Hunt for Molecules
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HUNT FOR EARTH ICE CLOUDS USING MILLIMETER AND SUB-MILLIMETER OBSERVATIONS

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Abstract. We suggest that millimeter and sub-millimeter satellite observations can help characterizing the Earth ice clouds. The role of high cloud in meteorology and climate studies is first underlined. Then the sensivity of this wevelength range to ice cloud properties is analyzed. Lastly, a satellite mission project for cirrus characterization with millimeter and sub-millimeter measurements is briefly described.

1 Introduction

Operational meteorological satellites perform microwave measurements up to 190 GHz from polar orbits to measure Earth atmospheric and surface parameters such as the temperature and water vapor atmospheric profiles, the cloud liquid water content, or the wind speed at the surface ocean.

There is now a need for millimeter and sub-millimeter observations for meteorological applications.

First, for nowcasting and observations of severe weather, higher satellite orbits are desirable to provide the adequate revisiting times. The problem is that to achieve necessary spatial resolution on the ground, the diameter of the required antenna is proportional to the orbit height and inversely proportional to the frequency. With a ratio of ∼ 45 in distance between polar

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and geosynchronous orbits, adequate spatial resolution is difficult to achieve from geostationary orbit at low microwave frequencies with an antenna of reasonable size. One solution is to use higher frequencies. Millimeter and sub-millimeter instruments for geostationary satellite are now planned for meteorological applications. The NASA-NOAA Geosynchronous Microwave Sounder Working Group developed the project of a sub-millimeter wave GEosynchronous Microwave sounder and imager (GEM) equipped with a 2 m scanning antenna, with channels in the oxygen bands (54, 118, and 425 GHz) and in the water vapor lines (183 and 340/380 GHz) (Staelin et al. 1998). The Geostationary Observatory for Microwave Atmospheric Sounding (GOMAS) project was also proposed recently to the European Space Agency by Bizzari et al. (2005) as a Next Earth Explorer core mission, with channels similar to the GEM ones.

Second, studies show that satellite measurements in the millimeter and sub-millimeter could help supplement the infra-red and the visible observations to characterize the cloud ice phase (Evans et al. 2002, 2005) and satellite projects are planned to explore this frequency range.

This paper will concentrate on the applications of the millimeter and sub-millimeter observations from satellite for ice cloud characterization. Section 2 will briefly summarize the role of high cloud analysis for meteorology and climate studies. Then the sensivity of millimeter and sub-millimeter observations to ice cloud properties will be analyzed (Section 3) and Section 4 will conclude with the description of a satellite mission for cirrus characterization.

2 High cloud characterization for meteorological and climatological applications

On average, ~ 20% of the globe is covered by high clouds (Rossow & Schiffer 1999; Wylie et al. 1999), with substantial impact on the global radiative budget. Depending on their optical properties, ice clouds can have a net warming effect (green-house effect) because their cold temperatures trap longwave radiation on their way into space or a net cooling effect from shortwave reflection, as shown by numerical studies (e. g., Stephens & Webster 1981). Ice cloud parameterizations have been included in climate models to predict ice mass, but have not been validated yet, and climate simulations are extremely sensitive to small changes in cirrus cloud parameterizations.

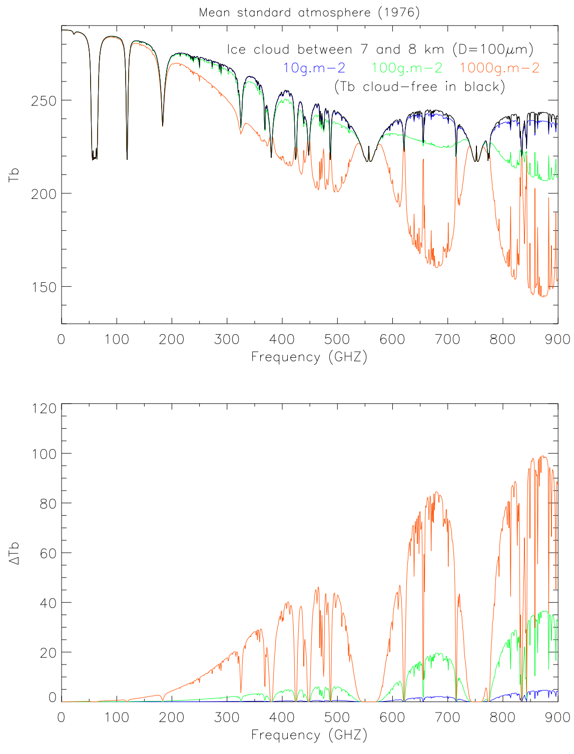


Fig. 1. Top: Simulated brightness temperatures between 1 and 900 GHz, for a mean standard atmosphere (water vapor content of 14.2 $\mathrm{kg\,m^{-2}}$ and surface temperature of 288 K), including an ice layer between 7 and 8 km. The incidence angle is 53° and surface emissivity is equal to unity. Density of ice is 0.9 and we consider single size spherical particles. Results are presented for different ice water paths IWP for a fixed particle size of D=100 μm. Bottom: Corresponding ΔTb i.e. T_b depression with respect to the simulation without ice.

In addition, the formation and growth of ice particles in convective systems are key processes to determine rainfall intensity. Ice water amounts reflect the strength of the convection and the stage of the cloud in its life cycle.

Among the most important cloud physical properties are liquid/ice water path and cloud particle sizes (water spheres/ice crystals) and their distributions within clouds. These quantities are especially difficult to determine for ice clouds and are currently only indirectly estimated with large uncertainties. It is also important to infer the cloud vertical structure and thus the cloud vertical heating profile.

Only satellite observations are capable to give a continuous survey of the cloud cover characteristics over the whole globe. However, despite the large amount of existing satellite observations, our knowledge of ice clouds still remains limited and this inhibits our ability to constrain current climate models. In situ measurements of cirrus clouds indicate that satellite observations must accurately retrieve Ice Water Path (IWP) over a range of 5-1000 g/m^2 and the mean effective particle diameter (D_e) between approximately 10 to 1000 μm. No existing satellite instrument alone is capable of observing the complete range of IWP and D_e. Due to the wavelength-to-size ratio, visible techniques are very sensitive to particle shape and size. Thermal infrared methods require accurate estimates of the cloud temperature. Both thermal and infrared techniques become insensitive for particle diameters above 100 μm, and for optically thick clouds. In the microwave domain, the index of refraction makes ice absorption insignificant and microwave radiation interacts primarily with ice particles through scattering. For particles that are not too small compared to the wavelength, ice clouds essentially depress the upwelling microwave signal. The change in microwave radiation is well correlated to the ice column, and is insensitive to cloud temperature. However, microwave radiation is insensitive to small ice particles, below $\sim$ 100 μm for frequencies below 400 GHz. A global determination of ice cloud characteristics will necessarily combine information from different techniques, to sense accurately the large variety of IWP and crystal habits.

3 Sensitivity of passive microwave, millimeter, and sub-millimeter observations to high clouds

A radiative transfer model has been developed that includes a full treatment of scattering by hydrometeors: Atmospheric Transmission at Microwaves (ATM). It combines into a single code an up-to-date model of the microwave gas absorption in the atmosphere (Pardo et al. 2001), T-matrix routines to calculate the scattering by non-spherical particles (Mishchenko 1991), and “doubling and adding” polarized radiative transfer through plane parallel

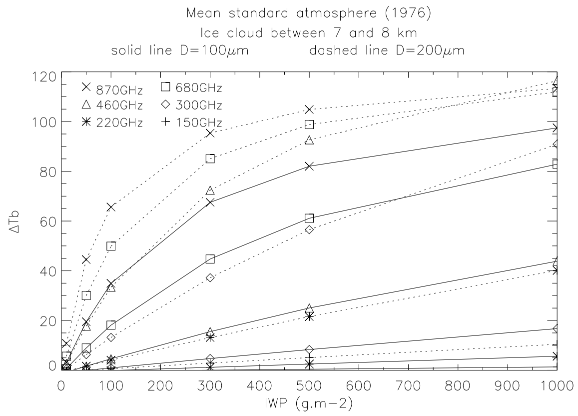


Fig. 2. For window frequencies, ΔTb versus IWP, for the same type of ice cloud between 7 and 8 km, with D=100 μm and D=200 μm

layers composed of such particles (Evans & Stephens 1995).

In the millimeter wave region, the refractive index of ice is smaller than that of water and is weakly dependent on frequency, the real part being close to 1.8 and the imaginary part being much smaller. As a consequence, absorption by ice is very weak, and radiation interacts with the ice particles primarily by scattering. For small particles with diameters D $\leq$ 50 μm, radiation up to 900 GHz is barely affected by ice particles, neither by absorption nor by scattering.

3.1 Sensitivity to ice water path

Brightness temperatures have been simulated for frequencies up to 900 GHz, for a mean standard atmosphere (water vapor content of 14.2 $\mathrm{kg\,m^{-2}}$ and surface temperature of 288 K), including an ice layer between 7 and 8 km (Fig. 1, top). The incidence angle of observation is 53° and the surface has an emissivity equal to unity. The density of ice is 0.9 and single size spherical particles are used. A size distribution could be simulated, but single size particle analysis highlights the particle size impact. The ice contribution is estimated in terms of T_b depression ΔTb with respect to the corresponding cloud-free T_{b0}. ΔTb is also plotted on Fig. 1 (bottom). Results are presented for different ice water paths IWP for a fixed particle size of D=100 μm. Frequencies below 500 GHz are not suitable for the detection of thin cirrus with $IWP < 10$ g m^{-2} with particle diameter below 100 μm. ΔTb increases with increasing IWP and with frequencies. For frequencies located in window regions, ΔTb versus IWP is plotted on Fig. 2, for the same type of ice cloud between 7 and 8 km, with D=100 μm and D=200 μm. For frequencies up to 300 GHz, ΔTb increases almost linearly with IWP but is not measurable at low frequencies for low IWP. On the contrary, small IWP can be detected at frequencies above 400 GHz but the signal saturates for large IWP. This shows the necessity of selecting a broad range of frequencies in order to estimate the large variability of IWP, from thin cirrus to thick anvils. However, it is clear from Fig. 2 that particle size plays a major role in ΔTb, and that the retrieval of IWP cannot be performed without information on the particle size.

3.2 Sensitivity to particle size

The effect of particle size can be seen on Fig. 3, which is similar to Fig. 1 but for different particle sizes with a fixed IWP of 10 g.m^{-2}. At low frequencies, for a given IWP, ΔTb increases with particle size. At higher frequencies, still for a constant IWP, ΔTb increases for smaller particles but levels off as the particle size approaches the wavelength. Detection of small particles will require high frequency radiometers with a good sensitivity. Figure 4 presents the ratio of ΔTb at two distinct frequencies versus the particle size, for IWP of 10 and 100 g.m^{-2}. ΔTb ratios are sensitive to particle size while being rather insensitive to IWP. ΔTb ratios for 870 and 460 GHz for example are particularly sensitive to particle size, without ambiguities as observed for other ratios (600 GHz/300 GHz for example). As a consequence, particle size estimation should be possible with a thorough analysis of ΔTb ratios at various frequencies. However, one has to keep in mind that the variability of other parameters such as the particle size distribution or the cloud altitude, combined with uncertainties in dielectric properties of ice or particle shapes will inevitably add uncertainties to the retrieval.

3.3 Sensitivity to particle shape and orientation

Over convective cloud systems, polarized scattering signals have been measured from satellites at 85 GHz that measure in two orthogonal polariza-

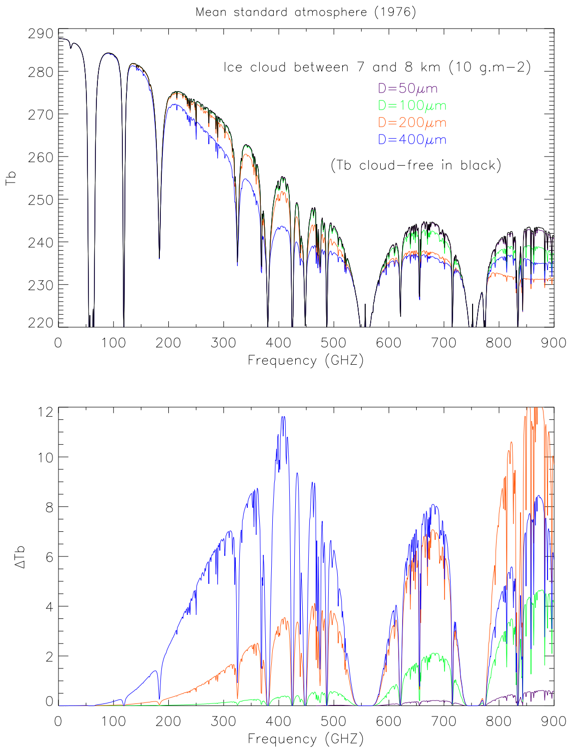


Fig. 3. Same as Fig. 1 but for different particle sizes with a fixed *IWP* of 10 $\mathrm{g\,m^{-2}}$

tions with a 53^o viewing angle. Significant polarization differences can only be explained by the presence of mostly oriented non-spherical particles, as shown by radiative tranfer simulation. ATM incorporates the possibility of simulating the presence of prolate and oblate particles that are randomly oriented within an angle α_0 with respect to the vertical or the horizontal.

In a first simulation set, oblate spheroids that are mostly horizontally oriented (Fig. 5, top) are considered. Large positive polarization differences are obtained, that can explain the satellite observations. In the more stratiform region of the cloud system, forces on falling non-spherical particles

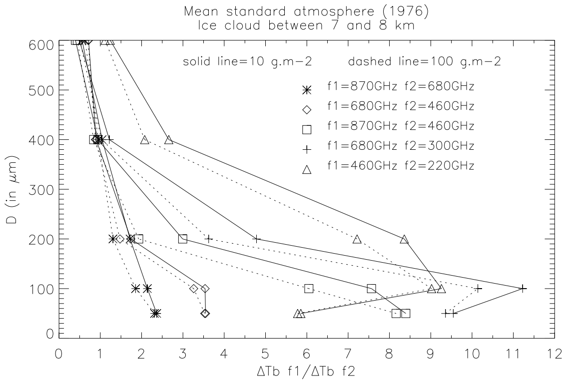


Fig. 4. Ratio of ΔTb at two distinct frequencies versus the particle size, for IWP of 10 and 100 g.m^{-2}

are expected to align them horizontally, especially the largest precipitation-sized particles (the forces being size dependent). This is consistent with the occurrence of the positive polarization (TbV-TbH>0) observed in the most homogeneous part of the cloud structure (Prigent et al. 2001).

In a second simulation set, prolate particles essentially vertically oriented are examined (Fig 5, bottom). Significant negative polarization differences are then obtained. In the deep convective cores of the cloud systems, vertically oriented non-spherical particles related to the electrical processes are present. Using coincident satellite lighting detector and passive microwave observations, we showed the relationship between the presence of the negative polarization differences and the strong electrical activity in the cloud (Prigent et al. 2005).

4 Conclusions and suggested instrumentation for a dedicated ice cloud satellite mission

Passive observations in the millimeter and sub-millimeter range can provide unique information on the ice cloud characteristics, namely the ice water path, the particle size distribution, the particle shape and orientation. These high frequency instruments have not flown yet for this purpose and it is expected that the retrieval of each ice parameter will be difficult, being

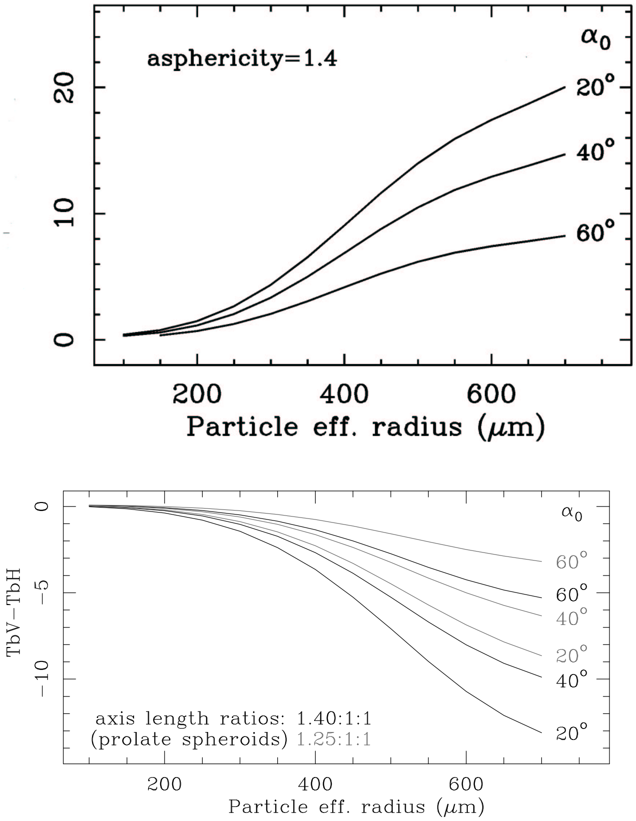
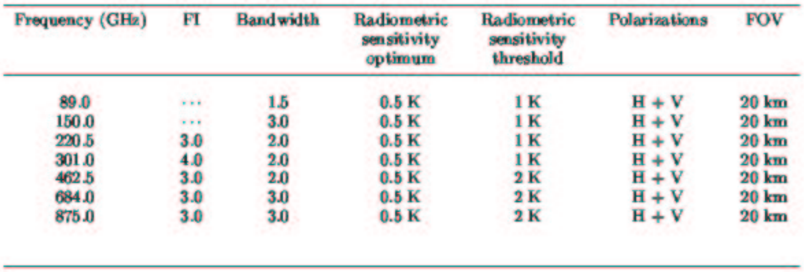


Fig. 5. For an observation with a 53^o zenith angle, sensitivity of the 85 GHz polarization difference to the orientation of the oblate (top) and prolate (bottom) particles as a function of particle size. The orientation of the particles is random within α_0 from the horizontal axis (top) and within α_0 from the vertical axis (bottom).

highly non-linear and depending upon a large number of auxiliary variables.

Several satellite mission projects have been recently designed to provide the necessary millimeter and sub-millimeter measurements for cirrus characterization (e. g. Evans et al. 1999; Goutoule et al. 2003; Buehler et al.

Table 1. Recommanded Frequency Channels



Frequency (GHz)	FI	Bandwidth	Radiometric sensitivity optimum	Radiometric sensitivity threshold	Polarizations	FOV
89.0	···	1.5	0.5 K	1 K	H + V	20 km
150.0	···	3.0	0.5 K	1 K	H + V	20 km
220.5	3.0	2.0	0.5 K	1 K	H + V	20 km
301.0	4.0	2.0	0.5 K	1 K	H + V	20 km
462.5	3.0	2.0	0.5 K	2 K	H + V	20 km
684.0	3.0	3.0	0.5 K	2 K	H + V	20 km
875.0	3.0	3.0	0.5 K	2 K	H + V	20 km

2005). For example, the EADS/LERMA project suggest the use of 7 isolated channels between for the detection of both thin cirrus and thick anvils. Table 1 summarizes the suggested channels and their main characteristics. An indication for the necessary radiometric sensitivity and absolute accuracy has been specified for each receiver. A constant incident angle is highly recommended. An incident angle around 50° is suggested. All channels will be observed in the two linear polarizations.

Adding this instrument will enable to estimate regional distributions of ice water path and ice particle effective diameter over extended conditions. It will first provide new independent measurements of these variables, and will ultimately be combined with other sensor observations for a global characterisation of ice cloud properties.

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