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Estimating glaciation temperature of deep convective clouds with remote sensing data

Tianle Yuan,[1,2] J. Vanderlei Martins,[1,2,3] Zhanqing Li,[4,5] and Lorraine A. Remer[2]

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[1] Major uncertainties exist for observing and modeling ice content inside deep convective clouds (DCC). One of the difficulties has been the lack of characterization of vertical profiles of cloud hydrometeor phase. Here we propose a technique to estimate the DCC glaciation temperature using passive remote sensing data. It is based on a conceptual model of vertical hydrometeor size profiles inside DCCs. Estimates from the technique agree well with our general understanding of the problem. Furthermore, the link between vertical profiles of cloud particle size and hydrometeor thermodynamic phase is confirmed by a 3-D cloud retrieval technique. The technique is applied to aircraft measurements of cloud side reflectance and the result was compared favorably with an independent retrieval of thermodynamic phase based on different refractive indices at 2.13 μm and 2.25 μm. Possible applications of the technique are discussed. **Citation:** Yuan, T., J. V. Martins, Z. Li, and L. A. Remer (2010), Estimating glaciation temperature of deep convective clouds with remote sensing data, *Geophys. Res. Lett.*, *37*, L08808, doi:10.1029/2010GL042753.

1. Introduction

[2] Cloud hydrometeors rarely change from liquid droplets into ice particles when they are moved immediately above the 0°C level [*Pruppacher and Klett*, 1997]. Homogeneous freezing is inefficient at temperatures much warmer than the homogeneous freezing temperature around −38°C, at which temperature most water droplets transform into ice particles instantaneously. At warmer temperatures the phase change requires certain ice nuclei (IN) to be present to initiate the freezing [*DeMott et al.*, 2003a, 2003b], except for extremely large drops. In situ observations have confirmed this [*Rangno and Hobbs*, 2005, and references therein] and in certain conditions all cloud water content remain in the liquid phase until the temperature gets as cold as −38°C and all liquid instantaneously freezes into ice at higher altitude [*Rosenfeld and Woodley*, 2000]. Because the freezing of cloud liquid water releases a large amount of latent heat the cloud condensate phase transition can affect the dynamic interactions between the convection and the stratified atmosphere [*Emanuel*, 1994]. Knowledge about the vertical structure of latent heat release is needed to better understand our global atmosphere circulation and better predict future climate [*Baker*, 1997]. For example, significant cloud radiative forcing on the order of 4 ~ 8 Wm^{-2} can be introduced as the consequence of glaciation [*Fowler and Randall*, 1996]. Currently, there is no good observational constraint on glaciation temperature (GT), the temperature above which water content inside clouds is all in ice phase, in our climate models [*Zhang et al.*, 2003; *Tompkins et al.*, 2007]. This adds an additional layer of uncertainty in the effort to the already poorly handled problem of properly treating deep convective clouds (DCCs) in a global model [*Arakawa*, 2004]. Cloud ice, for which DCCs are a dominant source [*Luo and Rossow*, 2004], plays important roles in Earth's radiation budget [*Liou*, 1976; *Chen et al.*, 2000], precipitation formation [*Lau and Wu*, 2003], and upper troposphere and low stratosphere water vapor concentration [*Fueglistaler et al.*, 2009; *Sherwood et al.*, 2003; *Hartmann et al.*, 2001] among other physical processes [*Waliser et al.*, 2009]. Yet, even though numerous studies have attempted to characterize cloud ice there is no consensus among them, even for the global average value [*Waliser et al.*, 2009]. In fact, estimates from both general circulation models and various remote sensing products vary several folds in magnitude [*Waliser et al.*, 2009, and references therein]. There are many factors related to instruments, retrieval methods, model parameterizations, etc. that contribute to this large uncertainty.

[3] We argue that in addition to factors just mentioned, the lack of observational constraints on basic variables like GT makes it impossible to fully address the issue. In most models and some retrieval techniques a threshold of GT is assumed and another for freezing level, below which clouds are all liquid, is prescribed globally and the partition between liquid and ice is linearly interpolated [*Zhang et al.*, 2003; *Tompkins et al.*, 2007; *Austin et al.*, 2009]. These assumptions are not realistic given the fact that in situ observations have provided large variations inside clouds under various conditions [*Rosenfeld and Woodley*, 2000; *Black and Hallett*, 1986; *Rangno and Hobbs*, 2005]. In this study we propose a new technique to estimate GT from an ensemble of remote sensing data.

2. Method

[4] Our technique is based on a conceptual model of the vertical evolution of cloud hydrometeor sizes inside a deep convective cloud as presented in Figure 1a. Figure 1a is a slightly different version of the model by *Rosenfeld and Woodley* [2003] with additions from *Yuan and Li* [2010],

[1]Joint Center for Earth System Technology, University of Maryland, Baltimore County, Baltimore, Maryland, USA.
[2]Laboratory for Atmosphere, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
[3]Department of Physics, University of Maryland, Baltimore County, Baltimore, Maryland, USA.
[4]Department of Atmospheric and Oceanic Sciences, University of Maryland, College Park, Maryland, USA.
[5]Earth System Science Interdisciplinary Center, University of Maryland, College Park, Maryland, USA.

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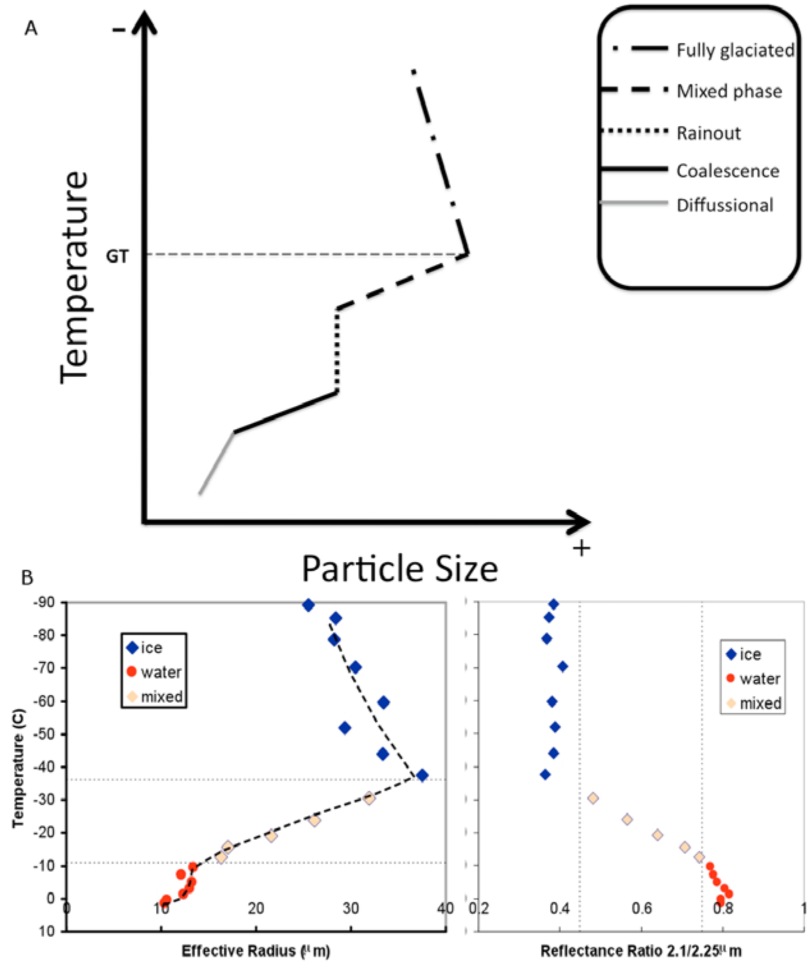

Figure 1. (a) A conceptual diagram of cloud particle size vertical evolution inside a DCC. It is a slightly modified picture from *Rosenfeld and Woodley* [2003] based on results of *Yuan and Li* [2010]. (b) Cloud side scanner retrievals of (left) particle size and (right) cloud phase. Independent reference can be made about the glaciation level from either one of these plots using indirect (Figure 2b, left) and direct arguments. This validates main arguments used in this paper. Figure is extracted from *Martins et al.* [2007].

in which we identified a positive correlation between cloud particle size and cloud temperature once clouds are already glaciated. In this paper we extend the analysis to include warmer temperatures to detect glaciation temperature, while *Yuan and Li* [2010] is concerned with the general properties of deep convective clouds as revealed by MODIS product.

[5] Cloud hydrometeor growth is separated conceptually into five stages. A slow diffusional growth stage is followed by an efficient collision/coalescence growth stage once the effective radius of droplets exceeds a critical value [*Rangno and Hobbs*, 2005; *Rosenfeld and Lensky*, 1998]. Rain out then follows if the coalescence process produces large enough drops. Once ice is initiated either by homogeneous freezing of large drops or heterogeneous freezing with presence of ice nuclei, the mixed phase stage begins. The mixed phase stage is characterized by a fast rate of cloud particle size increase with height, or decrease with temperature. Three factors contribute to this fast rate of growth. First, the Bergeron-Findeisen process takes place in which ice particles take advantage of the difference in supersaturation between ice and water, growing at the expense of supercooled drops. Second, rimming and accretion processes effectively increase ice particle sizes similarly to collision/coalescence for droplets. Third, the feedback of latent heat release unto cloud scale dynamics through microphysical processes maintains the required vertical velocity to sustain large ice particles in the air by counteracting gravitational settling. These processes determine that cloud particle size increases with height for these stages. Once the cloud is fully glaciated, i.e., no supercooled liquid water content is left, which usually happens at very cold temperatures, the supersaturation of water vapor is insufficient to sustain the growth, large ice particles are no longer transported upward and only smaller ice particles have low enough terminal velocities to continue to move upward inside weakened updrafts. This so-called "size sorting effect" creates a positive correlation between temperature and ice particle size, i.e. the colder it gets, the smaller the ice particle sizes. Also, small ice crystals from homogeneous freezing of aerosol particles may also contribute to the reduction in ice particle size with height [*Heymsfield et al.*, 2009]. Between the fast growing mixed-phase stage and the fully-glaciated stage the particle size dependence on temperature switches signs. In other words, we would expect a turning point in a

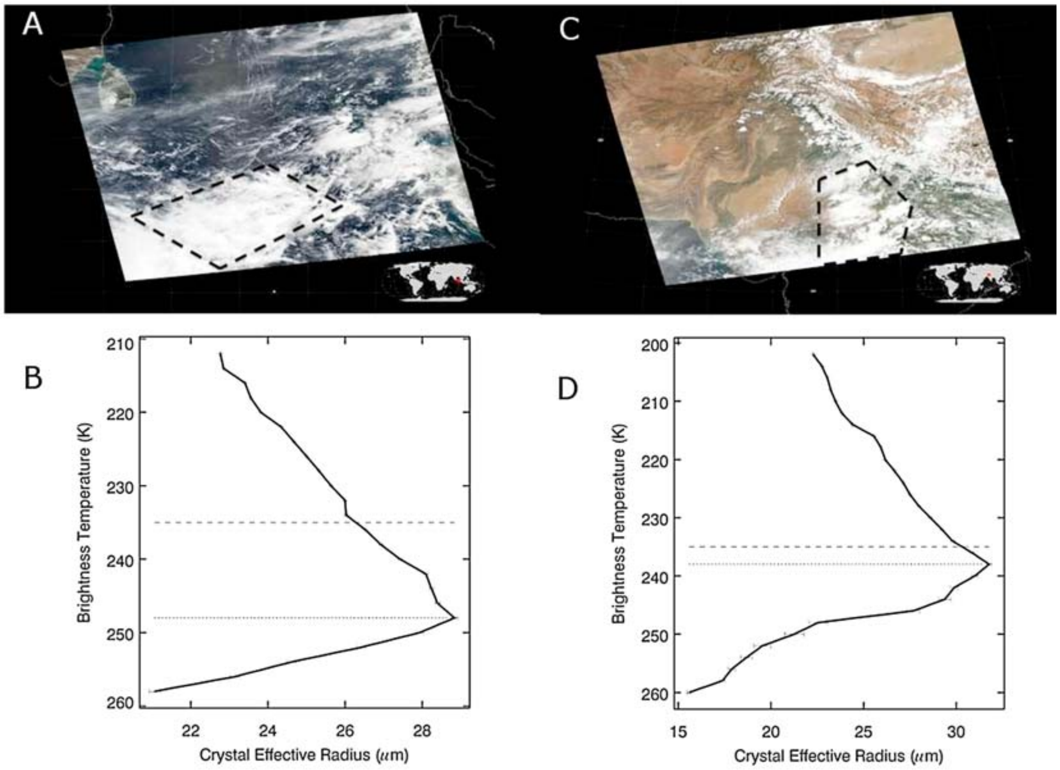

Figure 2. (a) Aqua MODIS true color image at 0815 UTC on 18 July, 2006. Analysis is done for the maritime cloud system (illustrated with black dashed lines). (b) The CER-BT profile for the DCC system selected in Figure 2a. The estimated glaciation temperature is about 248K (dotted line). The dashed line denotes the 235K (or −38°C) level. (c) Aqua MODIS true color image at 0730 UTC on 8 July, 2006. A deep convective cloud system located over the Indo-Gangetic Plain is encircled by dotted lines. (d) The CER-BT profile for the DCC system selected in Figure 2c.

temperature versus cloud particle size (T-PS) diagram, which is illustrated in Figure 1a as GT. Using these arguments we construct T-PS diagrams based on large statistics of MODIS cloud product [*Platnick et al.*, 2003] as detailed by *Yuan and Li* [2010]. Briefly, quality control and filters are first applied based on MODIS QA flags. We only include clouds that have cloud optical depth larger than 30 and cloud top temperature less than 260K. The MODIS standard level-2 cloud product ice particle size retrievals are then binned according to cloud brightness temperature and the average cloud particle size is calculated for each temperature bin. The 'kink', or turning point in the T-PS profile is assumed to be the approximate glaciation temperature. The technique requires a large amount of data, at least hundreds of cloudy pixels for each temperature bin, to average out the natural variability and retrieval uncertainty associated with the size parameter. Therefore, it is strongly recommended to apply the technique to large cloud systems or a large ensemble of clouds within a region, and not to small individual clouds. Because of this requirement, we utilize the time-space exchangeability of convective clouds [*Rosenfeld and Lensky*, 1998; *Lensky and Rosenfeld*, 2006; *Andreae et al.*, 2004; *Freud et al.*, 2008]. It says that clouds within the ensemble have similar vertical structure and horizontal cloud pixels with different cloud top temperatures can be related to represent a vertical profile of a single convective cell. The technique can be used to find broadly determined characteristics of GT on regional and seasonal scales, and establish correlative associations between GT and other cloud or meteorological parameters, again on regional and seasonal scales.

3. Testing the Assumption

[6] The inherent assumption in our technique is that the kink in the T-PS profiles is directly related to the level of glaciation in the cloud. Although the assumption is based on a conceptual physical model with limited observational evidence, Figure 1b (extracted from *Martins et al.* [2007]) shows a validation of this assumption. The cloud in question is a 16 km deep convective system viewed over the northeast Brazil by the UMBC/GSFC cloud scanner system aboard the INPE Bandeirante aircraft in 2002. The cloud scanner observes reflected sunlight from the sides of the convective cloud from 350 nm to 2500 nm at 1 nm resolution. Using the measured 2100nm and 870nm reflectance, particle size is retrieved using 3D radiative transfer techniques [*Marshak et al.*, 2006; *Martins et al.*, 2007; *Zinner et al.*, 2008]. The vertical profile of the resulting size parameter retrieval is shown in Figure 1b. In an independent retrieval making use of the differences in refractive indices between water and ice at wavelengths 2.13 and 2.25 μm, we can also determine vertical profiles of thermodynamic phase [*Martins et al.*, 2007; *Pilewskie and Twomey*, 1987]. We note that the kink in the particle size profile at around −38°C corresponds directly to the thermodynamic phase change from mixed phase to all ice. These aircraft observations gives strong support to the use of vertical particle size profiles as a proxy

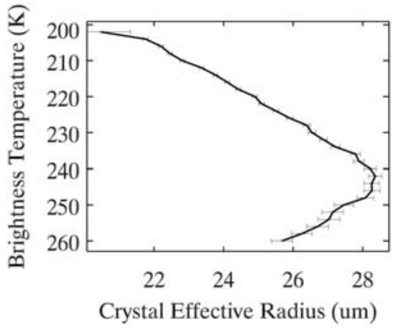

Figure 3. Smoke affected areas over Amazon show elevated glaciation height (or lower temperature). The glaciation temperature inferred from this ensemble profile is around 242K.

for identifying thermodynamic phase changes and glaciation temperature in deep convective clouds.

4. Examples

[7] Examples of the satellite technique applied to individual convective cloud systems are provided in Figure 2 for two cloud systems, one continental over northern India and the other maritime over the Indian Ocean. The general characteristics of the conceptual model profile are captured in these remote sensing data constructed T-PS profiles, which lends confidence to the conceptual model and to the method in general. Through its T-PS profile the GT for the continental cloud system over India (Figure 2d) is suggested to be around −38°C, almost the lower limit because of homogeneous freezing. The maritime cloud system has very different GT (Figure 2b), which is around −25°C. The difference in GT between two cloud systems, around 10°C, can be roughly translated into at least 2km in height. Another example of ensemble cloud T-PS profile is shown in Figure 3. This time the cloud data are collected for an area bounded by −72W and −68W in longitude and −4S and −8S in latitude over the Amazon region during biomass burning season between August to October 2002. The regional profile shows similar characteristics to Figure 2. There may be some minor differences. For example, a regionally and seasonally averaged profile (Figure 3) is usually smoother as a result of averaging larger data samples. The turning point can be less well-defined because of the averaging of different GTs for individual convective systems inside the region and during the sampling period (examples not shown here).

5. Discussion and Conclusion

[8] The technique presented here that uses particle size versus temperature to infer the glaciation temperature in deep convective clouds offers a powerful tool to fill in the sparse observational record of the level of cloud phase transition. The technique can be applied at the regional and global scales to give better constraints on the glaciation level currently assumed in passive and active retrieval method of ice water path and in global regional models. We also perceive this information offering opportunity to supplement latent heat and precipitation retrievals from the TRMM satellite now [*Tao et al.*, 2006] and from GPM in the future. Furthermore, as we saw from the example over India and the Indian Ocean, the glaciation level in a cloud is sensitive to environmental conditions such as continental versus maritime. Part of those differences can be traced to the different thermodynamic conditions and atmospheric circulations, while part may be also due to the availability of aerosols: cloud condensation nuclei and ice nuclei that affect the cloud microphysical structure. With the method presented here we can investigate the correlations between environmental conditions, aerosol concentrations and cloud glaciation properties on regional to global scales. By separating out any thermodynamic and dynamic influences it will help us unravel the complex aerosol effects on deep convective clouds [*Fan et al.*, 2009; *Rosenfeld et al.*, 2008], which will have major implications for aerosol-induced changes to latent heat release, precipitation patterns and radiative properties of DCCs.

[9] The method is limited to relatively large convective systems and regional-seasonal ensembles, which assume a level of conformity of cloud characteristics within the ensemble. For studying individual small storms, instruments like UMBC/GSFC cloud side scanner provides a better solution. However, this ensemble method provides a unique method for determining cloud glaciation levels from passive satellite instruments over a global scale.

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Z. Li, Department of Atmospheric and Oceanic Sciences, University of Maryland, 5825 University Research Ct., Ste. 4001, College Park, MD 20742, USA.

J. V. Martins, Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Cir., Baltimore, MD 21228, USA.

L. A. Remer and T. Yuan, Laboratory for Atmosphere, NASA Goddard Space Flight Center, Mail Code 613.2, Greenbelt, MD 20770, USA. (tianle.yuan@nasa.gov)