Land-surface controls over evaporation variance

Randal Koster
GMAO, NASA/GSFC
randal.d.koster@nasa.gov

Reasoning (and assumptions) behind this talk's emphasis:

1. We are interested in how soil moisture variations may feed back on the atmosphere ⇨ soil moisture as a potential source of predictability.

Reasoning (and assumptions) behind this talk's emphasis:

1. We are interested in how soil moisture variations may feed back on the atmosphere ⇨ soil moisture as a potential source of predictability.

2. Soil moisture affects the overlying atmosphere mainly through its impact on the surface energy balance.

3. Variations in the surface energy balance can be keyed, to first order, to variations in evaporation (which, by the way, also lies at the heart of the surface water balance).

Reasoning (and assumptions) behind this talk's emphasis:

1. We are interested in how soil moisture variations may feed back on the atmosphere ⇨ soil moisture as a potential source of predictability.

2. Soil moisture affects the overlying atmosphere mainly through its impact on the surface energy balance.

3. Variations in the surface energy balance can be keyed, to first order, to variations in evaporation (which, by the way, also lies at the heart of the surface water balance).

4. Synoptic-scale variations in evaporation (the type that may influence feedback) are tied to year-to-year variations in seasonally-averaged evaporation – where one is high, so is the other. (*Particularly assumed to be true for the soil moisture-controlled component of evaporation – see later slide.*)

Reasoning (and assumptions) behind this talk's emphasis:

1. We are interested in how soil moisture variations may feed back on the atmosphere ⇨ soil moisture as a potential source of predictability.

2. Soil moisture affects the overlying atmosphere mainly through its impact on the surface energy balance.

3. Variations in the surface energy balance can be keyed, to first order, to variations in evaporation (which, by the way, also lies at the heart of the surface water balance).

4. Synoptic-scale variations in evaporation (the type that may influence feedback) are tied to year-to-year variations in seasonally-averaged evaporation – where one is high, so is the other. (*Particularly assumed to be true for the soil moisture-controlled component of evaporation – see later slide.*)

5. Under these assumptions, we can look at the interannual variance of seasonally-averaged evaporation to get a first-order handle on feedback potential.

Evaporation Variability

We consider here the quantity

$$\sigma^2_E{}^* = \sigma^2_E \; Corr^2(E,W)$$

which is interpreted as the portion of the temporal evaporation variance (σ^2_E) that is "explained" by variations in land moisture content.

We examine the interannual variance of seasonal (MJJAS) evaporation means.

Note: we focus here on the *spatial pattern* of $\sigma^2{}_E{}^*$ rather than its absolute magnitude. We can generate this spatial pattern across CONUS using three <u>independent</u> sets of observations!

$$\sigma^2{}_E{}^* = \sigma^2{}_E \ \mathrm{Corr}^2(E, W)$$

To get the right spatial pattern, we can use observational <u>proxies</u> for evaporation.

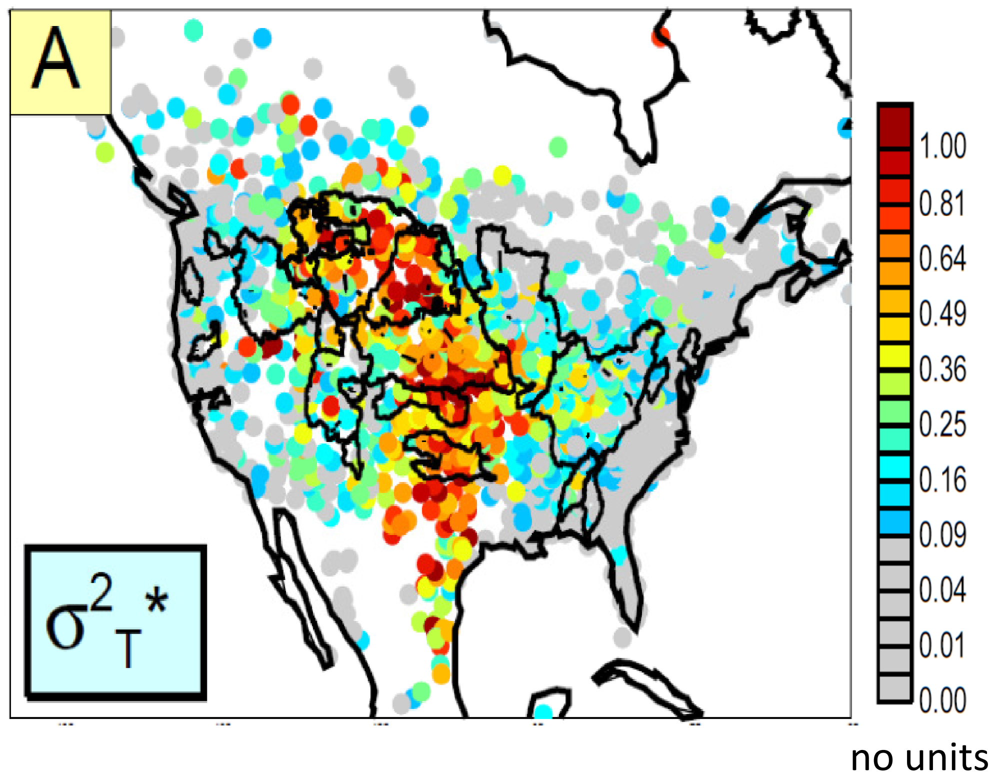
Model-independent estimates of soil moisture spanning the continent do not exist, so we use yearly precipitation (P) as a proxy for W. P is taken from Higgins et al. (2000).

Data set #1: Seasonally-averaged (MJJAS) air temperature

Evaporation proxy: MJJAS air temperature (T)

Temperature over multiple decades taken from GHCN dataset.

Justification: Greater seasonal evaporation implies a greater latent cooling of the surface and thus cooler temperatures. (Known to work this way in a GCM…)



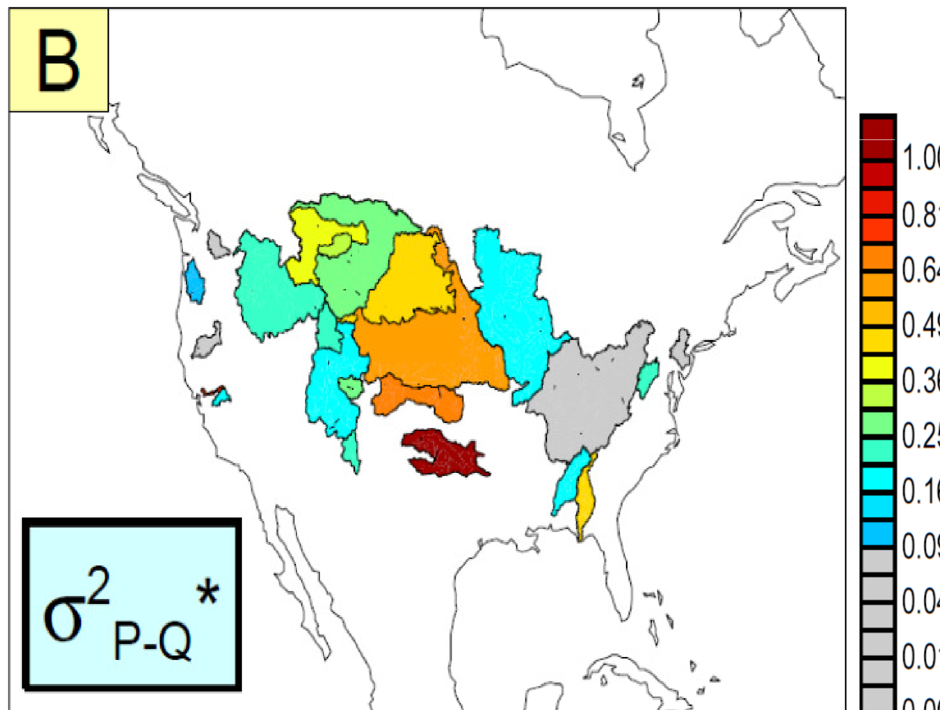
Data set #2: Streamflow

Evaporation proxy: P-Q

Yearly streamflow (Q) over multiple decades are “naturalized” versions of stream gauge observations.

Justification: P-Q approximates E because interannual variations in storage are relatively small. It approximates MJJAS E given strong seasonality of the evaporation cycle.

(with scaling factor applied to account for differences in basin size)



no units

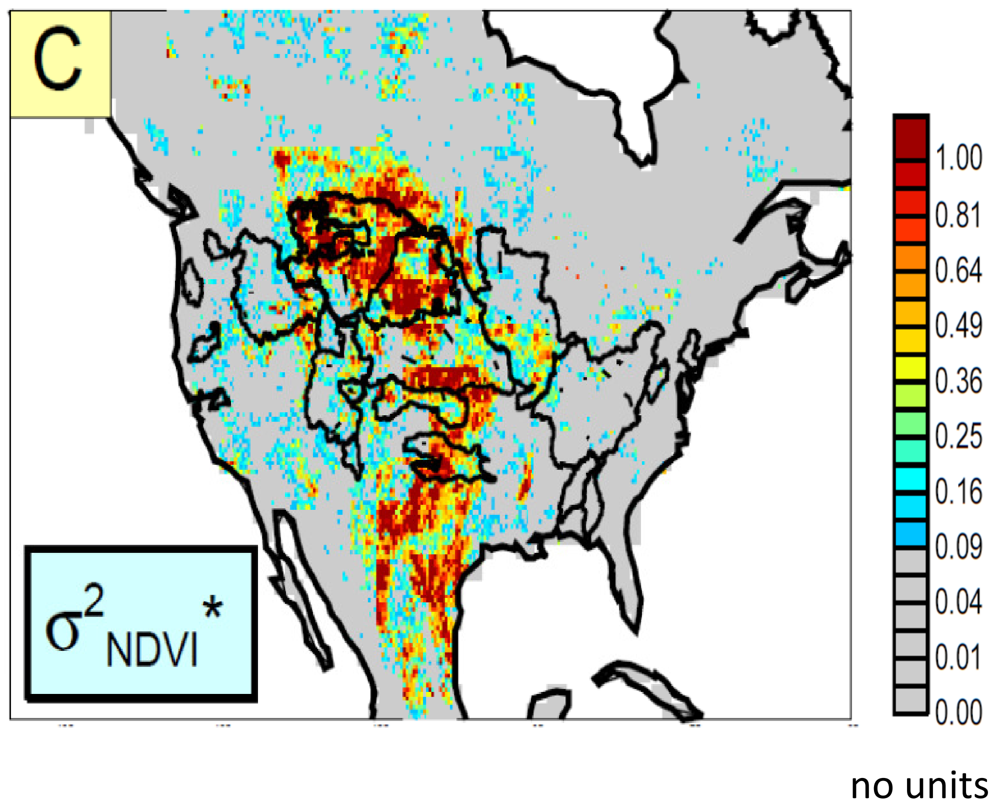
Data set #3: NDVI data

Evaporation proxy: Average NDVI for August-September.

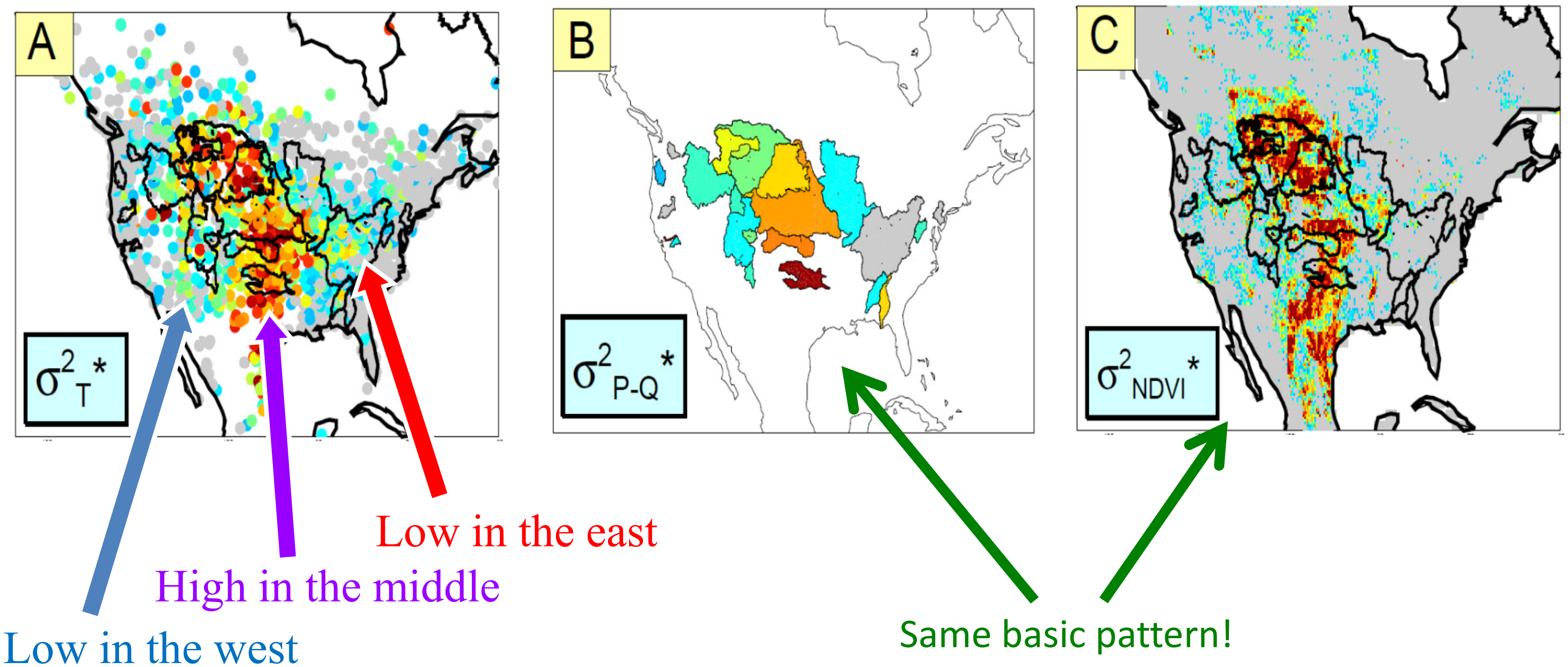
NDVI over multiple decades are available from the GIMMS data set.

Justification: Larger NDVI late in the season implies healthy vegetation during the season ⇨ larger seasonal transpiration.

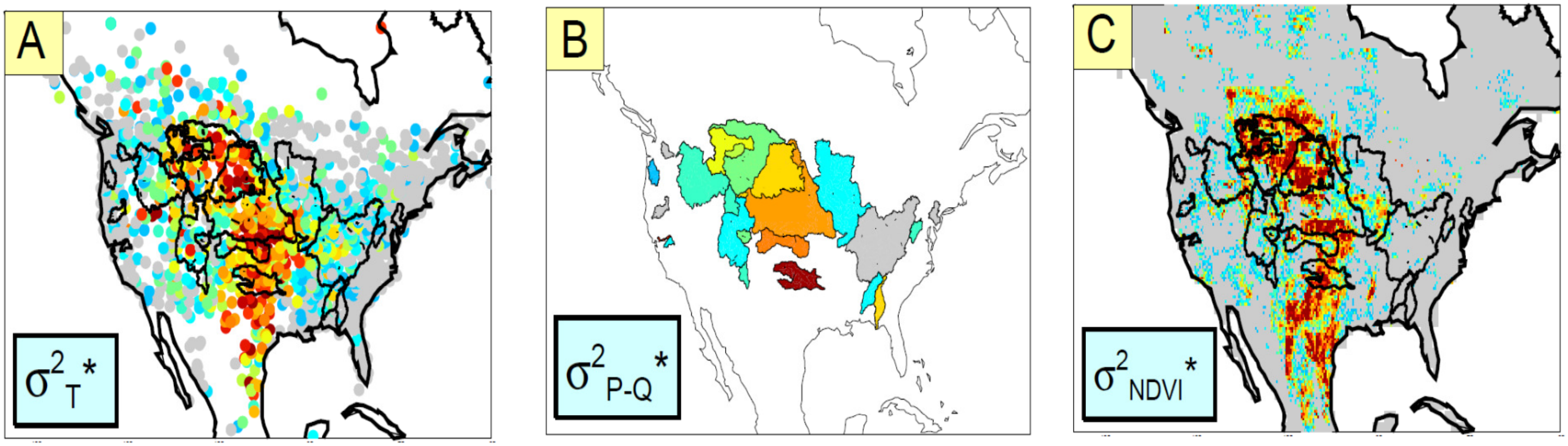
(Note: similar patterns seen when processing Jung et al. derived evaporation data.)

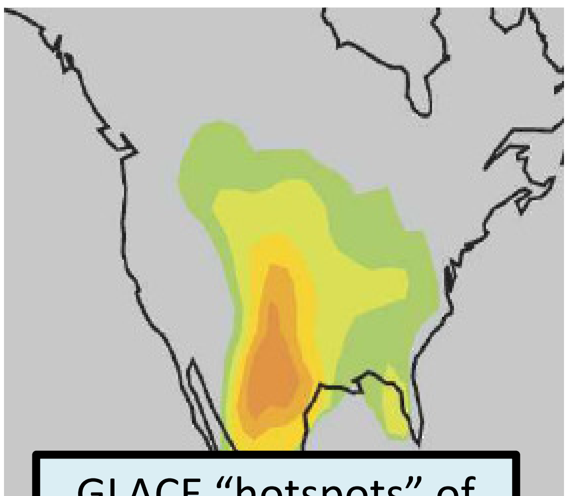


A clear pattern is seen in each of these independently-derived spatial patterns:

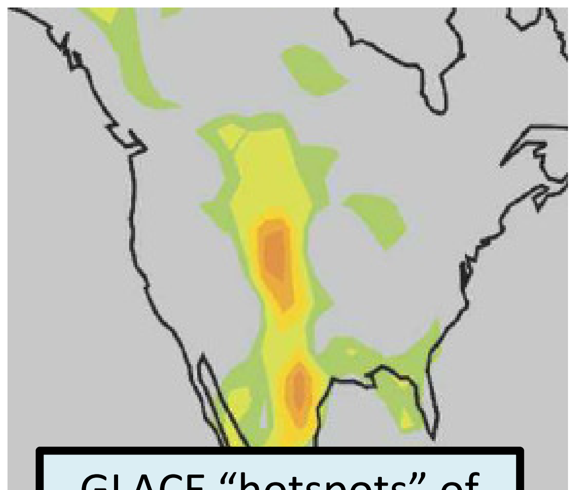


A clear pattern is seen in each of these independently-derived spatial patterns:





GLACE “hotspots” of coupling strength: precipitation

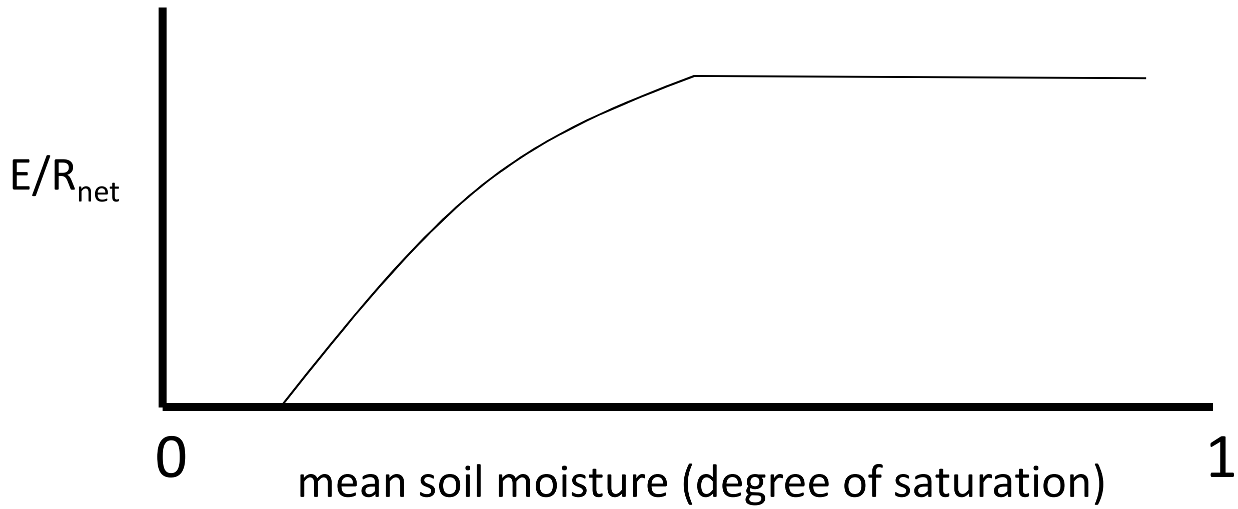


GLACE “hotspots” of coupling strength: temperature (different color bar)

The pattern roughly agrees with model-derived “hotspot” locations (e.g., from GLACE), but the maps above are based <u>strictly</u> on observations…

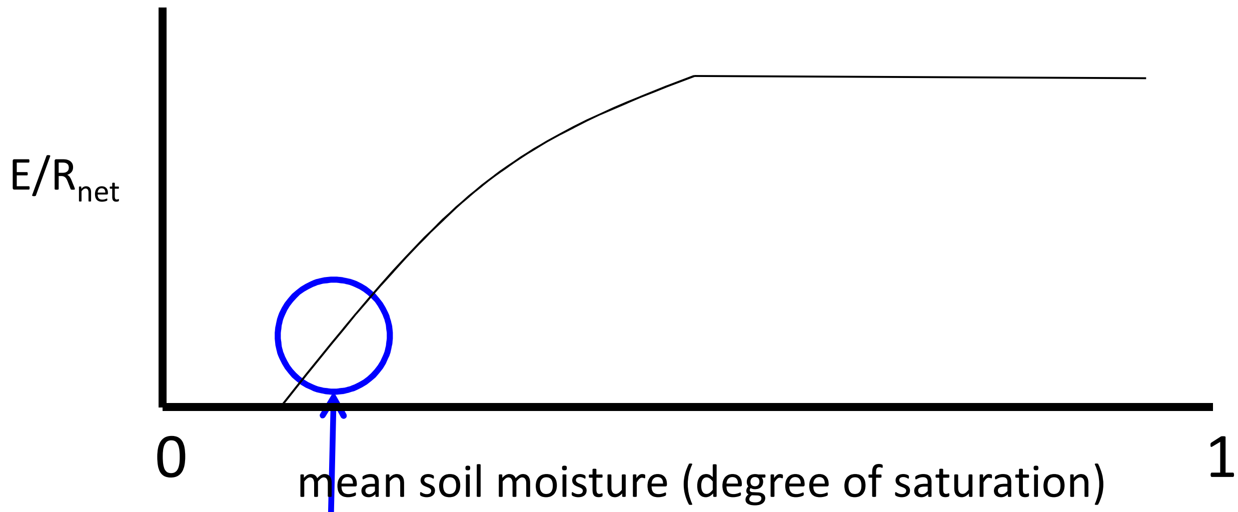
Why does land moisture have an effect where it does – what is the explanation for these spatial patterns? For a large soil moisture impact, two things are needed:

- a large enough evaporation signal
- a coherent evaporation signal – for a given soil moisture anomaly, the resulting evaporation anomaly must be predictable.

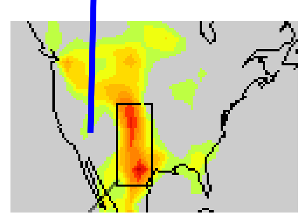


Why does land moisture have an effect where it does – what is the explanation for these spatial patterns? For a large soil moisture impact, two things are needed:

- a large enough evaporation signal
- a coherent evaporation signal – for a given soil moisture anomaly, the resulting evaporation anomaly must be predictable.

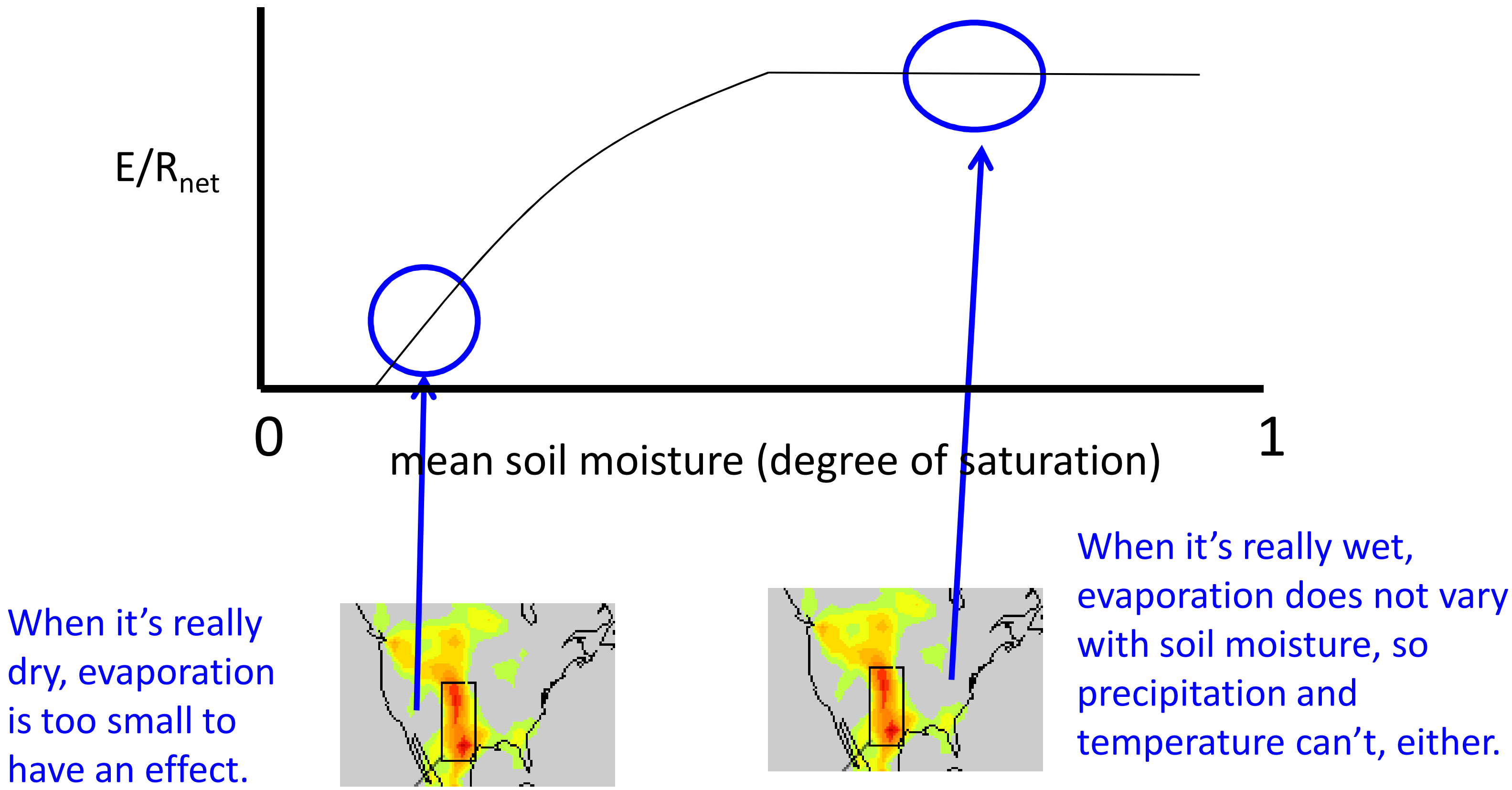


When it's really dry, evaporation is too small to have an effect.



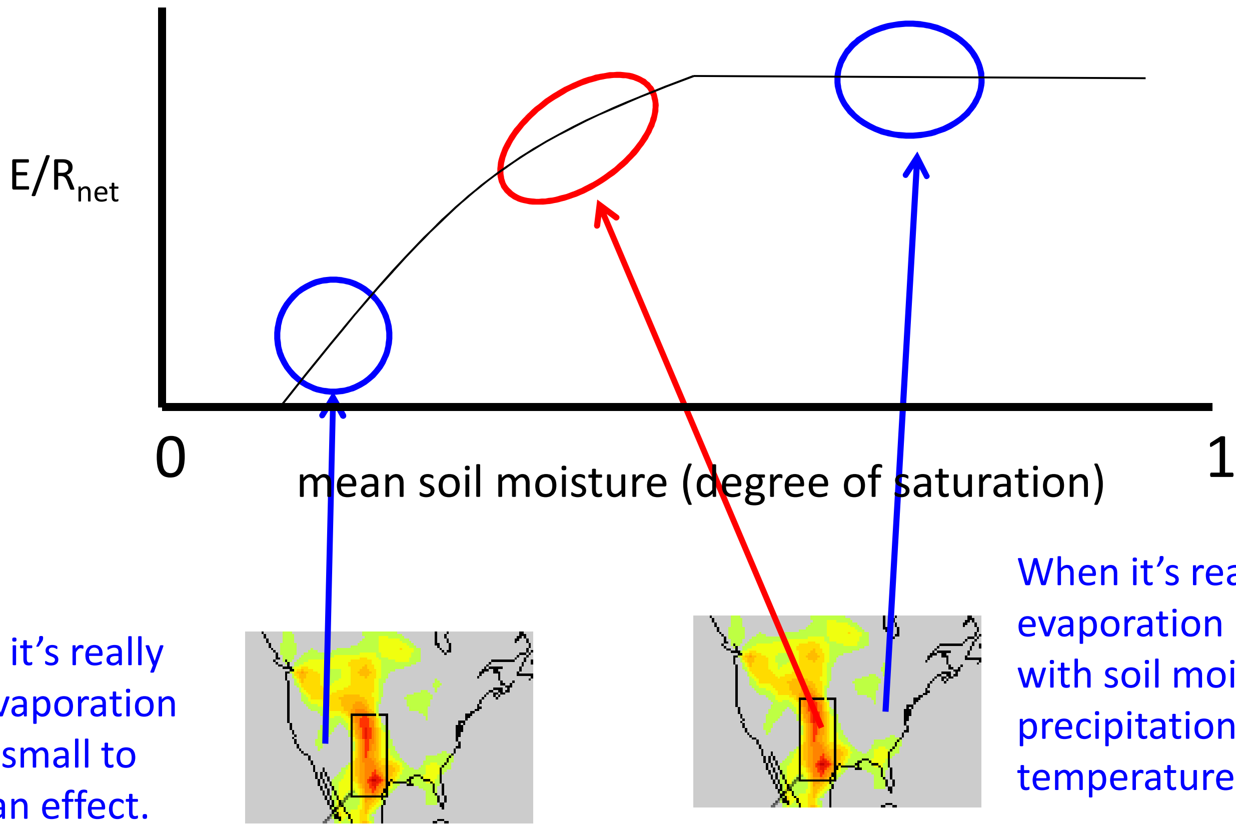
Why does land moisture have an effect where it does – what is the explanation for these spatial patterns? For a large soil moisture impact, two things are needed:

- a large enough evaporation signal
- a coherent evaporation signal – for a given soil moisture anomaly, the resulting evaporation anomaly must be predictable.



Why does land moisture have an effect where it does – what is the explanation for these spatial patterns? For a large soil moisture impact, two things are needed:

- a large enough evaporation signal
- a coherent evaporation signal – for a given soil moisture anomaly, the resulting evaporation anomaly must be predictable.



When it's really dry, evaporation is too small to have an effect.

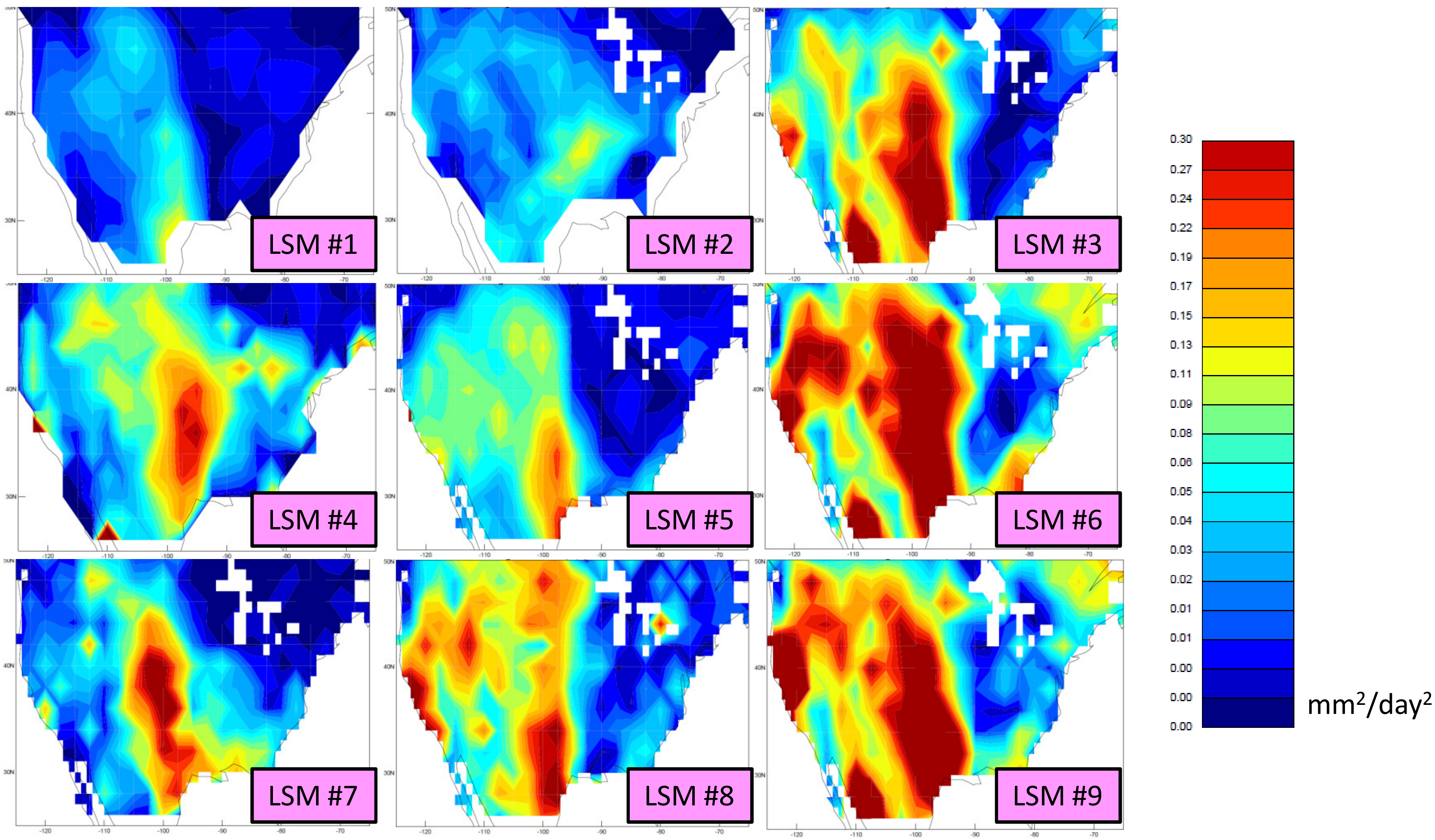
When it's really wet, evaporation does not vary with soil moisture, so precipitation and temperature can't, either.

You only get an impact in the transition zones: not too dry and not too wet.

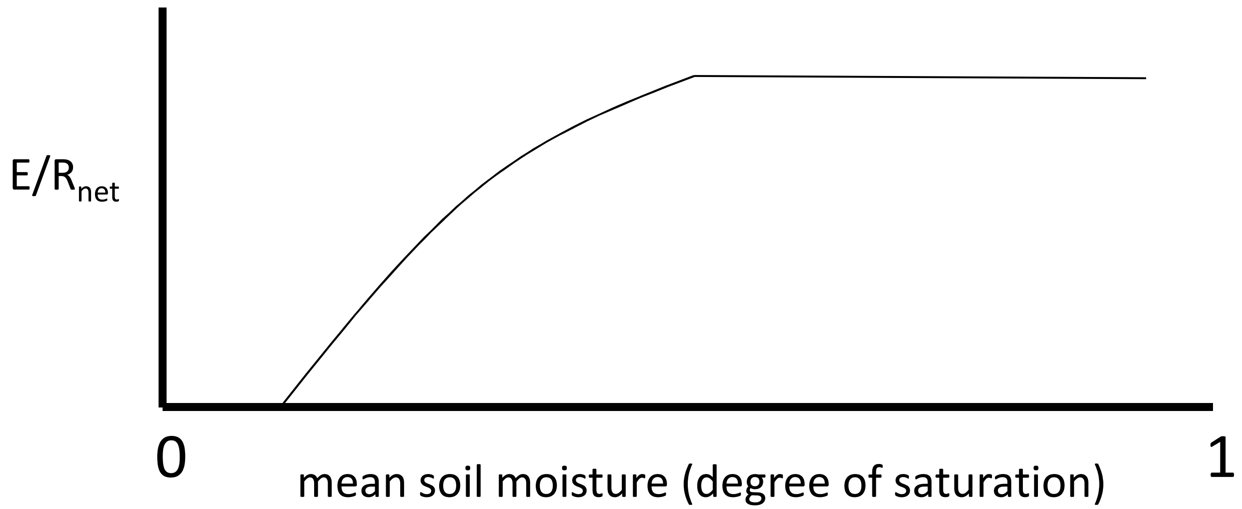
How well do various LSMs do? Better than you might think…

We examined simulation output produced by a number of different state-of-the-art LSMs. Each LSM was driven offline over CONUS with multiple decades of observations-based forcing.

The magnitudes of the simulated $\sigma^2{}_E{}^*$ fields differ greatly, but the patterns are roughly correct.

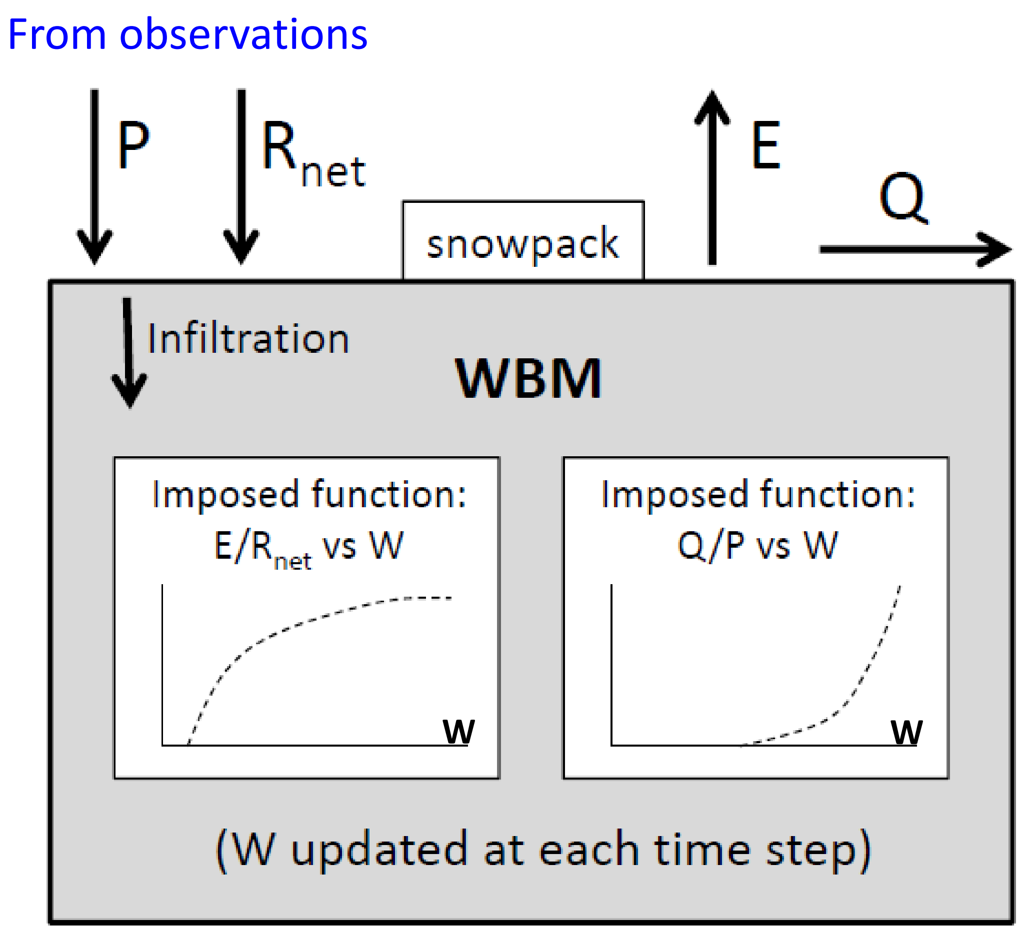


So… does this mean that the standard LSM captures accurately the relationship between soil moisture and evaporation?



No. That's simply too much to hope for!

Exploration tool: Simple water balance model (WBM)



Time step: daily

Integration time: ~ 50 yr

Domain: Continental U.S.

Reference: Koster and Mahanama, J. Hydromet., 13, 1604-1620, 2012

Yes, this tool is *simple*:

- The same functions are used everywhere within region studied (e.g., ignoring spatial variability in vegetation and topography) and at all times (e.g., ignoring seasonality in vegetation).
- It lacks treatments of (for example) baseflow and interception loss.
- It lacks a treatment of the surface energy balance.
- And so on… And so on…

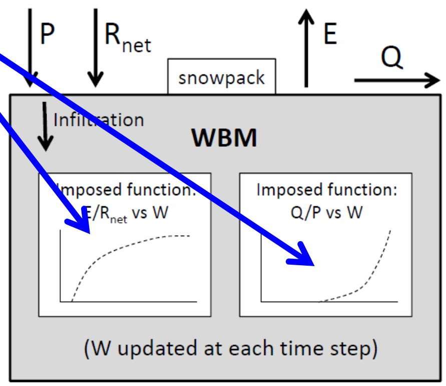
Even so, we have found (Koster and Mahanama 2012) that it successfully captures, to first order, the important controls on hydroclimatic variability operating in a complex land surface model and (presumably) in nature.

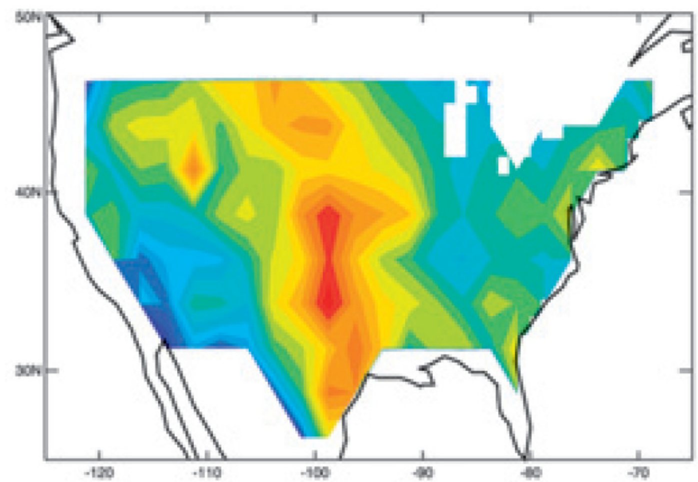
Analysis approach:

1. Select set of E/R_{net}-vs-W and Q/P-vs-W curves.

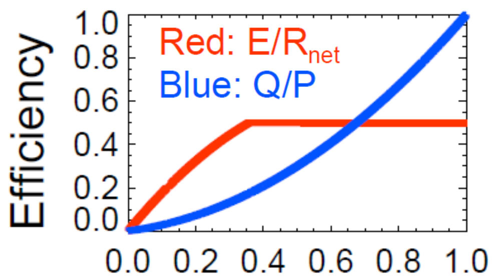
2. Drive the WBM across CONUS with obs-based forcing ⇨ produce simulated evaporations.

3. Compute spatial pattern of $\sigma^2_E{}^*$.

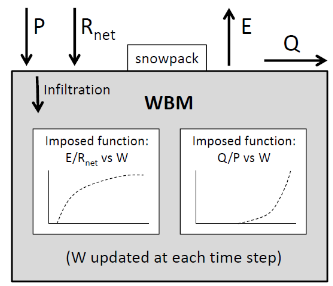


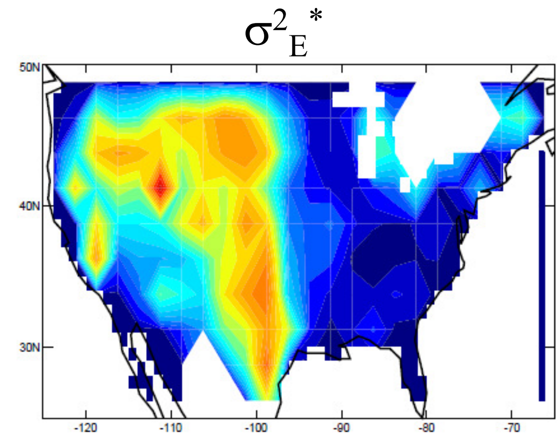


Examples

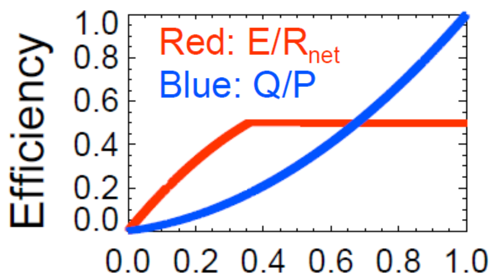


Forcing Data

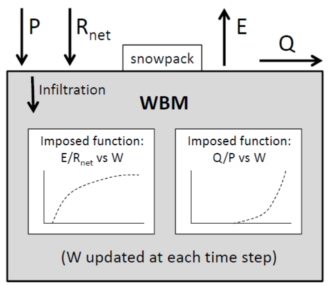


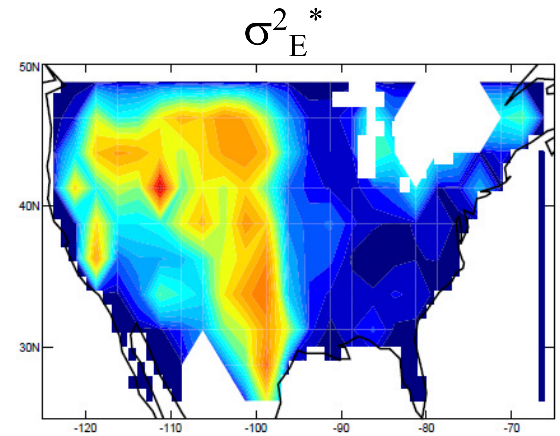


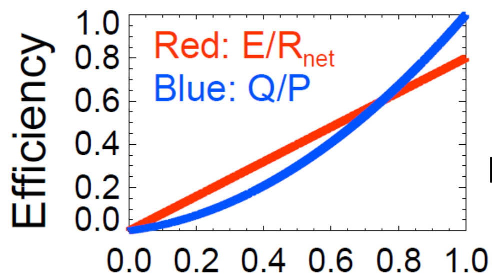
Examples



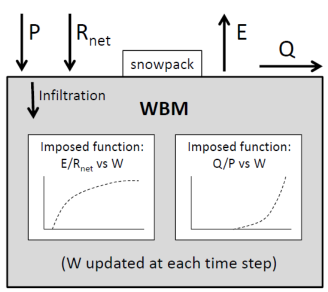
Forcing Data

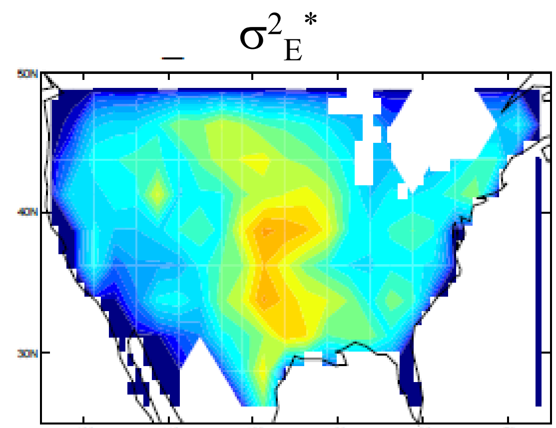




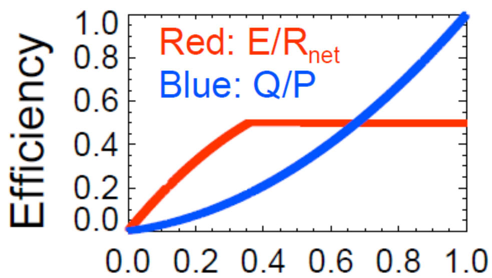


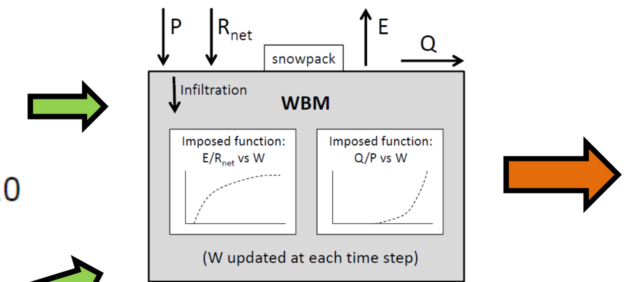
Forcing Data



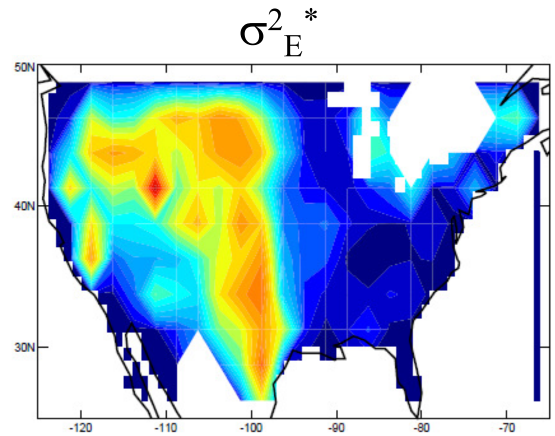


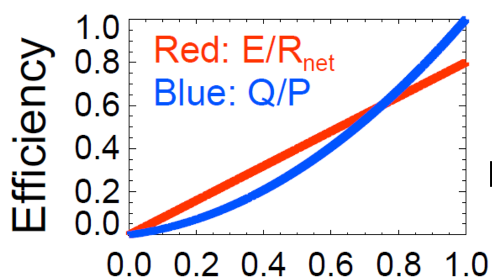
Examples

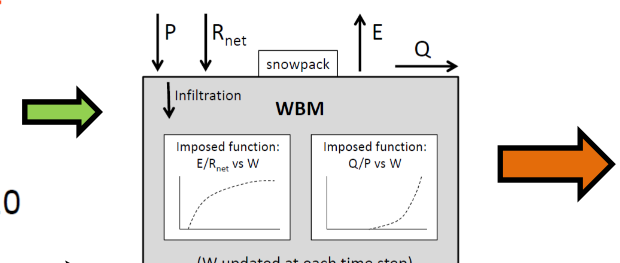


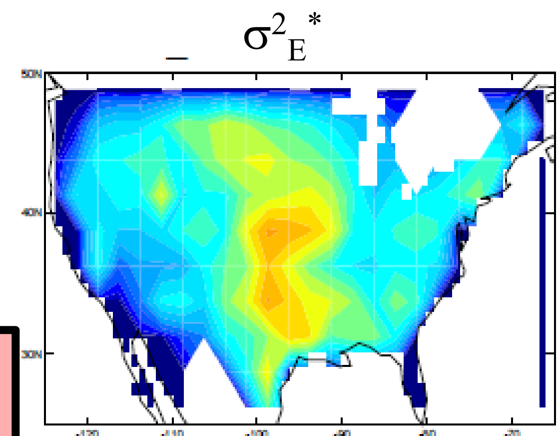


Forcing Data



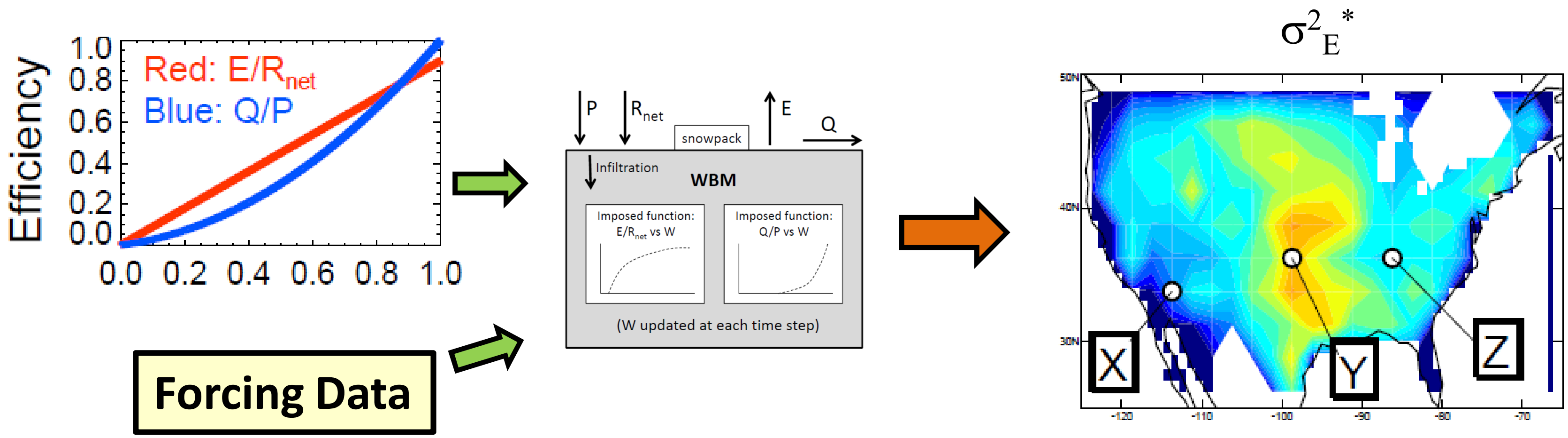


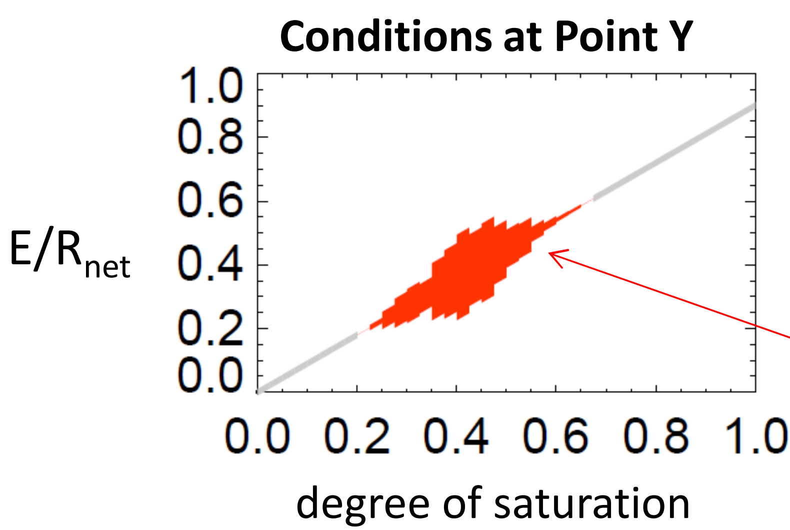




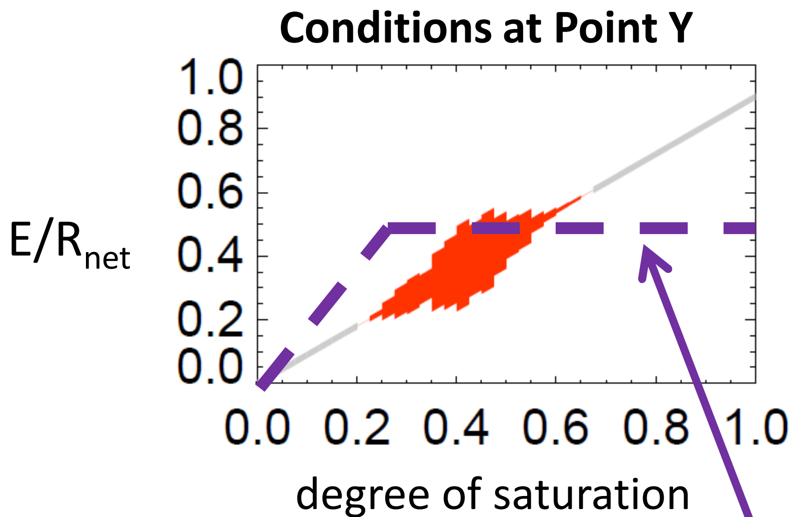
What's going on? Why is the overall $\sigma^2_E{}^*$ pattern (if not the magnitude) somewhat insensitive to the shape of the evaporation efficiency function?

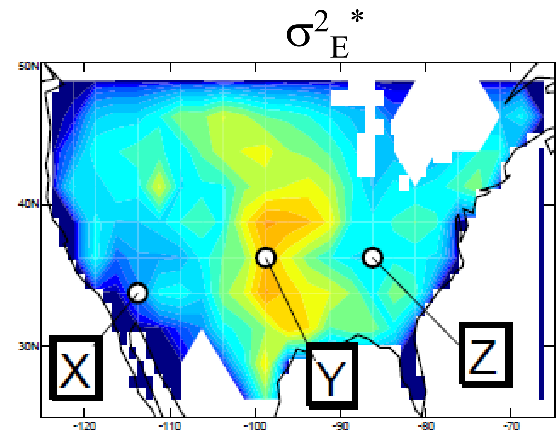
Consider first the point “Y”, with high $\sigma^2_E{}^*$.



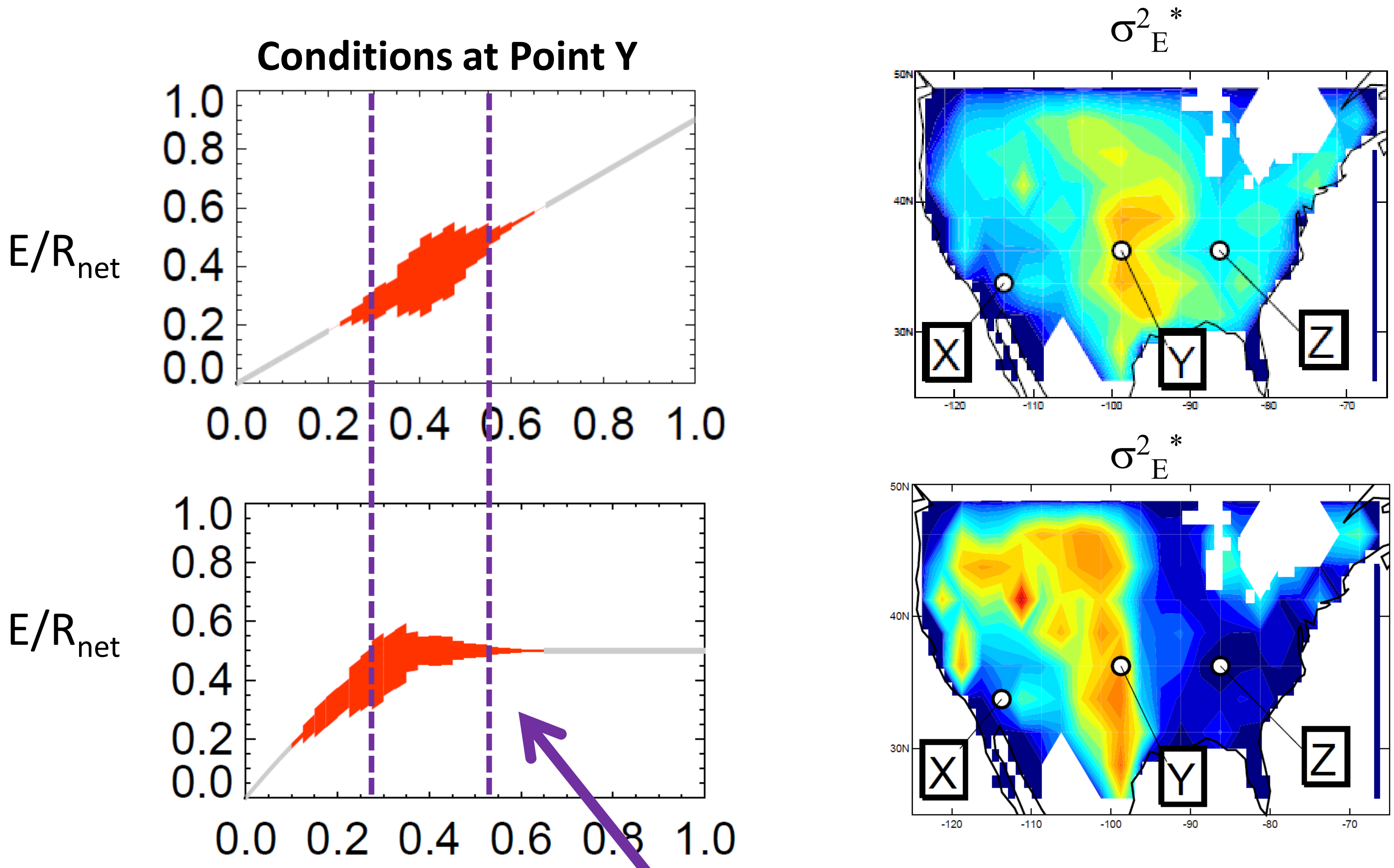


thickness indicates summer soil moisture distribution at Point Y



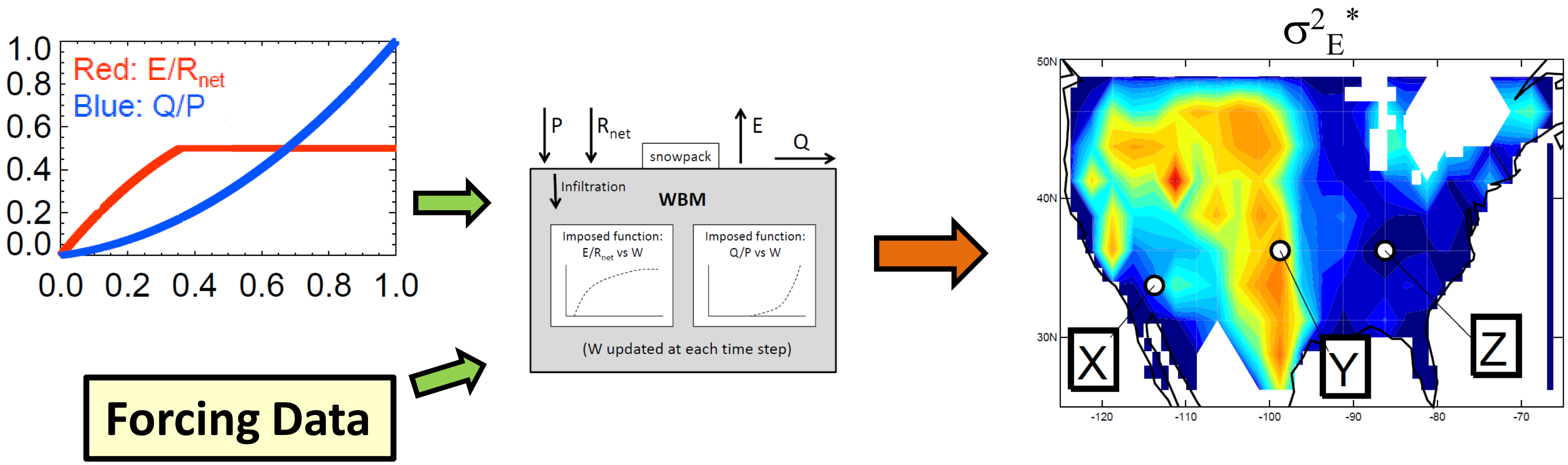


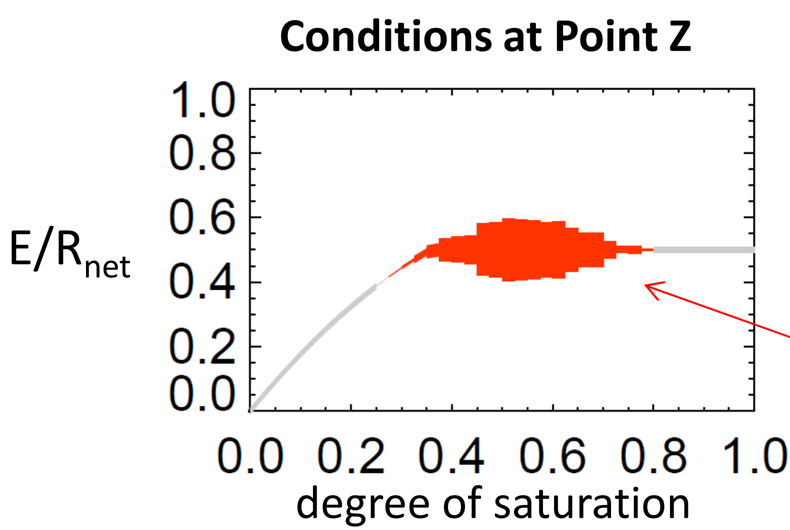
What happens if we rerun the system, forcing the evaporation efficiency curve to be flat at the soil moistures characterizing Point Y?



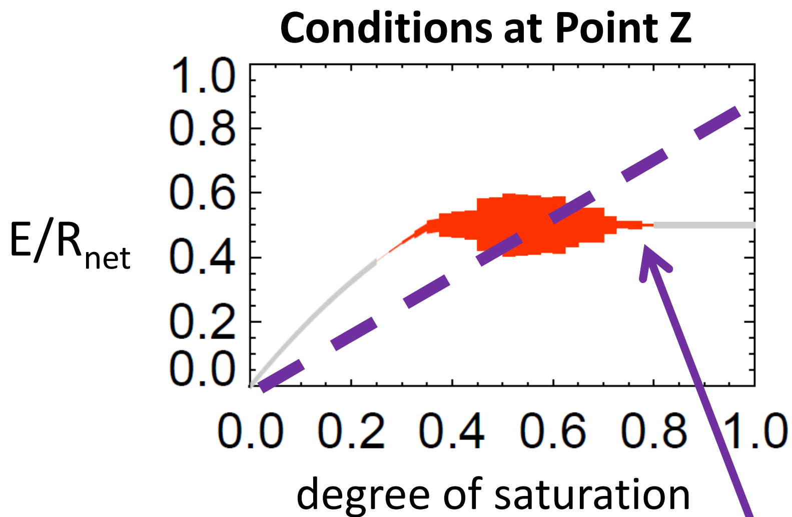
When we rerun the system, the soil moistures "move over" into the sensitive regime, and high $\sigma^2_E{}^*$ at Point Y is maintained.

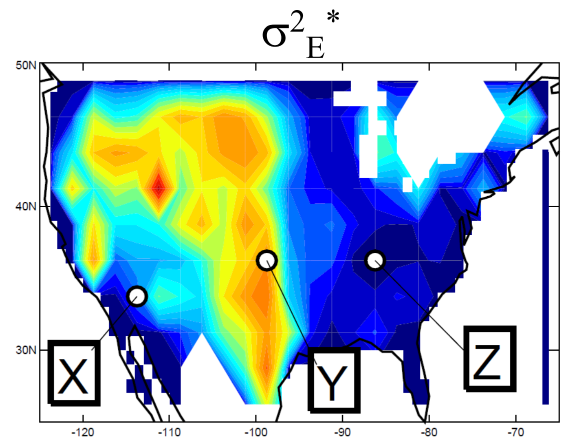
Now consider the point "Z", with low $\sigma^2_E{}^*$.



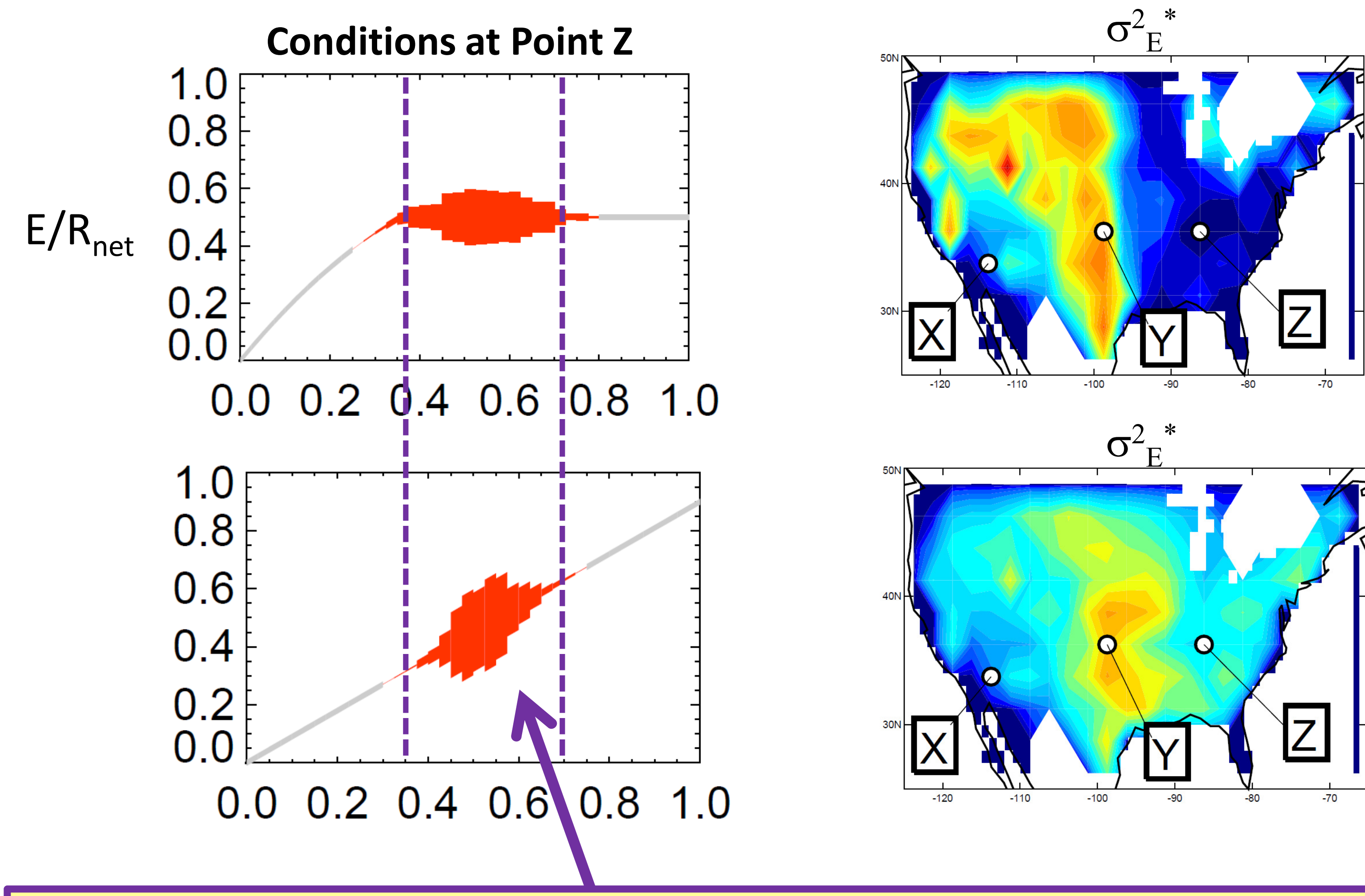


Again, thickness indicates summer soil moisture distribution





What happens if we rerun the system, forcing the evaporation efficiency curve to be <u>sloped</u> at the soil moistures characterizing Point Z, to ensure sensitivity?



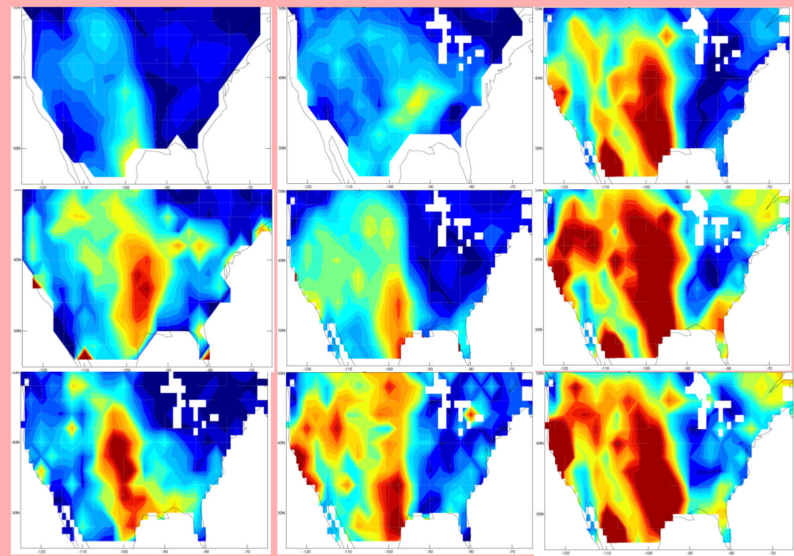
When we rerun the system, variance of soil moistures at Point Z is reduced, mitigating the increase in $\sigma^2_E{}^*$.

Implication (from the above and from many other analyses with the simple model):

Soil moisture tends to "adjust itself" so that evaporation behavior remains largely a reflection of the incident forcing.

⇨The general success of LSMs in capturing the overall spatial pattern of $\sigma^2_E{}^*$ in CONUS (low in the west and east, high in the center) is not due to realistic treatments of evaporation and runoff formulations in these models. Rather, the patterns are predetermined in large part by the meteorological forcing, i.e., by the "climate regime.

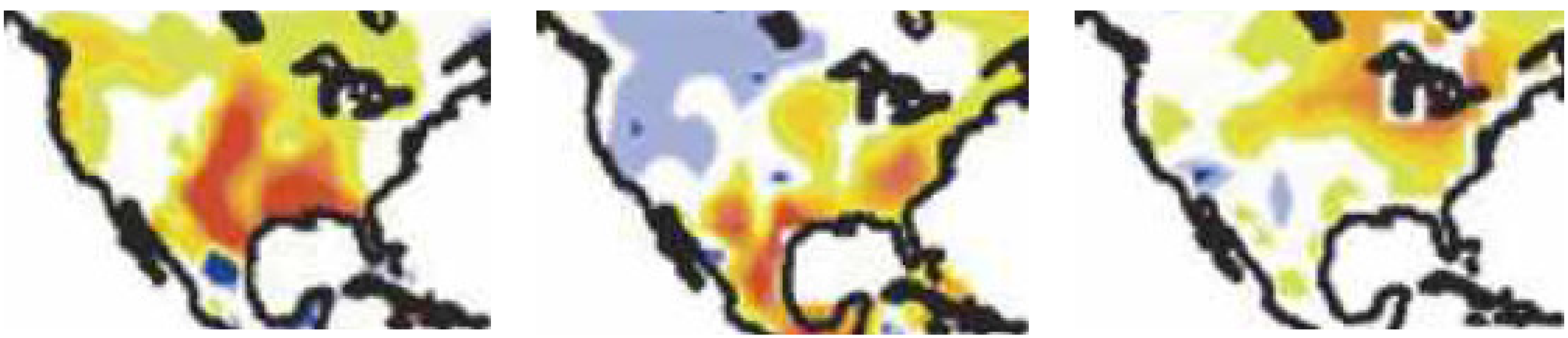
$\sigma^2_E{}^*$ from 9 LSMs, run offline



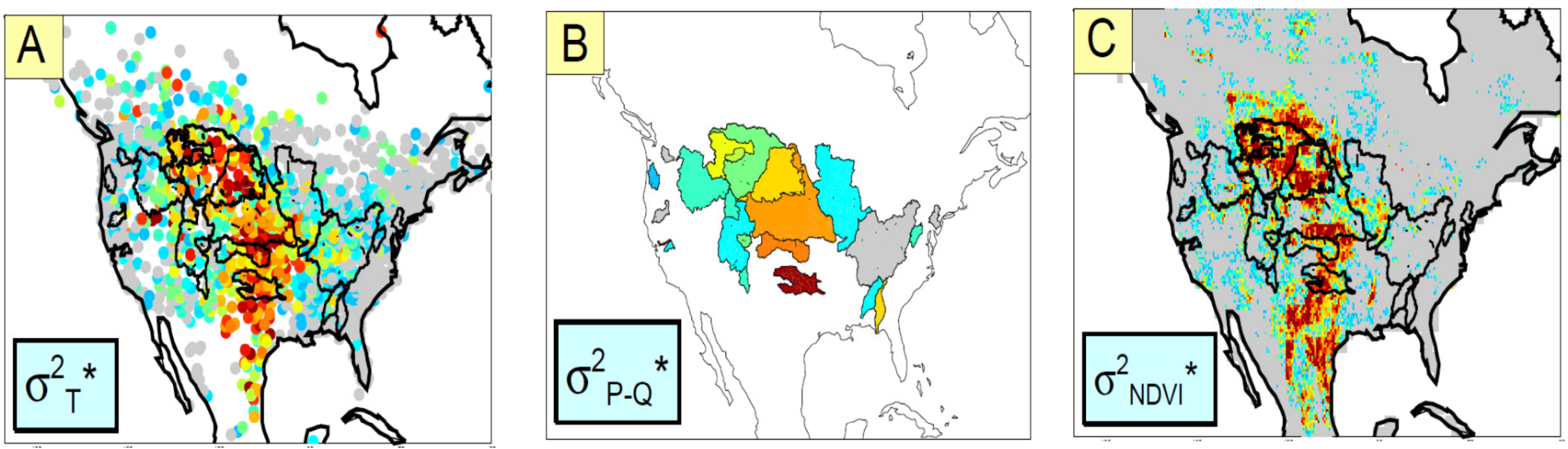
In other words, even poor land surface models can locate land-atmosphere "hotspots" in the correct locations, if the meteorological forcing is accurate.

Corollary 1: Inter-model differences in land-atmosphere coupling strength patterns (as identified in GLACE) are likely a result of model-specific biases in atmospheric forcing rather than land representation.

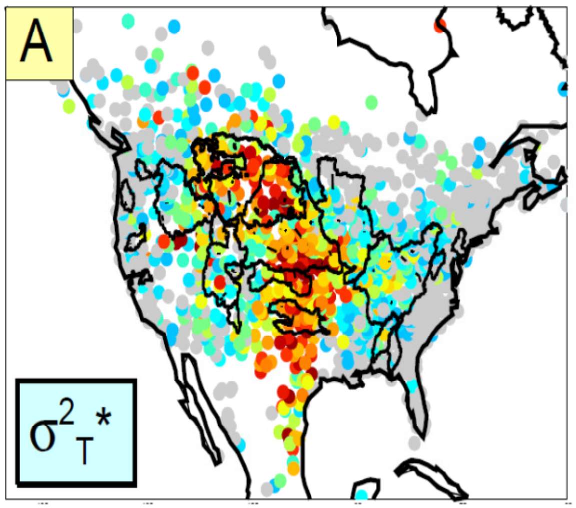
$\Omega_T(S) - \Omega_T(W)$ for three land models (from 2006 GLACE paper)

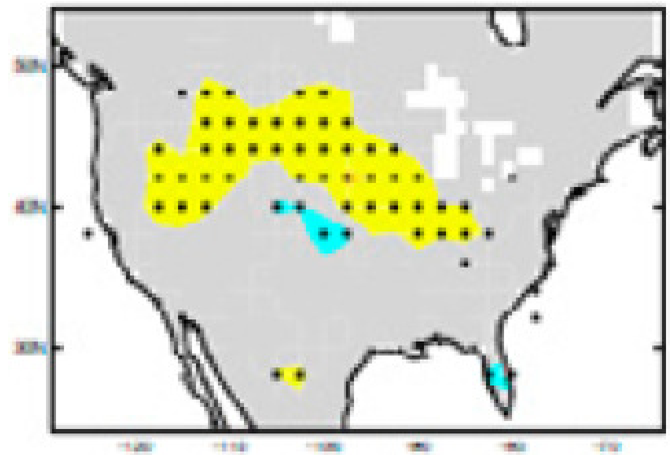


Corollary 2: Regardless of the land surface model used, soil moisture initialization in the middle of the country is likely to have a large impact on NWP and subseasonal forecasting.

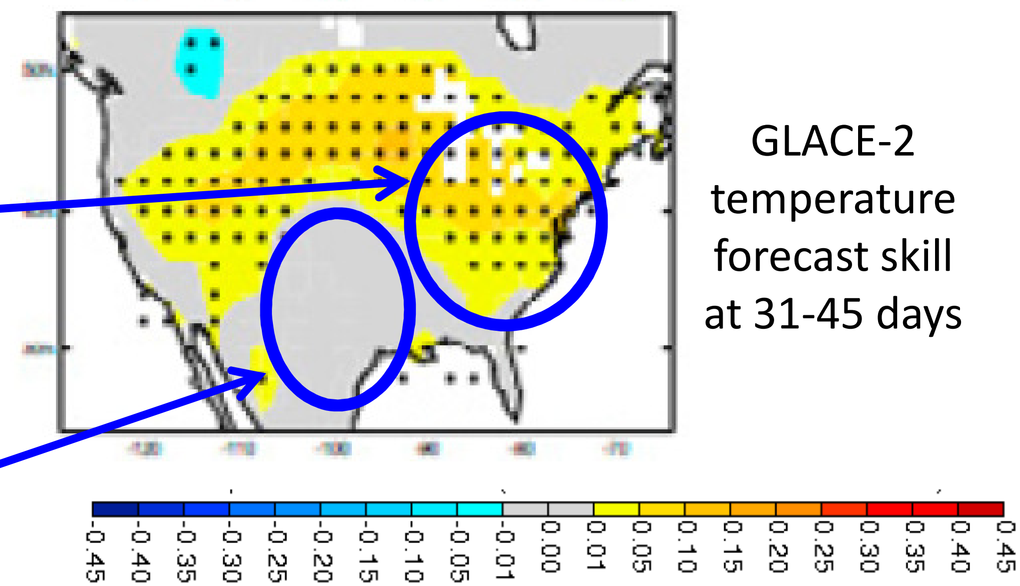


A caveat: given the above, we would expect forecast skill to be maximized in a swath down the center of the continent. GLACE-2, which quantified soil moisture-related forecast skill, shows soil moisture initialization to have positive impacts in some “unexpected” regions:





GLACE-2 precipitation forecast skill at 31-45 days



GLACE-2 temperature forecast skill at 31-45 days

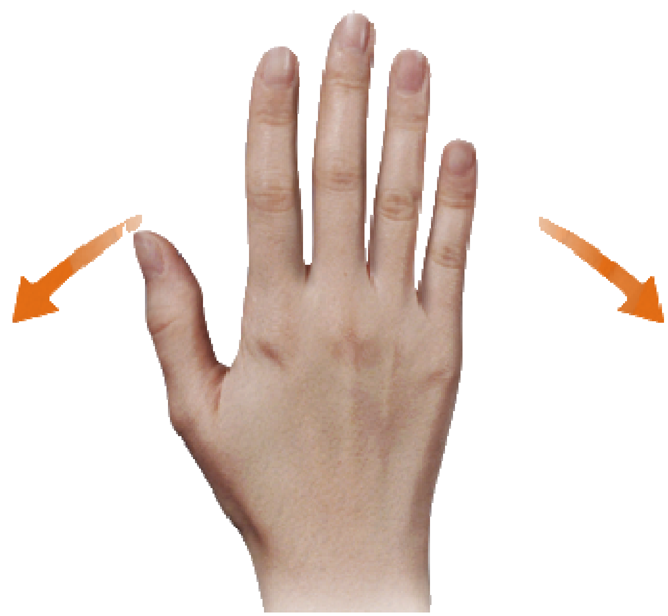
Why is there skill here…

…but not here?

Reference: Koster et al., GRL, 38, L02402, doi:10.1029/2009GL041677, 2010

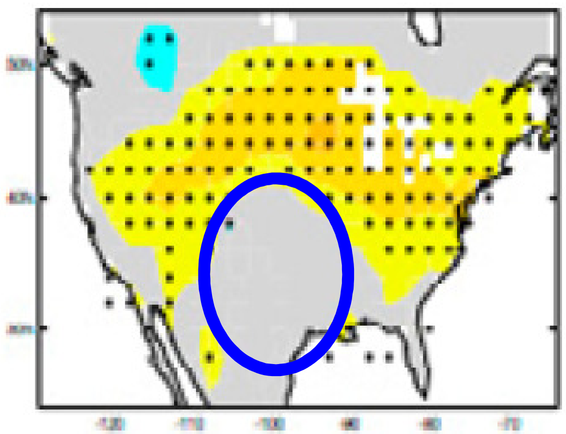
The reasons for the apparent discrepancy are still unclear – it's an important question and a potentially fruitful topic of future research.

For now, we can use a less scientific approach to explaining things…

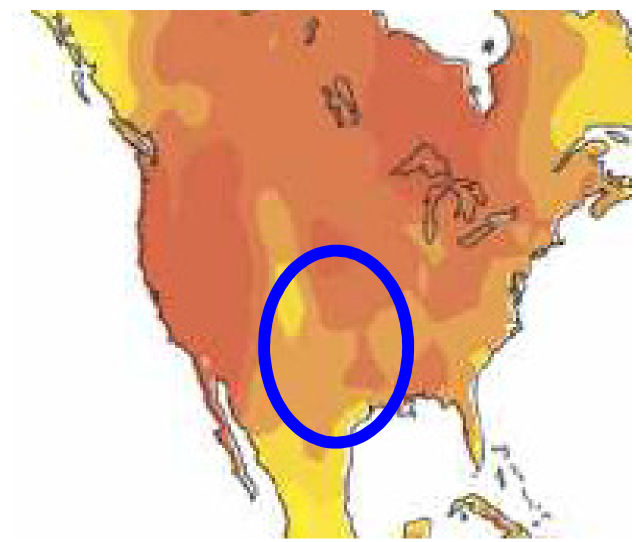


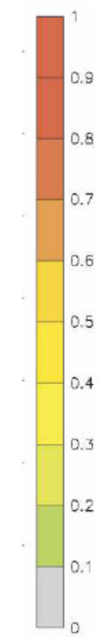
The low GLACE-2 skill levels in the south-central U.S. may be related to lower soil moisture memory there.

GLACE-2 temperature
forecast skill at 31-45 days



Multi-model estimate of 1-month-
lagged soil moisture autocorrelation

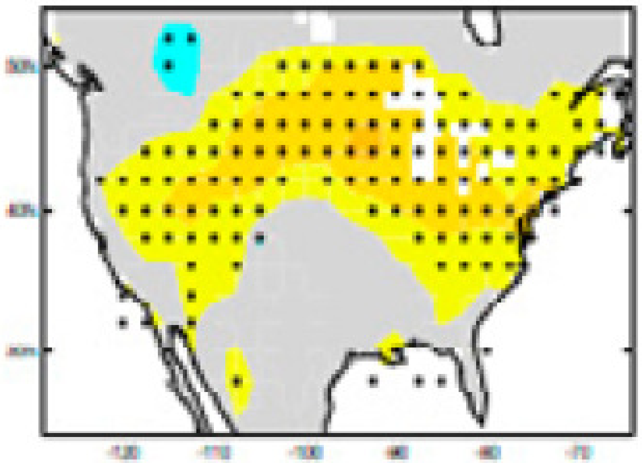




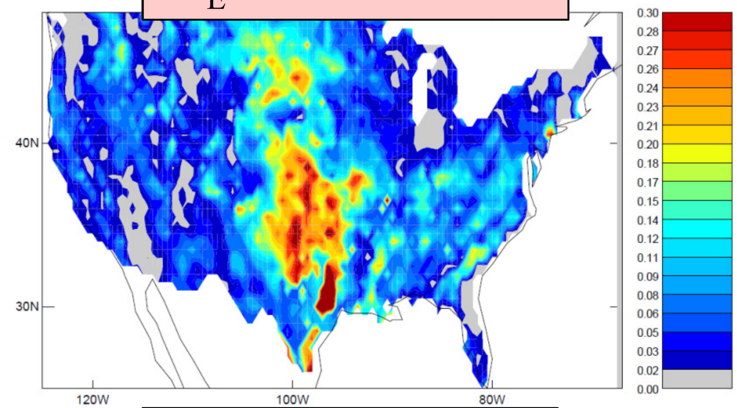
Reference: Seneviratne et al., J. Hydromet., 13, 1090-1112, 2006

The high levels in the east may have something to do with our assumption regarding the equivalence of <u>evaporation variability at the seasonal scale</u> (which can be estimated from observations) and <u>evaporation variability at the synoptic scale</u> (of relevance to forecasts).

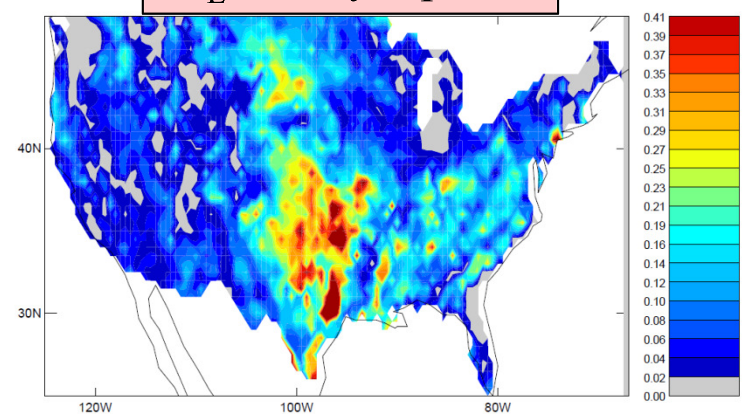
GLACE-2 temperature
forecast skill at 31-45 days



$\sigma^2_{E}{}^*$ for seasonal E



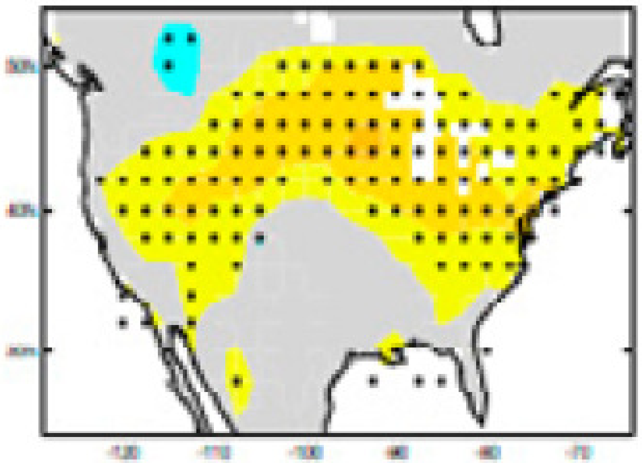
$\sigma^2_{E}{}^*$ for synoptic E



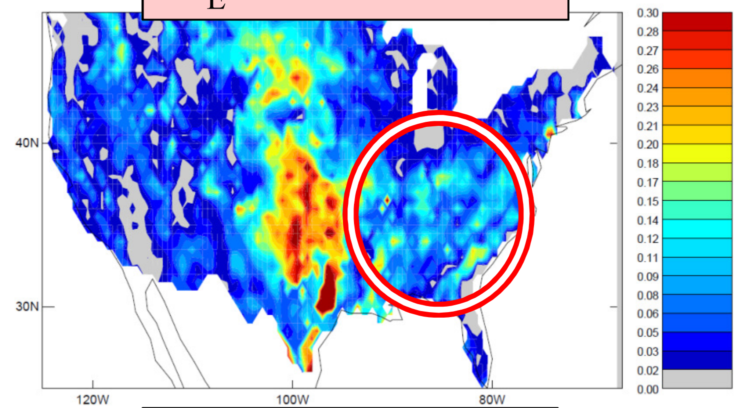
From an offline model run

The high levels in the east may have something to do with our assumption regarding the equivalence of evaporation variability at the seasonal scale (which can be estimated from observations) and evaporation variability at the synoptic scale (of relevance to forecasts).

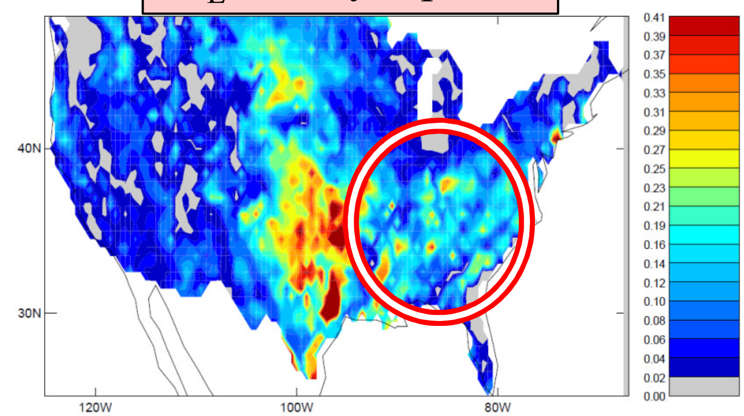
GLACE-2 temperature
forecast skill at 31-45 days



$\sigma^2_E{}^*$ for seasonal E

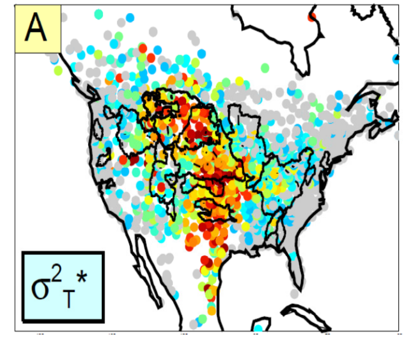


$\sigma^2_E{}^*$ for synoptic E



As assumed, the seasonal-scale and synoptic scale patterns of $\sigma^2_E{}^*$ are very similar. The synoptic scale values, however, are a little larger in the east. (Not a great explanation, but…)

Summary



1. The spatial pattern of the evaporation variability associated with soil moisture variations, key to land-atmosphere feedback, can be estimated from observations alone.

2. Land surface models, when driven with realistic atmospheric forcing, tend to reproduce this pattern, but not because they are inherently accurate; they are successful because the pattern is largely determined by the imposed climatic regime.

3. The pattern, considered by itself, suggests that soil moisture estimation in the swath down the center of the continent would have the greatest positive impact on NWP and subseasonal forecasts. However, for yet-unknown reasons, GLACE-2 skill results show some alternative regions of impact. This needs to be investigated further.