Assessing the Radiative Impact of Clouds of Low Optical Depth

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Introduction

Analysis from the International Satellite Cloud Climatology Project (ISCCP) reveals that the global mean cloud optical depth is surprisingly low (i.e., $\tau = 3.8$). While this value is probably dominated by extensive fields of cirrus, the average for liquid water clouds is also likely smaller than expected. It is in this regime (τ <10) where remote measurements of cloud optical thickness or liquid water path (LWP) are most difficult. Microwave radiometers tend to be noisy for low liquid water content and methods relying on solar transmission are complicated by scattering that is somewhere between being single-scattering and primarily diffusive. A new effort is now being launched to improve techniques for retrieving cloud properties for liquid water clouds of low optical depth. The accuracy required for climate studies should be based on how errors in the retrieval of cloud optical depth propagate through the radiative budget. In this study, we investigate the sensitivity of the shortwave and longwave radiative budget to perturbations in cloud optical thickness. This analysis is performed using a radiative transfer model (SBDART) with model inputs guided by observations from the Atmospheric Radiation Measurement (ARM) climate research sites at the Southern Great Plains (SGP), the Tropical Western Pacific (TWP), and North Slope of Alaska (NSA). By using these data the sensitivity analysis is constrained within realistic boundaries. The results should provide a better understanding towards determining the accuracy required for measuring cloud optical thickness as it relates to the radiation reaching the Earth’s surface, being reflected back to space and absorbed in the atmospheric column.

Cloud Property Retrievals

Determining the retrieval accuracy of cloud optical thickness and LWP is a difficult endeavor since in-situ measurements of vertically integrated cloud liquid water are presently not possible. The long-term robustness of these retrievals may be appreciated by comparing histograms of LWP measured from the microwave radiometer (MWR) and optical thickness inferred from radiometric observations in the visible by the multi-filter rotating shadowband radiometer (MFRSR). From these retrievals, the cloud droplet size distribution can be estimated.

The methodology for obtaining these properties for single layered liquid clouds is described in the accompanying flowchart (Figure 1). Cloud optical thickness is estimated from a look up table generated by SBDART that uses atmospheric transmission and surface albedo as input. Observations from the multi-filter radiometer (MFR) combined with the MFRSR provide the surface albedo. Atmospheric transmission is obtained by using MFRSR observations for the surface downwelling irradiance and the Barnmich value-added product for the top of the atmosphere (TOA) flux. The MWR provides cloud LWP. While many years of observations for the MWR and MFRSR are available, the analysis performed here is limited by the TOA flux data for the years 2000-2003. Atmospheric profiles are obtained from radiosondes and are used to screen the fields for cirrus and multiple cloud layers. The cloud optical thickness and LWP are used to compute the cloud droplet effective radius.

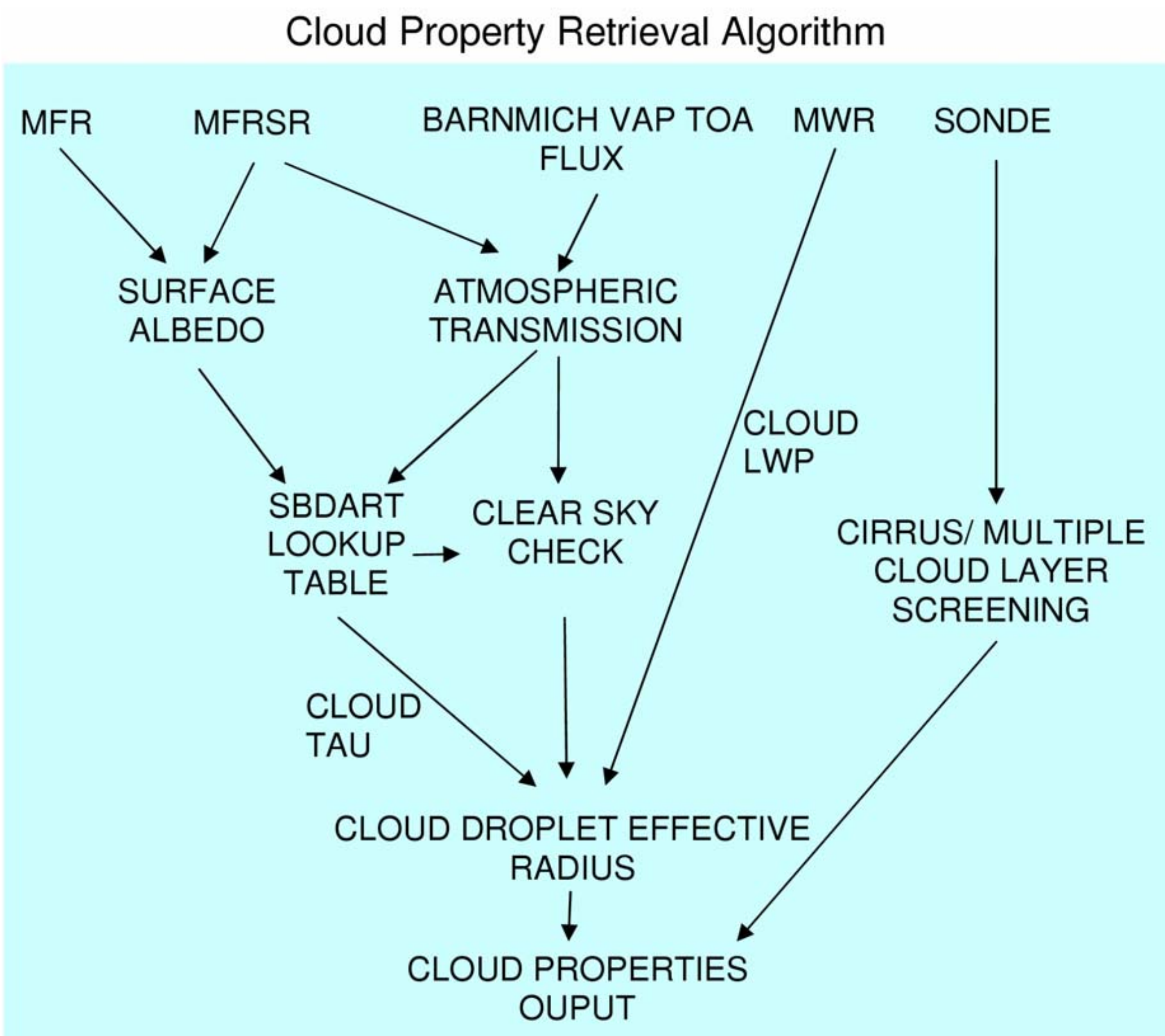

Figure 1. Cloud property retrieval algorithm.

Histograms in percent for cloud optical thickness and LWP are computed for the three ARM sites (Figure 2). Interestingly, for vastly different climatic regimes the difference between the mean cloud optical thickness for single layer clouds at the SGP ($\langle\tau\rangle$= 10.7) and TWP ($\langle\tau\rangle$= 11.6) is less than 10%. For the NSA site the clouds are optically thinner ($\langle\tau\rangle$= 8.8). This estimated value is probably too high because of the difficulties of retrieving optical thickness for steep solar zenith angles and often high surface albedos encountered at this site. Assuming an effective radius of 6 microns, the MWR histogram is binned by intervals equivalent to two optical depths. In general, the agreement between the shapes for the two histograms at each site is excellent outside the area where the MWR observations are noisy (light blue shading). The large difference between the histograms for τ <8 and LWP <.0025 cm shows the difficulty in measuring clouds of low optical depth. This problem is further demonstrated in Figure 3 where the mean cloud droplet effective radius is plotted against cloud optical thickness at SGP. Here, the calculated droplet size has a trend opposite the normal assumption that it should scale with optical depth.

Sensitivity Analysis

The sensitivity analysis is performed for conditions that represent the environments of the SGP, TWP, and NSA. Atmospheric profiles of relative humidity, temperature, and pressure are obtained from the radiosonde observations. Cloud layer locations are a function of the vertical profile of relative humidity. Aerosols and surface albedos are based on the geographical location of the ARM site. Simulations are performed for solar zenith angles of 0.0, 41.41, 60, and 75 degrees. The clouds used in the model runs initially have optical depths of 2, 4, 8, 16, 32, 64, and 128 and effective radii of 5 and 12 um. To simulate the impact of retrieval errors, the optical depth is systematically increased and decreased by 5%, 10%, and 20% and the radiative transfer computations are repeated for each perturbation. For the entire sensitivity analysis approximately 20,000 model runs were performed.

In Figure 4, the shortwave fluxes are presented. The thick line represents the percent error in the shortwave TOA upwelling and surface downwelling irradiance and column atmospheric absorption for the various deviations in cloud optical thickness input. The thin line represents the 2-sigma difference. The errors in the longwave are expressed in Wm^{-2} for downwelling at the surface and TOA upwelling irradiance (Figure 5).

For the shortwave, the results show that for the downwelling (upwelling) surface irradiance the sensitivity to cloud optical thickness increases (decreases) as clouds become optically thicker. For clouds of moderate thickness, it requires an approximately 3% change in cloud optical thickness to produce a corresponding 1% change in downwelling or upwelling fluxes. At the NSA site, the spread (i.e., 2-sigma) in the results for the downwelling irradiance is higher than that for the SGP or TWP because of the extreme range of surface albedos used for this location in the model computations. For all sites, atmospheric absorption in the shortwave is very insensitive to perturbations in cloud optical thickness. For the longwave clouds with optical depths between 2 and 8 are most sensitive to perturbations, but the impact is generally much less than 5 Wm^{-2}.

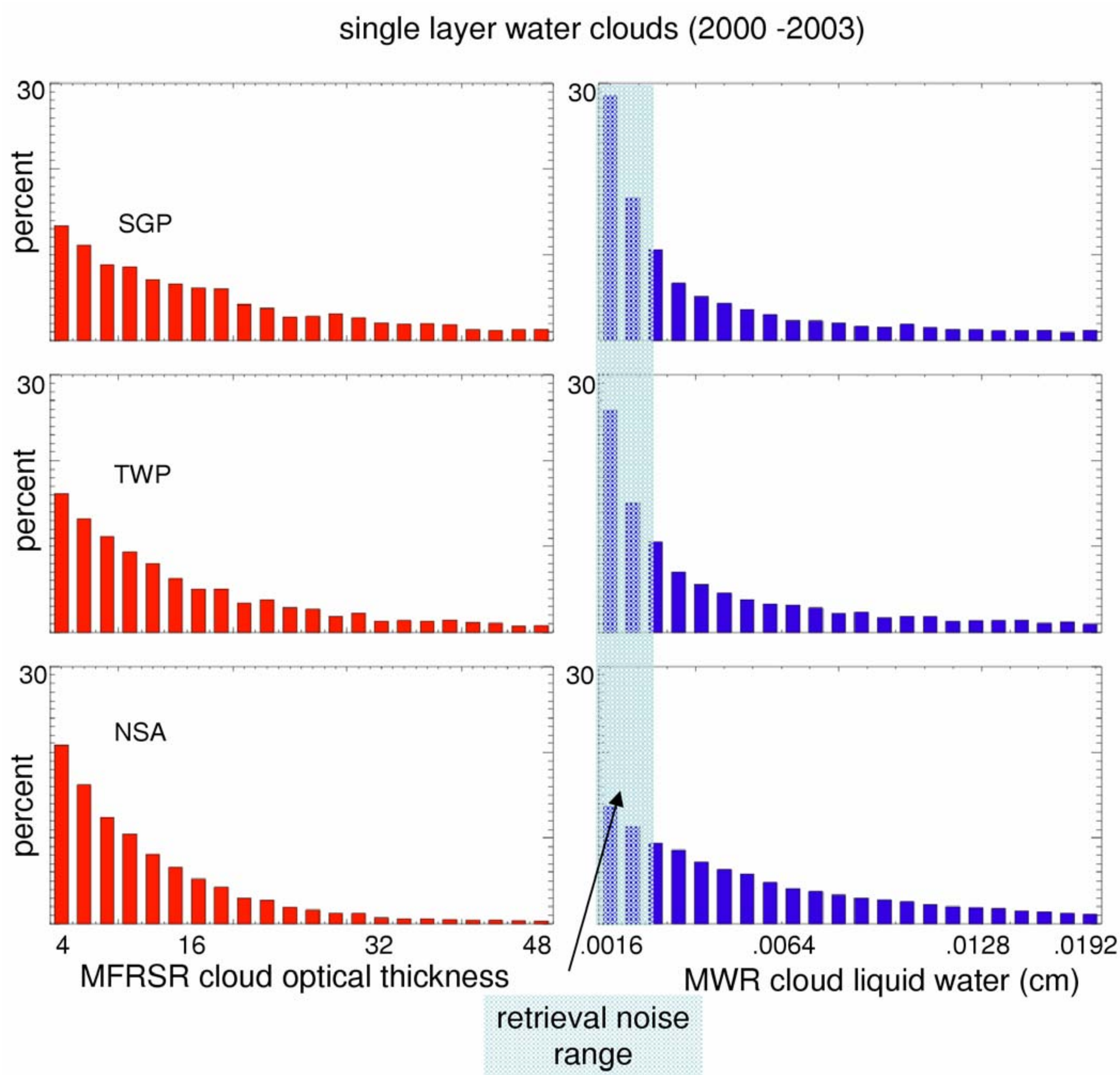

Figure 2. Histogram in percent for cloud optical thickness retrieved using the MFRSR and cloud liquid water retrieved using the MWR. The shaded blue area in the MWR histogram represents values where the MWR is reported to be inaccurate.

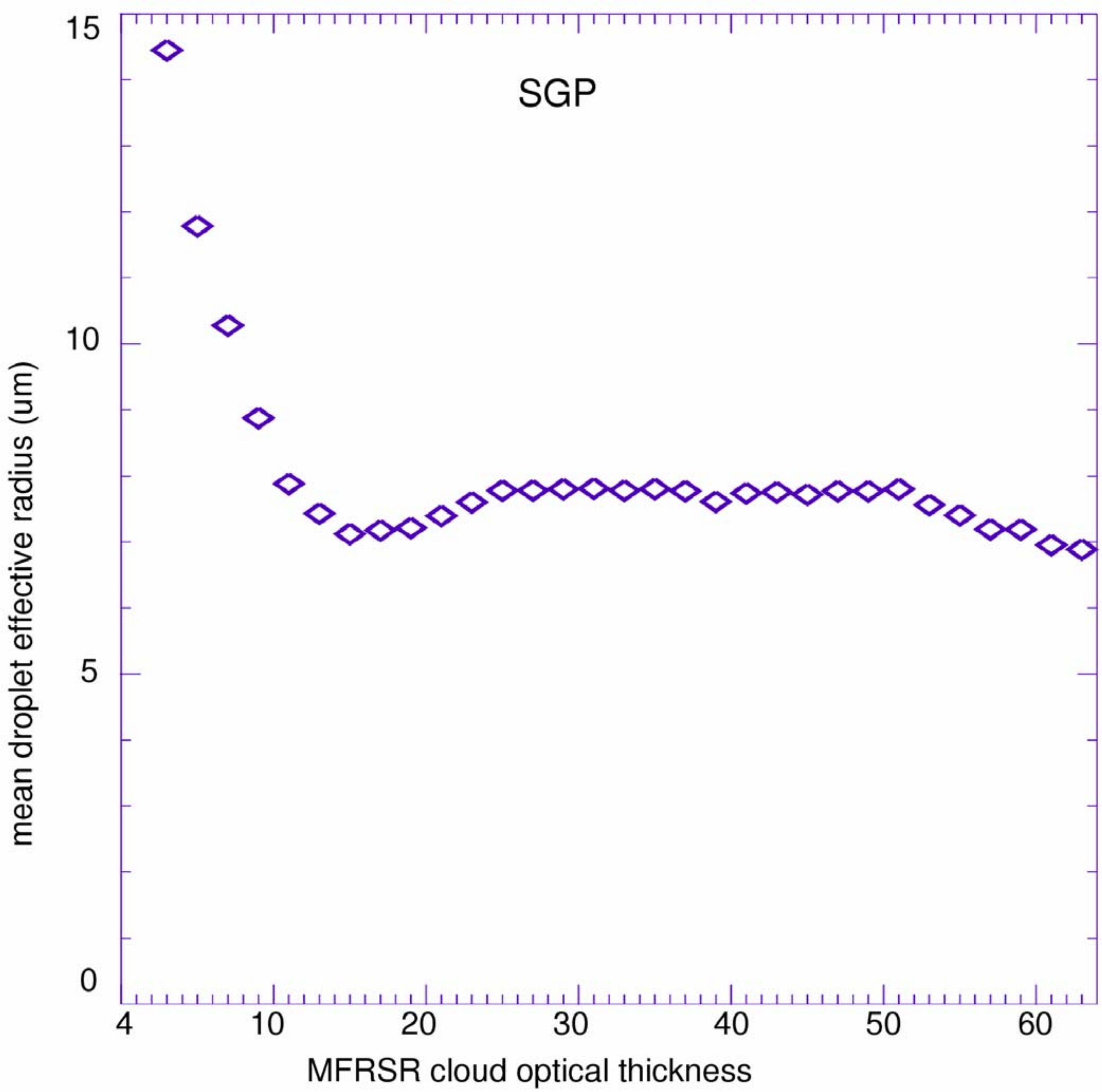

Figure 3. Cloud optical thickness plotted against computed cloud droplet effective radius averaged over all cases using 2 τ bins.

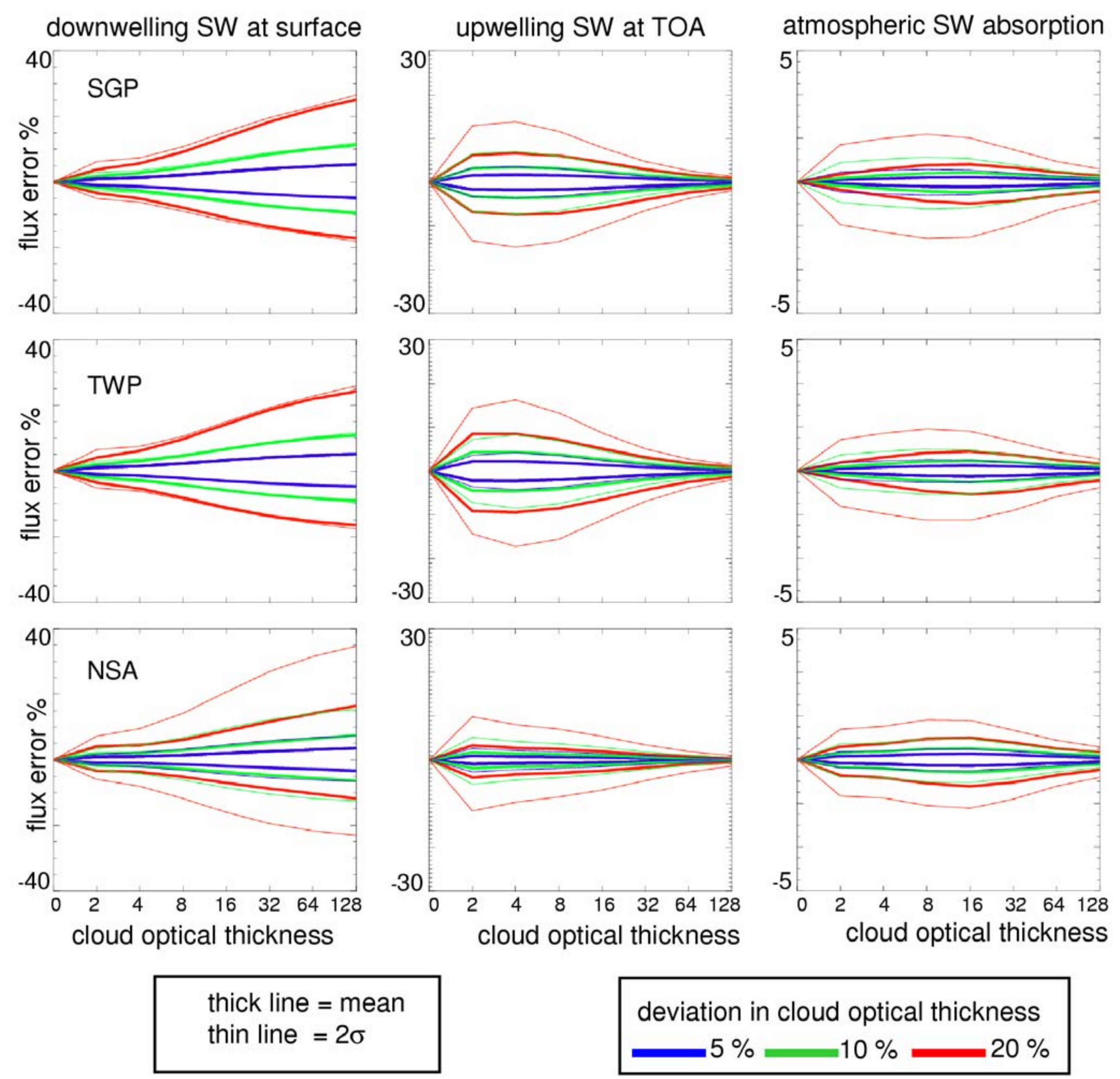

Figure 4. Modeled flux errors in percent for shortwave downwelling at the surface, upwelling at the TOA and total column atmospheric absorption. Error is the difference in flux between the radiative field computed for a give optical depth and that field using an optical depth plus or minus a percent deviation. The thick line is the mean error for all cases and the thin line represents the 2-sigma error.

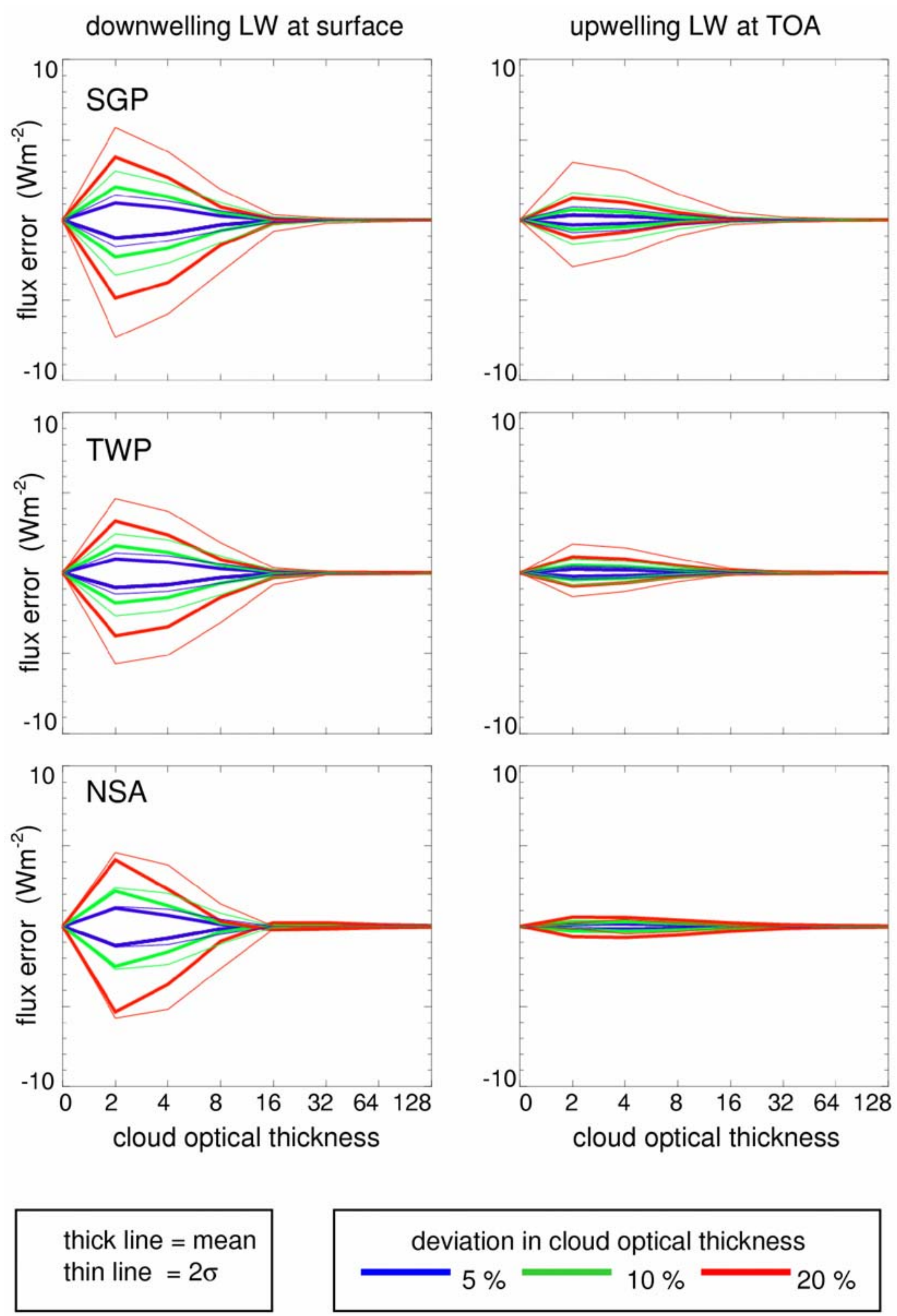

Figure 5. Same as in Figure 4, but for longwave upwelling and downwelling irradiance error expressed in Wm^{-2}.

Conclusion

The reported problems of retrieving clouds of low optical depth are manifested in the long data record for all three ARM sites. For the SGP and TWP site, the LWP retrieved by the MWR is biased high for values less than 0.0025 cm and at the NSA both retrieval methods have difficulties. For assessing the impact on radiative fluxes, the modeling study can provide some guidance as to the required accuracy needed for retrieving cloud optical thickness or liquid water path. For clouds of $\tau < 10$, the retrievals should have an accuracy of 15% to insure that upwelling and downwelling shortwave irradiances are within 5% of their true value. This 15% accuracy will impact estimates in shortwave atmospheric absorption by less than 2%. For the longwave, the 15% retrieval accuracy will limit discrepancies in downwelling and upwelling fluxes to a maximum of 3 Wm^{-2}.

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