THE GLOBAL DISTRIBUTION OF LIGHT PRECIPITATION FROM SPACEBORNE CLOUD RADAR

Tristan S. L'Ecuyer

Colorado State University
Fort Collins, CO 80523

1. INTRODUCTION

Closing the global water cycle is fundamental to our ability to understand and predict change in the global climate system. Central to this challenge is an accurate assessment of the regional and temporal distribution of precipitation. Despite recent advances in global precipitation measurement, many contemporary satellite sensors inherently lack the required sensitivity to accurately identify and delineate areas of light rainfall and snowfall yet these forms of precipitation may represent a significant source of fresh water for both agricultural use and human consumption, particularly at latitudes poleward of 30 degrees. Furthermore, recent evidence suggests that light precipitation may play crucial roles in modulating climate through the impact of snow cover on surface albedo, aerosol-precipitation interactions that can influence cloud lifetime, and the re-evaporation of light precipitation that can play an important role in rehydrating the lower troposphere with consequences for the strength of the general circulation. The millimeter-wavelength Cloud Profiling Radar (CPR) aboard CloudSat provides a unique opportunity to address the need for more precise detection and quantification of both light rainfall and snowfall globally [1]. By virtue of its sensitivity to the full spectrum of atmospheric condensed water phenomena, CloudSat can be thought of as providing a missing link between optical sensors that are primarily sensitive to cloud droplets and microwave sensors that are best suited to measuring larger precipitating hydrometeors.

Three algorithms have been developed to exploit CloudSat's unique new observations in conjunction with those provided by other sensors in the A-Train constellation to characterize the distribution and intensity of light rainfall and snowfall on the global scale. This presentation will review several key insights into the global distribution of light precipitation that have emerged from these new CloudSat precipitation products. Physical considerations for retrieving rain and snowfall from millimeter-wavelength cloud radar will be discussed and the new retrieval frameworks at the root of light precipitation retrievals based on reflectivity observations from the CPR will be introduced. Multi-year precipitation climatologies emerging from these products underscore the value of using CloudSat and complementary A-Train observations to quantify the contribution of light rainfall to the global hydrologic cycle and better understanding the factors that may modify its distribution in a changing climate.

2. THE GLOBAL DISTRIBUTION OF LIGHT RAINFALL

Although driven by a requirement to retrieve cloud properties, the -30 dBZ sensitivity of the CPR also makes it ideally suited to detecting drizzle, light rainfall, and snow. In fact, due to the small size of cloud droplets, warm-topped clouds detected by CloudSat are more likely to contain drizzle than not. Furthermore, the strong attenuation of liquid rain drops at the 94 GHz frequency of the CPR means that even very light drizzle can cause an appreciable reduction in the backscattered signal from the Earth's surface. This is the underlying principle behind CloudSat's 2C-PRECIP-COLUMN algorithm for identifying rainfall over the global oceans [2]. The algorithm uses a parameterization of the clear-sky surface return based on wind speed and sea surface temperature (SST) and compares this with the observed surface return in the CPR reflectivity profile. Differences are attributed to attenuation by hydrometeors in the column and the estimated path-integrated attenuation (PIA) is used to provide an estimate of column-mean rainfall rate that includes a rigorous model of attenuation through the melting layer and multiple-scattering from both liquid and ice hydrometeors.

Preliminary evaluation of this approach, presented in Figure 1, shows excellent agreement in zonal mean rainfall incidence statistics with observations from the Comprehensive Ocean-Atmosphere Data Set (COADS) ship-borne dataset [3].

CloudSat estimates of the fraction of clouds that precipitate (in red) lie within reasonable uncertainty bounds derived from the range of different COADS pixel classifications represented by the grey bars in Figure 1. At higher latitudes in the winter hemisphere CloudSat rainfall fractions fall off but good agreement with COADS is restored when CloudSat estimates of frozen precipitation incidence are included in the analysis (green curve). Rainfall intensity estimates from the 2C-PRECIP-COLUMN dataset have also been used in conjunction with corresponding estimates Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) to provide the most complete characterization of the distribution of tropical rainfall intensity to date [4].

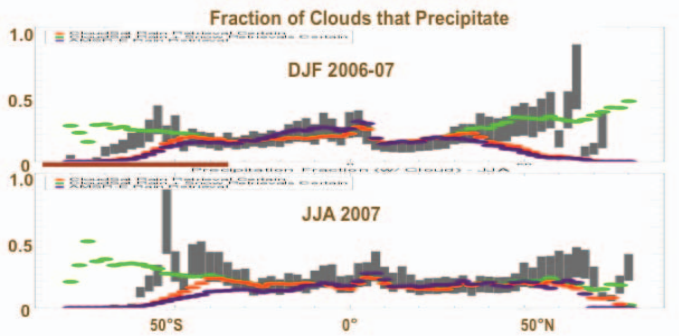

Figure 1: The fraction of clouds that precipitate in the northern hemisphere winter (top) and summer (bottom). Red and green curves represent CloudSat estimates with and without snowfall included. Grey bars represent the range of estimates obtained from co-located COADS ship-based observations using the different scene categories. Adapted from [3].

More quantitative estimates of surface rainfall rate and the vertical distribution of light rainfall within the atmospheric column require a more sophisticated algorithm that rigorously accounts for attenuation and multiple-scattering at every CPR range-gate as opposed to just the surface. Building off the 2C-PRECIP-COLUMN algorithm, a rainfall profiling algorithm has been developed for CloudSat that uses a variational retrieval technique known as optimal estimation (OE) to iteratively perturb a Marshall-Palmer drop size distribution (DSD) to obtain the best match against the observed CPR reflectivity profile subject to a PIA constraint [5,6]. The latest version of the algorithm includes a fast multiple-scattering model and the same melting-layer that is employed in the rainfall detection algorithm described above for consistency. Annual rainfall intensity statistics from the resulting 2C-RAIN-PROFILE product are presented in Figure 2 demonstrating CloudSat's ability to retrieve very light rainrates that are often missed by conventional rain sensors. There is, however, a notable absence of intense precipitation in the deep tropics indicative of the strong attenuation at 94 GHz that limits CloudSat's retrievals in heavier rainfall.

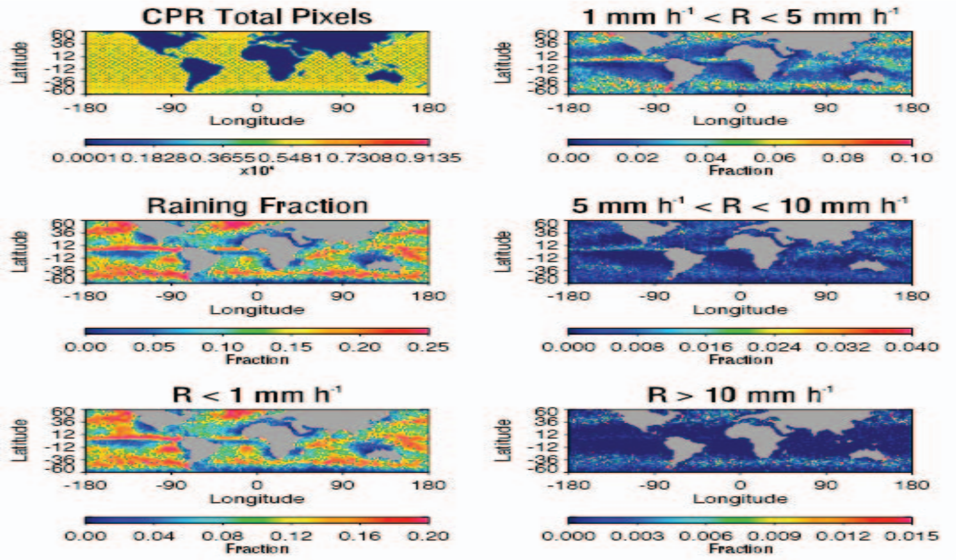

Figure 2: The distribution of rainfall intensity from 60N-60S from CloudSat observations in 2007.

3. GLOBAL OBSERVATIONS OF FALLING SNOW

The CloudSat 2C-PRECIP-COLUMN product also seeks to discriminate rainfall from snowfall at the surface based on ECMWF temperature and humidity profiles coupled to a quantitative melting layer model that predicts the melting of snow crystals as a function of height below the 0ºC level from thermodynamic considerations. A pixel is considered to be snowing if the melted fraction at the surface is less than 10 % and the observed near-surface reflectivity exceeds -7 dBZ. The observed global distribution of rain, snow, and mixed-phase precipitation from 2C-PRECIP-COLUMN are illustrated in Figure 3a. The results clearly demonstrate the transition from primarily liquid precipitation between 40°N and 40°S to include some probability of observing mixed rain/snow events particularly in spring and fall (seasonality not shown) and then snow in the winter. Also evident are the strong bands of precipitation associated with the storm tracks and frequent snow events off the Antarctic coast.

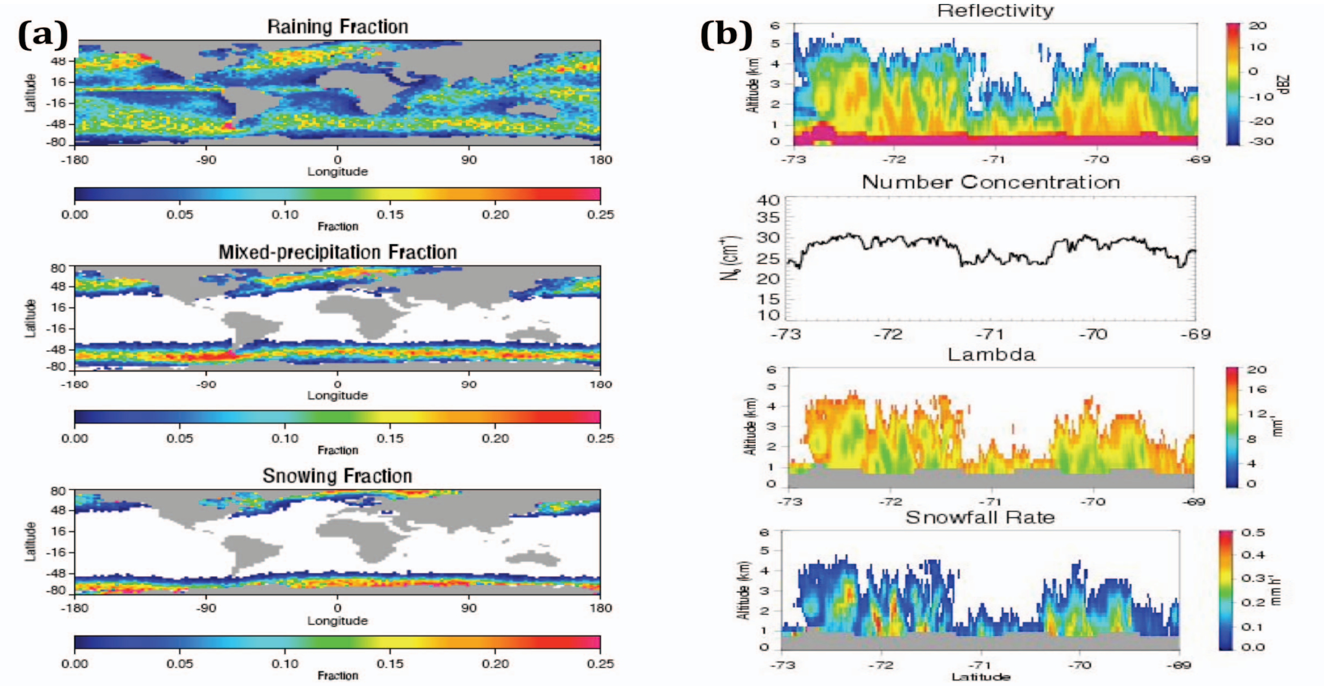

Figure 3: (a) Frequency of occurrence of rain, mixed precipitation, and snowfall from CloudSat observations. (b) Example of a snowfall intensity retrieval from CloudSat reflectivity observations.

It is generally more difficult to retrieve snowfall intensity from single frequency radar observations due to the variable nature of snow density and the possible presence of super-cooled water in the column. As a result, any attempt to retrieve snowfall rate from CloudSat observations necessarily relies heavily on a priori information from focused regional field experiments. This is the underlying principle of CloudSat's 2C-SNOW-PROFILE algorithm that seeks to retrieve quantitative profiles of snow water content and surface snowfall rate based on CPR observations [7]. The algorithm leverages a priori information regarding snow crystal shape, density, and fall-speed from recent field experiments including the Canadian CloudSat/CALIPSO Validation Project (C3VP), Tropical Composition, Cloud and Climate Coupling (TC4), and Tropical Warm Pool-International Cloud Experiment (TWP-ICE) to create a database of realistic snowfall scenes with associated scattering tables. The algorithm, built in the same optimal estimation framework as 2C-RAIN-PROFILE for consistency, iteratively adjusts the slope and intercept parameters of an exponential snow crystal particle size distribution (PSD) at each CPR range gate to obtain the most probable snowfall profile for each CloudSat pixel.

A sample CloudSat snowfall retrieval near Antarctica is presented in Figure 3b. Observed reflectivities in the upper panel are used to retrieve a vertical profile of the slope parameter, Λ, and a column-mean value of the intercept parameter, N_0, of a PSD of the form, $N(D) = N_0\exp(-\Lambda D)$. This distribution is then used in conjunction with a fall-speed parameterization to infer the snowfall rates presented in the lower panel that range from a background water equivalent of ~0.1 mm h^{-1} to values as high as 0.4 mm h^{-1} in a few isolated cores. While the uncertainties in the resulting snowfall estimates are large and heavily reliant on the ground observations used to construct the a priori database, CloudSat provides the first active sensor capable of directly sensing snowfall from space and thus provides the first quantitative snowfall estimates available on global scales. These estimates not only yield a first glimpse at the importance of snowfall in the global water cycle, but also provide valuable training datasets on which high frequency passive microwave (PMW) snowfall algorithms may be developed and tested.

4. SUMMARY

CloudSat observations now provide nearly four years of global observations of light rainfall and snowfall. The products outlined here are shedding new light on the frequency of precipitation at higher latitudes, quantifying the importance of snowfall in the global water cycle, and leading to important insights into the impact of aerosols on precipitation on global scales. Extensive evaluation of CloudSat's precipitation products is currently underway that leverage ground-based radar observations and data from past focused field experiments. Furthermore, a focused Light Precipitation Validation Experiment (LPVEx) is planned to directly assess the ability of current and future satellite precipitation sensors to detect and quantify the intensity of light rainfall and snowfall at high latitudes. LPVEx represents a unique collaboration between NASA's CloudSat and Global Precipitation Measurement (GPM) missions, the Finnish Meteorological Institute, Environment Canada, and several other partners to make detailed microphysical and remote sensing observations in the Gulf of Finland in the early fall, a season characterized by frequent light precipitation in the transition between rainfall and snowfall. These observations will provide valuable observations with which to evaluate and improve CloudSat's rainfall products and develop high-latitude precipitation products for GPM.

5. REFERENCES

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