Judging the Dance Contest: Metrics of Land-Atmosphere Feedbacks

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Primer on Land-Atmosphere Coupling

- That the atmosphere, i.e., weather and climate (mean and anomalies), affects the land (via water, energy, carbon cycles) is a given.

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- That the atmosphere, i.e., weather and climate (mean and anomalies), affects the land (via water, energy, carbon cycles) is a given.
- The feedback of land surface states onto the atmosphere is often more subtle and variable in space and time.
- To illustrate how land can exert a control on the atmosphere, let's look at the example of cloud/precipitation formation generated though the water <u>and</u> energy cycles.

Three ways to make a cloud

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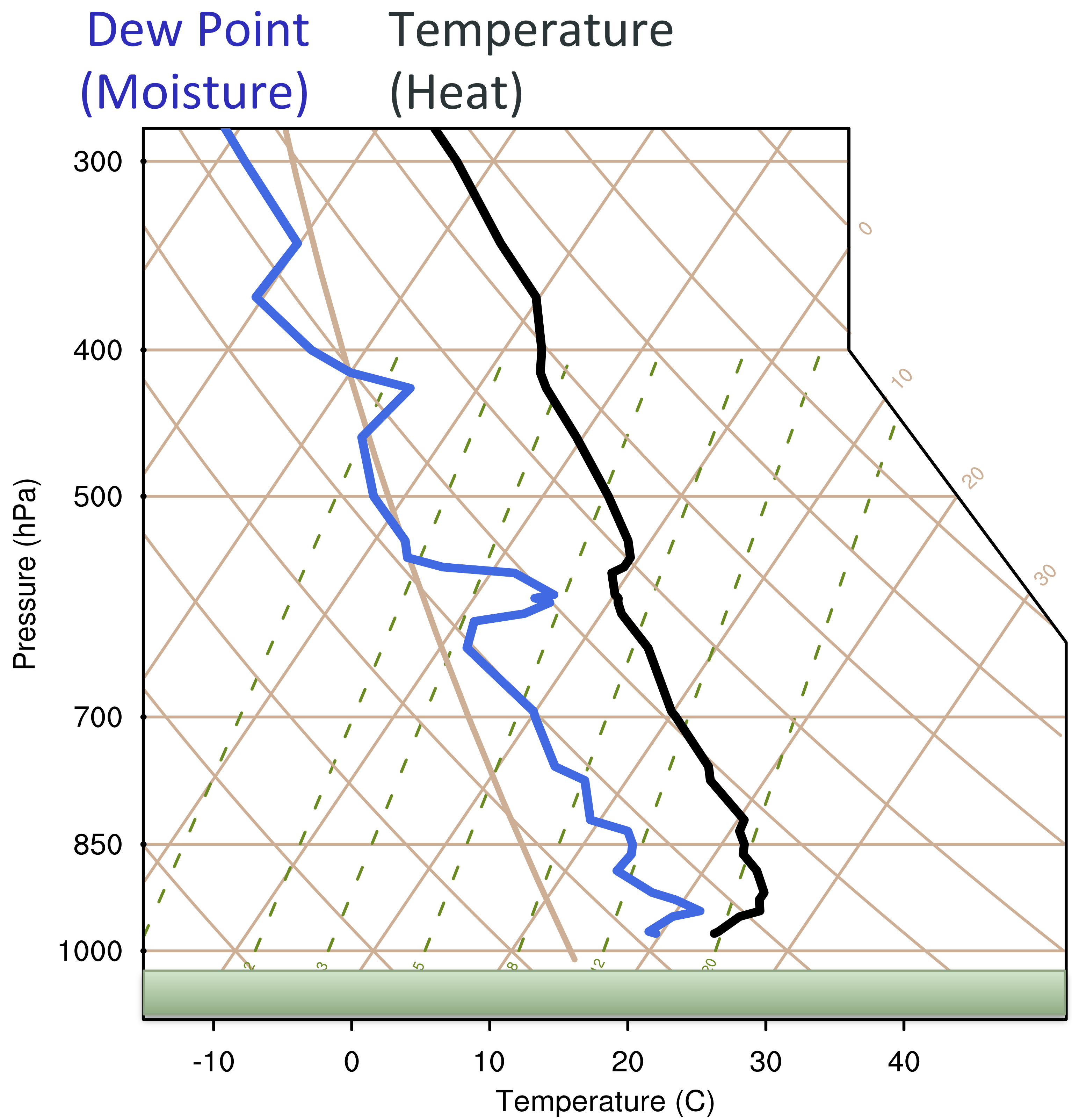
Three ways to make a cloud

1. The "kinematic / dynamic" way – induce vertical motion that lifts moist air, cooling it to its dew point, saturation occurs and clouds form.
2. The "dry thermodynamic" way – heat the air from below until enough buoyancy is generated to lift air to its dew point (averaged over the depth where air is mixed thermally).
3. The "moist thermodynamic" way – pump moisture into the air until it reaches saturation and clouds form.

Land surface feedbacks act on 2 and 3, as we shall see…

A Sounding

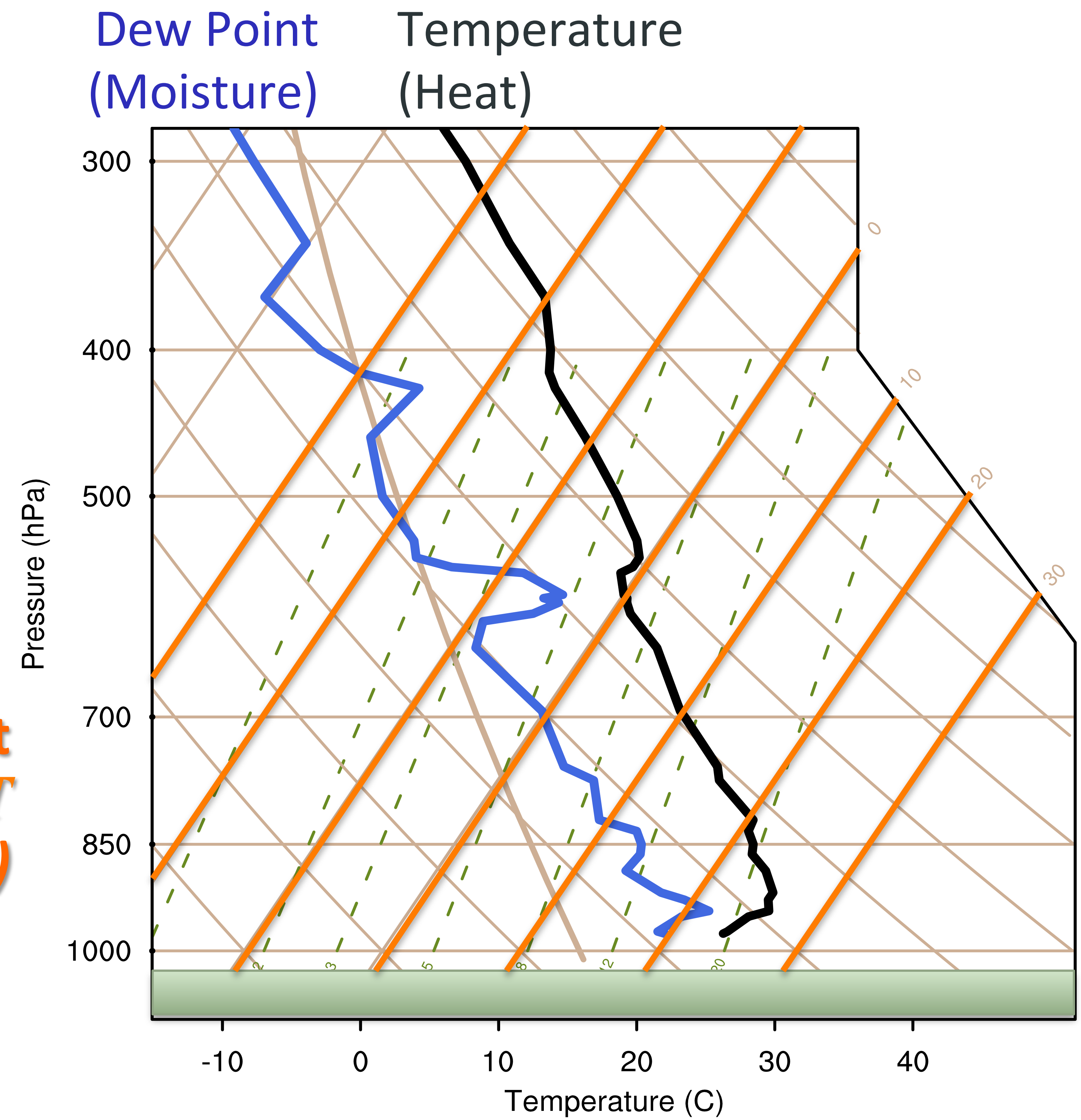
- Vertical meteorological profile of temperature (black) and dew point (blue) through atmosphere.
- Vertical coordinate is atmospheric pressure, which drops with height [$\ln(P) \sim z$].



A Sounding

- Vertical meteorological profile of temperature (black) and dew point (blue) through atmosphere.

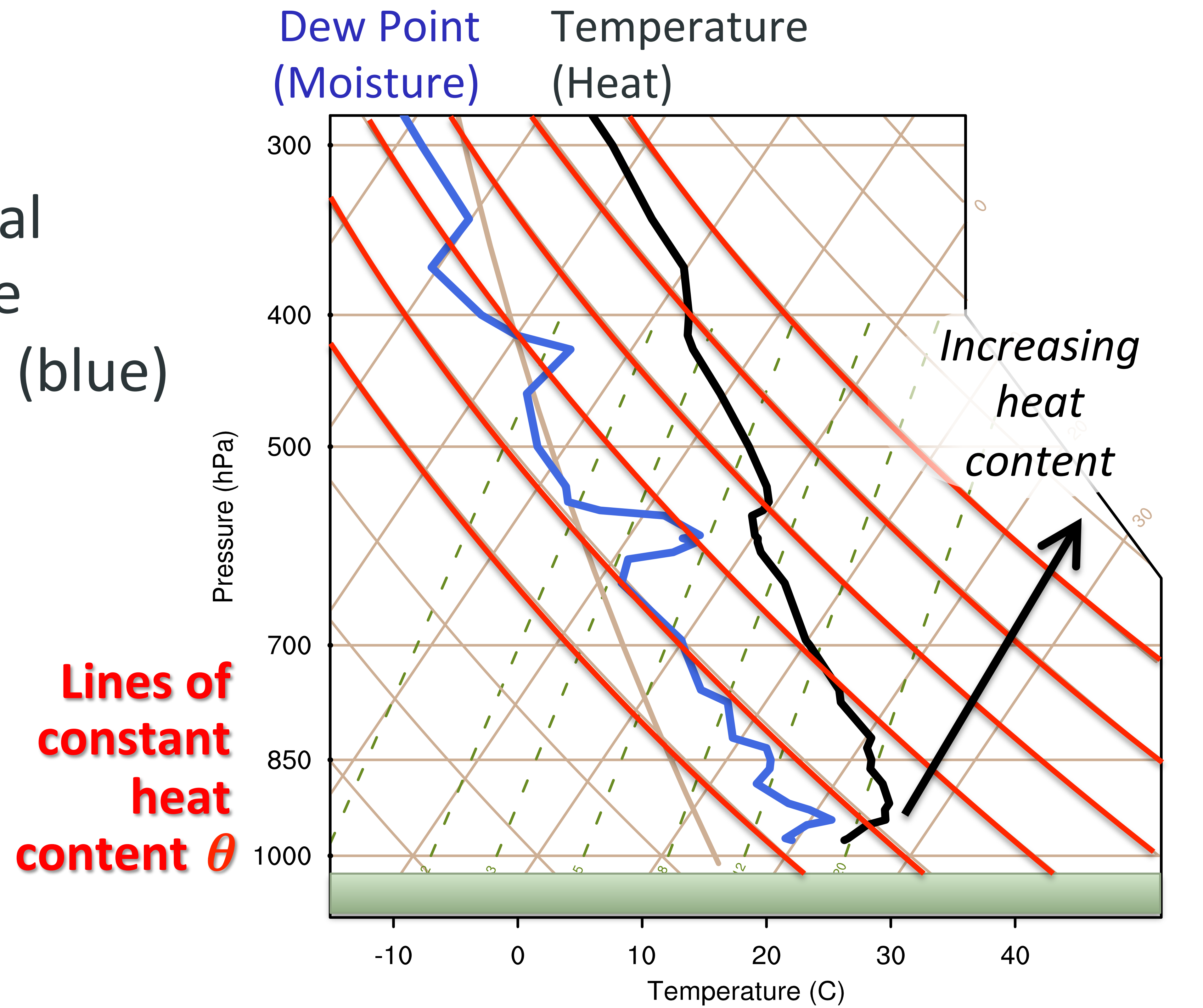
Lines of constant temperature T (or dew point T_D)



A Sounding

- Vertical meteorological profile of temperature (black) and dew point (blue) through atmosphere.
- Temperature ≠ Heat
  - Changes in air density, pressure can change temperature without altering heat content of air.

$$P = \rho R T$$



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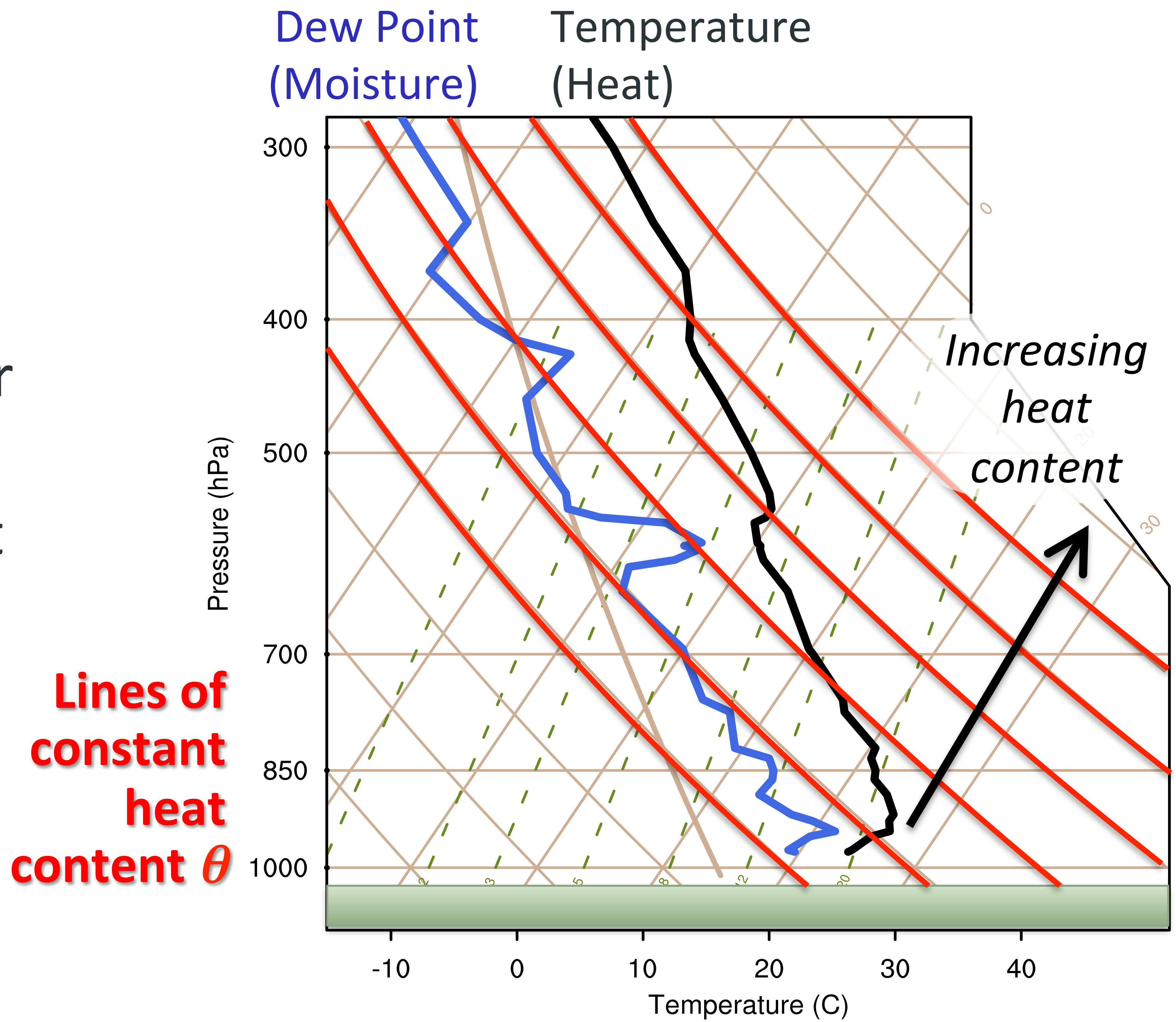
Stability

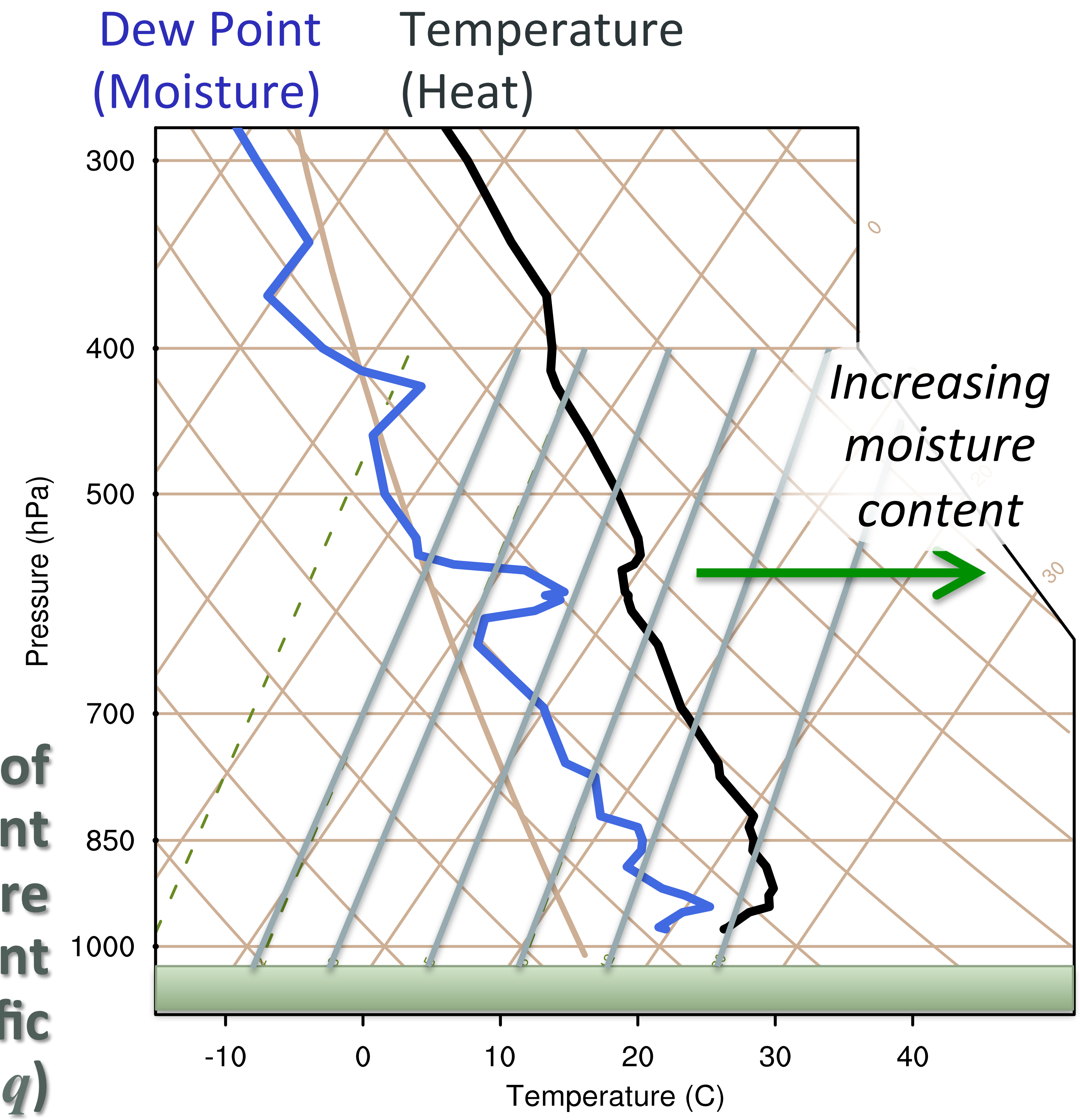
- As you go up in the atmosphere, the temperature of the air gets colder, but the heat content (per unit mass) gets greater!
- This imparts stability to the air column.
- Heating from below can cause buoyancy, instability, convection.



Humidity

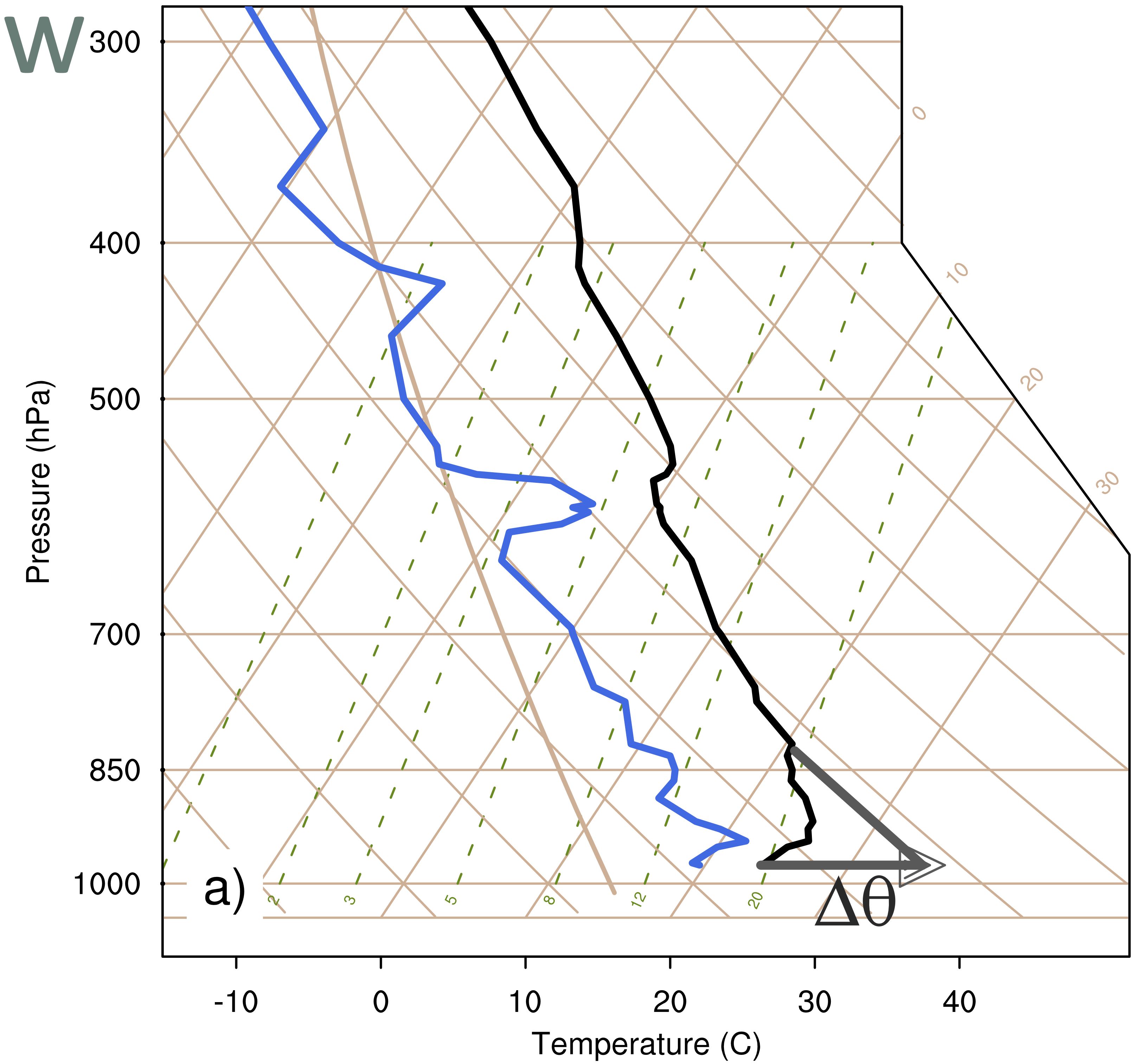
- To form cloud, dew point temperature must reach actual temperature (relative humidity = 100%).
- Moisture also adds buoyancy (H_2O is lighter than N_2, O_2).

Lines of constant moisture content (specific humidity *q*)



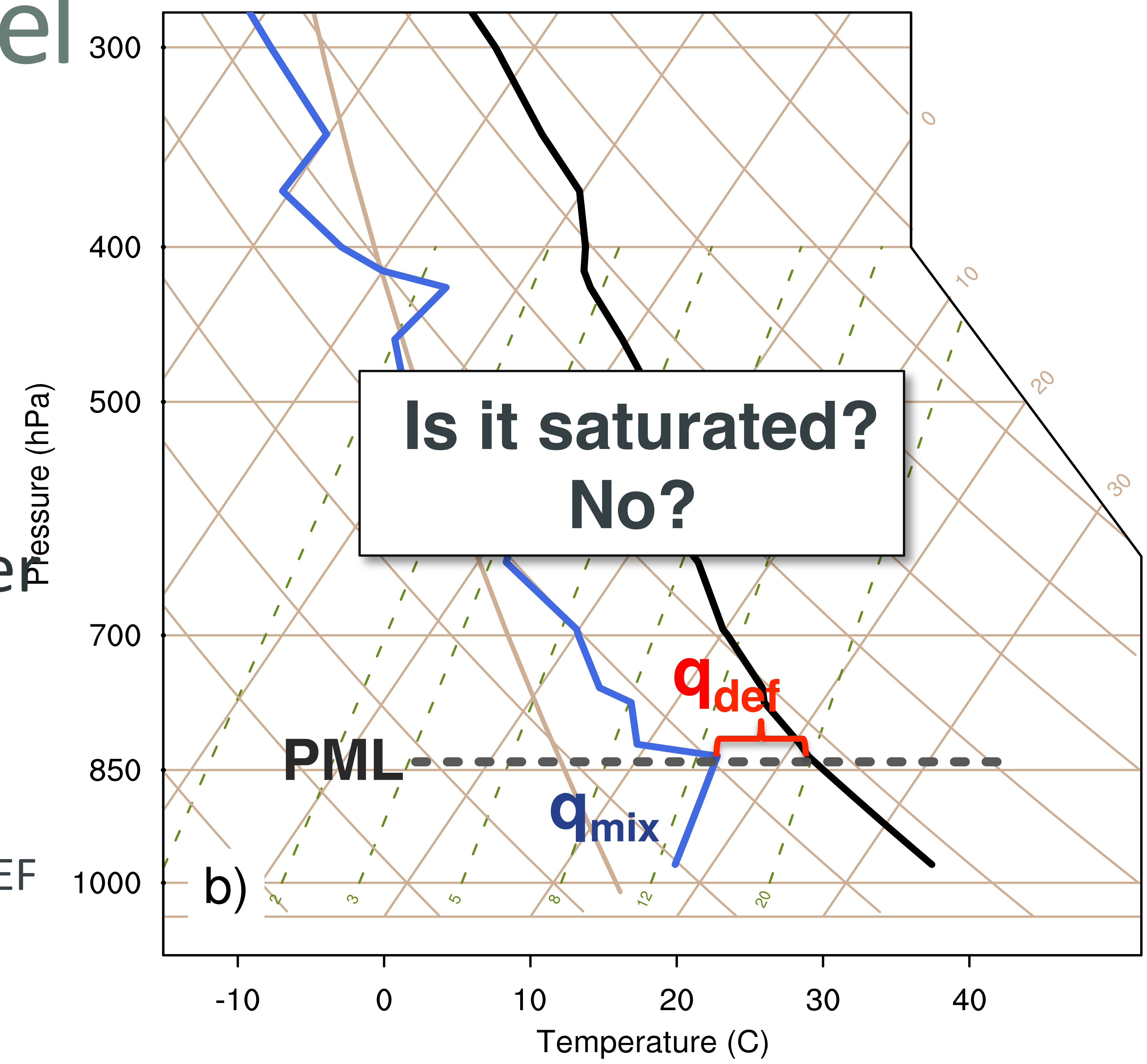
Heating from Below

- Land surface heats (e.g., by morning sunshine), raising surface temperature and mixing heat upward through atmosphere.



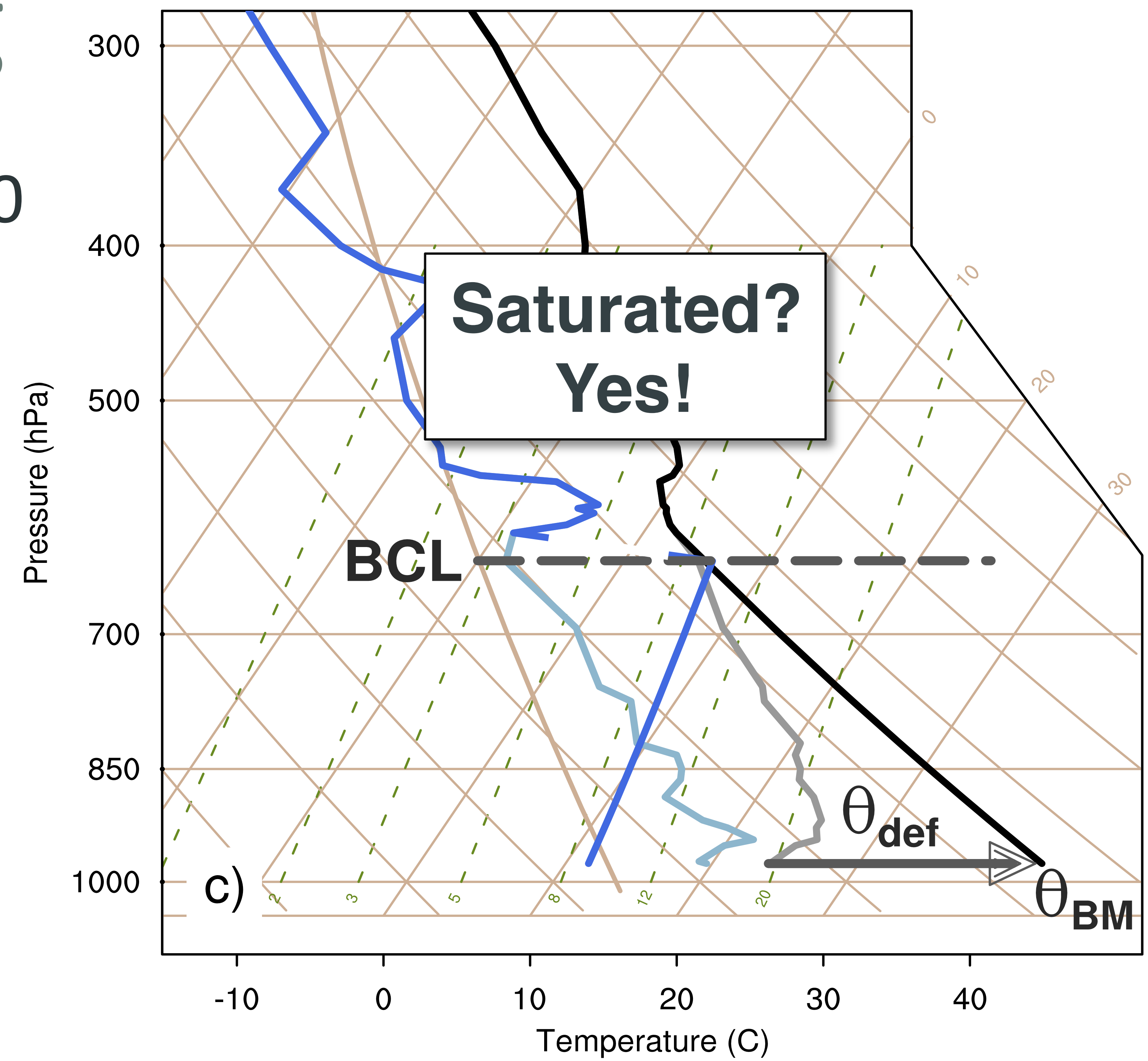
Potential Mixed Level

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



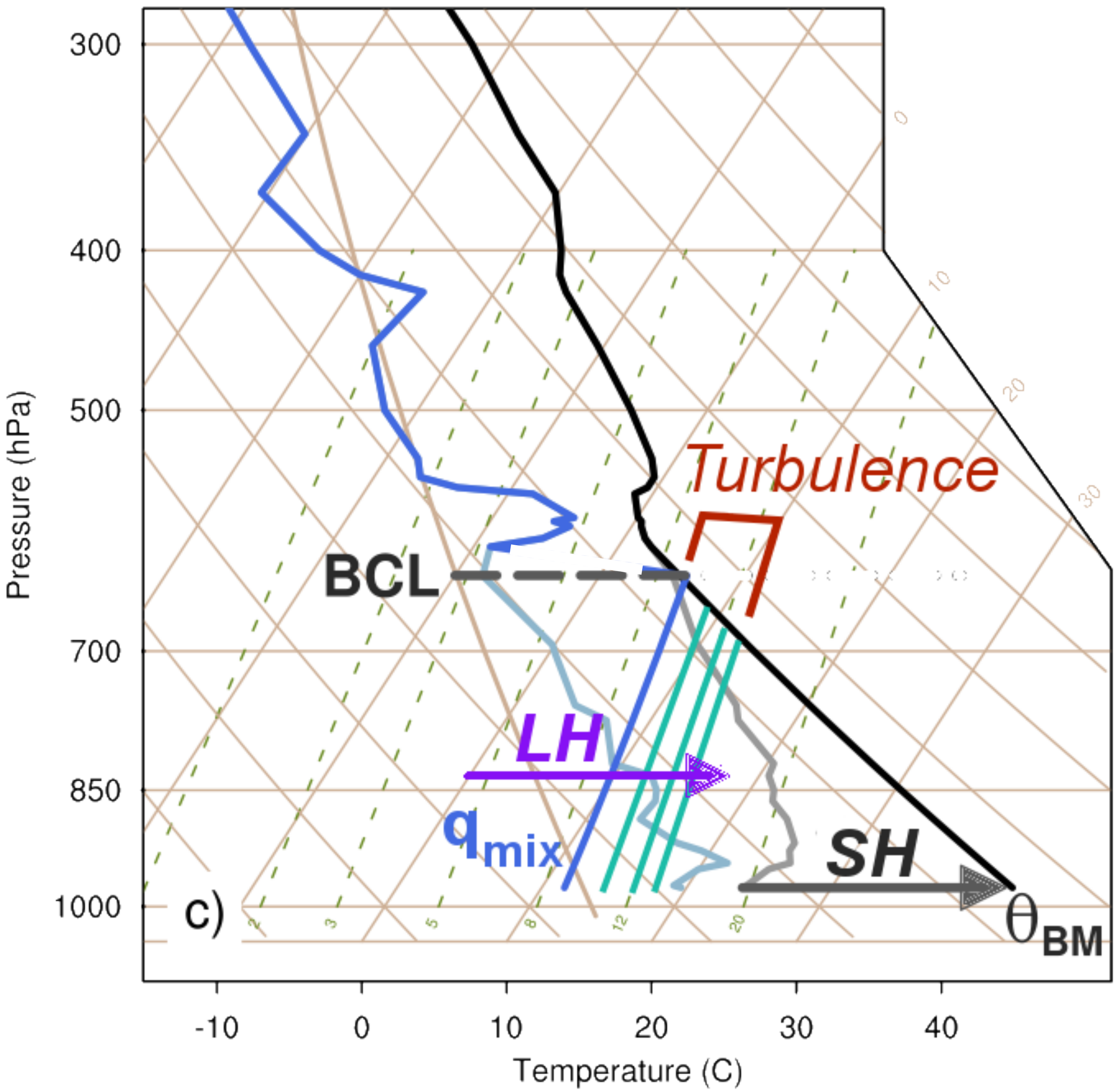
Clouds via Heating

- Add heat and mix until q_{DEF}=0
- This is the buoyant condensation level (BCL) – accomplished with surface sensible heating only.
- Of course, we could use less sensible heat (SH) if we instead evapo-transpired more moisture into the atmosphere (latent heat; LH) ...



Moisture vs. Heat

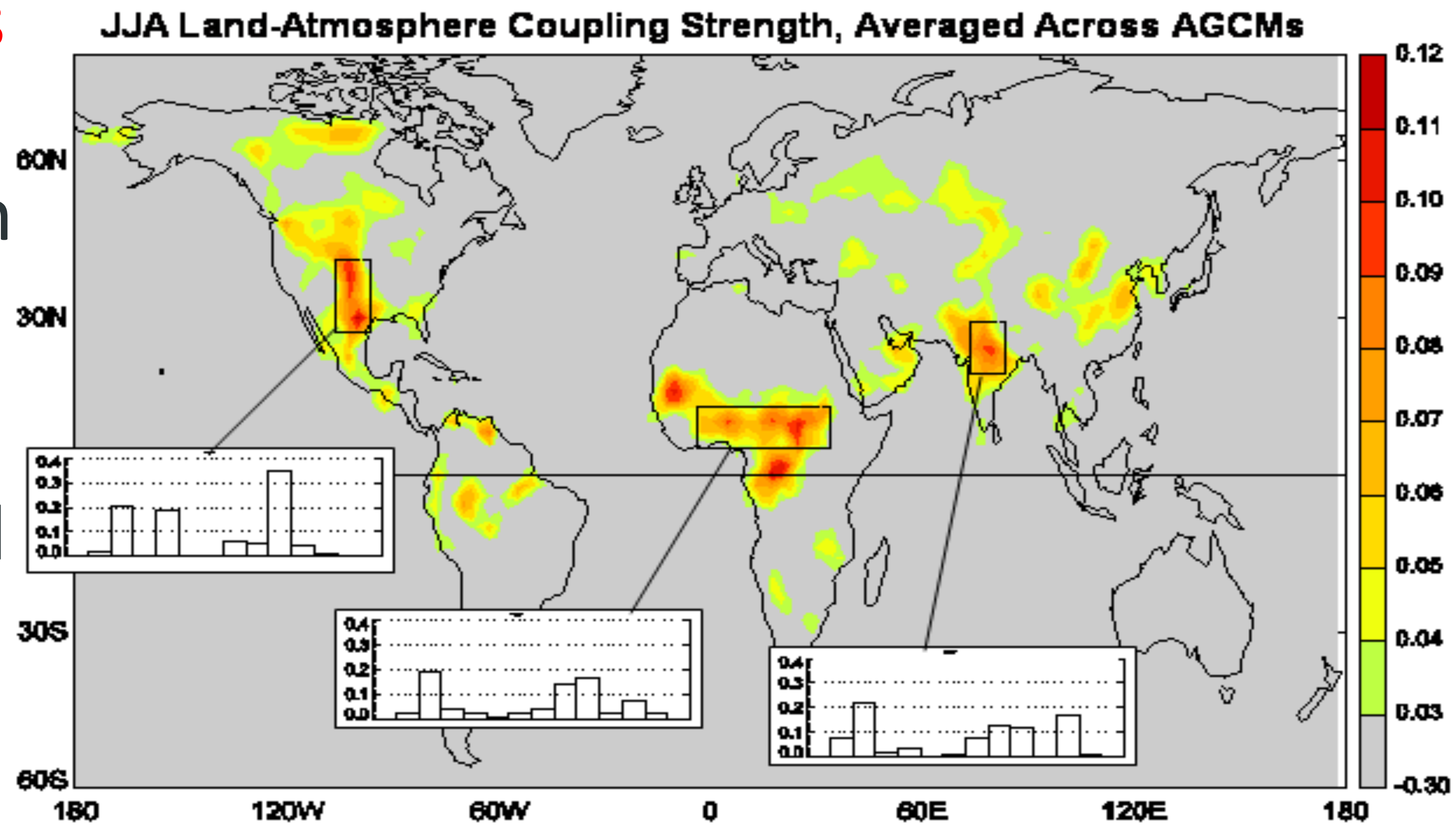
- Surface sensible heating grows the boundary layer, mixing moisture vertically.
- Added moisture from latent heat flux can make saturation easier to reach (lowering the cloud base).
- LH and SH draw from same energy (net radiation) – which is more efficacious to form cloud?
- Land surface controls partitioning (soil moisture availability, surface roughness, canopy resistance, albedo (net radiation).



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

GLACE Global Land-Atmosphere Coupling Experiment

- GLACE model study motivates much of the attention on land-atmosphere feedbacks in the water and energy cycles.
- "Hot spots" of land surface "control" on precipitation and temperature (through terrestrial and atmospheric legs) are in transition regions between semi-arid to semi-humid areas with ample net radiation (Ag areas!!).



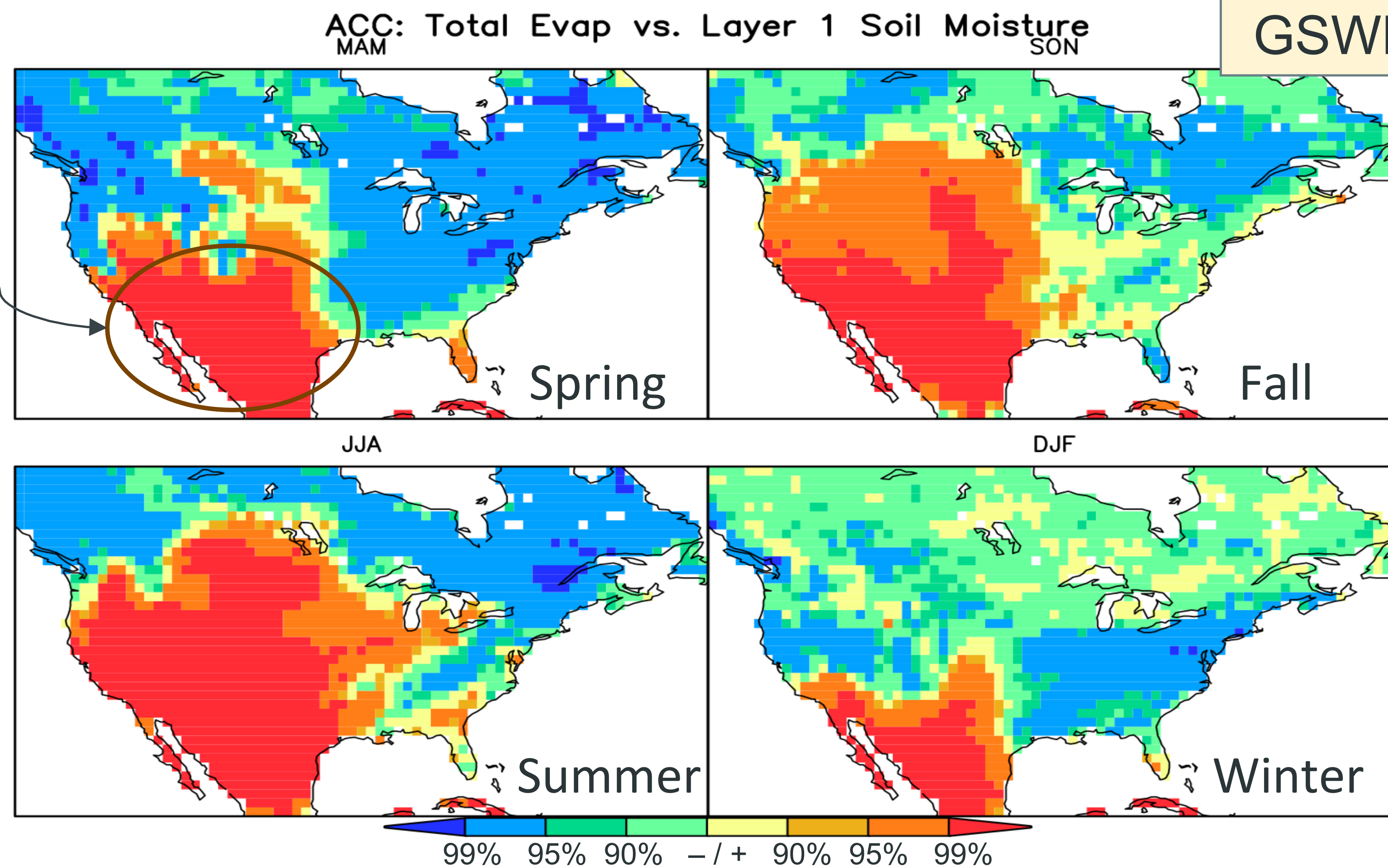
"Famous" figure from *Science* paper which became used (and over-used) to justify the role of the land surface in climate.

Koster et al. (2004; *Science*)

Water Cycle: ΔP ➔ ΔSM → ΔE → ΔP

GSWP-2

Moisture limited:
SM controls E

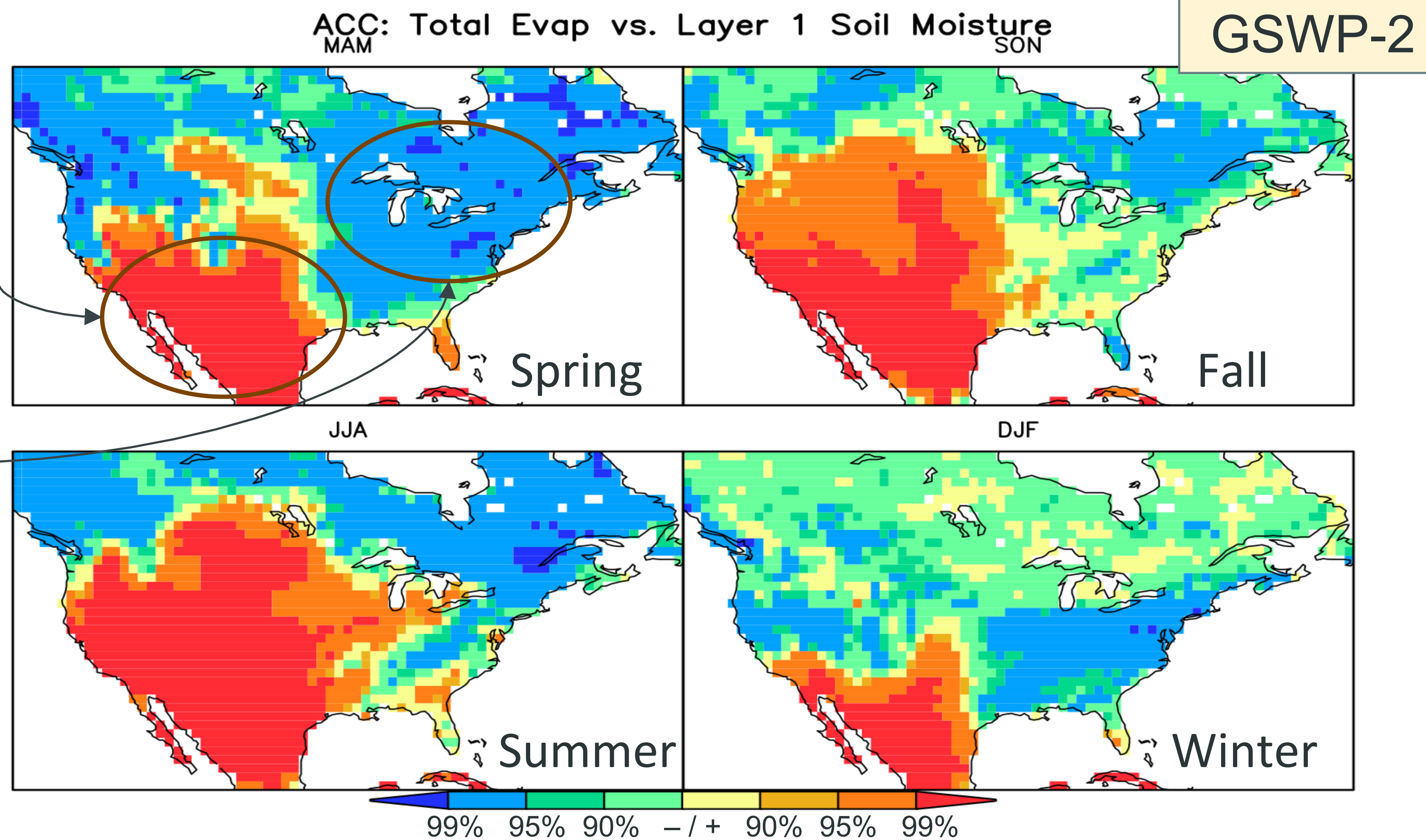


Dirmeyer et al., 2009: *J. Hydrometeor.*, 278-

Water Cycle: ΔP → ΔSM → ΔE → ΔP

Moisture limited: SM controls E

Sufficient moisture: E controls SM



So we can have: ΔSM ← ΔE

Dirmeyer et al., 2009: *J. Hydrometeor.*, 278-

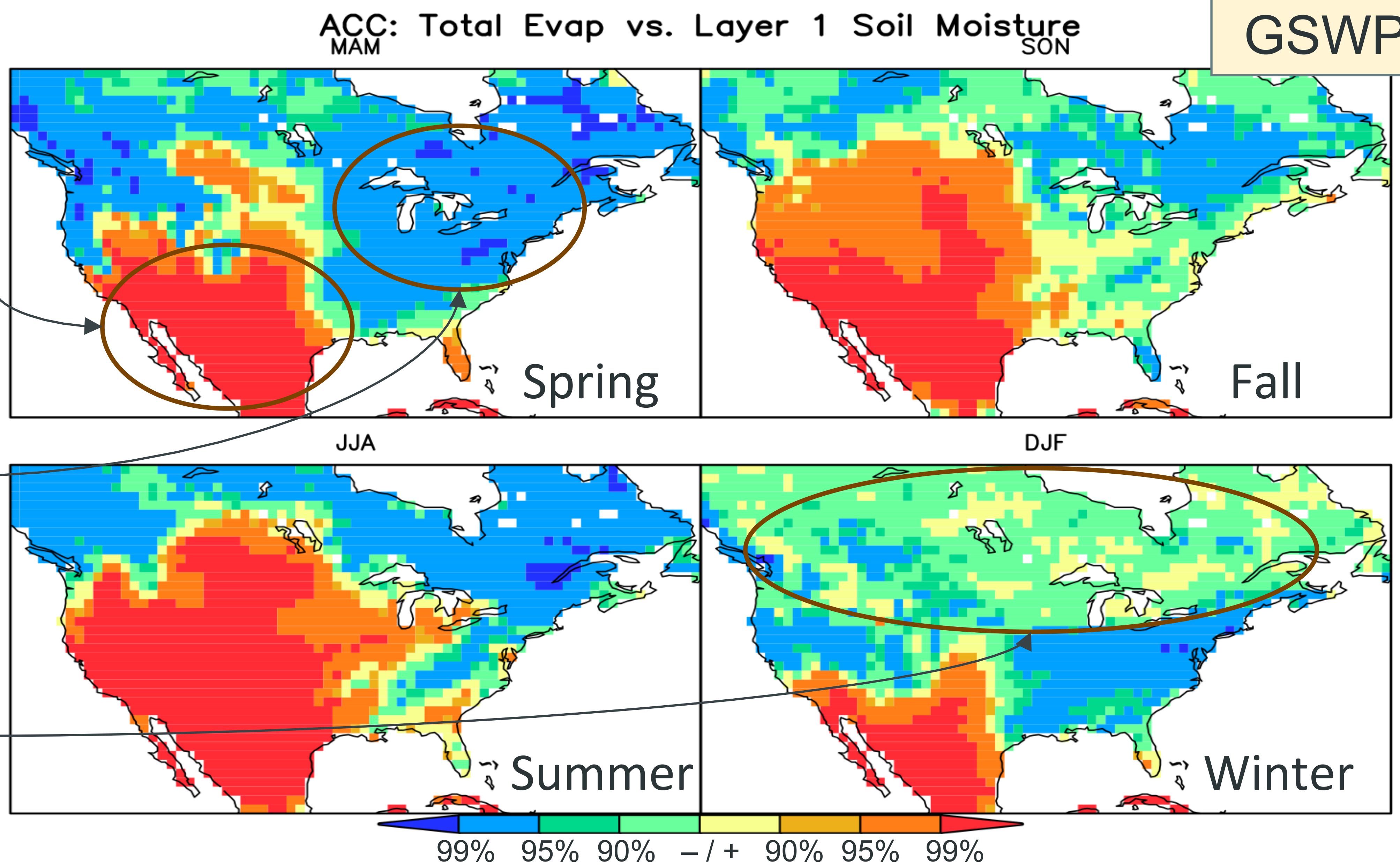
Water Cycle: ΔP → ΔSM → ΔE → ΔP

GSWP-2

Moisture limited: SM controls E

Sufficient moisture: E controls SM

Snow cover cuts connection between SM & E



Dirmeyer et al., 2009: *J. Hydrometeor.*, 278-

Terrestrial Coupling Index

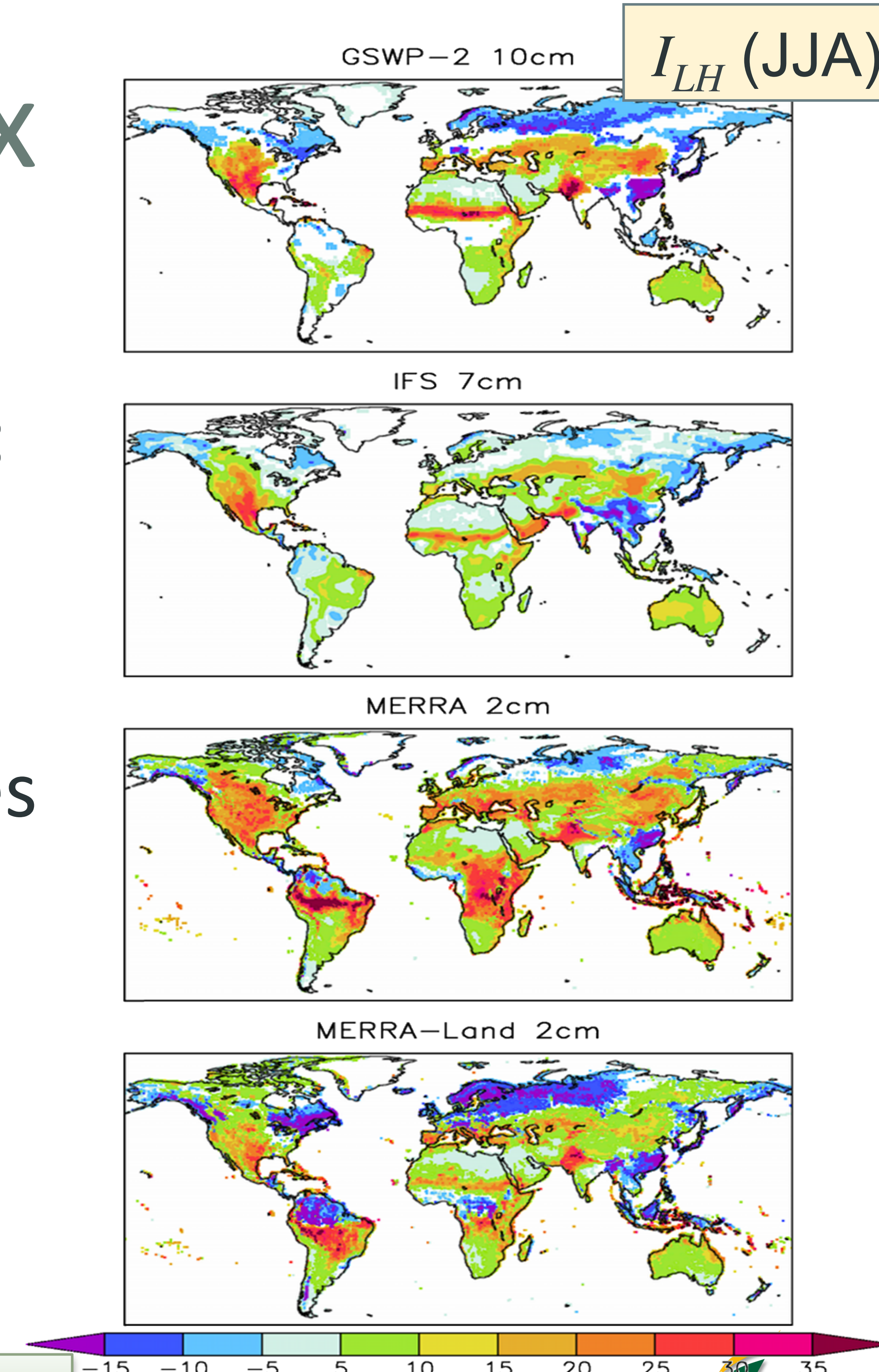
- For surface flux Φ, coupling to soil wetness W we define a coupling index:

$$I_{\Phi} = \frac{\partial \Phi}{\partial W} \sigma_W = r(\Phi, W)\, \sigma_{\Phi}$$

- Applied to sensible or latent heat fluxes (or *atmospheric*: e.g., to fluxes & PBL!)
- Strong correspondence to hot-spots.
- Multivariate illuminates processes!!

ΔSM → ΔE *water cycle*

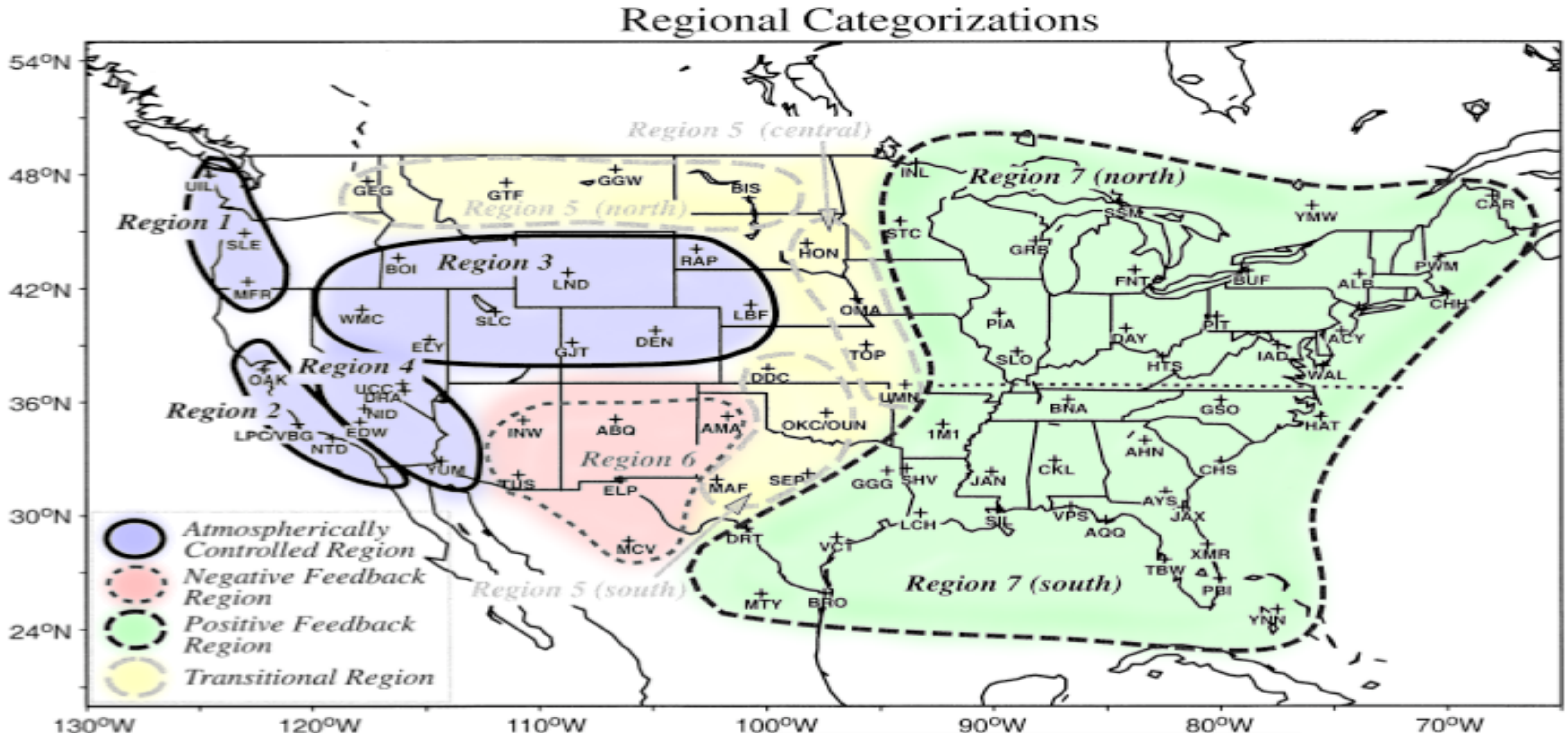
ΔSM → ΔH *energy cycle*



Dirmeyer, 2011: *GRL*, L16702.

Categorized by Region

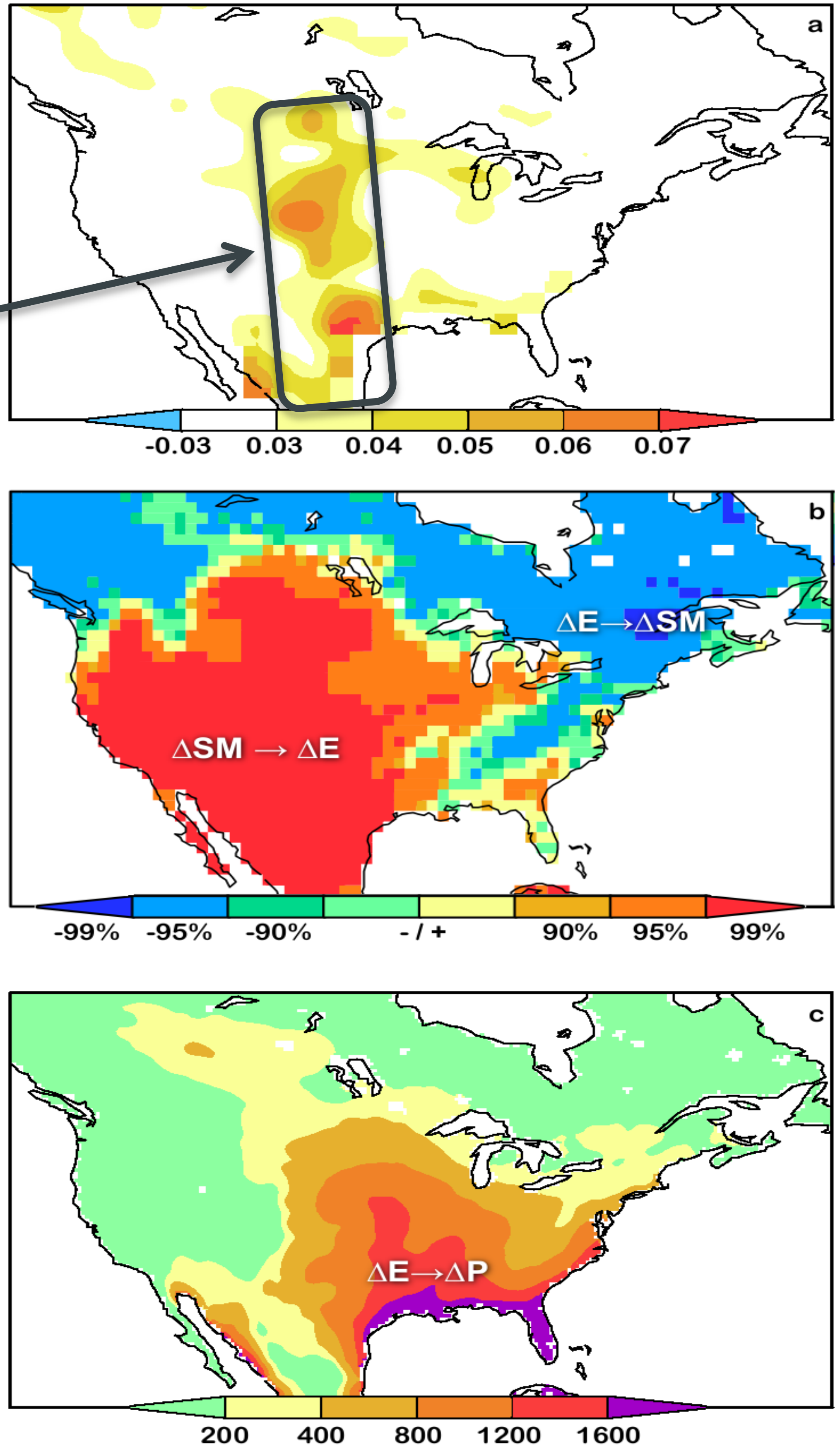
- All of the radiosonde sites in and around CONUS are assessed based on their climatologies of CTP and HI_{Low}.



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

Feedback Via Two Legs

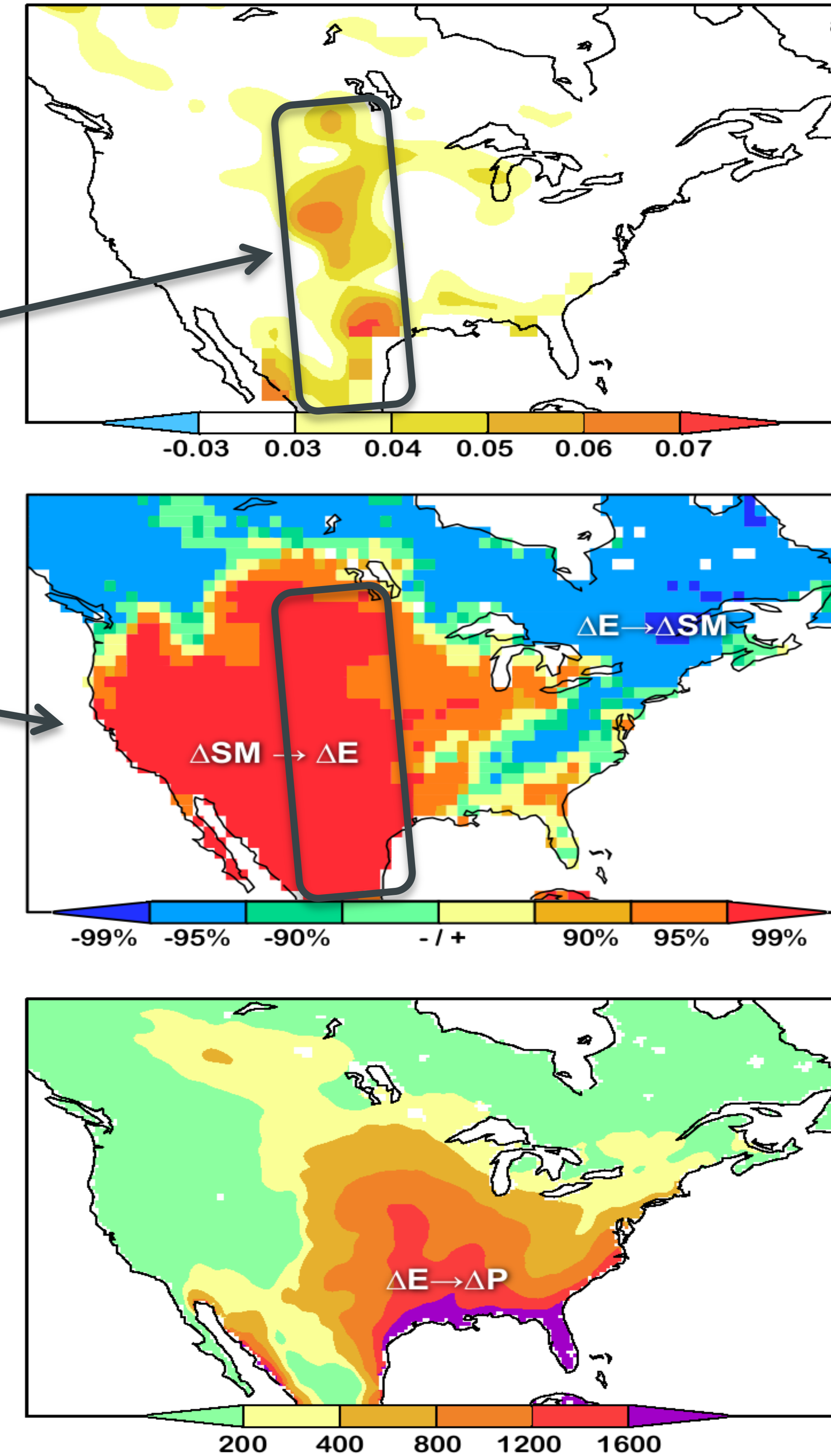
- GLACE coupling strength for summer soil moisture to rainfall (the Plains "hot spot") corresponds to regions where there are both of these factors:



$\Delta P \rightarrow \Delta SM$

Feedback Via Two Legs

- GLACE coupling strength for summer soil moisture to rainfall (the Plains “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…



$$\Delta P \Rightarrow \underbrace{\Delta SM \rightarrow \Delta E}$$

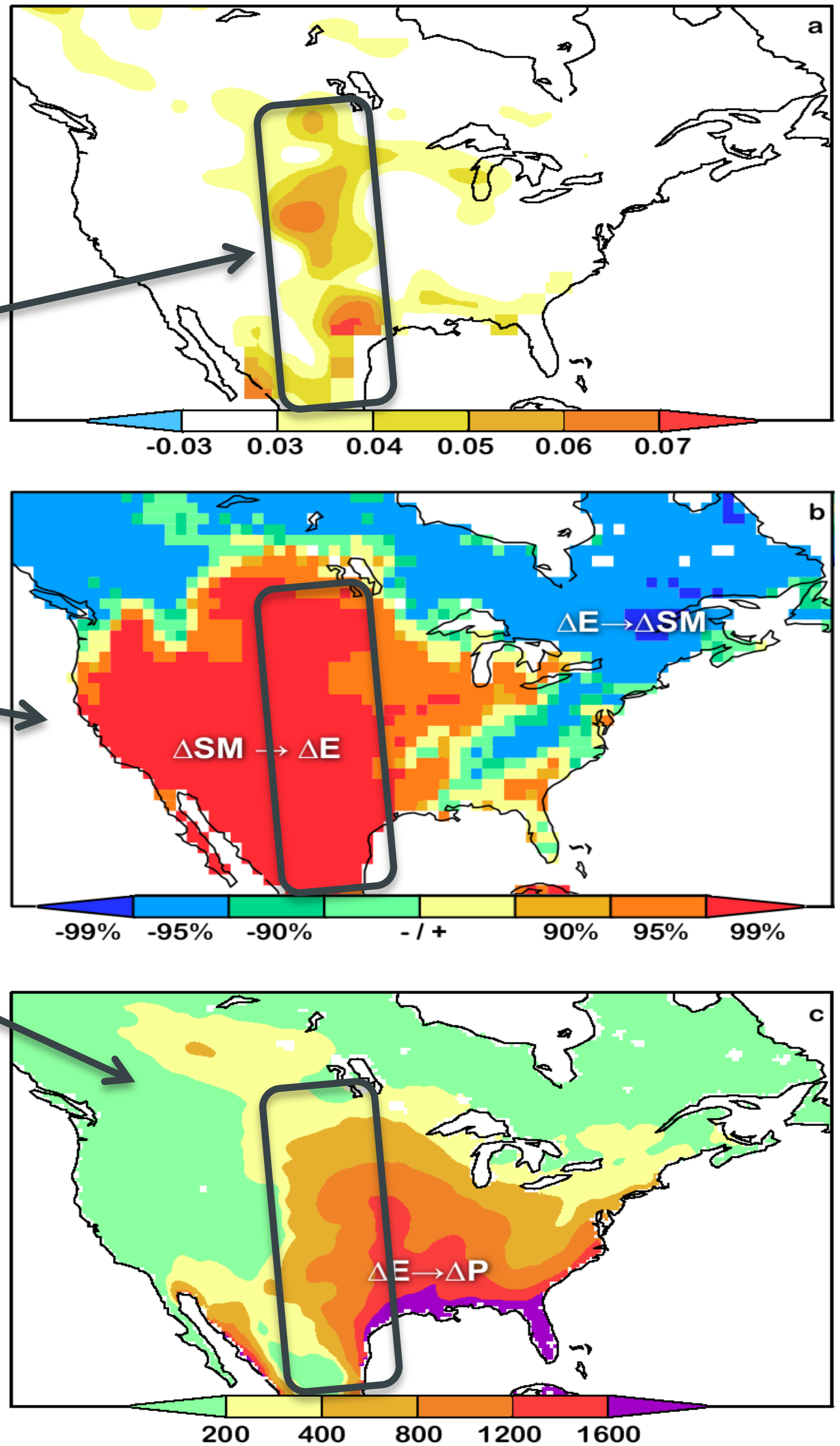
Feedback path: Terrestrial leg

Feedback Via Two Legs

- GLACE coupling strength for summer soil moisture to rainfall (the Plains “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…
- Primed atmosphere: high CAPE [from the North American Regional Reanalysis, J/kg]

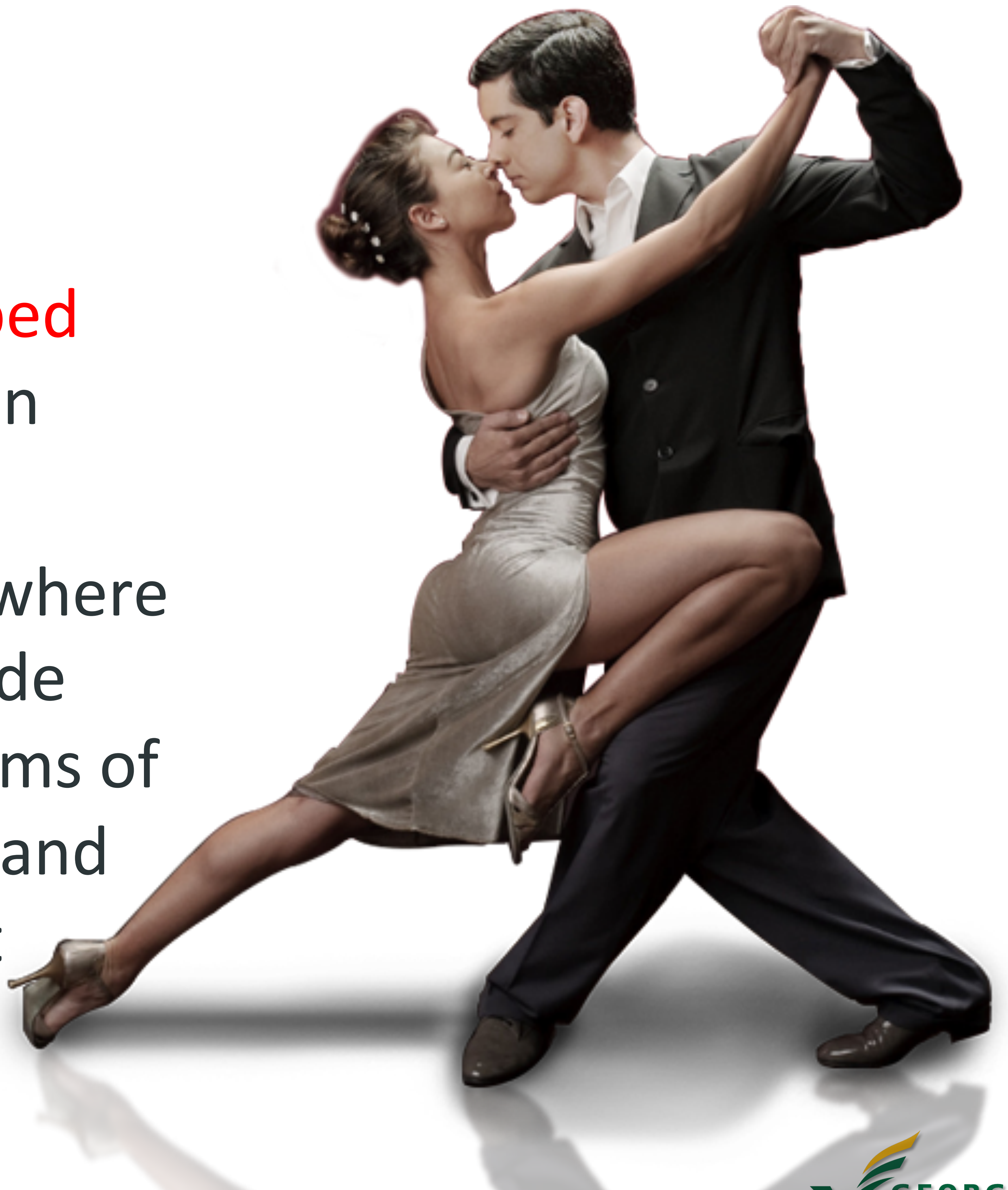
$\Delta P \rightarrow \Delta SM \rightarrow \Delta E \rightarrow \Delta P$

Feedback path: Terrestrial leg Atmospheric leg



Back to the Dance

- Historically land models and atmosphere models are developed separately (in isolation), and then plugged together.
- Land models become the place where atmospheric modelers try to "hide their sins". Treating the symptoms of atmospheric model errors with land surface model "corrections" just creates more problems – it's a coupled system.



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World Climate Research Programme

ABOUT PANELS ACTIVITIES EVENTS

HOME RESOURCES

LOCO

Local Land-Atmosphere Coupling (LoCo) Project

- LoCo Working Group
- LoCo Working Group Publications

The original structure of the GEWEX Global Land/Atmosphere System Study (GLASS) was designed to support four modes of land-surface modeling: (1) local-scale off-line; (2) large-scale off-line; (3) local-scale coupled; and (4) large-scale coupled (van den Hurk et al., 2011). To date, each of these has been addressed through organized, community-wide intercomparison studies, such as the Project for the Intercomparison of Land Surface Parameterization Schemes (PILPS), the Global Soil Wetness Project (GSWP), and the Global Land-Atmosphere Coupling Experiment (GLACE), with the exception of local land-atmosphere coupling (LoCo). The LoCo Project has instead evolved and, in recent years, gained momentum through process-level modeling and observational studies that focus on the development and application of coupling diagnostics. This has lead to the development of the Coupling Metrics Toolkit (CoMeT), which is a set of fortran modules containing the most widely used coupling diagnostics.

GEWEX

LOCO

LOCO WORKING GROUP

LOCO WORKING GROUP PUBLICATIONS

UPCOMING EVENTS

3-5 MAY 2016
WORKSHOP ON A NEW NORTH AMERICAN REGIONAL HYDROCLIMATE PROJECT

28-30 JUNE 2016
GEWEX SOILWAT WORKSHOP

Coupling Metrics

- GLASS/LoCo is compiling univariate and multi-variate metrics including both terrestrial and atmospheric legs for process understanding and model development.
- These focus on energy and water cycles; extendable to carbon cycle as well as BGC-hydro connections.

Name	Land State	Surf. Fluxes	Atm. State	Local Space	Local Time	Obser-vable	Type
Two-Legged Metrics	Y	Y	Y	Y	Y	Y	Stat
Mixing Diagrams	N	Y	Y	N	Y	Y	Phys
LCL Deficit	N	N	Y	Y	Y	Y	Phys
Betts Relationships	Y	Y	Y	Y	N	Y	Stat
Priestley-Taylor Ratio	N	Y	Y	Y	Y	Y	Phys
Heated Condensation Framework	N	Y	Y	Y	Y	Y	Phys
RH Tendency	N	Y	Y	Y	Y	Y	Phys
CTP-HI_{Low}	N	N	Y	Y	Y	Y	Phys
GLACE Coupling Strength	Y	Y	Y	Y	Y	N	Stat
Notaro's Feedback Parameter	Y	Y	Y	Y	N	Y	Stat
Conditional Correlation	Y	Y	Y	Y	N	Y	Stat
Associated Predictability Ratio	Y	Y	Y	Y	Y	N	Stat
Soil Moisture Memory	Y	N	N	Y	N	Y	Stat
Granger Causality	Y	Y	Y	N	N	Y	Stat
P-T metrics	N	N	Y	N	N	Y	Stat
Zeng's Gamma	Y	Y	Y	Y	Y	Y	Stat
Coupling Drought Index	Y	N	Y	Y	N	Y	Phys
Bulk Recycling Ratio	N	Y	Y	N	N	Y	Phys
Vegetated Coupling (ω)	N	Y	Y	Y	Y	N	Phys
Latent Heating Tendency	Y	Y	Y	Y	Y	N	Phys

Does method require terrestrial (Land) or atmospheric (Atm) variables, or surface flux data? Is it limited to local in space (no horizontal relationships, only in the vertical) or in time (no lagged relationships)? Can it be applied only to model output (Obsble=N)? Is the Type primarily a statistical metric (physical linkages implied) or based directly in physical processes?

http://cola.gmu.edu/dirmeyer/Coupling_metrics.html

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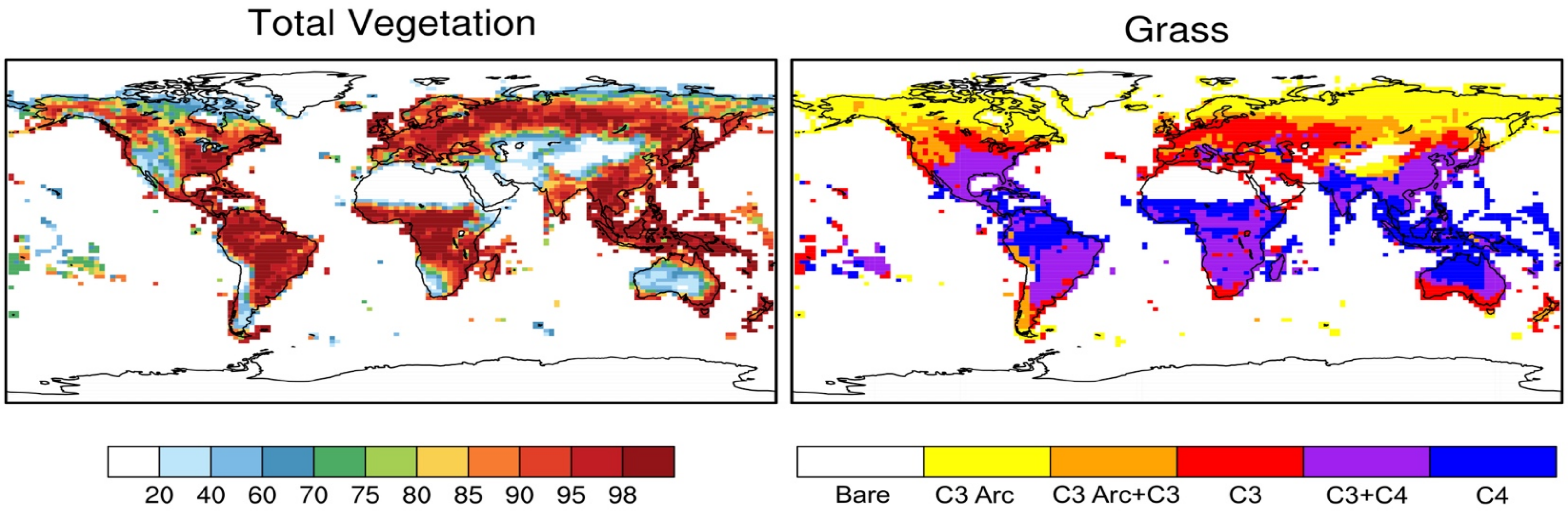
Examples

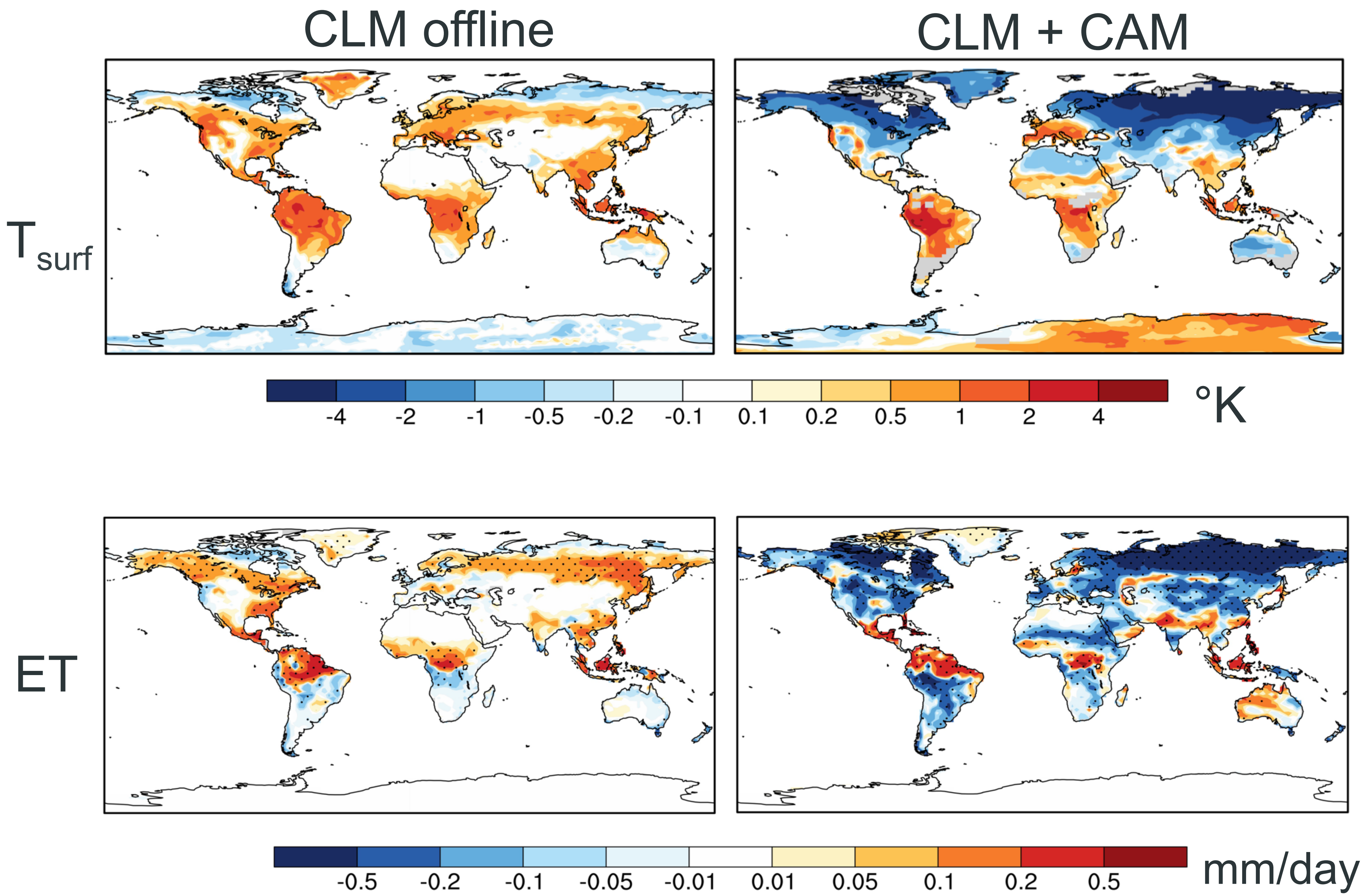
- We have already seen a few examples in previous slides, when discussing the "two legs" of land-atmosphere coupling.
- Here we present metrics of relevance to modeling of land use / land cover change, and climate change.
  – Different responses between land model only (uncoupled / offline) and coupled land-atmosphere models (The Dance).
  – Extension of observational biogeophysical metrics of land use change to coupled Earth System models.
  – Changing L-A coupling in a changing climate.

Land Cover Change Test



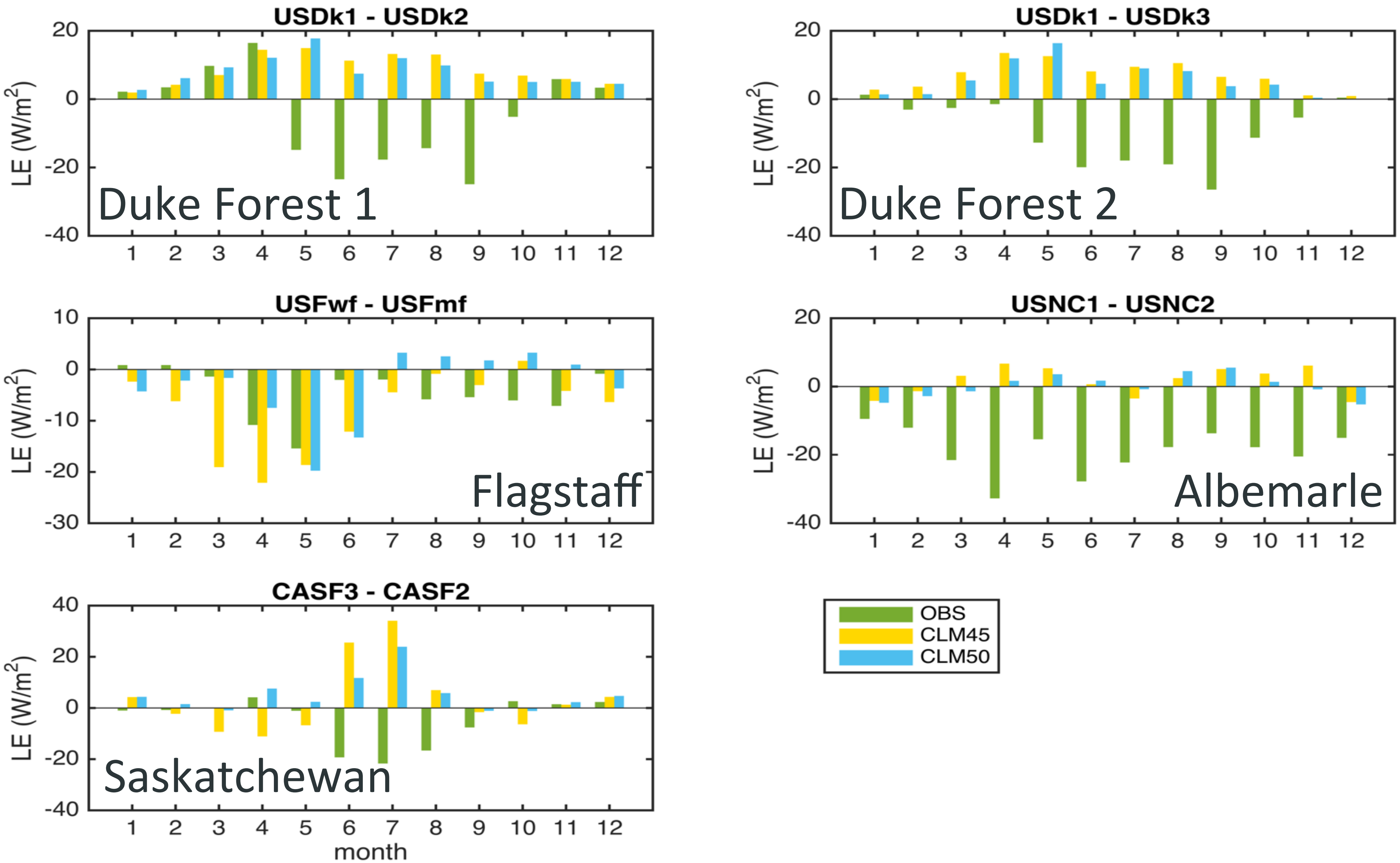
- PFTs in 1850 changed to all grass (diagnostic run for CLM)
- CESM1.2.2: Two configurations
  - CLM4.5 offline (uncoupled)
  - CAM4.5 + CAM5 (coupled)
- 25-year simulation; 20 years analyzed

T_{surf} and ET change *AllGrass – 1850*



- Mid-latitude response is opposite when coupled!
- The danger of cal/val or "benchmarking" only uncoupled models.

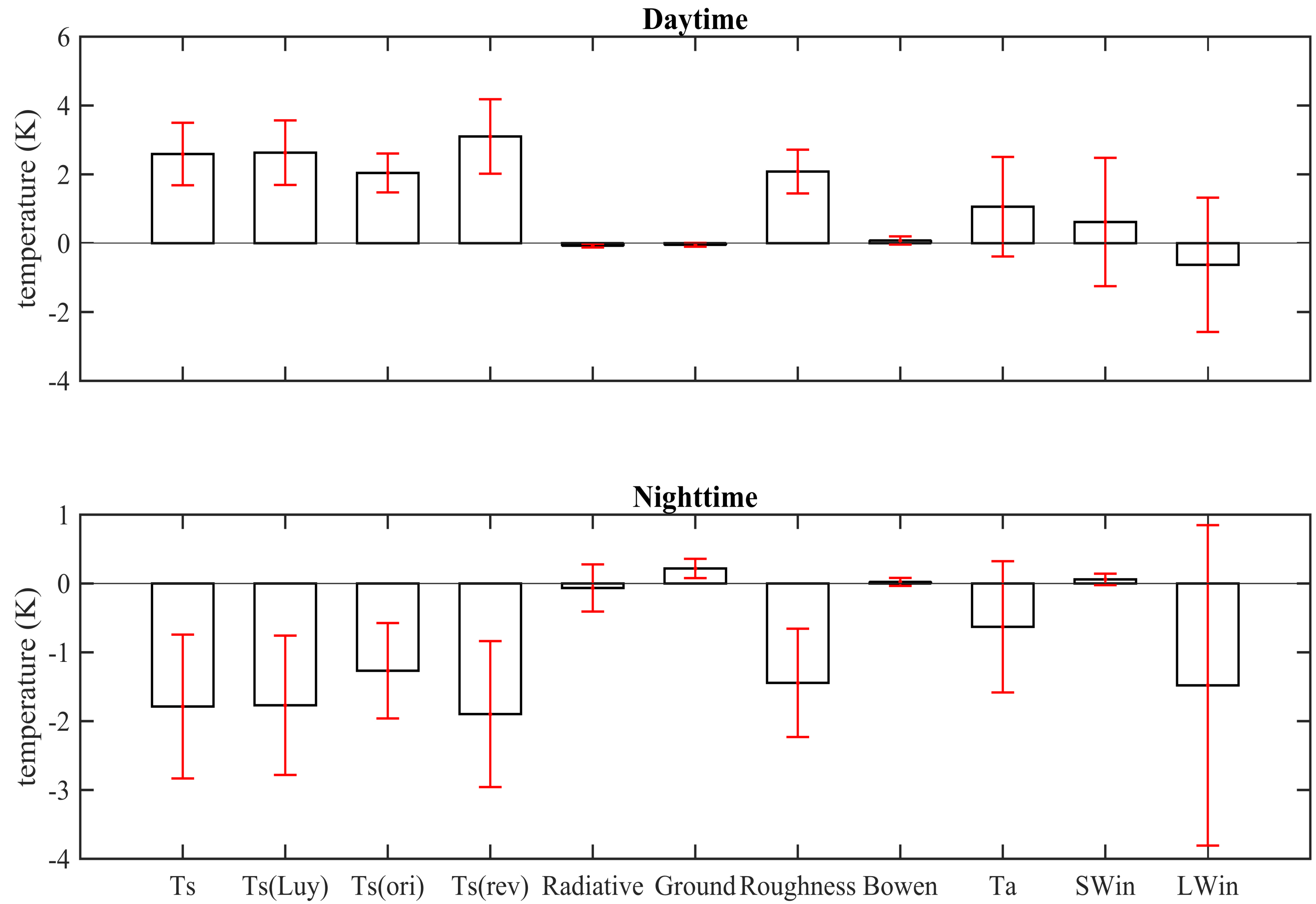
Paired FLUXNET Sites; Change in ET



- Another example – offline only.
- LSM shows increased ET with deforestation, (except for semi-arid Flagstaff).
- Observations consistently show decrease.

Obs. Metrics Applied to Models

- Lee et al. (2011) and Luyssaert et al. (2014) site-based estimates of energy budget contributions to T_S changes with LULCC have been adapted to climate models.
- Expanded coupled approach elucidates "indirect" feedbacks.



Chen & Dirmeyer (2016; *ERL*)

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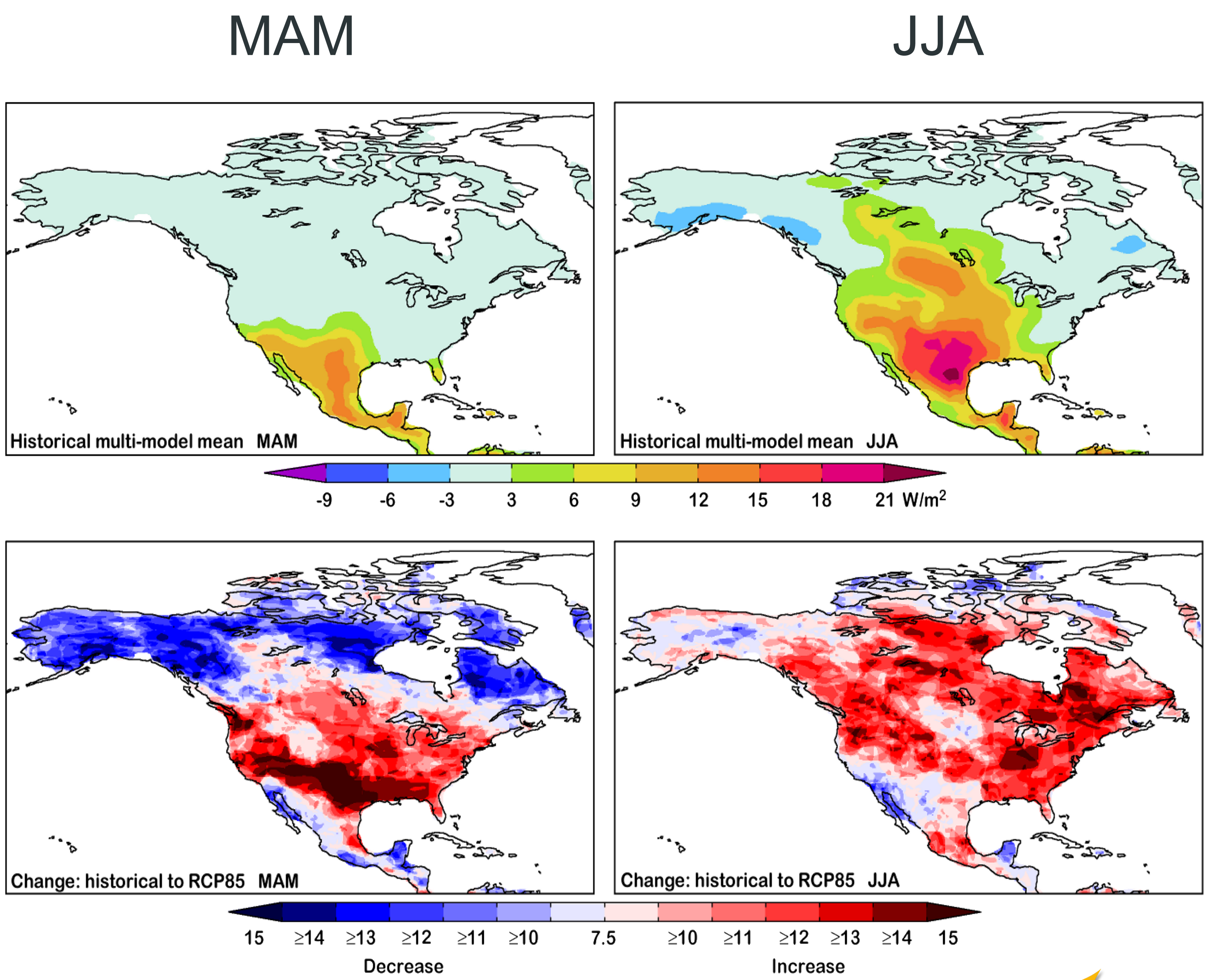
Climate Change and L-A Coupling

- In a warming climate, CMIP5 models indicate that the NA “hot spot” will set in earlier in Spring, expand over a larger area in Summer.
- Accompanies drying, increased land surface control on atmosphere, more sensitivity to ongoing LUCC!



Dirmeyer et al. (2013; J Climate).

Conclusions

- LSM-only metrics are not the whole story. We must benchmark coupled land-atmosphere models (and full ESMs) as well.

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- LSM-only metrics are not the whole story. We must benchmark coupled land-atmosphere models (and full ESMs) as well.
- Multivariate metrics essential to diagnose processes in models.
- A lot of work on coupling metrics has been done in GEWEX that could be leveraged / expanded for BGC-hydro applications.

EXTRA SLIDES

Focus 4

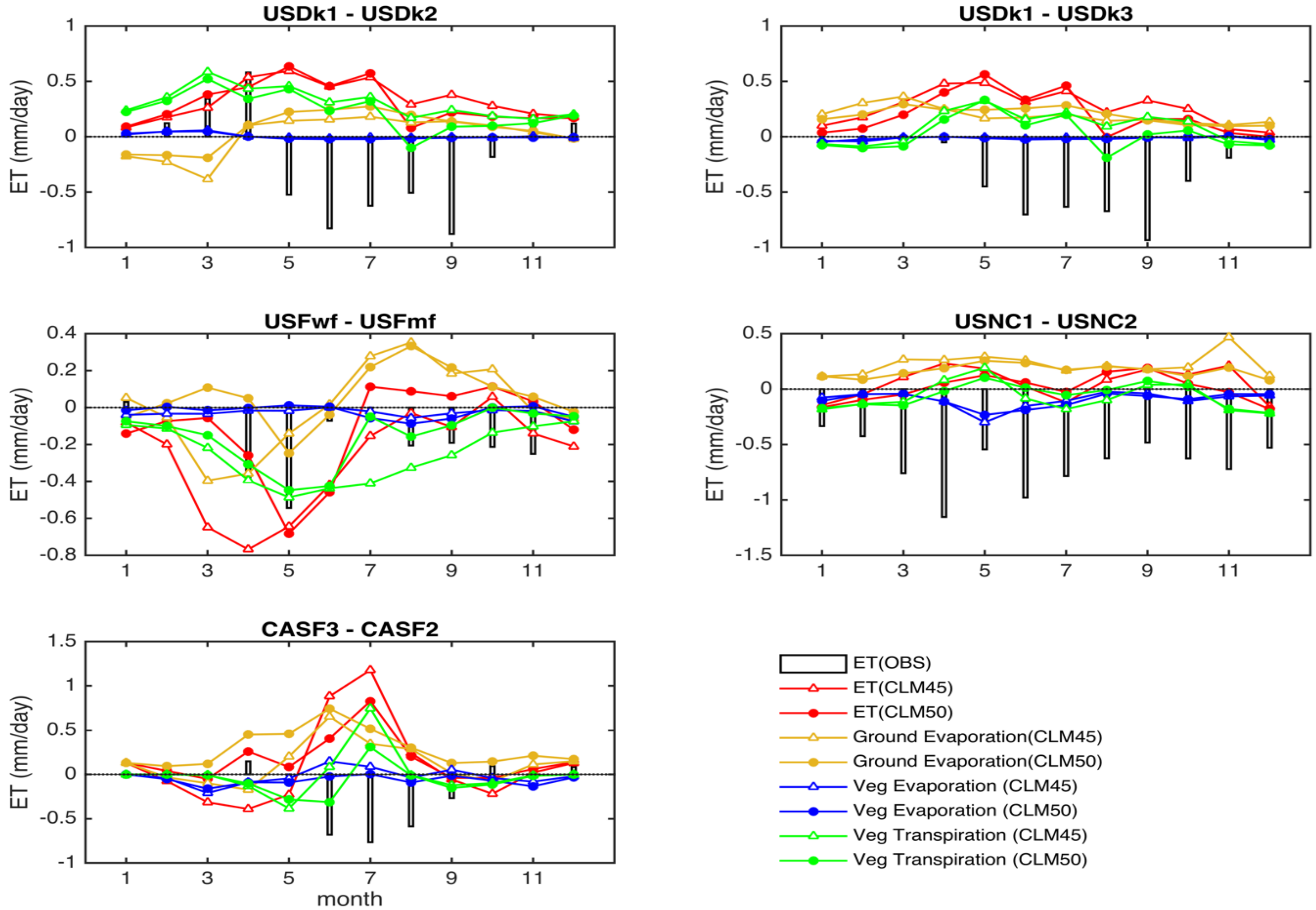
- Can land surface models capture the observed impacts of land cover change on ET at paired FLUXNET sites?

source: GoogleEarth

FLUXNET paired sites

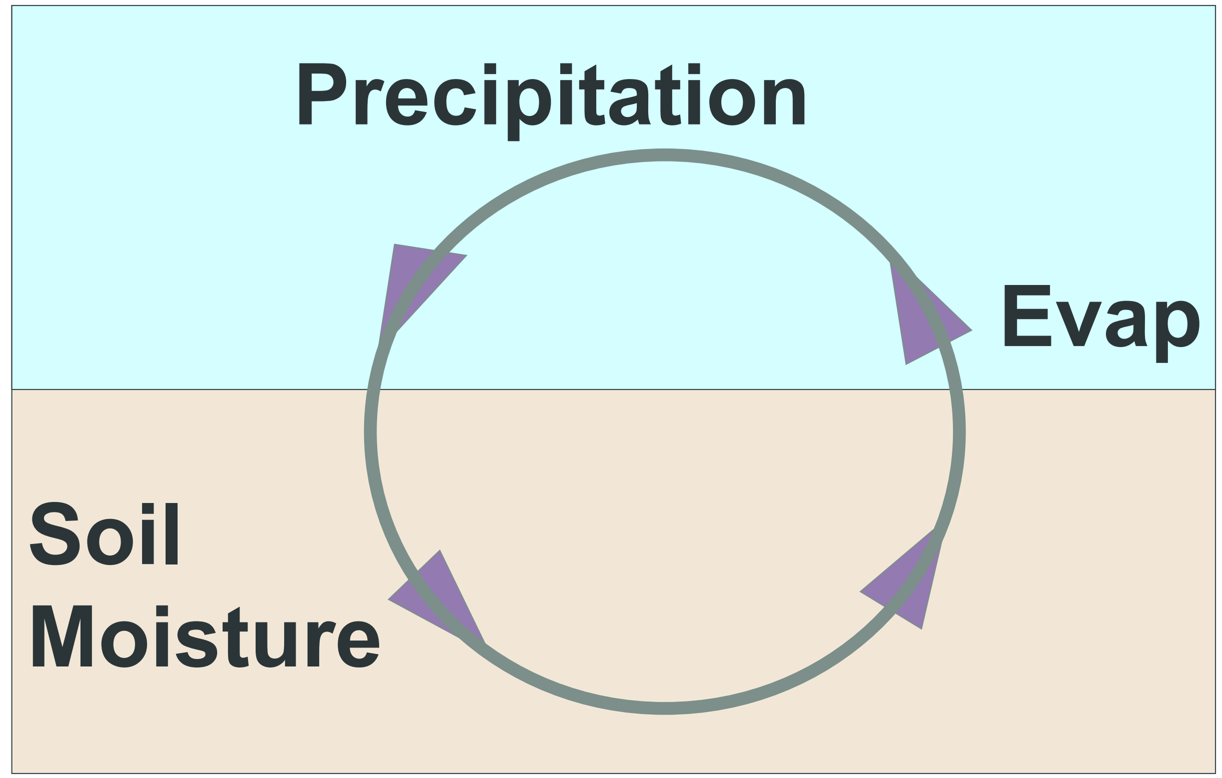
Pair	Period	Location	Name	Latitide	Longitude	Elevation (m)	Land cover	Separation (km)
1	2001-5	Duke Forest, NC	US-DK1	35.9712	-79.0934	168	grassland	0.69
			US-Dk2	35.9736	-79.1004	168	deciduous broadleaf	
2	2001-5	Duke Forest, NC	US-DK1	35.9712	-79.0934	168	grassland	0.78
			US-Dk3	35.9782	-79.0942	163	evergreen needleleaf	
3	2006-10	Flagstaff, AZ	US-Fwf	35.4454	-111.7718	2270	grassland	33.84
			US-Fmf	35.1426	-111.7273	2160	evergreen needleleaf	
4	2006	Albemarle, NC	US-NC1	35.8118	-76.7119	5	open shrub	4.04
			US-NC2	35.8030	-76.6685	5	evergreen needleleaf	
5	2004	Boreal, SK	CA-SF3	54.0916	-106.0053	540	open shrub	19.90
			CA-SF2	54.2539	-105.8775	520	evergreen needleleaf	

Change in ET components

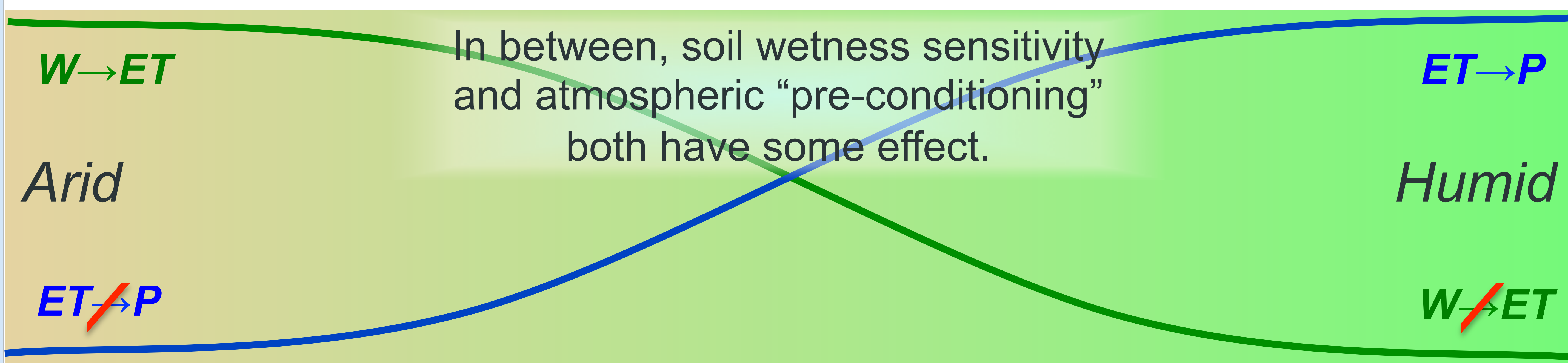


Arid regime:
ET (mostly surface evaporation) is very sensitive to soil wetness variations, but the dry atmosphere is unresponsive to small inputs of water vapor.

Coupled Feedback Loop

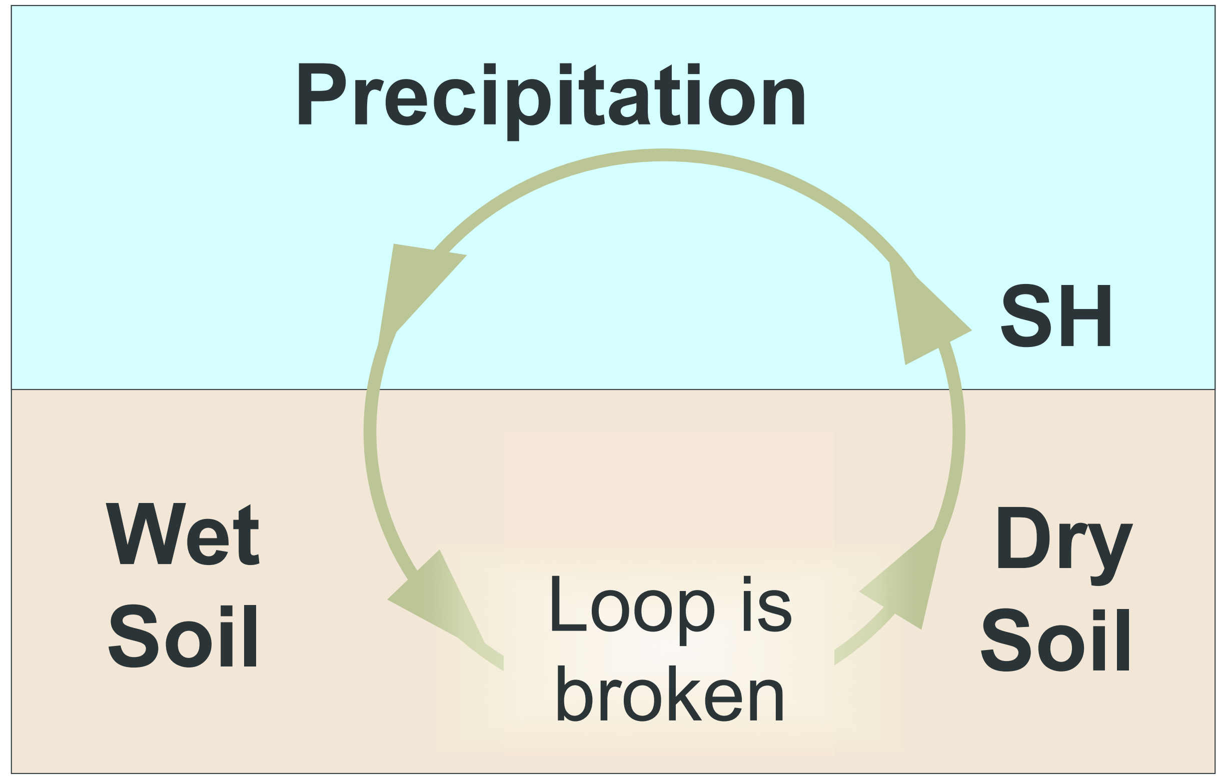


Humid regime:
Small variations in evapo-ration affect the conditionally unstable atmosphere (easy to trigger clouds), but deep-rooted vegetation (transpiration) is not responsive to typical soil wetness variations.

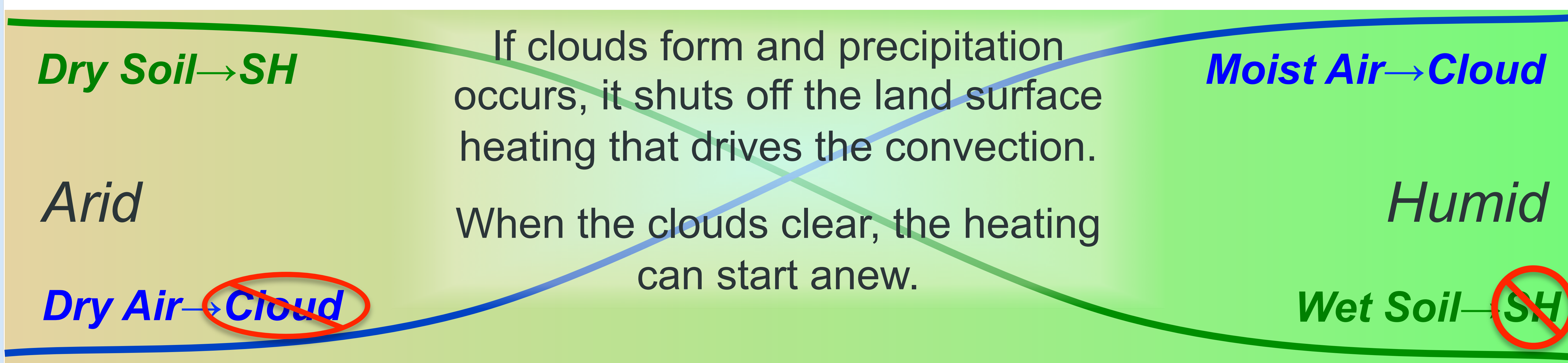


Arid regime:
Dry air must be lifted great distances to cool enough to form clouds – strong sensible heat flux can build necessary deep turbulence and generate convection.

Negative Feedback

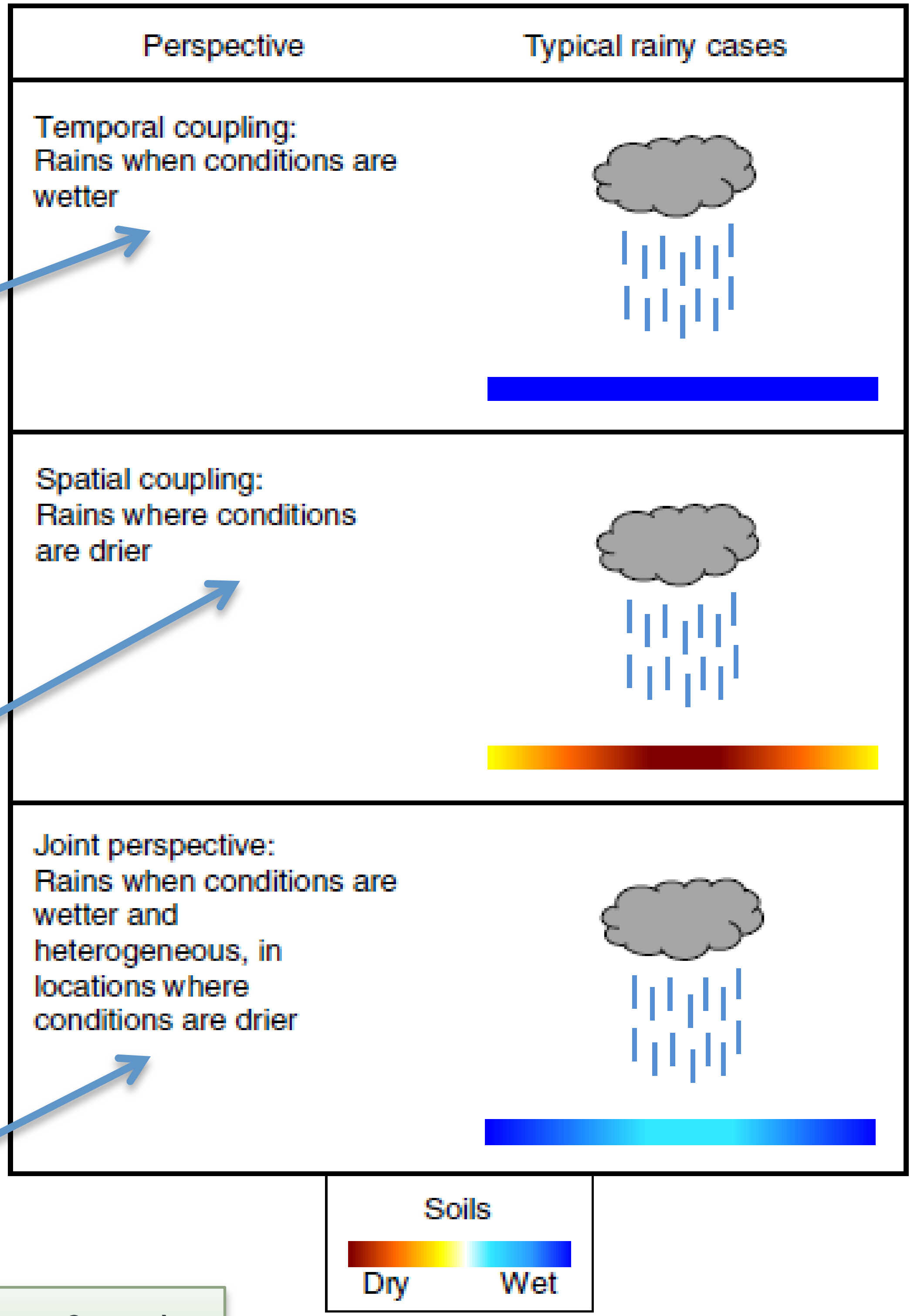


Humid regime:
Moist air can more easily form clouds with a low cloud base. Usually sensible heating is in short supply when cloudy (and possibly rainy), but not when clear. Again, a negative feedback.



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.*)