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MEASUREMENTS FROM IN-SERVICE AIRCRAFT: WHAT ARE THE POSSIBILITIES?

Linnea M. Avallone

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309, USA

ABSTRACT

Measurements of atmospheric chemical species and state parameters have been made on a limited number of in-service aircraft, including the NASA GASP program from the 1970s and the on-going MOZAIC program in Europe. In this presentation, I will review the accomplishments of such programs and describe a similar project proposed for US aircraft several years ago. I will discuss the types of data that can be gathered, and the scientific questions and issues that might be addressed with such a dataset.

INTRODUCTION

Oceanographers have made great use of "ships of opportunity", chance passage on freighters or ocean liners during which data of scientific consequence can be gathered. This notion is much less common in the atmospheric sciences, yet such a concept may prove valuable in addressing scientific questions, particularly those requiring extensive datasets. A majority of *in situ* sampling of atmospheric constituents (gas- or condensed-phase) takes place during focussed thematic campaigns, often employing multiple instrumented airborne platforms. Yet these campaigns give us only a fragmented picture of the state of the atmosphere because they typically target special events or situations.

Why sampling programs on in-service aircraft?

The short answer to this question is that in-service aircraft address the need for near-global and high temporal resolution data necessary to study a variety of interesting scientific questions. As noted above, observations obtained during organized campaigns tend to be centered on a fairly compact geographic area and are typically targeted at sampling a particular phenomenon (e.g., outflow of Asian pollution to the Pacific, or the chemical evolution of polar ozone). The flight patterns of commercial aircraft, on the other hand, sample much more of the globe than individual, focussed campaigns do, and sample much more regularly, at least once per week on most routes, if not once per day. Sampling from other in-service aircraft, such as cargo planes or SOFIA, can provide similar advantages.

The European Community has sponsored the MOZAIC (Measurement of Ozone by Airbus In-Service Aircraft) program, a cooperative effort between Airbus Industrie and research agencies in the United Kingdom, France, and Germany, to measure (originally) ozone and water vapor with instrument packages installed in A340 aircraft [*Marenco et al., 1998*]. The first phase of MOZAIC was so successful, that in subsequent phases, instruments to measure carbon monoxide and reactive nitrogen (NO_y) were added. As with the United States' Global Atmospheric Sampling Program (GASP), which reported measurements of ozone, water vapor, carbon monoxide, and particles from about 1977 to 1983, the problems that can be addressed by these observations are limited by the small number of species measured (and in the case of GASP, measured well). Nonetheless, results from GASP made fundamental contributions to the community's understanding of upper tropospheric cloudiness, ozone transport processes, and the spatial structure of temperature. An adequate description of the results obtained from

MOZAIC is beyond the scope of this paper, but the reader is directed to the webpage (http://www.aero.obs-mip.fr/mozaic/actual.html) for a list of publications about or using MOZAIC data.

Despite the successes of GASP and MOZAIC, a significant gap remains – routine sampling in the Pacific. In 1997, this author was funded[1] to develop an instrument package that could serve as a U.S.-based program similar to MOZAIC, operating on domestic carriers. The approach taken was unique for the time, because it is typical for observations of multiple chemical species to be made by multiple individual instruments. This is expensive, as each participating institution (and PI) requires monetary support and each instrument has its own data system, plumbing, inlet, etc., each contributing to the overall payload weight. For an aircraft, weight translates directly to fuel requirements, which translates to cost. In our project, dubbed Tropospheric Ozone and Tracers from Commercial Aircraft Platforms (TOTCAP), we proposed to fly four different sensors with common inlet, plumbing, and computer control system, resulting in a low-cost, relatively lightweight package (e.g., the equivalent of one airline passenger).

THE TOTCAP PROJECT

As part of the NASA Atmospheric Effects of Aviation Program, the main goal of TOTCAP was to obtain data that would support the program's efforts to quantify the effects of commercial aviation on the atmosphere. One of the largest uncertainties that the AEAP faced was determining the extent to which atmospheric transport processes influenced the dispersal of aircraft exhaust (and other pollutants) in the troposphere. We proposed to address this issue by measuring a suite of species that would provide data with which to test the transport schemes in atmospheric models, and would ultimately provide constraints on parameters such as the average rate of vertical transport in the troposphere and the amount of stratosphere-to-troposphere exchange.

What species were chosen and what role does each play?

The ideal species for this experiment would have well-understood sources and source strengths, a well-known tropospheric lifetime (e.g., lifetime against destruction by reaction with hydroxyl radical or uptake by the ocean or land) and would be easy to measure accurately with existing instrumentation. The species that best meets all of these criteria is carbon dioxide. A combination of other favorable characteristics led to the choice of the following species: O_3, CO_2, H_2O, and C_2Cl_4, with possible expansion in the future to include other halocarbons. A brief description of the relevant characteristics of each of these species is given below.

Ozone:

Observations of ozone serve many purposes in this experiment. First of all, it is relatively easy to measure ozone accurately and precisely (± 1 ppbv), with rapid time response (less than 5 seconds per data point). Thus a continuous measurement of ozone can serve as an indicator of air mass changes and help to identify features of interest. Because ozone mixing ratio increases rapidly above the tropopause, it is a useful marker of stratospheric air and can help to identify and characterize the extent of stratospheric intrusions into the troposphere. Ozonesonde measurements indicate that, in some regions of the free troposphere, ozone abundances are increasing [*Logan, 1994*]. A more geographically extensive database of ozone observations could help to identify trends in tropospheric ozone abundances.

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[1] Funding was received from NASA's Atmospheric Effects of Aviation Program to develop a proof-of-concept instrument package and also from the EPA Early Career program, specifically for design of a portable gas chromatograph.

Carbon dioxide:

As noted above, CO_2 is a nearly ideal tracer of dynamical processes in the troposphere. Further, the rate of propagation of the seasonal cycle of CO_2 mixing ratio from the ground to higher altitudes gives additional information about intra- and interhemispheric transport on the month-to-year timescale. A few geographically limited studies of CO_2 have been carried out from in-service aircraft flying in the upper troposphere, documenting its variations with season and latitude [*Tanaka et al., 1987; Nakazawa et al., 1991*]. This information can be very helpful in the attempt to deconvolute the possible terrestrial and oceanic sources of CO_2, when used in conjunction with three-dimensional models. There are, however, two deficiencies in the existing databases – the information is restricted to the Pacific Rim (Australia, Alaska, and Japan) and the measurements were made with low precision and by trapping air samples in flasks that were returned to the laboratory for analysis. The first of these issues restricts the global utility of the data, while the second raises the spectre of contamination and inaccuracy, and limits the number of samples obtained to the number of flasks that can be accommodated on the aircraft.

Water:

Water vapor is perhaps the most important trace gas in the atmosphere, as it is critical in controlling weather and atmospheric circulation through latent heat, climate by its absorptive and emissive properties in the infrared and through formation of clouds, and atmospheric chemistry as the source of the hydroxyl radical (from $O(^1D) + H_2O$). Despite its impact, the distribution of water vapor in the troposphere is poorly understood, primarily due to lack of high quality observations. It is well known that water vapor mixing ratio falls off dramatically with altitude, from parts per thousand above the planetary boundary layer to only a few parts per million in the stratosphere. Measurements aboard commercial aircraft could significantly enhance our knowledge of the global water vapor distribution and may be helpful in identifying the source of recently observed increasing trends in lower stratospheric abundances [*Oltmans and Hoffman, 1995*]. Because of its characteristic vertical profile, observations of water vapor can also help to identify the origins of air masses encountered during flight: very low mixing ratios (a few ppm) would indicate air of stratospheric origin, whereas large mixing ratios might indicate recent transport from the lower troposphere, perhaps in convective outflow. In addition, simultaneous observations of water vapor mixing ratio, temperature, and pressure (from which to calculate saturation mixing ratio) would be useful in extending existing climatologies of upper tropospheric clouds.

Tetrachloroethene:

Tetrachloroethene, also known as perchloroethylene, is an anthropogenic compound that was used primarily as a dry cleaning agent and degreasing solvent until its phaseout under the Montreal Protocol. Given its uses, the emission pattern of C_2Cl_4 was expected to be similar to that of other chlorocarbons, with a higher concentration in the Northern Hemisphere. Based on its rate of reaction with hydroxyl radicals, one can estimate the lifetime of tetrachloroethene to be on the order of 3.5 months. With such a short lifetime and well-defined sources and sinks, the distribution of C_2Cl_4 would have provided excellent information regarding transport from the surface to the upper troposphere and from one hemisphere to the other. Were this instrument package proposed today, a different halocarbon would likely be chosen to serve as a tracer of relatively short-lived transport processes.

We proposed an instrument package that integrated four independent sensors into a single entity. Factors governing the choice of detection techniques include minimum size, weight, and power consumption for maximum precision, reliability, autonomy, and modest cost. To further minimize size and weight requirements, these experiments shared a common computer, data acquisition and control system, and flow/pump system. The techniques employed for the measurements of ozone, carbon dioxide, and water vapor are all well understood, flew on research aircraft at the time of the proposal, and required very little modification other than repackaging for specific airframe requirements. The gas chromatograph was an entirely new development. Table 1 summarizes the detection techniques.

Although TOTCAP never flew on commercial aircraft as originally proposed[2], it did fly on the NASA DC-8 aircraft during the 1999-2000 SAGE III Ozone Loss and Validation Experiment (SOLVE). A picture of the installment is shown in Figure 1. In total, the instrumentation and support equipment (such as the gas handling system) weighed 190 lbs (86 kg), well below the target of 250 lbs (113 kg). Moreover, the instrumentation operated autonomously and required minimal servicing between flights. Science-quality data were obtained from all four instruments, although the ozone data were compromised at high altitude due to poor flow conditions that resulted from sharing an exhaust port. The data have been used in two journal publications and in three Ph.D. theses.

TABLE 1. Demonstrated instrumental characteristics.

Species	Technique	Response Time	Precision
O_3	UV absorption	1 sec	1 ppb
CO_2	NDIR/absorption	0.5 sec	0.05 ppm
H_2O	TDL/absorption	1 sec	1-2%
C_2Cl_4	GC/ECD	5 min	~ 1 ppt

[2] Discussions were held with a number of airline and aircraft industry representatives who all agreed that there was merit to the project. However, no one was forthcoming with the funds required to integrate air-sampling instrumentation on existing aircraft, or even on those in production on the assembly line. With the end of the NASA AEAP, agency funding was also no longer available to pursue the intended application to revenue aircraft.

Fig. 1. TOTCAP instrumentation (outlined in red) on the NASA DC-8.

APPLICATIONS TO SOFIA UPPER DECK SCIENCE

Many of the scientific questions of interest when TOTCAP was originally proposed remain at least partially unanswered and the Pacific remains a seriously undersampled region of the globe. Moreover, new questions have arisen; for example, to what extent does outflow of pollution from Asia impact the United States. With minimum modification (upgrades to newer, smaller computer hardware, for example), the TOTCAP suite of trace gas sensors could be installed in the SOFIA upper deck to obtain measurements of ozone, water vapor, carbon dioxide, and some halocarbons during every flight of the aircraft. Powerful techniques now exist to assimilate randomly gathered observations into sophisticated atmospheric models. With the combination of data taken on long-range SOFIA flights and state-of-the-art atmospheric models, we can begin to investigate things such as the temporal behavior of stratosphere-to-troposphere exchange processes and the extent to which deep convection influences the chemical composition of the upper troposphere on a statistical basis. Moreover, these trace gas observations could serve as the baseline for a long-term look at the impact of climate change on the tropopause region of the atmosphere.

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E-mail address of L. Avallone: avallone@lasp.colorado.edu
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