

# Physical Properties of Tropical Cirrus Clouds Based on Satellite Measurements

I.L. Galkina and J.J. Sloan

Department of Earth and Environmental Sciences  
University of Waterloo, Waterloo, Ontario N2L 3G1 Canada

We report a study of ice aerosols in the tropical upper troposphere and lower stratosphere, based on retrievals of remote sensing measurements made by two instruments aboard the Canadian SCISAT satellite: the Vis/NIR imagers and the Atmospheric Chemistry Experiment-Fourier transform spectrometer (ACE-FTS). The observations are made in the solar occultation configuration, with a vertical resolution on the order of 4 km. The ACE-FTS measurements consist of infrared spectra in the range from 750 cm<sup>-1</sup> to 4400 cm<sup>-1</sup> with a resolution of 0.02 cm<sup>-1</sup>. The imagers have two filtered channels operating at 0.525 μm and 1.02 μm. The composition and size distributions of the aerosols are retrieved from these data, using methods based on laboratory measurements with cryogenic flowtubes that simulate the physical conditions in the tropopause region.

In the following, the retrieval procedures will be described briefly, together with the results obtained for selected measurements. We focus on tropical cirrus clouds observed during 2004 and 2005 in the latitude range between 25°N and 25°S. A special effort was made to detect upper troposphere-lower stratosphere convective exchange. Based on the results for the entire dataset, we report a comparison of the seasonal variations in the vertical profiles of ice particle number density and size distribution. We also report the averaged values of these properties for different seasons and consider several individual case studies of dense clouds

## 1. Introduction

The role of clouds in climate change is one of the most important problems in atmospheric science at the present time and climate-related influences of clouds are currently the subject of many studies (see for example [Brandefelt, J., 2006] and references therein). Computer models of Earth's General Circulation require accurate information about the seasonality, composition and particle size of clouds in order to determine their effects on radiative transfer [Ebert, E.E. and J. A. Curry, 1992]. This is particularly important in the tropics, where the insolation is high.

Cirrus clouds play a significant role in the tropical regions both radiatively and dynamically [Comstock, J.M. and C. Jakob, 2004]; the persistence and microphysical properties of such clouds are particularly important [Boehm, M.T. *et al.*, 1999]. In the tropics, cirrus clouds are often associated with deep convection in which they are influenced by large-scale vertical ascent [Mace, G.G. *et al.*, 2006] that subjects the air parcels to rapid cooling, which can induce non-equilibrium conditions that are difficult to predict from theory.

The climate effects of cirrus clouds stem from their absorption of upwelling infrared radiation emitted by the surface, which can trap heat that would otherwise escape, combined with their reflection and scattering of solar radiation, which reduces the amount that reaches the Earth's surface and causes cooling. It is thus very important to know whether these effects result in a net warming or cooling [Hartmann, D.L. *et al.*, 2001] but this is at present poorly understood since it depends in a complicated way on cloud altitude, thickness and ice crystal size distribution.

It is important to have as many direct measurements of the properties of cirrus clouds as possible, in order to provide empirical information that can be parameterized in models. The work reported here is devoted to such measurements of high cirrus clouds in the tropics. Special attention was paid to cloud locations, altitudes the relationship between cloud properties and temperature.

## **2. Measurements**

### **2.1 Instruments**

The measurements were done using the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) [Bernath, P.F., 2006]. This instrument was launched into a low Earth orbit (650 km), at high inclination (74 degrees) in August 2003 aboard the Canadian SciSat satellite. This orbit allows the study of a range of atmospheric properties in tropical, mid-latitude, and Polar Regions at latitudes from 85°N to 85°S. The retrievals include temperature, pressure and the volume mixing ratios of approximately 25 molecules. The measurements were recorded in solar occultation mode, providing information from cloud top to about 100 km.

The ACE-FTS is high spectral resolution ( $0.02 \text{ cm}^{-1}$ ) infrared Fourier Transform Spectrometer that operates in the wavelength range from 2.2 to  $13.3 \mu\text{m}$  ( $750 - 4400 \text{ cm}^{-1}$ ) with a vertical field of view (FOV) of about 4 km. Spectra are recorded in two occultations (sunrise and sunset) each orbit. These spectra are inverted to obtain vertical profiles of atmospheric constituents.

In addition, the satellite carries two filtered imagers at 0.525 and  $1.02 \mu\text{m}$ , to obtain images of the solar disk. The total field of view of the imagers is 30 mrad. They provide important diagnostics for pointing and also serve as sensitive detectors for the presence of clouds.

### **2.2 Retrievals**

After cloud detection based on total extinction using the imager signal, the FTS spectra that contain the cloud signatures were analysed using software developed in our laboratory [Zasetsky, A.Y. *et al.*, 2002] that enables us to retrieve the number density, size distribution and composition of the cloud particles. It includes techniques for the separation of the aerosol and gas phase spectra and the filtering and weighting of the condensed phase spectra to minimize the effects of heavily overlapped gas phase lines. The retrieval is carried out by a constrained least squares minimization using previously computed reference spectra of the materials being sought [Zasetsky, A.Y. *et al.*, 2004] assuming that the particle is spherical.

## **3. Results**

We report observations restricted to the latitude range between 25 S and 25 N during during 2004 and 2005. In order examine seasonal effects on clouds, occultations of one

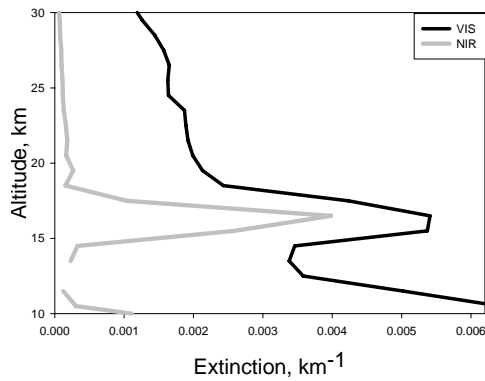


Figure 1: Vertical profile of extinction for occultation 7989

month representing the seasons in each hemisphere were taken. These were (for Northern and Southern hemisphere observations respectively) autumn - October and April; winter - February and August; spring - April and October; summer - August and February. Between 60 and 200 occultations were processed for each month. This study of seasonal effects was motivated by some seasonal difference in water vapor and temperature profiles that were observed by [Nassar, R. *et al.*,

2005].

A database of all tropical occultations was created and from this, occultations with and without clouds were selected (the latter were used for calculating the background extinction). For the purposes of this report, occultations having clouds at altitudes between about 12 km and the tropopause (about 17-18 km) were selected. In most

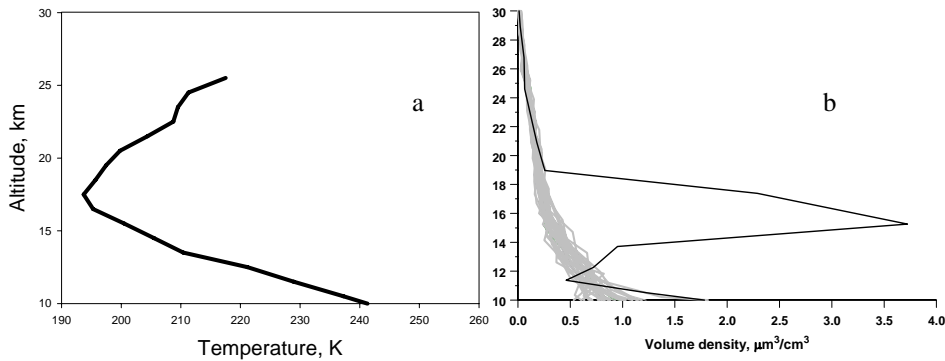


Figure 2. (a) Temperature profile and (b) volume density of occultation shown in figure 1. Grey curves in (b) are volume densities of 100 non-cloud occultations.

cases, the clouds were clearly identified from the extinction signatures observed by the imagers. A typical example is shown in Figure 1 for an occultation recorded on 5 February 2005 at 3.6°S;146°W. The temperature profile for this occultation and the volume density of the cloud are shown in Figure 2. The volume density is the sum of all condensed phase material that is retrieved using our method described above

It is clear that the maximum volume density of the cloud is located just below the cold point tropopause, which is at about 17 km in this case. The centres of the FOV for the measurements containing cloud signatures were at approximately 14, 16, and 18 km. Since the vertical FOV of the ACE-FTS is 4 km, the absence of a cloud signal in the measurement at 19 km indicates that the cloud top is at approximately 17 km.

The structure of the clouds were observed to change with seasons and to obtain a seasonal climatology of this phenomenon, we grouped all the observations for each season (as defined above) into 5 km vertical bins. The resulting volume densities for each of the seasons as defined above are shown in Figure 3.

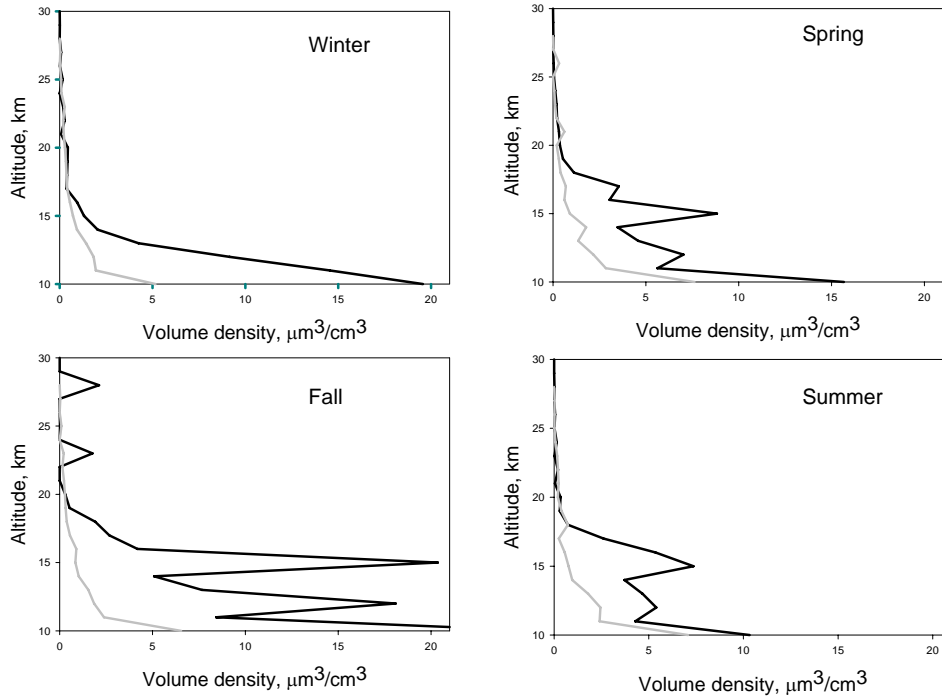


Figure 3. Volume densities of clouds observed during the seasons as defined above. Light grey indicates average background.

The relative absence of high clouds during the winter (northern hemisphere observations in February and southern hemisphere observations in August) and the prominent double cloud layer during the fall (northern hemisphere observations in October and Southern hemisphere observations in April) were persistent and obvious features. The other seasons showed more varied structure with relatively less dense clouds just under the tropopause, which in all cases was at approximately 17-18 km. The origins of these seasonal patterns are not clear at the present time.

Figure 4 shows the volume size distribution of the ice particles retrieved using the procedure of [Zasetsky, A. Y. *et al.*, 2004] with the occultation shown in Figure 2. (The volume size distribution is the number distribution multiplied by the volume of the sphere having the same radius.) This distribution consist of two groups of particle sizes (modes): a smaller one at about  $10\mu\text{m}$  and a larger one with radius larger than  $30\mu\text{m}$ . (The larger mode cannot be retrieved by our procedure in this case because the spectra of such large particles do not have characteristic features that make them identifiable in the least squares minimization.) This double-mode distribution is typical of the ice particle size distributions observed in this work, which usually consist of a small mode having radius between 5 and  $10\mu\text{m}$  and a larger one that usually extends beyond the upper limit of our retrieval technique.

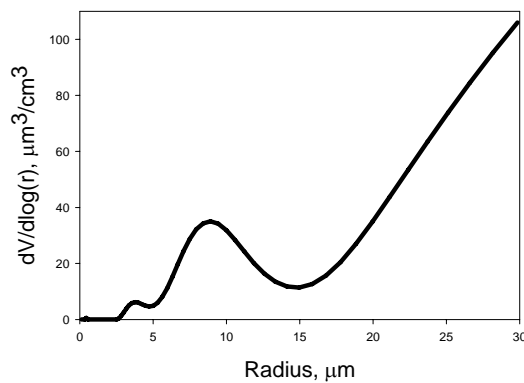


Figure 4. Size distribution of ice particles at the density maximum of the cloud in figure 3

Observations carried out using the solar occultation method have a very long horizontal path through the atmosphere. As a result, it is not possible to state whether the two particle size distributions shown in Figure 4 coexist in the same cloud or if they are separated geographically along the light path. Double-mode distributions having one small and one large mode are nearly ubiquitous in the observations made during this study, however, suggesting that tropical

cirrus clouds at this altitude likely consist of such a mixture of particle sizes.

In several occultations, these size distributions were observed to evolve smoothly with altitude as shown in Figure 5.

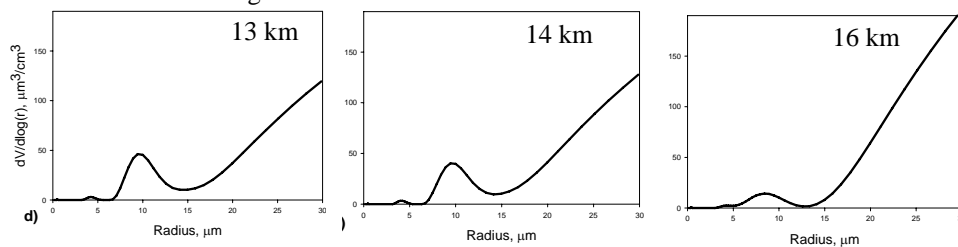


Figure 5. Evolution of size distribution with altitude in a single cloud.

We are presently investigating the meteorological conditions associated with this behaviour. It is possibly caused by dynamics associated with convective activity occurring during the cloud formation processes.

#### 4. Conclusions

The high tropical cirrus clouds reported here consist mainly of relatively large ice particles that are present in two modes: a smaller one between 5 and 10  $\mu\text{m}$  in radius and a larger one with radius exceeding 30  $\mu\text{m}$ . The latter appear to occur preferentially at higher altitudes, presumably due to particle growth during convective uplift. Usually the highest cirrus volume densities are observed just below the tropopause in the 15-16 km altitude range. There appears to be a seasonal variation in cloud density and structure. The densest and most complex clouds occur in the fall, while the winter season is nearly devoid of high cirrus in the tropics.

#### 5. Acknowledgements

We are grateful for the financial support of the Canadian Space Agency and the Natural Sciences and Engineering Research Council of Canada. We also acknowledge many helpful discussions with Dr. C. Boone of the ACE Science Team.

## 6. References

- Bernath, P. F., Atmospheric chemistry experiment (ACE): Analytical chemistry from orbit, *Trac-Trends in Analytical Chemistry* 25(7), 647-654, 2006
- Boehm, M. T. *et al.* On the maintenance of high tropical cirrus, *Journal of Geophysical Research-Atmospheres* 104(D20), 24423-24433, 1999
- Brandefelt, J., Atmospheric modes of variability in a changing climate, *Journal of Climate* 19(22), 5934-5943, 2006
- Comstock, J. M. and C. Jakob, Evaluation of tropical cirrus cloud properties derived from ECMWF model output and ground based measurements over Nauru Island, *Geophysical Research Letters* 31(10), 2004
- Ebert, E. E. and J. A. Curry, A Parameterization of Ice-Cloud Optical-Properties for Climate Models, *Journal of Geophysical Research-Atmospheres* 97(D4), 3831-3836, 1992
- Hartmann, D. L. *et al.* The heat balance of the tropical tropopause, cirrus, and stratospheric dehydration, *Geophysical Research Letters* 28(10), 1969-1972, 2001
- Mace, G. G. *et al.* Association of tropical cirrus in the 10-15-km layer with deep convective sources: An observational study combining millimeter radar data and satellite-derived trajectories, *Journal of the Atmospheric Sciences* 63(2), 480-503, 2006
- Nassar, R. *et al.* Stratospheric abundances of water and methane based on ACE-FTS measurements, *Geophysical Research Letters* 32(15), 2005
- Zasetsky, A. Y. *et al.* Characterization of atmospheric aerosols from infrared measurements: simulations, testing, and applications, *Applied Optics* 43(29), 5503-5511, 2004
- Zasetsky, A. Y. *et al.* A new method for the quantitative identification of the composition, size and density of stratospheric aerosols from high resolution IR satellite measurements, *Geophysical Research Letters* 29(22), 2002