RELATIVE ENTROPY AS AN EVALUATION METRIC FOR SUBGRID PARAMETERIZATIONS OF SPATIAL HETEROGENEITY

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LOCAL LAND-ATMOSPHERE INTERACTIONS

- We know that **L-A interactions play a major role** in determining local weather and climate (Santanello et al. 2018)

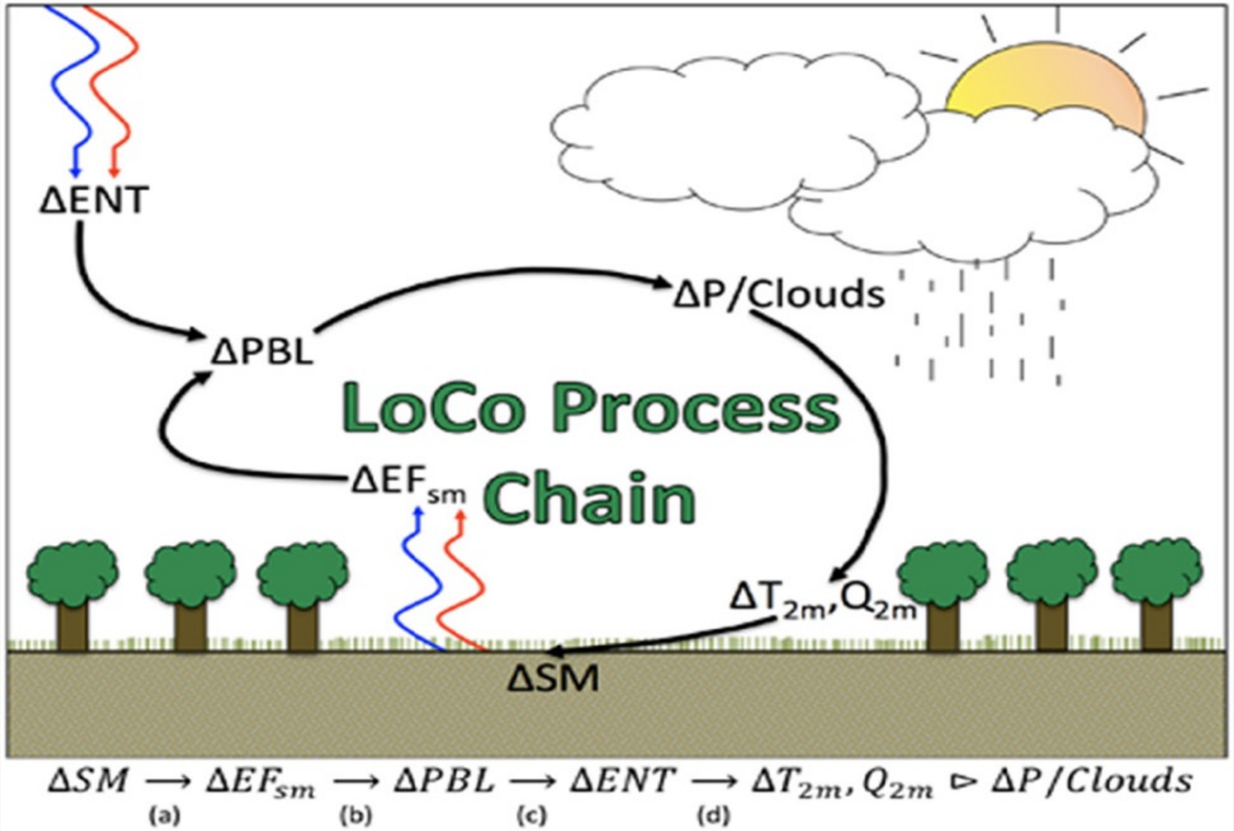
- The land surface **can influence the atmosphere across a wide range of spatial scales** from turbulent/microscale (mm to 1 km) to mesoscale (1-100s km) and synoptic (100+ km) scales

- However, global climate models (GCMs) operate with grid cells of ~100 km; this **wipes out the effect of** finer scale, "subgrid" **surface variations** (i.e. heterogeneity)

Therefore…

The effect of subgrid **land surface heterogeneity** must be ***parameterized***

Figure 2 from Santanello et al. (2018): process chain of local land-atmosphere interactions



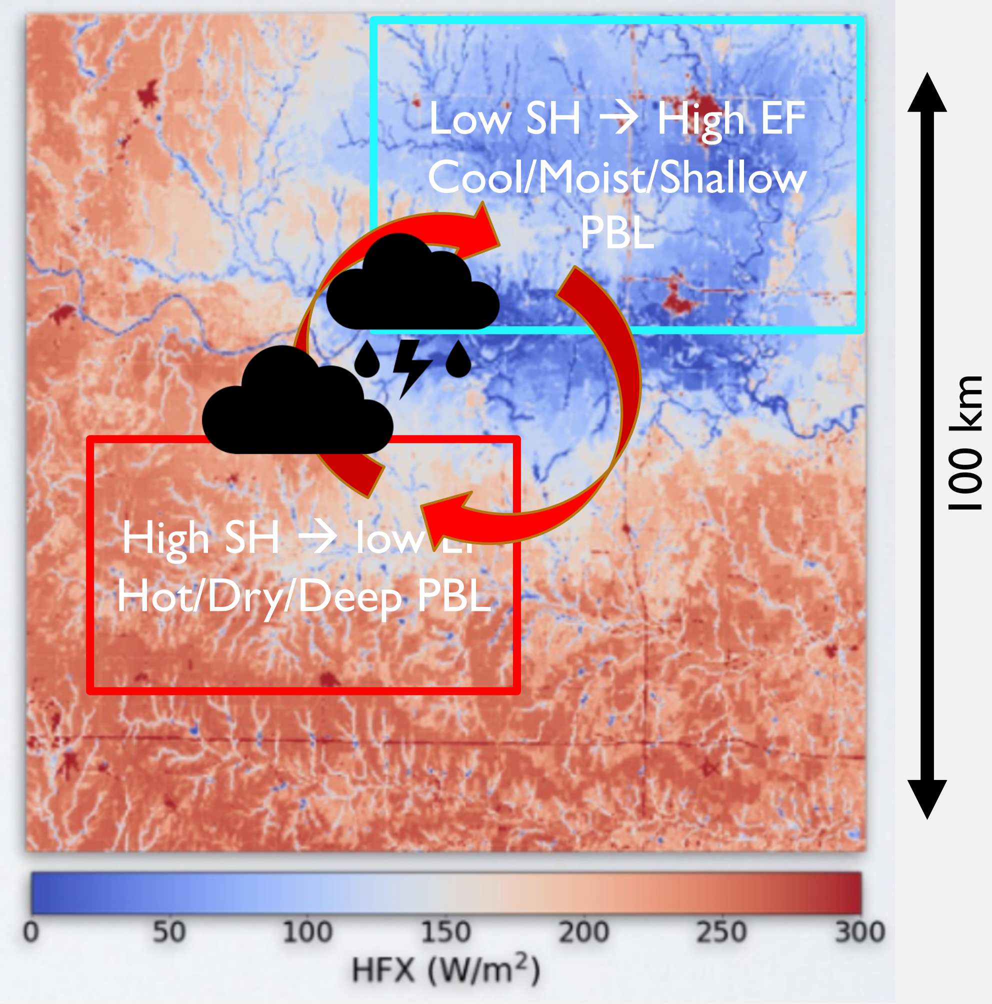
EFFECTS OF HETEROGENEITY

- Surface characteristics (land cover type, roughness length, etc.) drive shifts in the surface fluxes, **which may vary considerably** over small spatial scales <100km [Phillips & Klein, 2017]

- Likelihood of coupling **depends on atmospheric profiles** of temperature and humidity [Findell & Eltahir 2003, Ek et al. 2004]

- Organized **mesoscale circulations may be triggered**, aiding the development of local convection and possibly rainfall AND these **circulations are strongest** when length scale of **heterogeneity is on the order of 10-40 km** [van Heerwaarden et al. 2014]

- This effect of surface heterogeneity, driving shifts in atmospheric properties, is **not captured in today's GCMs**



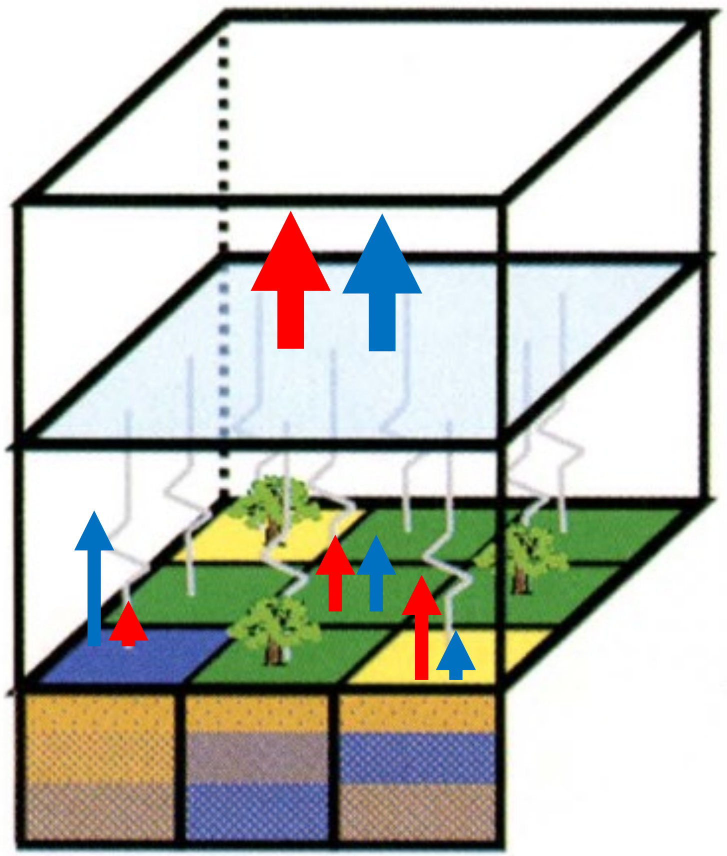
HydroBlocks LSM surface sensible heat flux output over SGP site

HOW IS HETEROGENEITY REPRESENTED IN TODAY'S CLIMATE MODELS? (LAND)

Most climate models currently use a mosaic **Tile Method** to represent subgrid ***land surface*** heterogeneity in coupling:

- Different **land use/land cover (LULC) types** in grid cell represented by **"tiles"** w/ fractional area coverage
- LSM computes **surface fluxes for each tile**
- Tile fluxes are aggregated with an **area-weighted average** and passed to coupling scheme
- Atmosphere just "feels" aggregated flux; this **wipes out any dynamical effect** of heterogeneity

Figure from Mengelkamp et al. (2006)



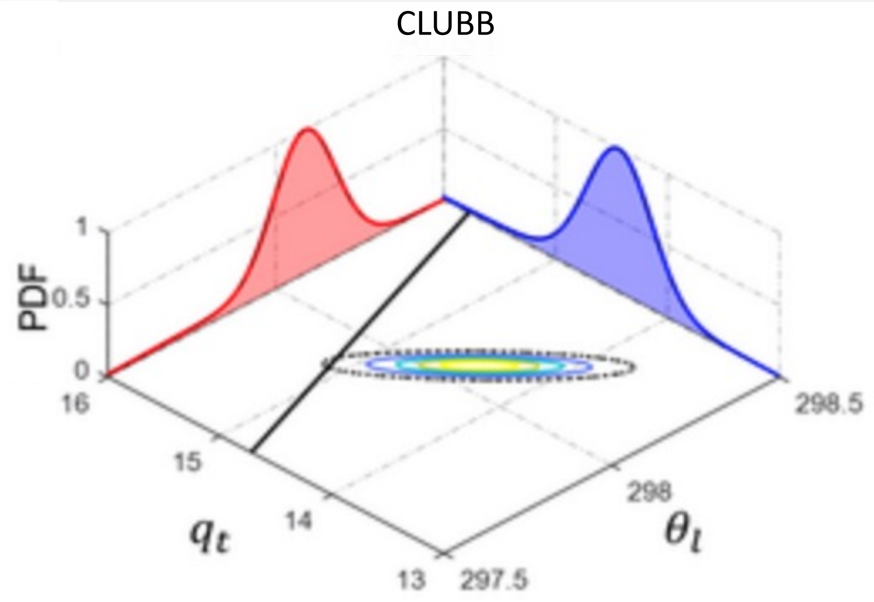
HOW IS HETEROGENEITY REPRESENTED IN TODAY'S CLIMATE MODELS? (ATMOSPHERE)

A common method for representing ***atmospheric*** heterogeneity is to use **subgrid probability density functions (PDFs)**:

- Cloud Layers Unified by Binormals (CLUBB) parameterizations
- Each level, atmospheric fluxes (w'T', w'q', etc.) computed from multivariate **subgrid, *spatial* distributions** of temperature (T), moisture (Q), and vertical velocity (w)
- Subgrid **heterogeneity represented statistically**; cloud properties diagnosed from PDF
- Can have **trouble representing extremes** values of distributions (Fitch 2019)

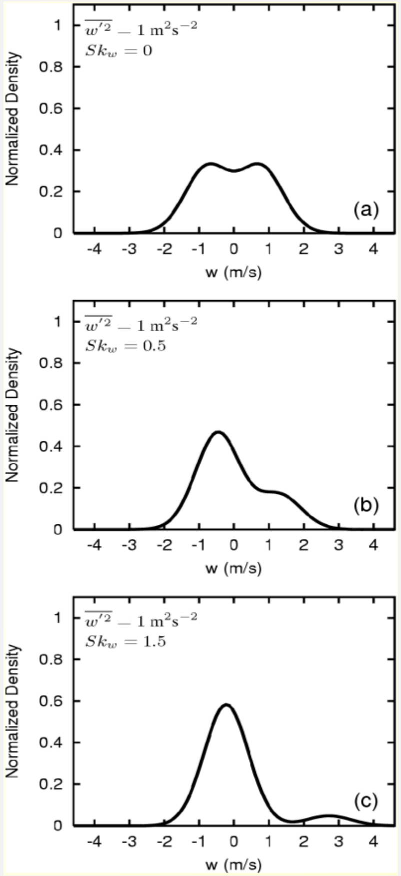
Li et al. (2022)

CLUBB



Example of multivariate subgrid PDF for temperature (Θ_l) & moisture (q_t)

Larson et al. (2012)

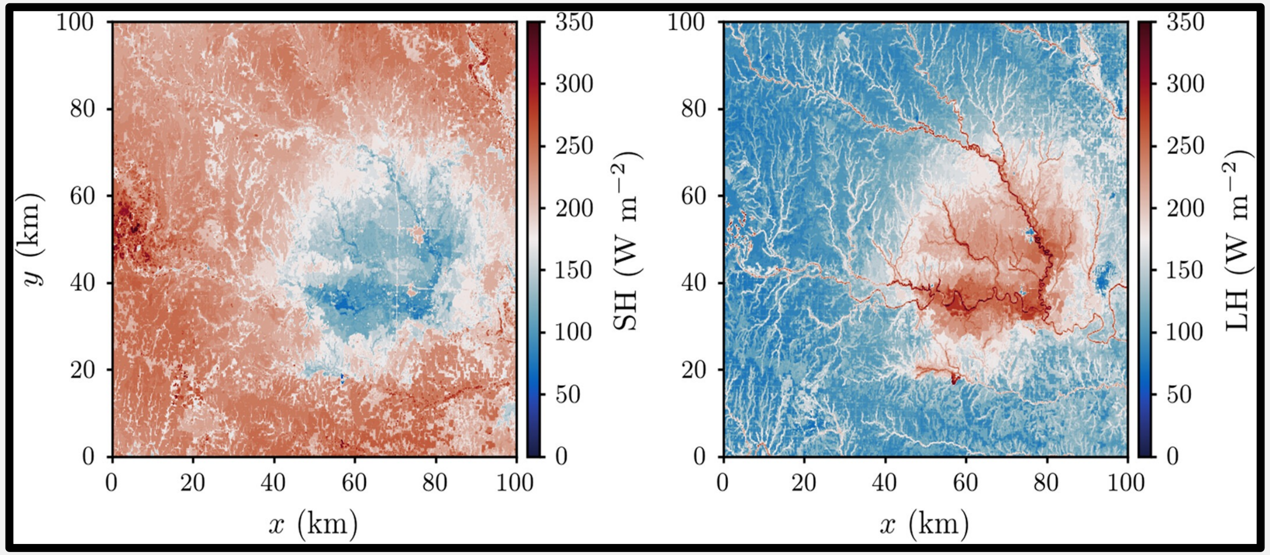


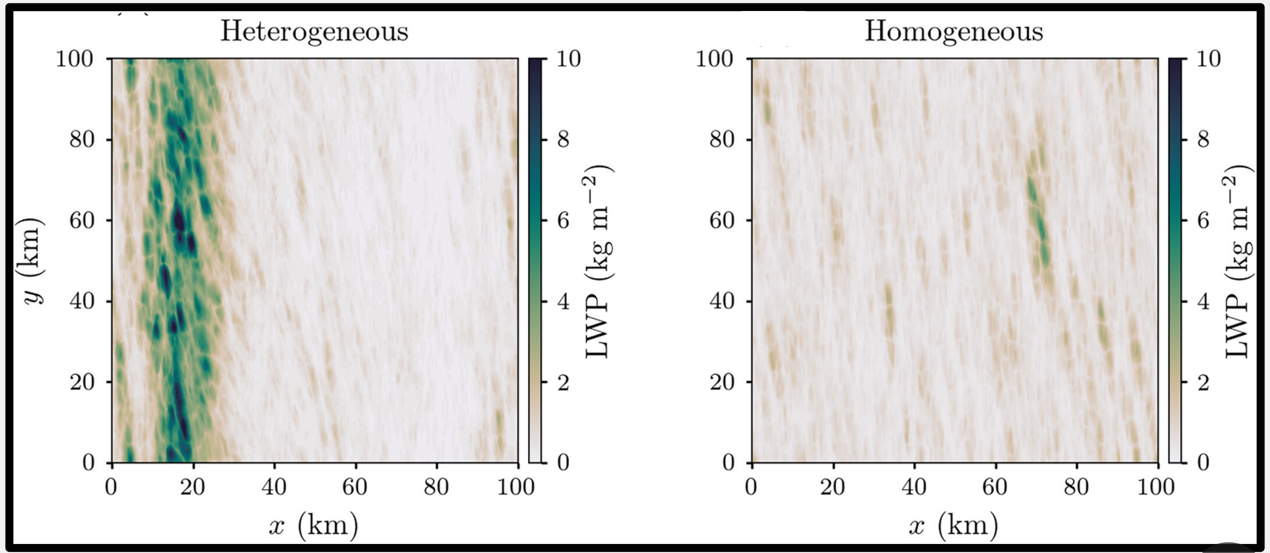
Examples of subgrid PDFs of w; equal variance ($\overline{w'^2}$), varying skewness (Sk_w)

WHAT IS HAPPENING IN REALITY?

High-resolution large-eddy simulation (LES) give us an idea of real-world behavior:

- Simon et al. (2021) and Simon et al. (2024; under review) conducted an LES study to analyze the effects of surface spatial heterogeneity on local convection and cloud development
  - 92 shallow convection days from summer 2015-18, 250m spatial resolution
  - Found that a higher variability of surface sensible heat flux was associated with increased cloud liquid water content





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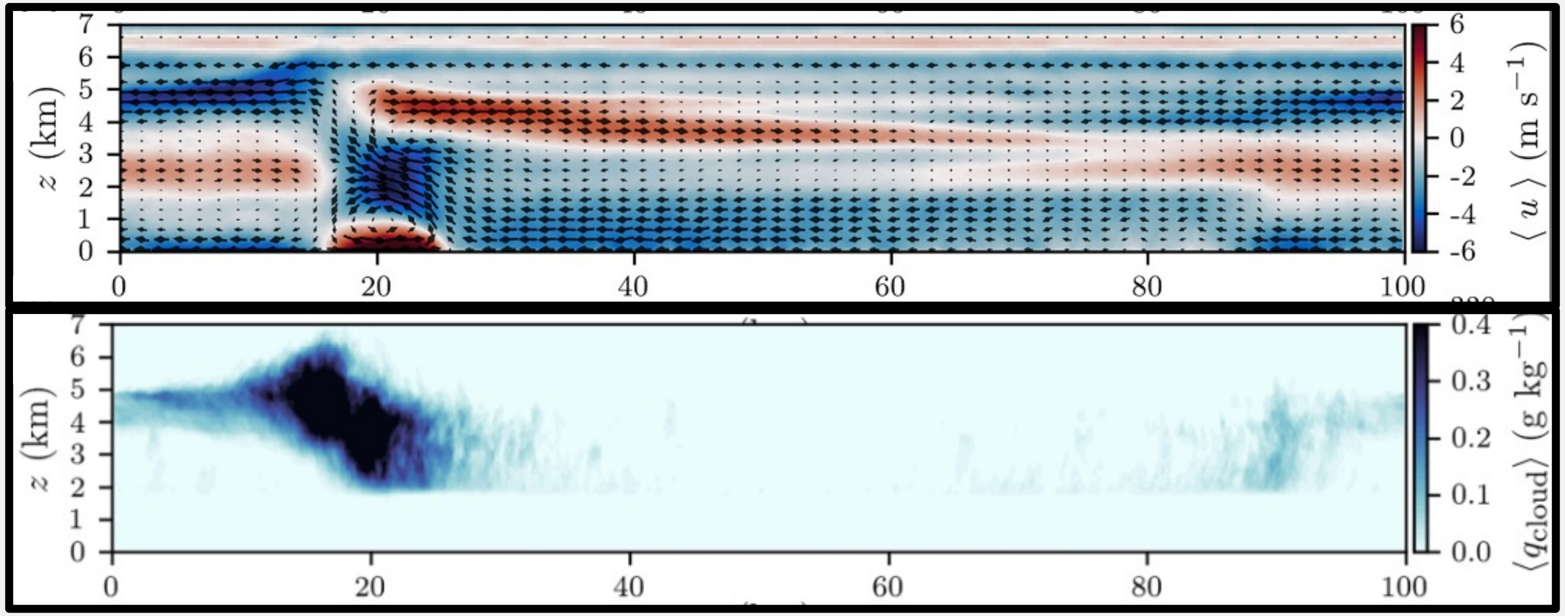

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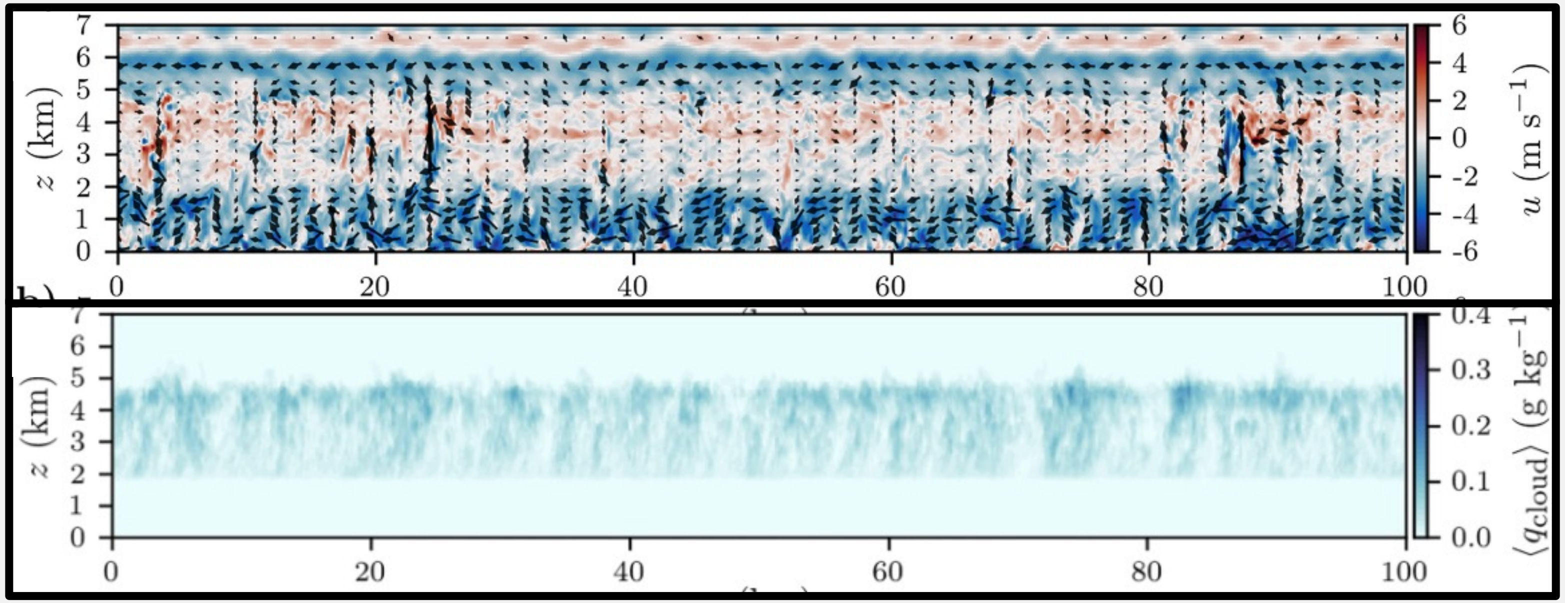

UP-AND-COMING PARAMETERIZATIONS

ATMOSPHERE

Heterogeneity in Convection

- Witte et al. (2022) introduced an augmented version of the CLUBB parameterization
- This version accounts for explicit mass-flux plumes along with subgrid PDF, allowing for a better representation of distribution tail

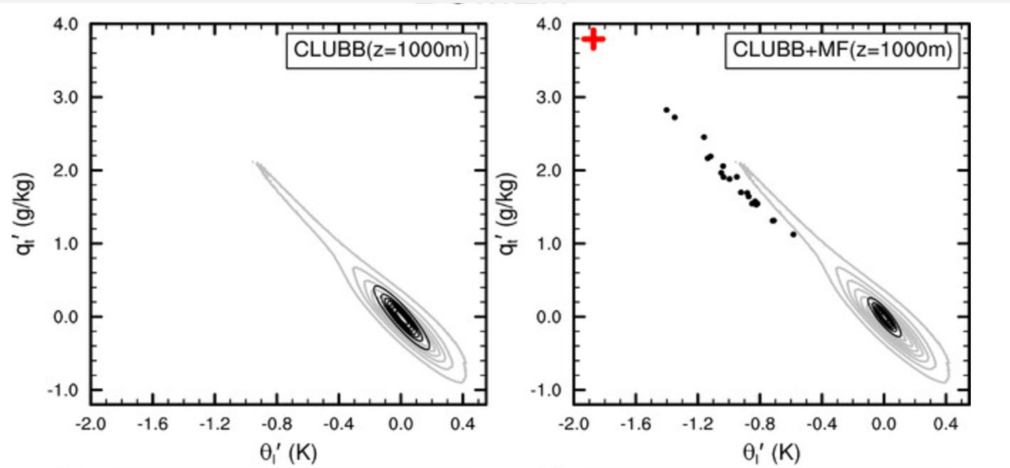

Figure 3 from Witte et al. (2022) illustrating augmented CLUBB PDF approach with stochastic mass-flux plumes.

LAND

Heterogeneity in Surface Fluxes

- Machulskaya & Mironov (2018) defined new method of coupling in ESMs
- Accounts for tile-level spatial variability in surface boundary conditions
- Improved variances used as CLUBB lower BCs

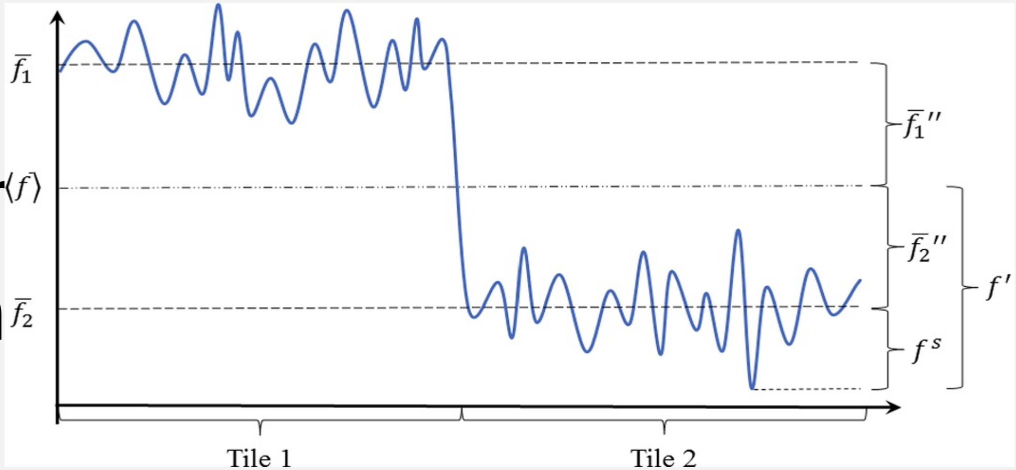

Figure 1 from Machulskaya & Mironov (2018) illustrating tile variability decomposition.

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Ongoing efforts to assess the effect of combining these two parameterizations in CESM2 & E3SM1!

HOW CAN WE ASSESS THE FIDELITY OF PARAMETRIZED SPATIAL HETEROGENEITY IN GCMS?

RELATIVE ENTROPY AS A METRIC: DEFNITION & METHODOLOGY

A measure of distance between two distributions (Kullback & Liebler, 1951):

$$\boldsymbol{R} = \int_{-\infty}^{\infty} \boldsymbol{p} \ln\left(\frac{\boldsymbol{p}}{\boldsymbol{q}}\right) dx$$

$\boldsymbol{p}$: "known" distribution

$\boldsymbol{q}$: predicted distribution

If distributions Gaussian:

$$\boldsymbol{R} = \frac{1}{2}\left[\ln\left(\frac{\sigma_q^2}{\sigma_p^2}\right) + \frac{\sigma_p^2}{\sigma_q^2} + \frac{\mu_p^2}{\sigma_q^2} - 1\right]$$

Tippett et al. (2004)

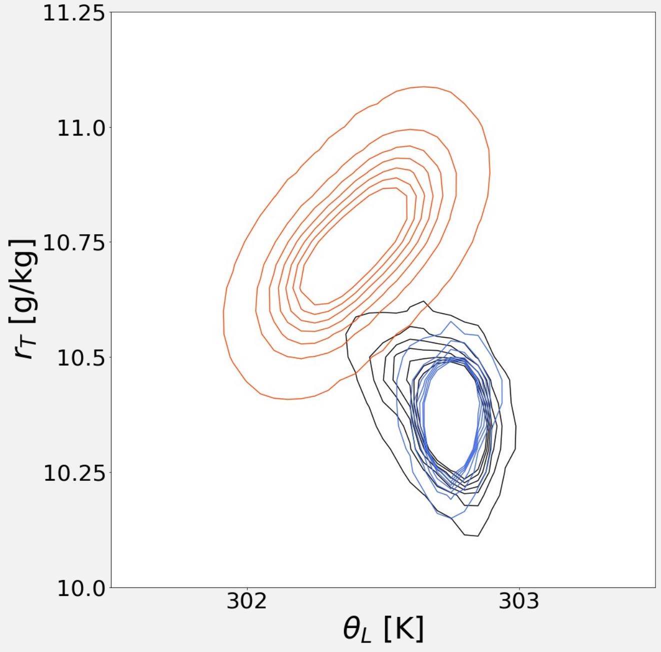
Method: Use Relative Entropy to evaluate representation of spatial heterogeneity in CESM2

$\boldsymbol{p}$: Explicit spatial distributions of atmospheric variables from 92 LES simulations w/ heterogeneous surface conditions from Simon et al. (2024; under review)

$\boldsymbol{q}$: Implicit spatial distributions of atmospheric variables from CLUBB, from single-column CESM forced with identical dataset as LES; for details on model setup, see Hay-Chapman & Dirmeyer (2023)

$\boldsymbol{q}$ (bonus): Homogeneous LES simulations, same as $\boldsymbol{p}$ above, but with fluxes averaged to domain-mean

RELATIVE ENTROPY AS A METRIC: EXAMPLE CASES



Homogeneous LES:

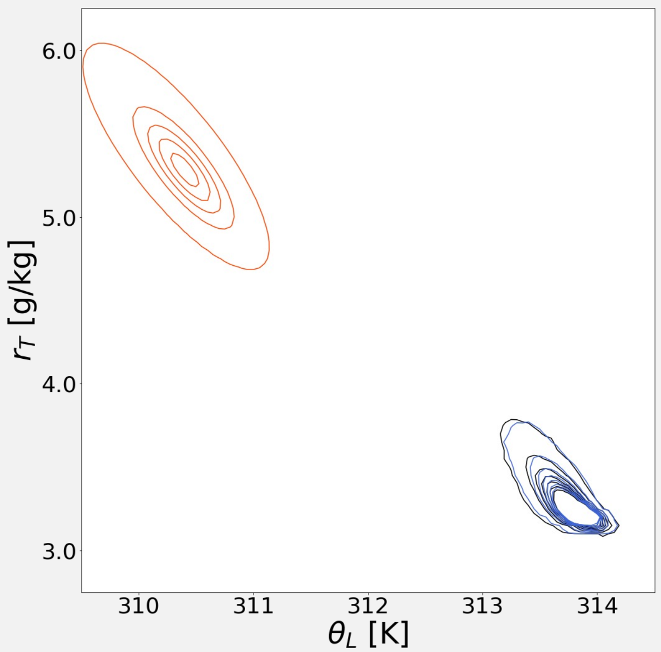
$R_{\theta_L} = 2.389$

$R_{r_T} = 0.232$

CESM2 – CLUBB:

$R_{\theta_L} = 9.401$

$R_{r_T} = 0.500$



Homogeneous LES:

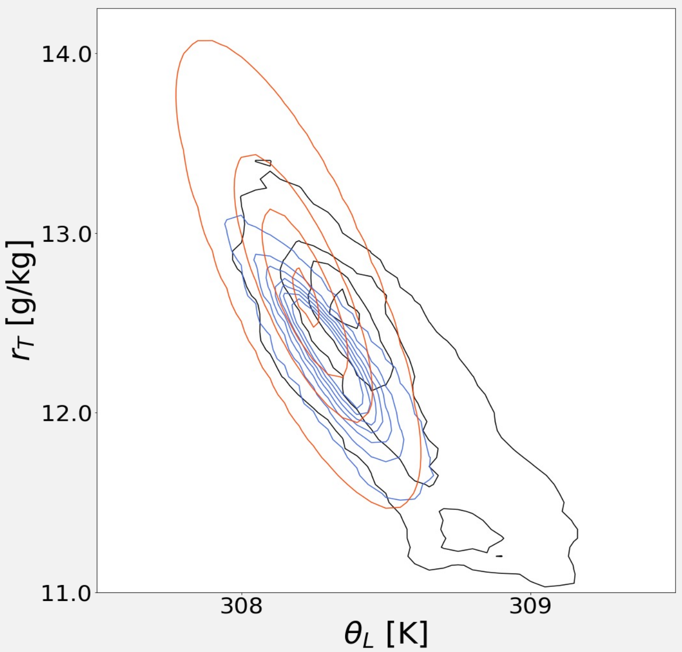
$R_{\theta_L} = 0.011$

$R_{r_T} = 0.010$

CESM2 – CLUBB:

$R_{\theta_L} = 62.581$

$R_{r_T} = 200.805$



Homogeneous LES:

$R_{\theta_L} = 1.931$

$R_{r_T} = 0.602$

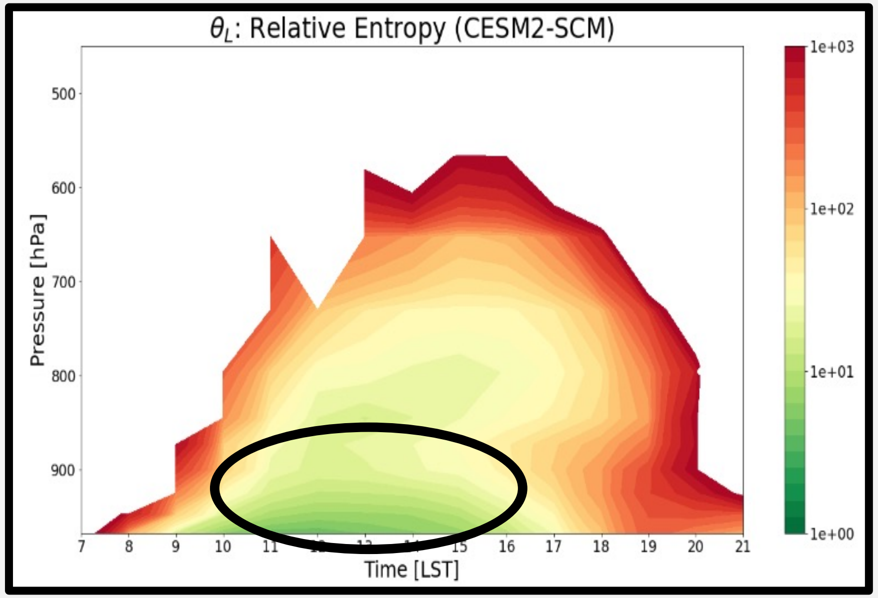
CESM2 – CLUBB:

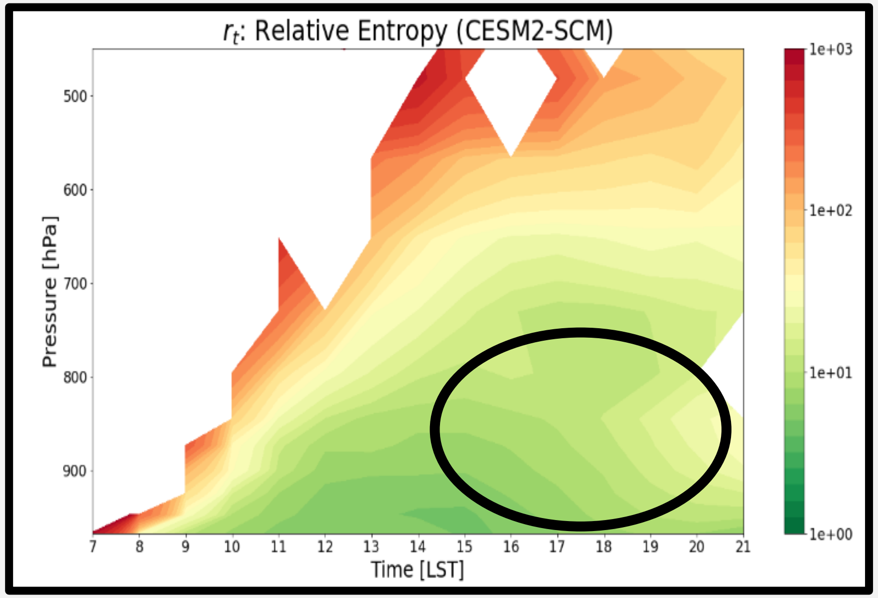
$R_{\theta_L} = 1.716$

$R_{r_T} = 0.840$

CESM2 – SINGLE COLUMN

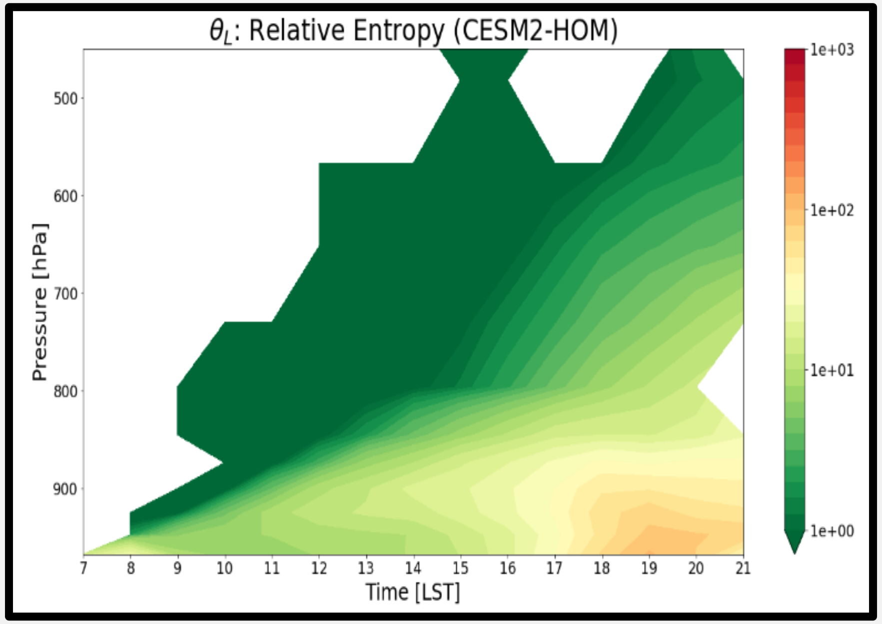
- Spatial variability of moisture (r_t) is better represented when compared to temperature (θ_l)
- Most comparable at surface
- Local maxima of R for θ_l distribution during afternoon, occurs later for r_t
- R decays much faster for θ_l than r_t

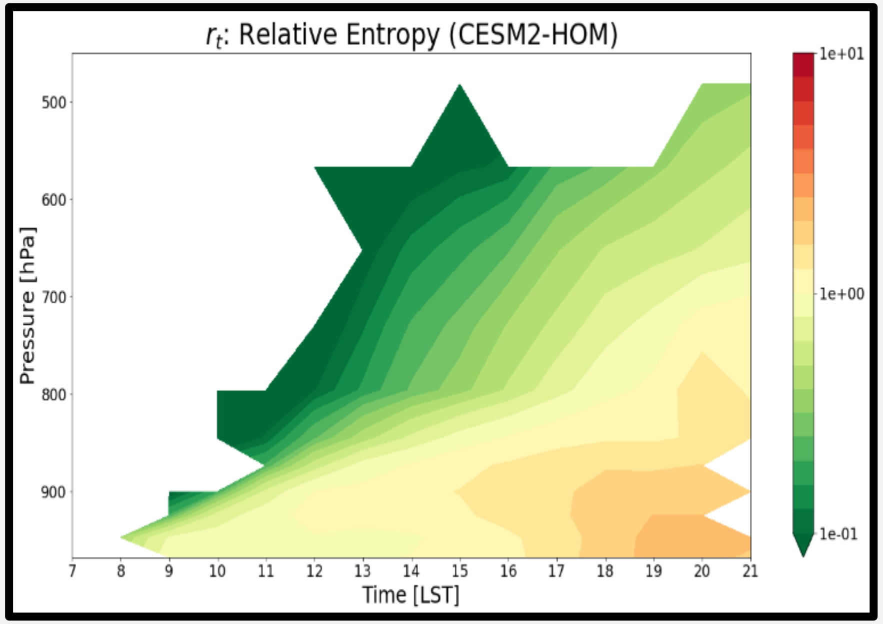




LES – HOMOGENEOUS

- In this case, **R** represents a measure of the impact of surface heterogeneity in the LES
- Mean has maximum in the surface, increases throughout the day
- Local maxima slightly aloft, within cloudy layers





SUMMARY AND FUTURE WORK

- Representing sub-grid heterogeneity in ESMs is a challenging problem; we need a way to evaluate model parameterizations

- Relative entropy, **R**, can be a useful metric for this, particularly for parameterizations based on subgrid probability distributions, like CLUBB

- Very preliminary results shown here, a full study comparing up-and-coming parameterizations with **R** is underway using same Southern Great Plains forcing data

- Future – repeat analysis for other hydroclimates GoAmazon, CACTI-Relampango

THANKS!