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Measurements of Cabin and Ambient Ozone on B747 Airplanes

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In response to recent concerns over possibly high ozone levels in the cabins of aircraft flying in the stratosphere, simultaneous measurements of the cabin and ambient ozone levels have been made as part of the NASA Global Atmospheric Sampling Program. Examples of the data taken on commercially operated Boeing 747-100 and 747SP airplanes are given for selected flights, together with summary statistics of over 5600 observations. Cabin ozone levels vary with the ambient level and, for unmodified aircraft, are higher on the 747SP than on the 747-100. Modifications to the ventilation system of the 747SP reduced cabin ozone levels by varying amounts up to a factor of 14.

Introduction

MEASUREMENTS of the ozone concentration in the cabins of two commercially operated Boeing 747 airliners have been routinely made since March 1977 as part of the NASA Global Atmospheric Sampling Program (GASP). The measurements were taken in response to the recent concern of the public[1,2] and the government[3,4] because of reports attributing illnesses of some people on long duration flights to excessive ozone exposure.

A brief measurements campaign in the early 1960s established that the ozone injested by aircraft operating in the stratosphere is only partially destroyed by the compression-ventilation system, so that cabin ozone levels may increase above levels commonly found in the troposphere.[5] Until now, however, sufficient measurements were not available to determine adequately any relationship between cabin and ambient (atmospheric) ozone levels, and no tests had been made to see what effect modifications to the aircraft ventilation system might have on ozone amounts in the cabin. The addition of the cabin ozone measurement capability to the GASP system on a 747-100 and 747SP has provided simultaneous cabin and ambient ozone data from flights of varying duration, altitude, and season. During the data collection period on the 747SP four cabin ozone reduction methods were tested.

The purpose of this paper is to present selected examples of the ozone data thus collected and a statistical summary of the results for over 5600 individual cabin and ambient ozone observations made from March through October 1977. Further, the results of the different ozone reduction methods used on the 747SP will be discussed. Complete presentations of all GASP cabin ozone data through December 1977 are given in Ref. 6.

Ozone Measurements System

GASP was initiated by NASA in March 1975 to collect data on atmospheric constituents using instruments placed on board commercial airliners. Due to the size of the basic GASP instrument package, only 747 aircraft could be used. Both the ambient and cabin ozone are measured by an ultraviolet spectrophotometer with an operating range of 0.003 - 20 ppmv (parts per million by volume) and with a sensitivity of 0.003 ppmv. Air from outside the aircraft is sampled by a special external probe extending beyond the boundary layer near the nose of the aircraft. The cabin air inlet is located about 1.5 m above the floor in the forward compartment of the 747, on the outside wall of the circular staircase. The GASP system is completely automated, with all data recorded on tape. The ozone readings are updated every 20 s, although they are normally recorded only every 5 min. During the data processing, the tropopause pressure height for each ozone data location and time are interpolated from the National Meteorological Center (NMC) tropopause analyses and merged with the GASP data. Other details on the basic GASP methods can be found elsewhere,[7,8] and examples of some of the early ambient ozone measurements are given in Ref. 9.

Ozone Variations

In the atmosphere the local ozone concentration varies with both space and time. Mean ambient ozone levels are typically less than 0.1 ppmv in the troposphere and greater than 0.2 ppmv in the stratosphere.[10] The mean ambient ozone varies with latitude, increasing from the equator poleward, and with season, having maximum values during spring.[11] However, superimposed on these variations of the mean values are the sometimes very large variations with synoptic weather systems.[9,12] The point is that as the cabin air is obtained from outside, cabin ozone levels might be expected to depend upon all of these factors. In addition, the cabin ozone level will depend upon how much ozone is destroyed in the ventilation system. The ozone retention ratio (cabin to ambient) can be expected to vary between aircraft types and will further vary if the ventilation system of an aircraft is modified. Each of these points will be shown by comparing the statistical results of data from the 747-100 and the unmodified and modified configurations of the 747SP. Before discussing the statistical results, we will present data from a typical GASP flight as an introduction to the type of records upon which the statistics are based.

Figure 1 shows the ambient and cabin ozone data along a flight of the 747SP from New York to Tokyo on April 26,

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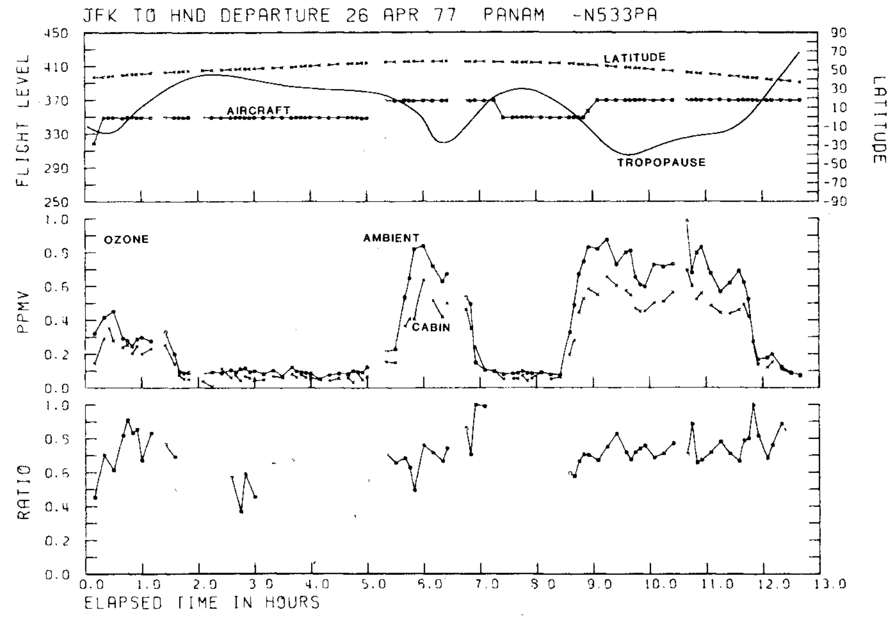

Fig. 1 Ozone flight record for PanAm 747SP from New York to Tokyo on April 26, 1977.

Table 1 Correlation between cabin and ambient ozone levels

Aircraft	Ozone destruction method	No. of individual observations	Retention ratio[c] Mean	Standard deviation	Correlation[d] coefficient
Boeing 747-100[a]	1) None March 26-June 13	941	0.465	0.201	0.86
Boeing 747SP[b]	1) None May 12-June 4	527	0.825	0.208	0.87
	2) 15th stage compressor bleed May 12-June 4	123	0.268	0.132	0.51
	3) Modified air recirculation June 4-Aug. 6	1955	0.552	0.191	0.81
	4) 2 and 3 combined June 4-Aug. 6	972	0.211	0.109	0.42
	5) Charcoal filter Aug 6-Oct. 31	1093	0.061	0.089	0.30

[a] Aircraft United N4711U. [b] Aircraft PanAm N533PA. [c] Ratio = cabin ozone/ambient ozone. Only data where ambient > 0.1 ppmv were used. [d] Correlation of cabin with ambient ozone.

1977, along with the aircraft latitude and pressure altitude data, the NMC tropopause pressure altitude, and the ratios of cabin/ambient ozone, all as a function of flight time. In this and the following figures, data for aircraft flight level, ambient ozone and retention ratio (cabin/ambient) are connected by solid lines except when gaps in the data exceed 10 min duration (ratio values are plotted only when ambient exceeds 0.1 ppmv). Latitude and cabin ozone data are connected by segmented lines. Tropopause pressure height is shown by a thin continuous line in the top panel. The label flight level (hundreds of feet) is used to signal that standard atmosphere equivalent pressure altitudes, rather than true geometric altitudes, are the coordinate. The changes in ozone when the aircraft ascended into the stratosphere at 5.5 h elapsed time, descended into the troposphere at 7.0 h, and then ascended into the stratosphere again at 8.4 h are very dramatic. Also noteworthy is the fact that at 0.5 h the flight is stratospheric at flight level 350, but at the same pressure altitude 7 h later it is tropospheric despite the higher latitude of the latter route segment (55N vs 42N). This illustrates that the tropopause location, and hence ozone levels, sometimes fluctuates in space contrary to the variation of the mean patterns due to local meteorological conditions.

An important point to note in Fig. 1 is that the cabin ozone curve closely follows the ambient ozone curve (the correlation coefficient is 0.72). The correlation coefficient between cabin and ambient ozone data for all flights taken on the unmodified 747SP is above 0.8 except for those cases when 15th stage compressor bleed was used (discussed below). The correlation coefficients may have been even greater, except there is a time lag of a few minutes while outside air is being mixed with the air in the cabin. For example, in Fig. 1 at about 6.9 h when the aircraft descended into the troposphere the ambient ozone immediately fell off, but the cabin ozone fell off less rapidly causing the ratio to be greater than 1.0 for a few minutes.

Table 1 summarizes the ozone retention ratio data for both GASP equipped aircraft. As we are concerned only about those times when ozone may be a problem, only those observations when the ambient ozone amount was above 0.1 ppmv were used when compiling Table 1. Thus, the statistics in Table 1 generally refer to stratospheric flights. Because of ventilation system modifications or changed operating procedures, the data for the 747SP are divided among the following categories: 1) unmodified, 2) unmodified with 15th stage compressor bleed, 3) increased air recirculation, 4) increased air recirculation with 15th stage compressor bleed, and 5) charcoal filter. There may be factors other than those listed which influence the retention ratio from flight to flight, or even within a flight, such as load factor or flight

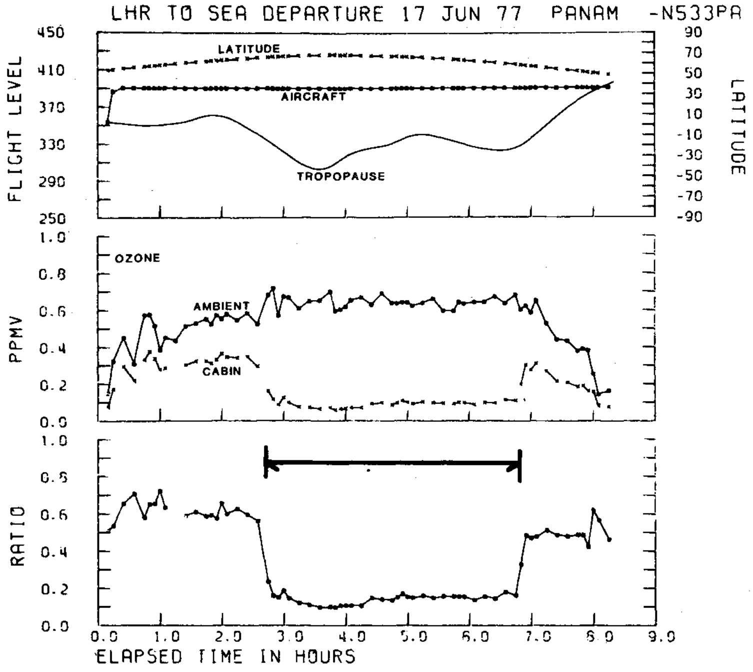

Fig. 2 Ozone flight record for PanAm 747SP from London to Seattle on June 17, 1977. Arrow indicates duration of 15th stage compressor bleed.

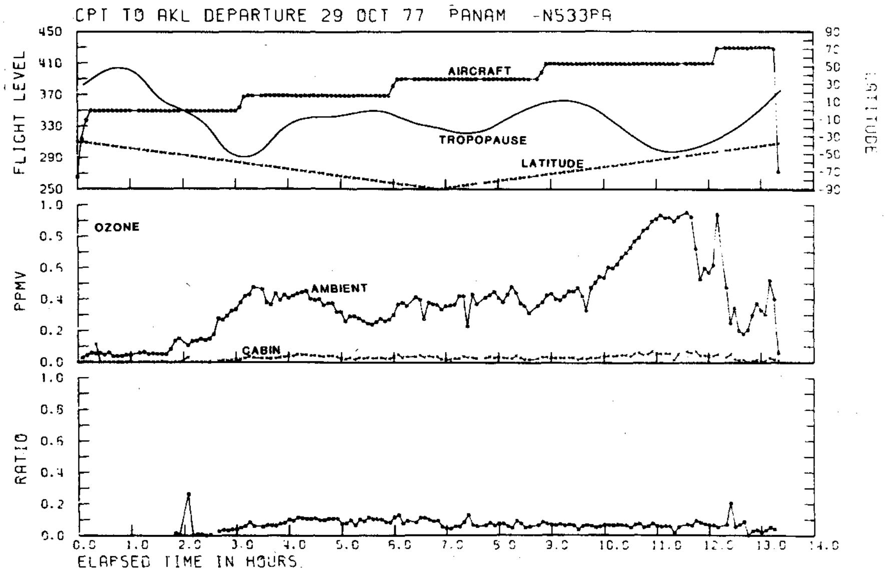

Fig. 3 Ozone flight record for PanAm 747SP from Capetown to Auckland on Oct. 29, 1977. Charcoal fiber was used on this flight.

duration,[13] but these are not considered here.

In Table 1, the retention ratio for the unmodified 747SP is 0.825, nearly double that of the 747-100. As the standard deviations and the correlation coefficients are nearly the same among these two data groupings, the difference in the mean values is probably genuine, and clearly indicates that retention ratios cannot be extrapolated among aircraft types with much certainty.

Four different methods were used to reduce the cabin ozone on the 747SP. Increased surface contact was promoted by increased recirculation of the cabin air, which caused the mean ratio to fall from 0.825 to 0.552 (Table 1). Note, however, that despite the air recirculation, the mean ratio for the 747SP aircraft was still higher than that for the 747-100 aircraft.

Another method was the use of 15th stage compressor bleed for the cabin air, rather than the normal 8th stage compressor bleed. The higher temperature (340-480°C) associated with the 15th stage causes much more of the ozone to dissociate before entering the cabin. Fifteenth stage bleed was used intermittently both on the unmodified aircraft and after the air recirculation modification, and the results are listed separately in Table 1. Even with air recirculation, the effect on ozone of using 15th stage compressor bleed is dramatic, as shown in the flight record in Fig. 2. The times when the 15th stage was used are indicated by arrows in the ratio panel. For this flight, the mean retention ratio with 15th stage bleed in use was 0.144, compared to a mean ratio for corresponding data on all flights of 0.211. Although 15th stage bleed was used occasionally before May 12, 1977, no indication of its use was recorded with the GASP data before then, and so only data taken after May 12, 1977 are included in Table 1 for the 747SP.

On Aug. 6, 1977, a charcoal filter was installed in the ventilation system of the 747SP aircraft. This filter destroyed nearly all of the ozone entering the cabin as illustrated in Fig. 3 and summarized in Table 1. For all observations from Aug. 6 through Oct. 31 using the charcoal filter, the mean ratio was only 0.061.

Summary

Several examples of simultaneous measurements of the cabin and ambient ozone along commercial air routes have been given, along with statistical results on the effect of four ozone reduction schemes. The fraction of ambient ozone retained in the cabin was found to be 0.465 for a 747-100. This was 44% lower than for an "as manufactured" 747SP. However, the retention ratio for the 747SP was reduced by 33, 68, and 93% respectively as a result of increased cabin air recirculation, use of high temperature bleed for cabin air, and installation of a charcoal filter.

While the ensemble of flights summarized in this paper represent conditions routinely encountered by the GASP equipped aircraft, the examples in Figs. 1-3 were carefully selected to illustrate specific points. The high ozone amounts shown in these figures are not necessarily typical of conditions encountered by all aircraft. Further, the ozone retention ratio depends greatly upon the aircraft type and the configuration of is ventilation system. Whether or not a given flight will encounter high ozone levels depends upon many factors, including time of year, altitude, location, and local meteorological conditions.[12,14] A more representative sampling of conditions encountered is provided by the data and plots in Ref. 6.

Acknowledgment

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