Lidar Measurements of Relative Humidity and Ice Supersaturation in the Upper Troposphere

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ABSTRACT

We compute upper tropospheric relative humidity profiles using water vapor profiles measured by an airborne DIAL and a ground-based Raman lidar. LASE water vapor and MTP temperature profiles acquired from the NASA DC-8 aircraft during the recent Pacific Exploratory Mission Tropics B (PEM Tropics B) field mission in the tropical Pacific and the SAGE-III Ozone Loss and Validation Experiment (SOLVE) in the Arctic as well as water vapor profiles derived from the ground-based DOE ARM Southern Great Plains (SGP) CART Raman lidar are used. Comparisons of the lidar water vapor measurements with available in situ measurements show reasonable agreement for water vapor mixing ratios above 0.05 g/kg. Relative humidity frequency distributions computed using LASE data indicate that ice supersaturation occurred about 5-11% of the time when temperatures were below -35°C. While a higher frequency of ice supersaturation was observed during SOLVE, higher peak values of relative humidity were observed during PEM Tropics B. The relative humidity fields associated with cirrus clouds are also examined.

1. Introduction

Accurate measurements of upper tropospheric relative humidity are important for initializing numerical weather models, computing shortwave and longwave radiation fluxes and cooling rates, forecasting the formation of aircraft contrails, and understanding and modeling ice nucleation in cirrus clouds. Predicting the formation and persistence of cirrus clouds in particular requires accurate measurements of ice supersaturation at high altitudes and corresponding cold temperatures. Recent measurements by in situ sensors on radiosondes and aircraft have shown that large ice supersaturations may exist at low temperatures in both clear and cloudy conditions [1,2]. Since ice supersaturation often occurs in thin layers, the fraction of the upper troposphere where supersaturation exists may be considerably larger than deduced from in situ measurements, which suggests that the fraction of sky covered by optically thin cirrus clouds in moderately supersaturated regions can be large [2].

Both airborne and ground based lidars can provide additional high spatial and temporal resolution measurements to help quantitatively assess the frequency and location of these ice supersaturation regions and their relationship to ice clouds. Two lidar systems have been used for these investigations. The Lidar Atmospheric Sensing Experiment (LASE), which has most recently flown on the NASA DC-8 aircraft, measured water vapor, aerosol, and cloud profiles over the tropics during the Convection and Moisture Experiment-3 (CAMEX-3) and Pacific Exploratory Mission Tropics B (PEM Tropics B) missions, and over the polar regions during the SAGE-III Ozone Loss and Validation Experiment (SOLVE). The ground-based Cloud and Radiation Testbed (CART) Southern Great Plains (SGP) Raman lidar, which has been operated by the Department of Energy Atmospheric Radiation Measurement (ARM) program, has routinely measured water vapor, aerosol, and cloud profiles over the SGP site in northern Oklahoma. We discuss these lidar systems, describe their water vapor and cloud profile measurements, and show how they have been used to assess relative humidity and ice supersaturation in the upper troposphere.

2. Instrumentation

LASE is an airborne DIAL (Differential Absorption Lidar) system that was developed to measure water vapor, aerosols, and clouds throughout the troposphere [3,4]. This system uses a double-pulsed Ti:sapphire laser, which is pumped by a frequency-doubled flashlamp-pumped Nd:YAG laser, to transmit light in the 815-nm absorption band of water vapor. LASE operates by locking to a strong water vapor line and electronically tuning to any spectral position on the absorption line to choose the suitable absorption cross-section for optimum measurements over a range of water vapor concentrations in the atmosphere. For the DC-8 missions listed above, LASE operated using strong and weak water vapor lines in both the nadir and zenith modes, thereby simultaneously acquiring data both above and below the aircraft. LASE simultaneously measures aerosol backscattering profiles at the off-line wavelength near 815 nm. Typical horizontal and vertical resolutions for water vapor profiles extending between 0.2-1.4 km are 14-70 km (1-3 min) and 300-900 m, respectively. Comparisons of water vapor measurements made by airborne dew point and
profiles are then computed using the aerosol scattering ratio $R$ and the signal detected at the laser wavelength $\lambda$. Profiles of total scattering ratio are derived using the water vapor (PWV) from the microwave radiometer (MWR) (RUC) model. The CARL water vapor mixing ratio profiles were acquired during the first 8 science flights of the first SOLVE deployment. These flights were over the Arctic region between 70°N and 85°N and between 40°W and 85°E and occurred between November 30 and December 16, 1999. Since the DC-8 generally flew above the tropopause at altitudes between 10-12 km, LASE nadir measurements provided complete water vapor, aerosol, and cloud profile coverage throughout the troposphere.

Figure 1 shows examples of relative humidity (ice) (RHI) and cloud profiles derived from LASE and MTP data acquired during 02:00 to 05:00 UT on April 14, 1999 during the transit flight from Tahiti to Easter Island. Cirrus clouds were observed both above and below the aircraft during the flight as shown by the LASE total scattering ratio profiles. The aircraft also flew through cirrus clouds between 04:20-04:40 UT during this flight. The cryogenic and laser diode in situ sensors on the DC-8 indicated ice supersaturation conditions occurred during these in-cloud periods. The relative humidity profiles derived from LASE and MTP showed ice supersaturation occupied predominantly above the aircraft. The temperature at flight level (~10.2 km) was about −35°C. Figure 1 also shows a comparison of the relative humidity profiles derived from the ECMWF model along this same flight path. The model generally represents the large-scale humidity variations along the path, but misses the small scale, high relative humidity conditions near the cirrus clouds.

Frequency distributions of relative humidity and temperature constructed using the RHI and temperature profiles derived from the LASE and MTP measurements acquired during the PEM Tropics B and the first SOLVE deployments are shown in Figure 2. The SOLVE distributions in Figure 2 were constructed using preliminary LASE and MTP data; final distributions will be constructed after completion of the SOLVE mission and presented in this paper. These distributions were constructed using 1°C and 1% RH bin sizes. Note the change in scales from logarithmic
to linear from the PEM Tropics B to SOLVE results. These distributions show that ice supersaturation conditions occurred about 5% and 11% of the time during PEM Tropics B and SOLVE, respectively, and are consistent with the range of between 5-20% derived using in situ sensors on commercial and research aircraft [2]. The lower frequencies of ice supersaturation derived from the LASE and MTP data during PEM Tropics B are likely due to two reasons. First, the LASE water vapor retrievals were generally limited to altitudes below 14 km and, therefore, did not sample the region near the tropical tropopause where thin cirrus were often observed. Second, the PEM Tropics B flight tracks were often designed to avoid clouds to optimize lidar profiling of ozone and water vapor. Figure 2 also shows that higher ice supersaturation values were observed during PEM Tropics B than during SOLVE. These higher values may be associated with different aerosol properties (e.g. fewer aerosol sources and/or removal of aerosols via fallout of previously-formed ice crystals) associated with the tropical “maritime” environment [1].

4. Raman Lidar

Profiles of water vapor mixing ratio, relative humidity, total scattering ratio, aerosol and cloud backscatter, and depolarization ratio have been computed from CARL on a nearly continuous basis from April, 1998 through the present time. During this period, CARL operated nearly 50% of the time. CARL measurements of cirrus and upper tropospheric relative humidity are limited to nighttime because the increased daytime solar background limits water vapor retrievals to altitudes below about 4 km. Examples of these profiles acquired during the night of December 5, 1998 are shown in Figure 3. These measurements show ice supersaturation occurred near the cirrus clouds throughout much of this night. We shall discuss these and other CARL measurements in more detail at the meeting.

5. Summary

Upper tropospheric relative humidity profiles computed using airborne LASE and ground-based SGP CART Raman lidar show ice supersaturation occurs in both clear and cloudy regions. LASE data acquired during the PEM Tropics B and first SOLVE deployments indicate that ice supersaturation occurred about 5-11% of the time when temperatures were below ~35°C. These results do not indicate that in situ measurements significantly underestimate the fraction of the upper troposphere where supersaturation exists. However, since ice supersaturation often occurs in thin layers, the large vertical (~300 to 900 m) and horizontal (~14 to 70 km) resolutions of the LASE water vapor data may not fully capture the peak RHI values and, therefore, may underestimate the frequency and magnitude of ice supersaturation. Additional studies will be performed to investigate how the vertical and temporal resolutions of the LASE water vapor measurements affect the derived frequency of ice supersaturation.
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REFERENCES


Figure 2. Distribution of relative humidity (ice) as a function of temperature derived using LASE water vapor and MTP temperature profiles measured during PEM Tropics B (left) and first SOLVE deployments (right). The SOLVE results are computed using preliminary data. The dotted lines represent water saturation.

Figure 3. Cloud backscatter (top) and relative humidity (bottom) profiles measured by the SGP CART Raman lidar on December 5, 1998.