The fidelity of land-atmosphere interactions in CESM

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Theoretical Basis

- The notion of local coupling (LoCo) between land and atmosphere through water and energy cycles.
- Any broken links in the chain interrupt land surface impacts on weather, climate, predictability.
- Where and when are these feedbacks in place in *the real world*, and how strong are they?
- Do our models get this right?

Adapted from Santanello et al. (2018)

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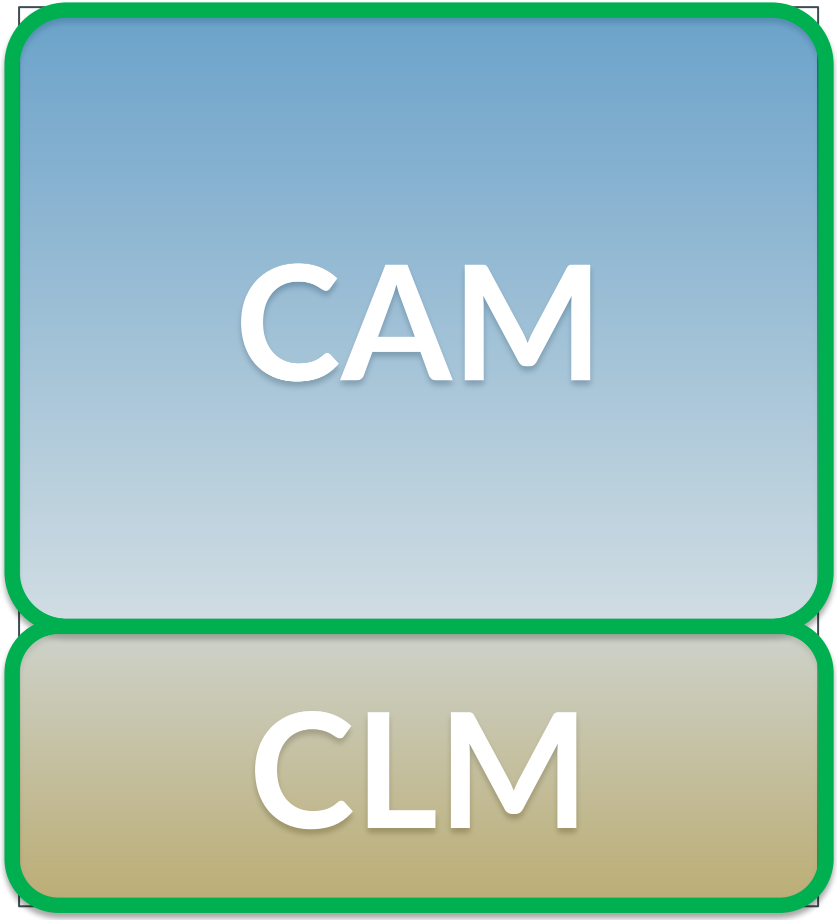

How Land Can Affect Atmosphere

- Evaporation (latent heat flux) requires energy and water – while sensible heat flux, ground heat flux & surface warming need energy only.

$$\frac{LE}{SH + LE}$$

Adapted from Seneviratne et al. (2010)

- Because of this, soil moisture can regulate energy (net radiation) partitioning, but only over part of its range.
  - wp = wilting point
  - csm = critical soil moisture

Models & Reanalyses

- CESM2.1.5 (CLM5 & CAM6) 0.9˚x1.25˚, F2000climo compset, 26y simulations
  - CLM only runs with GSWP3v1 met forcing
  - CLM+CAM runs have climo SSTs, sea ice

to assess CESM's behavior w.r.t. LoCo, which is foundational to S2S prediction skill

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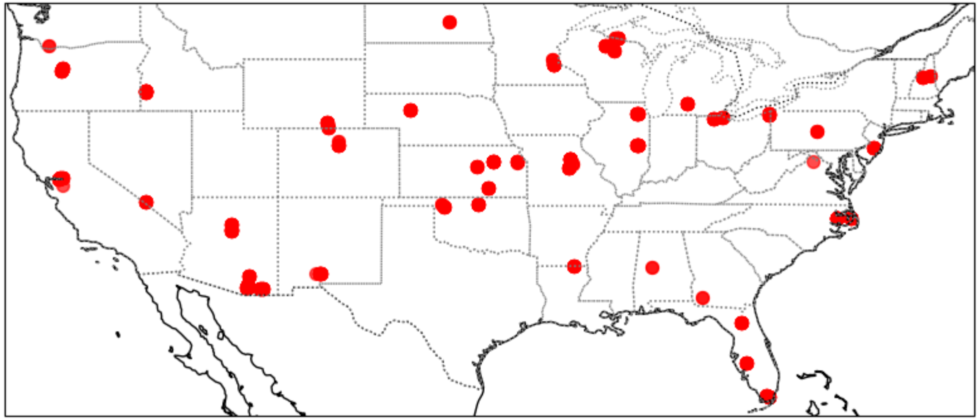
- ERA5 (global and flux-tower site comparisons)
  - On original reduced Gaussian grid (nominally 31*km*)
  - HTESSEL land model (no carbon cycle or predicted phenology)
  - ASCAT soil moisture assimilated
- MERRA2 (flux-tower site comparisons)
  - 0.625˚x0.5˚
  - Catchment land model, no soil moisture assimilation

Flux Tower Data

- Daily AmeriFlux data over CONUS
- Stations with excessive missing, incomplete or short time span data were omitted
- Exact number of sites varies by season, each site has different years and days available / missing: typically have ~60-70 stations
- For consistent comparisons, model and reanalysis data at the grid cell for each tower site only include the exact days present in the observational data.



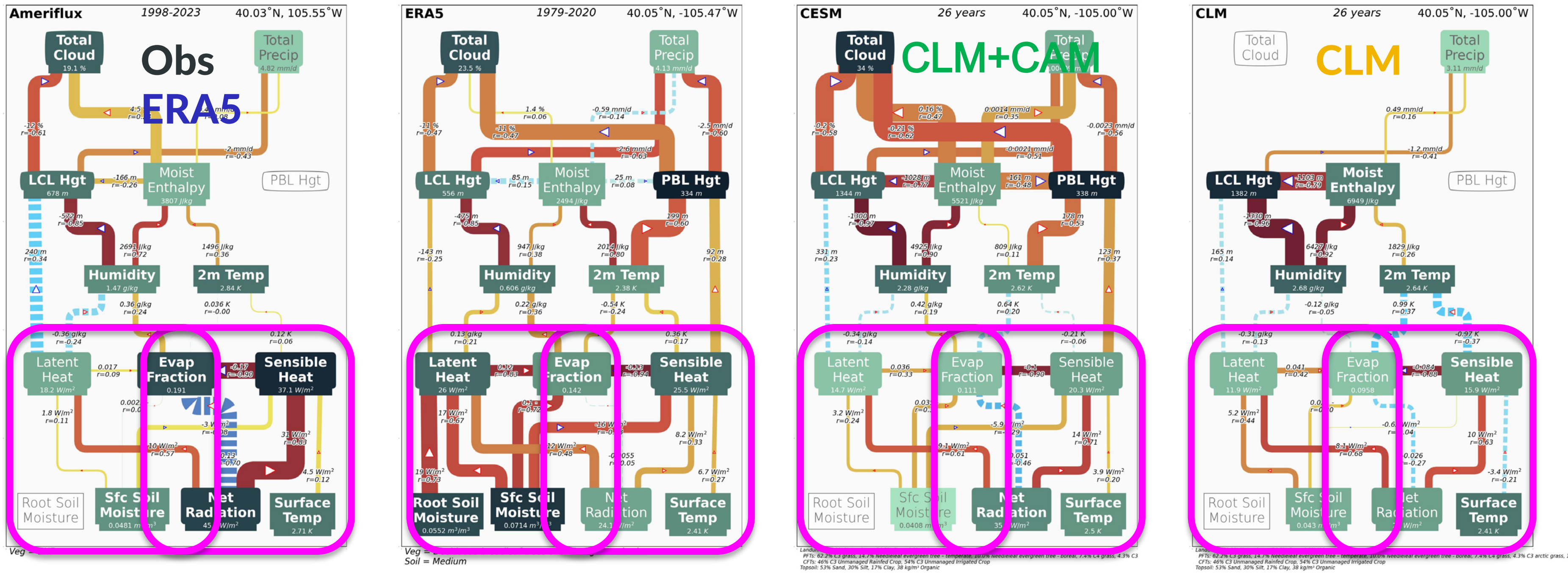
Coupling Metrics

- Pearson's temporal correlation: $r(SM\!:LE), r(SM\!:SH), r(SM\!:EF)$
  - Reveals covariability between soil moisture and surface fluxes, an important clue for causality, process identification (identifies water-limited versus energy-limited evaporation regimes)
- Variability: $\sigma(SM),\ \sigma(LE),\ \sigma(SH),\ \sigma(EF)$
  - Correlation doesn't mean much if these quantities rarely change.
  - There must be fluctuations the atmosphere can *feel*.
- Coupling Index: $I = \sigma(LE) \cdot r(SM\!:LE)$, etc…
  - Puts a magnitude of response onto the correlation information
  - These can be chained to find links between land states, surface fluxes, near surface atmospheric states, boundary layer characteristics, cloud formation and precipitation.

Evaluations at Specific Sites

US-NR1: Niwot Ridge Forest (LTER NWT1), USA

Season: JJA



Source (S) ▷ Target (T)

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

Temporal standard deviations: 0 — 99th

Link correlations: uncoupled -1 — 0 — 1 coupled

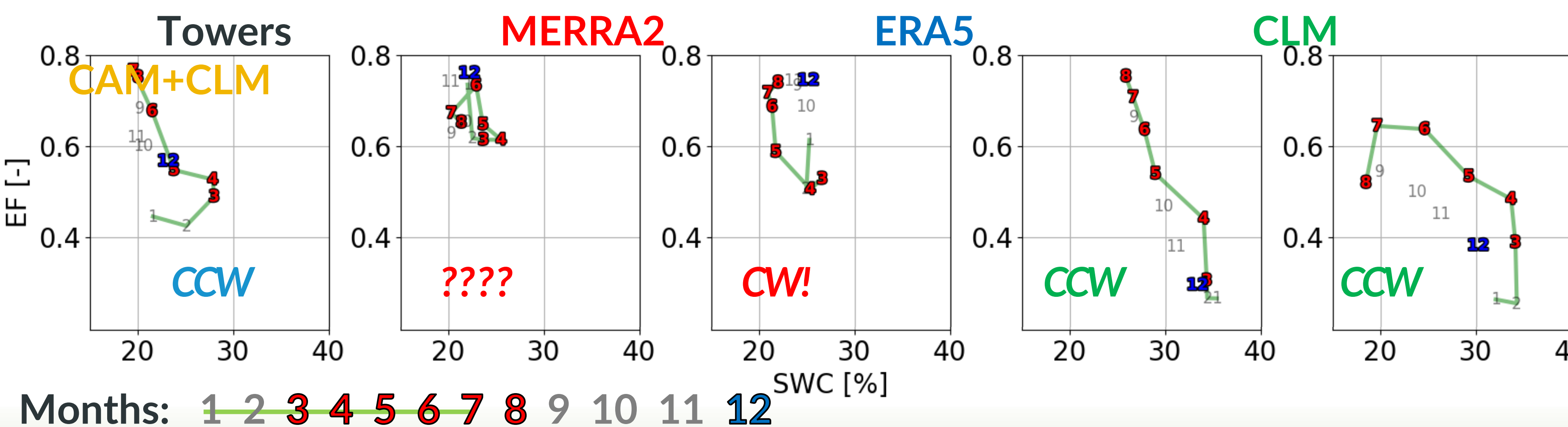
Link width is proportional to coupling index magnitude: $|\sigma(T)r(S,T)|$

Dashed blue links indicate severed feedbacks

Coupling indices list units; correlations are shown as: 'r='

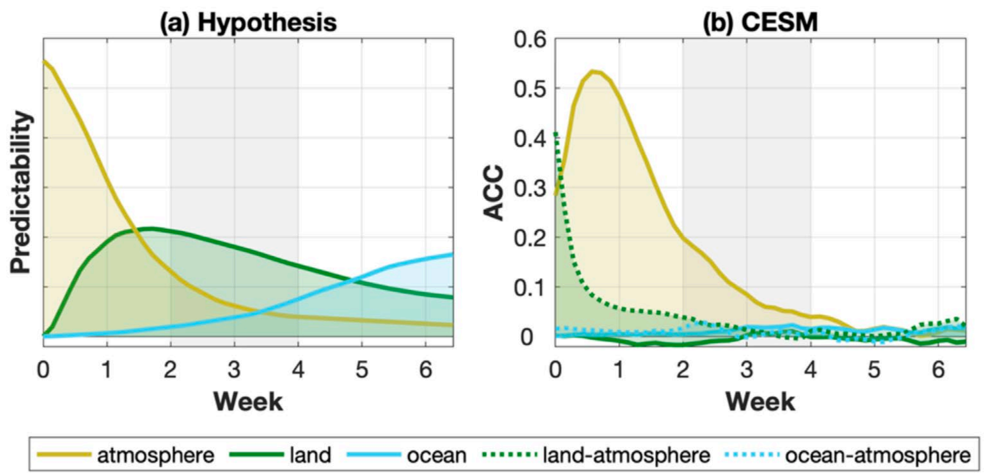
Seasonal Cycle of EF versus SWC

- At flux tower sites, the average seasonal cycle has minimum EF in Jan-Feb, maximum during July.
- Reanalyses have minimum EF in spring, maximum in winter
- CLM is better than CAM+CLM, but both fail to maintain dry soil through autumn.

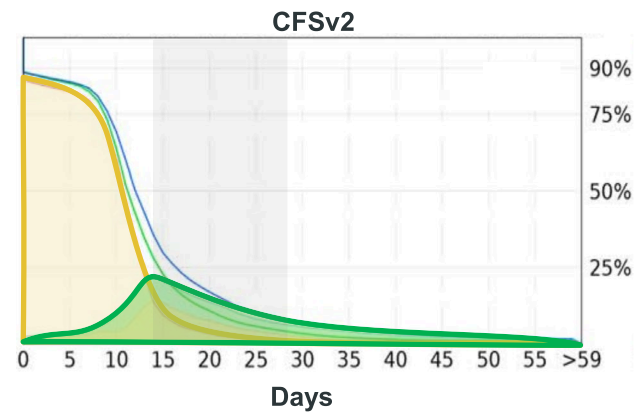


ESP: Yaga's Paper

- In an S2S prediction framework, CESM appears not to exhibit the predictability from land that other forecast models do....



From Richter et al. (2024)

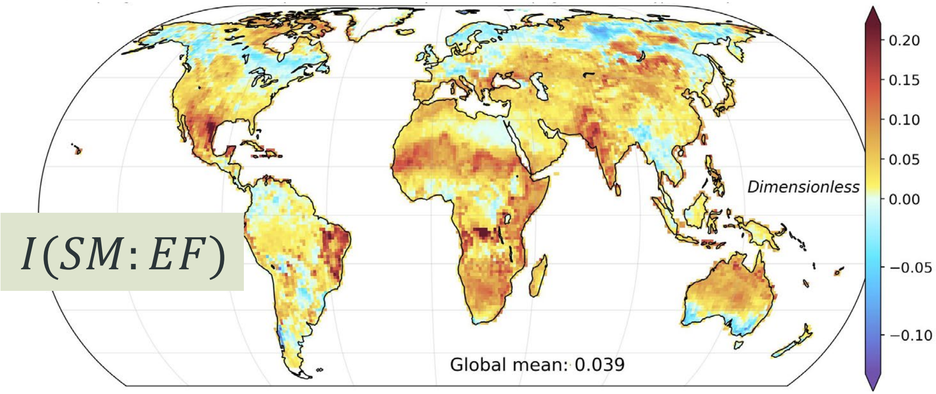


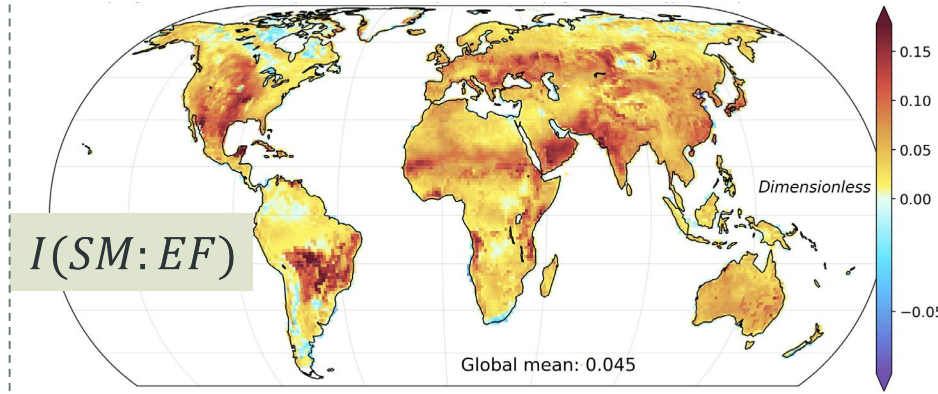
From Dirmeyer et al. (2018)

Global Analysis

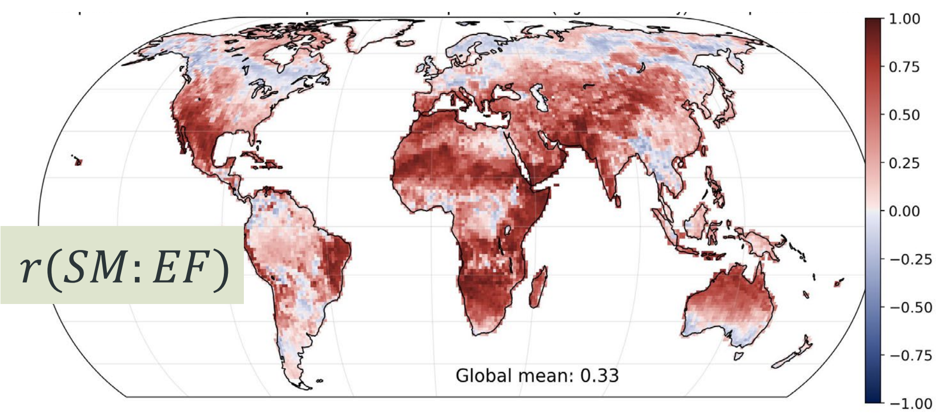
- Historically, our notions of L-A coupling and feedbacks have come from climate model simulations (e.g., GLACE).
- Locally, using flux tower or field campaign data, we can measure aspects of L-A coupling in nature.
- To best understand L-A coupling in the Earth system, and to validate our models, a global picture of the structure, intensity and variability of coupling metrics is needed.

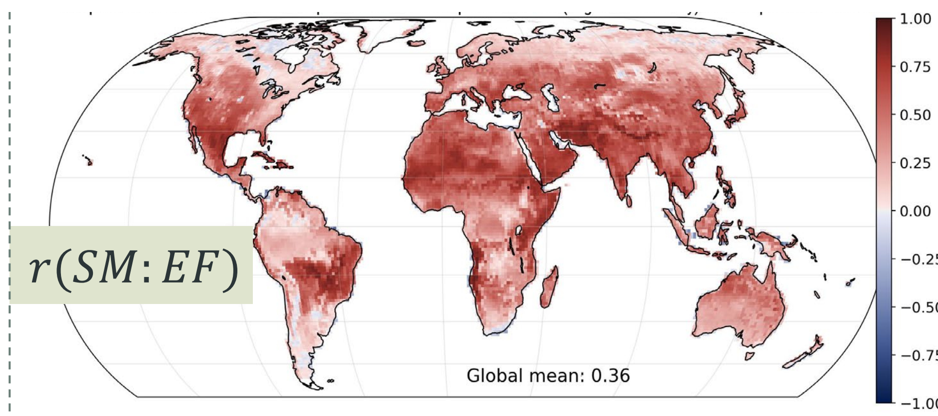
$SM\!:\!EF$ CLM CLM+CAM



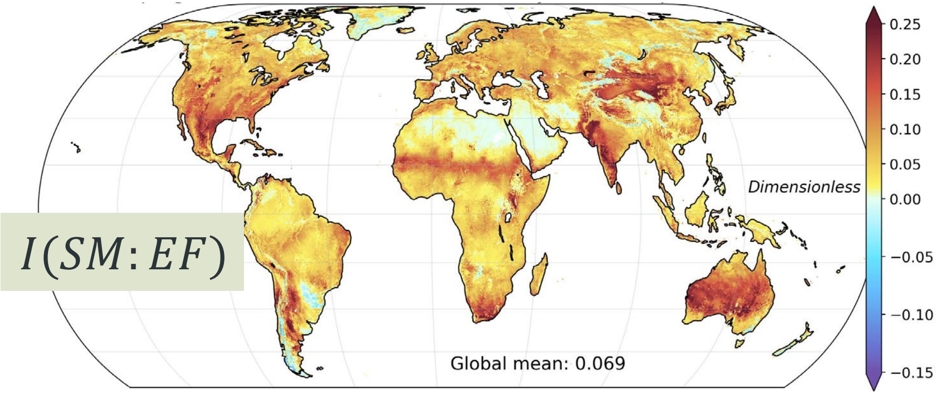


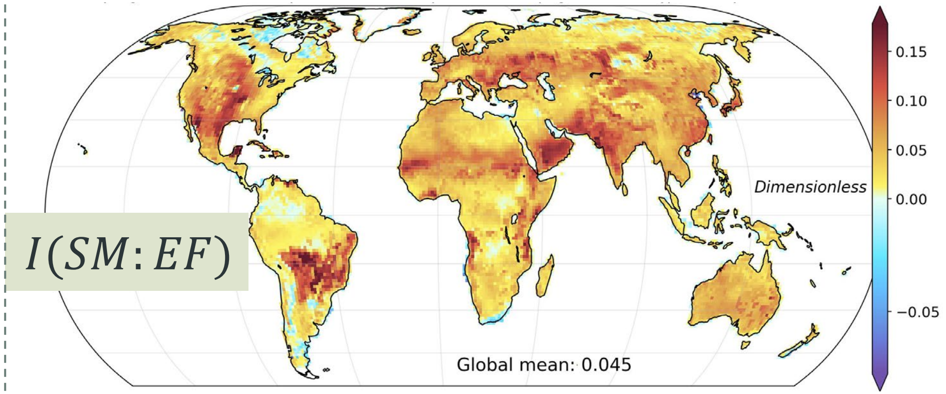
- The stronger and more widespread coupling in CLM+CAM (above) is largely driven by its stronger correlations (below)



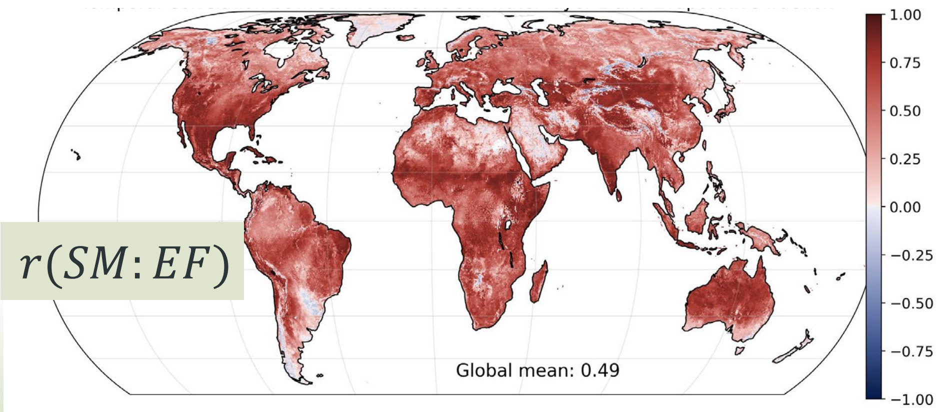


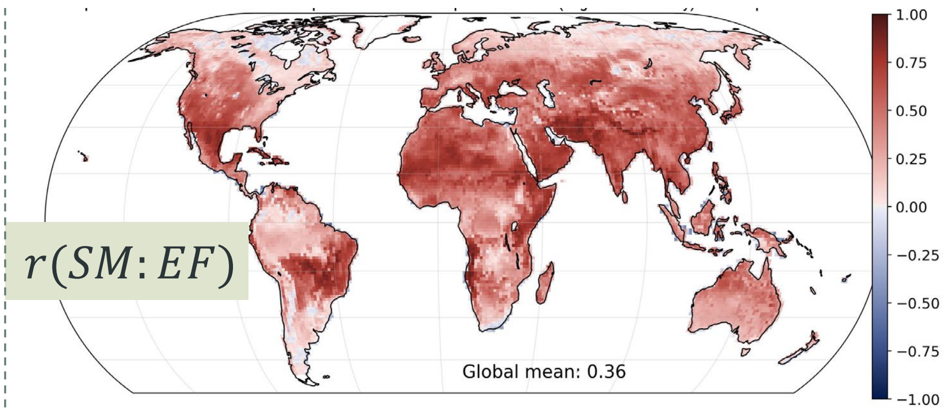
$SM: EF$ ERA5 CLM+CAM





- ERA5… OK, fine, but reanalysis isn't *really* observations for things like surface fluxes.
- We saw ERA5 is iffy at individual sites. **What can we do to validate models globally?**





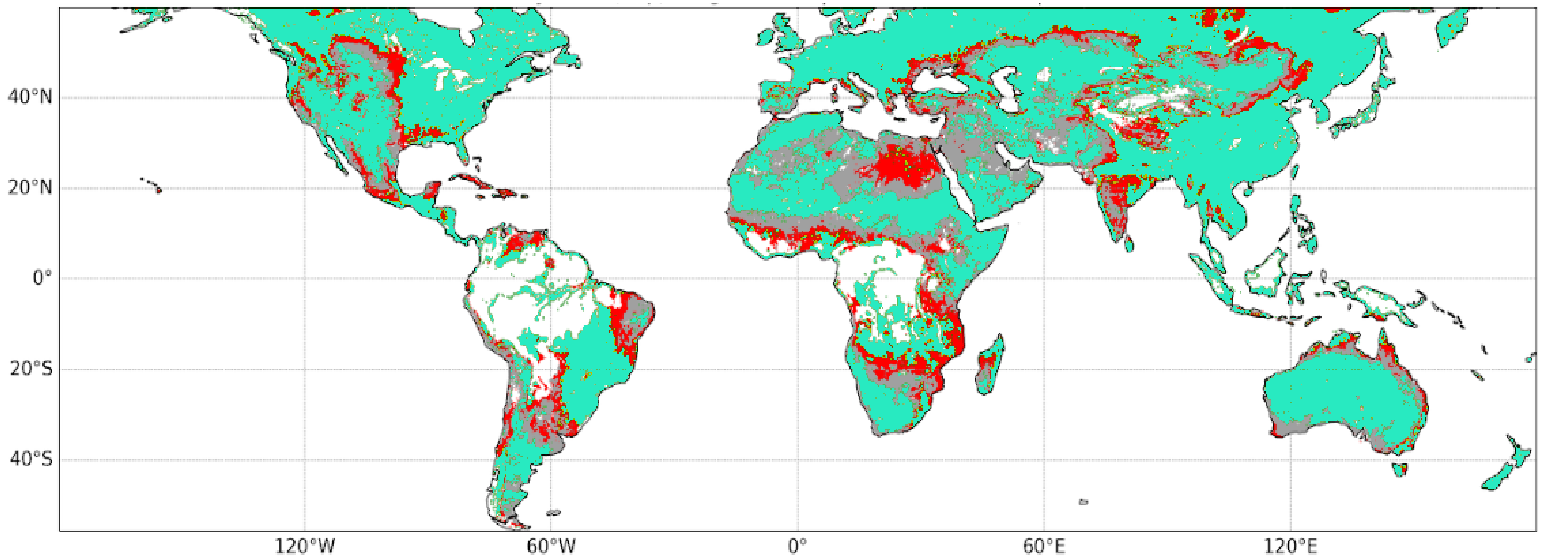
Data for Global Coupling Metrics

- Three soil moisture datasets (all corrected*):
  - **SMAP** (NASA, 2015-) *high information content, limited duration*
  - **CCI** (ESA, 1982-) *multi-platform composite, great coverage*
  - **SoMo.ml** (MPI-Jena 2001-2019) *uses ML to interpolate subsurface soil moisture*
- Three surface flux datasets:
  - **FLUXCOM XBASE** (Fluxnet + Satellite data + ML) *LE only*
  - **GLEAM4.1a** (Fluxnet + Satellite data + reanalysis + ML) *also has SH*
  - **CAMELE** (a multi-product composite) *LE only*
- Everything interpolated to ¼ ° common grid, daily intervals
- 3x3 = 9 ways to combine these: *spread treated as uncertainty*

*removes impact of random noise (*Vinnikov et al. 1996, Dirmeyer et al. 2016*)

Regimes & Uncertainty

- Red areas – where we are uncertain about boundary between energy & moisture limited regimes (based on $SM:LE$, not $SM:EF$). Remarkably tight agreement!



Confidence: *no data* **low** **medium** **high**

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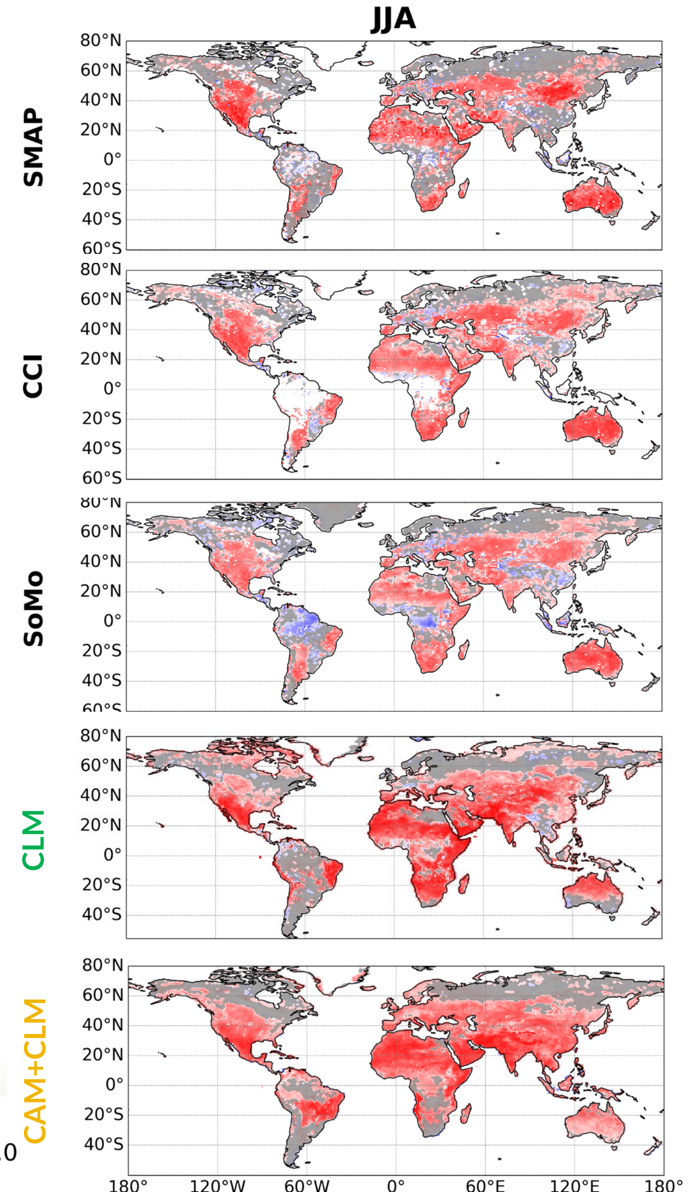
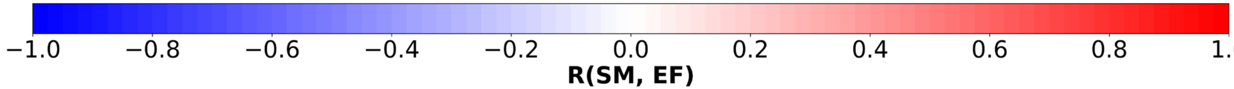
$r(SM:EF)$

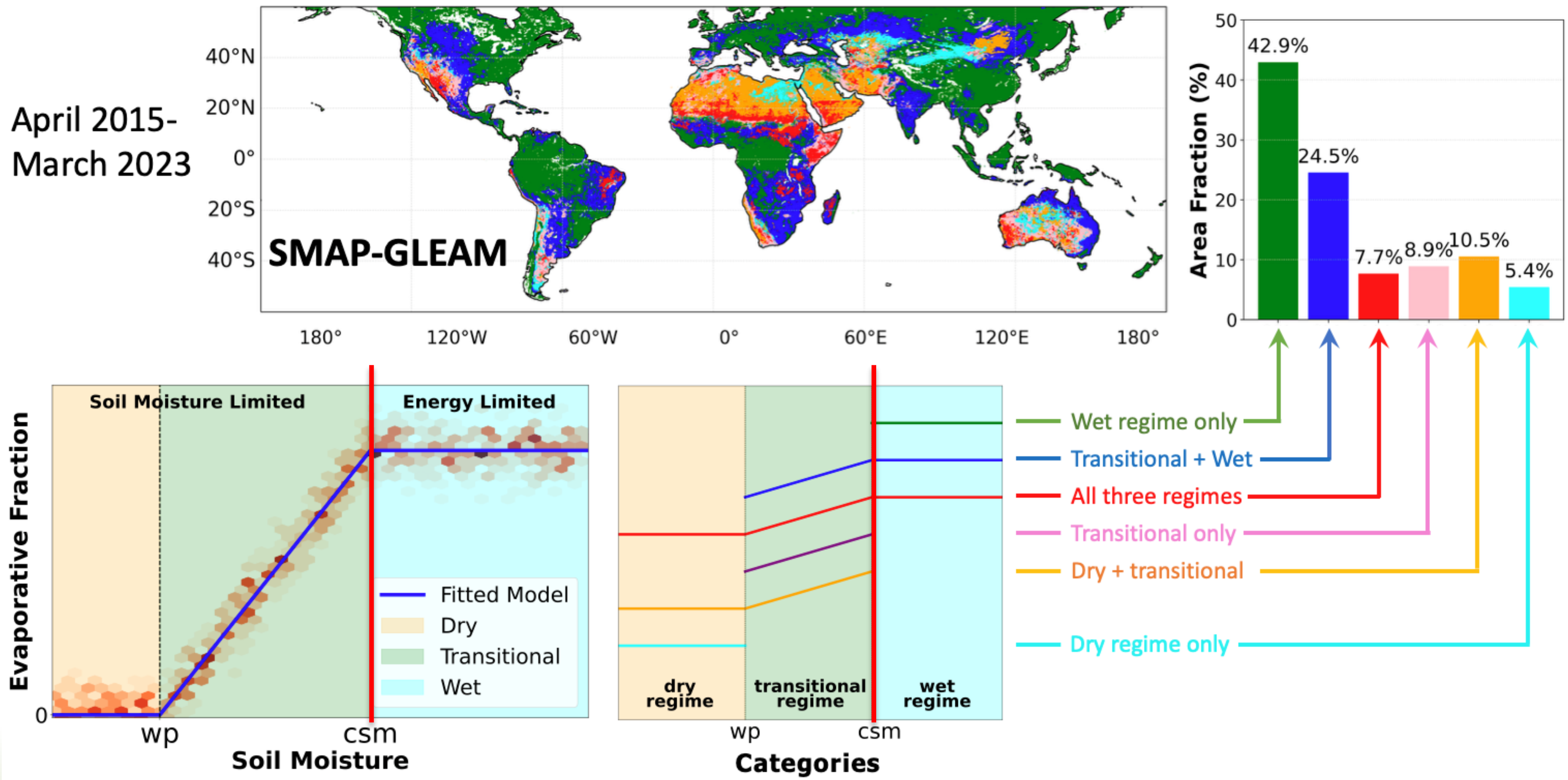
- Here, all using GLEAM for fluxes (it matches the best with tower data)…
- Very strong agreement on pattern among SM datasets – mainly the scale shifts.
- CLM and CAM+CLM have:
  - Consistently stronger coupling ($r > 0$ means moisture limited, SM controls fluxes)
  - Consistently more area with significant positive correlations
  - CAM+CLM is more egregious than CLM in these regards



grey = correlations not significant, p>0.05,   white: no data



Coming Back to Regimes



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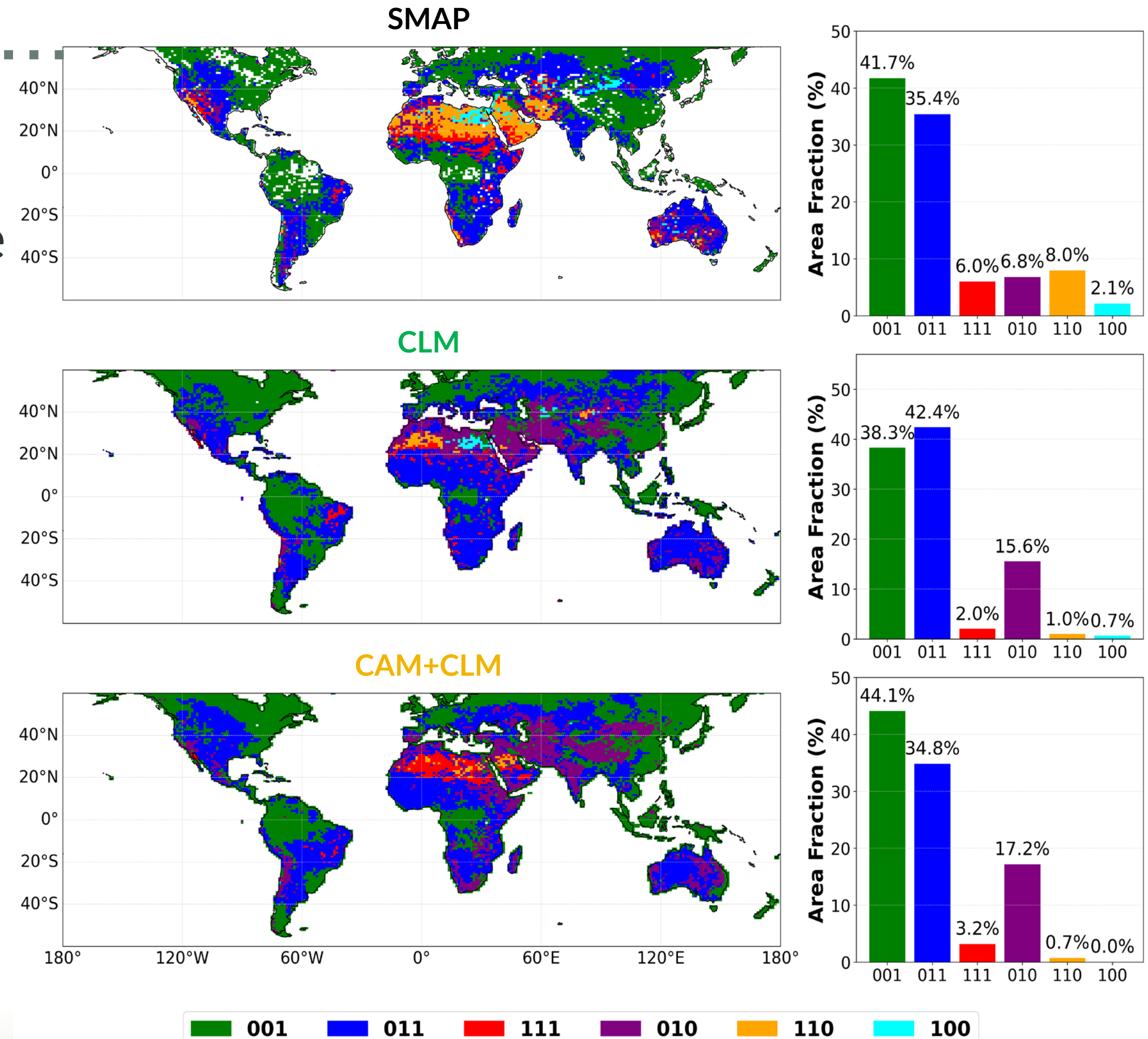
Very Preliminary…

- Both CESM configs seriously underestimate coverage of dry regime.
  - Especially crucial for extreme heat forecasts
- A key validation metric: the location of boundaries between regimes…



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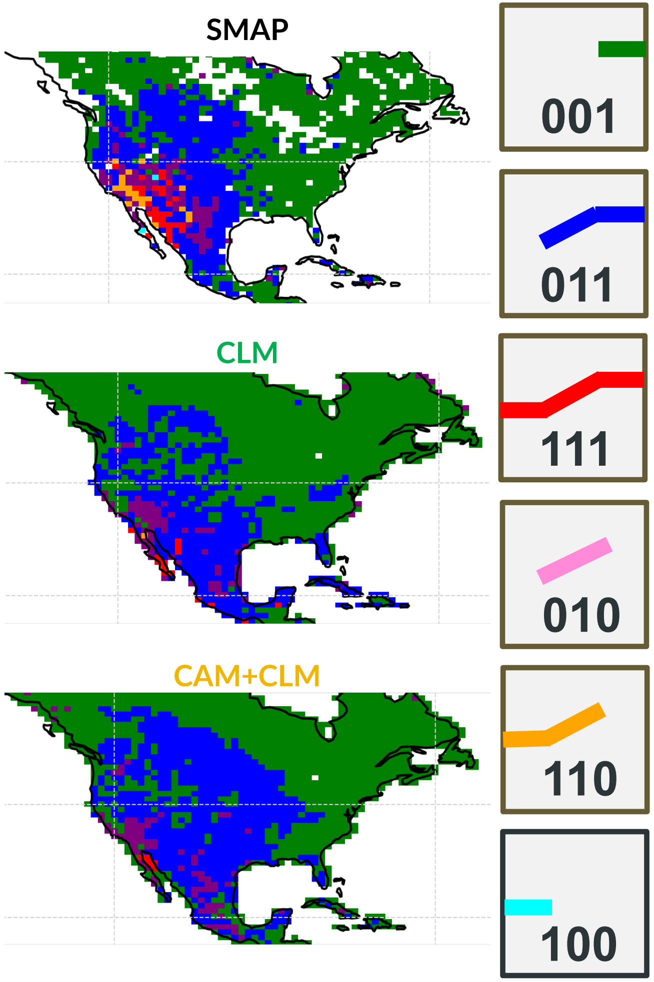
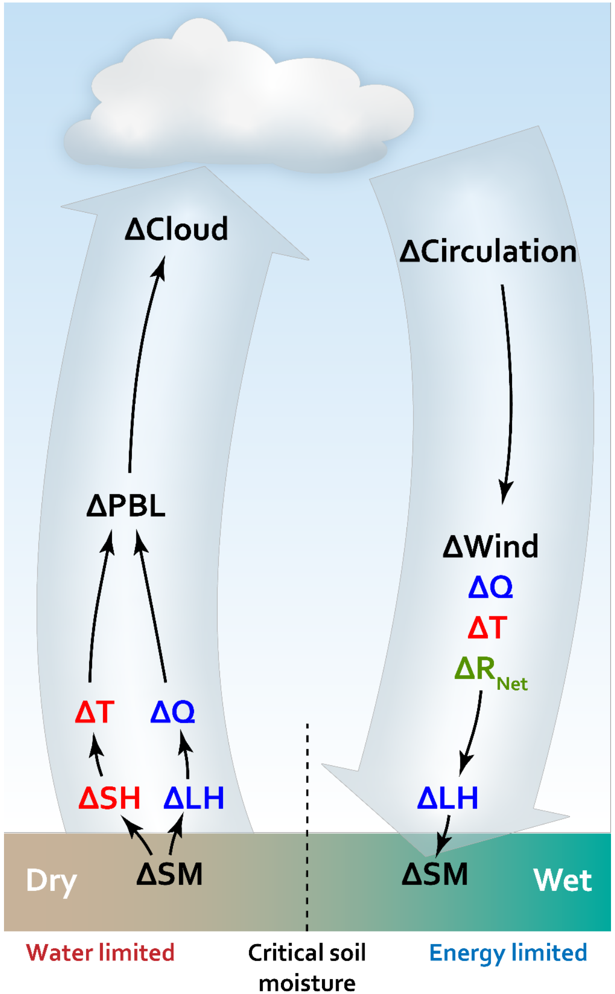
If We Zoom in…

- These may appear to be subtle differences, but they can have major consequences for:
  - Fidelity of climate simulations
  - Response of climate to anthropogenic forcings
  - Simulation of extremes (drought, extreme heat
  - Overall S2S forecast skill



Summary

- Beginning to look at the coupled L-A behavior of CESM *from the bottom up*.
- A key resource to properly validate models is observational estimates of coupling metrics that illuminates the coupled process chains linking land to atmosphere.
- We are producing global gridded observational analyses for this purpose.
- Not explicitly discussed here: **Vegetation (namely stomatal conductance) is a linchpin that integrates water, energy and carbon cycle drivers of L-A coupling.**



From Seo et al. (2024)