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

R. L. Herman1, A. J. Heymsfield2, B. A. Ridley*, T. P. Bui3

1 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, rherman@jpl.nasa.gov
2 National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA
3 NASA Ames Research Center, Mail Stop 245-5, Moffett Field, CA 94035, USA

Abstract

Aircraft condensation trails (contrails) and cirrus clouds are studied by instruments on the NASA WB-57F high-altitude aircraft during the NASA CRYSTAL-FACE mission. Persistent contrails and optically thick cirrus clouds were observed by nadir viewing instruments on the WB-57F and ER-2 aircraft. These contrails were located immediately below the cirrus clouds, where ambient temperatures were very low (−76°C). The contrails were detected by an array of images in NO2 and a simultaneous abrupt decrease in ice supercooled liquid. Within the contrails, the relative humidity was close to 100%, with respect to ice. The relative humidity was lower than expected from theory. Outside the contrails, the water cloud 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 conditions 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 Cirus Regional Study of Tropical Anvil and Cirrus Layers (CIRRUS) experiment was conducted to study upper tropospheric clouds in the subtropics and tropics. One of the specific scientific questions addressed in this mission was to determine the relative humidity in the upper troposphere. Are the supersaturations measured in cloud regions and within clouds consistent with our understanding of ice nucleation in the upper troposphere? This is important for climate models, which cannot account for observed supersaturations due to the model parameterization of cloud formation. In situ aircraft, satellite, and ground observations were included in this mission, but we focus here on simultaneous aircraft measurements from the NASA WB-57F high-altitude aircraft on 12 July 2002 in the subtropical upper troposphere.

Instrumentation

The Jet Propulsion Laboratory (JPL) Laser Hygrometer (JLH) is a single-channel, near-infrared (1389 nm), tunable diode laser spectrometer for measurement of atmospheric water vapor [May, 1988]. The open-path design eliminates the need for a sampling inlet and reduces potential interference from evaporation of condensed water. JLH utilizes harmonic absorption spectroscopy, a common sensitivity-enhancing technique employed in diode laser spectrometry (Webster et al., 1988), yielding a water detection range of 0 to 200 T (H2O) with 0.05 T(H2O) precision and 10% accuracy.

The Meteorological Measurement System (MMS) on-board the WB-57F provides aircraft surface and atmospheric data [Scott et al., 1990], which are utilized in this study. This includes processing of water vapor concentrations into volume mixing ratios, frost points, and relative humidity with respect to ice (RHl) and liquid water (RHw). Vertical wind velocities reported by MMS are also utilized in this analysis. We utilize refractive indices (NO2) as an indicator of aircraft altitude. The measurements of NO2 are from the NCAR NO2CN instrument, which utilizes the chemiluminescence detection technique (Chippendale et al., 1984).

Data and Results

On 12 July 2002, the region near the tropopause (14.6 km) was dominated by cirrus clouds from the tropopause by the ER-2 aircraft and the WB-57F aircraft (Figure 2). Based on previous observations of cirrus, we expect that cirrus clouds fully developed became activated and homogenously nucleate ice (e.g., Schroeder et al., 2000, and Heymsfield et al., 2000). Within the ER-2 contrail, 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 (RHl) converged to a narrow range of 12% to 14%. Vertical velocity and RHl showed no correlation in either contrail.

Model and Discussion

In order to drive the growth of ice particles, prevent condensation, and maintain a persistent contrail, RHl must be greater than 100% (Heymsfield, 1998, Juras et al., 1998; Heymsfield et al., 1998). Within contrails, it is expected that large concentrations of growing ice crystals will maintain RHl close to 100% (Juras et al., 1998; Heymsfield et al., 1998).

We simulate the ice nucleation processes in the upper atmosphere with a cloud microphysical model (e.g., Heymsfield and Mccarthy, 1985). Nucleation rates are based on the results of Kooi et al. (2009). Initial conditions are 10 cm heterogeneously nucleated 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 (RHl=100%) within 130 seconds.

Summary

The measured relative humidity with respect to ice (RHl) is 125-140% in cold aircraft contrails (−76°C). Theoretical predictions of RHl must be 100% in the contrails. The measured RHl in clear air as high as 180%, even though theory predicts that, at temperatures of −76°C, heterogeneous nucleation should occur at 157 to 162% RHl (Kooi et al., 2009). The cause of this discrepancy is unknown.

Uncertainties yet to quantify:

Does 100% RHl represent saturation vapor pressure for another component?

Is the content of contrast spatially homogeneous?

Will the water remain out of the air into the contrail?

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

Acknowledgements

We thank S. E. Gao for help with calculations, R. E. Troy, B. Fogarty, and J. A. Blumen for assistance with the project, the NASA WB-57F aircraft project and NO2CN, and the CRYSTAL-FACE support staff. Support was provided by the NASA Upper Atmospheric Research Program (EARLY) and Radiative Transfer Sciences Program (RSTS). Part of the research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

References


