3D Solar Radiative Transfer in Fields of Small Tropical Marine Cumulus Clouds Derived from Radar

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3D Cloud Radiative Transfer for Climate Applications

• Cloud heterogeneity affects domain average fluxes and heating rates.

• Two distinct aspects:
  1. 1D heterogeneity effect
     ➔ handled by the Independent Pixel Approximation
  2. Finite cloud 3D effect
     ➔ requires 3D radiative transfer
     ➔ theoretical finite cloud studies indicate this is potentially a large effect
1D Heterogeneity Albedo Bias

- Optical depth distribution has lower albedo than a uniform cloud.
- Bias is not due to horizontal photon transport.
- Resolved by integrating over the distribution, as does the Independent Pixel Approximation.
Finite Cloud Albedo Bias

Welch and Wielicki (JAS, 1984)

- Bias from horizontal photon transport (3D radiative transfer).
- Bias depends on cloud aspect ratio (Height/Diameter).
- High sun albedo is lower than plane-parallel (side leakage).
- Low sun albedo is higher than plane-parallel (side illumination).
How Large is the 3D Solar Radiative Transfer Effect in Real Clouds?

- Specific questions:
  1. Is 3D or 2D radiative transfer necessary for accurate calculation of domain average fluxes in small tropical cumulus?
  2. How large are the plane-parallel and independent pixel approximation errors in a large sample of such clouds?

- To answer these: Need realistic 3D cloud structure.
- Cloud radars can give cloud microphysical profiles.
- Need to generate 3D cloud fields from vertical cloud profiles.
Research Approach

1) Retrieve profiles of liquid water content and effective radius for nonprecipitating tropical cumulus clouds from the ARM Nauru cloud radar.

2) Use a Principal Component Analysis method to generate 2D and 3D stochastic cloud fields with the same statistics as radar observed clouds.

3) Perform Monte Carlo broadband radiative transfer in observed and stochastic cloud fields.
Radar Cloud Retrieval Method

- Radar reflectivity to $\text{LWC}/r_{\text{eff}}$ look up table based on output of Bayesian algorithm of McFarlane et al. (JGR 2002), which combines radar and microwave radiometer data with prior information from in situ cloud probes.
Example Retrieved LWC Fields
Stochastic Cloud Field Generation Method

- Assumes translational invariance in horizontal (not vertical).
- Assumes isotropic statistics for horizontal directions.
- Use wind speed to convert time-height sections to X-Z.
- Generates ensembles of 2D or 3D fields of LWC and $r_{\text{eff}}$.
- Ensemble of stochastic output fields exactly match input histograms of LWC and $r_{\text{eff}}$ for each level.
- Stochastic fields approximately match correlation function of the binary mask (clear/cloud) of input fields. Concept is that cloud boundaries are important for 3D radiative transfer.
Stochastic Cloud Field Generation Algorithm

- Based on Principal Component transform of gaussian noise.
- Translational invariance $\Rightarrow$ PC transform $=$ Fourier transform.

1. Generate independent gaussian noise field ($N_x \times N_y \times N_z$).

2. Filter: multiply noise by amplitudes to get PC coefficients. Filtering amplitudes are designed so the output cloud mask field has correct correlation function, $R(x_1-x_2; z_1, z_2)$.

3. PC Transform: Transform stochastic PC coefficients to real space gaussian field: multiplication by eigenvector matrix for vertical transform, 2D FFT for horizontal transform.

4. Use a look up table to convert to nongaussian LWC field (another stochastic field is converted to $r_{eff}$ field with look up table that depends on LWC values).
Stochastic Field Generation Procedure

Gaussian White Noise

Filter Noise: PC components

Vertical PC Transform

Horizontal Fourier Transform: Gaussian Field

Convert Histogram: Liquid Water Content

Liquid Water Content (g/m³)
Stochastic Fields Generated for Nauru

- Radar LWC/$r_{eff}$ retrievals for June - August 1999
- Use 25 range gates (90 m) from 500 to 2750 m; 20 sec data.
- Convert time to distance using 915 MHz radar profiler winds.
- 744 images (from 0.7 to 3.0 hours) of valid radar retrievals.
- Generate 100 2D (512x25) and 100 3D (256x256x25) fields.
Example 2D Stochastic LWC Fields
Example Stochastic 3D Cloud Optical Depth
Comparison of Input and Stochastic Statistics

- 744 input 2D fields
- 100 2D stochastic fields
- 100 3D stochastic fields

- input 2D fields
- 2D stochastic fields
- 3D stochastic fields

Cloud Fraction vs. Height (km)

Mean cloud LWC (g/m³) vs. Height (km)
Binary Cloud Mask Correlation Function Agreement

- Weighted average over 25x25 matrix
- Weighted difference between input and 2D fields
- Weighted difference between input and 3D fields

Correlation vs. Lag
Input and Stochastic Optical Depth Distributions

Cumulative Distribution Function vs. Cloud optical depth

- Black: Input fields
- Red: 2D stochastic
- Green: 3D stochastic

Input cloud fraction: 0.178
2D stochastic fraction: 0.173
3D stochastic fraction: 0.174
Cloud: $\tau > 0.5$, $\Delta z \geq 90$ m
Input and Stochastic Thickness Distributions

Cumulative Distribution Function

Cloud thickness (km)

- Input fields
- 2D stochastic
- 3D stochastic
Input and Stochastic Cloud Width Distributions

Cumulative Distribution Function

Cloud width (km)

Input fields
2D stochastic
3D stochastic
Radiative Transfer Experiments

- Broadband solar Monte Carlo model:
  - Mie scattering for cloud droplets
  - Fu’s k-distribution for TOGA suppressed sounding
- Compute reflected and column absorbed fluxes
  - 5 solar angles + tropical day time average
  - 3D transfer, independent pixel approximation, and plane-parallel (on clear/cloudy columns) approx.

1) Examine 1D heterogeneity effect:
   plane-parallel - independent pixel fluxes.
2) Examine finite cloud effect: IPA-3D fluxes in stochastic 2D and 3D fields.
• Cloud effect on reflected flux is 30 W/m² for daytime average
• Cloud effect on absorbed flux is 4 W/m² for daytime average
The 1D heterogeneity effect is significant for reflection.
The 1D heterogeneity effect is significant for absorption.
The IPA errors are small. 3D has larger effect than 2D.
3D Finite Cloud Effect on Absorbed Flux

- The IPA errors are small. 3D equivalent to 2D.
Conclusions

• For the nonprecipitating cumulus clouds at Nauru:
  1) 3D radiative transfer effects for overhead Sun are significantly larger in 3D clouds than 2D clouds due to leakage from cloud sides.
  2) The 1D heterogeneity error is significant;
     ➔ Climate models should use IPA type methods which consider optical depth variability.
  3) The 3D radiative effect appears to be small.
     ➔ Due to low cloud fraction, optical depth, and geometric thickness.