MISR-Derived Statistics of Cumulus Geometry at TWP Site

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Introduction

The multi-angle imaging spectro radiometer (MISR), recently launched on the National Aeronautics and Space Administration (NASA) Terra platform, provides high-resolution measurements of reflectance at nine different viewing angles. Multi-angle satellite observations have been successfully used to derive the cloud height (Diner et al. 1999). We have developed a new technique for retrieving cumulus vertical size (geometrical thickness) from multi-angle satellite data (Kassianov et al. 2003). We have evaluated the performance of this new multi-angle cumulus geometry retrieval technique by comparing the MISR data with ground-based observations at the Atmospheric Radiation Measurement (ARM) Tropical Western Pacific (TWP) site at Nauru Island. In particular, we have demonstrated that the satellite-retrieved average vertical thickness of cumulus clouds match closely the corresponding ground-truth value observed from radar measurements. This paper presents comparison of satellite-derived basic statistics (mean, variance, and probability density function) of vertical cloud size with the corresponding ground-based ones obtained from active remote sensors (e.g., combine radar and lidar observations).

MISR-Data Cloud Retrieval

To perform the multi-angle retrieval of low cumulus clouds, we use available satellite observations at the ARM TWP site at Nauru. The MISR passes over Nauru twice each 16 days at ~22:54 Universal Time Coordinates (UTC). Sixty-four available MISR overpasses from March 2000 to January 2002 were examined to determine appropriate overpasses with a well-defined single layer of low cumulus clouds (without cirrus cloud contamination) over Nauru and the surrounding area. We found that 14 overpasses met these requirements. Here we present results for only one of these appropriate overpasses (August 21, 2001). Figure 1 shows a large (110 x 110 km) MISR image, which includes Nauru, and a smaller (30 x 30 km) sub-scene. For this sub-scene we performed the multi-angle retrieval of cloud geometry.

There are two basic steps in the retrieval (Kassianov et al. 2003). The first step is the detection of cloud pixels. To separate cloud pixels from non-cloud ones, we used a new cloud analysis that relies on *angular* signatures of measured radiances. The output of this analysis is the horizontal distribution of cloud pixels (clouds). The second step is to obtain the vertical geometrical size of cloud pixels. A simple relationship between the nadir radiance and the cloud vertical geometrical thickness is assumed. Parameters in this relationship are chosen such that multi-angular MISR observations will match model calculations. The results of the cumulus geometry retrieval are presented in Figure 4a. In this case, it is assumed that cloud base is fixed.

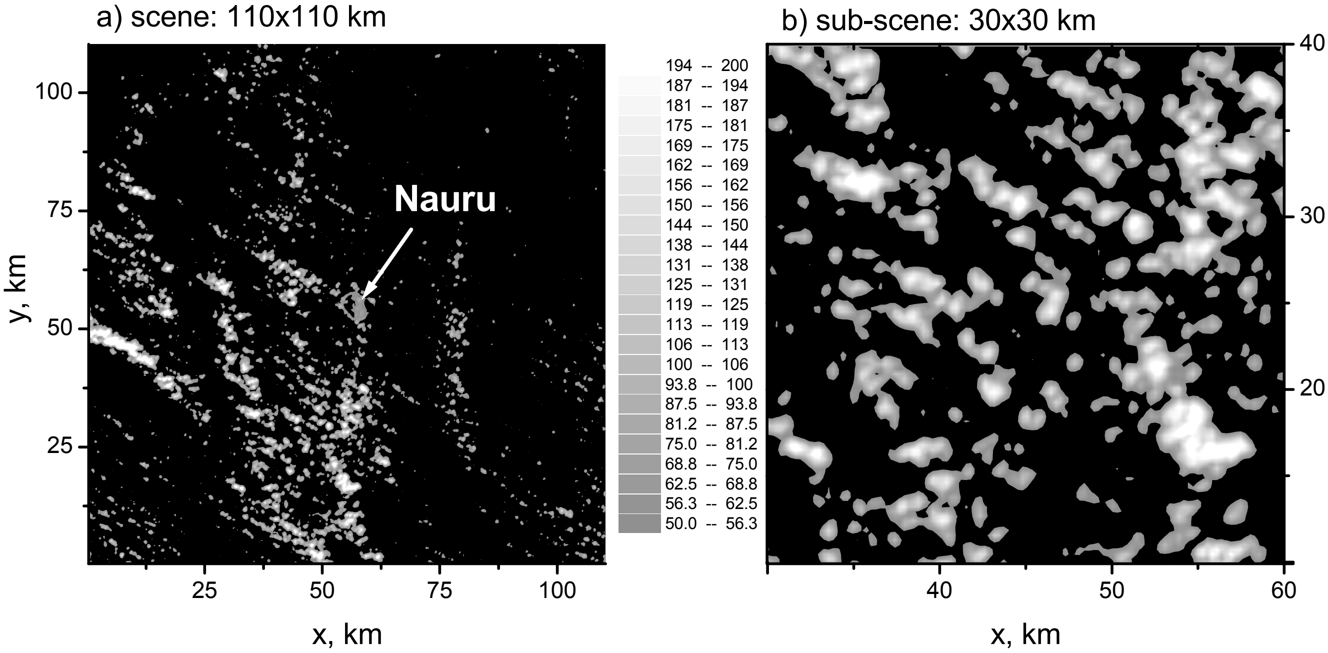

Figure 1. a) Cumulus clouds from MISR (nadir radiance) in 110 x 110 km and b) 30 x 30 km regions surrounding the near ARM TWP site (August 21, 2001).

Cloud Retrieval from Ground Observations

To test the suggested approach, we used independent ground-based radar and lidar observations at the ARM TWP site at Nauru. This combination of active remote sensors allows one to generate the best estimate of cloud heights (Clothiaux et al. 2000). For these combined ground-based data, the temporal resolution is 10 sec, and the vertical resolution is set to 0.045 km. The linear interpolation of radar data (e.g., radar reflectivity) has been used to obtain these temporal and spatial resolutions.

We used a 1.5-hour temporal sample (Figure 2) for our analysis. We believe that during ~1.5-hour averaging period (1) the radar measurements collected enough cloud samples to provide a good estimate of the true value for the average vertical cloud size and (2) this estimate well represents the whole cloud field. Previously, we showed that the 1.5-hour average radar-derived vertical cloud size matches well with the MISR-retrieved vertical size of clouds (Kassianov et al. 2003). Boundaries of cumulus clouds are highly variable (Figure 3). For example, the range of cloud base fluctuations within an individual cloud can be ~ 0.45 km. The ground-based statistics of the cumulus geometry are presented in Figure 5a and Table 1a. There is a weak positive relationship between fluctuations of cloud base and cloud top (correlation coefficient is ~ 0.18).

Comparison Satellite-Retrieval with Ground-Truth Properties

First, we compare the average cloud vertical size (Figures 4a, 5a). As shown, the mean MISR-retrieved and ground-based retrieved values are the same. However, there are large differences between the

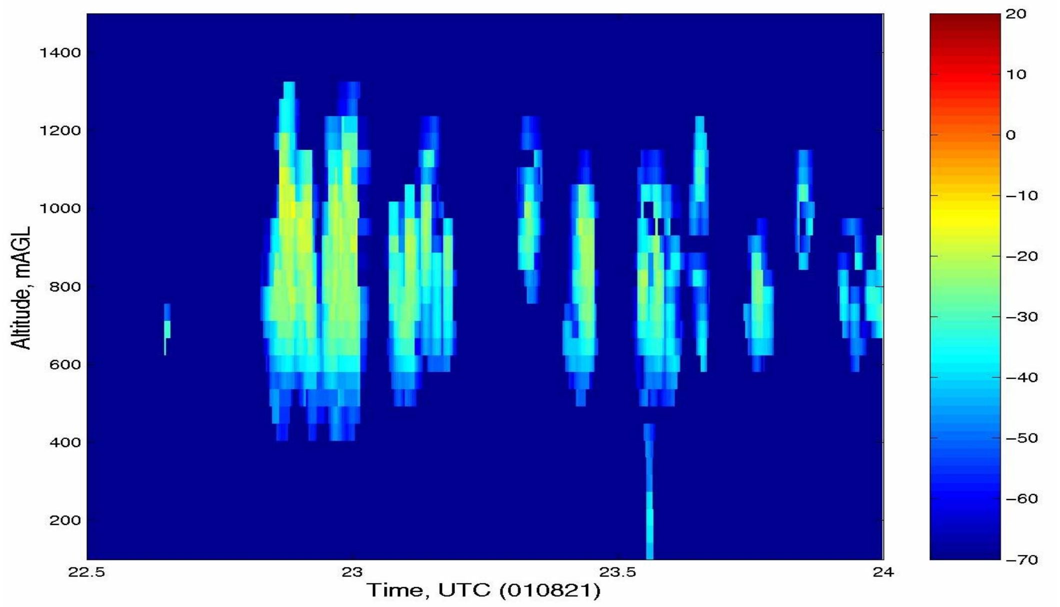

Figure 2. Cumulus clouds from ground-based radar measurements at the ARM TWP site (Nauru), August 21, 2001: time-height cross section of radar reflectivity.

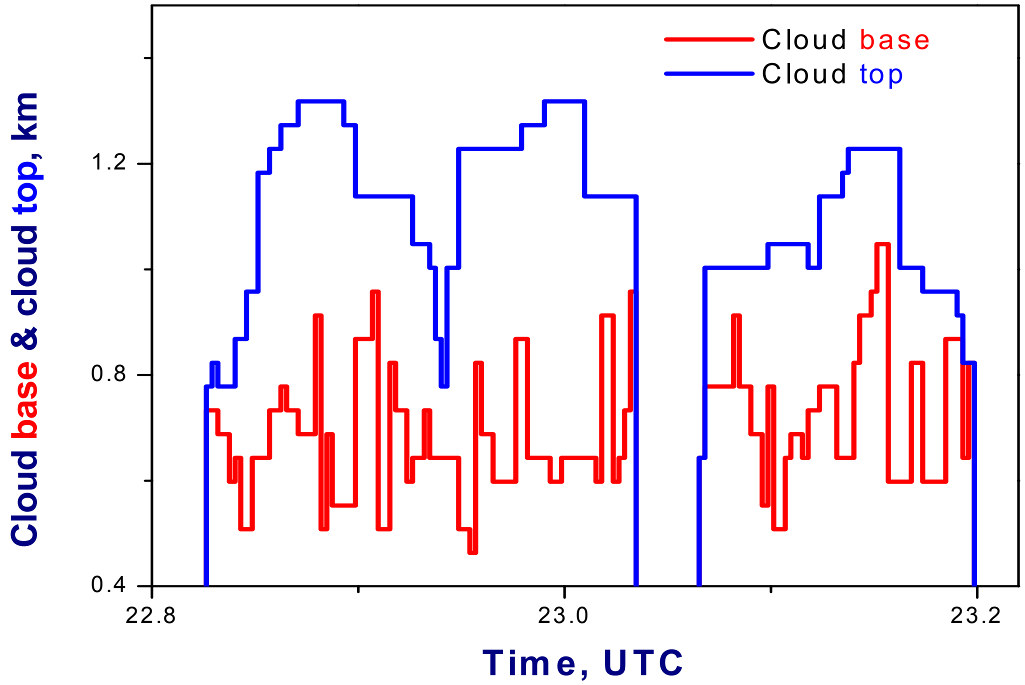

Figure 3. Cumulus clouds from ground-based active remote sensors at the ARM TWP site (Nauru), August 21, 2001: time-height cross sections of cloud base (red) and cloud top (blue).

corresponding standard deviations (SD). The same is true for the probability density functions (PDFs): the ground-based PDF of cloud vertical size is more than twice the width of the MISR-retrieved PDF. These large differences could arise for two main reasons. First, the satellite and ground-based statistics correspond to different spatial resolution. Second, the multi-angle satellite retrieval does not take into account the cloud base variability. Below, we consider these two possible reasons sequentially.

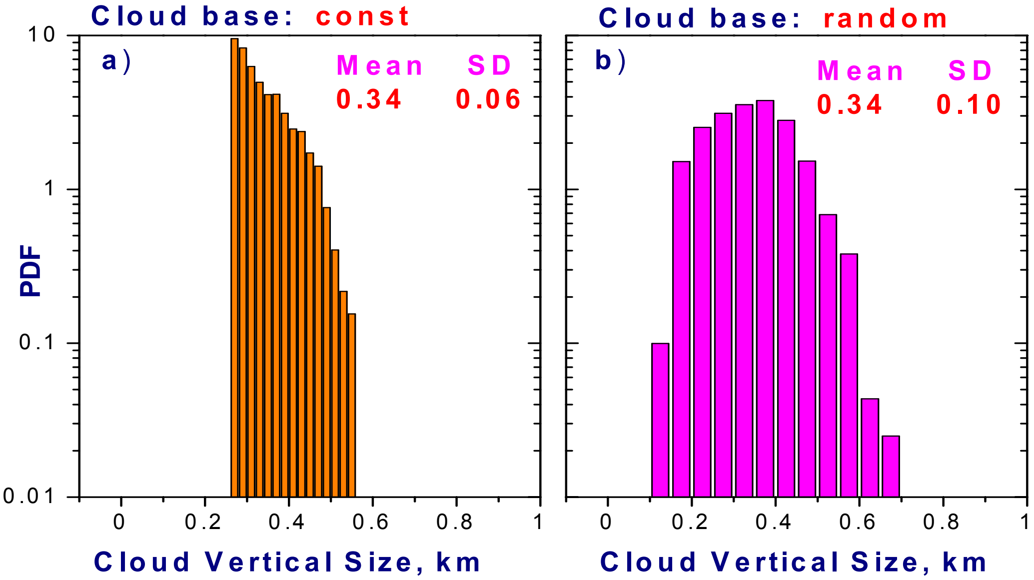

Figure 4. MISR retrievals at the ARM TWP site (Nauru), August 21, 2001: a) Probability density function of cloud vertical size for constant and b) random cloud base.

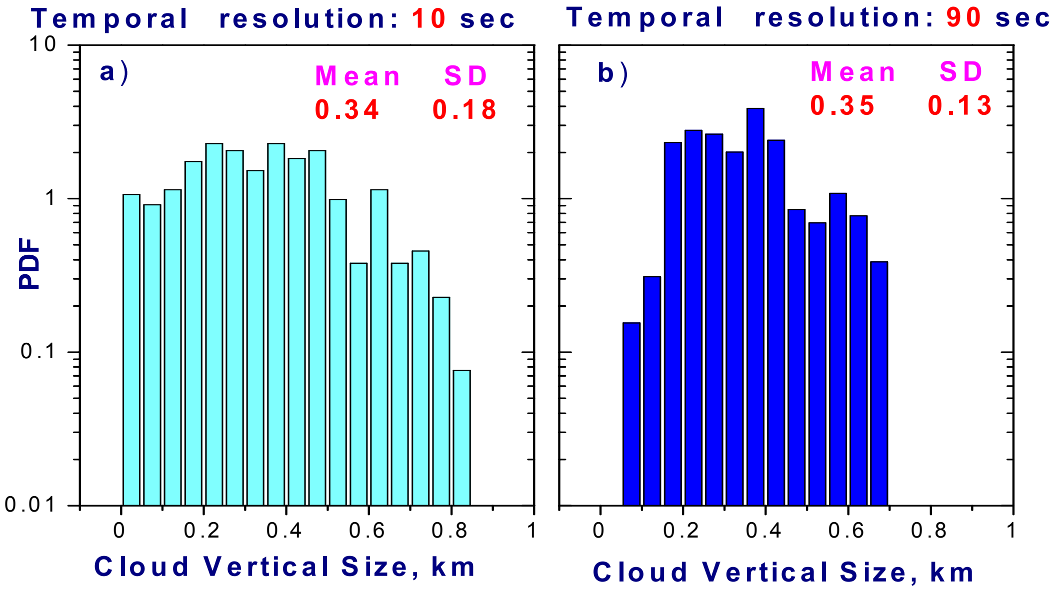

Figure 5. Ground-based retrievals at the ARM TWP site (Nauru), August 21, 2001: Probability density function of cloud vertical size for different temporal resolutions.

Different spatial resolution. For ground-based data, we link temporal statistics with spatial ones through the cloud-level wind speed. The radiosonde measurements (from 23:31 UTC) show that the average cloud-level wind speed is ~ 0.01 km/sec. Since the temporal resolution of the ground-based data is 10 sec, then the corresponding spatial one is ~0.1 km. High-resolution (~0.275 km) observations are available from the MISR. Therefore, the MISR footprint contains roughly nine (3 x 3) pixels with 0.1-km horizontal size. To estimate the impact of resolution on temporal/spatial statistics, we perform smoothing of ground-based data. A moving averaging (over nine data points) is applied and corresponding statistics are obtained (Figure 5b, Table 1b). Smoothing reduced the variability of cloud boundaries (Table 1) but almost does not change their statistical relationship (correlation coefficient is ~0.20). The variability of cloud vertical size becomes smaller as well (Figure 5, Table 1). As a result, the SD of the vertical cloud size decreases and the PDF is narrowed (Figure 5). However, there are still substantial differences between satellite-derived SD (Figure 4a) and ground-based SD (Figure 5b) of cloud vertical size. The same is true for the PDF. Thus, the differences in spatial resolution do not explain all of the distinctions between these statistics (SD and PDF) obtained from satellite and surface observations.

Table 1a. Statistics of cloud top, cloud bottom, and cloud vertical size for the ground-based dataset from 22.5 to 24 UTC, August 21, 2001. Temporal resolution is 10 sec.

	Mean, km	**Standard Deviation, km**	**Minimal, km**	**Maximal, km**
Cloud Top	**1.06**	**0.16**	**0.69**	**1.32**
Cloud Bottom	**0.72**	**0.12**	**0.46**	**1.05**
Cloud thickness	**0.34**	**0.18**	**0.05**	**0.81**

Table 1b. The same as Table 1a, but temporal resolution is 90 sec.

	Mean, km	**Standard Deviation, km**	**Minimal, km**	**Maximal, km**
Cloud Top	**1.07**	**0.13**	**0.76**	**1.31**
Cloud Bottom	**0.72**	**0.08**	**0.59**	**0.95**
Cloud thickness	**0.35**	**0.13**	**0.08**	**0.68**

Cloud base variability. From ground-based data, the cloud vertical size, *h*, is obtained as a difference between cloud top, *ht*, and cloud base, *hb*. Therefore, the variance of *h* can be written as (Feller 1971)

$$Var(h) = Var(ht) + Var(hb) - 2\rho(hb, ht)\sqrt{Var(ht)}\sqrt{Var(hb)} \tag{1}$$

where $\rho(hb, ht)$ is the correlation coefficient between *ht* and *hb*. Note, the variance of cloud base, $Var(hb)$, is comparable with the variance of cloud top, $Var(ht)$ (Table 1a).

For the MISR retrieval (Figure 4a), we assumed that cloud base does not change. Therefore, the variability of the cloud vertical size results from the cloud top fluctuations only. To include the *hb*-variations into the MISR retrieval, one can assume that (1) the cloud top and cloud bottom are independent random variables ($\rho(hb, ht) = 0$) and (2) the cloud base fluctuations can be described as

$$hb_{random} = Hb + \left(Hb - hb_{\min}\right)\alpha \tag{2}$$

where α is a random variable uniformly distributed on (-1,1) interval, Hb and $hb_{\min}$ are the average and minimal values of cloud base, respectively.

We perform an additional MISR retrieval using Eq. (2). The radar-retrieved parameters (Table 1b) are applied for Hb and $hb_{\min}$ (Figure 4b). The satellite-derived SD and PDF (Figure 4b) are similar to those (Figure 5b) from ground-based data. Therefore, in addition to the resolution effect, we conclude that the cloud base fluctuations are likely responsible for large differences between the height distributions derived from satellite (Figure 4a) and surface (Figure 5a) observations.

Summary

To test the potential for deriving the basic statistics (mean, standard deviation, and probability density function) of the cloud vertical size from multi-angle satellite measurements, we use both MISR data and ground-based observations of low cumulus clouds at the ARM TWP site (August 21, 2001). Combination of active surface remote sensors provides high-resolution data of the cumulus boundaries. Analysis of the surface data shows that (1) the variance of cloud base is comparable with the variance of cloud top and (2) the cloud top and cloud base are weakly related (correlation coefficient is ~0.2). We perform MISR retrieval for two cases. The only difference between these two retrievals is the assumption about cloud base. In the first retrieval, cloud base is fixed. In the second retrieval, cloud base is random and independent of cloud top. We found that the satellite-derived basic statistics are similar to those from ground-based measurements if the cloud base variability is included into the MISR retrieval. Long-term surface observations of cumulus boundaries can provide a very valuable statistical dataset for improving satellite multi-angle retrievals.

Acknowledgments

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