An Assessment of Aircraft-Generated Contamination on In Situ Trace Gas Measurements: Determinations from Empirical Data Acquired Aloft

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ABSTRACT

Results are reported from an experiment conducted aboard the NASA DC-8 research aircraft to determine whether cabin air vented upstream of investigator’s inlets had potentially contaminated ambient air samples obtained aboard the aircraft during previous airborne scientific expeditions. For the study, three multiport inlet rakes were mounted in windows downstream of an exhaust vent in locations forward, above, and aft of the right wing. These were used to make impact pressure measurements for determining boundary layer thickness ($d$) as well as to collect ambient air samples at various distances outward from the airframe. The fraction of cabin air in the samples was determined by doping the vent air with a metered amount of CO$_2$, then monitoring air at the inlet ports for differential CO$_2$ enhancements. Data were collected at altitudes ranging from the surface to 12 km, at various indicated airspeeds, pitch and yaw angles, and during vertical ascents and descents. Results indicate that $d$ varies from about 13 to 37 cm and depends on inlet position, as well as the aircraft velocity, altitude, and pitch angle. The CO$_2$-doped vent air was observed to mix throughout the depth of the boundary layer, but to be confined vertically to a narrow stream so that its interception by any particular inlet probe was highly dependent upon the aircraft-indicated airspeed and pitch angle. The inlet located forward of the wing was the most highly impacted, as samples collected there contained up to 0.8% cabin air at cruise altitudes under typical aircraft operating conditions. The implications of these findings on previous datasets are discussed, and a modified formula for calculating $d$ values appropriate for the DC-8 is proposed.

1. Introduction

Since 1987, the National Aeronautics and Space Administration (NASA) has operated a Douglas DC-8-72 jet aircraft as a flying laboratory to acquire data for airborne science research. Scientific investigators use the aircraft for a wide variety of experiments including earth, atmospheric, and celestial observations. Missions focused on atmospheric chemistry research are frequently conducted aboard the DC-8 as observations acquired aloft provide insight into atmospheric photochemical processes and spatiotemporal distributions of trace gas species above the earth’s surface. In situ measurements of these species typically require the placement of an inlet external to the fuselage of the aircraft for ambient sampling. Since many species of interest are present in the atmosphere in trace amounts (at \(\leq\) ppb levels) or exhibit small changes in overall concentration, it is crucial that measurements obtained through these sampling probes are free from contamination traceable to the aircraft. Potential sources of measurement contamination by the aircraft platform include engine exhaust products, fuel tank vents and fuel seepage, oil leakage from engines, and cabin air leakage from doors, windows, and vents.

The impetus to investigate the near environment of the NASA DC-8 for possible sources of contamination arose from the discovery during the SAGE III Ozone Loss and Validation Experiment (SOLVE) mission in December 1999 that air drawn from inlet probes located on the starboard side of the aircraft could be highly contaminated by cabin air exhausted through a vent located upstream of all the sampling inlets. Discovery of the contamination problem was facilitated during SOLVE because it was the first time that a suite of fast-response instruments sensitive to the most abundant hu-
man respiration by-products, CO$_2$ and H$_2$O, were deployed on the right-hand side of the aircraft. Over the years, NASA has sponsored a number of DC-8-based chemical survey expeditions that deployed starboard sampling probes to quantify species that may be present in either enhanced or depleted levels within cabin air. Therefore, an assessment of possible cabin air pollutants and the anticipated fraction of vent air present at various probe positions along the airframe were needed.

In this paper we initially describe the design and measurement approach of a cabin air contamination study conducted aboard the NASA DC-8 in the fall of 2000. Chemical and pressure data acquired during the experiment are then examined as a function of distance from the aircraft skin at selected port positions along the aircraft under varying flight conditions. Based on these results, we discuss the possible ramifications of cabin air pollution on prior datasets.

2. Experimental

a. Approach

During SOLVE, in situ measurements of CO$_2$ and N$_2$O (Sachse et al. 1987) were obtained by investigators using a 22.86-cm sample probe located at starboard station 570, which is forward of the aircraft wing. Two hundred centimeters upstream of their inlet was the Jet Propulsion Laboratory (JPL) laser hygrometer featuring an external 50-cm optical path, located 15.24 cm from the fuselage, for in situ measurements of H$_2$O. Carbon dioxide and H$_2$O typically exhibit a very compact relationship with N$_2$O in the stratosphere; however, an examination of these concurrent measurements during the early portion of the initial SOLVE deployment showed that they were very poorly correlated particularly during level flight legs at high altitude. Enhancements of up to 3.5 ppmv in CO$_2$ (Fig. 1a) and 10 ppmv in H$_2$O were seen in some cases. The explanation for these observations is that cabin air, enriched in respiratory H$_2$O and CO$_2$ from the 40 people on board the aircraft, was continuously being vented upstream of their inlet at a rate that increased with decreasing ambient pressure. Indeed, measurements of CO$_2$ within the aircraft cabin during SOLVE exhibited enhancements on the order of 45%–59% above the mean ambient background concentration of 366 ppmv observed in the lower stratosphere. Subsequent to these observations, the forward DC-8 air vent was permanently sealed to prevent recurrence of the contamination problem and the resulting uncontaminated ambient measurements obtained are illustrated in Fig. 1b.

To assess the potential fraction of cabin air in ambient samples an experiment was thus designed that involved introducing a known level of CO$_2$ as a nontoxic tracer gas into air escaping from the forward air vent. The enhanced level of that tracer as a function of distance from the aircraft skin was then measured at selected port positions along the starboard side of the aircraft under varying flight conditions.

b. The aircraft and mission

The Douglas Aircraft Company manufactured the NASA DC-8-72 in 1969 as a long-range passenger and cargo transport. The jet aircraft is 48.0 m long with a 45.2-m wingspan and is powered by four General Electric CFM56-2-1C turbofan engines. It operates over a range of altitudes from 0.3 to 12.8 km at typical true airspeeds at cruise of 218–252 m s$^{-1}$. There are 24 standard passenger windows on the starboard side of the aircraft and 27 on the port side that can be replaced by metal plates thus accommodating the mounting of sampling inlets. The aircraft has a total pressurized volume of 394 m$^3$ with a variable turnover time of 150 s to 7 min yielding a maximum flow rate through the cabin of approximately 2600 L s$^{-1}$. The relative flow out the forward port is discussed below.

The DC-8 cabin air contamination assessment was conducted during the Atmospheric Radiation Measurement First International Satellite Cloud Climatology Project Regional Experiment (ARM-FIRE) Water Vapor
Experiments (AFWEX) mission in the fall of 2000. The contamination study was essentially a “piggy back” experiment flown aboard the DC-8 on a noninterference basis with the other AFWEX experiments. This particular campaign presented an ideal opportunity for the contamination assessment as AFWEX consisted of a small instrument payload permitting access to the desired sampling stations, it offered the necessary flexibility in flight planning, and it entailed a series of over flights of the Cloud and Radiation Testbed (CART) site in Oklahoma. Data for the contamination study were typically acquired during straight and level runs over the CART site at pressure altitudes ranging from 1 to 12 km. For each level flight leg, a series of speed runs were conducted at 103, 129, and 154 m s\(^{-1}\) of indicated airspeed (IAS; 200-250- and 300-kt IAS), which is independent of altitude. Additionally, air samples were monitored for contamination induced by streamline perturbations related to changes in aircraft pitch, roll, and yaw. The particular flight parameters and aircraft maneuvers selected for this study were based on the flight patterns of prior chemical survey missions.

c. Sampling strategy

The sample inlet rakes employed in this study were based on designs used in earlier contamination studies conducted on the NASA Convair CV-990 (Condon and Vedder 1984) and NASA Lockheed L-188 (Hoell et al. 1990) and were fabricated at NASA Dryden Flight Research Center. Each of the four rakes had nine inlet ports spaced 4.88, 15.04, 18.85, 22.66, 26.47, 30.28, 35.36, 40.44, and 45.52 cm outward from the fuselage for sampling both within and outside the aircraft surface boundary layer (Fig. 2). Port spacings were based on a survey of probe lengths used by prior investigators; the port at 45.52 cm exceeded the longest probe length previously utilized by 5.08 cm. The rakes were mounted on window plates at stations 530 (rake 1), 770 (rake 2), and 930 (rake 3) on the aircraft right-hand side (rhs) and at 610 (rake 4) on the left-hand side (lhs) and tilted to angles of \(-4.3^\circ, +2.0^\circ, +8.7^\circ, -10.6^\circ\) to align with the nominal, modeled airflow direction at each of the respective locations along the airframe. An additional inlet port was mounted flush with each window plate to provide a static reference for subsequent stagnation pressure measurements made on each of the forward-facing rake inlets. Rake placement was determined by frequency of station use during prior missions, whereas the rake angles match those of inlet probes previously installed at these particular stations. Figure 3 shows the location of the rakes in front of the wing, over the wing, and at the trailing edge of the wing. Continuous “clean-air” reference samples were obtained through the 45.52-cm port of rake 4 mounted on the lhs at station 610.

Associated with each rake was a box containing 10 electronically actuated solenoid valves (one for each port plus a spare), a stainless steel (SS) manifold common to the 10 valve outlets, an absolute and a differential pressure transducer, and two additional valves to connect the sample manifold to either the pressure transducers or a remotely located CO\(_2\) instrument. A three-way valve was used to couple the pressure sensors to the manifold so that when CO\(_2\) was being measured the pressure transducers were connected to the static pressure tap on the window plate. This provided frequent checks on the zero drift of the differential pressure transducer as well as absolute static pressure measurements for comparison to values determined by the aircraft meteorological measurements system. The boxes were mounted on the cabin floor adjacent to the window-mounted rakes and were connected to the individual inlet ports with flexible tubing. Components of the valve boxes were computer-controlled permitting continuous and simultaneous sampling of CO\(_2\) and pressure. A sampling sequence consisted of initiating CO\(_2\) measurements on rake 1, sampling each port for 30 s beginning with the outermost port and proceeding toward the fuselage, while cycling through each port on rakes 2 and 3 for 5 s to acquire impact and stagnation pressure data. A 2-s delay was programmed into the opening and closing of each port-dedicated valve so that a relatively constant pressure could be maintained in the CO\(_2\) sampling system. The program would subsequently cycle to rake 2 for CO\(_2\) measurements and rakes 1 and 3 for pressure data thus completing the entire circuit of all three rakes in 11 min. The spare solenoid valve was also plumbed to the 4.88-cm inlet permitting repeat sampling at this position thus providing frequent checks of measurement precision. Data were acquired and stored at 10 Hz then averaged to 1 Hz for analysis.
d. Carbon dioxide instrument and doping system

Carbon dioxide measurements were made using the same fast-response, differential absorption CO₂ instrument deployed during SOLVE, which was a modified LI-COR model 6252 having a response time of <1 s with a corresponding precision of ~50 ppbv. A detailed description of the CO₂ measurement system and its operation can be found in Anderson et al. (1996) and Vay et al. (1999). Since CO₂ is not easily lost to tubing or inlet walls, samples can be siphoned from ports at any point along the airframe and brought to a conveniently located instrument rack for CO₂ assay. For the assessment, equal line lengths were maintained between the four valve boxes and rack to ensure identical flow characteristics in the lines.

During flight, pressurized air inside the aircraft continuously flows out the forward air vent line at a rate that is proportional to the differential in cabin and ambient pressures (Fig. 4). To produce known levels of CO₂ enhancement within the vent air, a metered amount of CO₂ gas was introduced into the vent line and its concentration determined by sampling the air in the line prior to it exiting the aircraft. In addition, both the vent line and CO₂ dopant gas mass flow rates were monitored and used to provide a continuous record of calculated CO₂ mixing ratio. Levels of 4000 ppmv were targeted for the vent air so that an ambient sample containing a 0.1% fraction of cabin air would exhibit a 4-ppmv enhancement in CO₂. To eliminate any uncertainties in the contamination data arising from changes in the background CO₂ concentration, the CO₂ reference gas for this particular application consisted of ambient air drawn from the outermost port of rake 4 rather than reference gas of a known concentration typically supplied from a gas cylinder. Therefore, enhancements observed while sampling from the rhs rakes were solely attributable to the doped vent air.

The CO₂ instrument was calibrated periodically in flight using standards obtained from the National Oce-
FIG. 5. Box and whisker plots showing how the DC-8 (a) indicated airspeed and (b) pitch angle typically vary as a function of altitude. These data were recorded during the Transport and Chemical Evolution over the Pacific mission, which was conducted during winter 2001. In this type plot, the central line indicates the median value, the boxes enclose the 25th and 75th percentiles, and the lines extend to the 5th and 95th percentiles.

FIG. 6. Velocity profiles derived from stagnation pressure measurements recorded on rakes 1 and 3 at a flight altitude of 7.5 km and indicated airspeed of 103 m s^{-1}. The values are normalized to the true airspeed calculated for the outermost port, which is assumed to be representative of the freestream velocity.

The maneuvers conducted during AFWEX were designed to access the various flight conditions typically flown by the DC-8 during chemical sampling missions. As an example, Fig. 5 shows plots of the aircraft velocity and pitch angle envelop recorded during a recent field experiment. Using these and similar data for a guide, flight plans for the contamination assessment included a series of 15-min-long, straight and level legs flown at altitudes between the surface and 12 km. Since pitch and airspeed are inversely correlated, speed runs were conducted to provide variations in the boundary layer depth for testing purposes. Legs with indicated airspeeds of 103, 129, and 154 m s^{-1} were flown at each altitude producing average pitch angles over the course of the experiment of 4.2°, 1.8°, and 0.7°, respectively. Additional maneuvers included 2° left and right yaws and roll angles of ±25° both in clockwise (CW) and counterclockwise (CCW) directions.

3. Results and discussion

The stagnation pressures recorded on each of the rake inlet ports were used to establish velocity profiles in the near field surrounding the aircraft and thus to determine the boundary layer thickness and how it varies as a function of flight conditions and sampling position. Figure 6 shows a set of profiles from rakes 1 and 3 recorded at 7.5-km altitude during a low airspeed maneuver; velocity values \(V\) recorded at each of the inner ports are normalized to the velocity recorded on the outermost port \(V_o\) that is assumed to be well outside the aircraft boundary layer and thus representative of the freestream velocity. In practice, true airspeeds (TAS) calculated for at least the two outermost ports (40.44 and 45.52 cm) on each rake were constant, although a few percent lower than those determined from the aircraft Pitot-static system. These lower apparent TAS values, primarily caused by the nonideal positioning of the static pressure reference ports on the window plates, did not affect the interpretation of the data as long as at least one port was exposed to freestream flow and could be used to normalize the velocities determined for the rest of the ports.

Assuming that the flow field surrounding the aircraft approximates that of turbulent flow over a flat plate, the velocity ratio values \(<1\) in Fig. 6 can be fit with power-
Fig. 7. Variation of median boundary layer depths ($d$) at rakes 1 and 3 as functions of (a) indicated airspeed and (b) aircraft pitch angle. Pitch and IAS vary inversely for normal flight operations, i.e., the higher the aircraft velocity, the lower the pitch angle. About 800 data points are represented in each of the curves shown above; standard deviations associated with the displayed points were typically 3±6 cm.

Fig. 8. Variation in $d$ at rakes 1 and 3 as a function of flow Reynolds number. This parameter was calculated from the aircraft true airspeed ($U$) and rake port positions ($L$) using the formula $Re = UL/\nu$, where $\nu$ is the kinematic viscosity of air that varies as a function of temperature and density. The dotted lines extending across the plot indicate $d$ calculated for the rake positions using the formula recommended in the DC-8 Airborne Laboratory Experimenter Handbook (NASA 2002). The curved red lines show values of $d$ calculated using flat plate theory.

Fig. 7 illustrates how the median $d$ at rakes 1 and 3 responded to changes in aircraft pitch and IAS, the two flight parameters that were varied in order to modify the vent airflow path down the starboard side of the aircraft for the contamination study. The values show a general decreasing trend with airspeed and lower pitch angles. As indicated in Fig. 6, the aircraft is nominally operated at 120–160 m s$^{-1}$ IAS and from 0° to 3° pitch, suggesting that the boundary layer would typically be between 14 and 22 cm deep at rake 1 and from 20 to 27 cm deep at rake 3. The depth at rake 2 was generally intermediate to that at rakes 1 and 3 and would vary from 15 to 25 cm for the typical DC-8 flight envelope.

Figure 8 shows how $d$ varied as a function of the flow Reynolds number (Re) and provides a comparison of the measured values with those determined from both flat plate theory and the empirical formula recommended in the DC-8 Airborne Laboratory Experimenter Handbook (NASA 2002) of $d = 1.2L/100$, where $L$ is the distance back from the aircraft nose. The theoretical values were calculated from the formula $d = cL/Re^{0.2}$, where $c$ is a constant equal to 0.37 for an ideal flat plate (Schlichting 1960). As shown in Fig. 9, the values calculated from the DC-8 handbook formula are generally larger than the median measured depths and hence provide good conservative guidance for selecting sample probe length. Conversely, although the theory correctly predicts the decreasing trend in $d$ with increasing Re, it consistently yields values that are lower than the measured medians by 10%–25%. A statistical analysis of the measured data suggests that a value of $c = 0.44 \pm 0.11$ provides a much more accurate prediction of the

law expressions of the form, $V/V_v = (z/d)^n$, where $z$ is the distance out from the airframe and $d$ is the boundary layer depth (Schlichting 1960). Thus a linear regression of $\ln(V/V_v)$ on $\ln(z)$ yields $n$ as the slope and one of $\ln(z)$ on $\ln(V/V_v)$ gives $d$ as the y intercept. Using this approach as well as interpolating between the data points in log–log space to find the $z$ value where $V/V_v = 0.99$, (Schlichting 1960), $d$ values were determined for the approximately 800 velocity profiles recorded on each rake under straight and level flight conditions. Individual values varied from around 10 cm at rake 1 for high speed, low angle-of-attack maneuvers to over 35 cm at rake 3 for low-speed, low-altitude flight patterns.

Figures 7a and 7b illustrate how the median $d$ at rakes 1 and 3 responded to changes in aircraft pitch and IAS, the two flight parameters that were varied in order to modify the vent airflow path down the starboard side of the aircraft for the contamination study. The values show a general decreasing trend with airspeed and lower pitch angles. As indicated in Fig. 6, the aircraft is nominally operated at 120–160 m s$^{-1}$ IAS and from 0° to 3° pitch, suggesting that the boundary layer would typically be between 14 and 22 cm deep at rake 1 and from 20 to 27 cm deep at rake 3. The depth at rake 2 was generally intermediate to that at rakes 1 and 3 and would vary from 15 to 25 cm for the typical DC-8 flight envelope.

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median and standard deviation of $\delta$ and should be adopted for use in calculating the DC-8 boundary layer parameters.

The fraction of cabin air measured as a function of distance from the aircraft skin is illustrated for rake 3 at 154 m s$^{-1}$ IAS in Fig. 10. Data presented are binned by altitude given the pressure dependence of the vent flow rate. Since the atmospheric pressure at 4.5 km is approximately 1/2 of that at the surface (57.2 vs 101.33 kPa) and 1/3 by 7.5 km (37.7 kPa), the highest vent flow rate and thus largest cabin fraction (0.18%) was observed at 7.5 km for this set of runs. Contamination emanating from the forward vent was observed extending out to 30 cm at the higher altitudes with the maximum enhancement measured at 15 cm from the aircraft fuselage.

As illustrated in Fig. 7b, changes in aircraft attitude, such as pitch, affect the streamline flow around the aircraft and thus boundary layer dynamics. Figure 10 demonstrates how the fraction of cabin air observed can vary with subtle changes in pitch for a constant IAS and altitude. Here the two runs acquired at 1.9$^\circ$ and 2.0$^\circ$ of pitch yield consistent cabin fraction amounts whereas the run with 1.8$^\circ$ of pitch exhibits an additional 0.1% enhancement at 18.85 cm. As discussed earlier, a spare solenoid valve connected to the innermost port of each rake permitted simultaneous repeat sampling at the 4.88-cm position and hence provided frequent checks of the measurement precision. A measure of the precision ($\pm 0.01\%$) is shown in Fig. 10 by the two data points plotted for each pitch line at 4.88 cm.

Since the measurements are more sensitive to pitch than IAS, color contour plots depicting the fraction of CO$_2$-enriched cabin air measured as a function of pitch and distance from the aircraft fuselage were constructed (Figs. 11 and 12). These plots were generated for three different altitude bins based on the data presented in Fig. 10. Data from only straight and level runs were utilized and additional run data obtained at intermediate airspeeds were also included. Rake 2, located over the starboard wing, showed no enhancements during straight and level flight therefore only plots of rakes 1 and 3 are presented. Cabin air contamination was not observed on any rake at 103 m s$^{-1}$ IAS. Evidently with the high pitch angle at that IAS, the streamline flow passed above the rakes.

On rake 1 we see the highest fraction (0.8%) was measured during level flight at 12.2 km with a pitch of 2.4$^\circ$ and an IAS of 111 m s$^{-1}$ (Fig. 11c). At the aircraft ceiling and thus maximum vent flow, contamination was observed extending out to 26.5 cm over a 1.2$^\circ$–2.5$^\circ$ pitch range. As the altitude and vent flow decreases, a more discreet contamination plume is seen in the midaltitude data (Fig. 11b) out to the 22.66-cm port with a lesser cabin fraction maximum at 15 cm. The contamination plume continues to be more contained at the lower altitudes (Fig. 11a) and in closer proximity to the aircraft fuselage extending only out to 15 cm over 0.7$^\circ$–1.9$^\circ$ of pitch with a maximum cabin fraction of 0.72% at the innermost sampling port. Figure 12 captures the contamination profile at the trailing edge of the wing as mapped with rake 3. Here we see enhancements of the CO$_2$-doped cabin air extending farther out at mid- and lower altitudes than observed ahead of the wing, consistent with the measurement of $\delta$ described earlier. The maximum fraction of cabin air measured is significantly less (0.2% vs 0.8%) farther downstream from the vent due to dilution effects and was observed at comparatively lower pitch angles. Enhancements in CO$_2$ over ambient background levels were noted over a wider range of pitch angles, giving rise to a much more diffuse rather than point source pattern.

The atmospheric research conducted aboard the DC-8 is often aimed at understanding the large-scale influences of anthropogenic and natural processes on the oxidative capacity of the troposphere. Vertical soundings of the atmosphere are typically made on each science flight for insight into the spatial variability of tracer...
species throughout the tropospheric column. Profiles frequently consist of spirals over a point at a rate of 0.3 km min$^{-1}$ conducted in both CW and CCW directions. A portion of this study was thus dedicated to investigating the effects of cabin air contamination on data acquired during spiral ascents and descents. The overall results given in Table 1 indicate that larger enhancements were observed during descents when there is a significantly lower pitch angle. Measurements obtained forward of the wing were consistently affected on CCW spirals, which have a negative bank angle, whereas contamination was only observed with the positive roll of a CW descent at the wing’s trailing edge. No enhancements in CO$_2$ were noted over the wing or during the CW ascent, which had the highest pitch angle.

Additionally, maneuvers with $\pm 2^\circ$ of sideslip (centerline of aircraft rotates relative to the velocity vector of the aircraft’s center of mass) were undertaken on upwind, downwind, and crosswind runs at several altitudes over the CART site. Differences attributable to position of the aircraft with respect to wind direction, slip angle, and pitch were noted. The maximum fraction of cabin air was measured on rake 1 in all cases. For upwind/downwind right sideslips ($+2^\circ$): CO$_2$ was elevated on both rakes 1 and 3 with the maximum fraction (0.45%) at the innermost ports and contamination was observed on rake 2 for the first time. Left sideslips ($-2^\circ$) on upwind/downwind runs: CO$_2$ enhancements were measured on rakes 1 and 3 with a maximum (0.5%) at the inlet in closest proximity to the aircraft fuselage. The most notable difference in the contamination profiles between level flight and these yaw maneuvers was therefore the shift in the maximum enhancements from 15.04 to 4.88 cm. In the northbound crosswind data illustrated in Fig. 13, a different pattern is revealed as we see a measurable increase in CO$_2$ on rake 3 for only the $+2^\circ$ crosswind condition and a maximum cabin air fraction at 15 cm ahead of the wing. Southbound crosswind data exhibited the same signature. Over the duration of the AFWEX mission, $\geq 1\%$ contamination by cabin air was measured during occasional high rate and uncoordinated maneuvers. These larger fractions were
observed on rakes 2 and 3 when the bank angle exceeded $-27^\circ$.

4. Conclusions

The potential for compromised datasets exists as starboard-side sampling probes have been deployed over the years to quantify species that may have been present in either enhanced or depleted levels within cabin air. Species possibly affected by the venting include those associated with human respiration (primarily CO$_2$ and H$_2$O), condensation nuclei, isotope ratios, nitrogen compounds, hydrocarbons, and various halogen species produced by fire extinguishers as well as any trace gases that may have escaped from instruments/systems aboard the aircraft. Indeed, whole air canister samples collected from the DC-8 cabin during the SOLVE deployment showed elevated concentrations of HFC-1211 (from fire extinguishers), HFC-134A (spray cleaner for optics), isoprene, and hexane. For a species such as H$_2$O, the implications of these findings are particularly important especially in regards to stratospheric measurements; H$_2$O mixing ratios in the stratosphere are typically $<10$ ppmv; therefore, a 10-ppmv enhancement traceable to the aircraft would result in a significant measurement error. In the case of CO$_2$, which exhibits relatively small changes in concentration over large spatial scales, a 1% measurement error would exceed the global annual growth rate, which is typically $<3$ ppmv yr$^{-1}$. The overall results of this study suggest that, within the precision

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<th>Direction of spiral</th>
<th>IAS (m s$^{-1}$)</th>
<th>Avg pitch ($\sigma$)</th>
<th>Roll at max cabin air fraction (deg)</th>
<th>Max cabin air fraction (%)</th>
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<tr>
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of these measurements, investigator’s sampling inlets that were ≥35 cm in length were positioned outside the potentially contaminated aircraft boundary layer in the freestream flow and thus their data were contamination free. Fortunately, the vast majority of investigators on prior missions meets or exceeds this inlet criterion.

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