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Distributional correspondence of 94-GHz radar reflectivity with the variation in water cloud properties over the northwestern Pacific and China

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ABSTRACT

This paper studied the behavior of 94-GHz radar reflectivity (Z_e) with variation in the properties of low-level water clouds, such as the effective droplet radius (r_e), geometrical thickness (D_{cld}), and liquid water path (LWP), over the northwest Pacific and China. The changes in the distribution of maxZ_e (the largest Z_e within a cloud layer) were examined in terms of variation in the cloud parameters such as small, mid and large categories, while maxZ_e had monomodal distributions regarding variation in r_e and D_{cld}, that appeared bimodal in the small category of LWP. It was confirmed that the small category of LWP contained both non-precipitating clouds in the incipient stage and raining clouds in the dissipating stage. Next, optically measured particle size was combined with LWP derived from the microwave measurement to classify the precipitation type. Applying maxZ_e and D_{cld} to the analysis of classified precipitation types corroborated the importance of D_{cld} for examining the occurrence of precipitation. Finally, the position of maxZ_e relative to the cloud top was investigated using a measure of the probability of precipitation (POP) according to variation in r_e. The results showed that the Pacific and China had 'bow' and 'funnel' shapes, respectively. The emergence of these shapes according to the variation in r_e was interpreted as the enhancement of Z_e due to droplet collisional growth and the attenuation of Z_e by the presence of large particles. Furthermore, a detailed analysis of smaller particles (<10 μm in radius) reinforced the idea of rapid, efficient particle growth in the lower part of the cloud.

1. Introduction

Clouds play several critical roles in maintaining and altering the Earth's climate, such as in radiation and hydrological processes [1]. In addition, increased diffuse radiation increases the efficiency of photosynthesis under cloudy conditions. For example, even small changes in the macrophysics (the areal extent, temporal frequency, height, geometrical thickness, and total amount of water) and the microphysics (particle size, number concentration, and mass density of water or ice particulates) can significantly alter the radiation budget and water cycle of the Earth. Aerosol indirect effects of the first kind [2] and the second kind [3], which involve changes in radiative properties and precipitation efficiency, respectively, have been studied through observations [4,5] and modeling [6,7]. This study mainly considers the observational aspect with satellite sensors.

Clouds are composed of water-, ice- and mixed-phase particles according to the temperature and the history of the formation of the cloud particles. Although it has been

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almost three decades since Randall et al. [8] pointed out that water clouds were climatically important due to their radiative role and less complicated than ice- and mixed-phase clouds, the water cloud-related problems as mentioned above are far from resolved [9]. Therefore, this study addresses only water clouds with a top temperature warmer than 273 K, and clouds signify low-level water clouds in the rest of this paper.

For almost a decade after the mid-1990s, passive remote sensing of cloud and aerosol properties was performed using Advanced Very High Resolution Radiometer (AVHRR) data. Han et al. [10] first succeeded in a near-global survey of particle size of water clouds. Nakajima and Nakajima [11] and Kawamoto et al. [12] later conducted detailed regional and global analyses of both optical depth and the particle radius of water clouds. During this time period, Higurashi and Nakajima [13] conducted the first global analysis of aerosol optical depth and the particle size index, but measurements were made only over an ocean because the reflection function over land was too uncertain to retrieve aerosol properties accurately. With these processes, thus Nakajima et al. [14] combined the cloud properties from Kawamoto et al. [12] and the aerosol properties from Higurashi and Nakajima [13] and completed the first global survey of aerosol–cloud interaction over ocean with AVHRR data. Soon after this analysis, Bréon et al. [15] used the Polarization Directionality of the Earth's Reflectivity (POLDER) device to globally depict aerosol–cloud interaction over both land and ocean. Regardless of the use of different data sets, both analyses yielded a similar tendency on the aerosol–cloud interaction (similar slope value of the change in cloud droplet radius according to the aerosol index) over the ocean.

Not only remote sensing measurements using shortwave channels such as visible and infrared wavelengths but also those combining passive microwave observations with shortwave have been made to date. Lin and Rossow [16] extracted the ice–water path (IWP) of oceanic cold non-precipitating clouds by taking the difference between the total water path retrieved from the International Satellite Cloud Climatology Project (ISCCP) and liquid water path (LWP) obtained from the Special Sensor Microwave Imager (SSM/I) data. Then Lin and Rossow [17] revealed the seasonal variation of LWP and IWP on a global scale, extending the method of Lin and Rossow [16]. Meanwhile, Lin et al. [18] used the optical (visible, near infrared, and infrared) and microwave measurements to estimate the frequency of multilayered clouds and the particle size of water clouds. Subsequently, Ho et al. [19] applied this method of Lin et al. [18] to data sets from the TRMM Microwave Imager (TMI) and the Visible and Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission (TRMM) to examine the frequencies of single-layered/overlapping non-precipitating clouds, and water paths of ice and water clouds. Their result proved the advantage of observing clouds using different sensors on the same platform. Moreover, to retrieve multilayered cloud properties, Huang et al. [20] developed a method combining satellite visible and infrared radiances and surface microwave radiometer measurements. Applying this method, they found that the ice-cloud height derived from traditional single-layer retrieval was underestimated, and the midlevel ice cloud coverage was over-classified.

However, conventional passive remote sensing techniques have a limitation with regard to vertically resolved measurements. The visible and near-infrared channels can only retrieve the column-integrated optical depth and particle size near the cloud top [21]. In 2006, the CloudSat satellite deployed the Cloud Profiling Radar (CPR) at 94-GHz, which can provide vertical cloud information. Combining the CPR data with data from passive instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS), new findings have been obtained [22–25]. This type of synergistic analysis combining passive and active sensing techniques has become available because of the advent of the A-Train constellation [1].

Taking this synergetic approach and using CloudSat and MODIS data, Nakajima et al. [26] proposed a new diagram called the contoured frequency by optical depth diagram (CFODD), which used radar reflectivity as the horizontal axis and in-cloud optical depth as the vertical axis. Using this diagram, Suzuki et al. [27] obtained new insights into the cloud–rain transition processes. These progresses in observations of clouds provide certain new tools in analyzing aerosol effects and in modeling the effect of low-level water clouds on global hydrological cycle. Considerable efforts have been made to merge satellite observations with modeling studies to identify and mitigate the model biases. For example, Suzuki et al. [28] undertook a synergistic analysis using CloudSat and MODIS data to evaluate global and regional cloud-resolving models in the context of their representations of the cloud-to-rain conversion processes. More recently, Suzuki et al. [29] focused on the aerosol indirect effect in a global high-resolution model by comparing their outputs with joint CloudSat and MODIS observations to expose fundamental model biases in representing the aerosol indirect effect of the second kind. Recently, Kawamoto and Suzuki [30] performed two types of analyses on the relationships between the radar reflectivity and cloud parameters. One was the probability distribution function of cloud parameters as a function of radar reflectivity, and the other was the fractional occurrence of the precipitation categories as a function of the cloud parameters over the mid-latitude land and ocean. Nevertheless, the current level of understanding on the cloud droplet transition and precipitation formation inside clouds is insufficient.

Under the above-mentioned circumstances, this study was performed with the following two objectives to enhance understanding of the behavior of radar reflectivity with the variation in water cloud properties using the collocated MODIS and CloudSat products. One was to examine the difference in the distribution of radar reflectivity with the variation in water–cloud properties. This examination will reveal the information content on precipitation in cloud properties. The other was to investigate the change in the vertical position of radar reflectivity inside the cloud layer with the variation in water cloud properties. In this way, the change in the relative position of the precipitation occurrence in a normalized cloud layer will be determined.