Representing the atmospheric impacts of land surface heterogeneity in the Community Earth System Model (CESM)

Megan D. Fowler[1], Adam R. Herrington[1], Richard B. Neale[1], Tyler Waterman[2], David M. Lawrence[1], Finley M. Hay-Chapman[3], Paul A. Dirmeyer,[3] Julio T. Bacmeister[1], and Nathaniel W. Chaney[2]

[1]NSF National Center for Atmospheric Research [2]Duke University [3]George Mason University

Motivation

- Small scale (O(1)-O(10) km) land surface heterogeneity can generate mesoscale circulations[1-3] that alter cloud cover and precipitation[4]
- Earth System Models operate on coarser scales, relying on parameterizations to capture subgrid-scale phenomena[5-7]
- Recognized importance of organized convection (vs. small-scale turbulence) for capturing atmospheric responses to heterogeneity in models[6-9]

Methods

Coupling representations of subgrid-scale heterogeneity in CESM

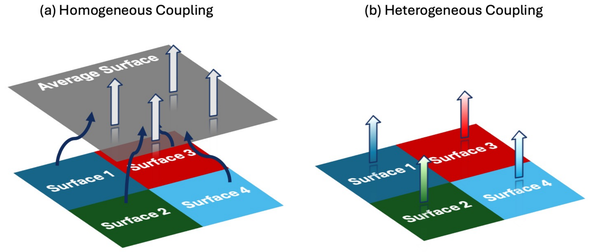
Community Land Model (CLM)

- Surface tiles represent different surface types (plant functional types, etc.) with individually-computed fluxes and states

Community Atmosphere Model (CAM)

- Default turbulence scheme (CLUBB[10]) computes subgrid (co)variances
- Recent development: a unified convection scheme (CLUBB+MF)[11] with a new mass-flux (MF) component captures larger, organized updraft plumes

We link these CLM and CAM subgrid-scale parameterizations by initializing CLUBB+MF updraft plumes directly from tile-level fluxes/states (*Fig. 1*).



Single-column (SCAM[12]) experiments with an idealized, highly heterogeneous surface

- 25 CLUBB+MF plumes are initialized when the buoyancy flux becomes positive
  - Homogeneous (**HOM**): All 25 are initialized when grid-mean flux >0
  - Heterogeneous (**HET**): Plumes divided evenly among surfaces; initialized when the tile-flux >0
- Stochastic entrainment with a constant length scale (250 m)
- DOE ARM Southern Great Plains site using LASSO VARANAL atmospheric forcing[13] for 2015-2016 Jun-Aug
- CLM surface modified to increase temperature and moisture heterogeneity *(Fig. 2);*
  - Grid covered by 25% each lake, urban, C3 grass, and irrigated cropland.

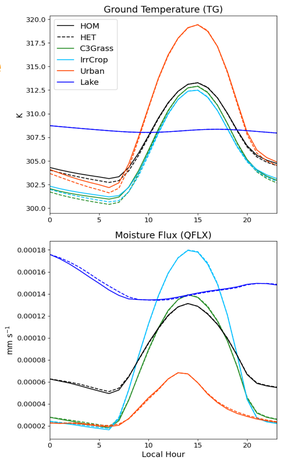


Figure 2: *Mean diurnal cycles in CLM-produced ground temperature and moisture flux for grid-means (black) and individual surface tiles.*

Results

1. Initializing updraft plumes from a grid-mean surface is different than averaging over plumes initialized over individual surfaces.

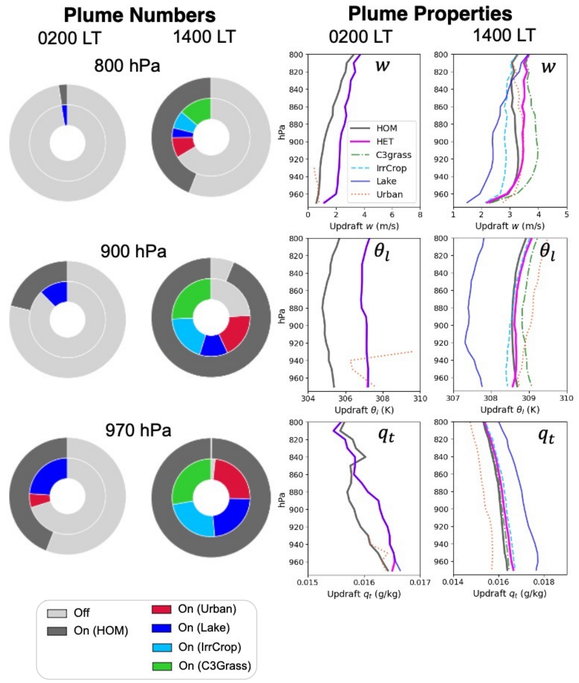


Figure 3: *(Left) Mean number of plumes active at each vertical level at 0200 and 1400 LT; HOM results are in the outer ring, and HET results in the inner ring, subdivided by surface type they are initiated over. (Right) Mean vertical profiles of plume properties (speed (w), temperature (θ_l), and humidity (q_t)) at 0200 and 1400 LT.*

2. Heterogeneity enhances the activity of convective plumes overnight, but reduces them during the day.

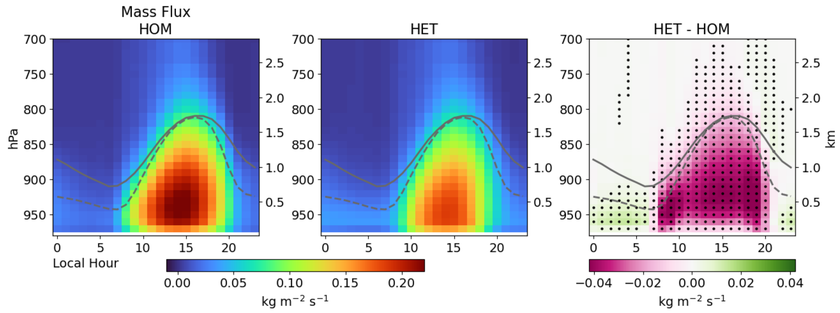


Figure 4: *Time-height plots of the mean mass flux from the MF parameterization on all days. The boundary layer height is overlaid in gray solid (HOM) and dashed (HET) lines. The difference in mass flux is shown on the right, with stippling indicating significance at the 95% level based on a student's t-test.*

3. Atmospheric responses to heterogeneity vary depending on synoptic condition.

	Cloud Liquid (cl)	Rainfall (P_r)	# of Days
Clear	$< c_l(50^{th})$	$< P_r(75^{th})$	86
Cloudy	$\geq c_l(50^{th})$	$< P_r(75^{th})$	39
Rainy	--	$\geq P_r(75^{th})$	45

Table 1*: Definition of synoptic conditions based on daytime averages (0060-1800) of cloud liquid (c_l) below 600 hPa and precipitation amount. Days must classify the same in HOM and HET to be counted.*

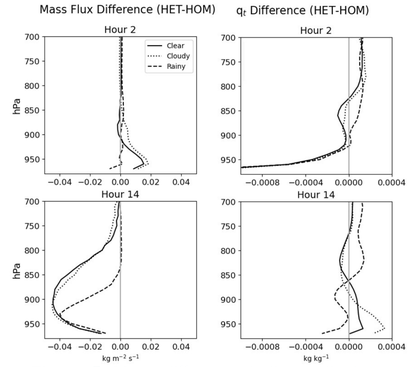


Figure 5: *Mean difference in the vertical profiles of mass flux and total moisture (q_t) at 0020 (top) and 1400 (bottom) local time.*

Conclusions

- Using CLM surface tiles to initialize CLUBB+MF updrafts directly drives key differences in plume properties and number.
- Nocturnal and day-time atmospheric responses to heterogeneity differ in sign and magnitude, and vary by synoptic condition.
- Ongoing work is needed to understand the breadth and realism of atmospheric changes, and to incorporate a representation of overturning secondary circulations, which requires horizontal exchange between at least some subset of CLUBB+MF plumes.

Citations

[1]Doran et al. (1995): Boundary layer characteristics over areas of inhomogeneous surface fluxes. *Journal of Applied Meteorology*
[2]Avissar, R., & Schmidt, T. (1998). An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using large-eddy simulations. *Journal of the Atmospheric Sciences*
[3]Bou-Zeid, E., et al. (2020). The persistent challenge of surface heterogeneity in boundary-layer meteorology: A review. *Boundary-Layer Meteorology.*
[4]Berg, L. K., & Stull, R. B. (2005). A simple parameterization coupling the convective daytime boundary layer and fair-weather cumuli. *Journal of the Atmospheric Sciences.*
[5]Huang, M. et al. (2022). Representing surface heterogeneity in land-atmosphere coupling in E3SMv1 single-column model over ARM SGP during summertime. *Geoscientific Model Development Discussions*
[6]Fowler, M. et al. (2024): Assessing the Atmospheric Response to Subgrid Surface Heterogeneity in the Single-column Community Earth System Model, version 2 (CESM2). *Journal of Adv. In Mod. Earth Sys.*
[7]Waterman, T. et al. (2024): A Two-Column Model Parameterization for Subgrid Surface Heterogeneity Driven Circulations. *Journal of Adv. In Mod. Earth Sys.*
[8]Arnold, N. P. (2024): Representing effects of surface heterogeneity in a multi-plume eddy diffusivity mass flux boundary layer parameterization. *Geo. Model Dev.*
[9]Simon, J. et al. (2024): Heterogeneous Land-Surface Effects on TKE and Cloud Formation: Statistical Insights From LES Cases. *JGR Atmo.*
[10]Golaz et al. (2002): PDF-based model for boundary layer clouds. Part I: Method and model description. *J. Atm. Sci.*
[11]Witte et al. (2023): Augmenting the Double-Gaussian Representation of Atmospheric Turbulence and Convection via a Coupled Stochastic Multi-Plume Mass-Flux Scheme. *Mon. Wea. Rev.*
[12]Gettelman et al. (2019): The Single Column Atmosphere Model Version 6 (SCAM6): Not a scam but a tool for model evaluation and development. *Journal of Adv. In Mod. Earth Sys.*
[13]Gustafson et al. (2019): Description of the LASSO data bundles product.

Contact for questions/more info:
Meg Fowler
mdfowler@ucar.edu