The emerging role of the land surface in weather and climate prediction

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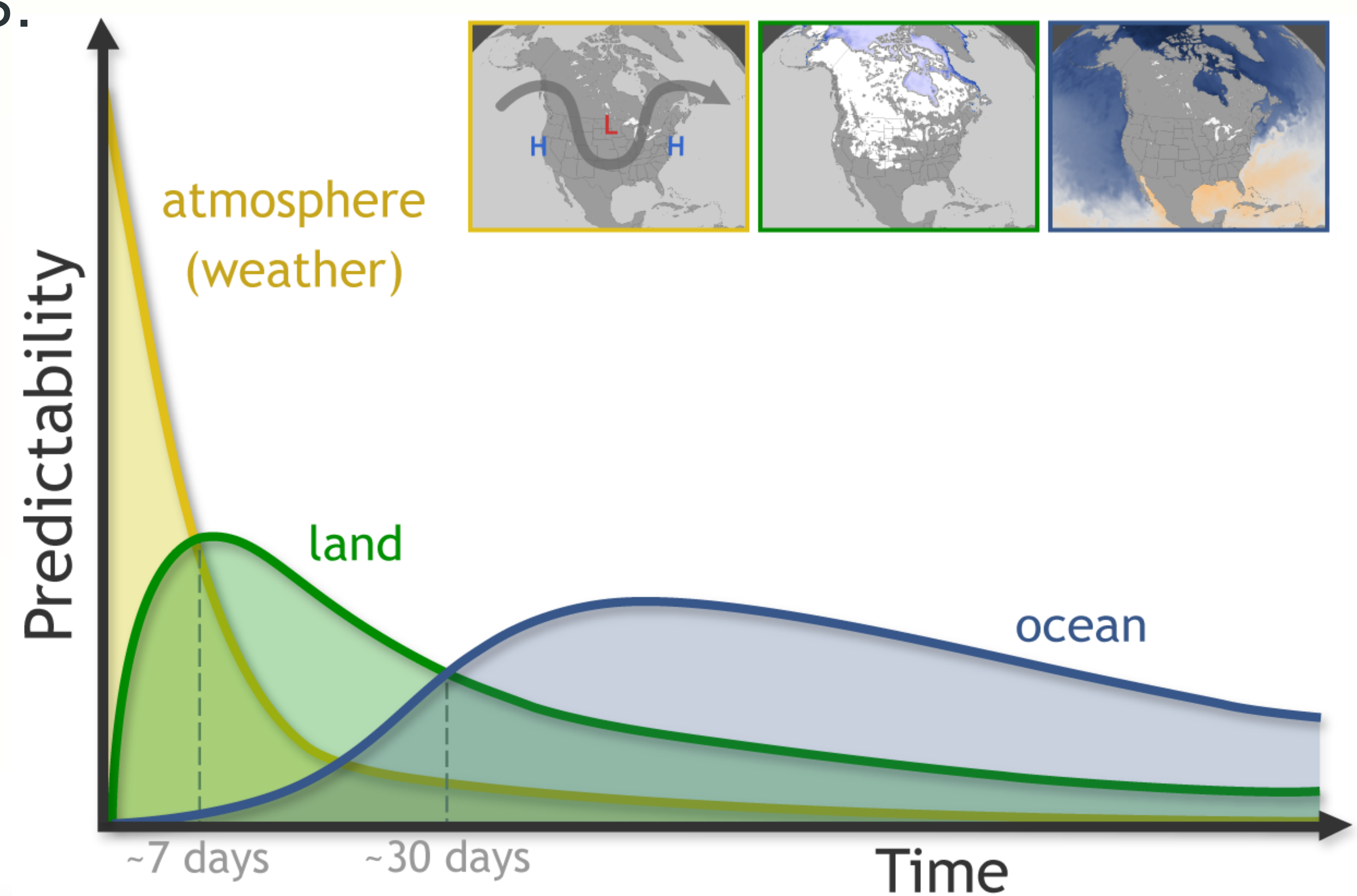
Predictability and Prediction

- Land states (namely soil moisture but also snow) can provide predictability in the window from deterministic (weather) to climate (O-A) time scales, peaking at S2S.



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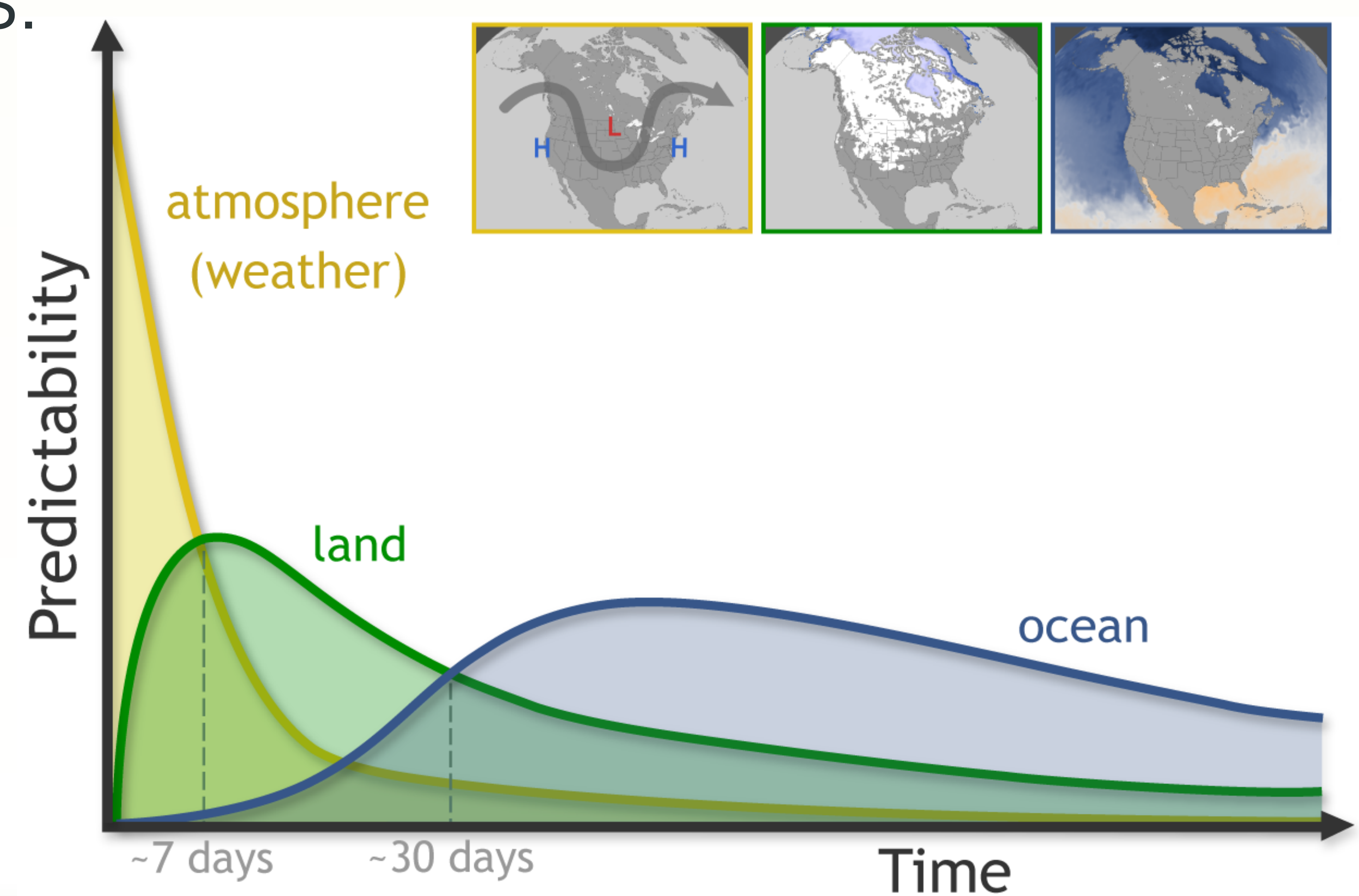

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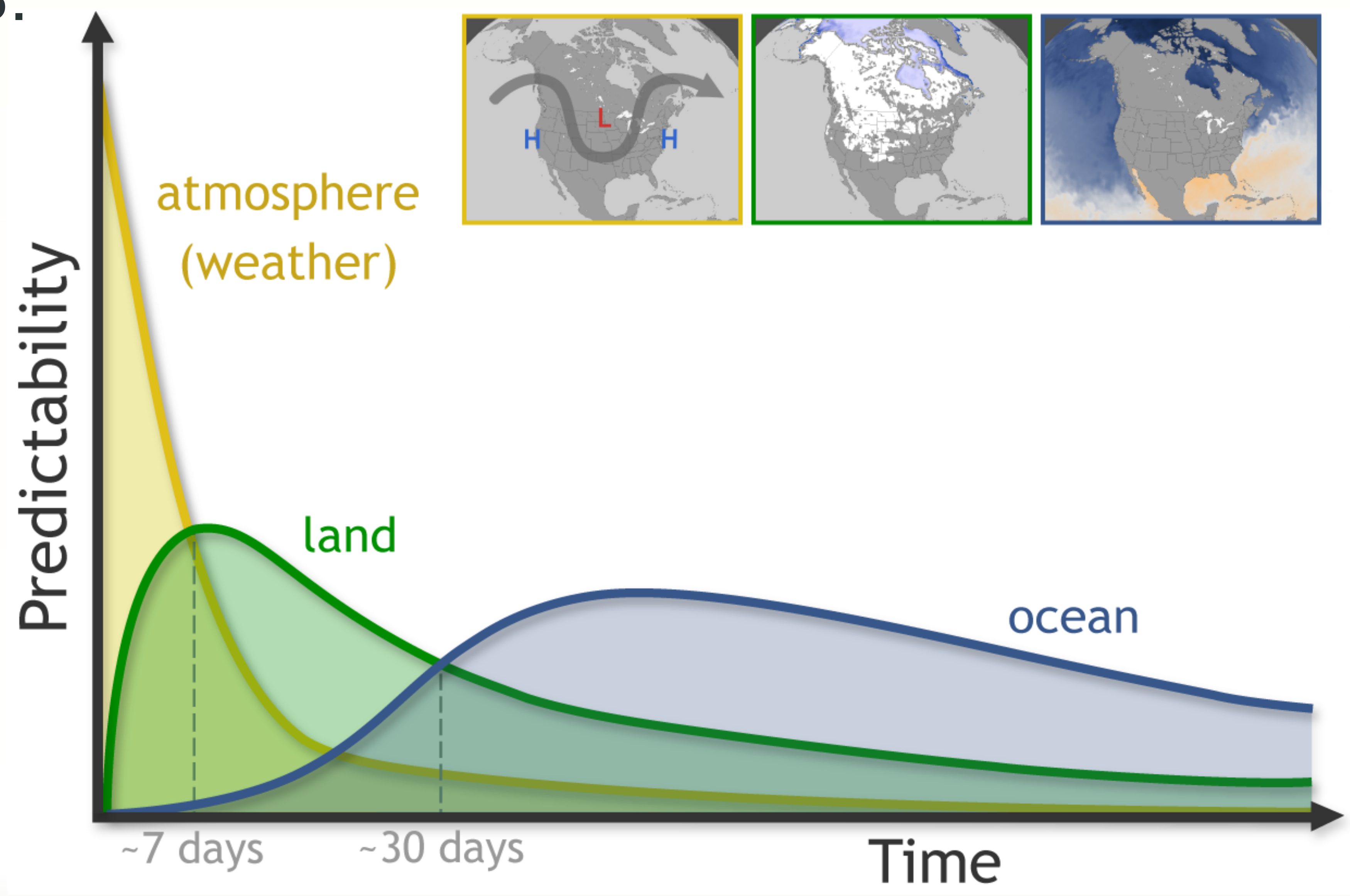

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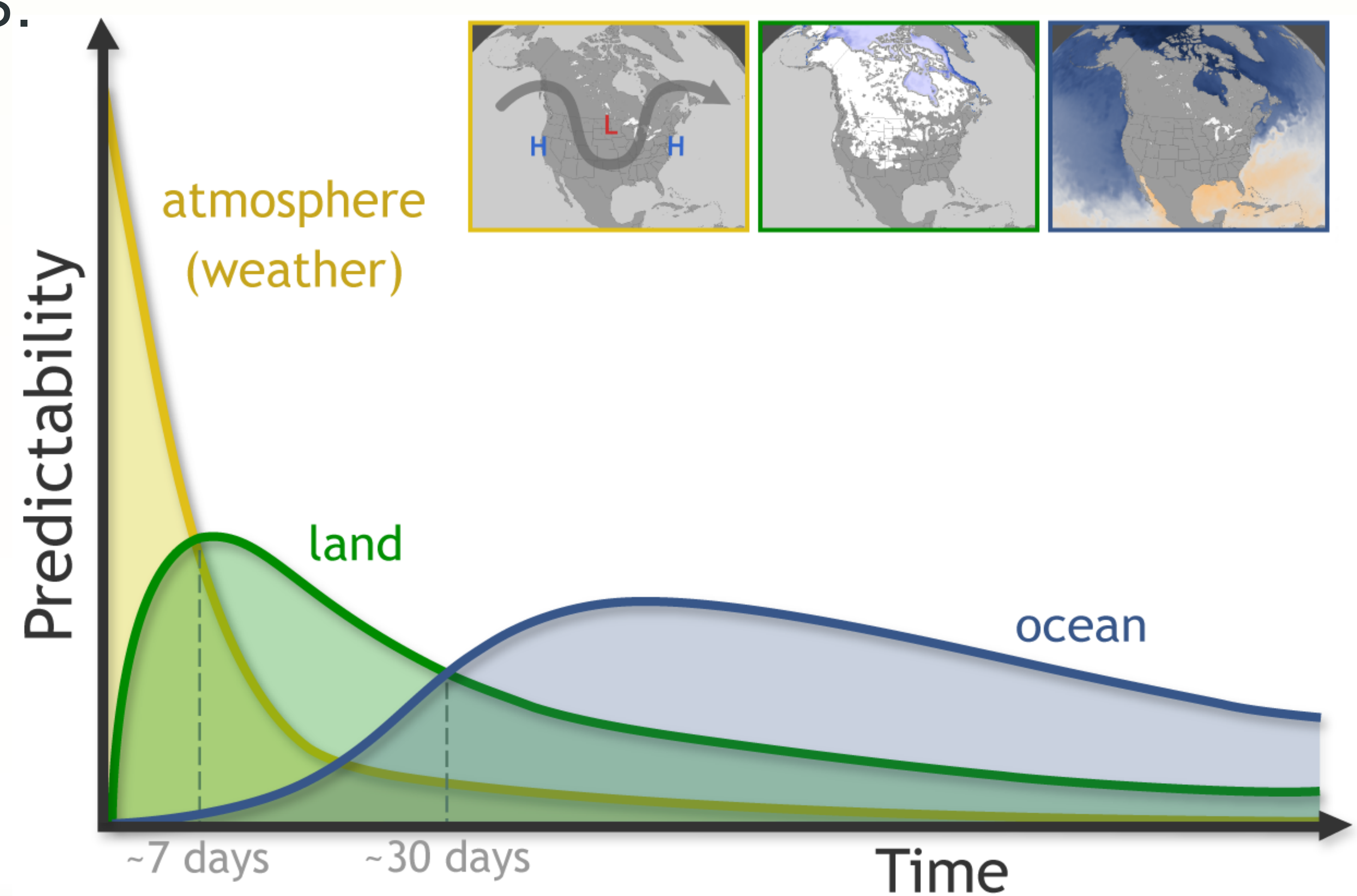
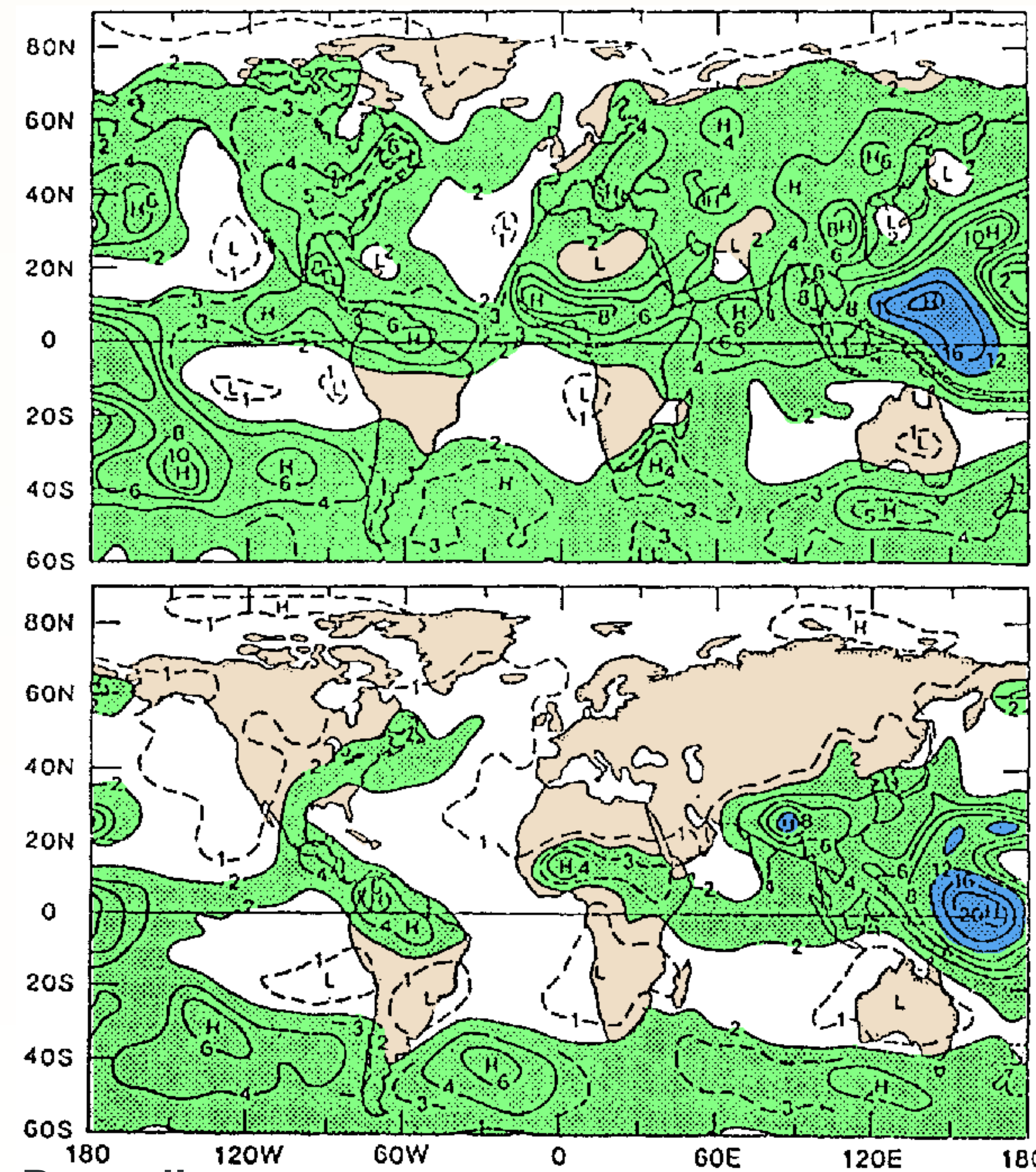
- L-A coupling is active where there is sensitivity, variability and memory.
- Good models and analyses (of atmosphere and land) needed to exploit this source of skill.



Shukla & Mintz 1982

- GCM simulation with uniformly wet soil (top) and dry soil (bottom).
- Most land areas have more rainfall over wet soil than dry.
- India is an exception – strong surface heating and low level convergence enhances monsoon.
- Early indication of the feedback between land evaporation and precipitation.

Wet soils

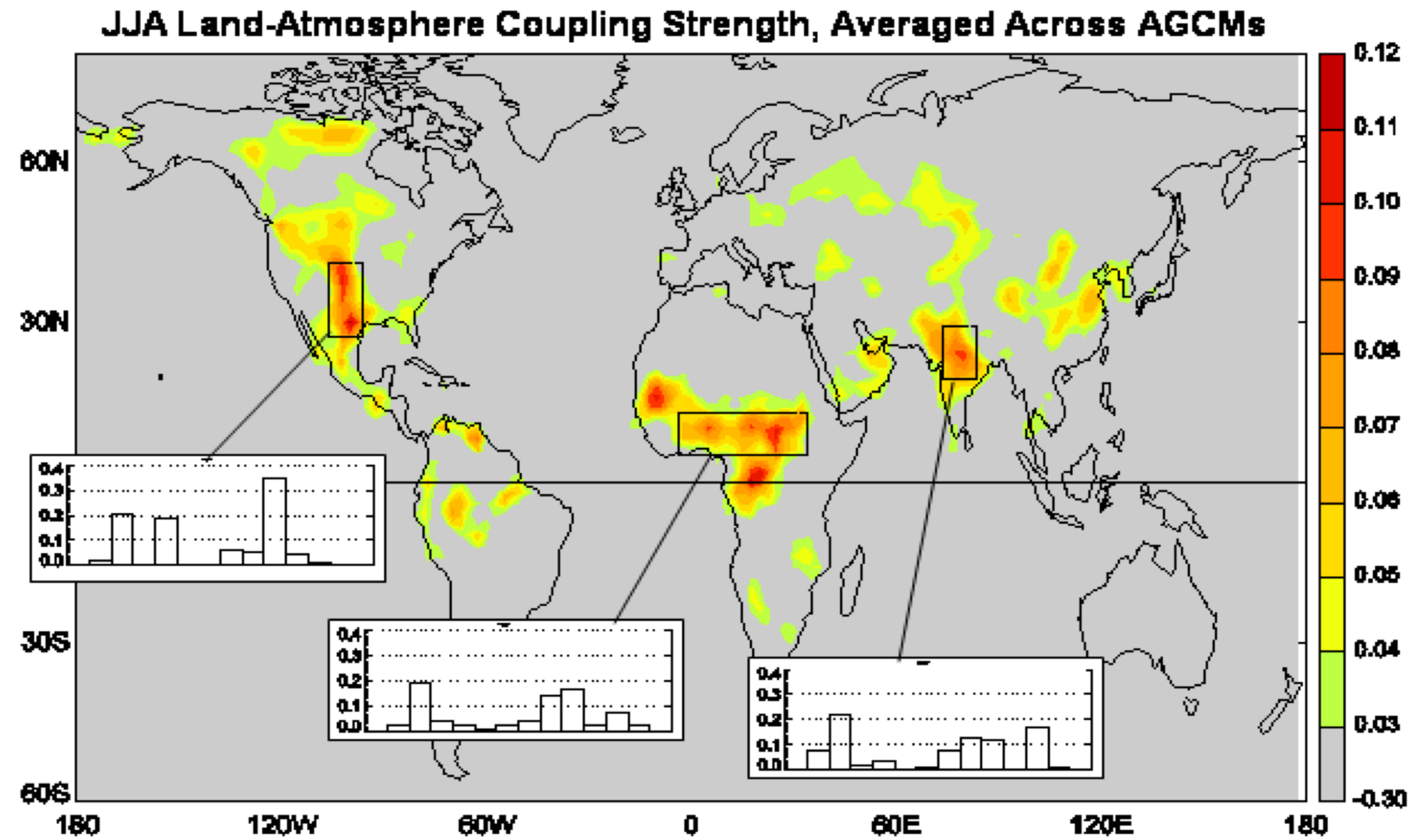


Dry soils

Shukla & Mintz (1982: *Science*)

Global Land-Atmosphere Coupling Experiment (GLACE)

- 12 weather and climate models differed in their land-atmosphere coupling strengths, yet "hot spots" emerged in transitions zones between arid and humid climates.
- These largely correspond to major agricultural areas.
- Thus, places of intense land management are also where atmosphere is very sensitive to land state!



"Famous" figure from *Science* paper which has become widely used to justify the role of the land surface in climate.

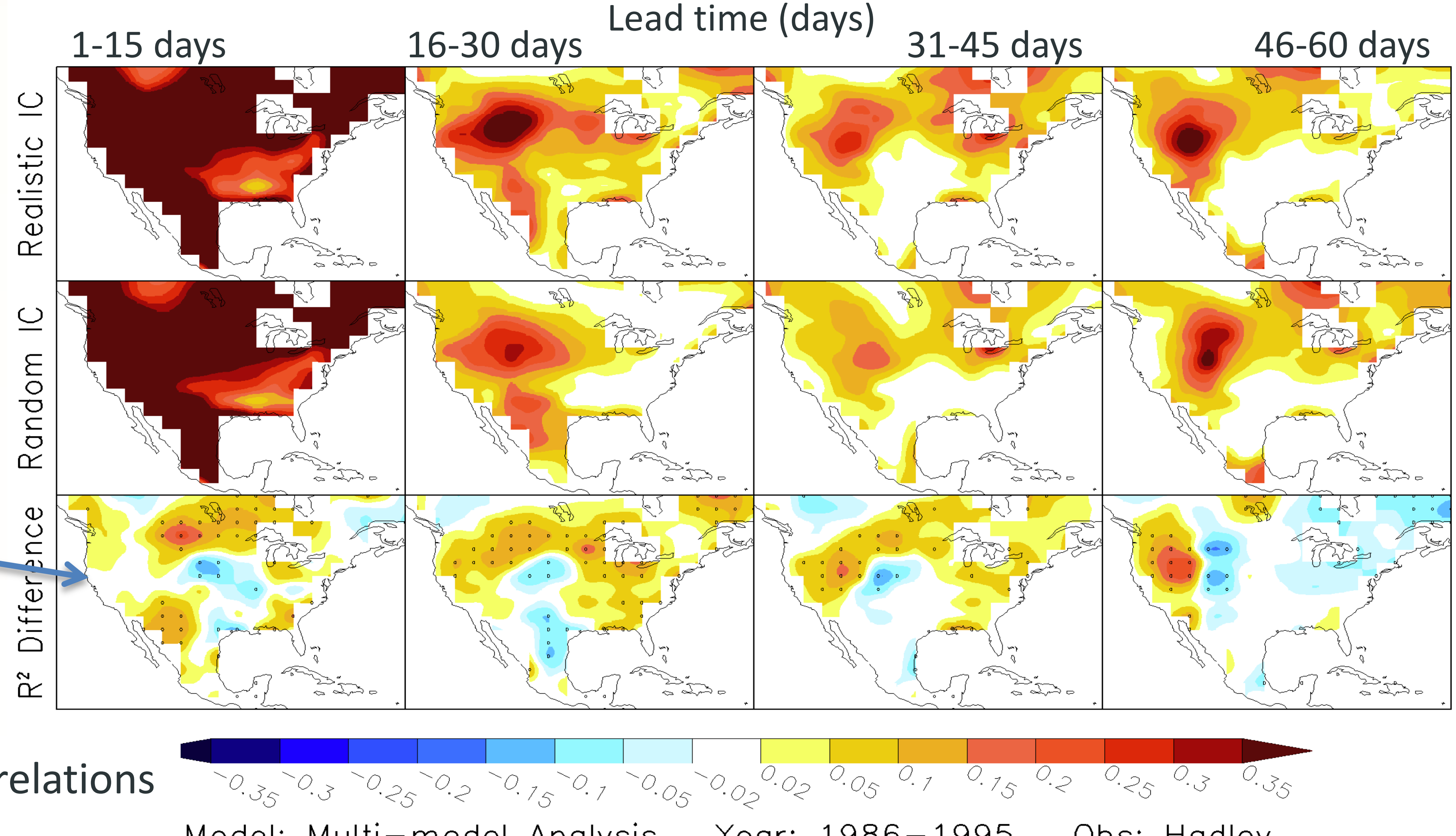
Koster et al. (2004: *Science*)

GLACE-2 Multi-Model Forecast Experiment

- 10 years, 10 start dates, 10-member ensembles
- Realistic soil moisture initialization improves forecasts.
- Improvements largest over North America – data quality effect?

Multi-model Analysis

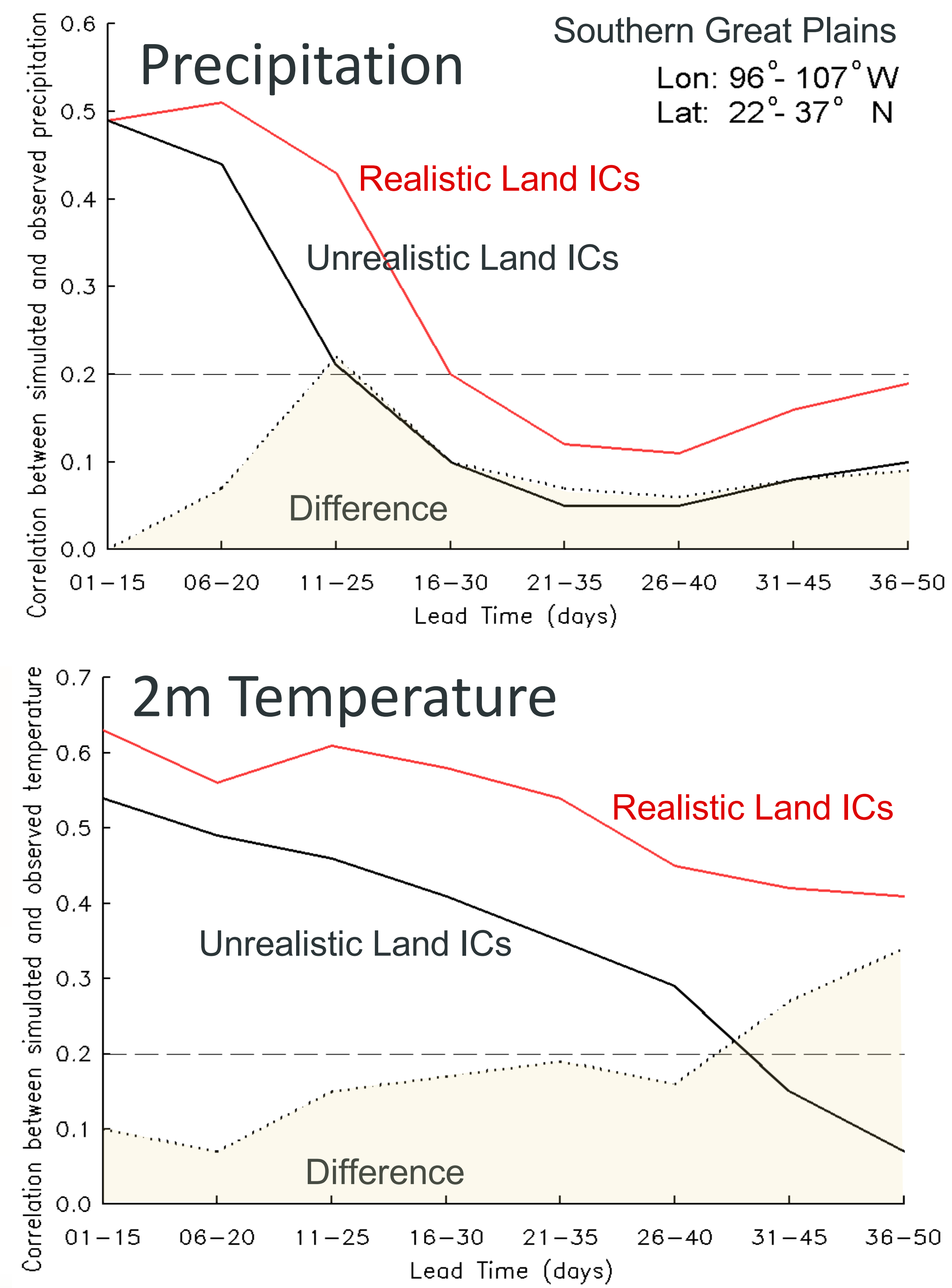
Land Impacts on Air Temperature Forecast Skill



Koster et al. (2010; *GRL*)

GLACE-2 Hindcast Skill

- Weaker impact at short lead times (deterministic forecast range) - atmospheric initial states dominate.
- Peak impact for precipitation around 2-3 weeks lead time.
- Positive impacts for temperature persist throughout forecast period.
- Only 4 of 12 models showed verifiable impacts from land surface initialization! COLA GCM shown here.



Courtesy: Z. Guo

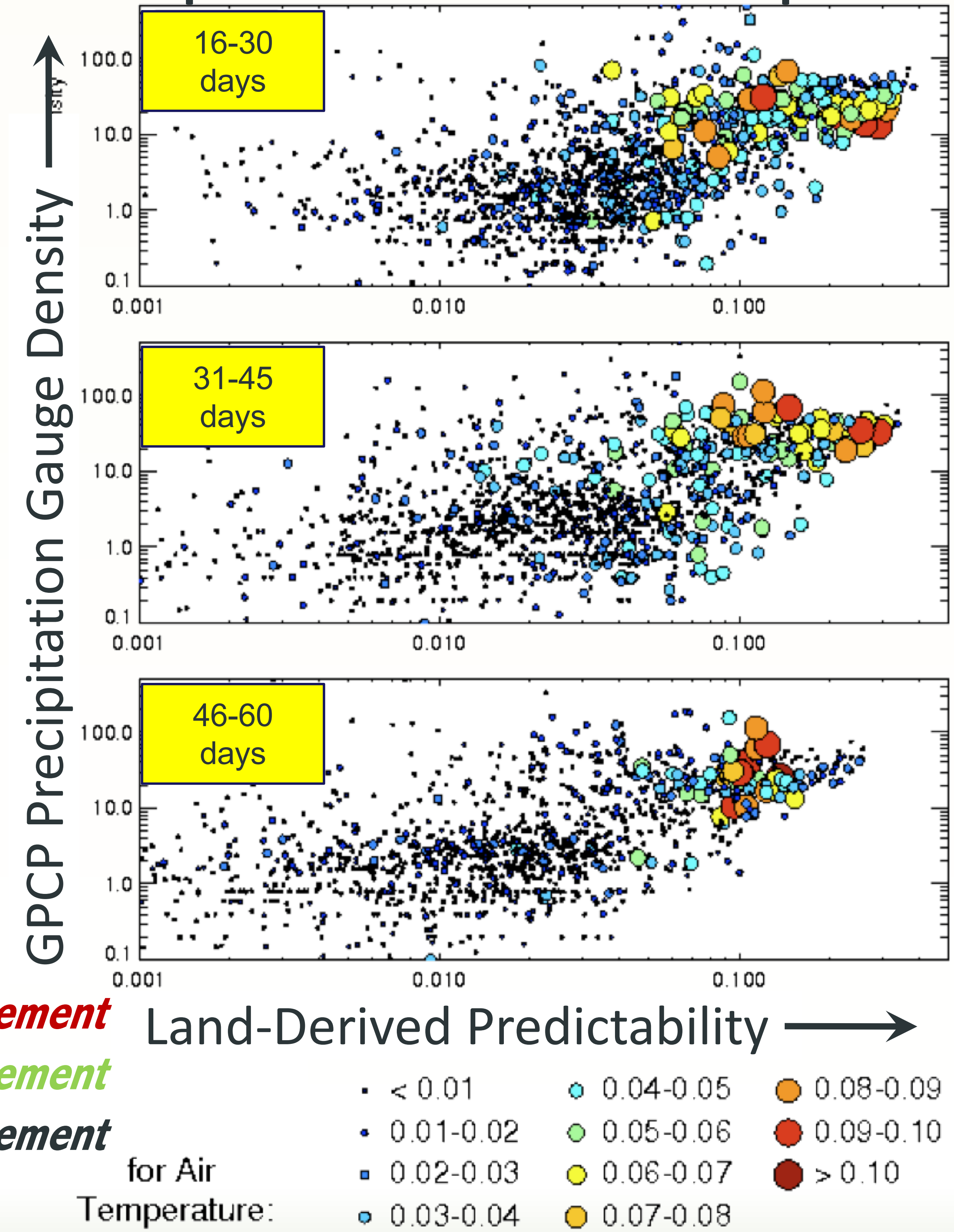
Skill Contributors

- Places that see the greatest skill impact from realistic land surface initialization have high rain gauge density (good rainfall data to generate initial soil moisture states) and high land-derived predictability (hot spots).

Garbage in, garbage out

Koster et al., (2011: *JHM)*

2m Temperature Forecast Skill Improvement



Red: Large Improvement
Green: Some Improvement
Black: No Improvement

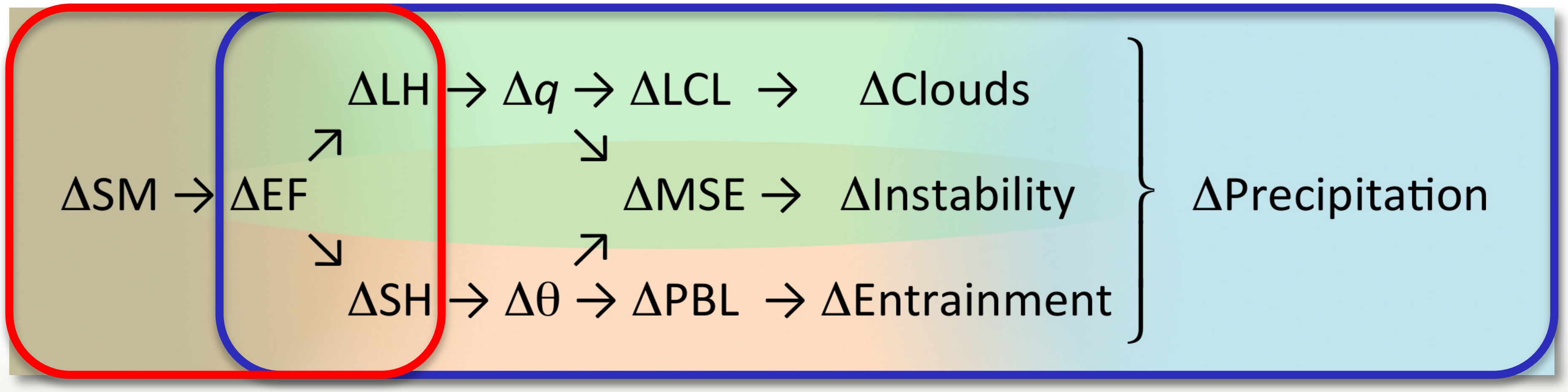
Land-Atmosphere feedback stands on 2 legs

$\Delta P \Rightarrow \Delta SM \rightarrow \Delta Fluxes \rightarrow \Delta PBL \rightarrow \Delta P$

Feedback loop: **Terrestrial leg** **Atmospheric leg**

- Terrestrial – When/where/how does soil moisture (vegetation, snow, etc.) control the partitioning of net radiation into sensible and latent heat fluxes?
- Atmosphere – When/where do surface fluxes significantly affect boundary layer properties, clouds and precipitation?

Process chains:



Climate Feedbacks: Three Ingredients

- Sensitivity
  - When and where is there an active coupling between climate components?

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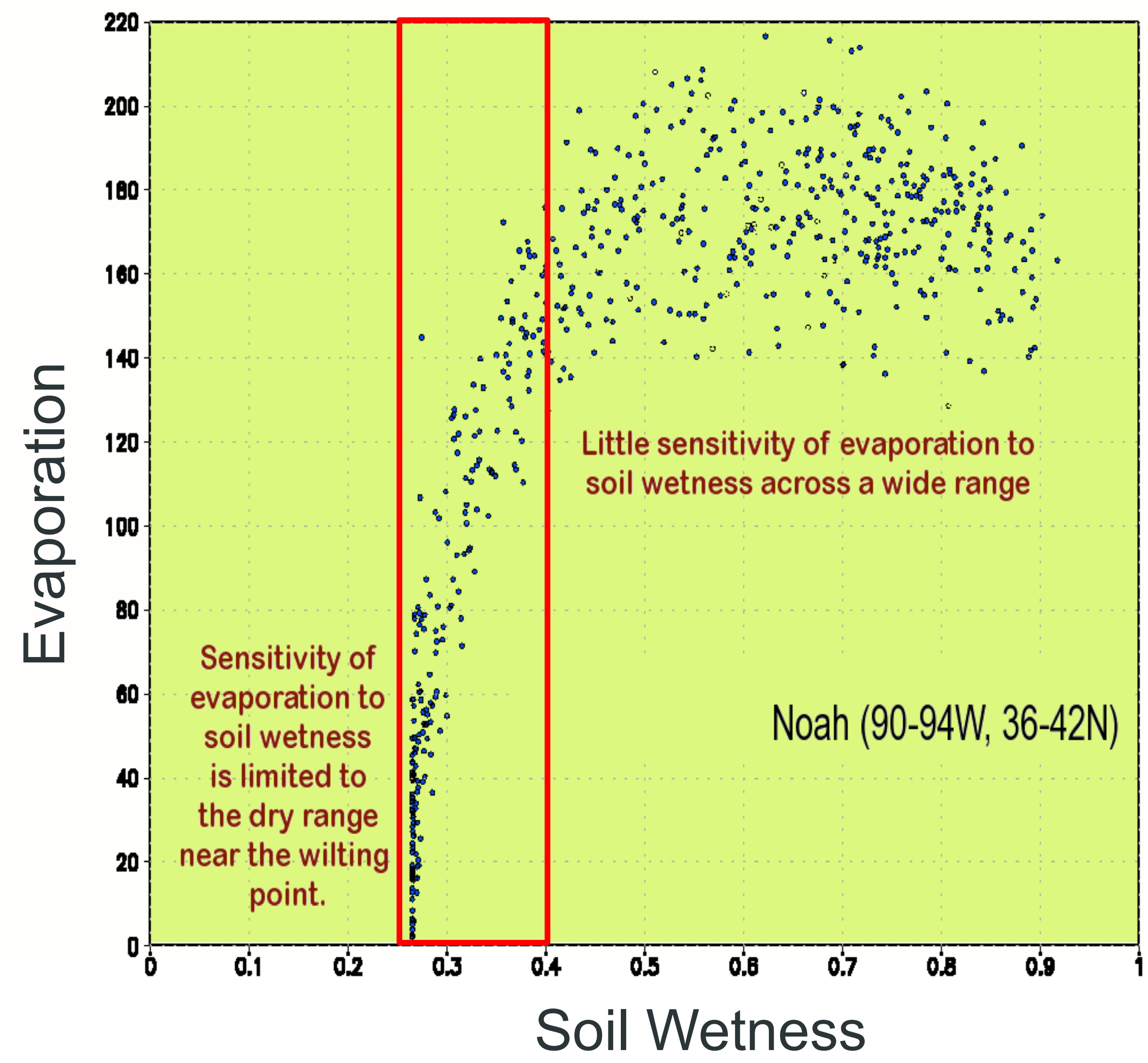
Ingredient #1: Sensitivity

- Over many parts of the world, there is a range of SM over which evaporation rates increase as soil moisture increases (soil moisture is a limiting factor – moisture controlled).



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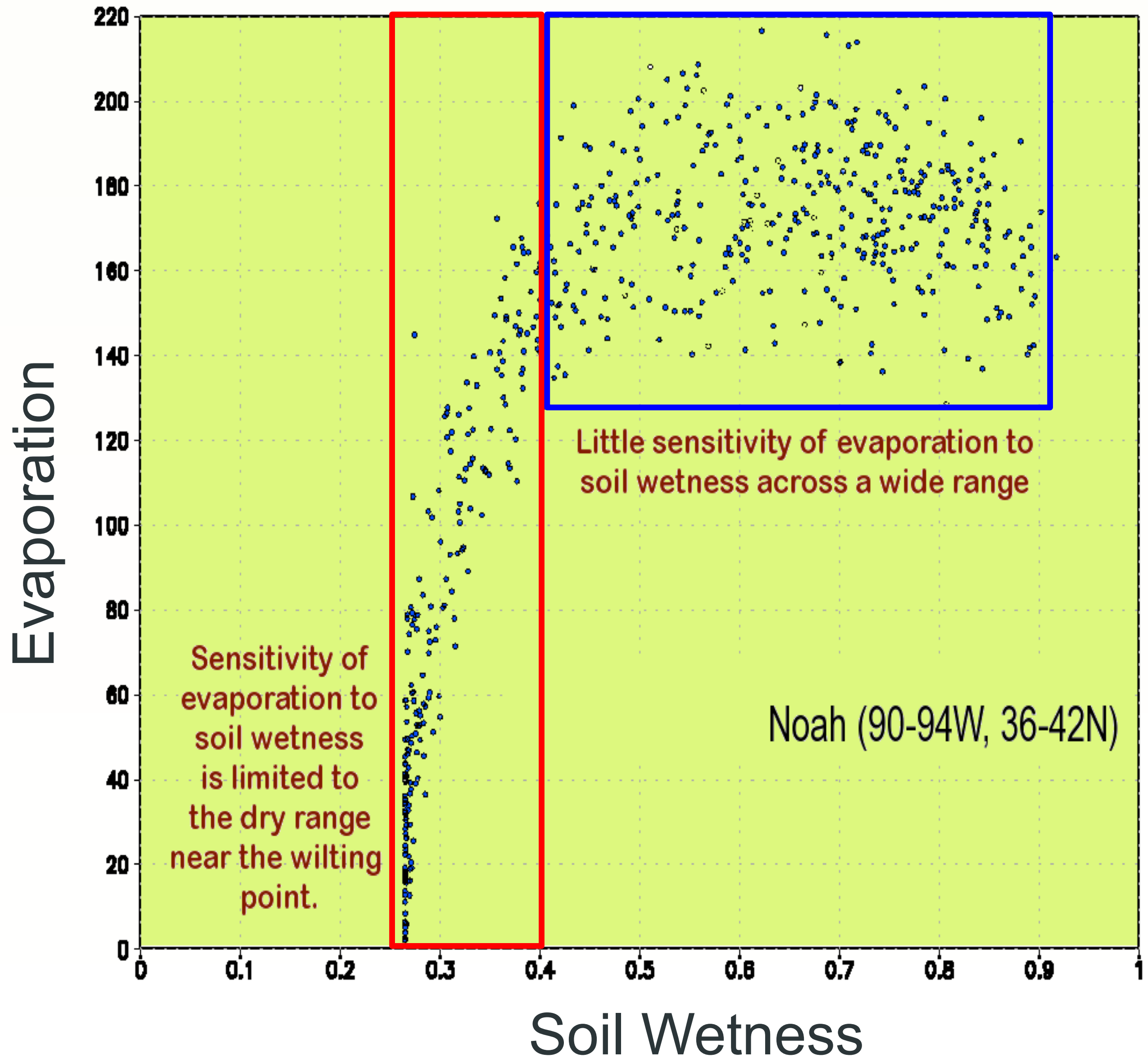

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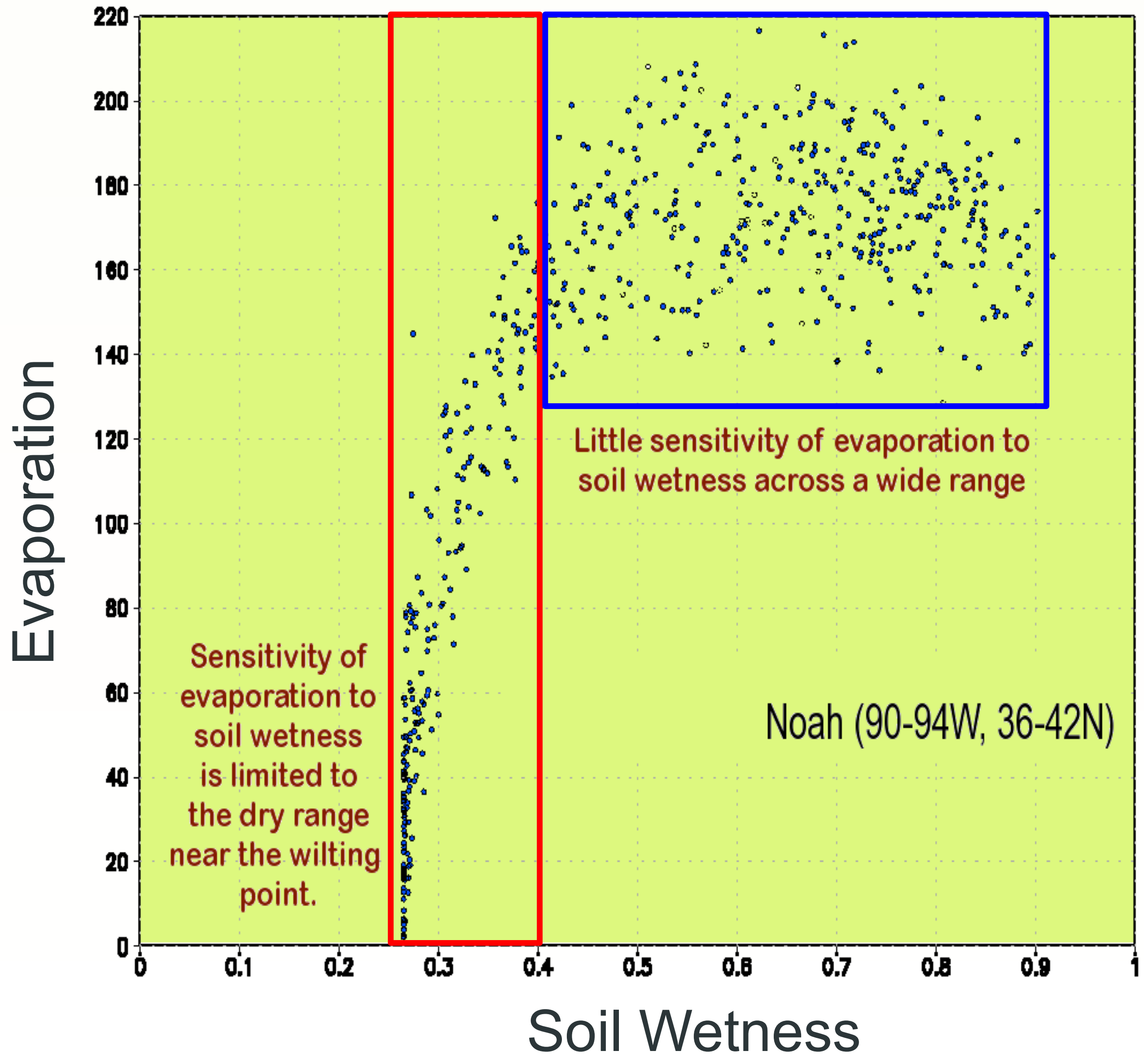

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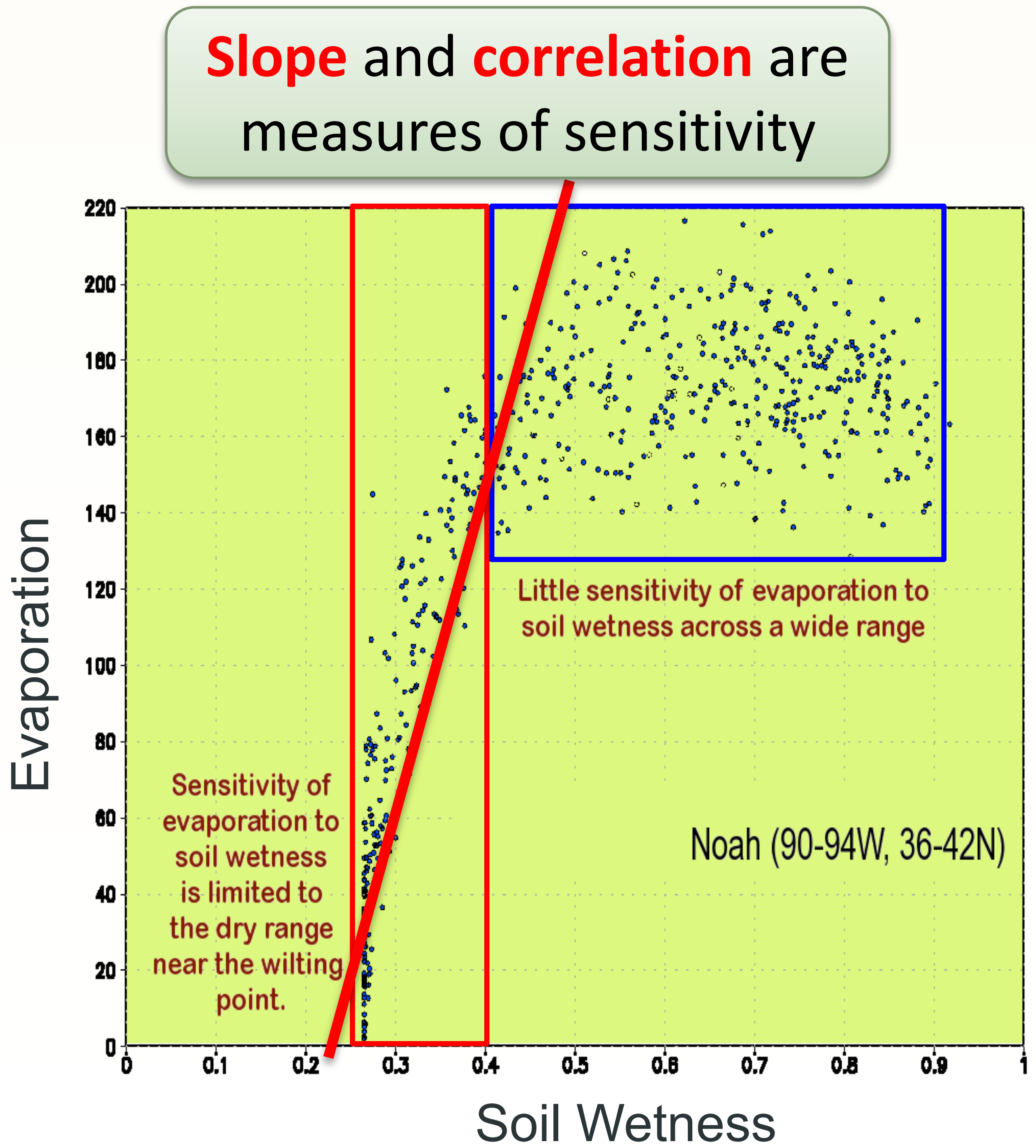
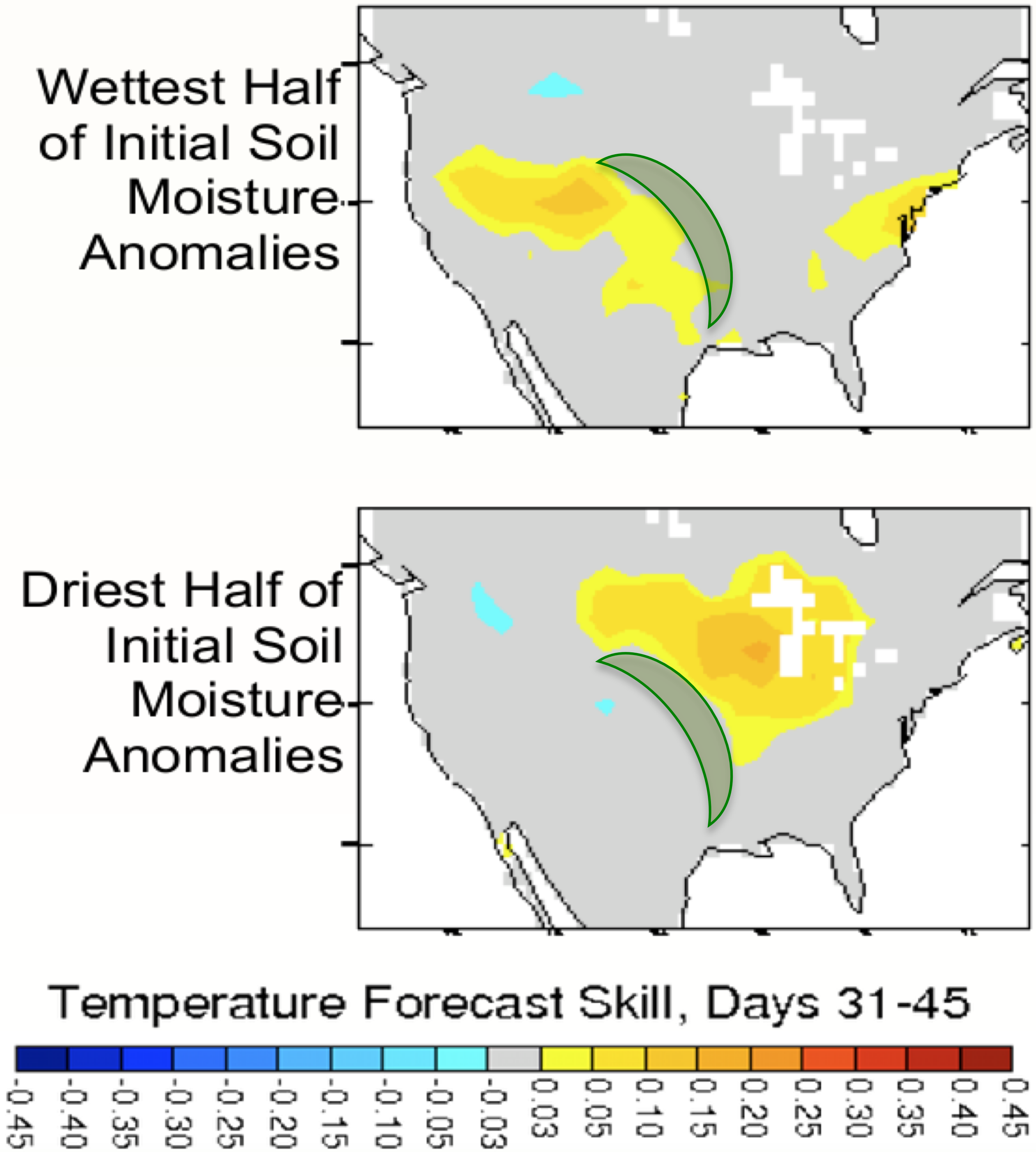


Sensitivity Affects Predictability in GLACE-2

- Soil moisture anomalies that push the local L-A system toward the regime of greatest sensitivity generate biggest improvements.



Koster et al., (2011: *JHM)*

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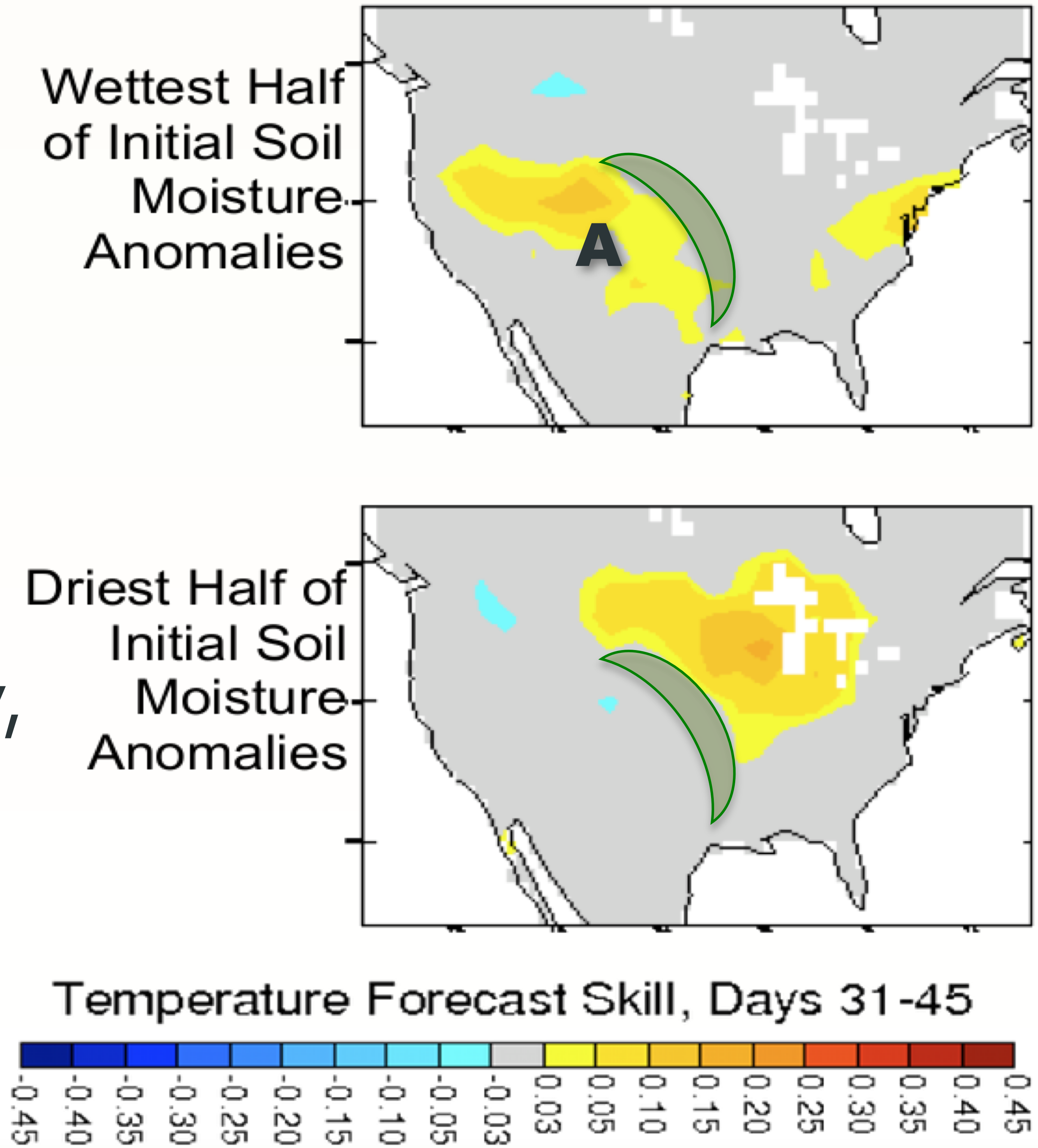

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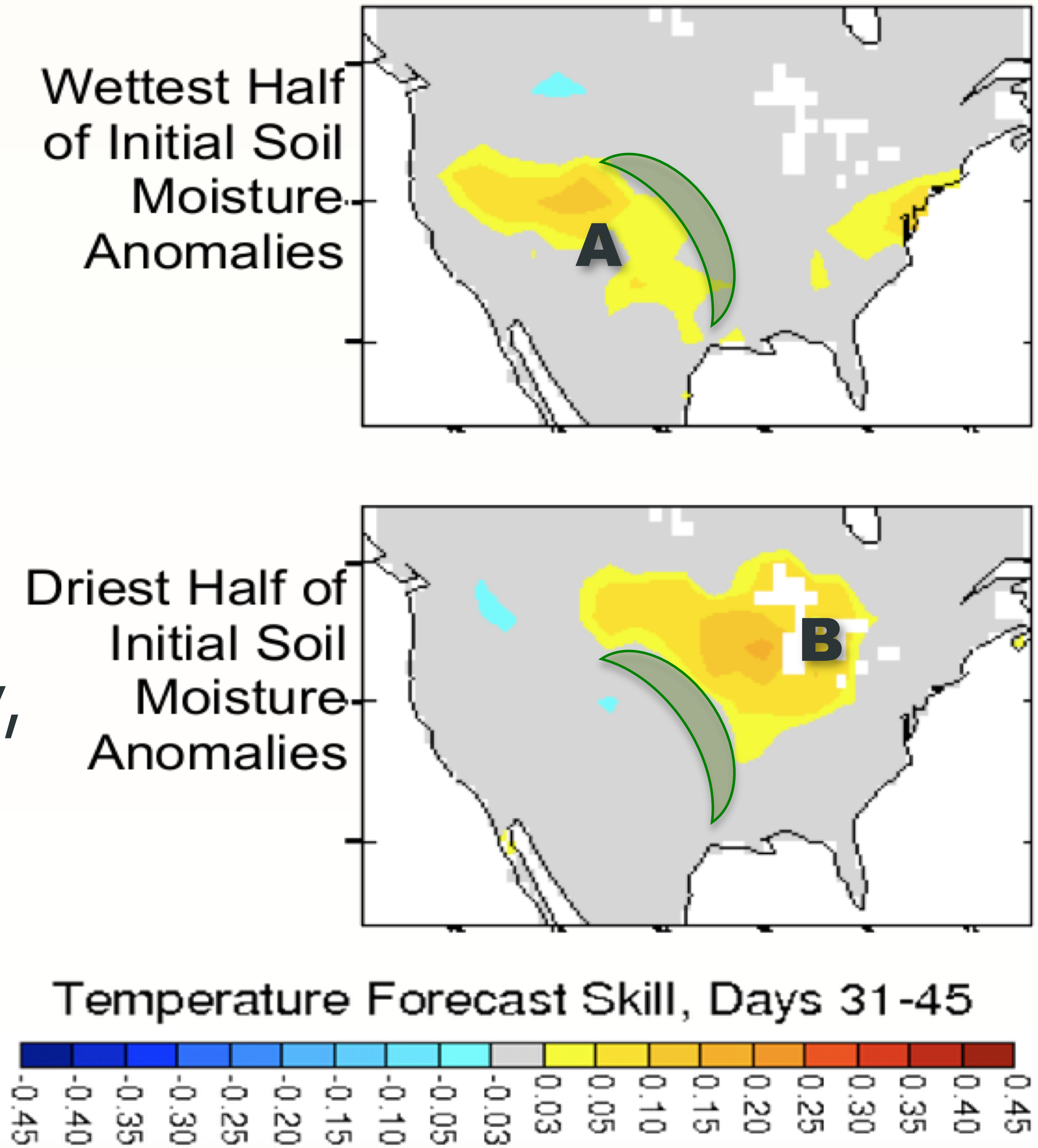

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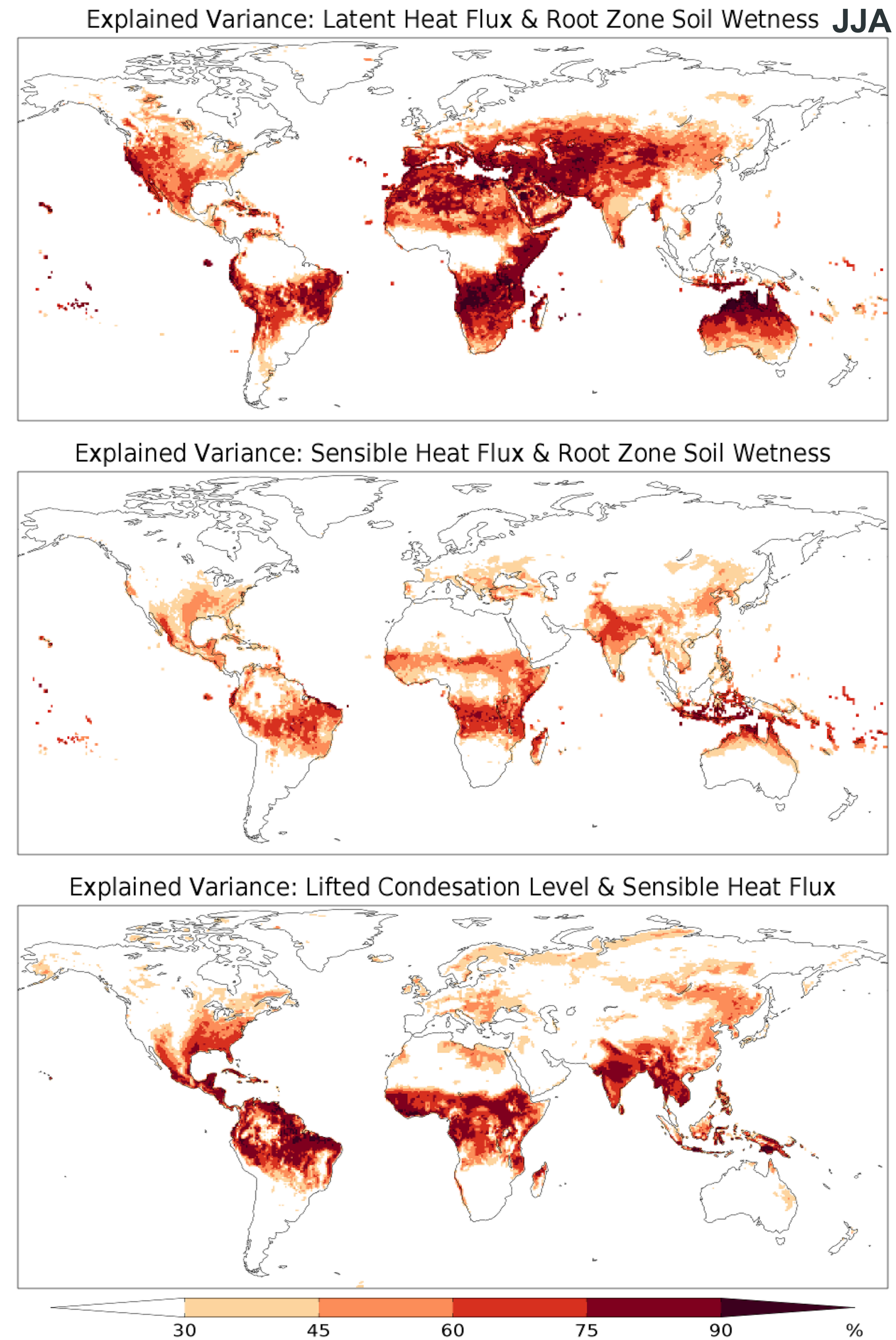
Sensitivity to Land States

- There is widespread sensitivity to soil moisture variations by surface latent (top) and sensible (middle) heat fluxes in MERRA-2.



Explained variance (%) based on correlations of daily means of indicated variables from MERRA-2 (1980-2015) during JJA.

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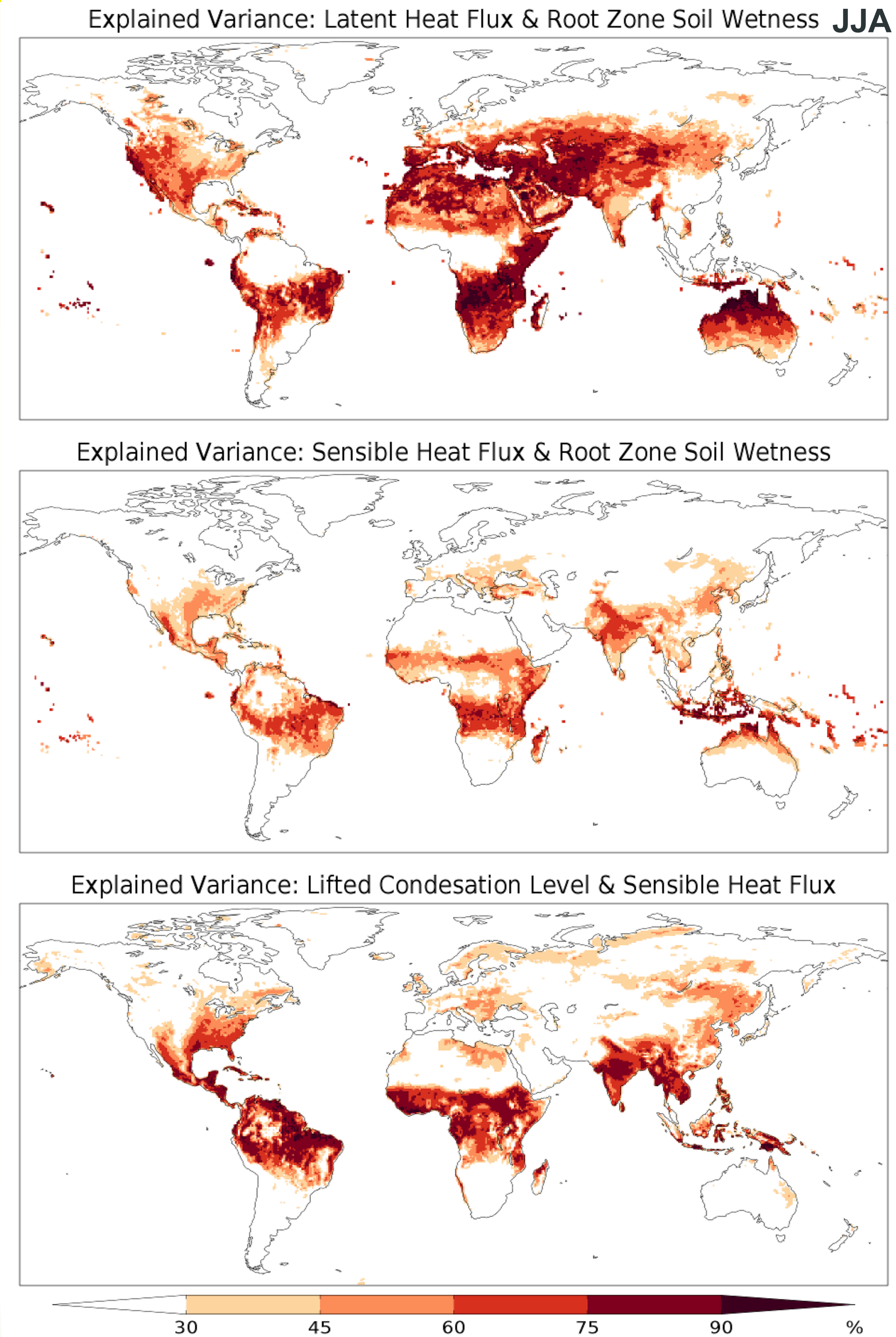
- This sensitivity propagates into the atmosphere, e.g., PBL height sensitivity to sensible heat flux (bottom).



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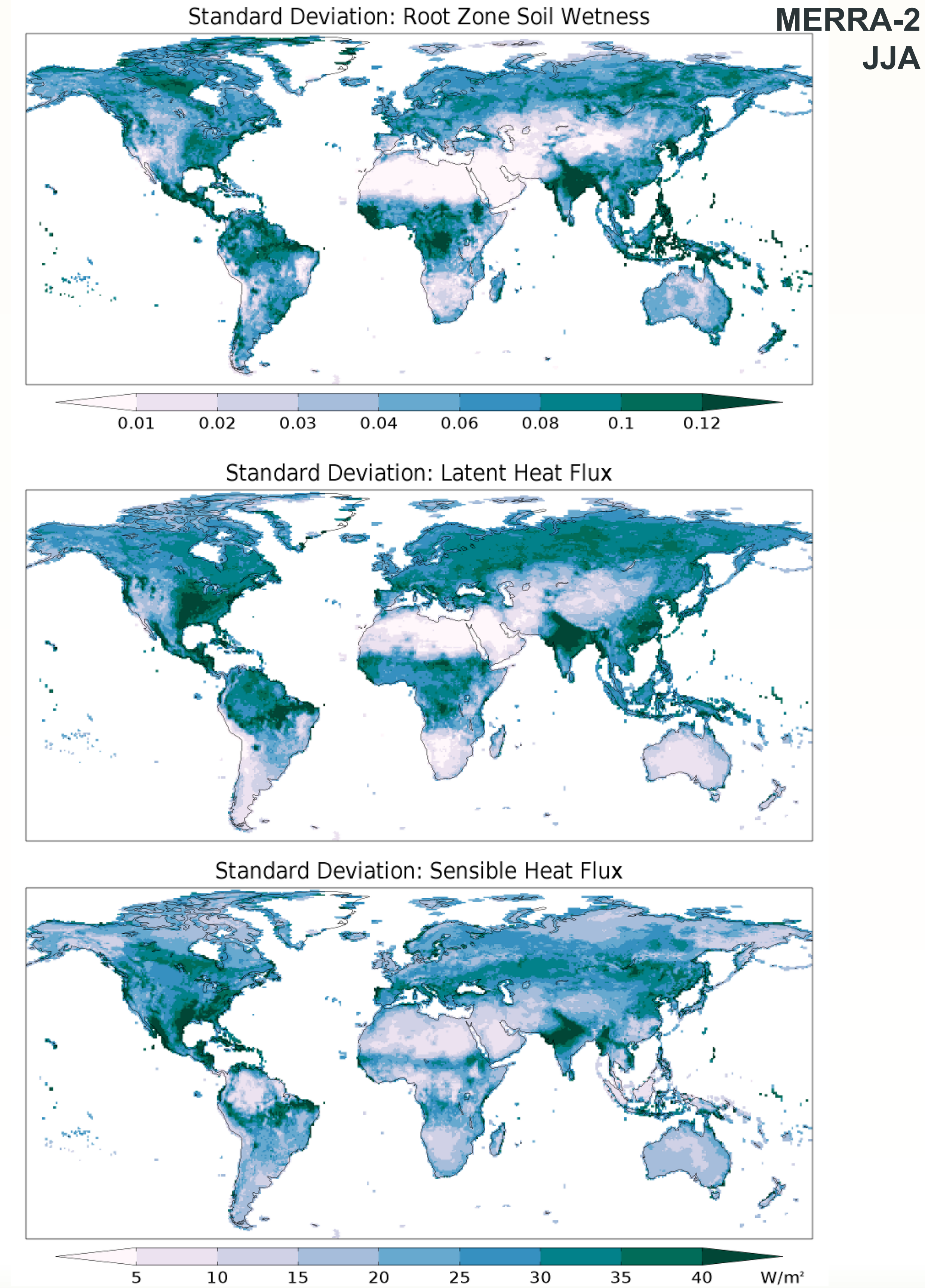
Ingredient #2 Variability

- Standard deviation of daily soil moisture (top) shows clearly that arid regions lack variability (rare occasions when there is significant soil moisture).
- Latent heat follows soil moisture
- Largest variability for sensible heat is associated with:
  - Transition zones (arid – humid)
  - Strong interannual variability (e.g., monsoon areas, SE U.S.)



Combining the First Two Ingredients

- Mathematically, sensitivity and correlation are directly related:

$$r_{a,b} = \beta_{a,b} \frac{\sigma_a}{\sigma_b}$$

- A "coupling index" between any two quantities with a process linkage combines concepts of sensitivity (correlation), and variance (magnitude of variability of key quantities).

$$\boxed{I_b(a)} = \boxed{r_{a,b}\sigma_b} = \boxed{\beta_{a,b}\sigma_a}$$

Index – how strongly is the response of b coupled to forcing a?

Correlation between a and b times standard deviation of b.

Sensitivity of b to a (slope) times standard deviation of a.

One of many L-A coupling metrics. See:
http://tiny.cc/l-a-metrics

Dirmeyer (2011: *GRL*,)

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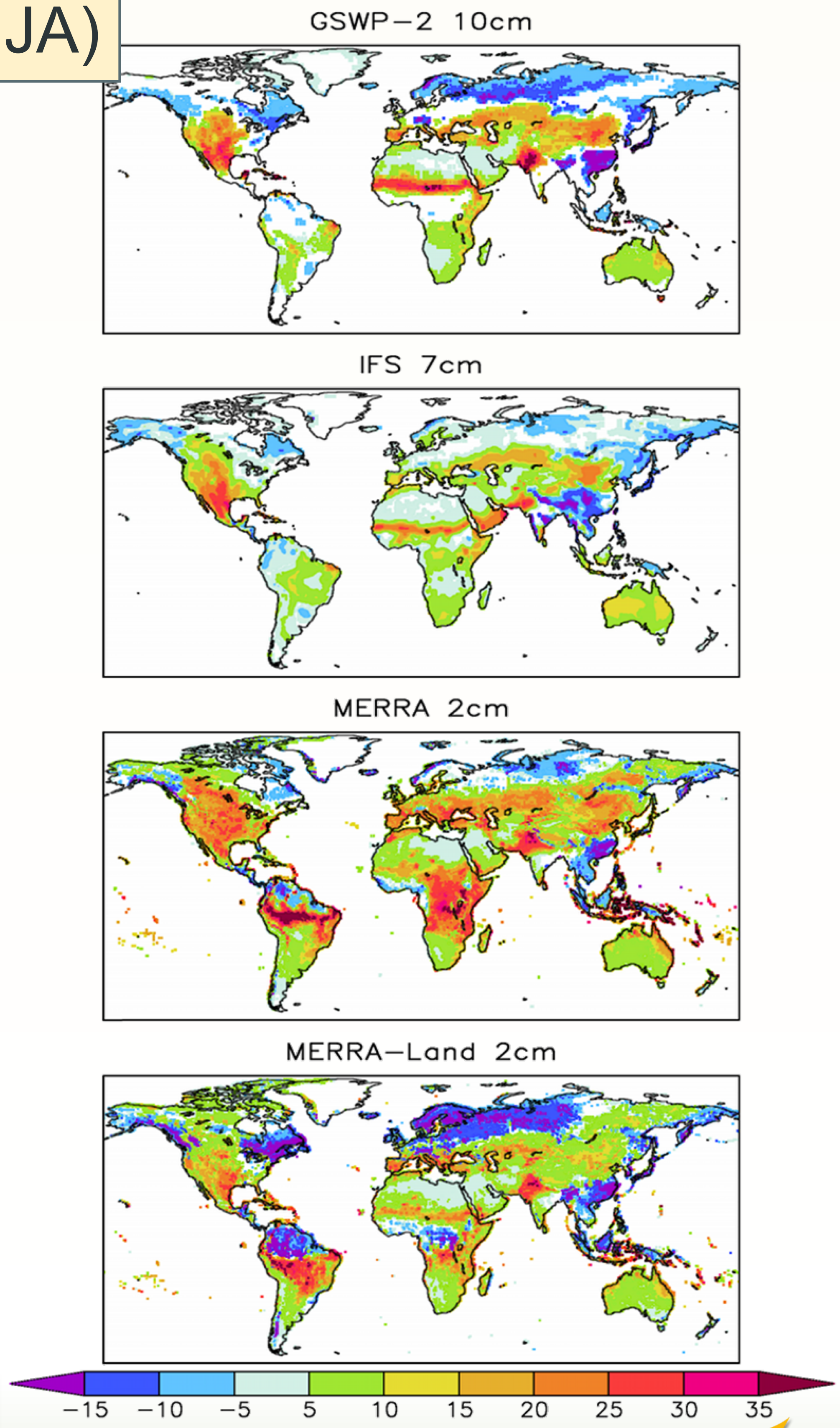
Terrestrial Coupling Index

- For latent heat flux coupling to surface soil wetness, there is strong correspondence to hot-spots (right; red colors).
- Remarkable consistency between (top to bottom) a multi-model offline (LSM-only) analysis, operational forecast model, reanalysis, and uncoupled land reanalysis with observed precipitation.
- Negative values: energy limited, atmosphere controls land, no feedback.
- Units are same as the flux [W/m²].

I_{LH} (JJA)



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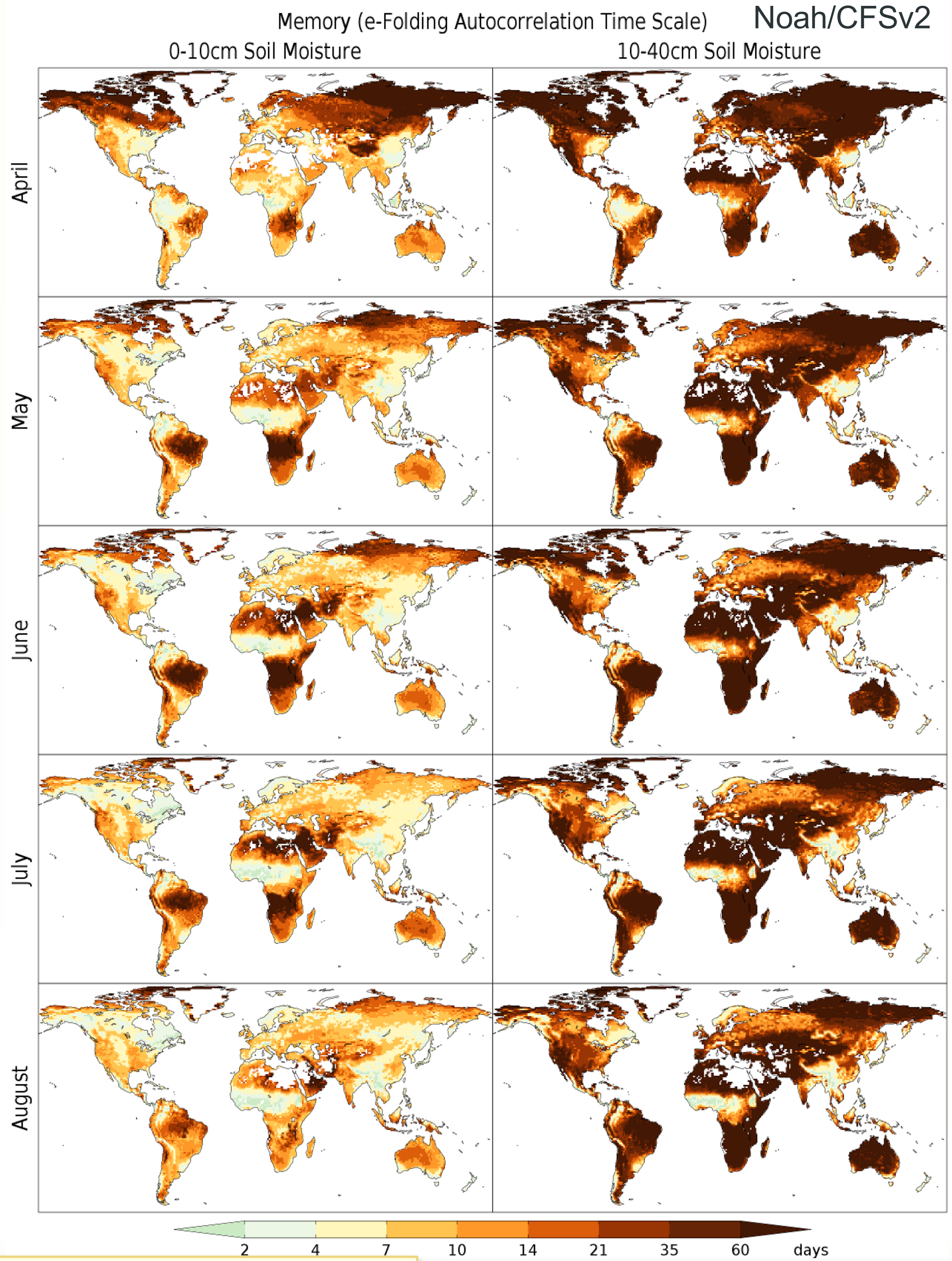
Ingredient #3: Memory

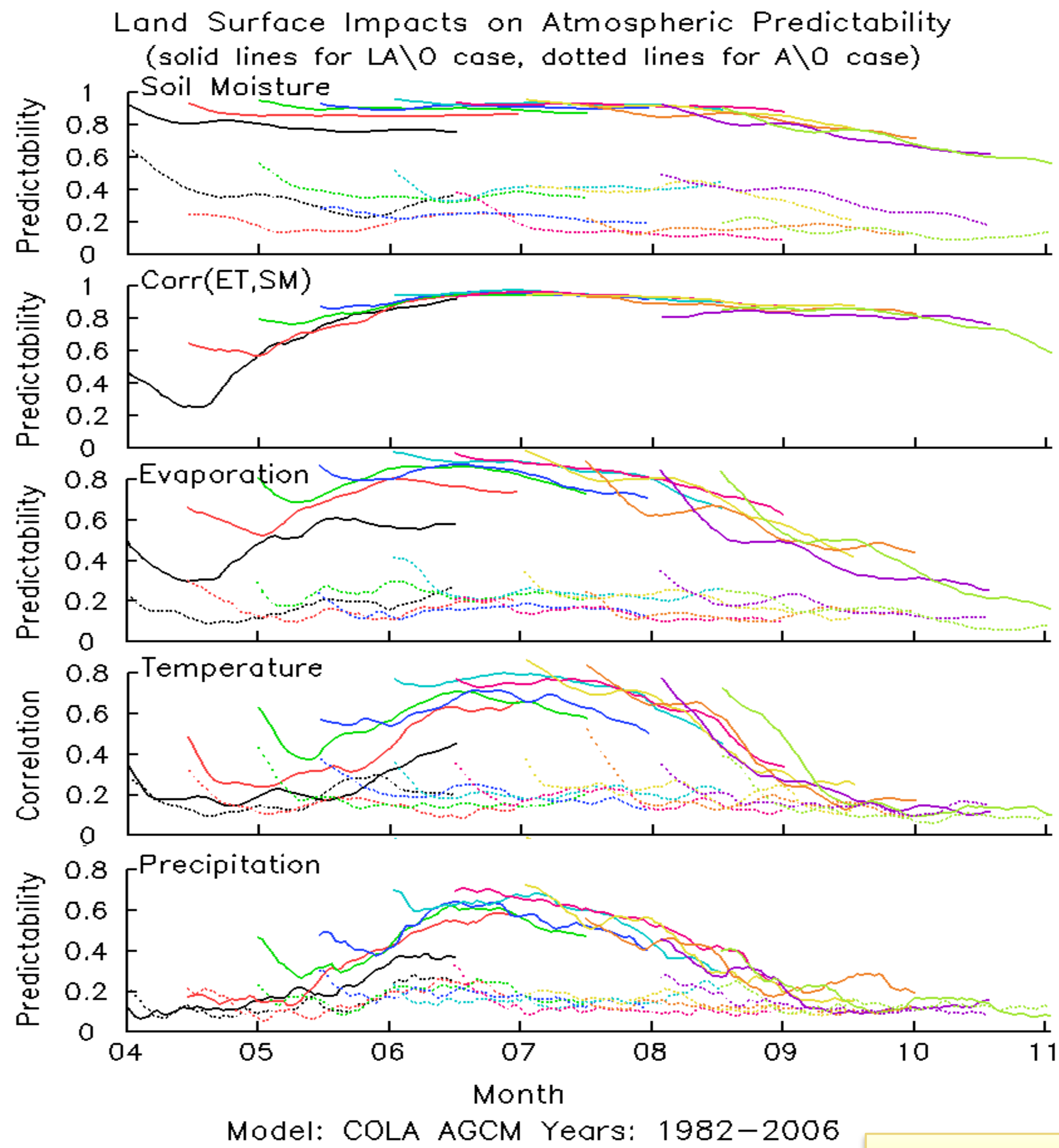
- Memory (persistence) strongly related to whether location is energy-limited or moisture-limited.
  - Long memory where arid.
  - Long memory where snow covered, frozen ground.
  - Short memory where humid, rainy.
  - Short memory under forests.
- Memory increases with depth into the soil.
- Soil texture, geology also factors.



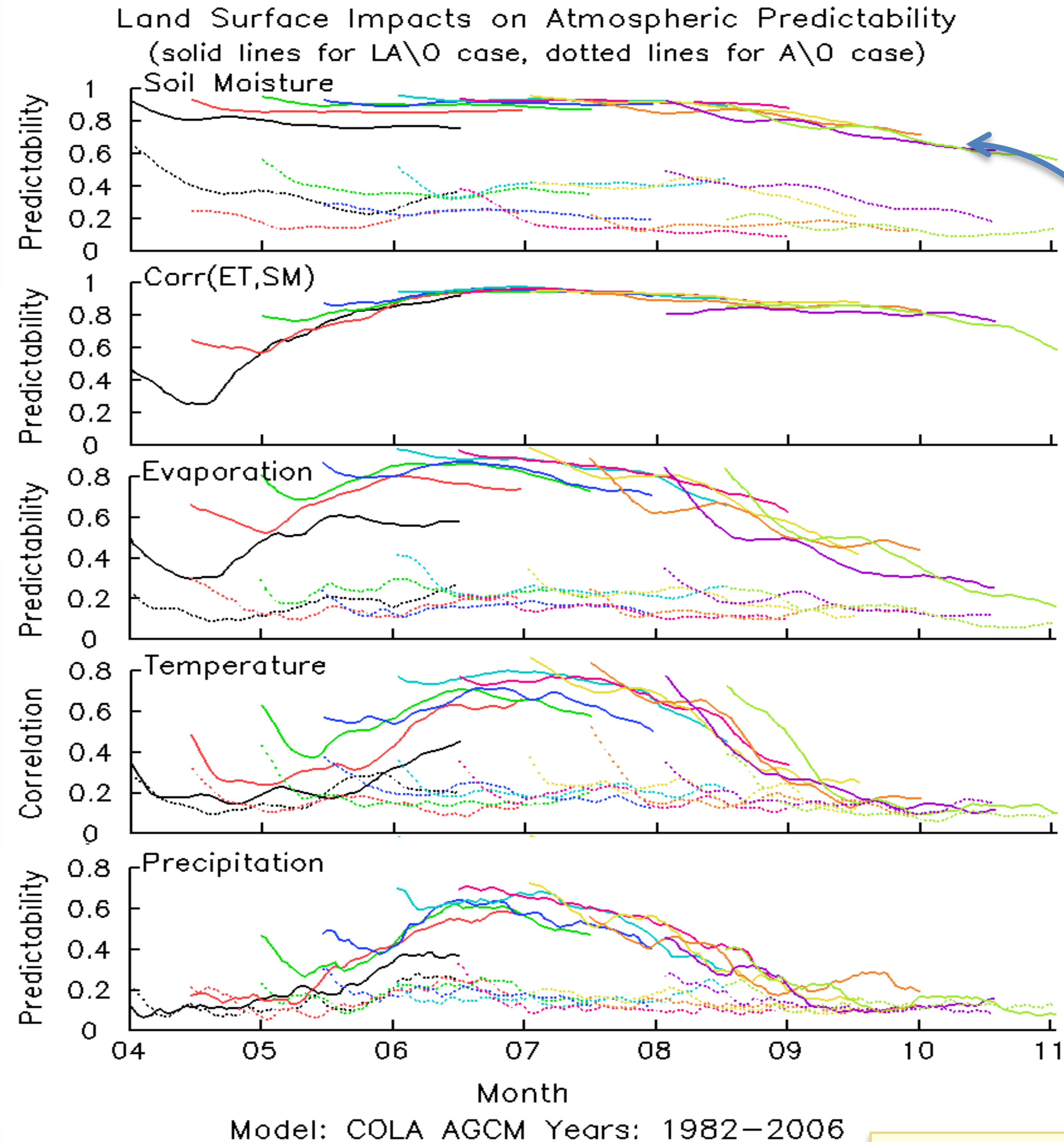
Dirmeyer & Halder, (2017: *JHM*)

GLACE-2 Predictability Rebound

- Box over US Great Plains.



Guo et al. (2013: *JHM*)



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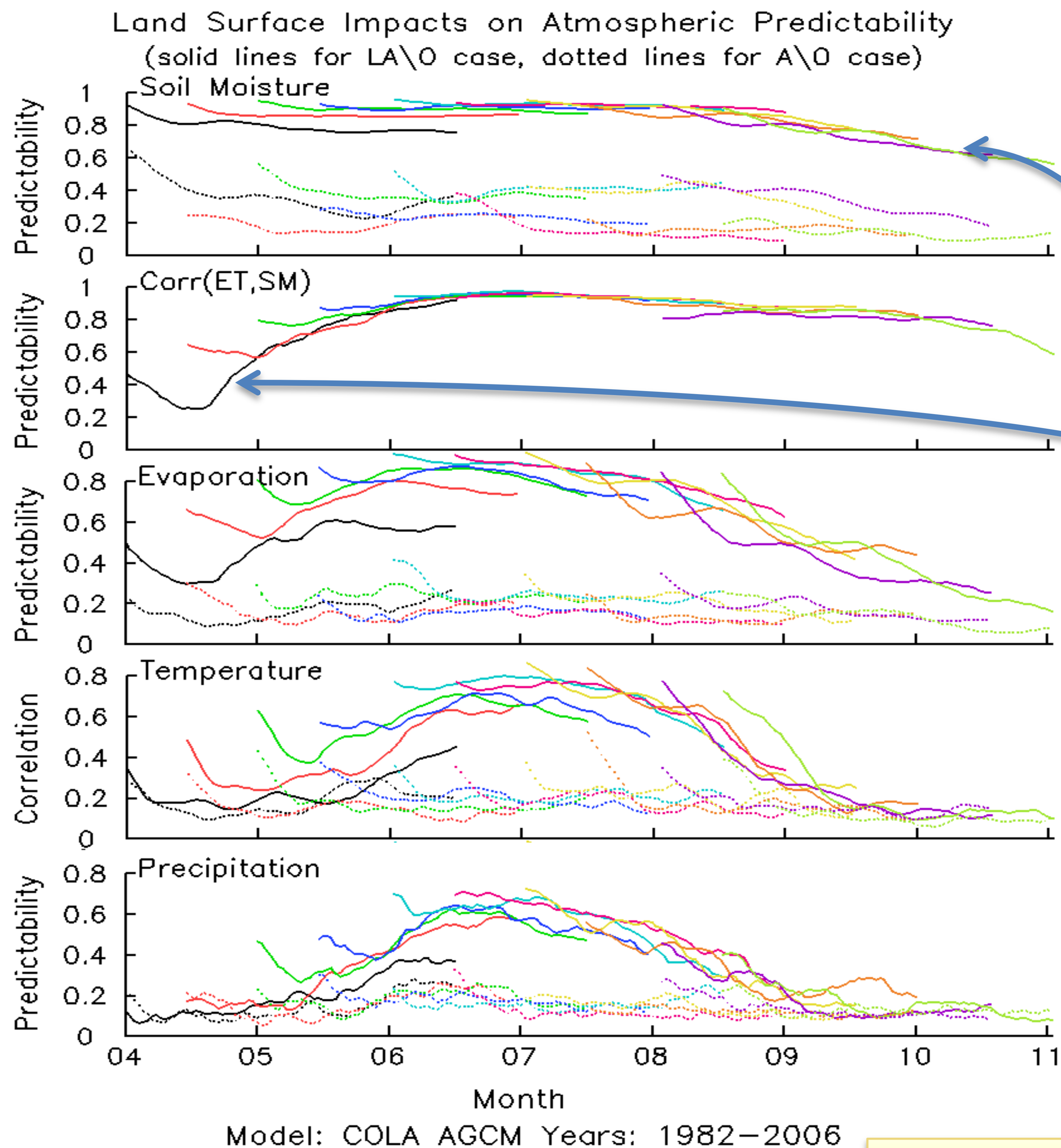

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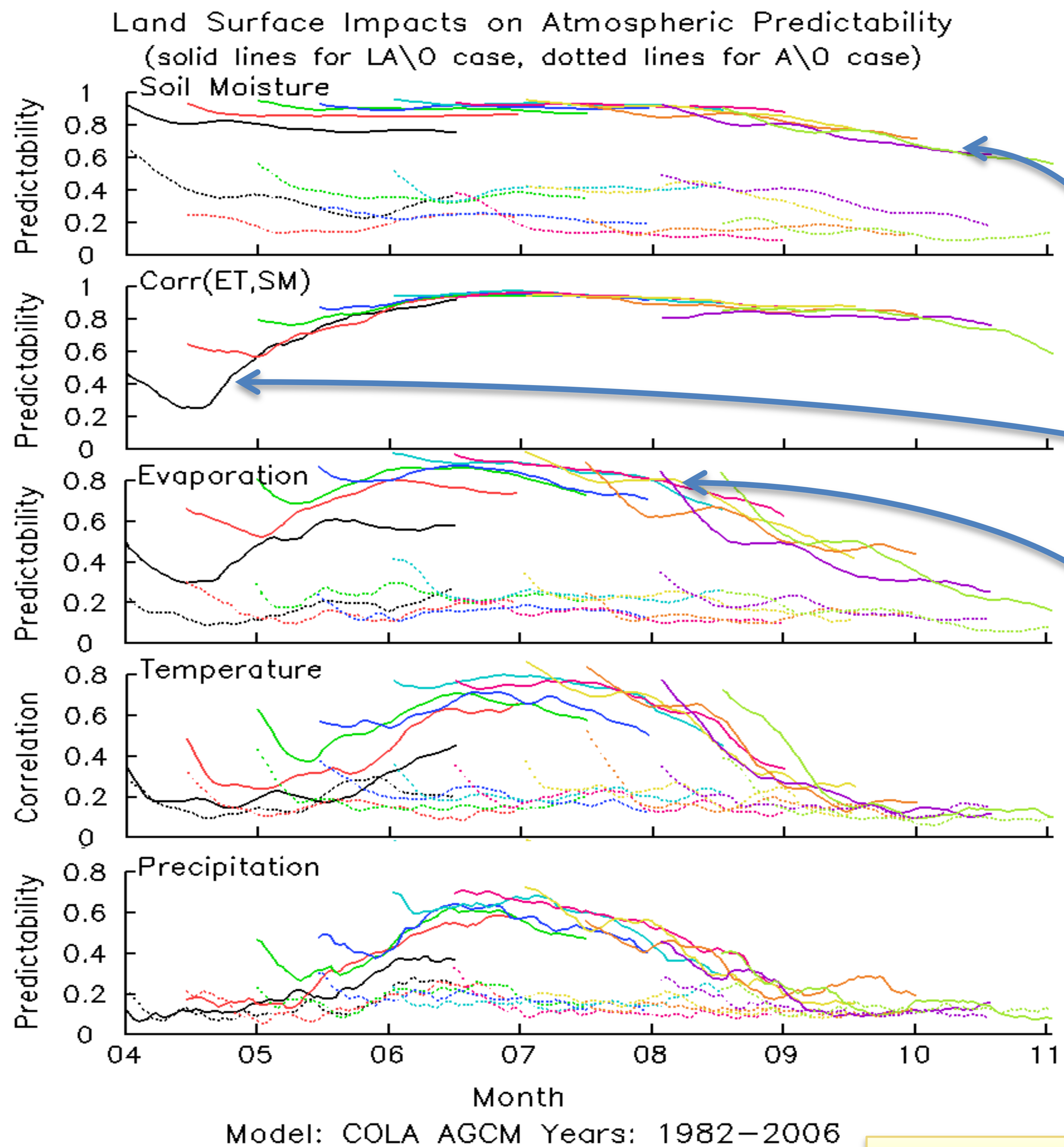

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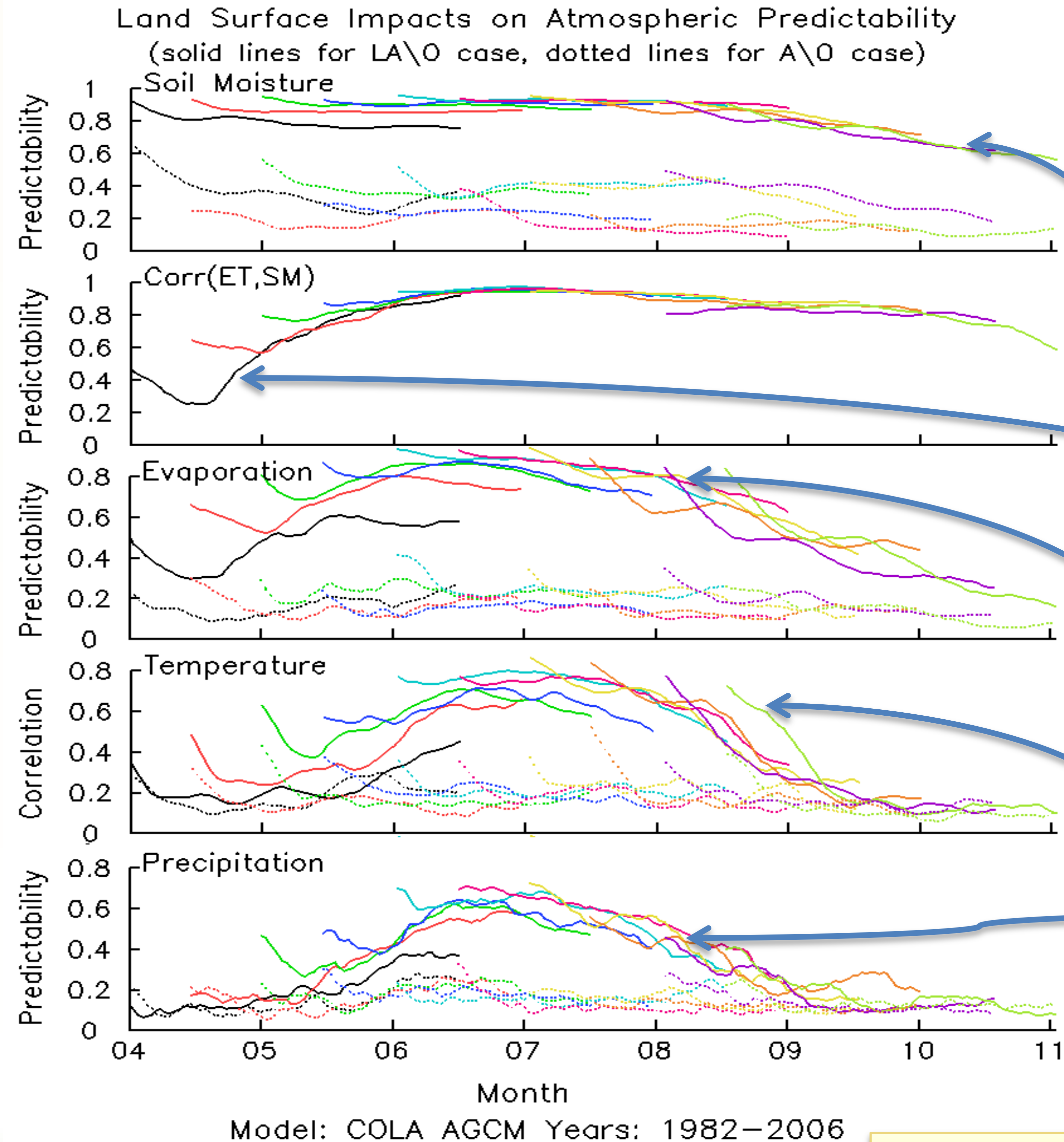

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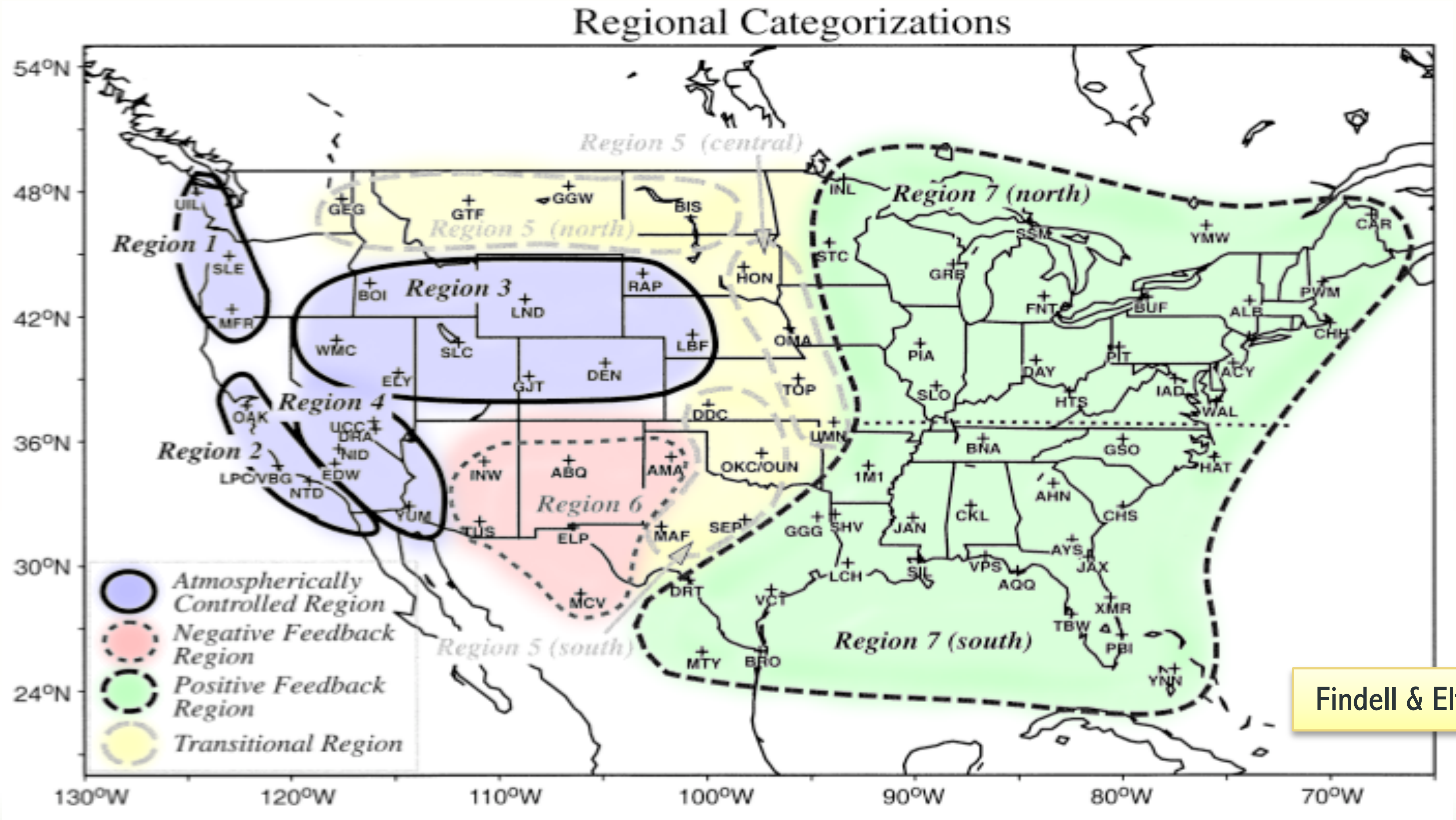
- In early spring soil moisture does not control ET.
- Late spring and summer, all pieces are in place.
- The impact of soil moisture on temperature and precip maximizes, predictability "rebounds"

Guo et al. (2013: *JHM*)

The Atmospheric Leg

- Radiosonde sites in and around CONUS in summer were assessed based on their climatologies of CTP and HI_{Low}.



Findell & Eltahir. (2003: *JHM*)

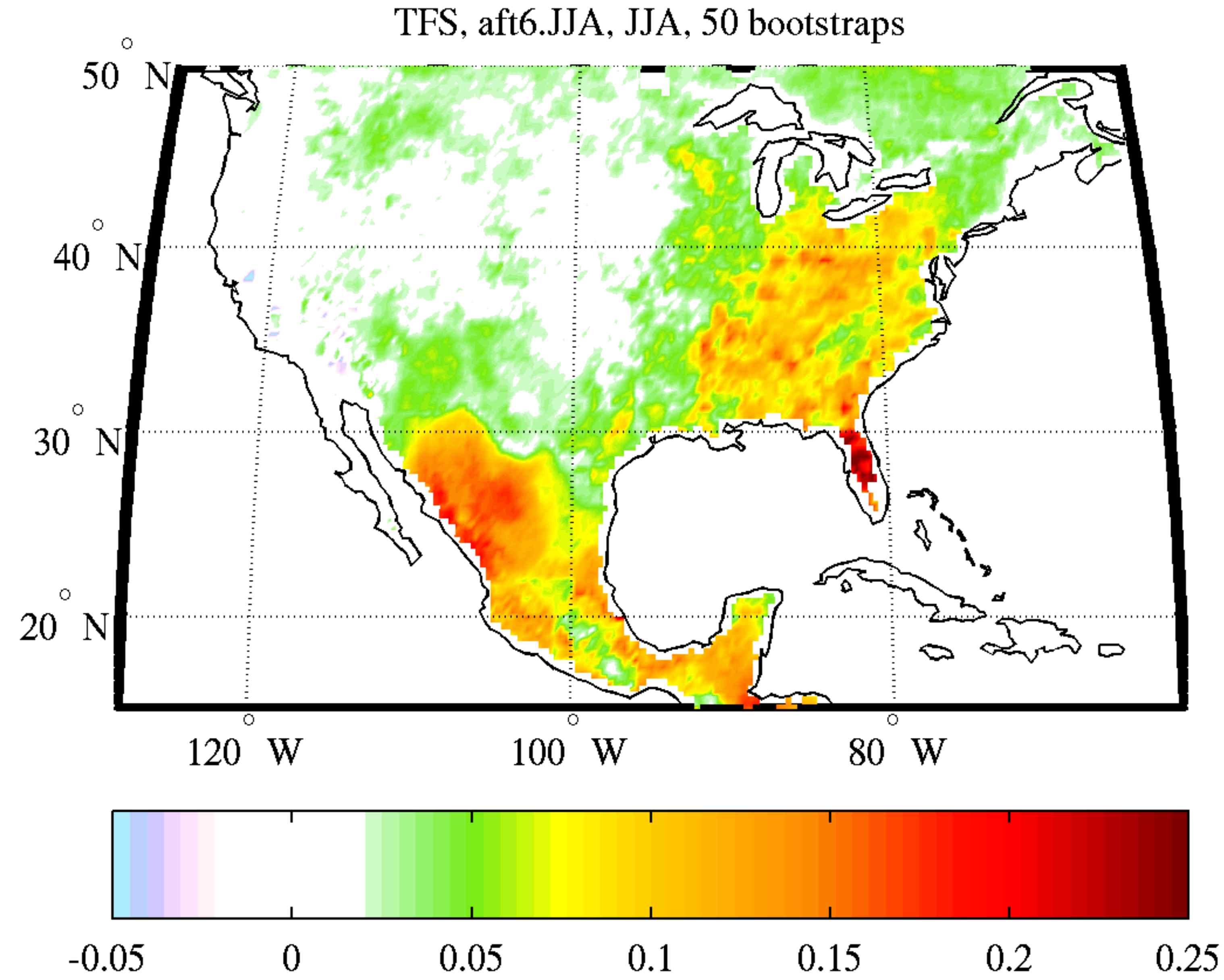
Dependence of Afternoon Rain on Evaporative Fraction

- Triggering Feedback Strength
  (in probability units):

$$TFS = \sigma_{EF} \frac{\partial \Gamma(r)}{\partial EF}$$

- Eastern US shows afternoon rainfall triggering dependent on land surface fluxes in NARR

- Maps created from 50 bootstrap samples



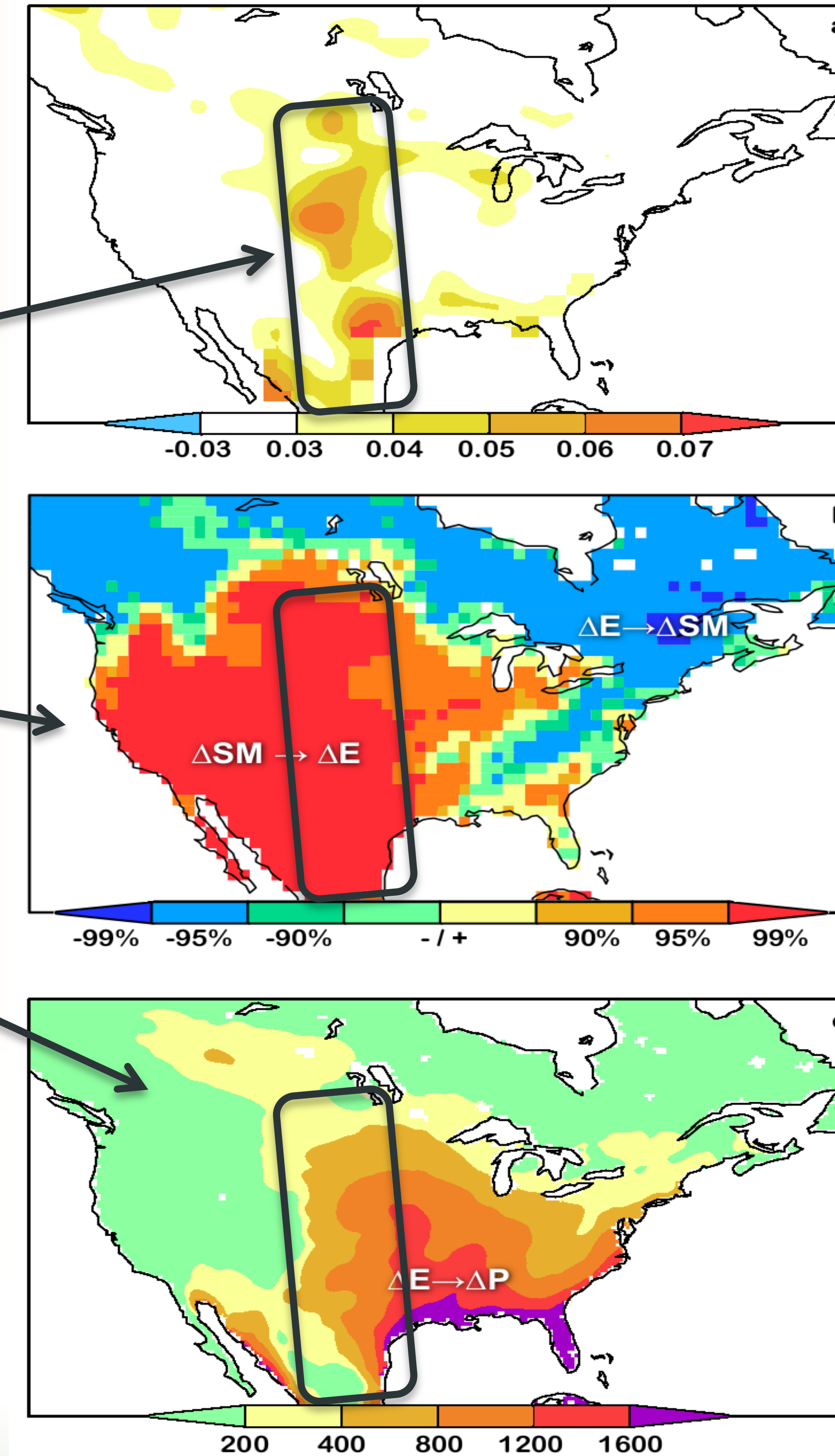
Findell et al. (2011: *Nat Geosci.*)

Feedback Via Two Legs

- GLACE coupling strength for summer soil moisture to rainfall (the “hot spot”) corresponds to regions where there are both of these factors:
- High correlation between daily soil moisture and evapotranspiration during summer [from the GSWP multi-model analysis, units are significance thresholds], and
- High CAPE [from the North American Regional Reanalysis, J/kg]

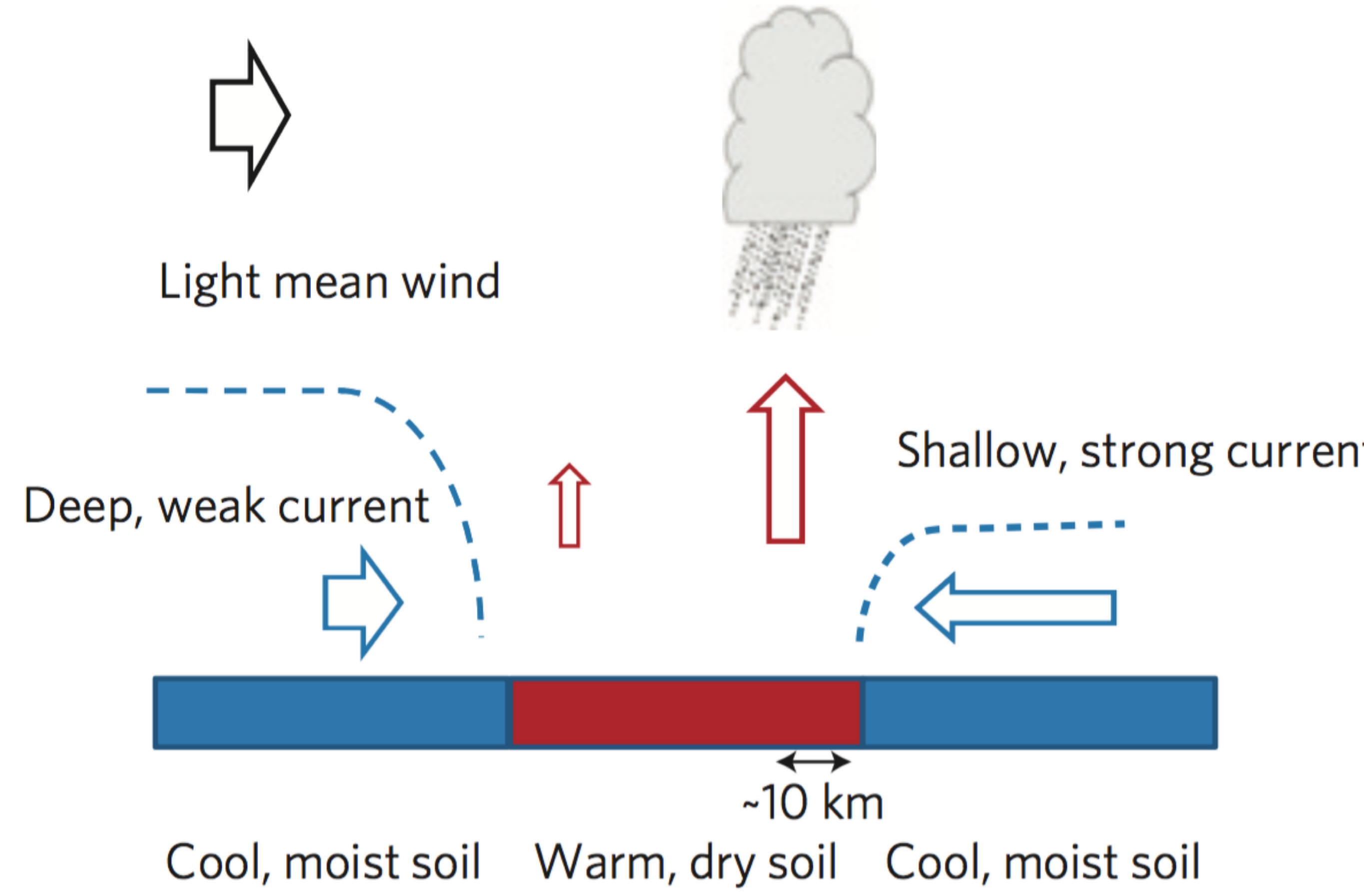
$$\Delta P \Rightarrow \Delta SM \rightarrow \Delta E \rightarrow \Delta P$$

Feedback path: Terrestrial leg Atmospheric leg



Leapfrogging of precipitation events

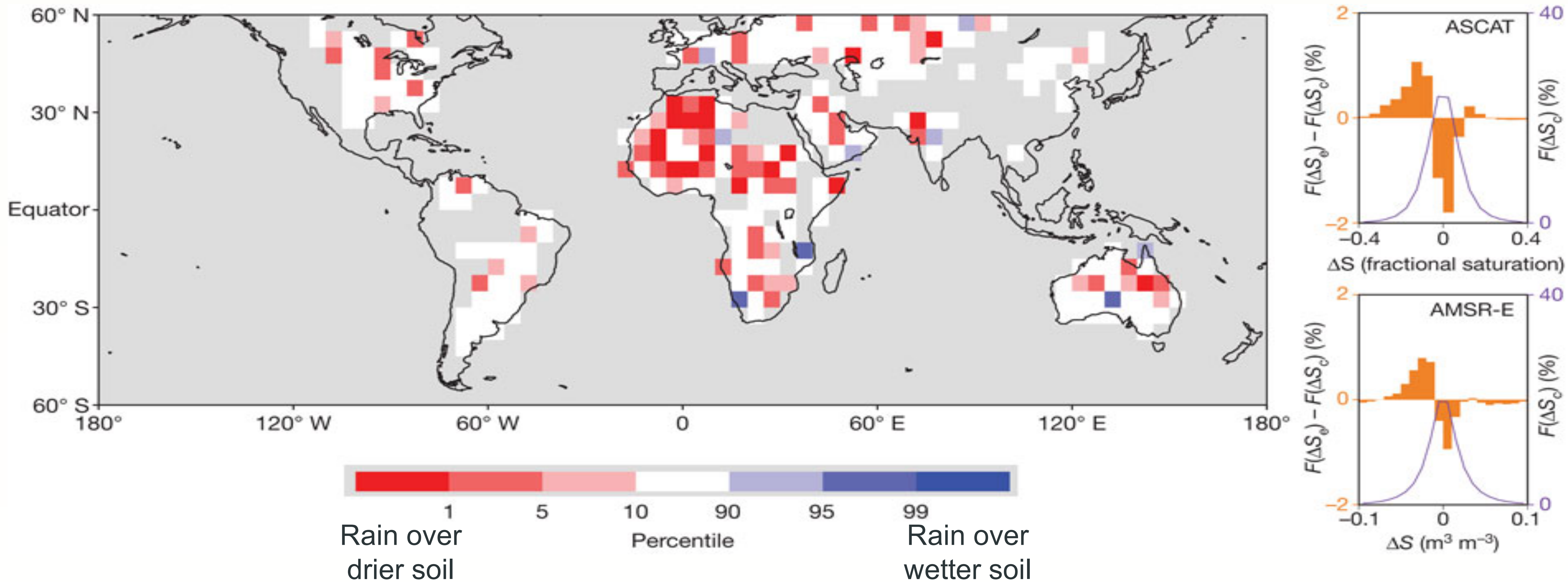
- In West Africa in particular, easterly waves bring disturbances and rainfall during the wet season.
- Convection and maximum rainfall occurs preferentially just "downstream" of previous rainfall event, not over wet ground.
- Surface moisture/temperature gradients set up the preference.



Taylor et al. (2011; *Nature Geosci.*)

Observations: Rain over Dry Soil

Shading: percentile of observed variable (mean soil moisture contrast) given no feedback



Apparent preference for afternoon rain over drier soil

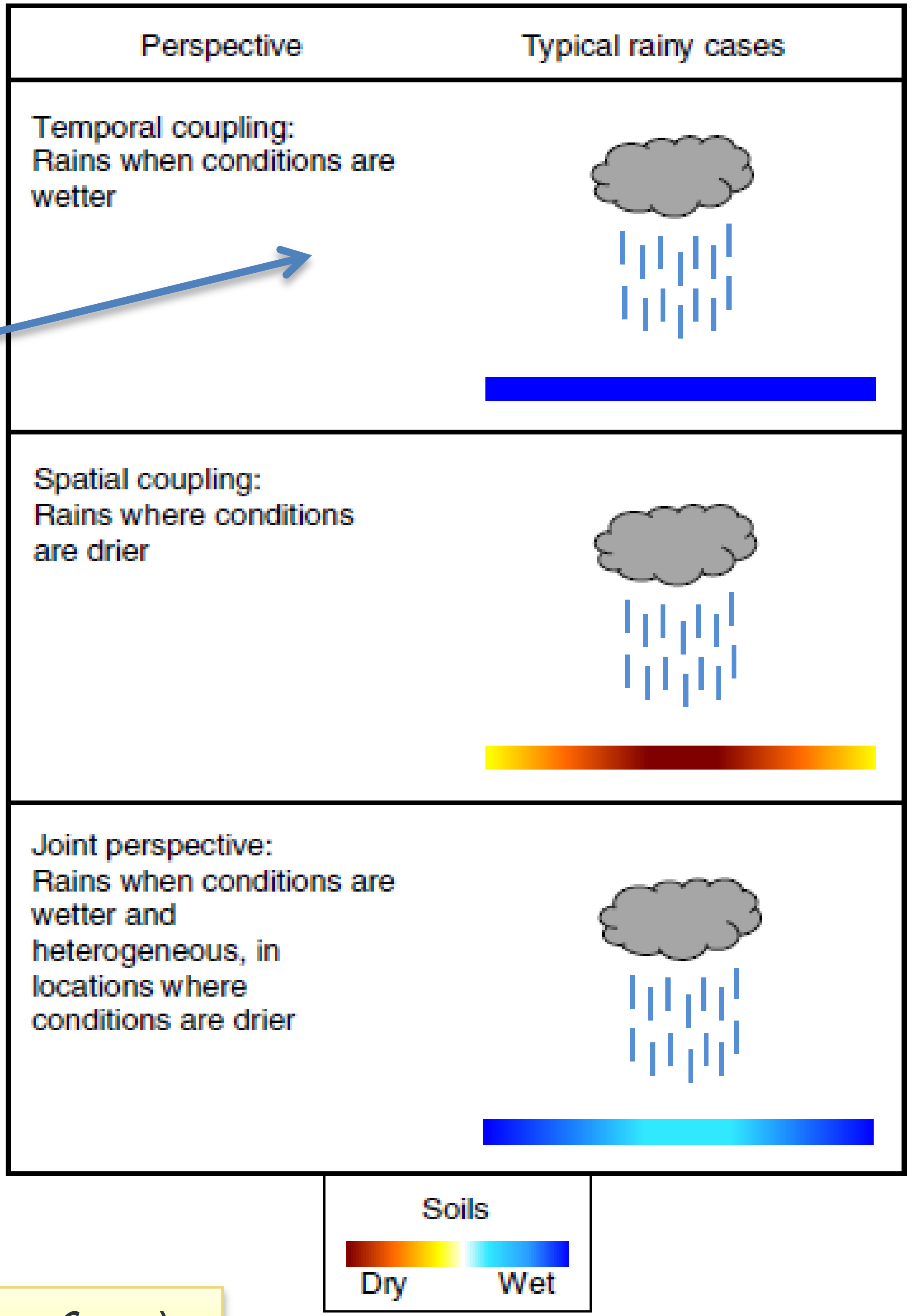
Far fewer blue pixels than expected by chance

Signal strongest in Africa and Australia

Taylor et al. (2012; *Nature*)

Reconciling Koster & Taylor

- Much of the difference may be due to <u>spatial vs. temporal scaling</u>.
- GLACE picked up on large-scale temporal coupling, where correlations and feedbacks are positive.



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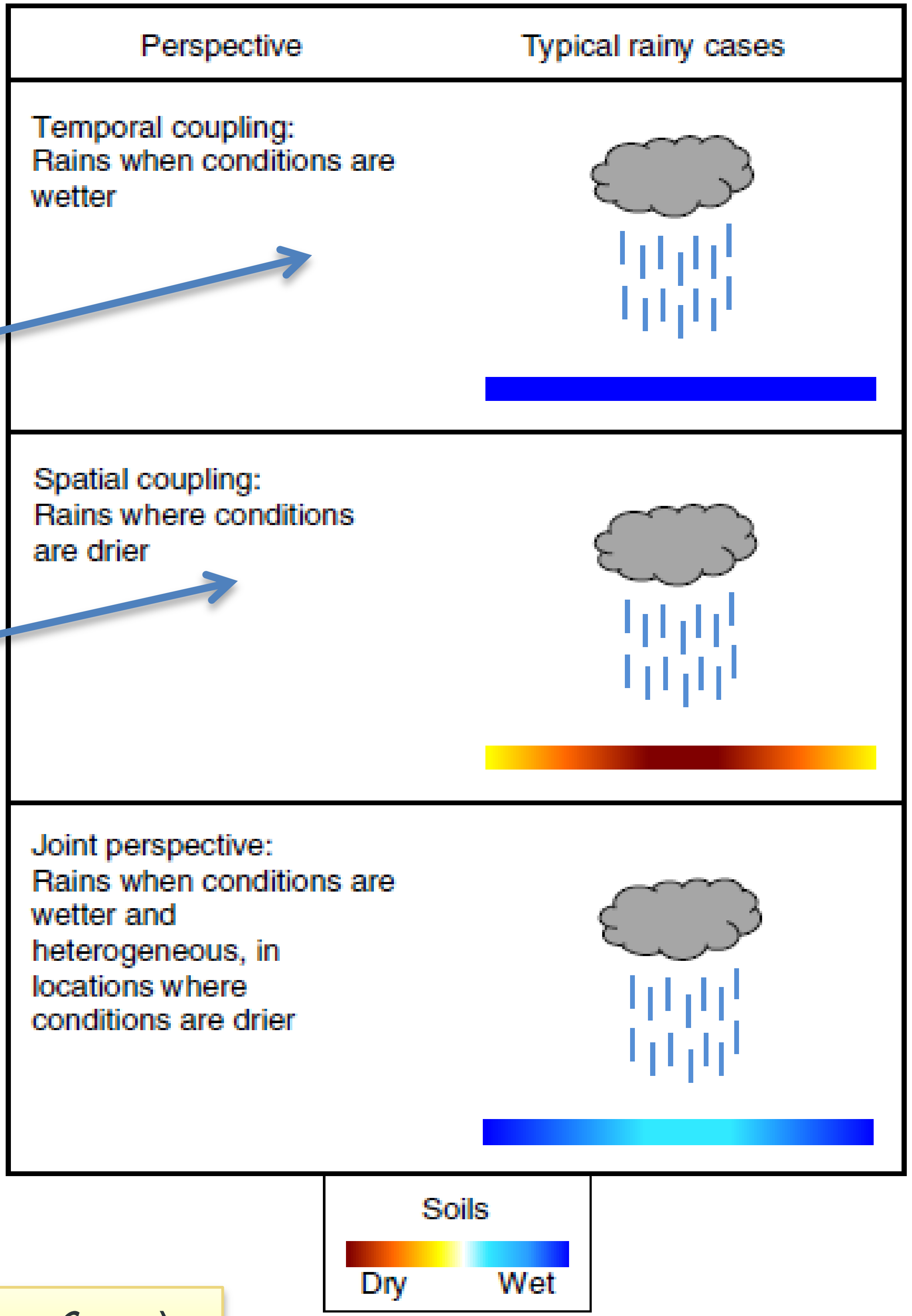

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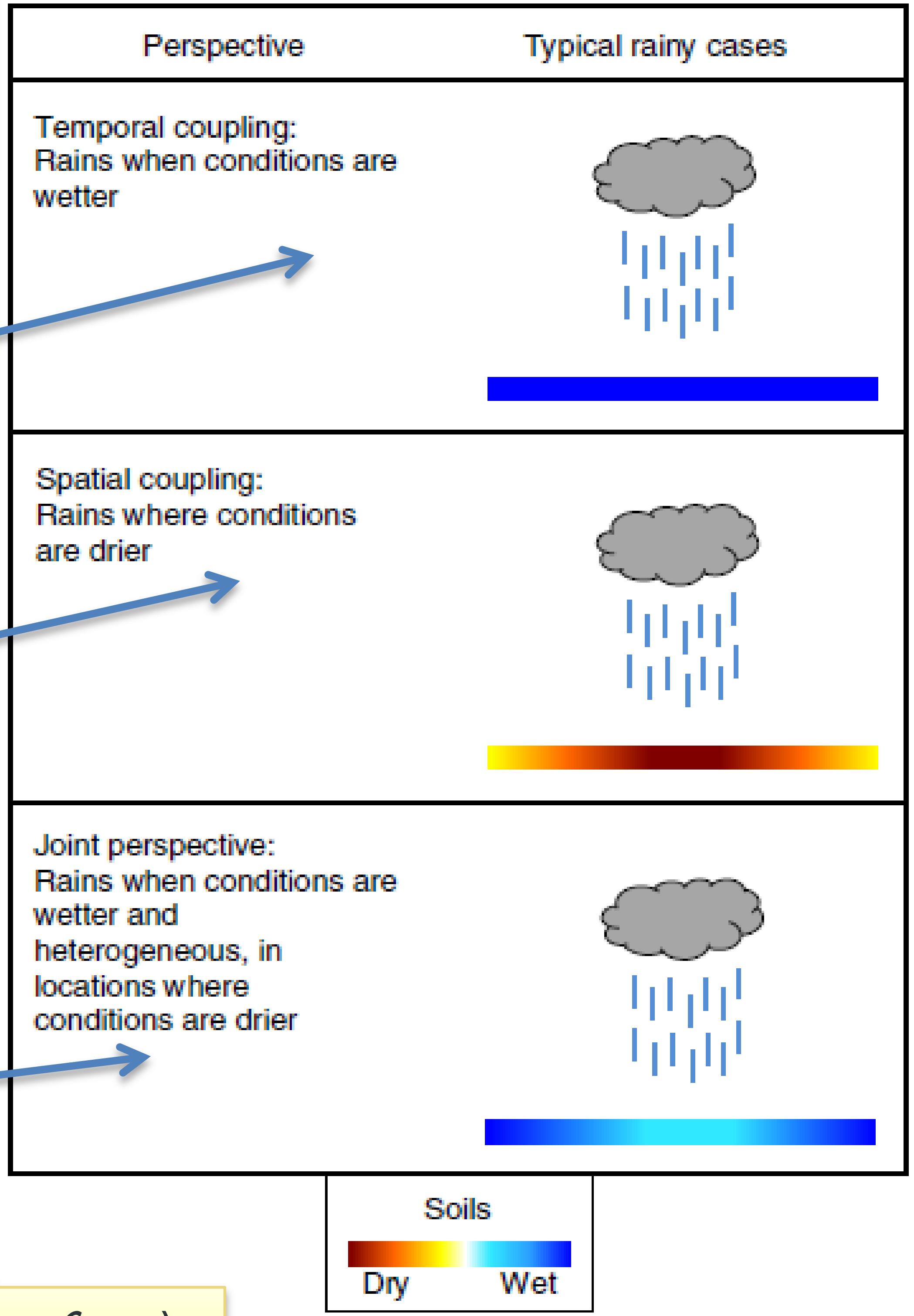
- Taylor picked up on small-scale spatial coupling that occurs at scales that are sub-grid in weather and climate models.
- They can coexist in nature, but not in models that parameterize convection conventionally.



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Land ICs in Forecasts

- 28 years of seasonal CFSv2 forecasts: 1 April, 1 May & 1 June ICs covering 1982-2009.
- 28-member ensembles, same atmosphere and ocean ICs; 27 members with land ICs from "wrong" years, 1 with "right" year.
- Additional case with land states specified from CFSR as BCs.

Atmosphere & Ocean ICs

	CFSv2	1982	1983	1984	…	2009
Land ICs	1982					
	1983					
	1984					
	…					
	2009					
BCs	Specified	1982	1983	1984	…	2009

"Wrong" Land ICs = Skill from A+O initialization

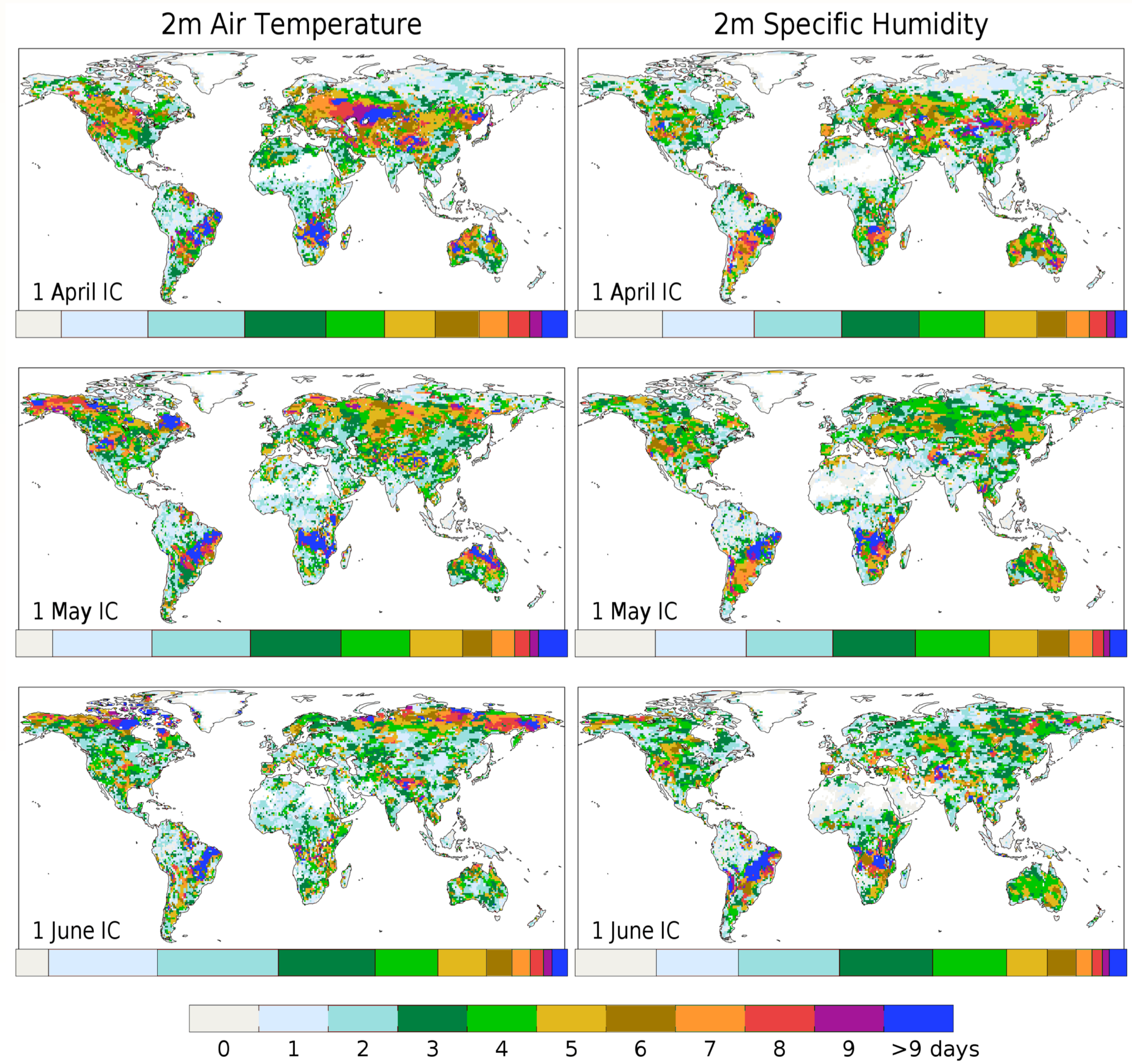
"Specified" vs "Wrong" = Maximum potential skill from land states

"Right" vs "Wrong" Land ICs = Harvested skill

"Specified" vs "Right" = Unharvested skill

Skill Manifests on Day 1

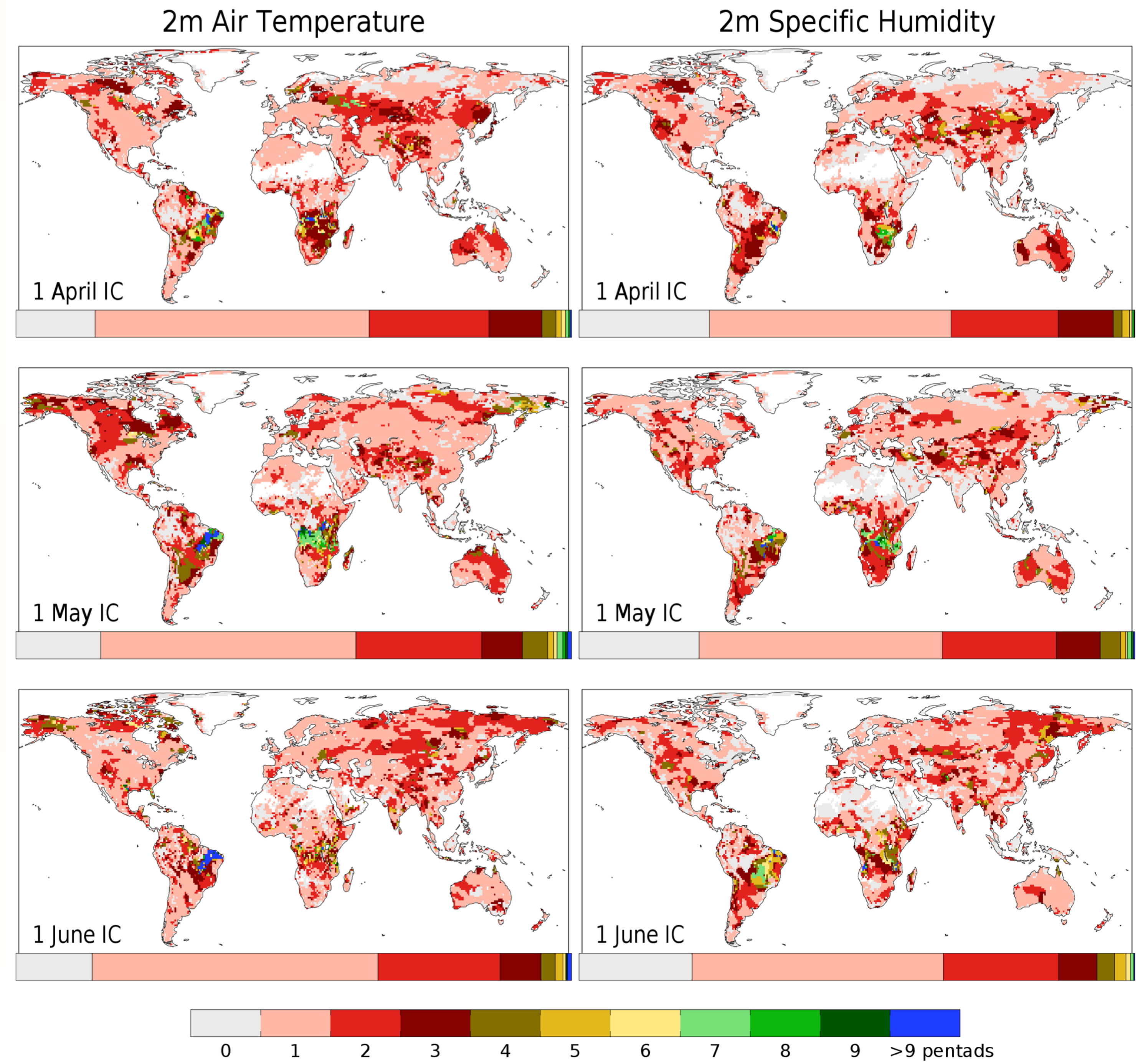
- Once the sun rises, the land surface begins to heat and interact with the lower atmosphere
- The "right" land surface initialization extends forecasts of daily means a median of 3 days (skill = ACC significance at 95% confidence) in CFSv2 for 2m temperature and humidity.
- On weather time scales, soil moisture and temperature are the main factors.
- This experiment did not consider vegetation effects.



Dirmeyer & Halder (2016: *W&F*)

S2S Skill from Land Surface Initialization

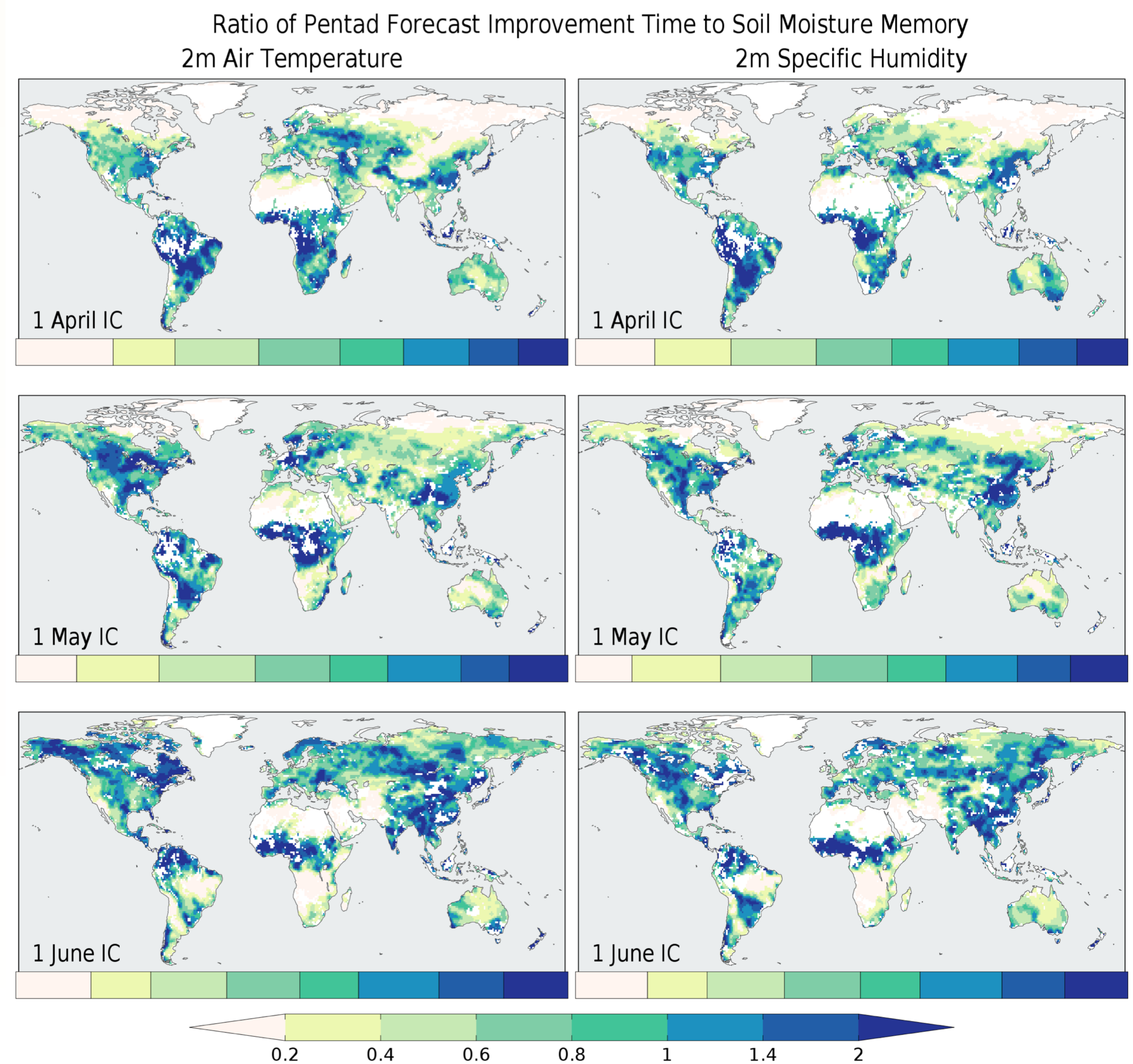
- Looking at longer time scales (pentad means); how many pentads is significant forecast skill (ACC) extended by using the "right" land ICs?
- ~40% of globe has skill extended by 2 pentads or more, ~80% at least 1 pentad.
- For monthly means, 30-50% area has skill extended ≥1 month.
- **Neglecting land surface initialization seriously degrades forecast skill.**



Dirmeyer & Halder (2017: *JHM*)

How Much Memory is Harvested as Skill?

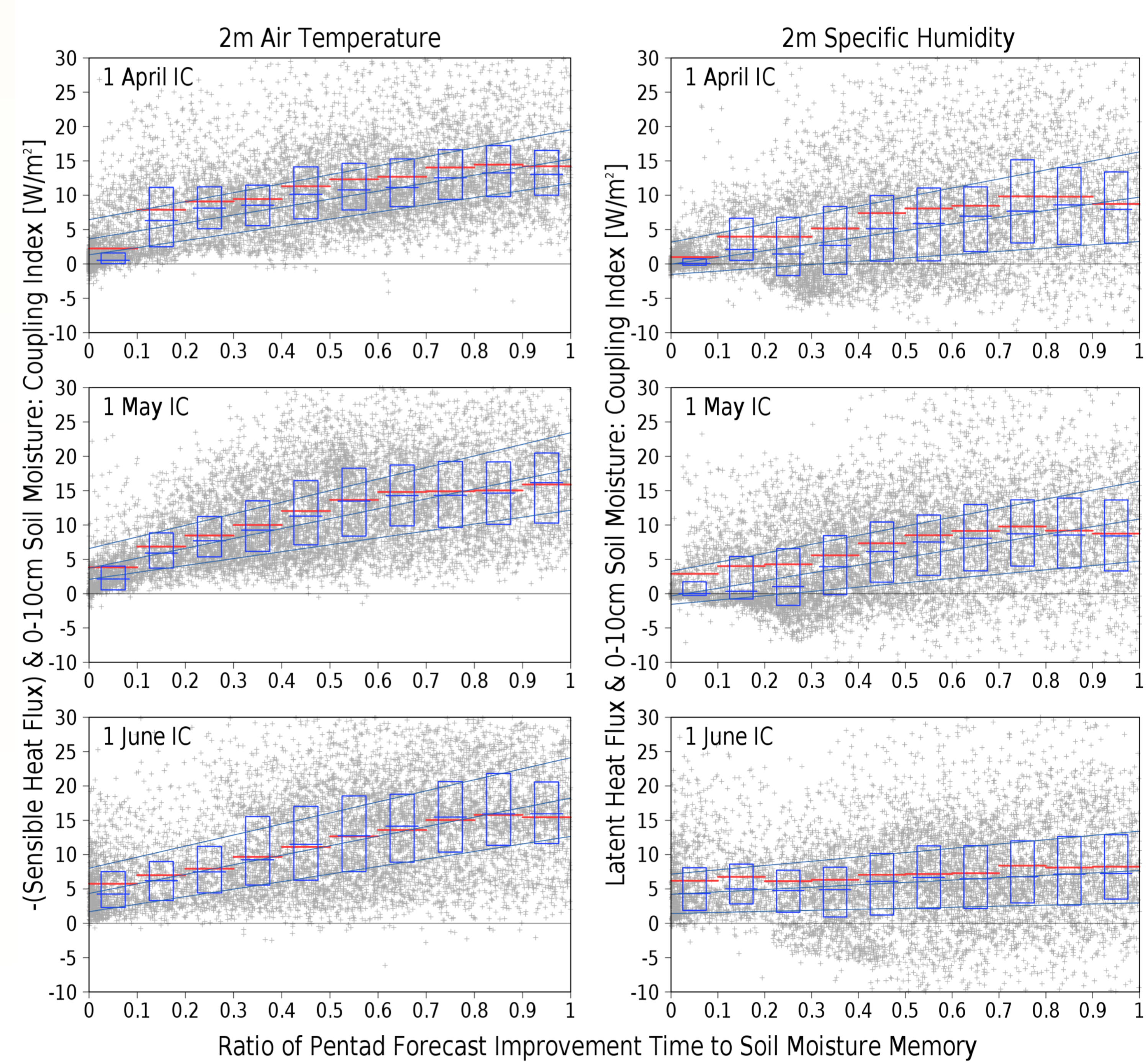
- Ratio of forecast improvement time to soil moisture memory in CFSv2 (a sort of "efficiency").
- Light areas: potential impact of land surface not realized – why?
  - Inherent lack of sensitivity or variability (other two ingredients)
  - Model parameterization errors
  - Poor quality land initialization
- Dark areas: land contribution realized – again, why??



Dirmeyer & Halder (2017: *JHM*)

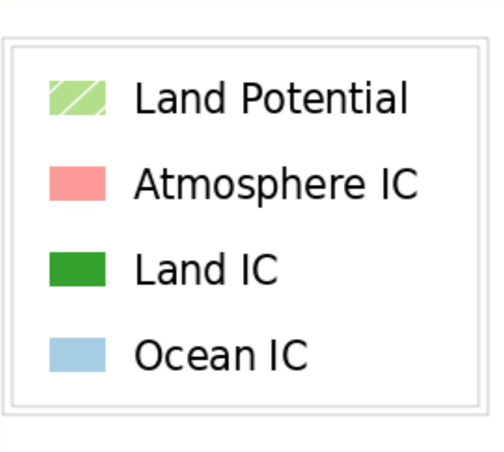
Compare Efficiency to Coupling Indices

- Clear correlation evident between (X-axis) "efficiency" of converting good land ICs into forecast improvement, and the strength of L-A coupling.
- So the "inherent sensitivity" is a contributing factor (for CFSv2)! Those other 2 ingredients matter.
- In other words, we can wring skill from improved land surface initialization in this model.



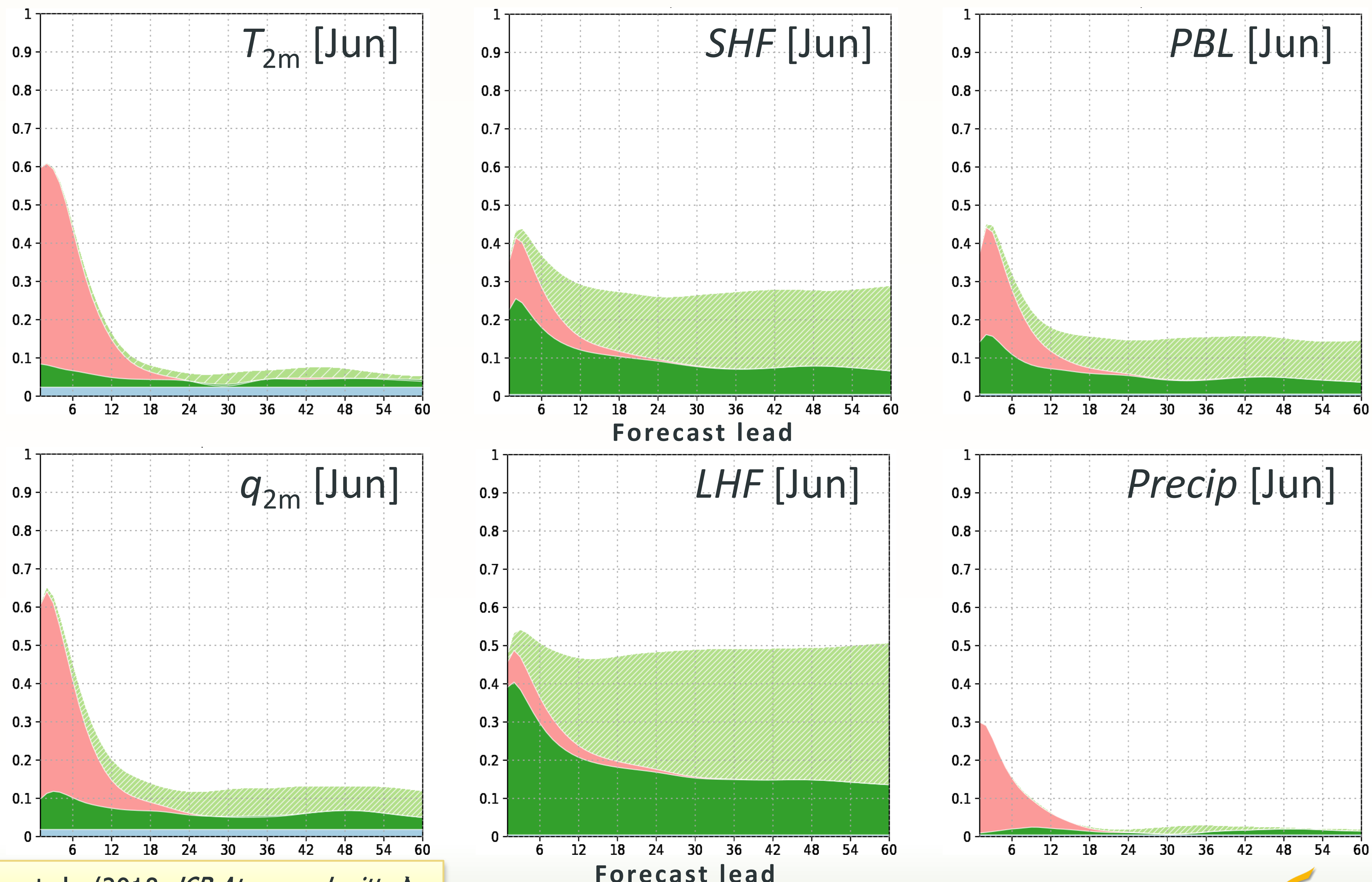
Dirmeyer & Halder (2017: *JHM*)

Contributions to Skill in CFSv2



Convective parameterizations can decouple precipitation from PBL development and land surface influence.

"Potential" is model-specific, unmeasurable.



Dirmeyer et al., (2018; *JGR-Atmos. submitted*)

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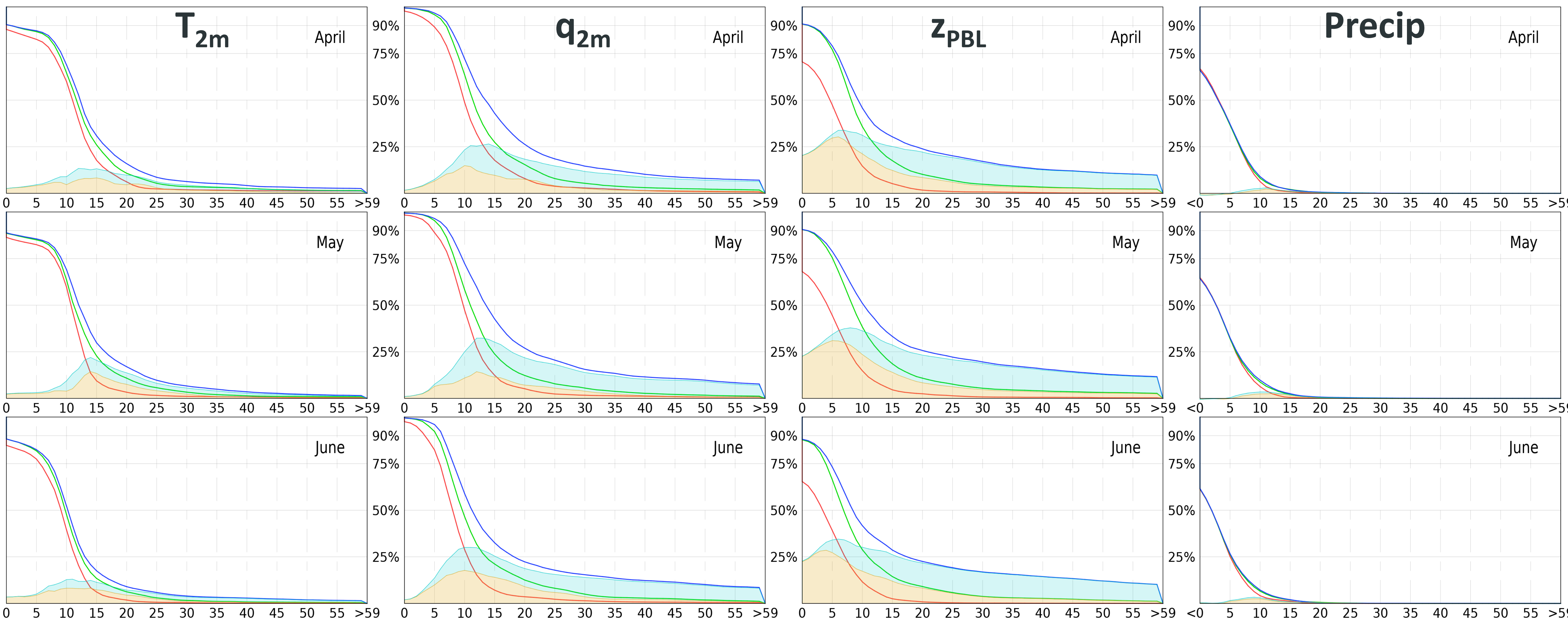
The fraction of land area exhibiting significant skill as a function of forecast lead time with specified land states (blue), right land ICs (green) and wrong land ICs (red). Shaded curves show the difference between green and red curves (tan) and between blue and green curves (pale blue).



L-A Science: A Backwards Scientific Path

- The science of land-atmosphere interactions has proceeded backwards from the traditional progression from observation of natural phenomena, formulation of hypotheses, development of experiments and construction of models.

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- The science of land-atmosphere interactions has proceeded backwards from the traditional progression from observation of natural phenomena, formulation of hypotheses, development of experiments and construction of models.
- LSMs were developed initially to provide BCs for AGCMs, before there were wide-ranging observations of the land surface or land-atmosphere interactions applicable to model development.
- Early LSMs consisted of poorly-validated collections of conceptual and/or empirical parameterizations that were calibrated on a handful of locations at best (e.g., Sellers and Dorman, 1987) then applied globally out of necessity.

L-A Model Bias

- Climate drift's effects and thus its causes were not obvious over land like over ocean (SSTs well observed).
- 2m air temperature biases were the clearest symptom of flux imbalance.
- Since there were no observational global data sets of soil moisture, it became the "tuning knob" to address biases.
- ECMWF *still* nudges initial soil moisture to minimize near-surface temperature and humidity biases.

Sequential Assimilation of Soil Moisture from Atmospheric Low-Level Parameters. Part I: Sensitivity and Calibration Studies

F. Bouttier, J.-F. Mahfouf, and J. Noilhan

Météo-France/CNRM, Toulouse, France

(Manuscript received 30 July 1992, in final form 31 December 1992)

ABSTRACT

This paper and its companion report on the development of a sequential assimilation technique based upon optimum interpolation in order to initialize soil moisture in atmospheric models. A previous study by Mahfouf has demonstrated that it is possible to estimate soil moisture from the evolution of atmospheric temperature and relative humidity near the surface. The main purpose of this paper is to examine more precisely the dependence of atmospheric low-level parameters upon soil moisture and how this dependence is affected by various factors (soil characteristics, vegetation type, low-level wind). The sensitivity of atmospheric parameters to soil moisture is expressed as the statistical quantities of the optimal interpolation. The importance of observation errors, which define the relevance of the atmospheric parameters for the assimilation procedure, is also investigated. An analytical formulation of the optimal interpolation coefficients is proposed. Finally, the usefulness and limitations of this work for soil moisture analysis in three-dimensional models are discussed.

The Influence of Initial Soil Wetness on Medium-Range Surface Weather Forecasts

R. Yang, M. J. Fennessy, and J. Shukla

Center for Ocean–Land–Atmosphere Interactions, Department of Meteorology, University of Maryland, College Park, Maryland

(Manuscript received 3 February 1993, in final form 7 September 1993)

ABSTRACT

The influence of initial soil wetness on surface weather forecasts was quantitatively assessed through the use of the Center for Ocean–Land–Atmosphere Interactions (COLA) general circulation model with an advanced simple biosphere model. The sensitivity of the COLA GCM to changes in initial soil wetness (ISW) is determined by repeating three 10-day integrations with the same initial and boundary conditions as the control runs except the values of ISW, which are revised at 69 model grid points covering much of the continental United States. It is found that the relationship between the changes in the 5-day mean forecasts of surface air temperature and surface specific humidity and the changes in ISW depends upon vegetation type and the values of ISW, and is approximated by regression equations. With the ISW revised based on these regression equations, the first 5-day mean surface air temperature and mean surface relative humidity forecast errors over the relatively dry western portion of the domain are reduced from 2.9° to 1.1°C and from 15% to 7.6%, respectively. Somewhat smaller surface forecast improvements occur for the following 5 days. The impact on the upper atmosphere is small and is largely confined to lower levels.

It is also found that the model soil wetness has strong persistence. Therefore, additional forecast experiments are carried out in which the initial soil wetness for a 10-day integration is revised based on the surface forecast

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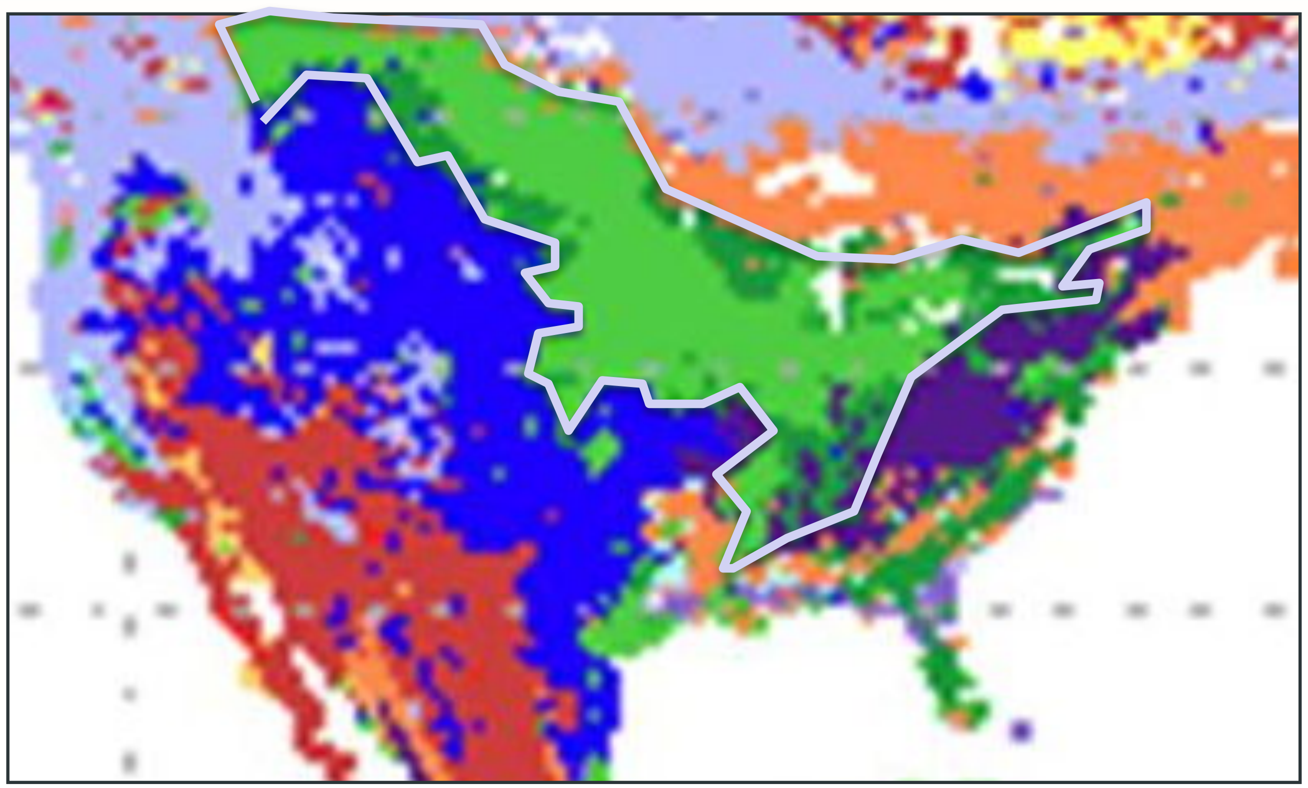
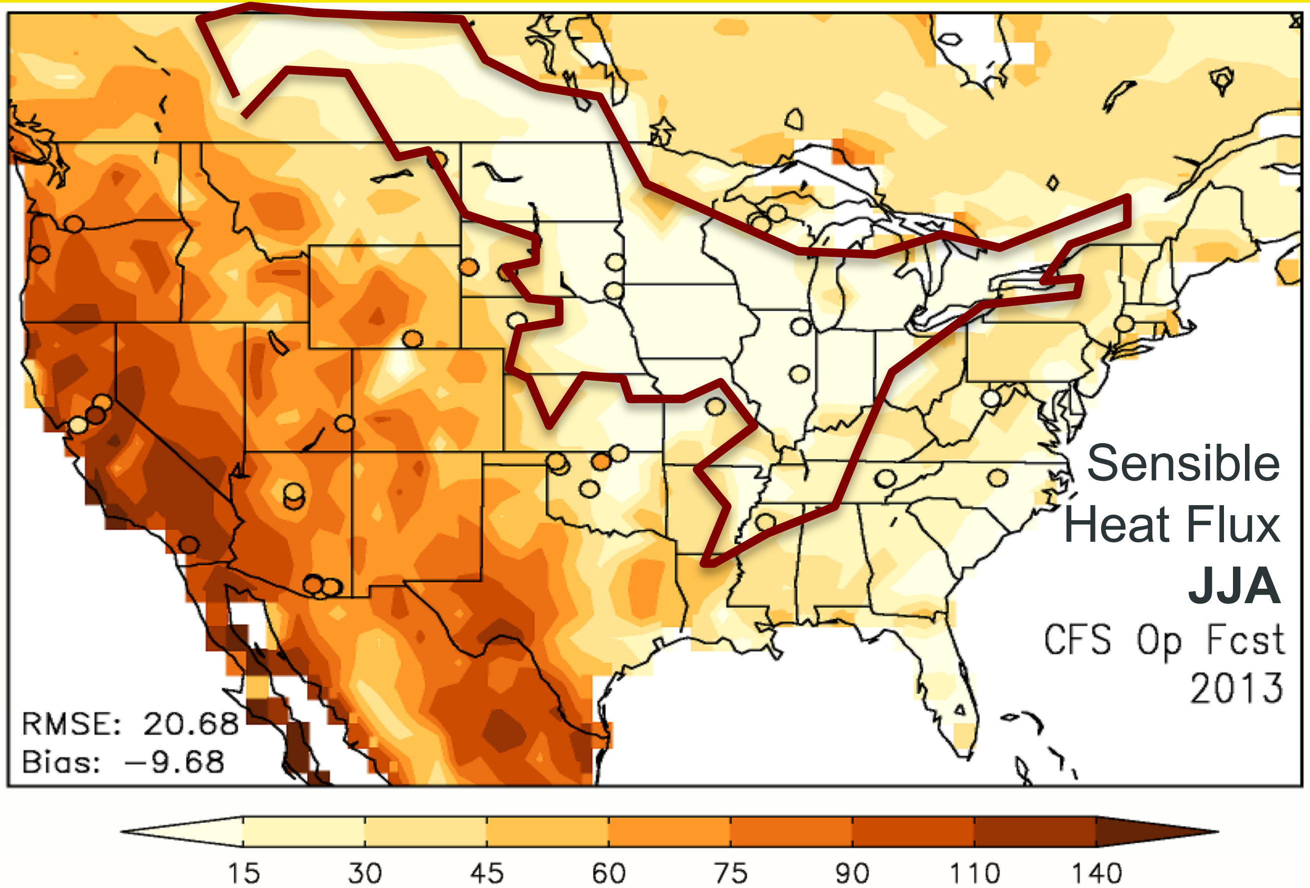
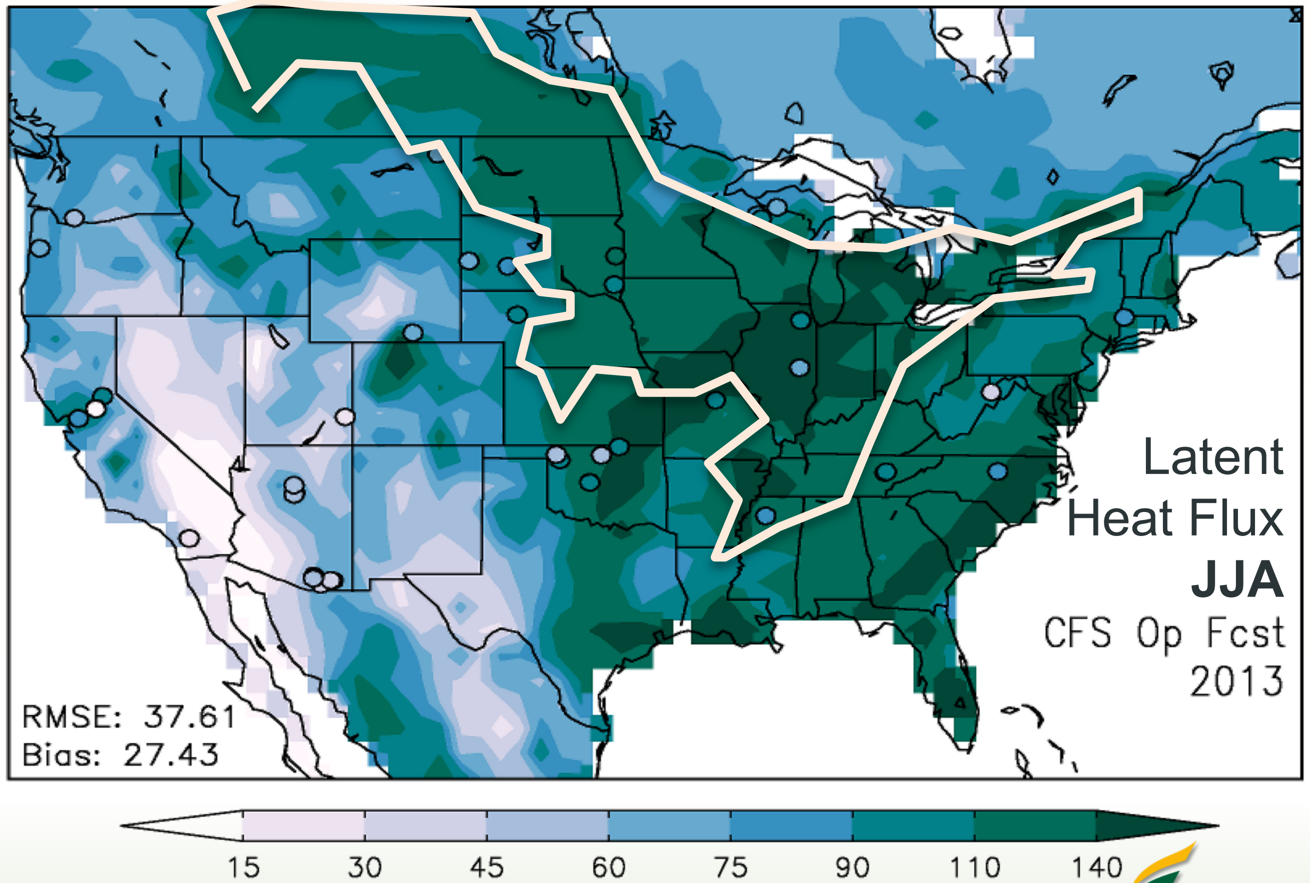
LSM as Scapegoat

- To correct warm biases in CFSR, roots for Noah crop vegetation type were extended to all 4 soil layers; it transpires too freely.



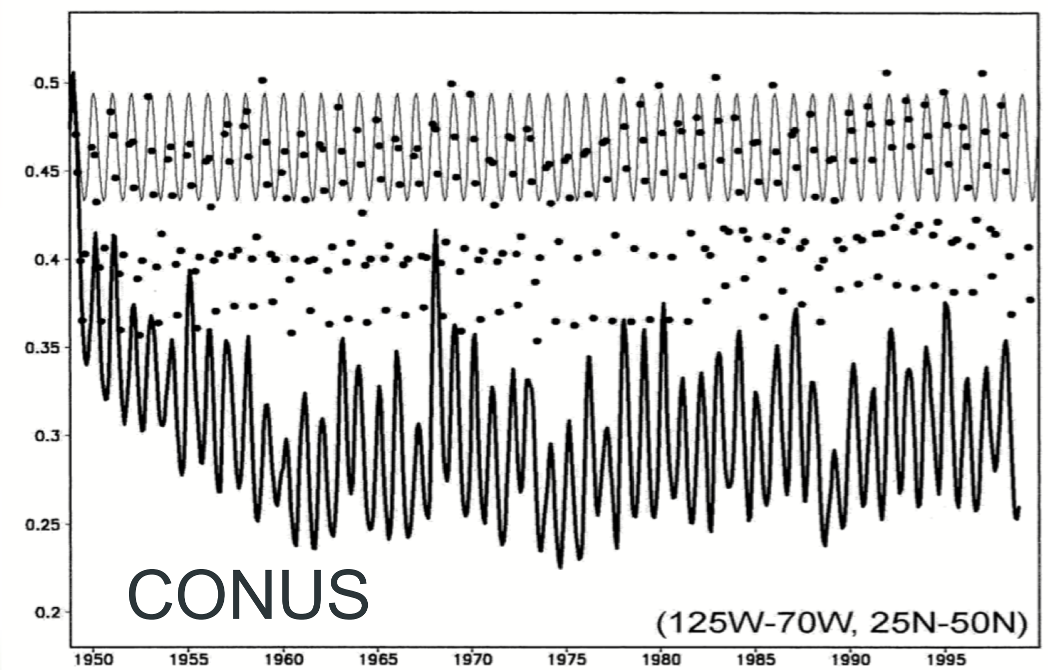
Green: Total and partial cropland

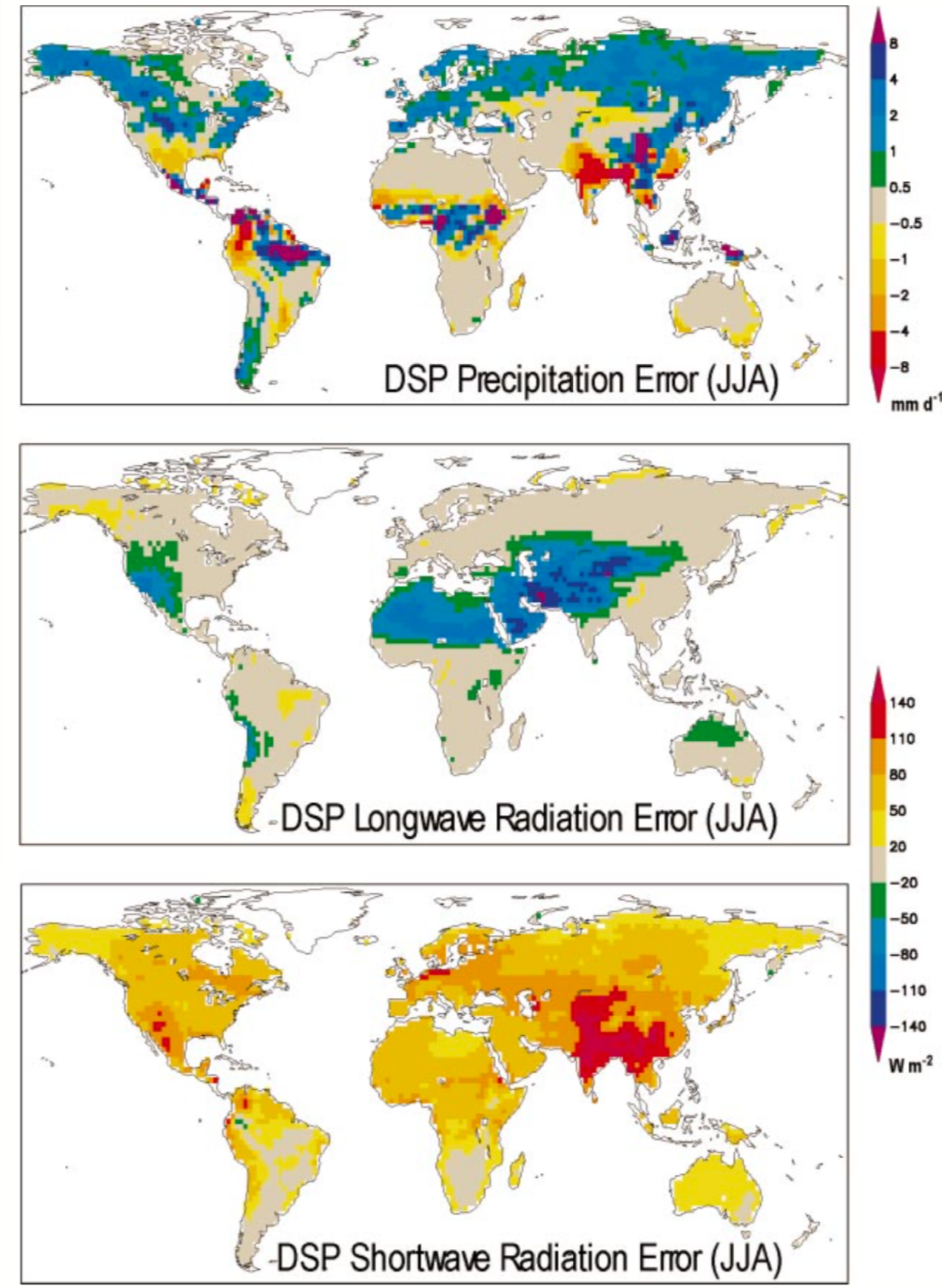




Multiple Culprits

- Biases in precipitation and downward radiation at the land surface, unrelated to land surface processes, put LSMs at an immediate disadvantage (right).
- As a result, soil moisture (below) drifts in the first months (dots) and years (bold line).
- An early clue regarding L-A coupling problems.

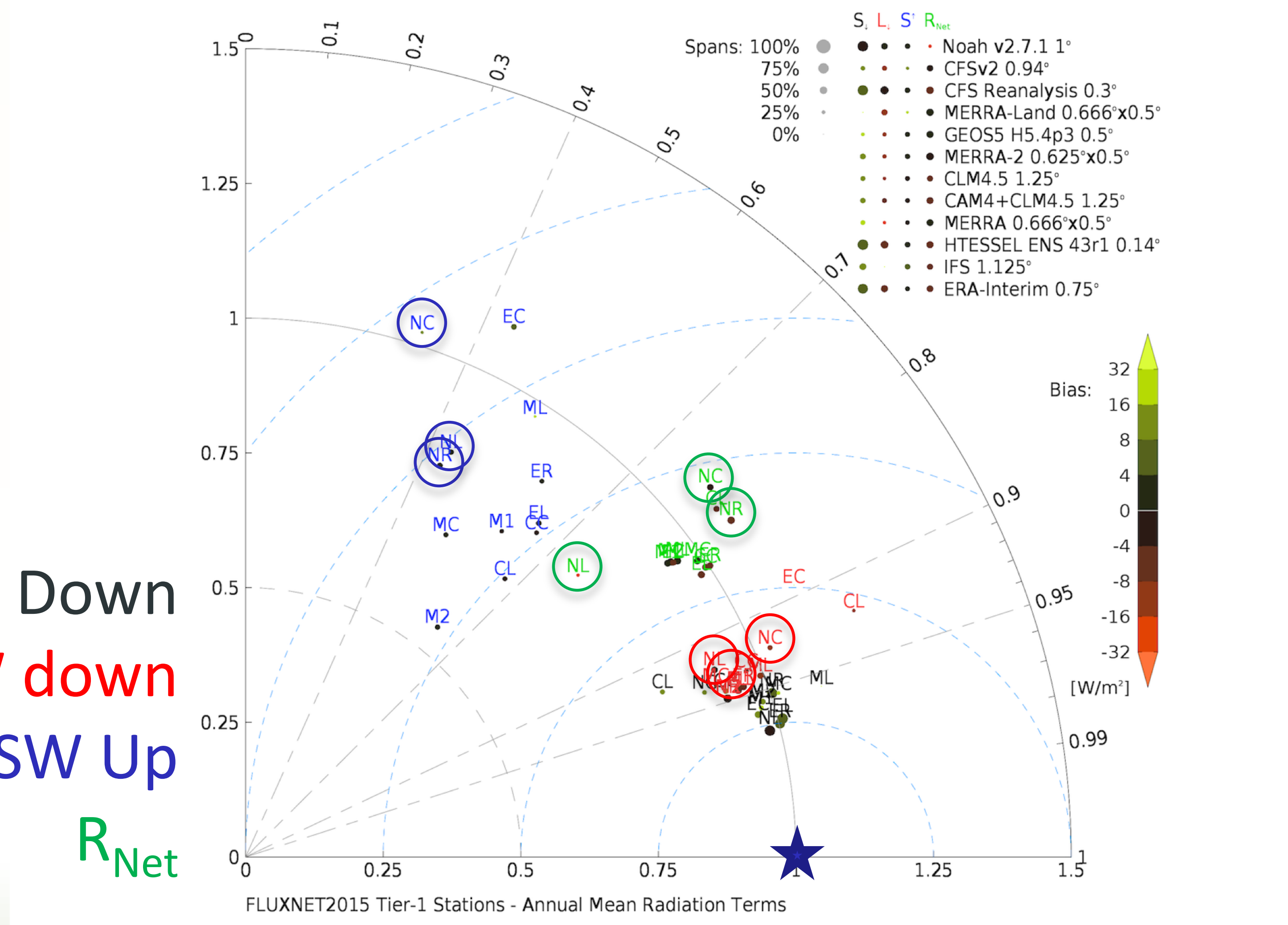




Dirmeyer (2003; JHM)

Problems Persist

- Compared across ~160 FLUXNET sites, today's models still struggle.
- There also appears to be a real problem with LSM surface albedos (below).

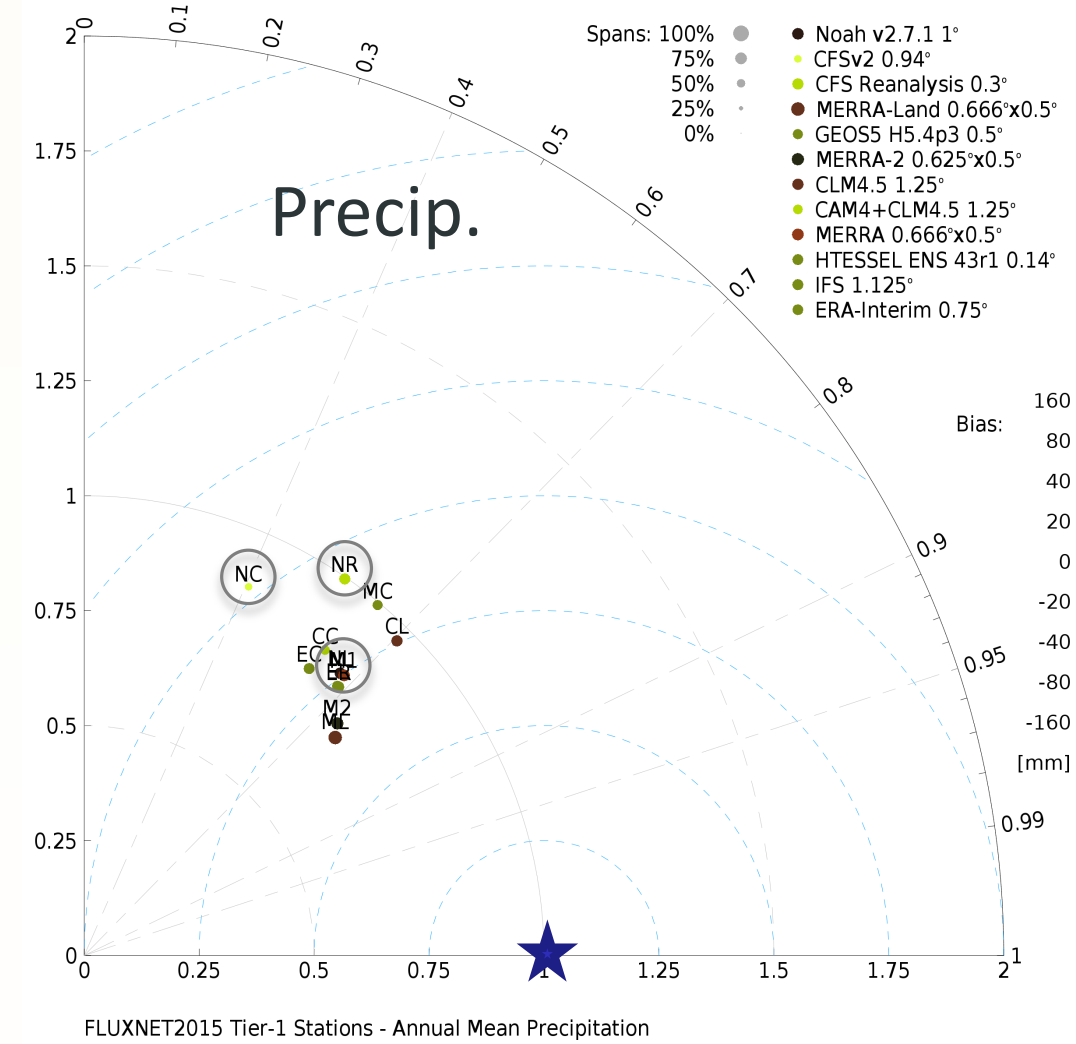


SW Down

LW down

SW Up

R_{Net}

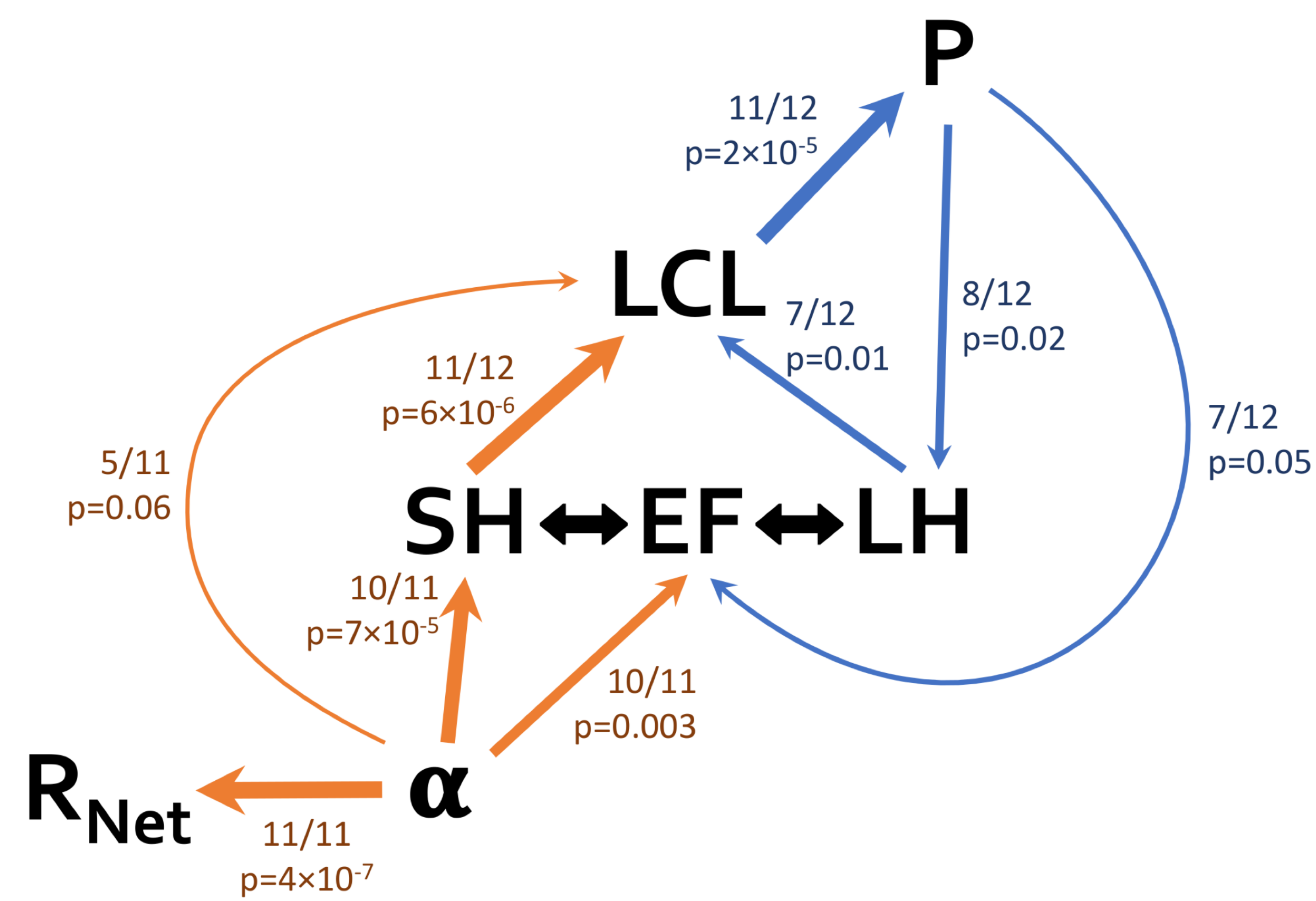


Basic errors impair simulation of surface sensible and latent heat fluxes!

Dirmeyer et al. (2018; JHM)

Error Propagation in Coupled L-A Models

- Propagation of errors estimated from their rank correlations across FLUXNET2015 stations.
- Ratios show the number of models with p-values below 0.10, based on average of correlations across 4x3 models.



Dirmeyer et al. 2018: (*JHM*)

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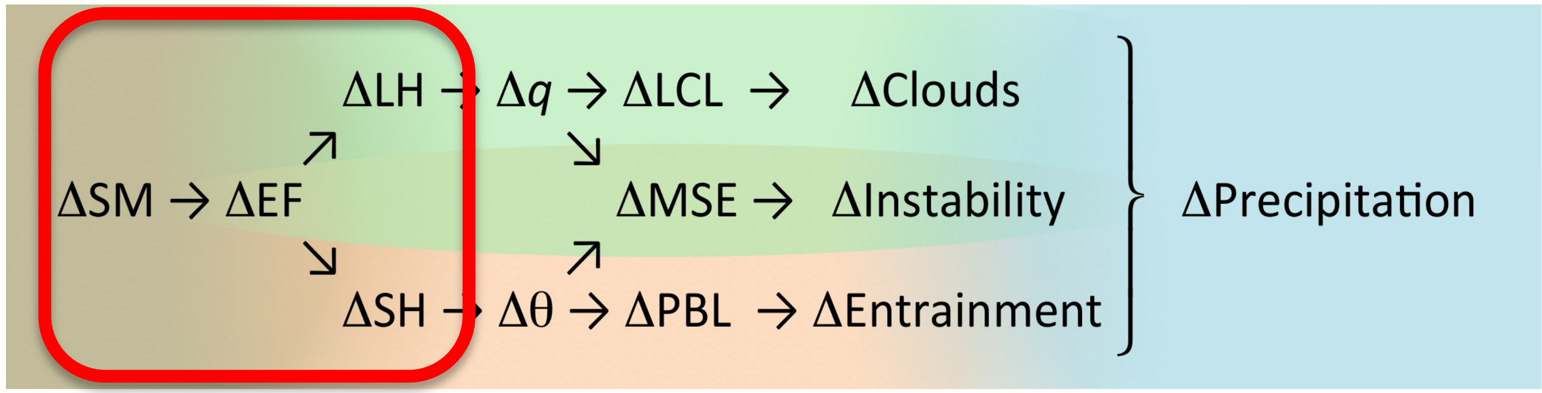

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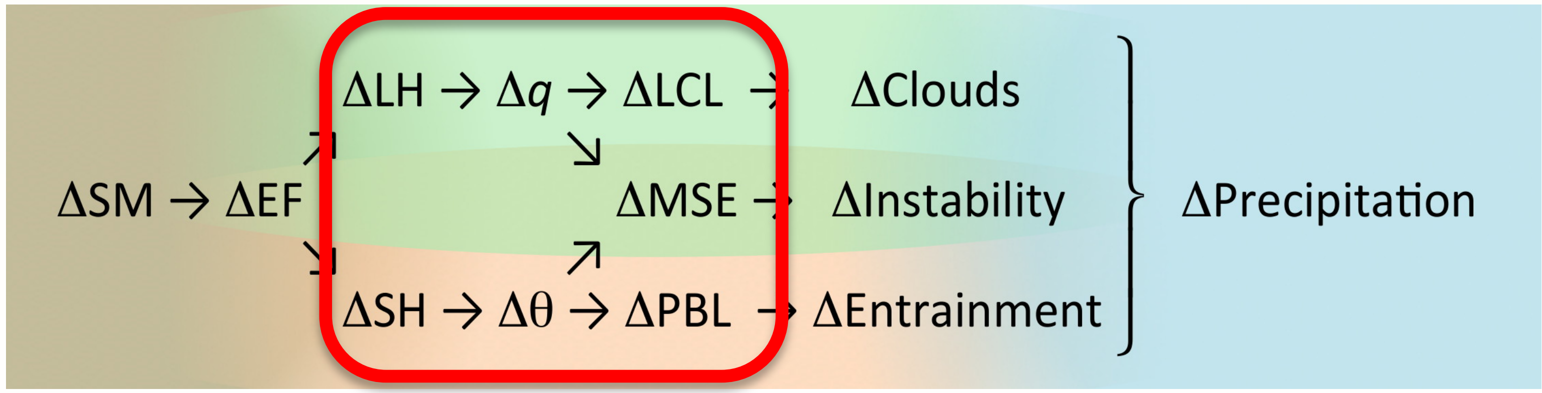


- The atmospheric leg (surface fluxes to PBL properties, clouds and convection) is too weak in the coupled L-A models compared to what can be inferred from FLUXNET2015 sites.

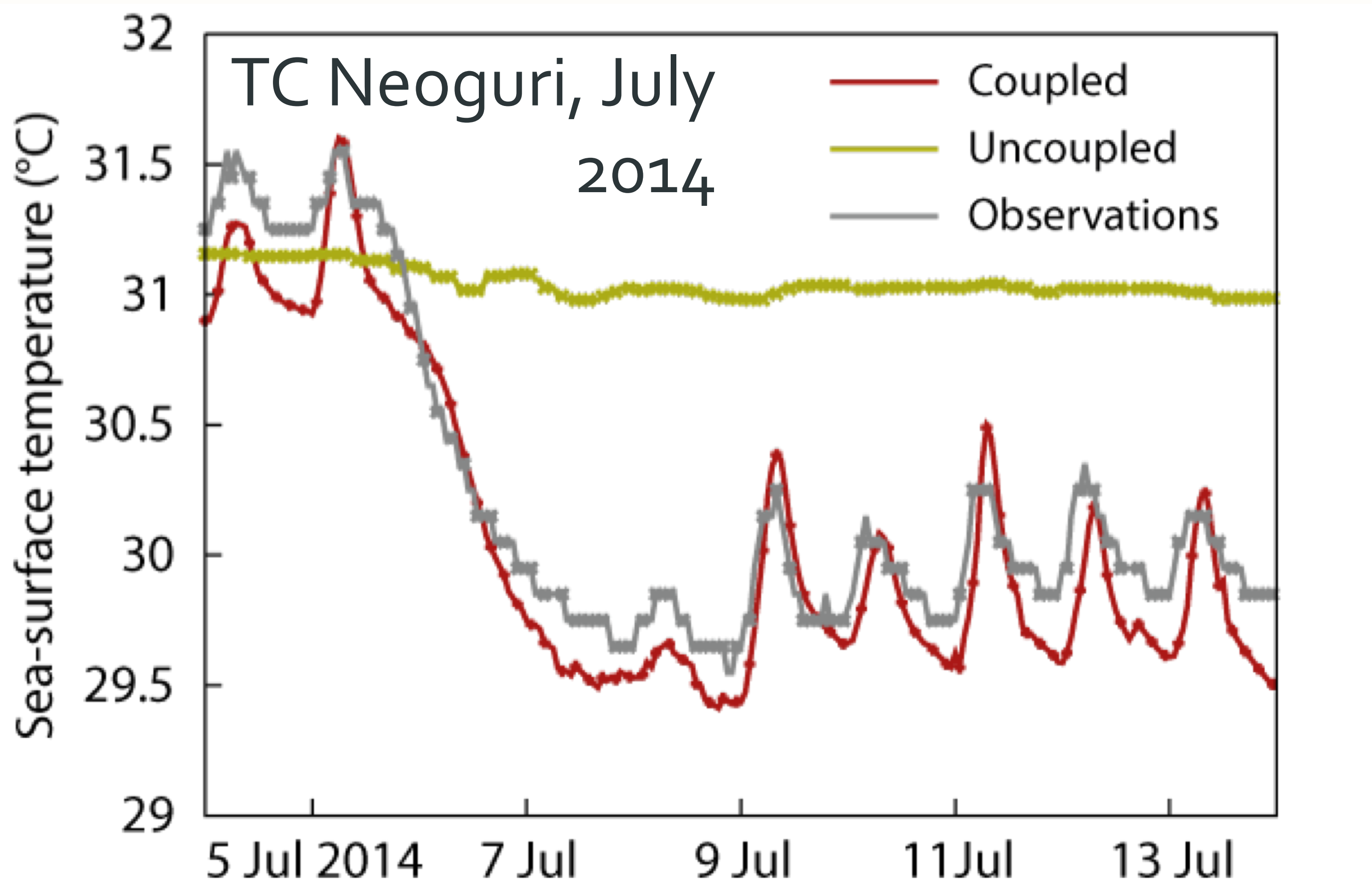
Dirmeyer et al. 2018: (*JHM*)

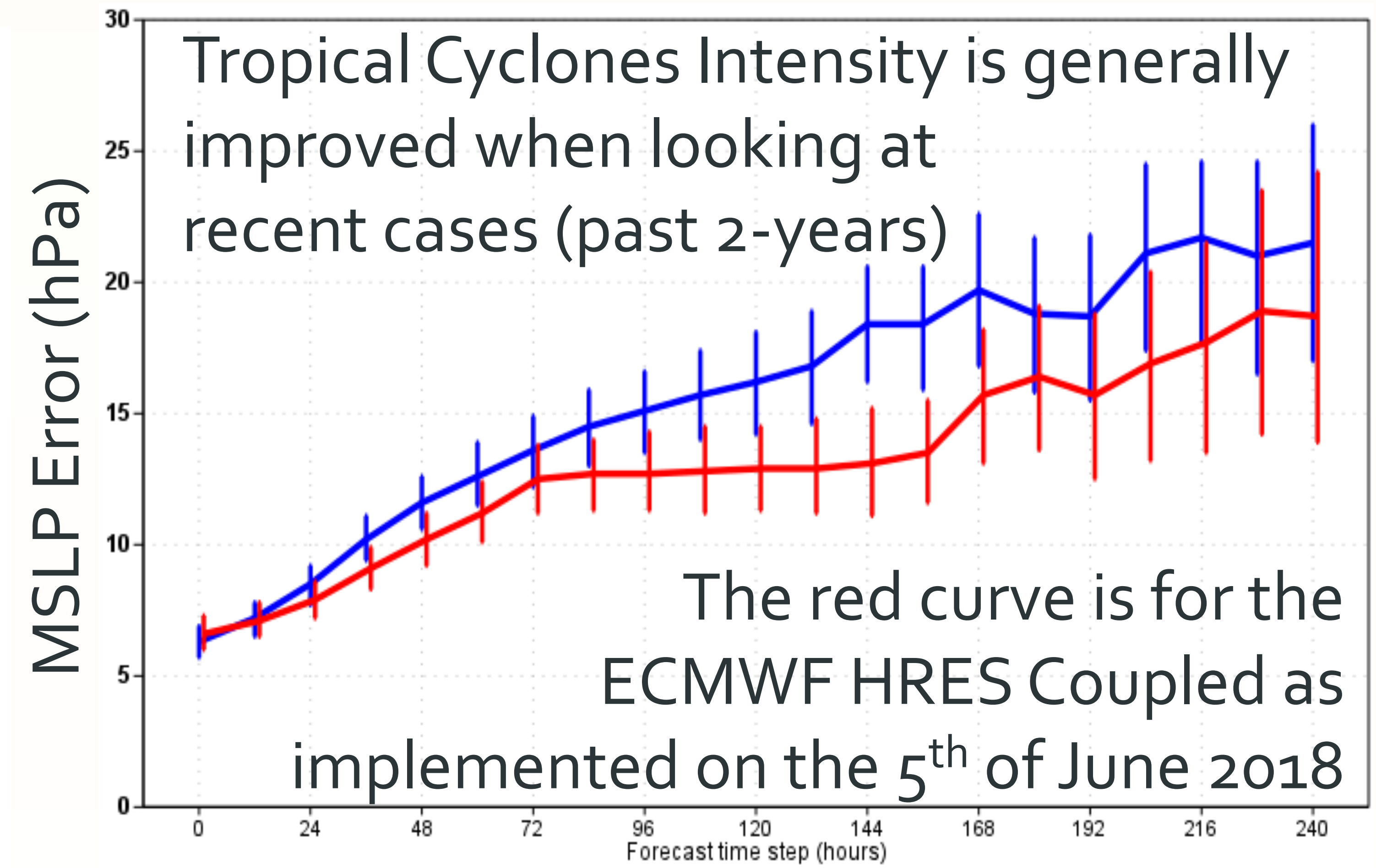
Models Are Balances of Errors

- Remove one model error, and the *tuning* that compensated for its presence becomes out of balance.
- This is why model development, calibration and validation must be carefully pursued and documented, and not done *ad hoc*.
- In coupled model systems, the scope of development and calibration grows broader; a system-level model development plan in necessary.

ECMWF Developments

Impact of Ocean-coupling on Tropical Cyclones and relevance for 2018 season





Mean-sea-level-pressure, MSLP in hPa, of new 45r1 (red) & 43r3 (blue). The data sample includes about 750 cases at initial time, decreasing to about 200 at forecast day 5-6 and to about 50 at day 10. Bars indicate 95% confidence.

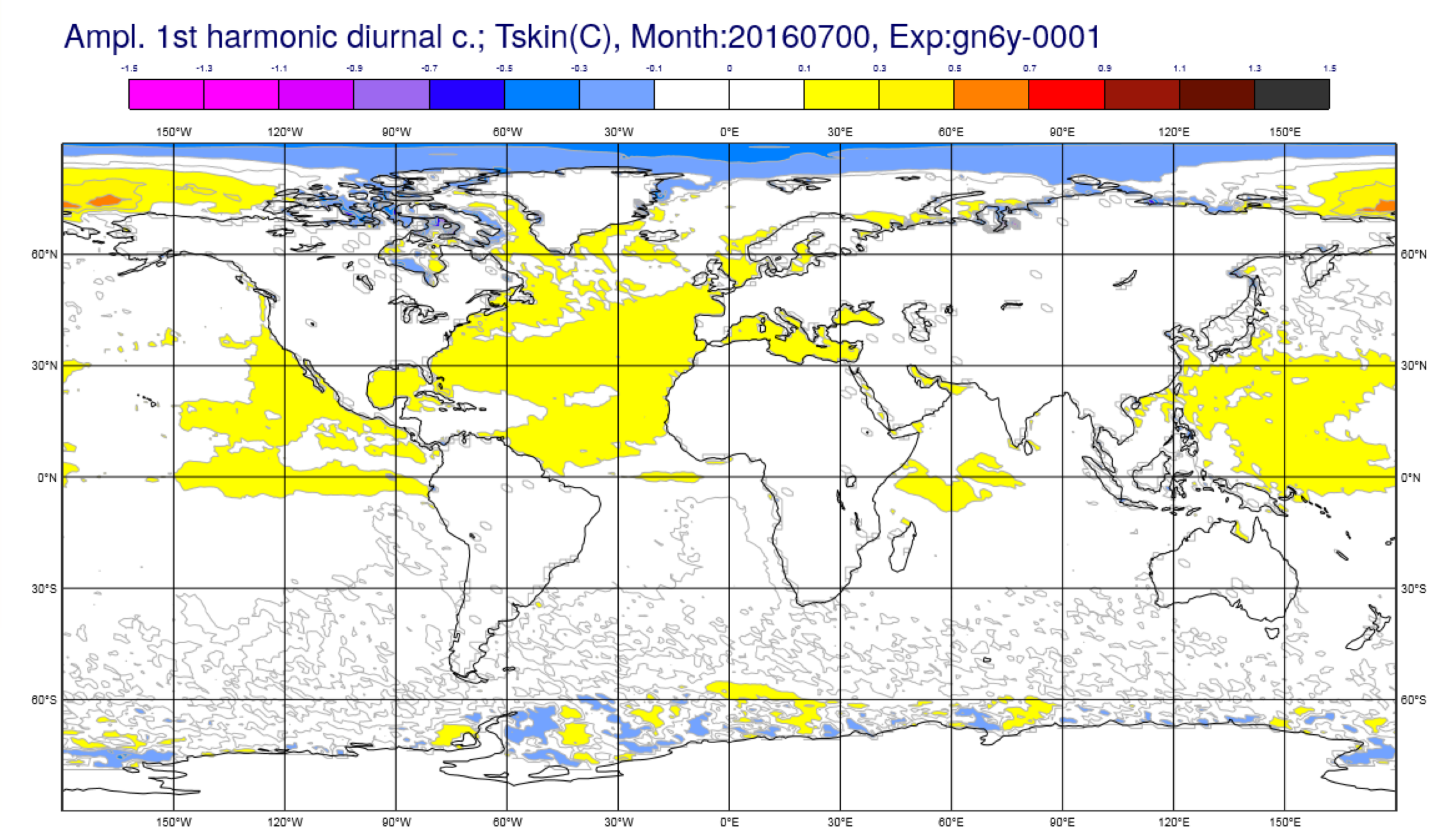
Courtesy: G. Balsamo

Thanks to Kristian Mogensen & Fernando Prates

What happens to the temperature diurnal cycle enhancing surface coupling?

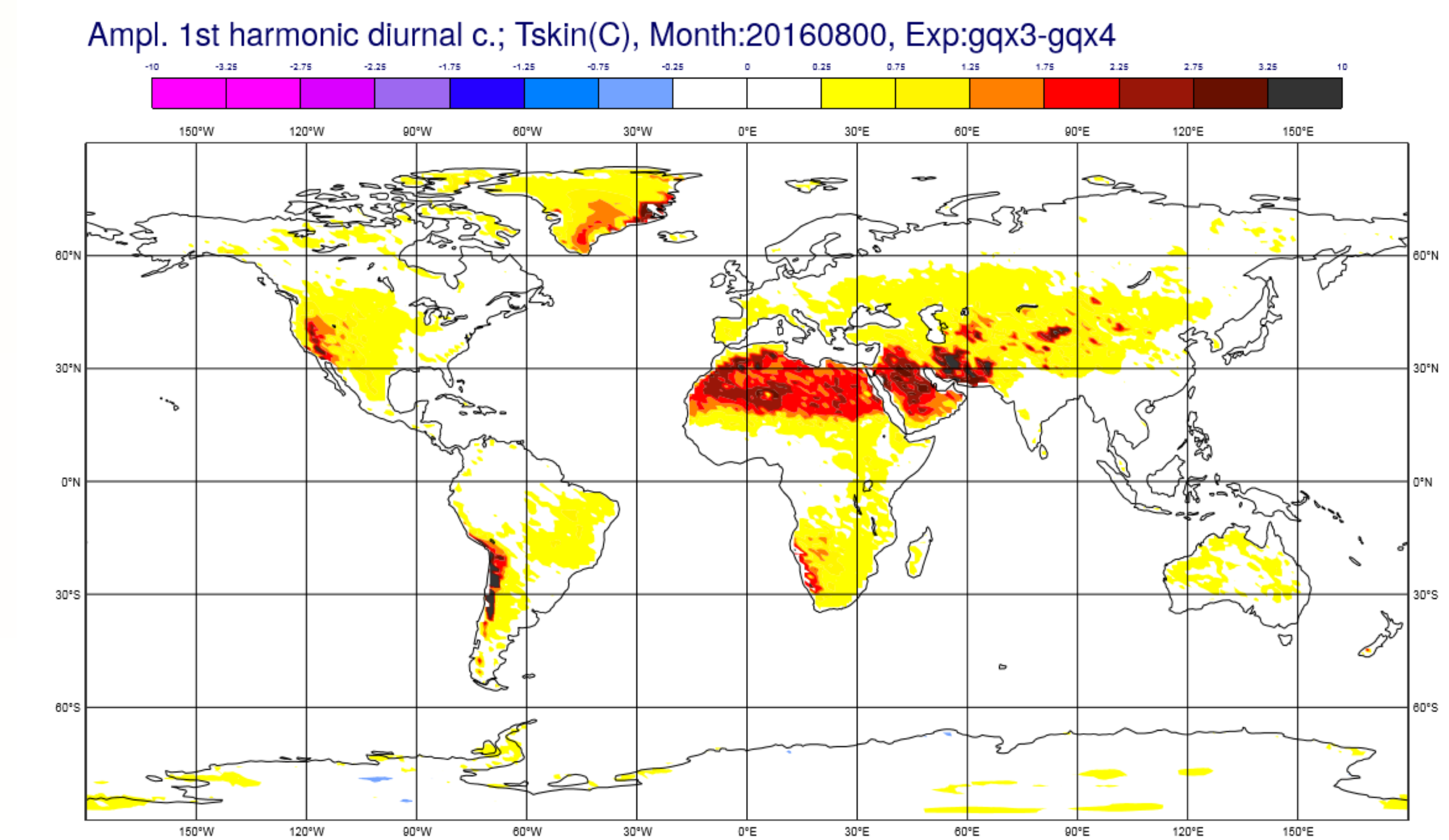
- Towards more realistic surface temperature (skin and below) particularly in clear/sky
- Towards increased variability and surface responsiveness to atmospheric forcing

Ocean skin



Difference in diurnal cycle amplitude due ocean-coupling

Land skin

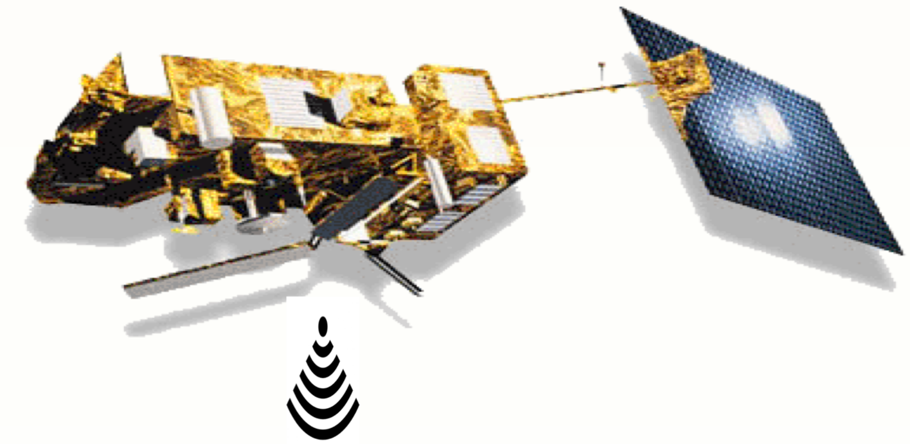


Difference due to enhance multi-layer land-coupling

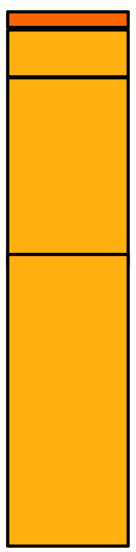
Courtesy: G. Balsamo

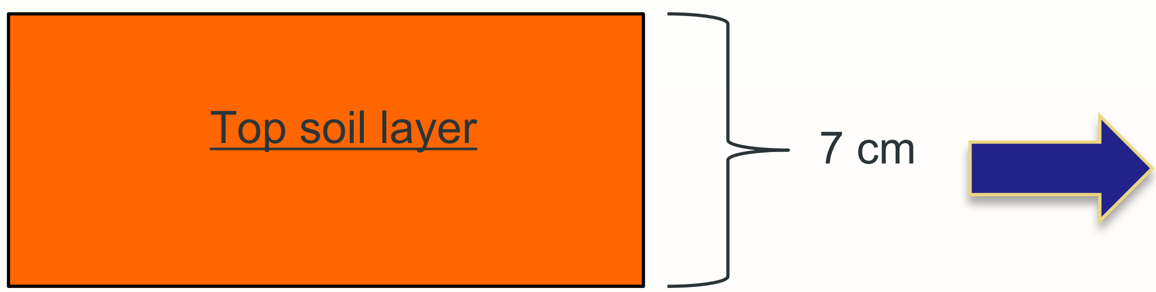
Increased soil model vertical resolution to improve use of satellite data

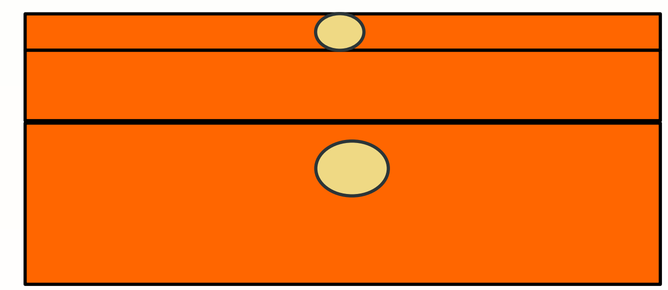
An enhanced soil vertical layer is motivated by land data assimilation as it's shown to better correlate with satellite soil moisture products



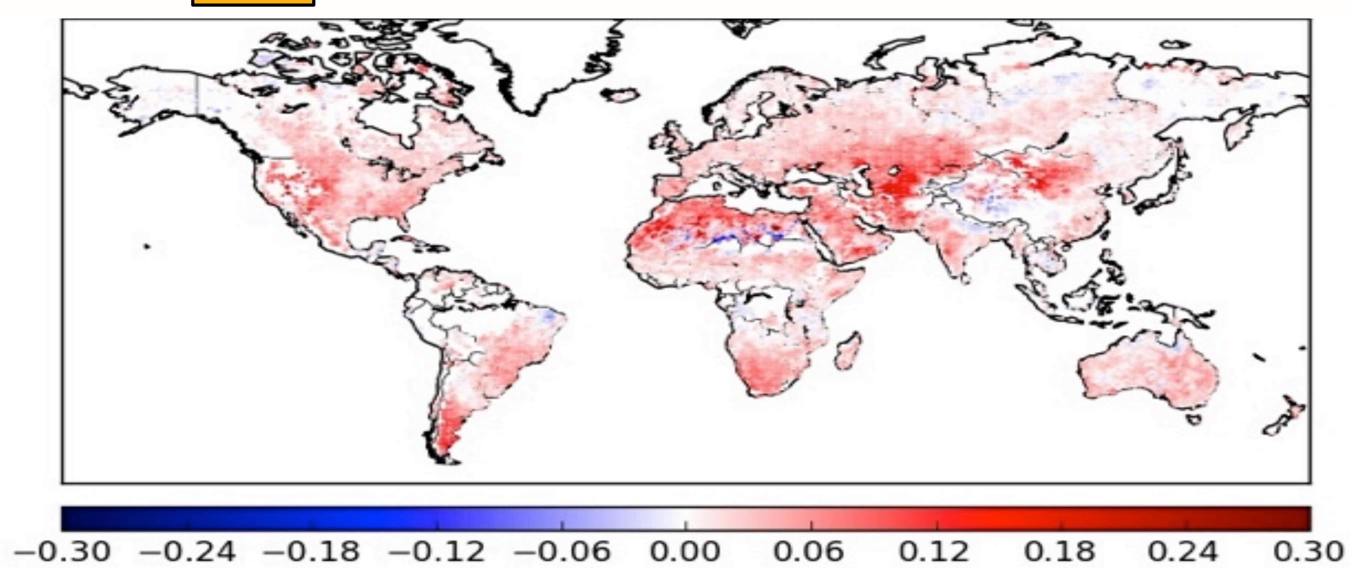
4-layers:
 # 0-7 cm
7-28 cm
28-100 cm
100-289 cm







9-layers:
 # 0-1 cm
 # 1-3 cm
 # 3-7 cm
7-15 cm
15-25 cm
25-50 cm
50-100 cm
100-200 cm
200-300 cm



Comparison with ESA-CCI soil moisture remote sensing (multi-sensor) product.(1988-2014). A finer soil model improves the correlation with measured satellite soil moisture

Globally Improved match to satellite soil moisture (shown is Anomaly correlation ΔACC calculate on 1-month running mean)

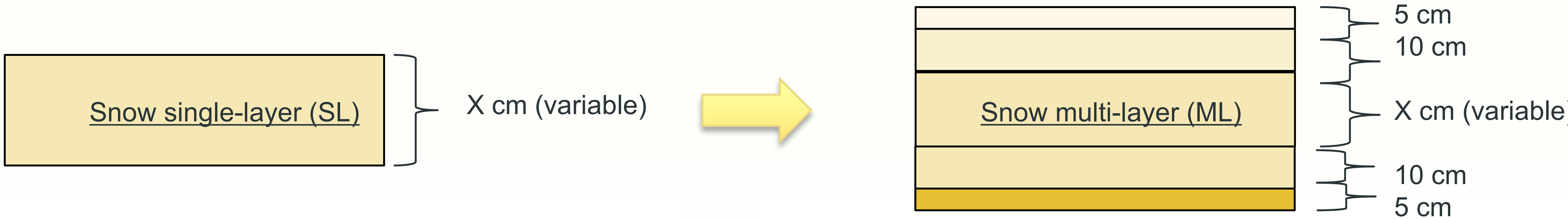
Dorigo et al. (2017 RSE)

Courtesy: G. Balsamo

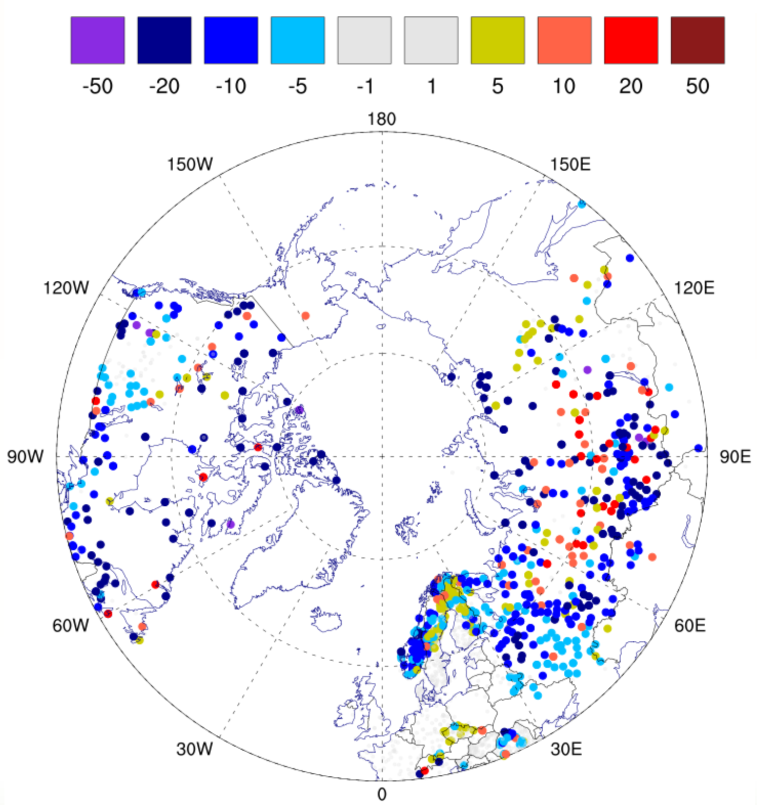
Thanks to Clément Albergel, Patricia De Rosnay, LDAS-Team

Increased snow model vertical resolution: impact in cold regions climate

Increased vertical discretization of the snowpack (**up to 5 layers**) permits a better physical processes representation

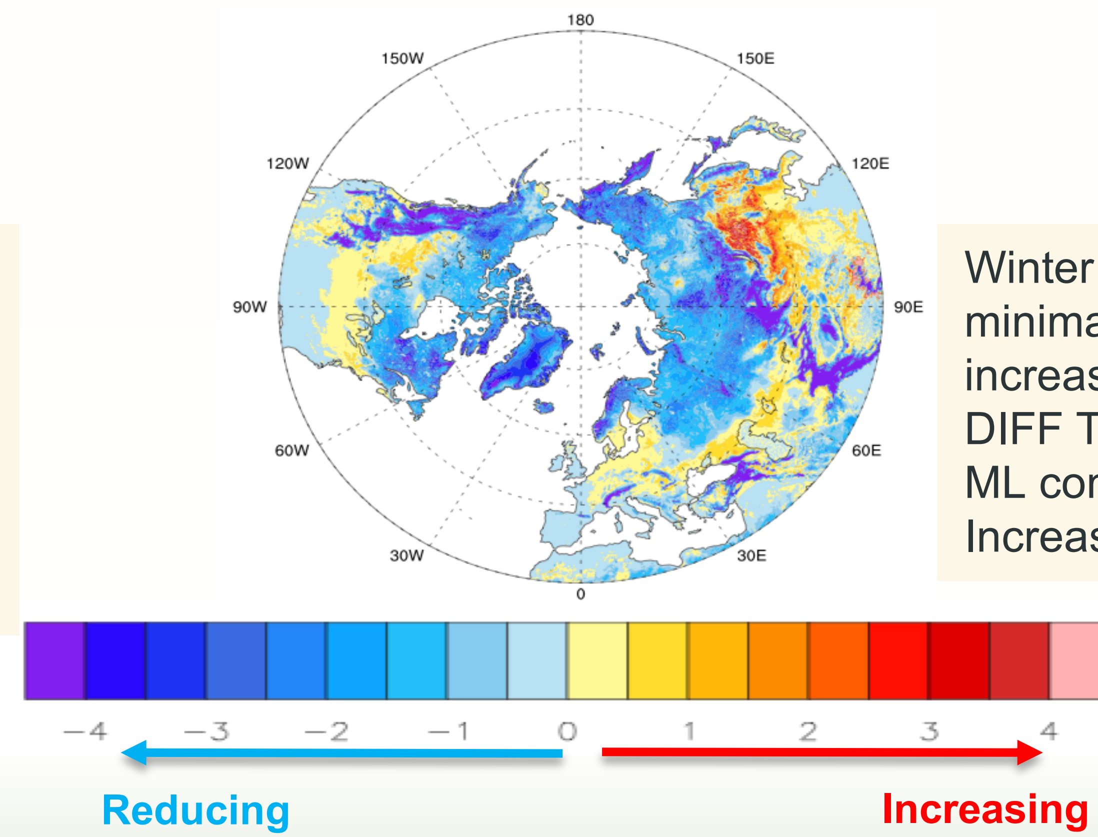


Difference ML- SL in Snow depth RMSE winter (DJF)



An improved snow depth (ML – SL) evaluated with in-situ SYNOP snow depth. RMSE of 0.19m (0.23m) in ML (SL). This is 17% RMSE error reduction in snow depth.

Difference ML - SL in T_{skin} minimum winter (DJF)



Winter reduction of the 2m minima temperatures with increasing diurnal-cycle. DIFF T*min* 2-4 K colder in ML compared to SL snow. Increased variability

Thanks to Gabriele Arduini, Jonny Day, Linus Magnusson

Courtesy: G. Balsamo

ECMWF