Capturing the Effects of Surface Flux Heterogeneity on the Lower Sub-grid Atmosphere in Earth System Models with a Multi-Column Approach

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Abstract

Earth System Models (ESMs) traditionally operate at large horizontal resolutions, on the order of 100 km, which can obscure the effects of smaller scale heterogeneity. When examining land surface states and fluxes in ESMs, one common approach to mitigate this issue is to divide the sub-grid land surface into distinct homogeneous clusters and then resolve the water, energy, and biogeochemical processes on each cluster or tile. The literature, as well as work in the Coupling of Land and Atmospheric Subgrid Parameterizations (CLASP) project, indicates that surface heterogeneity has important implications for atmospheric processes as well. Previous work using large-eddy simulation (LES) shows that spatial variability in surface heating can produce significant secondary circulations closely related to the type and scale of heterogeneity that are not captured by single column models. This presentation aims to address this persistent weakness by using a clustering or tiling approach, similar to that used with land surface processes, for the atmosphere. To accomplish this task, we run the Cloud Layers Unified By Binomials (CLUBB) single column model, a sub-grid turbulence and cloud parameterization scheme, over a 100 km box centered at the Southern Great Plains site in Oklahoma for a variety of surface and atmospheric conditions. The model is run independently over multiple surface clusters defined by surface sensible heat fluxes in the given domain. Results indicate that significant differences exist for some cases between the single column and multicolumn cases for liquid water path (LWP) as well as the turbulent kinetic energy (TKE) budget, and that results converge on consistent results with a fairly low number of clusters (i.e., atmospheric columns). We follow this up with a connected multicolumn setup where each column is dynamically connected with the other columns throughout the run to qualitatively capture the circulations observed in the LES output. The existing results show promise for capturing the effects of subgrid scale surface flux heterogeneity on the lower atmosphere in ESMs with the application of a multicolumn CLUBB setup.

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Background and Motivation

In the lower atmosphere in Earth System Models (ESMs) currently use single column models, such as Cloud Layers Unified by Binomials (CLUBB)

Why is that a problem? -- With a homogenized surface, single column models cannot capture secondary circulations that can be induced by large, close proximity patches with significant differences in sensible heat

Large-Eddy Simluation (LES) can capture these circulations and shows that they increase Liquid Water Path (LWP), which measures vertically integrated liquid water.

Why isn't LES a solution? -- LES is too computationally intensive for ESMs

Can a two column CLUBB setup with modeled circulations approximate the heterogeneity induced secondary circulations seen in LES?

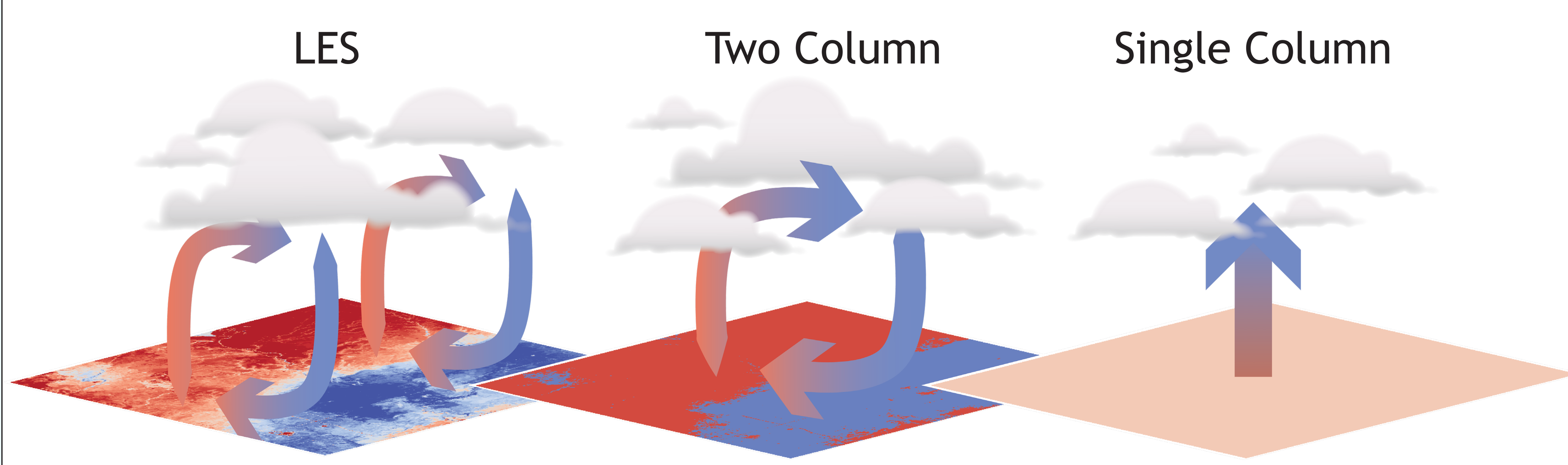

Figure 1. Illustrating the difference between representations of secondary circulations in three different modelling approaches

Two Column Coupled CLUBB Setup

Circulation flux Specification

- Circulation depth set to 1km
- Initiation based on surface heating
- Recirculated with mass balance at height where virtual potential temperature profiles of the 'hot' and 'cold' column cross
- Magnitude a function of virtual potential temperature differences, and a lengthscale of heterogeneity based on sensible heat

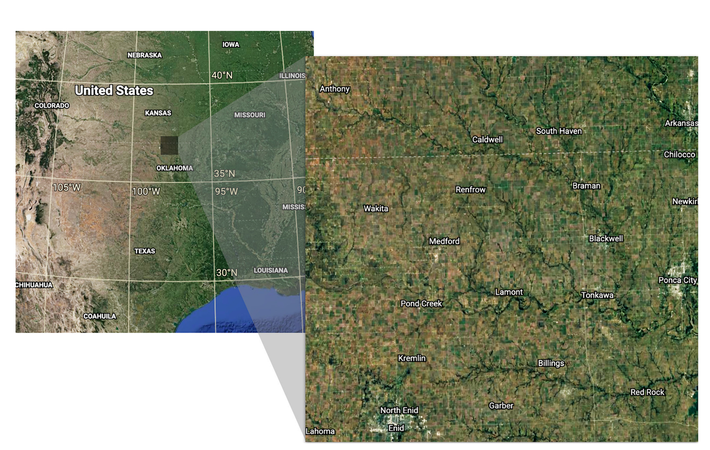

Figure 2. Site in the Southern Great Plains, 100 km by 100 km 39 simulation periods of 15 hours from 7 am to 10 pm

Two Column Model Results

- Little difference from one and two columns when uncoupled
- Large increase in LWP when the circulations flux is added (Figure 3a)
- LWP increase still present after circulation stops
- Magnitude of circulation flux on order of changes due to atmospheric forcing or smaller

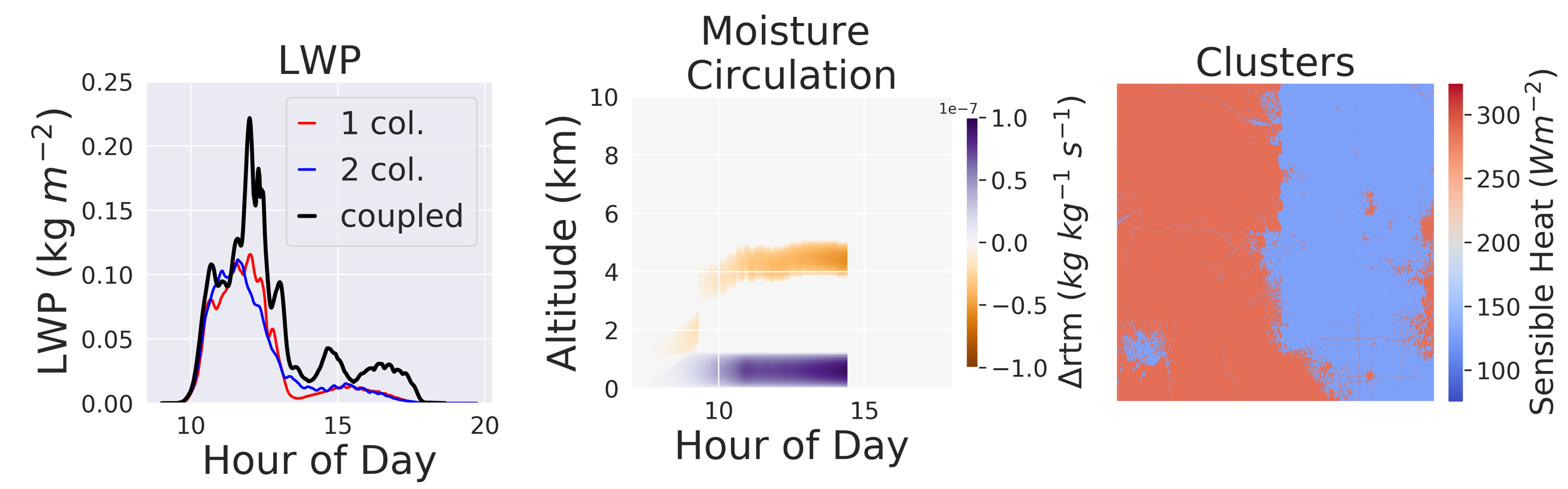

Figure 3a. (left) LWP for a single column, two column, and two column coupled case for 2017-7-16. **Figure 3b. (center)** magnitude and vertical coverage of the modeled moisture circulation flux for the same period. **Figure 3c.** (right) two surface clusters based on sensible heat flux.

Sensitivity of LWP to Circulation Flux

Generally, increasing the magnitude of the circulations yielded one of four responses.

A. Increased LWP

B. No changes until some critical threshold is reached, where LWP then increases

C. No Changes

D. Complex, non-linear changes to LWP

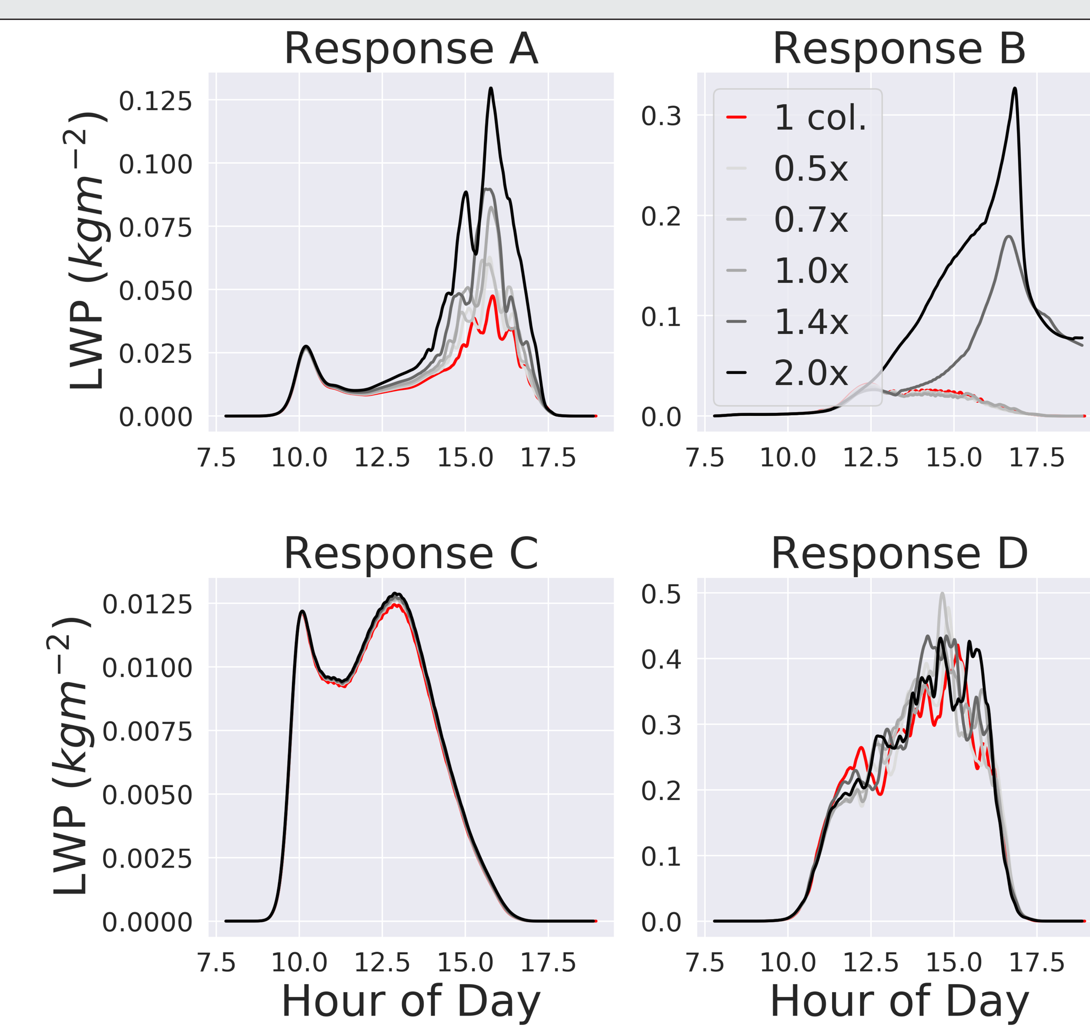

Figure 4 (a-d). LWP for a single column and 5 two-column coupled cases with circulation flux magnitude varied by 0.5, 0.7, 1, 1.4 and 2 times.

Comparison with Large-Eddy Simulation

- CLUBB Single Column is analogous to the homogeneous LES, and CLUBB Multi-Column analagous to heterogeneous LES
- LES and CLUBB don't always match, but when the homogeneous LES matches the single column CLUBB, **we see similar responses to heterogeneity in the LWP from LES and multi-column CLUBB**
- Adding heterogeneity yields same response, generally increases in both cases.

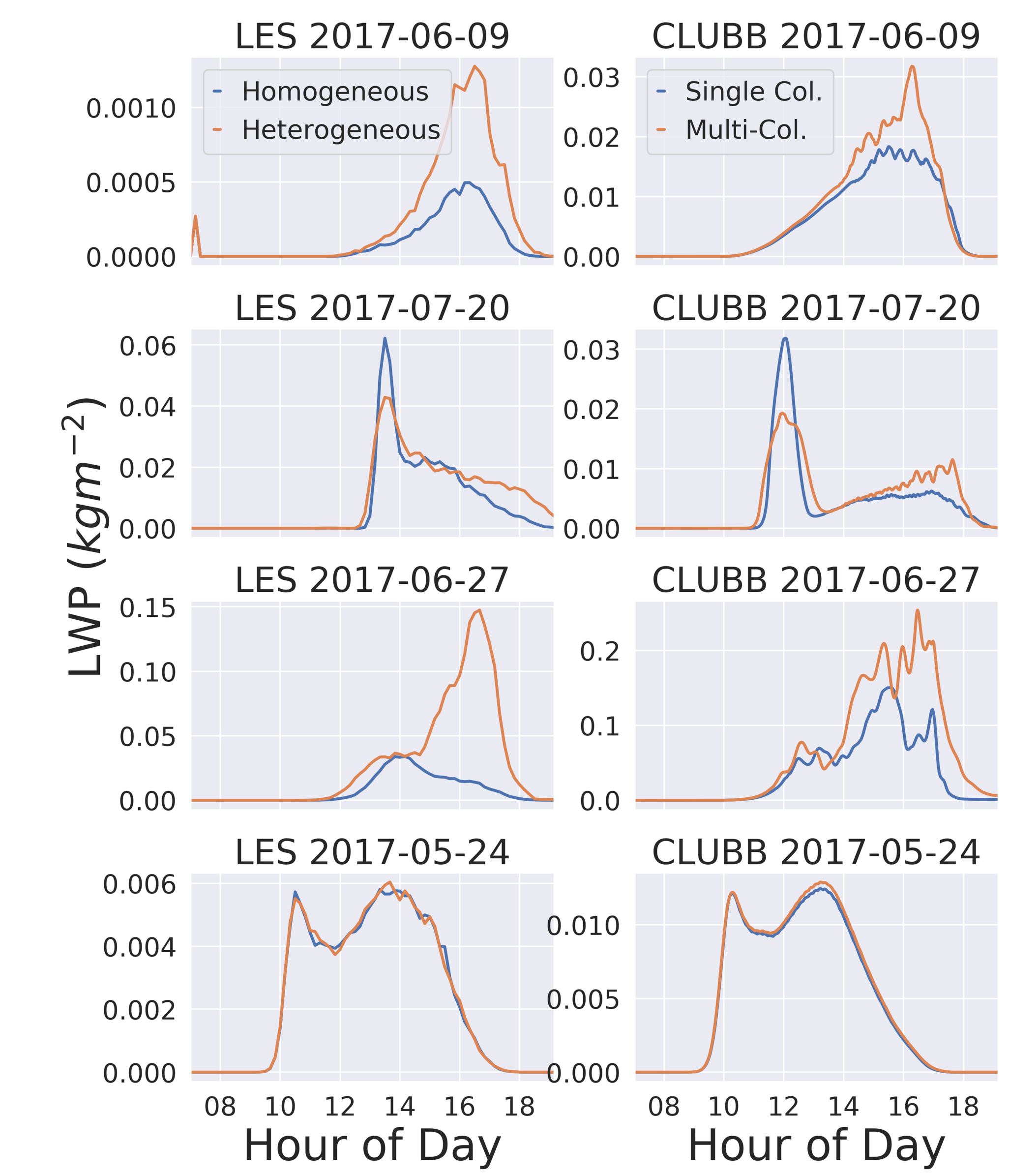

Figure 5. LES vs CLUBB results for LWP in homogeneous and heterogeneous cases

Conclusions

- **Heterogeneity induced secondary circulations**, which are not moddled in ESMs and cannot be resolved by existing single column models, **can be modeled with two CLUBB columns**
- **Atmospheric response to modeled circulations appears dependent on atmospheric state**
- **Similar atmospheric responses are seen to heterogeneity in a coupled two column CLUBB model and LES**

References:
Simon, J. S., Bragg, A. D., Dirmeyer, P. A., & Chaney, N. W. (2021). Semi-coupling of a field-scale resolving land-surface model and WRF-LES to investigate the influence of land-surface heterogeneity on cloud development. Journal of Advances in Modeling Earth Systems, 13, e2021MS002602. https://doi.org/10.1029/2021MS002602

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