An overview of land-atmosphere feedbacks as a source of predictability on S2S timescales

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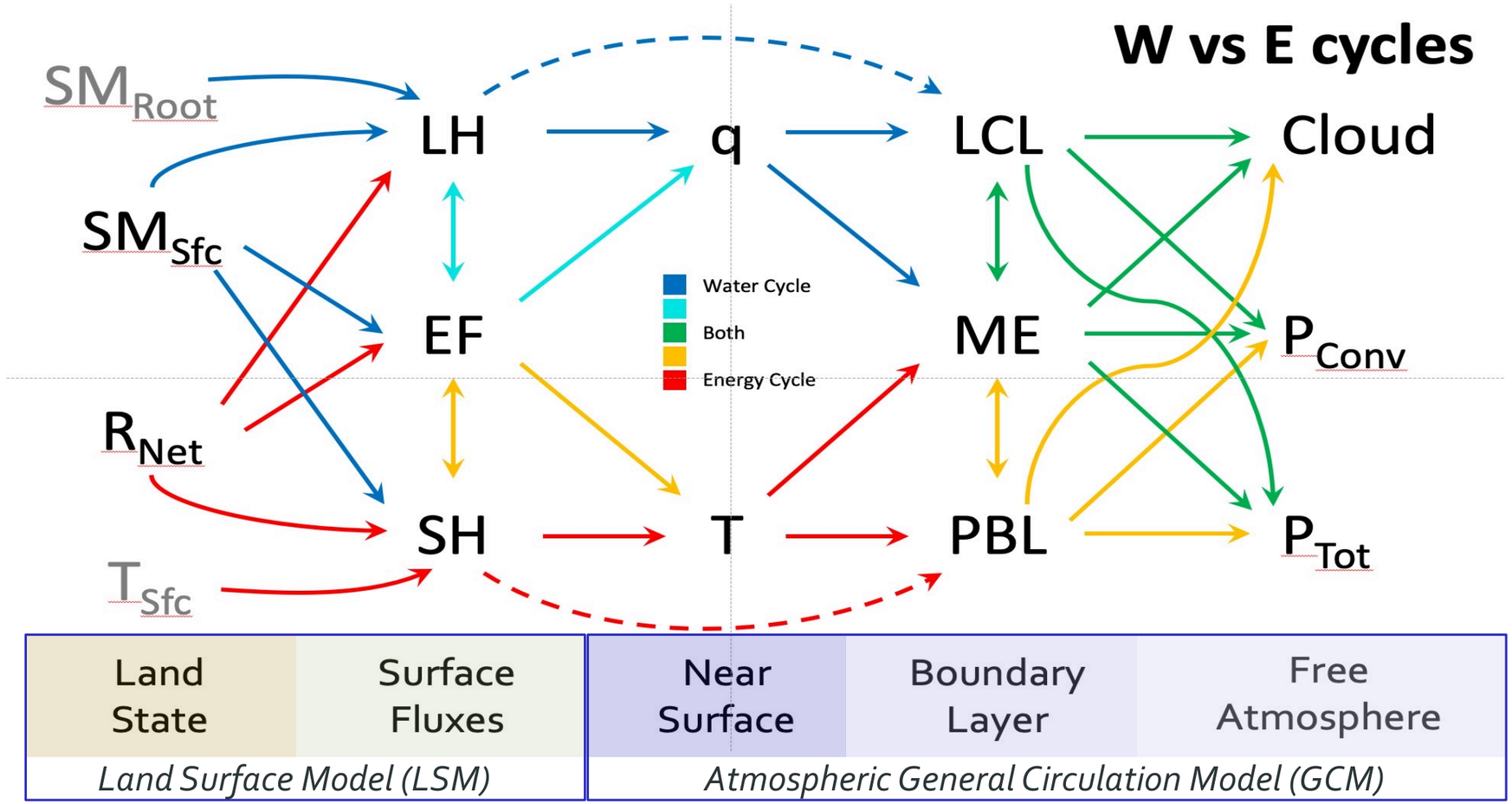
An Analogy for Subseasonal Forecasting

- Subseasonal to seasonal climate anomalies are often driven by persistent large-scale circulation features that have remote sources, communicated to affected regions by Rossby-wave propagation.
- Thus, predictable phenomena are delivered by the atmosphere in much the same way that a freight company delivers packages, or the Internet delivers data.

New Analogy for Subseasonal Forecasting

- Just like telecommunications or shipping, the biggest problems are in the "last mile"; once the delivery is *in the neighborhood*, 30% of the cost and most of the failures occur in that final step to the customer's door.
- In a forecast model, if the land surface is poorly initialized, or **coupled L-A processes** are not well represented, the delivery is broken, or lost, or garbled.

Land-Atmosphere Feedbacks Act through Process Chains



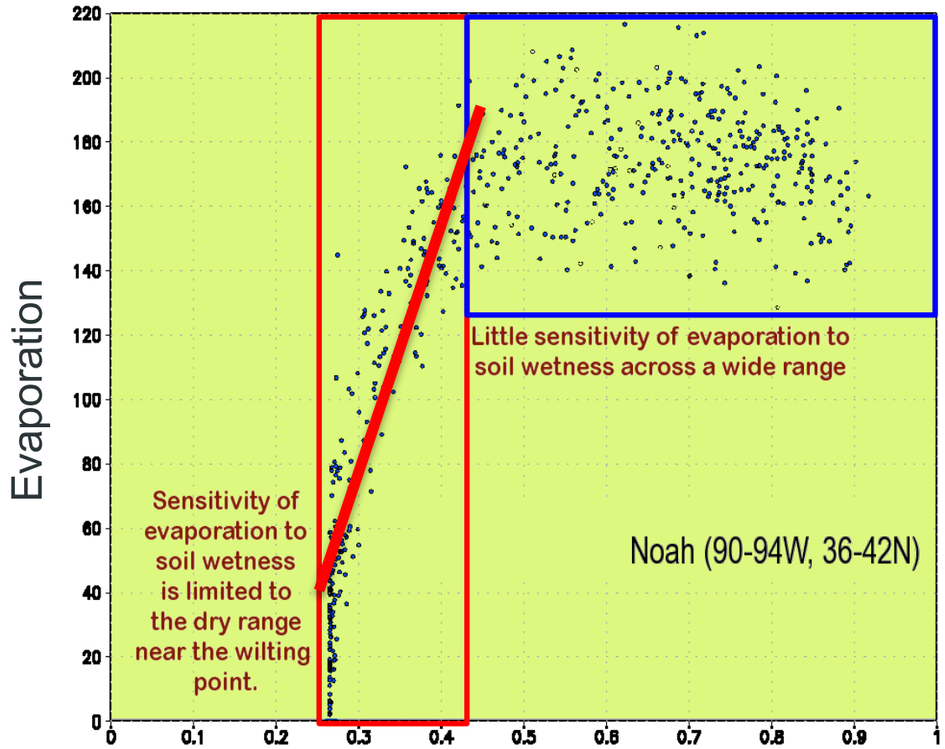
This is the Local Coupled (LoCo) view – a simplification that neglects the role of atmospheric circulation.

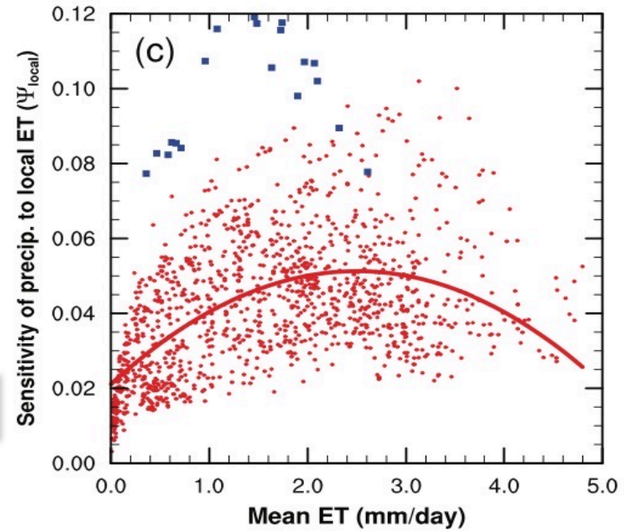
- Pathways involve the water cycle, the energy cycle, or both (linked via evaporation).
- Arrows make it seem *sequential*, and computer models necessarily represent processes in a sequence of subroutine calls, but in reality, everything is happening at the same time! This makes it challenging to untangle.

Sensitivity of A to L

Slope and **correlation** are measures of sensitivity

- Over many parts of the world, there is a range of SM over which evaporation rates in(de)crease as soil moisture in(de)creases (soil moisture is a limiting factor – moisture controlled).
- Above some amount of moisture in the soil, evaporation levels off.
- In that wet range, moisture is plentiful, and is no longer controlling the partitioning of fluxes (it's energy controlled).



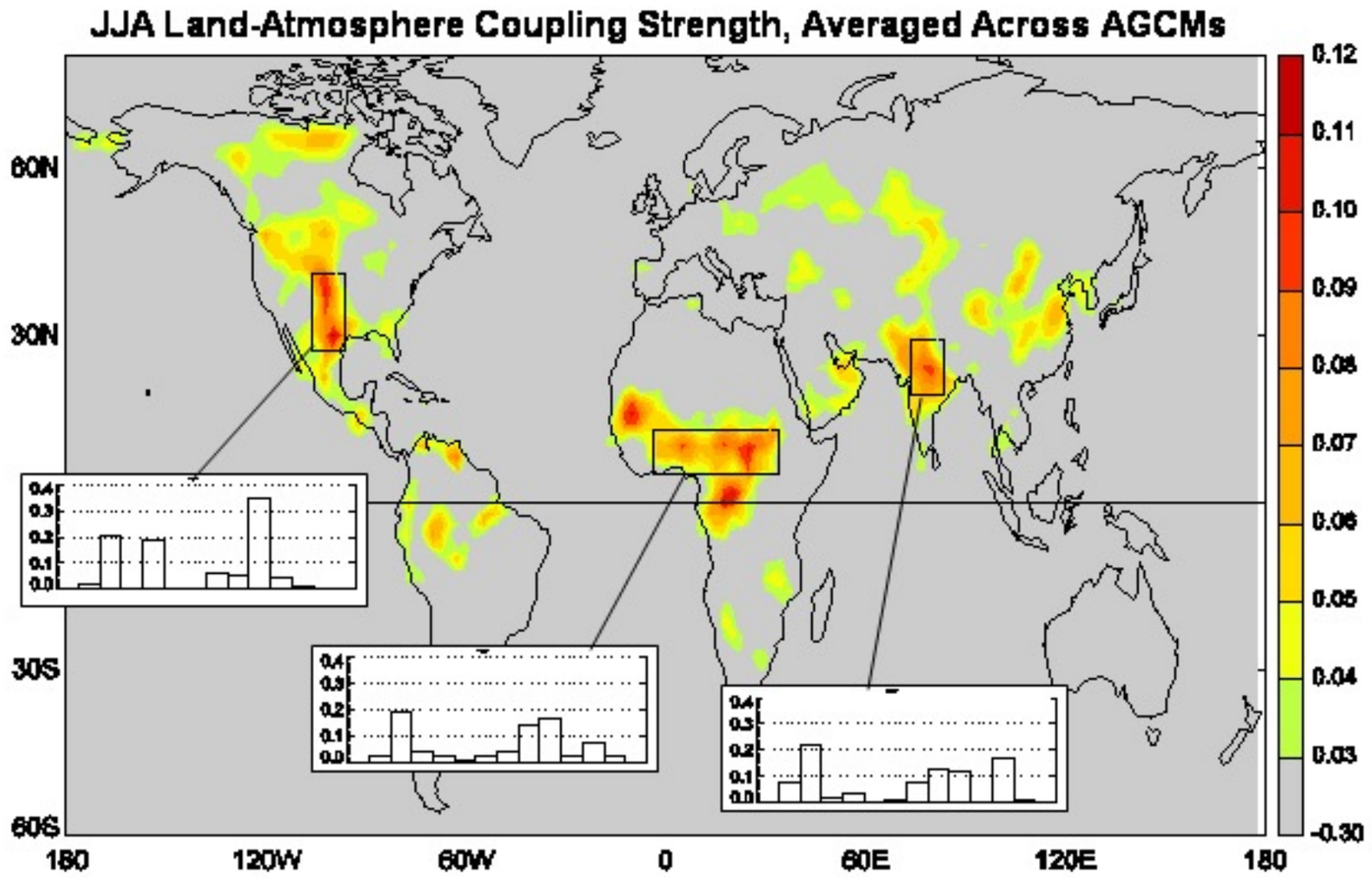


Wei & Dirmeyer 2019: *Geophys. Res. Lett.*

Global Land-Atmosphere Coupling Experiment

A sensitive to L

The GLACE project showed that while the 12 participating models differ in their land-atmosphere coupling strengths, certain features of the coupling patterns emerge from the models. These features, or "hot spots" are brought out by averaging over all of the model results.



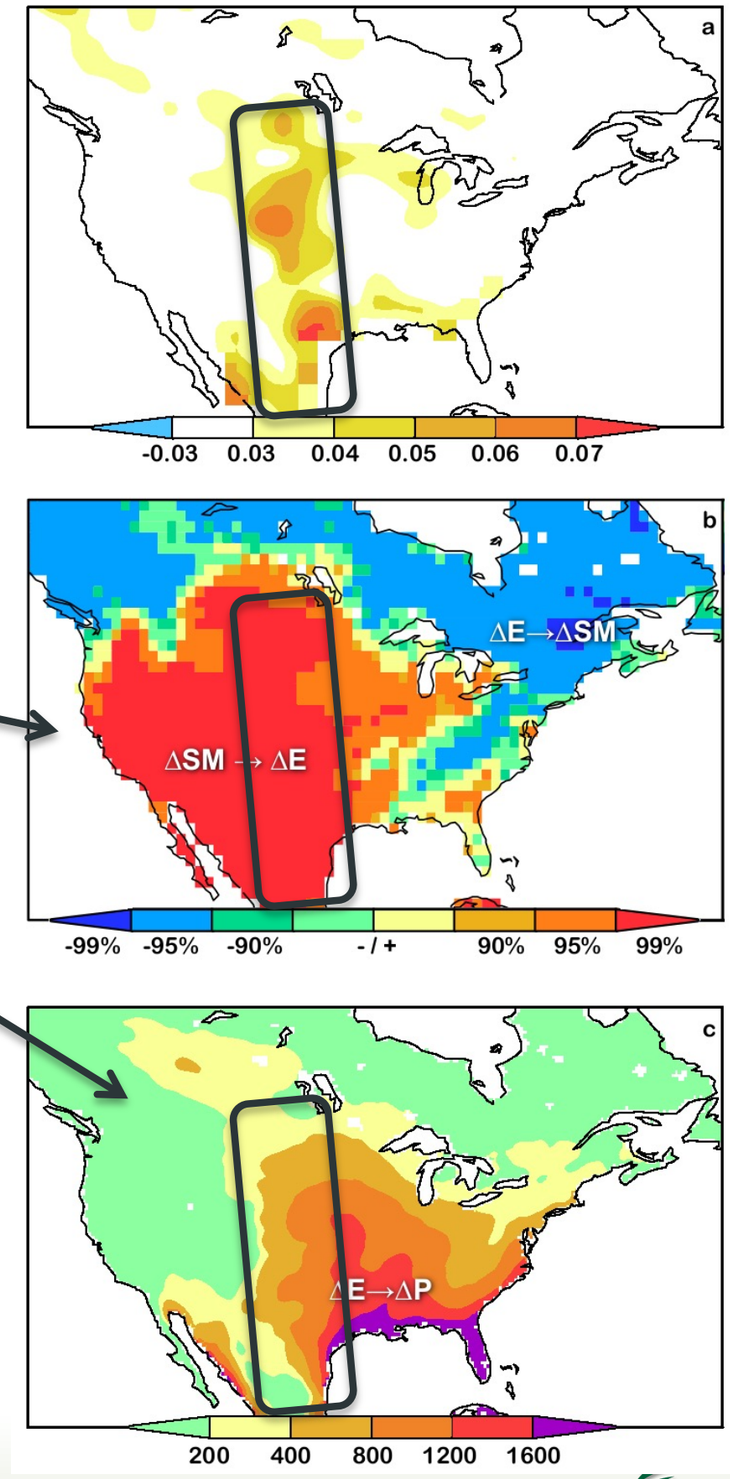
Koster et al., 2004: *Science.,* 1138-

Links in the Process Chain

- GLACE coupling strength for summer rainfall [S vs W case; *top*] corresponds to regions where there are both factors:
- High correlation between daily soil moisture and evapotranspiration during summer [from the GSWP multi-model analysis, units are significance thresholds; *middle*], and
- High CAPE [from the North American Regional Reanalysis, J/kg; *bottom*]

$$\Delta P \Rightarrow \underbrace{\Delta SM \rightarrow \Delta E}_{\text{Terrestrial leg}} \rightarrow \underbrace{\Delta P}_{\text{Atmospheric leg}}$$

Feedback path: Terrestrial leg Atmospheric leg



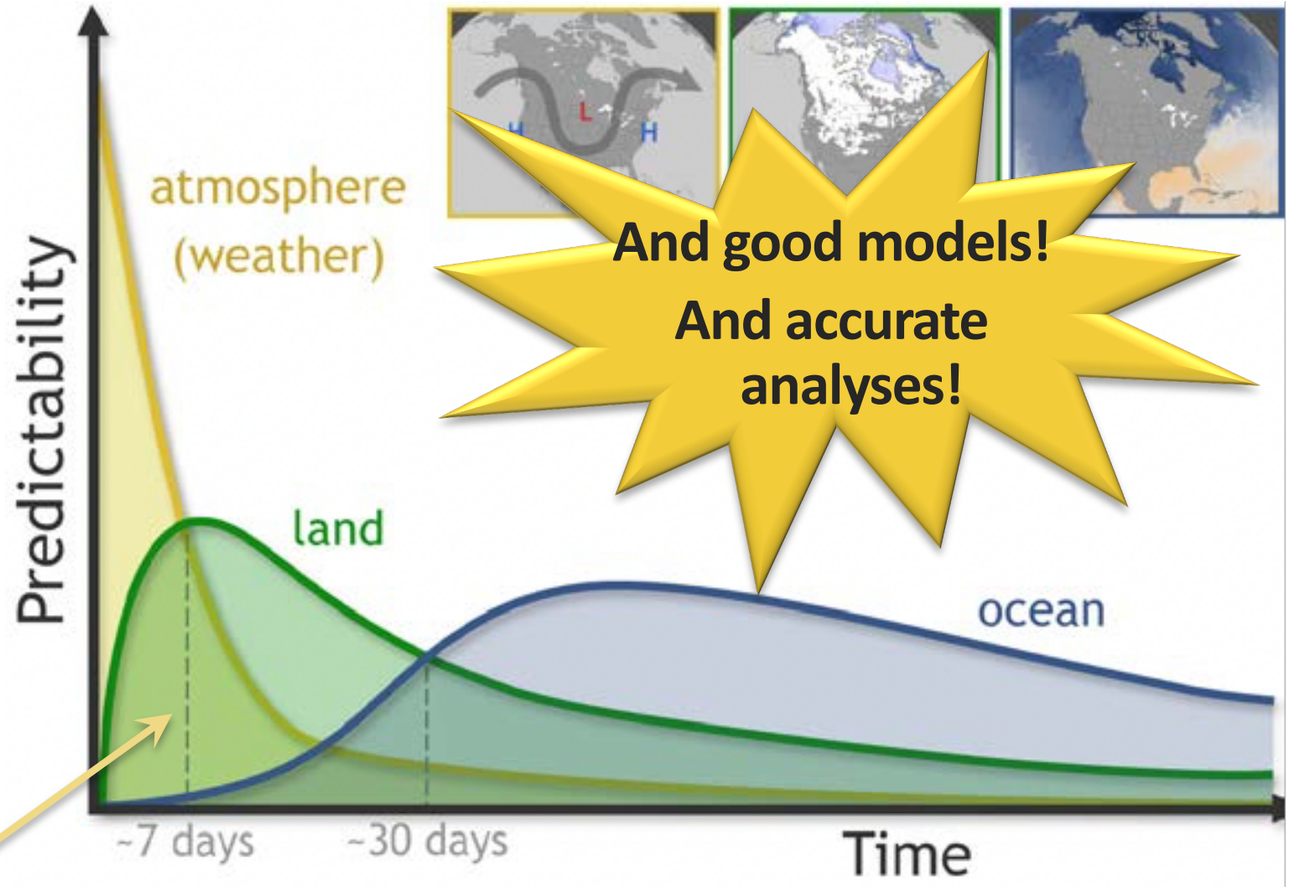
Land-Atmosphere Feedbacks: 3 Ingredients

- Sensitivity
  - When and where is there an active coupling from land to atmosphere?
- Variability
  - A coupling results in a significant impact only when the land surface anomalies are large enough.
- Memory
  - If the coupling and anomalies are not persistant, the effect on the atmosphere will be short-lived, impact minimal.

Subseasonal Predictability and Prediction

- Land states (namely soil moisture*) can provide predictability in the window between deterministic (weather) and climate (O-A) time scales.
- The 2-4 week "subseasonal" range is a hot topic in operational forecast centers now.
- Active where we have sensitivity, variability and memory.

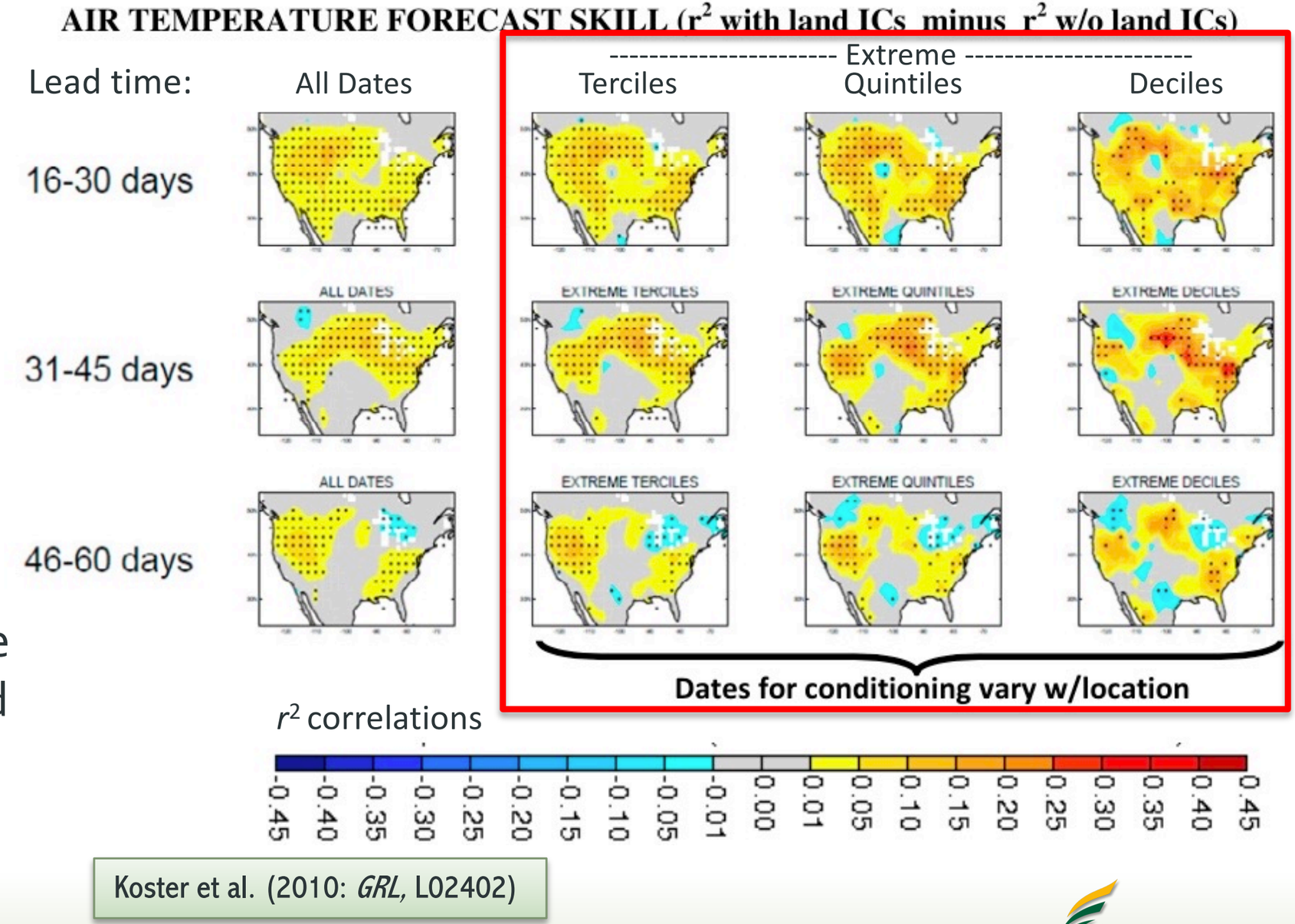
Representative of a mid-latitude mid-continental location



*Snow and vegetation too!

GLACE-2 Multi-Model Analysis

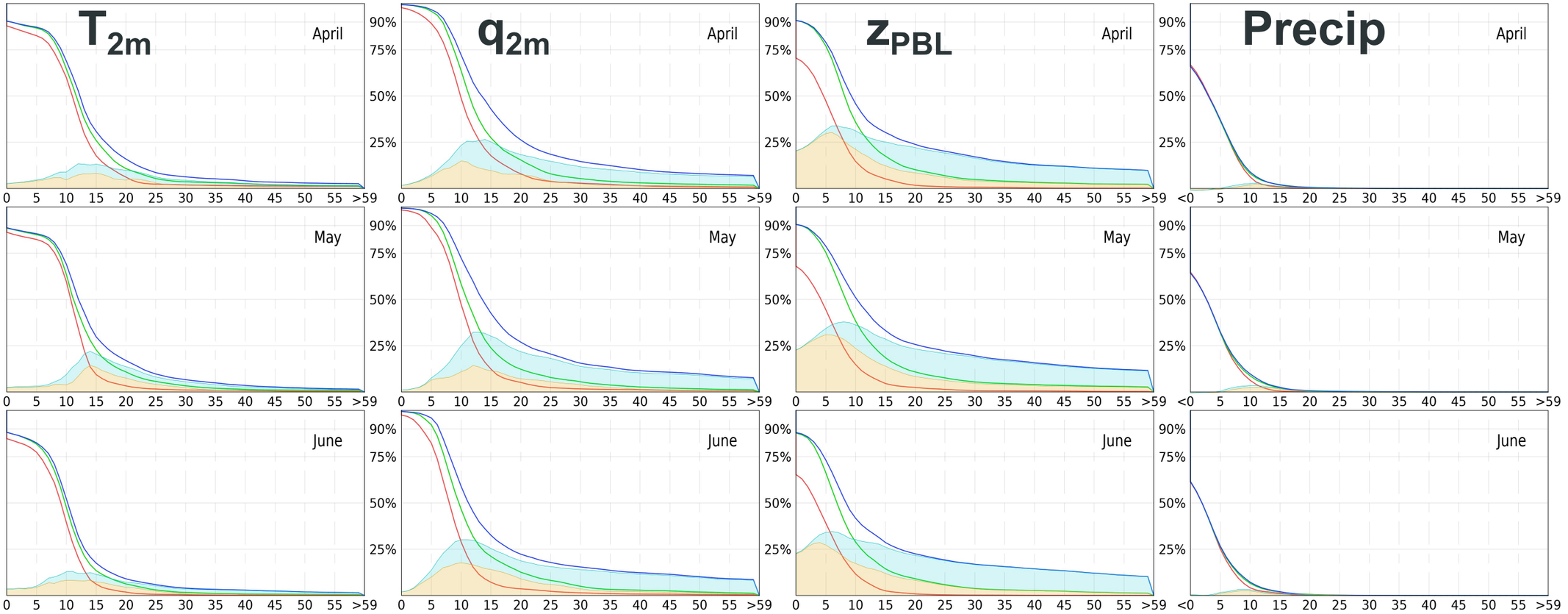
- Realistic soil moisture initialization improves forecasts.
- Extremes really contribute to prediction skill!
- Skill impact is longer where there is "memory" – land anomalies persist.



Koster et al. (2010: *GRL*, L02402)

Land impact on prediction skill

The fraction of land area in CFS exhibiting significant skill as a function of forecast lead time with specified land states (blue), right land ICs (green) and wrong land ICs (red). Shaded curves show the difference between green and red curves (tan) and between blue and green curves (pale blue).



Dirmeyer et al. 2018: (*JGR; 10.1029/2018JD029103*)

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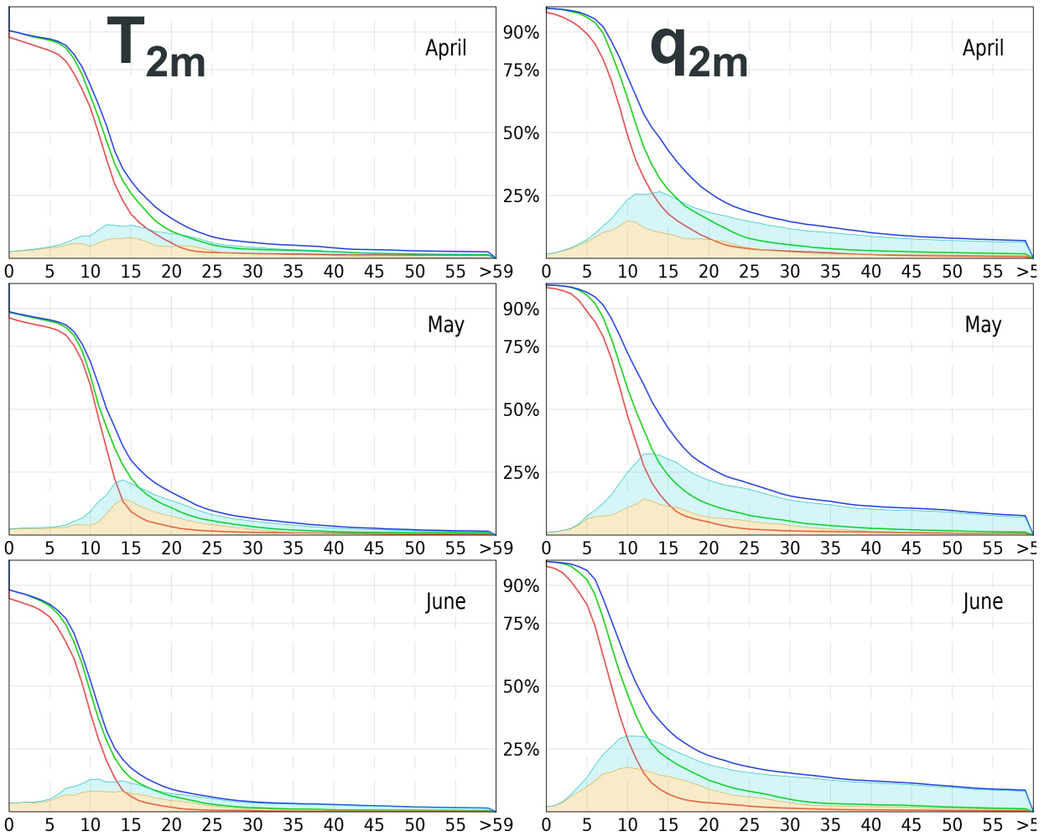

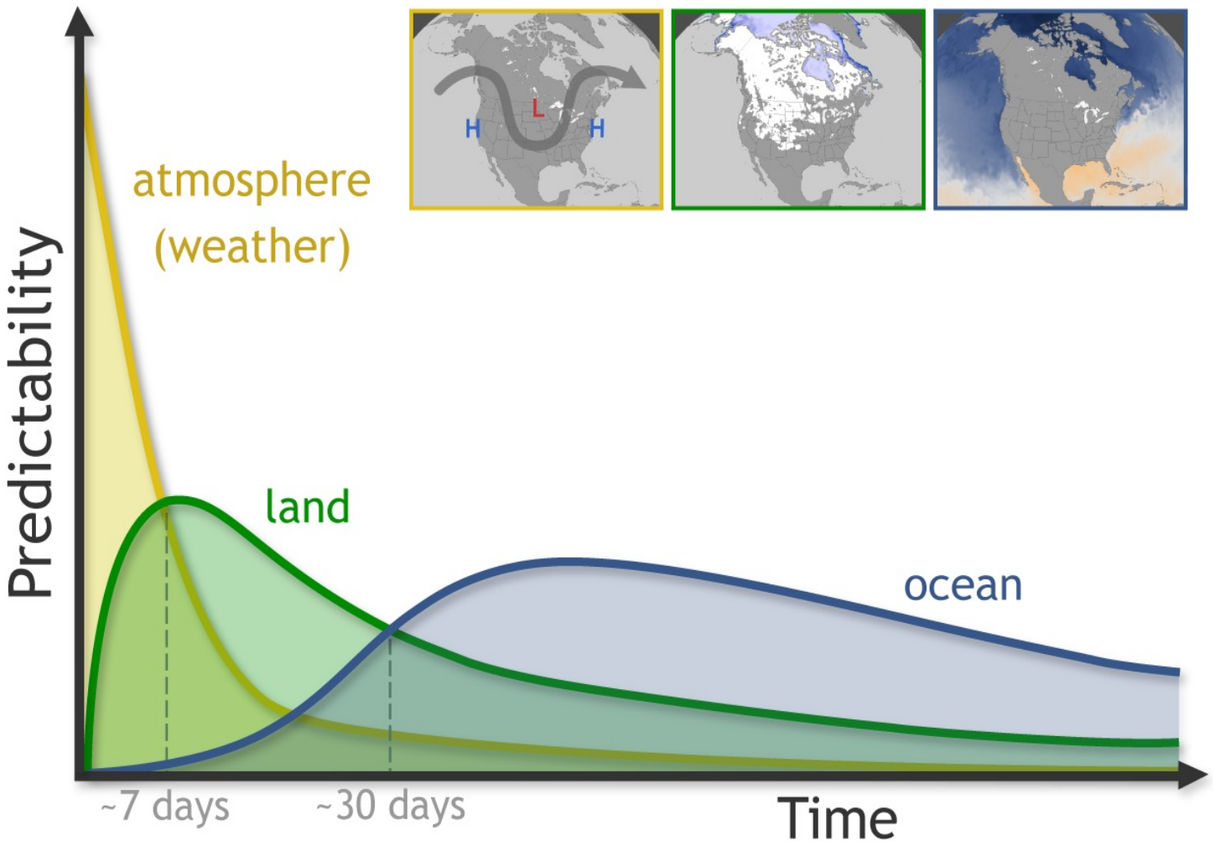

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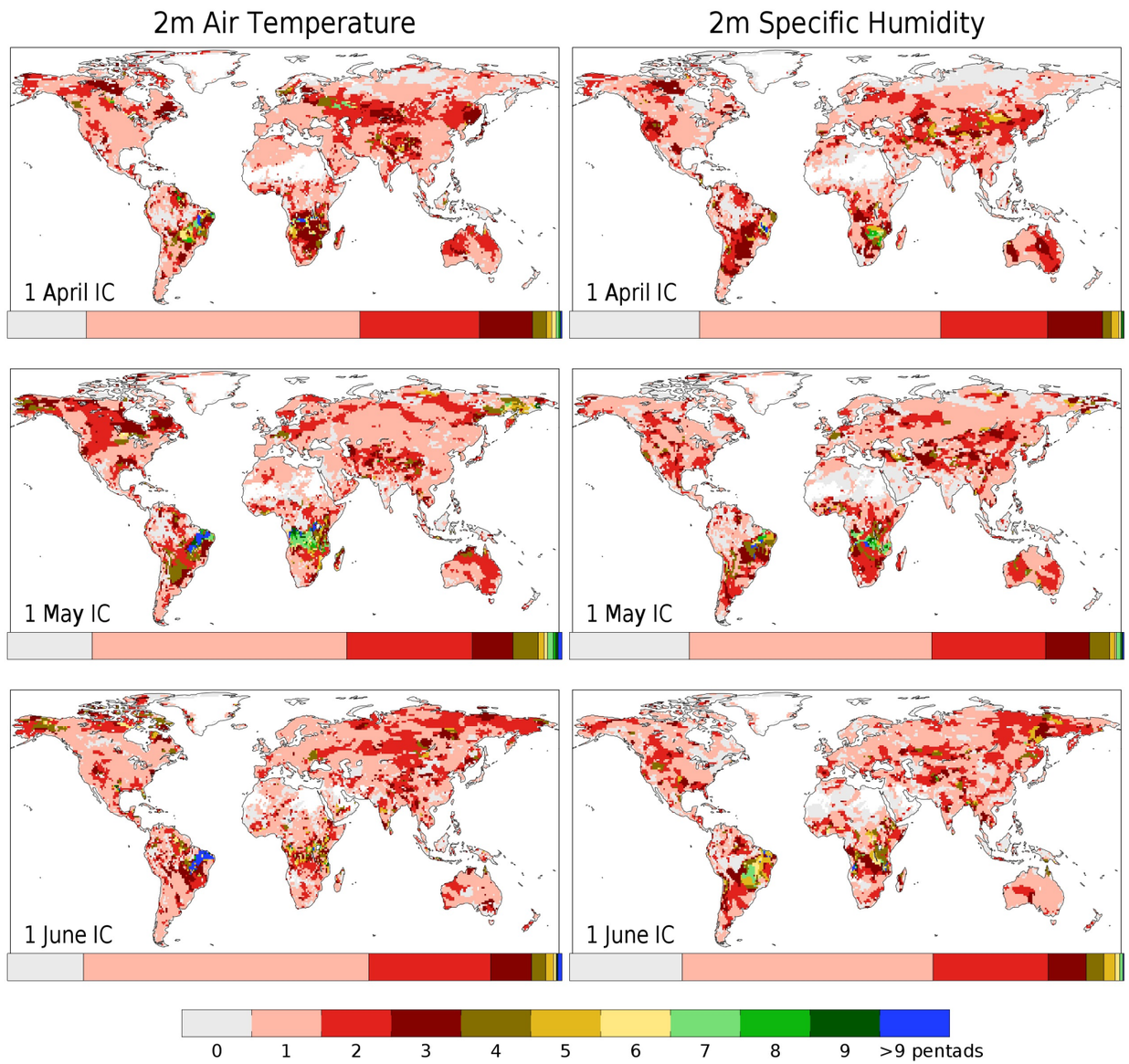
Land impact on prediction skill

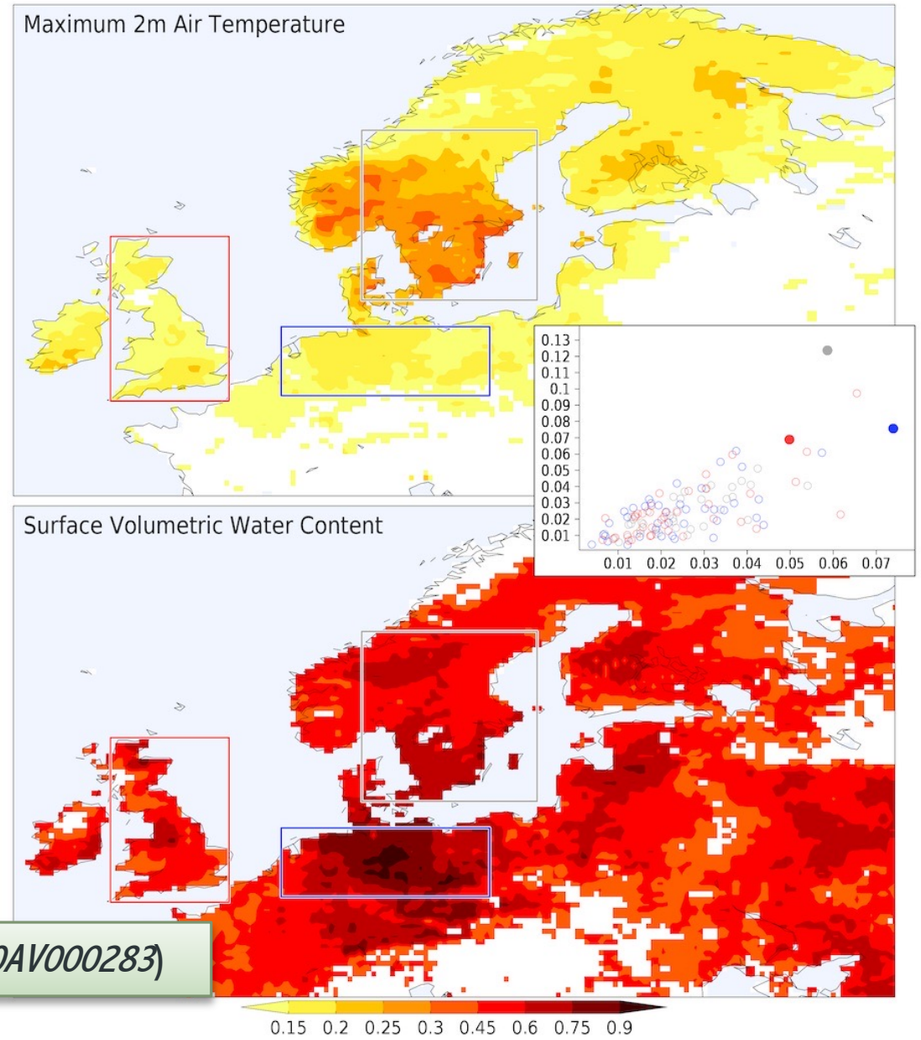
- 28 years of seasonal CFSv2 forecasts: 1 April, 1 May & 1 June ICs
- 28-member ensembles, same atmosphere and ocean ICs; land has 27 members with ICs from other years, 1 with "right" year's ICs.
- How many pentads is significant pentad-average forecast skill (ACC) extended by using "right" land ICs?
- ~40% of globe has skill extended by 2 pentads or more, ~80% at least 1 pentad.
- **Neglecting land surface initialization seriously degrades forecast skill.**

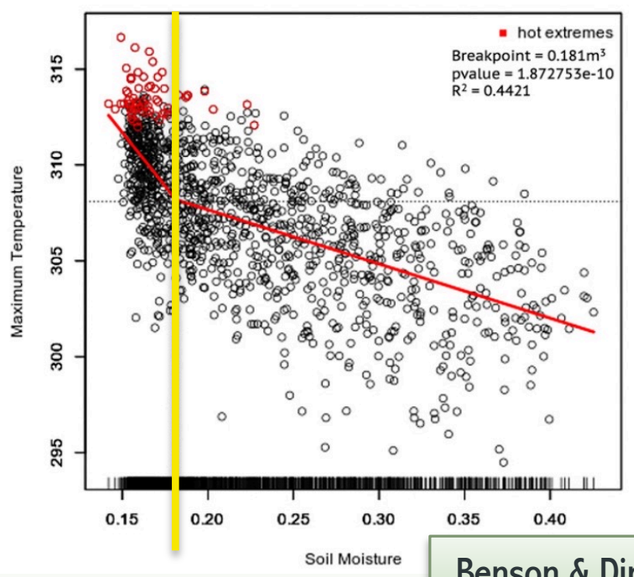


Dirmeyer & Halder 2017: (JHM; *10.1175/JHM-D-16-0064.1*)

2018 European Heat Wave

- Fraction of days in MJJA among 5% of warmest max T_{2m} (top); 25% driest surface soil moisture (bottom); compared to 1979-2018 in ERA5.
- Inset shows areal average of the fractions for soil moisture (x-axis) and max T_{2m} (y-axis) over land in the indicated rectangles for each of the 40 years; 2018 is indicated by filled circles.





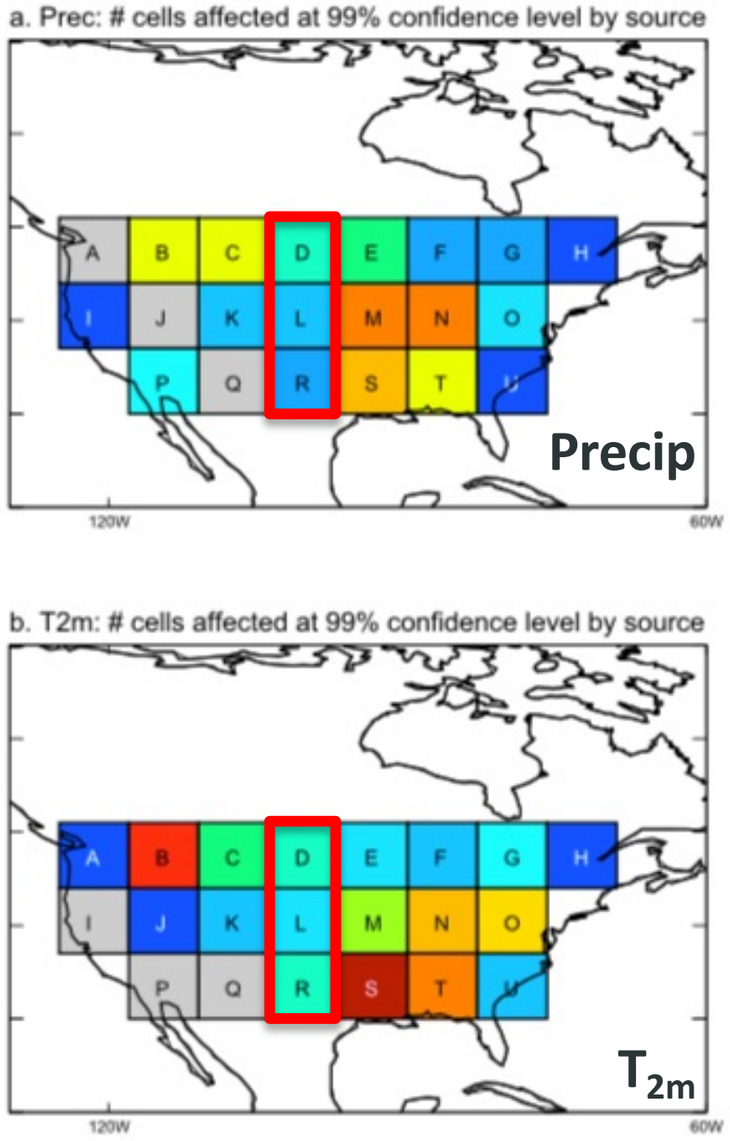
Dirmeyer et al., (2021; *AGU Advances; 10.1029/2020AV000283*)

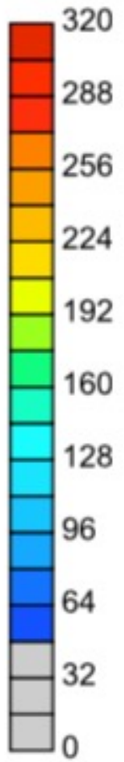
- Left: Below a local threshold soil moisture, extreme temperatures become hypersensitive to drying soil, driven by increased sensible heat flux, shutdown of evaporation…

Benson & Dirmeyer (2021; *J. Clim.; 10.1175/JCLI-D-20-0440.1*)

What is the non-local effect of land on forecasts?

Getting more from L-A



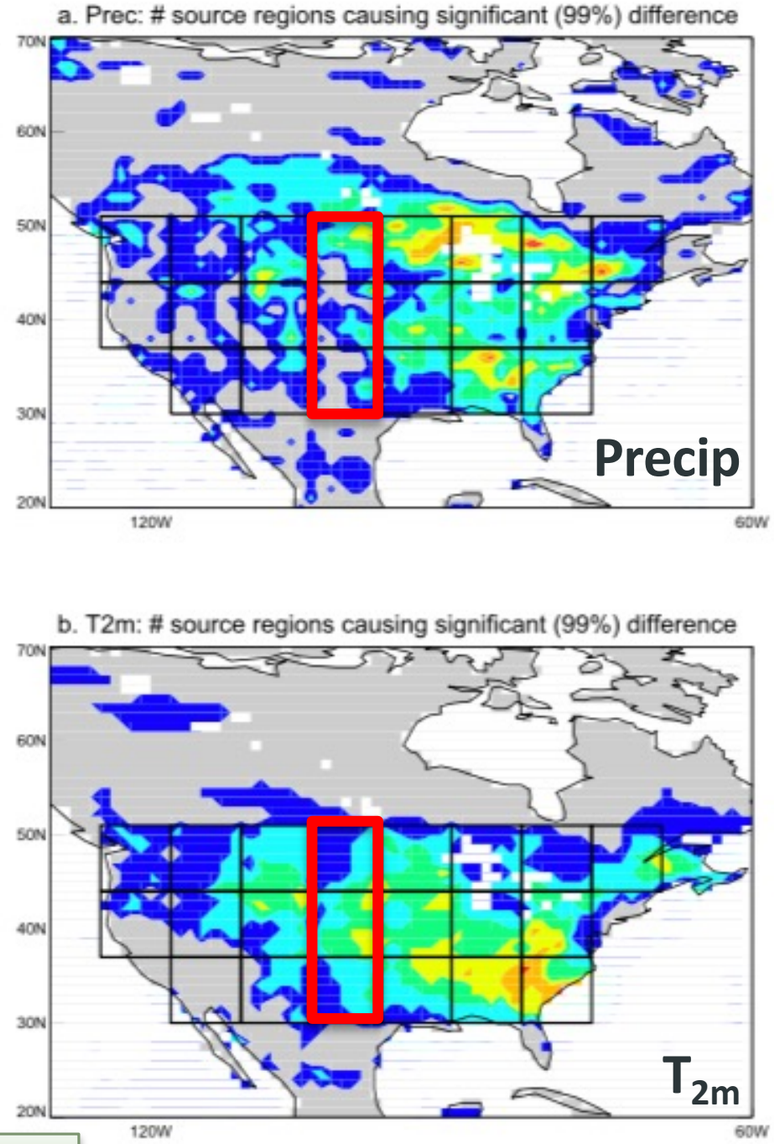


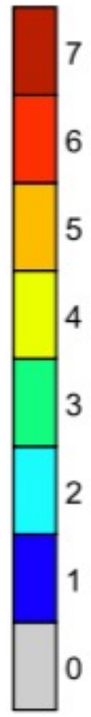
Non-local sensitivity of AMJ precip on JJ climate in GEOS5.

← SM anomalies in these areas affect NA precip, T_{2m}.

Areas most affected by SM anomalies anywhere →

- "Hot spots" not evident as source of IC predictability!

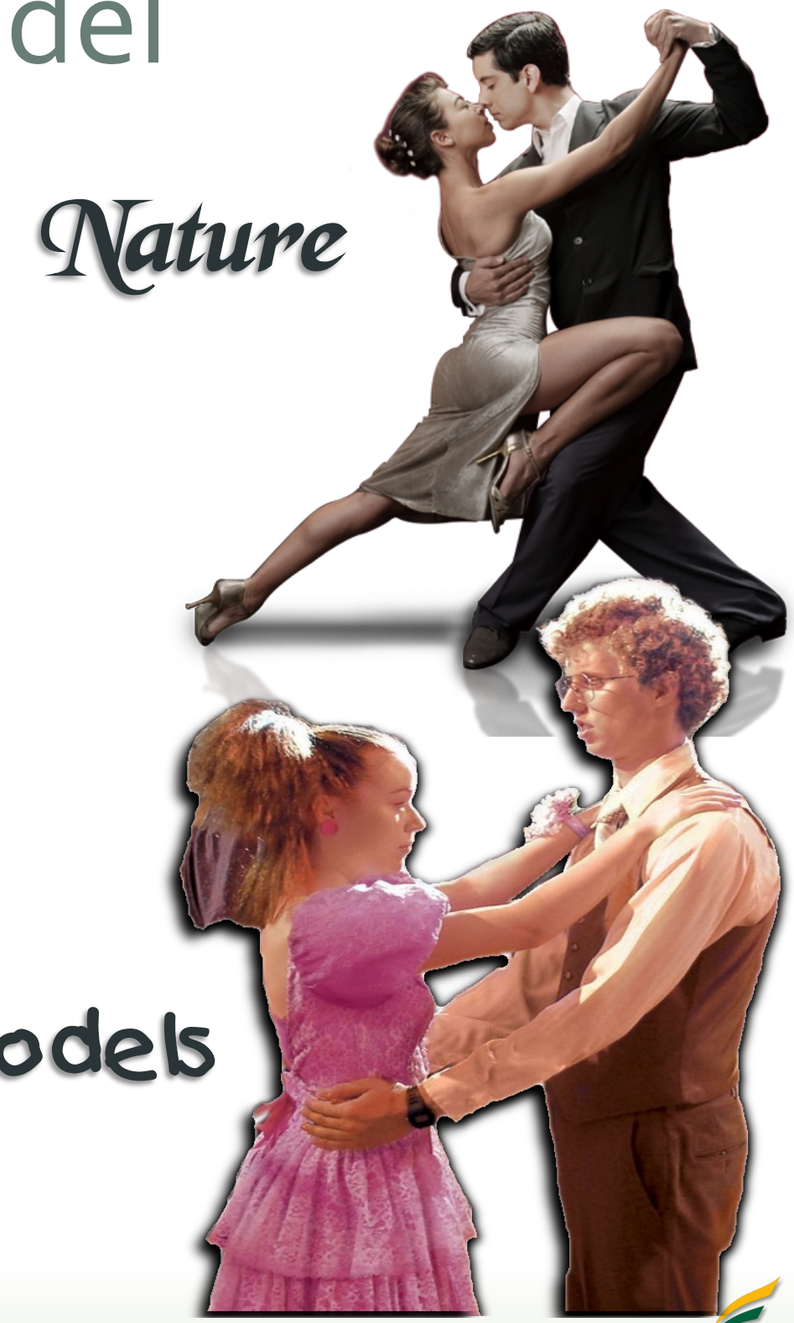




Koster et al., (2016; *J.Clim;* 10.1175/JCLI-D-16-0192.1)

Pursuing Coupled L-A Model Development

- Land models and atmosphere models have been developed separately (in isolation), then plugged together without much coupled validation. Not good for simulating L-A interactions.
- Until recently, it was not feasible to pursue model development and validation in a coupled way. With new understanding and data, now we can, and we are!
- We have a chance to model nature much better and improve subseasonal predictions – it's a coupled system.



UFS Development

- We are applying L-A coupling metrics in UFS R2O effort…
- P7 (includes NoahMP LSM) vs P6 (Noah LSM)
- Validation of coupling indices across flux tower sites:

P7 vs P6	FLUXNET (Global) - 177 stations				Ameriflux (CONUS) - 158 stations			
JJA	SM→Fluxes	Fluxes→T_{2m}	T_{2m}→MSE	MSE→Precip	SM→Fluxes	Fluxes→T_{2m}	T_{2m}→MSE	MSE→Precip
Correlation across sites	0.44 +0.20	0.43 +0.11	0.93 +0.02	0.50 +0.06	0.60 +0.51	0.57 +0.21	0.95 +0.01	0.46 -0.02
ΔRMSE	-20%	-18%	-8%	-14%	-38%	-28%	-11%	-8%
Δ|Bias|	-29%	-73%	+61%	-38%	-45%	-83%	-79%	-32%

- Statistics are even better when confined only to sites whose vegetation matches the model grid cell type.

X→Y defined as: $r(X,Y)\sigma(Y)$

Summary

- Predictability of weather/climate from land surface states comes when/where there is a feedback from land to atmosphere via water and/or energy cycles.
- Two legs in the feedback path, and three necessary ingredients for significant feedback.
- Land initialization effects start with the first day (boundary layer growth), peak impact around 1-3 weeks forecast lead depending on the variable, can last months.
- Coupled L-A model quality as well as accurate land state initialization are essential to realize skill improvement.