Estimating Three-Dimensional Cloudy Radiative Transfer Effects from Time-Height Cross Sections

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Introduction

Clouds in the atmosphere are finite in extent and variable in every direction and in time. Long data sets from ground-based profilers, such as lidars or cloud radars, could provide a very valuable set of observations to characterize this variability. We may ask how well such profiling instruments can represent the cloud structure as measured by the magnitude of the three-dimensional (3D) radiative transfer effect.

The 3D radiative transfer effect is the difference between the domain average broadband solar surface flux computed using 3D radiative transfer and using the independent column approximation (ICA). In the ICA approximation, a cloud is subdivided into columns. The radiative transfer is applied to each column and the overall radiative transfer is computed by summing the contributions from the individual columns. The ICA approximation ignores the net transfer of radiation between the columns. As a result, there can be large errors in the 3D radiative transfer effect and these errors depend on the solar zenith angle. The ICA approximation neglects both cloud side leakage (for overhead sun photons strike the tops of clouds and leak from their sides) and cloud side illumination (when the sun is low on the horizon, photons strike the sides of clouds and exit the tops). Missing these effects, the ICA transmitted flux is underestimated when the sun is high and it is overestimated when the sun is low.

The estimates of the 3D effect made from a time series of cloud profiles can differ from the truth for at least three reasons. First the time-series of cloud profiles measured at a single point are interpreted as spatial variations of the cloud field by invoking the frozen turbulence assumption and using an advection velocity. We don't know how generally applicable this idea is. Second, the profilers sample only a small portion of the total cloud field. We don't know whether this sampling is sufficient. Third, the profilers construct two-dimensional (2D) slices from 3D clouds. Horizontal transport is less important in 2D clouds than in 3D clouds since the photons are not allowed to travel in the third dimension.

In this paper, we assess the degree to which 3D radiative transfer effects can be estimated from time-series obtained by profiling instruments in fields of small cumulus clouds.

How to Assess the Magnitude of the 3D Effect?

We define the *3D effect*: E as the difference between the domain average broadband solar surface flux computed by 3D radiative transfer and by ICA radiative transfer divided by the total flux cloud effect (i.e., cloudy sky fluxes minus clear-sky fluxes at the surface):

$$E = (F_{ICA}-F_{3D}) / (F_{3D}-F_{clear})$$

where

F_{3D}	=	the surface flux computed with the 3D radiative transfer
F_{ICA}	=	the surface flux computed with the ICA approximation
F_{clear}	=	the surface flux for clear-sky

The 3D effect is not realized in the real world and its magnitude can only be assessed though simulations. We compute the 3D effect by generating clouds fields with a large-eddy simulation (LES) model, then computing broadband solar fluxes and the 3D effects with a Monte Carlo model.

Generating Cloud Fields with a LES Model

We generate 210 hours of shallow, non-precipitating cumulus in a small domain over the Atmospheric Radiation Measurement (ARM) South Great Plains (SGP) site with the Bjorn Stevens's LES. The LES domain is 8 km x 8 km x 4.36 km with a grid spacing of 50m x 50m x 40 m.
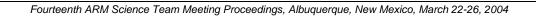
We create two cloud fields as shown in Figure 1.

- the "truth": the 3D cloud fields are saved every 5 minutes.

- the "observations": the cloud fields as would be seen by a profiler are simulated by recording the state of the central column every 10 seconds. We call these cross-sections the *soda straw cloud fields* to indicate they are constructed from individual columns at different timesteps. The soda straw fields are accumulated over 1-hour interval.

A Monte Carlo Model to Compute the 3D Effect

The ICA and 3D radiative transfer calculations are performed with the Frank Evans's Monte Carlo model using 10^6 photons pre scene across the solar spectrum. The model computes the broadband domain average solar fluxes for 3D and ICA radiative transfer.

We compute the 3D effect both in 3D clouds (E_{3D}) and in soda straw clouds (E_{ss}) and we compare the 3D effect in a 1-hour window of soda straw clouds to the corresponding 1-hour mean of the 3D effect in 3D clouds.
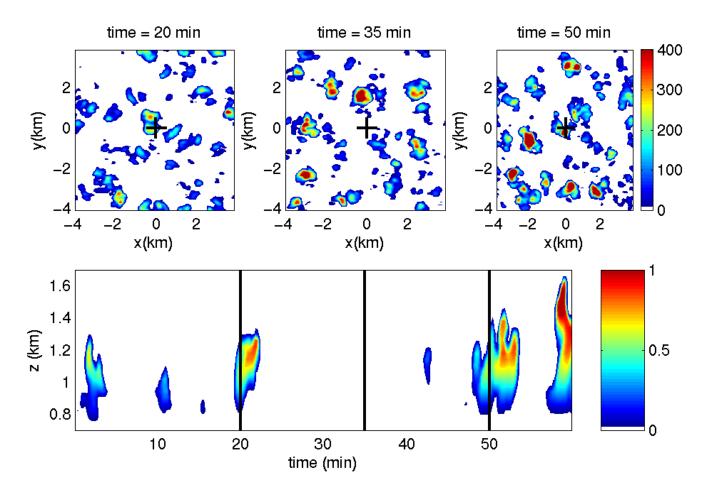
Figure 1. 3D cloud fields (upper plots) and soda straw cloud fields (lower plot). The upper plots display the liquid water path (LWP in g/m2) at times 20, 35, and 50 minutes. The lower plot displays the cross section of liquid water content (LWC in g/m3). The time and location correspondences are indicated by bold black lines and arrows.

Figure 2 shows the 3D effect as a function of the solar angle:

- In 3D clouds, the 3D effect ranges from -30% to 50% of the total cloud effect. For overhead sun, the ICA neglects the leakage of photons from the cloud side; the transmitted ICA flux is underestimated and the 3D effect is negative. For low sun, the transmitted ICA flux is overestimated as ICA neglects the cloud side illumination.

- The magnitude of the 3D effect in soda straw clouds is underestimated. The difference between the 3D effect in soda straws and in 3D clouds ranges from 0.1 to -0.2 and this also depends on solar zenith angle.
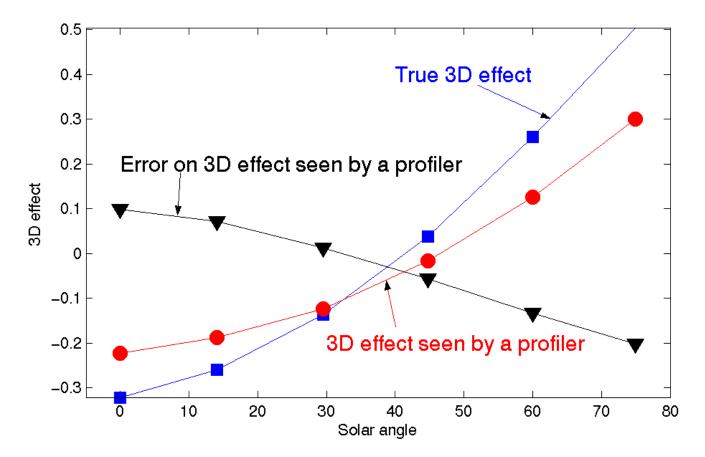
Figure 2. The 3D effect estimated from 3D and soda straw clouds as a function of the solar angle. The blue and red lines show respectively the 3D effect for 3D clouds (E_{3D}) and the 3D effect for soda straw clouds (E_{ss}). The error ($E_{ss} - E_{3D}$) is shown in black.

Why is the 3D Effect from Soda Straw clouds Incorrect?

Sources of Errors in the Estimates of the 3D Effect from a Profiler

In the introduction we have identified three reasons why the estimates of the 3D effect made from a time series of cloud profiles can differ from the truth: the frozen turbulence assumption, sampling, and dimensionality.

We assess the magnitude of each error by computing the magnitude of the 3D effect in a series of cloud scenes that decompose the overall error in its three components as illustrated in Figure 3.

- The difference between *2D and 3D radiative transfer* can be computed by comparing the 3D effect computed from all scenes decomposed into 2D slices ($E_{2D,all}$) with the full calculation (E_{3D}).

- The impact of *sampling* is the difference between the 3D effect computed from a single 2D section extracted from the 3D scene ($E_{2D,one}$) and the 3D effect computed from every slice from of the 3D scenes ($E_{2D,all}$).

- To assess the importance of the *frozen turbulence assumption*, we remove errors caused by temporal evolution by comparing the 3D effect obtained from the soda straw calculations (E_{ss}) to the effect computed in a single 2D slice ($E_{2D,one}$).
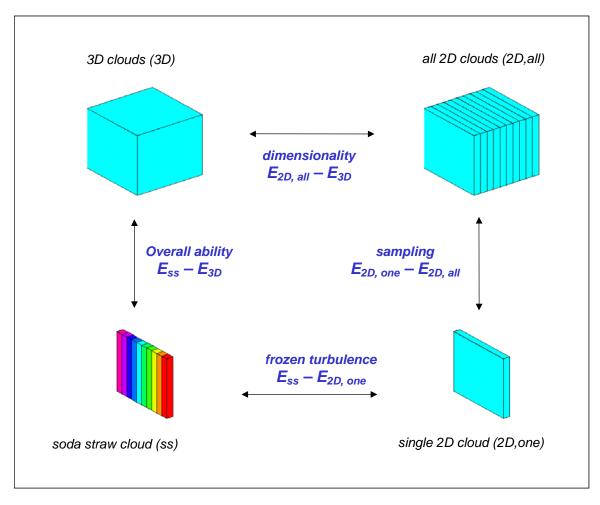

Figure 3. Sources of errors in the estimates of the 3D effect from a profiler. The overall error (E_{ss}-E_{3D}) is decomposed in 3 components: the dimensionality error ($E_{2D,all}$-E_{3D}), the sampling error ($E_{2D,one}$-$E_{2D,all}$) and the frozen turbulence error (E_{ss}-$E_{2D,one}$).

What is the Importance of Each Error?

Figure 4 shows the magnitude of the errors in the 3D effect from soda straw clouds. Both the "frozen turbulence" assumption and the small sampling make individual estimates quite noisy but cause small errors in the mean, which implies that our sampling is sufficient and the frozen turbulence assumption holds for cumulus clouds. The largest error in estimating the 3D effect comes from the dimensionality. There is fundamental difference between the three-dimensional radiative transfer and two-dimensional radiative transfer for cumulus. Estimates of the 3D effect based on 2D cloud fields will always be biased because they ignore variability in the third dimension.
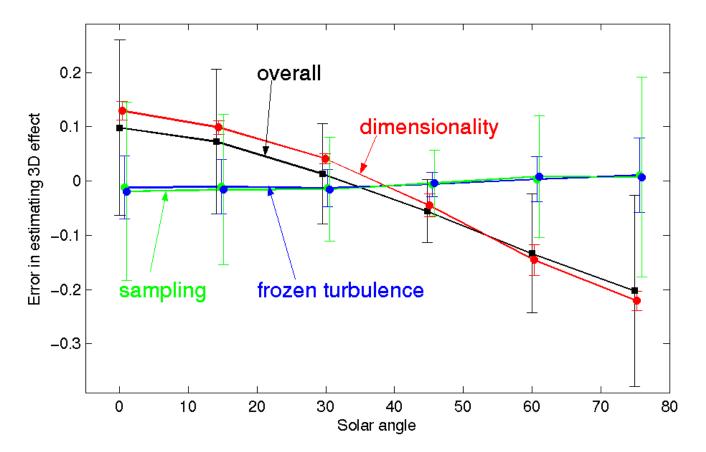
Figure 4. Errors in the estimates of the 3D effect in soda straw clouds. The overall error is in black, the dimensionality error in reed, the sampling error in green, the frozen turbulence error in blue. The error bars show the standard deviation.

Acknowledgements

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