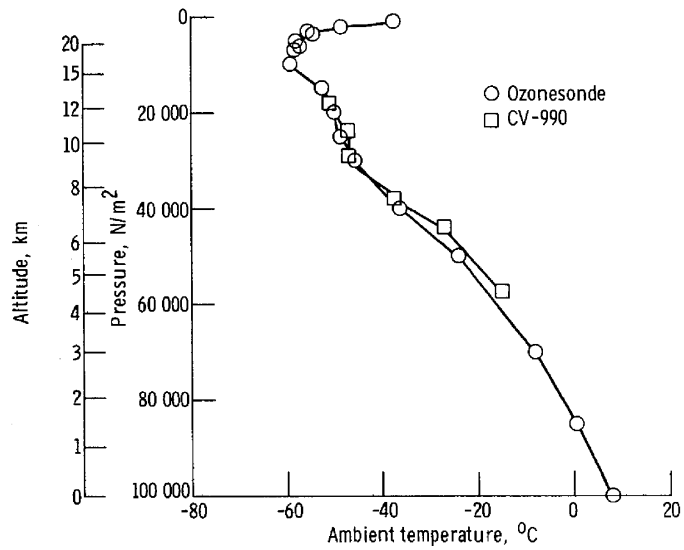

Figure 3. - Static temperature profiles as measured from ozonesonde and CV-990.

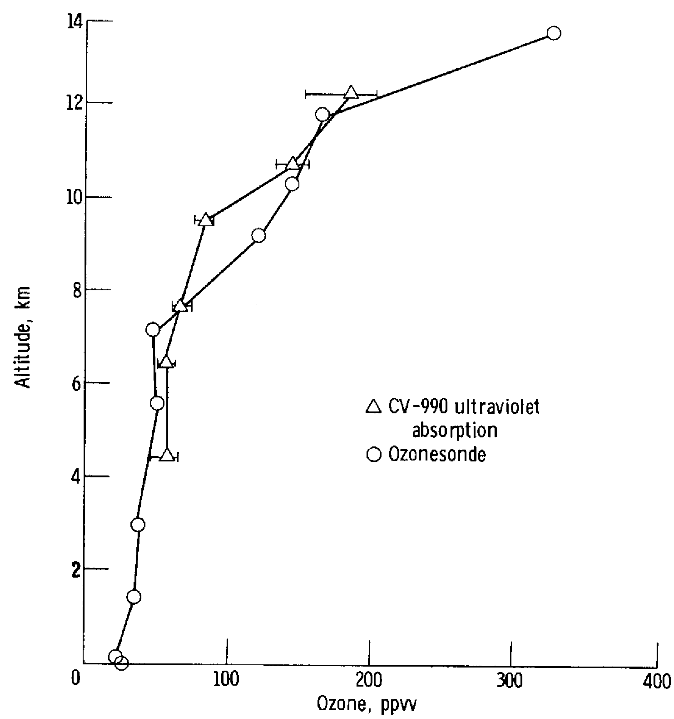

Figure 4. - Ozone profiles as measured by balloon ozonesonde and ultraviolet absorption instrument on board CV-990.

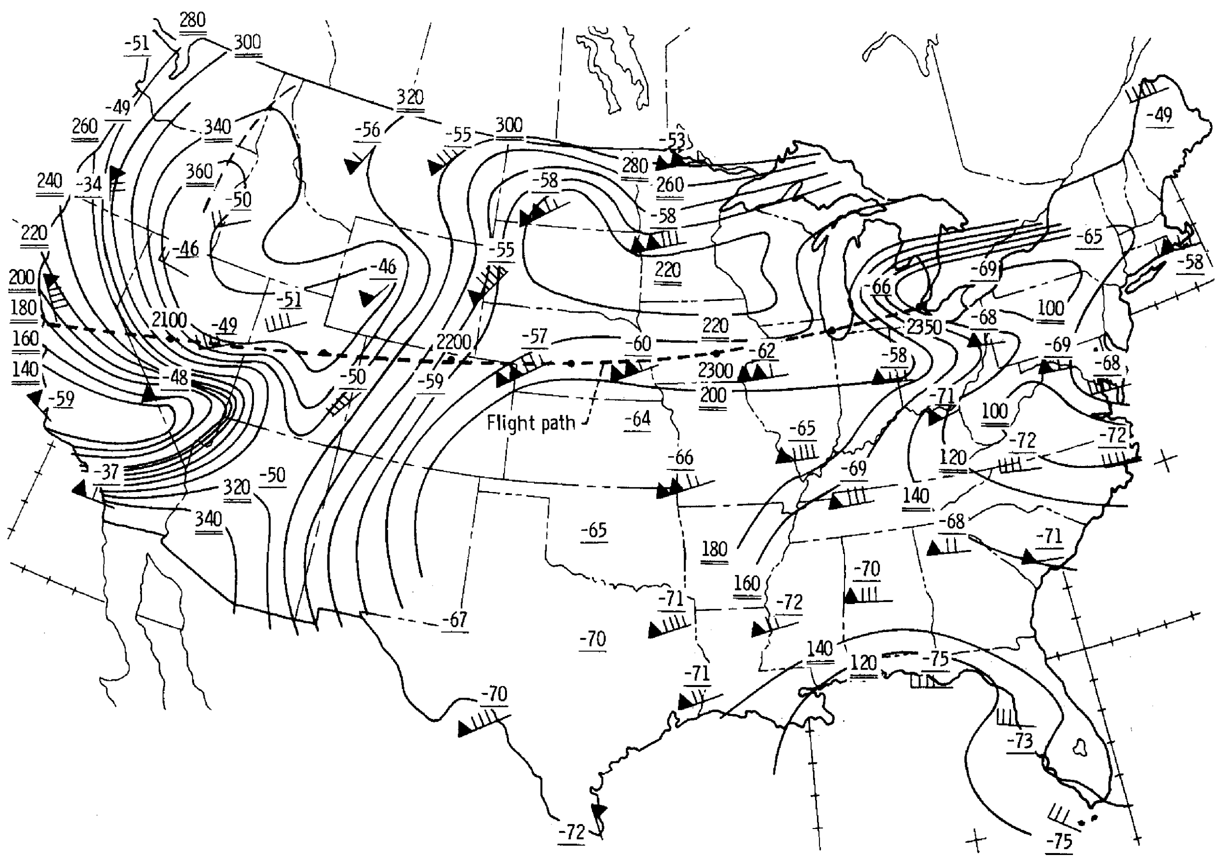

Figure 5. - Flight path of CV-990 for ozone comparison experiment on November 28, 1975. Also included are tropopause temperature and winds and tropopause pressure analysis derived from National Weather Service (NWS) data. Wind barbs follow NWS conventions. Four digit numbers near flight path are GMT. Single underlined numbers, tropause temperatures in °C; double underlined numbers, tropopause pressure in hectopascals.

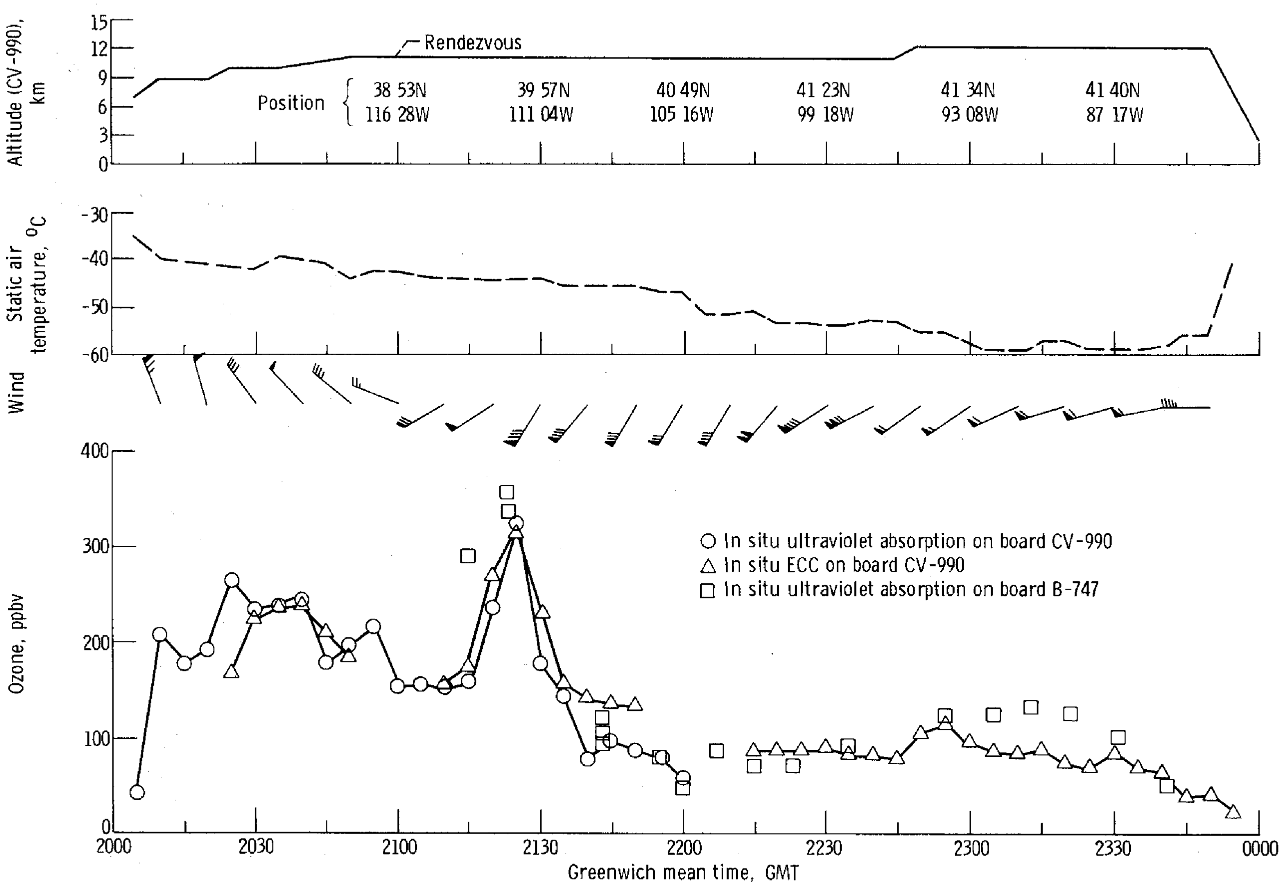

Figure 6. - Altitude, position, static air temperature, wind, and in situ ozone data from CV-990/B-747 chase flight, November 28, 1975. Altitude and static air temperature data from CV-990. Wind barbs follow National Weather Service conventions.

NASA-Langley, 1977 E-8951