Revisiting mechanisms and regimes of soil moisture influence on convective initiation

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Motivation: Climate Predictability

Approaches to improve climate prediction:

- Provide better surface boundary conditions (e.g., soil moisture, vegetation state)
- Improve model physics governing feedbacks (e.g., convection, evapotranspiration)

Possible consequences on decadal-centennial timescales:

- Summer warm and dry bias in climate models (e.g., Xu et al. 1996, Ma et al. 2018, Lindvall et al. 2013)
- Erroneous collapse of forests in some Earth System Models (Bonan and Levis, 2006)

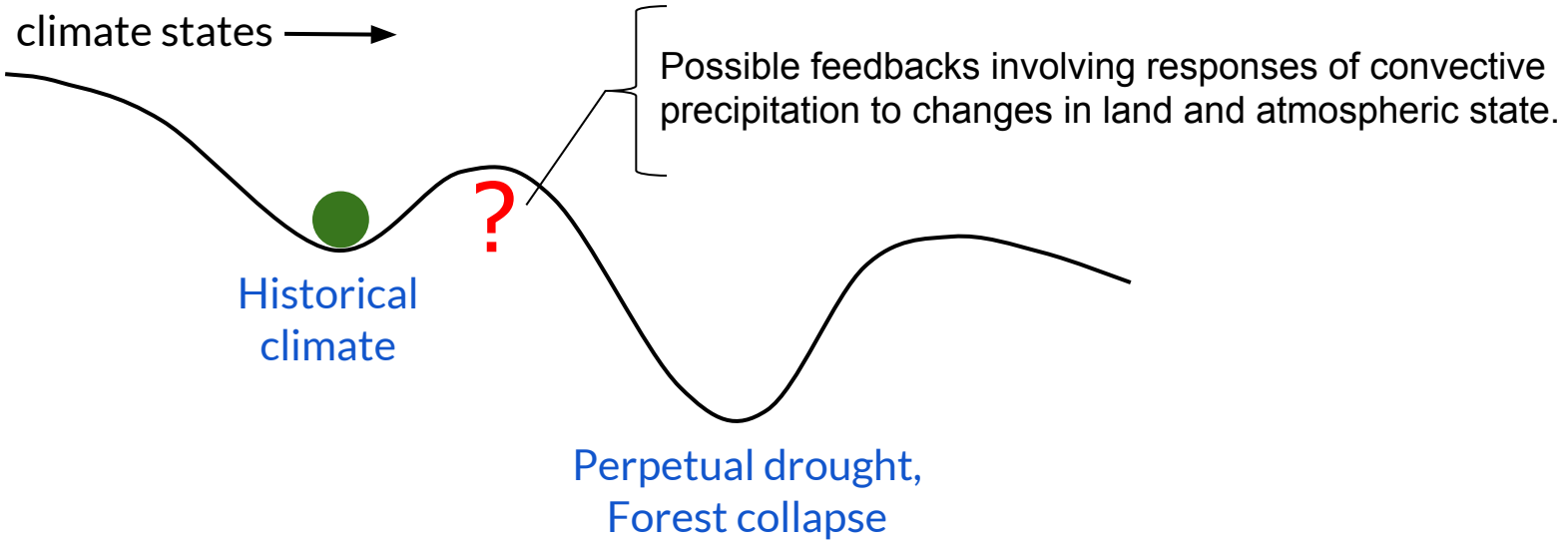
California drought, 2011-2017

Oklahoma, 2006

Texas, 2011

Importance of feedbacks for climate predictability

Destabilizing (positive) *and* stabilizing (negative) feedbacks are important for abrupt change.



Are feedbacks missing, and how can they be represented in Earth system models?

Convective triggering feedback

What is convective triggering?

The initiation of deep convection by a sequence of processes leading to the production of buoyant, cloudy air. [The Level of Free Convection (LFC) diagnoses where clouds are buoyant.]

Why convective triggering?

1. Precursor of most summer precipitation events, and organized convective systems.
2. Not well represented in current climate models.
3. Could act as a positive or negative soil moisture-precipitation feedback mechanism.

Feedbacks depend on tropospheric and land-surface states

Wet- and dry- advantage regimes (Findell and Eltahir, 2003; Gentine et al. 2013)

Regime: Set of tropospheric states.

Wet-advantage: Triggering by adding LH

- Lower the LFC to PBL.

Dry-advantage: Triggering by adding SH

- Grow the PBL up to the LFC.

Wet: High EF= LH / (SH+LH); "Evaporative Fraction"

- Wet soil or unstressed vegetation*

Dry: Low EF

- Dry soil or vegetation stress*

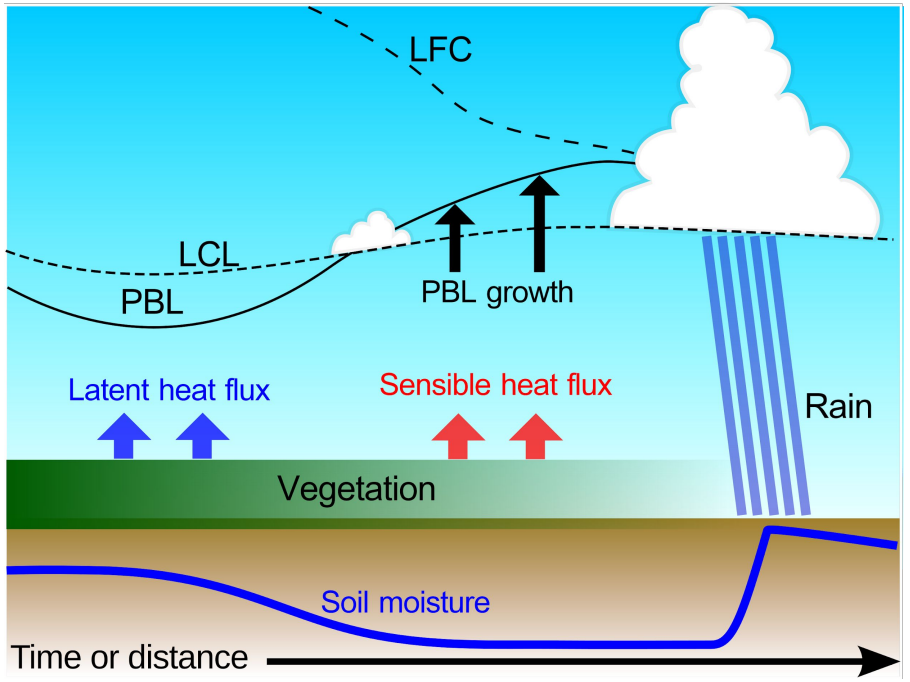


Figure: Hypothesized negative feedback mechanism in the dry-advantage regime.

* Williams, I. N., and M. S. Torn (2015), Vegetation controls on surface heat flux partitioning, and land-atmosphere coupling, Geophys. Res. Lett., 42, doi:10.1002/2015GL066305.

Approaches to identify triggering feedback in observations

- Infer the triggering feedback from observed covariation (Findell et al, 2011; Ferguson and Wood, 2011; Roundy et al. 2013; Song et al. 2016; Tawfik and Dirmeyer, 2014)
- Compare observations to soil moisture experiments (Koster et al. 2003).

- **Compare observations to model column physics experiments (this study).**

Approach: Model experiments compared to observations

Can we falsify model-based hypotheses for the triggering feedback mechanism?

1. **Develop model *without* triggering feedback:**
   - Soil moisture ✗ → EF
   - PBL ✗ → triggering
2. **Compare to model *with* triggering feedback mechanism:**
   - Soil moisture ✓ → EF
   - PBL ✓ → triggering
3. **Include realistic forcing, radiation, clouds, moist turbulence; to compare to observations**
   - Revisit FE03 to include full column physics forced with advective tendencies.

Approach: Modeling + observations in the U.S. Southern Great Plains

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Single-column model*:

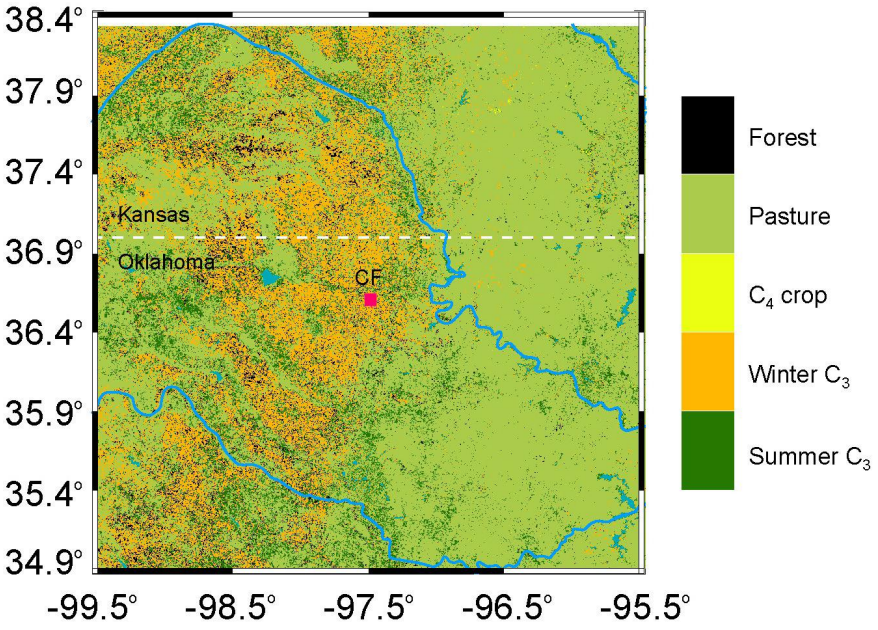
- NCAR/DOE Community Earth System Model (CESM1.2.2)
- Prescribed large-scale forcing (Xie et al. 2004)
- MODIS LAI (Riley et al., 2009)

Simulations:

- Daily 'hindcasts' initialized at 00-12 UTC
- Years 2003-2011 (May 1-September 1)

Observations:

- Variational analysis product (e.g., T, RH)
- Network of surface flux measurements



LAI over the US Southern Great Plains domain
(Torn et al., 2011)

* Williams, I. N., Y. Lu, L. M. Kueppers, W. J. Riley, S. C. Biraud, J. E. Bagley, and M. S. Torn (2016), Land-atmosphere coupling and climate prediction over the U.S. Southern Great Plains, J. Geophys. Res. Atmos., 121, doi:10.1002/2016JD025223.

Experimental design

Model experiments:

- **Perturbed soil moisture** (as in FE03)
- **Modified land model physics***
  - Default Community Land Model CLM4.0/CLM4.5
  - Increased stomatal conductance and increased soil resistance to evaporation (**ModVeg**).
- **Modified convection scheme**
  - Default Zhang-McFarlane (**ZM-on**) deep convection scheme.
  - No deep convection scheme (**ZM-off**); using Park and Bretherton 'shallow' convection scheme.

Assign observed days to wet or dry advantage regimes

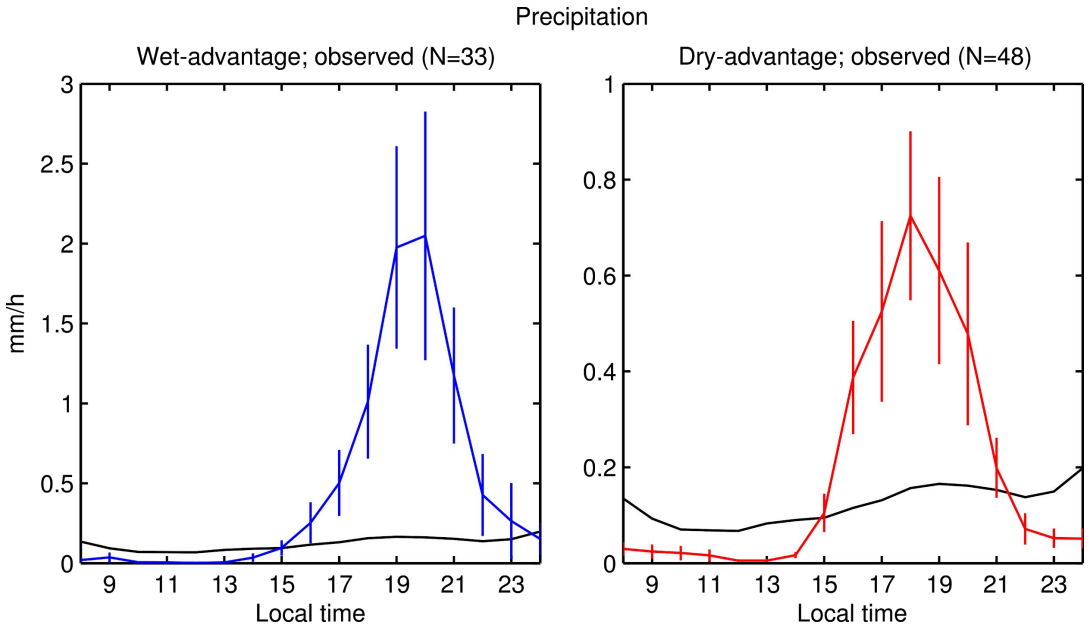
Weaken the relationship between soil moisture and EF

Restore the relationship between PBL turbulence and convective triggering

* Williams, I. N., Y. Lu, L. M. Kueppers, W. J. Riley, S. C. Biraud, J. E. Bagley, and M. S. Torn (2016), Land-atmosphere coupling and climate prediction over the U.S. Southern Great Plains, J. Geophys. Res. Atmos., 121, doi:10.1002/2016JD025223.

Focus on afternoon deep convection

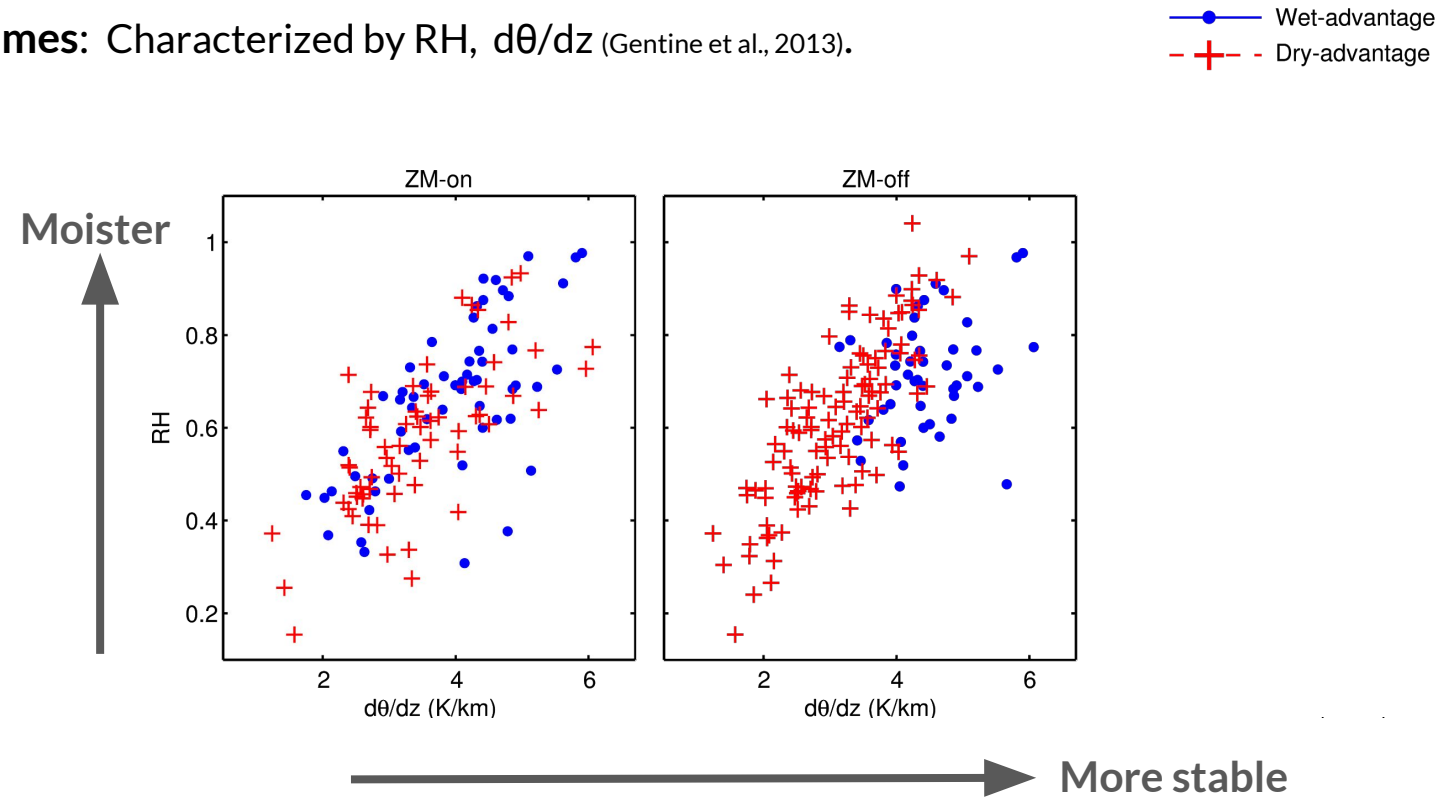
Triggering event: Day with daytime precipitation maximum greater than 1 mm/h (Zhang and Klein, 2013).



- 24% of observed triggering events fall in the wet regime; 33% in the dry regime.
- Wet regime days are defined when triggering only occurs in the wet soil perturbation experiment; likewise for dry regime days.

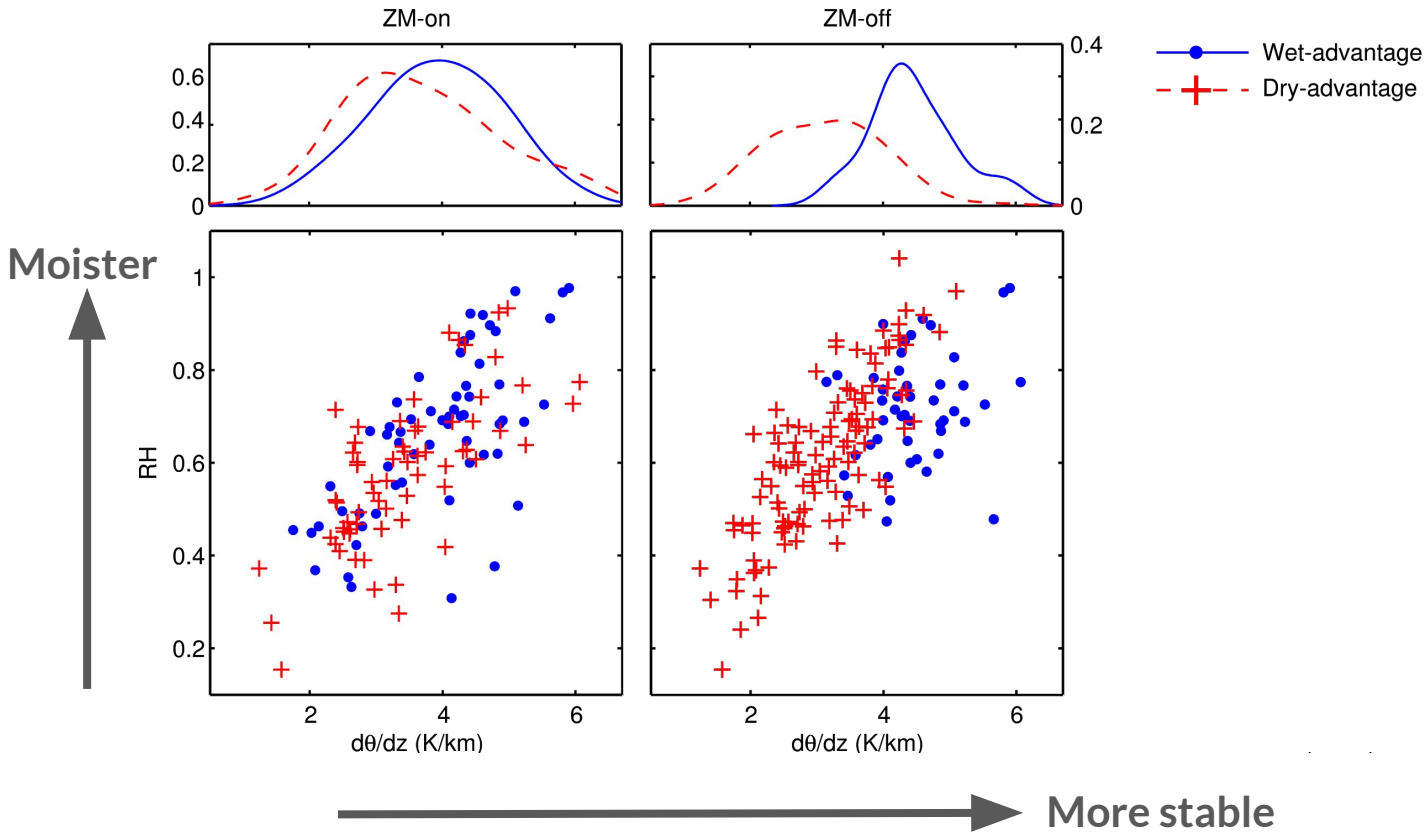
Model results: Perturbed soil moisture experiment

Regimes: Characterized by RH, dθ/dz (Gentine et al., 2013).



- ZM-on: Almost a "null hypothesis" for the triggering feedback mechanism.
- ZM-off: Recovers regime-dependent negative and positive triggering feedback.

Model results: Perturbed soil moisture experiment



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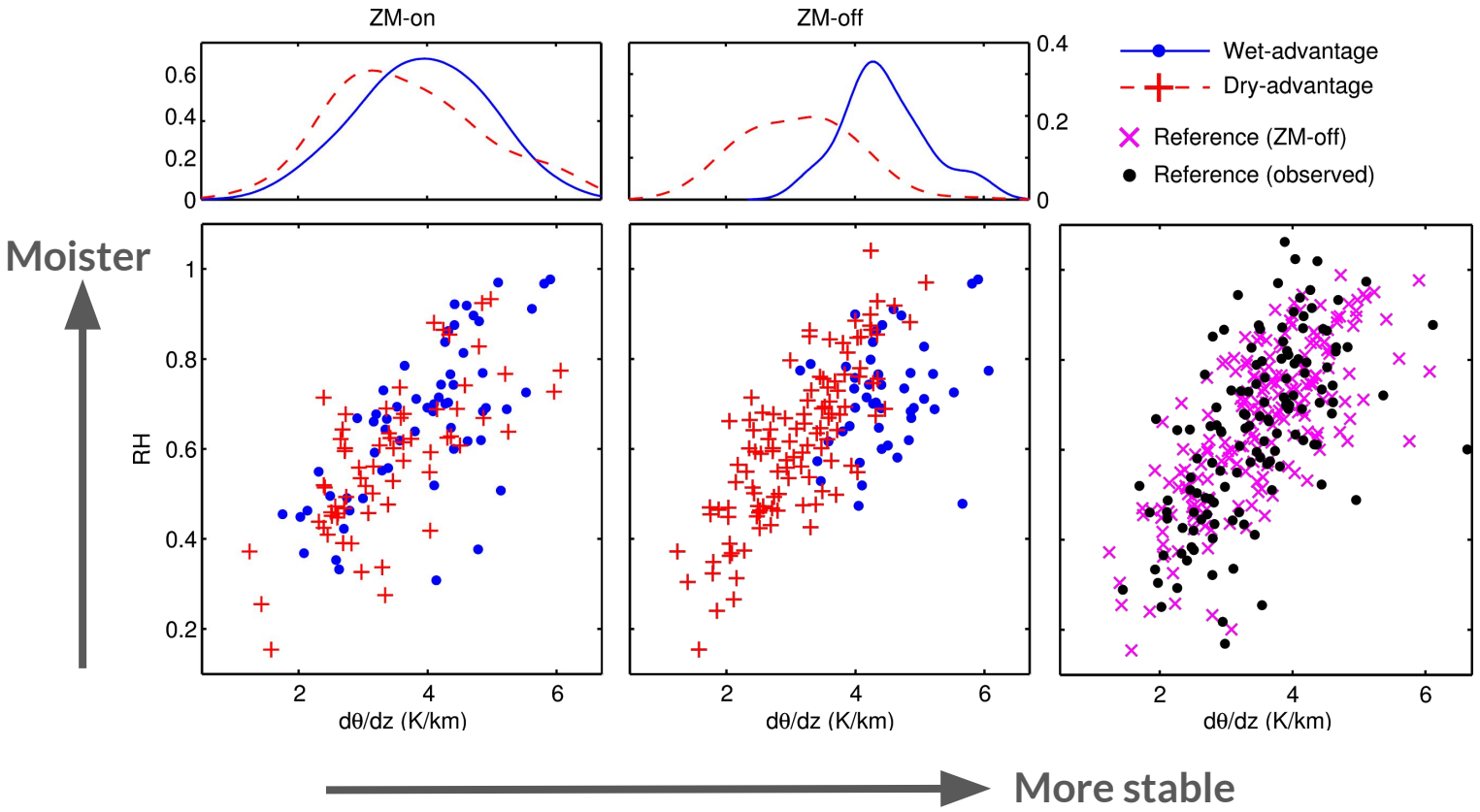
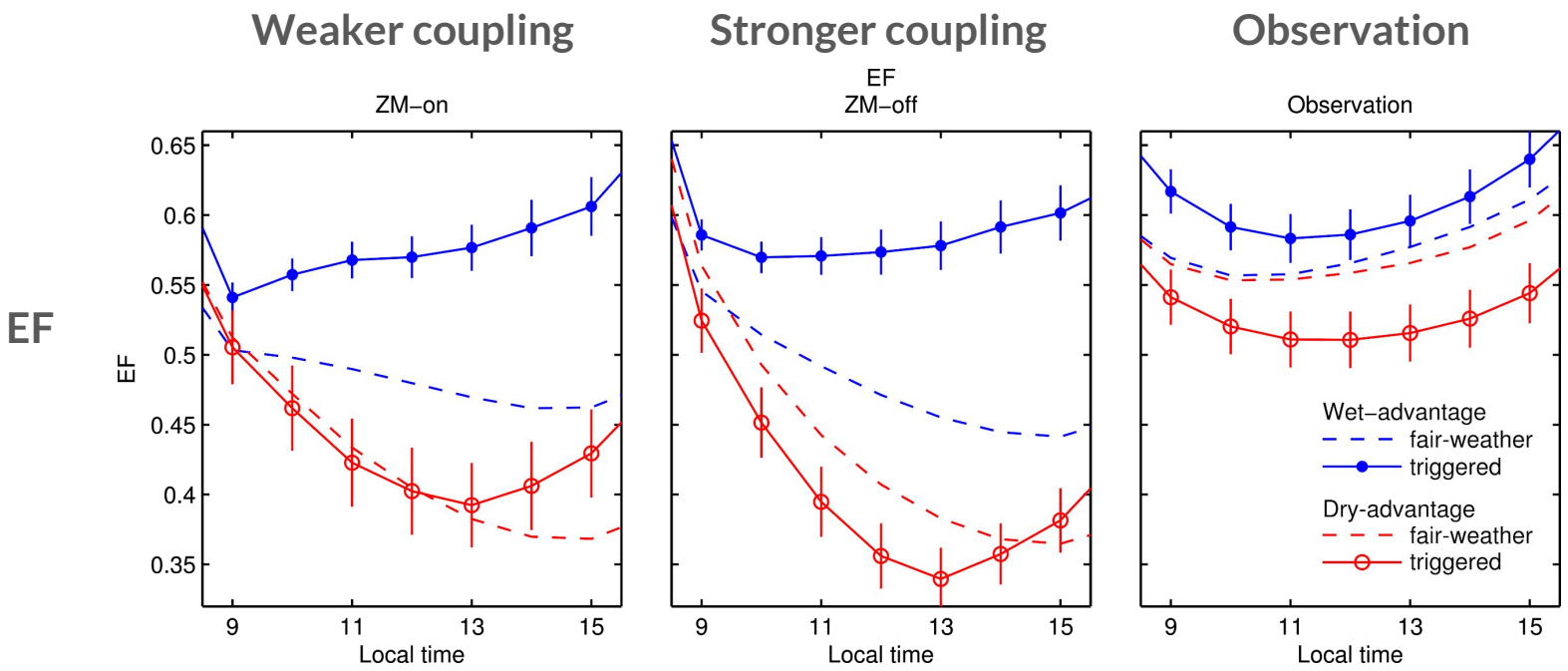
Model results: Perturbed soil moisture experiment vs. reference



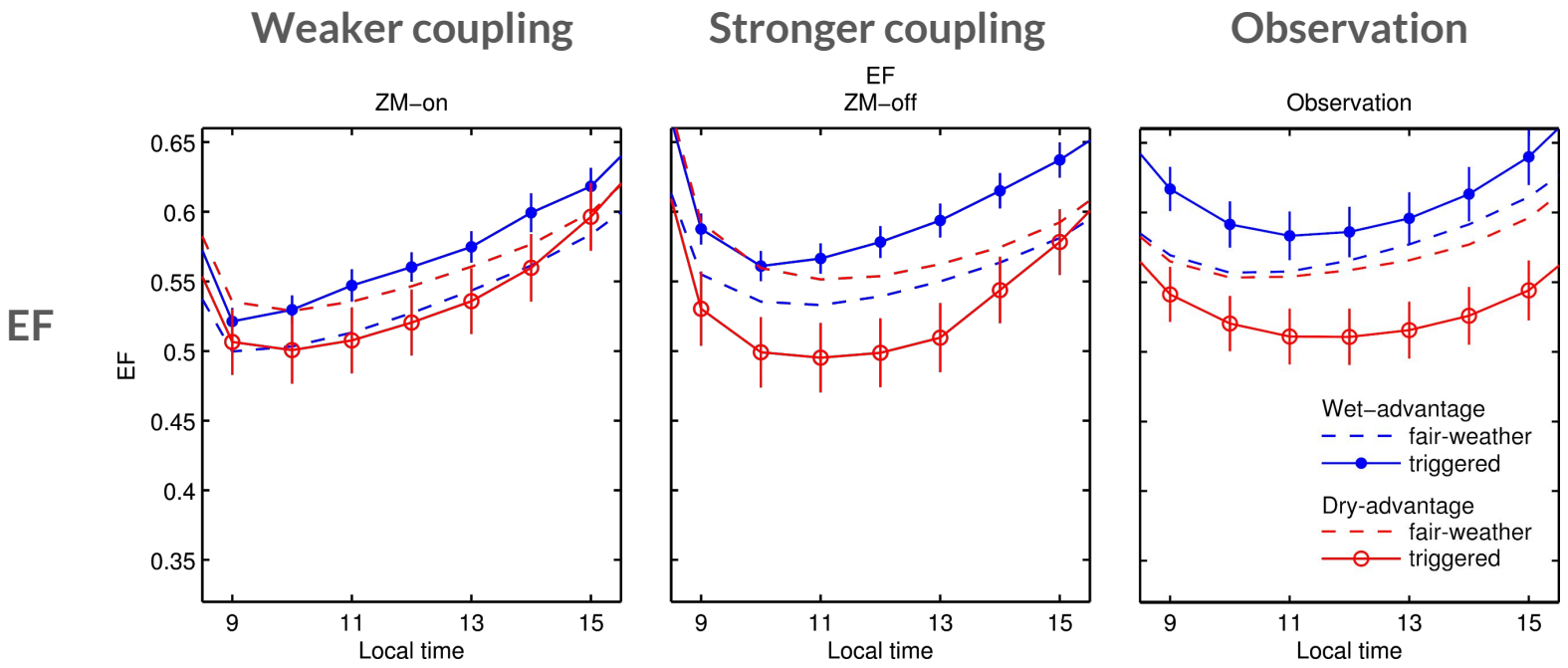
- ZM-on: Almost a "null hypothesis" for the triggering feedback mechanism.
- ZM-off: Recovers regime-dependent negative and positive triggering feedback.
- Modeled and observed events have similar distributions in the phase space.

Can we falsify model hypotheses? Hindcast with default CLM



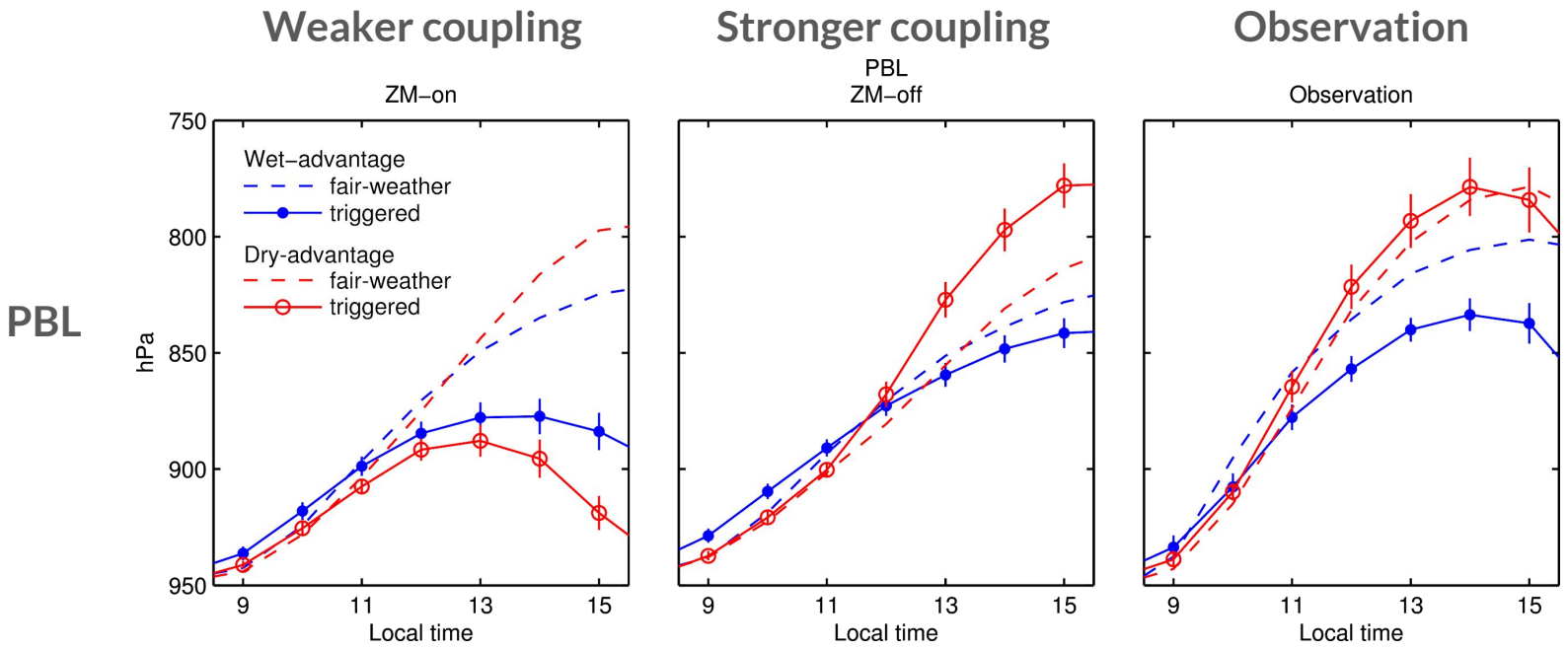
- Default CLM overpredicts regime-dependence of the EF-triggering relationship.

Can we falsify model hypotheses? Hindcast with ModVeg CLM

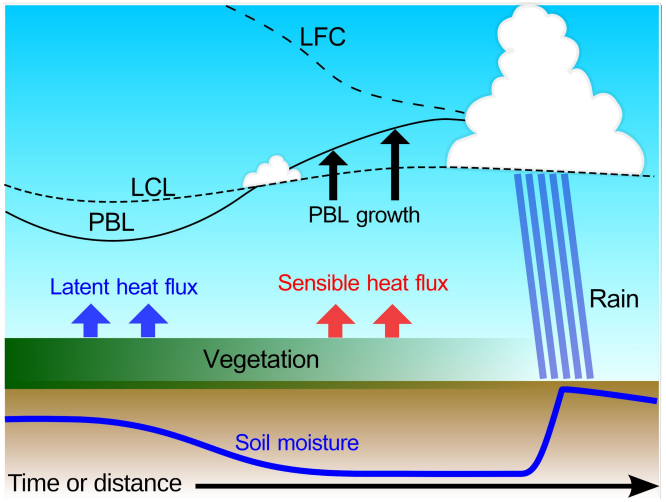


- ModVeg CLM improves the predicted regime-dependence of EF.
- ZM-off with ModVeg CLM better represents the observed EF - triggering relationship.
- Differences in EF are small, so it's difficult to falsify the weak coupling hypothesis...

Can we falsify model hypotheses? Hindcast with ModVeg CLM



… but PBL differences are much larger: Dry regime triggering involves PBL growth.



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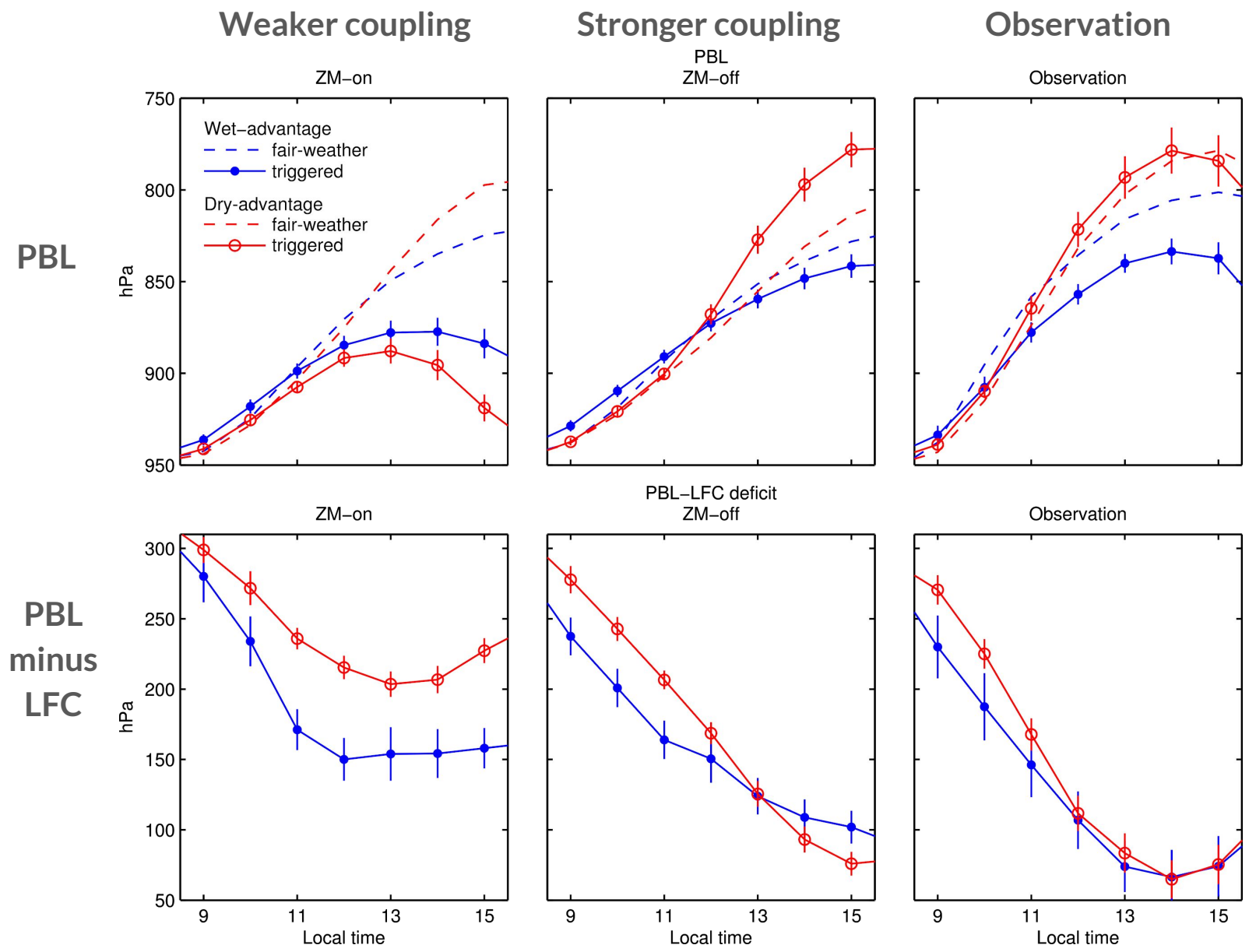
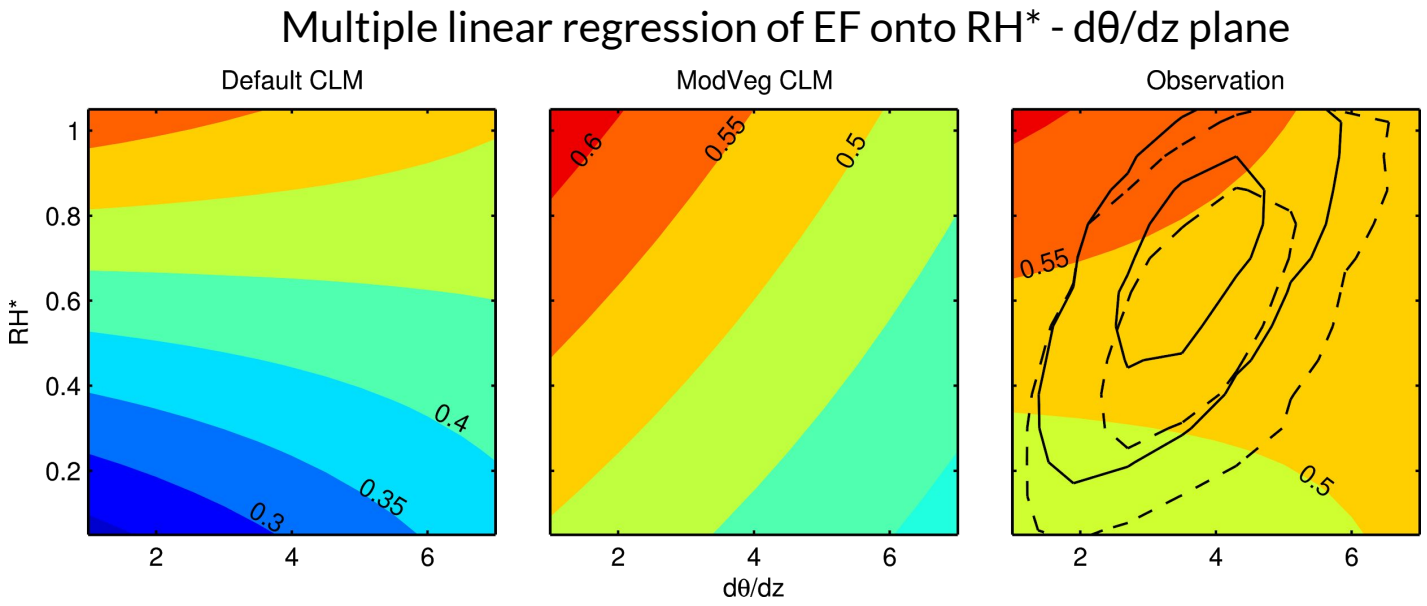


Summary

- Triggering feedback mechanism is weak or non-existent in the column physics of CESM.
- It can be recovered by switching from a CAPE- to a CIN/TKE-based convection scheme.
- Including the mechanism better predicts observed EF-PBL-triggering relationships, depending on ET parameters in CLM4.0/4.5.

- Spatial heterogeneity is not necessary for soil moisture-triggering feedback mechanism.
- Next steps will address precipitation dynamics and convective organization.

Covariation of EF with tropospheric state



- Tropospheric state covaries with EF; fair weather days are in drier, stable states.
- Default CLM predicts too-strong gradient of EF in the thermodynamic phase space.
- This is a potentially useful way to evaluate land model physics to better represent coupling.

Response of triggering probability to EF