Combining observations and model experiments to improve soil moisture-precipitation feedback in Earth system models

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Motivation

Convective parameterizations are evolving to allow more pathways for convective clouds to interact with surface turbulence

- CAPE-based mass flux closure (Zhang-McFarlane 1995):
  - $M_b \sim CAPE / \tau$
- CIN or 'energy barrier' closure (Mapes 2000; Hohenegger et al. 2011):
  - $M_b \sim \exp(-CIN/TKE)$
- PDF-based parameterizations (e.g., Golaz et al. 2002; Storer et al. 2015):
- 'Super-parameterization' (Khairoutdinov et al., 2005)
  - Clouds coupled to surface through thermodynamics and dynamics

Motivation

How do modeled clouds respond to variations in land-surface properties and is there evidence of those responses in observations?

Are there systematic responses that can drive feedbacks?

- Important because feedbacks can amplify or extend drought.
- ESMs can drift and lock into warm and dry states (e.g., Klein et al., 2006).

Approach

Traditional approach:

Observation
↓
Empirical Model
↓
Coupling Metrics
↓
Model-Observation Comparison

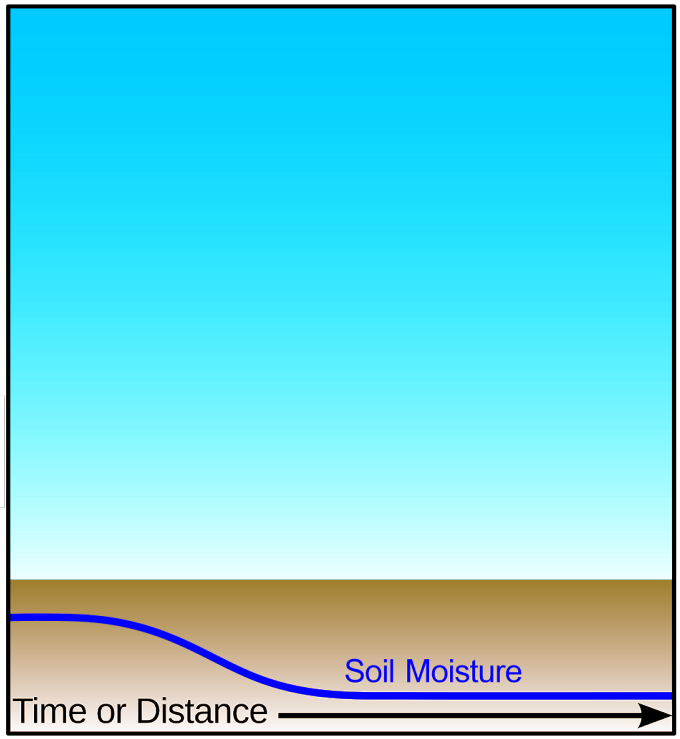
Experimental approach:

Model or Field Experiment
↓
Mechanistic Hypothesis
↓
Observational Evidence
↓
Model Development

Experimental approach requires hindcast framework to falsify mechanistic hypotheses using observations.

Models must be sufficiently constrained by realistic forcing (e.g., boundary conditions) to facilitate comparison to observations at cloud system scales.

Hypothesis: Convective triggering feedbacks



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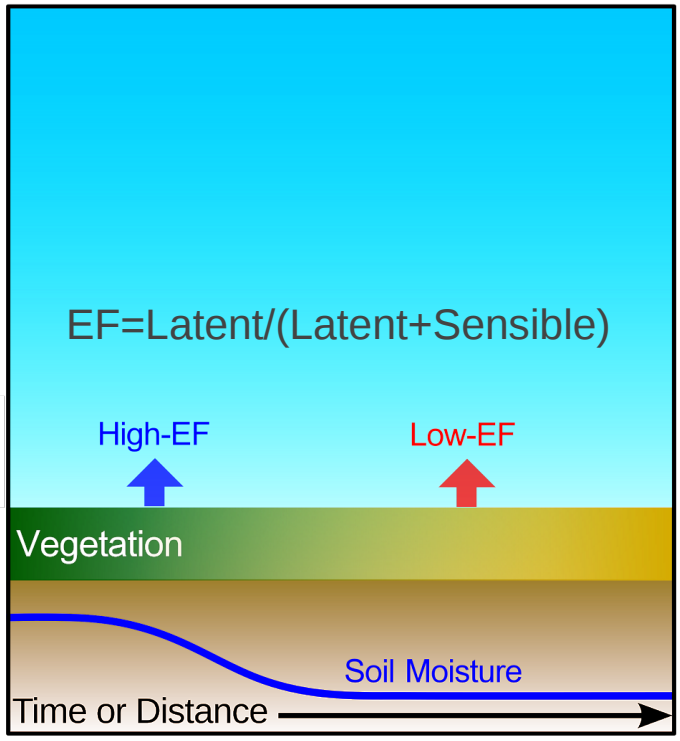
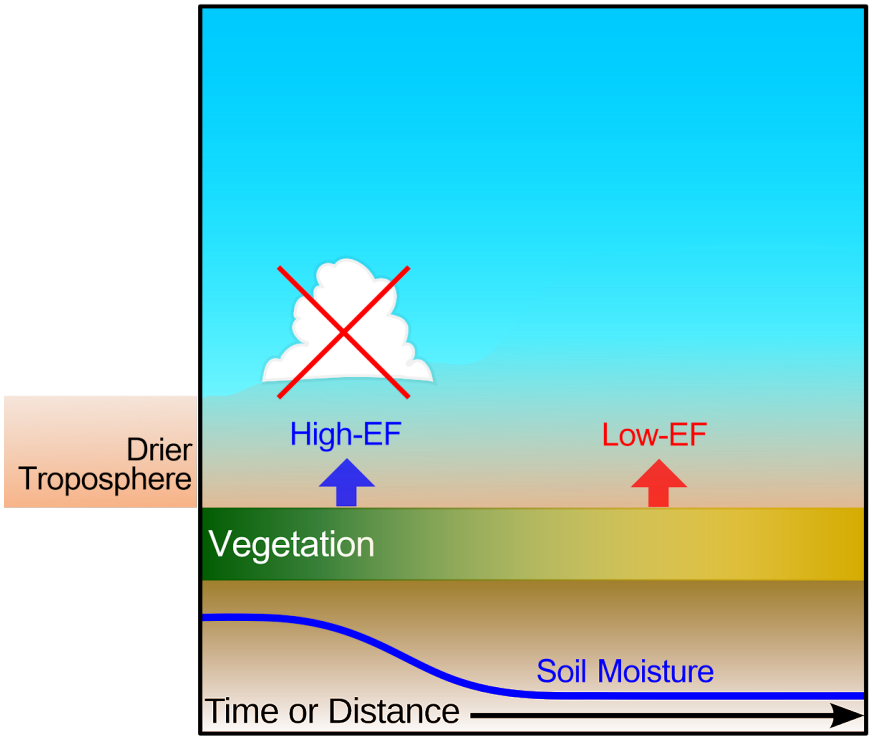


Energy partitioning depends on vegetation state

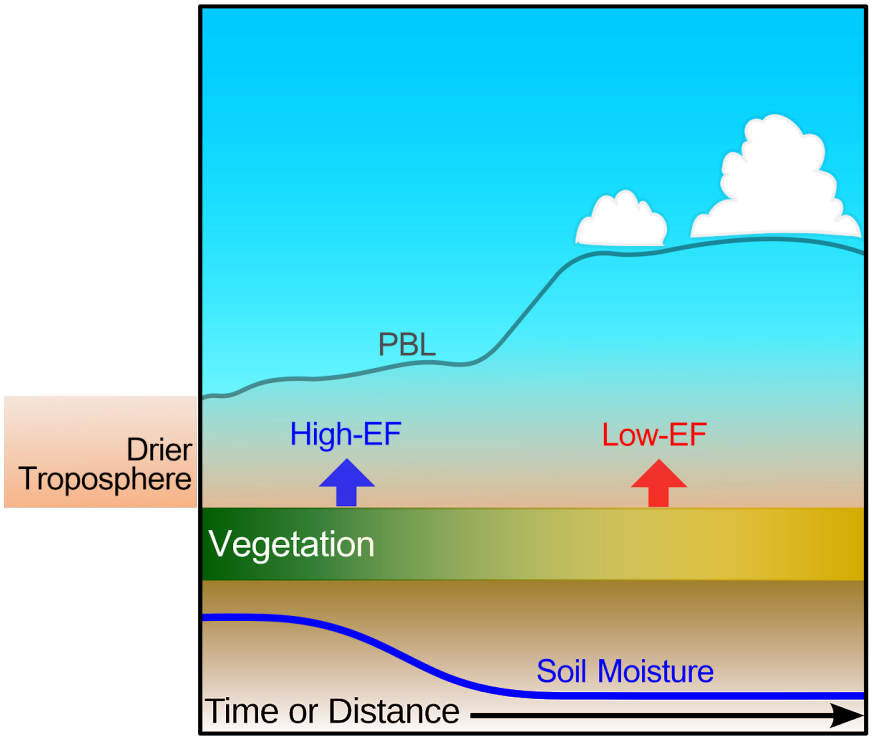
(Williams and Torn 2015, GRL)

Hypothesis: Convective triggering feedbacks



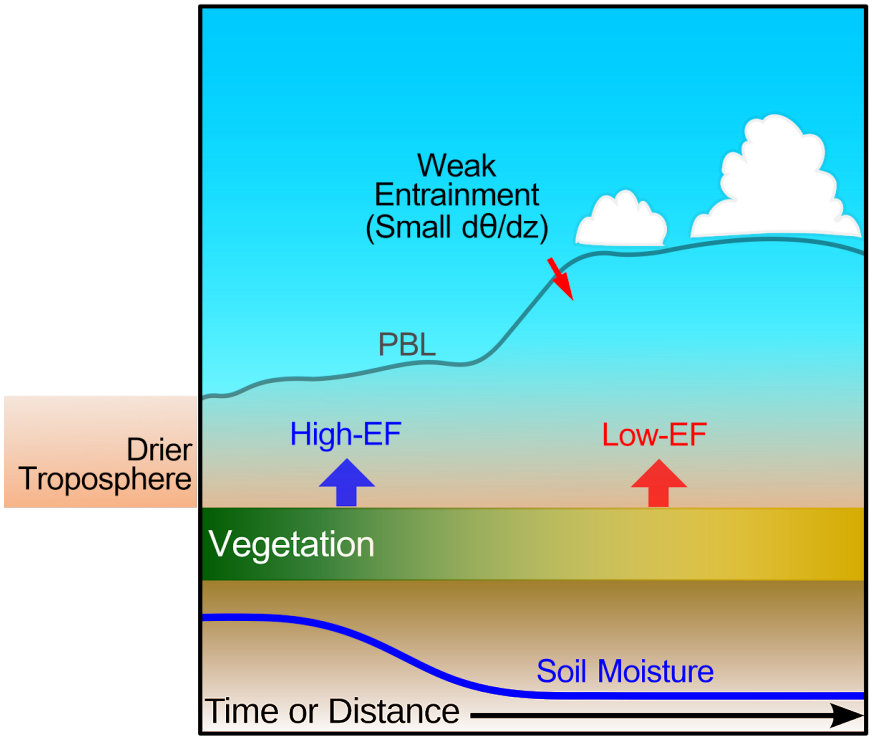
In very dry atmosphere, no amount of surface evaporation is sufficient, so a wetter surface does not trigger convection.

Hypothesis: Convective triggering feedbacks



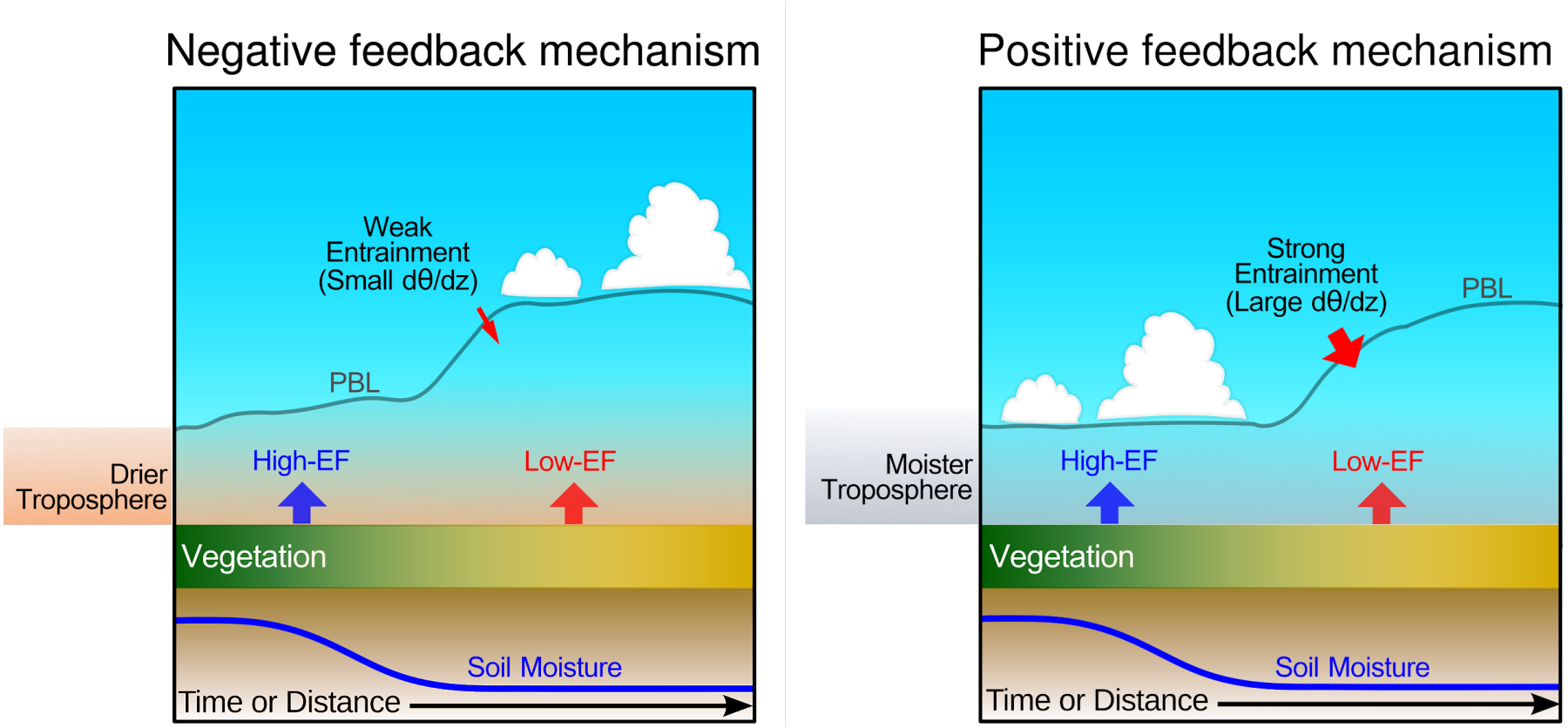
However, a high sensible heat flux (low-EF) can drive a deeper PBL and lift air to saturation by adiabatic cooling...

Hypothesis: Convective triggering feedbacks



…but effect is tempered by entrainment, requires a smaller temperature gradient.

Hypothesis: Convective triggering feedbacks



Discovered in idealized models: Ek and Mahrt 1994; Findell and Eltahir 2003; Gentine et al. 2013

Numerous studies with mixed or contradictory observational evidence.

Idealized models lacked realistic forcing and physics needed to compare against observations.

Outline

This talk: Combine observations and complex model (and field) experiments

1. ‘Field experiments’
2. Single-column hindcast experiments
3. Cloud-permitting hindcast experiments

‘Field Experiments’ at SGP Central Facility

1. ‘Field experiment’ approach

Surface turbulence is measured at two neighboring fields having same atmospheric forcing but different vegetation

- Demonstrates land-surface control on evaporative fraction (Williams and Torn 2015; GRL)
- Informs selection of land-model parameters (Williams et al. 2016; JGR)
- Enables optimization of MODIS-based estimates of LAI

ARM-SGP site

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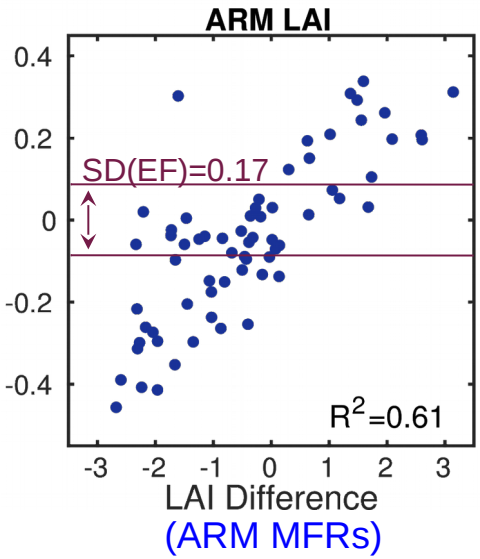
ARM-SGP site

EF Difference (wheat minus grass)



Williams, Lee, Zhang et al.; in preparation

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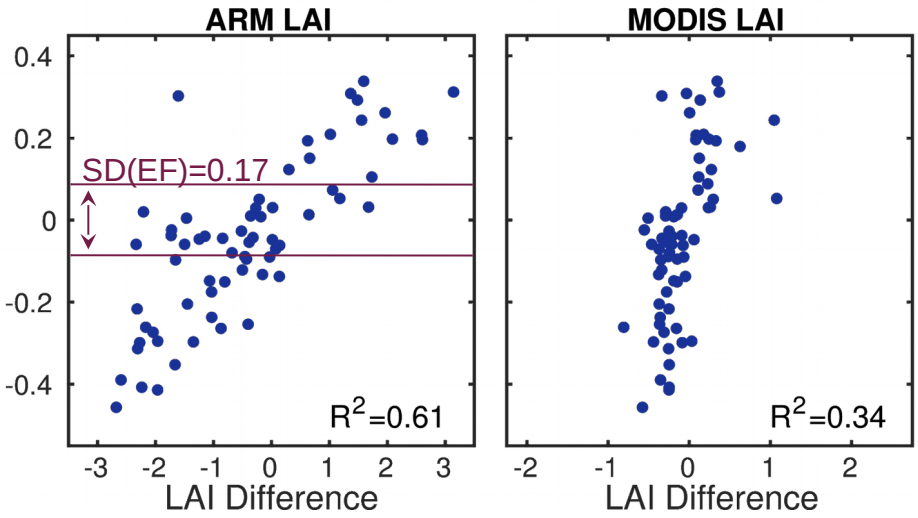

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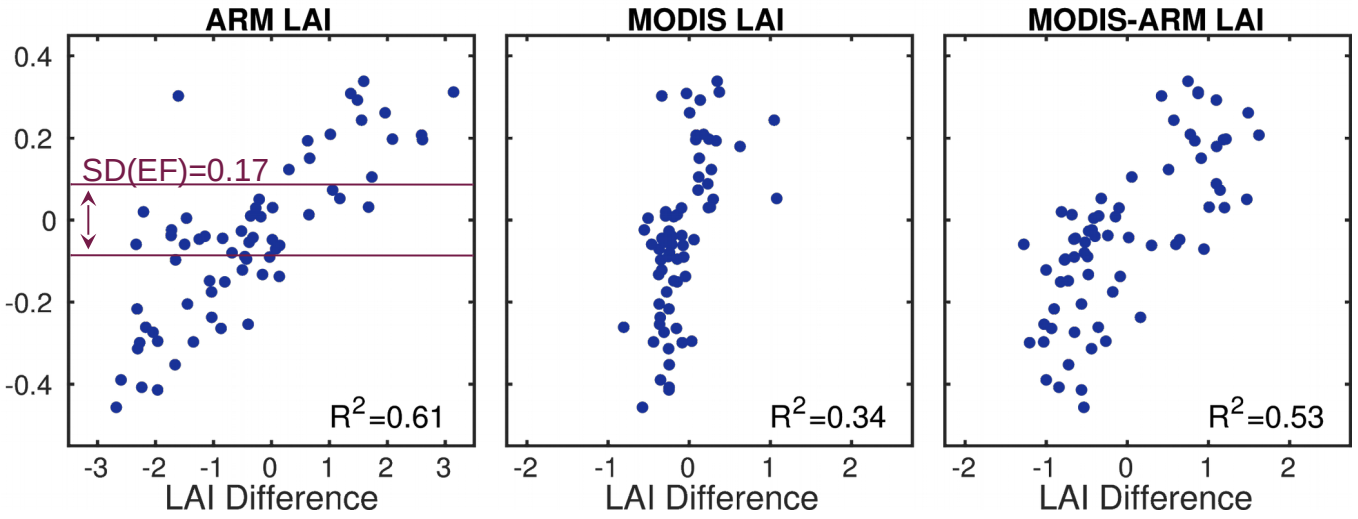

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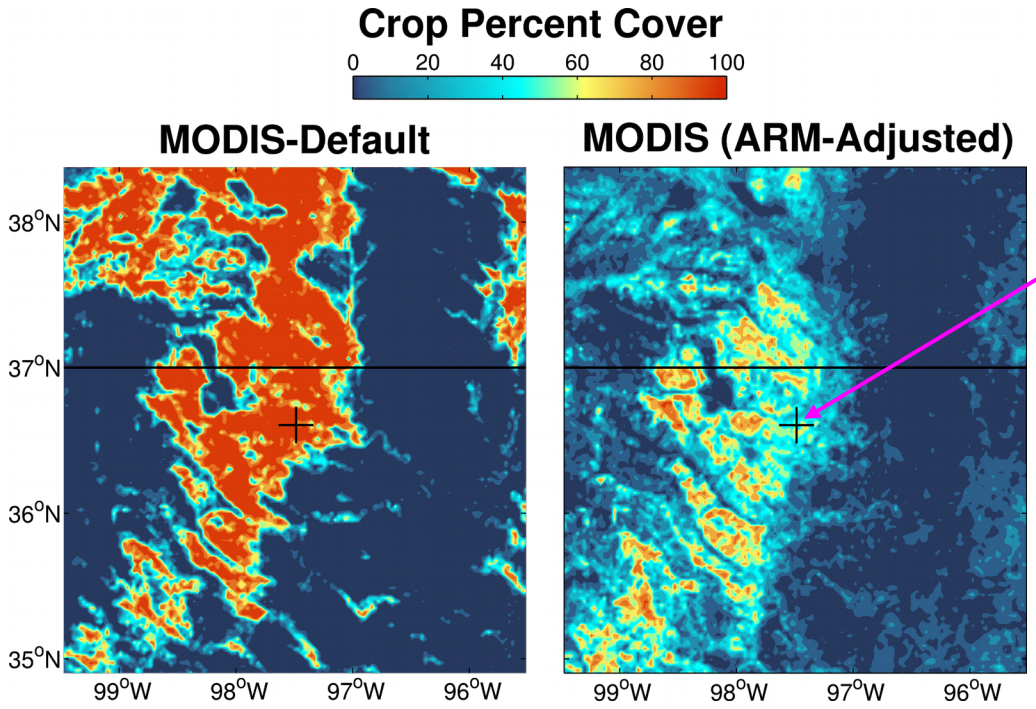
1. ‘Field experiment’ approach: Scaling up



- MODIS-ARM better captures the mixture of wheat and grasses.
- Enables consistent comparison of land models to observations at ARM extended facility sites.
- Currently used as land-model forcing for cloud-permitting hindcasts (WRF).

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Single-column hindcast experiments at SGP

2. Single-column hindcast experiments

Daily hindcast experiments in CESMv1.2:

- Perturbed soil moisture: Assign observed days to negative/positive feedback regimes
- Unperturbed soil moisture: Comparison to observation

2. Single-column hindcast experiments

Daily hindcast experiments in CESMv1.2:

- Perturbed soil moisture: Assign observed days to negative/positive feedback regimes
- Unperturbed soil moisture: Comparison to observation

Convective parameterization experiment:

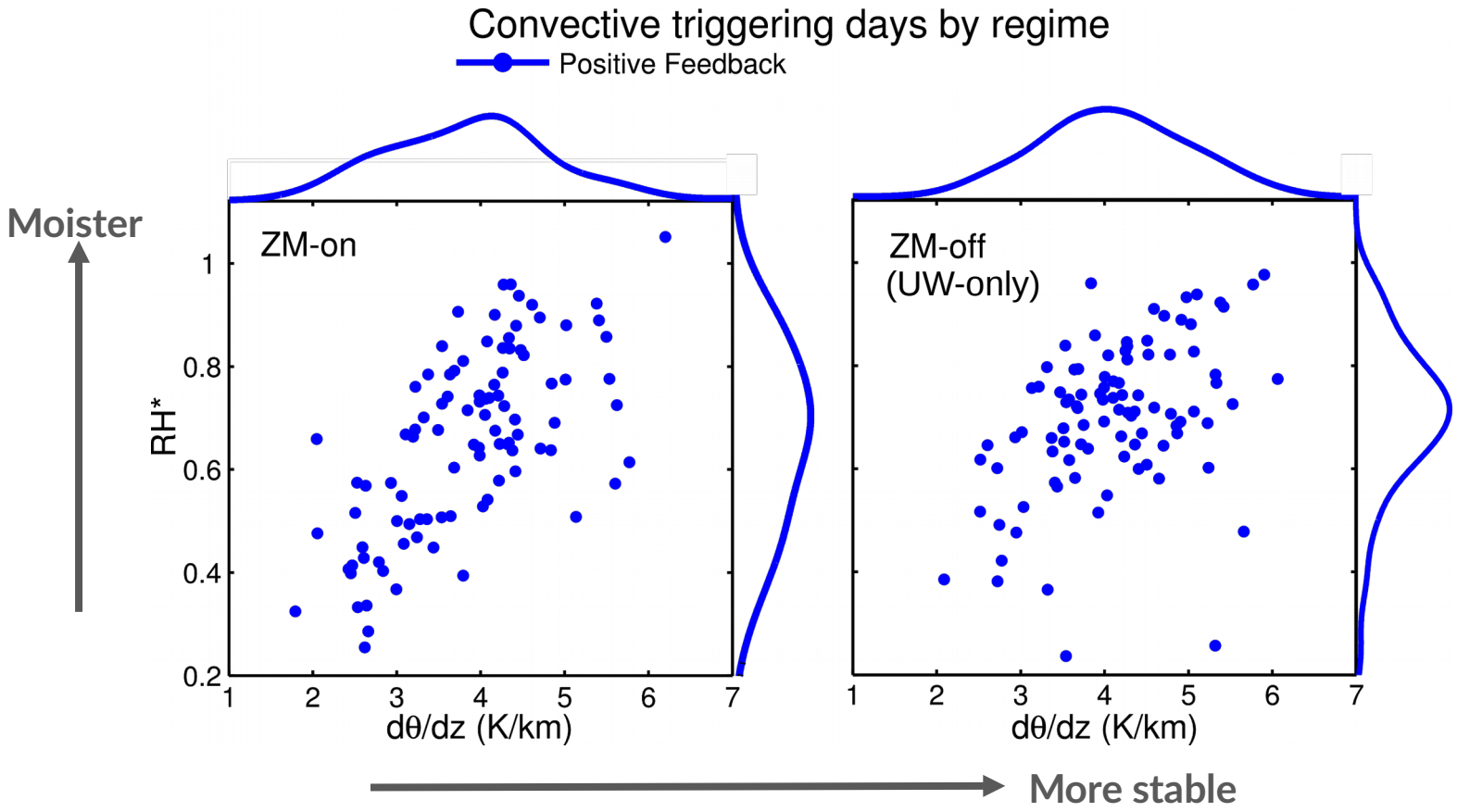
- Default Zhang-McFarlane scheme (ZM)
- ZM-off (only UW parameterization): Tighter coupling of surface and clouds. (Hohenegger and Bretherton, 2011)

$M_b \sim \exp(-CIN/TKE)$

Land-model parameterization experiment:

- Default CLM4
- CLM4-W16; Modified stomatal and soil resistances derived from ARM observations (Williams et al. 2016):

2. Single-column hindcast: Perturbed soil moisture results



Williams 2019, *JGR-Atmospheres*

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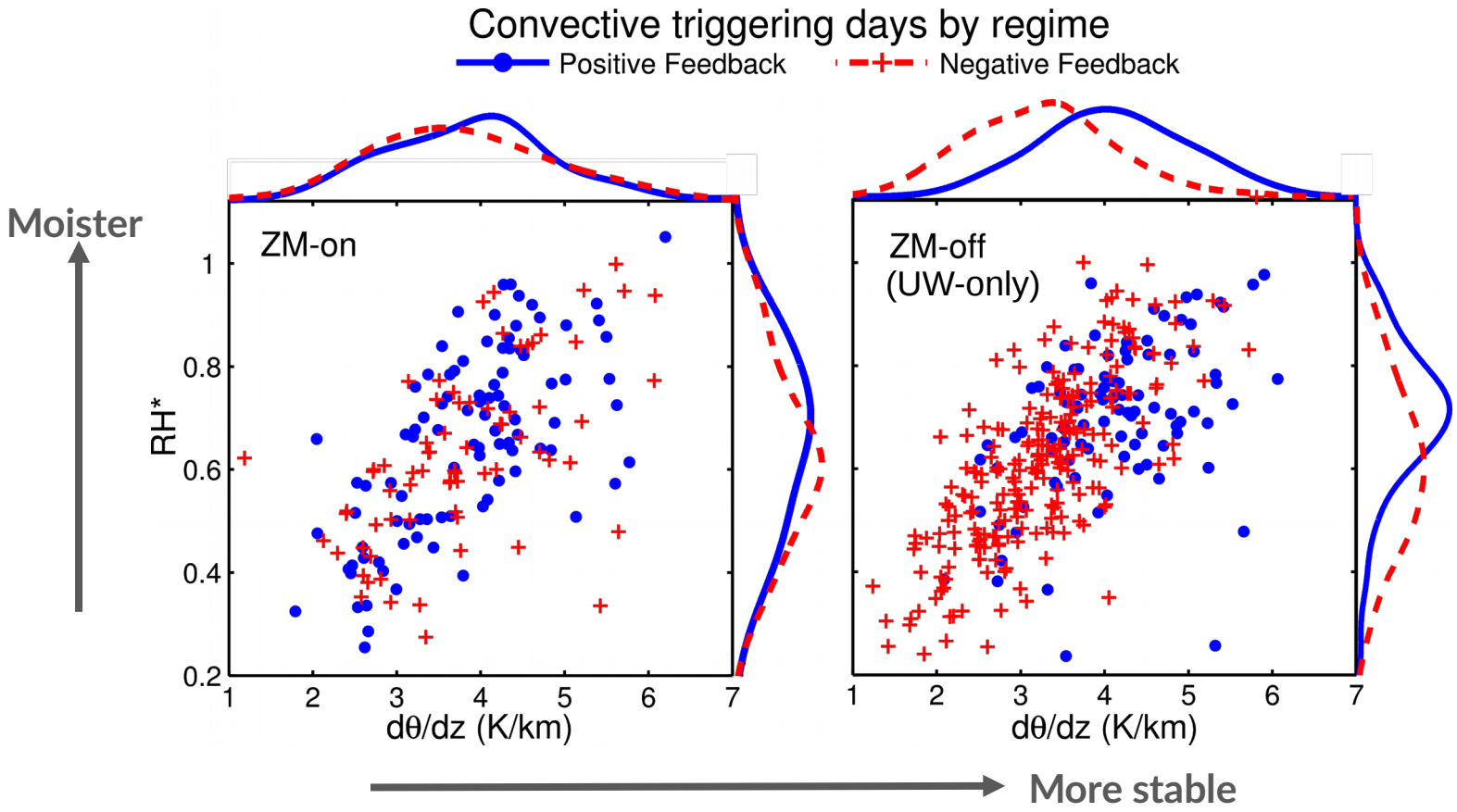

- ZM-off: Reveals state-dependent negative and positive triggering feedback.
- Used UW parameterization to define regimes.

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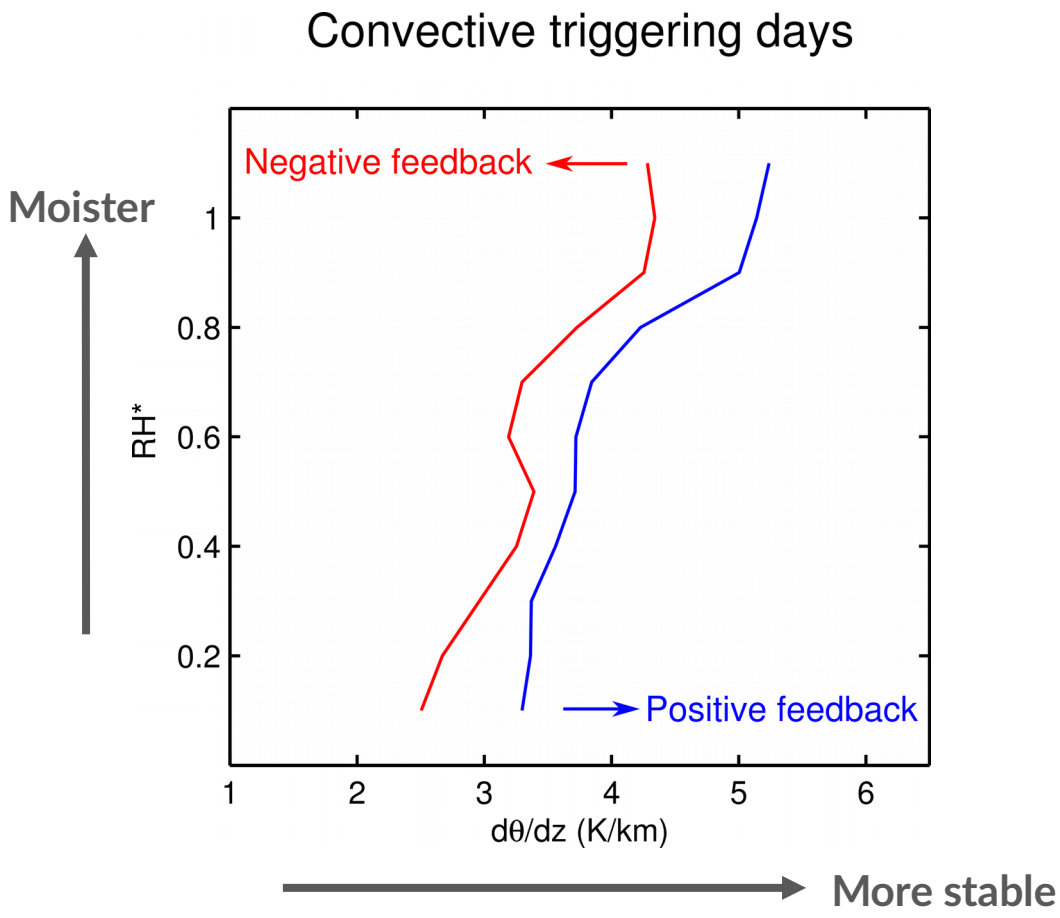
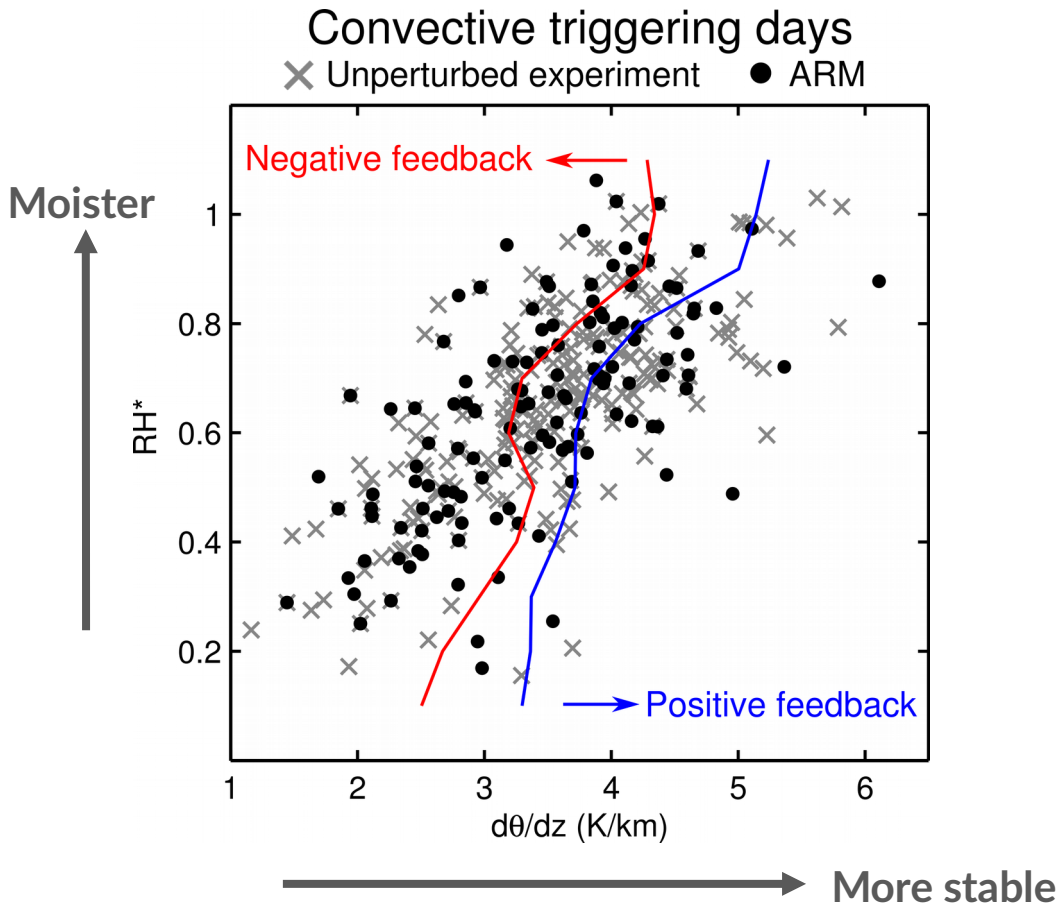
2. Single-column hindcast: State-dependence



- Defined negative feedback “regime” as the phase space where a dry soil perturbation is at least twice as likely to trigger rain as a wet soil perturbation.

Williams 2019, *JGR-Atmospheres*

2. Single-column hindcast: State-dependence



- 27% of triggering days fall in the negative feedback regime
- 23% in the positive feedback regime
- 50% of events were “atmospherically-controlled”

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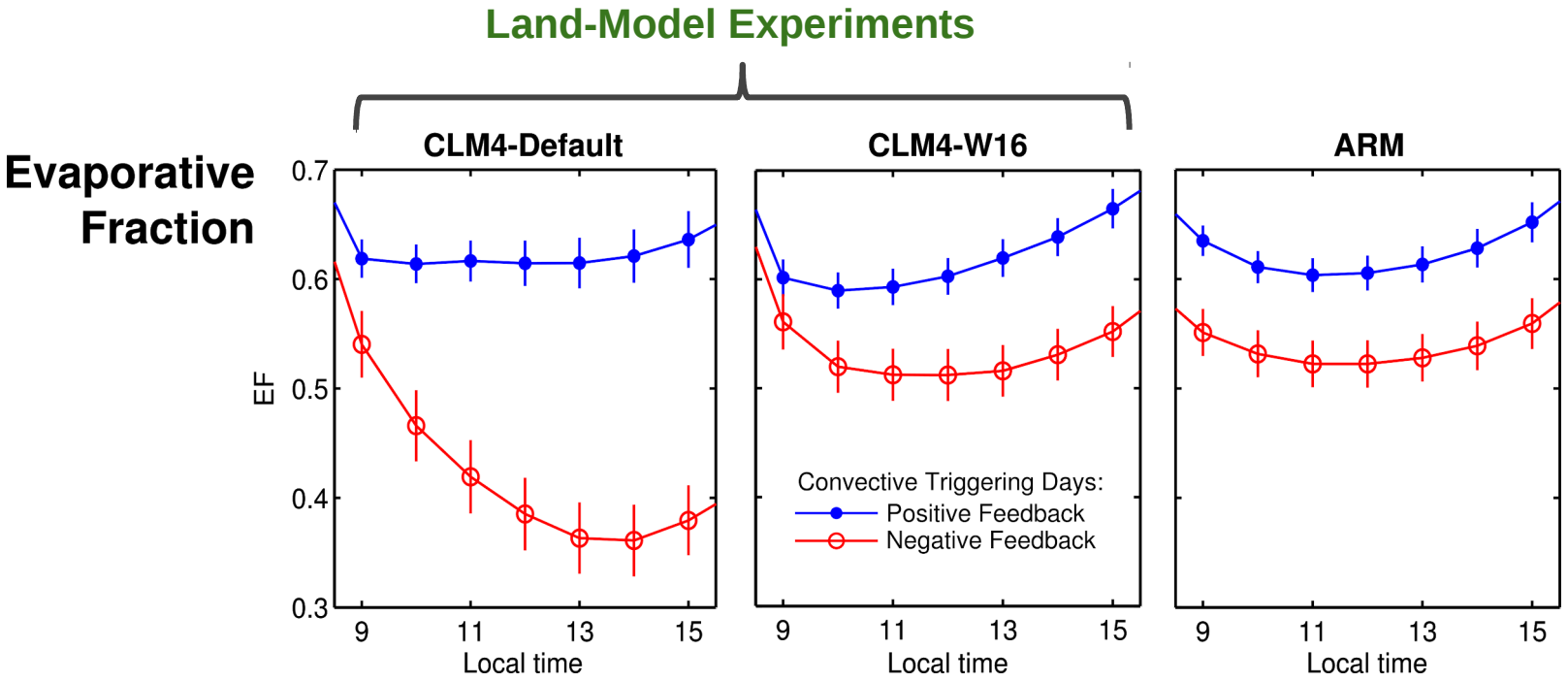
2. Single-column hindcast: Comparison to ARM observations

Do we see evidence of modeled feedback mechanisms in observations?



- The EF is lower on negative feedback days (in red), so the observations support the feedback hypothesis
- ARM data-informed parameters corrected the land-model bias in EF.

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2. Single-column hindcast: Comparison to ARM observations

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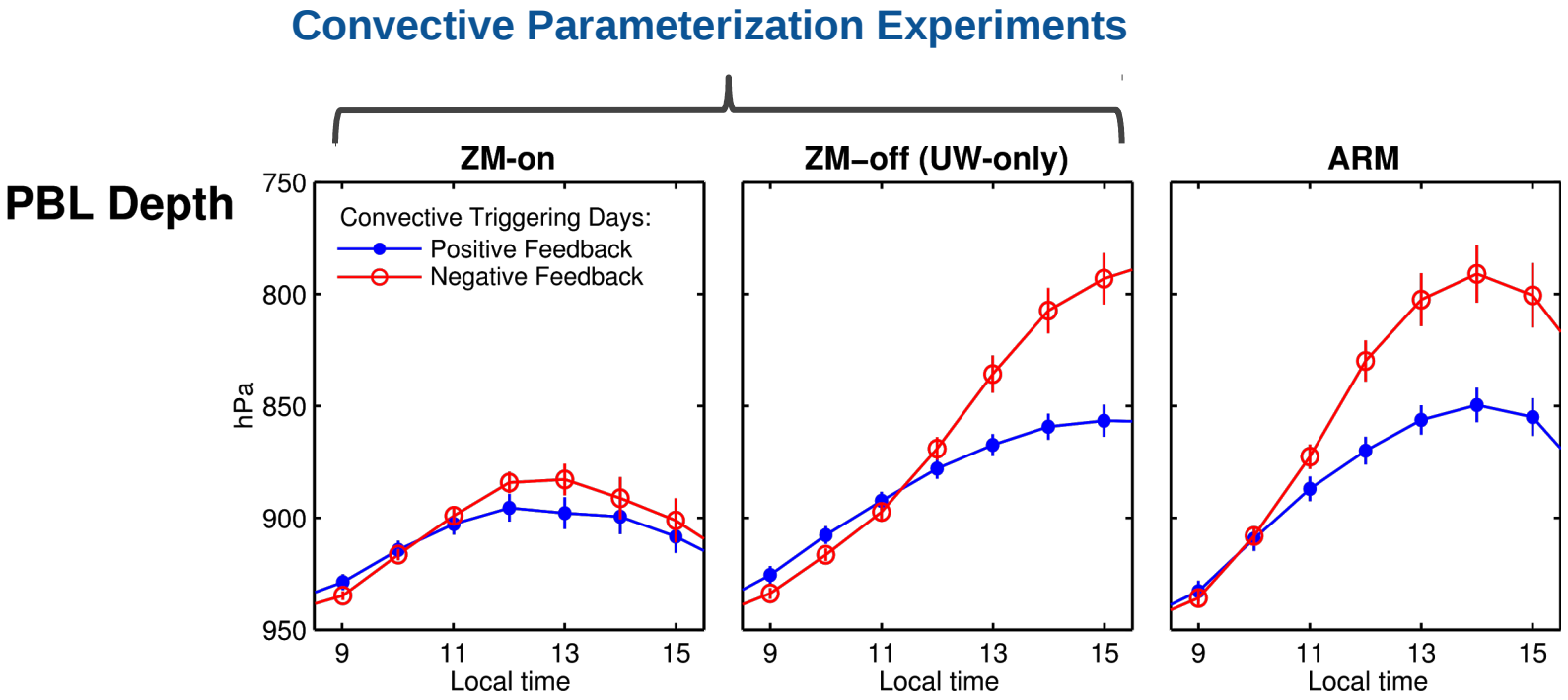

- ZM scheme does not allow negative feedback mechanism.
- Only UW (CIN-based) parameterization captures PBL response to surface.
- Observed and simulated (UW) PBL supports the feedback hypothesis.

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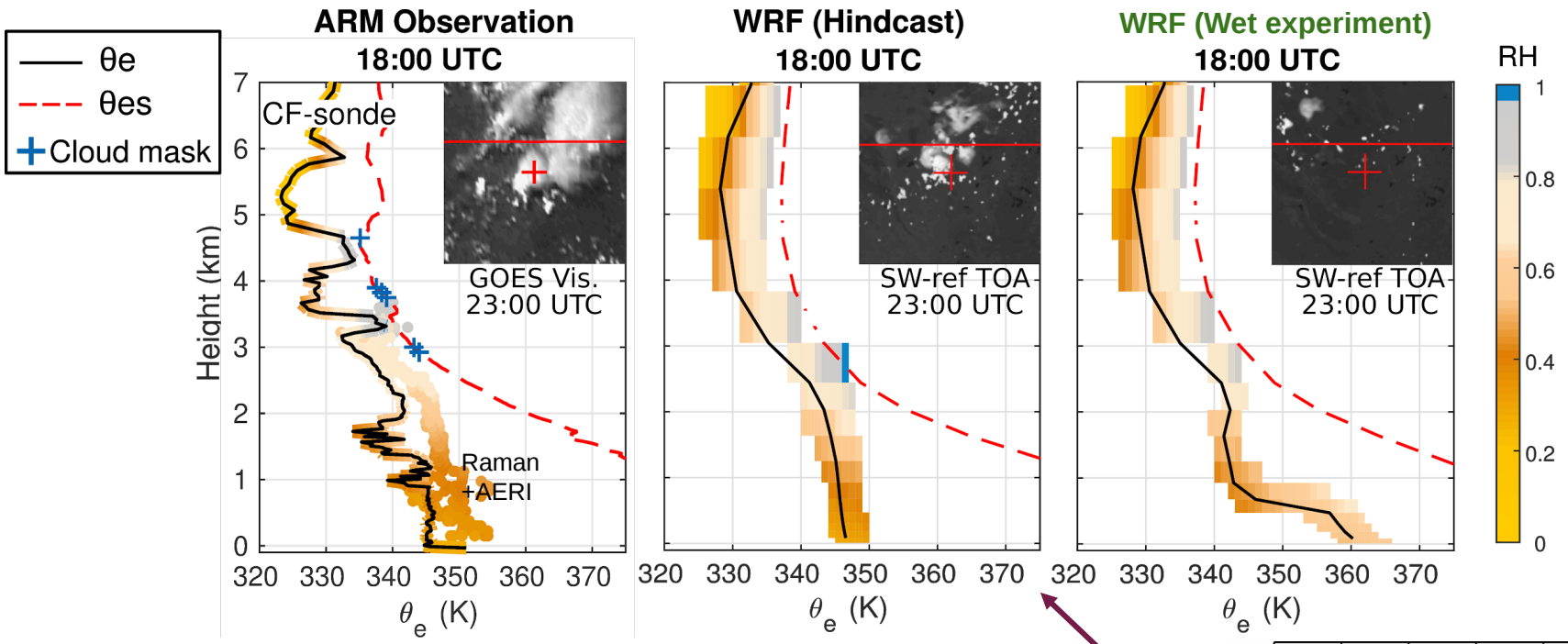
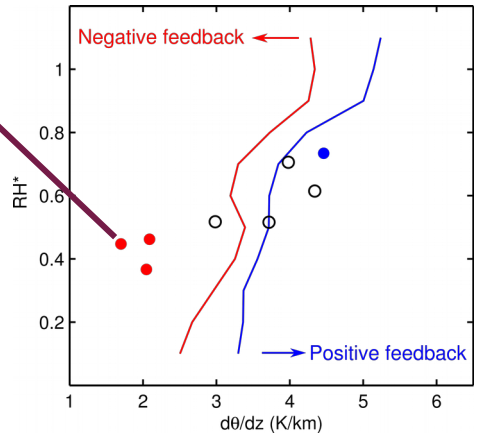
Cloud-permitting hindcast experiments at SGP
WRF-CLM (3km)

3. WRF convection-permitting experiments

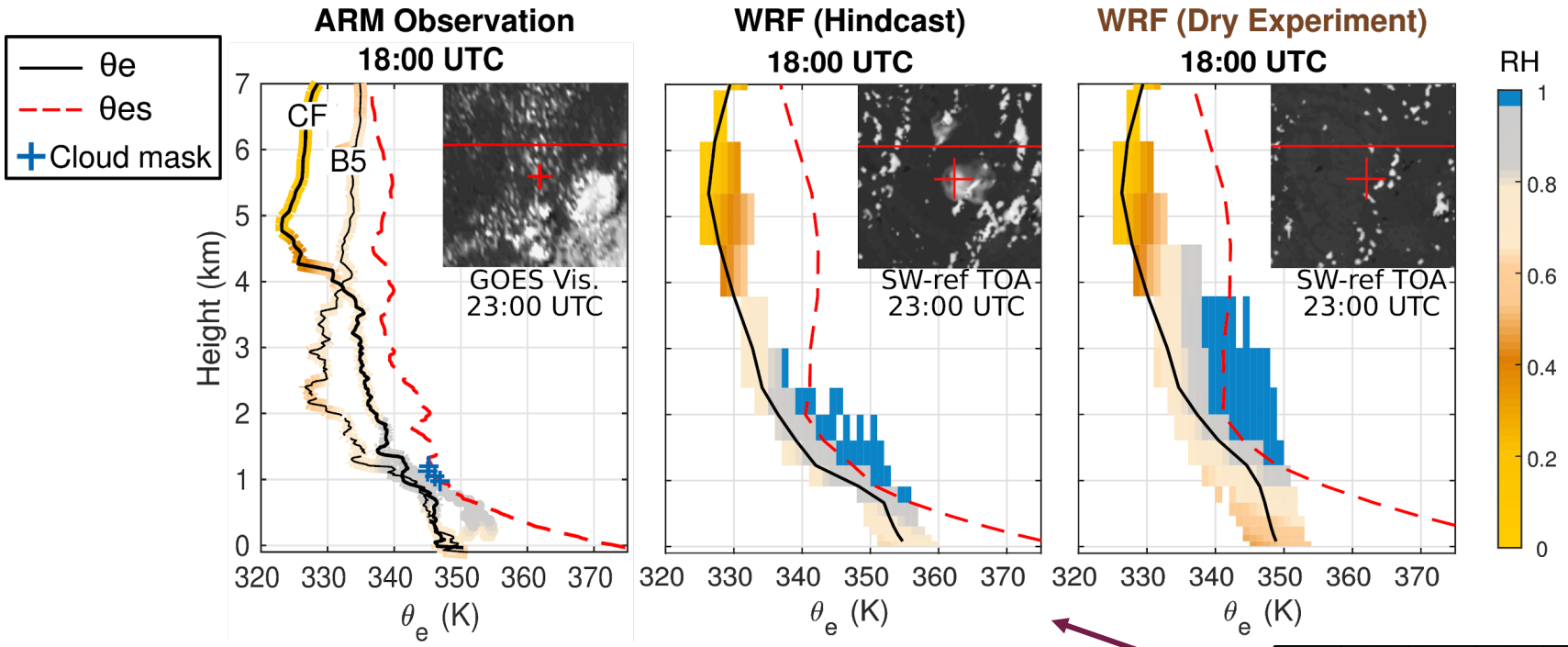


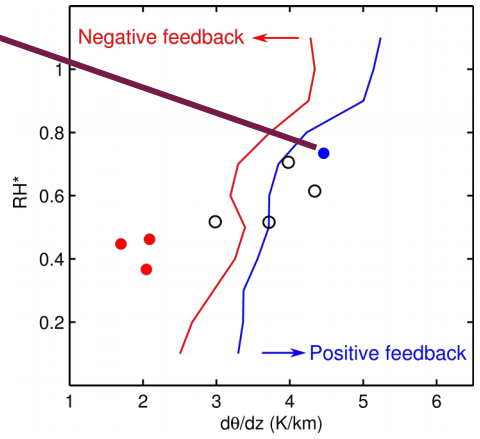


- Hindcasts (WRF 3km) capture thermodynamic structure and cloud onset in ARM soundings.
- In the negative feedback regime, the wet perturbation fails to initiate deep convection.
- Supports the negative feedback hypothesis.

Williams, Patricola, Qiu; in preparation

3. WRF convection-permitting experiments





- In the positive feedback regime, both hindcasts show shallow cumulus initially.
- But the dry experiment fails to trigger deep convection.
- Wetter surface with higher θe is favored.
- Evidence of the positive feedback mechanism.

Williams, Patricola, Qiu; in preparation

Summary

- ARM observations and observationally-constrained model hindcasts support the existence of negative and positive soil moisture-triggering feedback.
- ZM (CAPE-based) deep convection does not capture the negative feedback mechanism found in cloud-permitting simulations and CIN-based cumulus parameterizations.
- Suggests missing feedbacks on precipitation in ESMs, and potential mechanism for warm and dry biases and too frequent drought in some ESMs.