Land Surface Processes and Interaction with the Atmosphere

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Boundary Layer Modeling is Important!

- But what lies beneath the boundary layer?
  - A: the Earth's surface
- What surface is there where people live?
  - A: Land

The Role of an LSM

Vis-à-vis the Atmosphere:

- Absorb and emit the *right* radiation
- Provide the *right* drag to the flow
- Partition net radiation *properly* between sensible heat flux, latent heat flux, and ground heat flux
- Supply the *right* constituent fluxes; water (goes with latent heat flux above), carbon, etc.

But *right* and *proper* depend on scales, model assumptions, systematic and random model errors, etc.

Outline

- Coupled land-atmosphere processes
- Validation issues for land surface states and fluxes
- Going Forward

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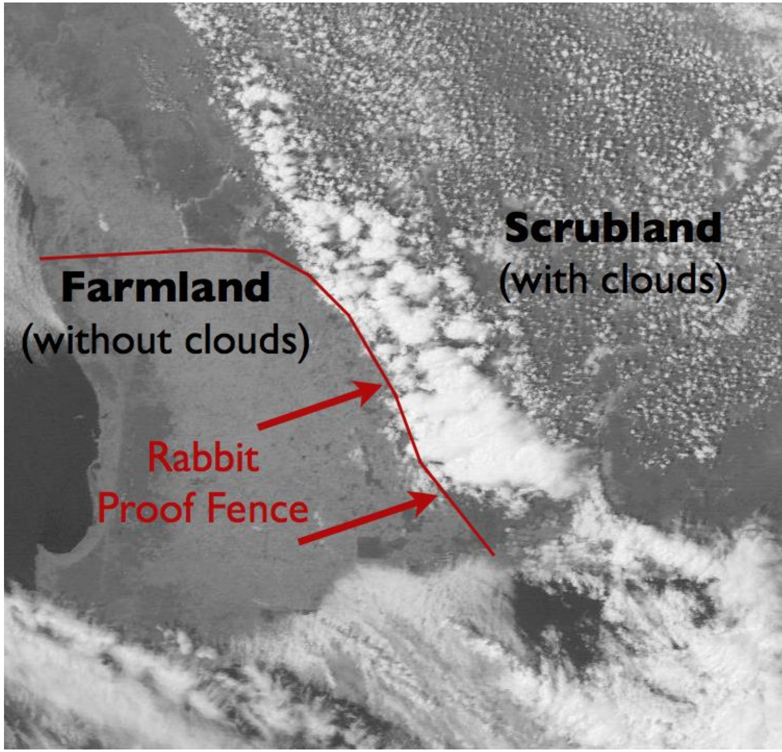
Coupled Feedback: Why Land Matters

- The feedbacks in land-atmosphere systems are rarely constant, but vary with space, time, and conditions.
- Thus feedback is often a function of land and atmospheric state variables, making it difficult to diagnose (nearly impossible from observations).
- One approach: collect large amounts of output from complex climate model sensitivity experiments.
- The concept of weather/climate predictability from the land states is predicated on the assumed existence of feedbacks, making this an important subject of current research.

Proving impact of L-A feedbacks

- Usually impossible to do attribution of weather or climate events from observations
  - Easy in models but do models mimic processes correctly?
- BuFEX – a rare example of cause and effect tied clearly to land conditions (right).
- But not usually so obvious – thus we rely on carefully developed statistical metrics.



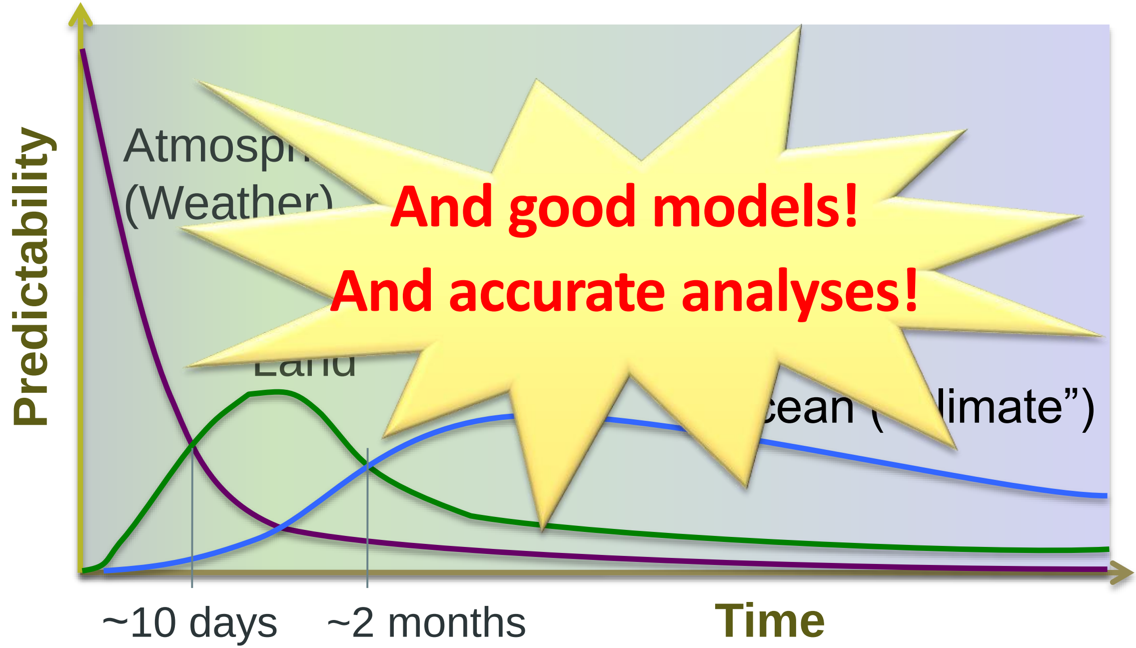
Western Australia – depending on conditions, clouds form preferentially on one side or other of "Bunny Fence."

Modern Land-Atmosphere Paradigm

- Coupling
  - When and where is there an active feedback from land surface states to the atmosphere?
  - Two-legged: land state to surface flux; surface flux to atmospheric properties/processes.
- Variability
  - A correlation results in a significant impact only where the forcing term fluctuates sufficiently in time.
- Memory
  - If the forcing anomaly does not persist, the impact will be minimal.

Predictability and Prediction

- Land states (namely soil moisture*) can provide predictability in the window between deterministic (weather) and climate (O-A) time scales.

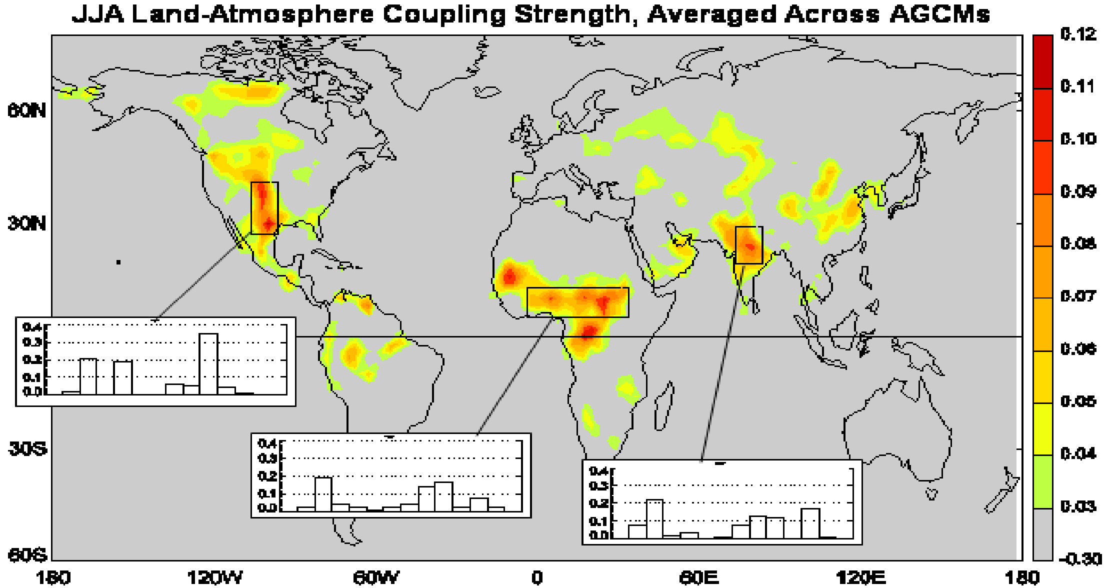


- The 2-4 week "subseasonal" range is a hot topic in operational forecast centers now.
- Active where we have sensitivity, variability and memory.

*Snow and vegetation too!

GLACE Global Land-Atmosphere Coupling Experiment

- 12 weather and climate models differ 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 became used (and over-used) to justify the role of the land surface in climate.

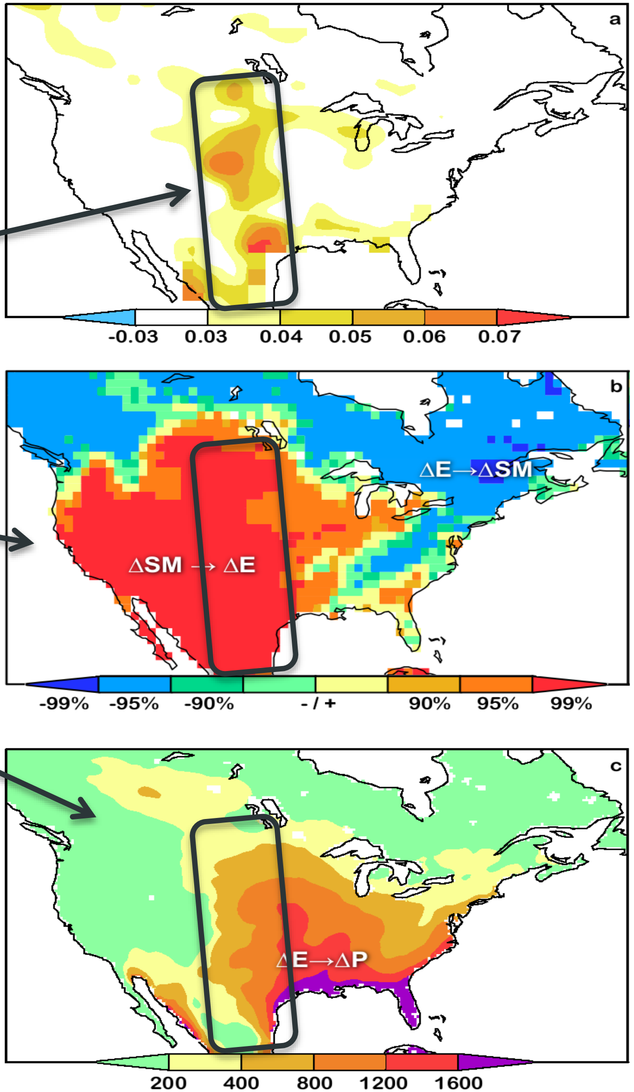
Koster et al. (2004; *Science*)

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]

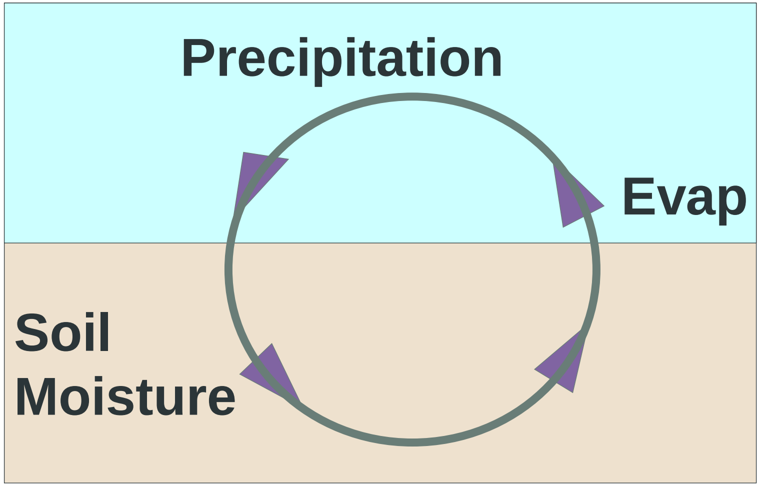
$$\Delta P \Rightarrow \Delta SM \rightarrow \Delta E \rightarrow \Delta P$$

Feedback path: Terrestrial leg Atmospheric leg

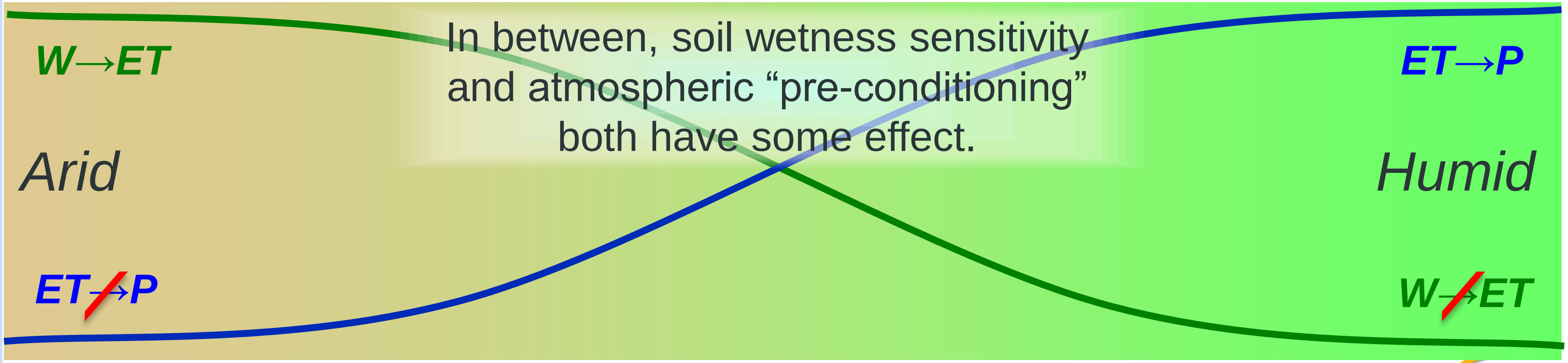


Arid regime:
ET (mostly surface evaporation) is very sensitive to soil wetness variations, but the dry atmosphere is unresponsive to small inputs of water vapor.

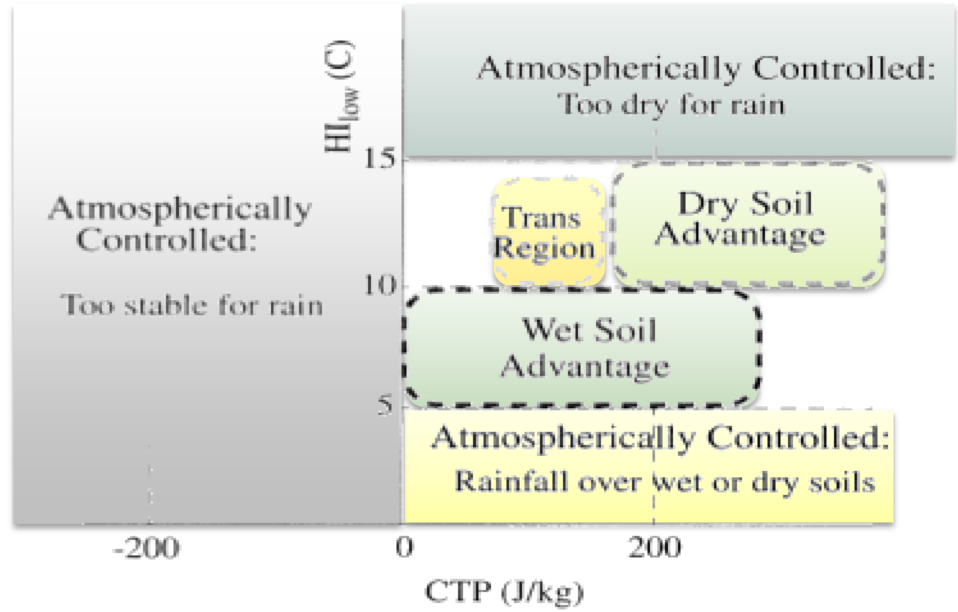
Coupled Feedback Loop



Humid regime:
Small variations in evapo-ration affect the conditionally unstable atmosphere (easy to trigger clouds), but deep-rooted vegetation (transpiration) is not responsive to typical soil wetness variations.



Regimes

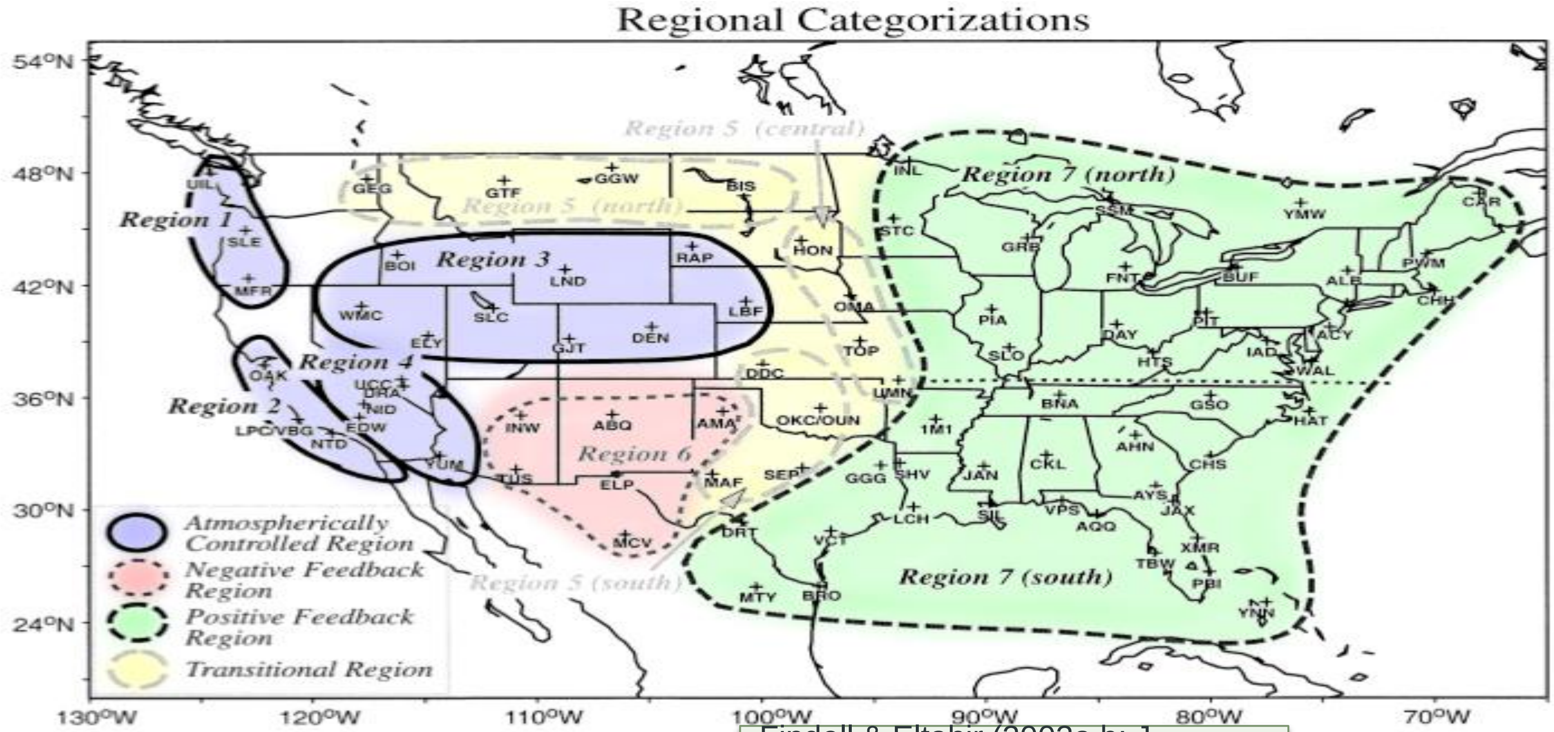


- PBL model runs over four other sites from arid to humid climates established the following categories:
- Atmospherically controlled regimes:
  - Air too dry to rain
  - Profile too stable to rain
  - Moist and unstable – rain occurs regardless of soil moisture
- Soil Controlled
  - High CTP, easy entrainment, builds deep boundary layers; convection favored over dry soils with large sensible heat flux.
  - Moist atmosphere, convection favored over wet soils.

Findell & Eltahir (2003a,b: J. Hydrometeor.)

Categorized by Region

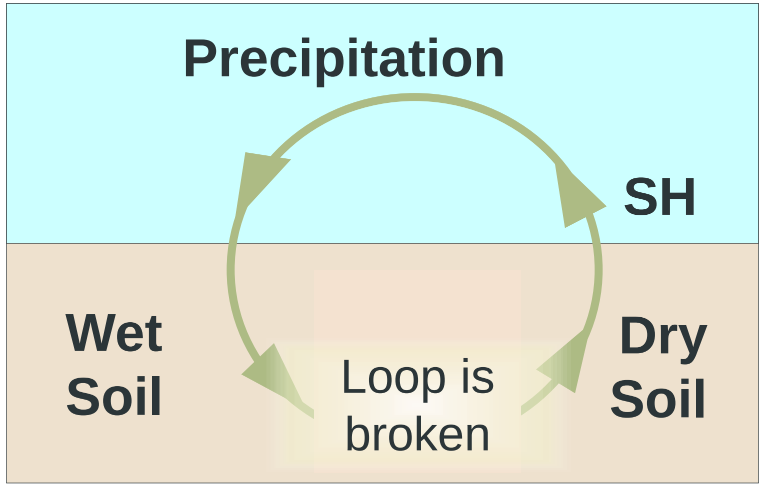
- All of the radiosonde sites in and around CONUS are assessed based on their climatologies of CTP and HI_{Low}.



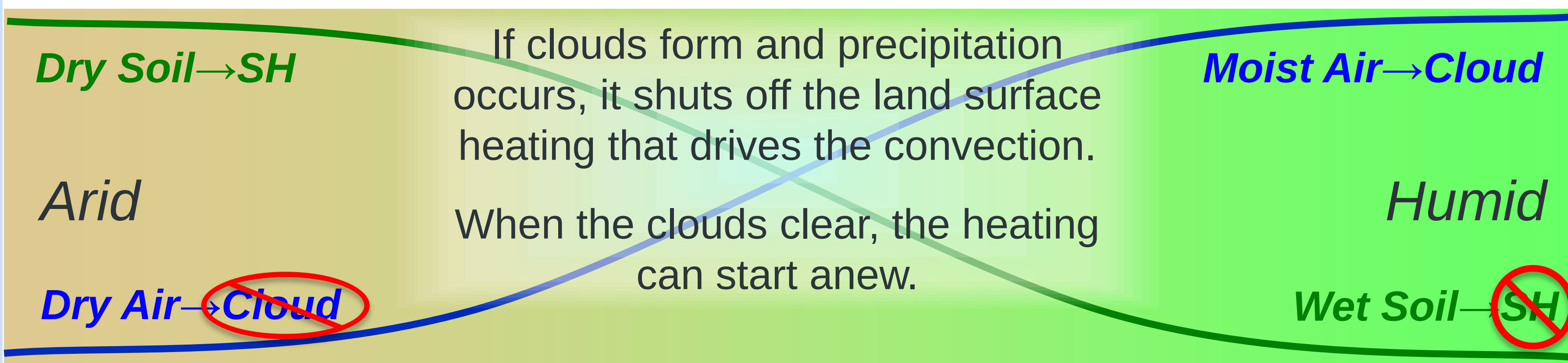
Findell & Eltahir (2003a,b: J. Hydrometeor.)

Negative Feedback

Arid regime:
Dry air must be lifted great distances to cool enough to form clouds – strong sensible heat flux can build necessary deep turbulence and generate convection.

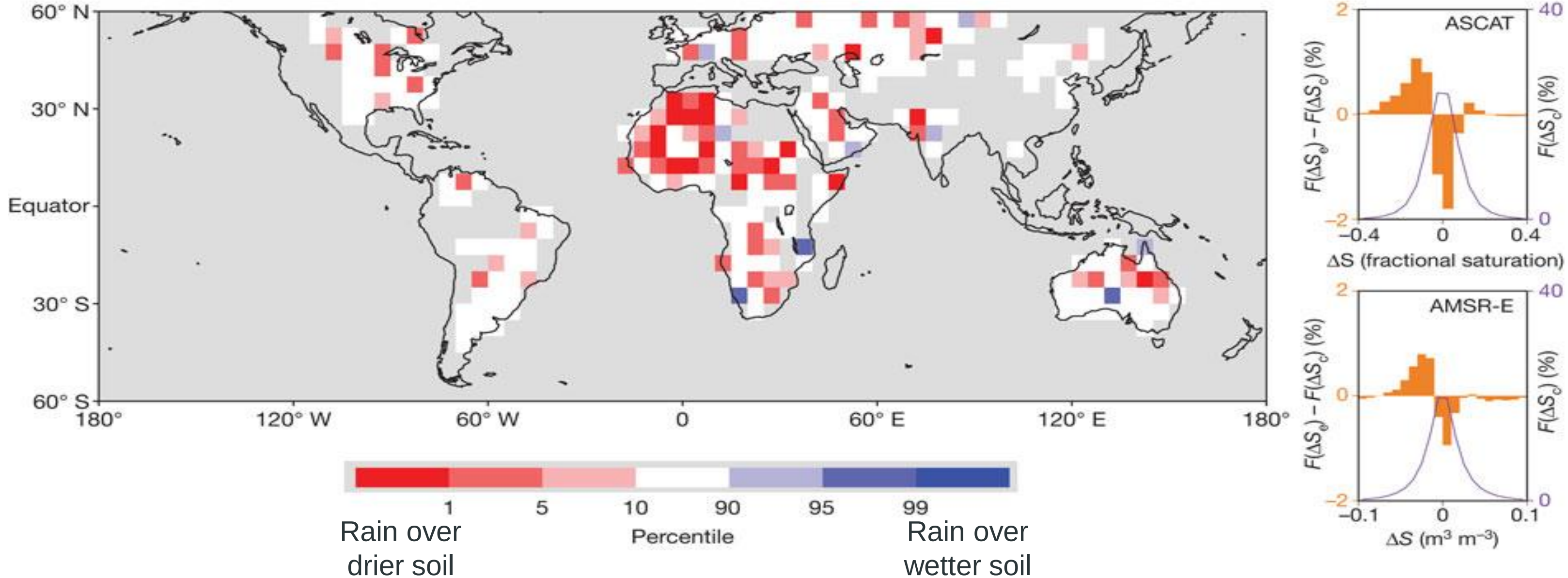


Humid regime:
Moist air can more easily form clouds with a low cloud base. Usually sensible heating is in short supply when cloudy (and possibly rainy), but not when clear. Again, a negative feedback.



Observations say otherwise?

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



Apparent preference for afternoon rain over drier soil

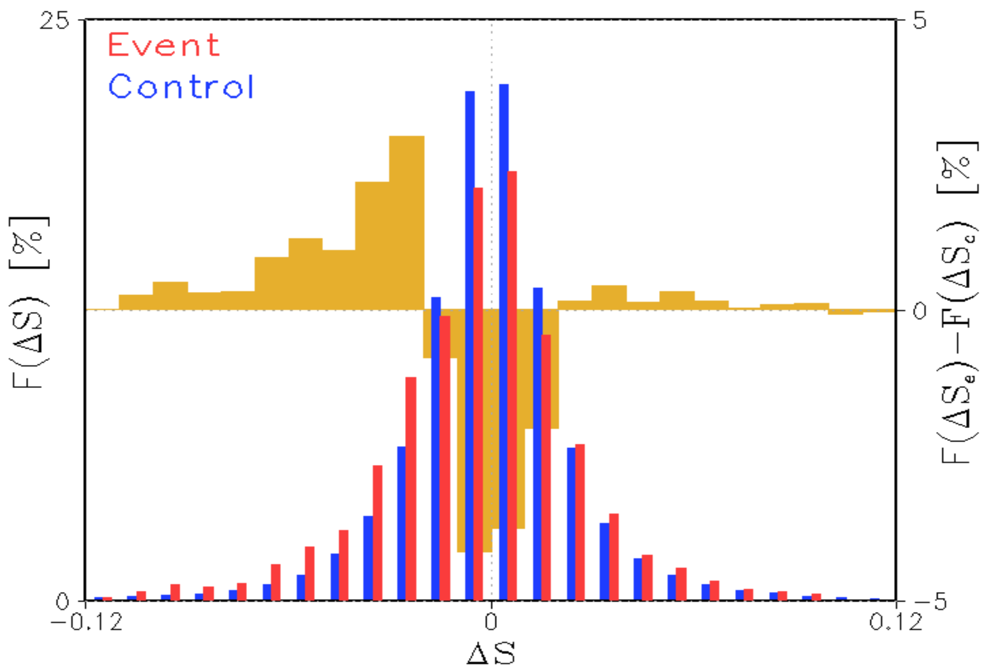
Far fewer blue pixels than expected by chance

Signal strongest in Africa and Australia

Taylor et al. (2012; *Nature*)

Preference for afternoon rain

- Statistics of 554 events in this region (5° x5°)
- Rain over drier soil found more frequently than expected
- Re-sampling indicates probability of this result occurring by chance 0.2%
- In fact, mesoscale circulations at wet/dry boundaries are important (Taylor et al. 2011; Nature Geo)

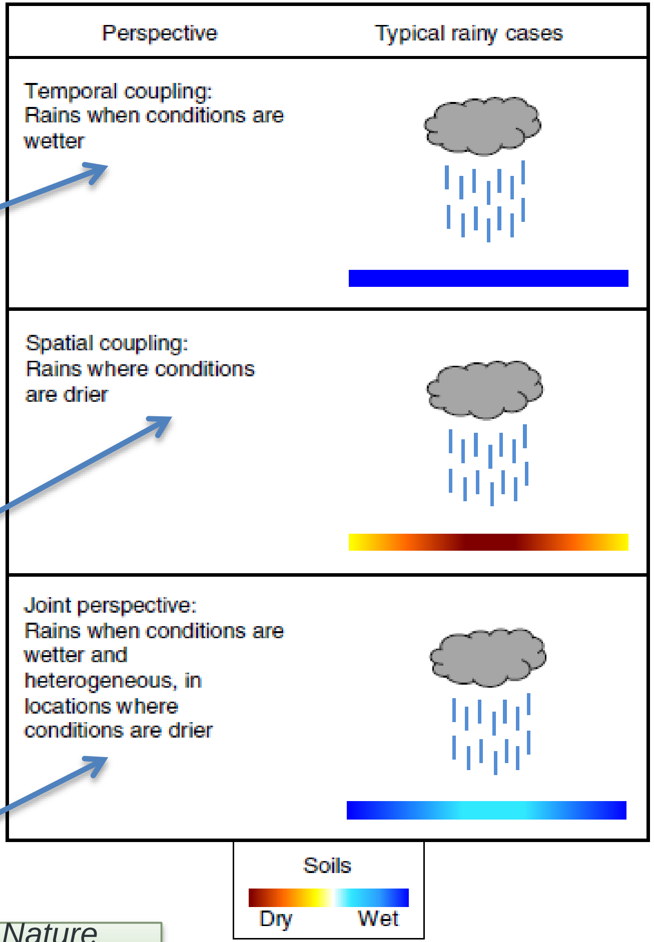


Difference in pre-event soil moisture between rainy and non-rainy pixels

Rain over drier soil ← → Rain over wetter soil

Reconciling Koster & Taylor

- Part of the difference may be due to spatial scaling.
- GLACE picked up on large-scale temporal coupling, where correlations and feedbacks are positive.
- Taylor picked up on small-scale spatial coupling that occurs sub-grid in weather and climate models.
- They can coexist in nature, but not in models that parameterize convection conventionally.



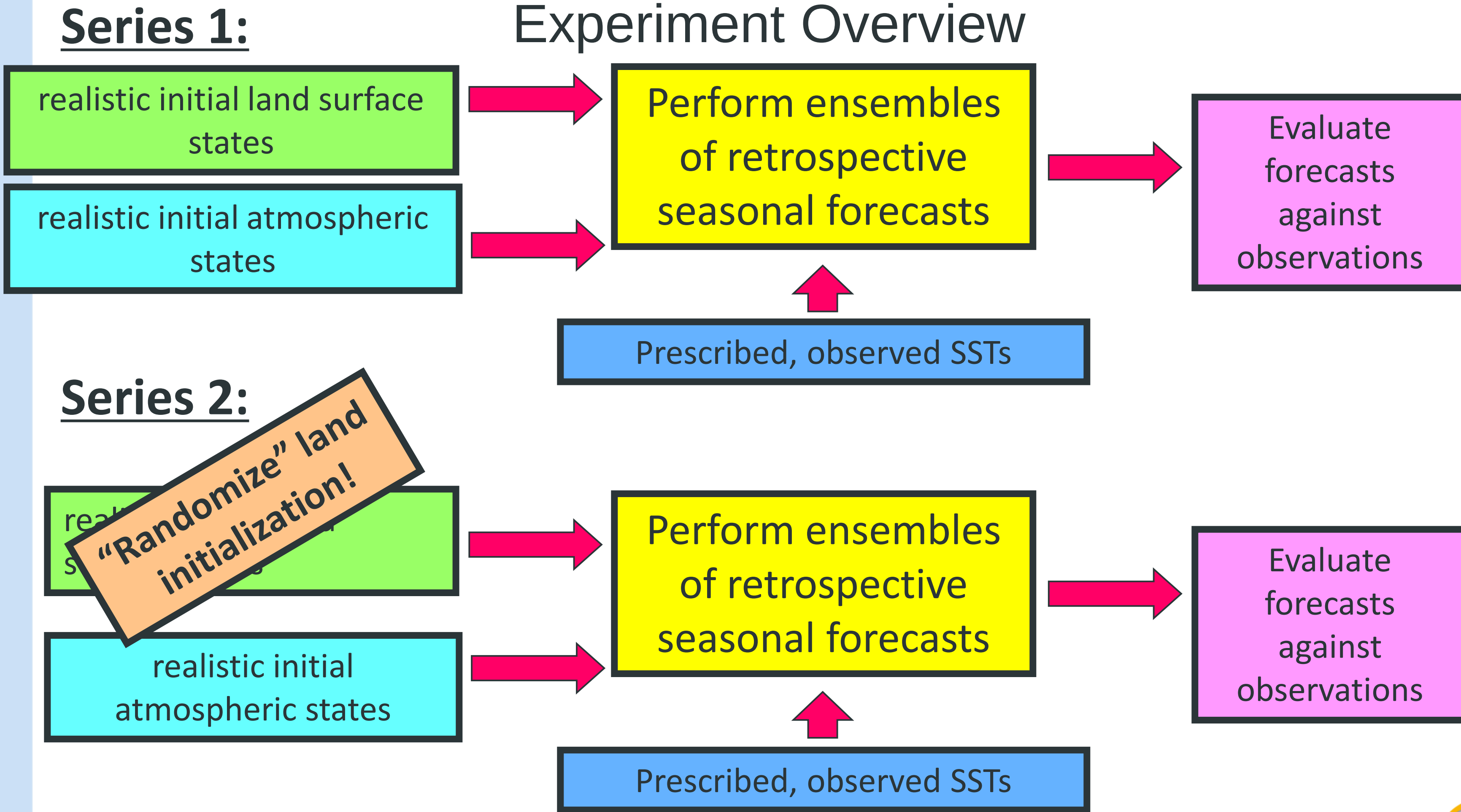
Guillod et al., (2014; *Nature Comm.*)

GLACE-2

- Once we established in GLACE that weather and climate models exhibited coupling and feedbacks between land and atmosphere, the next step was to examine the predictability and prediction skill that could be gained from accurate initialization of soil moisture in seasonal forecasts.
- GLACE-2 was designed as a prediction experiment – 10 years (1986-1995), 10 2-month forecasts per year (begun on the 1st and 15th of April, May, June, July and August), each forecast is an ensemble of 10 members.
- One case uses “realistic” soil moisture initialization (from offline GSWP-2 simulations or similar), the other case uses “unrealistic” (randomized) initial soil moisture.
- 10x10x10x2 = 2,000 forecasts per model and 12 models!

Koster et al., (2010; GRL) (2011; *JHM*)

GLACE-2:
Experiment Overview

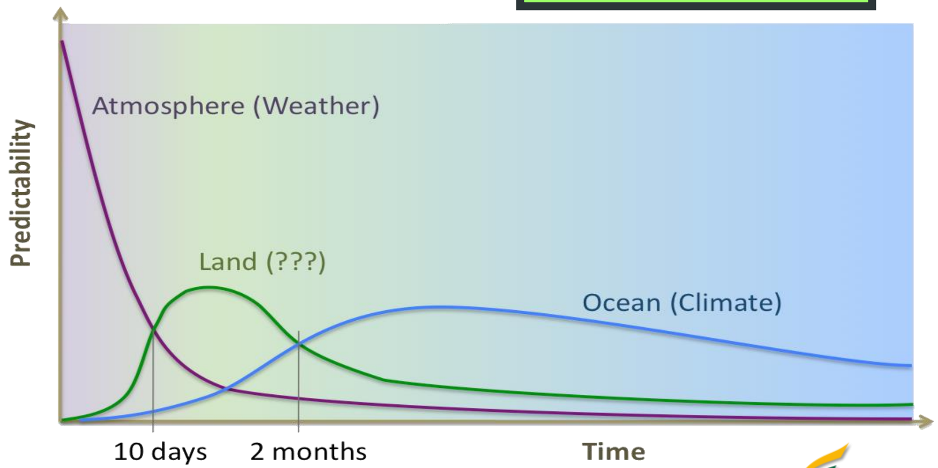


GLACE-2:
Experiment Overview

Step 3: Compare skill in two sets of forecasts; isolate contribution of realistic land initialization.

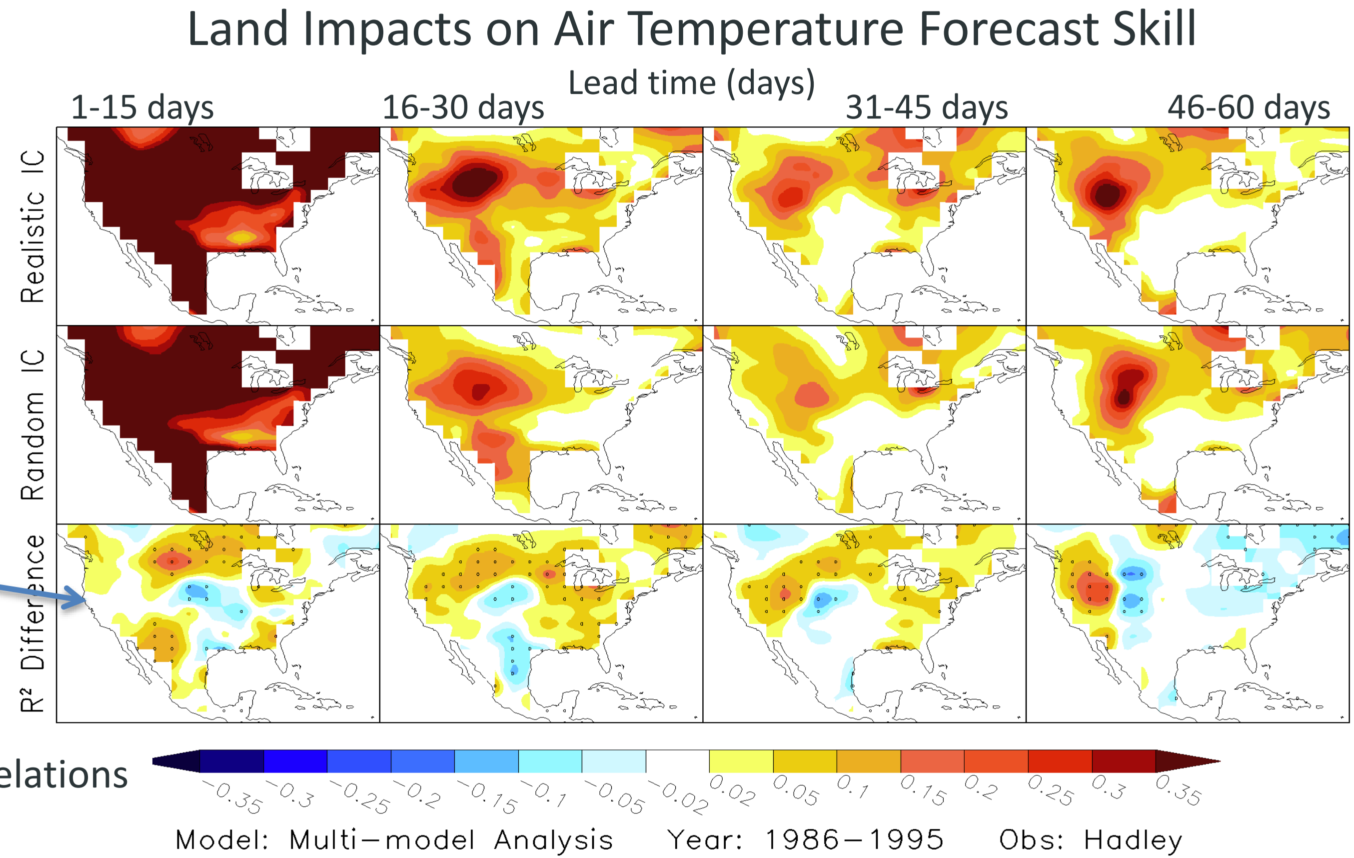
Forecast skill, Series 1 − Forecast skill, Series 2 = Forecast skill due to land initialization

- The 2-4 week "subseasonal" range is a hot topic in operational forecast centers now.
- Land surface data assimilation / initialization has a lot of promise to improve such forecasts.



GLACE-2 Multi-Model Analysis

- Realistic soil moisture initialization improves forecasts.
- Greatest improvements over North America – data quality effect?

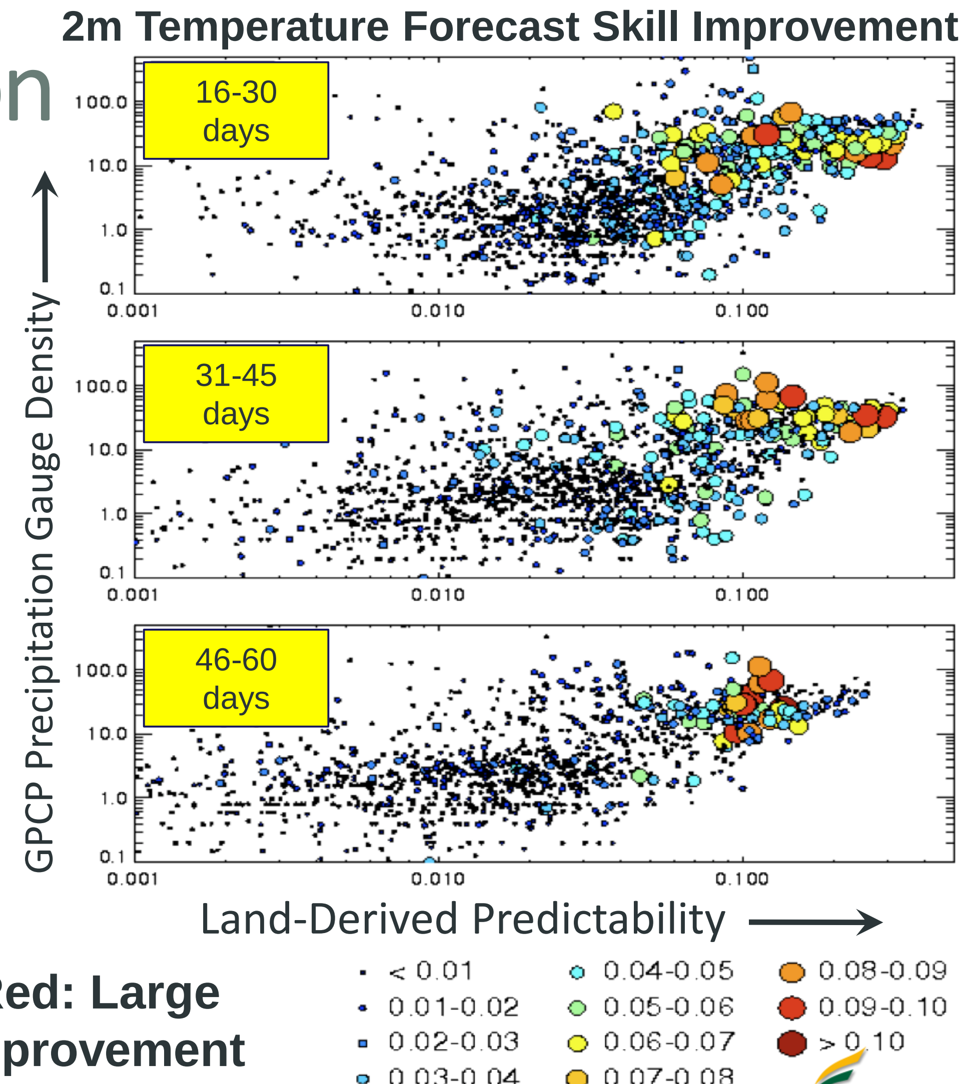


Koster et al. (2010; *GRL*)

Multi-model Analysis

Land Data Assimilation

- Garbage in – garbage out.
  - Need good meteorological forcing data as input to these “offline” land surface models, especially rainfall.
  - Greatest improvements in forecasts with “realistic” initial soil moisture are where there is coupling & variability & memory <u>& high rain gauge density</u>!
  - Land data assimilation *still not assimilating any data* – working on it.

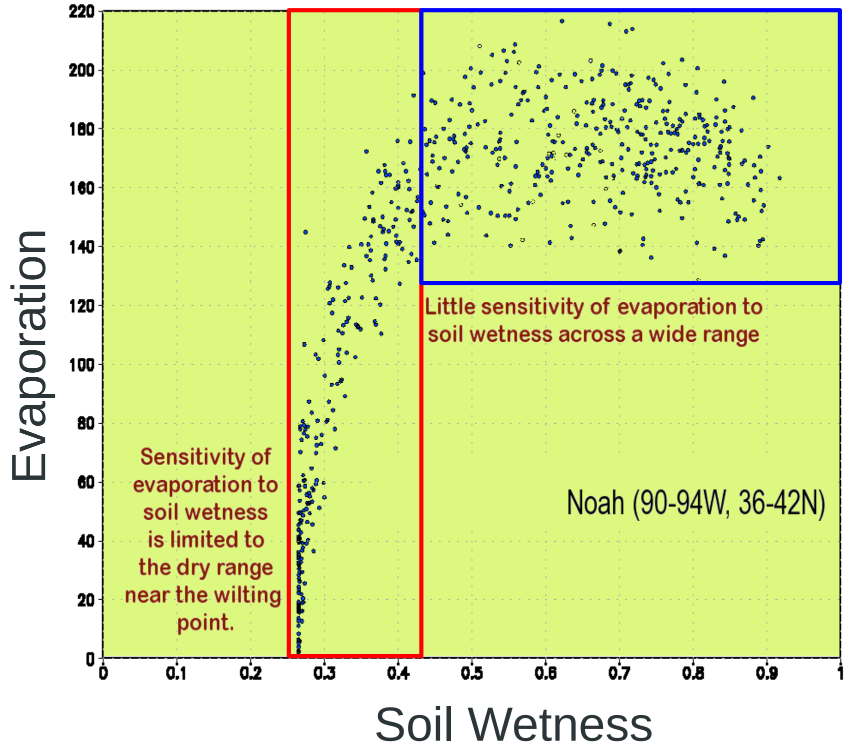


Red: Large Improvement
Black: No Improvement

Koster et al. (2011: *JHM*)

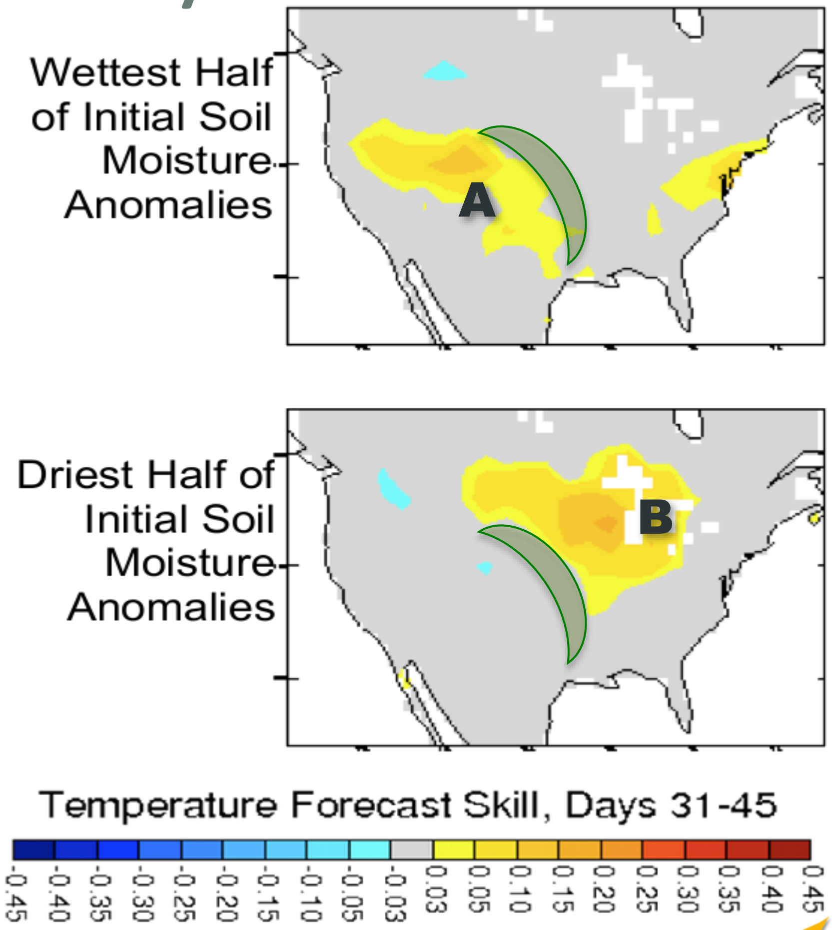
Soil Moisture Controls on Evaporation

- 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).



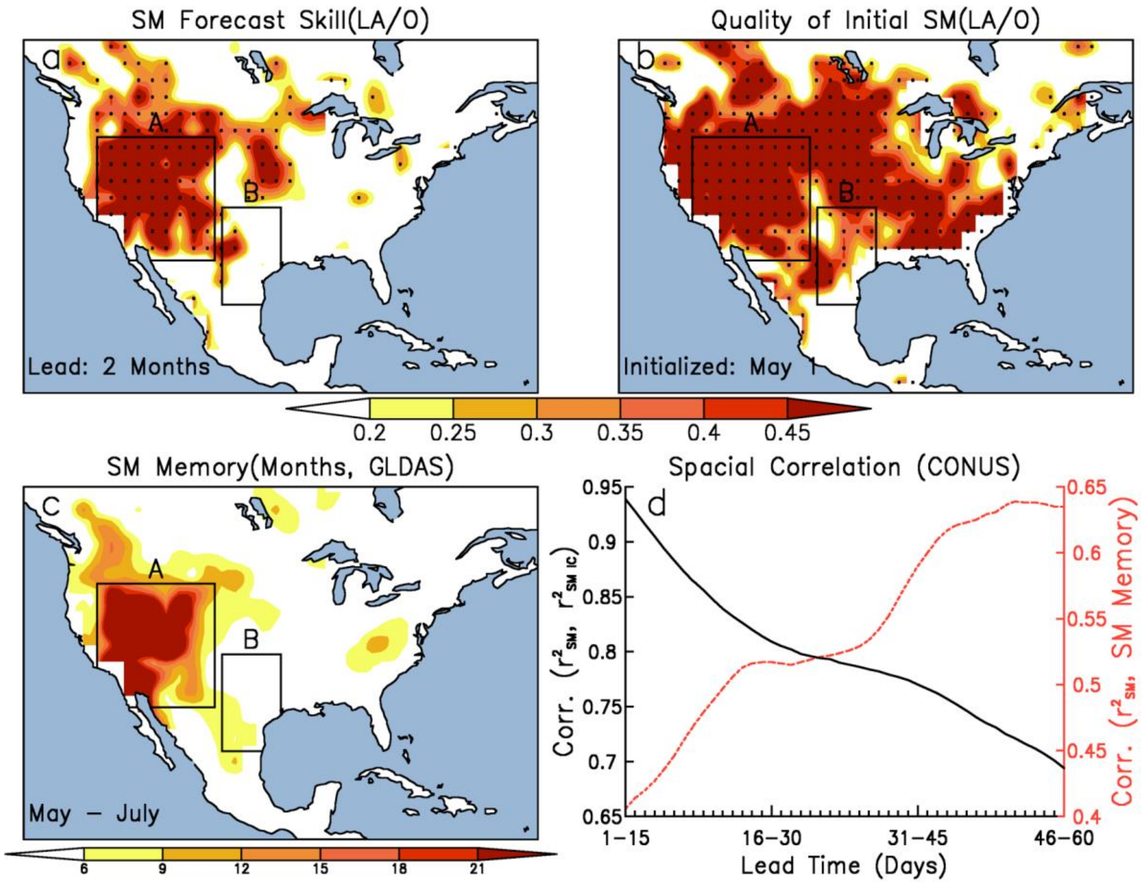
This Affects Predictability in GLACE-2

- Soil moisture anomalies that push the local L-A system toward the regime of greatest sensitivity generate biggest improvements.
- When a desert area becomes moist (**A**), it gains predictability, and thus skill.
- When a humid area becomes dry (**B**), it gains predictability, and thus skill.



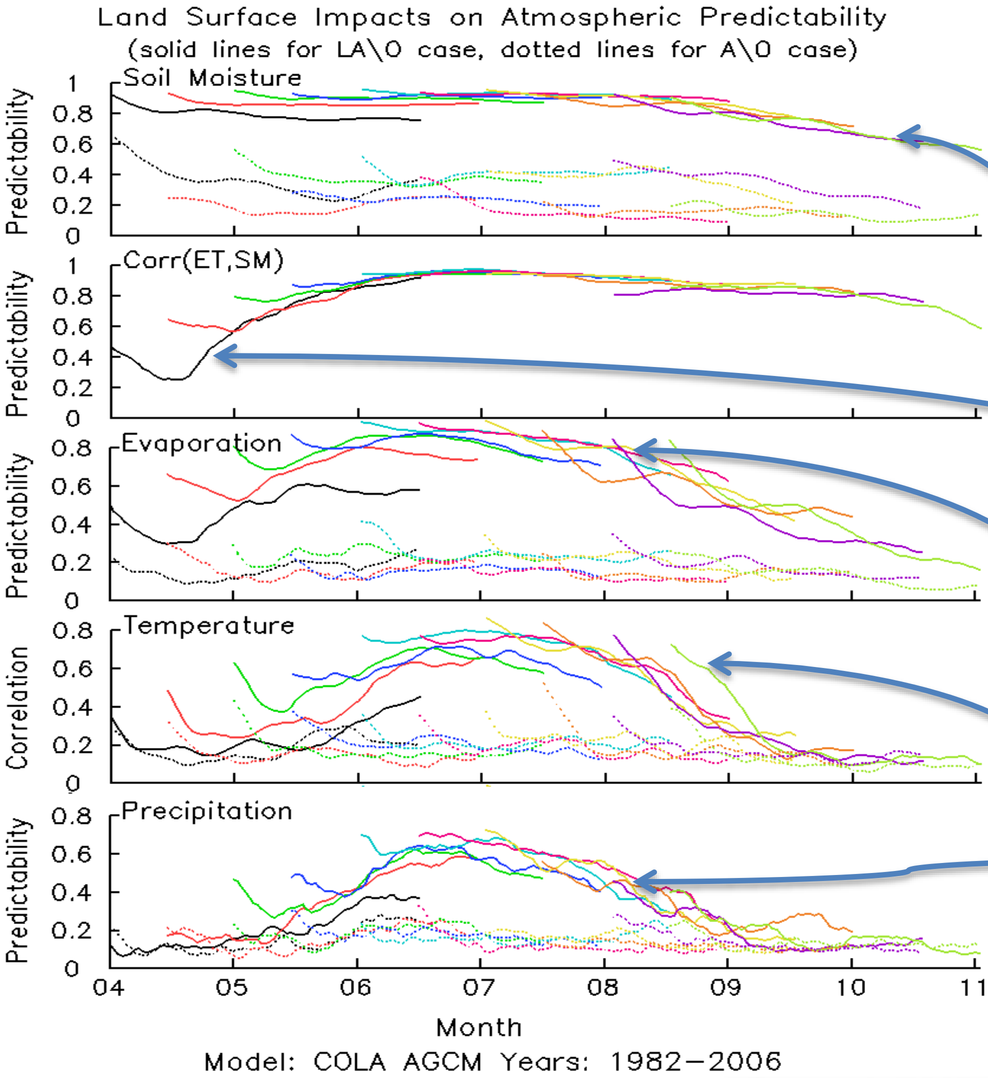
US Hotspot Weak on Memory?

- GLACE-2 found increased forecast skill from soil moisture initialization in subseasonal forecasts, but not centered over the “hotspot”.
- Reason may be a lack of persistence of anomalies there, compared to regions further west.



Guo, & Dirmeyer, (2015; *GRL*)

GLACE-2 Predictability Rebound



- Box over US Great Plains.
- Soil moisture memory is high during spring and summer.
- 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: *J. Hydromet*)

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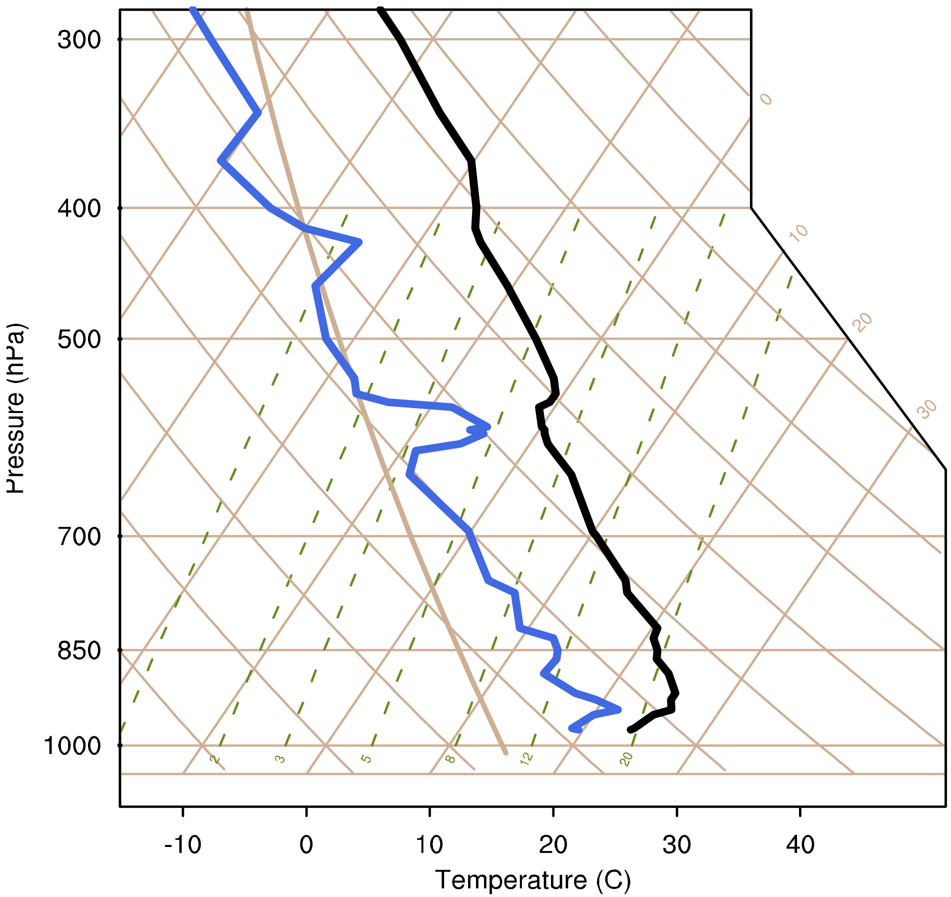
Heated Condensation Framework (HCF)

- Atmospheric "leg" of coupling
  - Quantifies how close atmosphere is to moist convection
  - Does not require parcel selection
  - Uses typically measure quantities
  - Is "conserved" diurnally
  - Can be used any time of year or any time of day
- Make prescriptive statements such as:
  - "Land surface unlikely to produce convection"
  - "Require X increase in lower atmosphere heating and Y additional moisture for triggering convection today"

Tawfik & Dirmeyer (2014; GRL)

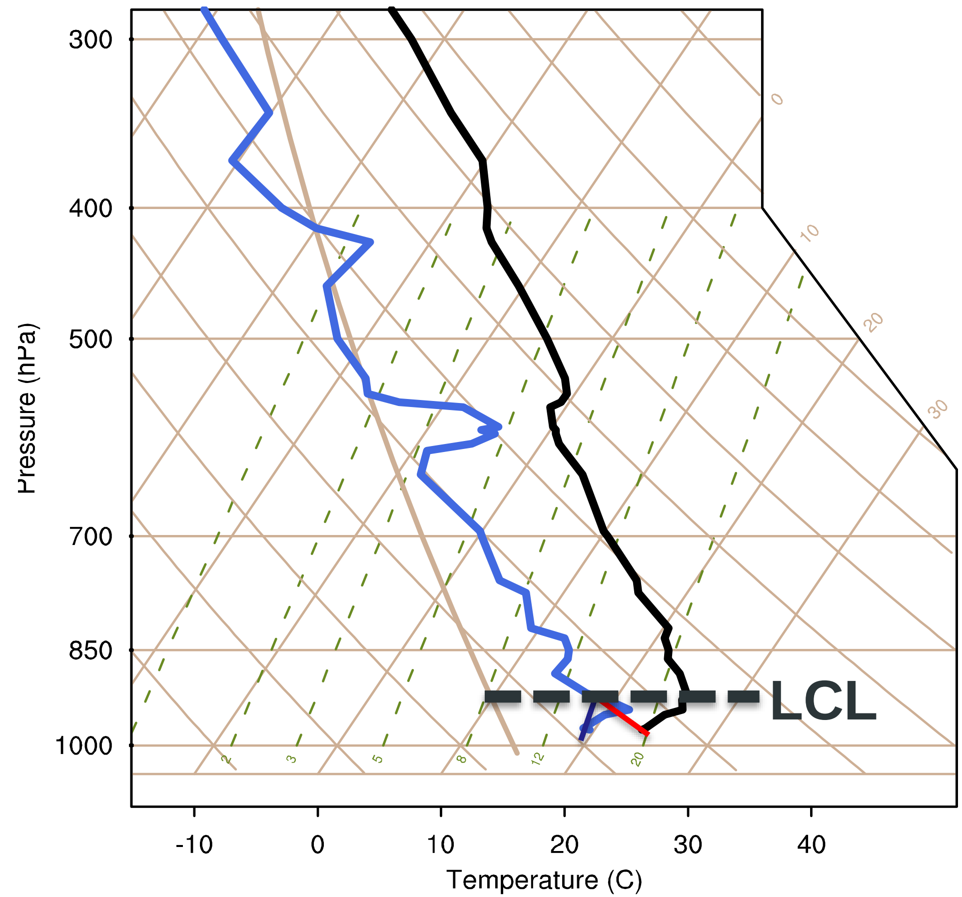
A Sounding

- Typical meteorological profile of temperature (black) and dew point (blue) through atmosphere.
- Heat and moisture input at ground modifies this profile.



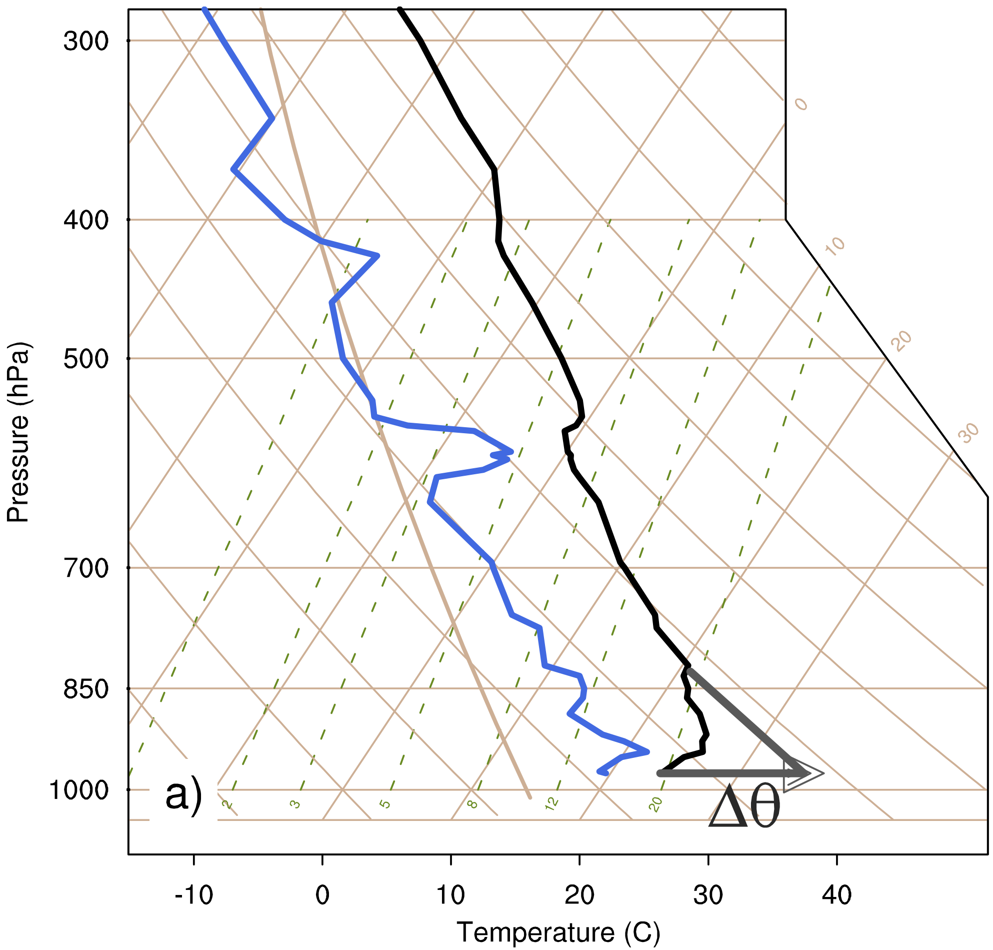
LCL

- Lifting condensation level (LCL) based only on 2m temperature and humidity.
- Easy to calculate, data readily available, but does not take into account the stratification of the atmosphere above.
- In this case, suggests a very low cloud base.



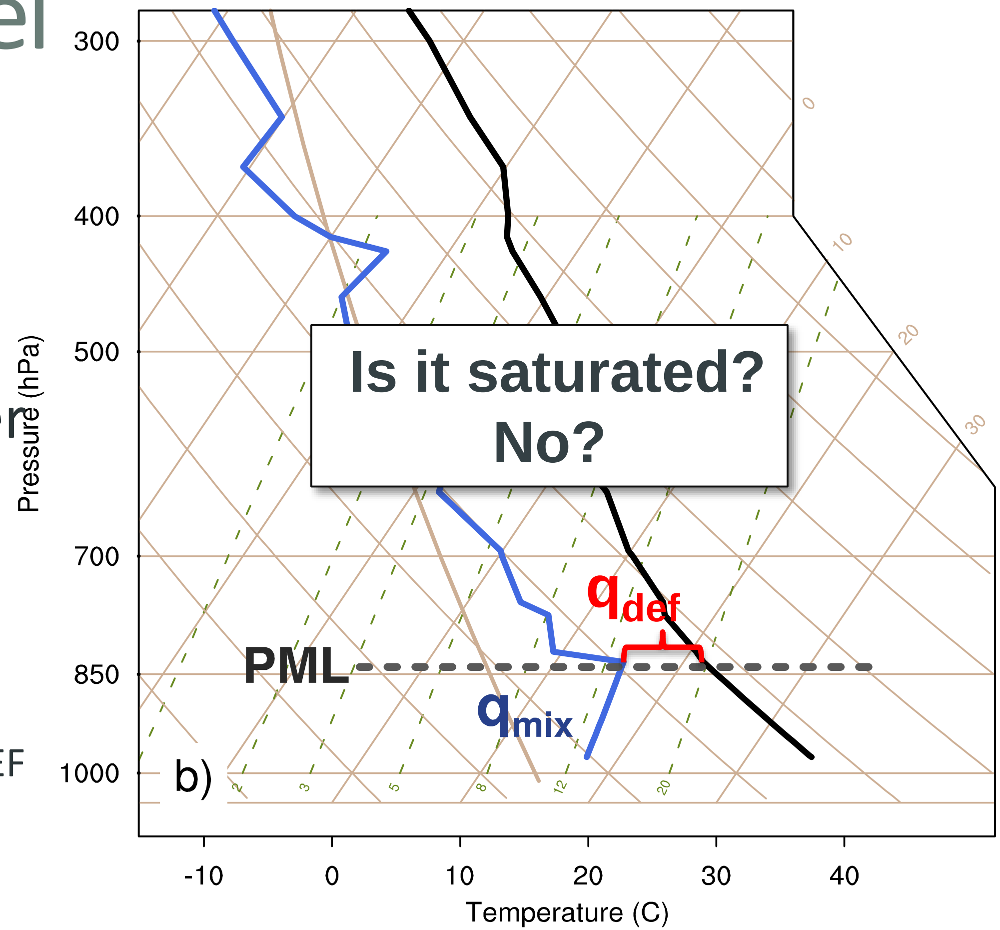
HCF Framework

- Let's add heat at surface, raising surface temperature and mixing adiabatically upward through atmosphere.
- We increment θ upward, see where dry adiabat intersects sounding = Potential mixed level.



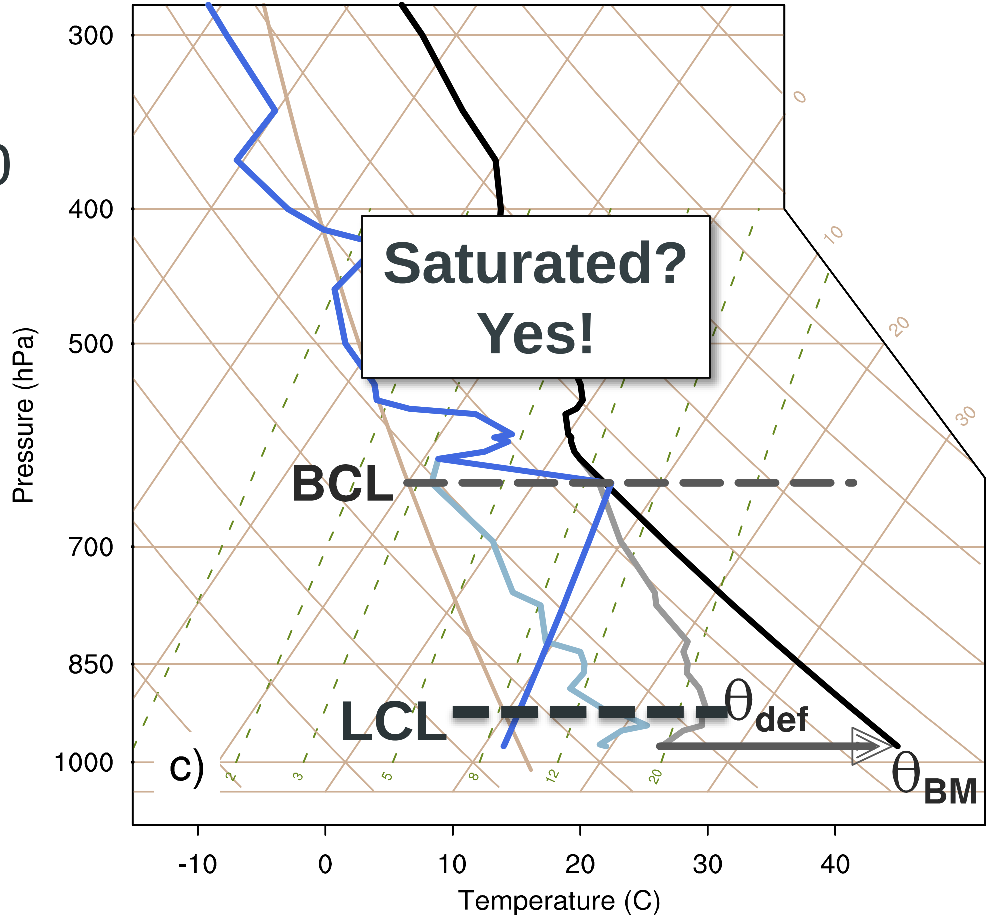
Potential Mixed Level

- Mix the moisture through that depth to a constant specific humidity
- At the "potential" mixed layer (PML) we can see that we have closed the deficit of humidity
- Saturation deficit at PML: $q_{DEF} = q_{SAT} - q_{MIX}$



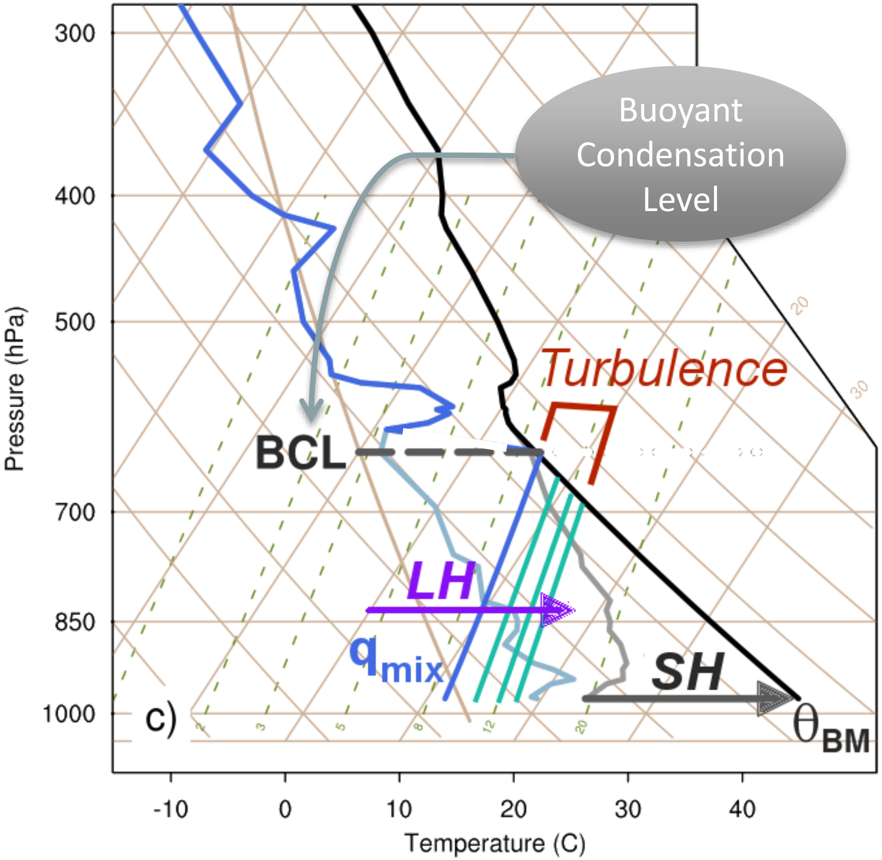
BCL

- Add heat and mix until $q_{DEF}=0$
- This is the buoyant condensation level (BCL) – accomplished with surface sensible heating only.
- Note difference from LCL



Moisture vs. Heat

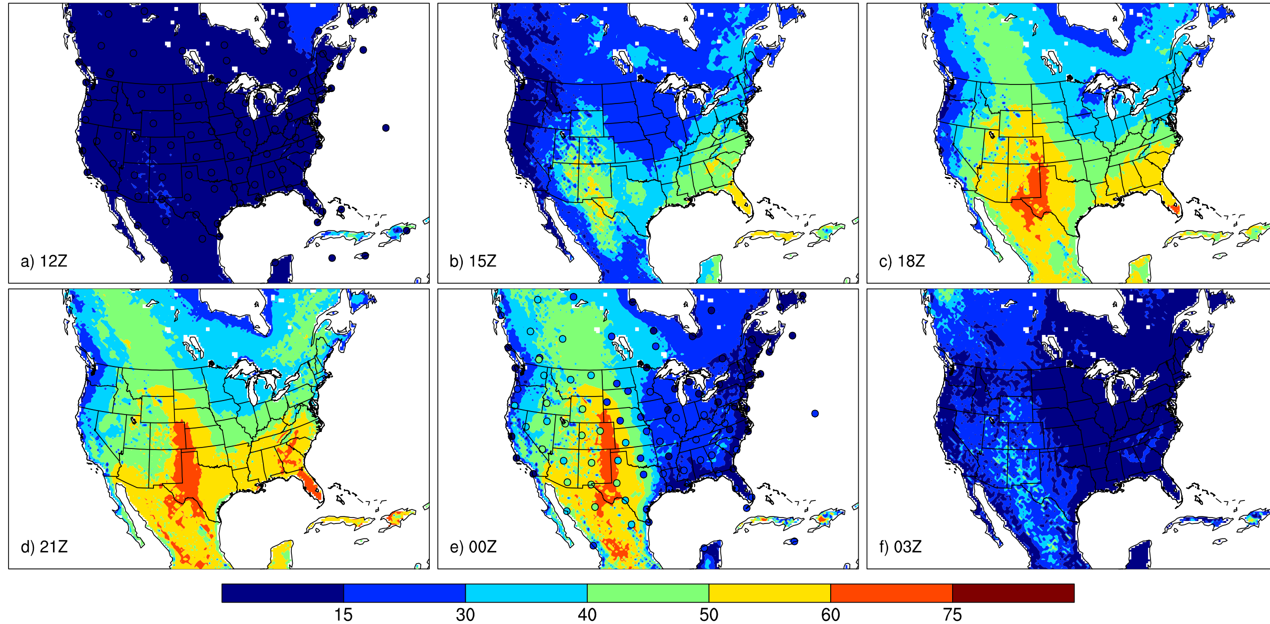
- Surface sensible heating grows the boundary layer, mixing moisture vertically.
- Added moisture from latent heat flux can make saturation easier to reach (lowering the cloud base).
- Can think of θ_{DEF} and q_{DEF} instead as SH_{DEF} and LH_{DEF}!
- LH and SH draw from same energy (net radiation) – which is more efficacious to form cloud?
- How would another W/m^2 get you closer to convection? Depends on profile, circulation & land surface.

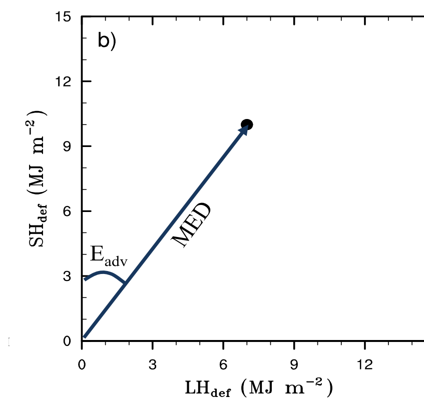


Tawfik et al. (2015a,b; J. Hydrometeor)

A Map

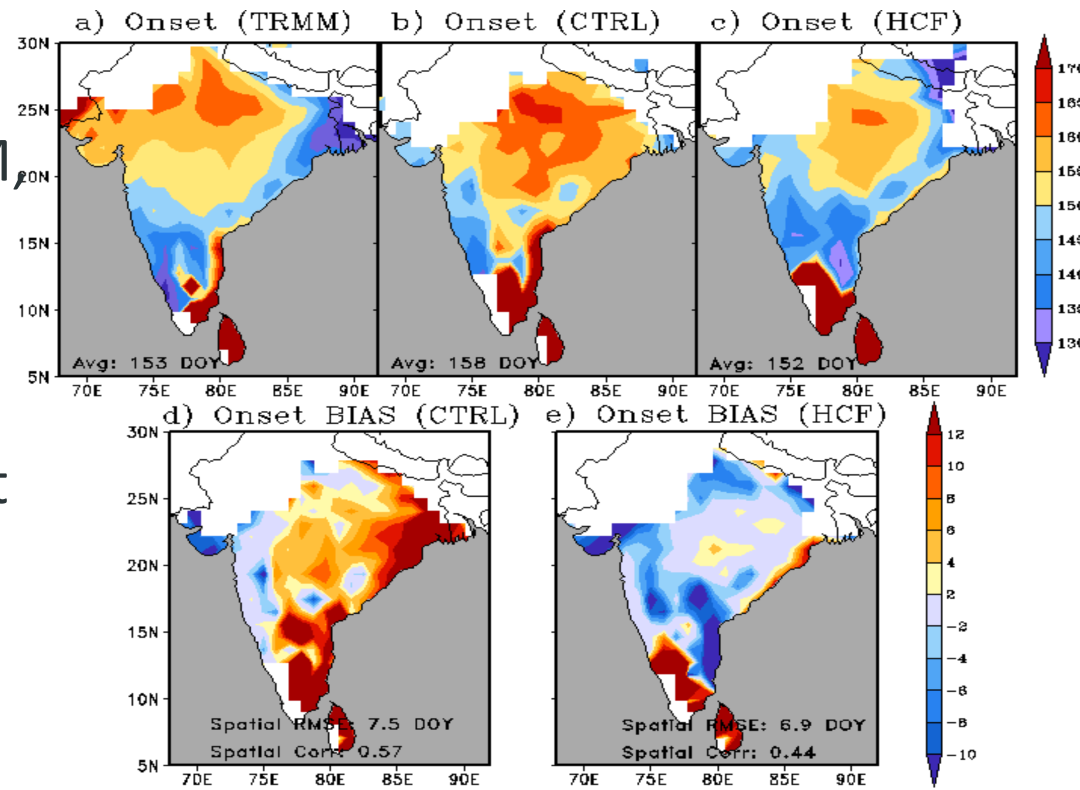
- Summer average diurnal cycle of the energy advantage “angle” (E_{adv}; degrees) from 1200UTC to 0300UTC. Contours are from NARR and markers are from obs IGRA soundings only at 0000UTC.
- Blues = moisture advantage; yellow/red = heating advantage





HCF as a Parameterization

- This has been applied within GCMs (NCAR CESM, NCEP CFS) as a parameterization of convective triggering.
- Promising results, not just for diurnal cycle, but also climate time scales (e.g., Indian monsoon onset in NCEP/CFS coupled O-L-A forecast model)



Bombardi et al. (2015; *Clim Dyn.*)

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Variability and Memory

- We will continue to talk mostly about "coupling" between land-atmosphere, and metrics to quantify it.
- But let's take a moment to consider "variability" and "memory" as well:
- Variability: Standard deviation (<u>soil moisture</u>, fluxes, precipitation, etc.) (<u>daily</u>, monthly, interannual, etc.)
- Memory: Lagged autocorrelation (<u>soil moisture</u>, snow, NDVI, etc.) (<u>daily</u>, monthly, etc.): $/ = t$ where $\ln(r) = -1$.

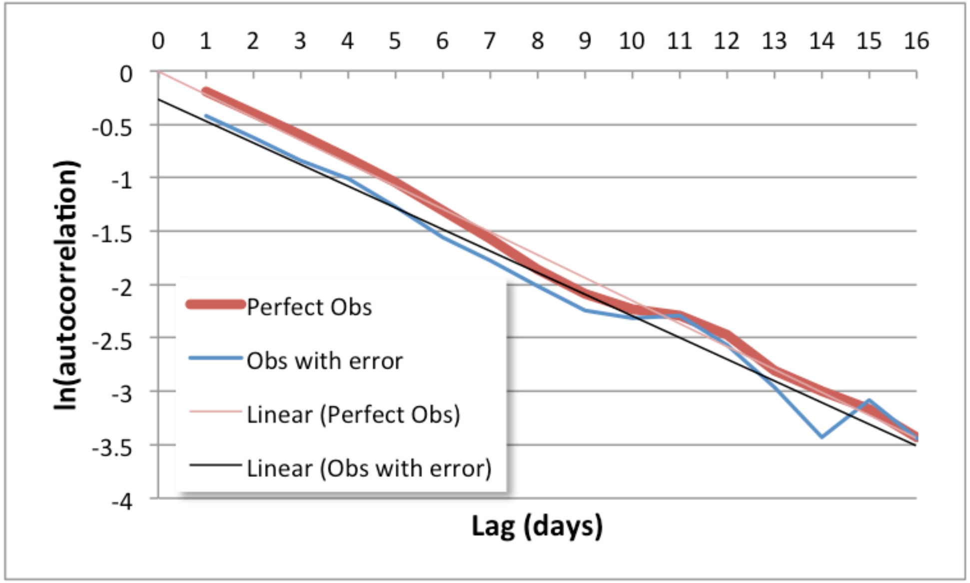
Soil Moisture Memory and Error

- Lagged autocorrelation of soil moisture drops exponentially with time: $r(t)=e^{-t/t}$, / can be estimated from correlations.
- A linear regression of $\ln(r)$ vs t does not pass through the point (t=0,r=1) due to measurement error. $r(0)=1-a$
- RMS of measurement error: $d=s\sqrt{a/(1+a)}$
- Relative measurement error: d/s; $s^2_{OBS}=s^2+d^2$

Delworth & Manabe (1988, 1989; J. Climate)

Vinnikov & Yeserkepova (1991; J Climate)
Robock et al. (1995; J. Climate)
Vinnikov et al. (1996; JGR)
Vinnikov et al. (1999; JGR)

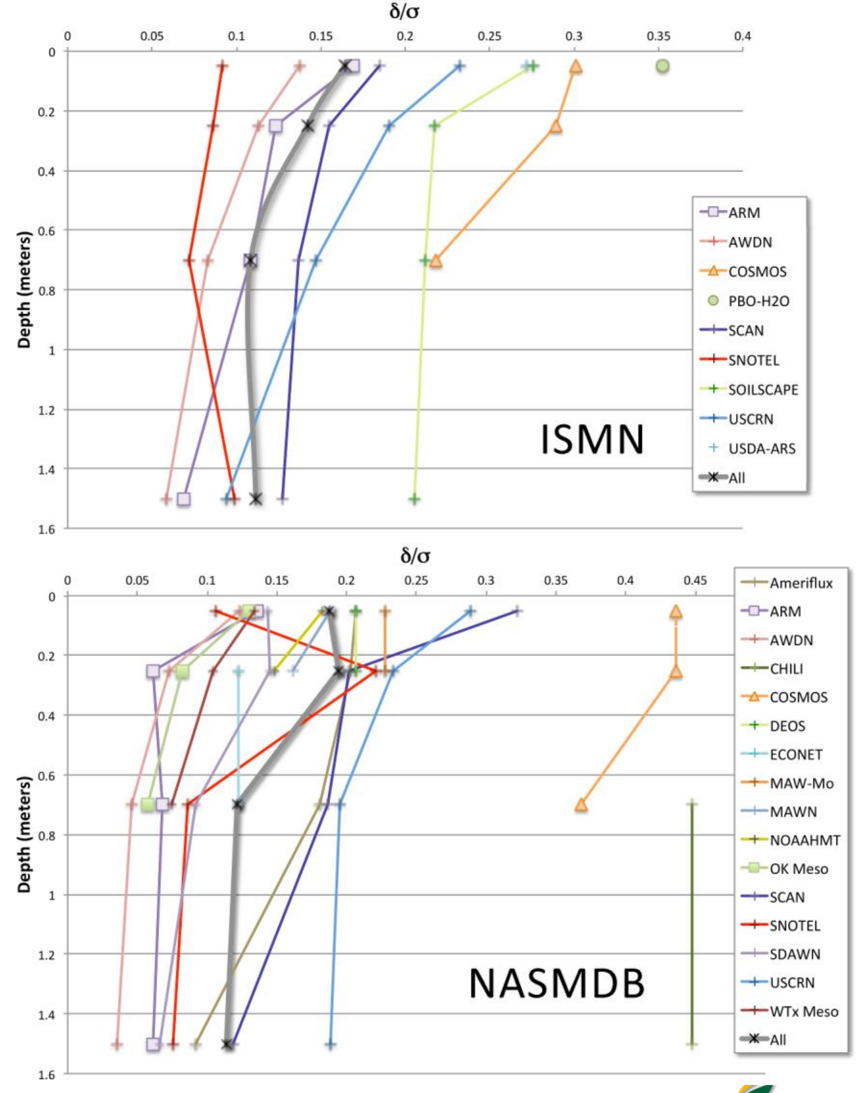
Example



- / = t where $\ln(r)$ = -1.
- Random errors in obs reduces apparent memory!
- In other words, the error characteristics of soil moisture instruments affect estimates of memory.
- Model output effectively has no measurement error (just truncation error; perhaps the only sort of “perfection” models can approach!)

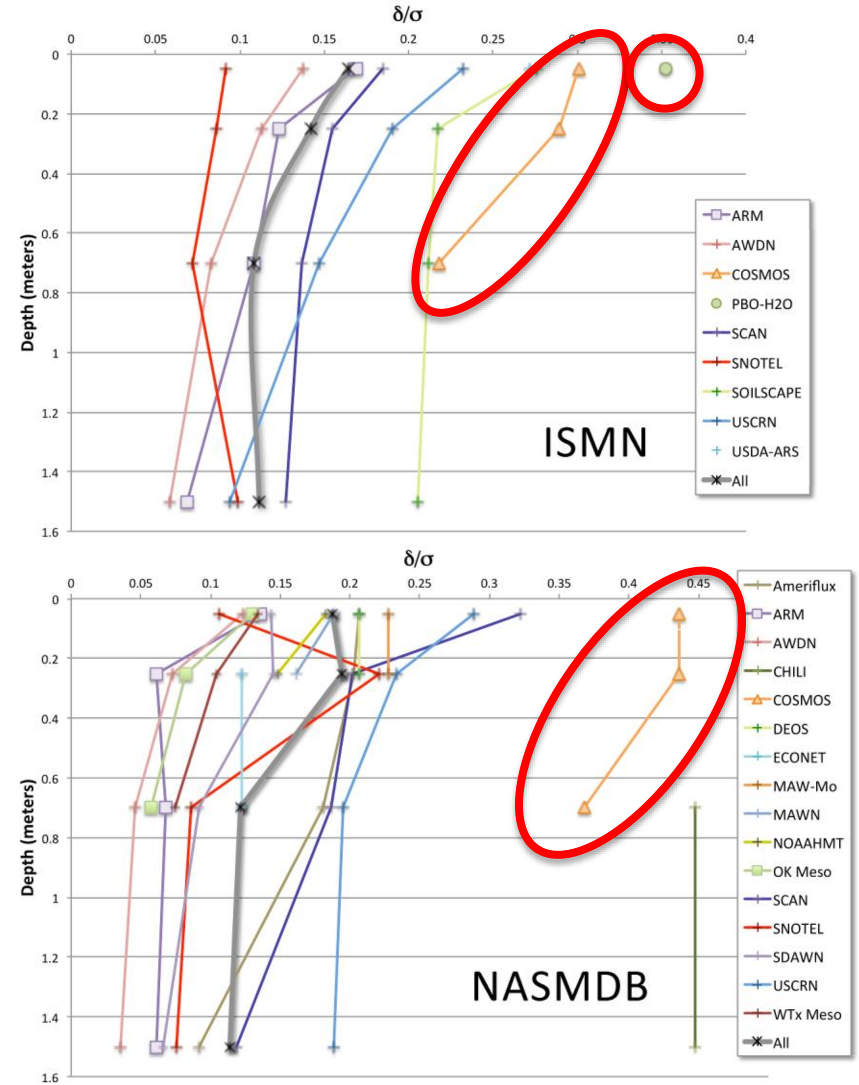
Error Profiles

- Aggregate data from a variety of soil moisture networks over US from International Soil Moisture Network (ISMN; TU Wien) and North American Soil Moisture Data Bank (NASMDB; Texas A&M) vertically interpolated to Noah land model levels analyzed to estimate *α* and thus *δ/σ*.
- Some networks appear in both data sets – slightly different processing, date ranges, included stations – a good sanity check.



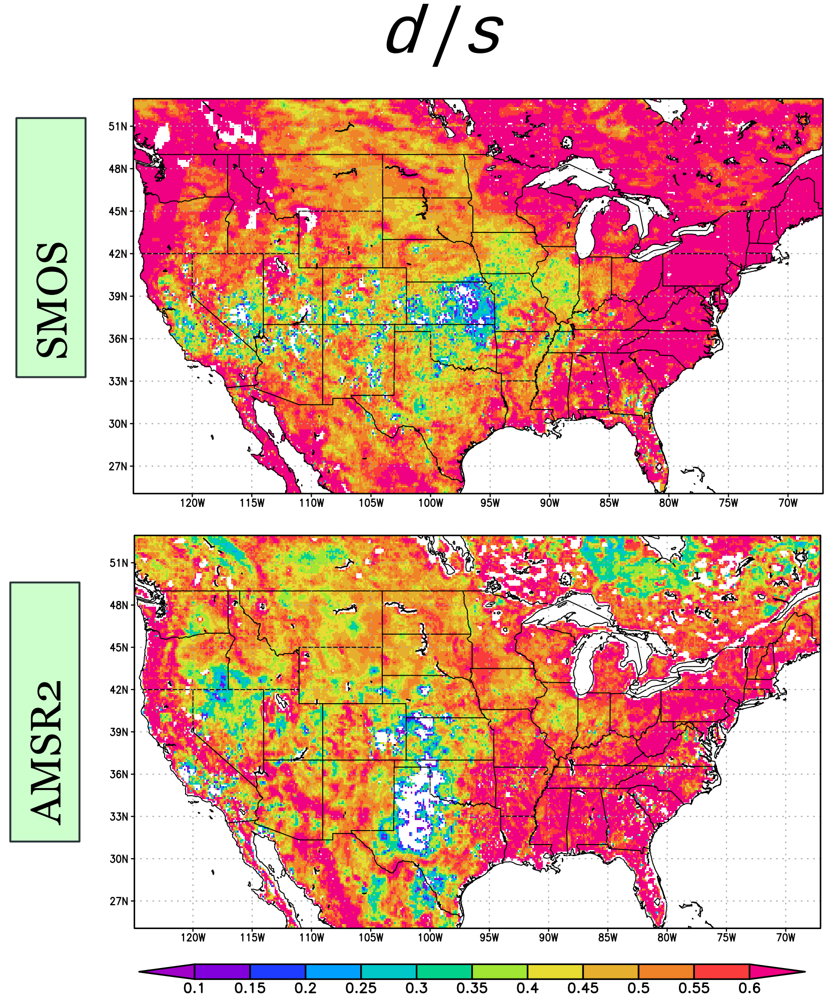
Error Profiles

- GPS and Cosmic-ray approaches (essentially near-field remote sensing) have large random error.
- In-ground sensors do better – heat dissipation sensors (e.g., ARM-SGP, Oklahoma Mesonet) have consistently low random errors.
- Dielectric sensors are highly variable (generally lowest cost) but can produce lower errors than heat-dissipation.



Remote Sensing

- Can apply to satellite data as well.
- We get some "interesting" accuracy hot-spots that seem to correspond to ground-truth cal-val sites! Suggests need much more ground truthing for satellite data than is usually done.
- Preliminary results – more to do….



Courtesy: Sujay Kumar (NASA/GSFC)

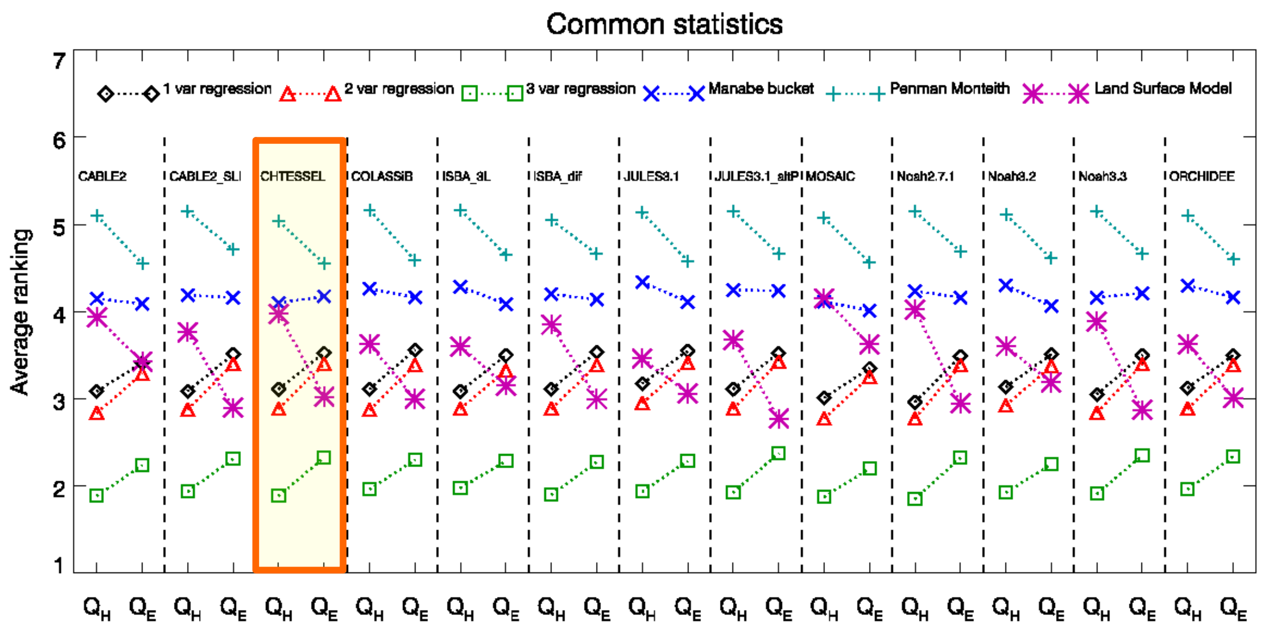
PLUMBER

- PALS Land sUrface Model Benchmarking Evaluation pRoject (PLUMBER)
  - where PALS = Protocol for the Analysis of Land Surface models (PALS; Abramowitz 2012; pals.unsw.edu.au)
- Compare today's LSMs to some very basic statistical regressions (against SW_{DOWN} (+T_2 (NL+q_2))) for estimating surface fluxes – who validates better?
- This is a "no-brainer", right? It must be the physically-based, complex land surface models. Right?
- RIGHT?!

Best et al. (2015; *J. Hydromet.*)

Results for 13 LSMs

- Avereged over 20 FLUXNET sites, Penman-Monteith always last.
- Manabe bucket usually second worst.
- Sadly, LSMs often beaten by basic linear regressions, especially for sensible heat!
- A bit unfair*, but still sobering.



*e.g., regressions have no diurnal cycle; obs don't perfectly close energy/water balances while models do.

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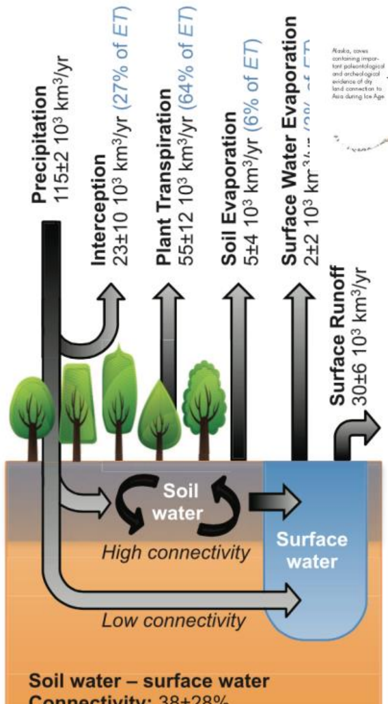
Metrics

- PLUMBER an example of benchmarking, but a number of physically and statistically based metrics have been derived to validate coupled land-atmosphere model behavior, and if properly applied, diagnose error sources and shortcomings.
- Key element of a useful metric is that it is measurable in nature.
- Issue: Necessary measurements are still sparse in space and time. Really only beginning to be able to pursue this properly.

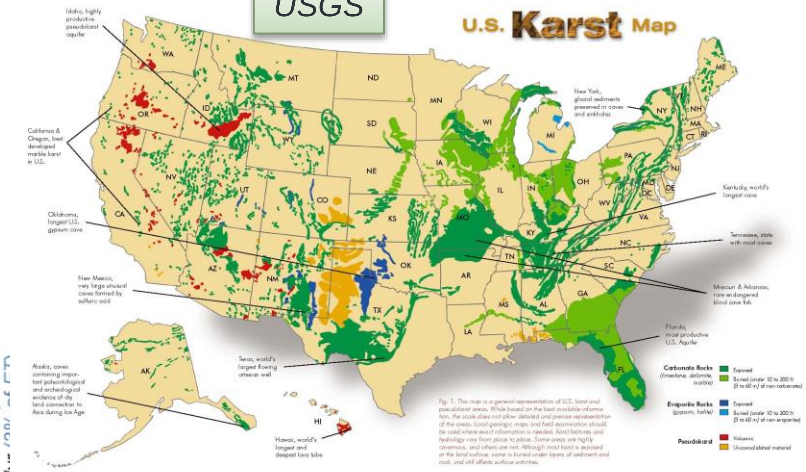
Missing Processes

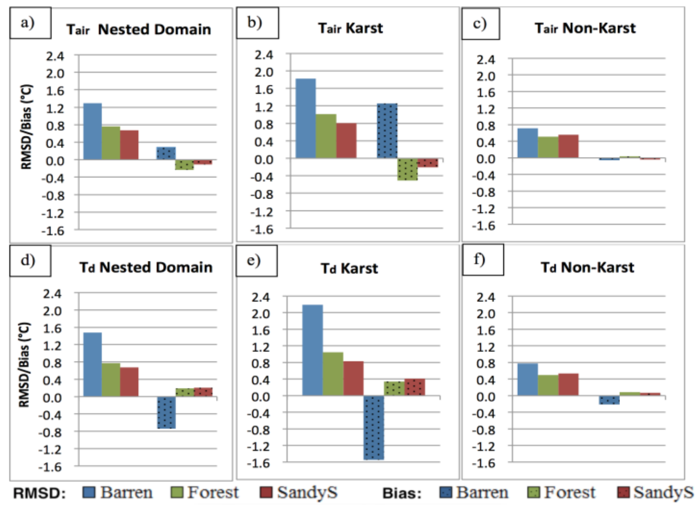
- Example: hydrology with low connectivity
  - Many locations have fractured soils, permeable subsurface (karst)
  - Isotope studies suggest much infiltration bypasses root zone, drains straight to water table.
  - Modeling studies show errors larger over karst, sfc. flux differences affect convection, circulation.



Good et al. (2015; *Science*)

USGS

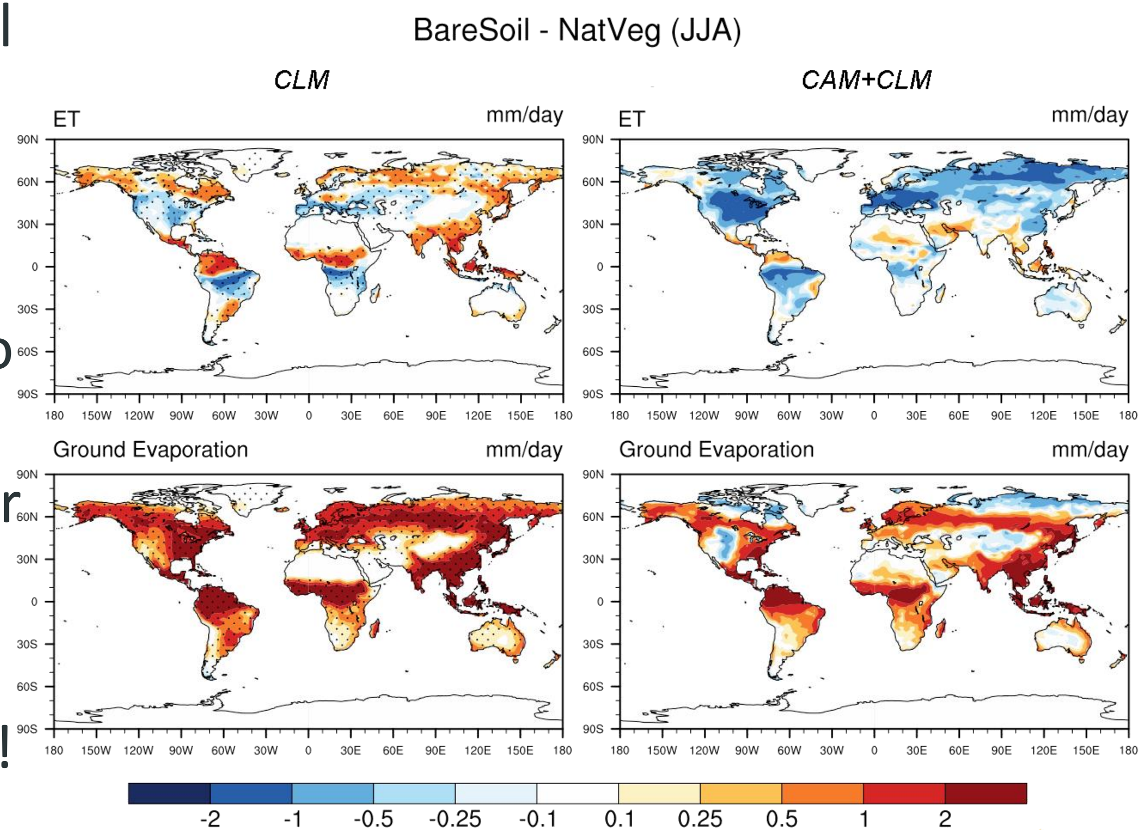




Courtesy: Xingang Fan

Coupled processes matter!

- Uncoupled LSM – global removal of vegetation leads to an increase in ET over many areas.
- When LSM is coupled to AGCM so feedbacks occur, ET decreases over most areas.
- Model development is also a <u>coupled problem</u>!



Thank You