# Brightness Fields in Statistically Inhomogeneous Clouds

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## Introduction

The angular structure of reflected and transmitted radiation provides important information needed for remote sensing of a cloudy atmosphere. The model angular distributions of radiation can be obtained by direct numeric simulation of three-dimensional (3D) clouds and radiation (*numerical averaging*), and the equations for the mean radiance (*analytical averaging*). The advantage of numerical averaging is that the needed statistical parameters of a radiation field may be obtained for any cloud model with accuracy as high as necessary. This makes it possible to use this direct method to estimate the accuracy of approximate methods (for a given cloud model). The disadvantage of the numerical averaging method is that it is laborious (it takes major expenditures of computer time), which makes this method practically unfeasible for operational purposes. Therefore, there is a need to suggest a relatively simple and practical useful statistical treatment to study the cloud-radiation interaction.

We have obtained equations for the mean radiance equations by using a new statistically inhomogeneous cloud model (e.g., Kassianov 2000). These approximate equations allow one to significantly speed-up (by a factor of 10 to 100) calculations of the mean radiative properties. Accuracy and robustness of these equations have been estimated for the mean solar fluxes (Kassianov et al. 2001). Here we present results of similar validation for the angular distribution histograms of reflected and transmitted solar radiation (Kassianov et al. 2003).

## Statistically Inhomogeneous Model

The suggested approach is based on the stochastic radiative transfer equation and a new statistically inhomogeneous Markovian model of broken clouds. The term "statistical inhomogeneity" is understood to mean that cloud statistics depend on the vertical coordinate. The vertical profile of the cloud fraction $p(z)$ is one of the input parameters of this statistically inhomogeneous model. Note, that vertical stratification of cloud fraction $p(z)$ is also required for the deterministic radiative transfer (RT) in vertically inhomogeneous cloudy atmosphere. In contrast to the deterministic RT, the suggested statistical approach has three additional input parameters. The first additional parameter $A(z)$ characterizes the mean horizontal cloud size in each layer. The second parameter $A^{up}(z)$ describes the statistical relationship between two adjacent layers in an upward direction. The third parameter $A^{dw}(z)$ specifies the statistical relationship between two adjacent layers in a downward direction.

This statistically inhomogeneous model has three appealing features. First, all input parameters can be derived from observations. This allows one to correctly compare theory predictions with field data. Further, the model flexibility makes it possible to describe the different combinations of random and maximum overlap, which are typical for the majority of multilayer broken clouds (e.g., Tian and Curry 1989; Mace and Benson-Troth, 2002). For example, if clouds are perfectly independent for any two adjacent layers (the random cloud overlap) then $A^{up}(z) >> 1$ and $A^{dw}(z) >> 1$. If $p(z)$ = const and clouds are perfectly dependent for any two adjacent layers (the maximum cloud overlap), then $A^{up}(z) = 0$ and $A^{dw}(z) = 0$. Hereafter we will use subscripts, *up*, and, *dw*, for upward and downward radiation, respectively. Finally, the statistically inhomogeneous model is a generalization of the statistically homogeneous ones (e.g., Titov 1990; Malvagi et al. 1993) that have been originally suggested for one-layer broken clouds. This circumstance makes it possible to apply a beautiful theory and an abundance of elegant numerical methods that have been developed for the statistically homogeneous models.

## Approach

We derived the approximate equations for the mean radiance of solar radiation (e.g., Kassianov 2000) and demonstrated that these equations could provide reasonable accuracy for the mean solar fluxes (Kassianov et al. 2001). In addition to the mean solar fluxes, here we validate the suggested statistical approach for the angular structure of diffuse radiation (both reflected and transmitted). Similar to our previous validation analysis (Kassianov et al. 2001), we performed the radiative calculations for two sets of input cloud parameters. The first set represents the full 3D cloud geometry (reference). The second set represents the bulk cloud statistics only (approximation). These bulk statistics ($p(z)$, $A(z)$, $A^{up}(z)$, and $A^{dw}[z]$) were obtained from the full 3D cloud geometry, and were the input of the statistically inhomogeneous model.

To further evaluate the accuracy and robustness of these equations, we performed reference (based on 3D geometry) and approximate (based on the bulk statistics) calculations of the angular distribution histograms of the transmitted $f_{dw}(\vartheta)$ and reflected $f_{up}(\vartheta)$ radiation:

$$f_{up\,(dw)}(\vartheta_{i+1}) = \frac{1}{2\pi(\vartheta_i - \vartheta_{i+1})} \int_0^{2\pi} d\varphi \int_{\vartheta_i}^{\vartheta_{i+1}} \langle I_{up\,(dw)}(\vartheta,\varphi) \rangle \, d\vartheta \qquad (1)$$

where $\vartheta_i = i \times 10$, $i = 0,\ldots,9$; $\langle I_{up(dw)}(\vartheta,\varphi) \rangle$ is the mean radiance of reflected and transmitted radiation at the cloud top and the cloud base, respectively; $\xi$ and $\varphi$ are the zenith and azimuth angles and $\vartheta = \cos\xi$.

We calculated these histograms by using 3D broken cloud fields, which were (1) produced by the Boolean stochastic model, (2) simulated by a large-eddy simulation (LES) model, and (3) derived from collocated and coincident multi-angle imaging spectro radiometer (MISR) and ground-based observations (Figure 1). Below we use the terms "Boolean cloud field," "LES cloud field" and "MISR cloud field," which correspond to cloud fields that are produced by the Boolean model, simulated by the LES model and derived from MISR measurements, respectively. Both the LES (single realization) and MISR (single realization) cloud fields represent a marine boundary layer broken clouds at the Atmospheric Radiation Measurement Program's (ARM) Tropical Western Pacific (TWP) site at the island of Nauru. The Boolean, LES, and MISR cloud fields and their bulk cloud statistics are discussed in Kassianov et al. 2001.

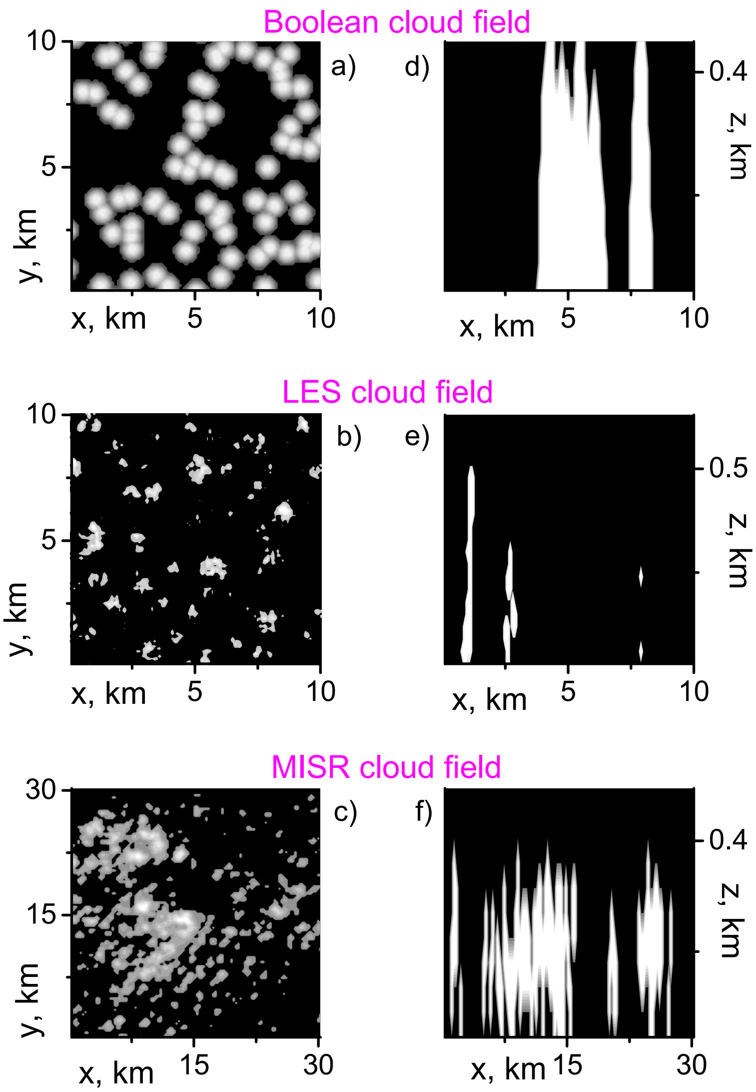


**Figure 1**. The horizontal (left column) and the vertical (right column) distributions of broken clouds that are provided by the Boolean stochastic model (Figures 1a, d), LES model (Figures 1b, e), and MISR cloud retrieval (Figures 1c, f). The vertical cross sections corresponding to $y = yl/2$, where $yl$ is domain size in *y*-direction. Brightness in the horizontal distributions (left column) is proportional to the geometrical thickness of clouds.

# Results

The radiative calculations are performed for a set of solar zenith angles (SZAs), but below we demonstrate results for two extreme values SZA = 0 (Sun is in zenith) and SZA = 70 (Sun is close to the horizon) only. All radiative calculations are corresponding to the *unit* solar flux at the top of a cloud layer. Aerosol-molecular atmosphere and underlying surface were not considered.

First, we estimate the accuracy of the suggested approach. To do that we compare the *ensemble-averaged* histograms (Figure 2) obtained for the Boolean model (Figures 1a, d). This model allows one to simulate quite easily the realizations of Markovian cloud field for a given cloud parameters (e.g., the nadir-view cloud fraction, the mean horizontal size). The values of these parameters are set to match the typical values for marine low-level cumulus clouds. The histograms (reference) are obtained by averaging over 10000 realizations of 3D cloud field. As can be seen, for the majority of zenith angle bins ($\Delta\vartheta_i = \vartheta_{i+1} - \vartheta_i, i = 0,\ldots,8$) the relative differences between the reference (3D geometry) and approximated (the bulk statistics) radiative properties do not exceed 20%. It means that, for the Markovian cloud fields, the suggested approach allows one to derive quite accurately the ensemble-averaged histograms of the reflected and transmitted radiation.

Second, we estimate the robustness of the suggested approach. To do that we compare the *domain-averaged* histograms (Figures 3 and 4) obtained for the LES (Figures 1b, e) and MISR cloud fields (Figures 1c, f). In contrast to the Boolean model, the single realization of LES cloud field and the single realization of MISR cloud field are applied. Similar to the Boolean cloud field, the domain-averaged histograms are calculated by using the full 3D cloud geometry (reference) and only the bulk cloud statistics (approximation). For the LES cloud field, the angular distribution histograms, which have been obtained by exact and approximated methods, are in good agreement (Figure 3).

Similar results are obtained for the MISR cloud field (Figure 4), except the maximum relative differences can be as large as 40% (Figure 4c). These large differences are exhibited for the transmitted radiation, large SZA (Sun is close to the horizon) and the large zenith angle bins ($\Delta\vartheta_i = \vartheta_{i+1} - \vartheta_i$, $i = 7, 8$). However, the contribution of each zenith bin to the total diffuse transmittance (integrated over all zenith angles) is proportional to the $\cos\left(\vartheta_i^*\right)$, where $\vartheta_i^* = (\vartheta_{i+1} + \vartheta_i)/2$, $i = 0,\ldots,8$. Therefore, the weight of these large differences is relatively small (in comparison with other angular bins). As a result, these large differences (occurred for $\Delta\vartheta_i = \vartheta_{i+1} - \vartheta_i$, $i = 7, 8$) have a slight effect on the distinctions between the transmitted fluxes (Kassianov et al. 2001).

# Conclusion

We further estimated the accuracy and robustness of the approximated equations for the mean radiance (Kassianov 2000). Previously we performed validation analysis for the mean solar fluxes (Kassianov et al. 2001). Here we extended the validation to the mean angular distribution histograms of the transmitted and reflected solar radiation. We used the 3D cloud fields provided by (1) the stochastic Boolean model, (2) large-eddy simulation model (LES cloud field), and (3) satellite cloud retrieval (MISR cloud field). The angular histograms were obtained by using the full 3D cloud geometry (reference) and the bulk cloud geometrical statistic (approximation).

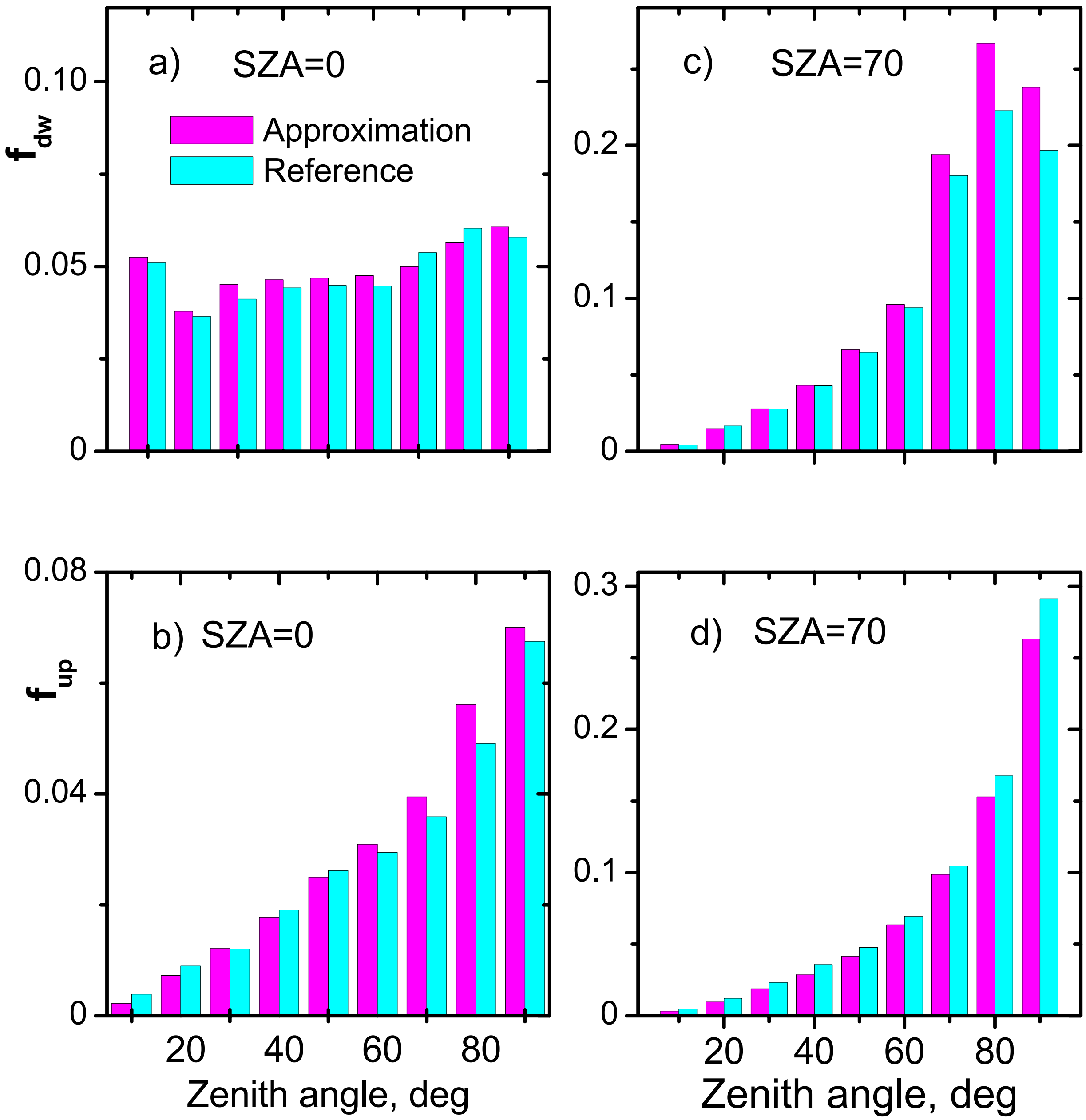


**Figure 2**. The Boolean cloud fields. The ensemble-averaged angular distribution histograms of the transmitted (a, c) and reflected (b, d) radiation. These histograms were obtained for two values of SZA by using the numerical averaging method (reference) and the analytical averaging method (approximation).

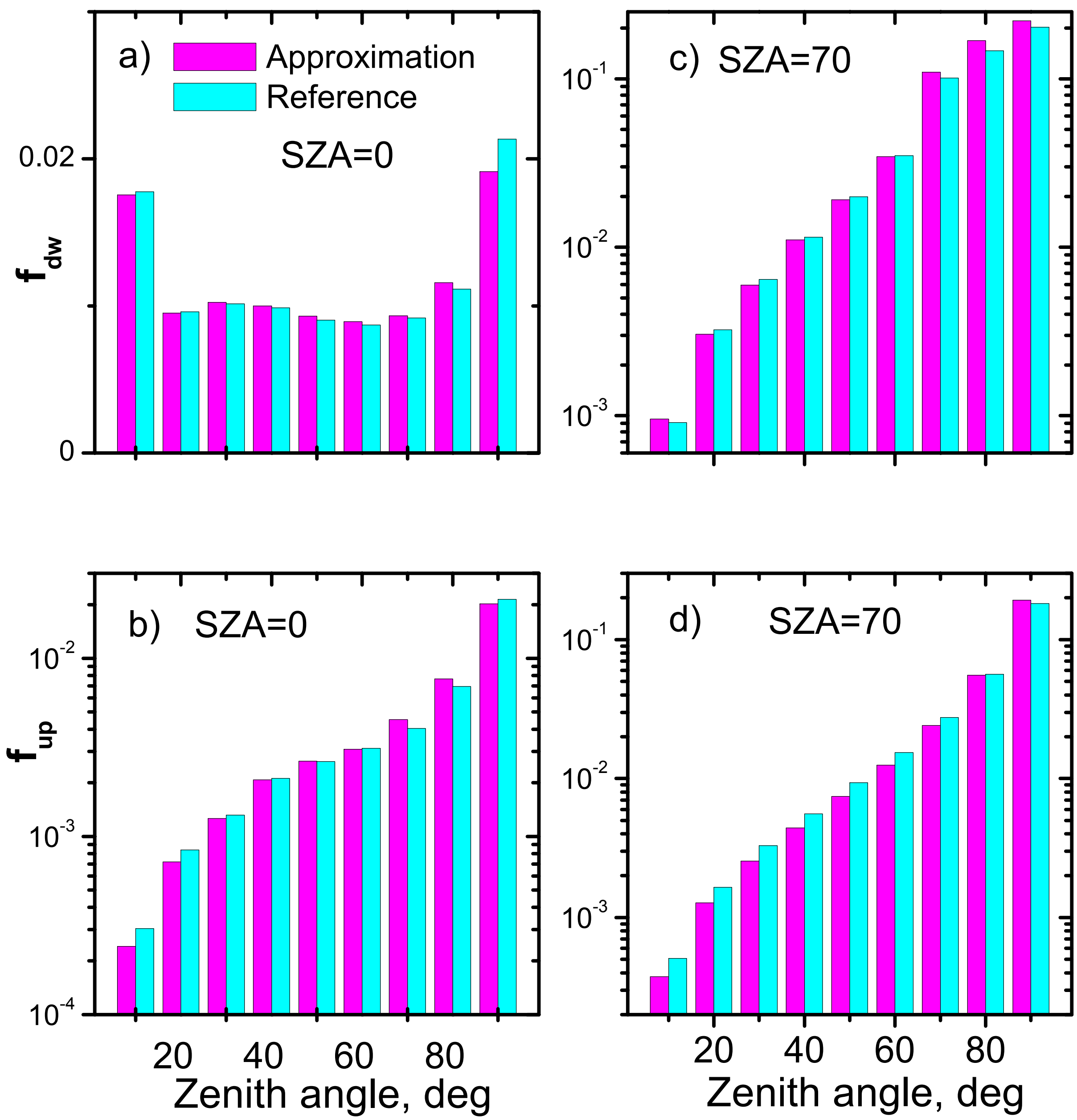


**Figure 3**. The LES cloud field. The domain-averaged angular distribution histograms of the transmitted (a, c) and reflected (b, d) radiation. These histograms were obtained for two values of SZA by using full 3D cloud structure (reference) and the bulk cloud statistics (approximation).

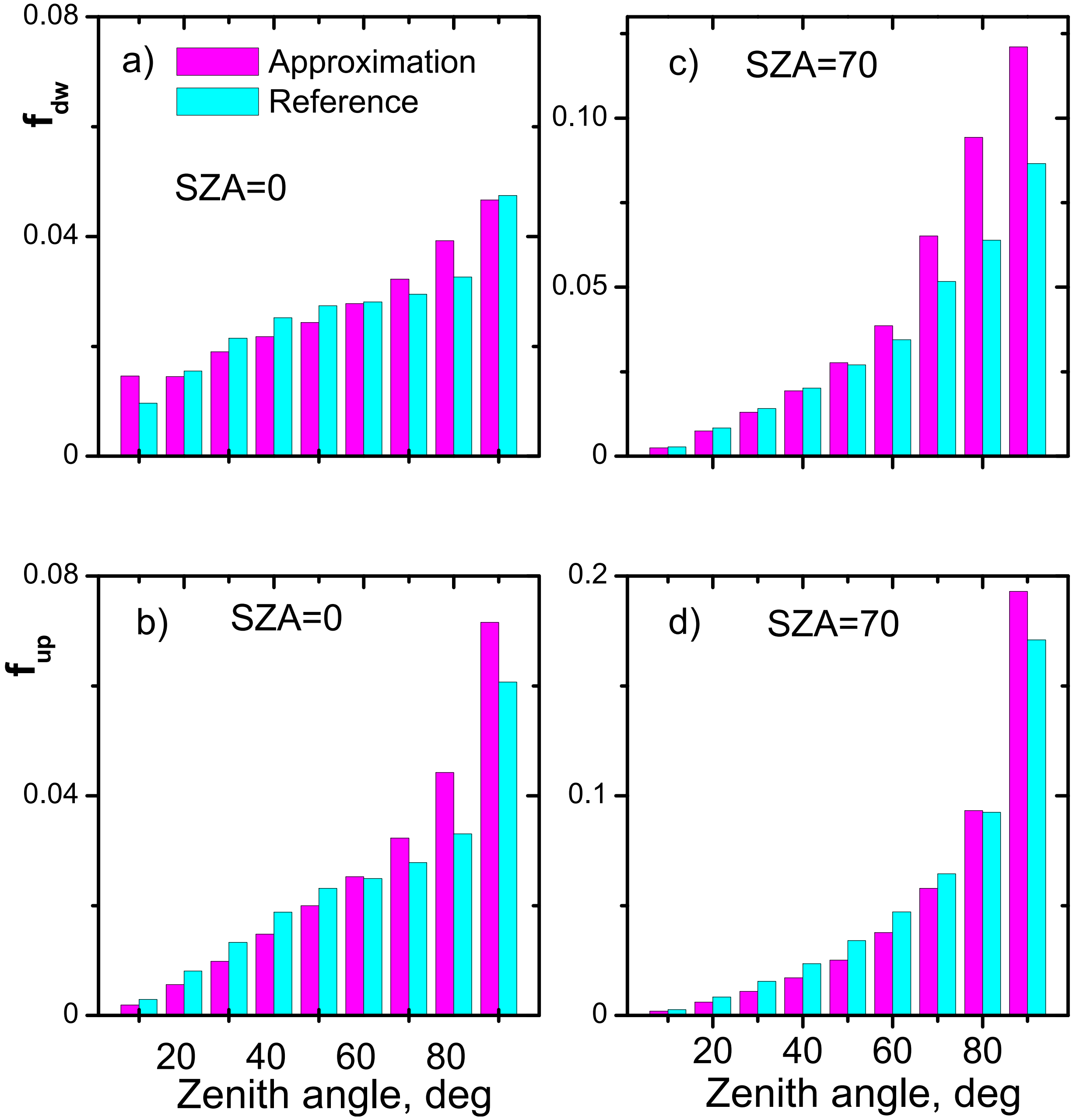


**Figure 4**. The same as in Figure 3, except that these results correspond to the MISR cloud field.

The accuracy of the obtained equations was evaluated by comparing the *ensemble-averaged* histograms (reference and approximation) calculated for the Boolean model. The robustness of these equations was estimated by comparing the *domain-averaged* histograms calculated for the LES and MISR cloud fields. It was shown that for the majority of cases, the approximated equations could provide reasonable accuracy (~20%) for both the ensemble-averaged and domain-averaged angular distribution histograms.

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