REMOTE SENSING OF CLOUD AND PRECIPITATION OF WARM CLOUDS BY PASSIVE AND ACTIVE SENSORS ABOARD A-TRAIN SATELLITE

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Though warm rain from low-level liquid clouds contributes significantly to the global precipitation and water cycle, it has been missed or underestimated by satellite remote sensing techniques. IR techniques miss all warm rain because they rely on cloud top temperature. Over land, passive microwave techniques miss all warm rain because they rely on ice scattering at high frequency channel. Over ocean, as revealed in this study, passive microwave techniques underestimate warm rain by nearly 48%, and most of the underestimation happens for clouds with top height less than 3.5 km. Using NASA's A-train satellites data, this study attempts to estimate rain rate by warm clouds by investigating the relationship between warm rain and cloud microphysical parameters. Analyzing the Aqua AMSR-E rain estimates, rain estimates from CloudSat CPR and AMSR-E, we determine the percentage of warm rain and the performance of space-borne passive microwave observation on warm rain estimation over ocean. For single-layer clouds, rain from warm clouds (top temperature higher than 0 ^{0}C) contributes 28.8% of rain occurrences and 17.6% of rain amounts over global ocean. The potential of cloud microphysical parameters on warm rain estimation is explored with the MODIS estimates of cloud microphysical parameters and the coincident CloudSat CPR warm rain estimates. Among various cloud microphysical parameters under study, liquid water path calculated from the retrieval of the profile of cloud particle size determined by the algorithm of Chang and L (2005) is found to have the best potential for both detecting warm rain and estimating warm rain amounts.

1. Introduction

Warm rain falls out of low-level liquid cloud and does not involve ice-phase processes. Warm rain is generally light but occurs frequently. Traditional precipitation estimation techniques generally failed to detect warm rain, let alone estimating rain rate. IR rain detection algorithms generally miss the presence of precipitation in warm clouds because they depend on the cloud-top temperature. Microwave techniques cannot detect warm rain over land either since they rely on ice scattering. Over oceans, microwave techniques may underestimate warm rain because warm rain is very shallow and contributes less emission than deep systems.

2. Data and Methods

Data collected during the first 20 days of 2008, from the MODIS/AMSR-E instruments on Aqua satellite and the CPR on CloudSat satellite, are used in this study. Because the CPR is a nadir-view instrument, only cloud samples along the nadir position of A-Train satellites track are used. To eliminate ice contamination, only warm liquid water clouds (cloud-top temperatures > 273 K) are selected. The study is also limited to cases over oceans.

MODIS measurements from Aqua satellite are used to estimate cloud parameters with the algorithm of Chang and Li (2002,2003). The estimated cloud microphysical parameters include cloud top temperature, cloud optical depth, DER at cloud top (r_{e1}), DER at cloud base (r_{e2}), DER at 2.1μm ($r_{e2.1}$), LWP calculated with $r_{e2.1}$ (LWP2.1), and LWP calculated with r_e profile (LWPrep). These parameters have a nadir resolution of 1×1 km^2. Only clouds with top temperature higher than 0°C are selected.

Rain is also estimated using the microwave brightness temperature observations made by the AMSR-E at 12 channels and 6 frequencies ranging from 6.9 GHz to 89.0 GHz employing the NASA/GSFC's GPROF algorithm (Kummerow et al., 2001). For rain rate estimation over ocean, the GPROF algorithm utilizes the microwave emission of rain droplets at 10.7 GHz, 18.7 GHz, and 36.5

GHz. For rain rate estimation over land, GPROF utilizes the attenuation of surface emission by cloud ice particles at 85 GHz. By comparing the GPROF estimates from TRMM microwave imager with the rain gauge measurements and the radar rain estimates, Kummerow et al. (2001) showed that the bias of GPROF monthly mean rain estimation is generally within 30%.

CloudSat carries the first millimeter wavelength radar on space to observe atmospheric hydrometer profiles (Stephens et al., 2002). The 94 GHz cloud profiling radar (CPR) is a W-band, nadir-pointing radar system. The vertical resolution of the CPR is 480m and over-sampled at 240m. The horizontal FOV size of the CPR is 1.7X1.3 km^2. The CPR's sensitivity is -28 dBZ and dynamic range of measurements is 80 dB. Relative to other sensors, the CPR shows good ability to measure the warm rain events from low level clouds (Fig. 1). For the deep convective system near tropics, the reflectivity measurements near ocean surface are significantly attenuated by the hydrometers.

3. Results

Figure 1 shows the CPR reflectivity profiles, the CPR rain rate estimates, the AMSR-E rain rate estimates, and the MODIS cloud optical depth estimates during 20:55~23:35 UTC at Jan. 06 over eastern pacific. The CPR reflectivity profiles show two types of rain, the shallow warm rains underneath stratocumulus clouds over southern hemisphere and the deep convective system at 6^0 N. The maximum rain rate estimated by the CPR is around 2 mm/hr for the warm rain and 9 mm/hr for the deep convective system. AMSR-E rain rate estimates miss most warm rains detected by the CPR. For the deep convective system at 6^0 N, the AMSR-E rain rate estimates are higher than the CPR rain rate estimates. MODIS cloud optical depth estimates are well correlated with the CPR warm rain estimates, but saturate for the deep convective system.

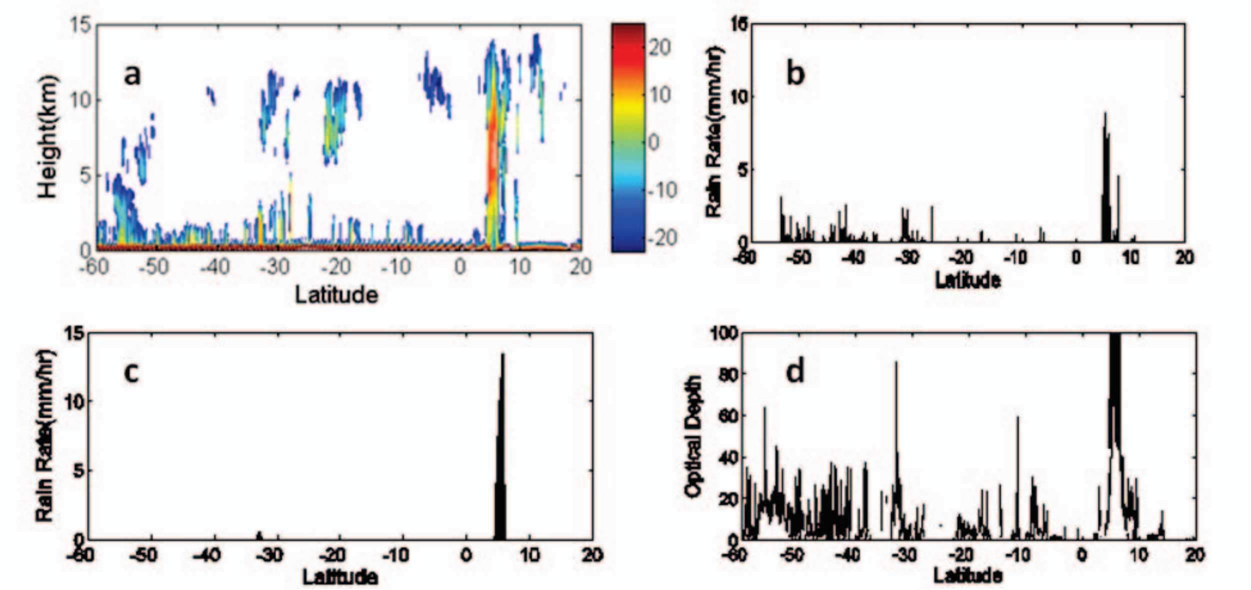

Figure 1 A-Train satellites observations during 20:55~21:35 UTC of Jan. 06.
a) CloudSat CPR reflectivity profiles; b) CloudSat CPR rain rate estimates;
c) Aqua AMSR-E rain rate estimates; d) Aqua MODIS cloud optical depth estimates

Global statistics of warm rain estimation

CloudSat CPR is the first space-borne active instrument sensitive to warm rain and the CPR rain rate product is the first dataset which gives warm rain estimates globally. Because the CPR rain rate estimates is not reliable for deep convective system (Haynes et. al., 2009) and the AMSR-E has problem to estimate warm rain, this study combines the rain rate estimates from these two instruments to obtain rain rate estimates globally. The CPR estimated cloud top heights are used to identify the deep convective system. Figure 2a shows the percentages of rain occurrence for different cloud top temperatures. The cloud top temperature for raining clouds could be as high as 20 ^{0}C. The warm rains contribute 28.8% of raining occurrences over global ocean. Figure 2b shows the percentages of rain amount for different cloud top temperatures. Though warm rains generally have smaller magnitude than rains involved ice process, warm rains contribute 17.6% of rain amount over global ocean. Chang and Li (2005) found that, over ocean, 36% of low-level clouds are underneath of high cirrus clouds. If multi-layer clouds are included, the low-level liquid clouds with cloud top temperature higher than 0 ^{0}C contribute 45.0% of raining occurrences and 27.5% of rain amount over global ocean.

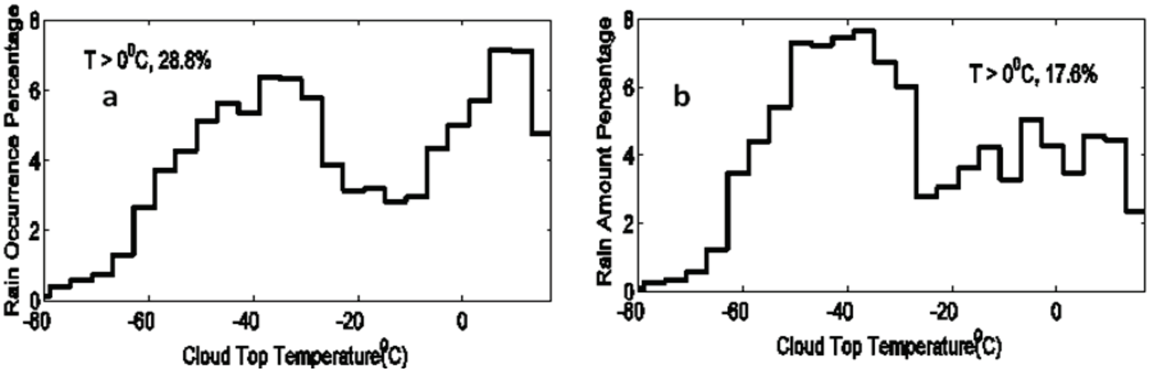

Figure 2 Contributions of rain occurrence and amount by warm clouds with top temperature > 0 ^{0}C

The potential of cloud microphysical parameters on warm rain estimation

Because of the lack of reliable global warm rain observation, little insight has been gained regarding the relationships between cloud microphysical parameters and warm rain. To find the relationships between warm rain and its cloud microphysical parameters, we analyze the MODIS estimates of cloud microphysical parameters and the coincident CPR rain estimates for the low-level liquid cloud samples. The selected cloud samples are required to be overcast to reduce the 3D effect of broken clouds. The cloud microphysical parameters used in this study include cloud optical depth, DER at cloud top (r_{e1}), DER at cloud base (r_{e2}), DER at 2.1μm ($r_{e2.1}$), LWP calculated with $r_{e2.1}$ (LWP2.1), and LWP calculated with r_e profile (LWPrep). The correlations between cloud droplet effective radiuses and surface rain rate are very weak (correlation coefficient 0.2). Cloud optical depth is correlated more with near-surface rain rate than effective radiuses (correlation coefficient 0.33). LWPrep is correlated most with near-surface rain rate because it combines cloud optical depth and r_e profile. The correlation coefficient with CPR rain rate estimates is 0.42 for MODIS LWPrep estimates, while it is 0.27 for AMSR-E rain rate estimates. The linear relationship between the LWPrep estimates and the CPR estimates of near-surface rain rate is $RR_{surface} = 0.062 + 1.504LWPrep$, where $RR_{surface}$ is in mm/hr and LWPrep is in mm.

Acknowledgements:

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Biography

Prof. Li received his Ph.D. degree from McGill University in 1991, M Sc and B Sc from Nanjing Institute of Meteorology (China) in 1983 and 1985 respectively. After one year of postdoctoral research at the Meteorological Service of Canada, he was employed as a research scientist at the Canada Centre for Remote Sensing in 1992. He became a full professor in the Department of Meteorology at the University of Maryland in 2001. Dr. Li has engaged in numerous meteorological and interdisciplinary studies concerning cloud, radiation budget, aerosol, UV radiation, terrestrial environment, forest fire and energy and carbon budget, etc. So far, he has published 140 peer-reviewed articles in leading journals including *Nature*, *Science, JGR, J. Climate, etc.* that have been cited over 2300 with a H-index 27. Currently, he serves on the editorial board of *J. Geophy. Res., Advances in Meteorology*.

Dr. Ruiyue Chen pursued his Ph.D study at the Dept of Atmospheric & Oceanic Science at the University of Maryland supervised by Prof. Zhanqing Li. He just finished his defense and joined the NOAA to work on satellite sensor calibration. He received his M.Sc degree from Texas A&M working on microwave remote of rain. To date, he has published 2 papers in the *J. Geophy. Res., and J. Atmos. Sci*.