Remote sensing of surface solar irradiance with corrections for 3-D cloud effects

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Abstract

Surface solar irradiance (I_{SFC}) can be inferred from satellite-observed radiance with retrieval algorithms based on the independent pixel approximation (IPA). As the spatial resolution of satellite sensors increases, the effects from spatially inhomogeneous cloud fields become more important. Clouds affect the distribution of radiation in a region larger than the resolution of an individual pixel and IPA is no longer justified. The objective of this study is to identify effects of clouds and find corrections for IPA to compensate for these effects. For this purpose, cloud fields are generated with the mesoscale model MM5 at high resolution. A shallow and a convective cloud field are then used as input for a 3-D Monte Carlo radiation model that computes the radiance distribution at the top of the atmosphere and at the surface. Surface irradiance is computed from the upwelling radiance with a method that simulates IPA retrieval. The retrieved irradiance is compared against the one computed with the 3-D model. Two effects of clouds are related to the solar and viewing geometry, noted as a shift of the apparent position of clouds and their shadows. Another cloud effect is the diffusion of radiation: Scattering removes part of the radiation from an atmospheric column and distributes it to neighboring columns. Corrections for these effects are suggested, which can improve the IPA-based retrieval of I_{SFC}. All corrections depend upon the cloud altitude, which may be difficult to obtain in operational applications. A sensitivity analysis suggests that a coarse estimate of the cloud top altitude is sufficient for the corrections. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Surface radiation budget; Clouds; Independent pixel approximation; Solar radiation; Monte Carlo modelling

1. Introduction

An accurate knowledge of the distribution of solar radiation at the surface is essential for understanding climate processes at the Earth–atmosphere interface. The net radiation flux at the surface determines, to a large extent, such climate parameters as sensible and latent heat fluxes. It is also a key component in describing the spatial variability of biological processes and in validating climate models. Over the past few decades, the scientific community has developed computation methods for estimating both downward and net surface solar irradiance from satellite observations (e.g., Bishop & Rossow, 1991; Darnell, Staylor, Gupta, & Denn, 1988; Dedieu, Deschamps, & Kerr, 1987; Gautier, Diak, & Masse, 1980; Gautier & Lansfeld, 1997; Li & Leighton, 1993; Masuda, Leighton, & Li, 1995; Möser & Raschke, 1984; Pinker & Ewing, 1985; Pinker & Laszlo, 1992; Tarpley, 1979; Whitlock et al., 1995). Reviews of the various techniques are presented in Pinker, Frouin, and Li (1995) and Schmetz (1989). Global data sets of monthly mean surface solar flux have been derived from the International Satellite Cloud Climatology Project (ISCCP, Bishop & Rossow, 1991) and from the Earth Radiation Budget Experiment (ERBE, Li & Leighton, 1993). The accuracy of these estimates (including bias errors) for spatial scales typical of General Circulation Model (GCM) grids is better than 20 W m\(^{-2}\) (Pinker et al., 1995). In the tropics, however, differences between these data sets range from 10 to 30 W m\(^{-2}\), with the largest discrepancies occurring in areas of significant convective activity (Saeger & Blumenthal, 1994).

The difficulty in assessing the accuracy of these techniques is that comparisons of satellite estimates with in situ data require spatial averaging for the retrievals and temporal averaging for ground measurements. As the resolution increases, the accuracy is reduced accordingly. Pinker and Laszlo (1991) noted that differences of up to 15 W m\(^{-2}\).
could occur in daily surface irradiance averaged over 2 months when changing the resolution from 8 to 50 km; the sign and magnitude of the difference vary with time and location. In an overview of nearly 20 retrieval studies, Schmetz (1989) showed root mean square (RMS) differences as percentages of the mean value for monthly, daily, and hourly retrieved solar irradiance measurements. The median RMS difference is 5% for monthly means, 10% for daily and nearly double that for hourly measurements. Both Gautier and Landsfeld (1997) and Gu and Smith (1997) demonstrate that algorithm accuracy is directly related to cloud amount with the poorest retrievals associated with overcast skies. These studies suggest that a significant part of the error in the retrievals may be associated with the way in which cloud fields are represented in the algorithms.

The common method to retrieve surface solar irradiance (I_{SFC}) from satellite is based on the independent pixel approximation (IPA). Each pixel in a satellite image is treated independently, thereby neglecting differences in horizontal flux between different columns caused by the 3-D variability of atmospheric constituents. The approximation is justified as long as averages over suitably large areas are considered (Barker, Stephens, & Fu, 1999; Cahalan, Ridgway, Wiscombe, Gollmer, & Harshvardhan, 1994; Zuidema & Evans, 1998). With increasing resolution, however, the performance of the retrieval method is reduced considerably because of 3-D radiative effects caused by clouds, water vapor, and aerosols. Clouds are by far the strongest modulator of the 3-D radiation field due to their spatial and temporal variability in conjunction with their strong interaction with solar radiation. The objective of the present study is to understand the impact of a 3-D cloud distribution on the remote sensing of and to develop efficient corrections for the IPA.

For this purpose, we start from arbitrary 3-D cloud fields simulated by a mesoscale atmospheric model with high resolution. The spatial distribution of top of the atmosphere (TOA) narrowband radiance (R_{TOA}) and surface (SFC) broadband irradiance is computed for these fields with a 3-D radiative transfer model (SB3D, O’Hirok & Gautier, 1998). The radiation fields obtained in this way are equivalent to observed ones, and we will refer to them as “observed.” The independent pixel satellite retrieval of I_{SFC} is then simulated by taking R_{TOA} for each pixel and relating it to SFC irradiance with help of a precalculated look-up table. The retrieved I_{SFC} is compared against the true distribution of I_{SFC} that has been computed by SB3D. By studying the difference between retrieved and observed I_{SFC}, we can identify the 3-D effects of clouds and explore possible corrections.

The present study is organized as follows: Section 2 describes the mesoscale model used to generate the cloud fields and the 3-D radiation model. Section 3 presents results from the radiation model and analyzes the effects of clouds. The corrections for solar and viewing geometry and for nonlocal diffusion are described in Section 4. The skills of the corrections are assessed in Section 5 together with an evaluation of the sensitivity of the corrections to the cloud height. Finally, a discussion of the results in Section 6 concludes this study.

2. Modeling the radiation fields

2.1. Generation of cloud fields

The 3-D distribution of clouds is generated with the Penn State/National Center for Atmospheric Research mesoscale model MM5 (Dudhia, 1993; Grell, Dudhia, & Stauffer, 1995). In a previous study, the model has shown its ability to simulate the development of cloud and storm systems in the TOGA-COARE region (Su, Chen, & Bretherton, 1999). However, the finest resolution of that study was 15 km and thus considerably larger than the resolution required to investigate 3-D cloud effects. Several recent studies have demonstrated the potential of simulations with MM5 for horizontal resolutions between 1 and 2 km (Davis, Warner, Astling, & Bowers, 1999; Grell et al., 2000; Reisner, Rasmussen, & Bruintjes, 1998). For this study, we choose a resolution of 1 km in a domain covering about 100 × 200 km. This innermost domain is embedded in three further domains with increasingly coarser resolution (see Table 1).

The model was initialized at 00:00 h UTC on 16 January 1993 for the TOGA-COARE region over the Western Pacific, and integrated for 58 h. The integration of the innermost domain was started after 42 h forecast time to allow for the spin-up of cloud water in the model. Local noon is around 23:00 h UTC and, hence, the 42–58-h forecast covers almost an entire day, starting at local time 07:00 h and continuing to 01:00 h the next morning. Time and location for the simulation were chosen to allow for a comparison against aircraft measurements from the TOGA-COARE experiment. In the vertical, the 23 σ levels extend from the surface to an altitude of about 15 km. The thickness of the layers increases from 70 m at the bottom to 1.8 km at the top of the model. The cumulus parameterization of Grell (1993) and Grell et al. (1995) is used in the 27-km domain. The Grell scheme is a single-cloud scheme that accounts for up- and downdraft fluxes within a grid cell. All interior domains do not parameterize cumulus convection but resolve the vertical motions and formation of clouds explicitly. The microphysics of ice and water is treated separately with the simple ice scheme of Dudhia

<table>
<thead>
<tr>
<th>Domain</th>
<th>Grid size</th>
<th>Resolution (km)</th>
<th>Timestep (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81 × 81</td>
<td>27</td>
<td>80.0</td>
</tr>
<tr>
<td>2</td>
<td>115 × 121</td>
<td>9</td>
<td>26.67</td>
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<tr>
<td>3</td>
<td>115 × 175</td>
<td>3</td>
<td>8.89</td>
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<tr>
<td>4</td>
<td>100 × 199</td>
<td>1</td>
<td>2.96</td>
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(Grell et al., 1995) in the 27- and 9-km domains, and with the Goddard scheme (Tao & Simpson, 1993) for the two innermost domains. The boundary layer parameterization is based on that of the National Center for Environmental Prediction (NCEP) medium range forecast model (MRF, Hong & Pan, 1996). Initial and boundary conditions for the coarsest domain were obtained from the European Centre for Medium Range Weather Forecasts (ECMWF) operational analysis.

How well does our model configuration simulate 3-D cloud fields? Fig. 1 shows a GMS image of visible albedo (Flament & Bernstein, 1993) and the modeled optical thickness for the same instant. The satellite image shows broken clouds in the region under consideration. The texture is more pronounced in the lower part of the image pointing to a large variability in the vertical extension of clouds, most likely an indication of convective clouds. The upper part of the image appears smoother, and the clouds are probably cirrus, which agrees with their low brightness temperature (not shown here). The modeled cloud field has a patchy structure and resembles more the lower part of the satellite image. A possible explanation for the discrepancy between simulated and observed cloud fields is an underestimation of the ice content with the chosen parameterizations of MM5. Closer inspection of some selected columns from the model reveals that the ice content is unusually low, while the water content seems to be more realistic. It is not clear yet what causes the shortcomings of MM5; possible reasons are a too weak transport of humidity to higher levels or a too strong depletion of ice by the generation of precipitation or by accretion.

Fig. 2 compares the observed cloud cover from three consecutive days against the modeled cloud cover. We estimate the cloud cover from the GMS image in the 100x200-km region that coincides with the 1-km domain. The satellite-observed albedo is not corrected for solar geometry and varies greatly between images taken on different times during the day. This variability is accounted for by normalizing the satellite data with their maximum value, assuming the brightest clouds have an albedo of 1 at every hour of the day. Note that the maximum for this normalization is taken for in an area measuring 500x500 km² and not only in the small region covered by the 1-km model domain. The separating albedo threshold between cloudy and cloud-free regions is chosen as 0.3, and the cloud cover is computed as the ratio of the number of cloudy pixels to all pixels. The threshold 0.3 seems to be high, but a visual inspection of all GMS images from that day revealed that the chosen threshold most effectively separates cloudy and cloud-free regions. The cloud cover of MM5 is defined as the fraction of all grid points for which the vertically integrated optical thickness exceeds 1. For this comparison, the model data has been averaged over 5 km to match the satellite resolution.

The cloud cover derived from GMS seems to be too low at late afternoon hours, most likely an artefact of the high solar zenith angle. On 18 January (45–55 h forecast time), the observed cloud cover is substantially larger than the modeled and the question arises if MM5 seriously underestimates the cloud cover. This possibility cannot be excluded, but we also found that the cloud cover was higher on 18 January than on both the previous and the following day (see Fig. 2). The modeled cloud cover would agree far better with the observations from the day before or after. Furthermore, if we extend the region for which the cloud cover is evaluated by 100 km on each side, the observed cloud cover drops by about 20%, yielding a better agreement of the simulated cloudiness. This further supports the idea that the satellite derived cloud cover may be on the high side on 18 January for the limited region of Domain 4. Overall, we consider the MM5-simulated cloud cover as realistic despite possible deficiencies in the thickness of ice clouds. It should be kept in mind that for this study, we do not attempt to model the true cloud field in all its details, the goal is merely to obtain a realistic 3-D distribution of clouds.
Fig. 3. Liquid water distribution of MM5 compared to several probes aboard the NCAR Electra. The relative frequency is computed with respect to all LWC values exceeding 0.001 g m$^{-3}$.

Fig. 3 compares the histogram of liquid water content ($W$) of MM5 against four different probes aboard the NCAR Electra operating in the area of Domain 4 on 18 January 1993. The 1-Hz aircraft data$^1$ are averaged over 10 s to yield approximately 1-km averages, given an aircraft velocity of about 100 m s$^{-1}$. Three consecutive hours, between 00:30 and 03:30 h UTC, were chosen for comparison. During the selected time period, the Electra was flying at altitudes below 500 m and, therefore, only the lowest four model levels (0–540 m) were taken from MM5. The histograms of both Electra and MM5 data were normalized with their respective number of in-cloud data. It follows from Fig. 3 that the simulated low-level clouds have, on the average, a higher water content than the observed. It is also evident from the figure that the spread between the different instruments is large despite being mounted on the same aircraft. Given this instrumental disagreement — and the fact that an aircraft measures a single point, whereas the model may have clouds in several layers — the modeled $W$ does not appear to be unrealistic even though it may be on the high side. Unfortunately, the two other airplanes (DC8 and 130) flying simultaneously aloft did not conduct liquid water measurements, and the distribution of $W$ remains unknown at altitudes above the boundary layer.

2.2. Monte Carlo radiation model (SB3D)

Model computations of spectral downwelling irradiance and top of the atmosphere radiance are based on the 3-D Monte Carlo radiative transfer model of O’Hirok and Gautier (1998). Simply, a weighted photon enters the model domain, travels a specified distance depending on the extinction coefficient of the atmosphere constituent (cloud, aerosol, and gas), is deweighted by the single scattering albedo of the constituent, and is scattered into a direction defined by the phase function. This process is repeated until either the photon exits the model domain or the weight of the photon is reduced to below a predefined threshold. The model domain consists of a 3-D structure of cells each representing an atmospheric volume that is completely homogeneous. The photon can traverse vertically and horizontally for the 3-D computations, but is confined to a single atmospheric column for IPA computations.

The optical properties for gaseous transmission are based on an 8- and 16-term $k$ distribution method derived from HITRAN (Yang, Richiazzi, & Gautier, 2000). Rayleigh scattering is included, but no aerosols are used in these computations. A standard tropical atmosphere is employed and the water vapor is saturated within cloudy cells. The surface is a Lambertian reflector and has an ocean albedo of 0.05. Cloud droplet microphysics is derived from the Mie theory (Wiscombe, 1980) for the various effective radii based on a drop size distribution specified by a gamma distribution. Radiance computations were conducted at a wavelength of 0.60 µm to simulate observations by a sensor spectrally located in the visible region. The surface irradiance represents the entire solar spectrum from 0.25 to 5.0 µm. Computations were conducted at a spectral resolution of 5 nm below 1.0 µm and 10 nm from 1.0 to 5.0 µm.

In its most simplistic form, estimating radiance via the Monte Carlo method is achieved by accumulating photon statistics within radiance bins that are centered on the viewing angle of a sensor. This method must assume a constant radiance across the aperture of the bin. Such an approach is computationally very expensive for all but the largest angular bins since only a limited number of photons exiting the top of the atmosphere will fall within a given bin. The approach taken here is that every scattering event within the model domain contributes a weighted photon to each viewing angle, thus greatly improving the radiance statistics and reducing the number of photons required for the convergence of the radiance field. For the radiance computations, 10,000 photons were used per pixel or 49 million photons per cloud field per solar zenith angle. The mean error for individual pixels is ≈1%. In the broadband, over 100 million photons were used for each run representing a mean pixel level error of less than 1%.

For the 3-D radiation modeling, we select two subdomains with 70 $\times$ 70 grid points from Domain 4 of the MM5 simulation: one scene with mainly stratiform or shallow cumuliform clouds and another scene with deep convection and towering clouds (Fig. 4). Liquid water clouds are largely predominant in the shallow case, whereas the convective case also has some mixed-phase and pure ice clouds (anvil) at higher altitudes. The nadir looking cloud fraction of the selected scenes are 0.40 and 0.49 for the convective and shallow case, respectively. The effective radius ($r_e$) for liquid water clouds is calculated from the

$^1$ TOGA-COARE aircraft data were extracted from the TOGA-COARE Workshop Integrated Data Set (TCWIDS), available from [http://www.atd.ucar.edu/rdp/tcwids/tcwids.intro.html].
water content by assuming a $\Gamma$ distribution for the droplet distribution (Eq. (1)),

$$n(r) = \frac{N_d}{\Gamma(p+1)r_p^{p+1}r_p\exp\left(-\frac{r}{r_m}\right)}$$  \hspace{1cm} (1)

with a total droplet concentration $N_d = 100 \text{ cm}^{-3}$, a shape parameter $p = 7$, and a normalization radius $r_m$ that can be computed from the water content. By using Eq. (2),

$$W = \int \frac{4\pi}{3}p_nr^3n(r)dr,$$

where $\rho_s$ is the liquid water density and the definition for the effective radius (Eq. (3)),

$$r_e = \frac{\int r^2n(r)dr}{\int r^2n(r)dr},$$

the effective radius for water clouds then becomes (Eq. (4)) (Wyser, 1998)

$$r_e = \left(\frac{3W}{4\pi\rho_srN_d}\right)^{1/3},$$

where $k = (p+1)(p+2)(p+3)^{-2}$. The effective radius in ice clouds is taken as a constant 106 $\mu$m and assumes spherical ice particles. In the setup for this study, each grid cell contains either liquid water or ice, but not mixed-phase clouds. Whether a cell is filled with water or ice clouds depends upon the respective contribution of liquid water and ice to the optical thickness in that cell. Optical thickness is given by Eq. (5)

$$r_x = \frac{3Q(\lambda)W_r\Delta z}{4\rho_sr_{e,z}},$$

where the index $x$ distinguishes liquid water (subscript liq) from ice clouds, $Q(\lambda)$ is the scattering efficiency and is set to 2 for solar wavelengths, and $\Delta z$ is the geometric thickness of the cell. All clouds are considered to consist of ice where $r_{\text{ice}} > r_{\text{liq}}$. The total optical thickness in a cell is given by $\tau = \tau_{\text{liq}} + \tau_{\text{ice}}$. Cloud top height is defined as the altitude where the integration of $\tau$ from the top of the atmosphere to the level under consideration exceeds unity. In a sensitivity experiment, all ice clouds in the convective case are replaced with water clouds of the same optical thickness. The smaller $r_e$ of water clouds makes them more reflective; the albedo in a few pixels is up to six times higher, but averaged over the whole scene, the albedo increases by a mere 1%. This low sensitivity to ice clouds likely results from a too low ice content in MM5.

The 3-D distribution of clouds is completely specified by $\tau$ and $r_e$. These fields are embedded in a tropical atmosphere that extends up to a 100-km altitude (McCleathey, Fenn, Selby, Volz, & Garing, 1972) and prescribes the temperature and humidity profiles. While the temperature profile is the same for all columns, the humidity profile is adjusted to reach saturation inside cloudy cells.

2.3. Independent pixel look-up table

To simulate IPA-based retrievals, the independent pixel mode of SB3D is employed to find a relationship between $R_{\text{TOA}}$ and $I_{\text{SFC}}$. In principle, such a relationship could be obtained much faster with a 1-D radiative transfer model such as a discrete ordinate radiative transfer model (e.g., SBDART, Ricchiazzi, Yang, Gautier, & Sowle, 1998). However, the computationally more expensive Monte Carlo computation in IPA mode is chosen to ensure identical treatment of all radiatively active ingredients and to avoid differences due to numerical processing and constraints. Of special concern is the phase function of cloud droplets that is resolved in discrete angular bins in SB3D but represented by a finite number of Legendre polynomials in SBDART. The two representations for the phase function differ in the forward and backward peak resulting in appreciable differences for exact forward or backward scattering.

The same cloud fields as for the full 3-D calculation are used for building the IPA look-up tables. This procedures ensures a wide variation of cloud thickness and cloud top height. Fig. 5 shows an example of the relationship between SFC irradiance vs. TOA irradiance computed in IPA mode. Solar zenith angle is $\theta_{\text{zen}} = 41^\circ$, viewing zenith angle $\theta_{\text{view}} = 30^\circ$, and relative azimuth angle $\phi_{\text{rel}} = 90^\circ$. Data sets like this have been used to construct look-up tables that simulate the IPA retrieval for all $\theta_{\text{zen}}, \theta_{\text{view}}$, and $\phi_{\text{rel}}$. 

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**Fig. 4.** 3-D view of the selected cloud fields, shown as isosurfaces of optical thickness 1. The brightness of the image does not reflect the optical properties of the clouds.

**Fig. 5.** SFC irradiance vs. TOA irradiance computed in IPA mode. Solar zenith angle is $\theta_{\text{zen}} = 41^\circ$, viewing zenith angle $\theta_{\text{view}} = 30^\circ$, and relative azimuth angle $\phi_{\text{rel}} = 90^\circ$. Data sets like this have been used to construct look-up tables that simulate the IPA retrieval for all $\theta_{\text{zen}}, \theta_{\text{view}}$, and $\phi_{\text{rel}}$. 

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RTOA and ISFC for a given solar and viewing geometry. Results for the shallow and the convective cloud field are nearly identical since the reflected radiance in the plane-parallel assumption depends mostly on the total optical thickness of the cloud water in a column but much less on its vertical distribution. The scatter in the data is partly due to the variability of the 3-D cloud water distribution and partly due to statistical noise from the Monte Carlo process. The SFC irradiance data are distributed into 30 bins of equal width. The median value of RTOA and ISFC within each bin are taken as the bin’s representative values, and these 30 sets of (RTOA, ISFC) pairs form the IPA look-up table. Fig. 5 illustrates how well the look-up table fits the computed data. The described procedure is repeated for each solar and viewing angle.

3. Results without corrections

Fig. 6 shows RTOA and the retrieved and observed ISFC for the convective cloud field for two different solar and viewing angles. In the left column of the figure (nadir looking satellite case with overhead sun), the retrieved distribution of ISFC highly resembles the observed one. However, a closer look at the observed ISFC reveals two features that are not captured by the retrieval. The first notable difference is the enhancement of clear-sky irradiance close to cloud edges. This bright rim around clouds is a manifestation of a 3-D cloud effect. Solar radiation is either reflected on cloud sides or is dispersed from the interior of the cloud, resulting in an enhancement of the SFC irradiance above its clear-sky value. The second feature is the smoothness of the observed ISFC field in cloud covered areas compared to the retrieved ISFC that shows more variability. Clouds diffuse the incoming solar radiation and, if the resolution in 3-D is fine enough, some of the radiation may leak to neighboring cells. This averages the radiation over several grid cells, which results in a smoother distribution. Radiative smoothing ultimately leads to the scalebreak at some 100 m found in Landsat images (Davis, Marshak, Cahalan, & Wiscombe, 1997). Here, we find indications of radiative smoothing already with a 1-km resolution.

A different category of 3-D cloud effects becomes apparent for oblique solar and/or viewing angles as illustrated in the right column of Fig. 6. Solar illumination is from the bottom of the figure with a 41° solar zenith angle. The distribution of RTOA shows a different structure than in the overhead sun case, the most noticeable difference is the dark area in the center of the image. This is not a cloud-free region as could be anticipated from the low reflectivity but merely the shadow of a cloud tower on a lower cloud. However, the independent pixel retrieval is based on the principle that a bright pixel indicates clouds, and the darker a pixel the more radiation is transmitted and reaches the surface. Thus, the dark region of RTOA corresponds to a region with high ISFC in an IPA retrieval, which is obviously wrong in this case. On the other hand, the illuminated side of the cloud appears very bright, which is interpreted as a thick cloud by the retrieval method and yields a too low ISFC. It is obvious from this example that a simple relationship between RTOA and ISFC based on a pixel-by-pixel approach is not valid any more if details of the cloud structure are resolved in the image.

Another problem that occurs in conjunction with oblique solar angles is the lateral shift of the cloud shadow. Comparing the observed ISFC in Fig. 6 for the two different sun angles, the cloud shadow is shifted upward in the case with higher solar zenith angle (θsun). This shift is caused by the oblique shadow projection of the cloud, and the higher the cloud, the more pronounced the shift. Such a displacement in the footprint of a cloud is not present in the RTOA image and, hence, the retrieval process is unable to capture sideways illumination beneath clouds. A pixel that appears cloudy from the satellite may, in fact, be illuminated by the sun and IPA leads to an erroneous retrieval.

Fig. 6. SB3D-simulated TOA radiance and SFC irradiance in the convective case; the computed ISFC is entitled ‘observed.’ Shown also are the results of the IPA-based retrieval of ISFC from RTOA. The left column is for overhead sun and nadir looking satellite while the right column is for illumination from the bottom (θsun = 41°) and satellite viewing from the right (θview = 30°, φrel = 90°).
An additional — although less obvious — problem is the mapping of the cloud as seen from a satellite. For nonnadir viewing angles, the apparent position of a cloud is shifted sideways depending on viewing angle and cloud altitude. This effect is not important at coarse resolution, but it is noted in the high-resolution images here. The cloud pattern in the $R_{\text{TOA}}$ image is shifted slightly to the left in the right column of Fig. 6. The assumed satellite position is on the right side of the image with a 30° zenith angle. This displacement of the radiance field is inherited by the retrieved field, which enhances the mismatch between retrieved and observed $I_{\text{SFC}}$.

The performance of the retrieval process is assessed with a scatterplot (Fig. 7) that compares observed and retrieved $I_{\text{SFC}}$ pixelwise. For nadir-looking satellite and overhead sun, the correlation coefficient is high ($r = 0.93$) as expected. However, the scatterplot also illustrates that the retrieval is not perfect. The maximum value for retrieved $I_{\text{SFC}}$ is the clear sky value (about 1000 W m$^{-2}$ in the example), but the data points organized in a horizontal “line” show that the observed clear-sky irradiance can exceed this theoretical value. On the other hand, there is a tendency for the retrieval to overestimate $I_{\text{SFC}}$ in cloudy pixels.

The correlation between retrieved and observed $I_{\text{SFC}}$ degrades rapidly with increasing solar and/or viewing zenith angle. The projection of a cloud and its shadow become spatially separated. The pixelwise comparison of retrieved and observed $I_{\text{SFC}}$ results in the chaotic scatter seen in the left image of Fig. 7. The correlation drops to $r = 0.43$ for moderate zenith angles ($\theta_{\text{sol}} = 41^\circ$ and $\theta_{\text{view}} = 30^\circ$) and worsens substantially for higher angles. The shortcomings of the retrieval when it comes to the enhancement of clear-sky radiation around clouds are noted even for general solar and viewing geometry. It is obvious from Fig. 7 that the IPA based retrieval may be sufficient for nadir-looking satellite and overhead sun, but it clearly cannot be applied in general.

All the described problems with the retrieval of $I_{\text{SFC}}$ in the presence of clouds are related to the spatial resolution. The 3-D cloud effects are not important at coarse resolution but become apparent for small pixel size. The displacement of a cloud and its shadow due to oblique solar and/or viewing angle is a purely geometrical problem only related to the position of the cloud in space. On the other hand, diffusion and the enhancement of radiation at cloud edges are optical effects caused by the 3-D interaction of radiation with clouds. Possible corrections for the various cloud effects will be presented in the next section.

4. Corrections for cloud effects

4.1. Viewing angle correction

For oblique viewing angles, the apparent position of a cloud as seen from the satellite will be off its true location (Fig. 8). This translation effect can be corrected for if the vertical distribution of cloud optical properties is known for each pixel. We simplify the process here by taking a single cloud top height for each column (pixel) and projecting this height to the surface for the given viewing geometry. The radiance observed at the projected location is then mapped back to the true position of the cloud. This process can leave a few pixels blank in the $R_{\text{TOA}}$ map since the upwelling radiance from these locations cannot be detected from the satellite as they are obscured by clouds.

4.2. Solar angle correction

For overhead sun, the position of a cloud is exactly above its shadow and, thus, high $R_{\text{TOA}}$ and low $I_{\text{SFC}}$ will match almost perfectly. At oblique sun angles, however, $R_{\text{TOA}}$ and $I_{\text{SFC}}$ loose this simple correlation as the cloud shadow becomes displaced from the projected cloud position (Fig. 9). To correct for this effect, we approximate the vertical distribution of cloud optical properties with a single cloud top height for each column (pixel) and projecting this height to the surface for the given viewing geometry. The radiance observed at the projected location is then mapped back to the true position of the cloud. This process can leave a few pixels blank in the $R_{\text{TOA}}$ map since the upwelling radiance from these locations cannot be detected from the satellite as they are obscured by clouds.

![Fig. 7. Comparison of observed and retrieved $I_{\text{SFC}}$ for the fields of Fig. 6, units are W m$^{-2}$. The inset shows the linear correlation coefficient for the data.](image1)

![Fig. 8. Principle of viewing angle correction. The horizontal displacement of the apparent position is a function of the cloud altitude and satellite viewing angle. A correction becomes necessary if the distance between apparent and true location exceeds the spatial resolution.](image2)
on the sunward side of a cloud. These pixels would be important in the context of the surface radiation budget as the downwelling radiation is strongly enhanced in the vicinity of the illuminated side of a cloud.

The viewing and the solar angle correction both improve the mapping of $R_{TOA}$ with respect to surface fluxes. It is important to do these corrections in the proper order as they do not commute. First, the viewing angle correction projects a cloudy pixel from its apparent to its true location, and second, the solar angle correction projects the cloud from its true location atop its shadow.

4.3. Nonlocal IPA

The observed $I_{SFC}$ is smoother beneath clouds and the values for $I_{SFC}$ exceed the clear-sky irradiance in the vicinity of cloud edges. These findings can be explained by radiative diffusion. The diffusion can be treated as a local source of radiation that acts not only locally but will affect neighboring pixels as well (Gabriel & Evans, 1996; Marshak, Davis, Cahalan, & Wiscombe, 1998). The diffusion induced by a localized source can be expressed with the help of a $\Gamma$ distribution for the cloud’s Green’s function (Marshak, Davis, Wiscombe, & Cahalan, 1995). Following this approach, we suggest the following diffusive smoother:

$$G(r) = cr^{(a-1)}\exp\left(-\frac{ar}{b}\right),$$

where $r^2 = x^2 + y^2$ is the distance from the diffusive element and $c$ is a normalization factor described below. Parameter $a$ describes the shape of the Green’s function, here, it is set $a = 1$. Parameter $b$ is a measure of the distance over which the diffusive effect of the cloud works. A series of preliminary experiments showed that this parameter is best approximated with half the average cloud top height of the scene under consideration. Motivation for this being that higher cloud tops occur usually with thicker clouds and the diffusion process itself increases with cloud thickness. A more careful investigation will probably relate $b$ not only to the average cloud top height but instead to a local estimate of the distance over which diffusion is acting. The cloud type—cirrus, convective, or stratiform—will certainly have to be considered in the setting for $b$ as well. However, the two examples of cloud fields used for this study do not justify a more elaborate investigation of $b$.

Unlike viewing and solar angle corrections that act on $R_{TOA}$, the nonlocal independent pixel method (NIPA) is invoked after the $I_{SFC}$ is retrieved with an IPA-based method. The irradiance map is separated into $I_{SFC}^{clear}$ and $I_{SFC}^{cloud}$ where each pixel is considered to be either cloud free or cloudy depending on its cloud top height. The cloudy portion is then convolved with the Green’s function (Eq. (7)),

$$I_{SFC}^{cloud} = I_{SFC}^{cloud} G(r),$$

which smoothes $I_{SFC}$ beneath clouds and distributes some of the subcloud irradiance to the cloud-free parts of the scene. The normalization factor $c$ in Eq. (6) is chosen as to conserve the total amount of irradiance (Eq. (8)), that is

$$\int I_{SFC}^{cloud} dA = \int I_{SFC}^{cloud} dA$$

where the integration extends over the whole image. Finally, the cloudy part is again added to the cloud-free parts (Eq. (9)),

$$I_{SFC}^{NIPA} = I_{SFC}^{clear} + I_{SFC}^{cloud},$$

to yield $I_{SFC}$ corrected for nonlocal cloud effects. Note that $I_{SFC}^{clear}$ and $I_{SFC}^{cloud}$ are distinct in the sense that each pixel is either cloudy or cloud free, whereas the smoothing algorithm removes this distinction and both $I_{SFC}^{clear}$ and $I_{SFC}^{cloud}$ can contribute to $I_{SFC}$ in the same pixel. Fig. 10 illustrates this procedure.
how well the NIPA corrected $I_{SFC}$ agrees with the observation. The SFC irradiance is smoother beneath the cloud and shows enhancement at cloud edges after applying NIPA in good agreement with observed $I_{SFC}$. The largest differences between NIPA corrected and observed $I_{SFC}$ are found for cloudy pixels just at the edge of clouds where the diffusion seems to act too strongly. This discrepancy is probably caused by the assumption of a single $b$ for the whole image which may overestimate the diffusion at cloud edges where the optical thickness is typically less than in the interior of the cloud and diffusion is weaker.

5. Testing the corrections

Fig. 7 has illustrated the degraded correlation between retrieved and observed $I_{SFC}$ for solar and viewing angles not too far off the vertical. The situation improves vastly if the suggested corrections are applied. The spatial correlation between retrieved and observed $I_{SFC}$ is much higher but at the cost of some pixels close to cloud edges that are obscured and cannot be retrieved. Irradiance becomes smoother below clouds and exceeds the clear-sky value just outside of the cloud boundaries in agreement with observed $I_{SFC}$. The improvements are confirmed by Fig. 11 that shows much higher correlation between retrieved and observed $I_{SFC}$. For both solar and viewing geometries shown in the figure, the correlation now achieves values larger than .9. Despite this obvious improvement, the scatter plot still unveils some shortcomings of the suggested corrections. The most notable feature is the separation of the retrieved $I_{SFC}$ in two distinct regimes, one with high and one with low $I_{SFC}$. Clear-sky and thick clouds are well treated with the corrections, but there still are problems with thin clouds. The difficulties are partly related to the simplified assumption about the typical distance $b$ of the diffusion, and partly to the asymmetry in illumination at high solar zenith angle. The cloud side facing the sun is brighter and appears to be optically thicker, which leads to an underestimated estimation of retrieved $I_{SFC}$, while the opposite effect is found for the shaded side.

After this phenomenological description, the effects of the suggested corrections will be discussed in more detail by comparing the statistics of retrieved and observed $I_{SFC}$ with and without corrections. Initially, $I_{SFC}$ is retrieved from $R_{TOA}$ without correction. Retrievals are then conducted with a correction for the viewing angle, corrections for both viewing and solar angles, and finally with all corrections including NIPA. The results are always compared against the observed $I_{SFC}$. The statistical measures used to evaluate the performance of the retrieval are the correlation coefficient, the bias, and the RMS error. These measures are evaluated for all pixels in a scene for which $I_{SFC}$ can be retrieved. The number of retrievable pixels depends upon the solar and viewing geometry and upon the characteristics of the cloud field under consideration. However, even in the worst case ($\theta_{sol} = 75^\circ$), more than 60% of the pixels can be processed in the convective and more than 70% in the shallow case for any viewing angle.

Fig. 12 illustrates the statistical skills of the various corrections for one solar angle. The viewing angle correction tends to average the statistical measures for the different viewing angles. The correlation coefficients in the uncorrected convective case, for example, are in the range between $-.04$ and $.69$, but this range narrows to between $.10$ and $.53$ when the viewing angle correction is applied. The viewing angle correction makes the quality of the retrieval independent of the viewing geometry. This is not necessarily an improvement at first sight. The correlation coefficient is larger without the viewing angle correction for certain azimuth angles since at small relative azimuth angles the viewing and solar geometry effects partly offset each other. In that case, the apparent position of a cloud seen from satellite is close to the cloud shadow and the correlation is high in the uncorrected image but worsens after the viewing angle correction has been applied. Despite this apparent decline for selected angles, the viewing angle correction is necessary before conducting further corrections.

The solar angle correction drastically improves the correlation coefficient and reduces the RMS. The effects on the bias are less distinct and will be discussed later. Finally, invoking NIPA during the $I_{SFC}$ retrieval further boosts the correlation coefficient and reduces RMS. In the example shown, the uncorrected correlation coefficient varies between $-.04$ and $.7$ depending on the viewing angle, but with all corrections applied, it exceeds $.85$ throughout. The RMS in the convective case is reduced from between 150 and 275 W m$^{-2}$ for the uncorrected retrieval to values around 100 W m$^{-2}$.

The bias does not improve in the same way as the other statistical measures. The uncorrected results have a predominantly positive bias in the convective case but a negative bias in the shallow case. The effects of the various corrections on the bias are ambiguous: For some viewing angles, the bias increases with a certain correction, while it decreases for other angles. The effects of the corrections also vary for the different cloud fields. Nevertheless, after all corrections are applied, a negative bias is found in general, smaller for shallow and larger for convective clouds.
although the variability of the bias is large for the various viewing angles.

Extending the investigation of the skills of the corrections to a wide variety of viewing and solar angles supports the findings. The largest improvement in the retrieval process is related to the solar angle correction. It should be kept in mind, though, that only the combination of viewing and solar angle correction is useful. Table 2 lists the averaged statistical measures for all zenith angles and the two cloud cases. Except for the shallow cloud and $\theta_{\text{sol}}=41^\circ$, there is a clear improvement of the correlation coefficient and RMS, but not for the bias. There already is a high correlation between retrieved and observed $I_{\text{SFC}}$ for the shallow cloud field at $41^\circ$ without any correction, indicating a probable — and purely random — alignment of the cloud structure and the solar zenith angle. All corrections together do not improve but also not worsen the preexisting high correlation or low RMS error in that case.

Not surprisingly, the retrieval yields better results for the shallow than for the convective cloud, the larger variability in the vertical associated with the latter leads to more pronounced 3-D effects. The suggested correction mitigates these effects, but the retrieval with corrections is still better in the shallow than in the convective case. A planned follow-up study will explore the difference of $I_{\text{SFC}}$ that follows from differences in the cloud structure. Both cloud fields show a decrease of the correlation coefficient between observed and retrieved $I_{\text{SFC}}$ with increasing solar zenith angle. Despite this degradation, the correlation for all solar angles below $60^\circ$ exceeds .85 which, for comparison, is higher than the correlation found for $30^\circ$ viewing angle and overhead sun without corrections. The normalized RMS is larger for higher $\theta_{\text{sol}}$ both before and after the corrections and the corrections reduce the RMS error considerably. The normalized bias does not show any distinct trend with solar angle. For almost all $\theta_{\text{sol}}$, the corrections do not improve the magnitude of the bias. In general, the corrections add some negative bias to the $I_{\text{SFC}}$ retrieval.

5.1. Sensitivity to cloud top altitude

As demonstrated so far, the viewing and solar geometry corrections depend largely on the distribution of cloud top heights. How well must the altitude of the clouds be known to allow for the suggested corrections of the $I_{\text{SFC}}$ retrieval? The answer to this question is sought with the same radiation fields but an arbitrary error is added to the cloud top height before applying the corrections. Three experiments are performed; in the first two, the cloud top height is lowered and risen by 25%, respectively. In the third experiment, the cloud top height for each pixel is changed randomly in the range bounded by $\pm 25\%$. The surface radiation is then retrieved with all corrections applied to $R_{\text{TOA}}$ and NIPA, and the resulting $I_{\text{SFC}}$ is compared against the observed $I_{\text{SFC}}$ using the same statistical measures as applied before.

The corrections produce reasonable estimates for $I_{\text{SFC}}$ even after these substantial variations of the cloud top height. Table 3 lists the results for the experiment with random variation of the height, the results for the other two experiments are similar. The statistical measures remain

### Table 2

<table>
<thead>
<tr>
<th>$\theta_{\text{sol}}$</th>
<th>Convective</th>
<th>Shallow</th>
<th>Convective</th>
<th>Shallow</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Correlation coefficient</td>
<td>Bias</td>
<td>RMS</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>0.0</td>
<td>.42</td>
<td>2.56</td>
<td>38.83</td>
<td>.93</td>
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<td>41.4</td>
<td>.41</td>
<td>0.87</td>
<td>39.70</td>
<td>.60</td>
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<td>50.0</td>
<td>.59</td>
<td>1.04</td>
<td>15.37</td>
<td>.92</td>
</tr>
<tr>
<td>60.0</td>
<td>.43</td>
<td>0.92</td>
<td>19.02</td>
<td>.91</td>
</tr>
<tr>
<td>75.5</td>
<td>.63</td>
<td>1.29</td>
<td>24.00</td>
<td>.79</td>
</tr>
</tbody>
</table>

All values are averaged over 10 different viewing angles; $\theta_{\text{sol}}$ denotes the solar zenith angle. Bias and RMS are normalized by the clear-sky irradiance and multiplied by 100.
largely independent of the viewing angle suggesting that the sum of all corrections is not very sensitive to the exact cloud top altitude and even a coarse estimate can drastically reduce the variability related to different viewing angle. The general picture remains the same as for the case with exactly known cloud altitude (Table 2): The correlation coefficient decreases and the normalized RMS increases with solar angle. No conclusions can be drawn from the bias, besides it being negative for all angles. The skills of the retrieval are generally lower in the disturbed cloud height experiment. However, even with poorly known cloud top altitude, the corrections are still able to improve the retrieval considerably for all except very high solar zenith angles. As in the undisturbed case, the retrieval works better in the shallow than in the convective cloud case.

6. Conclusions

The main objective of the present study was to investigate the problems related to remote sensing of the surface radiation budget at high spatial resolution in the presence of clouds. Previous studies have demonstrated that IPA is appropriate as long as the resolution is coarse or the radiation fields are averaged. With increasing spatial resolution, however, horizontal inhomogeneities in the atmosphere become increasingly important and reduce the accuracy of the retrieval at higher spatial resolution, especially in conjunction with high solar and viewing angles. The correlation between $R_{\text{TOA}}$ and $I_{\text{SFC}}$ vanishes and the radiation at the surface cannot be accessed directly from $R_{\text{TOA}}$ for individual pixels. We suggest three different corrections that, if applied in succession, extend the applicability of the retrieval to a broad range of viewing and solar geometries. These corrections will improve the ability of IPA based methods to retrieve the surface radiation budget.

Two of the corrections deal with the displacement in the apparent location of the clouds caused by oblique solar and satellite viewing angles. The corrections compensate these purely geometrical effects by adjusting the top of the atmosphere radiance map accordingly before retrieving $I_{\text{SFC}}$. The third correction, the nonlocal IPA, takes into account diffusion by clouds that can spread radiation to neighboring pixels. This effect is particularly important at cloud edges where the observed $I_{\text{SFC}}$ can exceed the theoretical clear-sky irradiance. Note, though, that NIPA is only successful after the geometrical effects have been corrected for; applying solely NIPA to a high-resolution satellite image will not yield any improvement when retrieving $I_{\text{SFC}}$.

The corrections boost the correlation coefficient and reduce the RMS error. The largest improvements are found for high solar zenith angles. Furthermore, the corrections decouple the skills of the retrieval from a specific viewing angle, the same skills are found for all viewing angles. However, the number of pixels for which $I_{\text{SFC}}$ can be retrieved is reduced with the corrections because some of the pixels are obscured by clouds. This problem is considered to be of minor importance as, for example, more than 60% of the pixels in the convective case can be processed for any solar and viewing geometry.

All suggested corrections require information about the vertical cloud structure which, as a proxy, is given by the cloud top height. It was found that the corrections are not particularly sensitive to the exact cloud altitude. A variation of top height by 25% did reduce the skills of the retrieval, but still the correlation between retrieved and observed $I_{\text{SFC}}$ by far exceed results from the uncorrected retrieval. Thus, the correction method promises to be robust as long as reasonable cloud top altitude estimates are used. However, retrieving cloud top height is a difficult problem, particularly in conjunction with semitransparent cirrus clouds. Most height retrieval procedures rely on brightness temperature, and since cirrus clouds can be transparent at visible wavelengths but opaque in IR, the cloud top altitude can be rather inaccurate. Where only a thin cirrus layer is present, the cloud top height can be adjusted properly. A more difficult problem is that of multilayer clouds—thin cirrus above optically thick clouds. In this case, the IR brightness temperature yields the cirrus height, but the surface irradiance is determined by the characteristics of the lower cloud. A possible solution may employ a multispectral multiresolution method (Baum et al., 1995) or a multiple platform approach (Kazansky, 1997). Despite potential difficulties with the retrieval of cloud top height, it should be kept in mind that a reasonable estimate is sufficient for the suggested improvement of the $I_{\text{SFC}}$ retrieval.

The corrections have been found to work well in the case of convective and shallow clouds, although the skills are, not surprisingly, better in the shallow cloud case. Pronounced vertical structures in the convective cloud field enhance the 3-D effects from clouds. The subject of future studies will be to explore more closely the relationship between cloud field texture and its impact on the surface radiation.

Corrections of the $I_{\text{SFC}}$ retrieval were tested with two cloud fields only. To confirm the promising results presented here, it will be necessary to apply the corrections to a larger variety of cloudy situations. However, high-resolution 3-D Monte Carlo simulations such as those performed for this study are intensive on computer time. This puts definite constraints on the number of cloud fields that can be processed with reasonable effort.
The 3-D cloud effects presented here have also implications on the evaluation and calibration of satellite instruments against ground-based observations. A sensor at a fixed SFC location is equivalent to a single pixel with very high spatial resolution. The results from this study indicate that 3-D cloud effects alter the distribution of radiation that reaches the surface. Cloud shadows, reflection from cloud sides, and diffusion of radiation by clouds all affect the measurements, and the effects are clearly different at the SFC and for the satellite instrument. Subsequently, this leads to differences in the data collected from space and on the ground. Many comparisons between remotely sensed and directly observed variables rely on temporal and spatial averaging to mitigate the effects from clouds. The present study demonstrates that high-resolution satellite imagery may be used for the remote sensing of surface properties if cloud effects are properly corrected for.

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