Measurements of Upper Tropospheric Humidity at Low Temperatures during CRYSTAL-FACE

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Abstract

Aircraft condensation trails (contrails) and thin cirrus were studied by instruments on the NASA WB-57F high-altitude aircraft during the NASA CRYSTAL-FACE mission. Persistent contrails and optically thin cirrus are contrasted by different levels of supersaturation with respect to ice. During the July 13, 2002, flight, the WB-57F aircraft intercepted visible contrails produced by both the WB-57F and ER-2 aircraft. These contrails were located immediately below the local tropopause, where ambient temperatures were very low (-76°C). The contrails were clearly indicated by an abrupt increase in NO and a simultaneous, abrupt decrease in ice supersaturation. Within the contrails, the relative humidity was close to 130% with respect to ice, higher than expected from theory. Outside the contrails was a persistent layer of subvisible cirrus extending from approximately 13 to 15 km altitude. This layer was characterized by significant supersaturations because the ambient concentrations of ice particles were insufficient to significantly deplete the ice supersaturation. We will discuss in situ measurements and model simulations of humidity.

Introduction

During summer 2002, the Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE) was carried out to study upper tropospheric cirrus in the subtropics and tropics. One of the specific scientific questions addressed by this mission was:

Are the supersaturations measured in clear-sky regions and within clouds consistent with our understanding of ice nucleation in the upper troposphere?

This is important for climate models, which often cannot reproduce observed supersaturations due to the model parameterization of cloud formation. Six aircraft, satellite, and ground observations were included in this mission, but we focus here on simultaneous, in situ measurements from the NASA WB-57F high-altitude aircraft on 13 July 2002 in the subtropical upper troposphere.

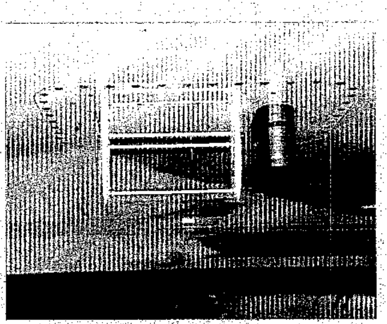

Figure 1. The 11.2-m, multi-pass, open-path optical cell of the JPL Laser Hygrometer (JLH). Laser, detector, and optical path are located 8.26 cm beneath the right wing of the WB-57F.

Instrumentation

The Jet Propulsion Laboratory (JPL) Laser Hygrometer (JLH) is a single-channel, near-infrared (1369-nm), tunable diode laser spectrometer for measurements of atmospheric water vapor [May, 1998]. The open-path design eliminates the need for a sampling inlet and reduces possible interferences from evaporation of condensed water. JLH utilizes harmonic absorption spectroscopy, a common sensitivity-enhancing technique employed in diode laser spectroscopy [e.g., Webster et al., 1988], yielding a water detection range of 1.0 to 2×10^4 ppmv with 0.05 ppmv precision and 10% accuracy.

The Meteorological Measurement System (MMS) on-board the WB-57F provides static temperature and static pressure data [Scott et al., 1990], which are utilized in JLH data processing to convert water vapor concentrations into volume mixing ratios, frost points, and relative humidity with respect to ice (RHI) and liquid water (RHw). Vertical wind velocities reported by MMS are also utilized in this analysis. We utilize nitric oxide (NO) as an indicator of aircraft exhaust. The measurements of NO are from the NCAR NO, NO_y, O_3 instrument, which uses the chemiluminescence detection technique [Ridley et al., 1994].

Data and Results

On 13 July 2002, the region near the tropopause (14.6 km altitude) was characterized by optically thin cirrus and very low temperatures (-76 to -77°C). The WB-57F aircraft sampled contrails deposited near the tropopause by the ER-2 (Figure 2) and WB-57F aircraft (Figure 3). Based on previous observations of contrails, we expect that aircraft exhaust particles readily become activated and heterogeneously nucleate ice [e.g., Schroeder et al., 2000, and Heymsfield et al.,1998]. Within the ER-2 contrail, clearly indicated by high NO, the relative humidity was much lower than in the surrounding air due to a large concentration of growing ice crystals. Outside the contrail, the environment was characterized by extremely high relative humidities. Apparently, there were not enough particles in the subvisible cirrus to deplete the supersaturated water vapor. In contrast to the ER-2 contrail, the WB-57F contrail was deposited in an environment with a wide range of humidities (Figure 4). Within the WB-57F contrail, the relative humidity with respect to ice (RHI) converged to a narrow range of 125 to 140%. Vertical velocity and RHI showed no correlation in either contrail.

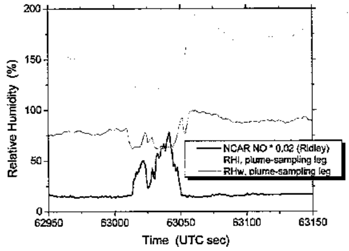

Figure 2. WB-57F measurements across the ER-2 visible contrail on 13 July 2002. The anticorrelation of NO and RHI indicate that growing ice crystals within the contrail deplete the water vapor to a nearly constant humidity. Note the large supersaturations in the environment external to the contrail.

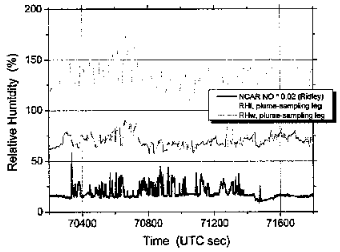

Figure 3. The persistent contrail of the WB-57F aircraft (aged 20-40 minutes) on 13 July 2002.

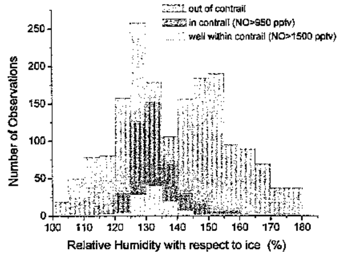

Figure 4. Histogram of RHI in the environment (red) and within the WB-57F persistent contrail (light and dark blue) indicates a convergence to approximately 130% RHI within the contrail.

Previous measurements by Schroeder et al. [2000] indicated a large range of relative humidities within visible contrails, using a slow cryogenic mirror technique to measure water. However, Heymsfield et al. [1998] reported RHI=100% in contrail cores at temperatures of -52°C. These measurements were made during the NASA SUCCESS mission with the NASA Langley Diode Laser Hygrometer (DLH), which is similar to JLH in both time-response and accuracy.

Model and Discussion

In order to drive the growth of ice particles, prevent evaporation, and maintain a persistent contrail, RHI must be greater than 100% [Gierens, 1996; Jensen et al., 1998; Heymsfield et al., 1998]. Within contrails, it is expected that large concentrations of growing ice crystals will maintain RHI close to 100% [Jensen et al., 1998; Heymsfield et al., 1998].

We simulate the ice nucleation process in the upper troposphere with a cloud microphysical model [e.g., Heymsfield and Miloshevich, 1995]. Nucleation rates are based on the results of Koop et al. [2000]. Initial conditions are: 10 cm^{-3} ice crystals, 1 micrometer in diameter, in an air parcel at rest, temperature of -75°C, relative humidity at saturation with respect to liquid water. Figure 5 demonstrates that the model ice crystals grow rapidly, bringing ice supersaturation to zero (RHI=100%) within 120 seconds.

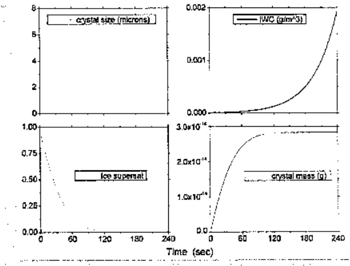

Figure 5. Model of ice particle growth indicates that large supersaturations cannot be sustained in the presence of many ice particles at low temperature (-76 °C).

Summary

The measured relative humidity with respect to ice (RHI) is 125-140% in cold aircraft contrails (-76°C). Theory predicts RHI should be 100% in the contrails. The measured RHI in clear air as high as 180%, even though theory predicts that, at temperatures of -76°C, homogeneous nucleation should occur at 157 to 162% RHI [Koop et al., 2000]. The cause of this discrepancy is unknown.

Uncertainties yet to quantify:

Does 130% RHI represent saturation vapor pressure for another compound?

Is solar heating of soot in the particles significant?

Is the contrail spatially homogeneous?

What is the rate of entrainment of outside air into the contrail?

Is there significant particle evaporation due to ram heating upstream of the wing?

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