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# DETERMINATING THE CHARACTERISTICS OF FAIR WEATHER CUMULUS CLOUDS THAT ARE IMPORTANT FOR THREE-DIMENSIONAL SOLAR RADIATIVE TRANSFER

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## 1. INTRODUCTION

The radiative effects of cloud horizontal inhomogeneity may be divided into two parts (e.g. Var-nai and Davies, 1999): 1) the heterogeneity effect due to optical depth variability, and 2) the horizontal transport effect of light moving between columns. For climate applications in which domain averaged fluxes are important, the independent pixel approximation (IPA) correctly addresses the first effect, but not the second. There is much evidence (Cahan et al. 1994; Barker, 1996; Zuidema and Evans, 1998; Fu et al., 2000) that the IPA accurately predicts domain average solar fluxes in stratocumulus. However, it is well known from previous Monte Carlo simulations of finite clouds (e.g. Welch and Wielicki, 1984) that there can be large errors in the IPA due to leakage from cloud sides and side illumination of finite clouds. These studies with simple cloud shapes have shown that size of the horizontal transport or “three-dimensional radiative” effect depends strongly on the cloud aspect ratio, cloud fraction, and solar zenith angle (SZA). However, some studies with more realistic broken cloud fields (Barker et al., 1998) indicate that the IPA may be sufficiently accurate.

In this paper we hypothesize that the cloud thickness field and its relation to the optical depth field is the key to the three-dimensional (3D) radiative effect in realistic fair weather cumulus clouds. We define the three dimensional radiative effect as the difference between the IPA and 3D domain averaged reflected or absorbed fluxes. Since the IPA does not depend on the horizontal distribution of columns, the optical depth and liquid water path (LWP) fields

alone control the IPA broadband solar fluxes. In the limit of geometrically thin clouds the IPA is exact, and thus the deviations of 3D radiative transfer from IPA should be controlled by the cloud thickness field.

The procedure we employ to investigate the hypothesis is to: 1) use many fair weather cumulus fields from a large eddy simulation model, 2) generate approximate fields with different methods for cloud base height and thickness while keeping the original LWP and optical depth, 3) calculate broadband domain average solar fluxes with a Monte Carlo model, and 4) compare the IPA-3D fluxes from the approximate and original fields.

## 2. LES FIELDS

The cumulus fields are generated with Bjorn Stevens’ large eddy simulation model. The simulation is modeled on a GCSS experiment of boundary layer cumulus over the Oklahoma ARM site forced by solar surface heating from morning to afternoon. The LES grid size is  $96 \times 96 \times 110$  with a grid spacing of  $66.67 \times 66.67 \times 40.0$  m<sup>3</sup>. Fields are sampled each hour from four LES runs: 1) uniform 10 m/s initial wind (base case), 2) 4 m/s/km wind shear applied, 3) zero initial wind, and 4) surface flux forcing reduced by 50%. These runs provide a variety of cloud fraction, cloud depth, and cloud shear. A total of 31 scenes is used in the analysis.

The LES model has no microphysics and thus represents clouds by liquid water content (LWC) only. The effective radius ( $r_{eff}$ ) is derived assuming a gamma distribution with effective variance of 0.1 and a fixed droplet concentration of 200 cm<sup>-3</sup>. Table 1 summarizes the physical and optical property statistics of the cloud scenes.

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Table 1: Table of cloud statistics over the 31 scenes.

Quantity	mean	std	min	max
Cloud fraction	0.196	0.095	0.004	0.344
Mean cloud $\tau$	10.13	6.75	1.00	24.05
Mean cloud LWP	58.8	45.7	3.2	160
Mean thickness (m)	227.1	105.2	71.5	418
Max thickness (m)	913.5	499.4	120.0	1680

### 3. APPROXIMATE FIELDS

Five approximate three-dimensional LWC and  $r_{eff}$  fields are made from each original LES field. Each approximate 3D field has the same 2D optical depth and liquid water path fields as the original. For each cloudy column the approximations are defined by:

1. True cloud top height ( $Z_{top}$ ) and cloud base height ( $Z_{base}$ ).
2. True  $Z_{top}$ ;  $Z_{base}$  fixed at median cloud base.
3. True cloud thickness ( $\Delta Z = Z_{top} - Z_{base}$ );  $Z_{base}$  fixed at median.
4. Thickness from optical depth using power law fit to columns from all 31 scenes:  
 $\Delta Z = (67.2 \text{ m})\tau^{0.604}$ ; fixed  $Z_{base}$ .
5. Thickness fixed at scene mean; fixed  $Z_{base}$ .

The extinction profile,  $\beta(z)$ , increases linearly to  $0.9\Delta Z$  and then decreases linearly to cloud top. The liquid water content profile is proportional to  $\beta(z)^{3/2}$ . Fig. 1 illustrates the five approximations.

### 4. RADIATIVE TRANSFER RESULTS

Broadband domain average solar radiative transfer is computed in the original and approximate 3D cloud fields. Molecular absorption for a standard midlatitude summer atmosphere is calculated with the shortwave RRTM k-distribution from AER (11 bands from 0.26 to 3.08  $\mu\text{m}$ ; altitudes from surface to 40 km). Cloud droplet optical properties are computed with Mie theory integrated over each spectral band for gamma distributions with the specified LWC and  $r_{eff}$ . Molecular Rayleigh scattering is included, but there are no aerosols. The 3D and IPA radiative transfer is performed with a maximal cross section forward Monte Carlo model using  $10^6$  photons across the solar spectrum. The surface has Lambertian reflectance with the spectral albedo of green grass from John Hopkins University measurements in the ASTER spectral library at JPL. Three solar zenith angles (SZA) are chosen ( $\theta_0 = 0^\circ, 45^\circ, 63.4^\circ$ ) and a daytime average is calculated by integrating

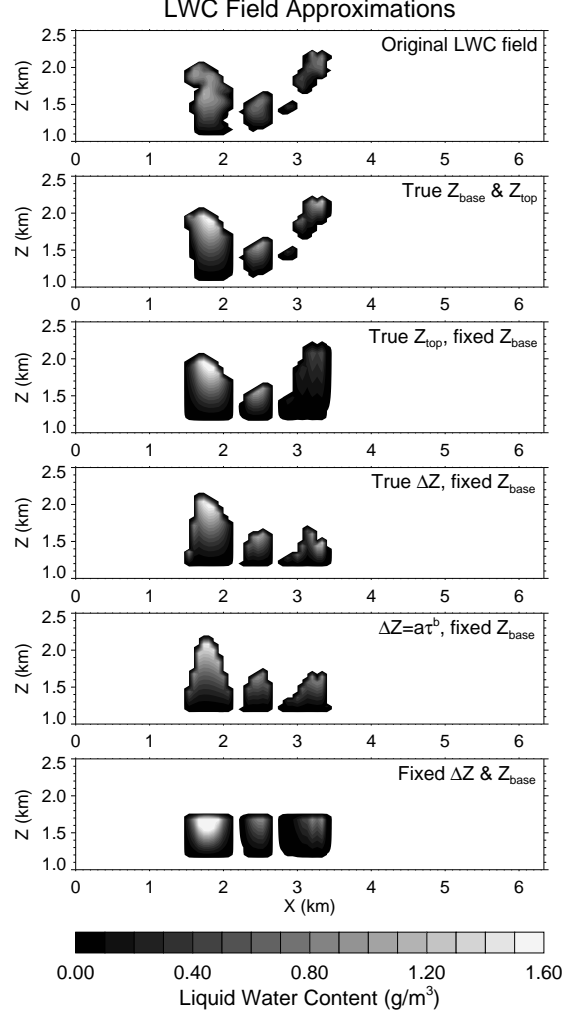


Figure 1: An example X-Z cross section of an original liquid water content field and the five approximate fields derived from it.

over SZA with the Sun overhead at noon. An integration over all solar azimuths is performed for each SZA case.

The modeling produces domain average reflected and atmosphere absorbed fluxes for 3D and IPA radiative transfer in the original and the five approximate fields for each of 31 LES scenes. Monte Carlo noise tests on a typical scene give rms noise from 0.4 to 0.7  $\text{W/m}^2$  in IPA-3D reflected flux and 0.15 to 0.30  $\text{W/m}^2$  in IPA-3D absorbed flux.

Fig. 2 shows the 3D radiative effect (IPA-3D reflected flux) for the original fields. For overhead or low Sun the 3D effect can be substantial for the higher cloud fraction scenes (up to 20  $\text{W/m}^2$ ). The reflected flux 3D effect is small when averaging over SZA due to cancellation of the cloud side leakage

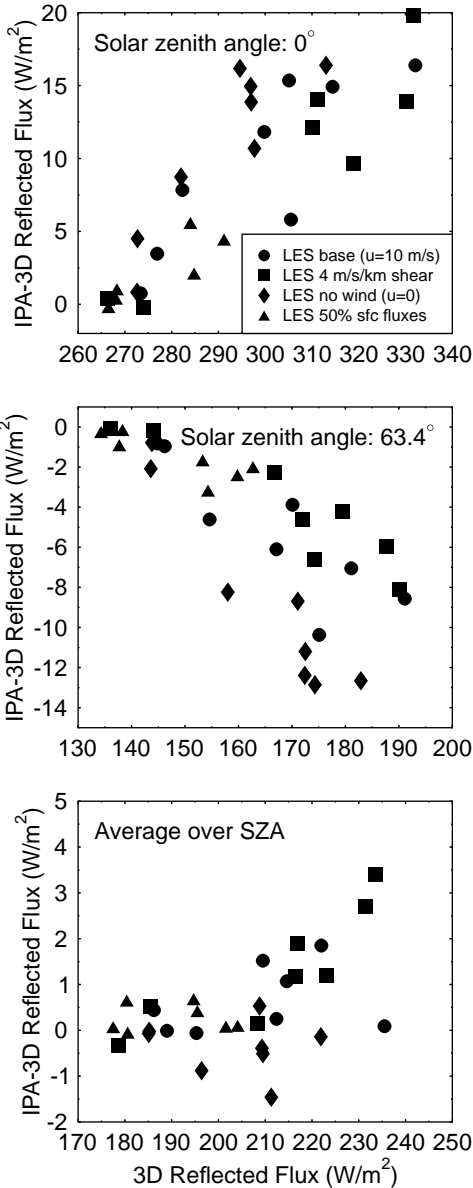


Figure 2: The 3D radiative effect (IPA-3D) for reflected flux as a function of the 3D reflected flux for the original LES fields.

(high Sun) and illumination (low Sun) effects. There is no such cancellation in the 3D effect for absorbed flux (not shown) which ranges from 0 to  $-3 \text{ W/m}^2$ . For high or low Sun the reflected flux 3D effect is correlated with the reflected flux.

Figs. 3 and 4 compare the 3D effect of the approximate and original fields. The reflected flux 3D effect is well captured with the correct cloud top and base height. The 3D effect is better represented using the true cloud thickness than the true cloud top height

Table 2: RMS IPA-3D flux differences between approximate and original LES fields. The rms of the original IPA-3D flux is also listed for comparison.

Reflected IPA-3D Flux Differences ( $\text{W/m}^2$ )						
SZA	rms	App1	App2	App3	App4	App5
0	10.22	1.05	1.40	1.70	1.83	3.60
45	2.44	0.85	2.53	1.45	1.44	4.10
63.4	6.40	0.66	2.80	2.22	1.79	2.56
Avg	1.10	0.60	1.46	0.78	0.90	2.75
Absorbed IPA-3D Flux Differences ( $\text{W/m}^2$ )						
SZA	rms	App1	App2	App3	App4	App5
0	1.12	0.48	0.55	0.60	0.58	0.74
45	2.37	0.26	0.33	0.29	0.43	0.76
63.4	2.41	0.20	0.21	0.29	0.32	0.82
Avg	1.51	0.30	0.33	0.34	0.36	0.54

(compare approximations 2 and 3). The 3D effect is more accurate when the cloud thickness is simply obtained from the optical depth than when it is fixed at the scene mean (compare approximations 4 and 5). Table 2 summarizes the 3D effect results for both reflected and absorbed flux.

## 5. CONCLUSIONS

The details of the internal extinction profile are not important for domain average flux 3D radiative transfer effects in cumulus; instead cloud boundaries and the optical depth and LWP fields are the key. It is more important to have correct cloud thickness than correct cloud top topography, except perhaps for overhead Sun. Deriving cloud thickness from optical depth works well for these cumulus clouds, but the power law relation must be tuned for the particular cloud ensemble.

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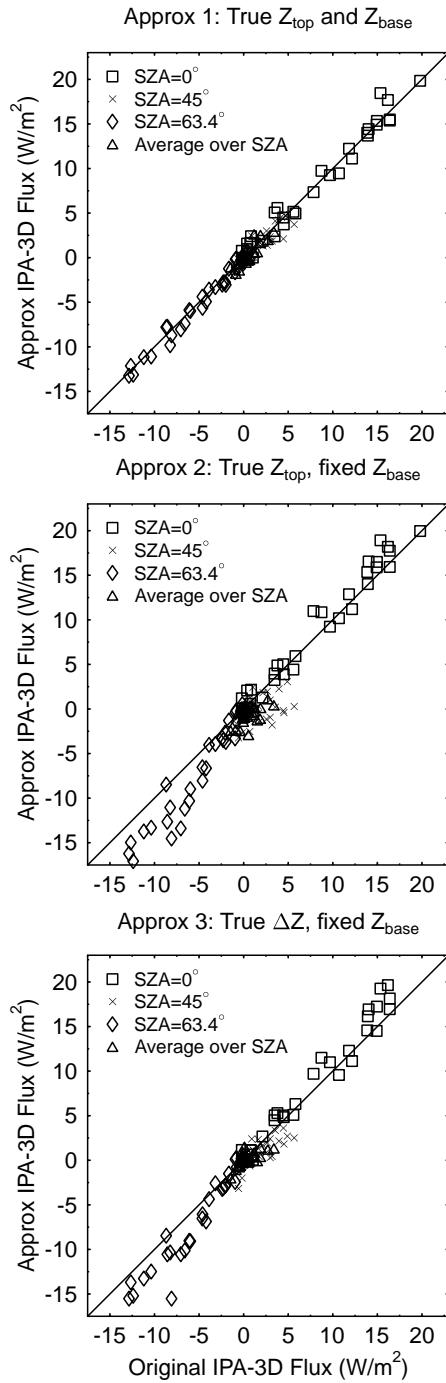


Figure 3: Comparison of the approximate and original reflected flux 3D radiative effect (IPA-3D) for the first three approximations.

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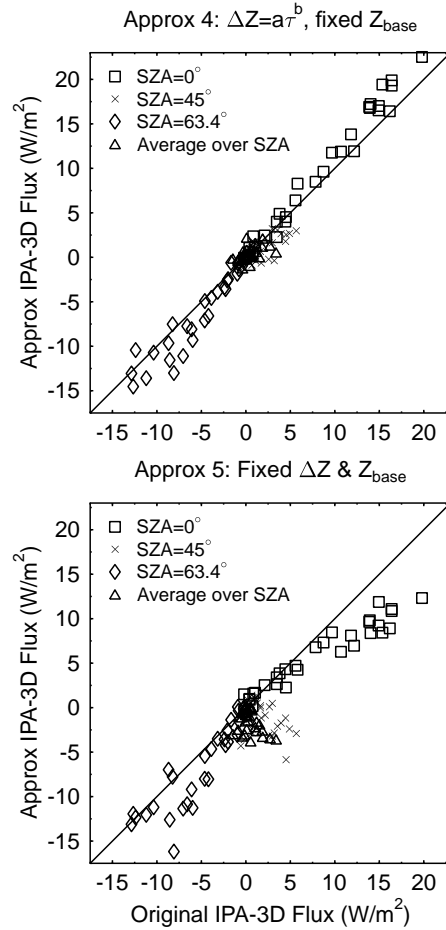


Figure 4: Comparison of the approximate and original reflected flux 3D radiative effect (IPA-3D) for the last two approximations.

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