Soil Moisture in the Climate System

Lecture slides by Randal Koster, Global Modeling and Assimilation Office, NASA/GSFC, Greenbelt, MD, USA
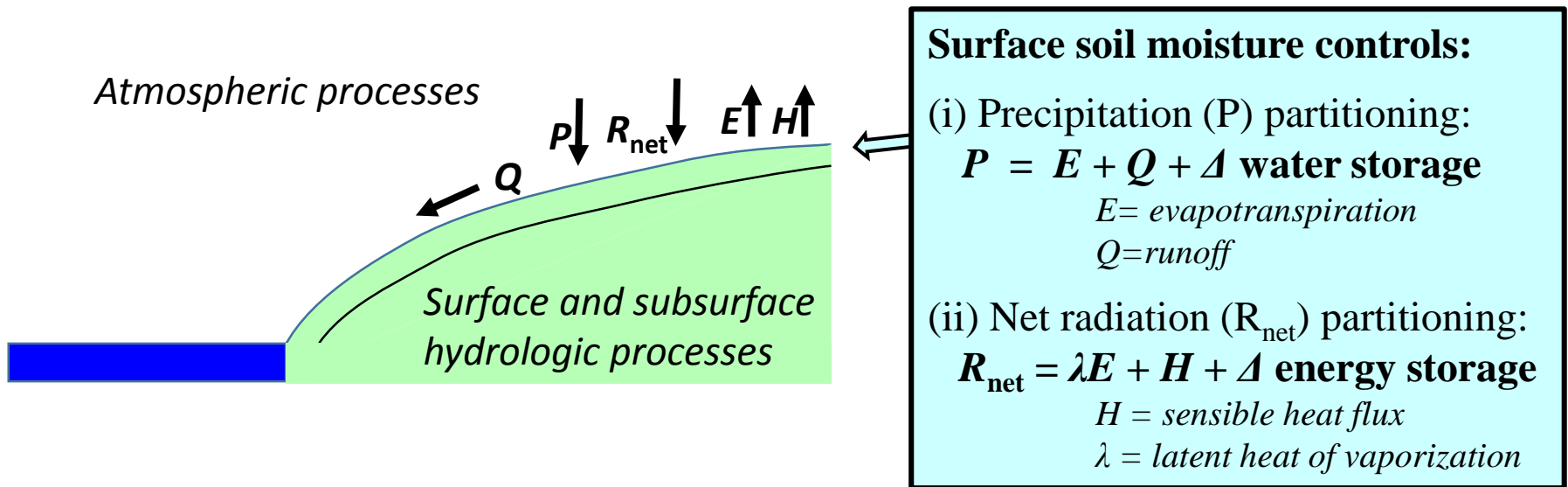randal.d.koster@nasa.gov

Soil Moisture in the Climate System

The moisture in the top two meters or so of soil is a tiny fraction (<0.01%) of the Earth's water. However, because it lies at the *interface* between the land and atmosphere, it has an *inordinate impact* on climate and its variability.

Atmospheric processes

P R_{net} E H

Q

Surface and subsurface hydrologic processes

Surface soil moisture controls:

(i) Precipitation (P) partitioning:

$$P \, = \, E + Q + \Delta \text{ water storage}$$

E= evapotranspiration
Q=runoff

(ii) Net radiation (R_{net}) partitioning:

$$R_{net} = \lambda E + H + \Delta \text{ energy storage}$$

H = sensible heat flux
λ = latent heat of vaporization

How Does Soil Moisture Affect Climate Variability?

Through its impact on the surface energy and water balances, as characterized by its impact on evapotranspiration.
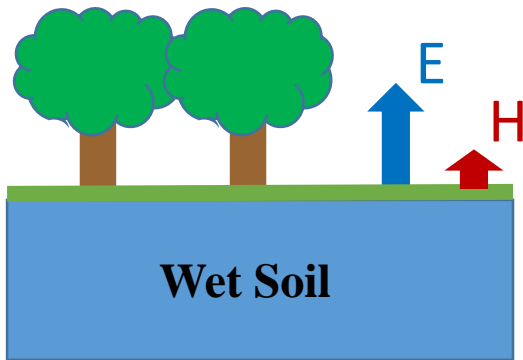
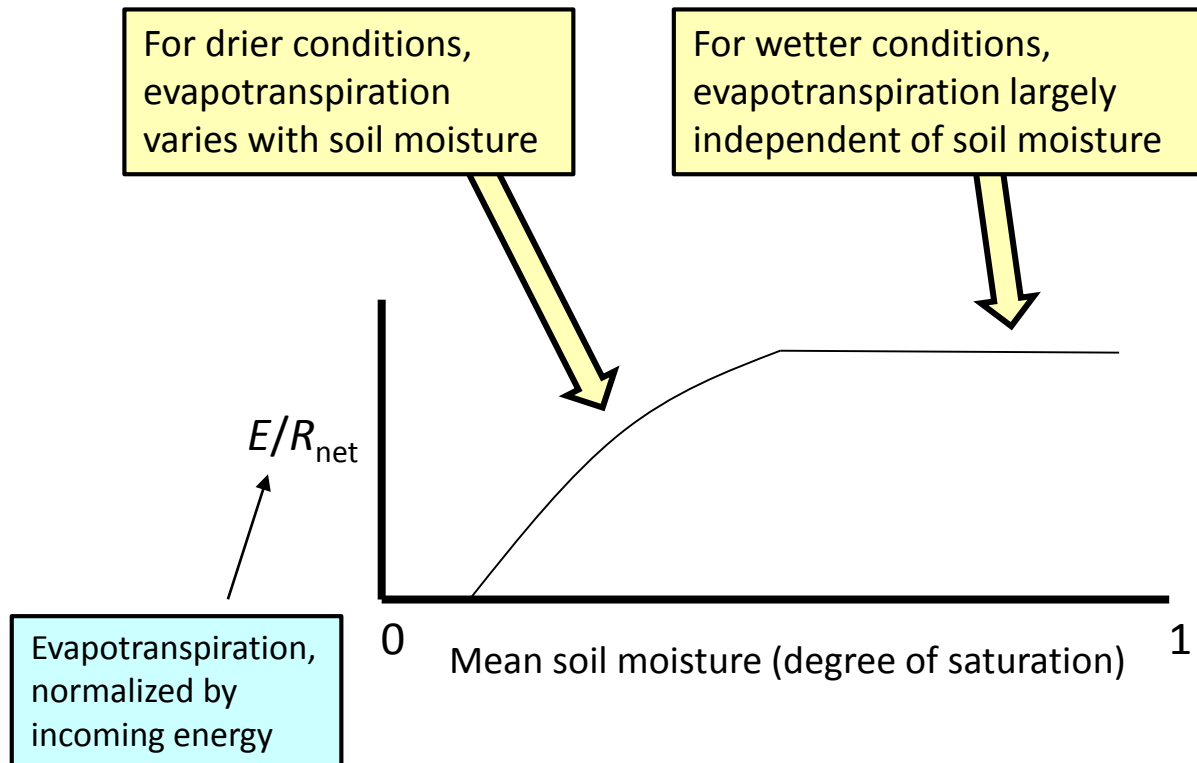For example:

Wet soil ⇨ higher evap., lower sensible heat flux

This can affect local air temperature:
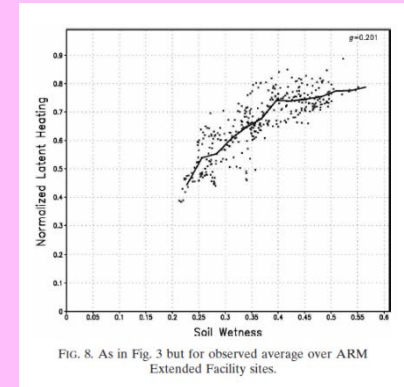　　　　⇨ more evaporative cooling
　　　　⇨ lower air temperature

It can also affect local precipitation:
　　　　⇨ boundary layer modification
　　　　⇨ conditions more conducive
　　　　　　(or perhaps less conducive)
　　　　　　to onset of moist convection

E

H

Wet Soil

Conventional Wisdom Regarding Control of Soil Moisture on Evapotranspiration

For drier conditions, evapotranspiration varies with soil moisture

For wetter conditions, evapotranspiration largely independent of soil moisture

Relevant observations are rare, but where they exist, they support this idea….

E/R_{net}

Evapotranspiration, normalized by incoming energy

0

1

Mean soil moisture (degree of saturation)

FIG. 8. As in Fig. 3 but for observed average over ARM Extended Facility sites.

Dirmeyer *et al.*, *J. Hydromet.*, 7, 1177–1198, 2006

Because of this relationship, the connection between soil moisture and the atmosphere (through the former's effect on evapotranspiration) is strongest in the <u>transition zones</u> between dry and wet areas.

Shown here: results from the multi-model GLACE experiment. Indicated is where soil moisture variability helps guide short-term boreal summer rainfall variability.
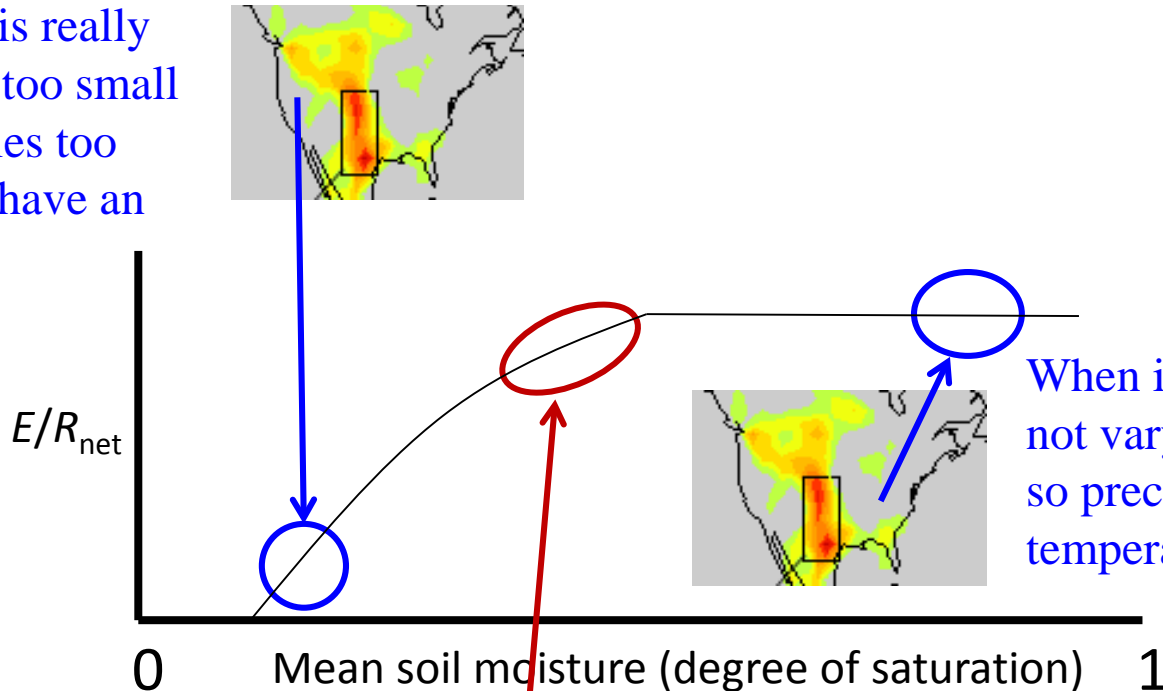
Why are the transition areas important? See next slide, which focuses on North America…
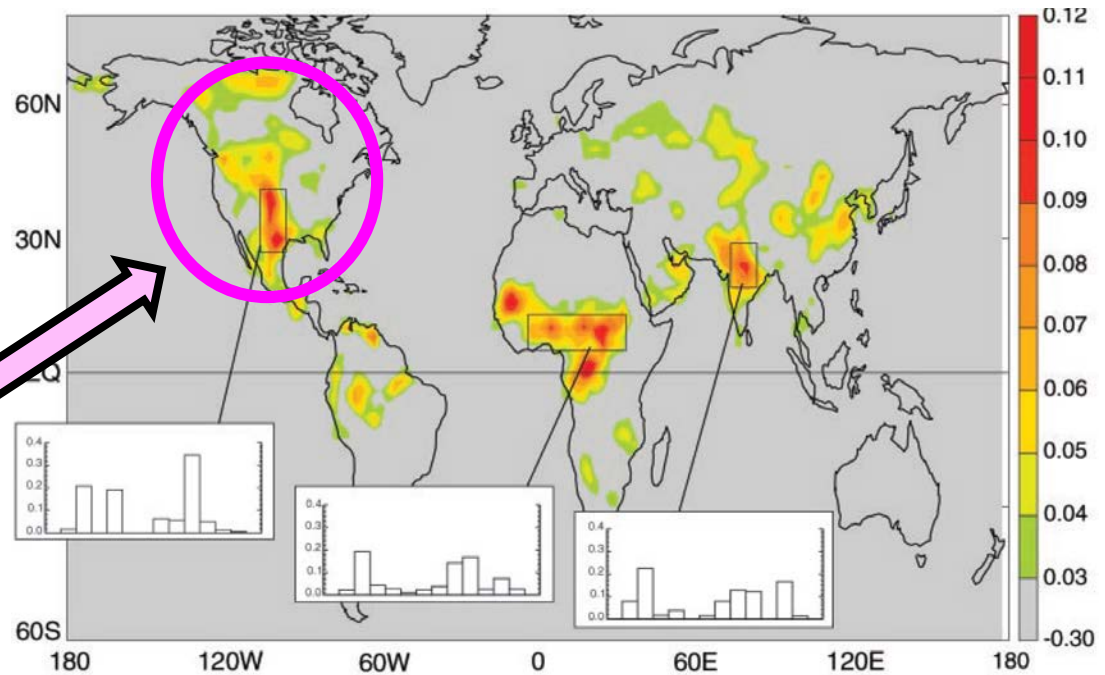
Koster *et al.*, *Science*, 305, 1138–1140, 2004

Explanation for Why Soil Moisture Feedback on the Atmosphere is Strongest in Transition Zones

When it is really dry, E is too small (and varies too little) to have an effect.

E/R_{net}

When it is really wet, E does not vary with soil moisture, so precipitation and temperature cannot, either.

0   Mean soil moisture (degree of saturation)   1

You mainly get an impact in the "sweet spot" in between:
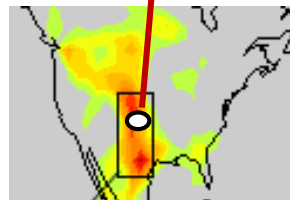
…in the transition zone, where E does vary with soil moisture and E is significantly large.

Direct evapotranspiration measurements are too sparse to show this pattern. However, the pattern <u>is</u> seen in measurements of E-related proxy variables.

Wanted: indication of where interannual variability of E is large. Plot instead: interannual variability of well-measured variables that vary with E. (Plot $\sigma^2_X Corr^2(X,W)$, where X is the proxy variable and W characterizes water availability.)

Proxy: JJA air temperature, *T*
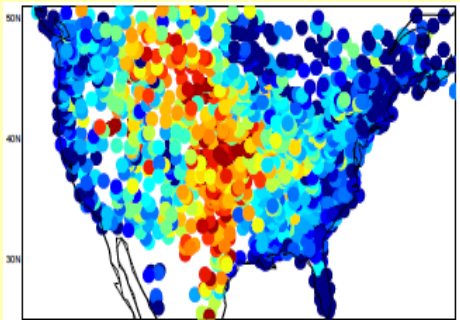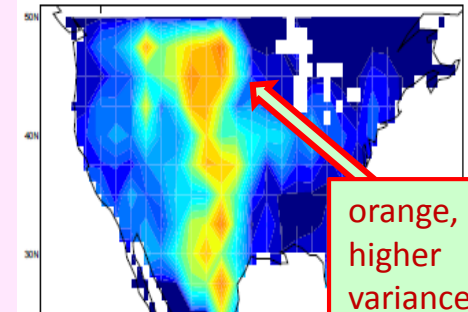

T varies with *E*: higher *E*
⇨ more evaporative cooling
⇨ lower *T*.

Proxy: annual precipitation minus streamflow, *P-Q*
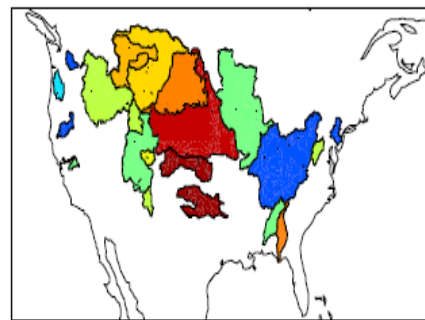
Q varies with *E*: higher *E*
⇨ lower *Q*, from water balance.

Proxy: Aug-Sept NDVI
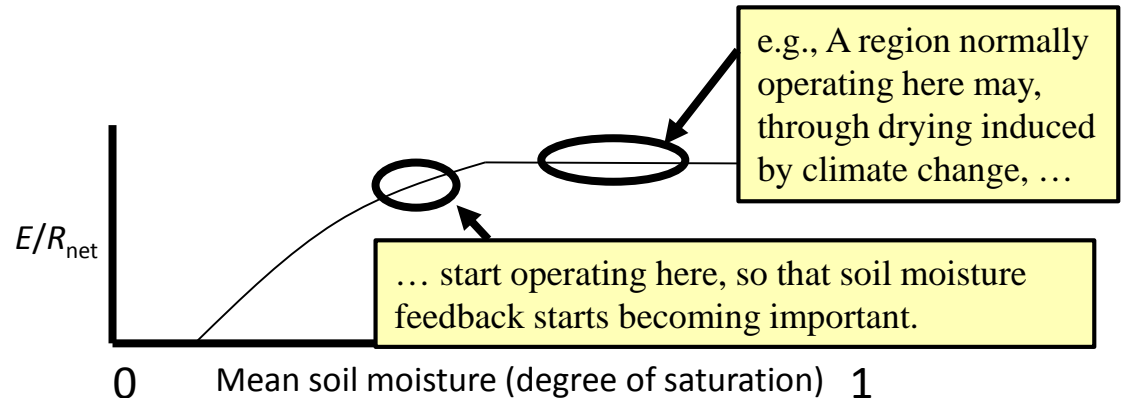

orange, red = higher variance

NDVI varies with *E*:
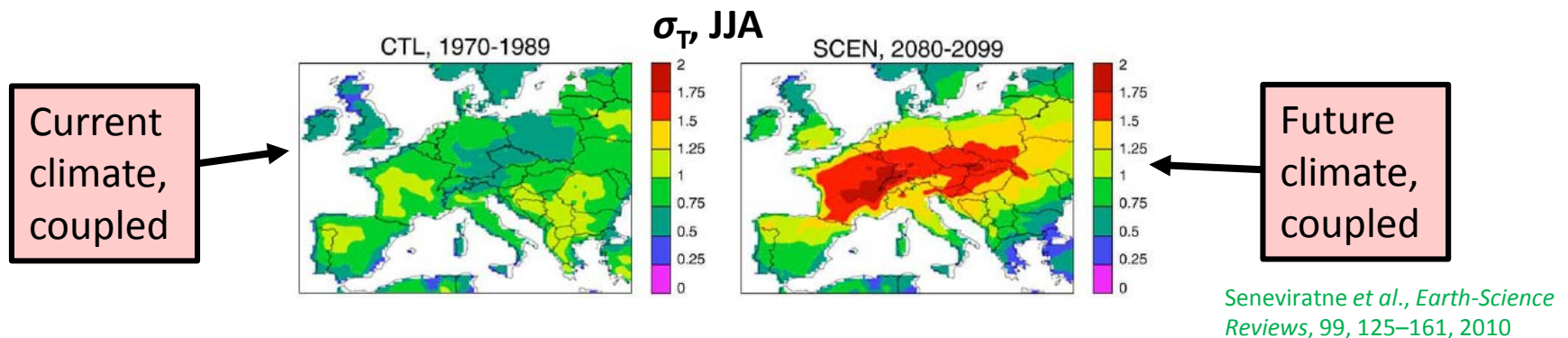lower soil moisture
⇨ lower *E*, lower NDVI.

Koster *et al.*, *Frontiers in Earth Science*, 2015

Soil Moisture in a Changing Climate

Climate change may lead to a shift in a region's hydroclimatic regime.

e.g., A region normally operating here may, through drying induced by climate change, …

E/R_{net}

… start operating here, so that soil moisture feedback starts becoming important.

0   Mean soil moisture (degree of saturation)   1

Models suggest such a shift in Europe, with soil moisture having a larger impact on climate variability during future climate.

σ_T, JJA

CTL, 1970-1989   SCEN, 2080-2099

Current climate, coupled

Future climate, coupled

Seneviratne *et al., Earth-Science Reviews*, 99, 125–161, 2010

Another relevant property of soil moisture: "memory". If the soil is anomalously wet today, it will probably be anomalously wet tomorrow, next week, and maybe even next month.
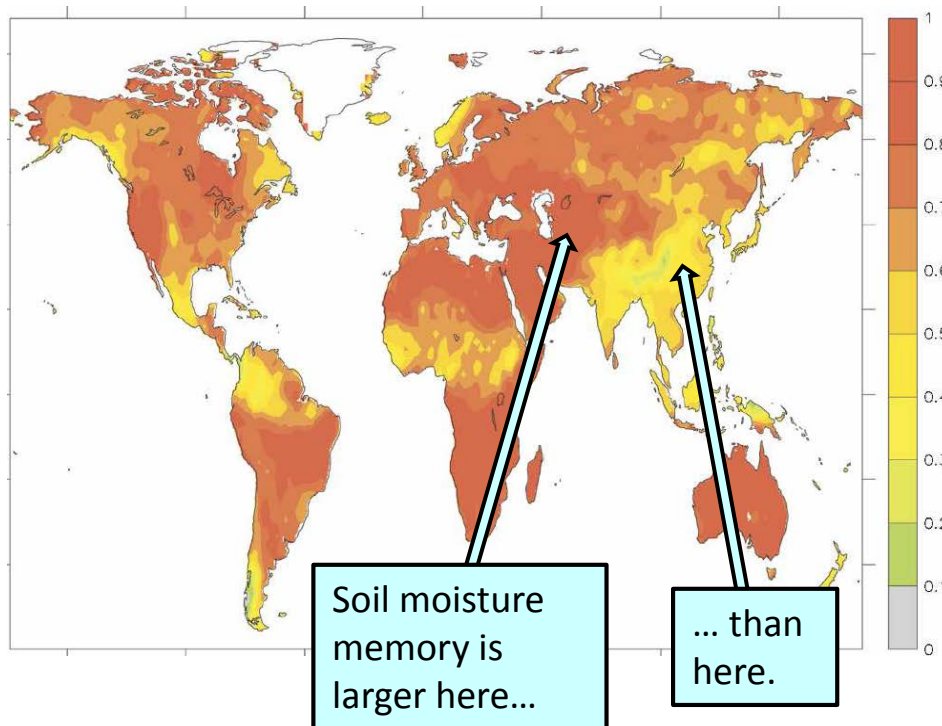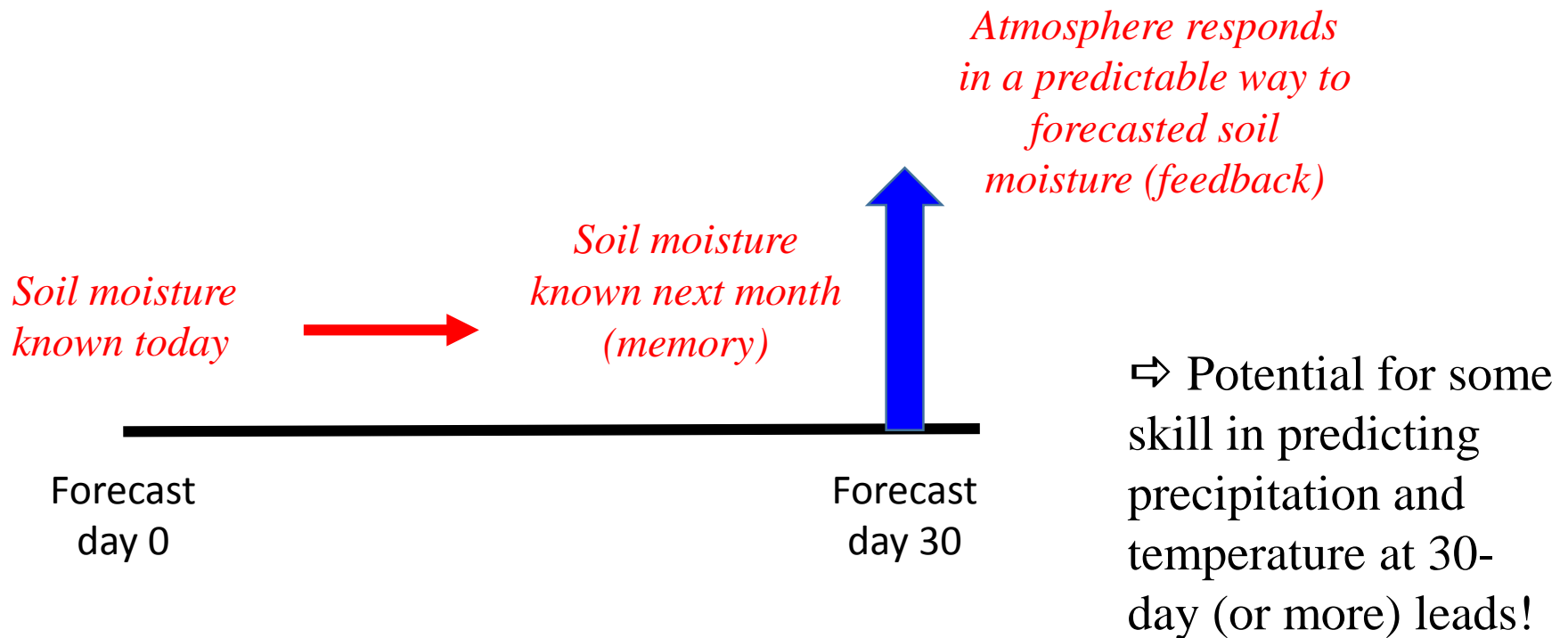

⇦ Multi-model estimate of 27-day-lagged autocorrelation of soil moisture (boreal summer).

Observed estimates for individual locations are sparse, but where they exist, the models roughly agree with them.

Soil moisture memory is larger here…

… than here.

Seneviratne *et al.*, *J. Hydromet.*, 7, 1090–1112, 2006

This memory, in combination with soil moisture's ability to feed back on the atmosphere, has an important implication:

Atmosphere responds in a predictable way to forecasted soil moisture (feedback)

Soil moisture known next month (memory)

Soil moisture known today

Forecast day 0

Forecast day 30

⇨ Potential for some skill in predicting precipitation and temperature at 30-day (or more) leads!

Estimations of Forecast Skill Associated with Soil Moisture Initialization
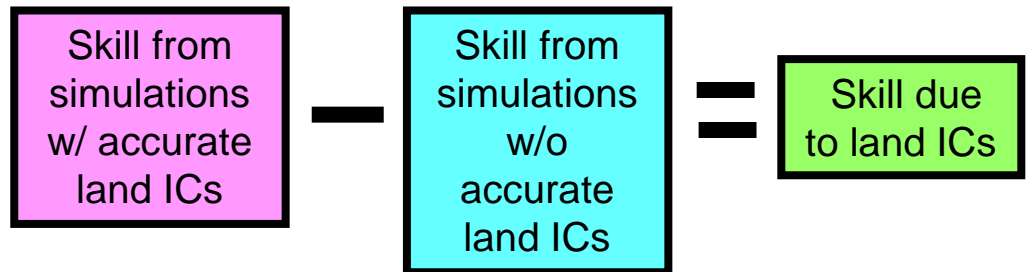
GLACE-2: The second phase of the **Global Land-Atmosphere Coupling Experiment** (an international, multi-institution project)
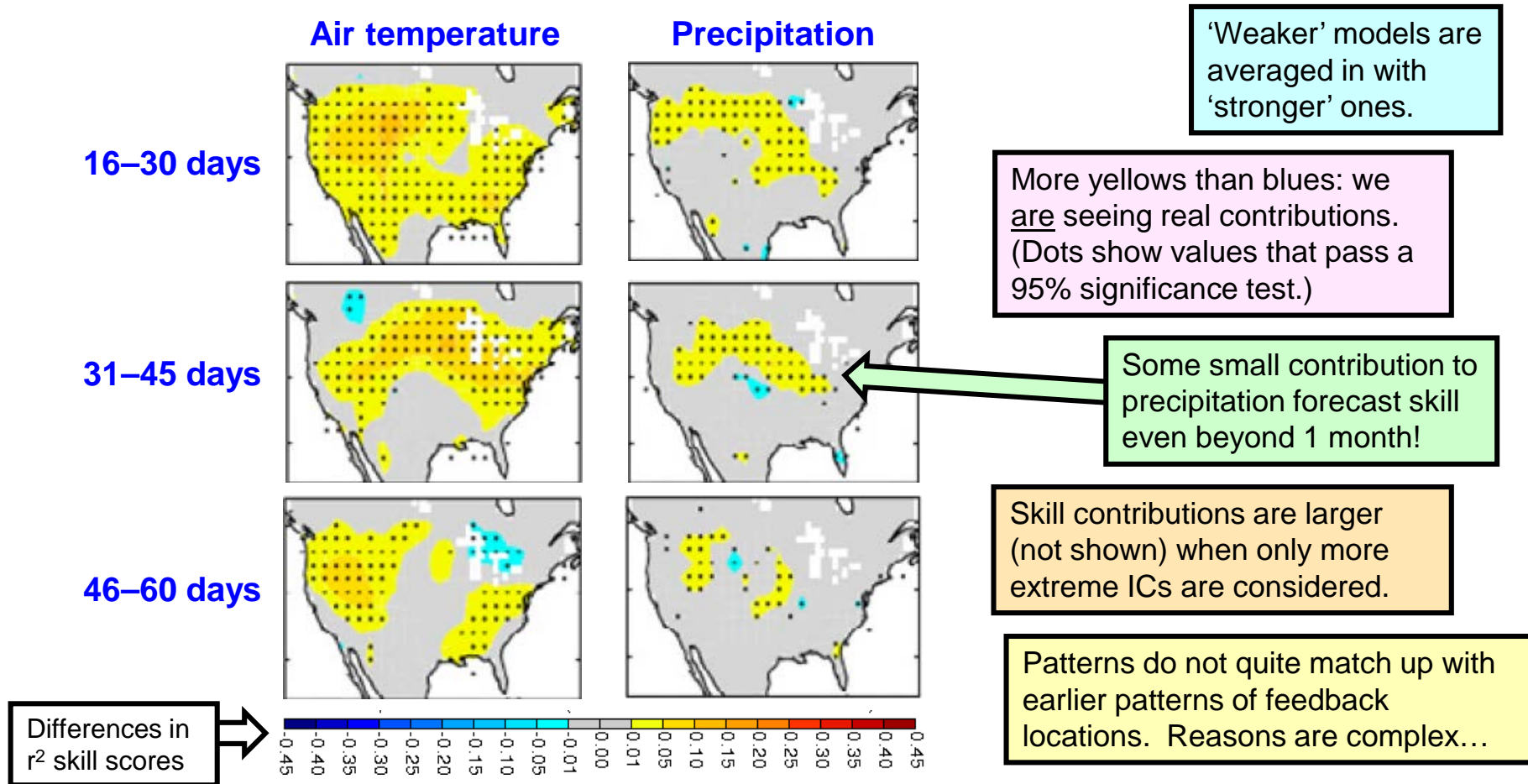
Koster *et al.*, *J. Hydromet.*, 12, 804-822, 2011

Gist of experiment:

1. Perform two sets of forecast simulations:
   (i) <u>with</u> accurate soil moisture initial conditions (ICs)
   (ii) <u>without</u> accurate soil moisture ICs

2. Compare forecasted P, T to obs.

3. Compute soil moisture contribution to forecast skill:

Skill from simulations w/ accurate land ICs	**−**	Skill from simulations w/o accurate land ICs	**=**	Skill due to land ICs

GLACE-2 Results: 'Consensus' Skill Contribution from Land Initialization (JJA)

Air temperature **Precipitation**

16–30 days

31–45 days

46–60 days

Differences in r² skill scores

'Weaker' models are averaged in with 'stronger' ones.

More yellows than blues: we <u>are</u> seeing real contributions. (Dots show values that pass a 95% significance test.)

Some small contribution to precipitation forecast skill even beyond 1 month!

Skill contributions are larger (not shown) when only more extreme ICs are considered.

Patterns do not quite match up with earlier patterns of feedback locations. Reasons are complex…

-0.45 -0.40 -0.35 -0.30 -0.25 -0.20 -0.15 -0.10 -0.05 -0.01 0.00 0.01 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45
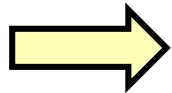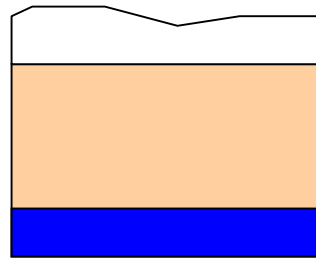
Soil Moisture and Streamflow Forecast Skill

**Snow (or rainfall) over <u>wet</u> soil:** most of the meltwater runs off into streams, reservoirs.
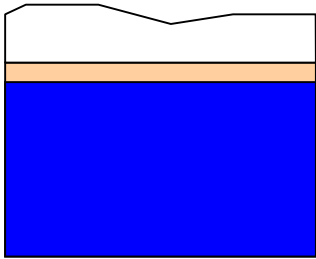
Snow (or rainfall) over <u>dry</u> soil: much of the meltwater infiltrates the soil and is lost to evapotranspiration ⇨ less to streams, reservoirs.

Forecast experiment: compute skill of March–July streamflow forecasts (vs. obs) associated solely with accurate soil moisture initialization:

Knowledge of winter soil moisture, coupled with soil moisture memory, provides springtime streamflow forecast skill.
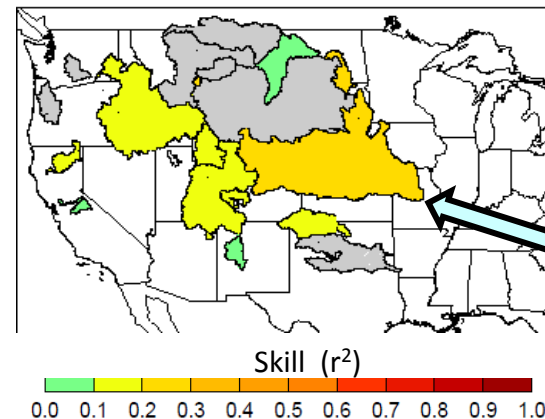
Real skill found in many basins!

Skill (r²)

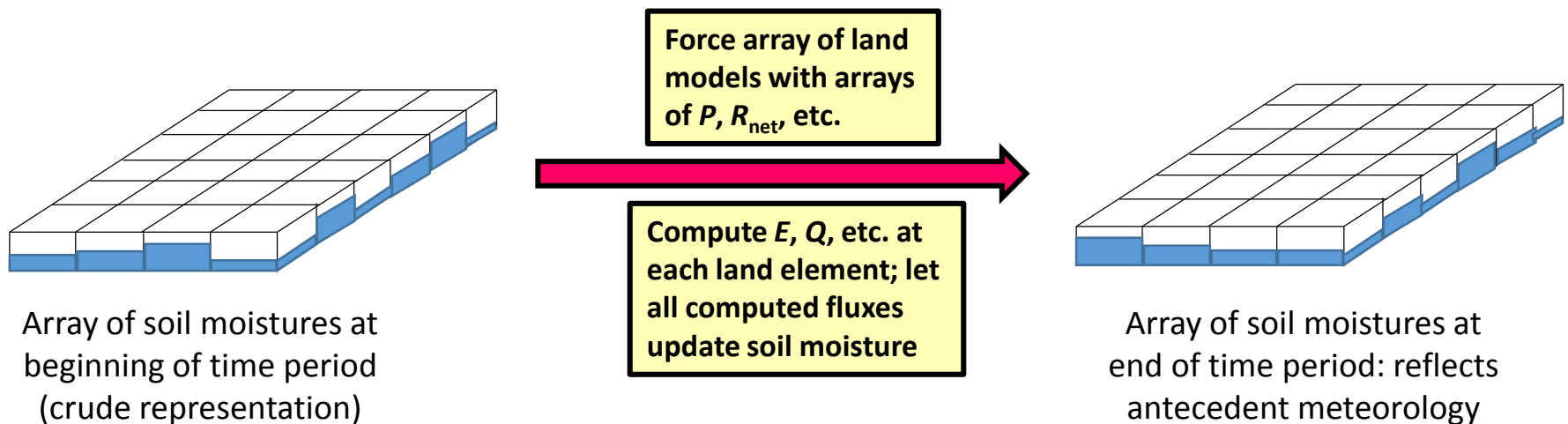0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Koster *et al.*, *Nature Geoscience*, 3, 613–616, 2010.

Soil Moisture in Earth System Models

How can we initialize soil moisture, e.g., for forecasts? From direct, in situ observations?
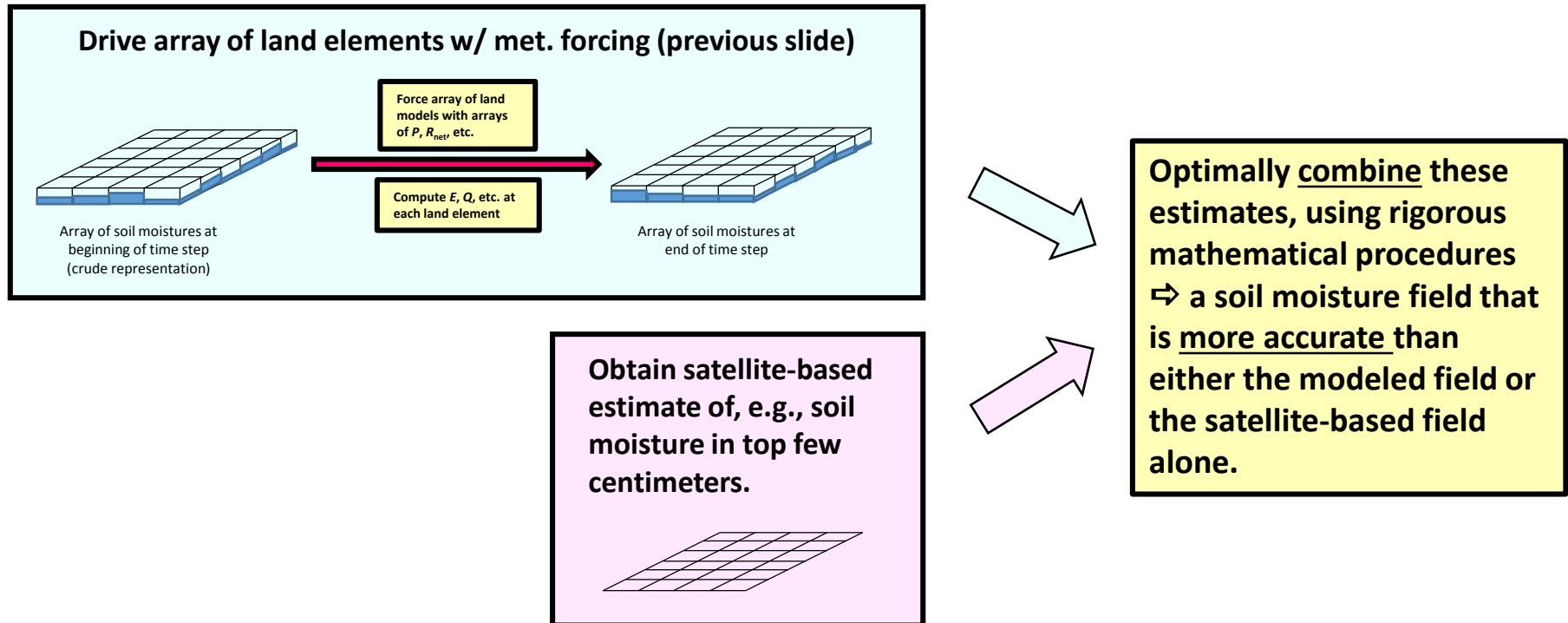   _No._ *In situ observations (certainly across large areas) are sparse to non-existent.*

Modeling approach: Force a gridded array of land surface model elements with arrays of observations-based meteorological forcing ⇨ let modeled soil moistures evolve in response to the forcing.

Force array of land models with arrays of P, R_{net}, etc.

Compute E, Q, etc. at each land element; let all computed fluxes update soil moisture

Array of soil moistures at beginning of time period (crude representation)

Array of soil moistures at end of time period: reflects antecedent meteorology

Soil Moisture in Earth System Models

Even better approach: Combine modeling and observations through <u>data assimilation</u>:

Drive array of land elements w/ met. forcing (previous slide)

Force array of land models with arrays of P, R_{net}, etc.

Compute E, Q, etc. at each land element

Array of soil moistures at beginning of time step (crude representation)

Array of soil moistures at end of time step

Obtain satellite-based estimate of, e.g., soil moisture in top few centimeters.

Optimally <u>combine</u> these estimates, using rigorous mathematical procedures ⇨ a soil moisture field that is <u>more accurate</u> than either the modeled field or the satellite-based field alone.
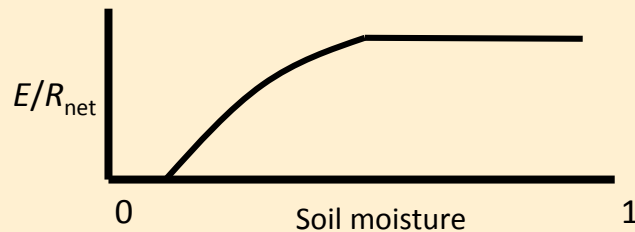
Soil Moisture in Earth System Models

New satellite-based L-band sensors have the potential to provide valuable global soil moisture data ⇨ A renaissance in soil moisture estimation through assimilation?

SMOS


SMAP

Spatial resolution : 36-km
Temporal resolution : every 3 days (at least)
How deep into soil: several cm (Level 1–3)
                                1 m (Level 4)
Accuracy: RMSE < 4 volumetric percent
Latency: short! (hours – days)
Baseline mission duration: 3 years

Soil Moisture in Earth System Models: Some Caveats

| As discussed earlier, evapotranspiration is controlled by soil moisture.	Similarly, the ratio of runoff to precipitation is controlled by soil moisture.
E/R_{net} 0 Soil moisture 1	Q/P 0 Soil moisture 1
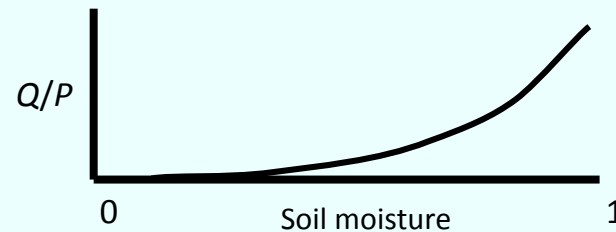
A land surface model has multiple complex formulations that interact with each other, implicitly producing some form of these two relationships (approximate–scatter will be large around them).

It is the **interaction** between these underlying relationships that determines how a land surface model behaves.

→
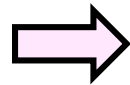
Important Modeling Take-home Lesson:
A 'perfect' evapotranspiration formulation does <u>not</u> imply accurate evapotranspiration rates. Accuracy in E is limited by the weaker of the evapotranspiration and runoff formulations. Model development requires suitable **balance**.

Koster and Mahanama, *J. Hydromet.*, 13, 1604–1620, 2012.
Koster, *Bull. Am. Met. Soc.,* 96, 393–396.

Also, soil moisture in a land surface model is a very <u>model-dependent</u> variable, more an 'index of wetness' than an actual physical quantity.
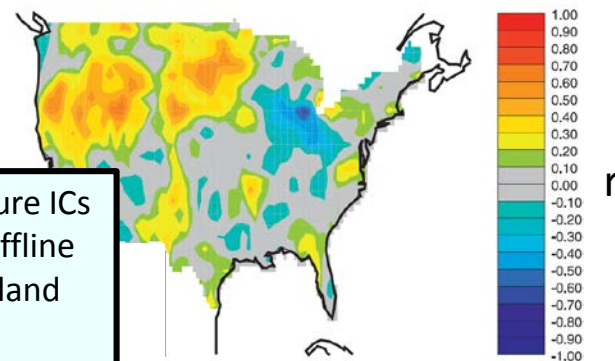
Another Important Modeling Take-home Lesson:
Taking soil moisture from one model (e.g., from a reanalysis) and using it in another can lead to serious problems. Scaling is essential.

Demonstration of problem: seasonal precipitation forecast skill

Using soil moisture ICs obtained from offline system w/same land surface model.

Using soil moisture ICs obtained from reanalysis that used <u>different</u> land surface model.

Skill greatly reduced!
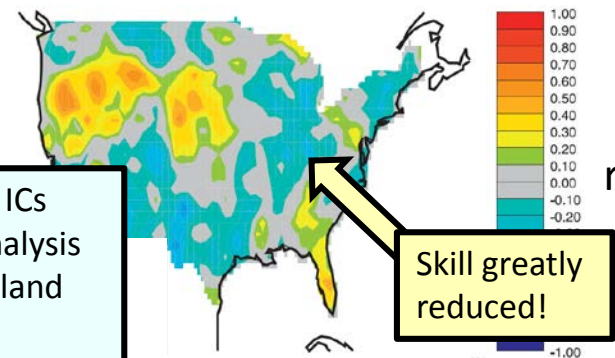
Koster *et al.*, *J. Climate*, 22, 4322–4335, 2009.

A Few Summary Statements

Variability in near-surface soil moisture can causally translate to variability in meteorological variables through the influence of soil moisture on the energy and water budgets at the land-atmosphere interface, particularly in transition zones.

This potential for feedback, combined with soil moisture's intrinsic memory, provides the basis for utilizing soil moisture information in monthly-to-seasonal forecasts.

The outlook for improved soil moisture estimation (e.g., for initializing forecasts) is optimistic given the advent of new satellite data, which can be assimilated into land surface models. Use of models, however, comes with important caveats:

- A model's overall performance is only as good as the weaker of its evapotranspiration and runoff formulations (not often appreciated!)

- Inserting soil moisture from one model (even from a trusted reanalysis) into another without performing climatology transformations can lead to significant problems (appreciated even less!)