Rainfall-Induced Changes in Actual Surface Backscattering Cross Sections and Effects on Rain-Rate Estimates by Spaceborne Precipitation Radar

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ABSTRACT

In this study, the authors used Tropical Rainfall Measuring Mission precipitation radar (TRMM PR) data to investigate changes in the actual (attenuation corrected) surface backscattering cross section ($\sigma_0^s$) due to changes in surface conditions induced by rainfall, the effects of changes in $\sigma_0^s$ on the path integrated attenuation (PIA) estimates by surface reference techniques (SRTs), and the effects on rain-rate estimates by the TRMM PR standard rain-rate retrieval algorithm.

Over land, $\sigma_0^s$ is statistically higher under rainfall than under no rainfall conditions (soil moisture effect) unless the land surface is densely covered by vegetation. Over ocean, the dependence of $\sigma_0^s$ on the incident angle differs under rainfall and no-rainfall conditions (wind speed effect). The alongtrack spatial reference (ATSR) method, one of the SRTs used in the standard algorithm, partially considers these effects, while the temporal reference (TR) method, another SRT, never involves these effects; its PIA estimates thus have negative biases over land. In the hybrid spatial reference (HSR) method used over ocean, different incident angles create different biases in PIA estimates. If the TR method is replaced by the ATSR method, the monthly rainfall amount in July 2001 all over the land within the TRMM coverage increases by 0.70%. The bias in the HSR method over ocean can be mitigated by fitting a $\sigma_0^s$–$\theta^o$ curve separately to smaller incident angles and to larger incident angles. This improvement increases or decreases the monthly rainfall amounts in individual incident angle regions by up to 10%.

1. Introduction

The Tropical Rainfall Measuring Mission precipitation radar (TRMM PR) was the first spaceborne precipitation radar and has continued to make measurements of rain for more than 8 yr. Compared to microwave radiometers, the radar has the following advantages for quantitative rainfall estimations. First, essentially the same algorithm is applied to retrieve rainfall rates over ocean and land surfaces. Second, a vertical rain profile is measured. However, because the distance from this satellite-based radar to the rain is larger than a typical observation range of ground-based precipitation radars, it is difficult to realize a satisfactory spatial resolution by a spaceborne radar if the radar beamwidth is the same. To mitigate this problem, the TRMM PR uses a relatively high-frequency channel (13.8 GHz; Ku band) to improve the spatial resolution under the limitation of antenna size. Consequently, TRMM PR observations can suffer from rain attenuation.

Because the TRMM PR observes rain downward toward the earth’s surface, the surface backscattering cross section (denoted as $\sigma^o$) can always be observed simultaneously. This cross section is beneficial for estimating rain attenuation. As $\sigma^o$ is determined by the system parameters (such as the incident angle, microwave frequency, and polarization) and surface conditions, it is necessary to understand how $\sigma^o$ is determined by these system parameters and the surface conditions to best utilize $\sigma^o$.

Over ocean surfaces, $\sigma^o$ is strongly related to the sea surface wind. When the incident angle (denoted as $\theta$) is more than $20^\circ$, resonance scattering dominates, and when the incident angle is less than $20^\circ$, quasi-specular scattering dominates. For the latter, the quasi-specular scattering theory, as shown in Eq. (1), is used to model $\sigma^o$ (Barrick 1974; Valenzuela 1978):
\[
\sigma^0 = \frac{|\Gamma(0)|^2}{S^2} \frac{1}{\cos^4 \theta} \exp \left( - \frac{\tan^2 \theta}{S^2} \right),
\]

where \( \Gamma(0) \) is Fresnel’s reflectivity and \( S^2 \) is the variance of the surface slope. Here \( \Gamma(0) \) is sensitive to sea surface salinity, but the natural variation of salinity is too small to change \( \sigma^0 \) significantly. However, \( S^2 \) varies greatly in relation to the surface wind speed. Generally, \( \sigma^0 \) is positively dependent on the wind speed at an incident angle larger than 10° but negatively dependent on the wind speed at an incident angle smaller than 10° (Wentz et al. 1984).

Over land, it is difficult to model \( \sigma^0 \) in a totally physical manner. The land surface is often simply modeled by the soil surface and vegetation cover (Ulaby et al. 1984; Prevot et al. 1993; Moran et al. 1998). Total scattering consists of single scattering at bare soil surfaces, at soil surfaces under vegetation, or at vegetation, and double scattering at vegetation and the soil surface.

Scattering at the soil surface is usually treated as surface scattering, while volume scattering becomes substantial under very dry soil conditions. Surface soil moisture and roughness are key variables that affect scattering at the soil surface (Ulaby et al. 1978). When the incident angle is small, specular scattering dominates, and a smooth surface yields higher \( \sigma^0 \) than a rough surface. However, at a large incident angle, a rough surface has a higher \( \sigma^0 \) than a smooth surface. At an incident angle around 10°, \( \sigma^0 \) is relatively insensitive to roughness. An increase in surface soil moisture leads to an increase in \( \sigma^0 \) for bare soil surfaces. However, for surfaces covered by dense vegetation, \( \sigma^0 \) is attenuated by the vegetation, and the sensitivity of \( \sigma^0 \) to soil moisture is weak. The attenuation by vegetation is related to the water content of vegetation. Scattering at vegetation is treated as volume scattering and has weak dependence on the incident angle.

The 250-m range resolution of TRMM PR is designed for rainfall observation but is not sufficiently fine to observe an impulse target such as land or ocean surfaces (Caylor et al. 1997). TRMM PR usually does not obtain the peak backscattering echo and thus tends to underestimate \( \sigma^0 \), a problem that is severer at small incident angles. TRMM PR samples radar echoes around the surface with a better sampling intervals of 125 m when the incident angle is less than 11° (Kozu et al. 2000).

Although TRMM PR is not designed for specialized observations of land/ocean surfaces, some previous studies have used TRMM PR data to monitor land surfaces and retrieve physical parameters. Freilich and Vanhoff (2003) used the \( \sigma^0 \) dataset observed by TRMM PR and the sea surface wind speed \( u \) retrieved from the TRMM Microwave Imager (TMI) data to find the statistical relationship between \( \sigma^0 \) and \( u \) for each incident angle. Li et al. (2004) proposed an algorithm that retrieves sea surface wind speed based on the Seasat Scatterometer (SASS-2) model. Satake and Hanado (2004) found that \( \sigma^0 \) shows a diurnal variation over Amazonia, and they concluded that the increase of \( \sigma^0 \) in the early morning is probably caused by dewdrops on leaves. Lee and Anagnostou (2004) developed a combined algorithm for soil moisture estimation from PR and TMI. In fact, the TRMM PR has several advantages as a land surface sensor; namely, incident angles between 0° and 18° are not often used by land surface sensors except for nadir observation data by altimeters. Furthermore, the TRMM PR has been providing very stable data over a long period of more than 8 yr.

TRMM PR measurements of \( \sigma^0 \) provide first estimates of path integrated attenuation (PIA) by the surface reference technique (SRT). The SRT compares apparent \( \sigma^0 \) under rainfall and no-rainfall conditions and estimates the PIA as the difference of \( \sigma^0 \) between these conditions. Because \( \sigma^0 \) is dependent on land/ocean surface conditions, the SRT should consider rainfall-induced changes in land/ocean surface conditions. However, very few studies have quantitatively investigated how actual \( \sigma^0 \) (“actual” \( \sigma^0 \) refers to the “attenuation corrected” \( \sigma^0 \), which is denoted as \( \sigma^e_0 \) hereafter) changes because of rainfall. Meneghini et al. (2000, 2004) acknowledged the change in \( \sigma^0 \) by rainfall, but no explicit consideration is involved in the standard algorithm (Iguchi et al. 2000) because of the complexity of quantitative treatment.

The following three problems are addressed in this paper: How does \( \sigma^e_0 \) change because of rainfall? How are PIA estimates affected by SRT biases? How are rain-rate estimates in the standard algorithm biased? To answer the above questions as quantitatively as possible, we analyze TRMM PR data. The next section gives an overview of the TRMM PR and its standard rain-rate retrieval algorithm. Section 3 describes the TRMM PR data and data analysis method. The following three sections (sections 4–6) correspond, respectively, to the above three problems. The final section (section 7) provides an overall summary.

2. Overview of TRMM PR and its standard algorithm

a. TRMM PR

Developed through an international project by the United States and Japan, the TRMM was successfully launched and began observations in December 1997 (Kummerow et al. 1998). The TRMM is on a non-sun-
synchronized orbit with an inclination angle of 35°, so that it observes the diurnal cycle of rainfall within 35° latitudes north and south. The altitude was initially 350 km but was changed to 402.5 km in August 2001 to save fuel and extend the satellite’s life.

Among the five sensors mounted on the TRMM, three [the PR, TMI, and Visible Infrared Scanner (VIRS)] can be employed for quantitative precipitation measurements. The PR is the first spaceborne precipitation radar. It scans in the cross-track direction and takes observations at 49 different incident angles within 0.6 s. In this study, the incident angle θ is approximated as θ = 0.75 × [i – 25], where i is the angle bin number from 1 to 49. At the scan edges (i = 1 or 49), θ is 18.0°, and at the center of the scan (i = 25), θ is 0.0° (nadir looking). The horizontal resolution at nadir is 4.3 km (5.0 km) both in the cross-track and along-track directions before (after) the boost. The PR uses the 13.8-GHz microwave and horizontal polarization both to transmit and receive. Both the range resolution and the sampling interval are normally 250 m, but the sampling interval improves to 125 m for surface observations at incident angles smaller than 11°.

b. The standard rain-rate retrieval algorithm

Figure 1 shows a flowchart of the standard rain-rate retrieval algorithm for TRMM PR. The received echo powers from rainfall and the ground are converted into the radar reflectivity factor \( Z_m \) and surface backscattering cross section \( \sigma^b_m \), respectively. Note that subscript m indicates the measured value. The vertical profile of \( Z_m \) is obtained at a resolution of 250 m from the surface to 15 km high at a minimum. However, because of ground clutter, \( Z_m \) is often contaminated near the surface. Here, \( Z'_m \) can be expressed by using the real effective radar reflectivity factor \( Z_e \) and attenuation coefficient \( k \) as in Eq. (2), where variable \( r \) is the distance from the radar and \( s \) is a dummy variable for \( r \):

\[
Z_m(r) = Z_e(r) \exp \left[ -0.2 \ln(10) \int_0^r k(s) \, ds \right].
\] (2)

PIA is defined in Eq. (3), where \( r_s \) is the distance from radar to the earth surface:

\[
PIA = 10 \log_{10} Z_m(r_s) - 10 \log_{10} Z_m(r_s) = 2 \int_0^{r_s} k(s) \, ds.
\] (3)

The standard algorithm is composed of two parts: attenuation correction (the conversion from \( Z_m \) to \( Z_e \)) and conversion from \( Z_e \) to rain rate \( R \). Iguchi et al. (2000) developed a hybrid method for attenuation correction based on the Hitschfeld and Bordan (1954, hereafter HB) method and the SRT. The HB method assumes a \( k-Z \) relationship [equivalent to assuming a drop size distribution (DSD) parameterized by a single parameter] and analytically solves \( Z_e \) from Eq. (2). If the \( k-Z \) relationship is expressed by the power law as Eq. (4), the solution to \( Z_e \) is given as Eq. (5):

\[
k(r) = \alpha(r) Z_e^{\beta(r)},
\] (4-1)

where

\[
\alpha(r) = e^{\alpha_0(r) / \beta_0(r)} = \beta_0,
\] (4-2)

\[
Z_e(r) = \frac{Z_m(r)}{[1 - e^{\zeta(r)}]^{1/\beta_0}},
\] (5)

where \( \alpha_0 \) is a function of \( r \), \( \beta_0 \) and \( e \) are constants, and \( \zeta(r) \) is defined as Eq. (6):

\[
\zeta(r) = 0.2 \beta_0 \ln(10) \int_0^{r_s} \alpha_0^{s}(s) Z_m(s)^{\beta_0} \, ds.
\] (6)

PIA calculated by the HB method (denoted as PIA_{HB}) is expressed as Eq. (7):

\[
PIA_{HB} = -\frac{10}{\beta_0} \log_{10} [1 - e^{\zeta(r_s)}].
\] (7)

Later in this paper, \( \zeta(r_s) \) is simply written as \( \zeta \).

The \( k-Z \) relationship must be properly set; if not set correctly, the HB method yields large errors or diverges as \( \zeta \) becomes larger than 1 for heavy rainfall. To avoid this problem, PIA estimates by the SRT (denoted as PIA_{SRT}) are used to modify the \( k-Z \) relationship. One method is to adjust \( \alpha \) (by changing \( e \)) in the \( k-Z \) relationship to make PIA_{HB} and PIA_{SRT} the same, and is called the \( \alpha \)-adjustment method. The hybrid method for the standard algorithm modifies the \( k-Z \) relationship by taking into account the uncertainties in \( \alpha \) and PIA_{SRT}. Since the modification of the \( k-Z \) relationship corresponds to the changes in the parameterized DSD model, the \( R-Z \) relationship is also modified to maintain consistency with the \( k-Z \) relationship. Attenua-
tion-corrected $Z$, is finally converted to $R$. A common framework of the standard algorithm as explained above is used over ocean and land surfaces.

c. Surface reference technique

The surface reference technique estimates $\Pi A_{\text{SRT}}$ using the surface backscattering cross section (Meneghini et al. 2000, 2004). $\Pi A$ for a rain pixel (denoted as $R$) is theoretically calculated as the difference between the observed apparent surface backscattering cross section $\sigma^0_{\text{m}} (R)$ and actual surface backscattering cross section $\sigma^0_e (R)$ at the same incident angles. However, $\sigma^0_e (R)$ cannot be observed by the satellite, therefore the SRT method refers to $\sigma^0_{\text{m}}$ at a no-rain pixel (denoted as $\text{NR}$) to estimate $\sigma^0_e$ at rain pixel $R$. $\Pi A_{\text{SRT}}$ can be calculated as Eq. (8), where $\sigma^0_{\text{SRT}}$ is an estimate of $\sigma^0_e (R)$:

$$\Pi A_{\text{SRT}} = \sigma^0_{\text{SRT}} - \sigma^0_{\text{m}} (R).$$  (8)

The referenced no-rain pixels must be close to the rain pixel $R$ because $\sigma^0$ values at different pixels are expected to be similar if the pixels are close to each other. As many no-rain pixels as possible should be referenced to remove the random noise in $\sigma^0$ caused by very small-scale variations of the land/ocean surface and observation error. Actually, the attenuations by cloud and atmospheric molecules ($\text{H}_2\text{O}$ and $\text{O}_3$) slightly affect the observation. However, the attenuations by the nonprecipitating particles are smaller than 1 dB, and the difference between attenuations under clear conditions and under rainfall conditions is much smaller than a fraction of a decibel and negligible for the discussion later in this paper.

Three SRT methods are selectively used in the standard algorithm. The alongtrack spatial reference (ATSR) method samples no-rain pixels at the same angle bin and with the same land/ocean flag as the target rain pixel $R$. Eight samples just before pixel $R$ are referenced. The temporal reference (TR) method samples no-rain pixels at the same incident angle and in the same grid ($1^\circ \times 1^\circ$ longitude) as the target pixel $R$. All the samples observed in the previous calendar month and satisfying the above conditions are used. Over land, the method that shows a smaller standard deviation of the referenced $\sigma^0_{\text{m}} (\text{NR})$ is selected among the two methods; $\sigma^0_{\text{SRT}}$ is calculated as the simple average of the referenced $\sigma^0_{\text{m}} (\text{NR})$.

If all the pixels in a scan are over ocean, a third method called the hybrid spatial reference (HSR) method is used. This method first applies the ATSR method to all the pixels (both rain and no-rain) in the scan. Then, the estimates at the incident angle $\theta$ are fitted to the quadratic function of $\theta$ such as $\sigma^0 = a\theta^2 + b\theta + c$. The combination of $(a, b, c)$ that minimizes $F$ in Eq. (9) is obtained:

$$F = \sum_{j=1}^{49} \frac{[\sigma^0_{\text{ATSR}}(\theta_j) - (a\theta_j^2 + b\theta_j + c)]^2}{S_{\text{ATSR}}(\theta_j)},$$  (9)

where $\sigma^0_{\text{ATSR}}$ is the estimate of $\sigma^0$ by the ATSR method and $S_{\text{ATSR}}$ is the standard deviation of samples referenced by the ATSR method. The approximated value $(a\theta^2 + b\theta + c)$ becomes the estimate by the HSR method. The quadratic function is employed as a simplified form of the quasi-specular model. If pixels over land and ocean are mixed in a scan, the HSR method is not applied even for the ocean pixels.

3. Data

a. Standard product

The TRMM standard products are produced and distributed by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). In this study, we used one of the standard products, called 2A25. 2A25 includes land/ocean flags, rain/no-rain flags, selected surface reference techniques, measured surface backscattering cross sections, $\Pi A$ estimates by the SRT, and vertical profiles of rain-rate estimates for each pixel. We used the 2A25 product for January 2000 to December 2000 and for July 2001.

b. Data processing

For the statistical analysis, the data were divided into boxes by latitude–longitude (resolution: $1^\circ \times 1^\circ$), incident angle (resolution: 0.75°), observation date (resolution: 1 month), and surface flag (land or ocean; data over the coast were not analyzed). In each box, $\sigma^0_{\text{m}} (\text{NR})$ was averaged in decibel scale to obtain the mean ($\langle \sigma^0_{\text{m}} \rangle$). The deviation of an instantaneous cross section from $\langle \sigma^0_{\text{m}} \rangle$ in the corresponding box is denoted with $\Delta$, as follows:

$$\Delta \sigma^0_{\text{m}} = \sigma^0_{\text{m}} - \langle \sigma^0_{\text{m}} \rangle.$$  (10–1)
$$\Delta \sigma^0_{\text{c}} = \sigma^0_{\text{c}} - \langle \sigma^0_{\text{m}} \rangle.$$  (10–2)
$$\Delta \sigma^0_{\text{SRT}} = \sigma^0_{\text{SRT}} - \langle \sigma^0_{\text{m}} \rangle.$$  (10–3)

Statistical analysis of these quantities enables us to distinguish the change of $\sigma^0$ caused by rainfall from the change of $\sigma^0$ in a large temporal and spatial scale. Table 1 lists the notation for the backscattering cross sections used in this paper.
within the TRMM coverage. In other words, higher \( \langle \sigma^0_{NR} \rangle \) at smaller incident angles and lower \( \langle \sigma^0_{NR} \rangle \) at larger incident angles are seen over the ocean around Indonesia, likely because the surface wind speed is relatively weak in this region. Li et al. (2004) showed that the wind speed in this region is relatively weak (\( \sim 2–3 \text{ m sec}^{-1} \)) both in January 1998 and in August 2000 using the data from TRMM PR, TRMM TMI, and Quick Scatterometer (QuikSCAT), separately. The two curves of \( \langle \sigma^0_{NR} \rangle \) around Indonesia and all over the ocean within TRMM coverage cross at the incident angle of 6°, which qualitatively corresponds with the study of Freilich and Vanhoff (2003) that showed the \( \sigma^0-0 \) for the wind speed of 2 m s\(^{-1}\) and that for 6 m s\(^{-1}\) cross at around 7°. Generally, it is known that the \( \sigma^0 \) becomes insensitive to the wind speed around the incident angle of 10°, but it is not the case for the weaker wind speed less than 4 m s\(^{-1}\). This is well explained in the study of Freilich and Vanhoff (2003). Over land, \( \langle \sigma^0_{NR} \rangle \) clearly differs by regions. The incident angle dependence is strong over the Sahara Desert, and \( \langle \sigma^0_{NR} \rangle \) at the nadir there is higher than that over ocean. The Sahel shows relatively strong incident angle dependence. Amazonia shows almost no incident angle dependence except for near the nadir. Over land, \( \langle \sigma^0_{NR} \rangle \) is fundamentally determined by the vegetation amount. The incident angle dependence is weak for the area covered by dense vegetation. A small discontinuity in \( \langle \sigma^0_{NR} \rangle \) is seen around 11° because \( \sigma^0 \) is calculated from the echo power at the single range gate where the return power is a maximum, even though the sampling interval between adjacent range gates differs depending on whether the incident angle is smaller than 11° or not.

### 4. Change in \( \sigma^0_e \) induced by rainfall

This section answers the first question of, How does \( \sigma^0_e \) change due to rainfall? Because satellite observations cannot directly acquire information on \( \sigma^0_e \) under rainfall conditions, two kinds of proxy data for \( \sigma^0_e (R) \) were employed in this study.

#### a. The value of \( \sigma^0_m \) under weak rainfall

Under rainfall, \( \sigma^0_m (R) \) should be lower than \( \sigma^0_e (R) \) because of rain attenuation, if there is no observation error. Therefore, \( \sigma^0_m (R) \) provides some information about the lower limit of \( \sigma^0_e (R) \). When rain attenuation is small, \( \sigma^0_m (R) \) can serve as a proxy data for \( \sigma^0_e (R) \).

Figure 3 shows \( \Delta \sigma^0_m (R) \) over land for different rain intensity categories. In this paper, estimated rainfall rate at the actual surface given by the 2A25 product as “SurfRain” is used for rain intensity. Negative \( \Delta \sigma^0_m \)
(R) under strong rainfall is caused by rain attenuation; however, positive $\Delta \sigma_{m}^{0}(R)$ under weak rainfall cannot be explained by rain attenuation. As $\Delta \sigma_{m}^{0}(R)$ should be higher than $\Delta \sigma_{m}^{0}(\text{NR})$, positive $\Delta \sigma_{m}^{0}(R)$ implies positive $\Delta \sigma_{m}^{0}(\text{NR})$; hence, $\sigma_{m}^{0}$ under rainfall is higher than $\sigma_{m}^{0}$ under no-rainfall conditions. Positive $\Delta \sigma_{m}^{0}(R)$ is seen with rain intensities up to 4 mm h$^{-1}$. The shaded area of Fig. 3 corresponds to the ratio of pixels with $\xi < 0.1$. If $\xi$ is less than 0.1, the SRT is ignored in the standard algorithm. Most of the pixels with surface rain intensities less than 2 mm h$^{-1}$ satisfy this condition. Therefore, we used the condition “$\xi < 0.1$” to define “weak rainfall.” The other two lines about $\Delta \sigma_{m}^{0}(\text{NR})$ in Fig. 3 will be explained later in section 5a.

The global map of $\Delta \sigma_{m}^{0}(R)$ under weak rainfall is shown in Fig. 4a. Noticeable positive $\Delta \sigma_{m}^{0}(R)$ can be seen in southwestern North America, southeastern South America, the Sahel of Africa, southern Africa, western India, areas of China above 30°N, and Australia. This positive $\Delta \sigma_{m}^{0}(R)$ suggests that in these regions $\sigma_{m}^{0}(R)$ is higher than $\sigma_{m}^{0}(\text{NR})$. In contrast, in southeastern North America, Amazonia, central Africa, and southern China, $\Delta \sigma_{m}^{0}(R)$ is almost 0, and the effect of rainfall on $\sigma_{m}^{0}$ is unclear. In a part of the Sahara Desert, $\Delta \sigma_{m}^{0}(R)$ appears to be negative but with small statistical significance because the total number of rain pixels is small in this region.

Over ocean, $\Delta \sigma_{m}^{0}(R)$ under weak rainfall is analyzed separately at different incident angles. The rest of Fig. 4 are maps of $\Delta \sigma_{m}^{0}(R)$ over ocean at incident angles from 0° to 3° (Fig. 4b), 6° to 9° (Fig. 4c), and 15° to 18° (Fig. 4d). Here $\Delta \sigma_{m}^{0}(R)$ is generally negative at small incident angles and positive at large incident angles. The tropical area generally shows weaker incident angle dependence than midlatitude areas. The ocean around Indonesia shows positive $\Delta \sigma_{m}^{0}(R)$ at incident angles from 6° to 9°, while most of other areas show near 0 $\Delta \sigma_{m}^{0}(R)$ at these incident angles. This tropical region also has strong incident angle dependence of $\Delta \sigma_{m}^{0}(R)$.

Figure 5 shows the incident angle dependence of $\Delta \sigma_{m}^{0}(R)$ in four regions: all the land within TRMM coverage, the Sahel of Africa, all the ocean within TRMM coverage, and the ocean around Indonesia. The incident angle dependence does not appear to be significant over land, except over the Sahel, where $\Delta \sigma_{m}^{0}(R)$ near the nadir is clearly higher than $\Delta \sigma_{m}^{0}(R)$ at larger incident angles. Over ocean, $\Delta \sigma_{m}^{0}(R)$ shows an increasing function with the incident angle and crosses 0 at approximately 11°. Over the ocean around Indonesia, $\Delta \sigma_{m}^{0}(R)$ has strong incident angle dependence (the difference between 0° and 18° is 3.8 dB, while it is 1.5 dB for all ocean areas within TRMM coverage), and the line of $\Delta \sigma_{m}^{0}(R)$ crosses 0 at approximately 6°, which is smaller than the angle for all ocean areas within TRMM coverage. The other four lines about $\Delta \sigma_{m}^{0}(\text{NR})$ in Fig. 5 will be explained later in section 4b.

b. The value of $\sigma_{m}^{0}$ adjacent to a rain area

Another source of proxy data for $\sigma_{m}^{0}(R)$ is $\sigma_{m}^{0}$ of no-rain pixels near rain pixels. Such a no-rain pixel is denoted as $\text{NR}$ to distinguish it from a general no-rain pixel, NR. No rain attenuation occurs for NR so that $\sigma_{m}^{0}(\text{NR})$ is equal to $\sigma_{m}^{0}(\text{NR})$. The surface condition of NR can be considered similar to that of the adjacent rain pixel R (more so than a general no-rain pixel NR) because a rain system may have passed over NR just before the observation.

The distance to the rain area is defined as the number of pixels from the closest rain pixel along the track. Distance and direction are considered. If NR is observed before (after) the most adjacent rain pixel, NR is located west (east) of the rain pixel, as the TRMM flies from west to east.

We analyzed $\sigma_{m}^{0}(\text{NR})$ located within 10 pixels of the neighboring rain pixel (Fig. 6). As before, the anomaly from $\langle \sigma_{m}^{0}(\text{NR}) \rangle$ of the corresponding box was taken and denoted as $\Delta \sigma_{m}^{0}(\text{NR})$. The $\Delta \sigma_{m}^{0}(\text{NR})$ 1 pixel away from the neighboring rain pixel over land is 0.3 dB, whether it is located west or east of the rain pixel. As distance from the neighboring pixel increases, $\Delta \sigma_{m}^{0}(\text{NR})$ decreases; at a distance of 10 pixels, $\Delta \sigma_{m}^{0}(\text{NR})$ is still positive. Over ocean, $\Delta \sigma_{m}^{0}(\text{NR})$ becomes
negative (−0.4 dB at a distance of 1 pixel; −0.2 dB at a
distance of 10 pixels) at θ = 0°−3° and positive (0.6 dB at a
distance of 1 pixel; 0.3 dB at a distance of 10 pixels) at
15°−18°.

The maps in Fig. 7 illustrate Δσ_m^0 (NR^*) 1 pixel away
from the neighboring rain pixel. Results over land are
shown separately for pixels west of the rain pixel (“west
side pixel”) in Fig. 7a and pixels east of the rain pixel
(“east side pixel”) in Fig. 7b. Positive Δσ_m^0 (NR^*) is
visible for southwestern North America, the Sahel,
western India, and Australia, where Δσ_m^0 (R) under
weak rainfall is also positive. Figure 7c shows the dif-
ferration in Δσ_m^0 (NR^*) between west side pixels and east
side pixels over land. For west side pixels, Δσ_m^0 (NR^*) is
higher than that for east side pixels in midlatitude areas,
but the reverse is true for the Sahel, located in the
Tropics. Such a clear difference between west and east
side pixels is not seen over ocean, as Fig. 7d shows for
the case of 15°−18°.

Figure 5 illustrates the incident angle dependence of
Δσ_m^0 (NR^*) 1 pixel away from a neighboring rain pixel.
Over land, weak incident angle dependence of Δσ_m^0
(NR^*) is observed. Over ocean, the incident angle de-
pendence of Δσ_m^0 (NR^*) is weaker than that of Δσ_m^0
(R), and the incident angle at which Δσ_m^0 (NR^*) be-
comes 0 is smaller than that for Δσ_m^0 (R). The incident
angle at which $\Delta \sigma^0_{\text{m}}$ (NR*) becomes 0 is $9^\circ$ on average over all ocean areas within TRMM coverage and $4.5^\circ$ over the ocean around Indonesia.

c. Discussion

The analysis above clearly shows that $\Delta \sigma^0_{\text{m}}$ (NR*) is positive over land at all incident angles and over ocean at large incident angles, but is negative over ocean at small incident angles. In this subsection, we discuss the kinds of land surface changes induced by rainfall and how these changes affect $\sigma^0_{\text{c}}$.

A change in surface soil moisture can increase $\sigma^0_{\text{c}}$ under rainfall conditions. Theoretical and experimental studies have shown that for bare soil, $\sigma^0_{\text{c}}$ increases as surface soil moisture increases (Ulaby et al. 1986). The sensitivity of $\sigma^0$ to surface soil moisture is weakened under vegetation cover, which attenuates microwaves, and may explain why $\sigma^0_{\text{c}}$ changes little over tropical rain forests. Even if water drops on leaves changes $\sigma^0_{\text{c}}$, the change is less than 1 dB (Satake and Hanado 2004). The change in $\sigma^0_{\text{c}}$ is positive at all incident angles. If a change in vegetation or roughness induces changes in $\sigma^0_{\text{c}}$, the sign of $\Delta \sigma^0_{\text{c}}$ should differ by incident angle. Direct physical mechanisms between surface soil moisture and $\sigma^0$ require further investigation; however, change in surface soil moisture can be one cause of increased $\sigma^0_{\text{c}}$ under rainfall. In this paper, we refer to this rainfall-induced increase in $\sigma^0_{\text{c}}$ over land as the “soil moisture effect.”

Because soil retains moisture after a rain system passes, the soil moisture effect can appear at no-rain pixels adjacent to rain pixels. This can explain why $\Delta \sigma^0_{\text{m}}$ (NR*) is generally positive. The difference in $\Delta \sigma^0_{\text{m}}$ (NR*) between west side and east side pixels can be explained by the dominant movement direction of rain systems. In the midlatitudes, rain systems generally move with temperate westerslies from west to east. Correspondingly, in these areas, west side pixels show the soil moisture effect more often than east side pixels. In the subtropics, rain systems are moved by trade winds from east to west; thus, the east side of a rain area tends to have higher soil moisture than the west side.

Change in $\sigma^0_{\text{c}}$ over ocean is probably caused by changes in surface wind speed. Negative $\Delta \sigma^0_{\text{c}}$ (R) at small incident angles and positive $\Delta \sigma^0_{\text{c}}$ (R) at large incident angles are reasonable results associated with strong winds accompanied with rainfall. We refer to this change in $\sigma^0_{\text{c}}$ over ocean as the “wind speed effect.”

Strictly speaking, we do not have any direct evidence on the change of $\Delta \sigma^0_{\text{c}}$ (R) under “heavy” rainfall such as $\zeta > 0.1$. However, it is hard to deny that the soil moisture effect and the wind speed effect appear under heavy rainfall as well as under weak rainfall at least qualitatively. Quantitative discussion, whether $| \Delta \sigma^0_{\text{c}}$ (R) is dependent on the rain intensity or not, should be done in a future study.

d. Estimation of $\Delta \sigma^0_{\text{m}}$ under rainfall

This section follows the previous discussion and tries to estimate the representative value of $\Delta \sigma^0_{\text{m}}$ (R) in each box ($1^\circ \times 1^\circ$ latitude–longitude, an incident angle bin, a month). Proxy data of $\Delta \sigma^0_{\text{c}}$ (R) have included $\Delta \sigma^0_{\text{m}}$ (R) under weak rainfall and $\Delta \sigma^0_{\text{m}}$ (NR*) adjacent to a rain area, but these values may differ from $\Delta \sigma^0_{\text{c}}$ (R). The
Rain attenuation included in $\Delta \sigma_{m}^0 (R)$ is not negligible, even when it is weak, and $|\Delta \sigma_{m}^0 (NR^*)|$ should be smaller than $|\Delta \sigma_{m}^0 (R)|$ because some NR* pixels are not affected by rainfall.

Because $\Delta \sigma_{m}^0 (R)$ includes rain attenuation, it is written as Eq. (11):

$$\Delta \sigma_{m}^0 (R) = \Delta \sigma_{m}^0 (R) - \langle \text{PIA} \rangle,$$

where $\langle \text{PIA} \rangle$ is the representative value of PIA for “weak” rainfall. Because the soil moisture effect and wind speed effect do not always appear at NR* pixels and because these effects become weaker as the distance from rain pixels increases, the relationship between $\Delta \sigma_{m}^0 (NR^*)$ and $\Delta \sigma_{m}^0 (R)$ can be written as

$$\Delta \sigma_{m}^0 (NR^*) = f \times \Delta \sigma_{m}^0 (R), \quad (0 < f < 1).$$

From Eqs. (11) and (12), we can obtain Eq. (13) by removing $\Delta \sigma_{m}^0 (R)$:

$$\Delta \sigma_{m}^0 (NR^*) = f \times (\Delta \sigma_{m}^0 (R) + \langle \text{PIA} \rangle).$$

Fig. 7. Shown are (a) $\Delta \sigma_{m}^0 (NR^*)$ for the pixel located 1 pixel west to rain area over land, (b) $\Delta \sigma_{m}^0 (NR^*)$ for the pixel located 1 pixel east to rain area over land, and (c) (b) minus (a). (d) Same as in (c), but for over ocean ($\theta = 15^\circ$–$18^\circ$).
To estimate \( f \) and (PIA), regression analysis is performed for \( \Delta \sigma^0_m (\text{NR}^*) \) and \( \Delta \sigma^0_m (R) \):
\[
\Delta \sigma^0_m (\text{NR}^*) \sim s \times \Delta \sigma^0_m (R) + c,
\]
where \( \Delta \sigma^0_m (\text{NR}^*) \) is the average of east side and west side pixels 1 pixel away from the neighboring rain pixels, and \( \Delta \sigma^0_m (R) \) is for \( \zeta < 0.1 \). Figure 8 shows the scatterplot of \([ \Delta \sigma^0_m (\text{NR}^*), \Delta \sigma^0_m (R) ]\), and the regression line as Eq. (14) over ocean and over land, separately. Over land, \( s = 0.448, c = 0.135 \), and the correlation coefficient is 0.554. Over ocean, \( s = 0.682, c = 0.169 \), and the correlation coefficient is 0.759. By comparing the Eqs. (13) and (14), \( f \) is determined to be the same as \( s \). The value of \( f \) over ocean is higher than over land, which suggests that the wind speed effect appears at neighboring pixels more often than the soil moisture effect. If (PIA) is considered over ocean and land separately, (PIA) is calculated as \( c/s \), resulting in 0.300 over land and 0.248 over ocean.

For each box, \( \sigma^0_m (R) \) can be estimated as \( \sigma^0_m (R; \zeta < 0.1) + \langle \text{PIA} \rangle \). This is a new surface reference technique and is named as weak rainfall reference (WRR) method in this paper. This is a kind of TR method because the fixed estimates of \( \sigma^0_m (R) \) are used within a box. However, this method uses \( \sigma^0_m (\text{NR}^*) \) as well as the ATSR method and further uses \( \sigma^0_m (R) \), which has not been previously used in any surface reference technique.

5. Biases in the surface reference technique

The previous section discussed the difference between \( \sigma^0_m \) under rainfall and no-rainfall conditions. However, the surface reference technique in the standard rain-rate retrieval algorithm does not explicitly consider the change of \( \sigma^0_m \) by rainfall. This section investigates bias in the \( \text{PIA} \) or \( \sigma^0_{\text{SRT}} \).

a. Over land

Over land, \( \Delta \sigma^0_{\text{SRT}} (\text{land}) = \sigma^0_{\text{SRT}} - (\sigma^0_{\text{NR}^*}) \) was analyzed separately in the two kind of cases: the cases in which TR method is selected in the standard algorithm and the cases in which ATSR method is selected in the standard algorithm; Fig. 3 shows an overview of the results. The \( \Delta \sigma^0_{\text{SRT}} \) given by the ATSR method is positive, but that given by the TR method is negative. Values of \( \Delta \sigma^0_{\text{SRT}} \) by both methods are almost independent of the rain rate. A rain rate of less than 4 mm h\(^{-1}\) results in a \( \Delta \sigma^0_{\text{SRT}} \) by the TR method of less than \( \Delta \sigma^0_{\text{SRT}} \) (R), indicating that \( \text{PIA}_{\text{SRT}} \) is negative. This is obviously an underestimation of the PIA, which should always be positive in a physical sense. In the cases that the ATSR method is selected, \( \Delta \sigma^0_{\text{SRT}} \) is almost the same for \( \Delta \sigma^0_m (R) \) for the weakest rain-rate category between 0.0 and 0.5 mm h\(^{-1}\). On the other hand, from these results, we cannot conclude whether the ATSR method underestimates PIA or not.

Figure 9 presents maps of \( \text{PIA}_{\text{SRT}} \) under weak rainfall (\( \zeta < 0.1 \)). The \( \text{PIA}_{\text{SRT}} \) given by the TR method is negative almost everywhere except for areas of tropical rain forest and the Sahara Desert, where the soil moisture effect is not seen. However, over the Sahel, India, and Australia, where the soil moisture effect is strong, PIA is severely underestimated. The ATSR method underestimates PIA for most grids, but the TR method produces even greater underestimation. Over the Sahel, both methods severely underestimate PIA.

The TR method does not represent the soil moisture...
effect because the no-rain pixels used are usually not located near rain pixels and do not show the soil moisture effect. However, the ATSR method can partly represent the soil moisture effect because no-rain pixels are taken near rain pixels. Quantitatively, however, the ATSR method cannot estimate PIA well because the soil moisture effect appearing outside the rain area is not as strong as that in the rain area. In the Sahel region, the soil moisture effect is strong for east side pixels, but the standard algorithm always samples west side pixels, resulting in severe underestimation of $\sigma^0_{\text{SRT}}$ and PIA$_{\text{SRT}}$ in this region.

**b. Over ocean**

Figure 10 shows $\Delta\sigma^0_m (R)$ and $\Delta\sigma^0_{\text{SRT}}$ under weak rainfall ($\zeta < 0.1$) in the two kind of cases: the cases in which HSR method is selected in the standard algorithm and the cases in which ATSR method is selected in the standard algorithm. The incident angle dependence of $\Delta\sigma^0_m (R)$ in which the ATSR method is selected is different from that in which the HSR method is selected. It is mainly because the ATSR method is selected near the coast while the HSR method is selected far from the coast.

In the ATSR method, the incident angle dependence line of $\Delta\sigma^0_{\text{SRT}}$ is almost parallel to that of $\Delta\sigma^0_m (R)$. This indicates that ATSR method works well at all incident angles including the wind speed effect over ocean.

The incident angle dependence of $\Delta\sigma^0_{\text{SRT}}$ by the HSR method is not parallel to that of $\Delta\sigma^0_m (R)$; $\Delta\sigma^0_{\text{SRT}}$ increases with the incident angle up to 12°, but decreases when the incident angle is over 12°. Here PIA$_{\text{SRT}}$ [= $\Delta\sigma^0_{\text{SRT}} - \Delta\sigma^0_m (R)$] is negative and apparently underestimated at incident angles smaller than 4.5° and larger than 17°, while PIA$_{\text{SRT}}$ is positive and highest at 12°. Because the HSR method fits the quadratic function of $\theta$ to the $\sigma^0_{\text{SRT}}$ given by the ATSR method, the bias of $\sigma^0_{\text{SRT}}$ by the HSR method should result from this fitting process.

In the fitting process, the quadratic function is used instead of a more theoretical quasi-specular model. However, the quadratic function may not result in a
good representation of the $\sigma^0-\theta$ relationship. To test which function better explains the $\sigma^0-\theta$ relationship, $\langle \sigma^0_{NR} \rangle (\theta = 0^\circ, \ldots, 18^\circ)$ over ocean was fitted by the quadratic function and the quasi-specular model. The $\langle \sigma^0_{NR} \rangle$ dataset did not distinguish the side of the swath; therefore, the first-order term ($b\theta$) is avoided in the quadratic function. To fit the quasi-specular model (which is a nonlinear function of $\theta$), the Marquardt method was used. The biases caused by the fitting process (fitted $\langle \sigma^0_{NR} \rangle$ – original $\langle \sigma^0_{NR} \rangle$) were averaged for all the ocean pixels within TRMM coverage, and the results are shown in Fig. 11. Both methods show similar results of positive biases around 12$^\circ$ and negative biases around 0$^\circ$ and 18$^\circ$; the amplitude is slightly larger using the quasi-specular model. An artificial discontinuity appears around 11$^\circ$ in Fig. 11, as for $\Delta\sigma^0_{RRT}$ by the HSR method in Fig. 10. This incident angle corresponds with the change in range sampling resolution. Both functions cannot well represent the incident angle dependence of $\sigma^0$ over ocean particularly at larger incident angles.

To reduce the bias caused by fitting process, fitting was performed separately for two incident angle ranges (0$^\circ$–11$^\circ$ and 11$^\circ$–18$^\circ$). The results by both the quadratic function and quasi-specular model are improved by this fitting method. Although a small underestimation at the edge of each range and small overestimation in the center of each range are observed, the amplitude of bias is much smaller than for the case of not dividing the incident angles into two ranges. Almost no difference is detected based on the type of functions. This method with a quadratic curve fitting is called HSR2 hereafter.

### 6. Effects of the biases on rain-rate estimates

This section answers the third question of how rain-rate estimates in the standard algorithm are influenced by biases in the surface reference technique. For this purpose, we executed the standard algorithm (2A25 version 6.67) with different surface reference techniques and analyzed the surface rain-rate estimates. We used data in July 2001 for this analysis.

#### a. Method

Five different surface reference methods (TR0, ATSR-W, ATSR-E, HSR2, WRR), as shown in Table 2, were employed separately instead of the original surface reference technique (denoted as STD). TR0 samples all the no-rain pixels observed in the month, in the same grid, at the same incident angle, and with the same land/ocean flags as the target rain pixel; $\sigma^0_{RRT}$ by TR0 is always the same as $\langle \sigma^0_{NR} \rangle$. This method is similar to the TR method, but the TR method takes samples in the previous month. ATSR-W is essentially the same as ATSR, but there is a small difference because ATSR-W is coded by us so that it can be applied for the

### Table 2. Surface reference techniques used in the standard algorithm and in the sensitivity analysis in this study.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Method</th>
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<tbody>
<tr>
<td>STD</td>
<td>The method used in the standard algorithm. It selects TR or ATSR over land, TR, ATSR, or HSR over ocean.</td>
</tr>
<tr>
<td>TR</td>
<td>Temporal reference method. The samples are taken in the same grid and in the previous month.</td>
</tr>
<tr>
<td>TR0</td>
<td>Temporal reference method, but the samples are taken in the same month with target pixel; $\sigma^0_{RRT}$ is always the same as $\langle \sigma^0_{NR} \rangle$.</td>
</tr>
<tr>
<td>ATSR</td>
<td>Alongtrack spatial reference method. The eight samples are taken just before the target rain pixel so that they are located west of the rain area.</td>
</tr>
<tr>
<td>ATSR-W</td>
<td>Same as ATSR, but coded by the authors.</td>
</tr>
<tr>
<td>ATSR-E</td>
<td>Same as ATSR-W; however, the samples are taken just after the target rain area so that they are usually located east of the rain area.</td>
</tr>
<tr>
<td>HSR</td>
<td>Hybrid spatial reference method. It is used for the scan that has only “ocean” pixels. First, ATSR is applied into all the pixels in the scan. Second, a quadratic function is fitted into $\sigma^0-\theta$ relationship.</td>
</tr>
<tr>
<td>HSR2</td>
<td>Improved version of HSR. Fitting a quadratic function into $\sigma^0-\theta$ relationship is done separately for the cases with smaller incident angles than 11$^\circ$ and larger incident angles.</td>
</tr>
<tr>
<td>WRR</td>
<td>Weak rainfall reference method; $\sigma^0_{RRT}$ is the sum of $\sigma^0_{RRT}(R)$ with $\xi &lt; 0.1$ and (PIA) (0.300 for over land, 0.248 for over ocean).</td>
</tr>
</tbody>
</table>
pixels where the standard algorithm selects TR or HSR. ATSR-E also uses the ATSR method, but the eight no-rain reference samples are taken just after the target pixel so that the samples are usually located east of the rain area. HSR2 is a modified version of the HSR method as described at the end of section 5. To mitigate the bias as shown in section 5b, the $\sigma^0_{SRT}$ estimated by ATSR method are fitted by quadratic functions separately for two incident angle ranges (0°–11° and 11°–18°). This method is applied only when the entire scan is over ocean, that is, only when the standard algorithm selects the HSR method. WRR is explained in section 4d; $\sigma^0_{SRT}$ is set as $\sigma^0_{m R}(R; \xi < 0.1) + \text{(PIA)}$ (where (PIA) is 0.300 over land and 0.248 over ocean).

b. Results

We then compared the generated product by the five methods and the standard product.

1) Over Land

Table 3 shows the results of $\Delta \sigma^0_{SRT}$ and monthly rainfall amount (mm month$^{-1}$) all over the land within TRMM coverage. As HSR2 cannot be applied over land, its results are excluded from this table. The results are separately shown for $\xi$ (under 0.1, over 0.1, or both) and method selected by the standard algorithm (ATSR, TR, or both). TR0 does not represent any soil moisture effect because $\Delta \sigma^0_{SRT}$ is always 0 in TR0. In other methods, the soil moisture effect is shown as $\Delta \sigma^0_{SRT}$ being positive. ATSR-W and ATSR-E produce relatively high $\Delta \sigma^0_{SRT}$ when the standard algorithm selects the TR method rather than the ATSR method. This suggests that selecting the method based on the criterion of a smaller sample standard deviation is not suitable for explaining the soil moisture effect. WRR results in the highest $\Delta \sigma^0_{SRT}$. All the methods also indicate that $\Delta \sigma^0_{SRT}$ is almost independent of $\xi$.

Rain-rate estimates increase (decrease) as $\Delta \sigma^0_{SRT}$ increases (decreases) when $\xi$ is higher than 0.1, while the rain rate is determined independently from SRT when $\xi$ is lower than 0.1 by the design of the standard algorithm. Higher $\Delta \sigma^0_{SRT}$ indicates higher PIA$_{SRT}$ and generally results in a stronger rain rate.

The standard product gives the monthly rainfall amount over all land within TRMM coverage for July 2001 as 61.8 mm month$^{-1}$. ATSR-W, ATSR-E, and WRR are slightly higher than the standard product by 0.70%, 0.91%, and 1.88%, respectively. Focusing on the pixels for which the TR method is selected in the standard algorithm, the above values become 4.45%, 1.56%, and 2.24%, respectively. Focusing on the pixels having $\xi$ higher than 0.1, these values become 0.99%, 1.28%, and 2.67%, respectively.

Table 4 shows the statistics for the Sahel region (10°–15°N, 0°–30°E). The difference between ATSR-W and ATSR-E is significant; $\Delta \sigma^0_{SRT}$ is 0.13 dB for ATSR-W and 1.24 dB for ATSR-E. The monthly rain amount is 112.44 mm for ATSR-W and 119.69 mm for ATSR-E. The difference in sampling strategy (west side or east side) makes a large difference in this region. Compared with the standard product, ATSR-E gives a higher rain-
fall amount by 7.83% (9.68% for the case of \( \zeta > 0.1 \)). Although TR0 uses a kind of temporal reference method, it gives a higher \( \Delta \sigma_0^\text{SRT} \) and stronger rain rate than TR. The \( \Delta \sigma_0^\text{SRT} \) and rain rate of TR0 are higher than those of TR by 0.55 dB and 2.99%, respectively. This indicates that normal no-rain surface conditions are quite different between June and July. WRR gives the highest \( \Delta \sigma_0^\text{SRT} \) and strongest rain rate among all the products.

2) OVER OCEAN

The \( \Delta \sigma_0^\text{SRT} \) and monthly rainfall amount (mm month\(^{-1}\)) was calculated for each incident angle over all ocean areas within TRMM coverage. Figure 12 shows the incident angle dependence of \( \Delta \sigma_0^\text{SRT} \) and \( \sigma_0^\text{SRT} \) (R) for the case that \( \zeta < 0.1 \) and the entire scan area is over ocean (the HSR method is selected in the standard algorithm). As is shown in the previous section, \( \Delta \sigma_0^\text{SRT} \) by the HSR method is not parallel to \( \sigma_0^\text{SRT} \) (R) and gives biased PIA\(_{\text{SRT}}\), however, the HSR2 method gives the \( \Delta \sigma_0^\text{SRT} \) almost parallel to \( \sigma_0^\text{SRT} \) (R) as well as ATSR-W, ATSR-E, or WRR. Please note that the \( \Delta \sigma_0^\text{SRT} \) by TR0 is always zero by definition so that the line is hidden by the zero line in this figure.

Figure 13 shows the incident angle dependence of monthly rainfall amount for the case that \( \zeta > 0.1 \) and the entire scan area is over ocean. It is characteristic of TRMM PR that weak- and low-rain systems tend to be missed at large incident angles. Therefore, the ratio of the number of rain pixels to the total number of pixels and the estimated monthly rainfall tend to be lower at large incident angles. The difference among the products is large, especially around 0° and 12°. The difference in rain-rate estimates among the products goes up to 20%. The monthly rainfall of the standard product that is produced by using the HSR method exhibits unnatural incident angle dependence. At nadir, the rainfall amount of the standard product is lower than those of other products; at 12°, the standard product shows the highest rain amount. TR0 has the strongest incident angle dependence; the estimate at nadir is higher than the estimate at 18° by approximately 25%. This is caused by biases due to the surface reference technique as well as by nondetection of weak- and low-rain systems near the edges of the scan. Because the

<table>
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<th>Selection by STD</th>
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<th>( \zeta &gt; 0.1 )</th>
<th>( \zeta &lt; 0.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>0.04</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ATSR-W</td>
<td>0.13</td>
<td>0.05</td>
<td>0.55</td>
</tr>
<tr>
<td>ATSR-E</td>
<td>1.24</td>
<td>1.20</td>
<td>1.50</td>
</tr>
<tr>
<td>WRR</td>
<td>1.50</td>
<td>1.44</td>
<td>1.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection by STD</th>
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<th>( \zeta &gt; 0.1 )</th>
<th>( \zeta &lt; 0.1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>111.00</td>
<td>93.92</td>
<td>17.08</td>
</tr>
<tr>
<td>TR0</td>
<td>115.04 (3.64)</td>
<td>97.45 (3.76)</td>
<td>17.59 (2.99)</td>
</tr>
<tr>
<td>ATSR-W</td>
<td>112.44 (1.30)</td>
<td>93.93 (0.00)</td>
<td>18.52 (0.45)</td>
</tr>
<tr>
<td>ATSR-E</td>
<td>119.69 (7.83)</td>
<td>103.41 (7.96)</td>
<td>18.28 (7.06)</td>
</tr>
<tr>
<td>WRR</td>
<td>121.93 (9.85)</td>
<td>103.02 (9.69)</td>
<td>18.91 (10.76)</td>
</tr>
</tbody>
</table>

![FIG. 12. The incident angle dependence of \( \Delta \sigma_0^\text{SRT} \) for all over the ocean within TRMM coverage. Results with different surface reference techniques are shown. Results are only for the case that HSR method is selected in the standard algorithm and \( \zeta < 0.1 \). As reference, \( \sigma_0^\text{SRT} \) (R) in these conditions.](image-url)
wind speed effect is not considered in TR0, the rain rate is overestimated at small incident angles. The incident angle dependence is relatively weak in ATSR-W and ATSR-E. In these products, rain-rate estimates at 18° are smaller than those at 0° by approximately 15%. Over ocean, where the ATSR method works well, this difference is mainly caused by surface clutter that appears to a higher altitude as the incident angle increases. HSR2, from the improved hybrid method, gives results similar to ATSR-W and ATSR-E. Compared with the standard product (HSR), HSR2 gives higher estimates by 11% at 18°, but gives lower estimates by 13% at 11.25°. The average across all the incident angles does not show large biases in the rain-rate estimates because overestimations at some incident angles and underestimations at other incident angles are cancelled out. The difference in total monthly rainfall between products TR0 and HSR2 is within 1%. WRR gives the lowest estimates among the various products, although the incident angle dependence is similar to those of ATSR-W and ATSR-E.

7. Conclusions

This study focused on the surface reference techniques that are applicable to the standard rain-rate retrieval algorithm for TRMM PR. Analyses of TRMM PR datasets over both the ocean and land revealed the following: The $\sigma_0^R$ observed under rainfall conditions is statistically different from $\sigma_0^R$ observed under clear conditions; the surface reference technique of the standard algorithm contains biases; and rain-rate estimates are affected by the bias in the surface reference technique.

1) Changes in wind speed accompanied by rainfall may affect surface reference estimates over ocean; however, previous studies had not confirmed this suggestion quantitatively. This study showed this “wind speed effect” using actual observation data. Generally, as the wind speed increases, $\sigma_0^R$ decreases at incident angles less than 9° and increases at incident angles more than 9°. An exceptional case is the ocean around Indonesia, where the incident angle at which $\sigma_0^R$ becomes insensitive to wind speed is as small as 4.5°, probably because normal wind speeds are low in this area. Over land, except for tropical rain forest and desert, $\sigma_0^R$ under rainfall is higher than $\sigma_0^R$ under clear conditions at all incident angles. The increase in surface soil moisture is probably one cause of this phenomenon.

In this study, pixels with weak rainfall and those adjacent to rain pixels are employed to prove the change of $\Delta \sigma_0^R (R)$ induced by rainfall. Strictly speaking, we do not have any direct evidence on the change of $\Delta \sigma_0^R (R)$ under “heavy” rainfall. However, it is hard to deny that the soil moisture effect and the wind speed effect appear under heavy rainfall as well as under weak rainfall at least qualitatively. Quantitative discussion, whether $| \Delta \sigma_0^R (R) |$ is dependent on the rain intensity or not, should be done in a future study.

2) In the surface reference technique, PIA over land tends to be underestimated because the soil moisture effect is not fully considered. The TR method does not take into account the soil moisture effect and results in underestimated PIA, except for areas such as Amazonia that do not show the soil moisture effect. The TR method partly takes into account the soil moisture effect because samples are taken from pixels near the rain area. However, the ATSR method does not sufficiently consider the soil moisture effect quantitatively, especially for the Sahel region. In this region, rain systems generally move from east to west, and thus samples located west of the rain area do not show the soil moisture effect as well as pixels east of the rain area. To reduce this bias, the ATSR method should take samples not only to the west but also to the east of the rain area.

Over ocean, bias is recognized by examining the incident angle dependence. The ATSR method performs better over ocean areas than over land areas; however, the HSR method yields biases when the first estimates by the ATSR method are fitted to a quadratic function. In that case, PIA is overesti-
mated at incident angles around 12° and underestimated at incident angles around 0°–3°. The fitting process should be performed separately for two incident angle ranges (0°–11° and 11°–18°).

3) The sensitivity of rain-rate estimates by the standard algorithm to the surface reference technique was also tested. When the TR method of the standard algorithm is replaced by the ATSR method, the rain rate over all land within the TRMM coverage increases by 0.70%. This value rises to 0.99% if the statistics are limited to \( \zeta > 0.1 \) cases. The negative bias in the TR method leads to a negative bias in the rain rate. Sensitivity analysis does not show very large effects on rain-rate estimates (within 10%); however, this result does not suggest that biases in the surface reference technique are trivial to rain-rate estimation. The standard algorithm does not entirely rely heavily on the surface reference technique to avoid the wrong corrections due to random errors in measurements of surface cross sections. Therefore, adjustment of the DSD does not work well, especially for weak rainfall cases. If the algorithm relies heavily on the surface reference technique, the biases in the rain-rate estimates become more apparent.

The ATSR method partly considers the soil moisture effect and wind speed effect; thus, this method creates relatively small bias in the PIA and rain rate. When the standard deviation of eight samples taken for the ATSR method is larger than that of samples for the TR method, the ATSR method is discarded in the standard algorithm. By this criterion, samples influenced strongly by the soil moisture effect are less likely to be selected because the soil moisture effect changes with distance. The HSR method is intended to reduce the random error in the ATSR method, but it produces bias error not found in the ATSR method.

In this study, we analyzed quantitatively the biases in different kinds of surface reference techniques, but to improve the overall performance of the rain retrieval algorithm we also need to consider other factors that may cause biases in the rain estimates. They include the nonuniform beam filling effect, the a priori DSD, and other numerous assumptions in the algorithm. Minimization of biases caused by these factors remains a work for the future.

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