Multiyear Statistics of 2D Shortwave Radiative Effects at Three ARM Sites

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ABSTRACT

This study examines the importance of horizontal photon transport effects, which are not considered in the 1D calculations of solar radiative heating used by most atmospheric dynamical models. In particular, the paper analyzes the difference between 2D and 1D radiative calculations for 2D vertical cross sections of clouds that were observed at three sites over 2–3-yr periods. The results show that 2D effects increase multiyear 24-h average total solar absorption by about 4.1, 1.2, and 0.3 W m^{-2} at tropical, midlatitude, and arctic sites, respectively. However, 2D effects are often much larger than these average values, especially for high sun and for convective clouds. The results also reveal a somewhat unexpected behavior, namely, that horizontal photon transport often enhances solar heating even for oblique sun. These findings underscore the need for fast radiation calculation methods that can allow atmospheric dynamical simulations to consider the inherently multidimensional nature of shortwave radiative processes.

1. Introduction

Mainly because of the prohibitive computational demands of three-dimensional (3D) radiative calculations, most atmospheric dynamical simulations use one-dimensional (1D) radiation models to calculate solar heating. However, several studies have indicated that the inherently multidimensional nature of cloud radiative processes can cause large errors in 1D calculations (e.g., O'Hirok and Gauthier 1998, 2005; Di Giuseppe and Tompkins 2003, 2005; Pincus et al. 2005; Hinkelman et al. 2007). Complementing the detailed case studies, two-dimensional (2D) radiative calculations using the 4-km-resolution clouds of a month-long global simulation also showed some significant departures from 1D theory (Cole et al. 2005). But even though such studies provided many valuable insights, it remains unclear how important the multidimensional nature of solar radiative processes is for atmospheric simulations.

The U.S. Department of Energy Atmospheric Radiation Measurement Program (ARM) Climate Research Facility (ACRF) offers excellent opportunities to address this issue by providing long-term detailed cloud observations at several sites. At these sites, ground-based vertically pointing instruments provide 2D vertical cross sections through the clouds drifting aloft. By comparing the results of 1D and 2D radiation simulations for clouds observed at tropical, midlatitude, and arctic locations, this paper provides some initial estimates on the typical magnitude of 2D radiative effects. Because the calculations do not include crosswind cloud variability, the presented 2D effects can be considered as conservative, lower-bound estimates for the full 3D effects (Pincus et al. 2005).

2. Dataset and methodology

This study uses the ACRF Microbase product as the main source of cloud information at all considered sites. At the Southern Great Plains (SGP) and Northern Slope of Alaska (NSA) sites we analyze three years of cloud data. At SGP we use 1999–2001, the only years for which (SGP-only) cloud classification data are also available. Because Microbase data are not yet available for the same years at NSA, there we use the 2005–07 period. Subsequent to our analysis at SGP and NSA, Microbase data also became available at the Tropical Western Pacific (TWP) site, where we analyze the two years (2003–04) for which Microbase data are available for the full year. The ACRF Microbase product combines millimeter-wavelength cloud radar, micropulse lidar, and microwave radiometer data to estimate cloud liquid and ice water content and particle size at 10-s temporal and 45-m vertical resolution. We convert these time-dependent vertical profiles into 2D spatial structures using each cloud

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TABLE 1. Multiyear 24-h average 2D effects on shortwave radiative fluxes, including nighttime and clear areas as well. The values indicate the difference between 2D and 1D fluxes simulated at full resolution. Uncertainties are standard errors based on the spread of results when the full dataset is divided into 25 subsets. These standard errors likely underestimate actual uncertainties because they assume that the 25 subsets are independent from each other.

Site	TOA reflected flux (W m^{-2})	Atmospheric absorption (W m^{-2})	Surface absorption (W m^{-2})
TWP	-4.10 ± 0.21	1.47 ± 0.03	2.63 ± 0.17
SGP	-1.21 ± 0.05	0.52 ± 0.02	0.68 ± 0.05
NSA	-0.28 ± 0.04	0.25 ± 0.01	0.02 ± 0.04

layer's mean wind speed from the ACRF Mergesonde product and the frozen turbulence assumption (e.g., Barker et al. 2004). Although the actual resolution of the obtained 2D fields varies with the wind speed (median values: 86 m at NSA, 141 m at SGP, and 74 m at TWP), for the radiative calculations we resample all data to a uniform 50-m resolution.

While the ACRF Microbase and Mergesonde products are certainly not perfect and are influenced by both instrument uncertainties and retrieval algorithm limitations (e.g., Miller et al. 2003; Turner et al. 2007), they arguably represent the current state-of-the-art for comprehensive, long-term, and detailed cloud structure datasets. This analysis considers all daytime data but excludes 10-km-wide swaths around data gaps and around data flagged with a low quality control flag. Because the continuous data stream is split into 50-km-long scenes for radiative calculations, the analysis reduces the impact of spurious 3D effects occurring at scene edges by also excluding all data within 5 km of the edges. Even so, the analysis includes $0.8–1.2 \times 10^6$ pixels, each 50 m in size, for each site.

We simulate both 1D and 2D radiative transfer through the observed clouds using a forward Monte Carlo model that was tested in the International Intercomparison of 3D Radiation Codes (I3RC) project (Cahalan et al. 2005) and through comparisons to broadband Santa Barbara discrete ordinate radiative transfer (DISORT) Atmospheric Radiative Transfer (SBDART; Ricchiazzi et al. 1998) calculations. The 2D simulations assume no variability in the crosswind direction and—to capture as much of the 3D radiative process as possible—they assume that the solar azimuth is parallel to the wind (e.g., Várnai and Marshak 2003; Pincus et al. 2005). To reduce the noise caused by random sampling, we perform two 2D simulations for each scene, with the sun on the downwind and upwind sides, respectively. (Both 2D and 1D simulations use the solar elevation of the time when the scene center was observed.)

Because the goal is to obtain robust statistics on the difference between 1D and 2D results—as opposed to obtaining accurate results for individual clouds—the simulations can use both relatively few photons (up to about 3000 for each 50-m column) and moderately complex radiative characteristics for the air surrounding clouds and for the underlying surface. Minor imperfections are not expected to greatly influence the obtained statistics because the 1D and 2D simulations use the same Monte Carlo radiative transfer model and setup.

The Monte Carlo model calculates gaseous absorption in the 0.2–5.0-μm range using the correlated-k method, with coefficients from SBDART (Ricchiazzi et al. 1998). The SBDART tropical atmospheric profile is used for the TWP site, and the SBDART midlatitude summer (winter) and subarctic summer (winter) profiles are used for the SGP and NSA sites during April–September (October–March), respectively. Cloud particle scattering and absorption parameters are from Mie calculations for liquid droplets, and from the publicly available database of B. Baum (available online at http://www.ssec.wisc.edu/~baum/Cirrus/Solar_Spectral_Models.html) for ice crystals. Rayleigh scattering is considered, but aerosol effects are not included.

Since Barker and Davies (1992) show that the angular pattern of surface reflection has only a modest influence on 3D radiative effects, all simulations use Lambertian surfaces with 5-nm-resolution spectral albedos. The sea surface albedos used at the TWP site are from the database described in Jin et al. (2004). The used albedo values depend on the local mean cloud optical thickness and solar elevation and assume a 5 m s^{-1} wind speed. Surface albedos for the SGP and NSA sites are specified by the SBDART model's "vegetation," "sand," and "snow" surface types. At SGP, the surface type is selected daily based on human observer reports about surface conditions (documented in ACRF's Surflog product), with the sand type used for days without snow or green vegetation. At NSA, where no such data is available, vegetation is used from June to September and snow for the rest of the year. These dates were selected based on snow cover data from the Rutgers University Global Snow Laboratory (available online at http://climate.rutgers.edu/snowcover/).

3. Results

We examine the influence of 2D radiative effects by comparing the results of 1D and 2D radiative simulations. Table 1 presents the influence of 2D effects on multiyear 24-h average solar radiative fluxes (including cloud-free periods and nighttime). The table shows that 2D effects are stronger at lower latitudes because of factors such as

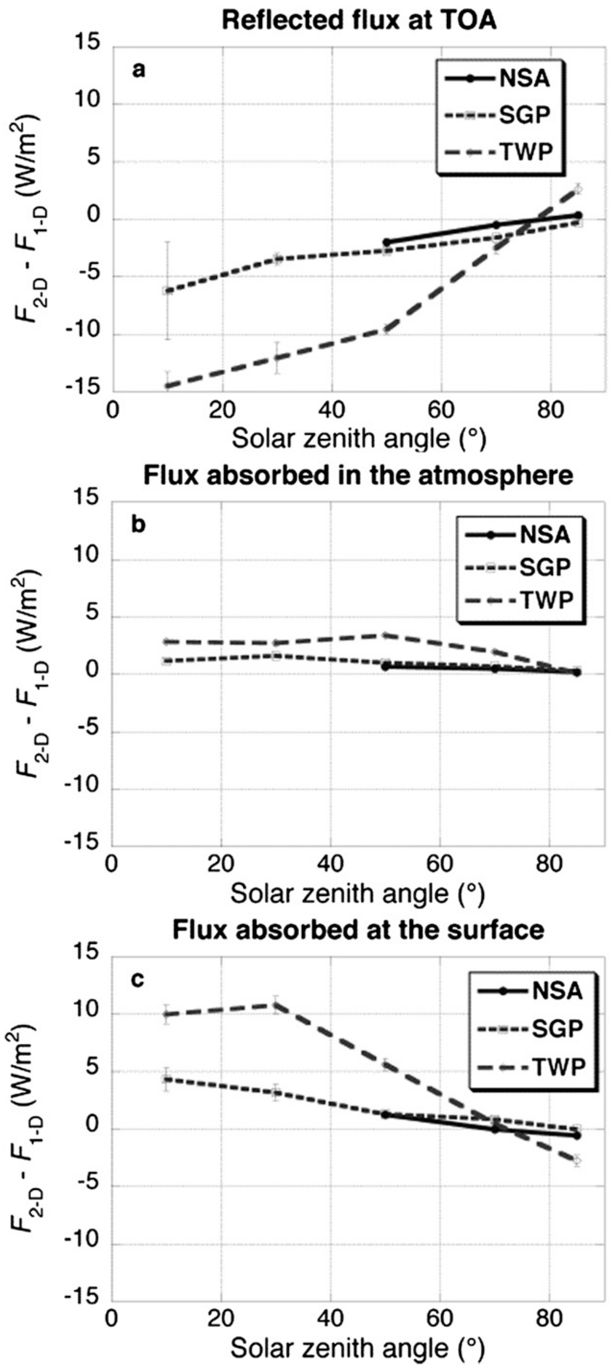

FIG. 1. Average 2D effects on radiative fluxes, as a function of solar zenith angle. (a) Reflected flux; (b) flux absorbed in the atmosphere; (c) flux absorbed at the surface. Error bars in this and subsequent figures show standard errors based on the spread of results when the full dataset is divided into 25 subsets. These standard errors likely underestimate actual uncertainties because they assume that the 25 subsets are independent of each other.

- more intense solar illumination,
- stronger convection creating more heterogeneous clouds, and
- more effective channeling process for high sun, guiding photons from opaque to thin regions where they can reach the surface more easily (e.g., Davis and Marshak 2001).

We note that the 2D effects in Table 1 may be considered as conservative, lower-bound estimates for the full 3D radiative effects, since earlier case studies found 3D effects to be about 30% stronger than 2D effects (e.g., Pincus et al. 2005). The difference arises because 2D calculations do not consider the crosswind cloud variability (perpendicular to the solar azimuth) that further reduces cloud reflection and enhances surface absorption through additional channeling.

We also note that in coarse-resolution cloud simulations, the errors of 1D albedo and surface absorption calculations are further increased by the plane-parallel bias caused by unresolved small-scale cloud variability (e.g., Cahalan et al. 1994). For example, if radiative transfer is calculated using 1D methods for a coarse representation of clouds, both the 1D approximation and the plane-parallel bias make models underestimate the surface absorption that might be observed in nature.

We also mention that for reflective surfaces, the influence of 2D effects is somewhat larger on downwelling fluxes at the surface than on surface absorption. This is because the surface reflects (and does not absorb) some of the downwelling radiation that reaches the surface only because 2D effects enhance atmospheric transmission.

Finally, one can also calculate 2D effects on cloud radiative forcing defined as the total radiative impact of clouds divided by the area covered by clouds. This is similar to calculating the average 2D effects for cloud-covered pixels only, but with the consideration that cloud-induced 2D effects can influence radiation at nearby clear areas as well. A simple division of the overall average 2D effects in Table 1 by the Microbase cloud coverage (0.72 at TWP, 0.47 at SGP, and 0.55 at NSA) shows that, on average, 2D effects caused by clouds in a 1 m^2 column reduce reflection and enhance total (atmospheric plus surface) absorption by about 5.7, 2.5, and 0.5 W at the three sites, respectively.

Numerous detailed case studies have indicated that solar elevation greatly influences 2D and 3D radiative effects (e.g., O'Hirok and Gauthier 1998, 2005; Pincus et al. 2005). Figure 1 shows how multiyear average 2D effects depend on solar zenith angle. The fact that 2D effects are largest for high sun means that they are strongest near noon and during summer. The figure also shows that for relatively less oblique sun, 2D effects are

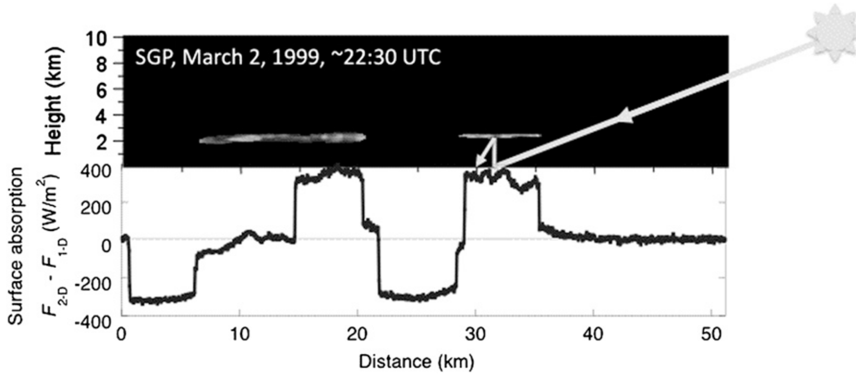

FIG. 2. Illustration of the photon trapping process that enhances surface absorption for oblique sun. (top) Illustration using an observed field of volume extinction coefficients. (bottom) Influence of 2D effects on simulated surface absorption values. The 2D effects enhance the scene average surface absorption by 9.6 W m^{-2}. The solar zenith angle is 69°.

nearly as strong at NSA as at SGP, which implies that Alaska clouds in the summer and near noon are almost as heterogeneous as Oklahoma clouds in the spring or fall, or in the morning or afternoon.

The figure also shows that 2D effects increase atmospheric absorption even for high sun. This might be explained by the trapping of sunlight in thicker cloud portions where it is more likely to get absorbed (e.g., O'Hirok and Gauthier 1998; Várnai and Davies 1999).

A somewhat unexpected feature of Fig. 1 is a behavior opposite to the dominant 2D effect discussed in most earlier case studies (e.g., McKee and Cox 1974) where, for low sun, cloud sides intercepting extra sunlight enhanced reflectivity and reduced transmission to the surface. Figure 1 shows that for solar zenith angles less than about 70°, 2D effects slightly increase, rather than decrease, average surface absorption. The slight increase arises because 2D effects often enhance surface absorption even for oblique sun. As Fig. 2 illustrates, this can occur when the incoming direct sunlight slips obliquely under an extensive cloud and, after reflection from the surface, gets intercepted and reflected back down again by the cloud above (O'Hirok and Gauthier 1998).

Naturally, 2D effects also depend on cloud type. We examine this issue using the ACRF cloud classification product (Cldclass) available at the SGP site (Wang and Sassen 2001). Figure 3 shows that 2D effects tend to be strongest for the more heterogeneous, convective cloud types. We note that 2D effects on average surface absorption near deep convective clouds are relatively modest in absolute terms because these highly reflective clouds greatly reduce surface absorption in both 1D and 2D simulations.

While average values can be informative, detailed histograms can also help in evaluating the importance of 2D effects. Figure 4 shows that local 2D effects are often much larger than the average values discussed above. For example at TWP, 2D effects change the total cloud absorption of 1-km columns by more than 20% in about a third of cases, and they change the total surface absorption of 10-km areas by more than 50 W m^{-2} in about a quarter of cases.

4. Summary

This study presents multiyear statistics on the influence of 2D shortwave radiative effects that are not considered in the 1D radiation calculations used by most atmospheric dynamical models. The influence of 2D effects on solar radiative energy budget calculations is presented for tropical, midlatitude, and arctic sites of the U.S. Department of Energy ARM Climate Research Facility. The results show that 2D effects

- Increase 24-h average total—surface plus atmospheric—solar absorption by about 4.1 W m^{-2} at the TWP site in Papua New Guinea, by 1.2 W m^{-2} at the SGP site in Oklahoma, and by 0.3 W m^{-2} at the NSA site in Alaska. The average 2D effect caused by clouds in a 1 m^2 column increases total absorption by about 5.7, 2.5, and 0.5 W at the three sites, respectively.
- Are often much larger than these average values, especially for high sun and for convective clouds. Such variations in 2D effects can change the spatial and temporal distribution of solar absorption.
- Often increase surface heating even for oblique sun. This can occur when the incoming direct sunlight slips obliquely under an extensive cloud, and much of the light reflected from the surface is then intercepted and reflected back down again by the cloud above.

The presented 2D effects can be considered as conservative, lower-bound estimates for the influence of horizontal photon transport not included in 1D radiation

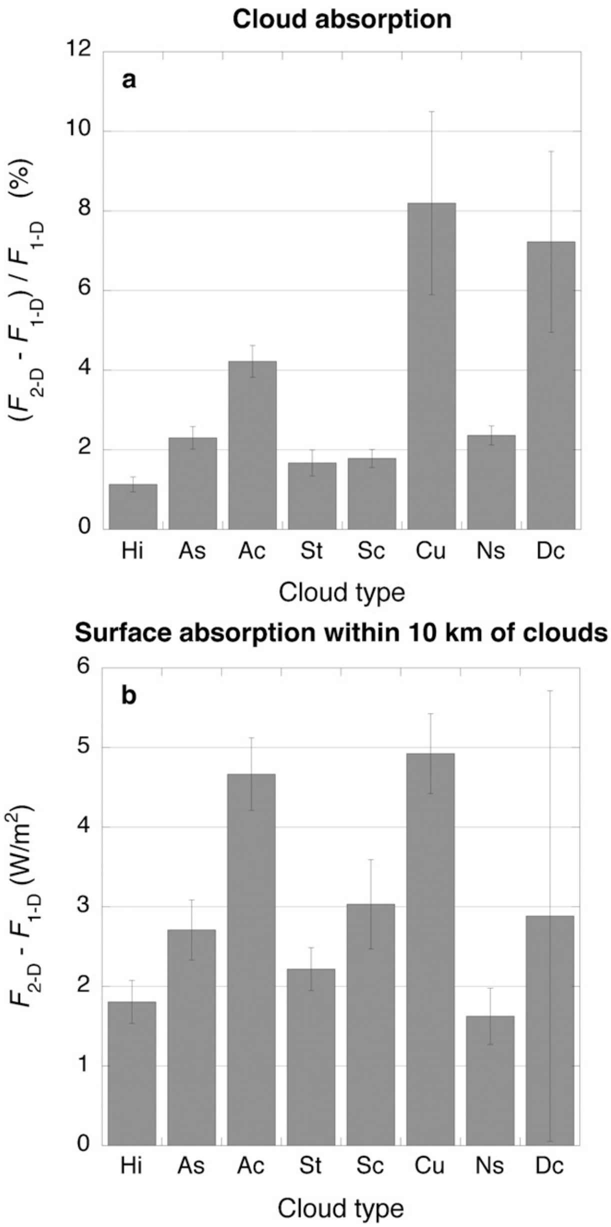

FIG. 3. Average 2D radiative effects for various cloud types at the SGP site. (a) Relative change in cloud absorption occurring inside clouds of each type. (b) Absolute change in daytime average surface absorption within 10 km of clouds of each type (W m^{-2}). ''Hi'' refers to high clouds; ''Dc'' refers to deep convective clouds.

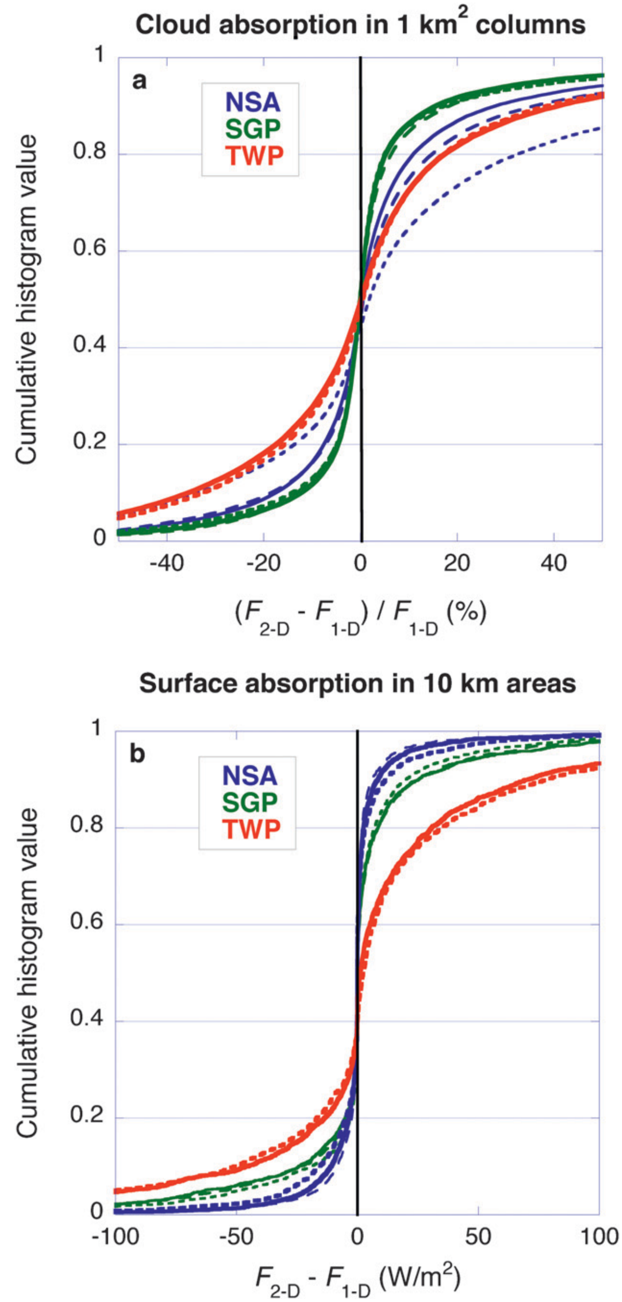

FIG. 4. Cumulative histogram of 2D effects on radiative fluxes. Each curve is for a different year. (a) Relative change in the total cloud absorption of 1-km columns. (b) Absolute change in the daytime average surface absorption of all 10-km areas, including clear regions.

calculations because 2D calculations do not consider crosswind cloud variability. In earlier case studies the full 3D effects exceeded 2D effects by about 30% (e.g., Pincus et al. 2005). We note that the upcoming installation of scanning radars at ACRF sites will offer new opportunities for fully 3D studies.

The results imply that considering horizontal photon transport can greatly improve both the interpretation of shortwave radiative flux measurements and the solar heating calculations in atmospheric dynamical models. This underscores the need for fast radiation calculation methods that can allow dynamical models to consider the inherently three-dimensional nature of shortwave radiative processes.

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