Surface-atmosphere interactions:

Lessons learned and outstanding scientific challenges

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Land-surface-atmosphere interaction

- Many interdependent processes
  - surface energy balance
  - shortwave and longwave fluxes
  - night-time boundary layer
  - role of water in the surface energy partition
  - vector methods
  - coupling between surface, boundary layer, precipitation
  - evaporation-precipitation feedback.
  - partition of moisture convergence into TCWV, cloud & precipitation
  - ratio of diabatic terms: cloud forcing to precipitation

- Adapted from papers of past 10-15 years
- *Many, many people have contributed*
- Reflect my idiosyncrasies; and many aspects of the ECMWF model

References – see http://alanbetts.com

- Betts, A. K. (2009), Understanding land-surface-atmosphere coupling in observations and models. *JAMES*. http://adv-model-earth-syst.org/index.php/JAMES/article/view/v1n4/JAMES.2009.1.4
- Betts, A. K., J.H. Ball, A.C.M. Beljaars, M.J. Miller and P. Viterbo, 1996: The land-surface-atmosphere interaction: a review based on observational and global modeling perspectives. *J. Geophys. Res.,* **101**, 7209-7225.
- Betts, A. K., 2004: Understanding Hydrometeorology using global models. *Bull. Amer. Meteorol. Soc*., **85**, 1673-1688
- Betts, A.K. and J.H. Ball, 1995: The FIFE surface diurnal cycle climate. *J. Geophys. Res.* **100**, 25679-25693.
- Betts, A. K. and J. H. Ball, 1997: Albedo over the boreal forest. *J. Geophys. Res.*, **102**, 28901-28910.
- Betts, A. K and P. Viterbo, 2005: Land-surface, boundary layer and cloud-field coupling over the south-western Amazon in ERA-40. *J. Geophys. Res*., **110**, D14108, doi:10.1029/2004JD005702.
- Betts, A. K., 2006: Radiative scaling of the nocturnal boundary layer and the diurnal temperature range. *J. Geophys. Res*., **111**, D07105, doi:10.1029/2005JD006560.
- Betts, A.K., J. Ball, A. Barr, T. A. Black, J. H. McCaughey and P. Viterbo, 2006: Assessing land-surface-atmosphere coupling in the ERA-40 reanalysis with boreal forest data. *Agricultural and Forest Meteorology*, **140**, 355-382. doi:10.1016/j.agrformet.2006.08.009. ERA40_PRS26_rev1.pdf
- Betts, A. K., 2007: Coupling of water vapor convergence, clouds, precipitation, and land-surface processes. *J. Geophys. Res.,* **112**, D10108
- Betts, A. K., M. Köhler and Y-C. Zhang, 2009: Comparison of river basin hydrometeorology in ERA-Interim and ERA-40 with observations. *J. Geophys. Res., 114*, doi:10.1029/2008JD010761. ECMWF tm568.pdf
- Betts, A. K. and M. A. F. Silva Dias (2010), Progress in understanding land-surface-atmosphere coupling over the Amazon: a review. *J. Adv. Model Earth Syst.,* http://adv-model-earth-syst.org/index.php/JAMES/article/view/v2n6/JAMES.2010.2.6
- Betts, A. K. and J. C. Chiu (2010), Idealized model for changes in equilibrium temperature, mixed layer depth and boundary layer cloud over land in a doubled CO2 climate. J. Geophys. Res. (in press), 2009JD012888. http://www.agu.org/journals/jd/papersinpress.shtml#id2009JD012888

Themes

- Evaluating models with field data
- FIFE (grassland);
- BOREAS/BERMS (boreal forest)
- GEWEX (river basins)
- ERA-40 river basin & grid-point comparisons
- Diurnal, daily mean, annual cycle
- *Land-surface climate*
- *SW and LW cloud radiative impacts*
- *Precipitation, evaporation, dynamics*

  – *Talk is mostly Figures: Betts, A. K. (2009) for details*

Surface Energy Balance

$$R_{net} = SW_{net} + LW_{net} = H + \lambda E + G$$

- the split between surface processes and atmospheric processes
- the split between SW and LW processes
- the partition between clear-sky and cloud processes in the atmosphere
- the partition of the surface R_{net} into H and λE, which is controlled largely by the availability of water for evaporation and by vegetation

Clouds & Surface SW_{net}

$$SW_{net} = SW_{down} - SW_{up} = (1- \alpha_{surf})(1- \alpha_{cloud})\ SW_{down}(clear)$$

- ***surface albedo***

$$\alpha_{surf} = SW_{up} / SW_{down}$$

- ***effective cloud albedo*** ***[per unit area surface]***

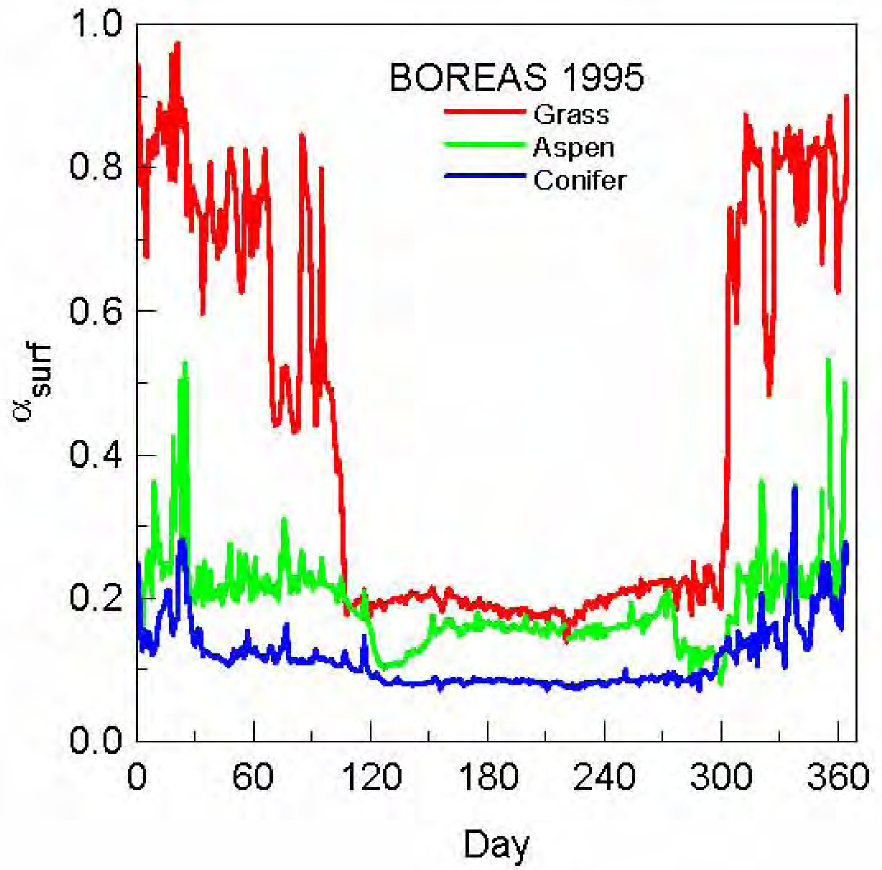
  - scaled surface **short-wave cloud forcing, SWCF**

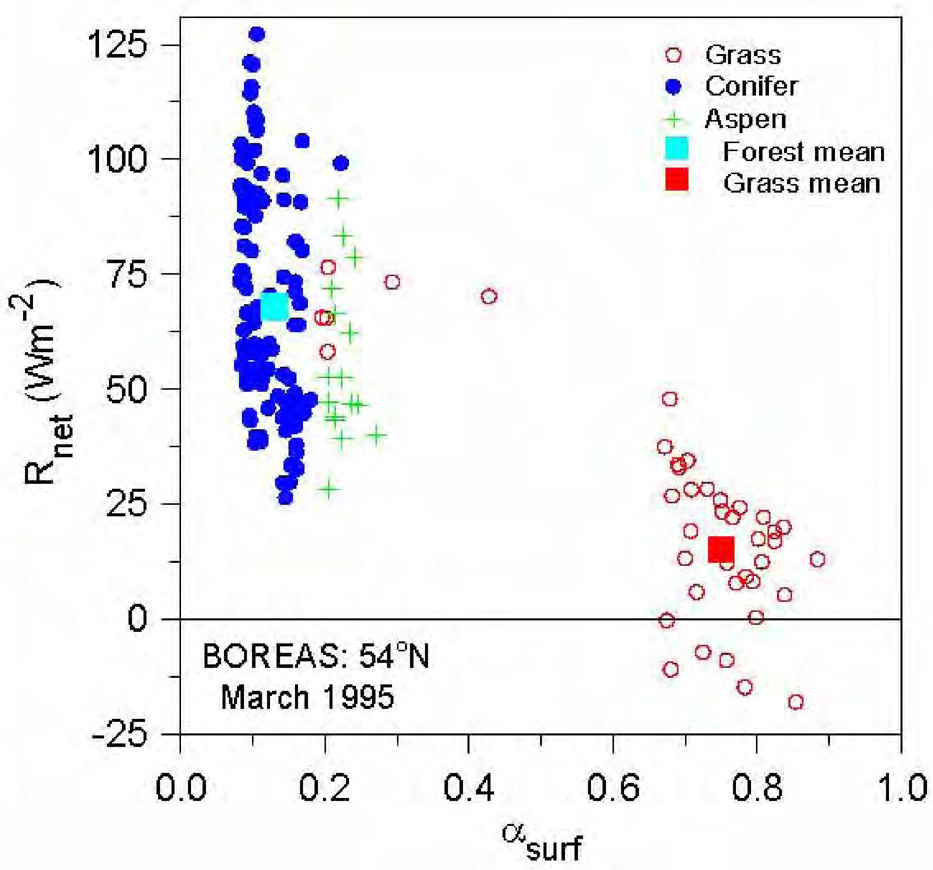
$$SWCF = SW_{down} - SW_{down}(clear)$$

$$\boldsymbol{\alpha_{cloud} = - SWCF/SW_{down}(clear)}$$

[Betts and Viterbo, 2005; Betts, 2007]

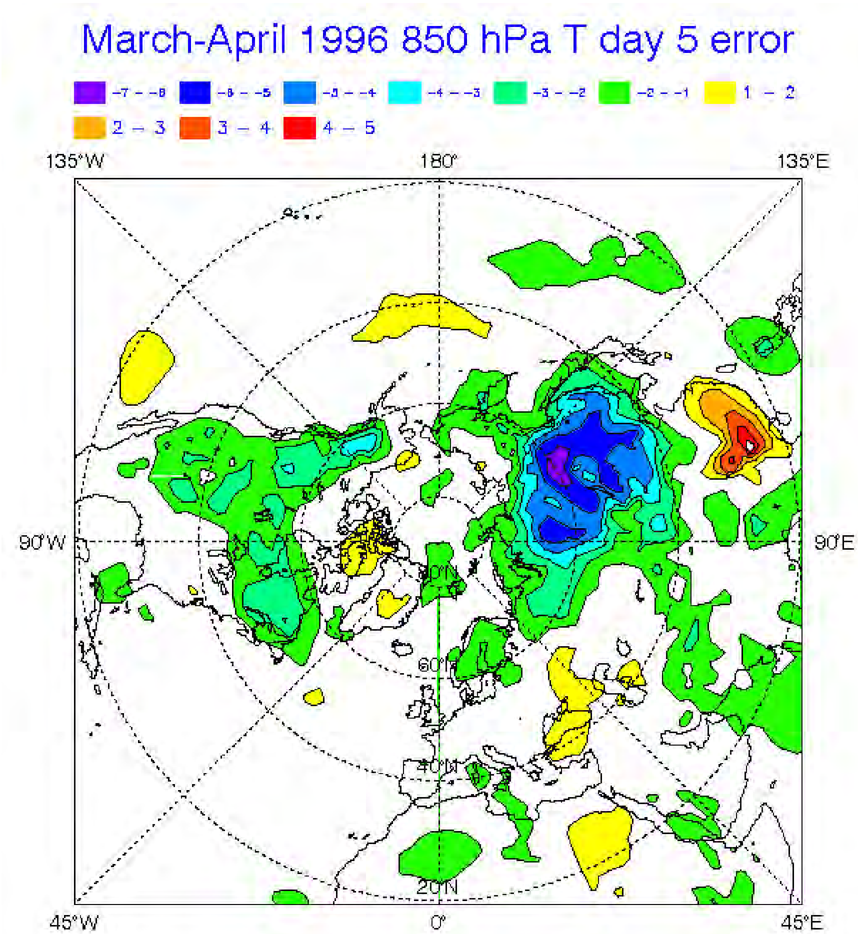
Surface albedo

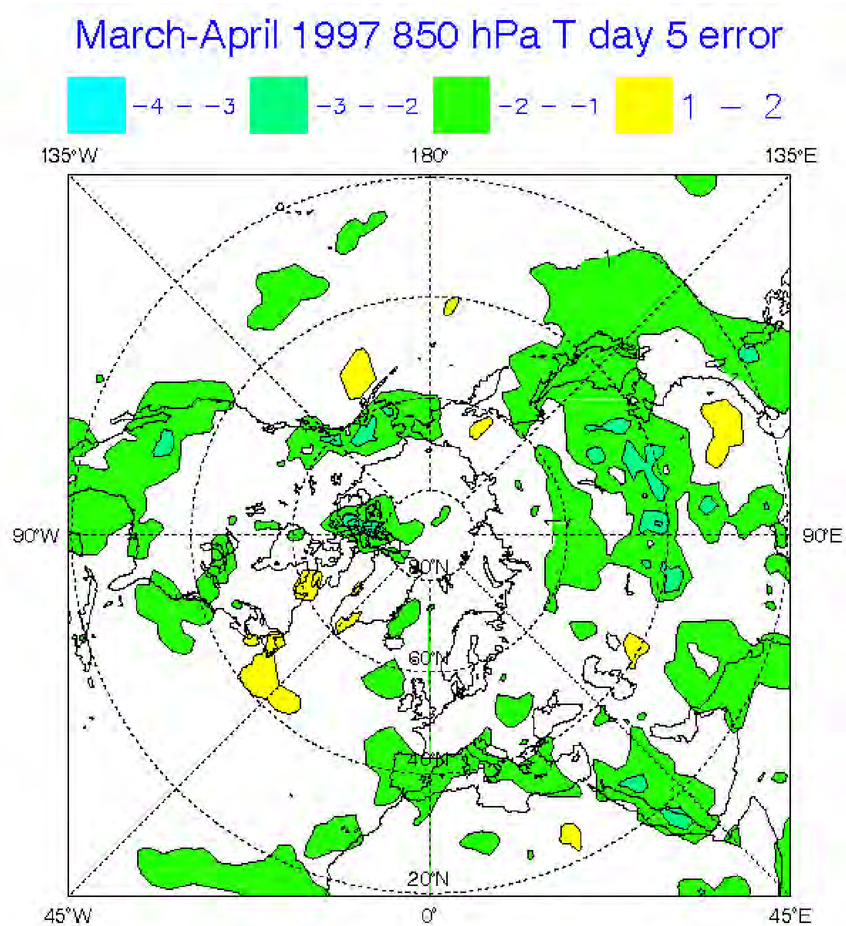




- Impact of landscape differences (forest/grass) on R_{net} are large in spring

Impact of reducing boreal forest α_{surf} from 0.8 to 0.2 (snow)





- Large systematic bias reduction; ***snow/ice-albedo feedback***
- NH 850 hPa T forecast skill improved Feb. to mid-May

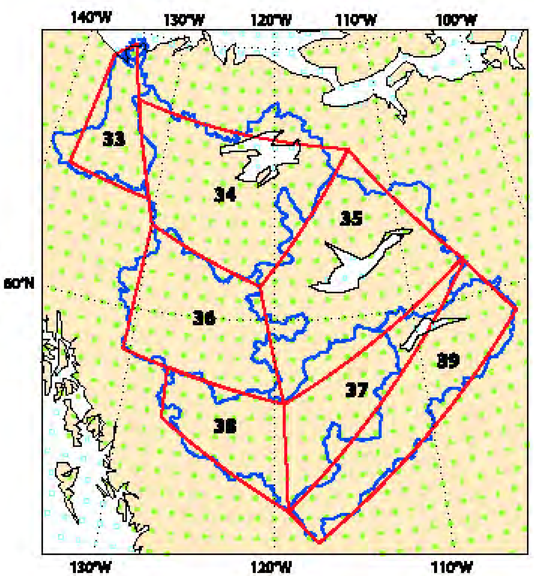
Winter climate transition

- **Sun is low; and snow reflects sunlight, except where trees!**
- **R_{net} low, sublimation small, clear sky, outgoing LW_{net} large, gets colder**

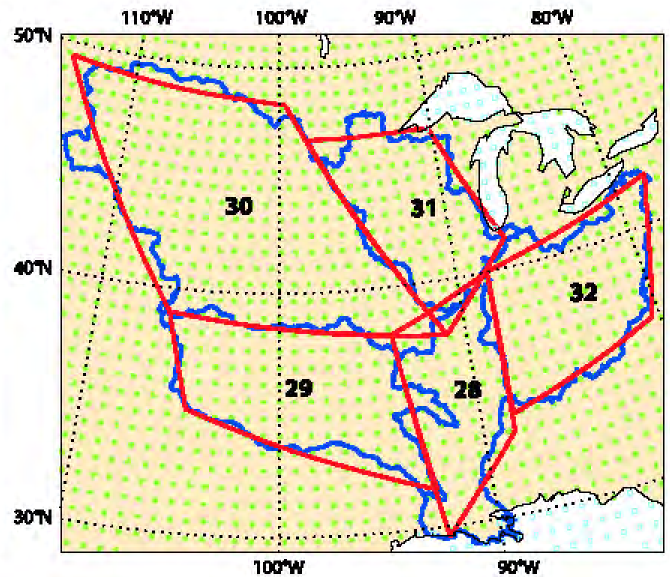
Aside

River basin archive

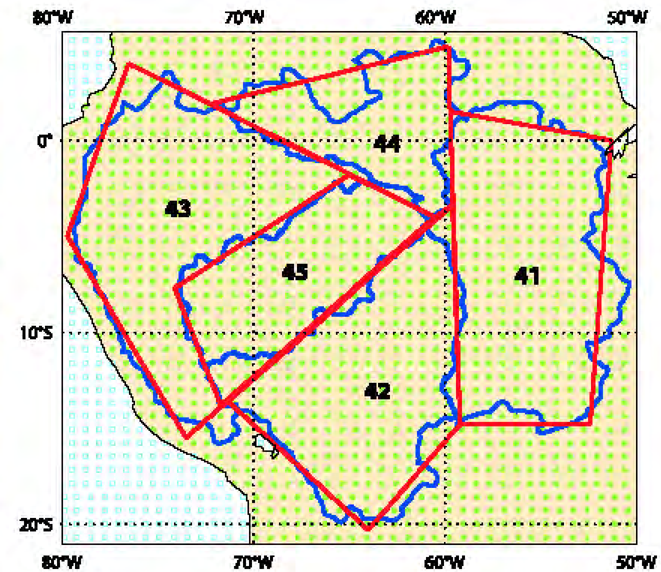
ERA-40 and ERA-Interim



Mackenzie



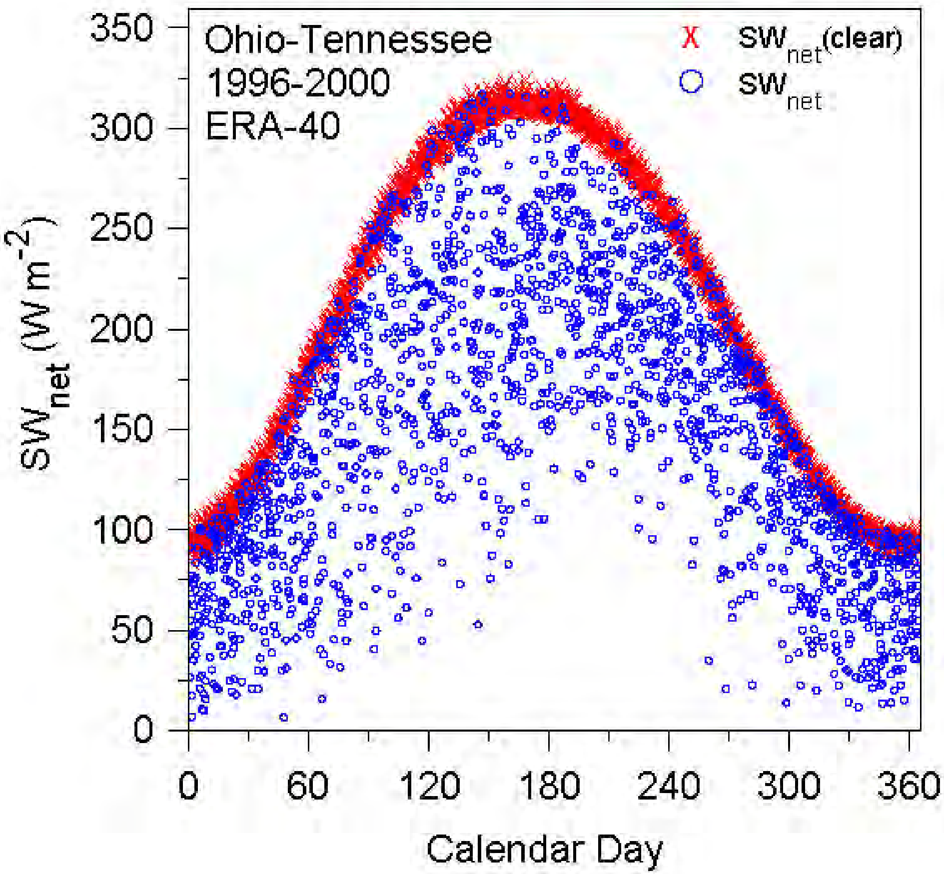
Mississippi

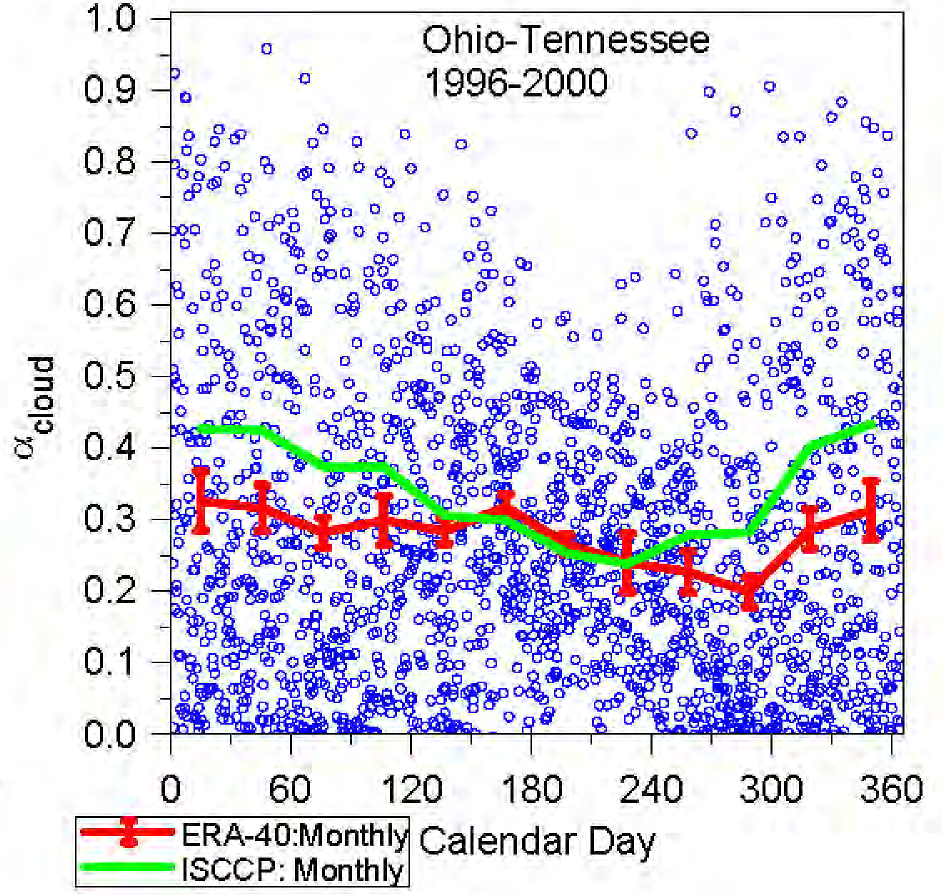


Amazon

Evaluation on river basin scale, starting from **hourly archive**

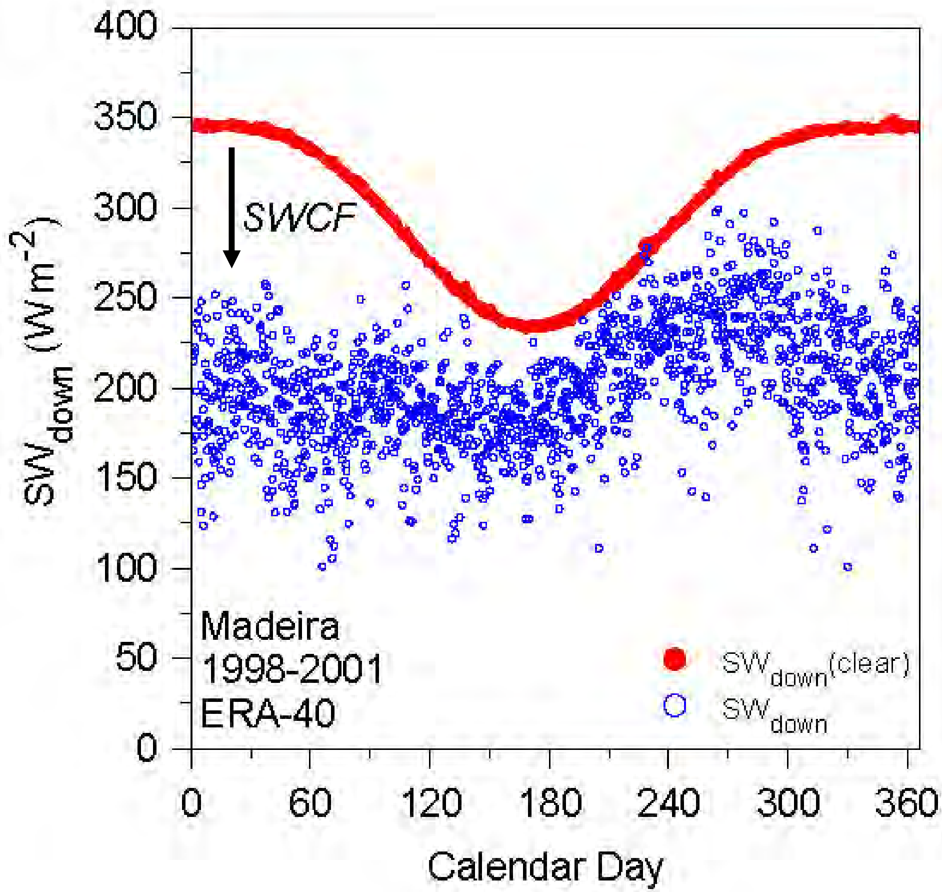
Effective Cloud albedo

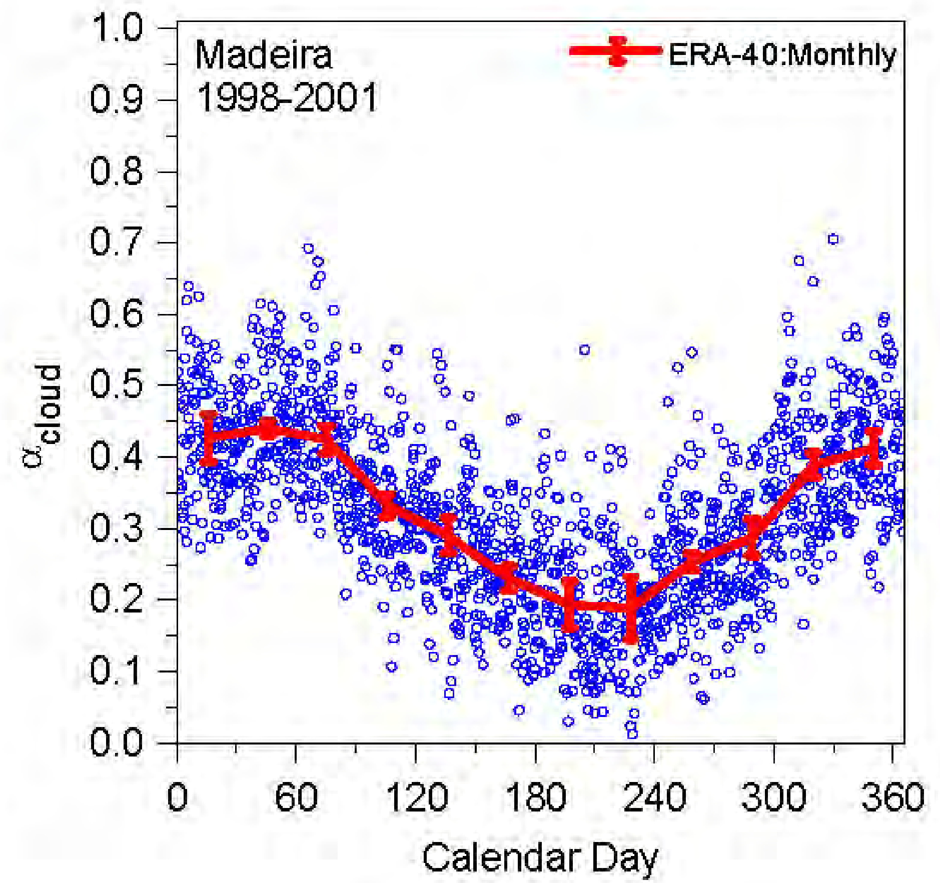




- Transformation of SWCF to α_{cloud}
- Large variability: 10% low bias in winter

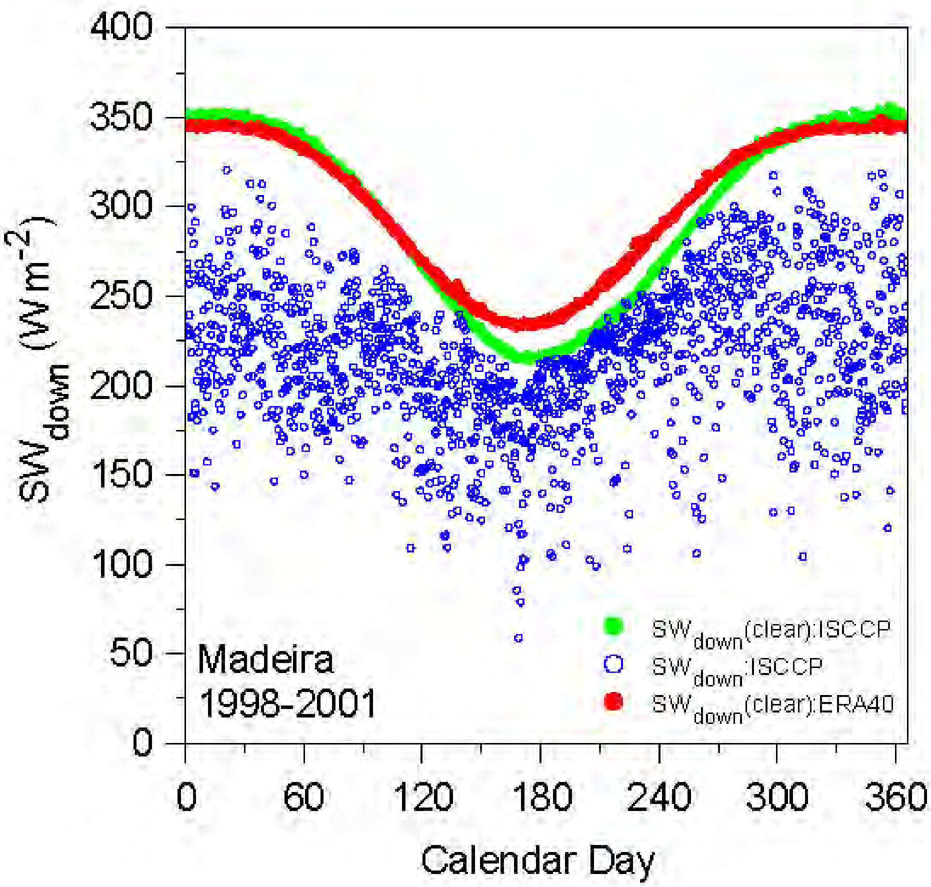
Eff. Cloud albedo: ERA-40 data

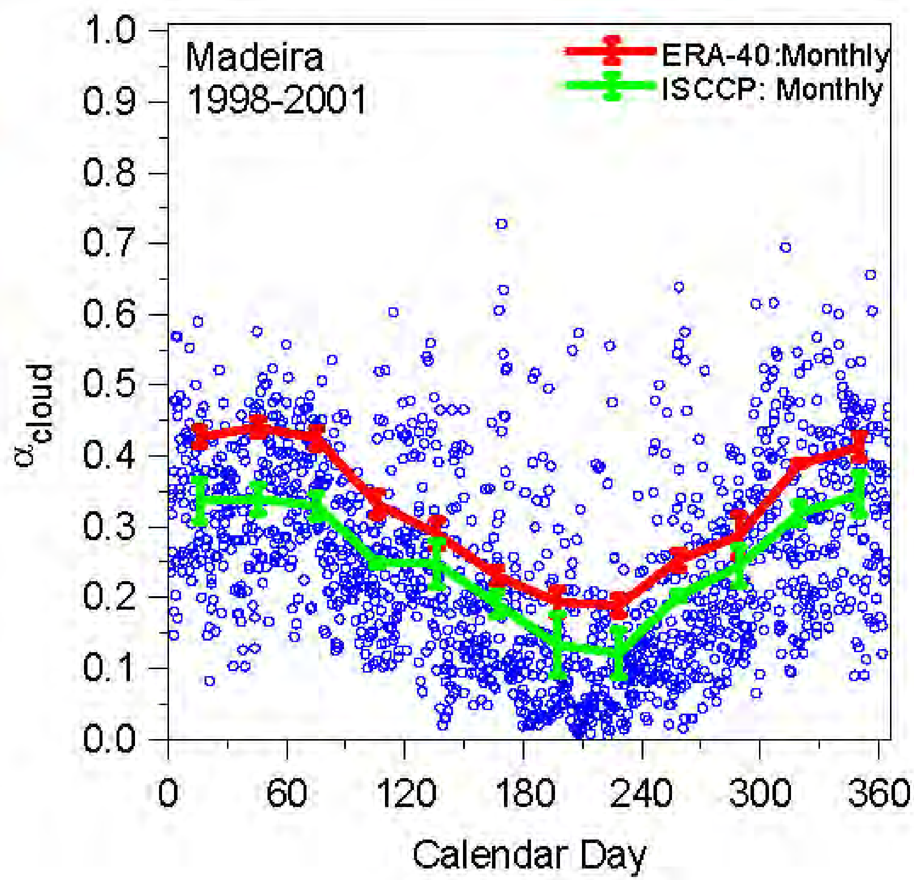




- Transformation of SWCF to α_{cloud}
- Seasonal cycle OK: small daily variability: biased???

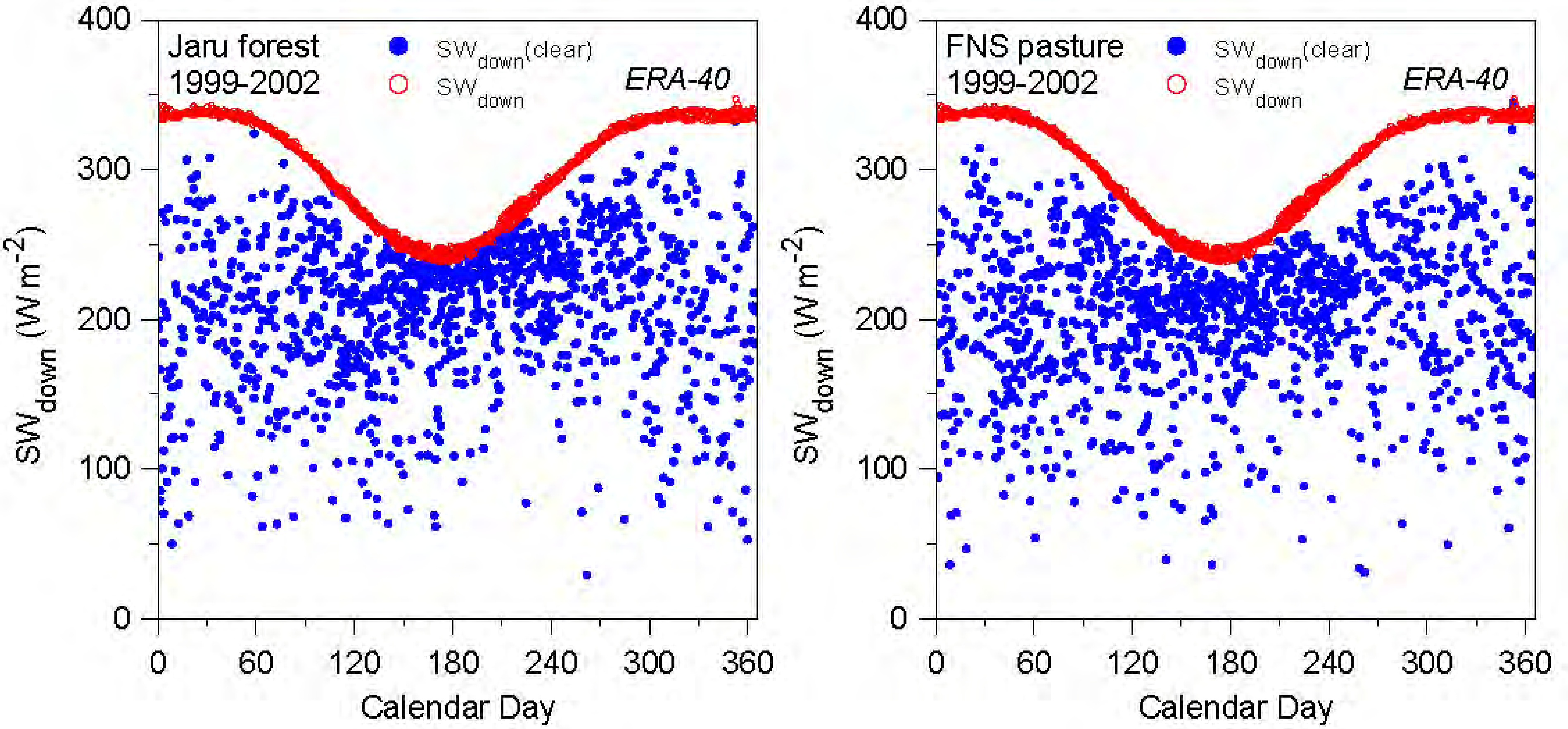
Effective cloud albedo: ISCCP





- Different clear-sky flux: Aerosol differences
- ERA-40 systematic high bias in α_{cloud} ≈ +7%
- ISCCP has more daily variability

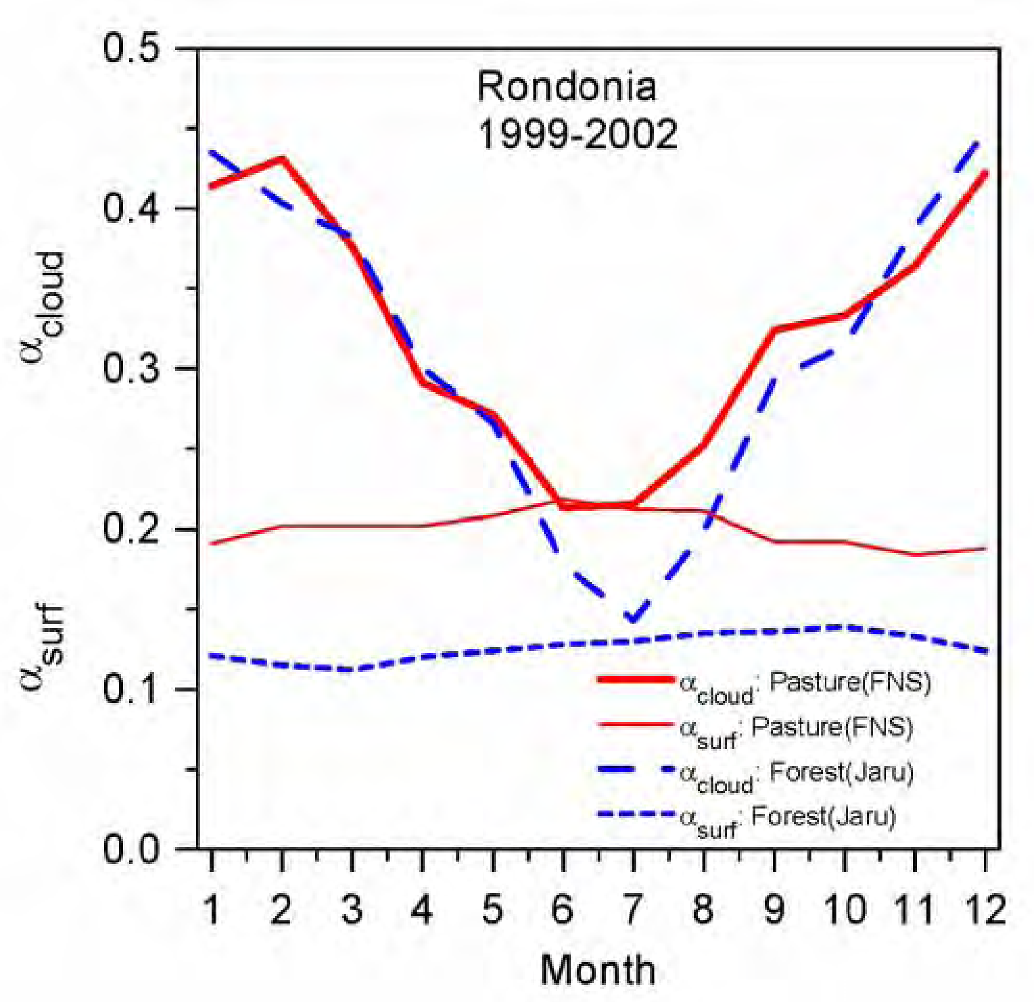
Rondonia forest & pasture : SWCF



- More dry season cloud over pasture
- Aerosol ‘gap’ in September burning season

Energy balance: forest and pasture

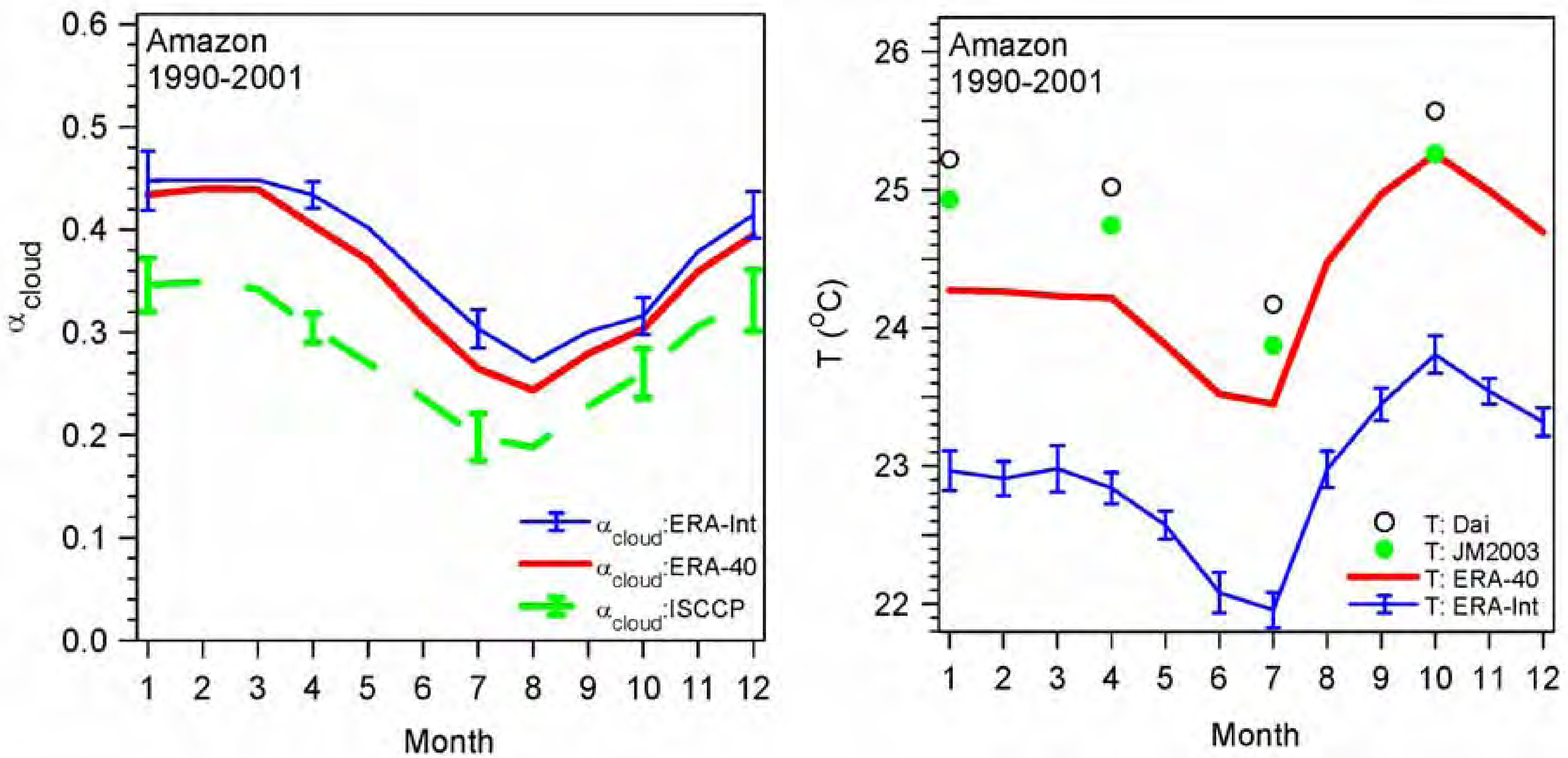
- In July, pasture has 8% higher surface albedo and 6% more cloud
- Pasture LW_{net} is greater (surface warmer, BL drier)
- Pasture $R_{net} \approx 14\%$ less than forest



BL cloud is surface coupled

SW

Tropics: Reanalysis bias

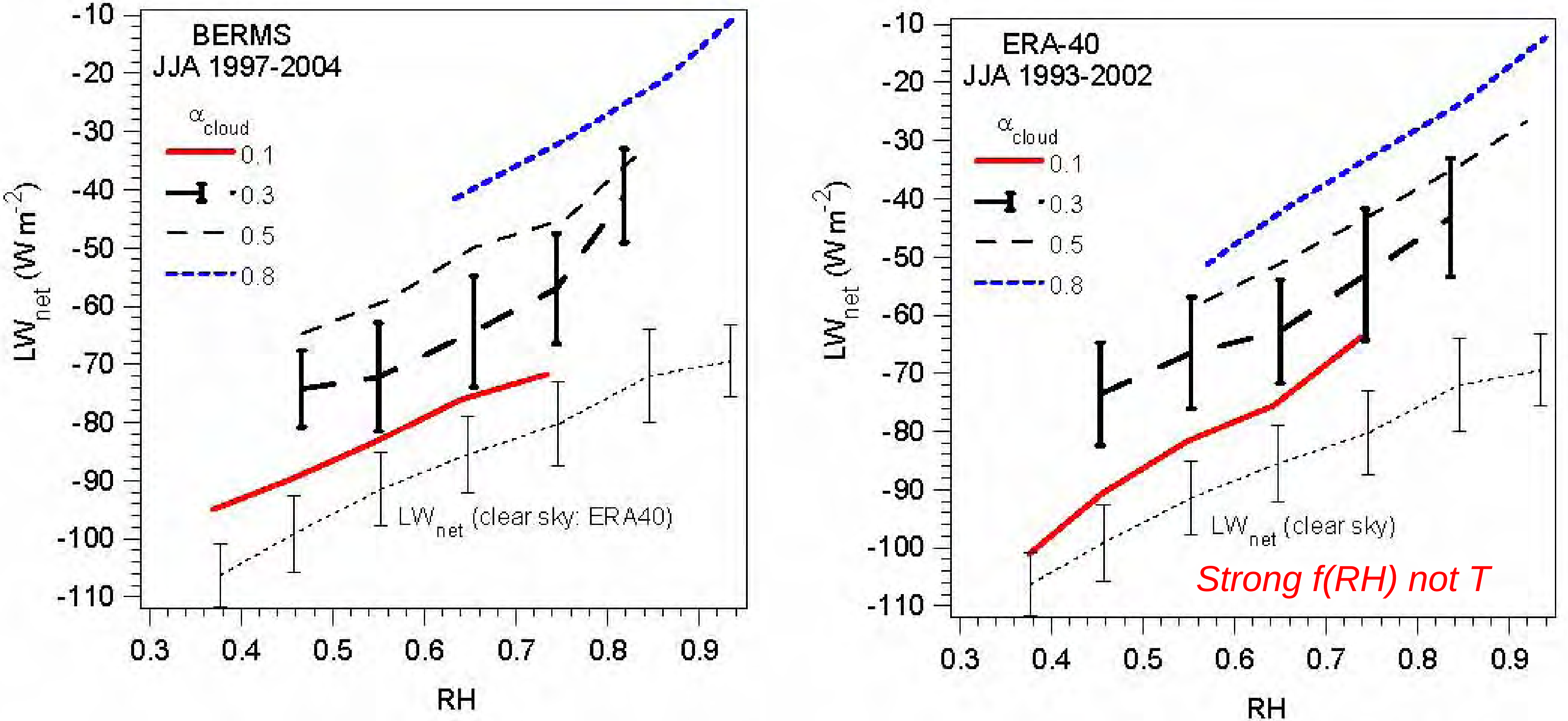


- Amazon: reanalyses α_{cloud} biased high
- ***Cloud-albedo feedback:*** *very non-linear?*
- ***Surface Temp biased low***

Longwave

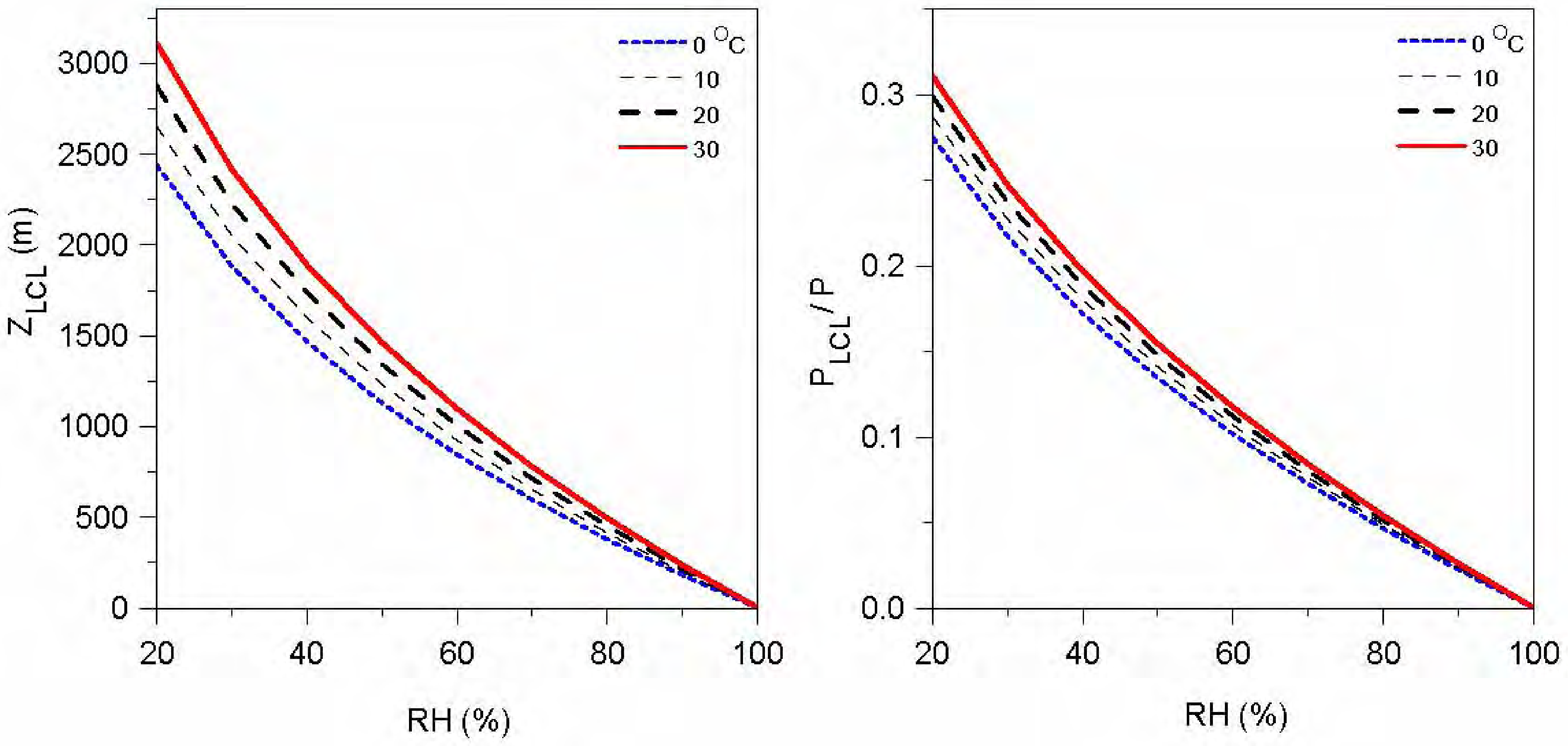
Surface LW_{net}

Water vapor & cloud greenhouse



- Point comparison: stratified by RH (LCL) & α_{cloud}
- Quasilinear **clear-sky and cloud greenhouse effects**
- Amazon similar

Aside: Relation of RH to LCL



- Z_{LCL} is fn(T) but not p P_{LCL}/p is weak fn(T)

Coupling of LW_{net} with diurnal temperature range and NBL

Define *diurnal temperature range*

$DTR = T_{max} - T_{min}$

Scale by 24h mean LW_{net}

$\Delta T_R = -\lambda_0 LW_{net24}$ where $\lambda_0 = 1/(4\sigma T^3)$

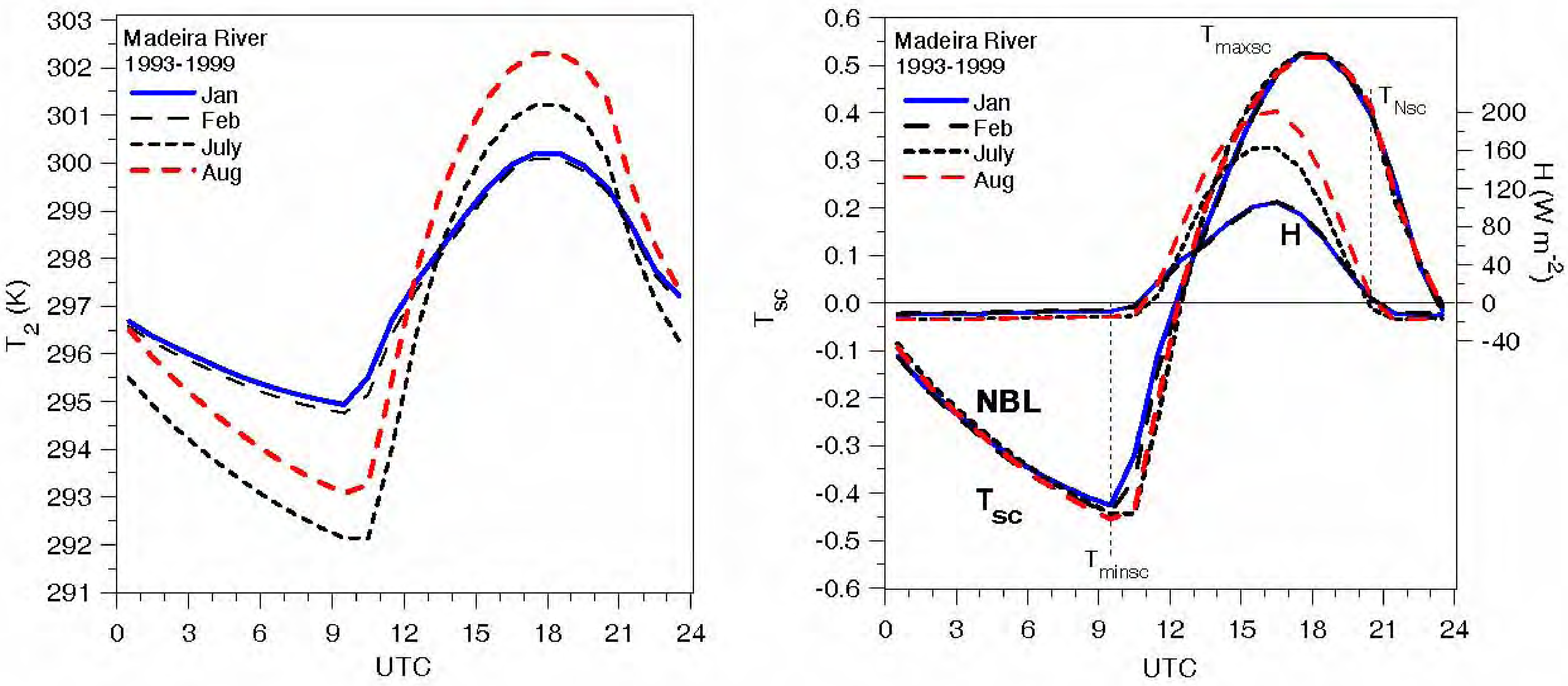
Slope Planck fn

$T_{sc} = (T_2 - T_{24}) /)T_R$

$DTR_{sc} = T_{maxsc} - T_{minsc} \approx 1$ (Amazon)

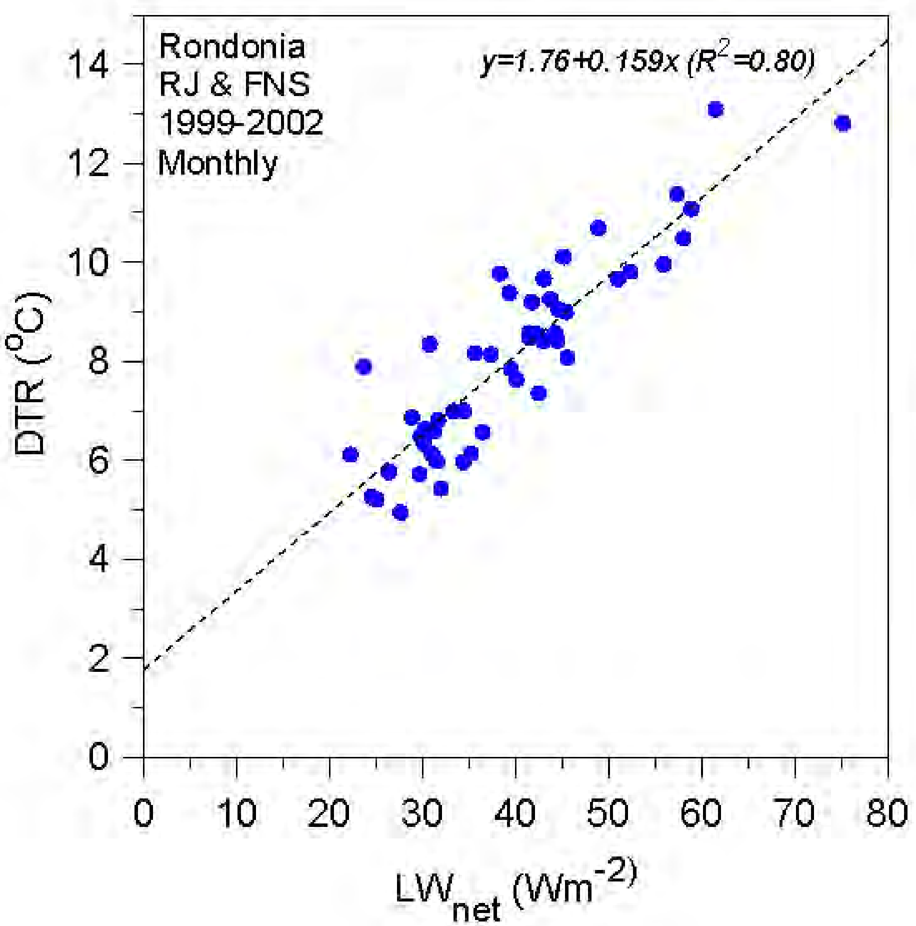
[Betts, JGR, 2006]

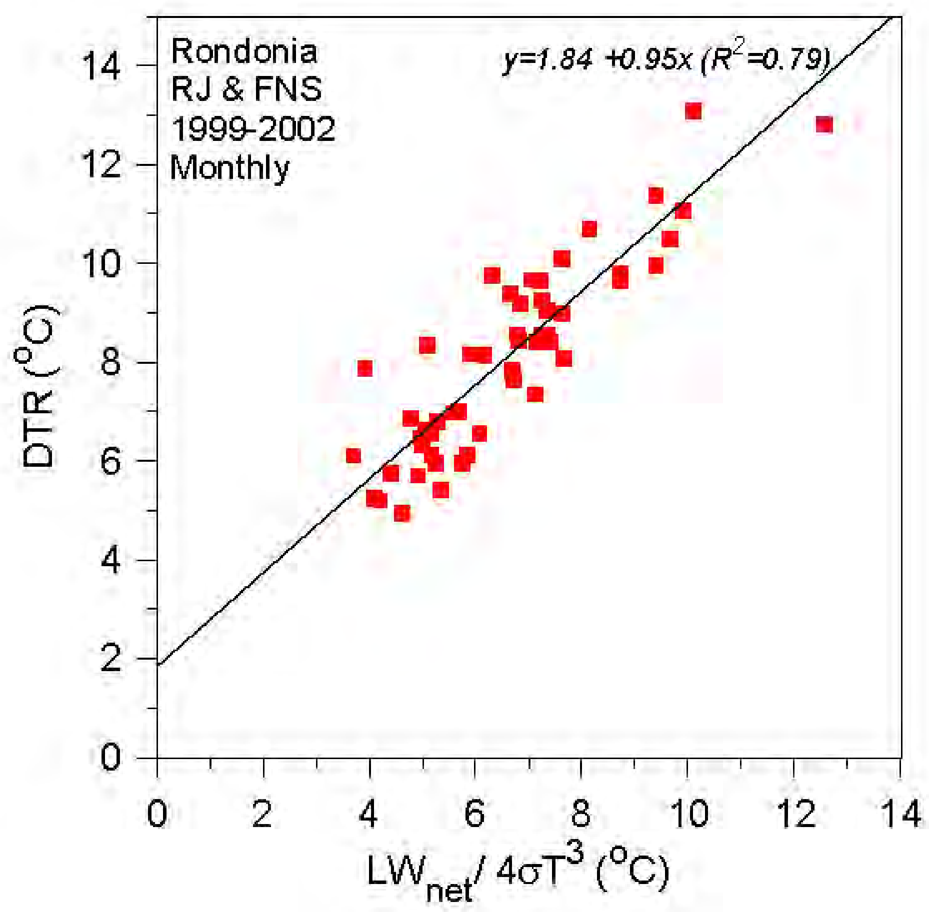
Mean diurnal cycle Madeira river



- DTR doubles in dry season (with LW_{net})
- $DTR_{sc} \approx 1$
- $\Delta T_{Nsc} = T_{Nsc} - T_{minsc} \approx 0.9\ DTR_{sc}$

LW_{net} and DTR – monthly mean data





- Mean LW_{net} and DTR correlated

[Betts: JGR, 2006]

Spring climate transition

- **Before leaf-out**

Little evaporation → Dry atmosphere, low RH

→ Deep dry BL

→ Large outgoing LW_{net}

Low water vapor greenhouse

→ Large DTR, warm days, cool nights

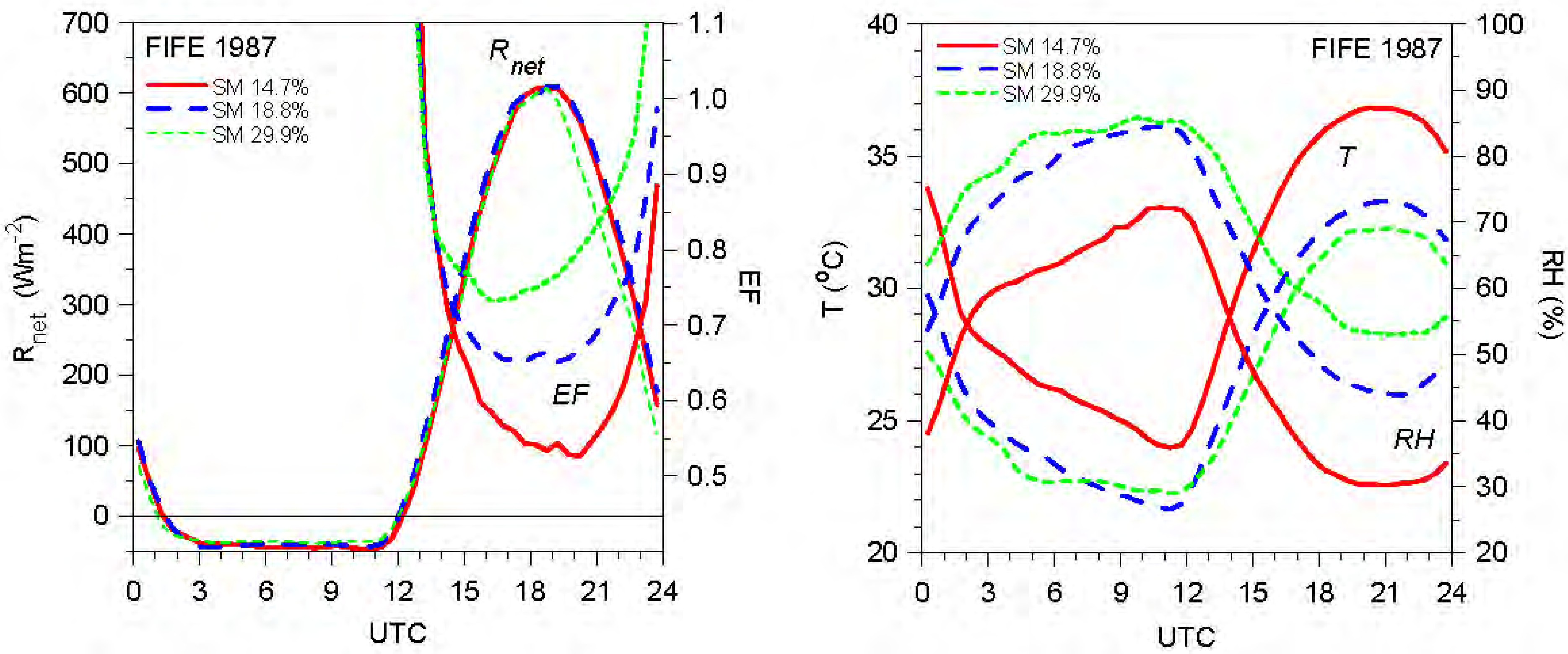
- **After leaf-out**

Large evaporation → Wet atmosphere, low cloudbase

→ Small outgoing LW_{net}

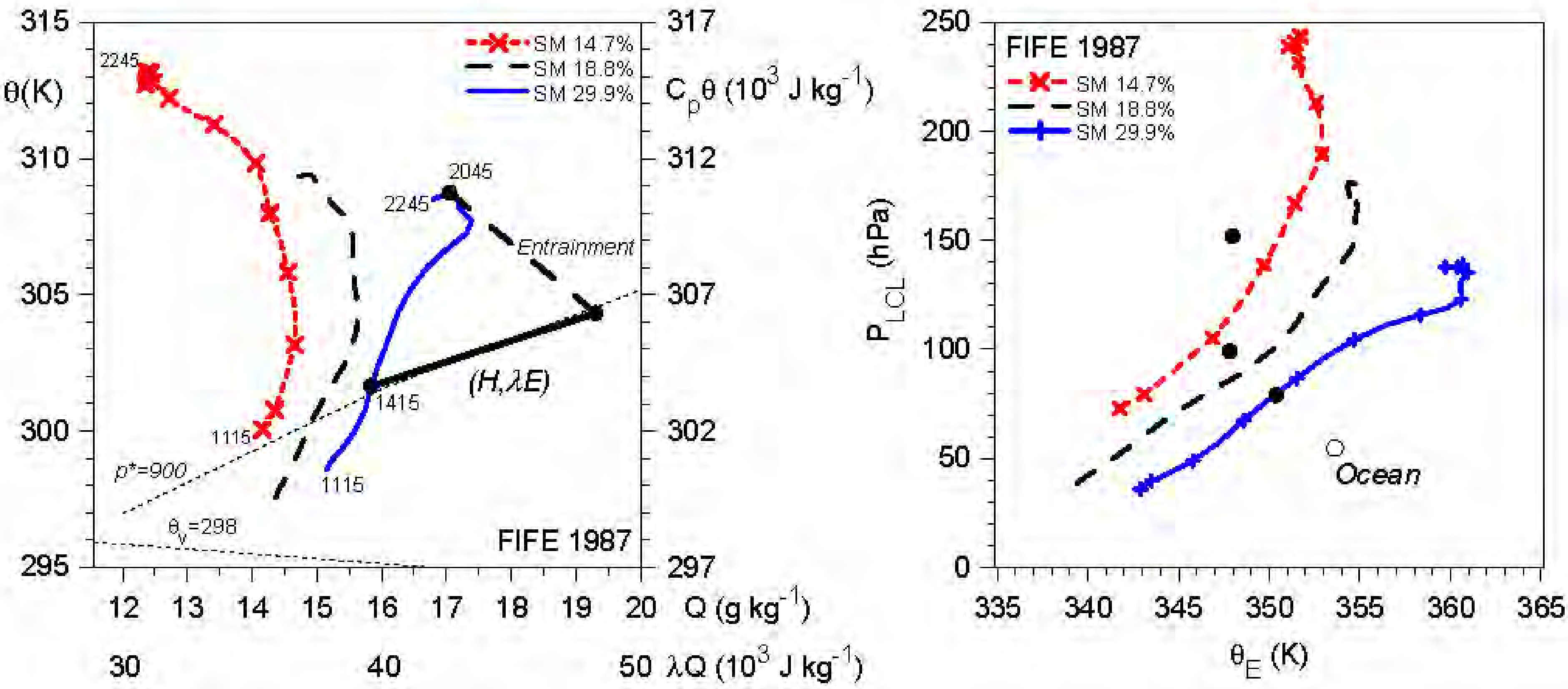
→ Reduced DTR, reduced T_{max}

Water availability & the surface energy partition



- FIFE grassland: partitioned by soil moisture
  - July & August; little cloud
- Evaporative fraction: EF = λE/(λE+H)

Diurnal cycle on vector diagrams

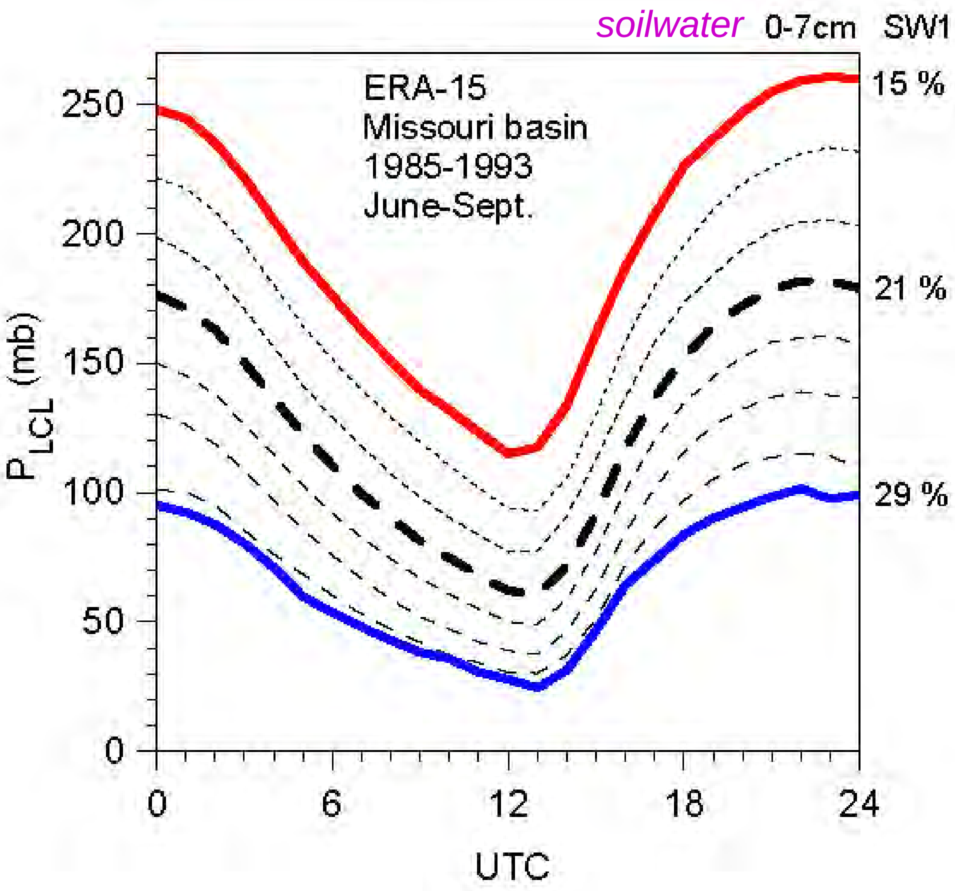


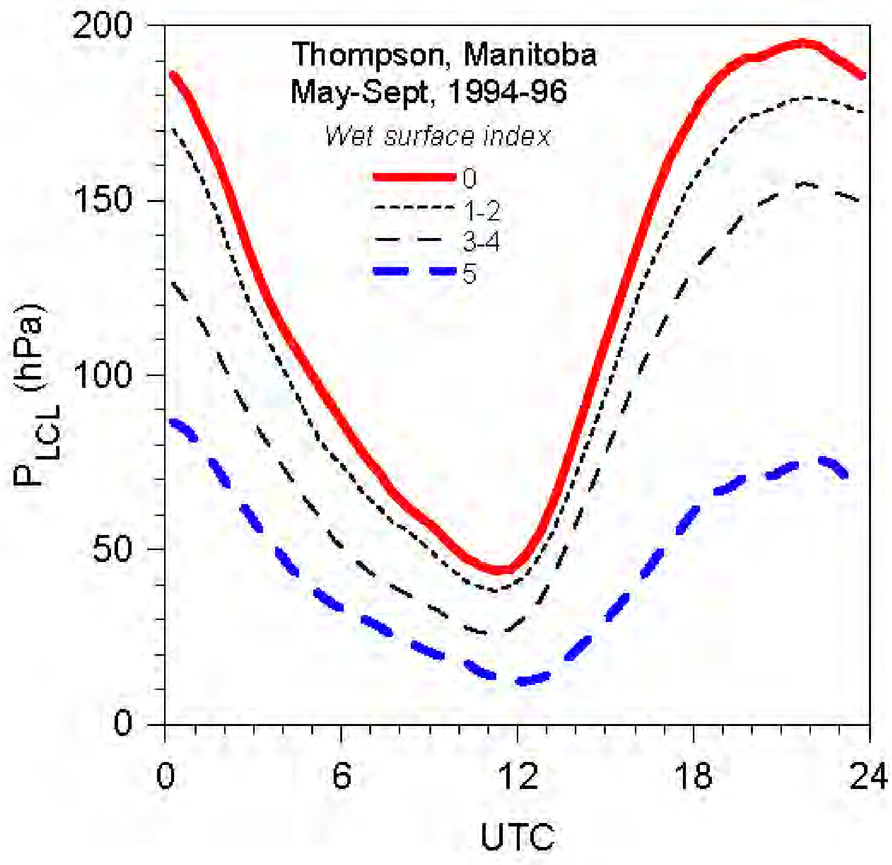
- $\Delta\boldsymbol{\xi}_m/\Delta t = (\mathbf{F}_s - \mathbf{F}_i)/\ \rho\Delta Z_i$ where $\Delta\boldsymbol{\xi}_m = \Delta(C_p\theta,\ \lambda Q)_m$
- $(H,\ \lambda E) = \Omega\ \Delta(C_p\theta,\ \lambda Q)$ where $\Omega = \rho\Delta Z_i/\Delta t$

Fluxes *vector* *BL growth*

Water availability, evaporation and LCL

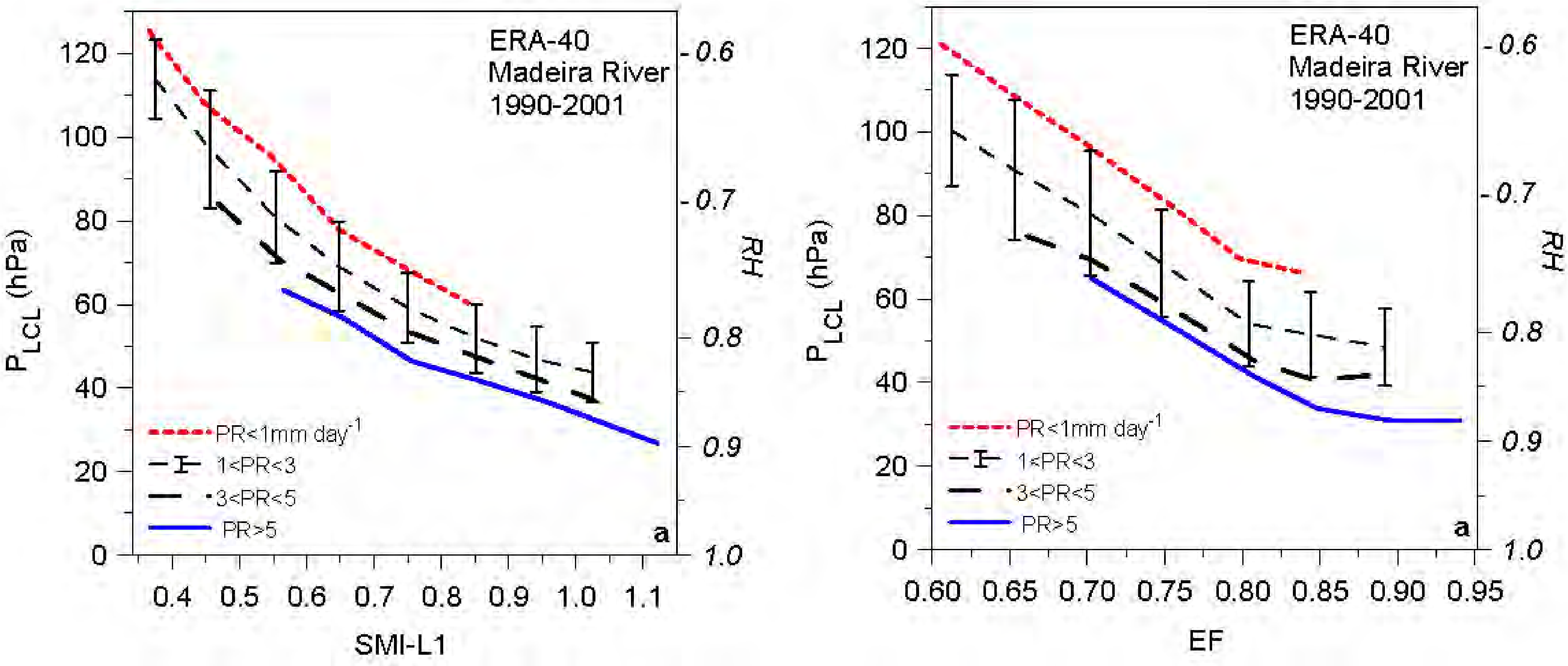
Why is cloud-base is higher over land?





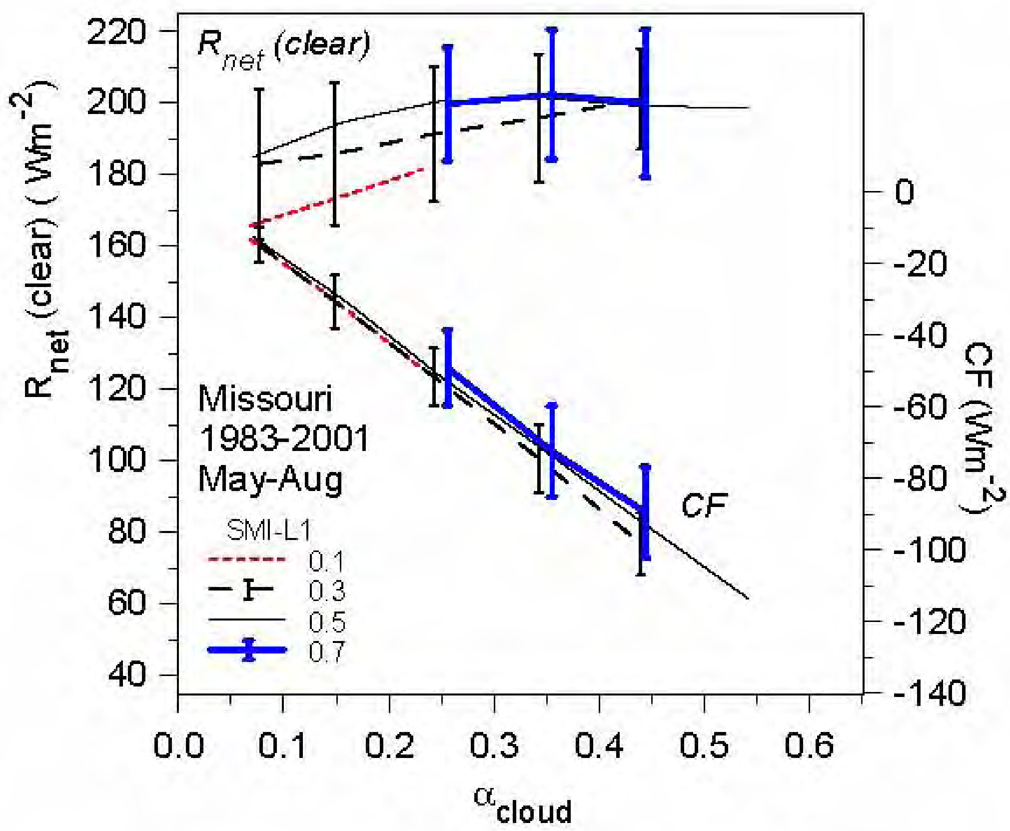
- ERA-15: SW-L1 Boreal forest & moss
- Resistance to evaporation → RH drop and LCL rise
- **Resistance coupled to water availability & carbon cycle**

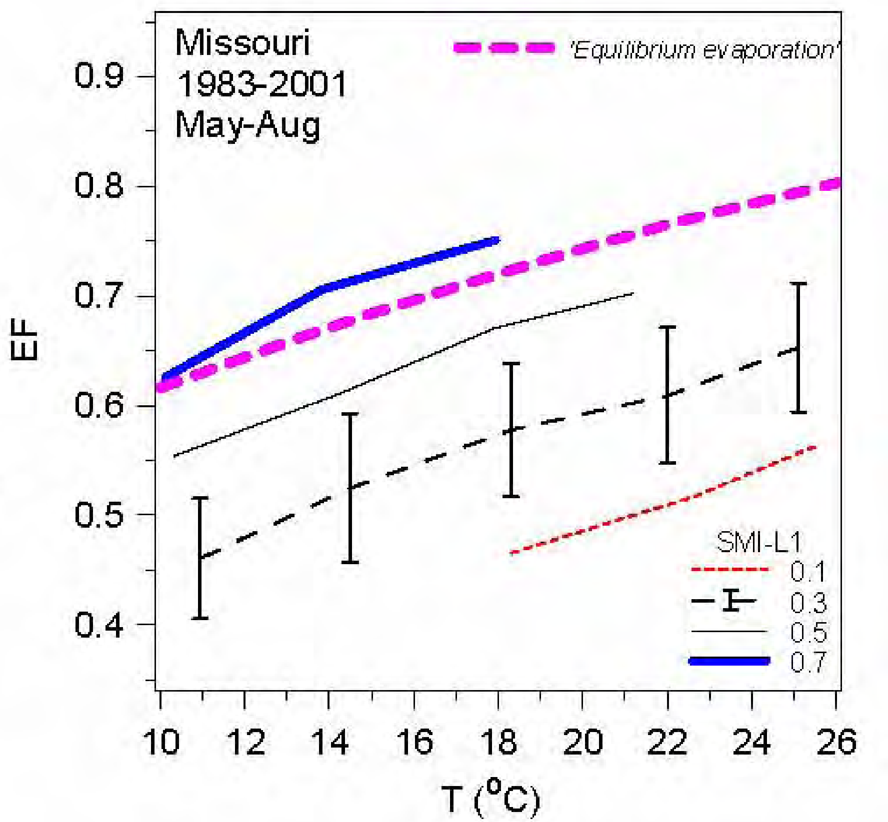
Land-surface-BL Coupling



- SMI-L1 = (SM- 0.171)/(0.323-0.171)
- P_{LCL} stratified by Precip. & SMI-L1 or EF
- Highly coupled system: **only P_{LCL} *observable***

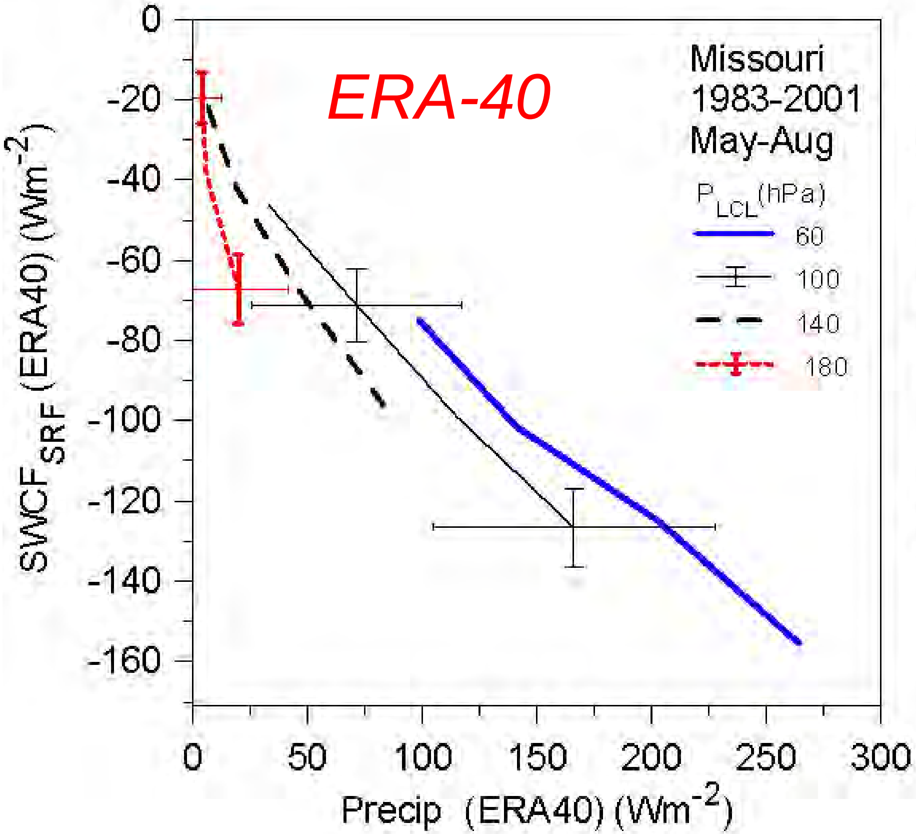
Separating cloud and surface controls on the SEB and EF

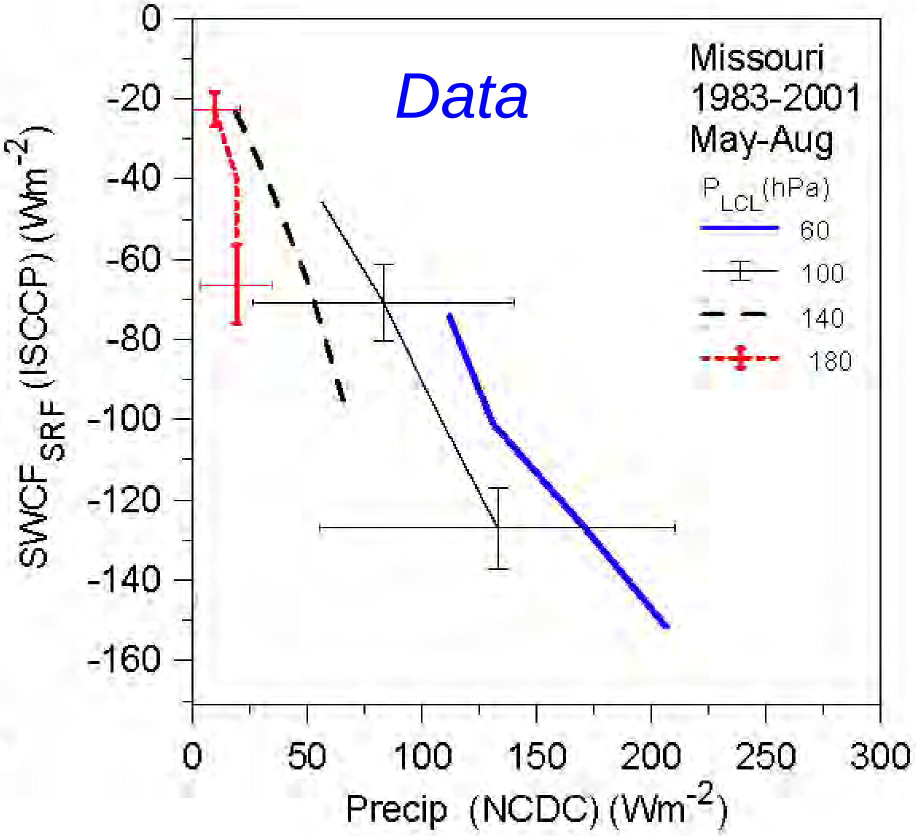




- R_{net} depends on *cloud cover*
- EF depends on *T* and *soil moisture*

Cloud forcing to Precipitation

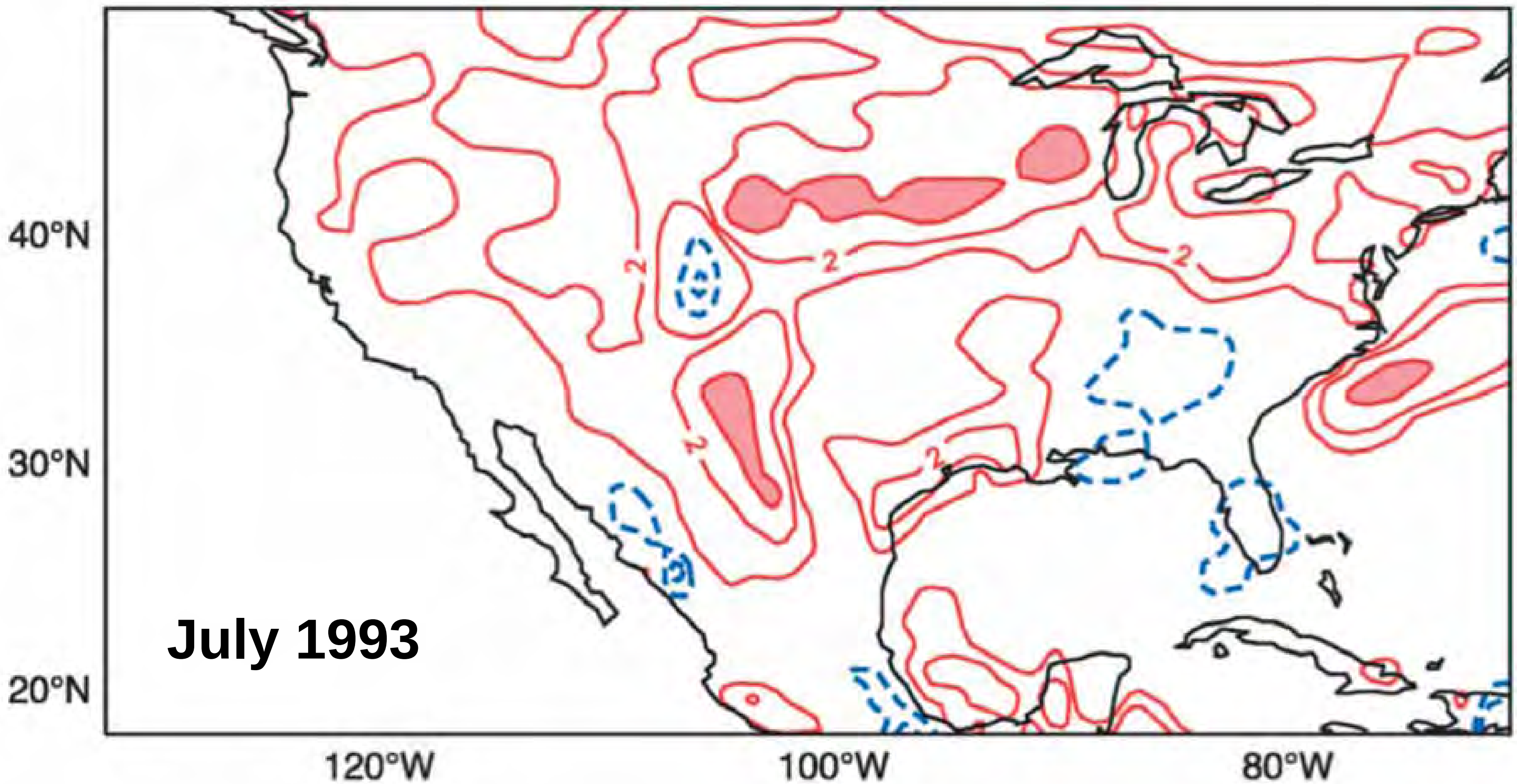




Energy units

- SWCF/precip less in ERA-40 (0.48) than *observed (0.74)*
- **Cloud radiative & diabatic forcing *comparable***
- *And closely coupled on all timescales in atmosphere*

Evaporation-precipitation feedback

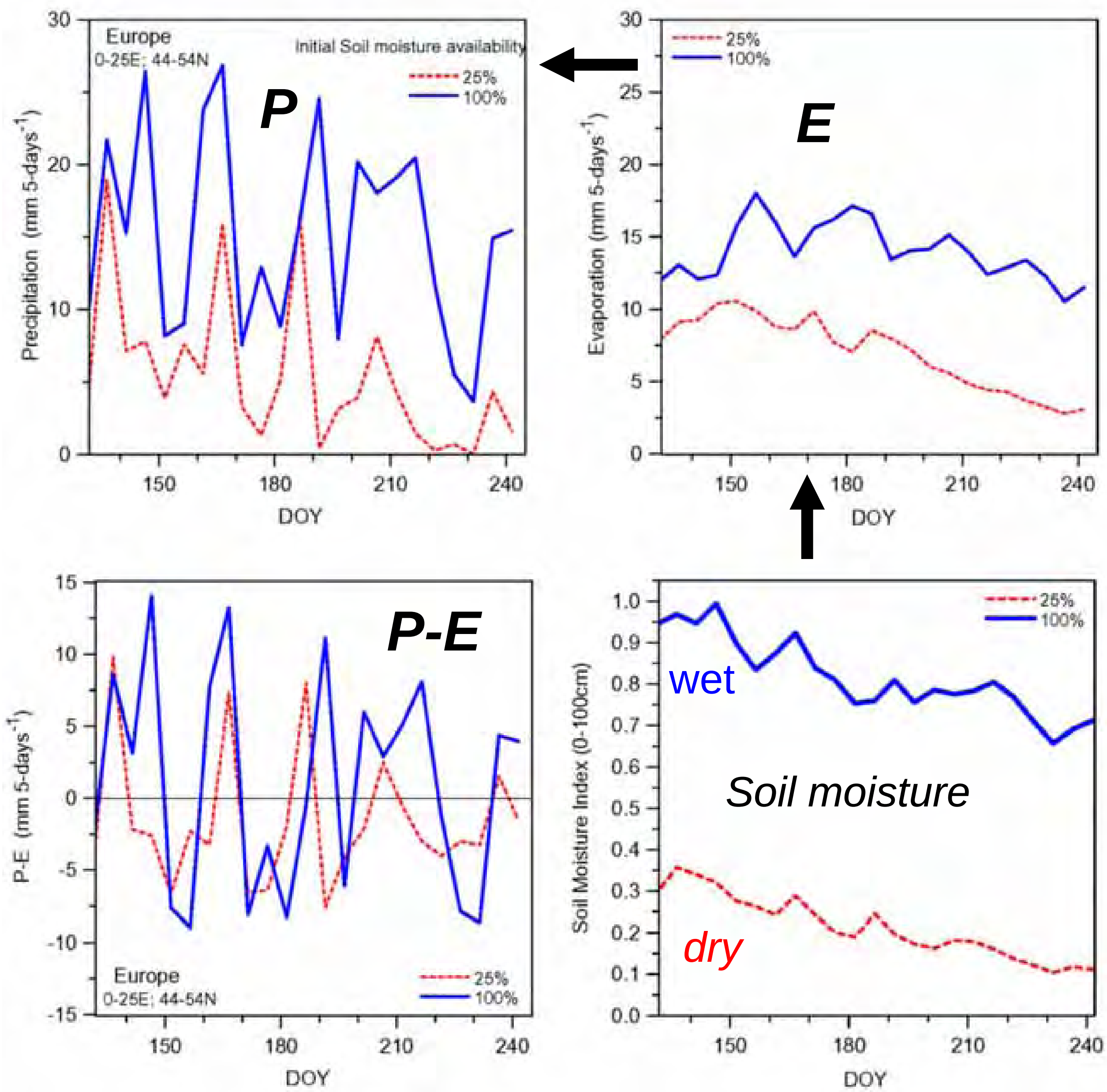


- *Difference* in monthly mean forecast precip. (in mm/day) starting with wet and dry soils *[Beljaars et al. 1996]*
- ***Mid-west peak difference is >125mm***

Evaporation-precipitation feedback in ERA-40

- Two 120-day FX from May 1, 1987, initialized with wet and dry soils
- Memory lasts all summer
- E and P fall with dry soil
- E-P changes little; variability drops

[Betts 2004]

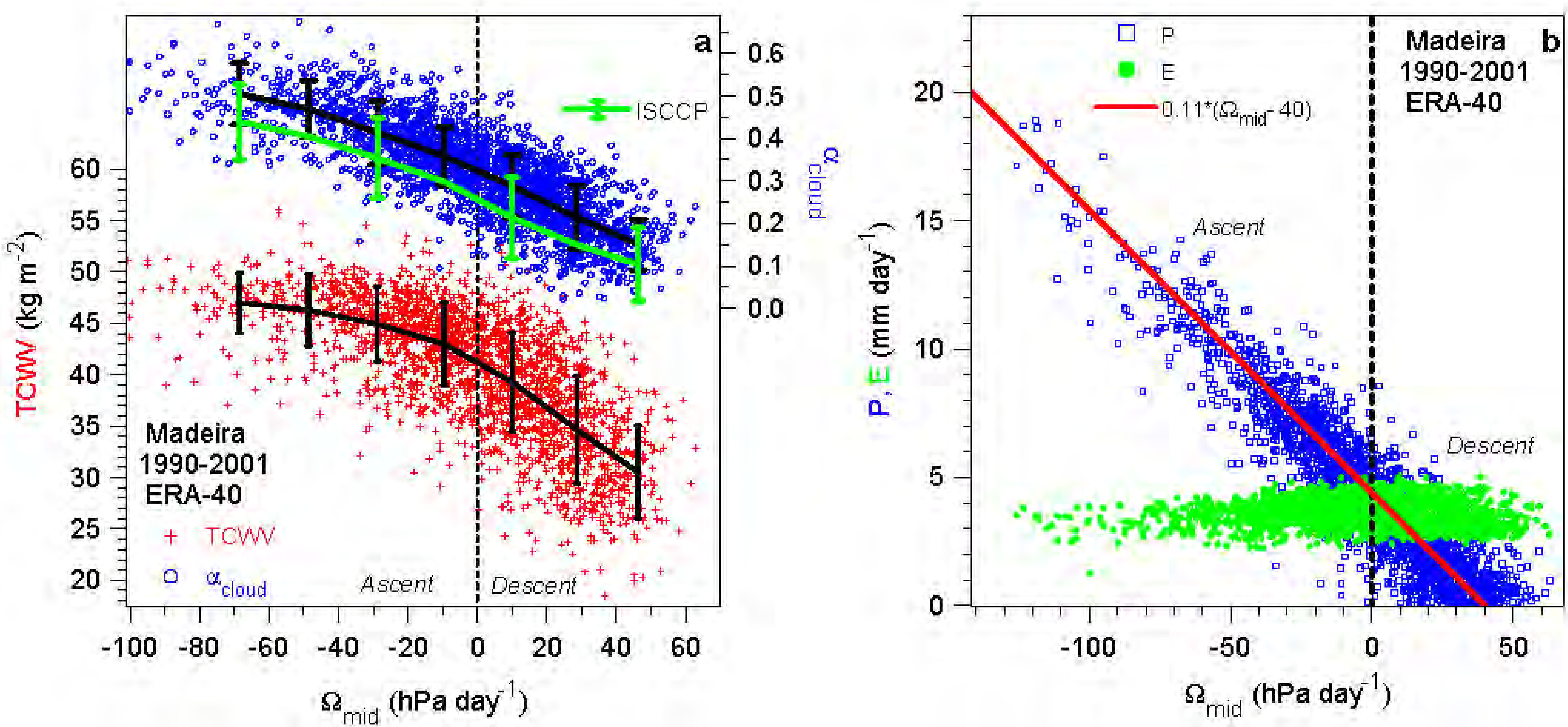


Is ERA-40 right?

Wet summers


- Both 2008 and 2009 were wet in Vermont!
- Direct fast evaporation off wet canopies
- Positive evaporation-precipitation feedback

Precipitation and cloud coupling to vertical motion *in ERA-40 reanalysis*



- Partition of *moisture convergence* into
  TCWV, α_{cloud}, and precipitation
- Note high bias of α_{cloud} from ISCCP; while precip. generally low

SW Amazon basin

[Betts and Viterbo, 2005]

Lessons Learned

- Look for relationships and information in the coupling of processes/ observables
- Models have only *limited value* without deep understanding of the coupling of processes – a "virtual reality"
- *Observations important for evaluation & to suggest processes that are simply missing*
- *Every model* needs analysis of relationships, diurnal, daily mean and seasonal, for both wet and dry seasons (or disturbed/suppressed conditions) *against observations* for tropical and mid-latitude climate regimes
- Identification and quantification of key physical processes and feedbacks is the challenge & the research opportunity
- Tractable as both global, regional and point time-series datasets improve