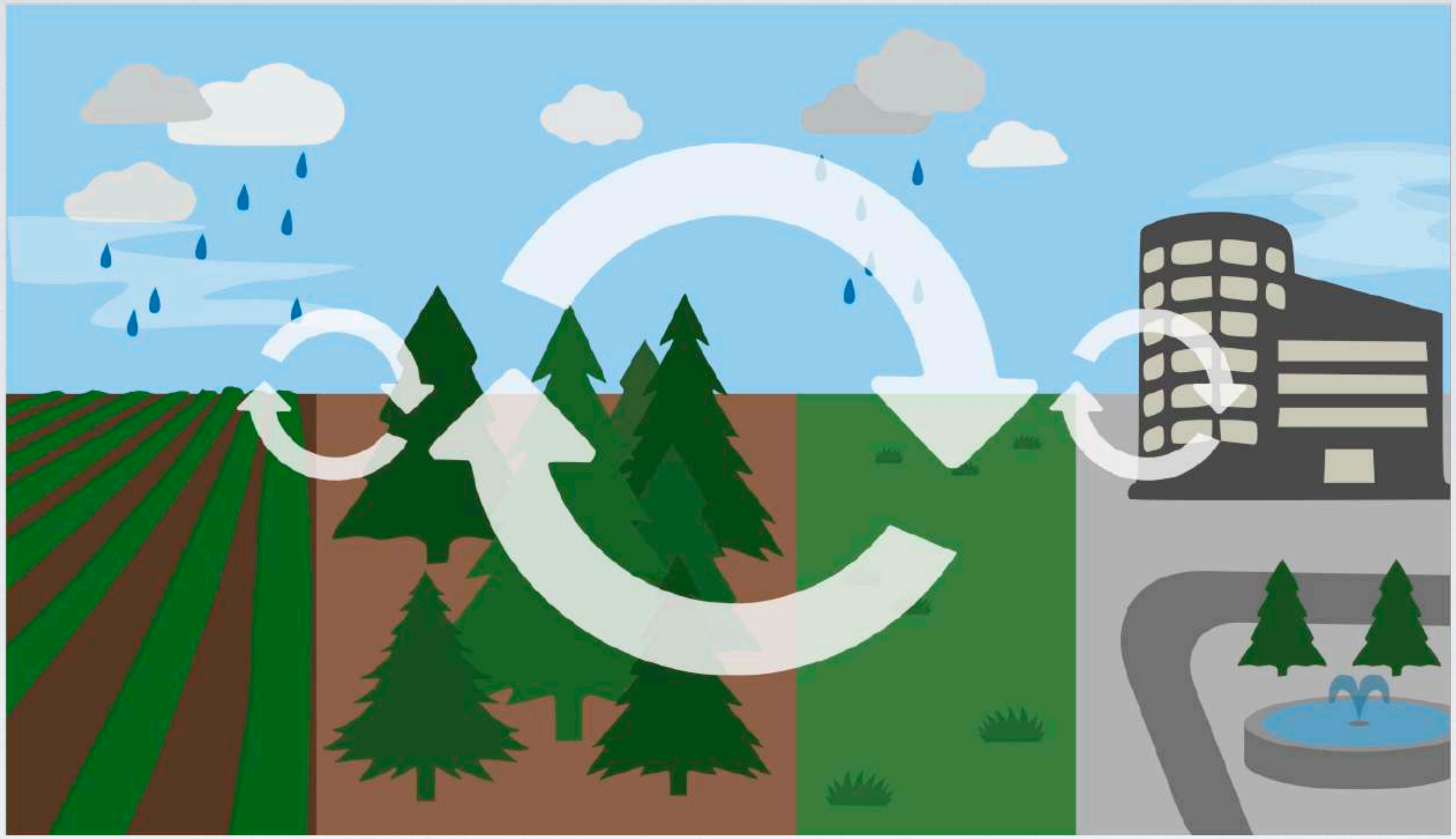
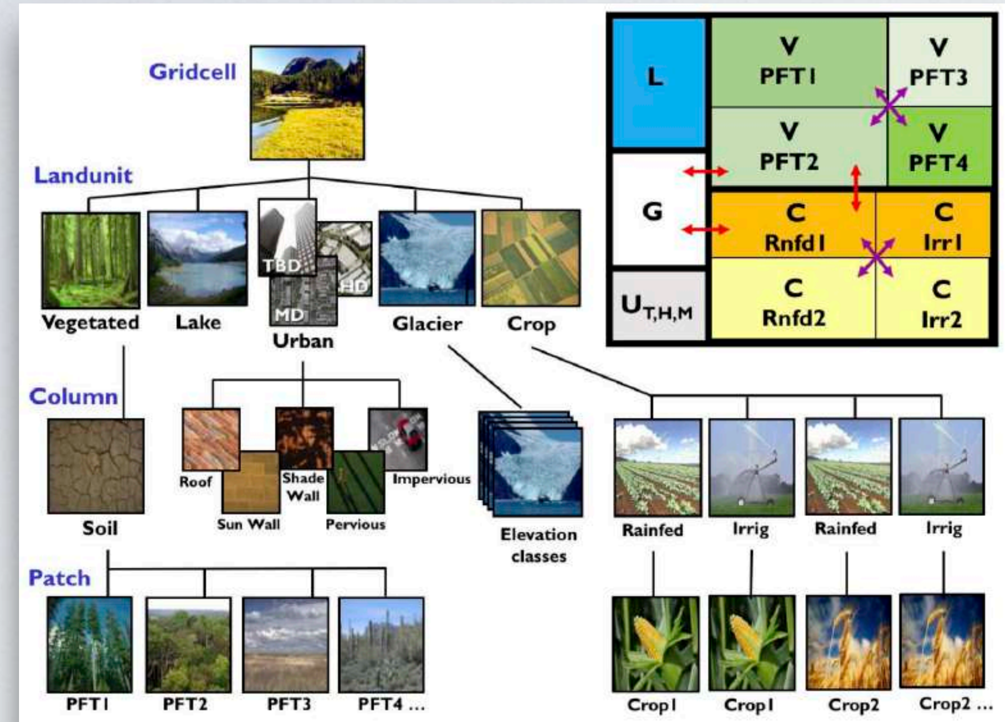


The **C**oupling of **L**and and **A**tmospheric **S**ubgrid **P**arameterizations (**CLASP**) Project

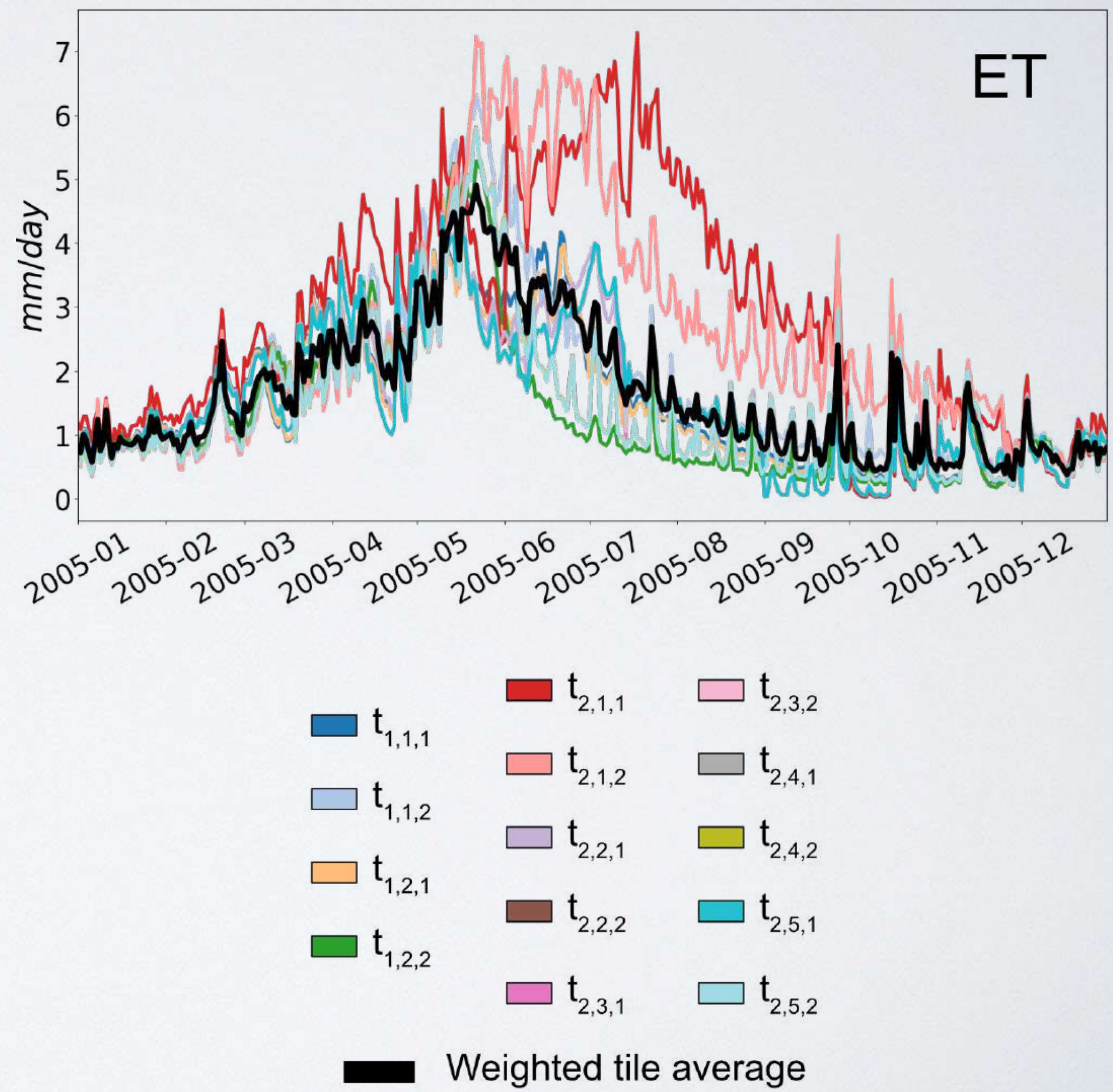
Nathaniel Chaney (*et al.*)

Sub-grid heterogeneity in the land components of Earth system models

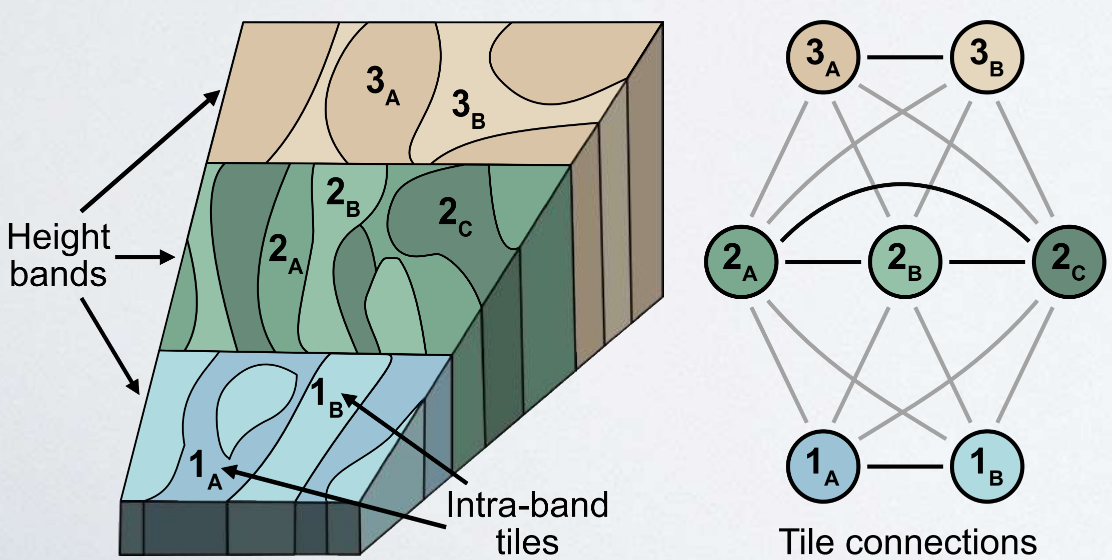


Lawrence et al., 2019

Example output from land model tiles of a 0.25 degree grid cell



Characteristic hillslope



Subin et al., 2014

Sub-grid heterogeneity in the atmosphere

CLUBB

(Cloud Layers Unified By Binormals; ~3rd order closure)

$$\frac{\partial \overline{r_t'^2}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{r_t'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'r_t'^2}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w'r_t'}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{+2\overline{r_t'\left.\frac{\partial r_t}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys}} \underbrace{-\epsilon_{r_t r_t}}_{\text{dissip}}$$

$$\frac{\partial \overline{\theta_l'^2}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{\theta_l'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'\theta_l'^2}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w'\theta_l'}\frac{\partial \overline{\theta_l}}{\partial z}}_{\text{turb prod}} \underbrace{+2\overline{\theta_l'\left.\frac{\partial \theta_l}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys}} \underbrace{-\epsilon_{\theta_l \theta_l}}_{\text{dissip}}$$

$$\frac{\partial \overline{r_t'\theta_l'}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{r_t'\theta_l'}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'r_t'\theta_l'}}{\partial z}}_{\text{turb adv}} \underbrace{-\overline{w'r_t'}\frac{\partial \overline{\theta_l}}{\partial z}}_{\text{turb prod 1}} \underbrace{-\overline{w'\theta_l'}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod 2}} \underbrace{+\overline{r_t'\left.\frac{\partial \theta_l}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys 1}} \underbrace{+\overline{\theta_l'\left.\frac{\partial r_t}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys 2}} \underbrace{-\epsilon_{r_t \theta_l}}_{\text{dissip}}$$

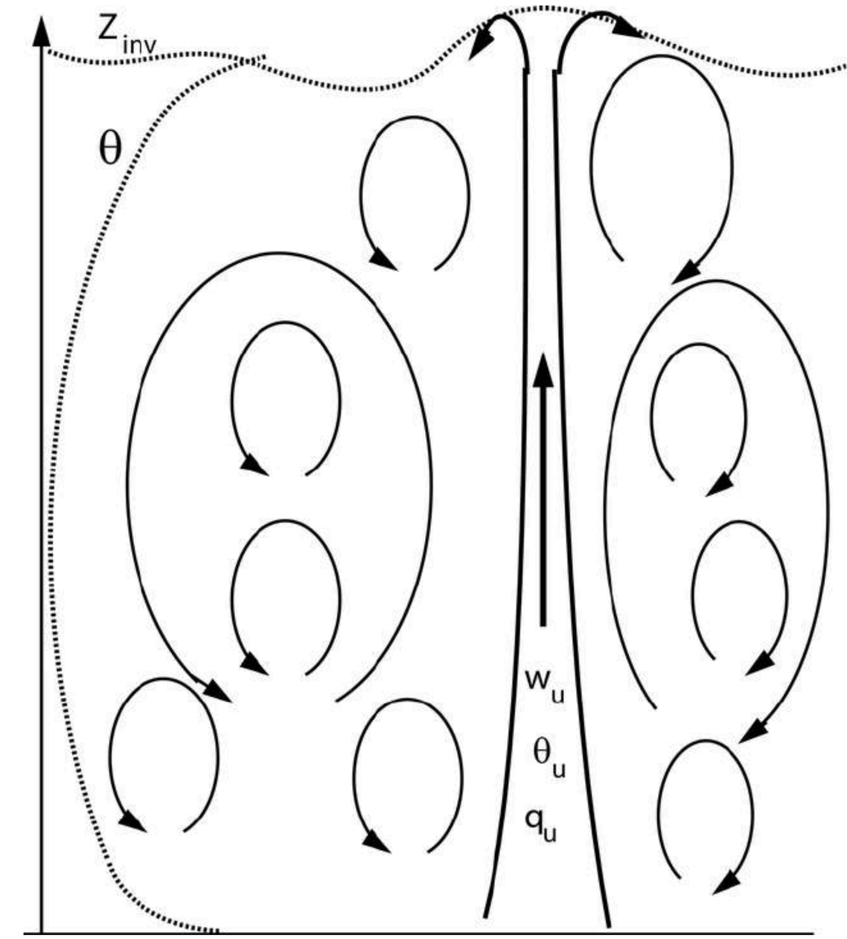
⋮

$$\frac{\partial \overline{w'^2}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{w'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^3}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w'^2}\frac{\partial \overline{w}}{\partial z}}_{\text{accum}} \underbrace{+\frac{2g}{\theta_{vs}}\overline{w'\theta_v'}}_{\text{buoy prod}} \underbrace{-\frac{2}{\rho_s}\overline{w'\frac{\partial p'}{\partial z}}}_{\text{pressure}} \underbrace{-\epsilon_{ww}}_{\text{dissip}}$$

Source: Larson, V., 2019

EDMF

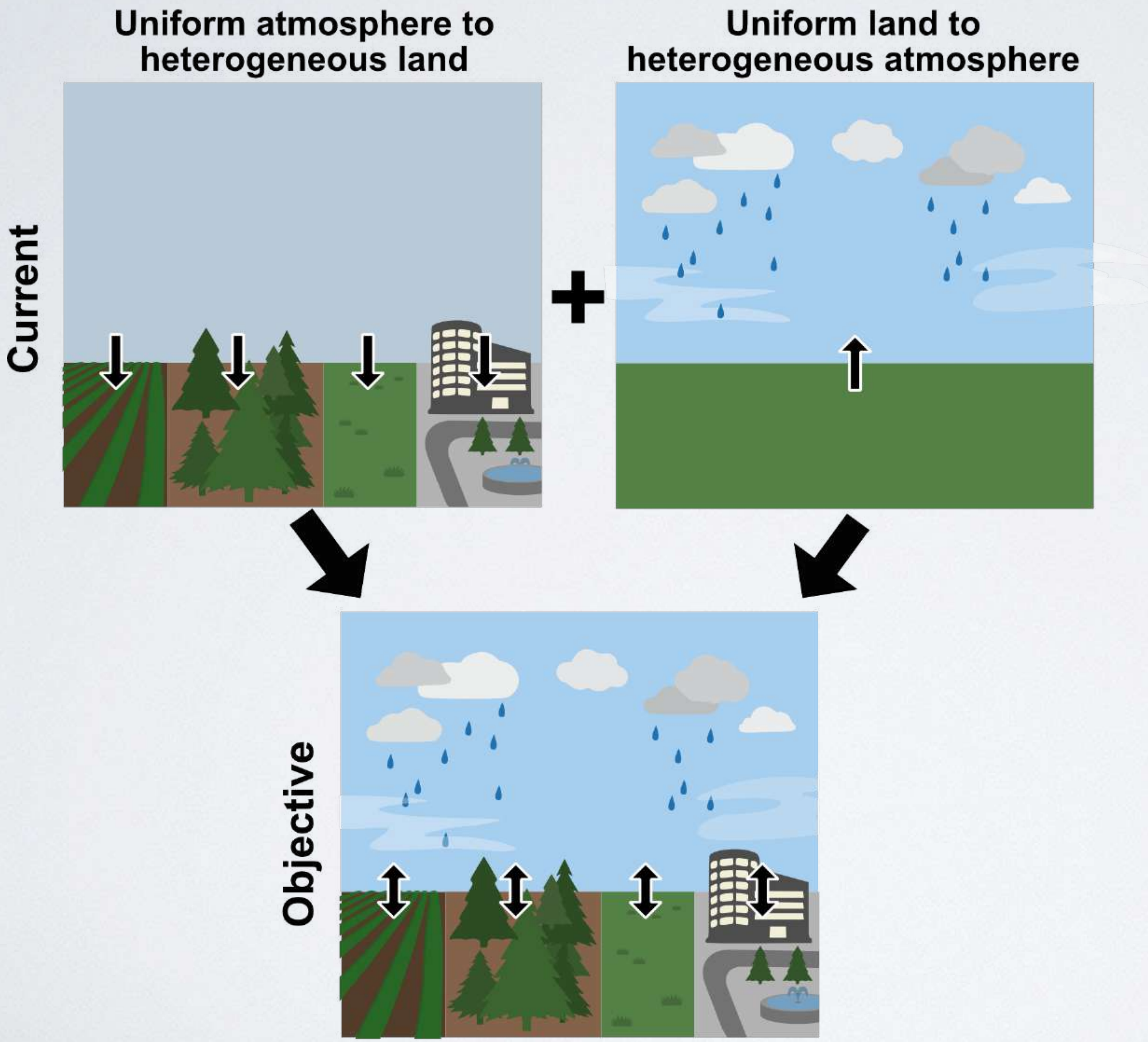
(Eddy Diffusivity Mass Flux)



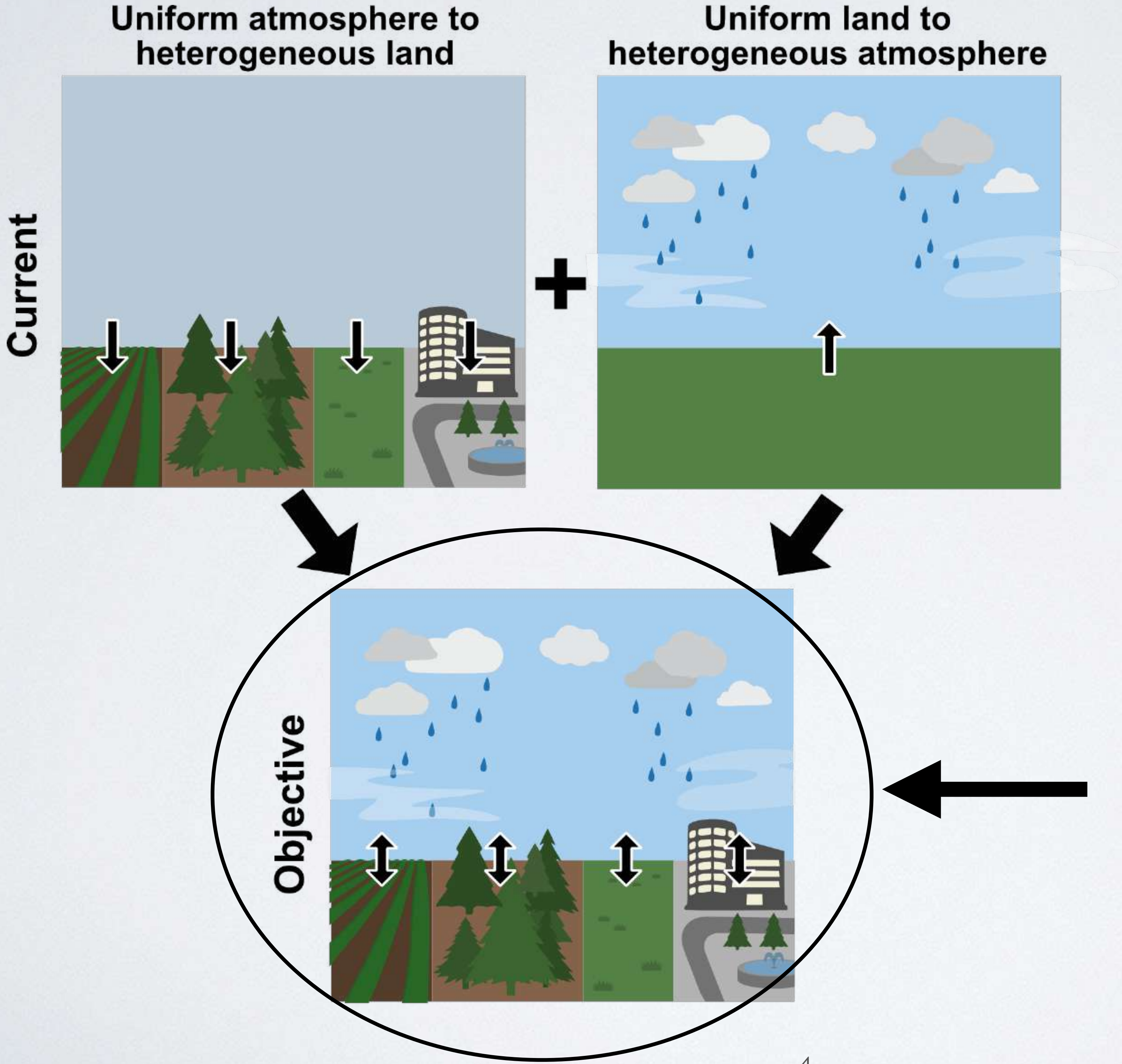
$$\overline{w'\phi'} = -K_\phi \frac{\partial \phi}{\partial z} + M_u(\phi_u - \bar{\phi})\Big|_{sfc} - M_d(\phi_d - \bar{\phi})\Big|_{Sc}$$

Source: Siebesma et al., 2007

How do we enable interaction between the "tiling" sub-grid approach over land and existing atmospheric sub-grid schemes?



How do we enable interaction between the "tiling" sub-grid approach over land and existing atmospheric sub-grid schemes?



Main objective of CLASP

CLASP Climate Process Team

Coupling of **L**and and **A**tmospheric **S**ubgrid **P**arameterizations

PIs

- Nathaniel Chaney (Duke)
- Paul Dirmeyer (GMU)
- Dave Lawrence (NCAR)
- Kirsten Findell (GFDL)
- Forrest Hoffman (ORNL)
- Po-Lun Ma (PNNL)
- Joe Santanello (GSFC)

Co-PIs

- Nathan Arnold (GMAO)
- Gaby Katul (Duke)
- Randy Koster (GSFC)
- Ruby Leung (PNNL)
- Elena Shevliakova (GFDL)
- Mike Ek (NCAR)
- Andy Bragg (Duke)

Co-Is and Research scientists

- Patricia Parker (GSFC)
- Sergey Malyshev (GFDL)
- Ming Zhao (GFDL)
- Nathan Collier (ORNL)

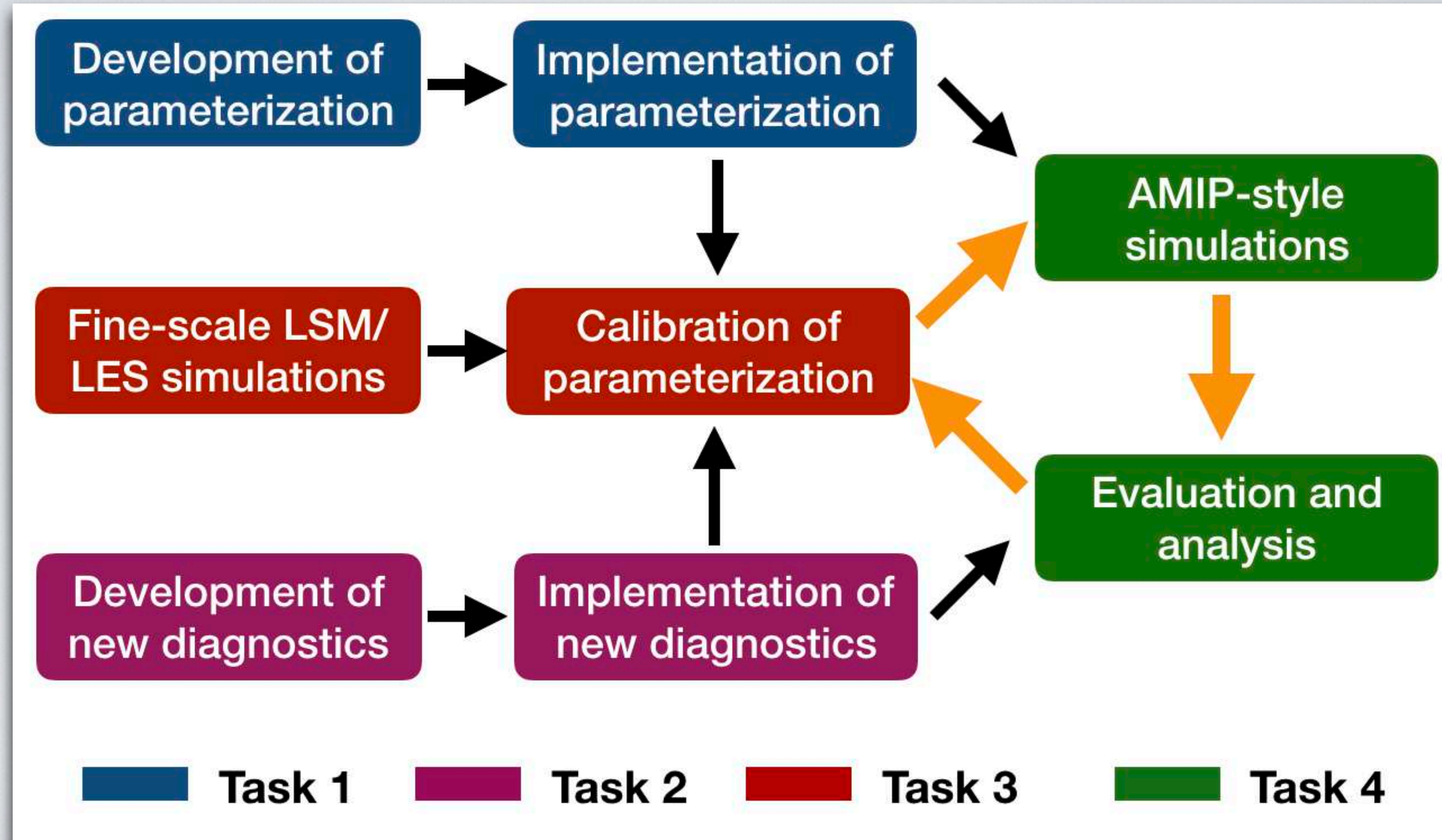
Postdocs

- David New (GMAO)
- Jason Simon (Duke)
- Megan Fowler (NCAR)
- Meng Huang (PNNL)
- Zun Yin (GFDL)
- Khaled Ghannam (GFDL)

PhD students

- Tyler Waterman (Duke)
- Finley Hay-Chapman (GMU)

CLASP framework



CLASP parameterization development and implementation

CLASP-CLUBB parameterization

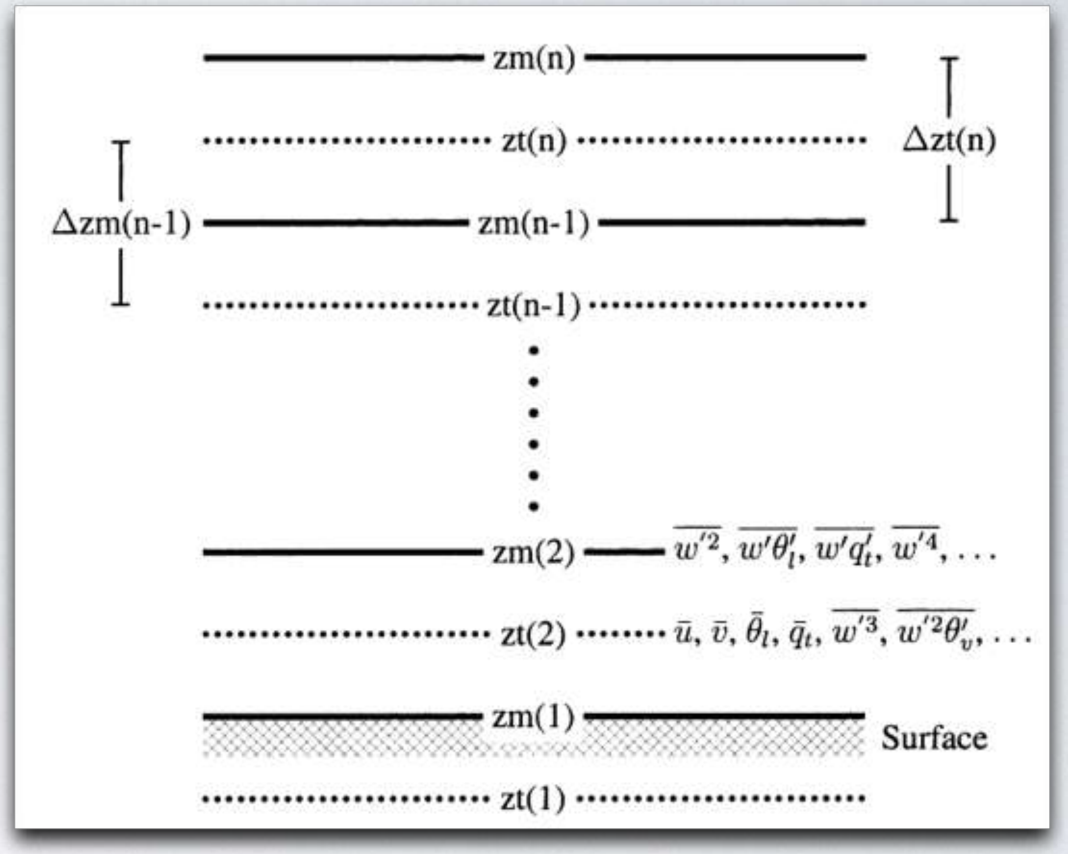
$$\frac{\partial \overline{r_t'^2}}{\partial t} = \underbrace{-\bar{w}\frac{\partial \overline{r_t'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w' r_t'^2}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w' r_t'}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{+2\overline{r_t' \left.\frac{\partial r_t}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys}} \underbrace{-\epsilon_{r_t r_t}}_{\text{dissip}}$$

$$\frac{\partial \overline{\theta_l'^2}}{\partial t} = \underbrace{-\bar{w}\frac{\partial \overline{\theta_l'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w' \theta_l'^2}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w' \theta_l'}\frac{\partial \overline{\theta_l}}{\partial z}}_{\text{turb prod}} \underbrace{+2\overline{\theta_l' \left.\frac{\partial \theta_l}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys}} \underbrace{-\epsilon_{\theta_l \theta_l}}_{\text{dissip}}$$

$$\frac{\partial \overline{r_t'\theta_l'}}{\partial t} = \underbrace{-\bar{w}\frac{\partial \overline{r_t'\theta_l'}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w' r_t'\theta_l'}}{\partial z}}_{\text{turb adv}} \underbrace{-\overline{w' r_t'}\frac{\partial \overline{\theta_l}}{\partial z}}_{\text{turb prod 1}} \underbrace{-\overline{w' \theta_l'}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod 2}} \underbrace{+\overline{r_t' \left.\frac{\partial \theta_l}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys 1}} \underbrace{+\overline{\theta_l' \left.\frac{\partial r_t}{\partial t}\right|_{\text{mc}}'}}_{\text{microphys 2}} \underbrace{-\epsilon_{r_t \theta_l}}_{\text{dissip}}$$

⋮

$$\frac{\partial \overline{w'^2}}{\partial t} = \underbrace{-\bar{w}\frac{\partial \overline{w'^2}}{\partial z}}_{\text{mean adv}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{w'^3}}{\partial z}}_{\text{turb adv}} \underbrace{-2\overline{w'^2}\frac{\partial \bar{w}}{\partial z}}_{\text{accum}} \underbrace{+\frac{2g}{\theta_{vs}}\overline{w'\theta_v'}}_{\text{buoy prod}} \underbrace{-\frac{2}{\rho_s}\overline{w'\frac{\partial p'}{\partial z}}}_{\text{pressure}} \underbrace{-\epsilon_{ww}}_{\text{dissip}}$$



- CLUBB is the turbulence closure scheme used in CESM2 and E3SM
- CLUBB relies on 10+ time-varying surface boundary conditions
- CLASP is leveraging these boundary conditions to account for the role of sub-grid land heterogeneity in CLUBB's modeled atmosphere

CLASP-CLUBB: E3SM + CESM

Meng Huang and Po-Lun Ma (PNNL)
Meg Fowler, Dave Lawrence, and Rich Neale (NCAR)

CLUBB surface moments

Homogeneous calculation of moments

$$\overline{q_t'^2}_{HOM} = \begin{cases} \frac{H_o^2}{u_*^2}\left[4(1-8.3\zeta)^{\frac{2}{3}}\right] & \zeta < 0 \\ \frac{H_o^2}{u_*^2}[4] & \zeta > 0 \end{cases}$$

$$\overline{\theta_l'^2}_{HOM} = \begin{cases} \frac{Q_o^2}{u_*^2}\left[4(1-8.3\zeta)^{\frac{2}{3}}\right] & \zeta < 0 \\ \frac{Q_o^2}{u_*^2}[4] & \zeta > 0 \end{cases}$$

$$\overline{\theta_l' q_t'}_{HOM} = \sqrt{\overline{\theta_l'^2}}\sqrt{\overline{q_t'^2}}$$

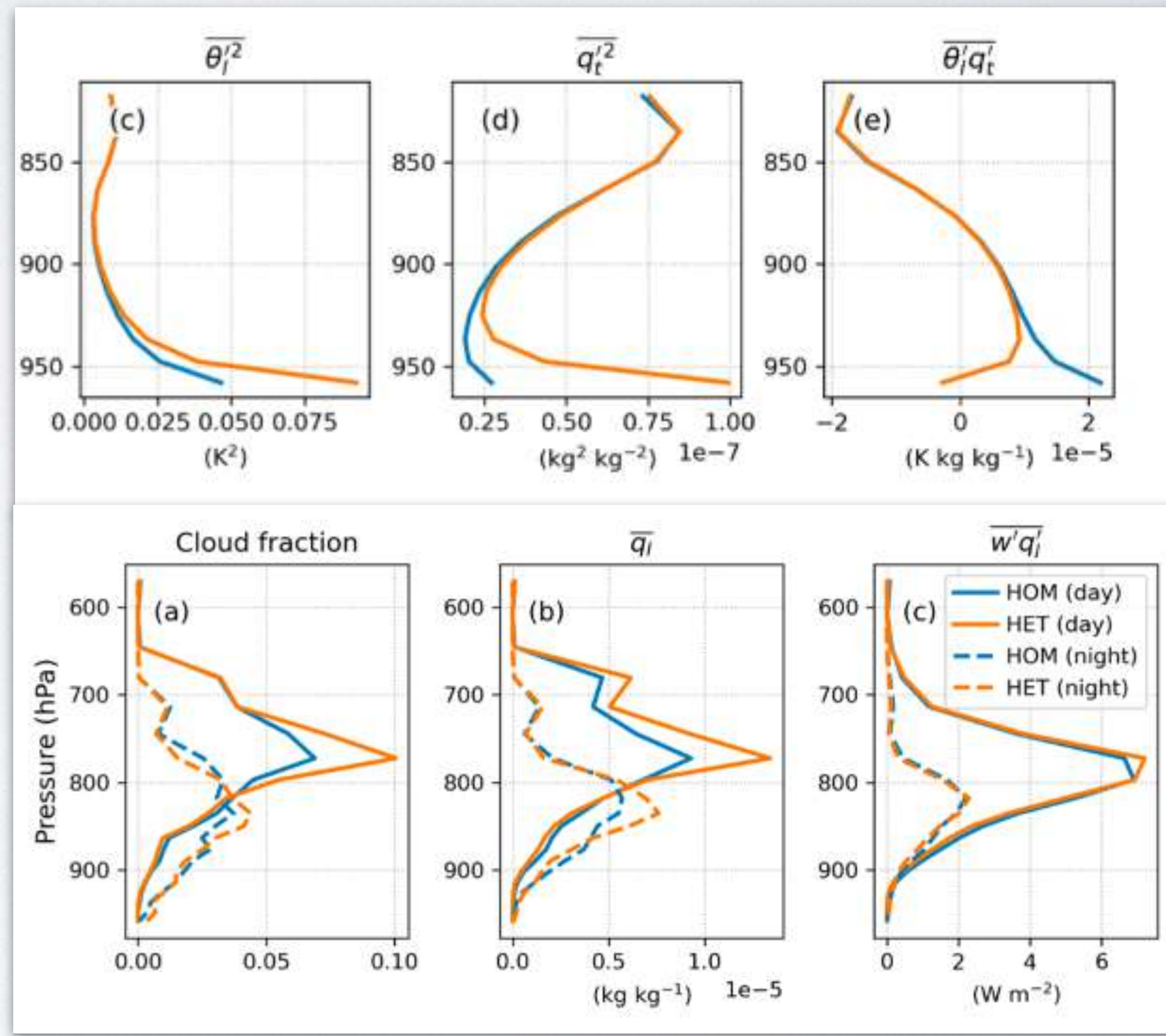
Heterogeneous calculation of moments

$$\overline{q_t'^2}_{HET} = \overline{q_t'^2}_{HOM} + \overline{\left(q_{t_{patch}} - \bar{q}_t\right)^2}$$

$$\overline{\theta_l'^2}_{HET} = \overline{\theta_l'^2}_{HOM} + \overline{\left(\theta_{l_{patch}} - \bar{\theta}_l\right)^2}$$

$$\overline{\theta_l' q_t'}_{HET} = \overline{\theta_l' q_t'}_{HOM} + \overline{\left(\theta_{l_{patch}} - \bar{\theta}_l\right)\left(q_{t_{patch}} - \bar{q}_t\right)}$$

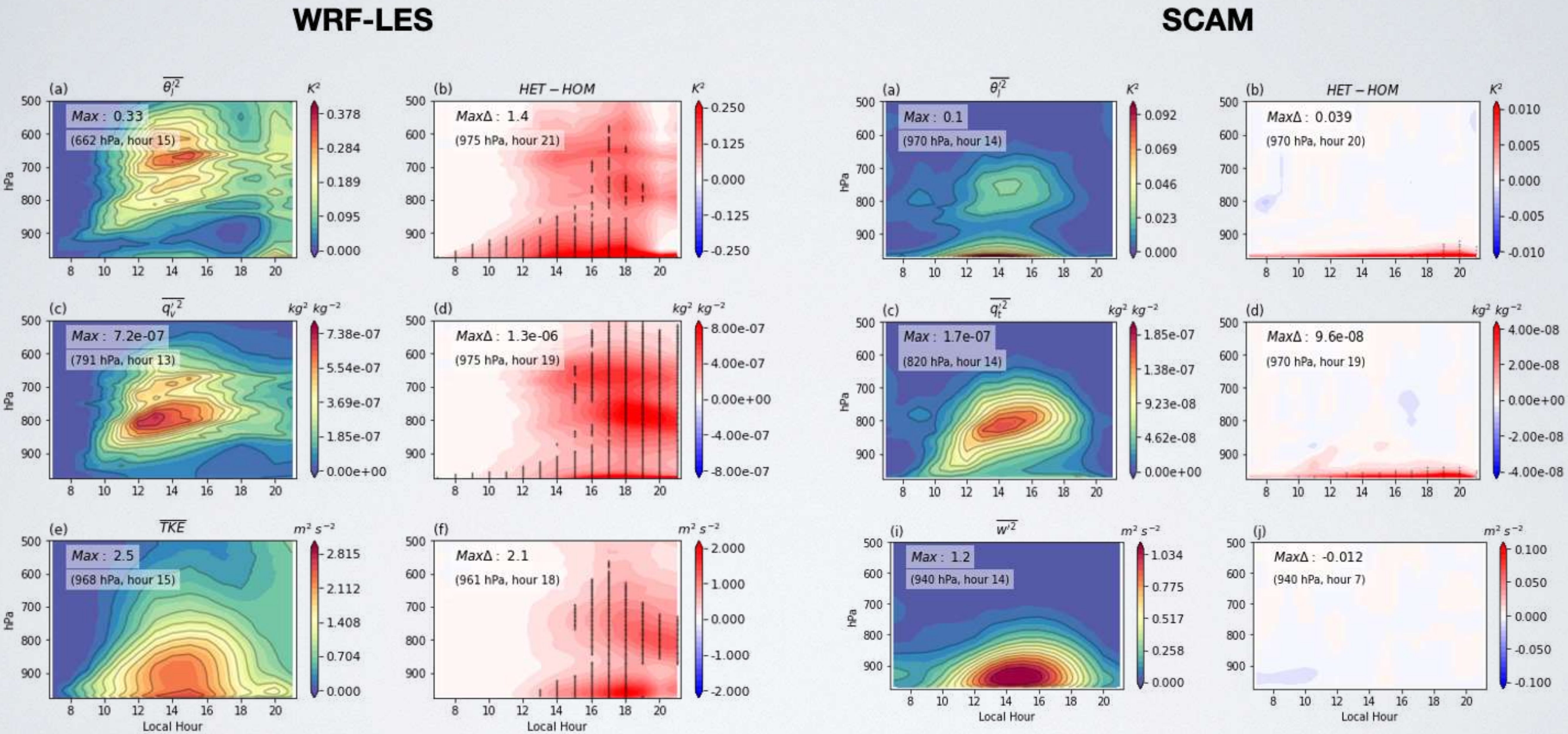
Sensitivity of CLASP-CLUBB over SGP in E3SM



Huang et al., 2022, Representing surface heterogeneity in land-atmosphere coupling in E3SMv1 single-column model over ARM SGP during summertime, GMD

CLASP-CLUBB vs. WRF-LES

Meg Fowler, Dave Lawrence, and Rich Neale (NCAR)

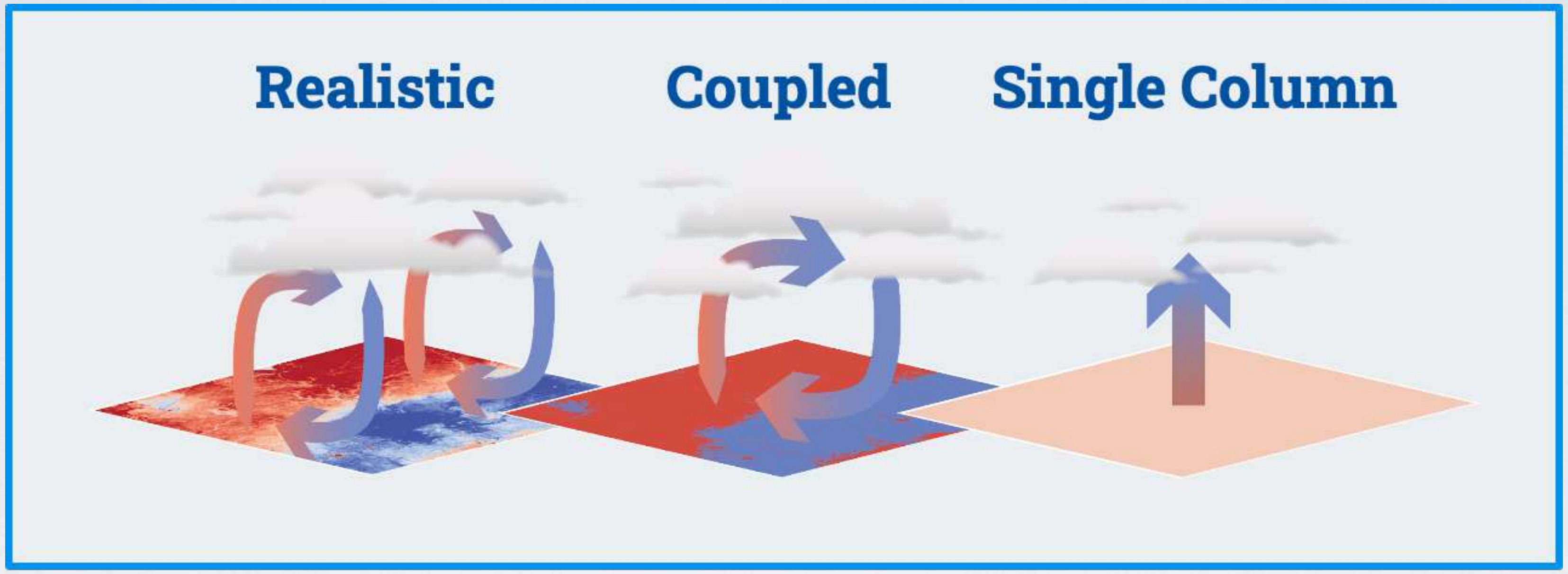


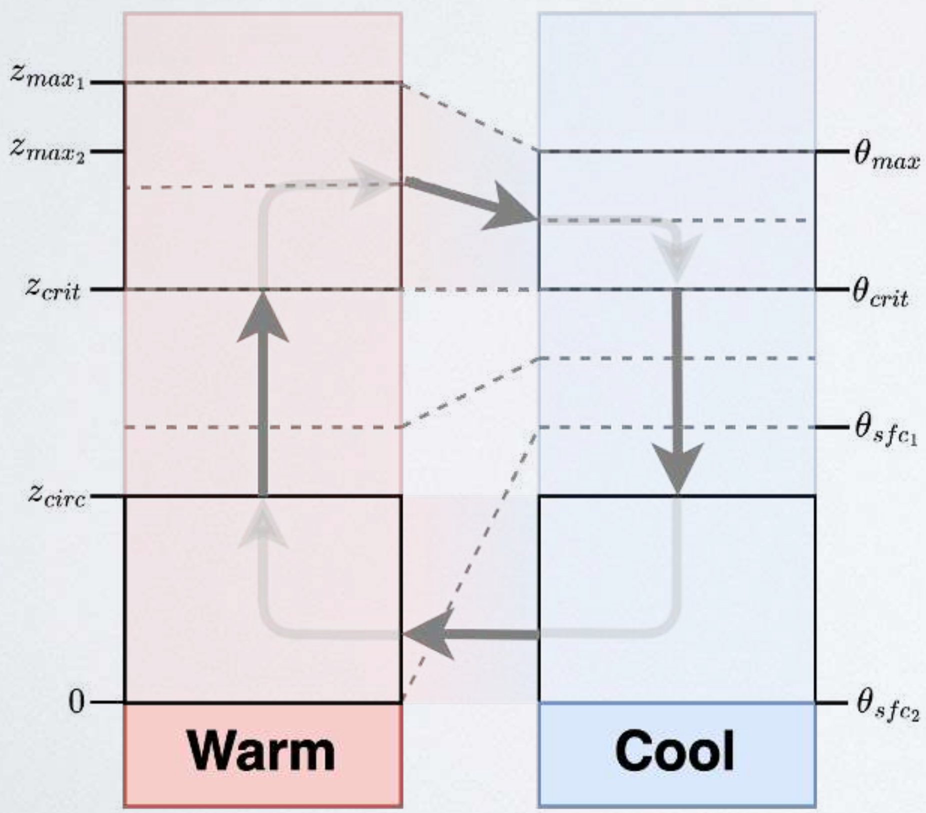
Time-height plots of (left) *HOM* and (right) *HET-HOM*, averaged over all 60 days; and (right) Stippling indicates significant differences at the 95% confidence level.

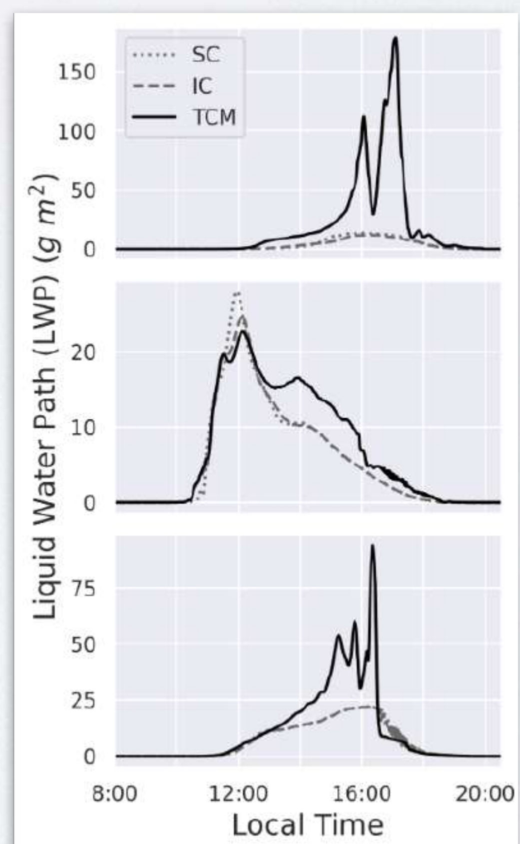
Fowler et al., Assessing the Atmospheric Response to Subgrid Surface Heterogeneity in CESM2, JAMES, 2024

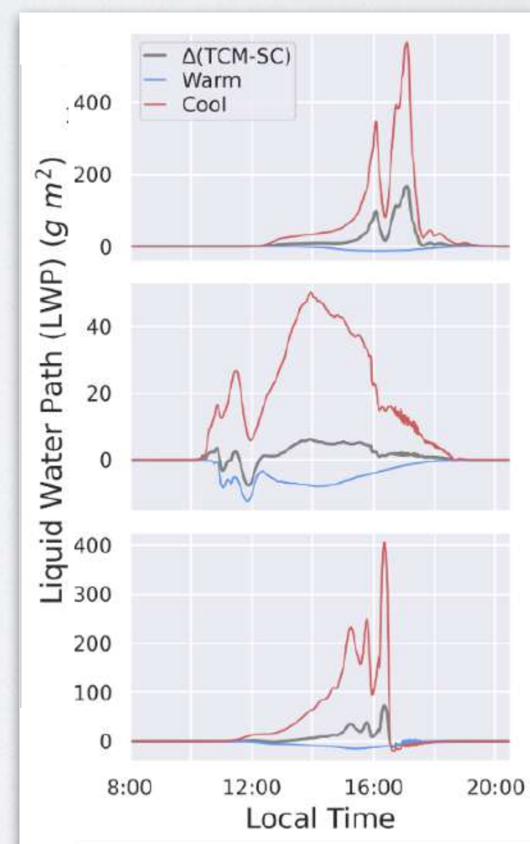
Two column CLUBB: Secondary circulations

Tyler Waterman and Nate Chaney (Duke)







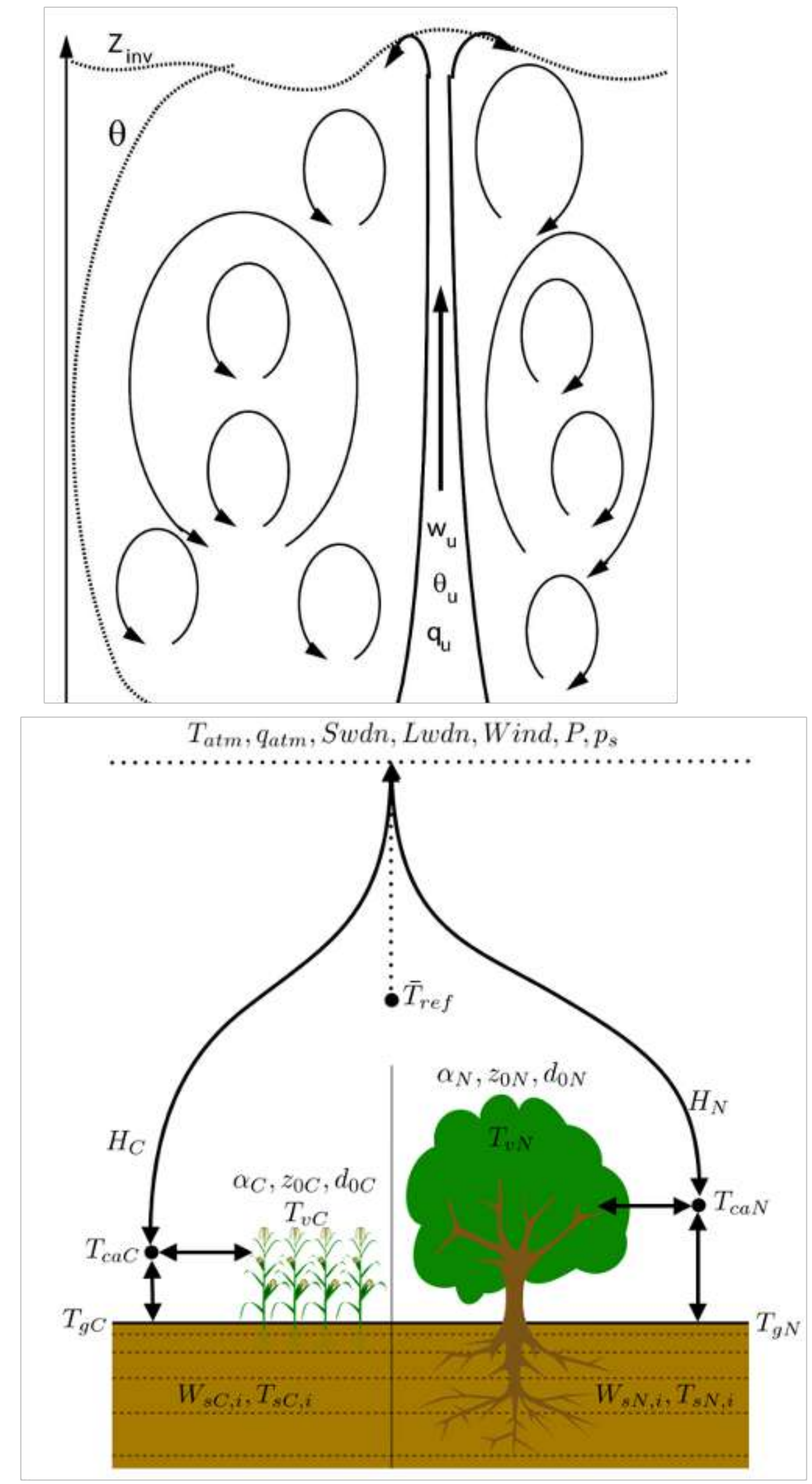


Waterman et al., 2024, A Two-Column Model Parameterization for Subgrid Surface Heterogeneity Driven Circulations, JAMES

CLASP-EDMF parameterization

- EDMF combines an eddy diffusivity with a mass-flux term (i.e., plumes) to model both turbulence and updrafts/downdrafts
- EDMF is used within AM4 (GFDL), GEOS (GMAO), and now CESM2 (NCAR; CLUBB-MF)
- Because land heterogeneity is known to produce secondary circulations, GFDL and GMAO have been focused most of their efforts on the updrafts in EDMF.

$$\overline{w'\phi'} = -K_\phi \frac{\partial \phi}{\partial z} + M_u(\phi_u - \bar{\phi})\Big|_{sfc} - M_d(\phi_d - \bar{\phi})\Big|_{Sc}$$



Courtesy: Khaled Ghanam

EDMF: Single Plume Approach

Khaled Ghannam, Sergey Malyshev, and Elena Shevliakova (GFDL)

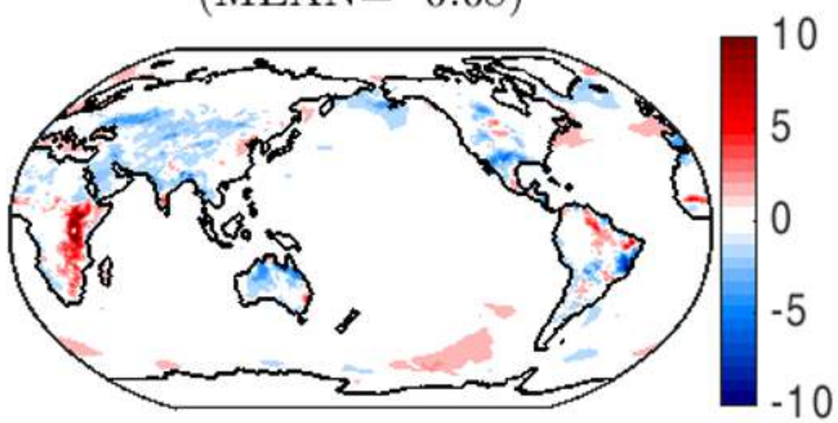
Table 1. Summary of the differences in the formulations between the eddy-diffusivity mass-flux (EDMF) scheme and its heterogeneity counterpart (EDMF-HET)

Component	Feature	EDMF	EDMF-HET
Mass Flux	Updraft area fraction	$a_u = 0.13$	$a_{u_i} = \int_{w_{min}}^{3\sigma_{w_i}} \mathcal{N}(0, \sigma_{w_i})\,\mathrm{dw}$
	Updraft vertical velocity	$w_u = 0$	$w_{u_i} = a_{u_i}^{-1} \int_{w_{min}}^{3\sigma_{w_i}} \mathcal{N}(0, \sigma_{w_i})\,w\mathrm{dw}$
	Updraft temperature perturbation	$\theta_{v,u} - \langle\theta_v\rangle = \frac{\langle w'\theta_v'\rangle}{w_s}$	$\theta_{u_i} - \langle\theta\rangle = R_{w\theta,i} w_{u_i} \sigma_{\theta_i} / \sigma_{w_i}$
	Updraft humidity perturbation	$q_u = 0$	$q_{u_i} - \langle q\rangle = R_{wq,i} w_{u_i} \sigma_{q_i} / \sigma_{w_i}$

Global Climatology Differences (CLASP vs. Baseline)

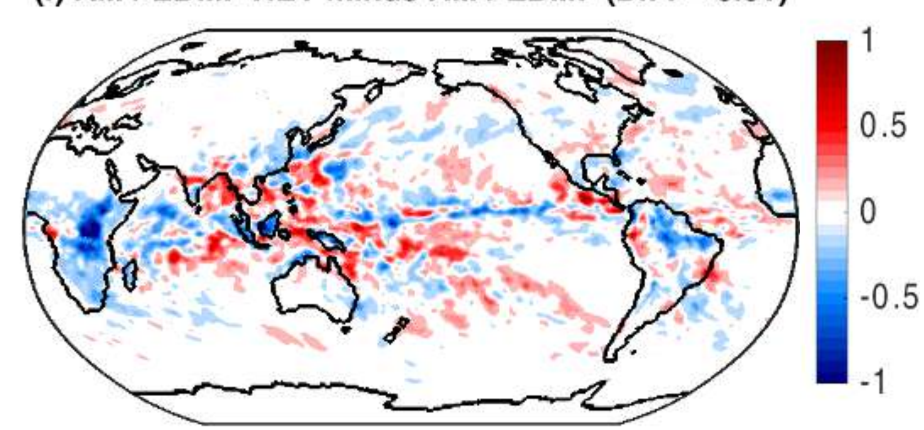
Sensible Heat Flux (W/m2)

AM4-EDMF-HET minus AM4-EDMF
(MEAN= -0.08)



Precipitation (mm/day)

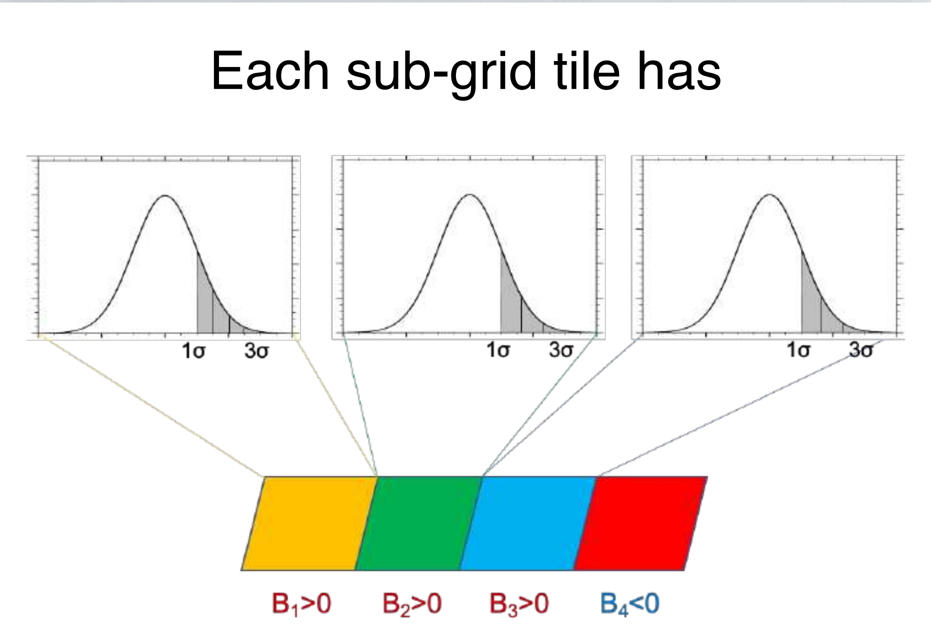
(f) AM4-EDMF-HET minus AM4-EDMF (DIFF=-0.01)

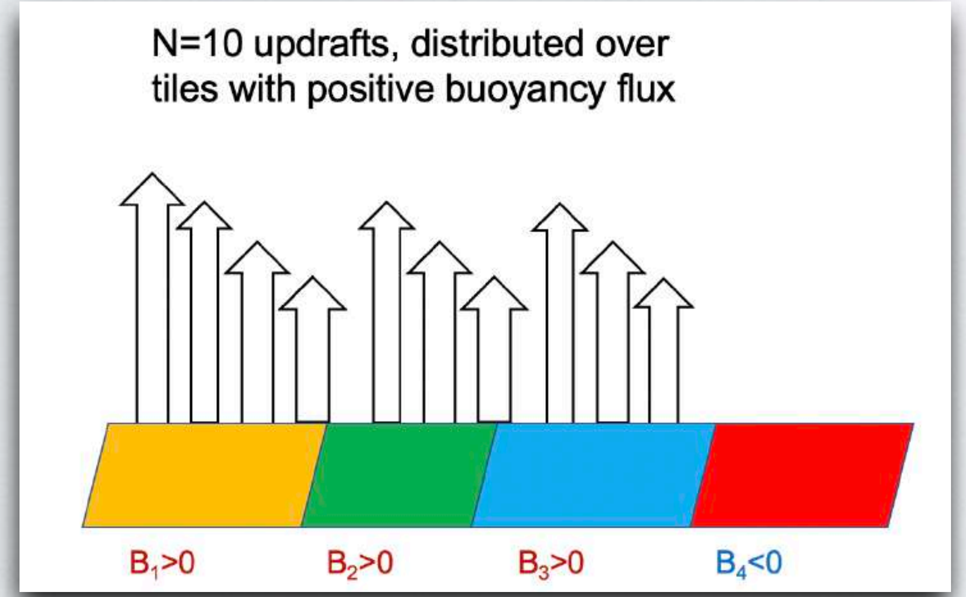


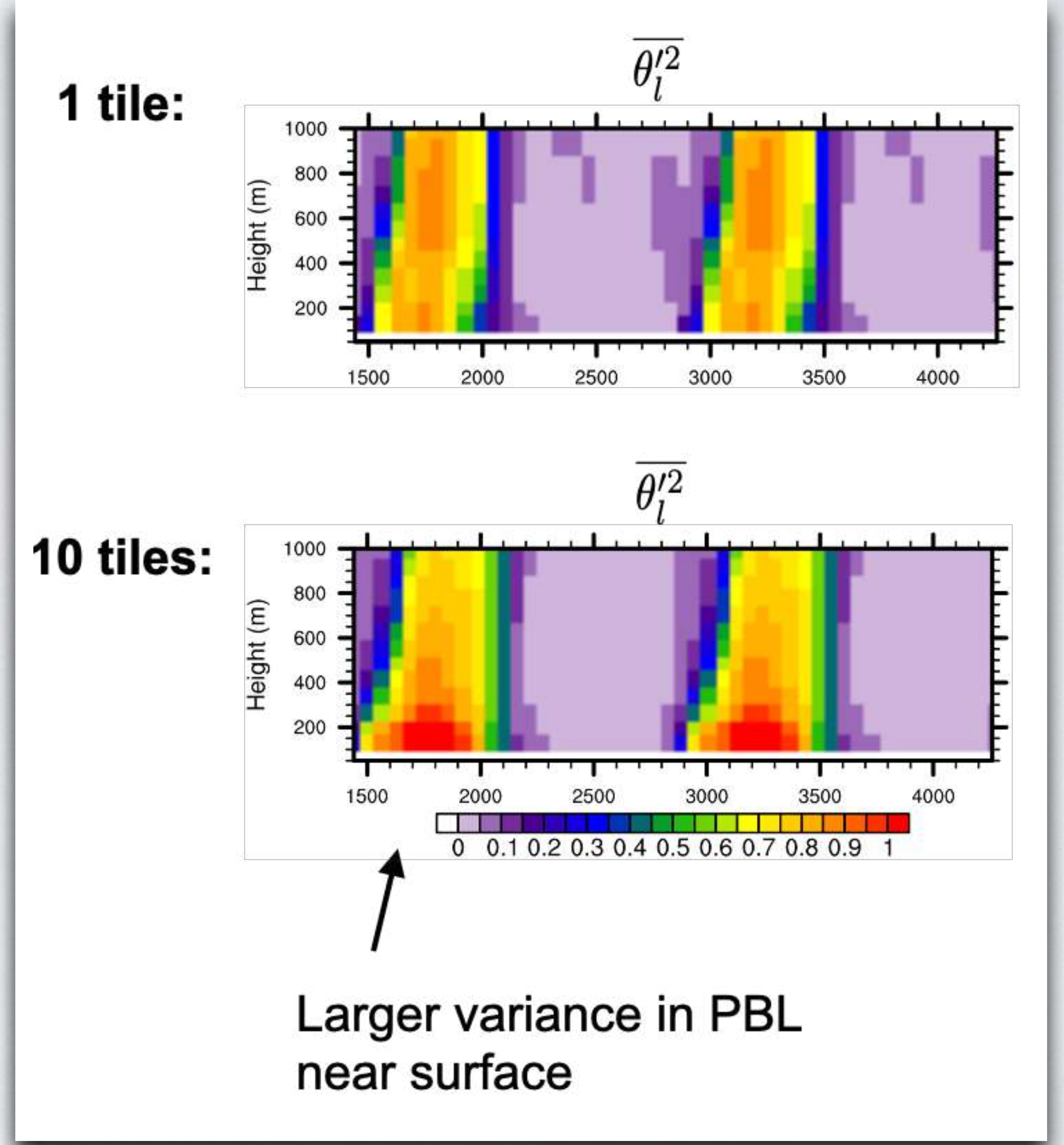
Ghannam et al., In preparation

EDMF: Multi Plume Approach

Nathan Arnold, Randy Koster, and David New (GMAO)



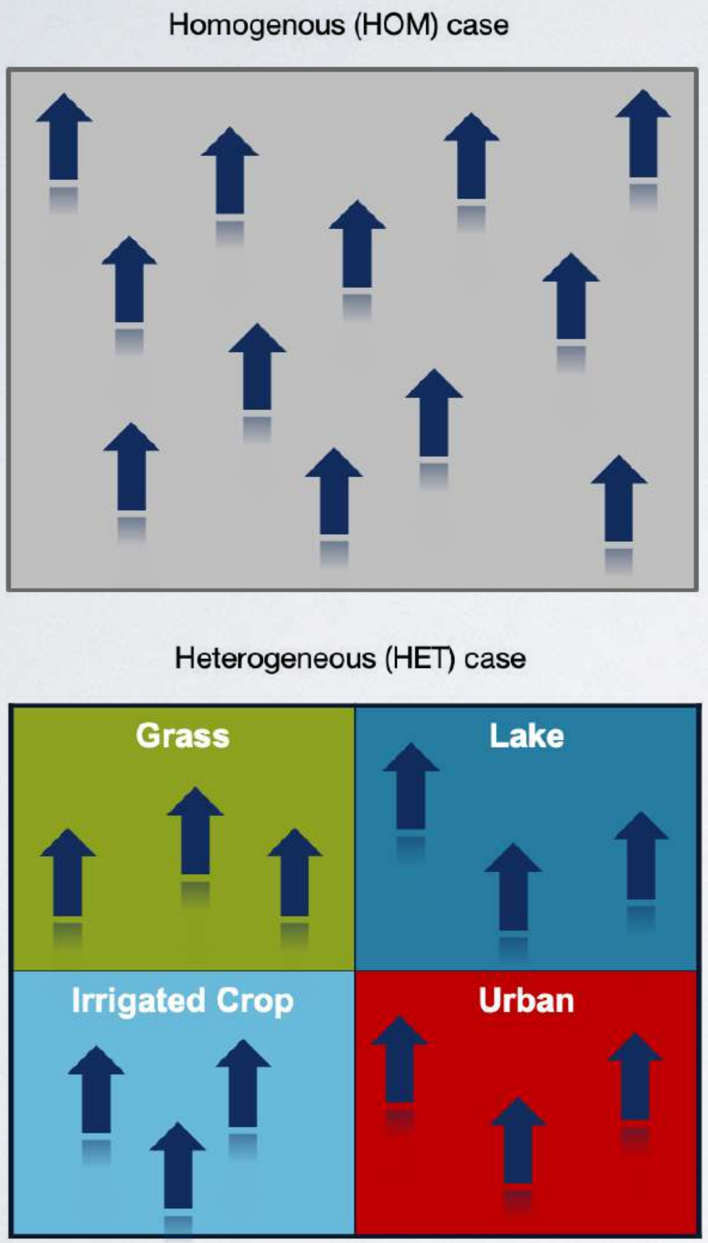




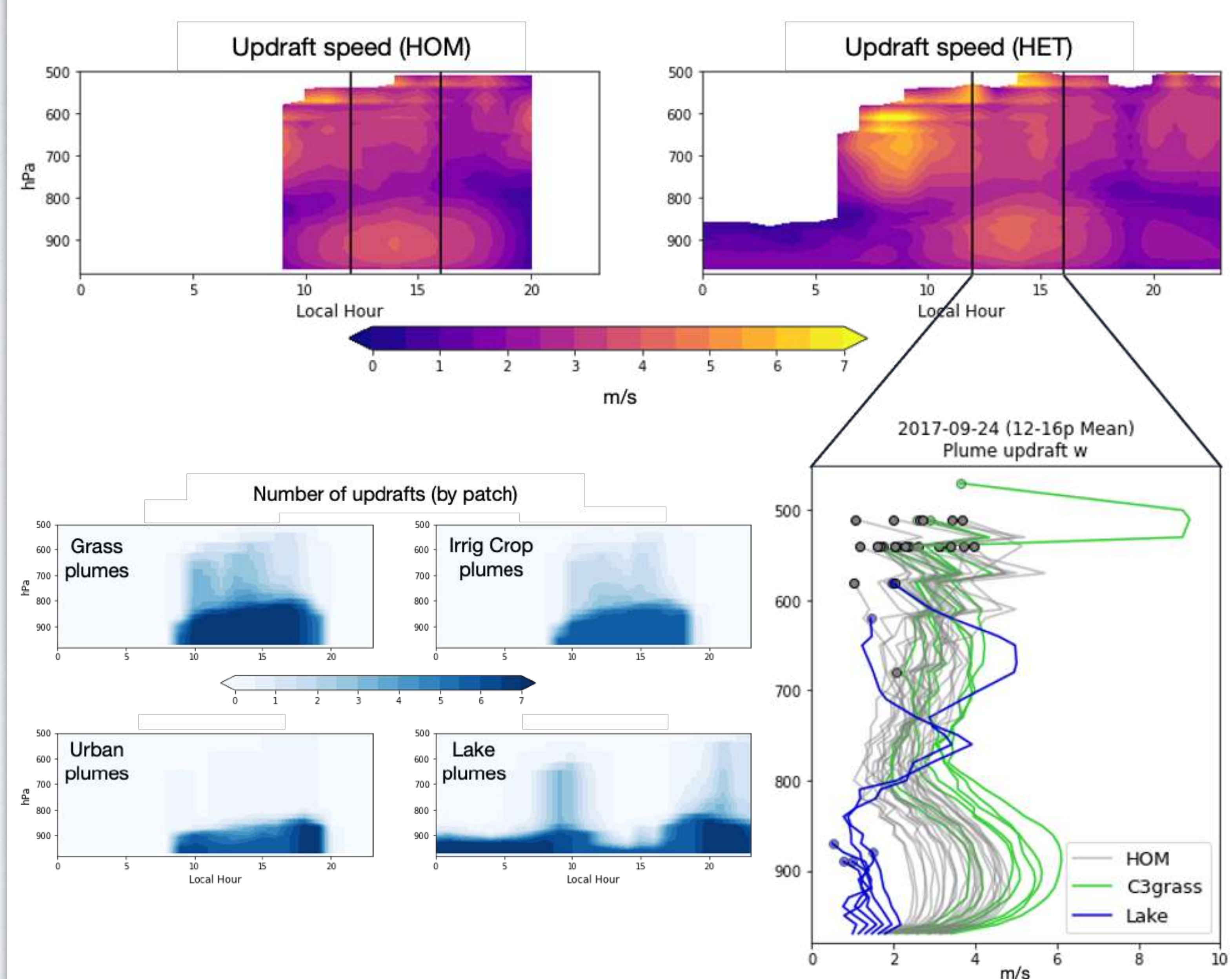
Arnold, N., 2024, Representing effects of surface heterogeneity in a multi-plume eddy diffusivity mass flux boundary parameterization, GMDD

CLUBB-MF: Multi Plume Approach

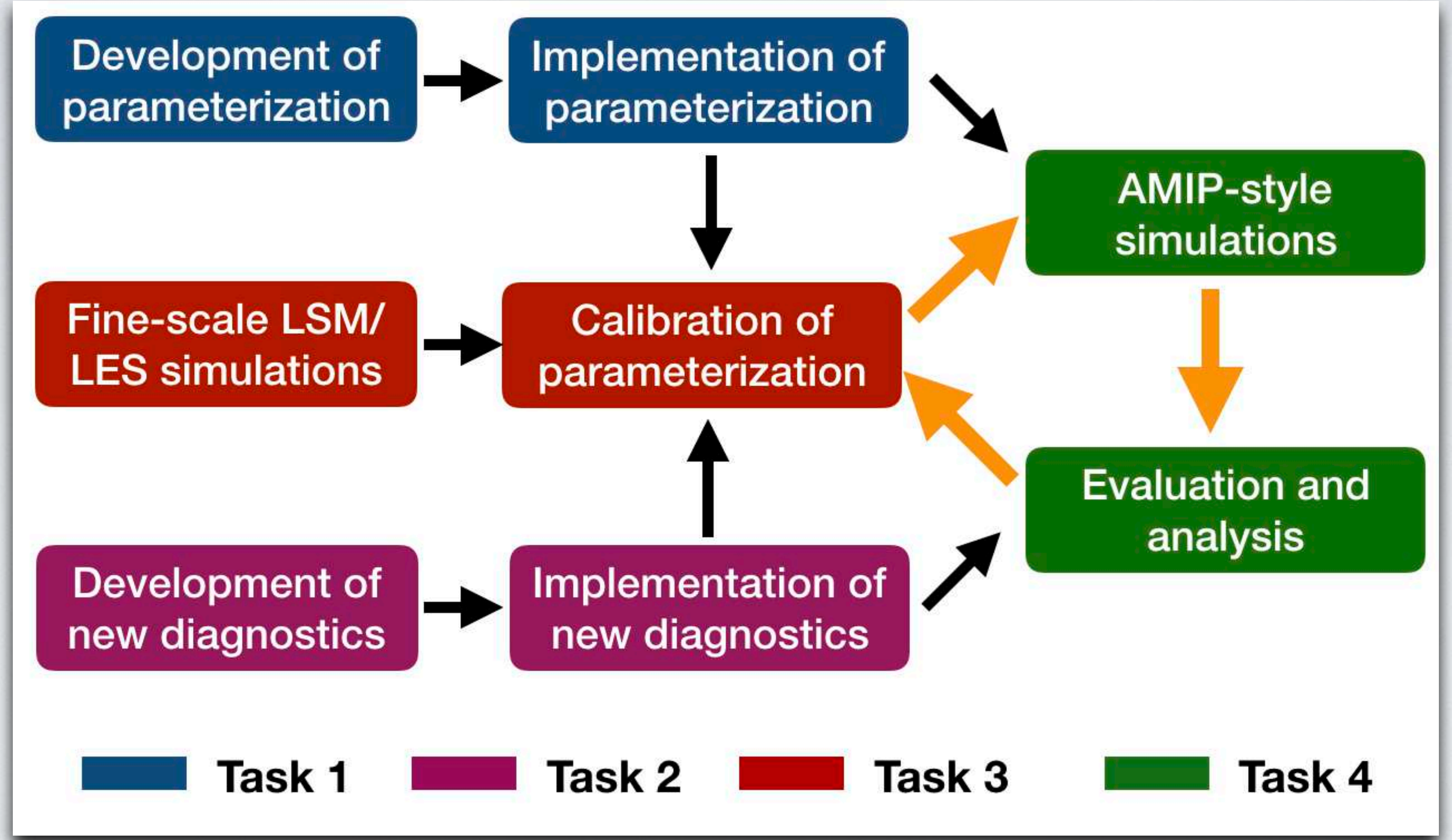
Meg Fowler, Dave Lawrence, and Rich Neale (NCAR)



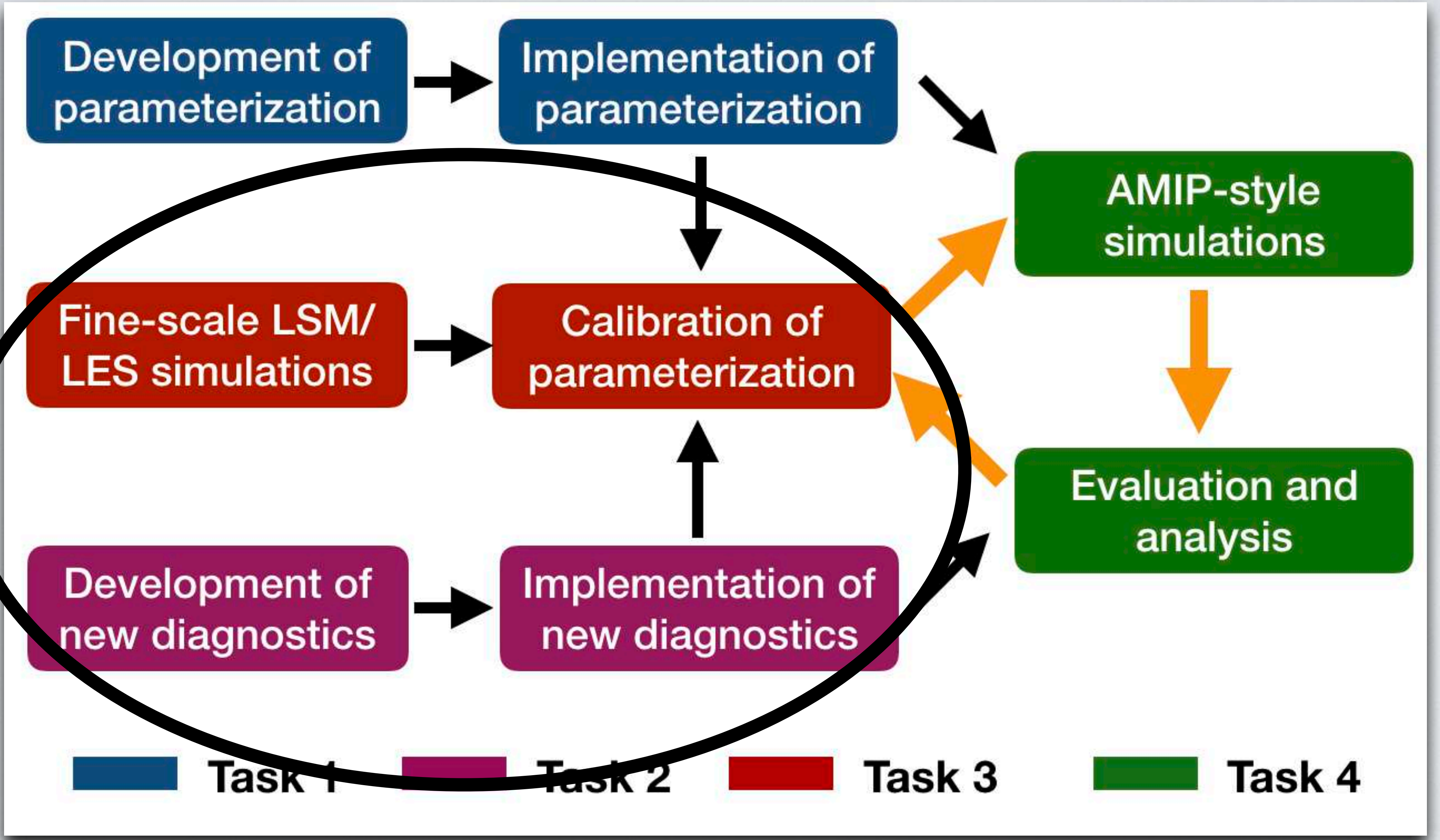
$$\overline{w'\varphi'} = \overline{w'\varphi'}_{\text{CLUBB}} + \sum_{i=1}^{I} a_i(w_i - \overline{w})(\varphi_i - \overline{\varphi}),$$



Multi-scale modeling and diagnostics to inform the parameterization development



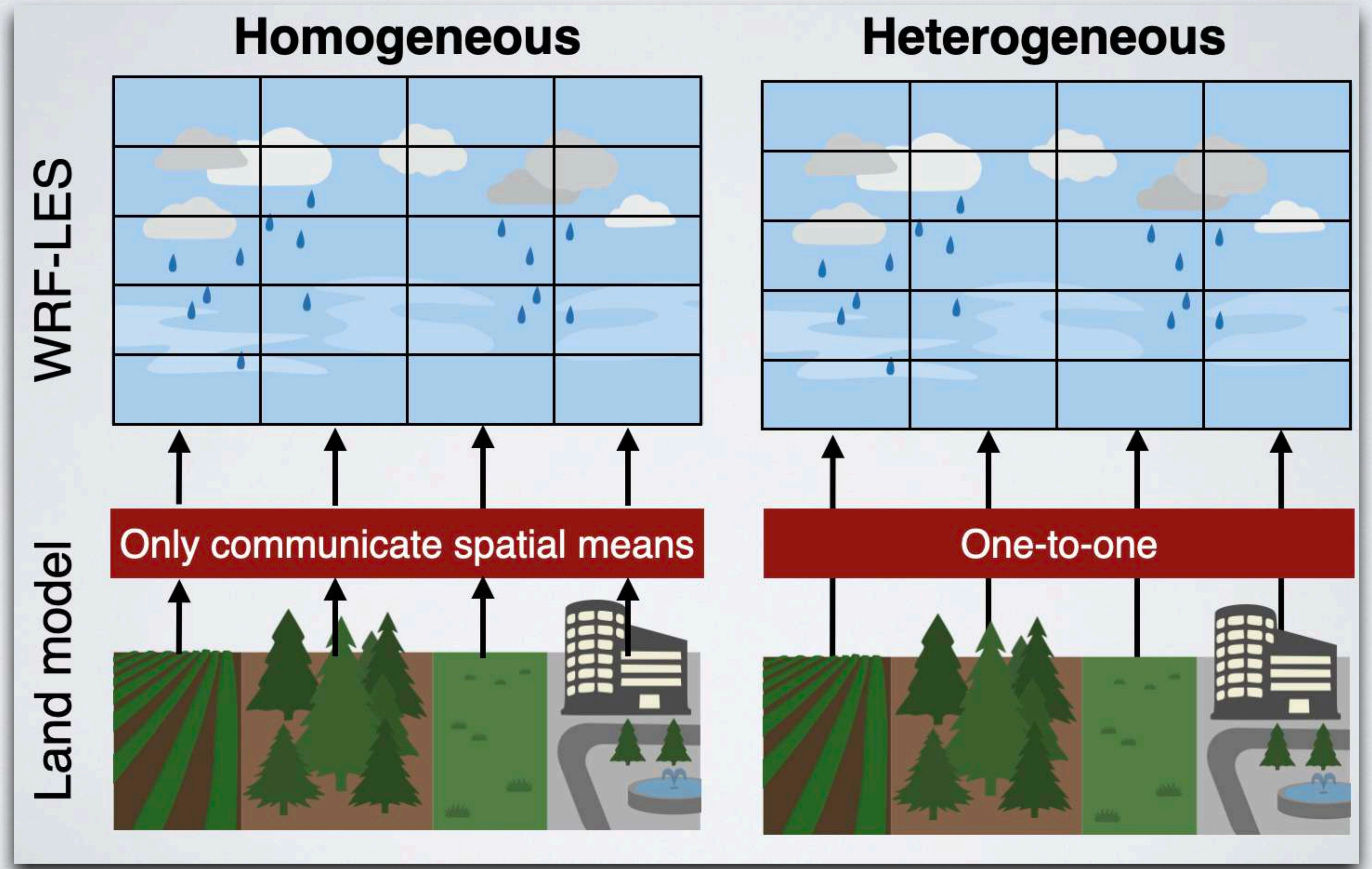
Multi-scale modeling and diagnostics to inform the parameterization development



CLASP large eddy simulations, mesocale modeling, and diagnostics

LES: Role of multi-scale land surface heterogeneity in cloud development

Jason Simon, Andy Bragg and Nate Chaney (Duke)



LES/LM: 100 km bounding box around ARM SGP central facility

- 100 km bounding box
- Use Large-Eddy Simulation (LES) ARM Symbiotic Simulation and Observation (LASSO) framework
- Atmospheric data: VARANAL
- Shallow convection days
- Here I will show simulations for 9/24/2017

manuscript submitted to *Journal of Advances in Modeling Earth Systems (JAMES)*

Semi-coupling of a Field-scale Resolving Land-surface Model and WRF-LES to Investigate the Influence of Land-surface Heterogeneity on Cloud Development

Jason S. Simon[1], Andrew D. Bragg[1], Paul A. Dirmeyer[2], and Nathaniel W. Chaney[1]

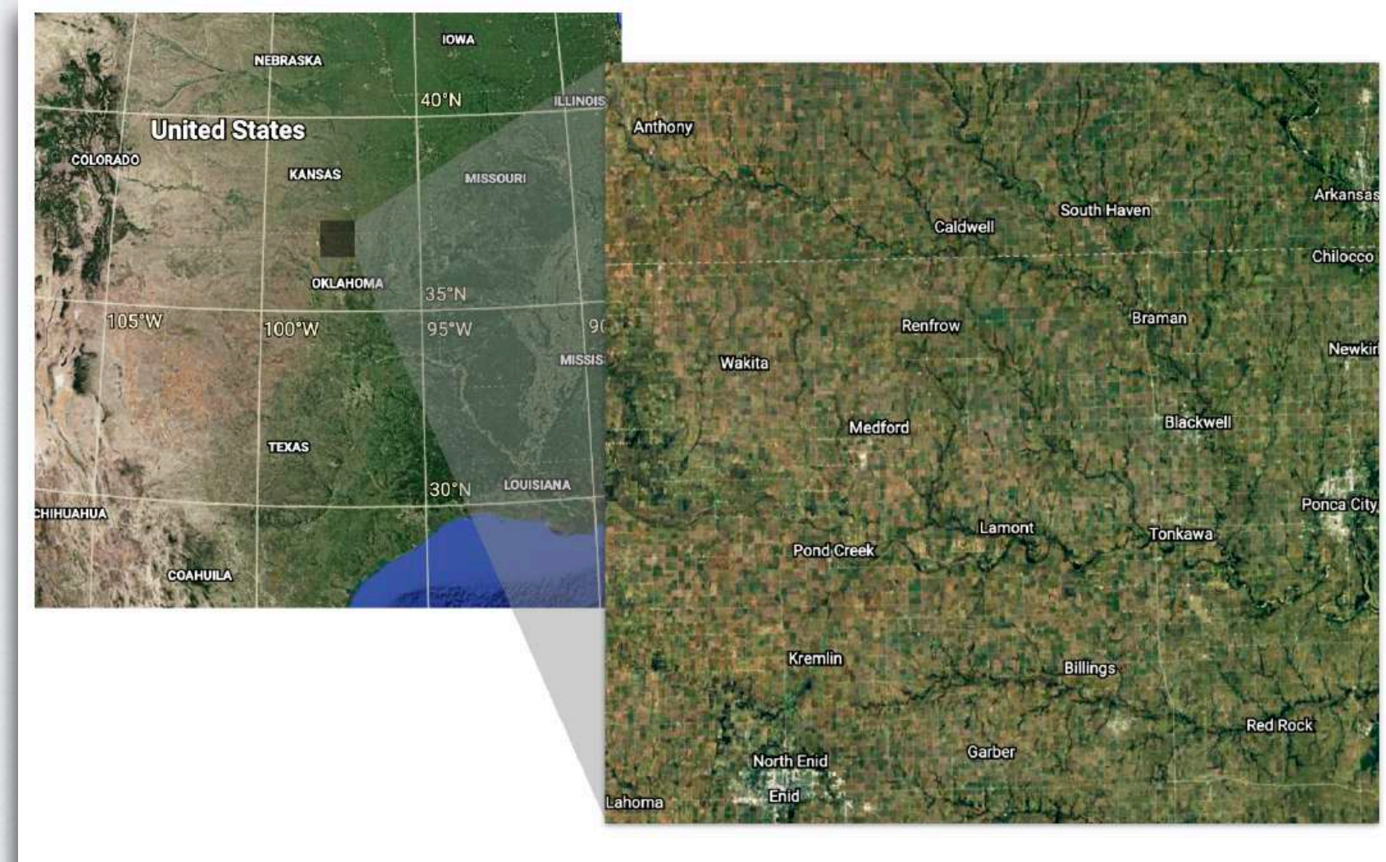
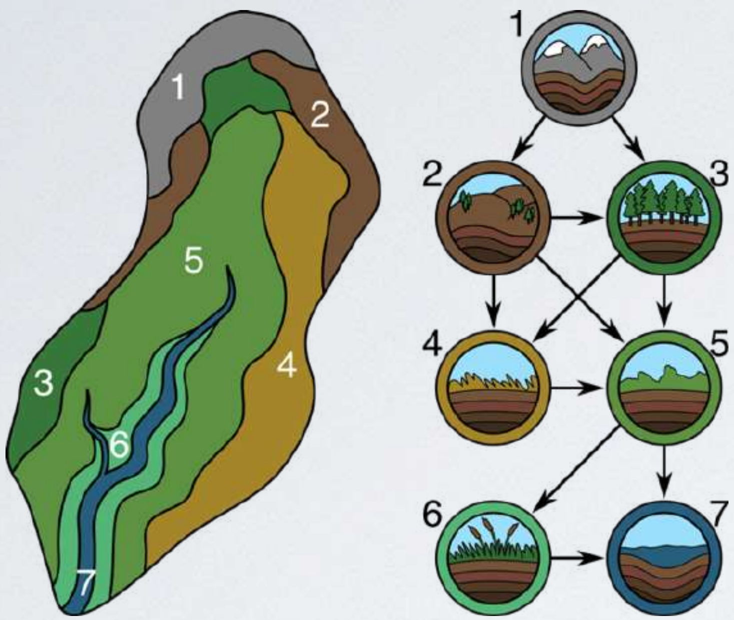
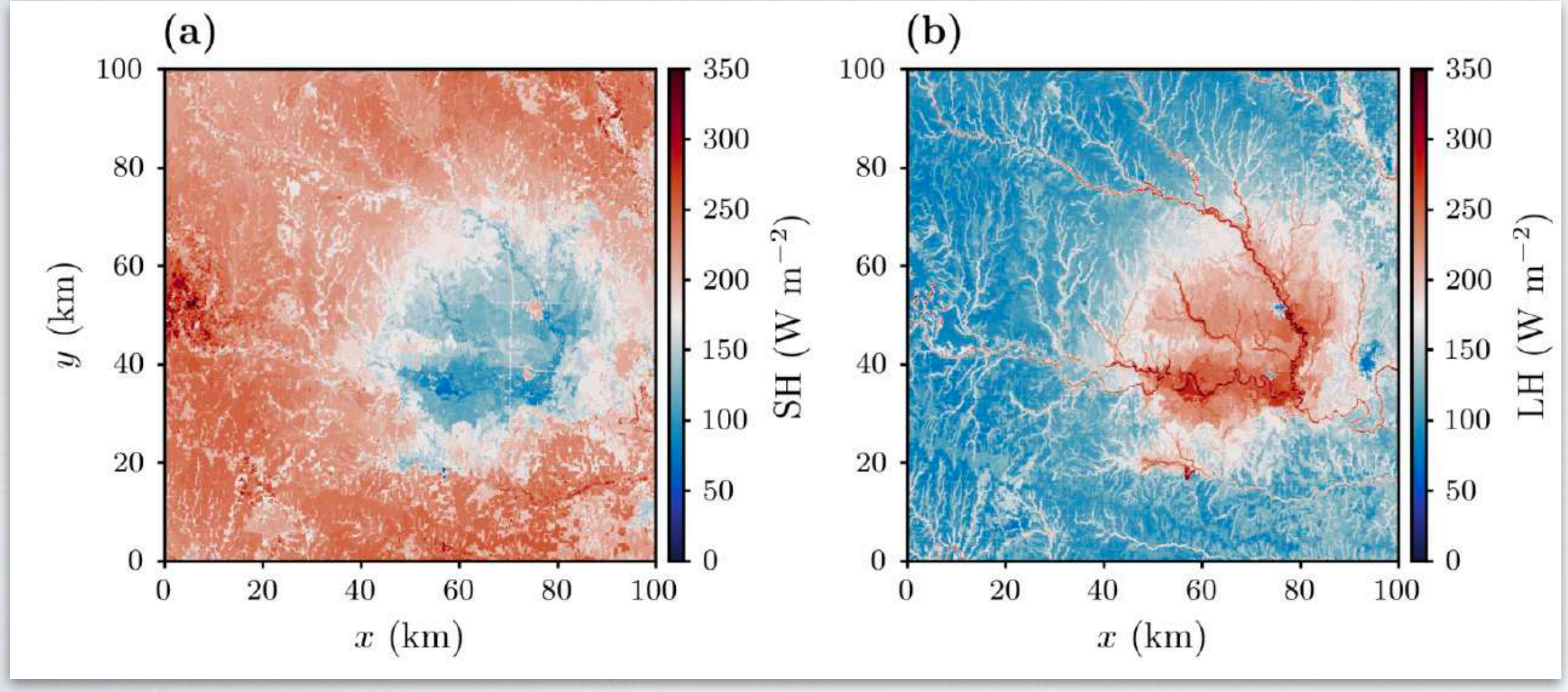


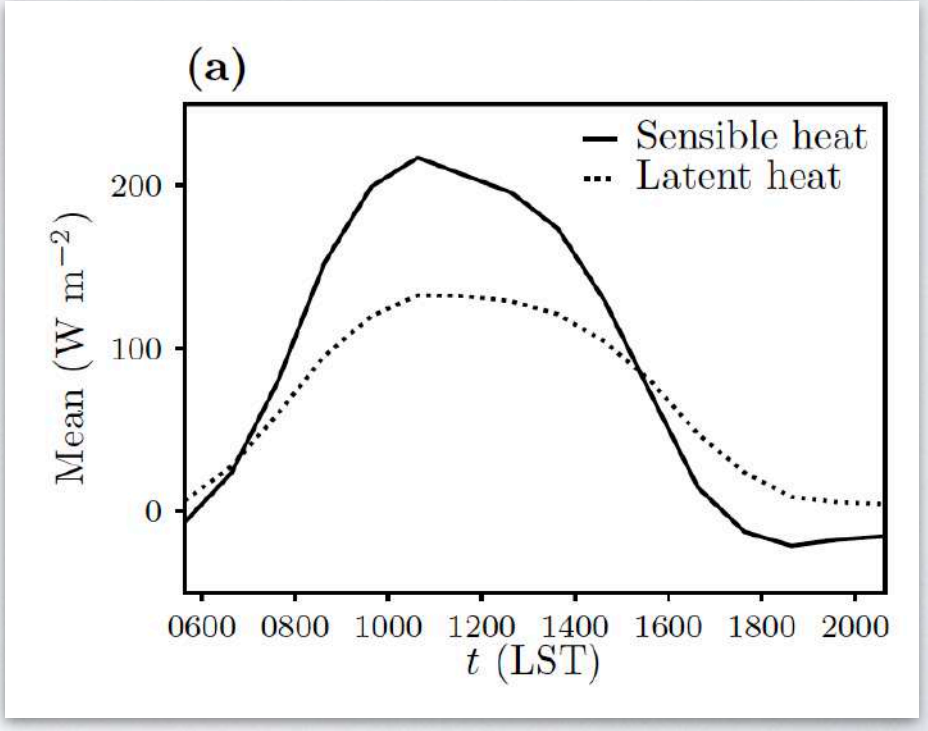
Figure 1. Map of the simulation domain, centered at the SGP site.

Land model: HydroBlocks



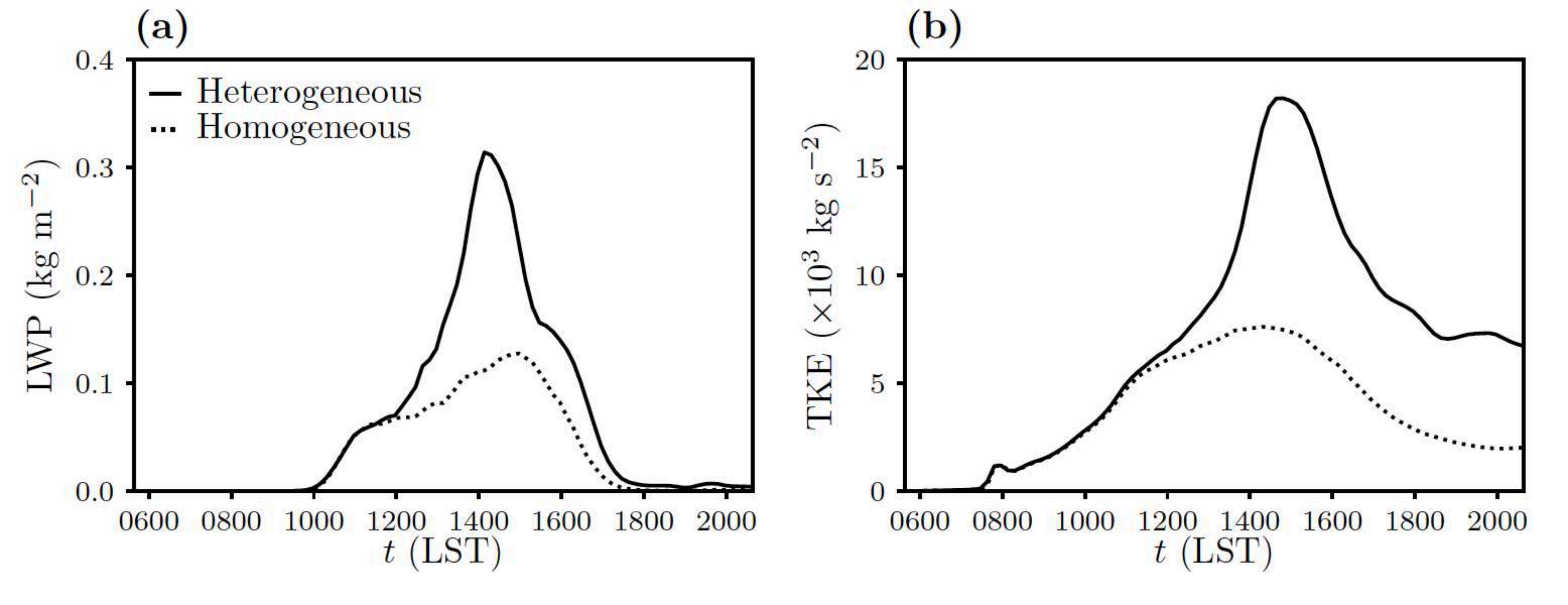
- Stage-IV radar rainfall (~4 km, hourly)
- Downscaled NLDAS-2 (~4 km, hourly)
- POLARIS soil properties (~30 m)
- NLCD land cover (~30 m)
- Run from 2015 through 2017
- Effective ~30 meter simulations





Surface fields from HydroBlocks on 9/24/2017 at ~12:00 LST

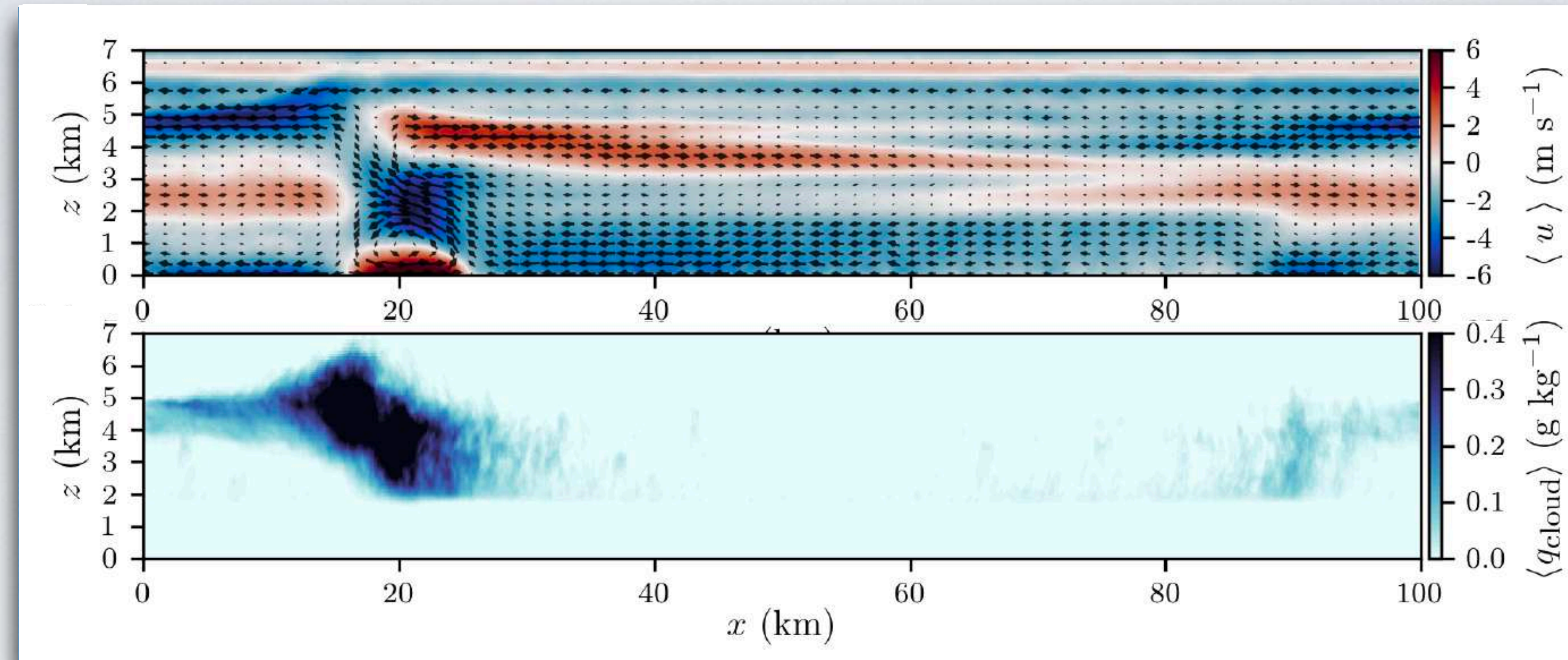
Homogeneous vs Heterogeneous



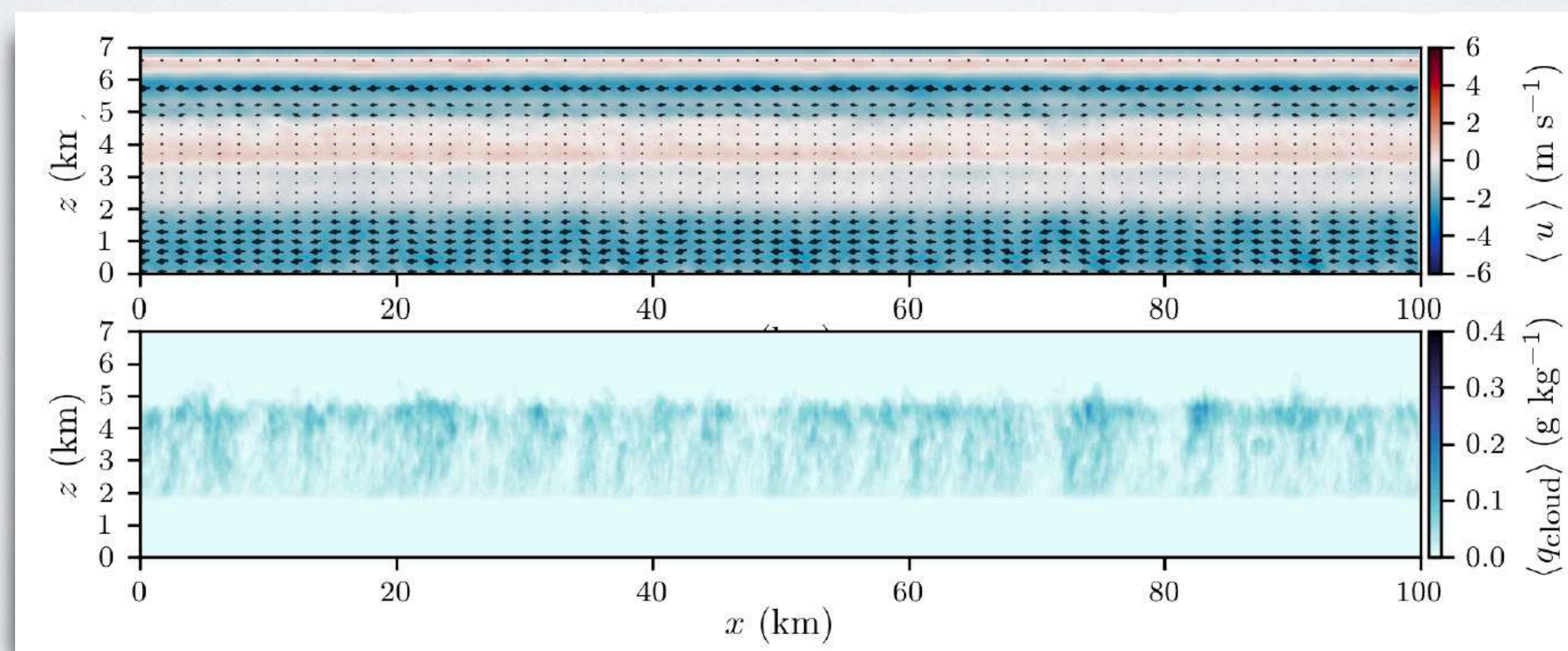
Domain-wide mean fields in time from the heterogeneous and homogeneous September 24, 2017 simulations: (a) LWP, (b) vertically integrated, mass-coupled TKE.

What drives the difference?
Secondary circulations

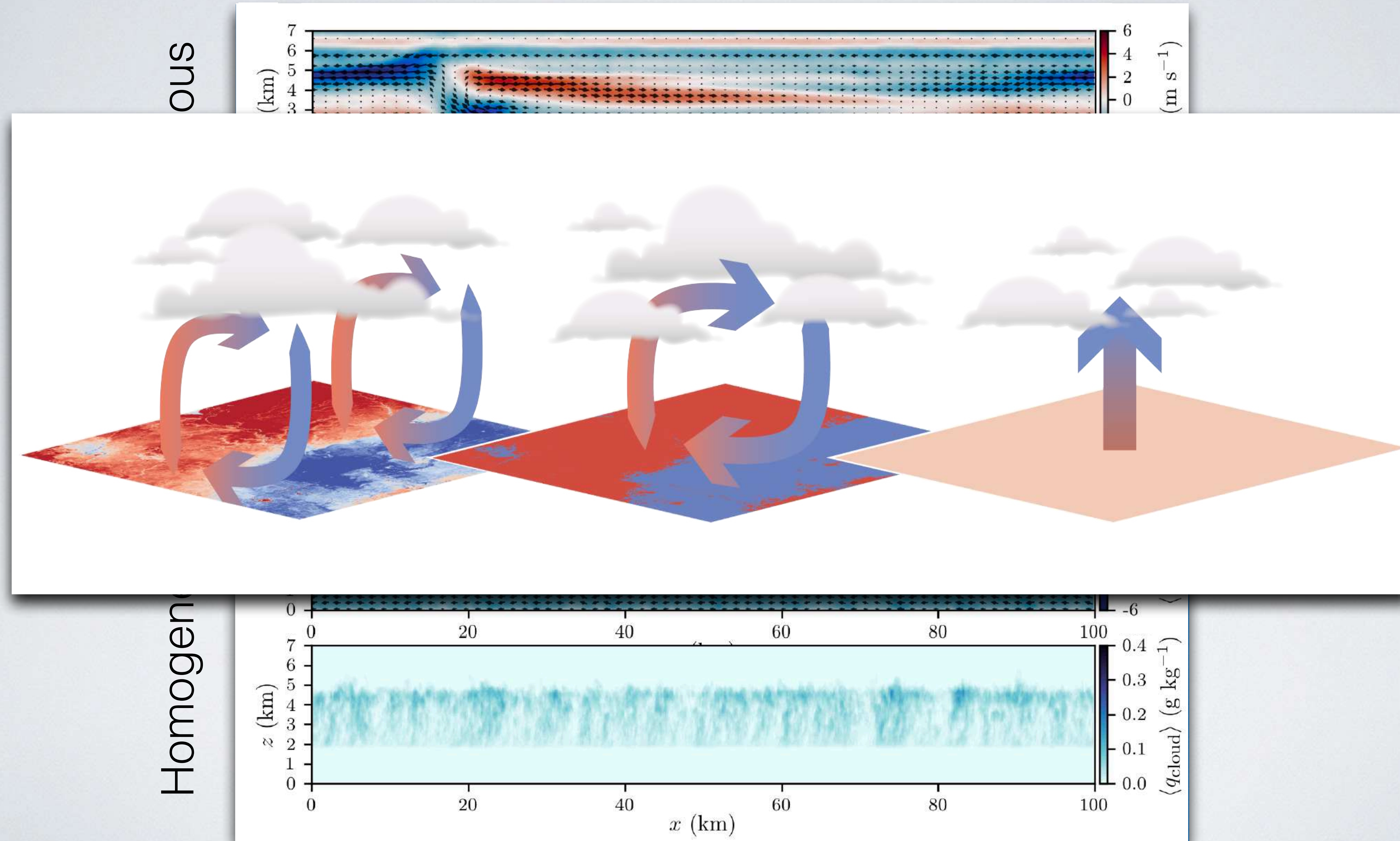
Heterogeneous



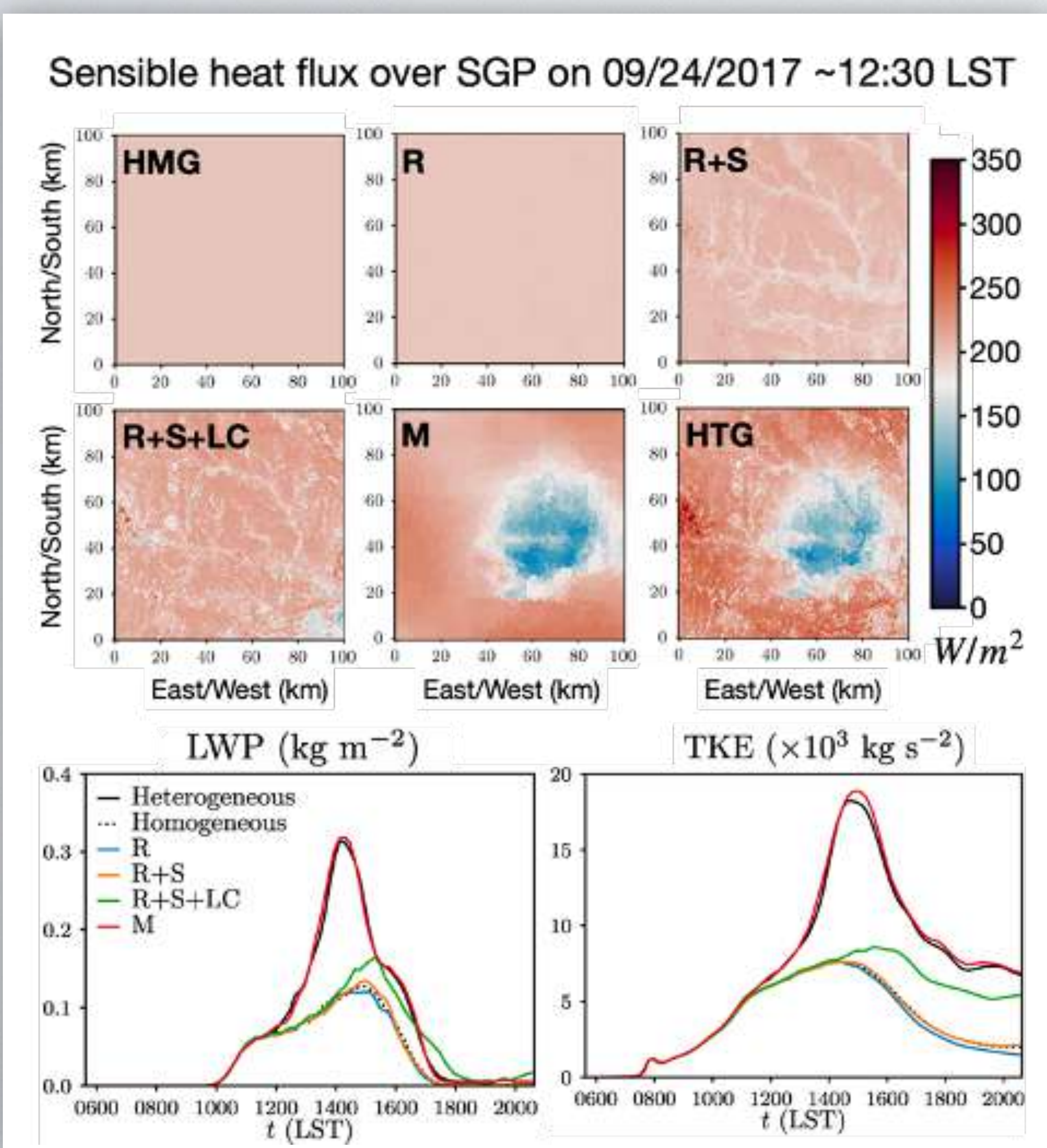
Homogeneous

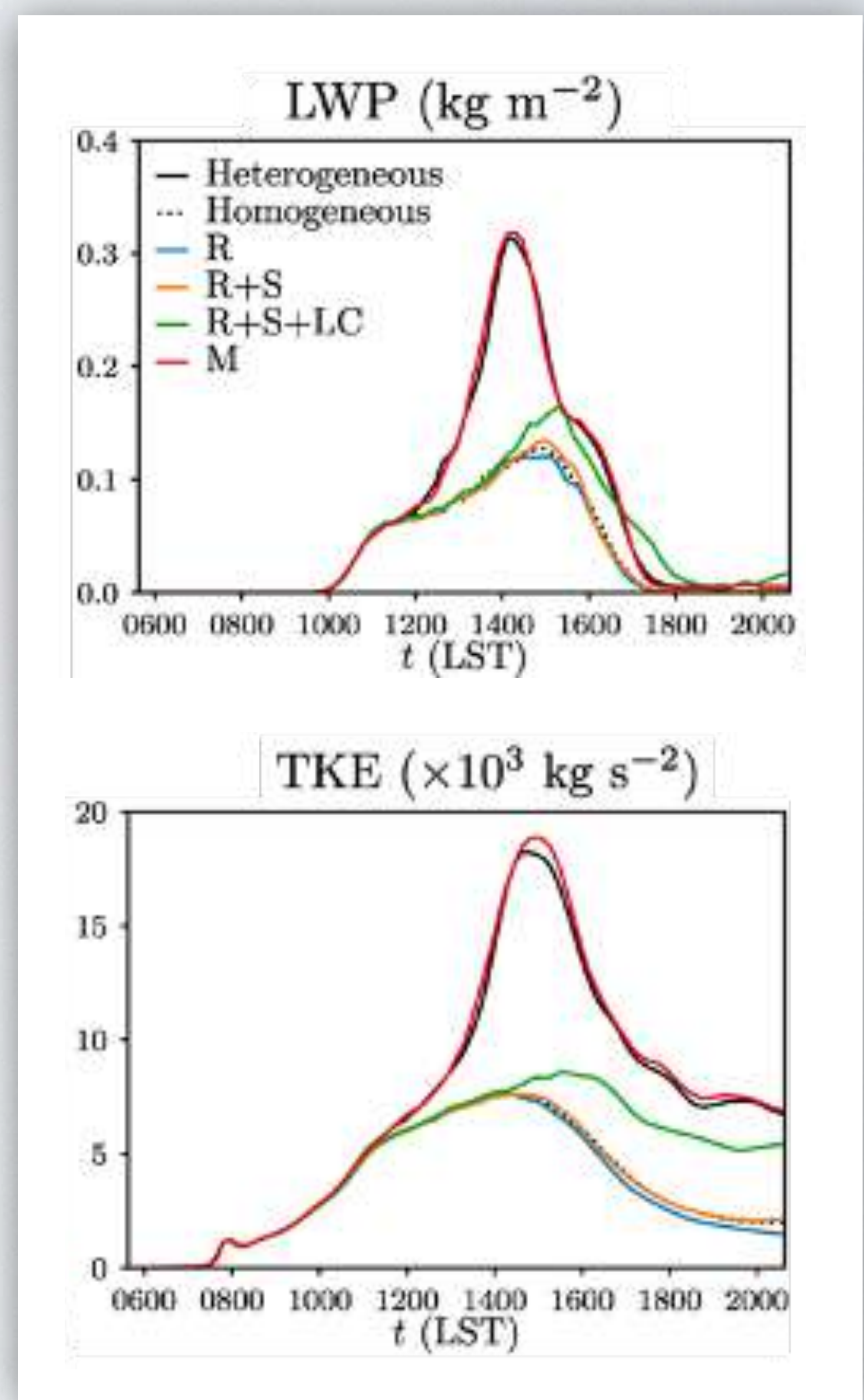


What drives the difference? Secondary circulations

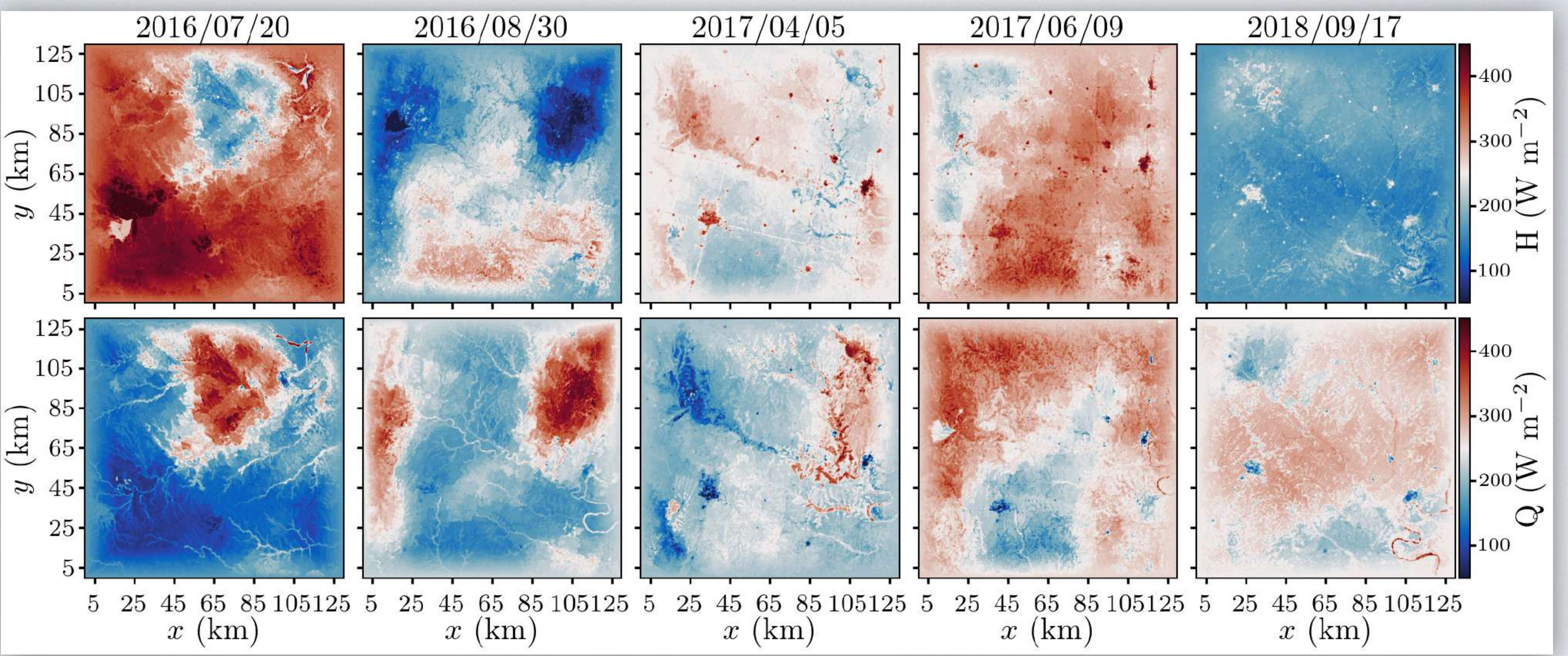


What source of heterogeneity drives the response?

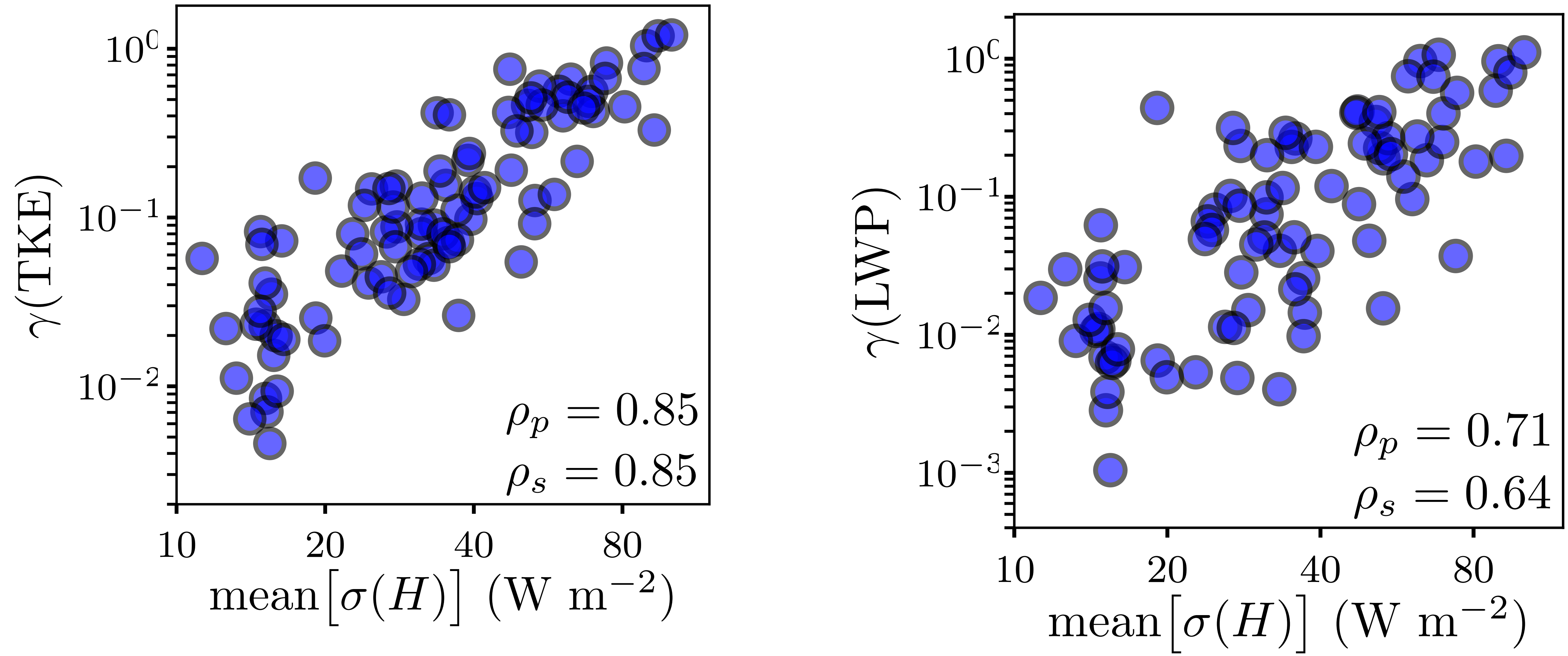




Expand LES over SGP to ~100 different shallow convection days (2015-2019)



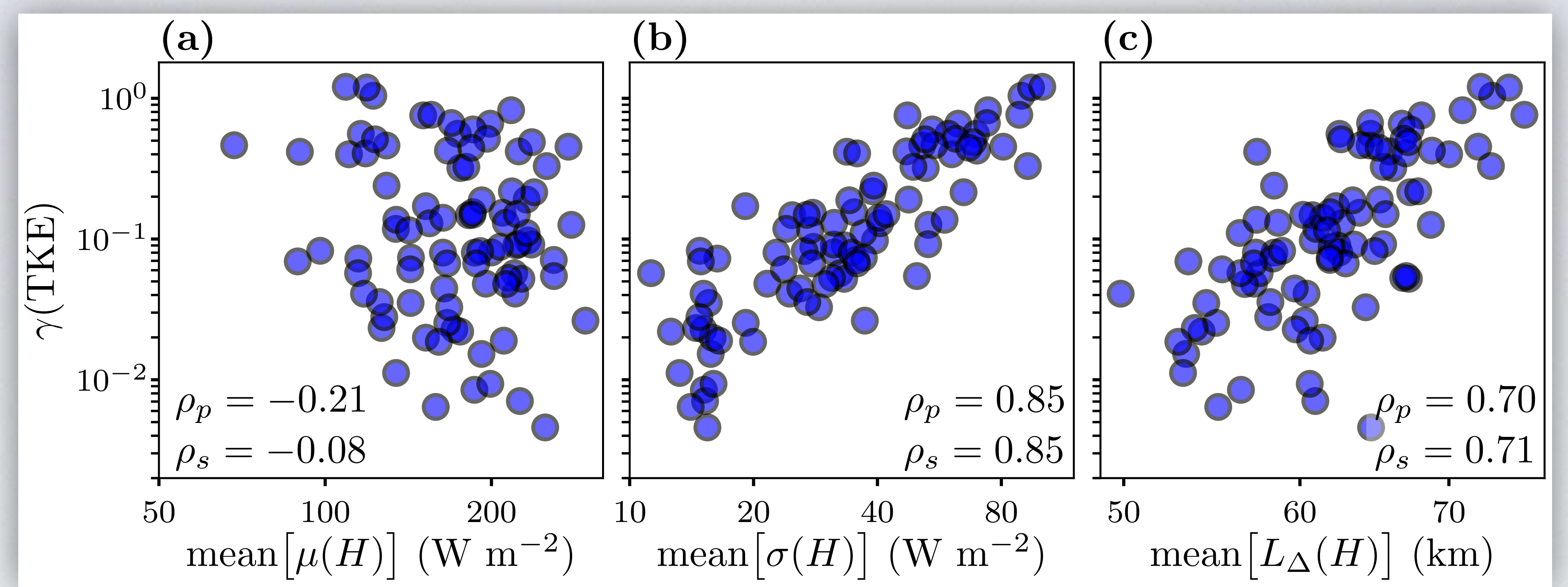
Connection between sub-grid spatial variance and differences between HTG and HMG experiments

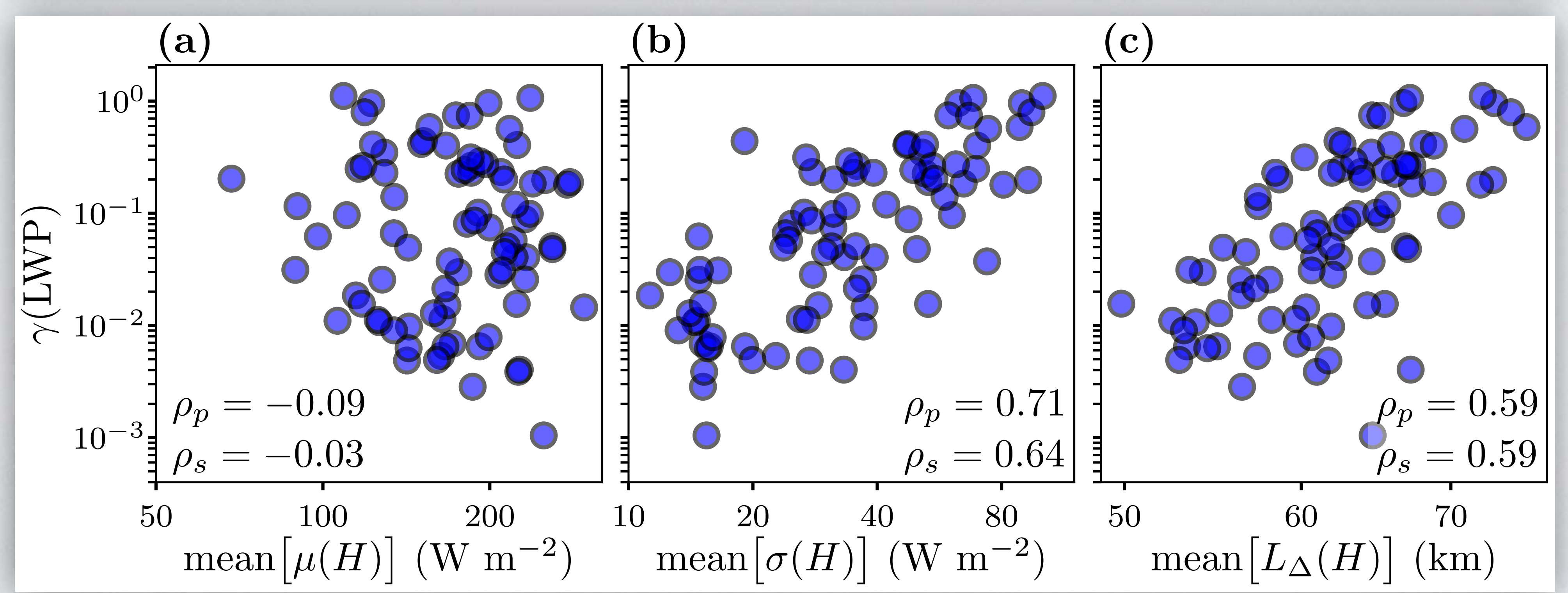


$$\gamma_t(\vartheta) = \frac{g_s \vartheta_{\mathrm{htg}} + 1}{g_s \vartheta_{\mathrm{hmg}} + 1}$$

$$g_s(t) = \begin{cases} 1 & : \quad s(t) > 0.05 \max(s), \\ 0 & : \quad s(t) \leq 0.05 \max(s), \end{cases}$$

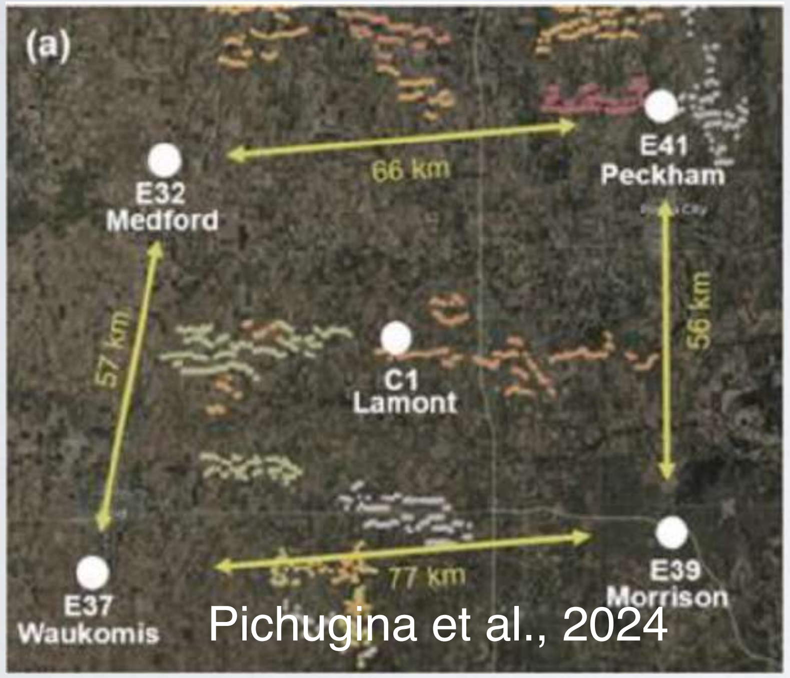
Relation between spatial mean, spatial variance, and correlation length and the atmospheric response (LWP and TKE)



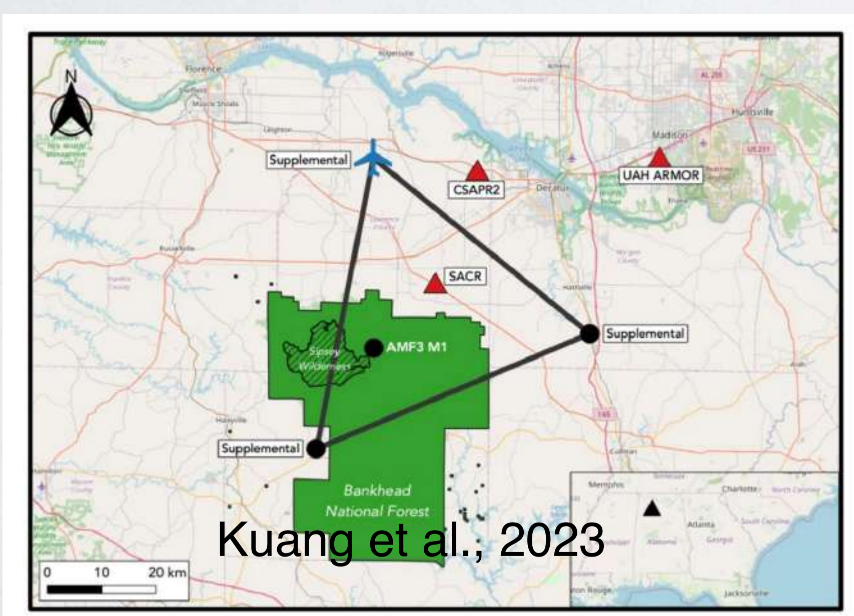


Leveraging proposed GLAFO-site networks of Doppler Lidars to quantify secondary circulations

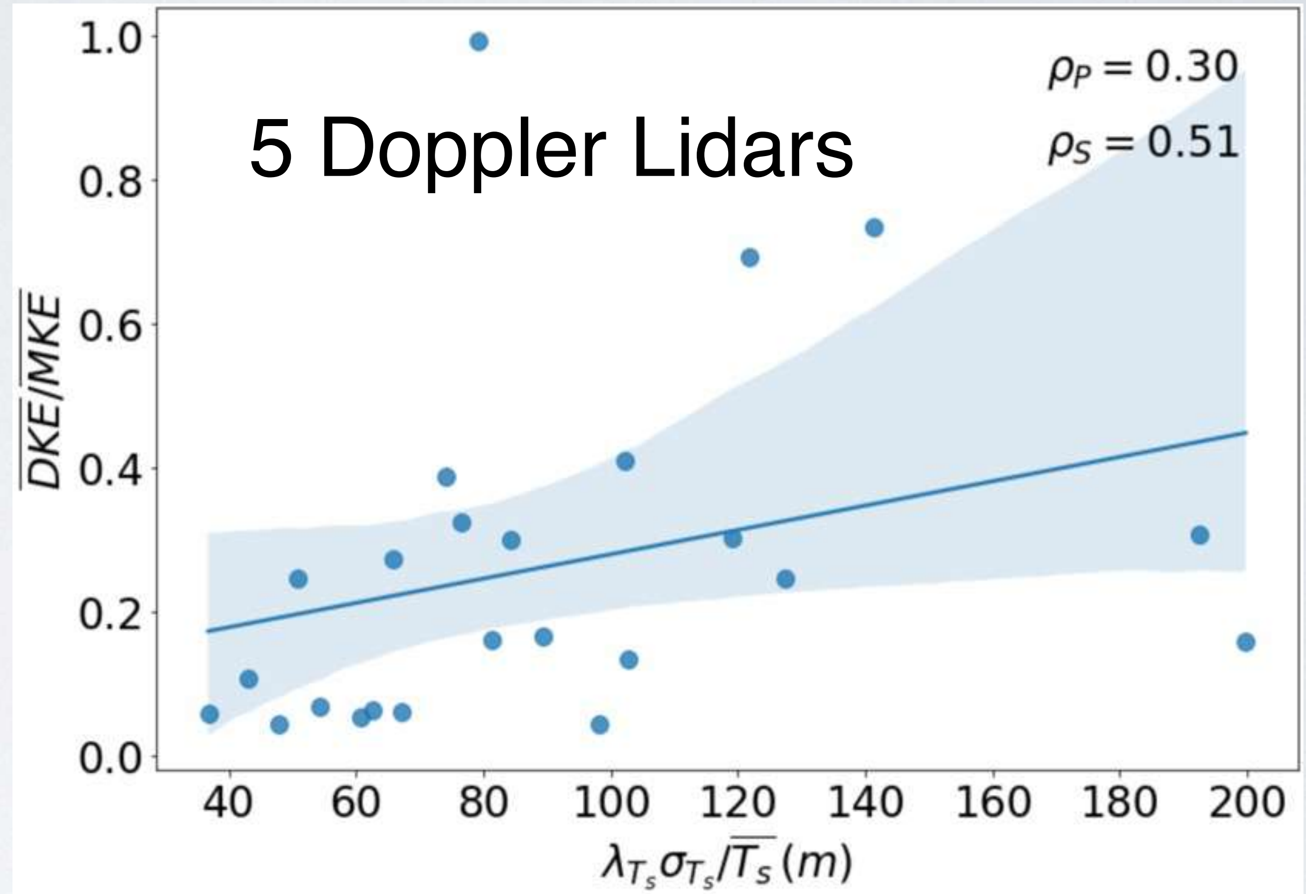
ARM SGP



ARM BNF3



Example over ARM SGP (2018-2019)



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Space-time average

Spatial perturbation after time averaging

Local temporal perturbation

$$f = \overline{\langle f \rangle} + \overline{f}'' + f'$$

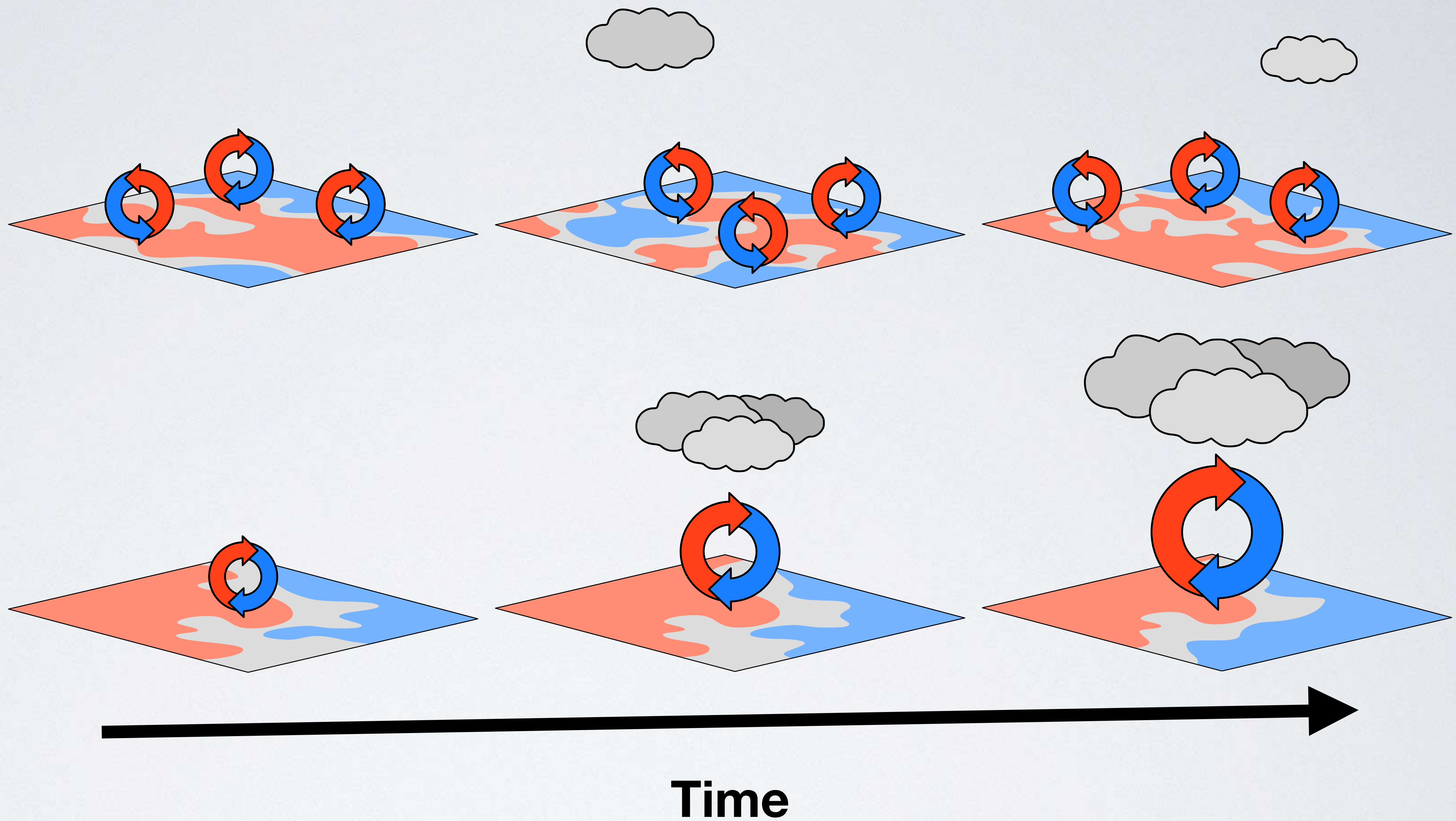
$$\overline{DKE} = \frac{1}{2}\int_0^{z_{top}} \rho\left(\langle \overline{u}''\overline{u}'' \rangle + \langle \overline{v}''\overline{v}'' \rangle + \langle \overline{w}''\overline{w}'' \rangle\right)\delta z \approx \frac{1}{2}\sum_{i=1}^{n} \rho_i \left(\sigma_{u_i}^2 + \sigma_{v_i}^2 + \sigma_{w_i}^2\right)\Delta z_i$$

DKE = Dispersive Kinetic Energy

Role of surface heterogeneity: Summary

Low surface spatiotemporal covariance

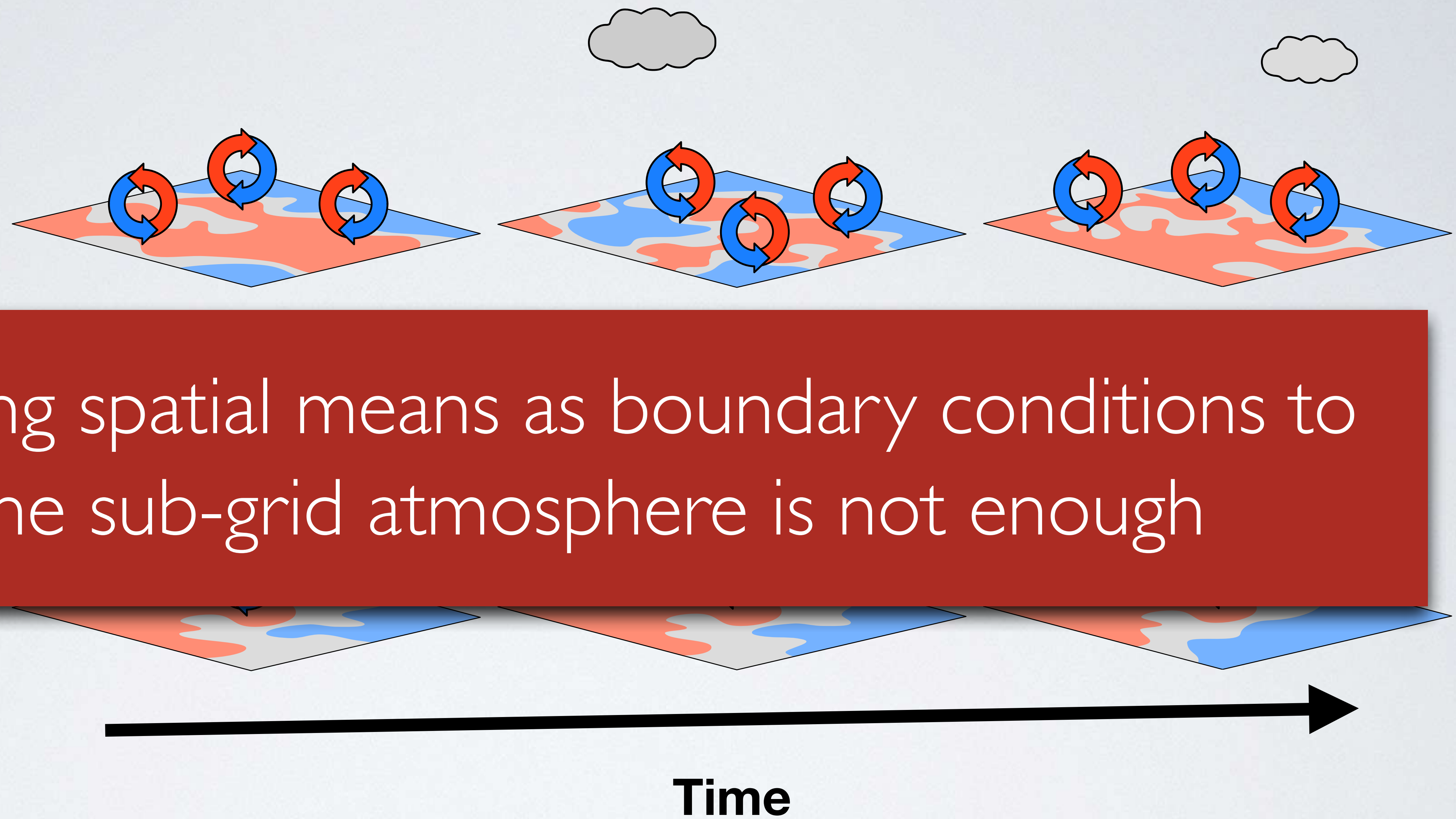
High surface spatiotemporal covariance



The spatiotemporal patterns of surface fluxes can play a determining factor in the development and enhancement of clouds in a convective boundary layer.

Role of surface heterogeneity: Summary

Low surface spatiotemporal covariance

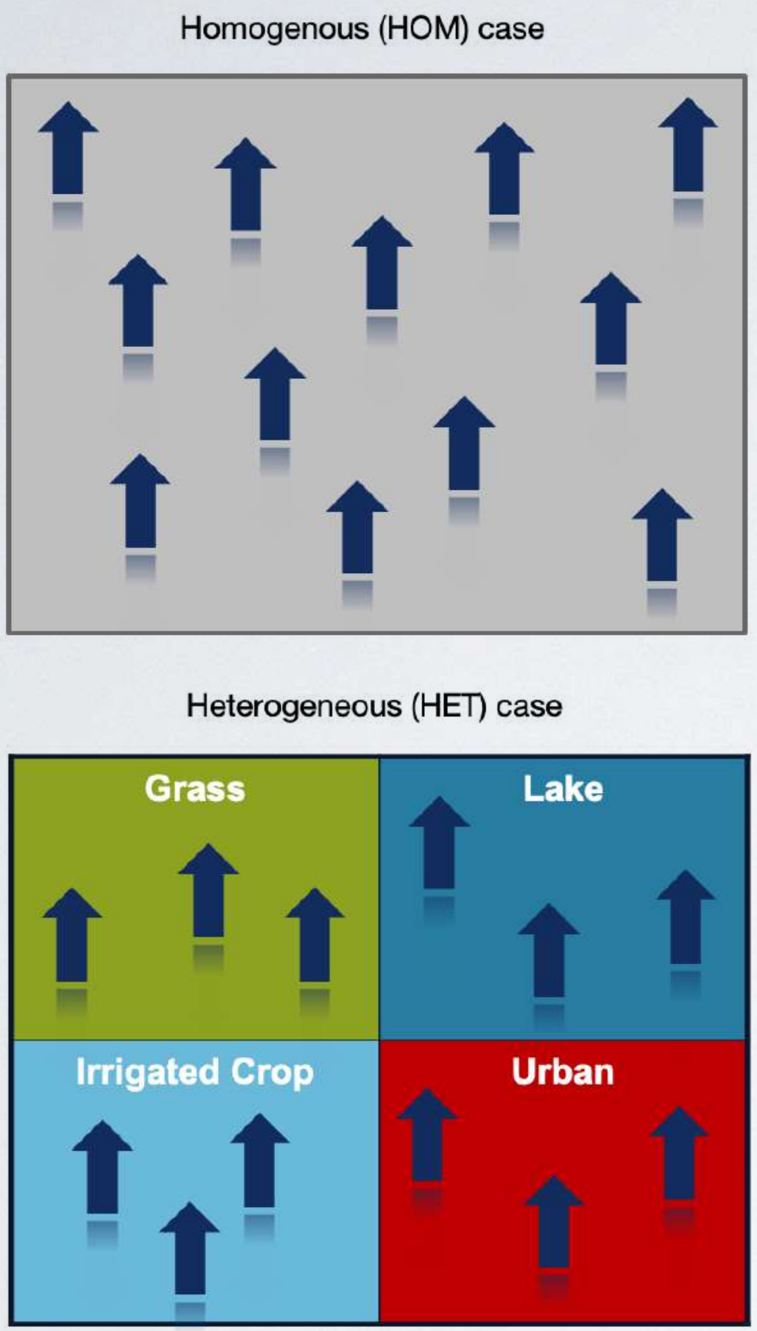


Feeding spatial means as boundary conditions to the sub-grid atmosphere is not enough

Hig
spatiotemporal
covariance

The spatiotemporal patterns of surface fluxes can play a determining factor in the development and enhancement of clouds in a convective boundary layer.

Future CLASP efforts: Parameterization



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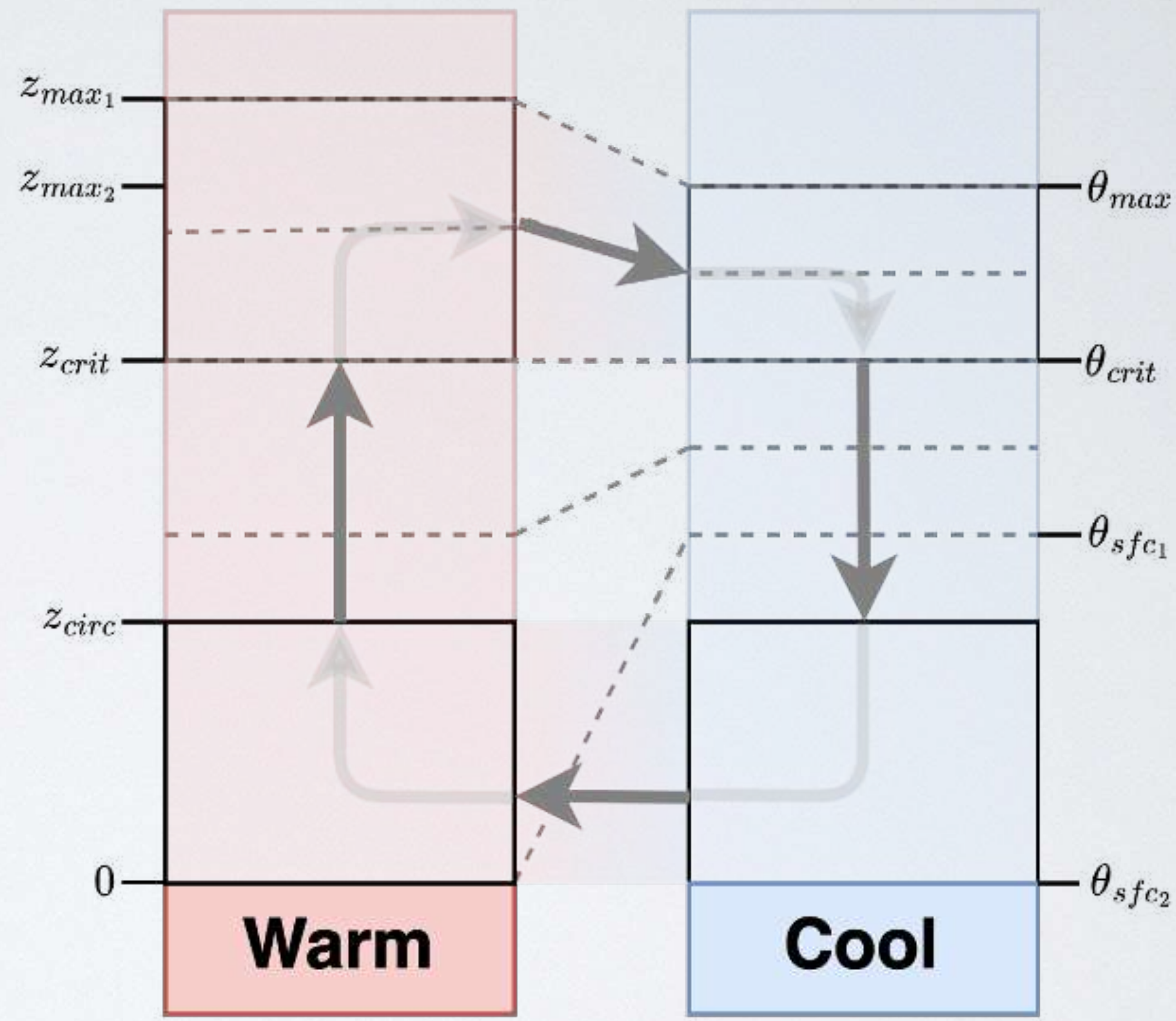
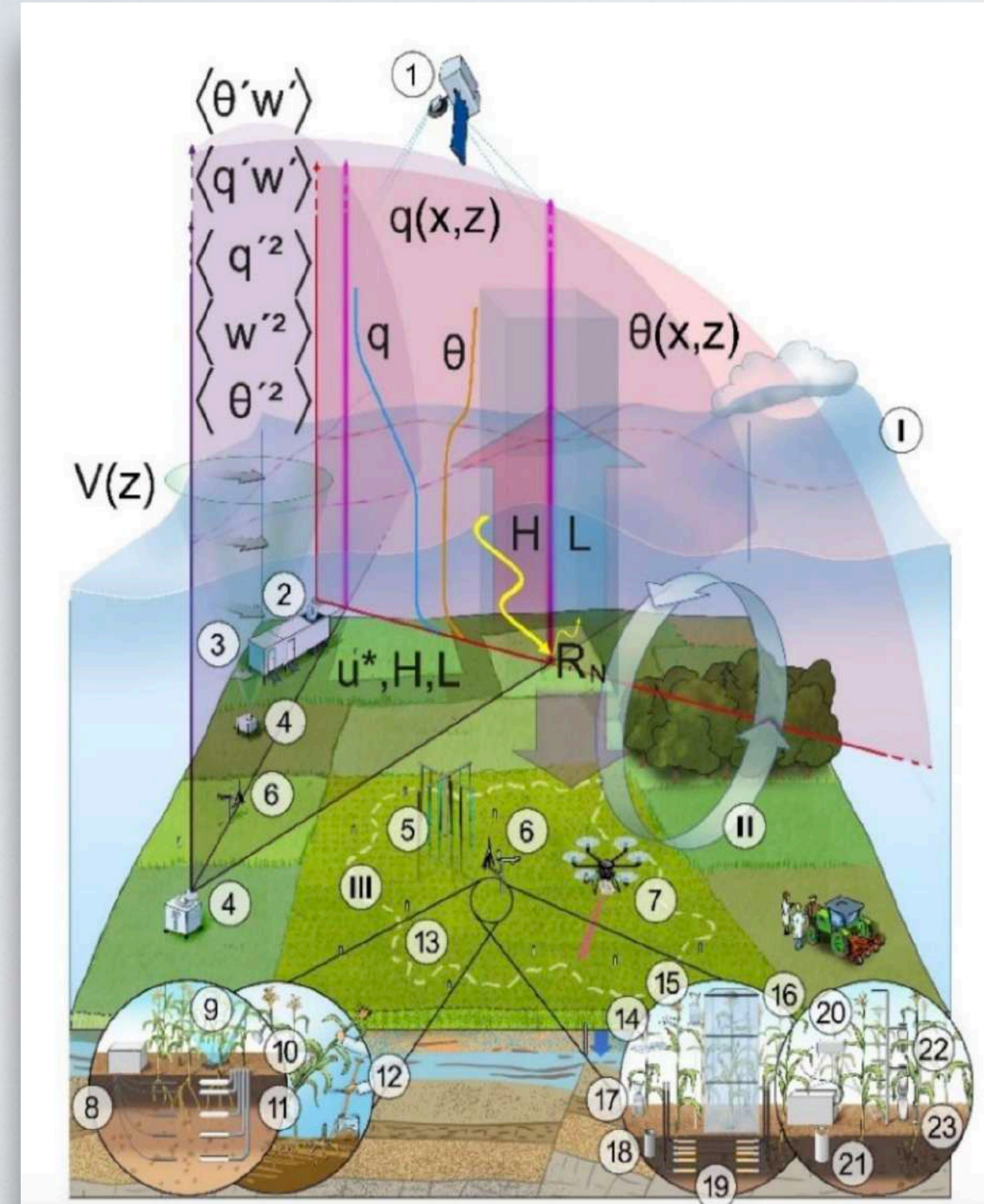
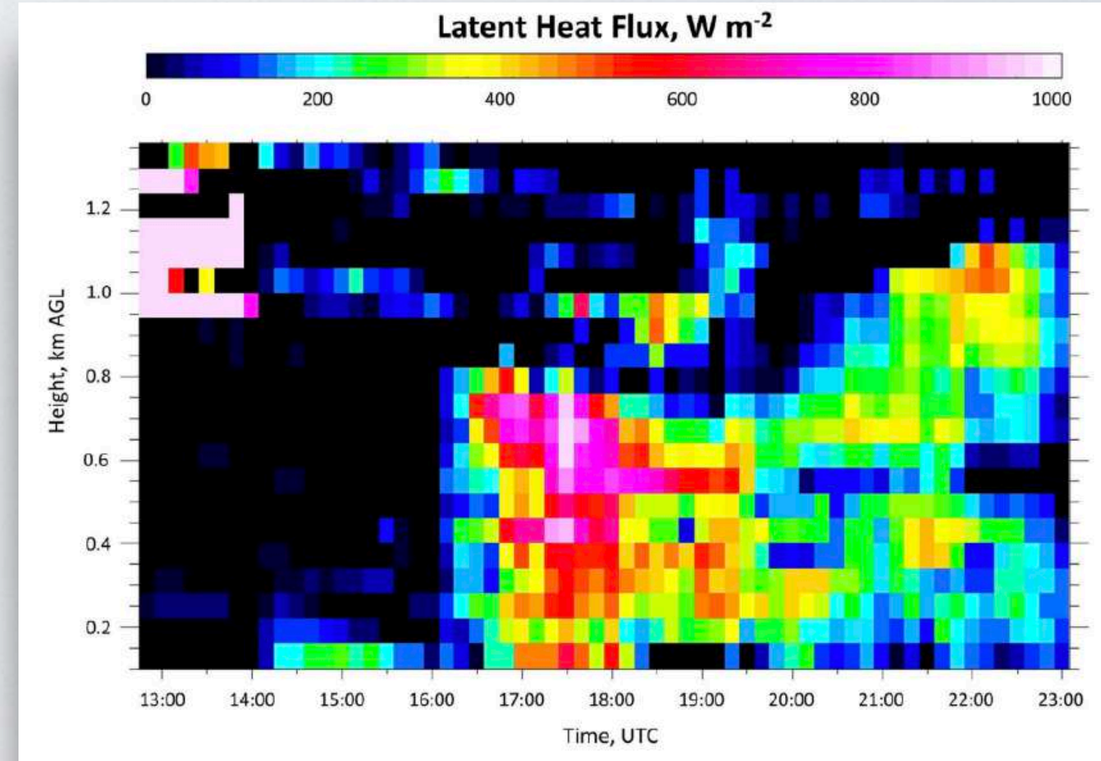


Combine the EDMF and SC approaches

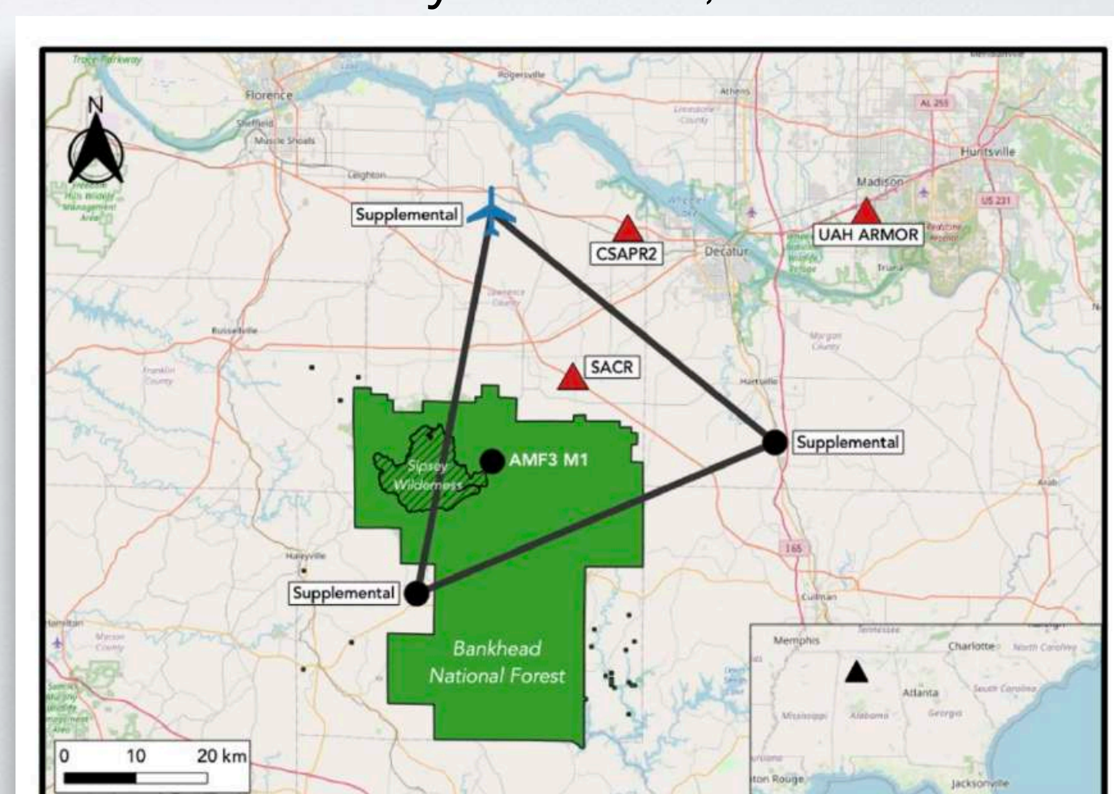
Future CLASP efforts: Leverage GLAFO-type sites



Wulfmeyer et al., 2019



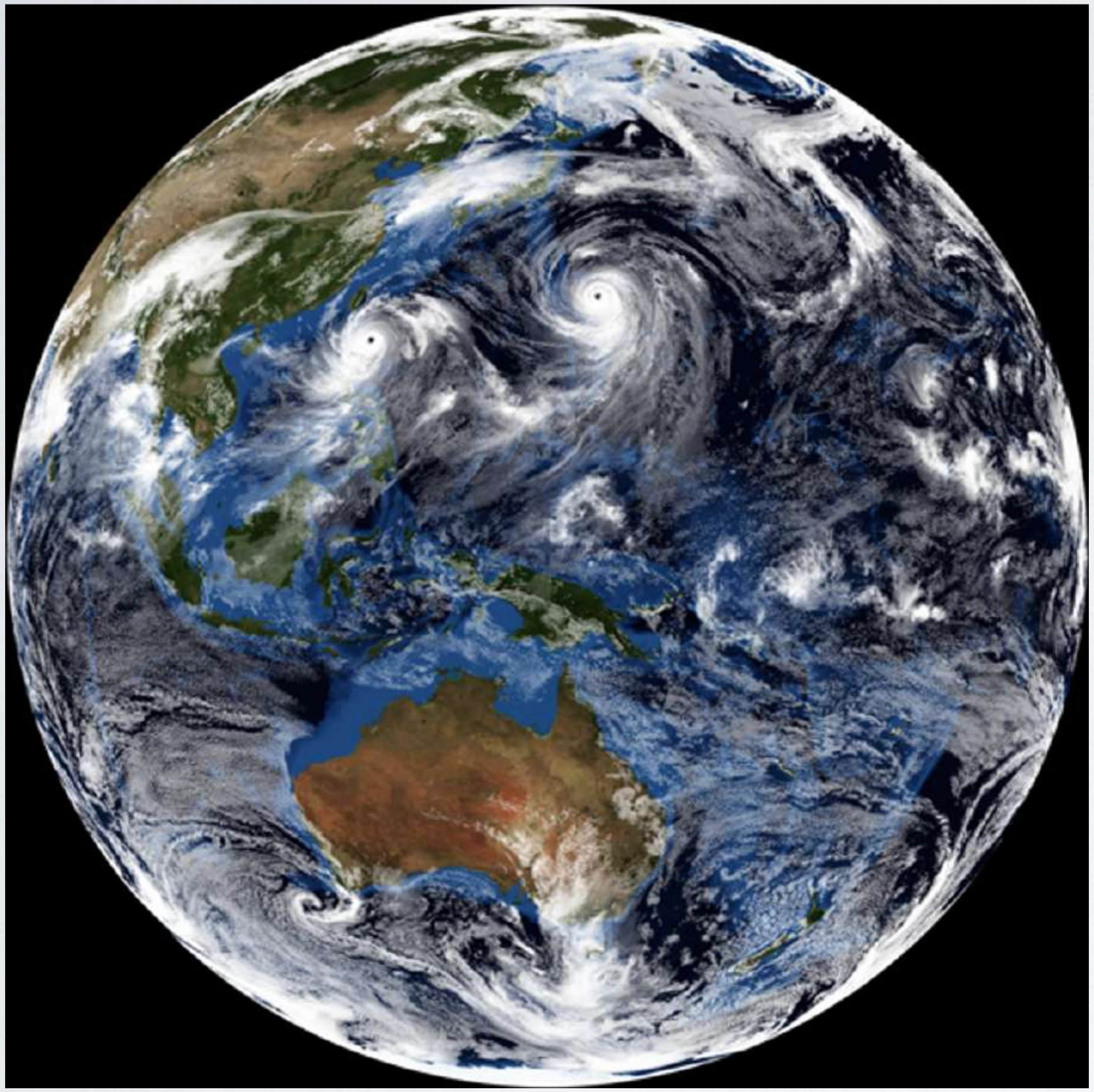
Wulfmeyer et al., 2019

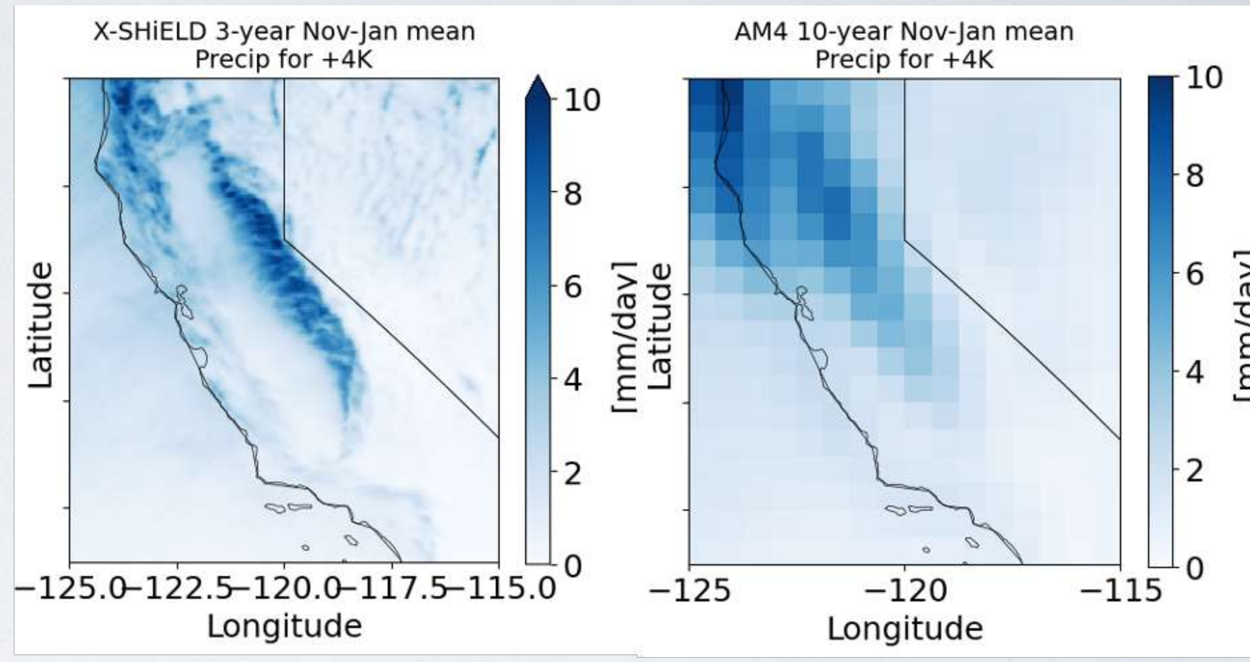


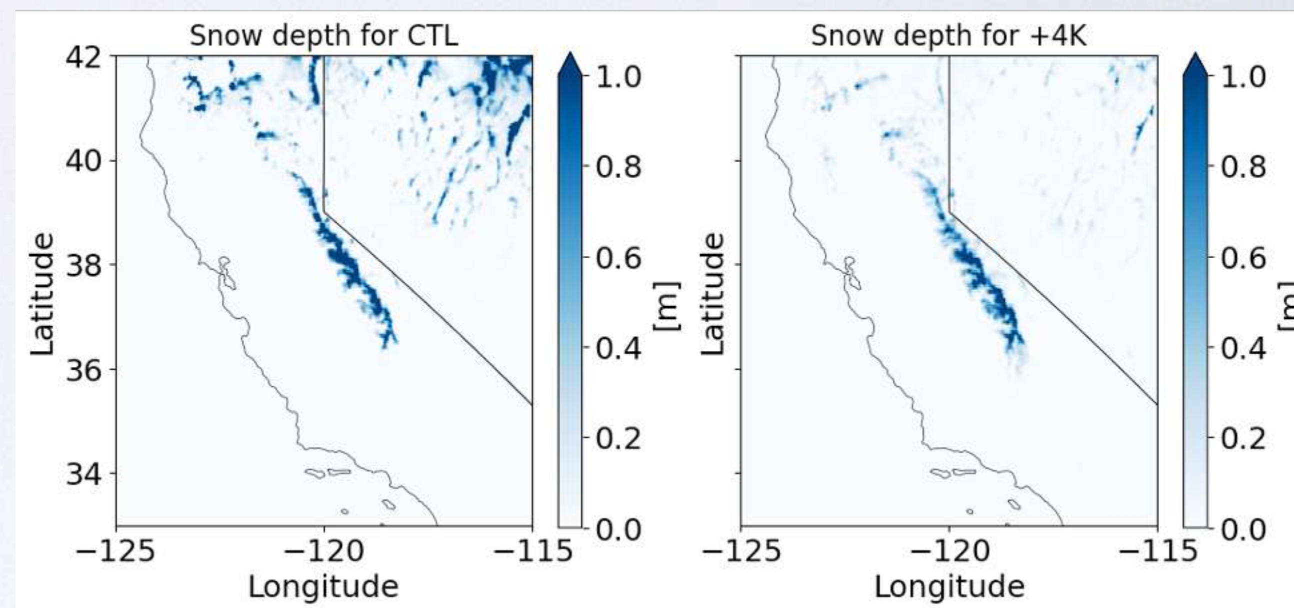
Kuang et al., 2023

Future CLASP efforts: GSRM models

GFDL FV3 simulation



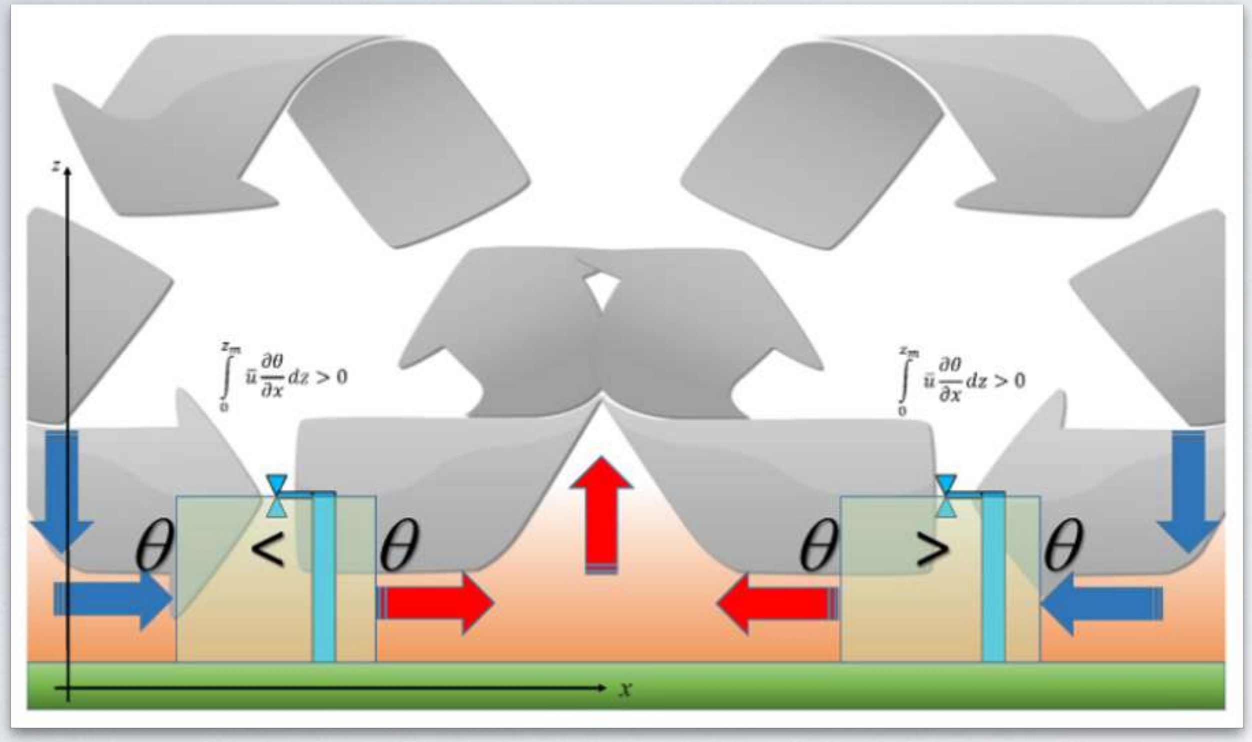




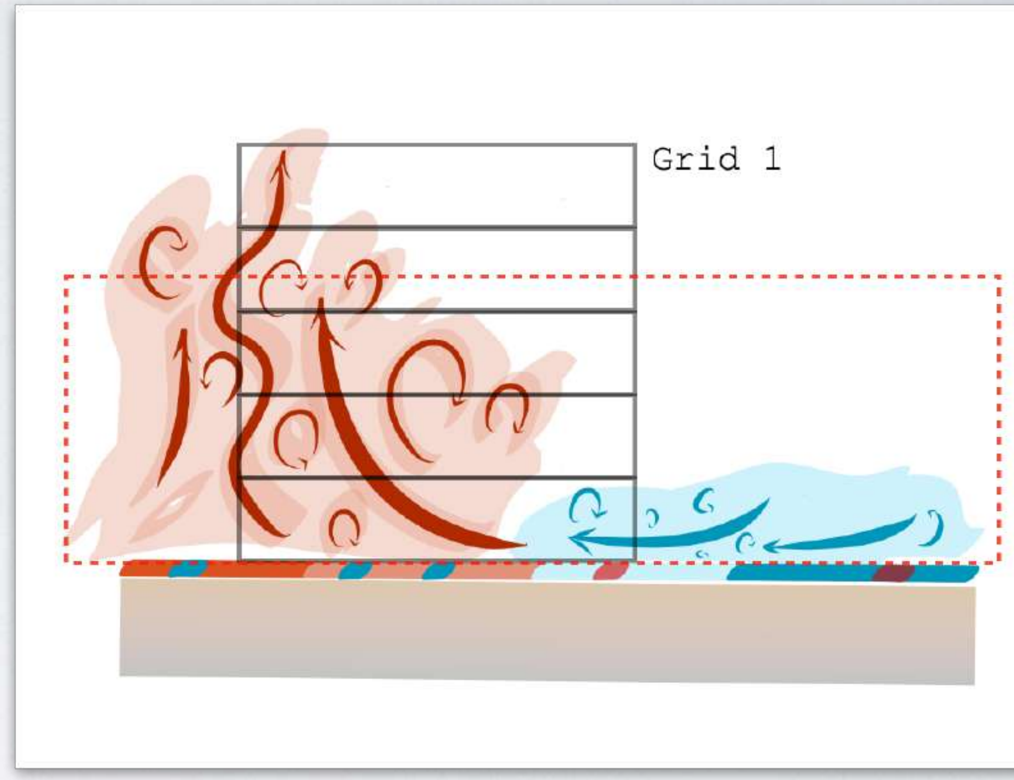
Courtesy: Lucas Harris

How should CLASP interact with ongoing Global Storm Resolving Model (~4 km dx) efforts?

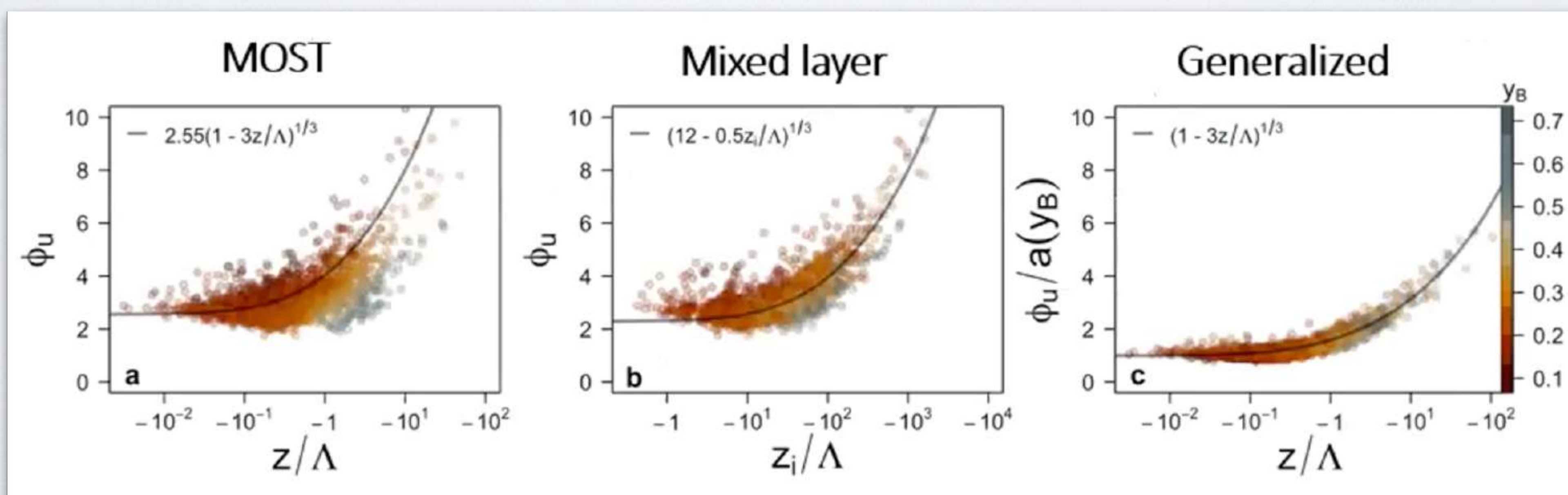
Future CLASP efforts: Monin-Obukhov



Mauder et al., BLM, 2020.

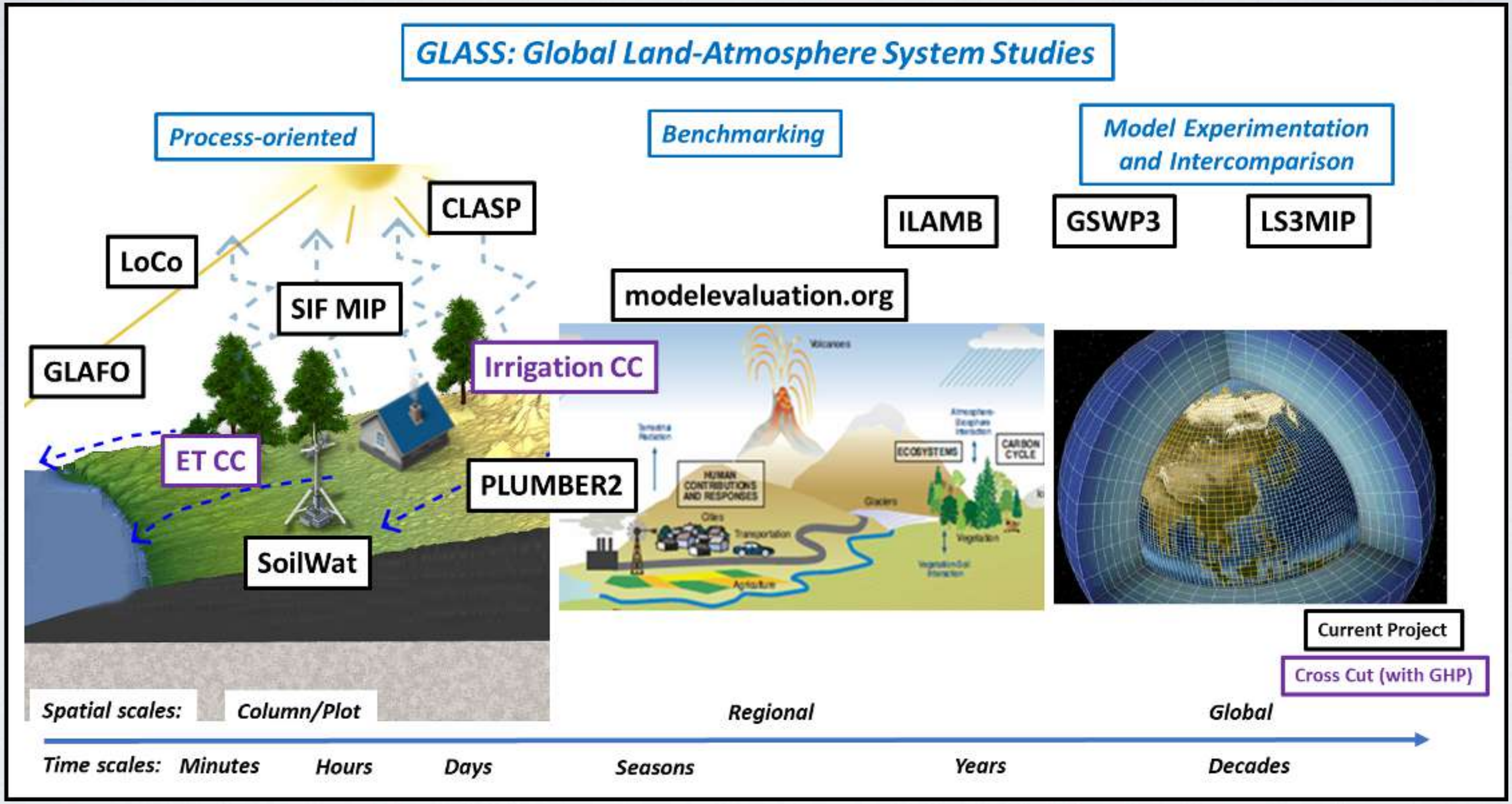


Turbulence anisotropy



Courtesy: Marc Calaf

Future CLASP: Moving beyond US project



GLASS Global Land - Atmosphere System Studies

GEWEX

CLASP meeting (May, 2023) at GFDL in Princeton, New Jersey