# 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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## 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?**

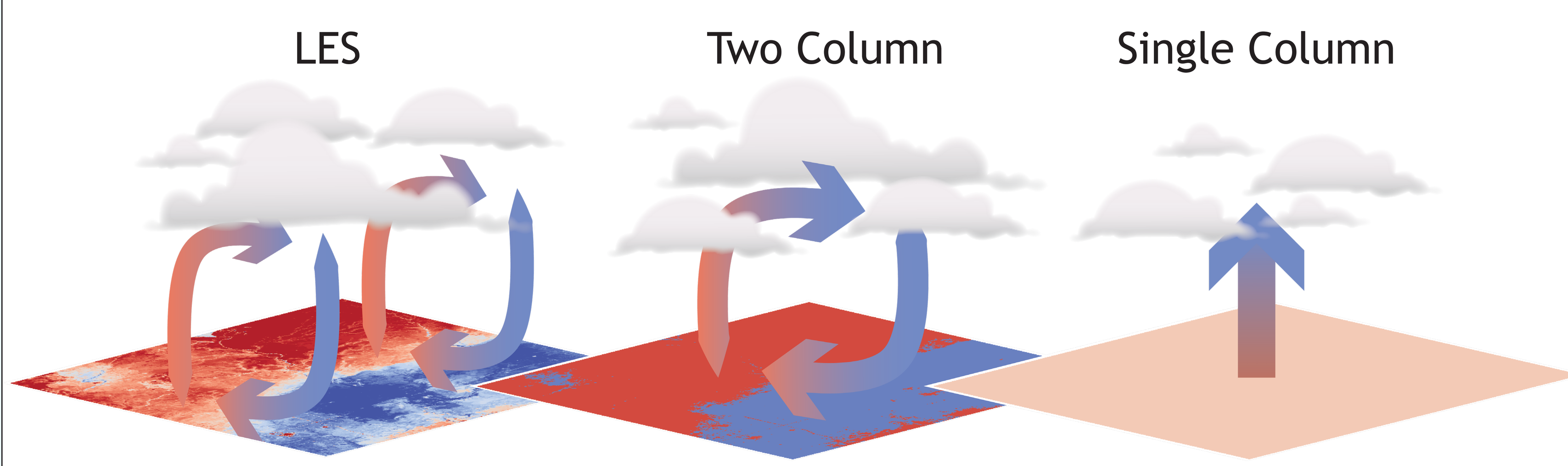


**Figure 1.** Illustrating the difference between representations of secondary circulations in three different modelling approaches

## 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

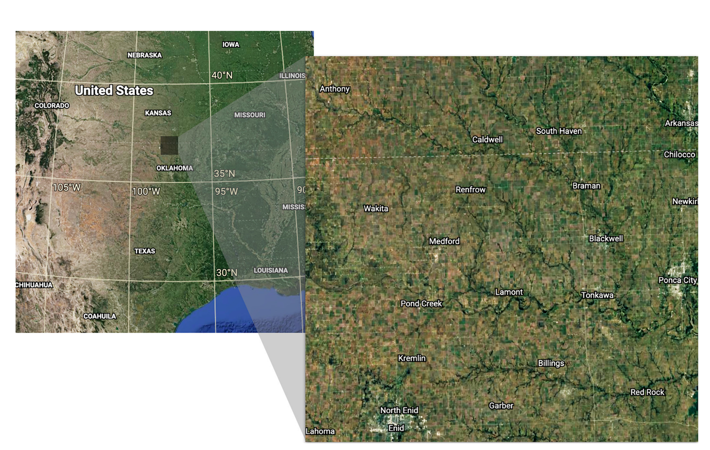


**Figure 2.** Site in the Southern Great Plains, 100 km by 100 km
39 simulation periods of 15 hours from 7 am to 10 pm

## 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

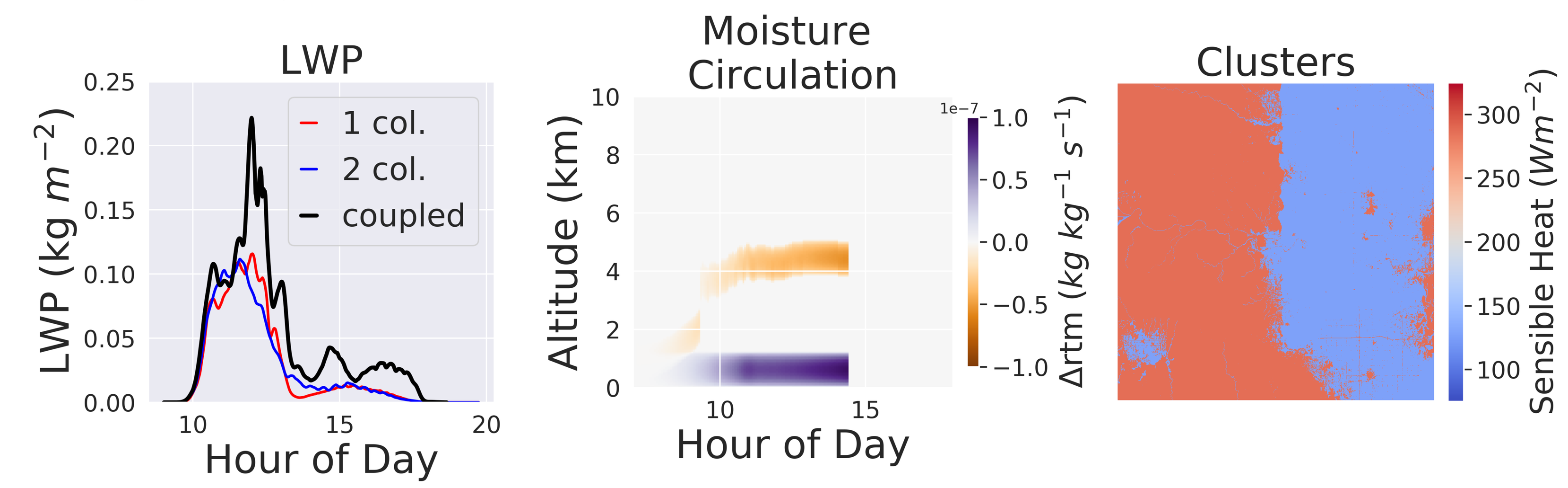


**Figure 3a. (left)** LWP for a single column, two column, and two column coupled case for 2017-7-16. **Figure 3b. (center)** magnitude and vertical coverage of the modeled moisture circulation flux for the same period. **Figure 3c.** (right) two surface clusters based on sensible heat flux.

## 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

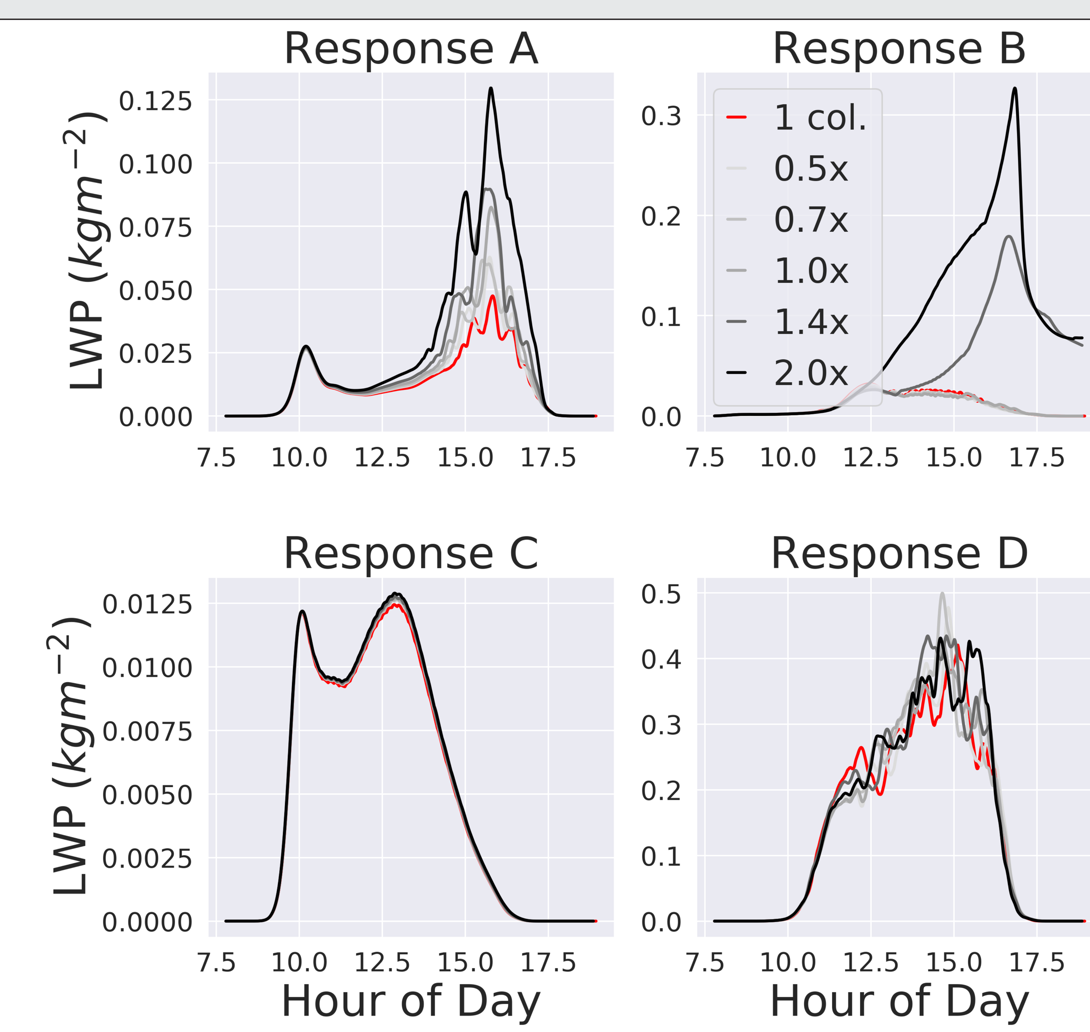


**Figure 4 (a-d).** LWP for a single column and 5 two-column coupled cases with circulation flux magnitude varied by 0.5, 0.7, 1, 1.4 and 2 times.

## 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.

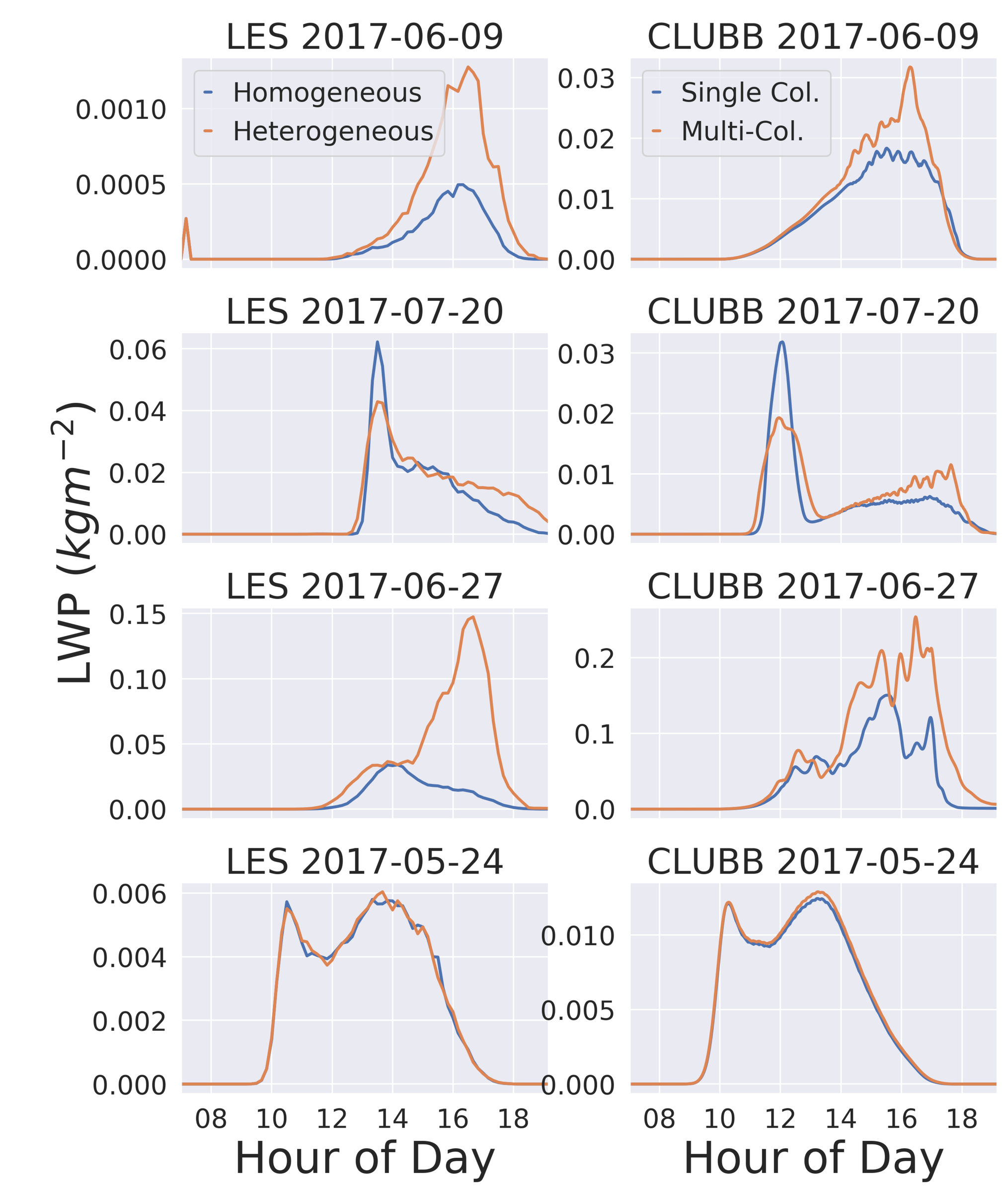


**Figure 5.** LES vs CLUBB results for LWP in homogeneous and heterogeneous cases

## Conclusions

- **Heterogeneity induced secondary circulations**, which are not modeled 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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