Systematic Changes in Shallow Cumulus Cloud Field Evolution due to Shortwave 3D Radiative Responses

Jake J. Gristey (Jake.J.Gristey@noaa.gov)[1,2,3] | C. Kevin Yang[4] | J. Christine Chiu[4] | Graham Feingold[2]

[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder [2]NOAA Chemical Sciences Laboratory (CSL) [3]Laboratory for Atmospheric and Space Physics (LASP), University of Colorado Boulder [4]Department of Atmospheric Science, Colorado State University

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Motivation & Aim

- Ubiquitous shallow cumulus clouds exhibit detailed 3D structure leading to complex interactions with shortwave (solar) radiation.
- While shortwave 3D radiative effects in this environment have been well documented, their influence on cloud field development, evolution, and persistence is less well known.
- We seek to couple large eddy simulation (LES) with a three-dimensional radiative transfer (3DRT) emulator to assess shortwave radiative responses across a large number of cases.

Summary

1. Three-dimensional radiative effects are substantial in shallow cumulus cloud fields, but previous assessments have often neglected how cloud evolution responds to these effects.
2. Recent efforts focusing on case studies indicate that the responses are non-negligible.
3. An emulator of three-dimensional radiative transfer is under development to be coupled to large eddy simulation, enabling assessment of three-dimensional radiative responses across many cases.

Simulation of Shortwave 3D Radiative Effects

- LES and Monte-Carlo 3DRT have been run for more than 40 separate days spanning the summers of 2015–2018 that each develop shallow cumulus clouds at the Southern Great Plains (SGP) Atmospheric Observatory in Oklahoma[1,2,3] (e.g., Fig. 1).

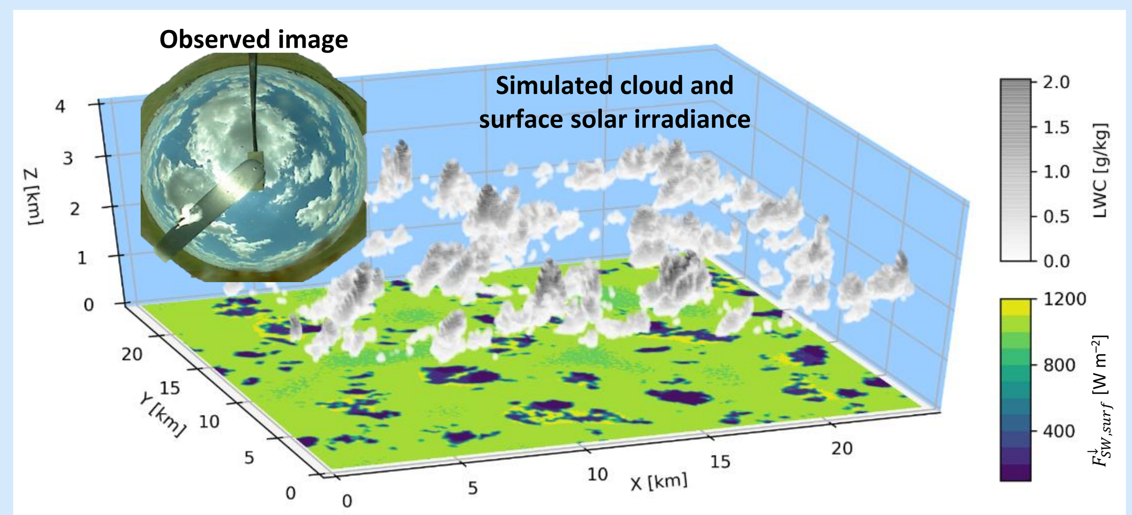

Fig. 1. Simulation of shallow cumulus clouds and associated surface solar irradiance at 14:30 on 27 June 2015 at SGP. An observed total sky image valid at the same location and time is provided for reference in the upper left.

- The observed shape of the surface solar irradiance ($F^{\downarrow}_{SW,surf}$) probability density function (PDF) beneath shallow cumulus clouds is only reproduced with 3DRT (e.g., Fig. 2).

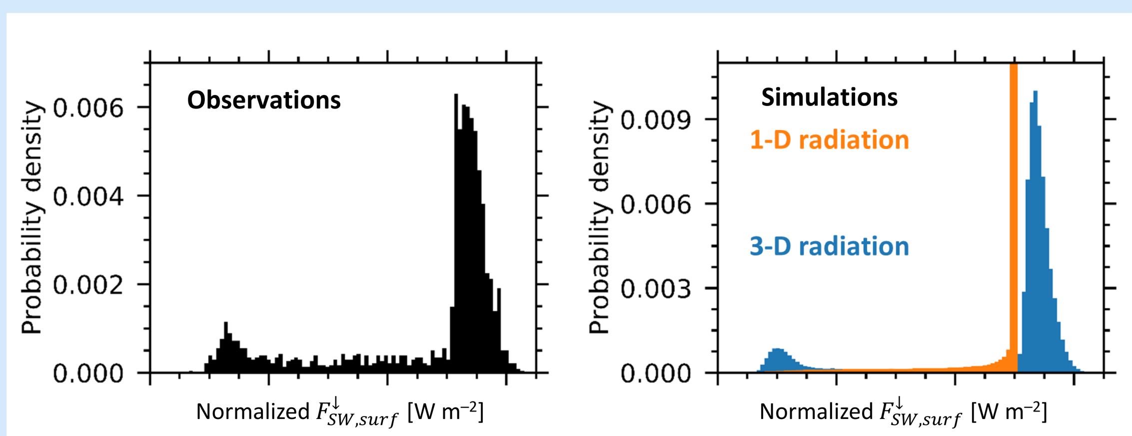

Fig. 2. Observations (left) and simulations (right) of the surface solar irradiance PDF on the afternoon of 27 June 2015 at SGP.

- The $F^{\downarrow}_{SW,surf}$ PDF has important implications for renewable energy and many other applications but, crucially, the 3DRT calculations shown above were performed offline meaning the 3D radiative effects do not influence cloud evolution.

Case Studies of Shortwave 3D Radiative Responses from Recent Literature

Fig. 3. Virtual photographs of shallow cumulus clouds from LES coupled with (top) TenStream and (bottom) 2-stream radiation. Adapted from original publication[4].

- 3DRT has been parameterized in LES with the TenStream solver:
  - ➢ A *relatively* efficient approach to capture 3D radiative effects.
  - ➢ Results in cloud streets[4] (e.g., Fig. 3) and larger/thicker clouds[5] mainly driven by differences in $F^{\downarrow}_{SW,surf}$ patterns.
- Parameterizations of $F^{\downarrow}_{SW,surf}$ have also been proposed for possible use in LES, via machine learning[2] or filtering the diffuse $F^{\downarrow}_{SW,surf}$[6].

- Monte-Carlo 3DRT, widely regarded as the most accurate technique but very computationally expensive, was recently coupled to LES for the first time[7] (e.g., Fig. 4), resulting in similarly notable responses.

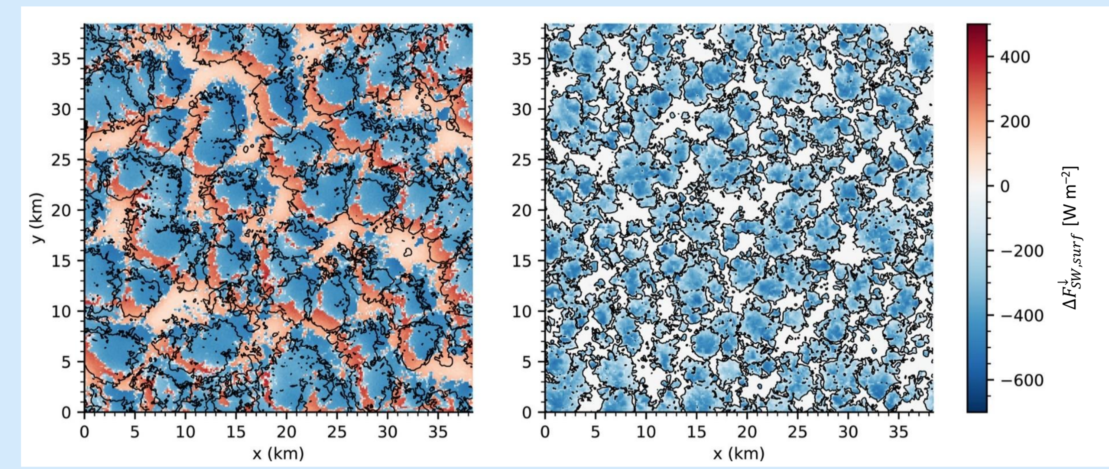

Fig. 4. All-sky minus clear-sky surface solar irradiance (colors) and cloud boundaries (black lines) for shallow cumulus clouds from LES coupled with (left) Monte-Carlo 3DRT and (right) 2-stream radiation. Adapted from original publication[7].

- In summary, there is a growing body of evidence hinting at the importance of 3D radiative responses, but they have been necessarily limited to a small number of case studies due to the expense of 3DRT and the approaches employed.

Machine-Learned 3DRT to Pave the Way for Coupled LES-3DRT Over a Large Number of Cases

- An emulator of shortwave 3DRT is under development using a convolutional neural network approach and SHDOM[8]:
  - ➢ Input: 3D cloud liquid water content and effective radius.
  - ➢ Output: $F^{\downarrow}_{SW,surf}$ and atmospheric heating rates.

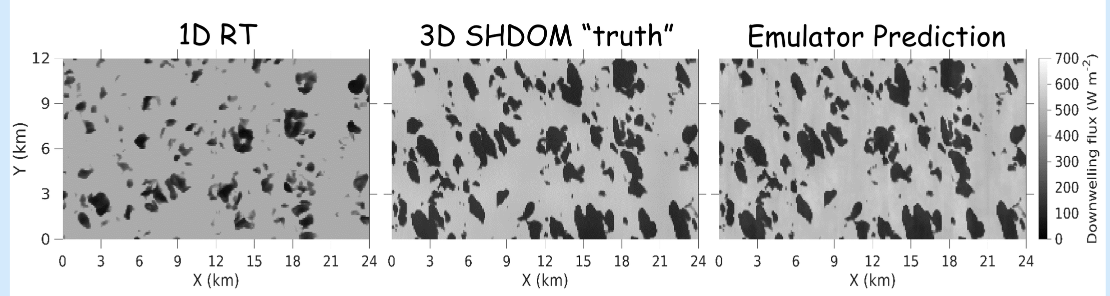

Fig. 5. Initial 3DRT emulator performance for surface solar irradiance spatial distribution.

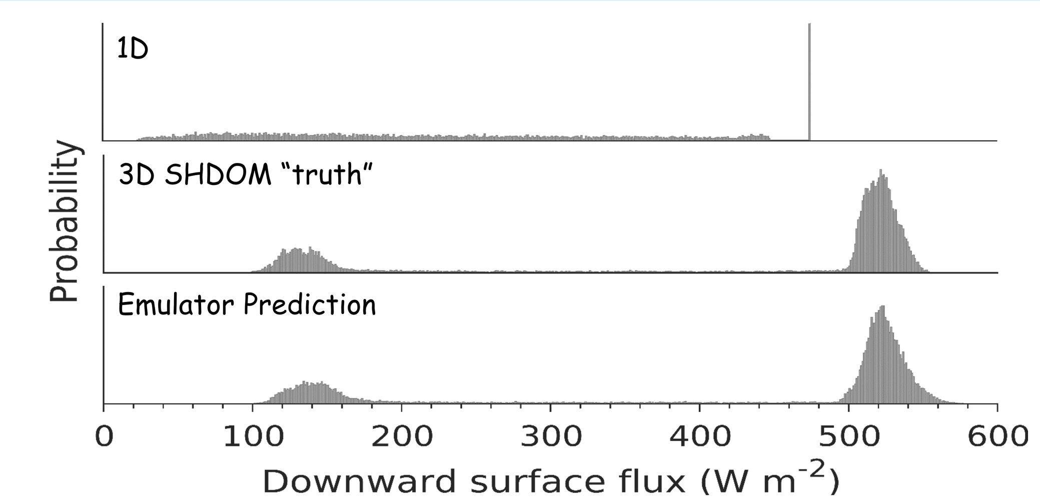

Fig. 6. Initial 3DRT emulator performance for the surface solar irradiance PDF.

- Initial implementation of 3DRT emulator captures the $F^{\downarrow}_{SW,surf}$ spatial distribution (Fig. 5) and PDF (Fig. 6) very well.

Ongoing and Future Work

- Coupling 3DRT emulator to LES in the System for Atmospheric Modeling (SAM):
  - ➢ Existing SAM setup[1,2,3] is coupled to RRTMG radiation.
  - ➢ Seek to replace RRTMG shortwave with 3DRT emulator.
- Coupling SAM with the Simplified Land Model (SLM):
  - ➢ Existing setup[1,2,3] uses SAM version 10 with uniform prescribed surface fluxes. The newest SAM version 11 includes SLM for coupled land-atmosphere interactions.
  - ➢ Seek to merge existing SAM setup with newest version for coupling with SLM.
  - ➢ Initial implementation appears reasonable (Fig. 7), but further testing is required.

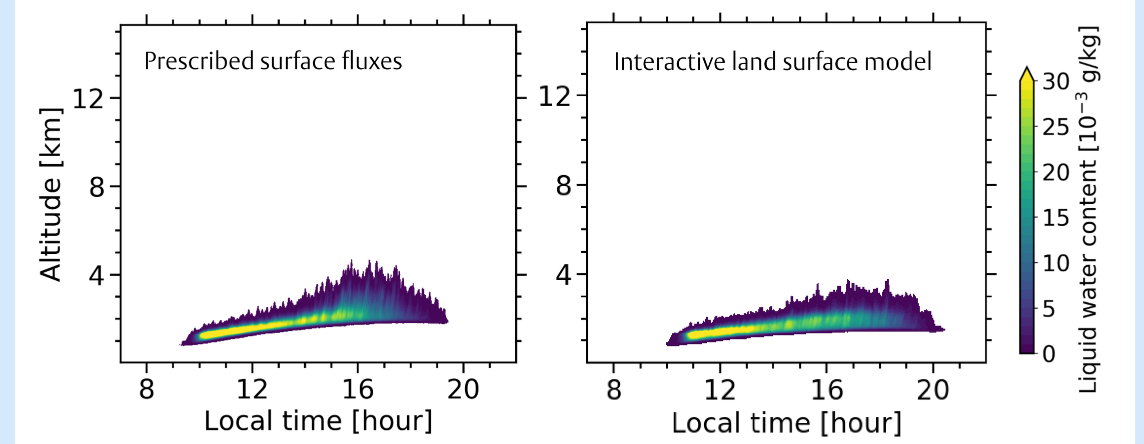

Fig. 7. Simulated diurnal evolution of horizontally-averaged cloud liquid water content for a case study on 22nd May 2018 at SGP with (left) prescribed surface fluxes and (right) surface fluxes calculated by the Simplified Land Model.

- Evaluation against observations:
  - ➢ Are the cloud fields from coupled LES and 3DRT more realistic?
  - ➢ Systematic simulation of many cases may enable a statistical comparison against observations, navigating inevitable case-to-case LES-observation differences.

References

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