Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Atmospheric Environment 40 (2006) 1590–1600
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

Measurements of relative humidity in a persistent contrail

R.S. Gao[a], D.W. Fahey[a,b,*], P.J. Popp[a,b], T.P. Marcy[a,b], R.L. Herman[c], E.M. Weinstock[d], J.B. Smith[d], D.S. Sayres[d], J.V. Pittman[d], K.H. Rosenlof[a], T.L. Thompson[a], P.T. Bui[e], D.G. Baumgardner[f], B.E. Anderson[g], G. Kok[h], A.J. Weinheimer[i]

[a]*National Oceanic and Atmospheric Administration, Earth System Research Laboratory/Chemical Sciences Division, 325 Broadway, R/CSD6, Boulder, CO 80305, USA*
[b]*Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, USA*
[c]*NASA Jet Propulsion Laboratory, 4800 Oak Grove Drive, 183-401, Pasadena, CA 91109, USA*
[d]*Atmospheric Research Project, Department of Chemistry and Biochemistry, Harvard University, 12 Oxford St., Cambridge, MA 02138, USA*
[e]*NASA Ames Research Center, M/S 245-5, Moffett Field, CA 94035, USA*
[f]*Universidad Nacional Autonoma de Mexico, Centro de Ciencias de la Atmosfera, Ciudad Universitaria, 04510 Mexico DF, Mexico*
[g]*NASA Langley Research Center, M/S 483, Hampton, VA 23681, USA*
[h]*Droplet Measurement Technologies, 5710 Flatiron Parkway, Unit B, Boulder, CO 80301, USA*
[i]*Atmospheric Chemistry Division, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA*

Received 25 July 2005; received in revised form 28 October 2005; accepted 9 November 2005

Abstract

Persistent contrails are a common feature of the upper troposphere. We describe two methods for intercomparing and evaluating RH_i measurements in a persistent contrail with calculated or expected values. The methods were applied to measurements made in the upper troposphere on board an NASA WB-57F aircraft while sampling its own contrail. Included in the analysis are measurements of water vapor pressure, temperature, ice particle number and size, and nitric oxide (NO). The systematic use of these contrail-sampling methods in future studies will improve our understanding of contrail microphysics and the performance of fast-response water and temperature measurements.

Keywords: Contrail; Relative humidity; Water vapor; Microphysics; Ice particles; Aircraft emissions; Nitric oxide

1. Introduction

Cirrus clouds and aircraft contrails in the upper troposphere consist of ice particles with diameters ranging from less than 1 μm to more than 1000 μm. These ice particles directly and indirectly affect the earth's climate (IPCC, 2001). The frequency, duration, and size distributions of cirrus clouds and contrails depend strongly on the relative humidity with respect to pure ice (RH_i) distribution in the upper troposphere. The distribution of RH_i is complex since studies have shown that regions of the upper troposphere are routinely found

*Corresponding author. NOAA, Earth System Research Laboratory/Chemical Sciences Division, 325 Broadway, R/CSD6, Boulder, CO 80305, USA. Tel.: +1 303 497 5277; fax: +1 303 497 5373.
E-mail address: david.w.fahey@noaa.gov (D.W. Fahey).

1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2005.11.021

supersaturated with respect to ice (Gierens et al., 1999; Jensen et al., 2001, 2005a). An understanding of the processes that control RH_i and its distribution in the atmosphere is therefore crucial for the development and testing of models of the present and future climate.

Contrails in the upper troposphere generally consist of high concentrations ($>10\,cm^{-3}$) of small ice particles ($<10\,\mu m$ diameter) (Schröder et al., 2000). The interactions between the entrained ambient water vapor and ice particles are expected to be near the kinetic regime due to the small particle sizes and high concentrations. Model calculations (Jensen et al., 1998a) indicate that with sufficient water vapor abundances, RH_i inside a contrail reaches 100% within 10 s. Consistent with this expectation, some in situ observations indeed show that relative humidity inside a contrail is significantly lower than that of the surrounding air (Heymsfield et al., 1998). Based on these observations, and our current understanding of the kinetic and thermodynamic processes controlling the vapor pressure of water over pure ice, measurements inside contrails have been proposed as a way of evaluating the accuracy of airborne RH_i determinations (A.J. Heymsfield, private communication, 2003).

RH_i in the upper troposphere generally is derived from airborne in situ water vapor, temperature, and pressure measurements and laboratory measurements of the water vapor pressure over pure ice. Thus, the uncertainty in measured RH_i depends on the combined systematic uncertainties of the component measurements. The uncertainty in water vapor pressure gives a proportional uncertainty in RH_i while the RH_i uncertainty depends exponentially on the temperature uncertainty. Due to technical limitations, in-flight calibrations of RH_i component measurements (water, pressure, and temperature) are usually not feasible. Thus, measuring in a contrail, where RH_i is expected to be 100%, potentially represents a convenient and globally accessible approach to evaluating airborne RH_i measurements in flight. This expected value assumes that ice crystal habit does not impede significantly the approach to equilibrium, which is likely the case since contrail particles are typically small (diameters $<3\,\mu m$). The high frequency of favorable contrail formation conditions at cruise altitudes, particularly in spring and fall, means that research flights would often be able to sample their own contrail or that from another aircraft. Contrail sampling also affords the opportunity to compare RH_i instruments at widely separated locations and times. One limitation to this approach follows from recent contrail measurements that show enhanced RH_i values in low-temperature ($<200\,K$) cirrus clouds and contrails. Gao et al. (2004) suggest that the reason is a consequence of the role of HNO_3 adsorbed on cloud ice particles. This recent result suggests that the microphysics of ice with impurities is not fully understood in the atmosphere. Thus, continued RH_i measurements of high accuracy made in low-temperature contrails also will be valuable in further defining the effect of impurities in contrail ice and other microphysical processes.

Here, we present two methods for studying airborne RH_i measurements and contrail microphysics by in situ sampling of a persistent contrail (defined as one lasting longer than a few minutes). The measurements were made with a suite of in situ instruments carried on board the NASA WB-57F aircraft, which also produced the sampled contrail. In Section 2, the general contrail conditions are reviewed. A contrail-sampling (CS) case is presented in Section 3. Using this particular CS case, the two evaluation methods for RH_i are presented in Section 4.

2. WB-57F aircraft measurements

The data used in this study were obtained with the WB-57F aircraft carrying a suite of 25 in situ and remote-sensing instruments for particles, trace gases, and meteorological parameters. The data were obtained during the NASA Cirrus Regional Study of Tropical Anvils and Cirrus Layers—Florida Area Cirrus Experiment (CRYSTAL-FACE) mission in July 2002. Measurements used in this study include water-vapor partial pressure, air pressure and temperature, ice particle number and size, and nitric oxide (NO). Flight track coordinates and aircraft avionics parameters were recorded by the aircraft navigation system. Pressure (p) and temperature (T) were measured by both NOAA and NASA Ames Research Center (ARC) (Scott et al., 1990). Their measurements agree within 0.2 mb and 0.4 K, respectively. The ARC data are used in this study. There were several ice particle-sampling instruments on board the WB-57F. The dataset from the Cloud and Aerosol Spectrometer (CAS) is used here because it is the only one that includes ice particles in the size range of contrail particles (0.5–3 μm diameter) (Baumgardner et al., 2002). The measured CAS size distributions (1-s sampling period) are used to