Understanding Hydrometeorology using global models

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Preamble

- Not a review talk
- Title is meant to be a paradox
- Simple models for understanding?
  Hydrometeorology is too complex
- Climate interactions of water
  [phase changes and radiation interactions]
  are central to climate
- Let us confront the challenge

A little New England nostalgia..

- As I was writing this, after 40cm of fluffy snow have just fallen, the sun glistened off the frozen fields and the dripping icicles outside my window, but the bare forested hills are dark. Water is everywhere, the rivers are in flood, but the sky is clear. Beneath the melting snow and a mulch of leaves, the ground is barely frozen, and my brussel sprouts are still good to eat.
- All these things (except my brussel sprouts) matter to the hydrometeorology and seasonal climate of New England……

Climate is both global and local

- Need coupled earth system models
- Need them locally to warn us of the first frost
  [local diurnal cycle in September]
- Improving our global models is central
- Global models can be used as tools to understand interacting processes
- Contrast our model world, which we dimly understand, and the real world, where we only understand fragments of a complex, living system.

What controls evapotranspiration?

- "Equilibrium evaporation".
  Raupach (BLM, 2000, QJRMS 2001)
- Models for the *growing daytime "dry BL"*
- Fascinating but simplified by ignoring some key real-world physics, which control evaporation for climate equilibrium.

What is this ignored physics?

- Cloud fields control cloud base, the surface net radiation, and dominate the cooling rate of the CBL

  [It is not the dry BL solutions that are relevant]

- Climate problem is a 24-hr mean problem, with a superimposed diurnal cycle

  [It is not just a growing daytime BL problem]

- First-order atmospheric constraints on evaporation. Global models with coupled cloud fields include these processes, so they can help us understand the coupling

Outline

a) Global scale feedbacks – seasonal forecasts

Idealized global soil moisture simulations
and evaporation-precipitation feedback over continents

b) Land-surface coupling at daily timescale
– 30 years of ERA40 river basin time-series

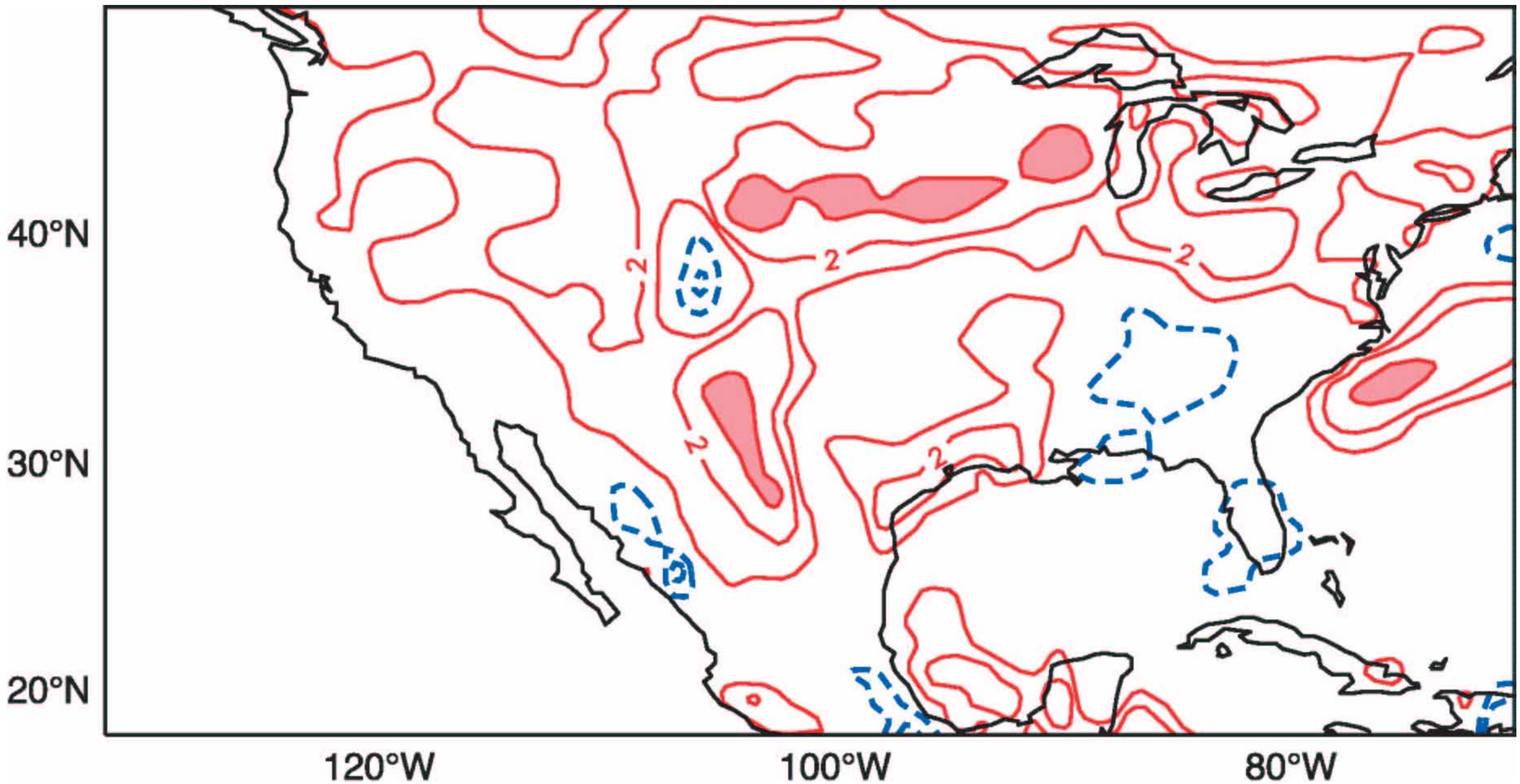
Coupling of **s**oil moisture, cloud-base, cloud cover, radiation
fields, sensible and latent heat fluxes and diurnal cycle

a) Global scale feedbacks -

Idealized soil moisture simulations and evaporation-precipitation feedback

- Serendipity, and great flood on the Mississippi of July 1993
- Parallel ECMWF suite with a 4-layer soil model to better represent soil moisture memory
- Soil moisture sensitivity experiments for July, 1993

July 1993: wet-dry soil initialization



- Increase of monthly forecast precipitation: peaking at over 4 mm/day or >125 mm/month *[Beljaars et al. 1996]*

Seasonal forecasts with idealized soil moisture

- ERA40 model: 120-day forecasts at T-95 L60 from May 1, 1987 (DOY=121)
- Identical except

  a) Soil moisture initalized at 100% field capacity for vegetated areas

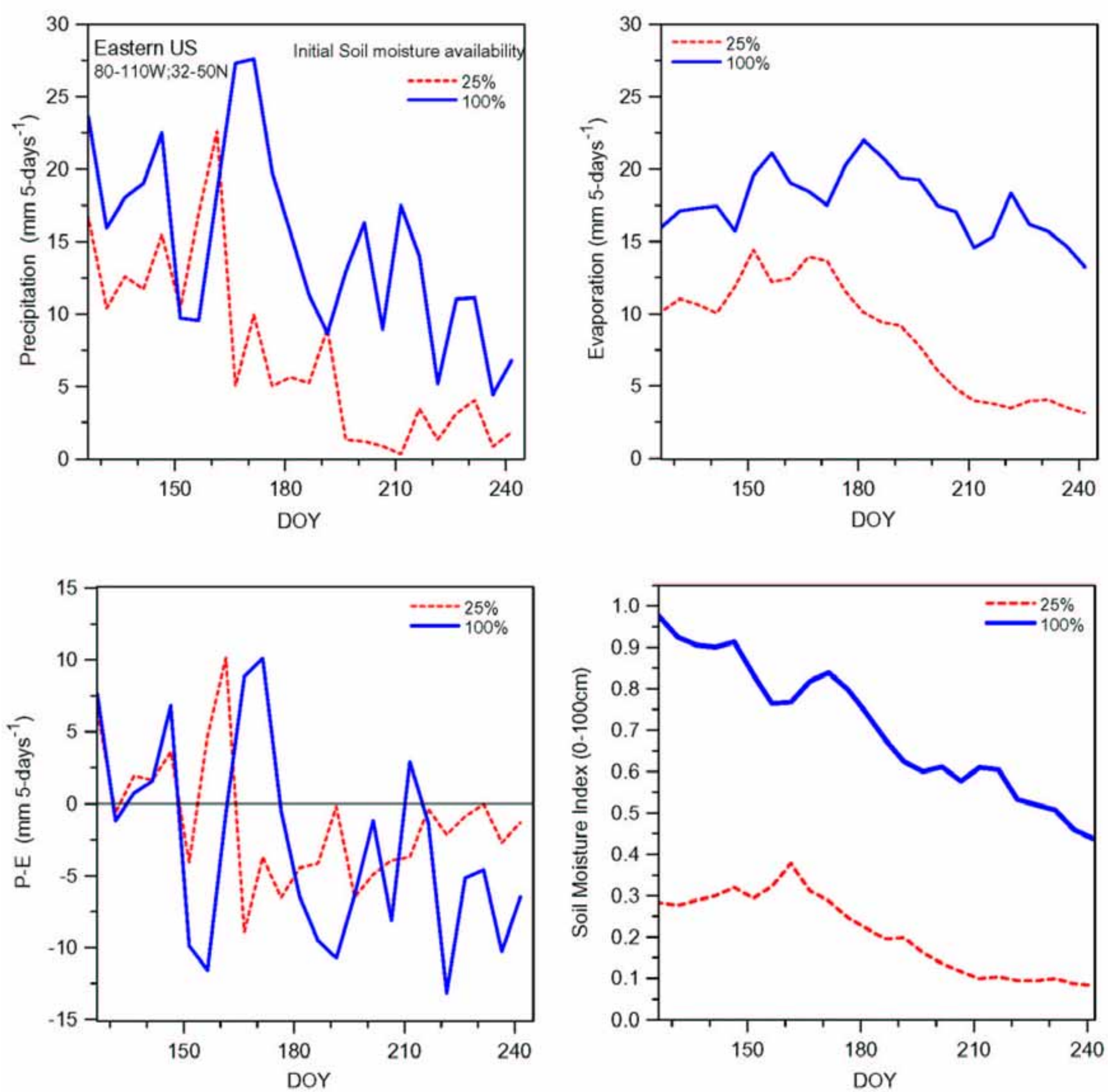
  b) Soil moisture initalized at 25%

-- Soil Moisture Index

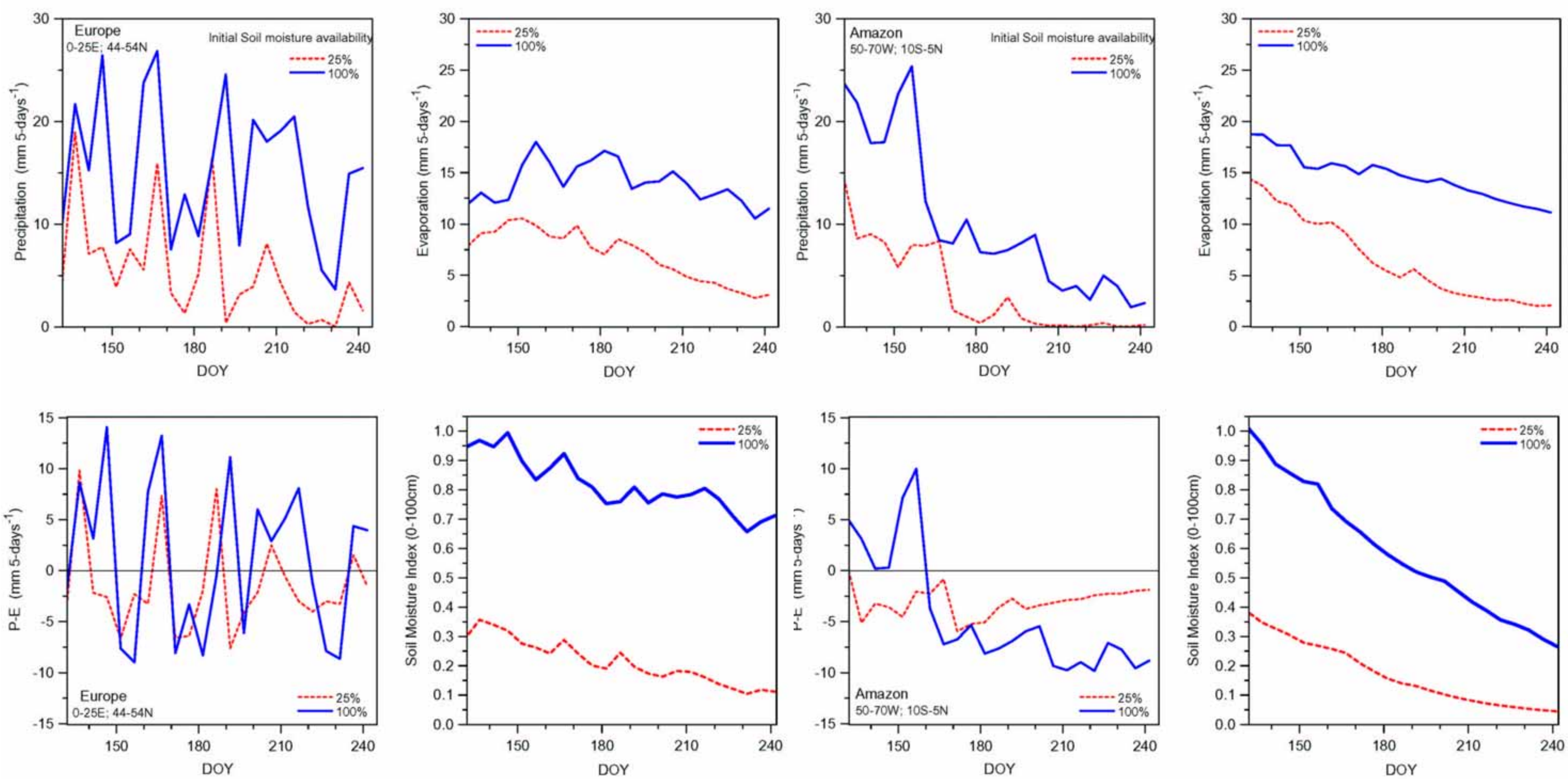
$0 < SMI < 1$ as $PWP < SM < FC$

P, E, P-E and SMI for Eastern US

- Reduction of SMI reduces precipitation, evaporation
- has little impact on P-E which averages to small values over summer
- Memory of soil moisture lasts all summer

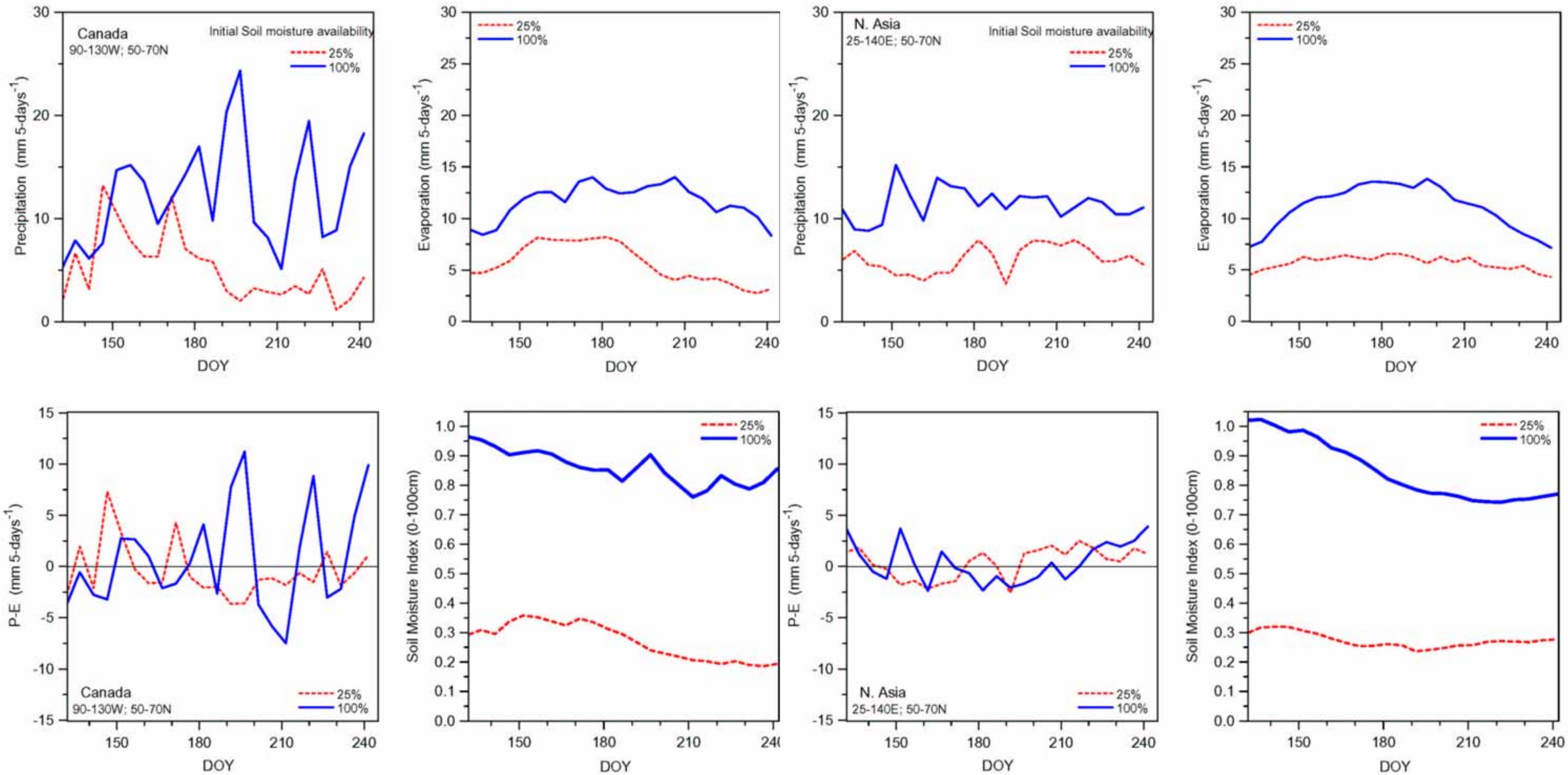


Europe   Amazon



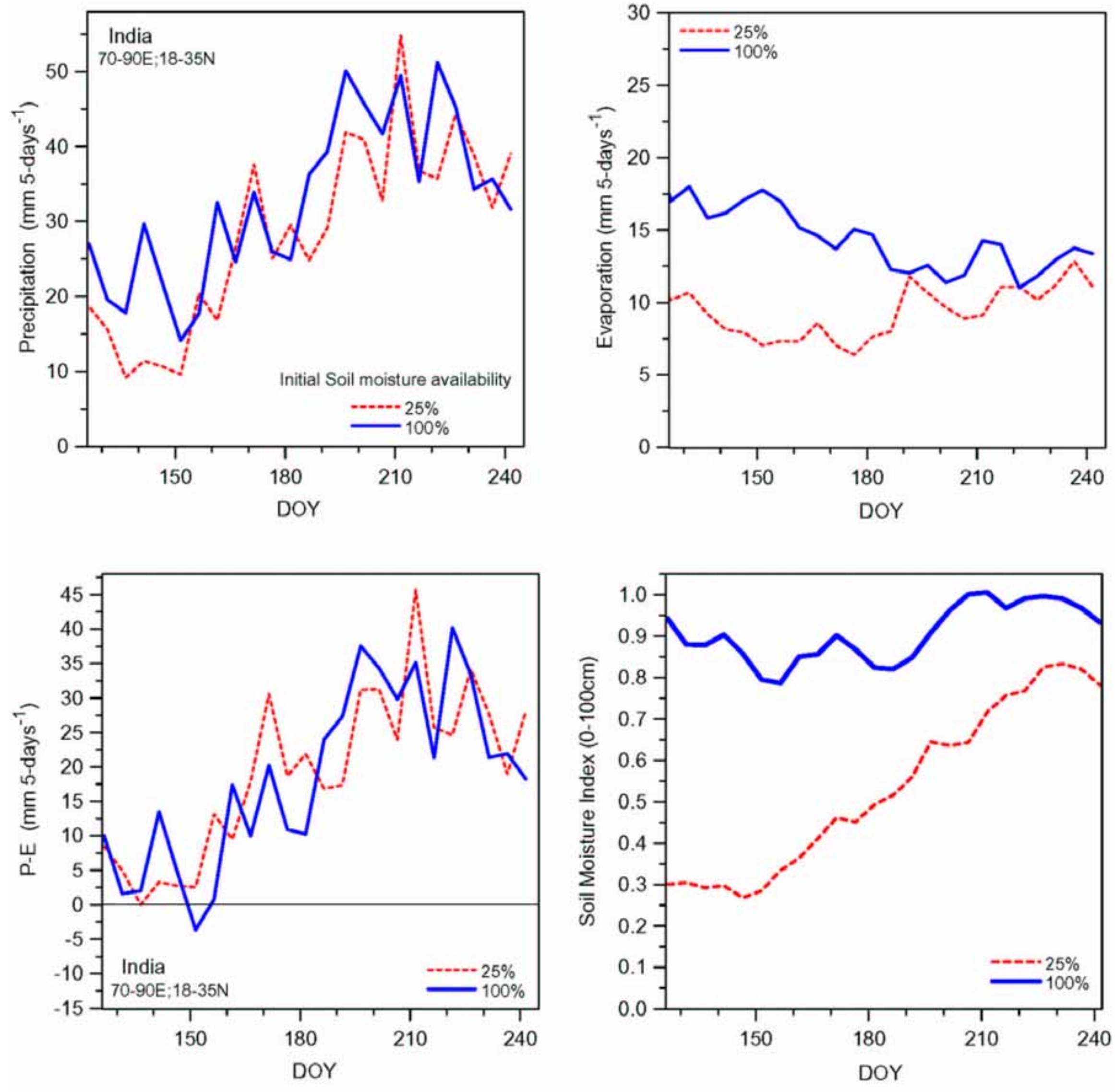
Canada

N. Asia



Monsoon India

Only in monsoon regions where P-E is large is memory of SMI reduced



Evaporation over land determines precipitation: [away from monsoons]

- So what controls evaporation?
- Not classic “equilibrium evaporation”
- Recast equilibrium evaporation as as a diurnally averaged problem, linked to cloud-base and cloud fields

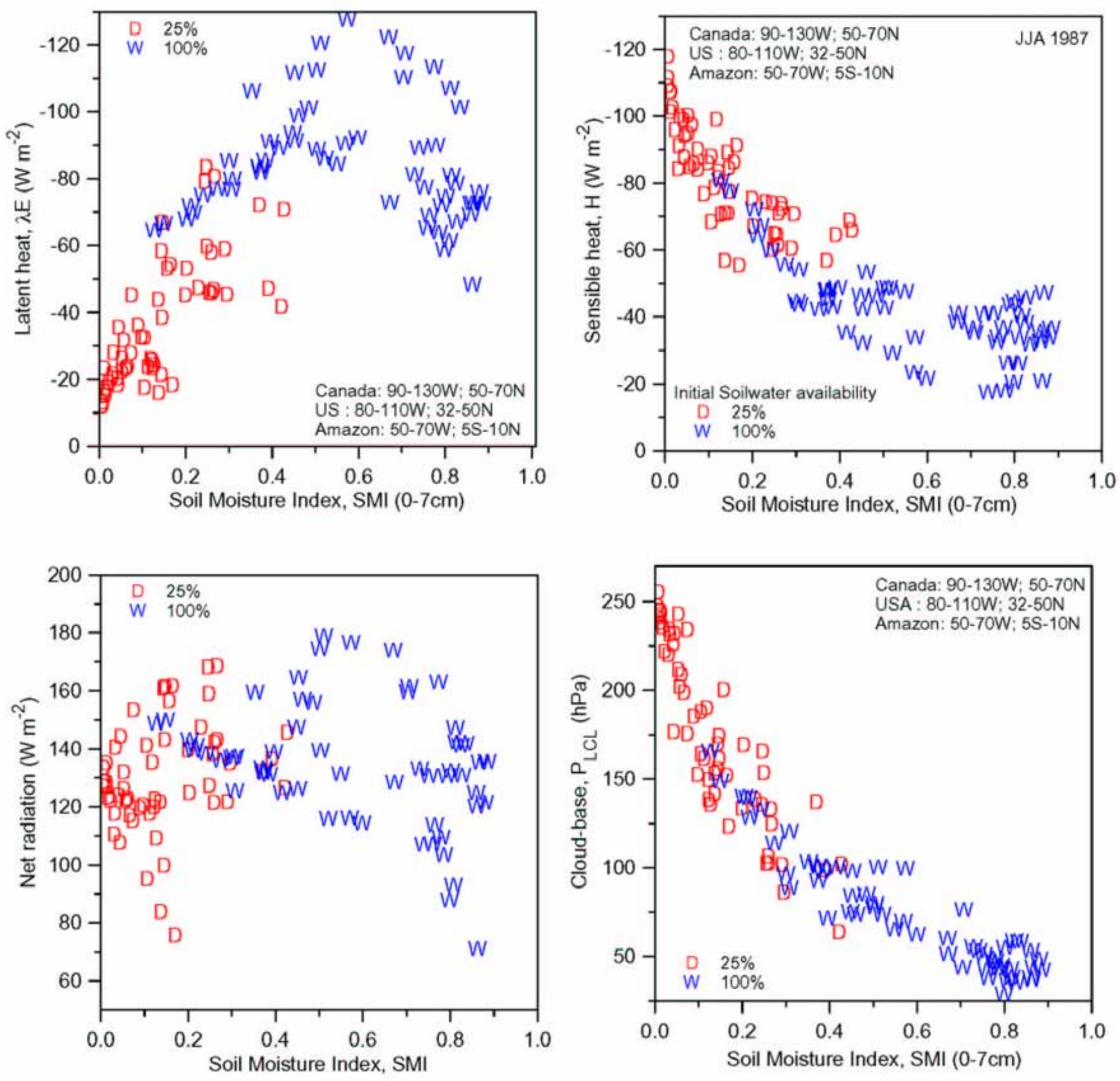
[Betts, JHM 2000; Betts et al., 2003; JGR, submitted]

Surface energy balance, and ML “equilibrium”

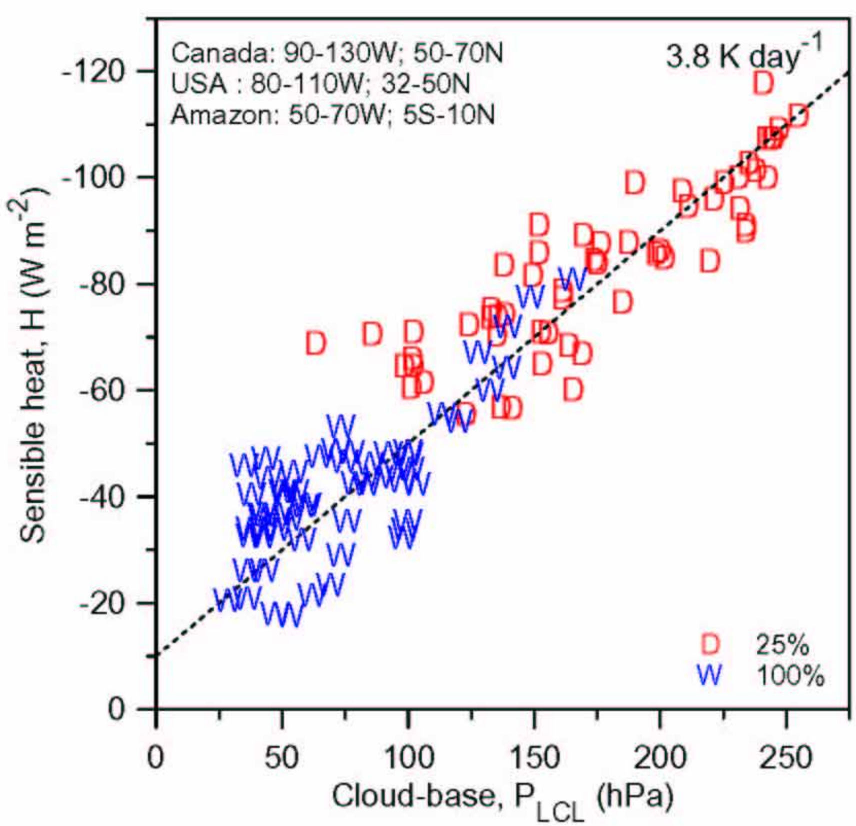
- **3 Americas regions**
- 5-day means:

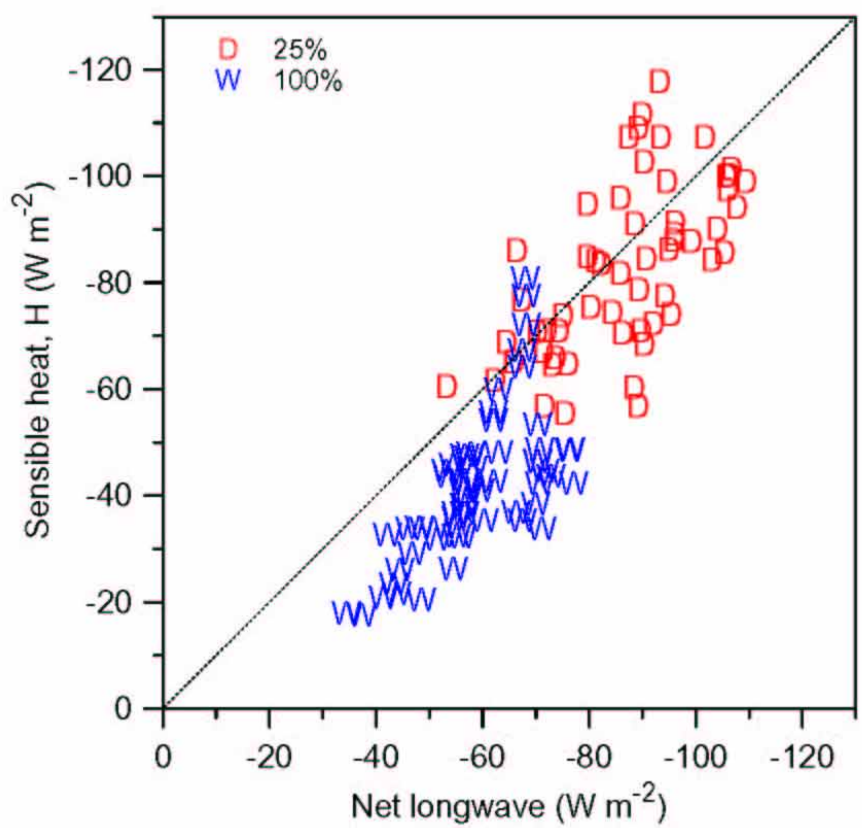
  of wet and dry simulations

- Latent heat λE against SMI: weak relation: sensitive to R_{net}
- Sensible heat H against SMI: tight relation
- linked to dependence of depth to cloud-base on SMI



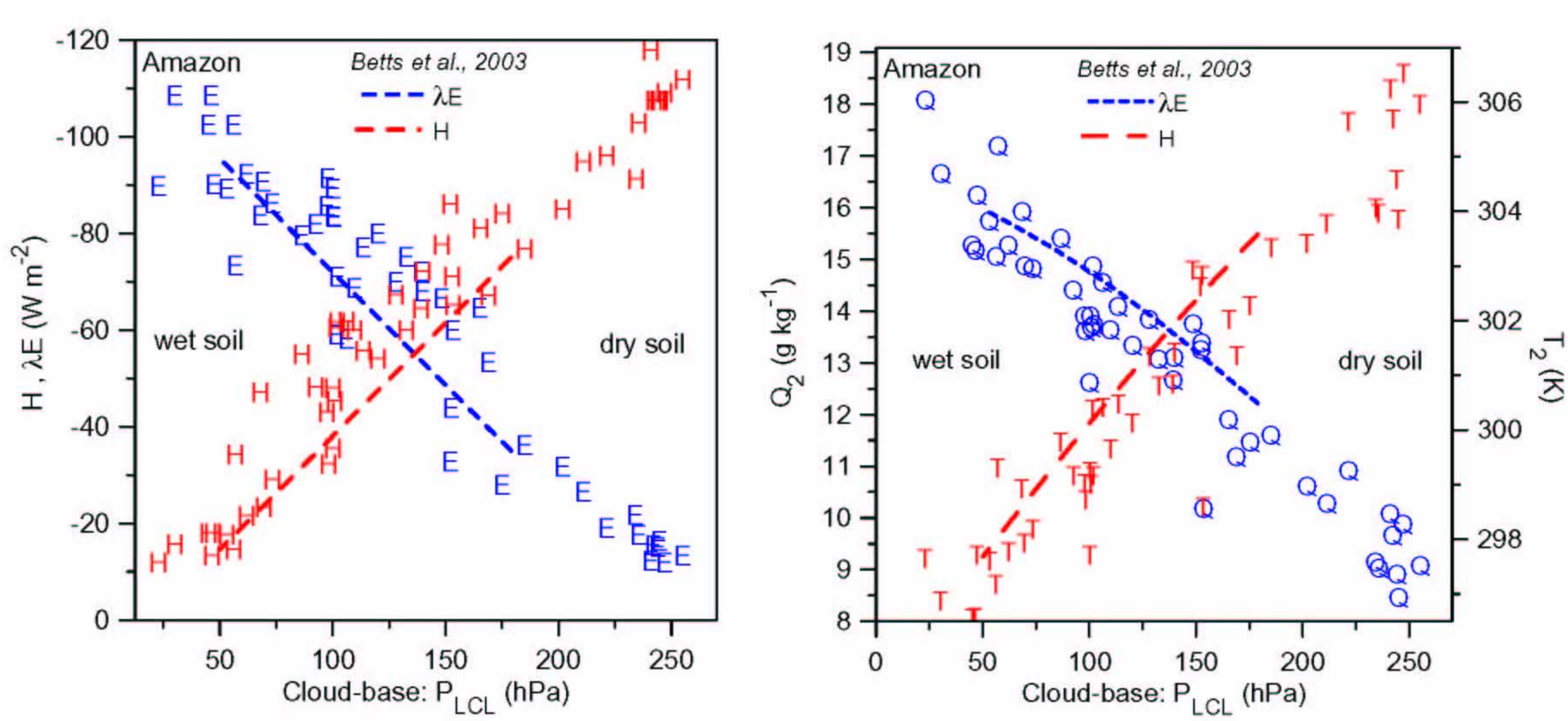
Sensible heat flux: H





- H against P_{LCL} : linear with slope related to cooling processes in ML
- H is constrained by ML cooling, constrained by cloud-base
- Net long-wave has similar behavior: coupled to P_{LCL}

Amazon basin in more detail

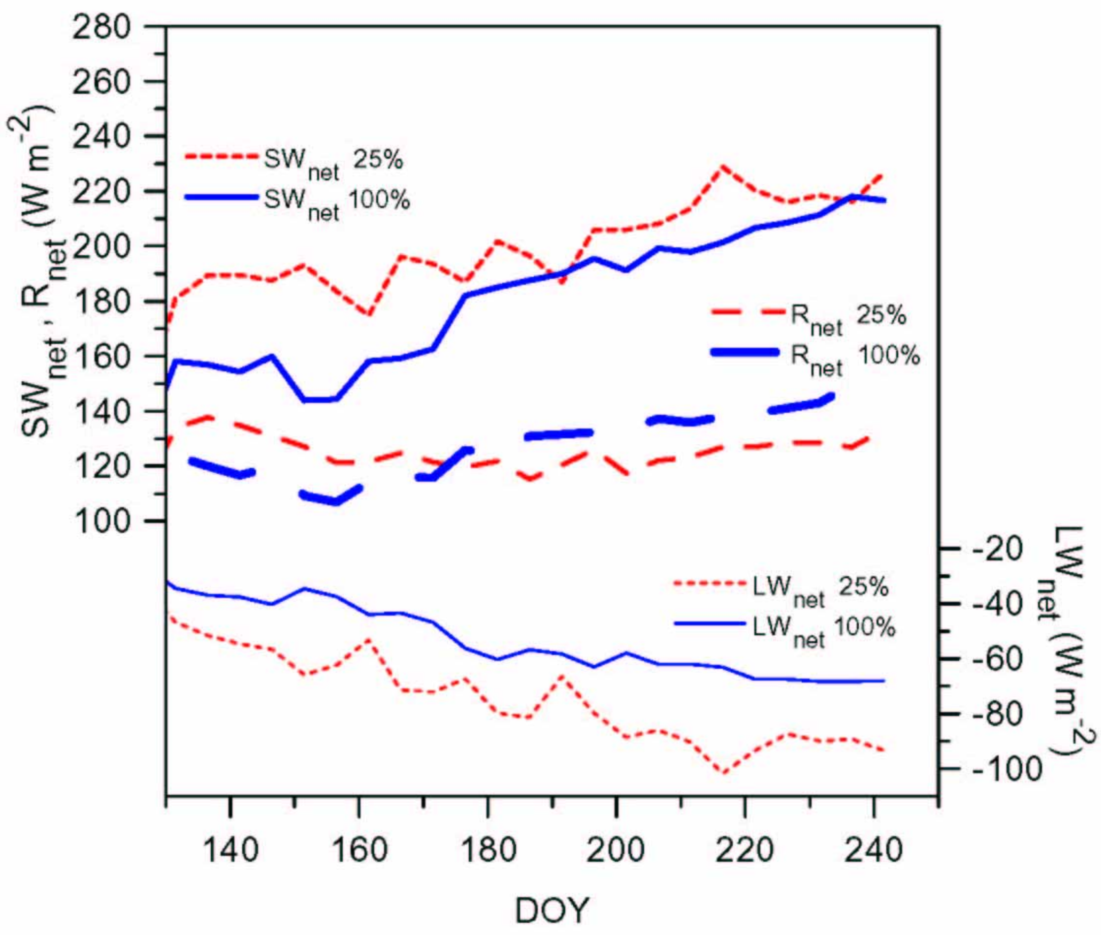


- H , 8E quasi-linear with P_{LCL}: 2-m Q and T quasi-linear with P_{LCL}
- Over wetter soils, E increases; T decreases and Q increases in ML
- *New coupled state* has lower LCL, with cooler, moister ML; reduced H and larger E

Radiation balance

- **LW and SW feedbacks**
- Wet soil: more cloud and water vapor
- SW_{net} down; $-LW_{net}$ down; with smaller effect on R_{net}

- In dry season, both SW_{net} and $-LW_{net}$ increase (regime shift in June) and longwave feedback dominates

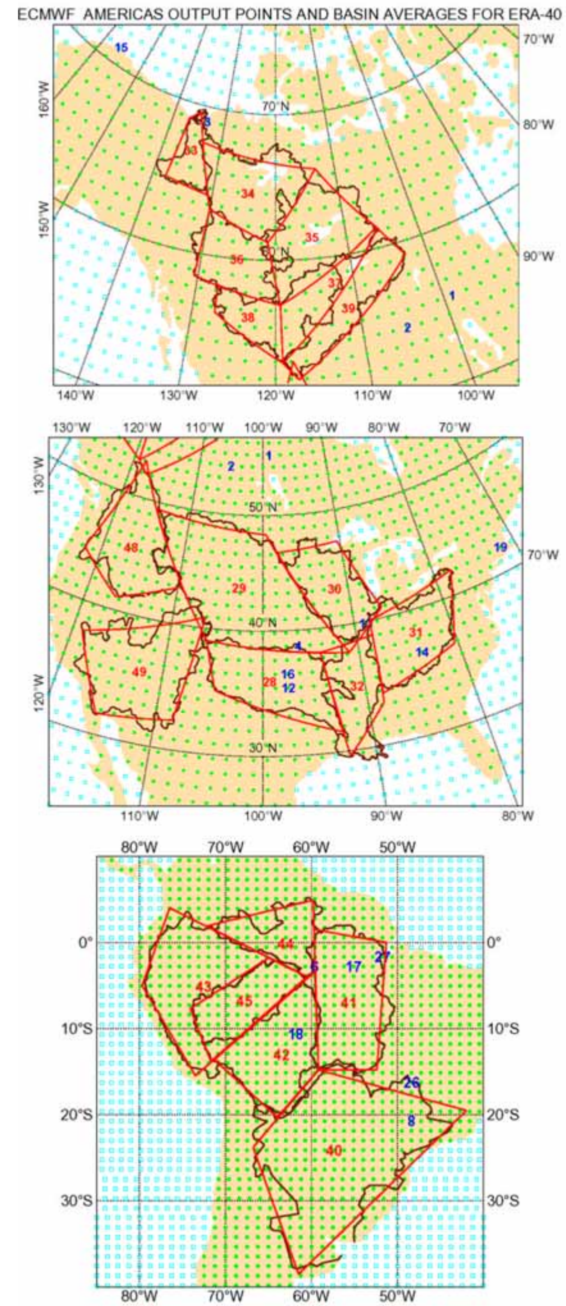


b) ERA40 river basin budgets

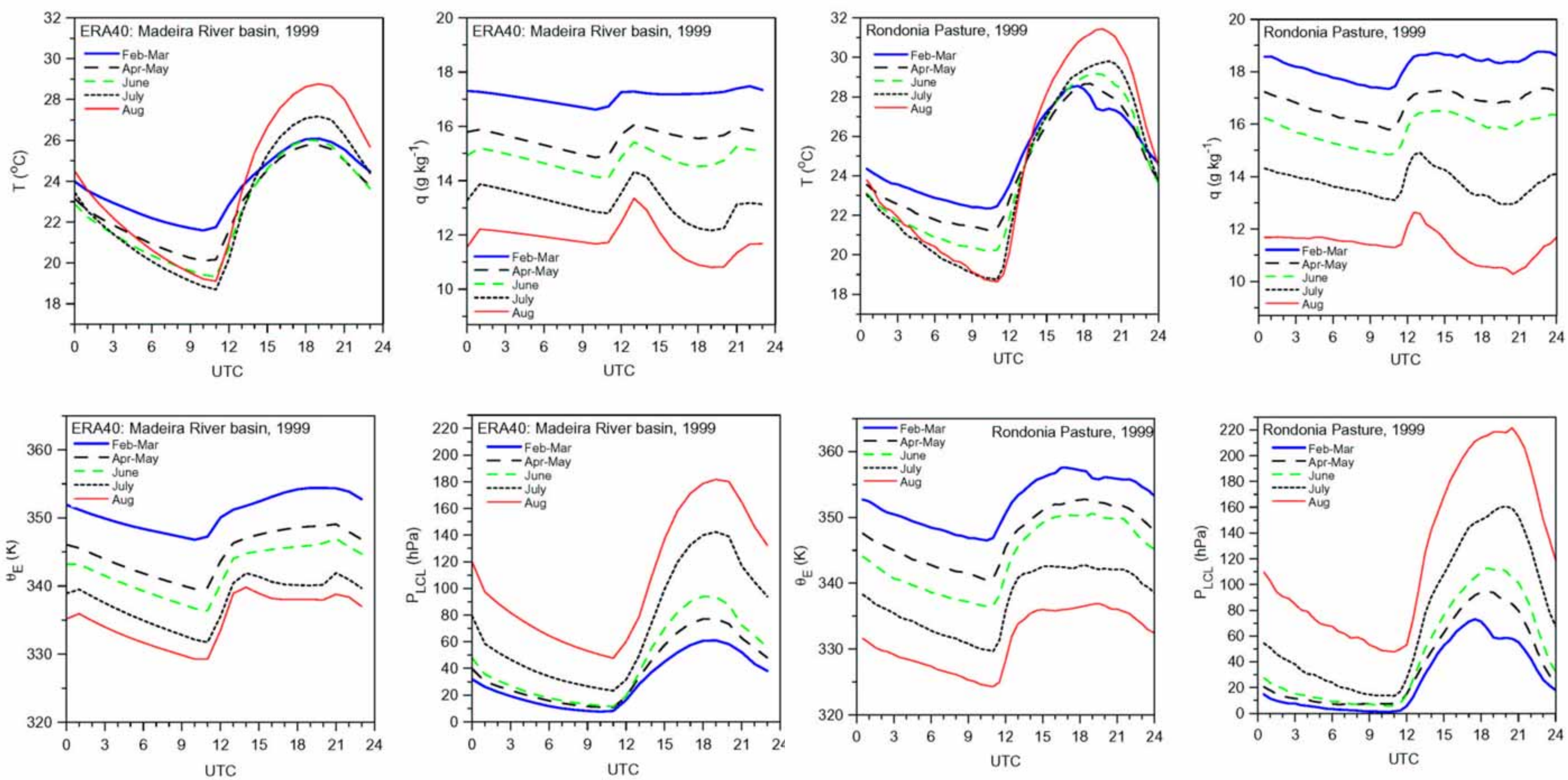
- **Basin averages: hourly archive**
- Daily averages:1972-2002 [11000 days]

- **Madeira : Amazon**
  Arkansas-Red : Mississippi
  Athabasca : Mackenzie

- *[ERA40 biases:see Betts et al. 2003a,b]*



ERA40 for Madeira River basin compared with LBA Rondonia pasture site: 1999

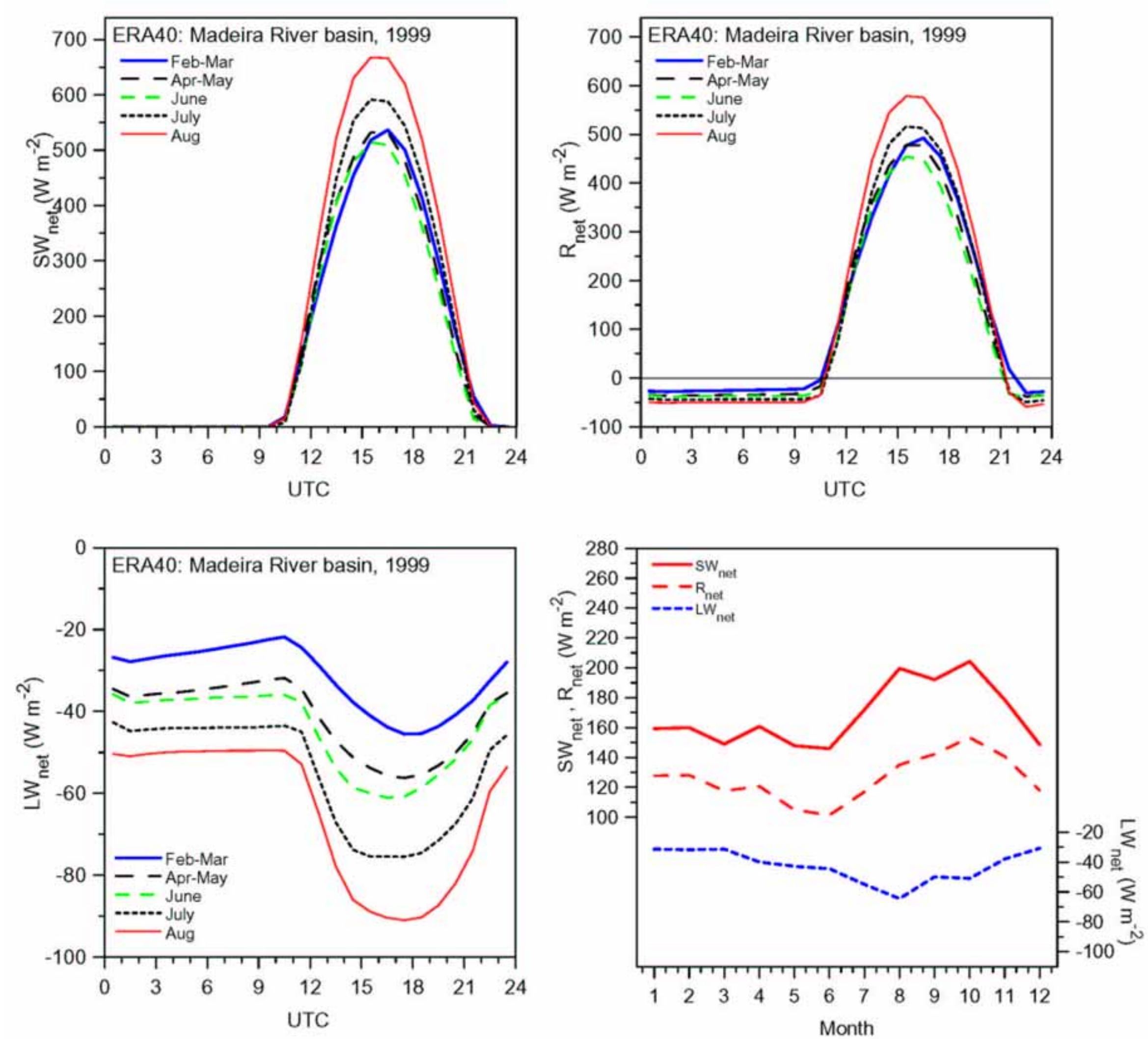


- Large seasonal change of diurnal amplitude
- ERA-40 basin ranges smaller than at pasture site

ERA-40 radiation fluxes

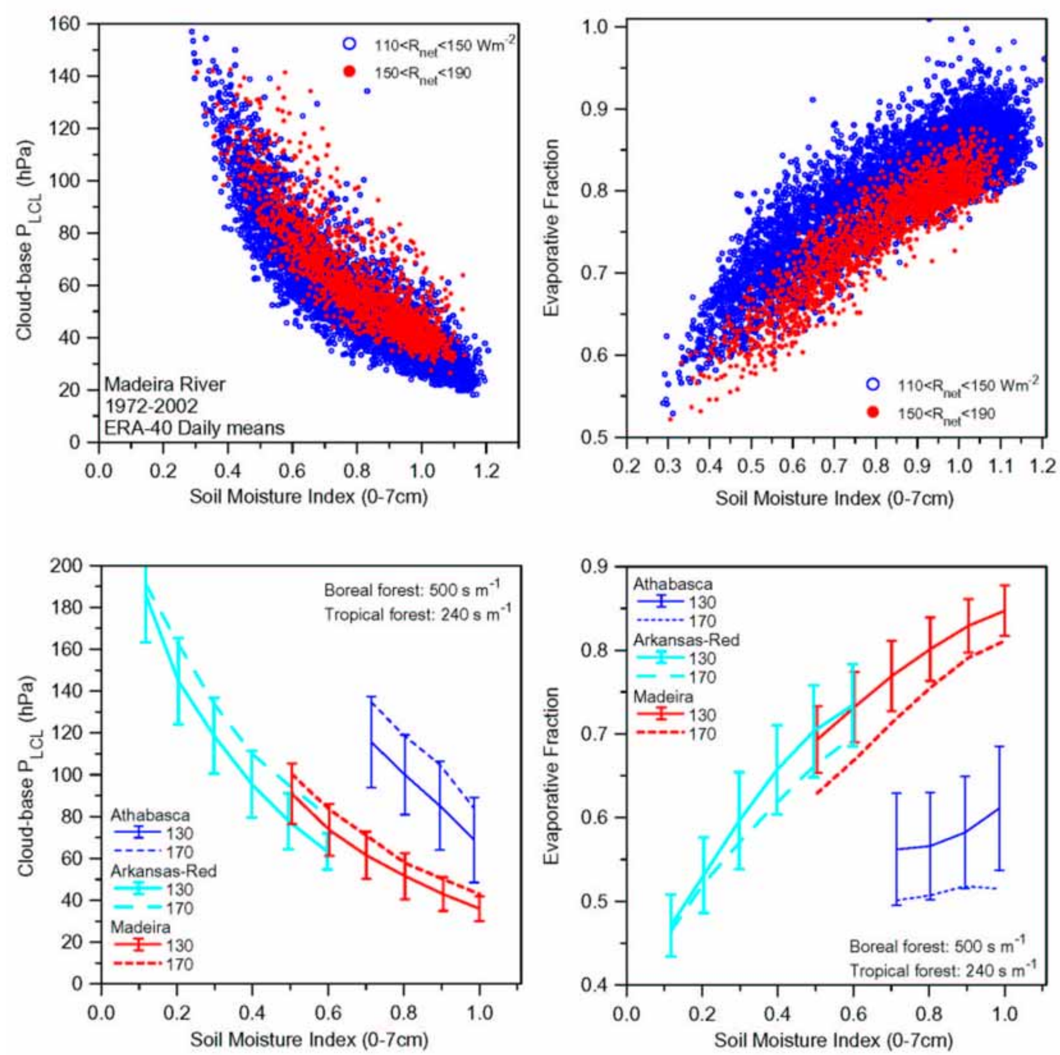
- Large seasonal cycle in LW_{net}, linked to the seasonal cycle of cloud cover and transition from the rainy season to a deep dry ML in August.

- Both SW_{net} and R_{net} have a minimum in June; maximum in October



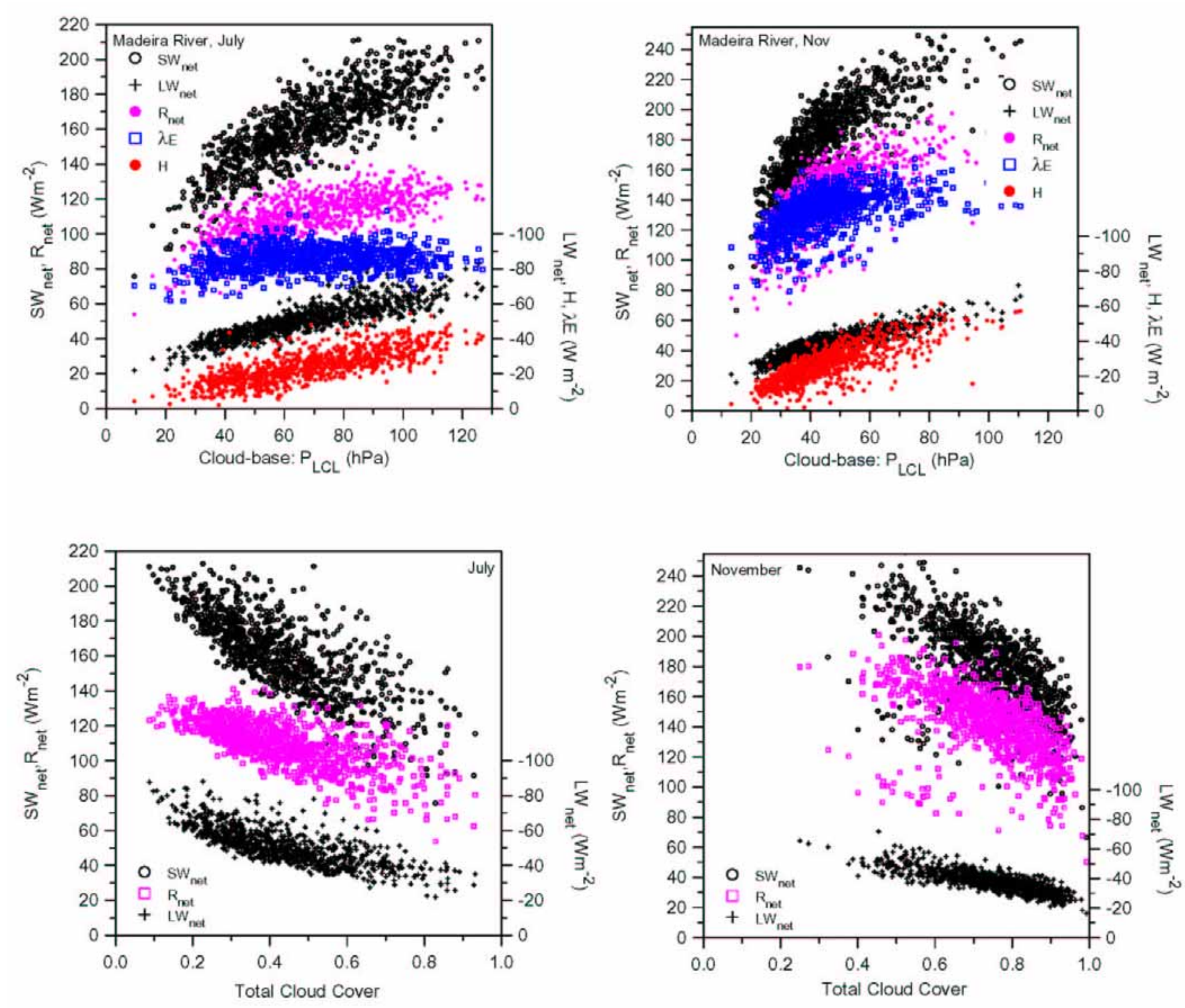
Coupling of soil moisture index, cloud-base height and Evaporative fraction

- Mean cloud-base height increases over drier soils and with larger surface R_{net}
- Evaporative fraction increases with soil moisture, and decreases with R_{net}
- 3 basins similar: with additional dependence on unstressed resistance



Madeira basin for July and November

- July: dry season
- Nov: wet season

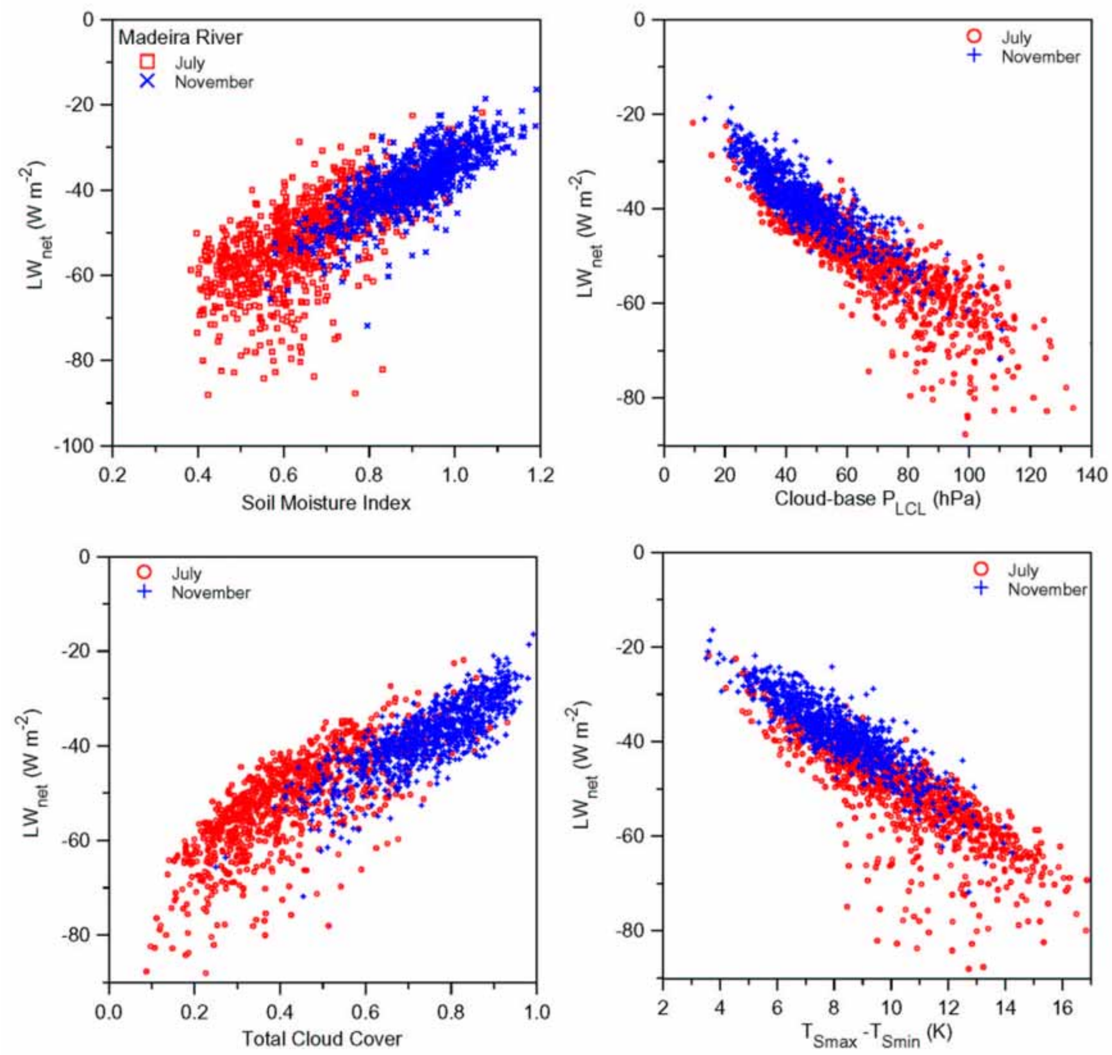


- Surface fluxes as function of cloud-base and cloud cover

LW_{net} dependencies

- Soil moisture index
- Cloud-base
- Total cloud cover
- Diurnal range: T_s

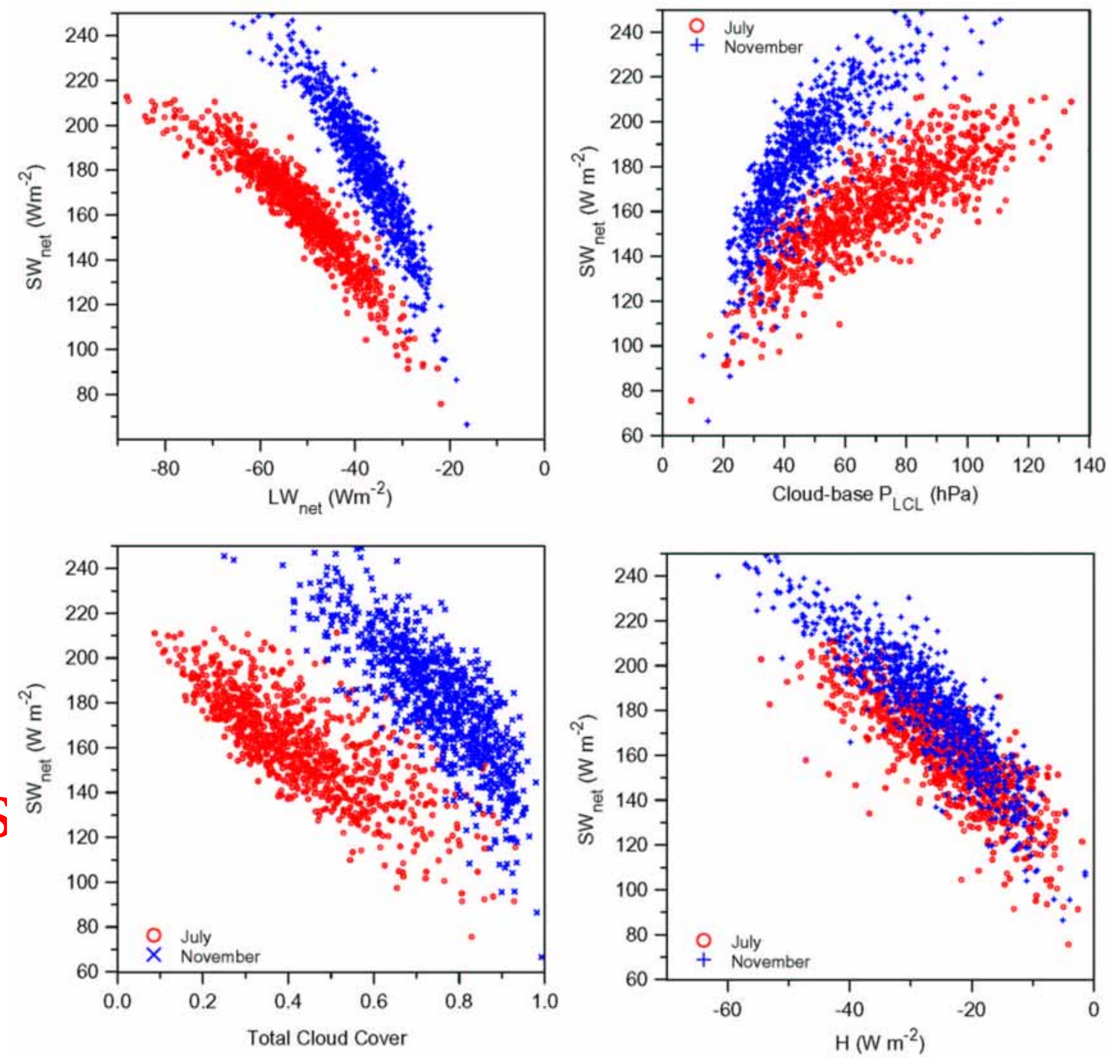
- 2 months merge to single quasi-linear distribution



SW_{net} dependencies

- Tight coupling to LW_{net}
- Cloud-base
- Total cloud cover
- Sensible heat flux H

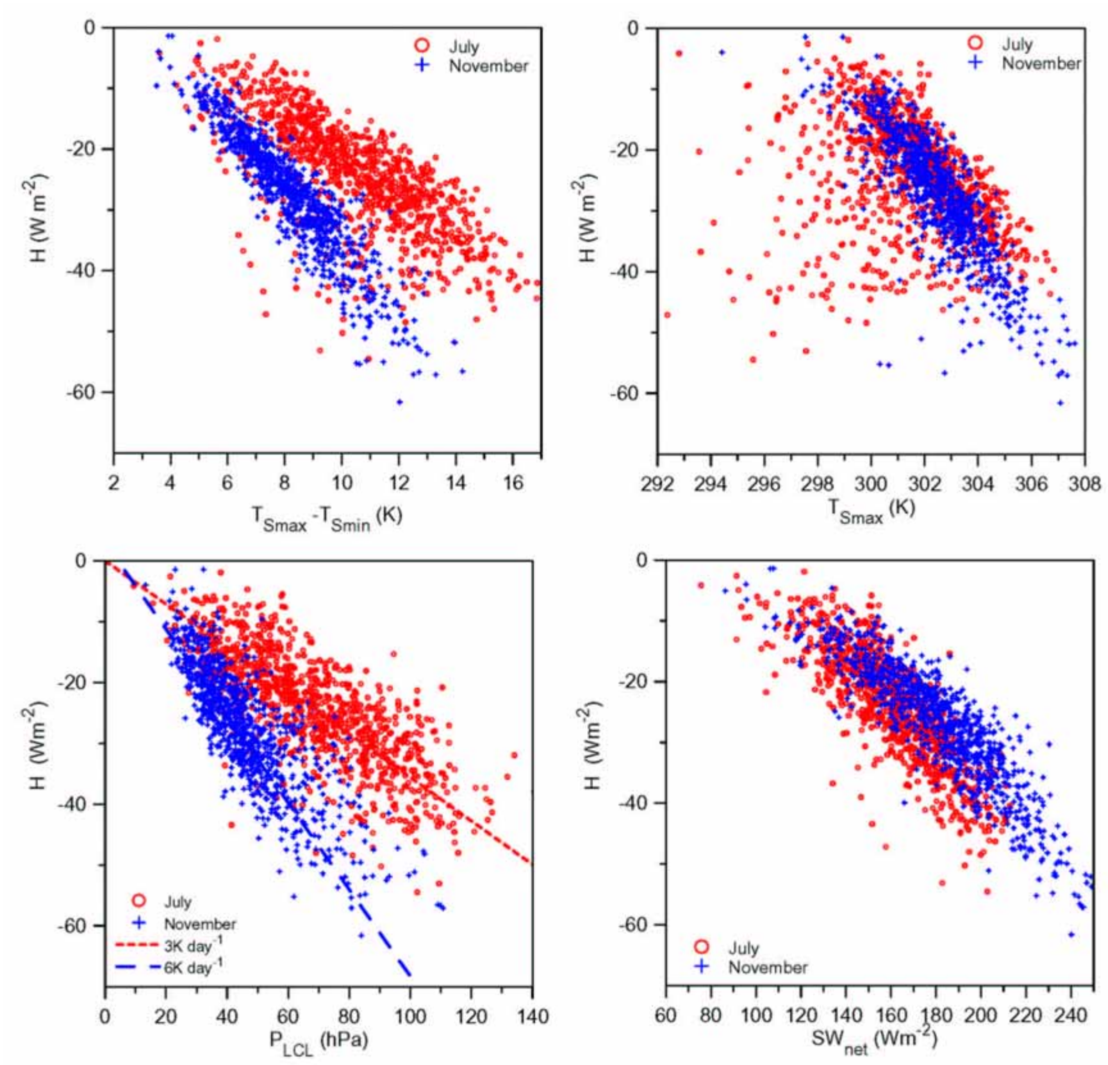
- Distinct distributions except for H



Sensible heat flux H

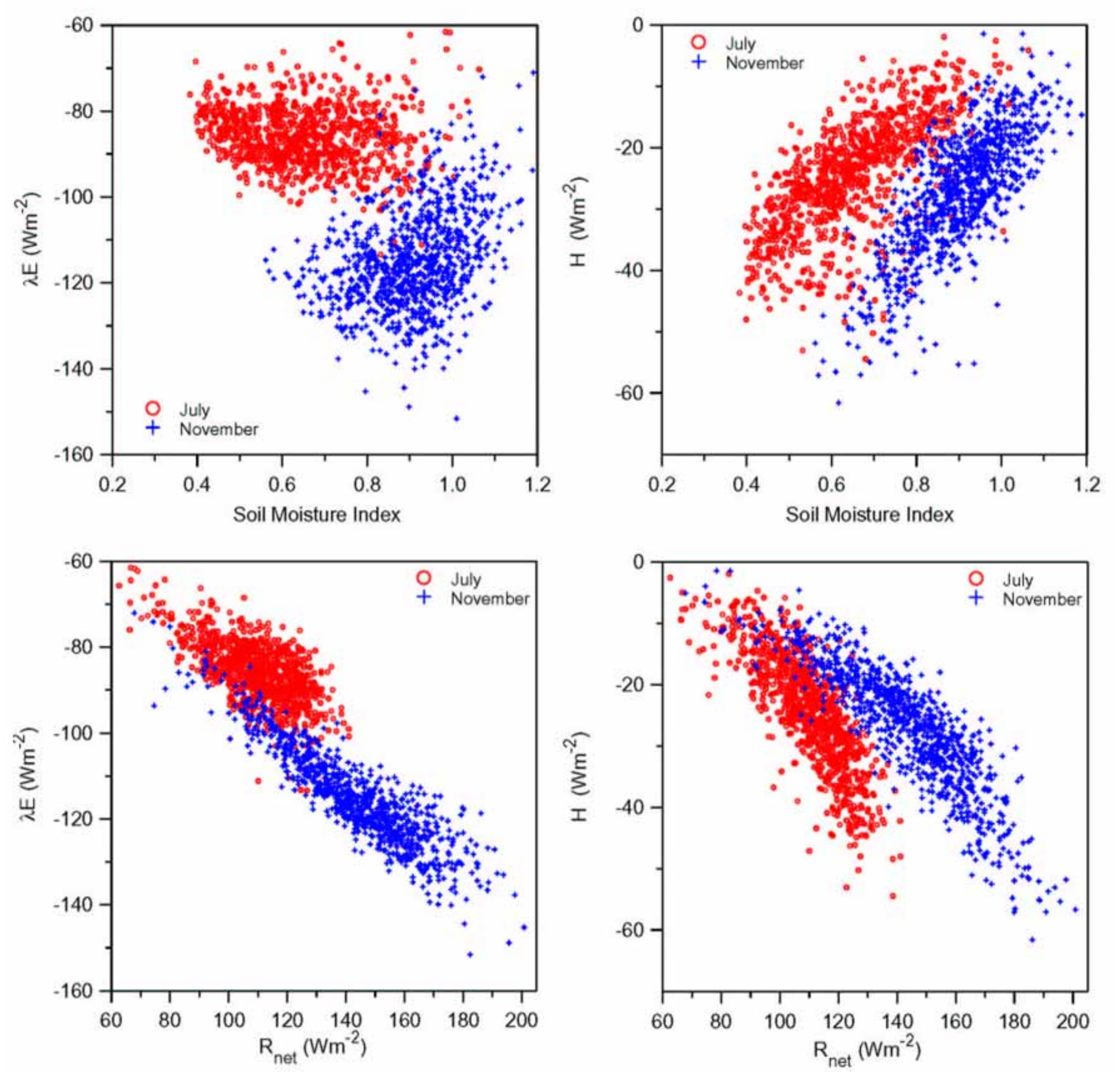
- Diurnal range: T_s
- Maximum T_s
- Cloud-base
- SW_{net}

- Distinct distributions except where coupled to SW_{net}
- Subcloud heating rates
- 3K/day in July
- 6K/day in November

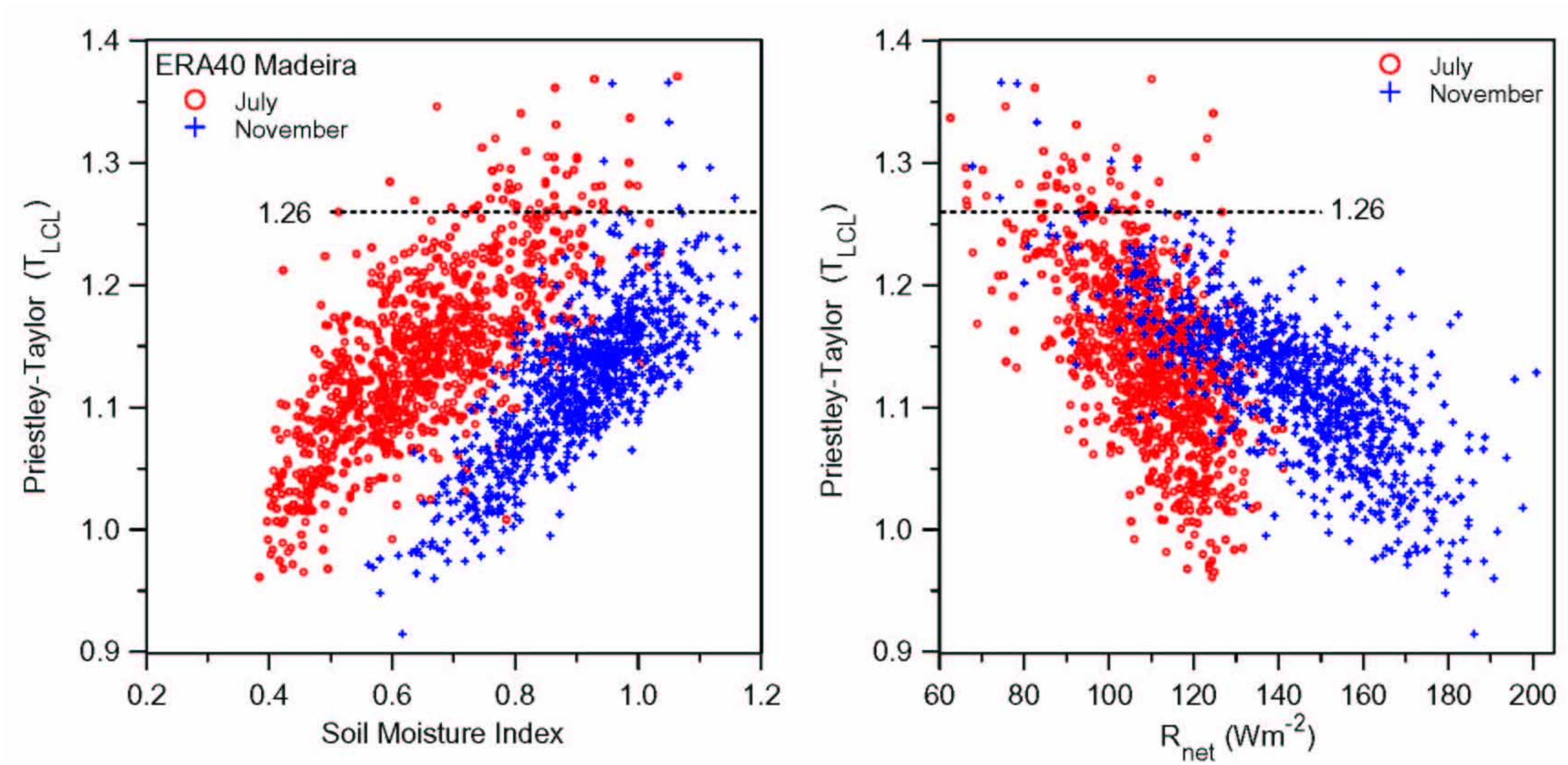


Latent heat flux λE and H

- Coupling of **H** to SMI through P_{LCL} stronger than coupling of **λE**
- λE has more variation with R_{net} in rainy season
- H splits into 2 branches as function of R_{net} [contrast SW_{net}]



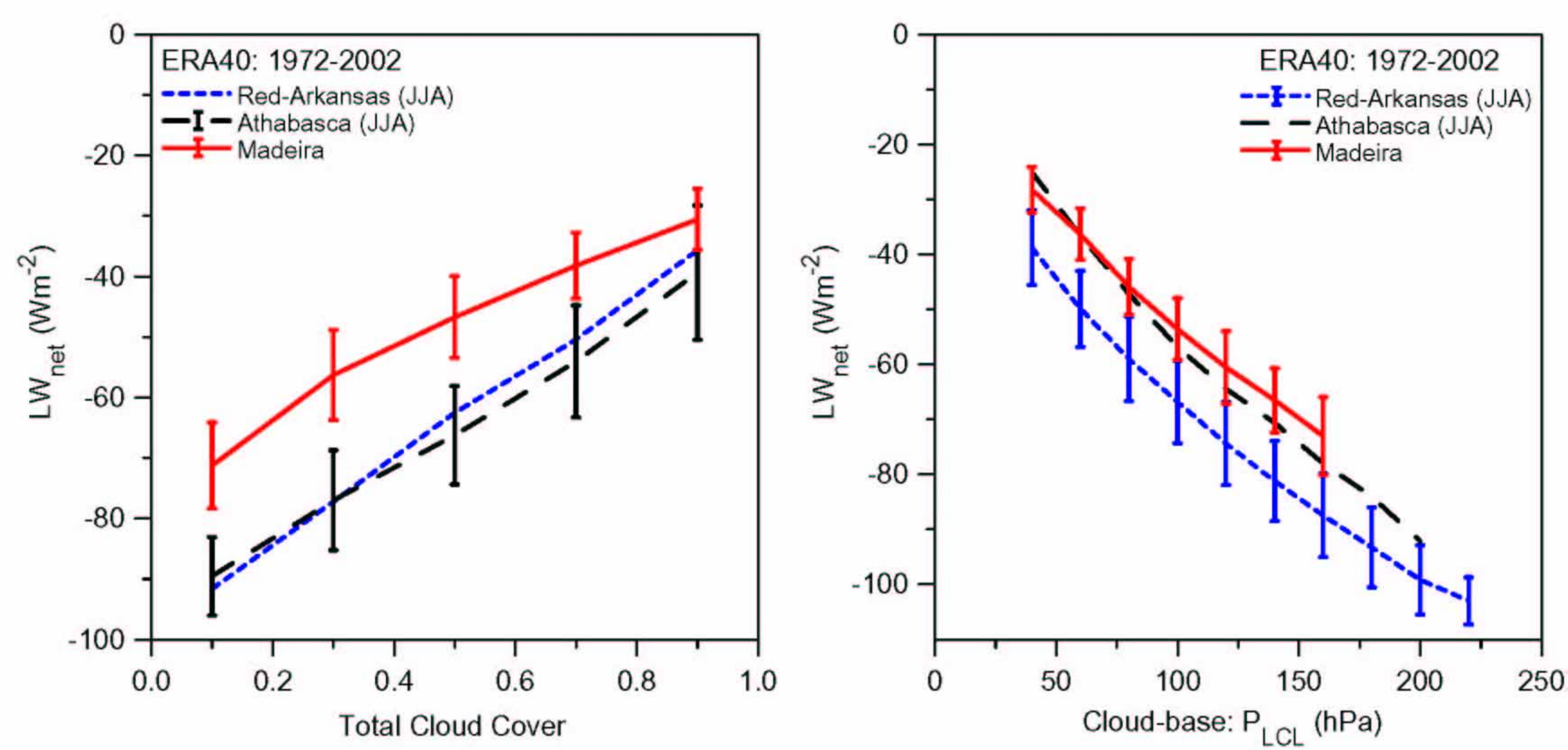
Priestley-Taylor ratio



- PT = EF(1+g)/g [EF = 8E/(R_{net}-G); g = (8/C_p)dQ_s/dT]
- Separate branches for July and November

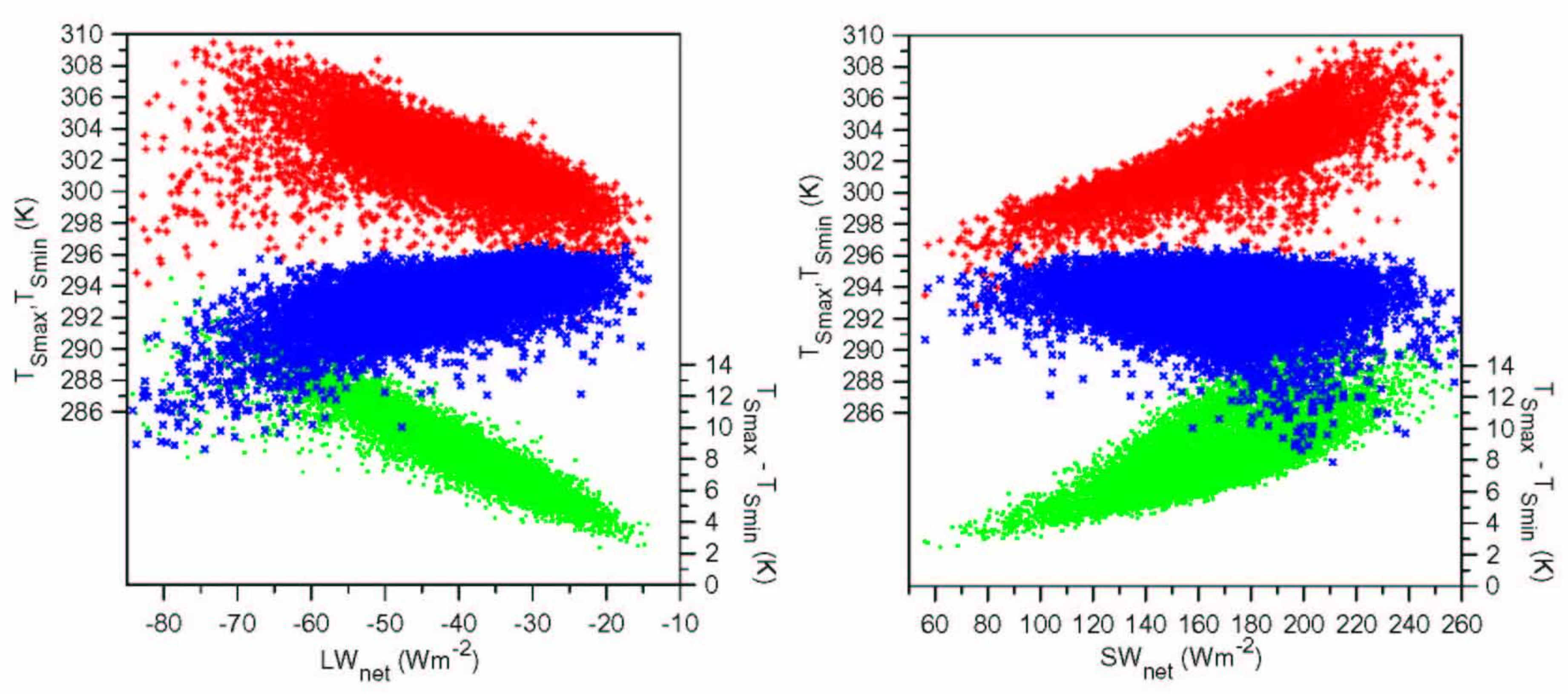
  with upper limit near 1.26

LW coupling for other basins



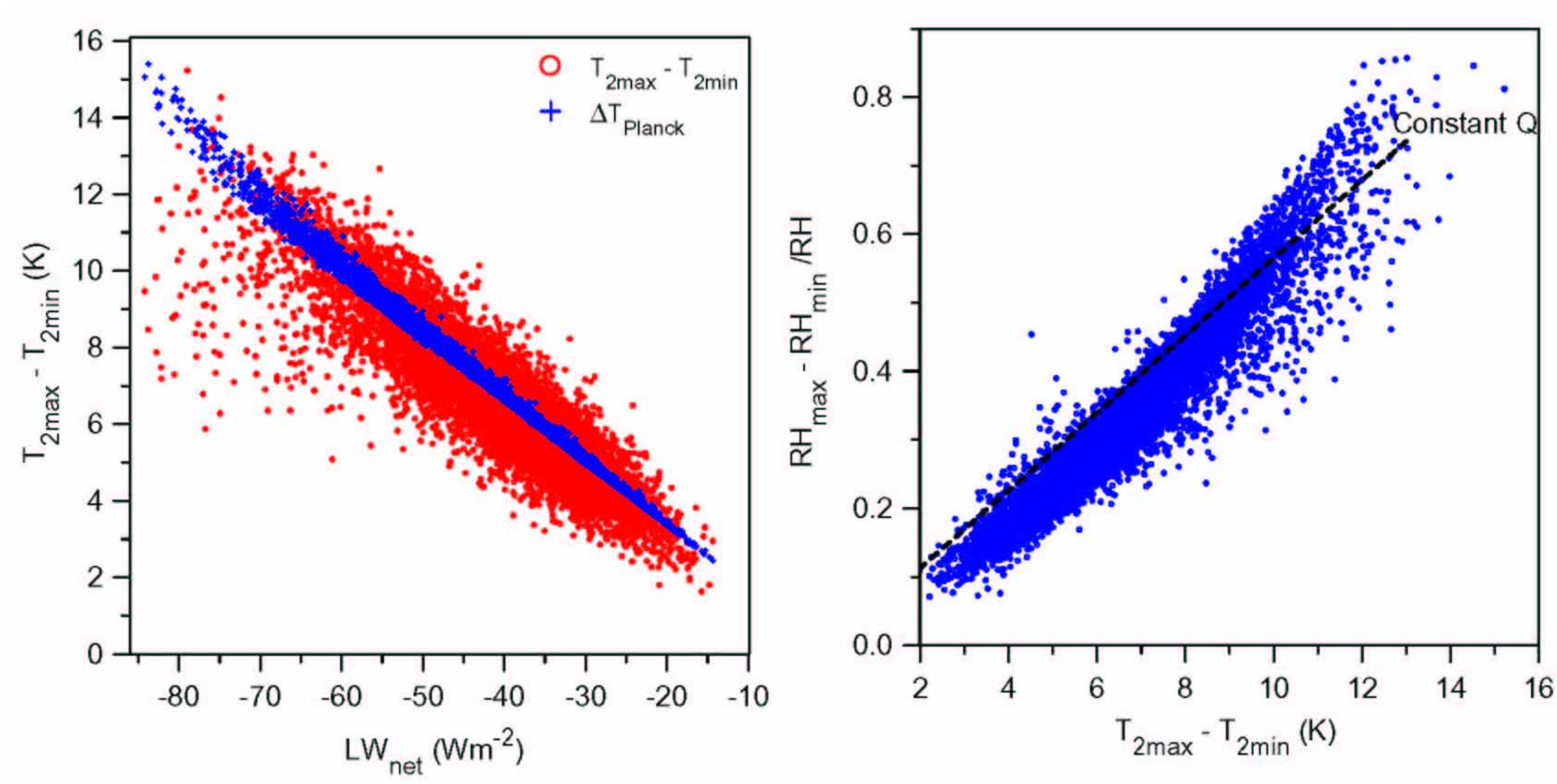
- LW$_{net}$ tightly coupled to cloud cover and cloud-base
- Madeira has 50hPa lower cloud-base
- Red-Arkansas has 0.25 lower cloud cover

Diurnal Cycle: Madeira



- LW$_{net}$ coupled to diurnal range of T$_S$
- SW$_{net}$ more closely related to T$_{smax}$

Diurnal range of 2-m T and RH



) $T_{Planck} = - LW_{net} / 4FT^3$ gives diurnal range of T

Diurnal range of RH and T coupled: Q variation small

Conclusions-1

- Climate and climate change over land depends critically on getting evaporation-precipitation feed-back right
- ERA-40 model has large E, P feedback over continents *[Is it right?]*
- The change in surface energy budget over dry and wet soils is consistent with a shift of the mean sub-cloud layer equilibrium

Conclusions-2

- Model data such as reanalyses can be used to understand coupling of processes
- Coupling of surface processes in ERA-40, though complex, is comprehensible.
- Soil moisture, cloud-base, cloud cover, the radiation fields and evaporative fraction are coupled quite tightly [sub-seasonally]
- Evaporation of precipitation below cloud-base and off wet canopies plays opposite roles in the surface energy balance

Conclusions-3

- Evaporation is controlled somewhat indirectly by the controls on net radiation and sensible heat flux
- The long-wave flux control by cloud-base height and cloud cover is particularly tight across all basins
- The sensible heat flux is coupled to cloud-base height, cooling processes in the sub-cloud layer, as well as directly to the shortwave flux [the BL is not in exact equilibrium on the daily timescale]

Conclusions-4

- Diurnal cycle of temperature is tightly coupled to the net long-wave flux
  [which in turn is controlled by mean cloud-base height and cloud cover]

- [Fundamental importance to NBL]

Conclusions-5

- Proposing a framework for analyzing model data for land-surface feedbacks
- Proposing analysis framework for comparing global models and climate observations

- *RH, cloud-base and cloud cover need to be measured with the radiation fields as* ***climate variables***
- *Climate modeling with interchangeable plug-in modules is fraught with peril, as the feedbacks change*

Thank-you!