Investigating the limited role of land on atmospheric predictability in CESM2

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Land Model Working Group
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Land anomalies have a large impact on the atmosphere

- Soil moisture anomalies can drive changes in surface fluxes, atmospheric circulation, and subsequent precipitation *(Doran et al., 1995; Avissar and Schmidt, 1998; Bou-Zeid et al. 2005; Simon et al 2021; Findell et al. 2024)*

- Impacts can extend to extremes like droughts *(Roundy et al. 2013; Wu and Dirmeyer 2020)* and floods *(Berghuijs et al. 2019; Fowler et al. 2019;)*

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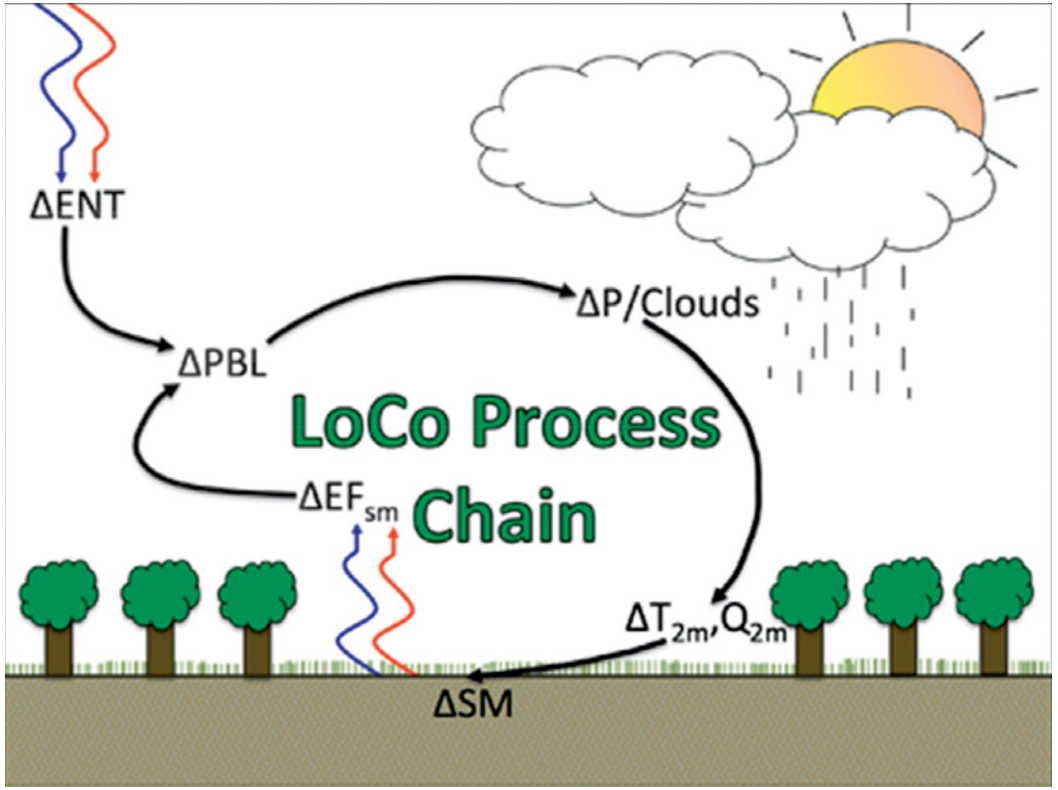
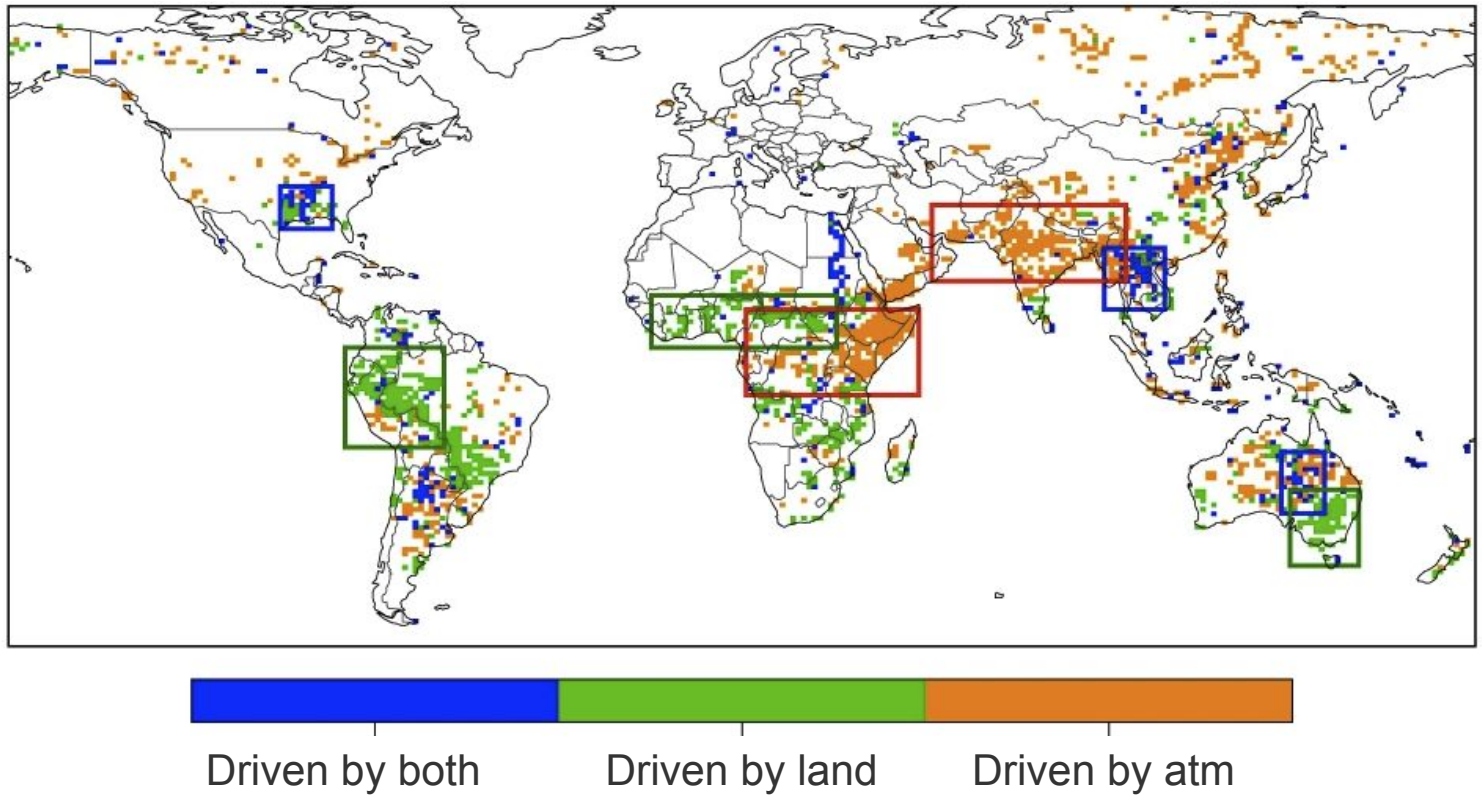


Santanello et al. (2017)

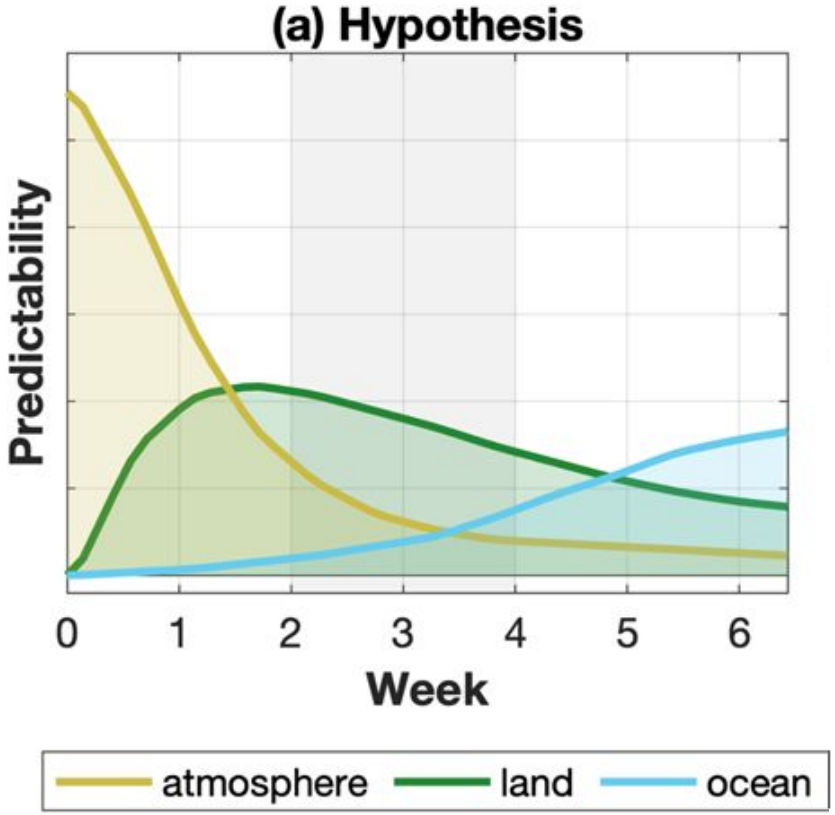
Land matters

Drivers of increased frequency of modern 100-year flood



Adapted from Fig. 1 of Fowler et al. (2019)

Expected to be a key source of predictability at subseasonal-seasonal (S2S) timescales…



Predictability sources for annual mean 2m temperature over mid-latitude northern hemisphere land, adapted from Paul Dirmeyer.

Figure 1 of Richter et al. *(2024)*

Expected to be a key source of predictability at subseasonal-seasonal (S2S) timescales…

...but recent results call this paradigm into question

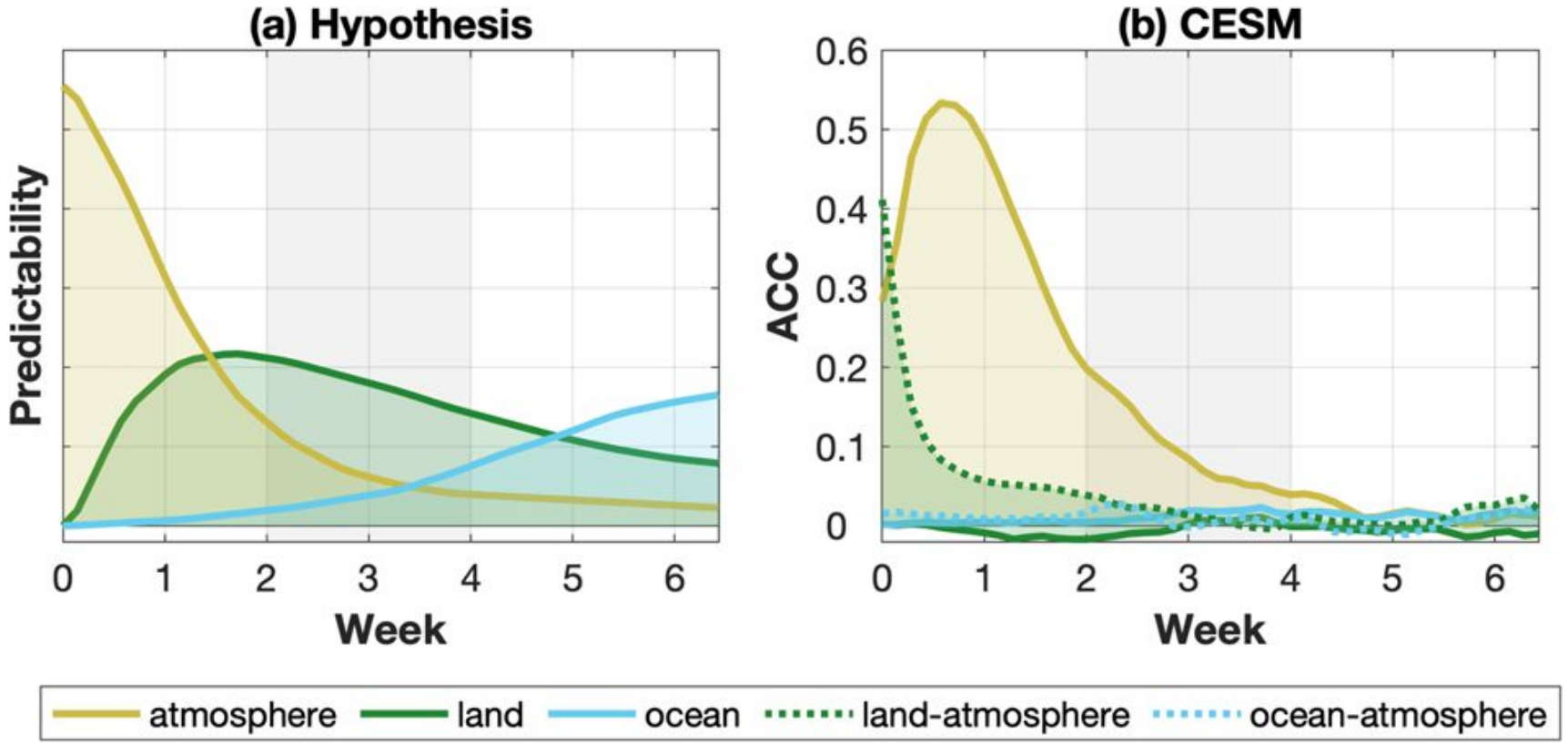


Figure 1 of Richter et al. *(2024)*

Do deficiencies in simulated land-atmosphere coupling explain the limited impact of land initialization?*

**a work in progress*

Methods

- Model simulations:
  - (Existing) CESM2.1.5 S2S Hindcasts (Richter et al. 2024)
  - Climatological AMIP runs with the same model configuration (25 years)
    - Control (default parameter settings)
    - Sensitivity experiment (increased land-atm coupling strength via CLM parameter change)
- Validation:
  - FLUXNET2015 tower observations (soil moisture, SHFLX)
  - ERA5 reanalysis

Do deficiencies in land-atmosphere coupling explain the limited impact of land initialization?

A land-based perspective:

How well does CESM capture the impact of soil moisture on surface flux anomalies?

Terrestrial Coupling Index

- Measures how sensitive a **response** variable is to variations in a **driving** variable

$$CI = \frac{covar(SM, SHFLX)}{\sigma_{SM}}$$

- See *Dirmeyer* (2011; GRL) for more information

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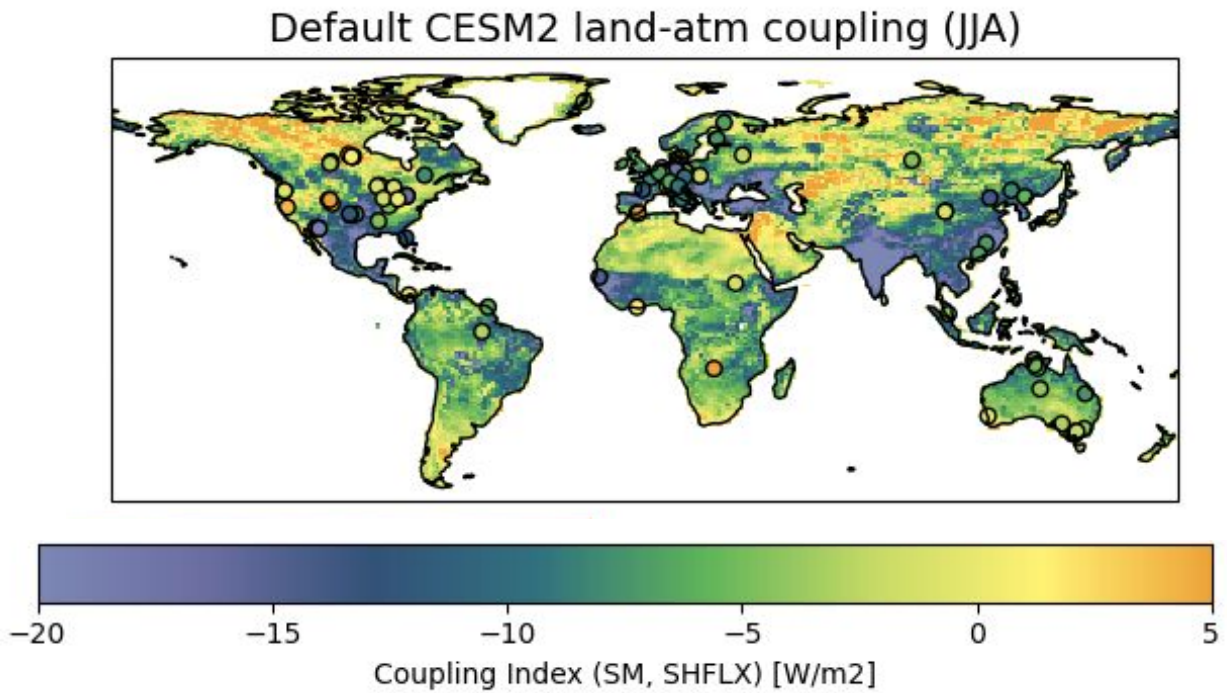
- Validated against FLUXNET2015 tower sites (circles)



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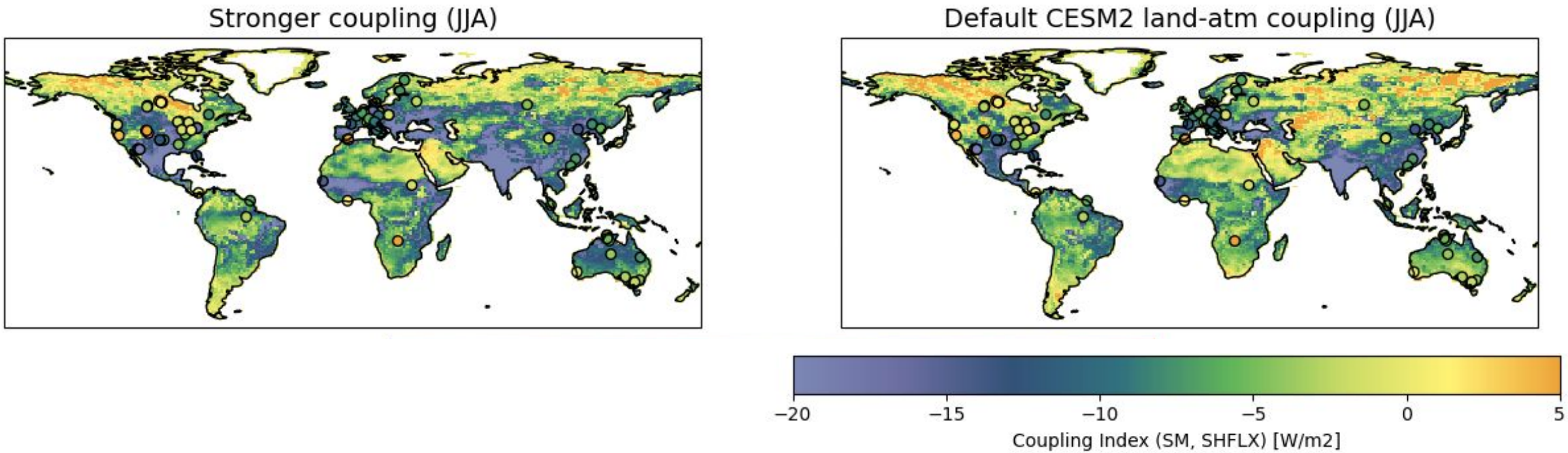

RMSE = 11.58 W/m2

RMSE = 9.34 W/m2

Do deficiencies in land-atmosphere coupling explain the limited impact of land initialization?

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How well does CESM capture impact of soil moisture on surface flux anomalies?

- Stronger coupling in the model = worse validation against tower obs
- Initial indication: terrestrial coupling leg does not seem to be the culprit for limited land-based predictability

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How sensitive is the atmosphere to variations in surface fluxes?

Convective Triggering Potential (CTP) Humidity Index (HI_{low})

- Developed by Findell & Eltahir (2003a; *J. Hydromet*.)
- CTP measures early morning (pre-sunrise) atmospheric stability
- Combined with humidity index, indicates how strongly the land surface could impact convection that day

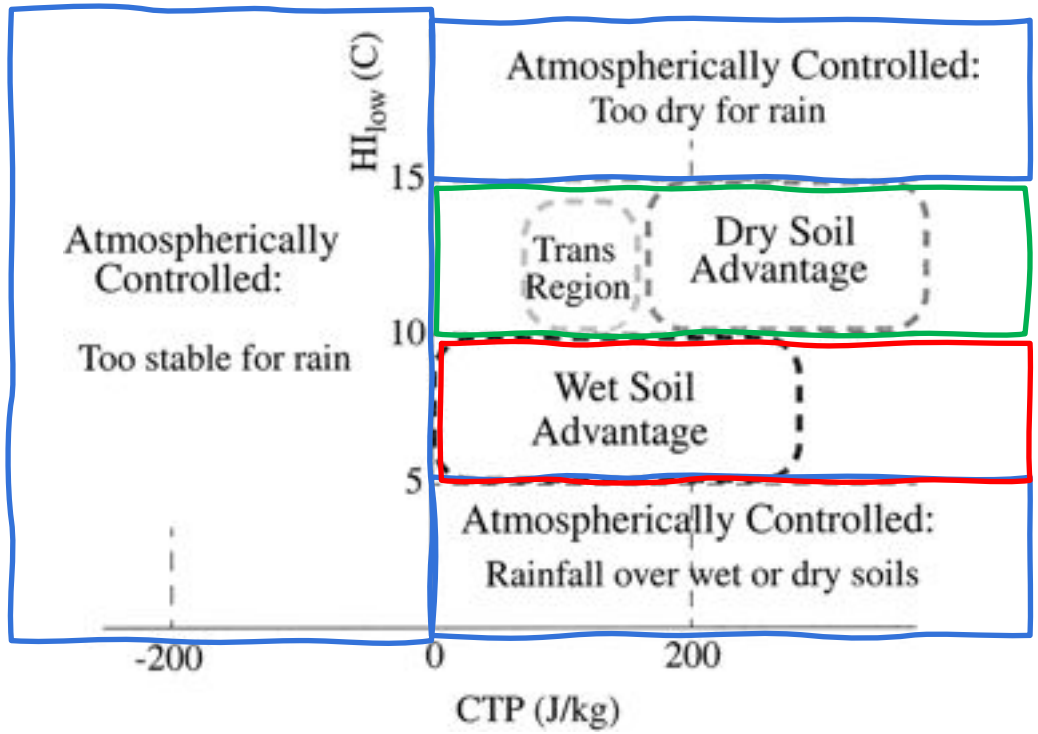

Fig 1. of Findell & Eltahir (2003b)

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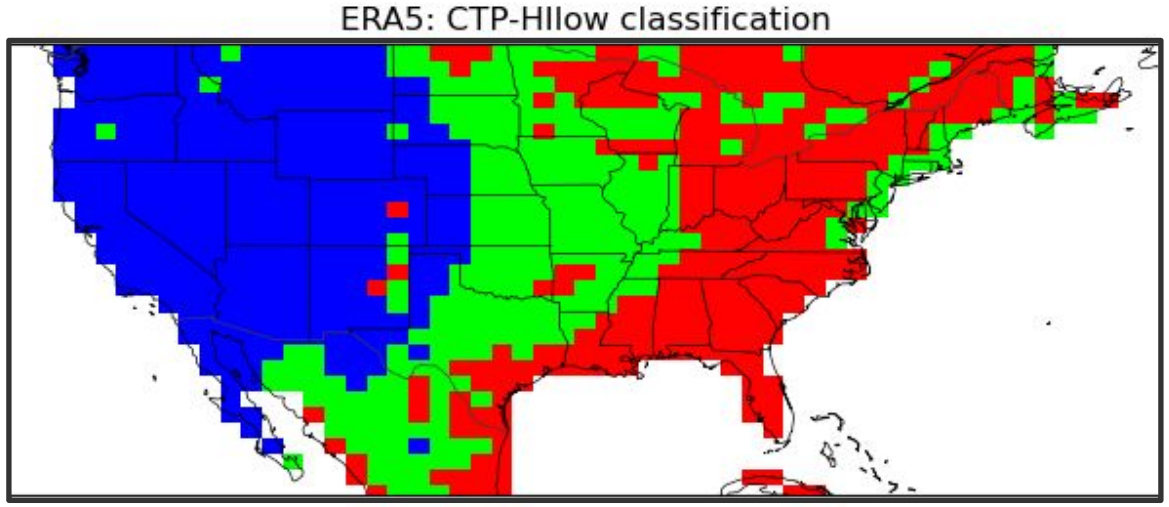

Atmospheric control

Dry soil advantage

Wet soil advantage

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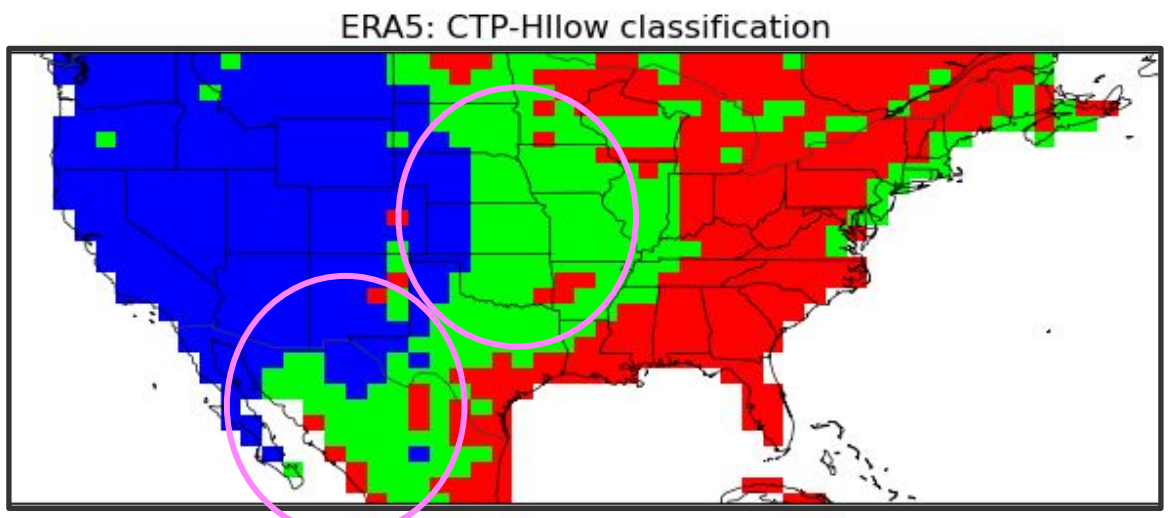

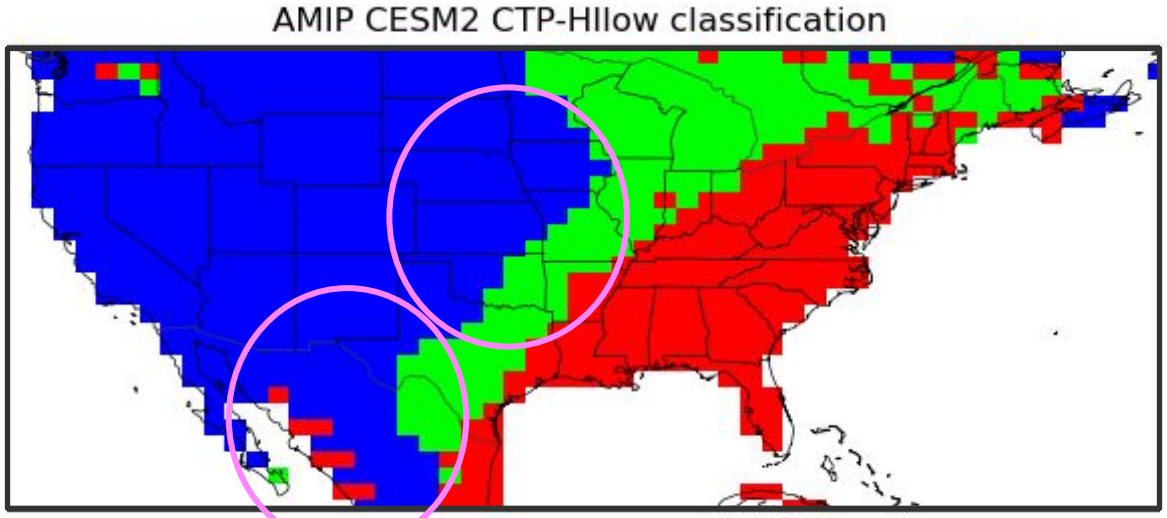

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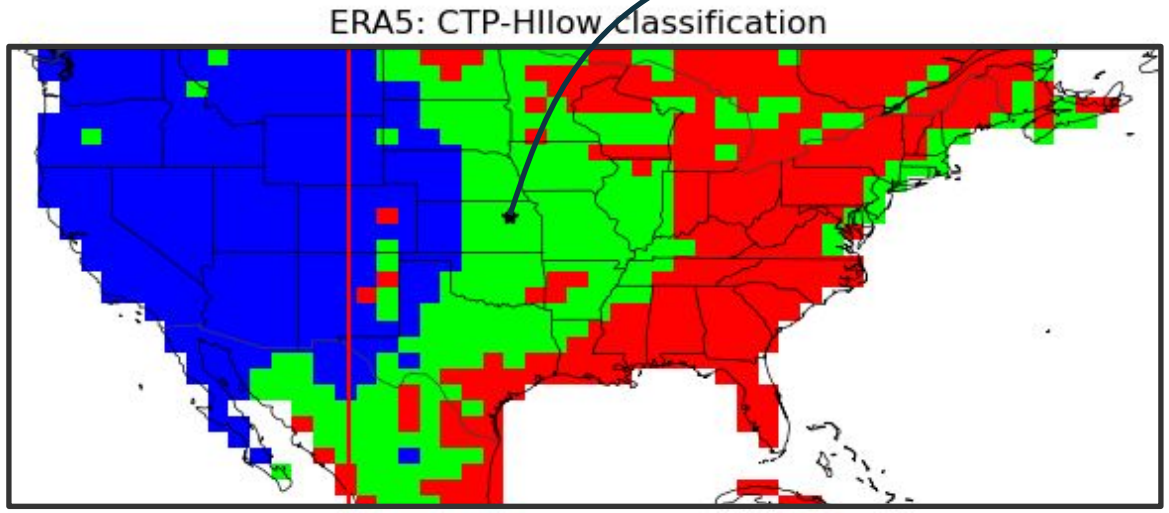
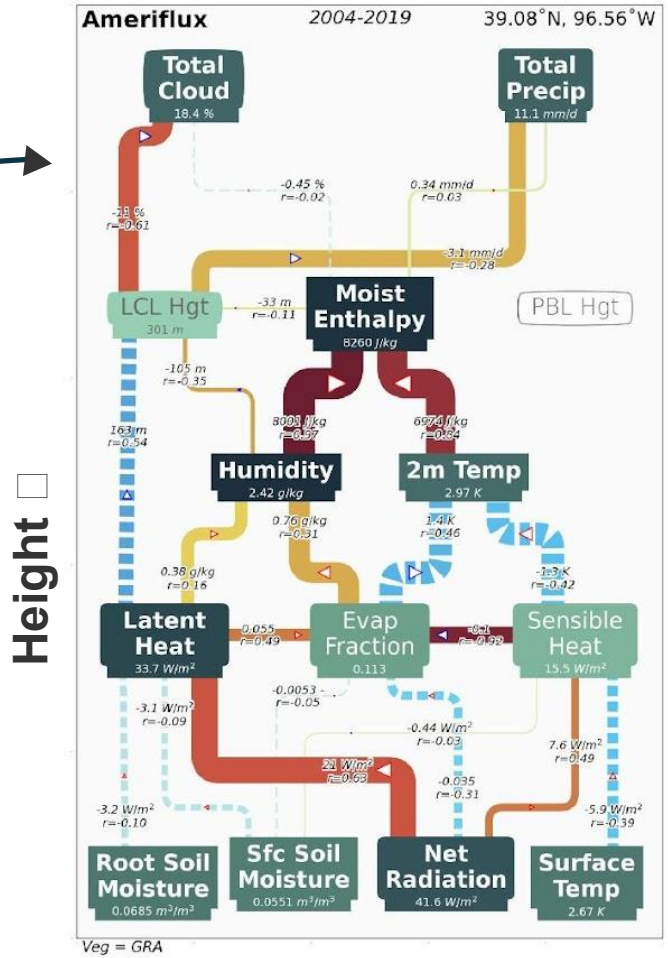
Can we look at the *full* process chain?

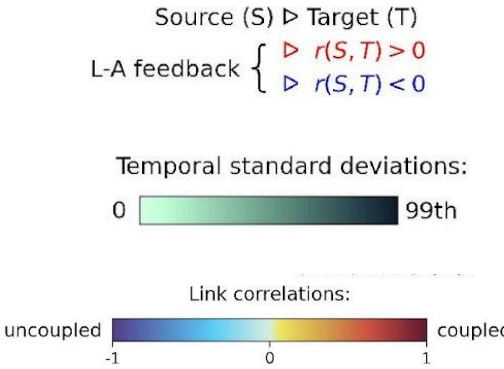
Can we understand how these link together?



Link width is proportional to coupling index magnitude: $|\sigma(T)r(S,T)|$
Dashed blue links indicate severed feedbacks
Coupling indices list units; correlations are shown as: 'r='



Pipe diagrams courtesy of P. Dirmeyer



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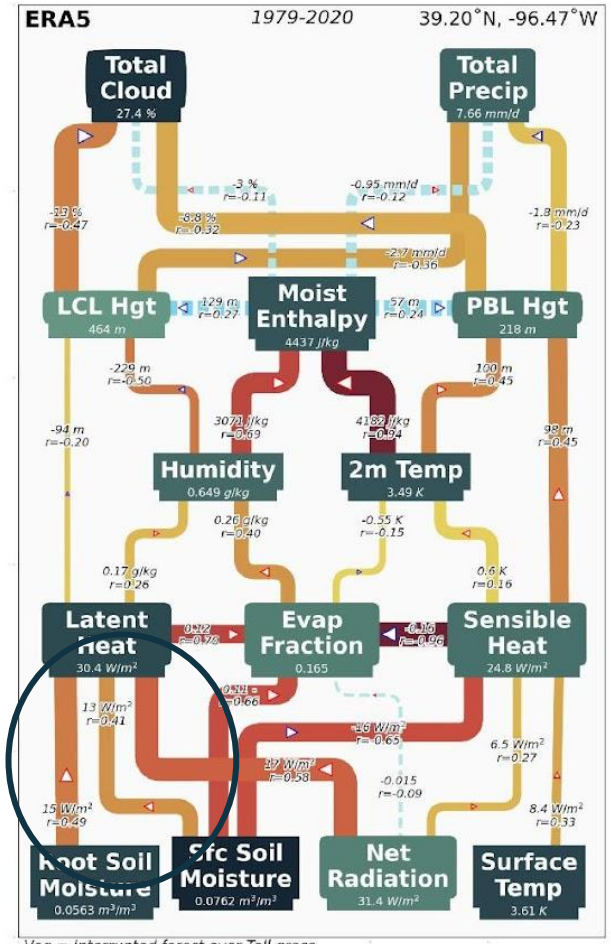
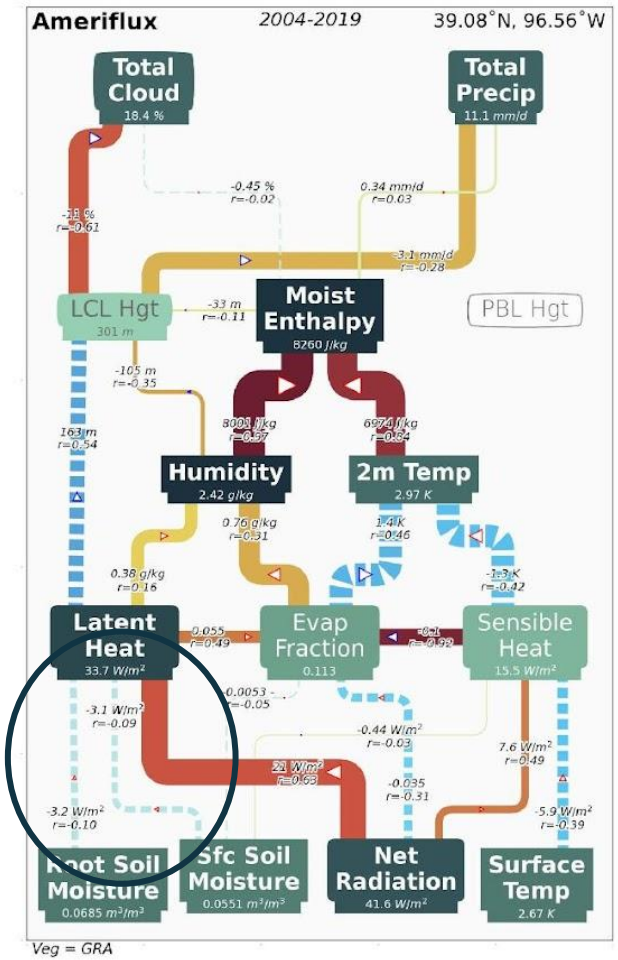
Observations and reanalysis may differ!

Link severed in observations, but strong/positive in reanalysis





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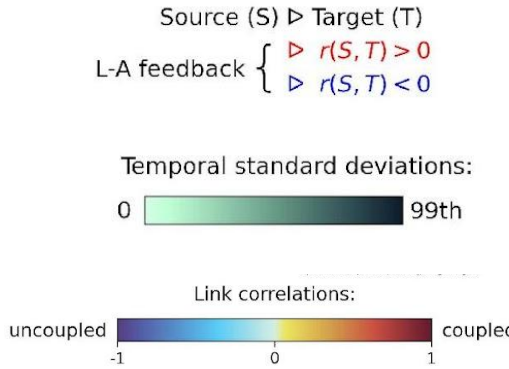

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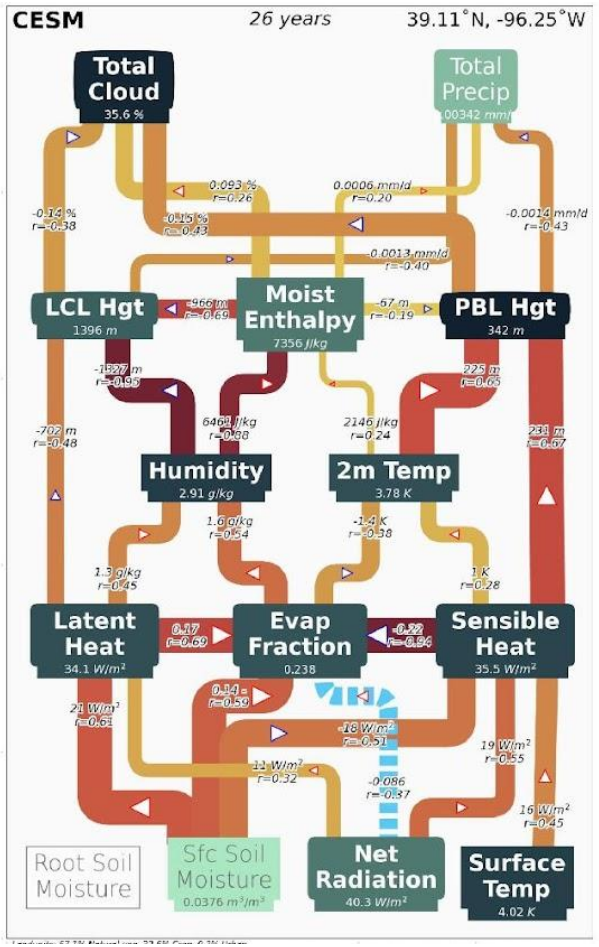

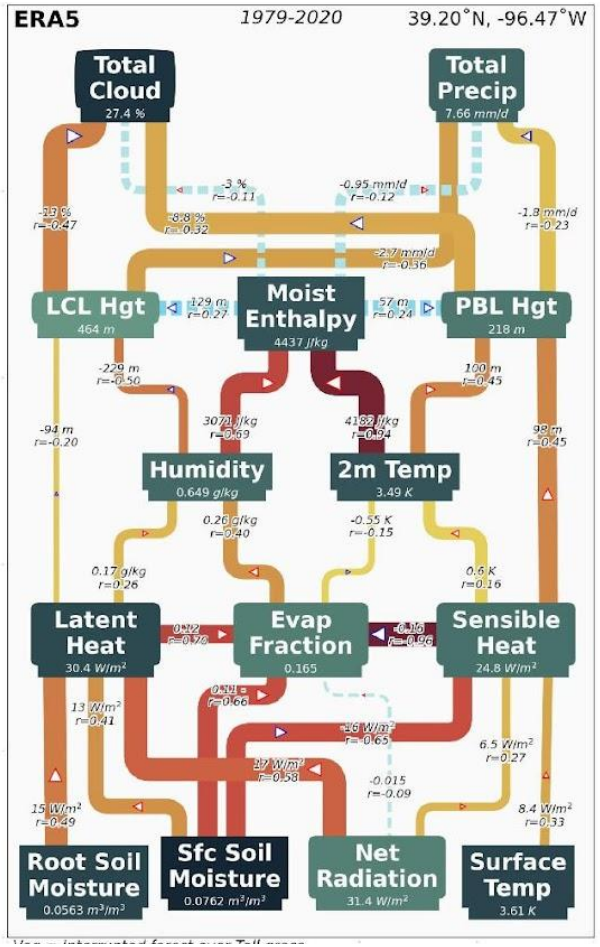

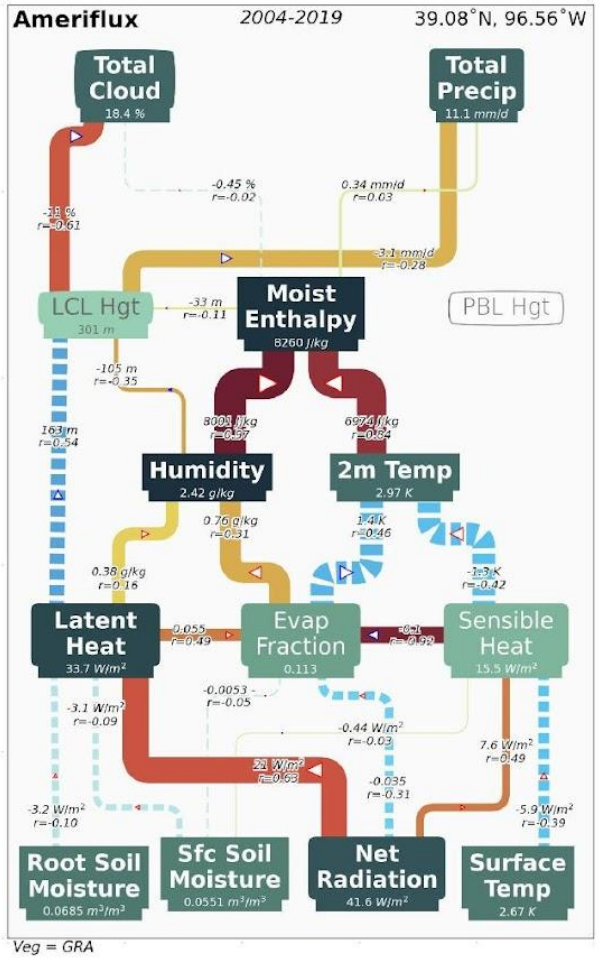

Pipe diagrams courtesy of P. Dirmeyer

Source (S) ▷ Target (T)

L-A feedback { ▷ $r(S,T) > 0$ ▷ $r(S,T) < 0$

Temporal standard deviations:

0 — 99th

Link correlations:

uncoupled — coupled

-1 0 1

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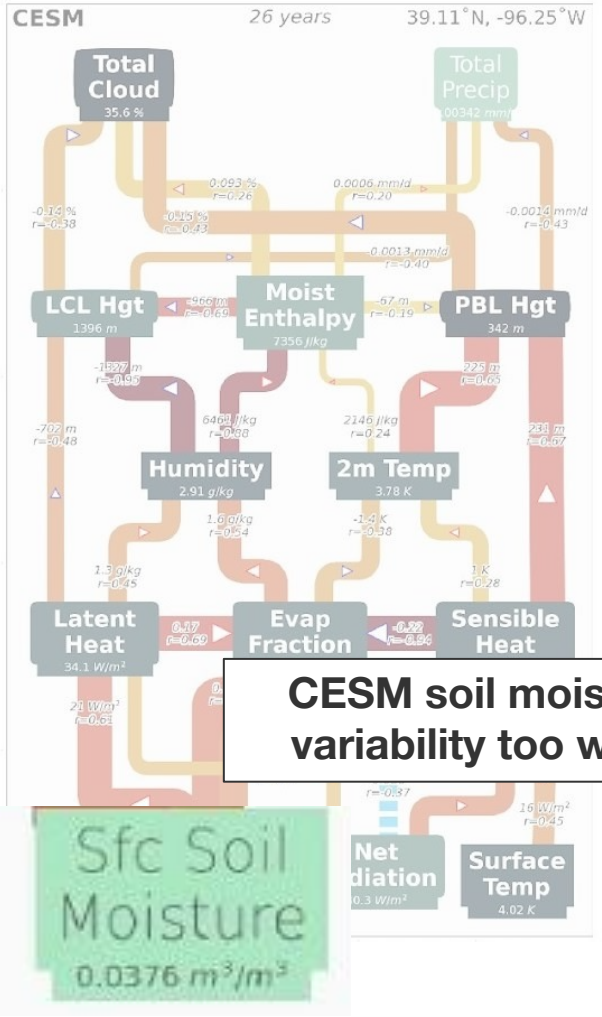
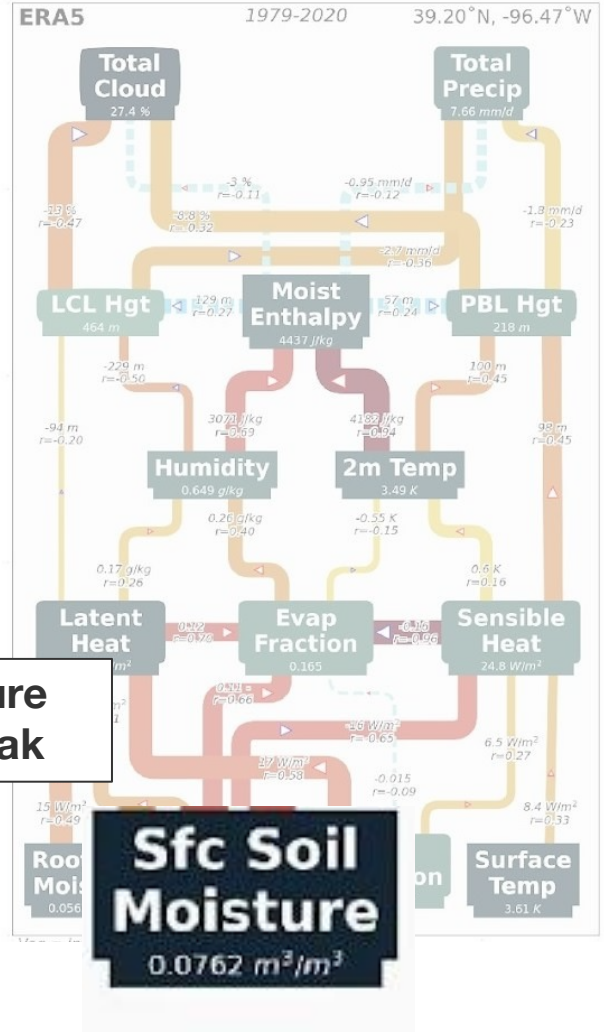
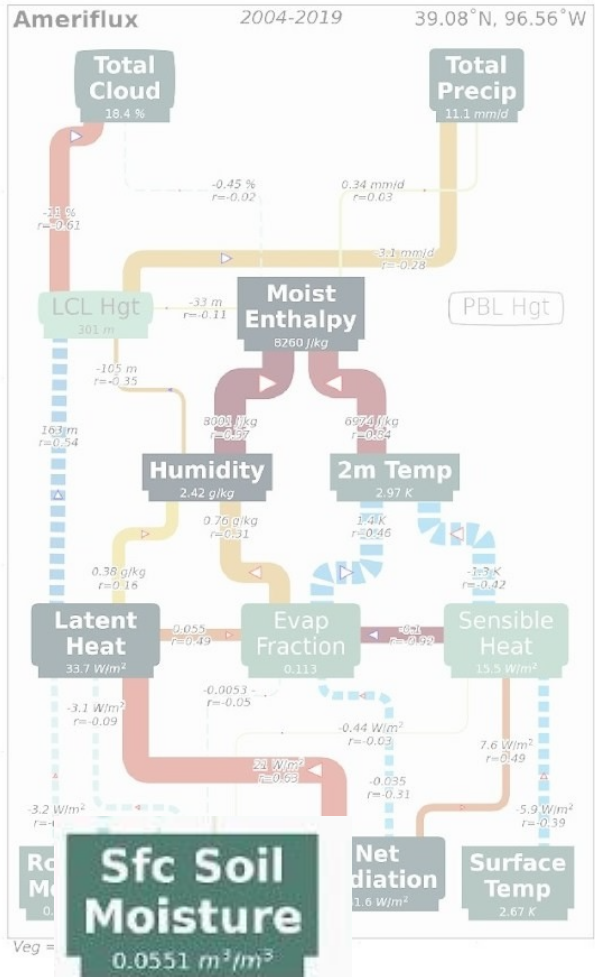


CESM soil moisture variability too weak





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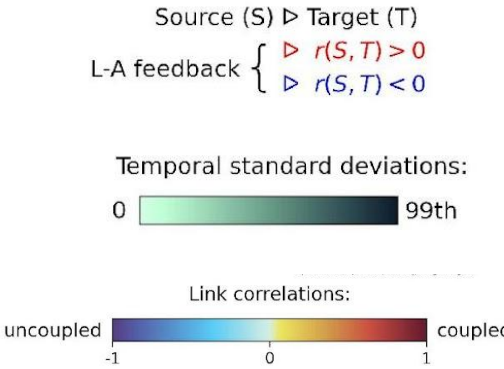

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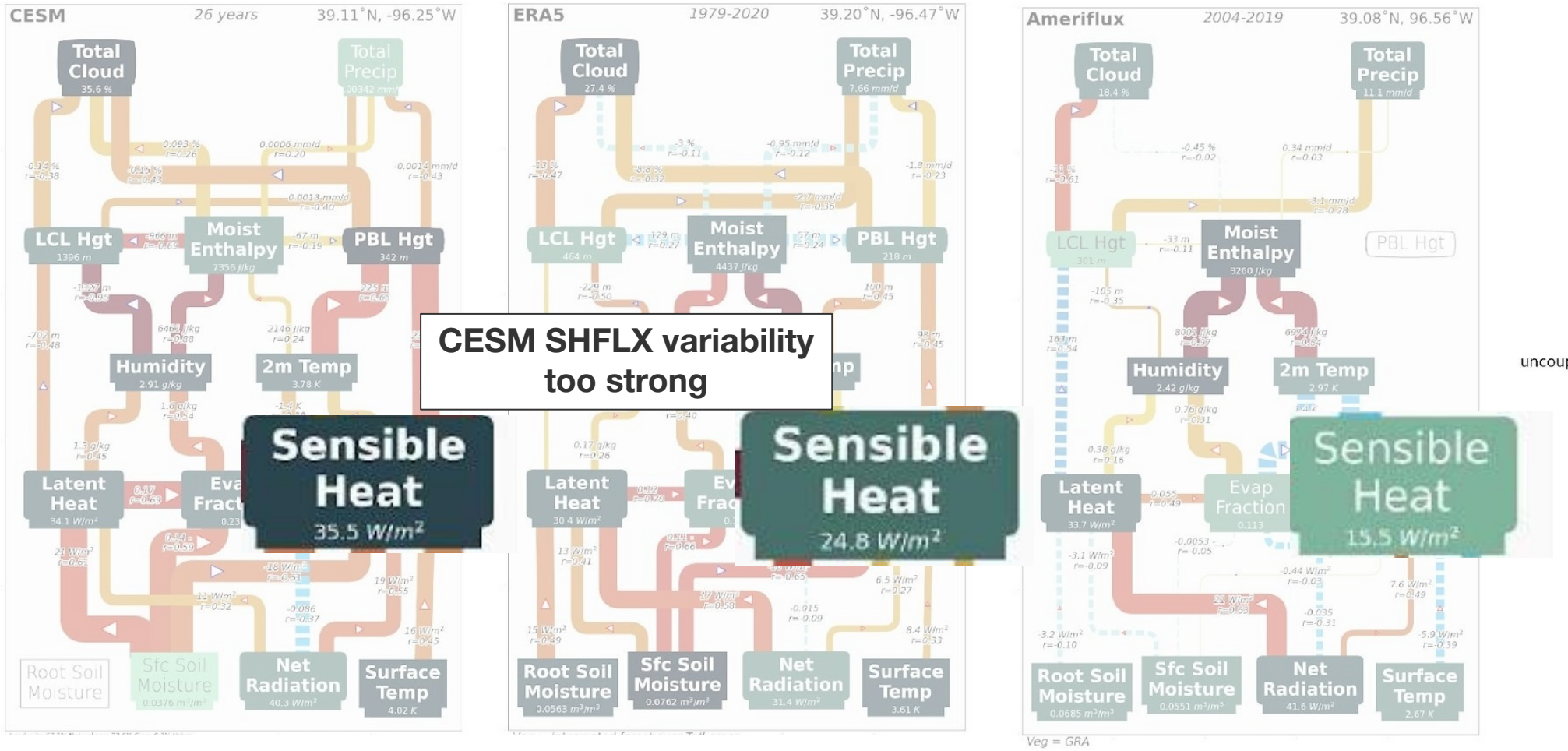

CESM SHFLX variability too strong

Source (S) ▷ Target (T)

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Temporal standard deviations: 0 — 99th

Link correlations: uncoupled — coupled (-1, 0, 1)

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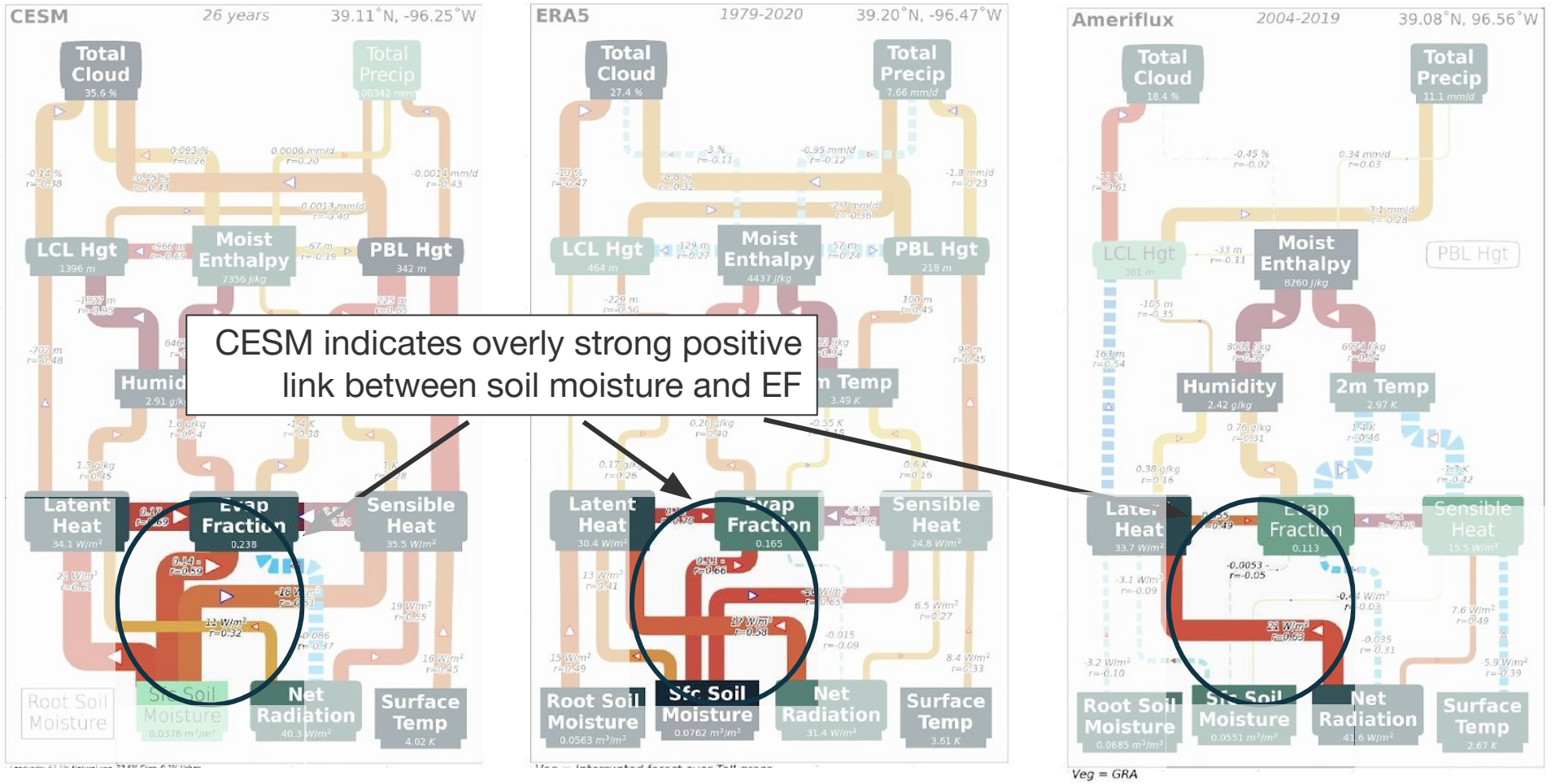

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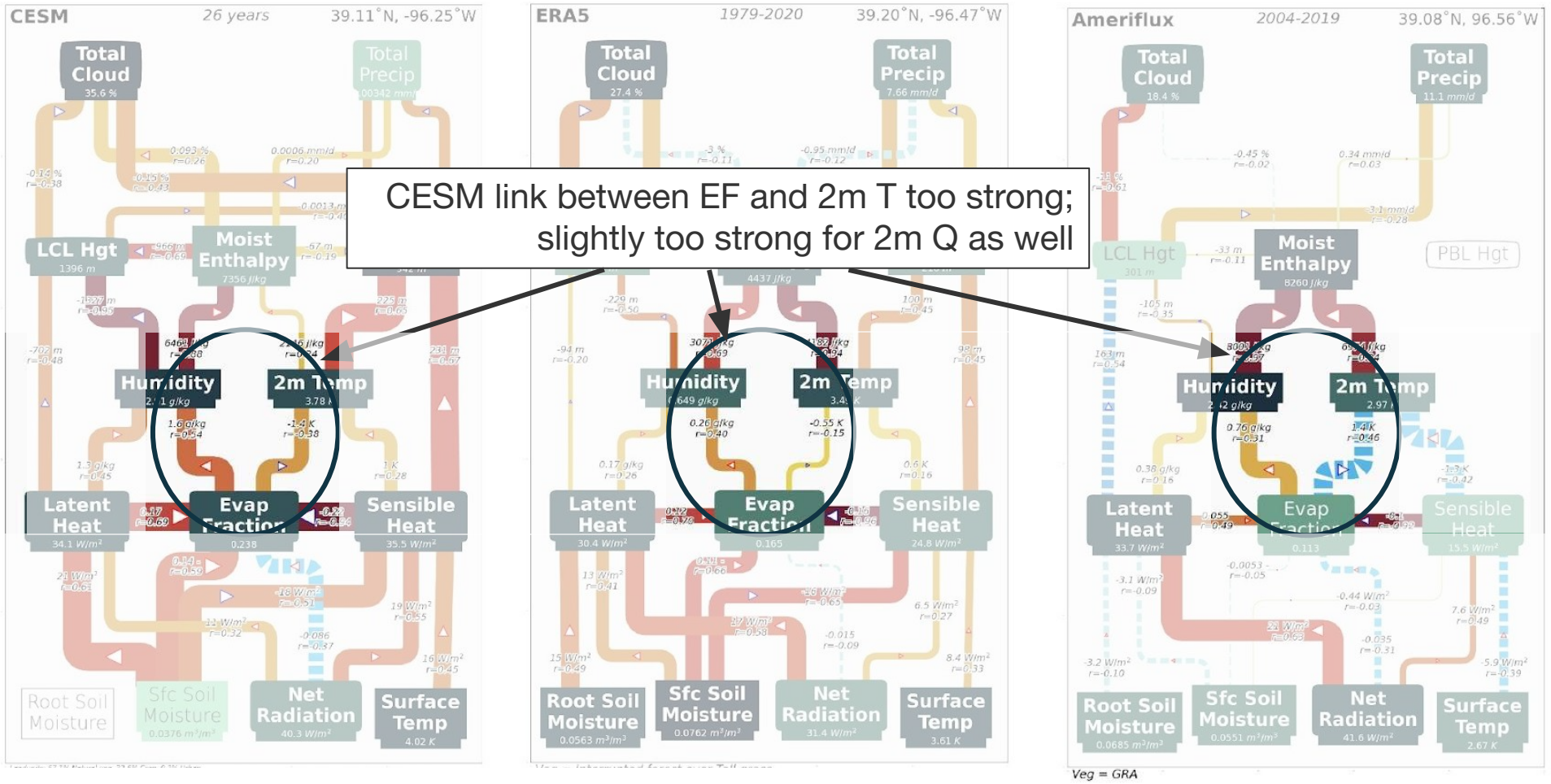
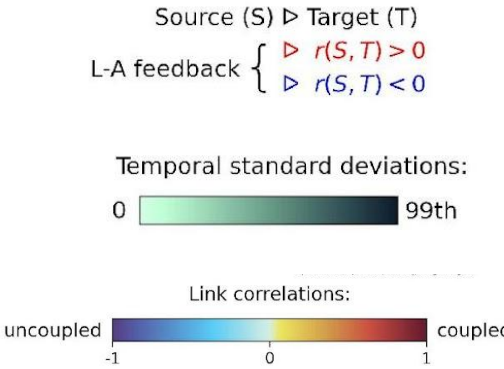


CESM link between EF and 2m T too strong; slightly too strong for 2m Q as well



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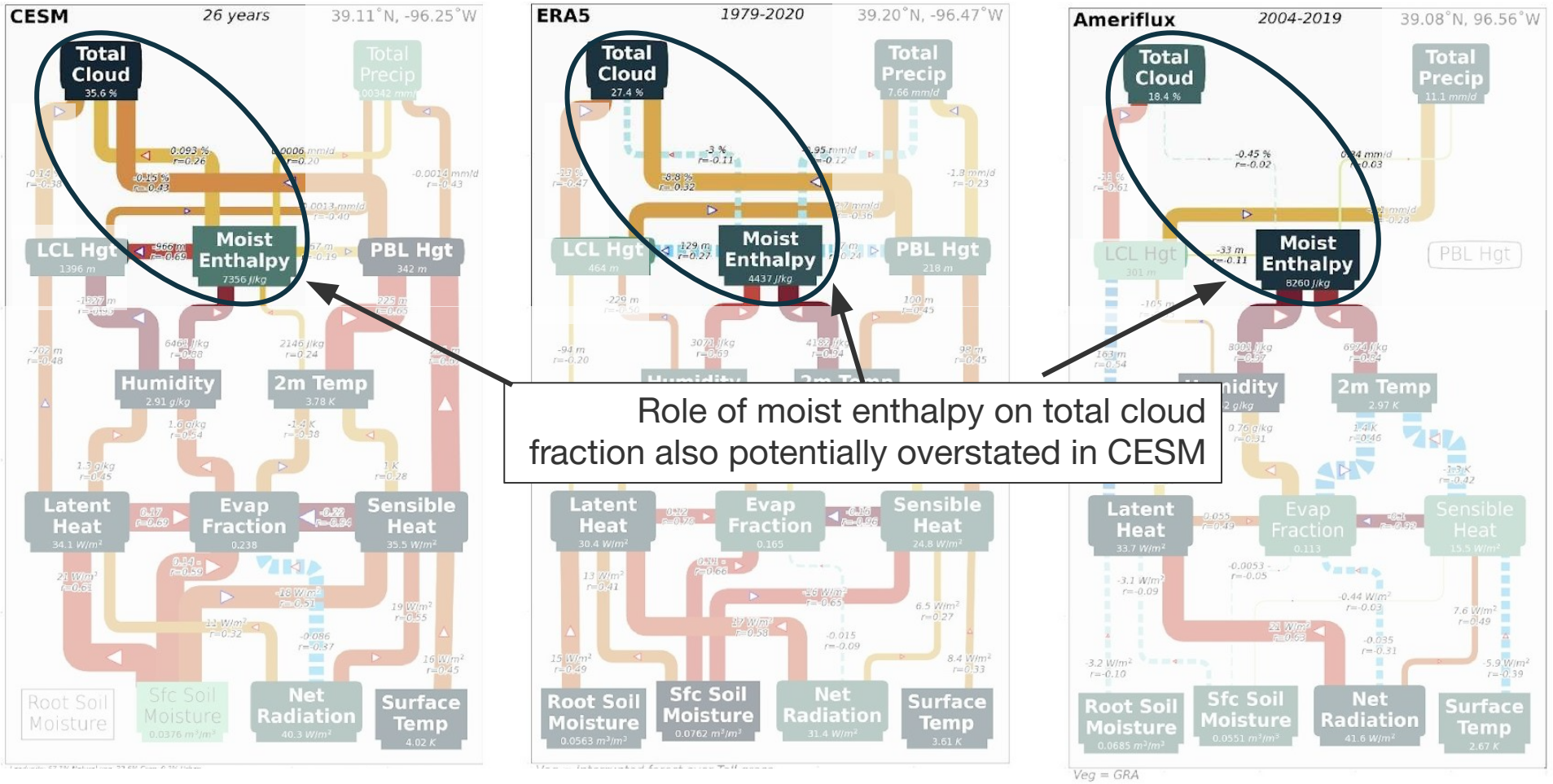
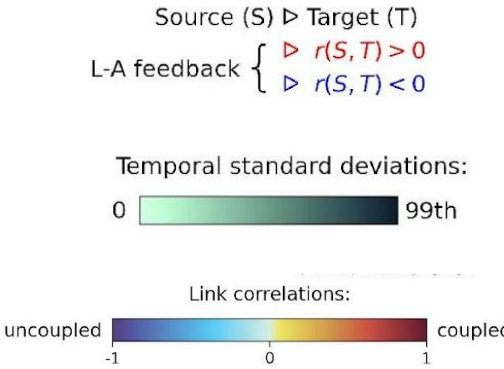


Role of moist enthalpy on total cloud fraction also potentially overstated in CESM



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An atmospheric-based perspective:

How sensitive is the atmosphere to variations in surface fluxes?

- CESM2 over-represents the area of CONUS that is atmospherically-controlled (particularly in the Central US)

Can we look at the *full* process chain?

- There are *many* sources of potential biases, and we'll want to look across climate regimes, land surface types/uses, seasons, etc.
- But we are developing the tools to do this, and investigating which metrics are most useful

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Next steps:

- Continue to assess the process chain from surface anomalies to atmospheric responses to identify potential biases across locations
  - Identify tuning/parameterization changes that might improve land-atmosphere coupling
- Leverage case studies to assess impacts on S2S predictability

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