Hydrometeorology and Climate

Alan K. Betts [akbetts@aol.com]

- 1. Understanding Hydrometeorology using global models
- 2. Boundary layer equilibrium
  - oceans and land [FL2-1001, Tues.10am]
- 3. River basin budgets from ERA40
  [Mesa-Chapman,Tues.3pm]
- 4. Diurnal cycle over land
  [FL2-Main seminar, Wed. 3.30pm]

AKB office is FL2-3006

http://alanbetts.com/research

Understanding Hydrometeorology using global models

- Alan K. Betts

  Atmospheric Research, VT

  akbetts@aol.com

American Meteorological Society, Robert E. Horton Lecture, 14 January 2004-Revised

•Thanks to NSF, NASA and NOAA for support

•Special thanks to Anton Beljaars, Pedro Viterbo and Martin Miller at ECMWF for two decades of extensive collaboration -- and to John Ball for 15 years of patient data processing

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

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

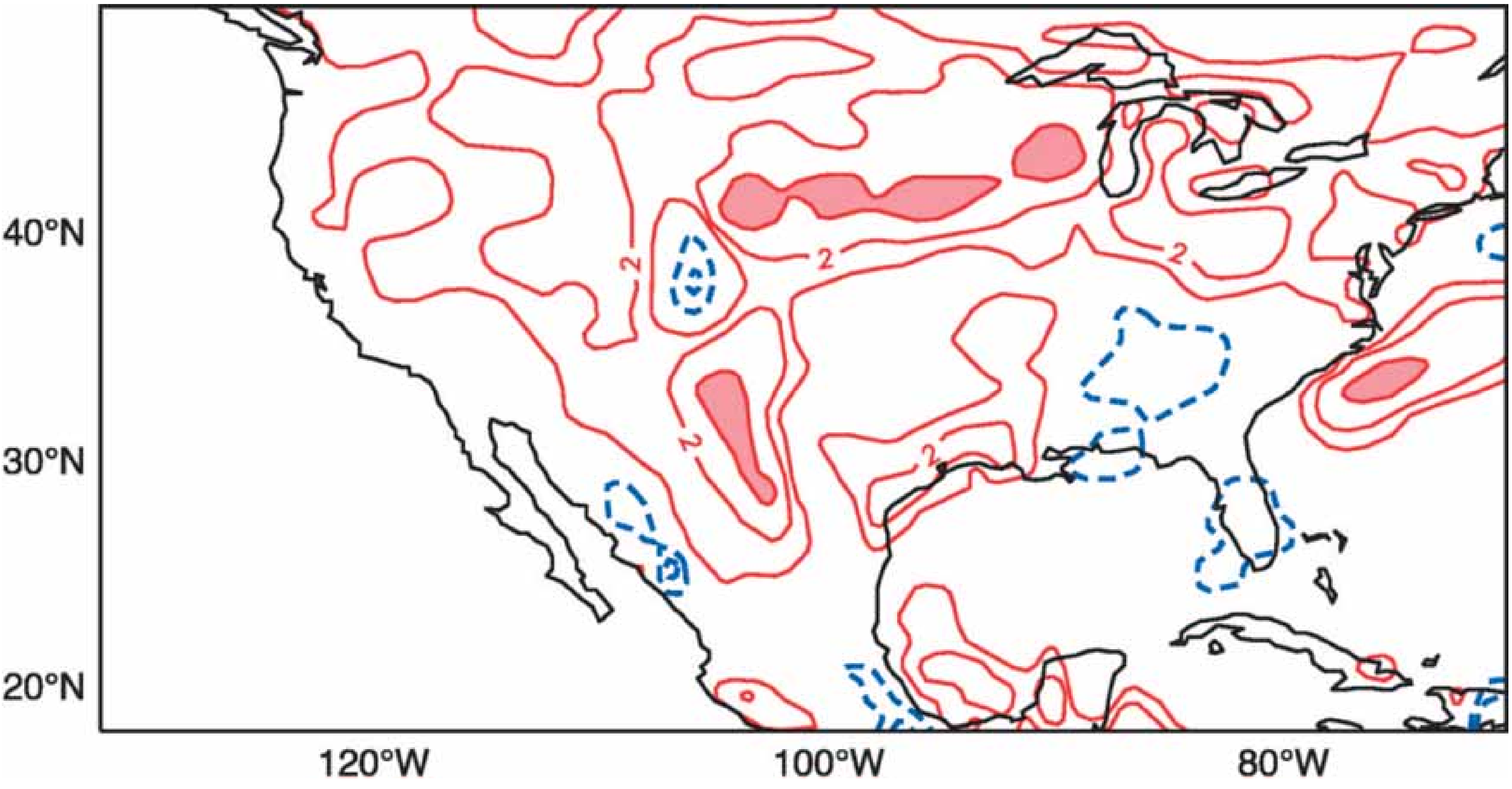
Coupling of **s**oil moisture, cloud-base, cloud cover, radiation fields, sensible and latent heat fluxes and diurnal cycle

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

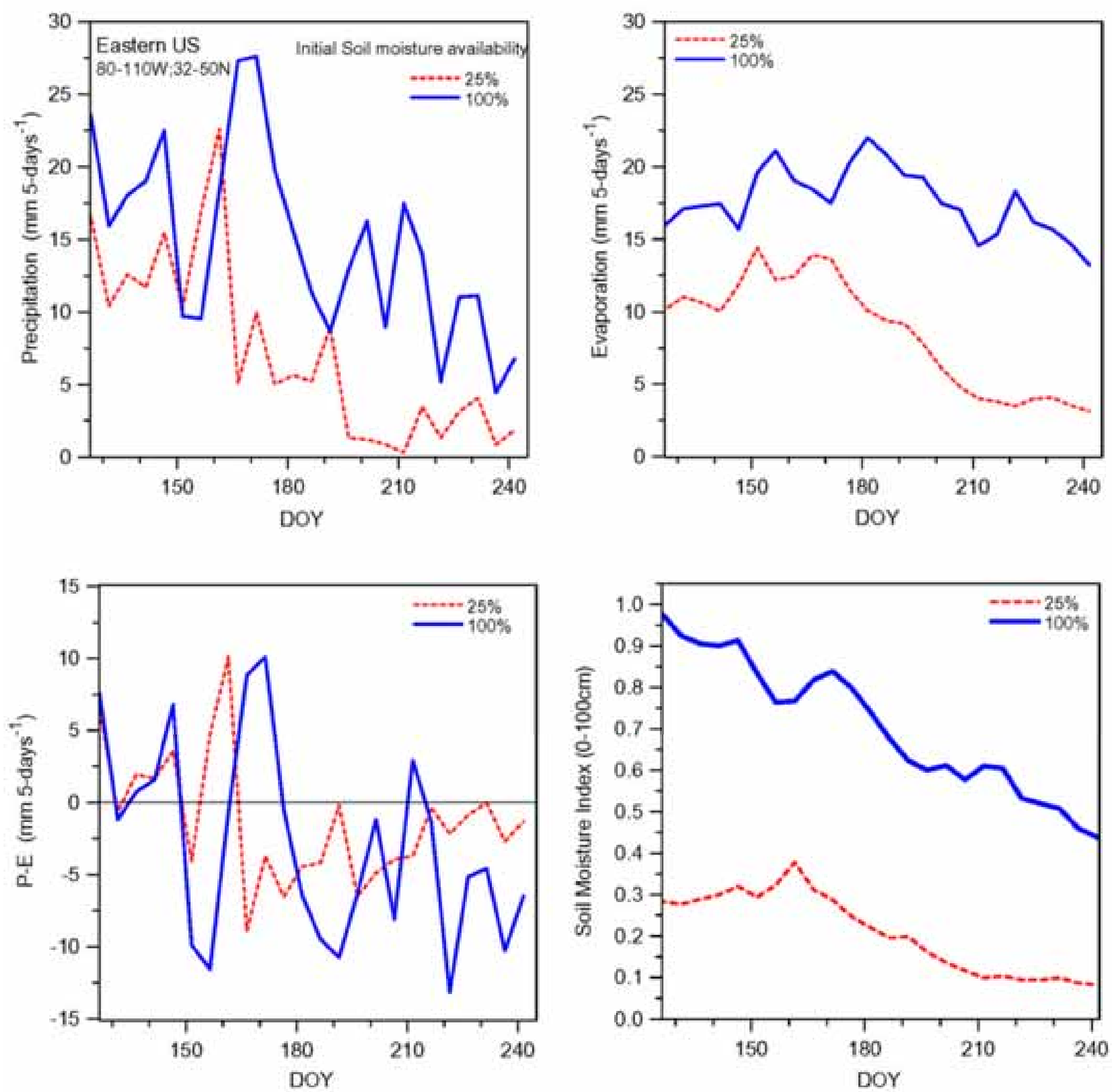
- ERA40 model: 120-day forecasts at T-95 L60 from May 1, 1987 (DOY=121)
- Identical except
  a) Soil moisture initalized at 100% field capacity for vegetated areas
  b) Soil moisture initalized at 25%

-- Soil Moisture Index

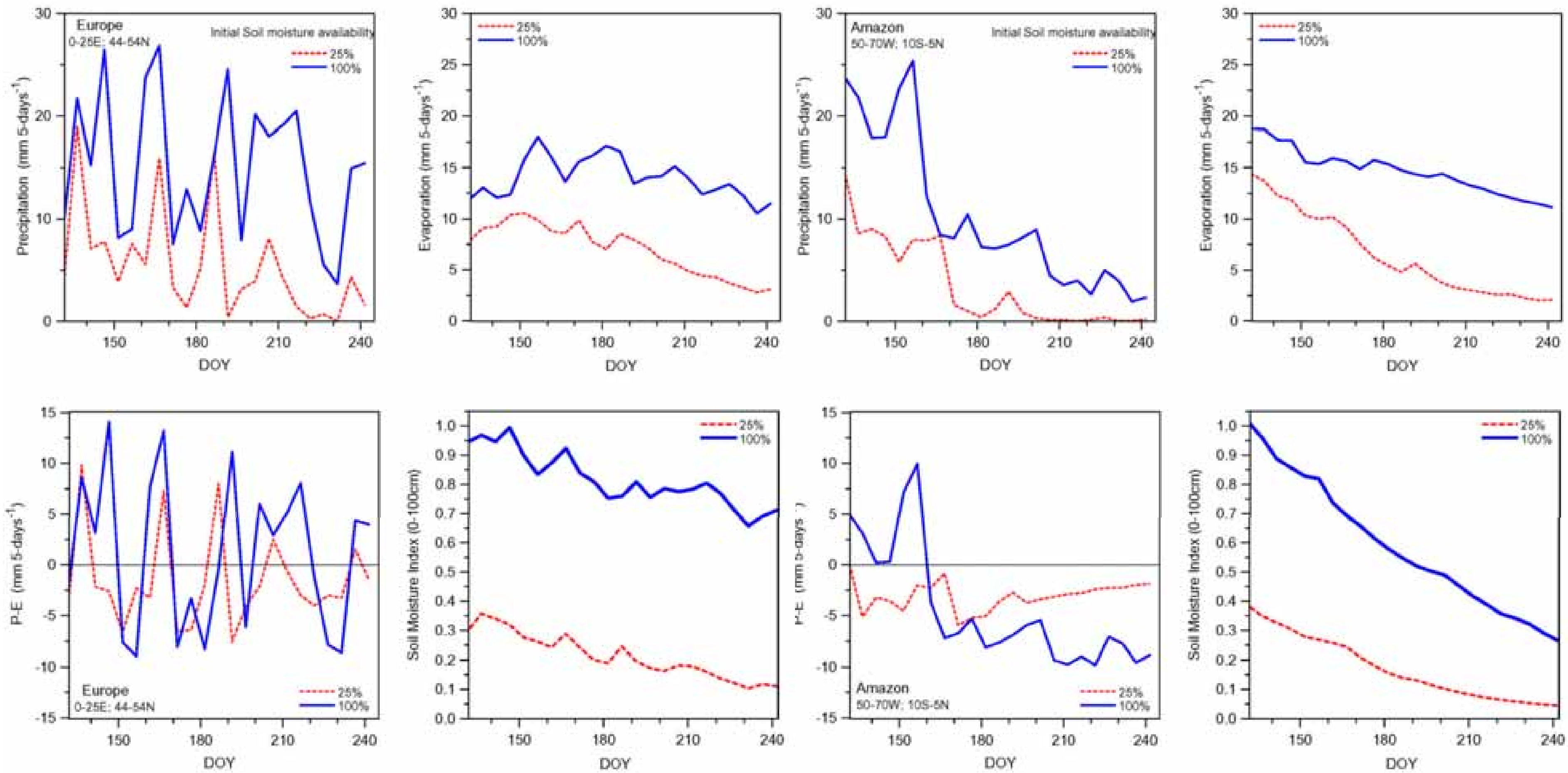
$0 < SMI < 1$ as $PWP < SM < FC$

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

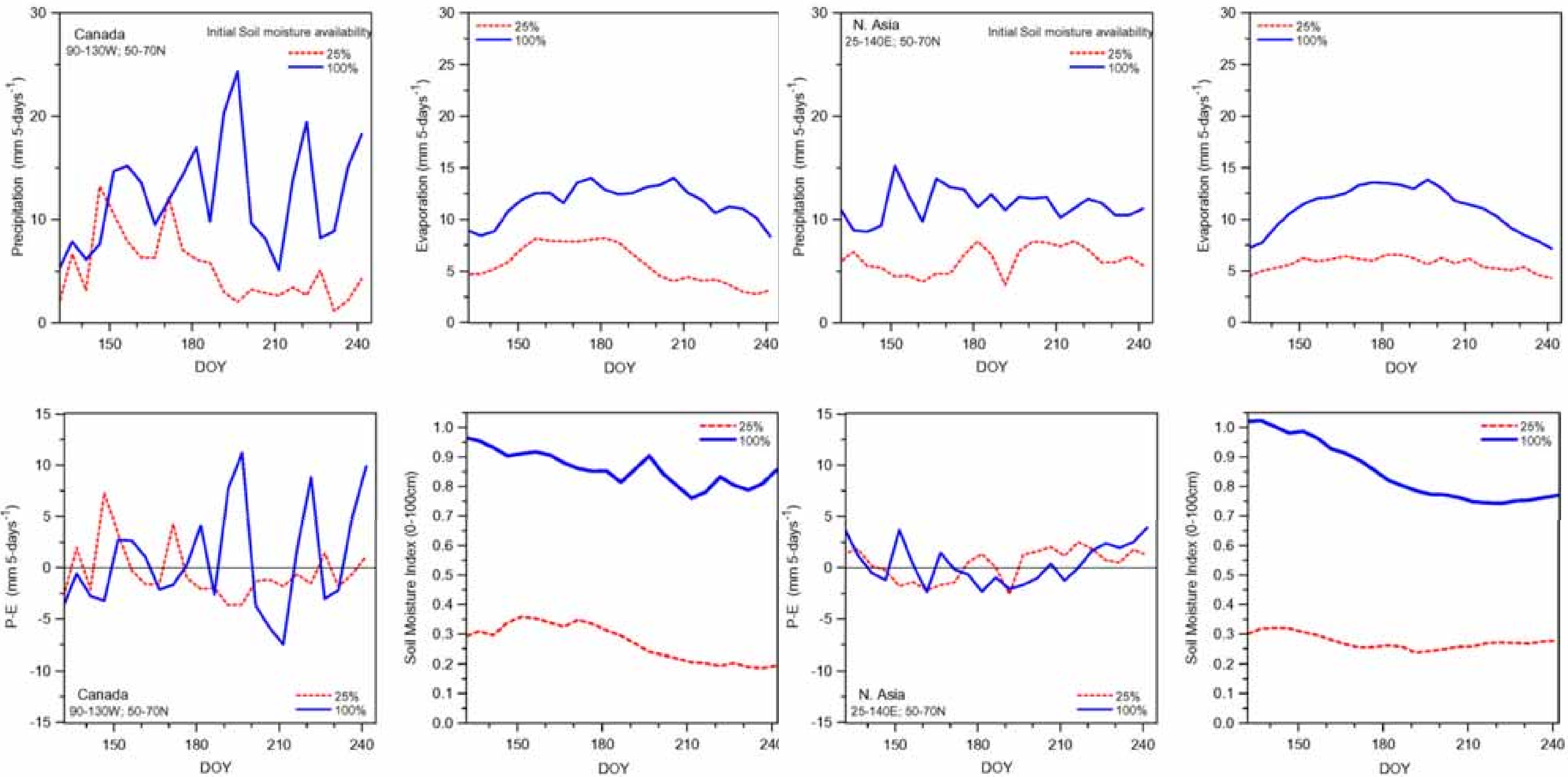


Europe Amazon



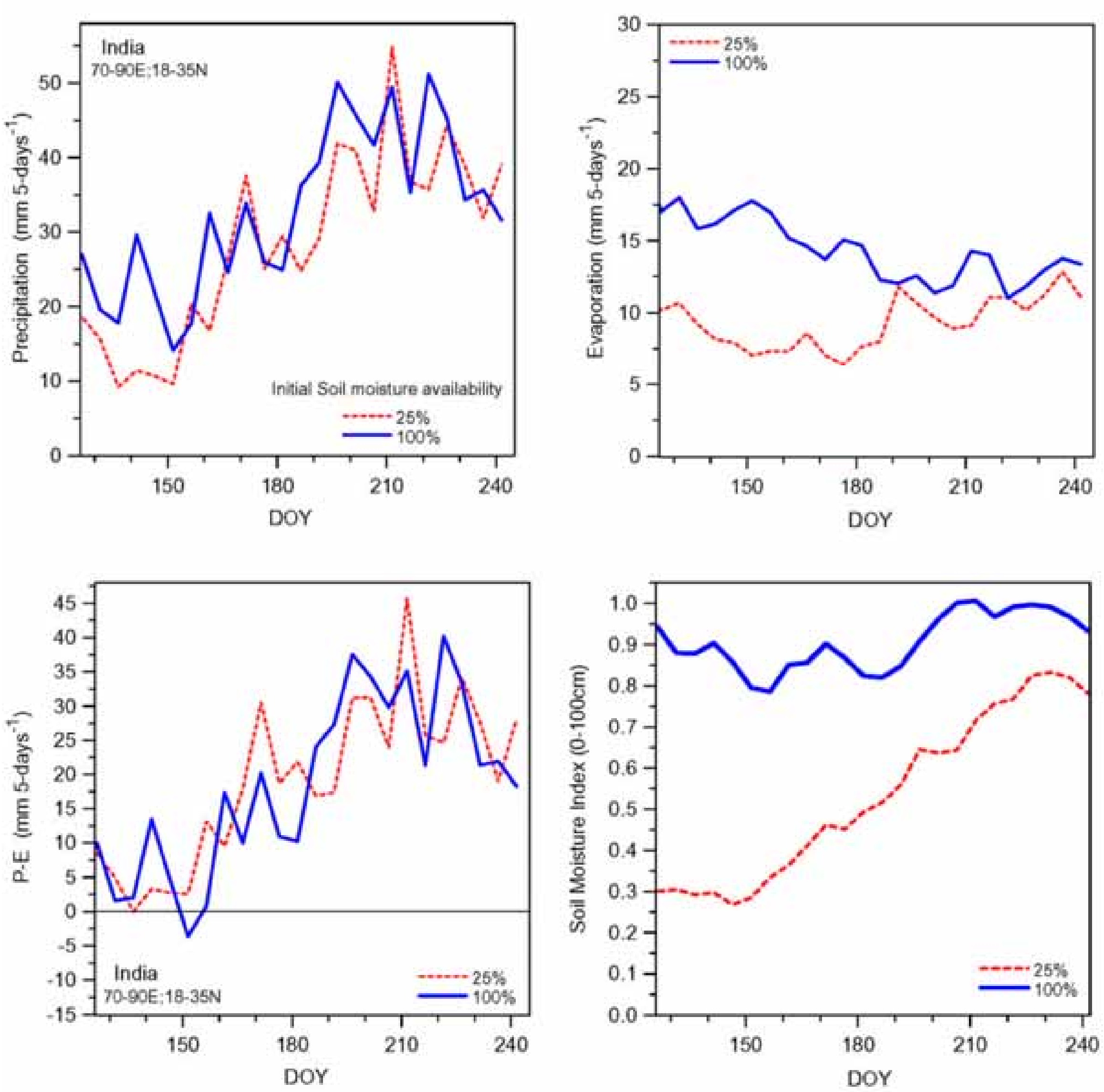
Canada

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]

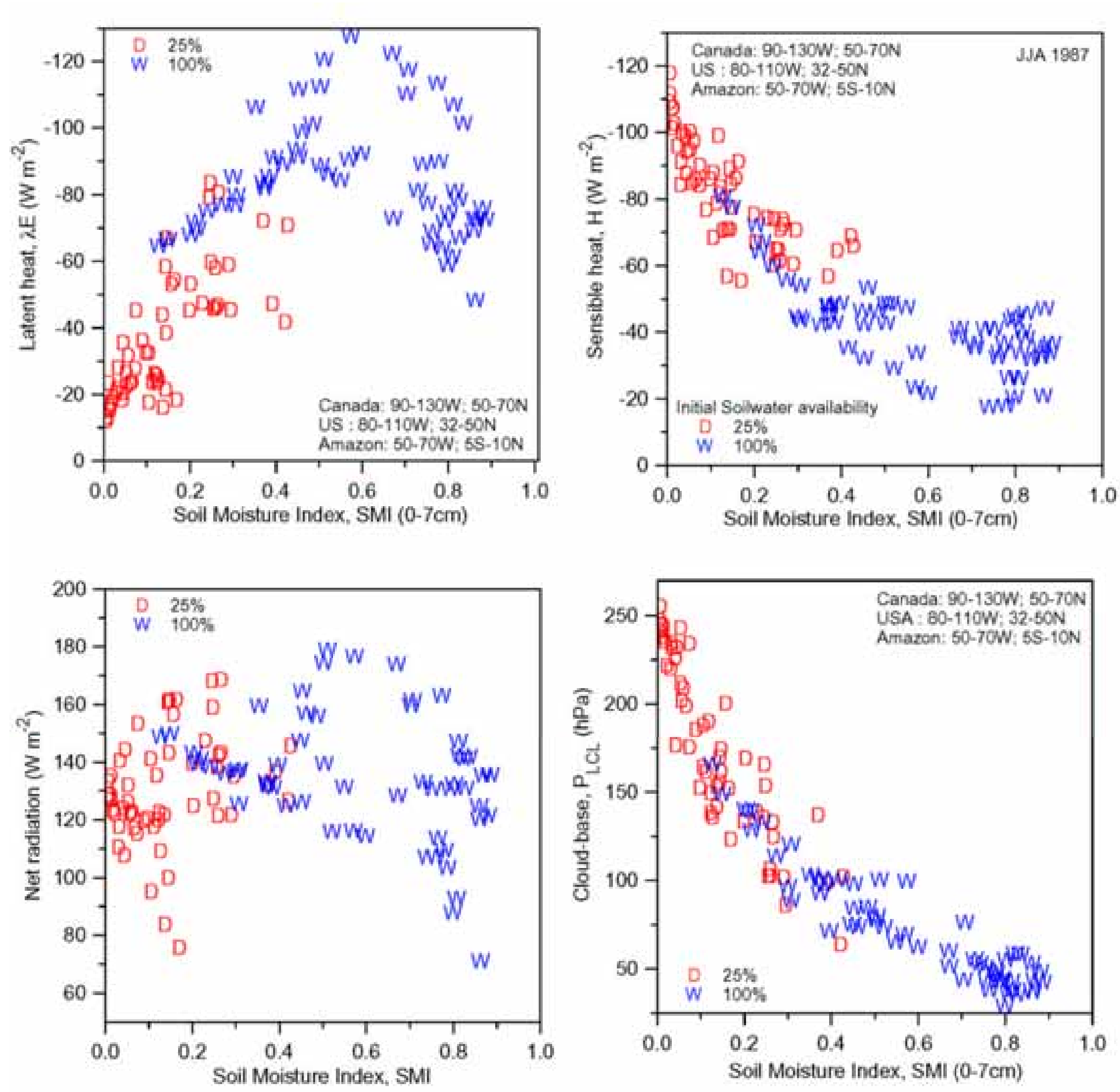
- So what controls evaporation?
- Not classic "equilibrium evaporation"
- Recast equilibrium evaporation as as a diurnally averaged problem, linked to cloud-base and cloud fields

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

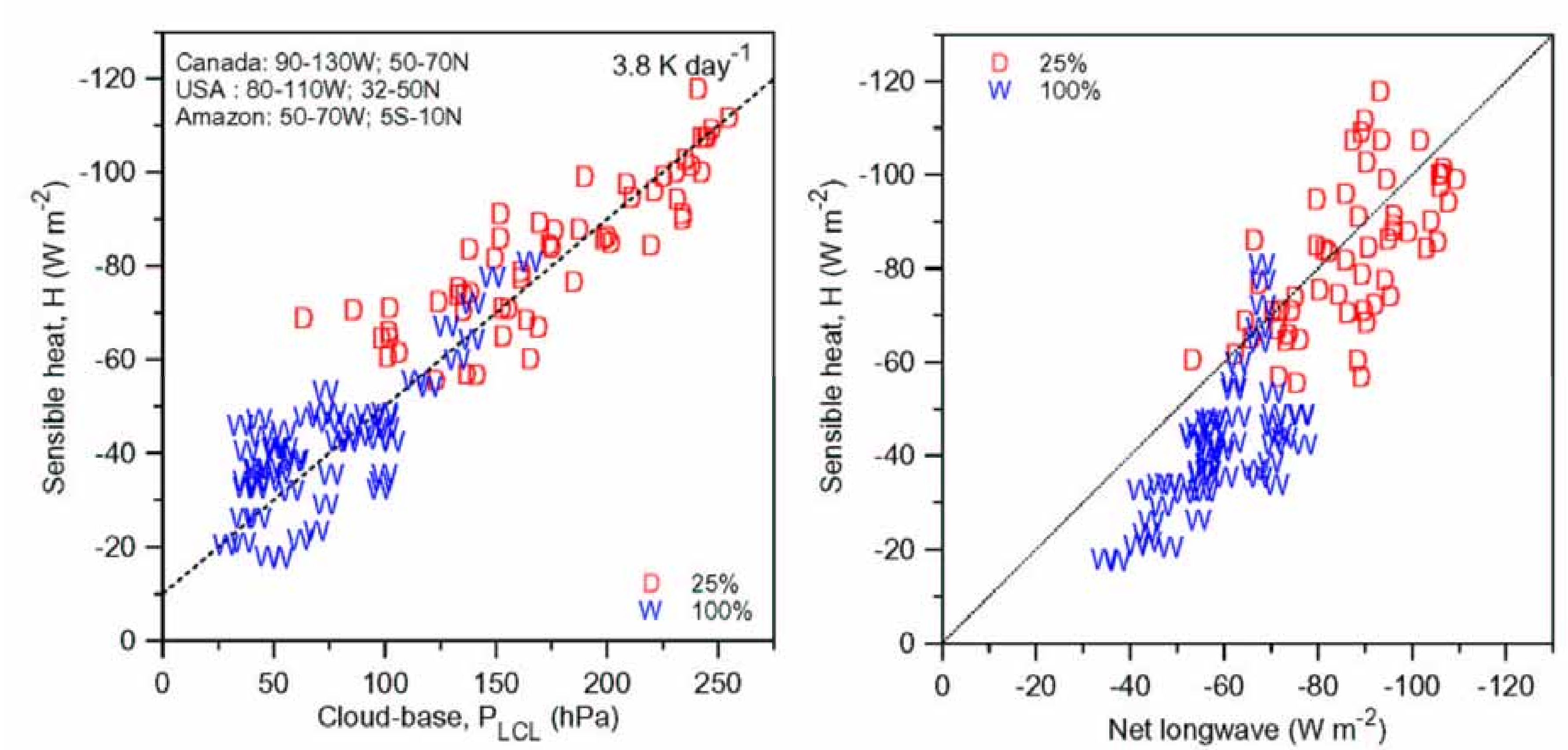
Surface energy balance, and ML “equilibrium”

- **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

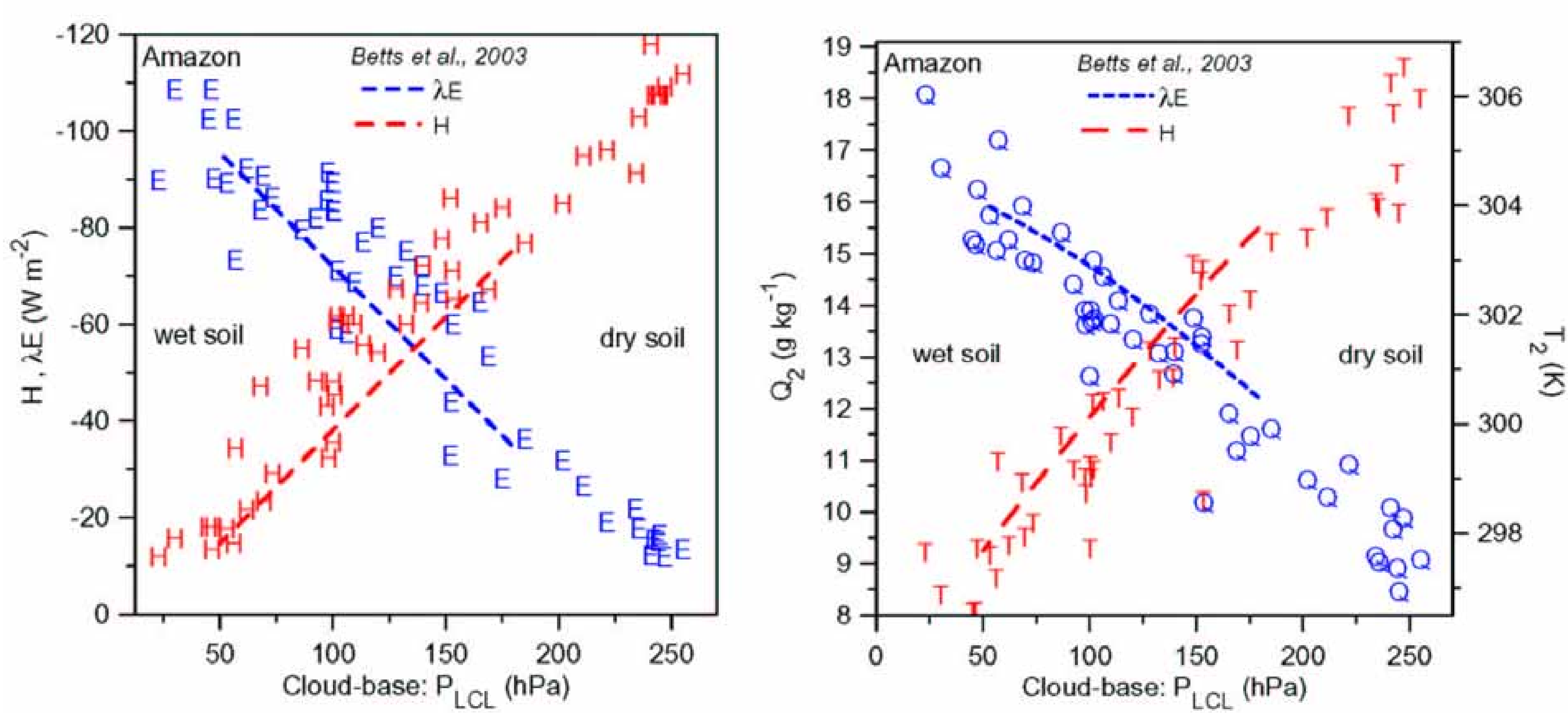


Sensible heat flux: H



- 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}

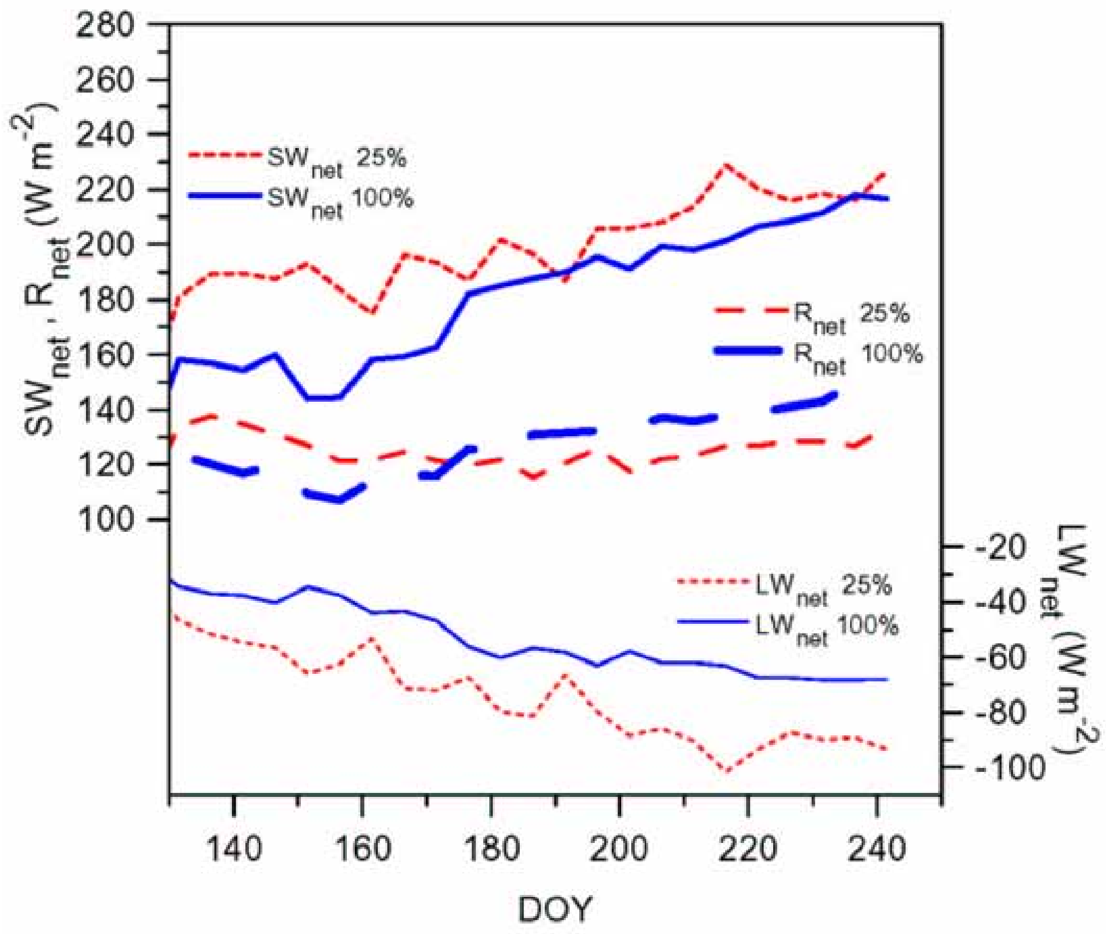
Amazon basin in more detail



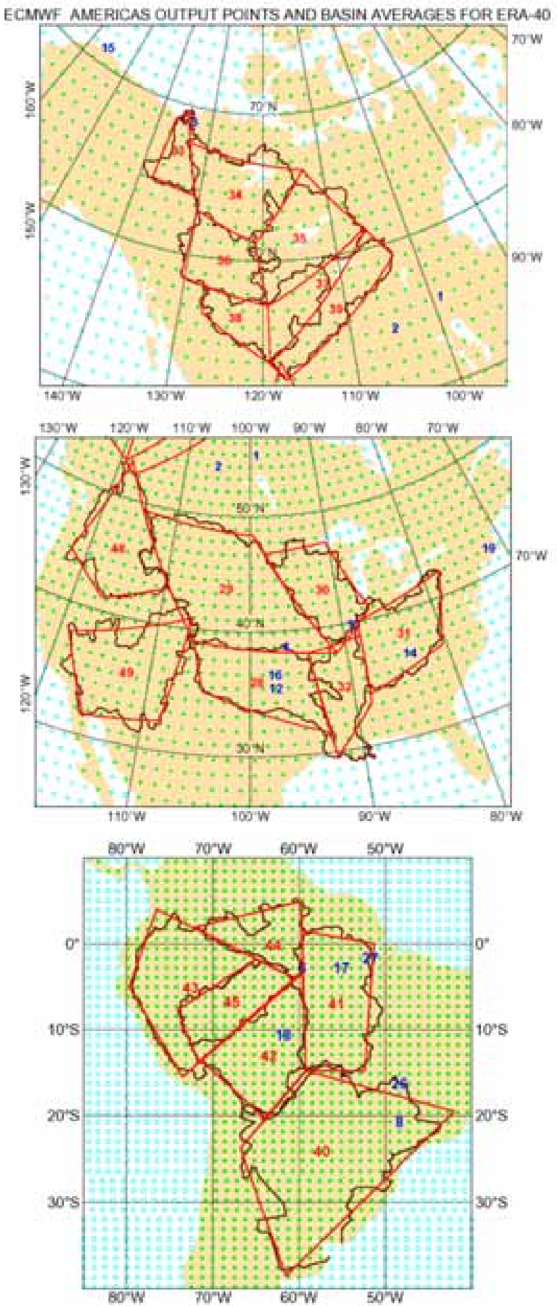
- H , **8**E quasi-linear with P_{LCL}: 2-m Q and T quasi-linear with P_{LCL}
- Over wetter soils, E increases; T decreases and Q increases in ML
- *New coupled state* has lower LCL, with cooler, moister ML; reduced H and larger E

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]

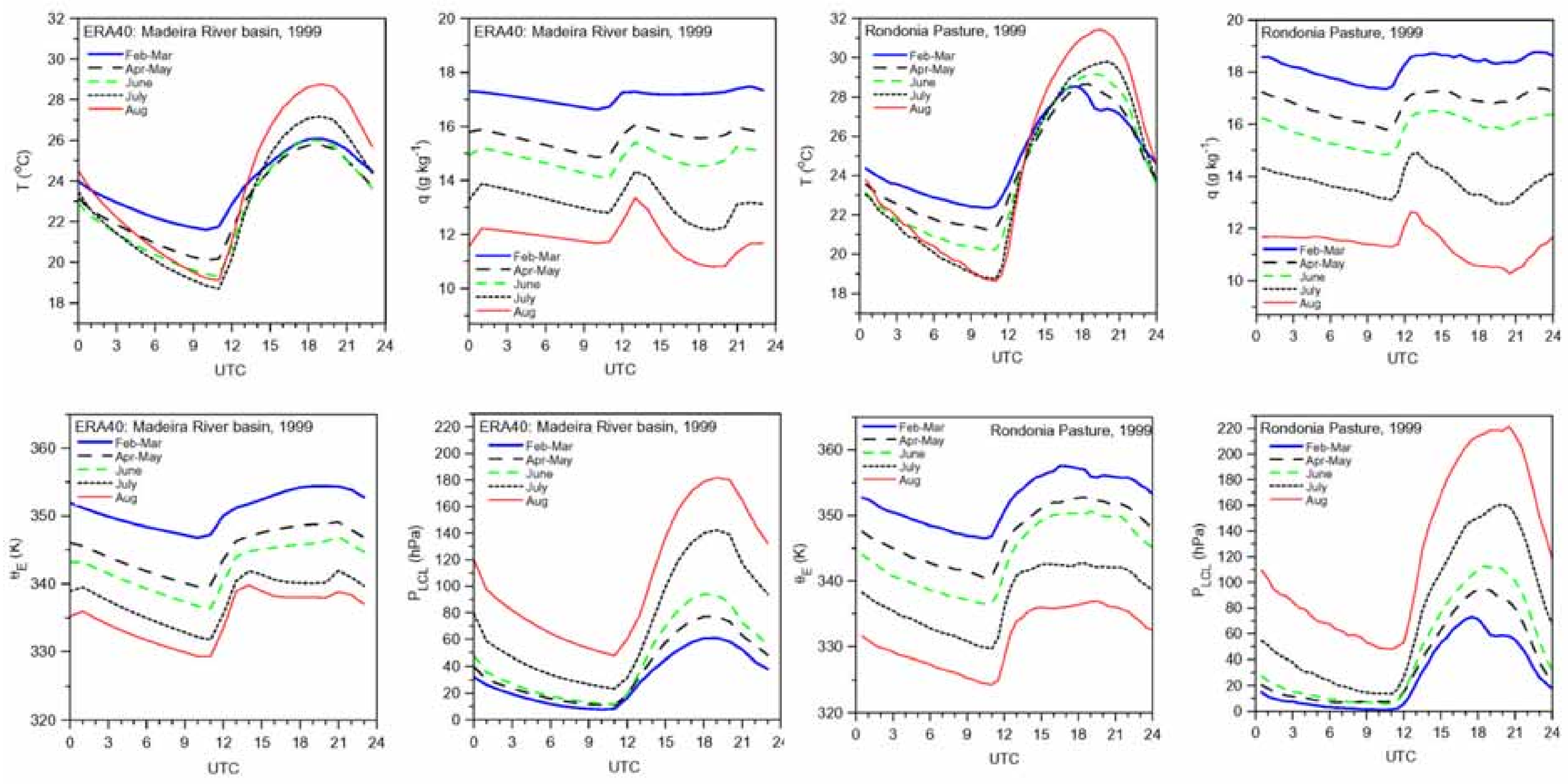
- **Madeira : Amazon**

  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

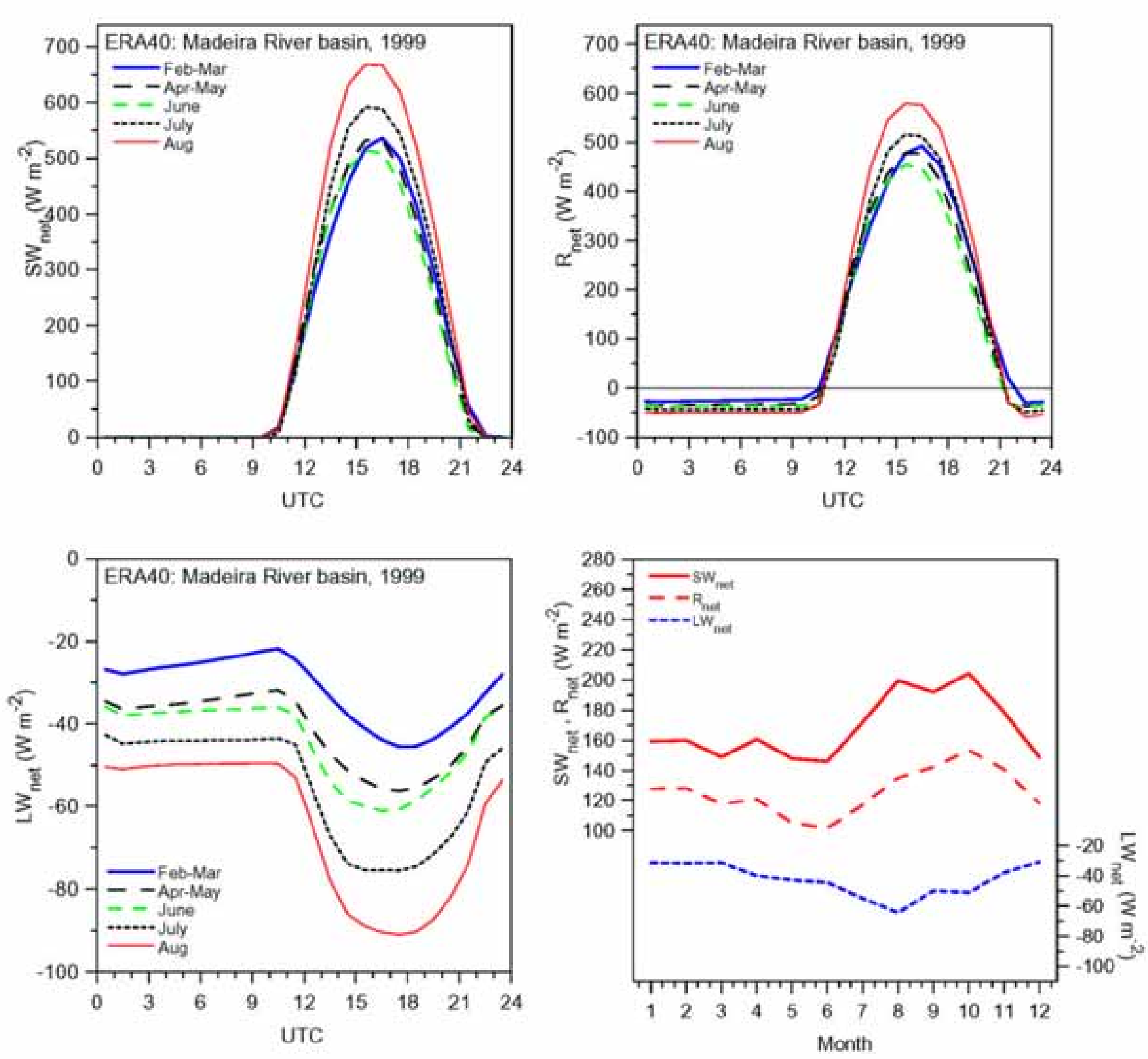


- Large seasonal change of diurnal amplitude
- ERA-40 basin ranges smaller than at pasture site

ERA-40 radiation fluxes

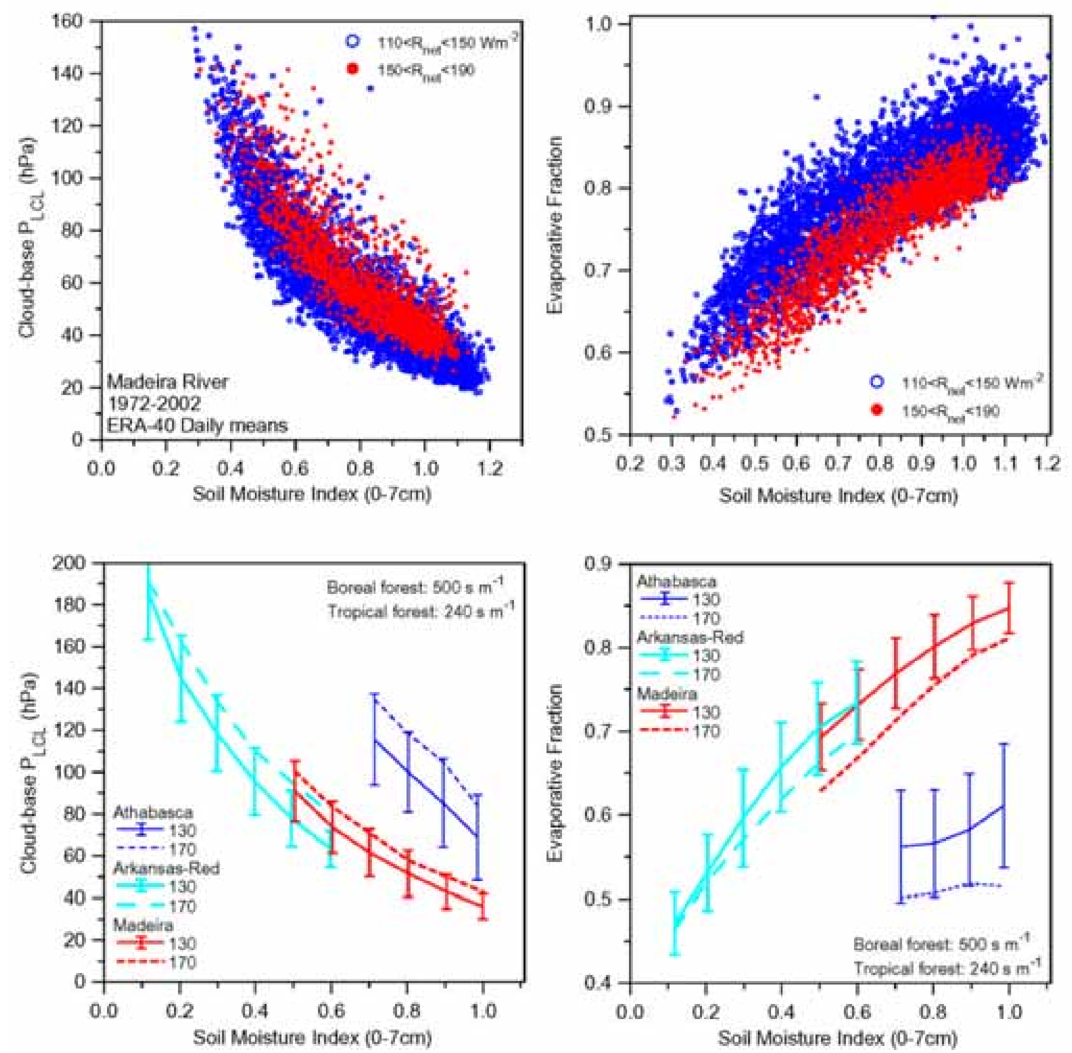
- Large seasonal cycle in LW_{net}, linked to the seasonal cycle of cloud cover and transition from the rainy season to a deep dry ML in August.

- 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

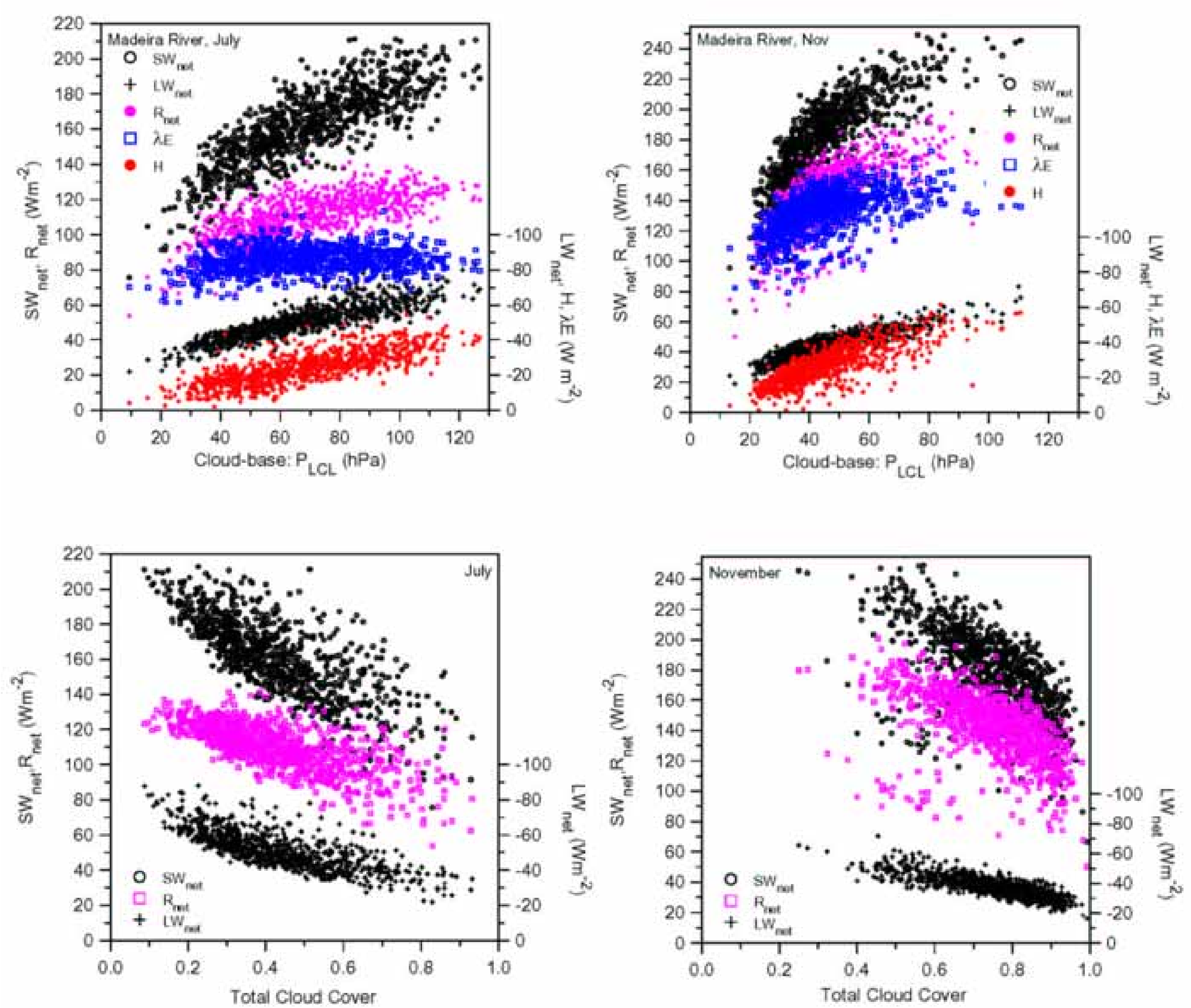
- Mean cloud-base height increases over drier soils and with larger surface R_{net}
- Evaporative fraction increases with soil moisture, and decreases with R_{net}
- 3 basins similar: with additional dependence on unstressed resistance



Madeira basin for July and November

- July: dry season
- Nov: wet season

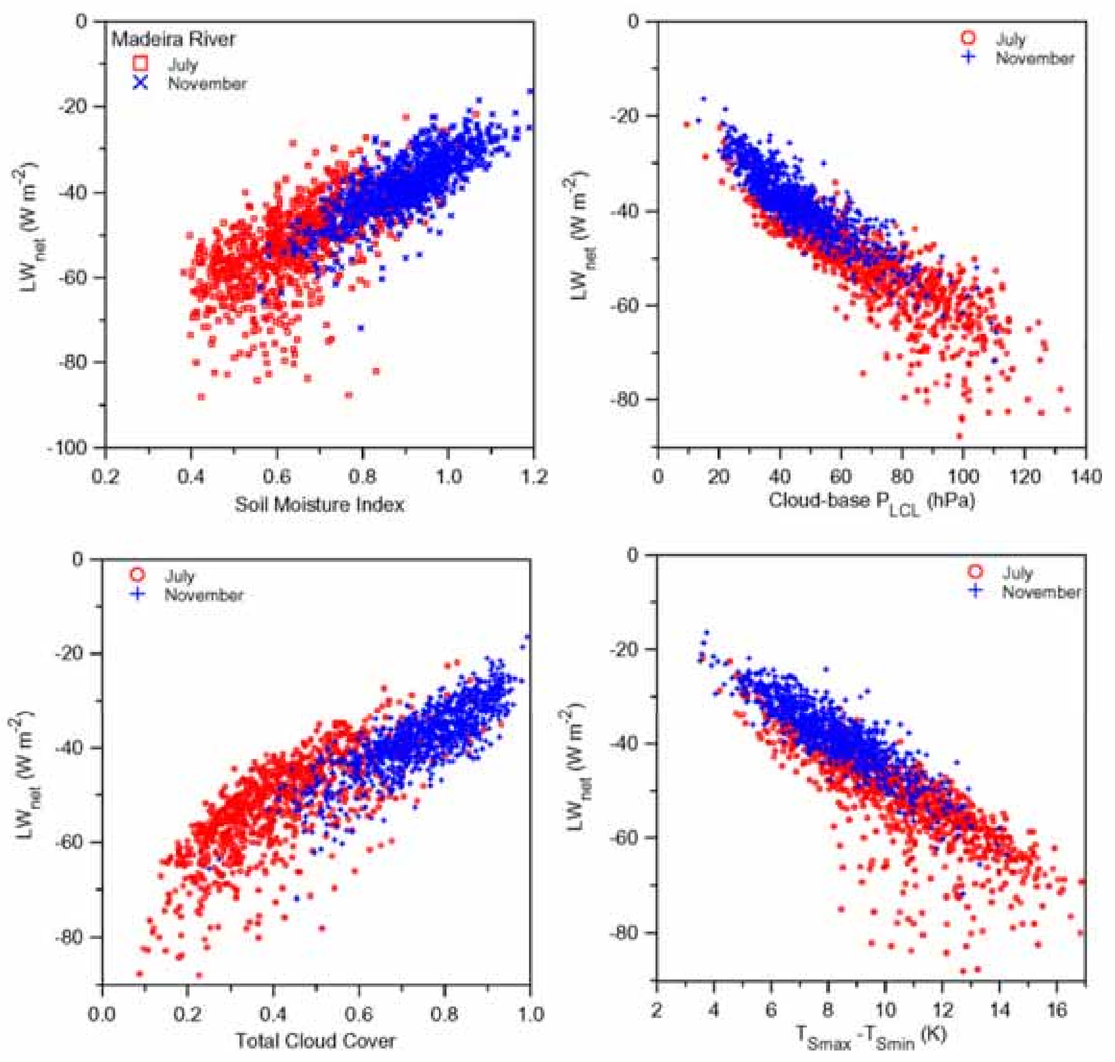
- Surface fluxes as function of cloud-base and cloud cover



LW_{net} dependencies

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

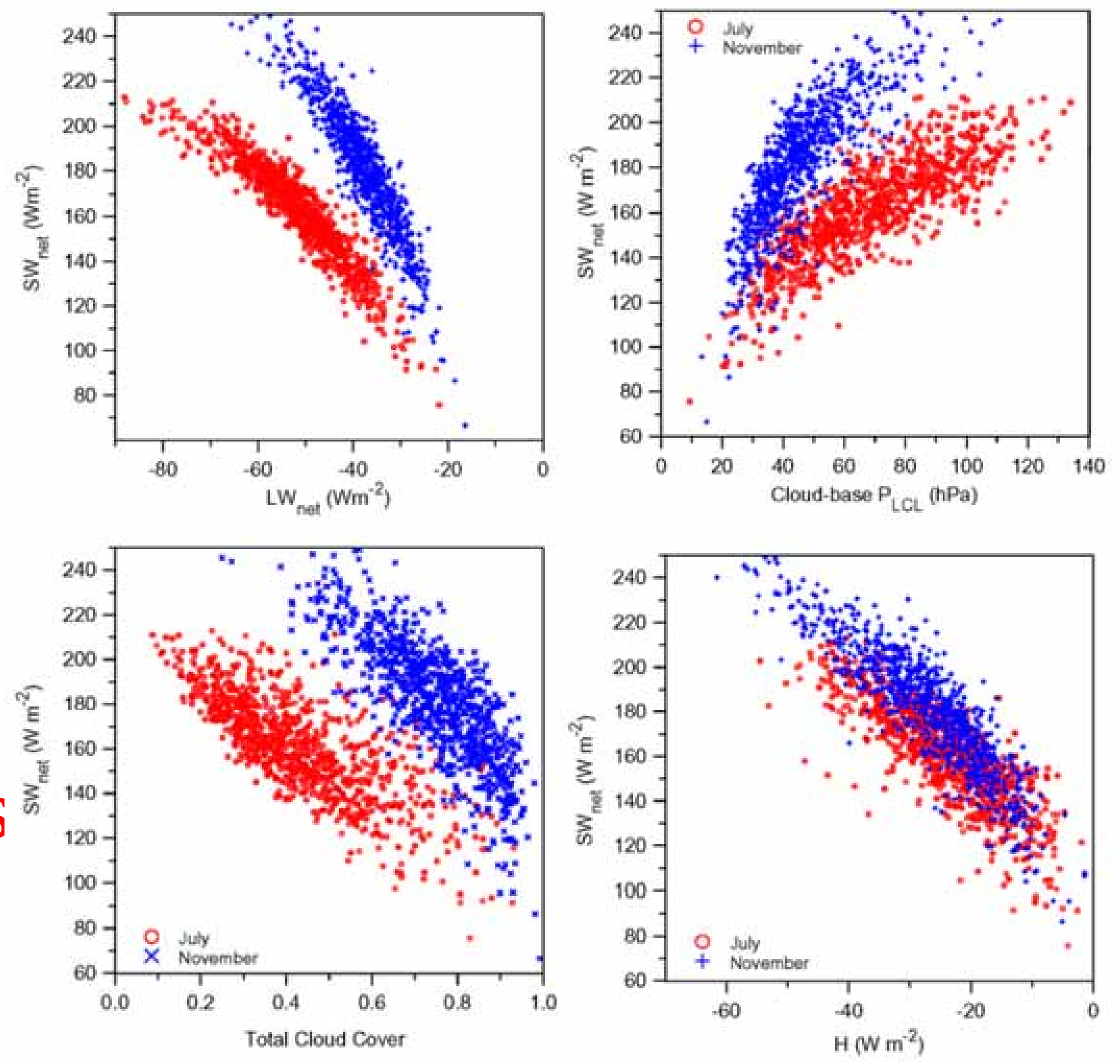
- 2 months merge to single quasi-linear distribution



SW_{net} dependencies

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

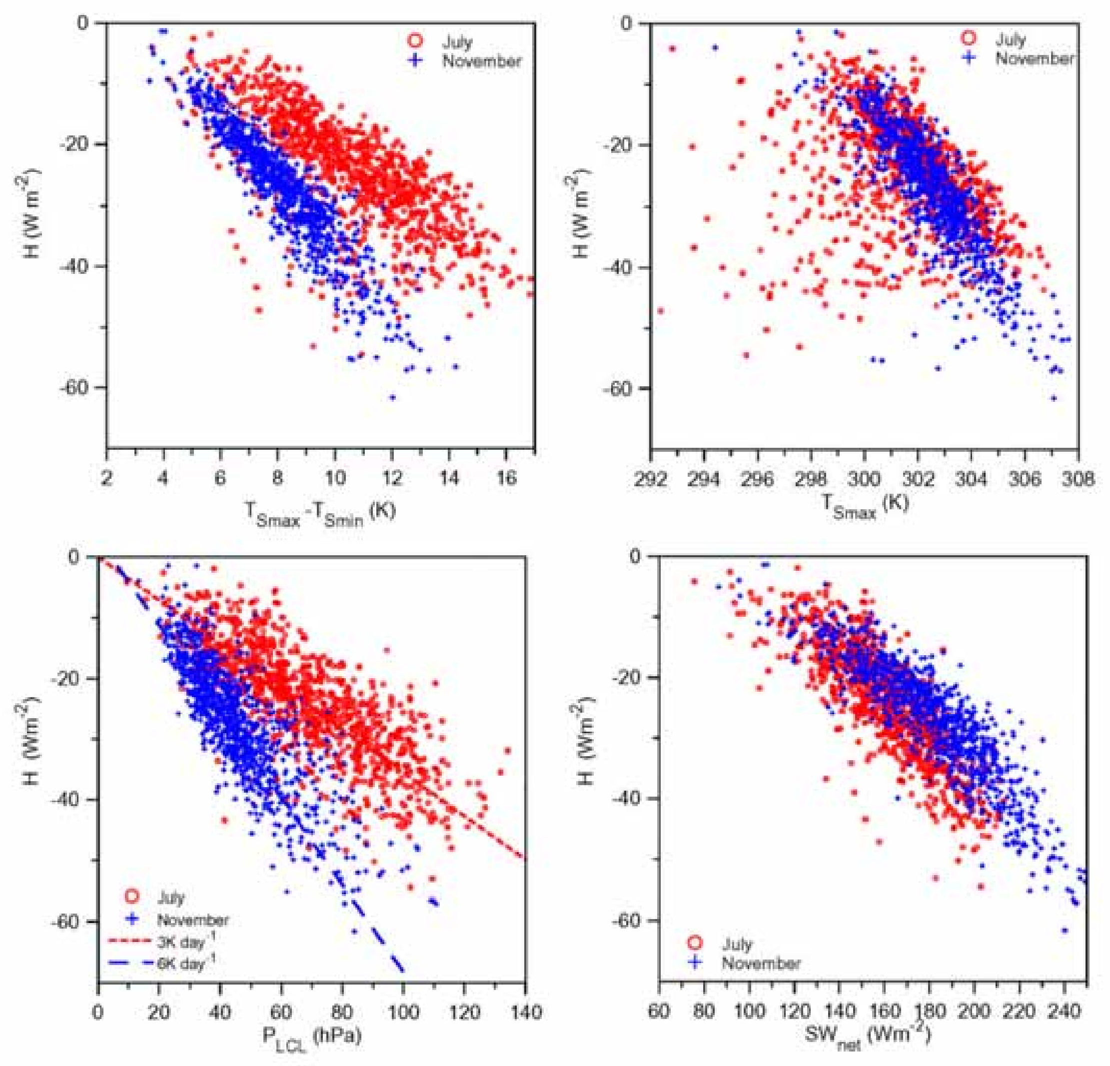
- Distinct distributions except for H



Sensible heat flux H

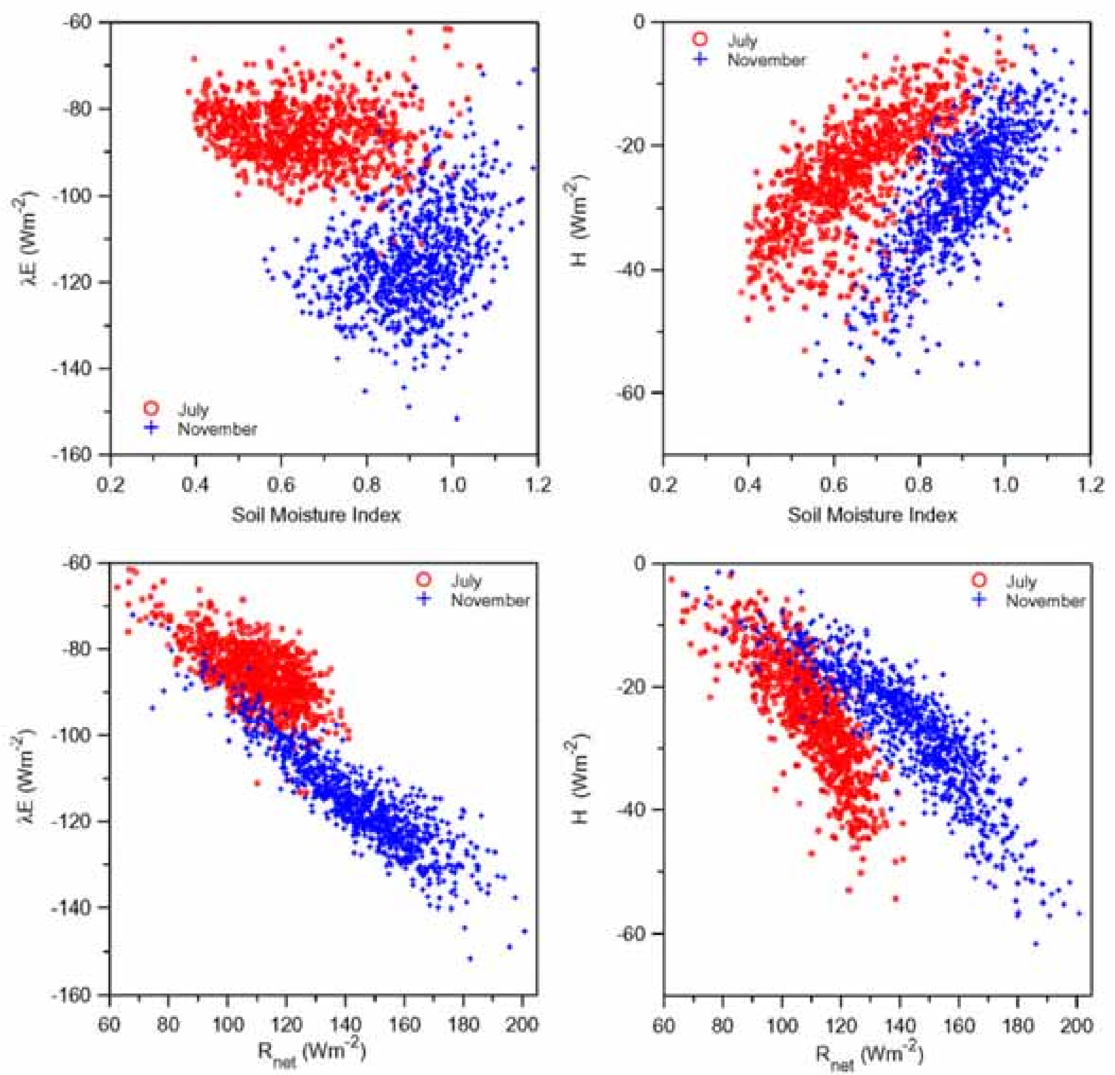
- Diurnal range: T_s
- Maximum T_s
- Cloud-base
- SW_{net}

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

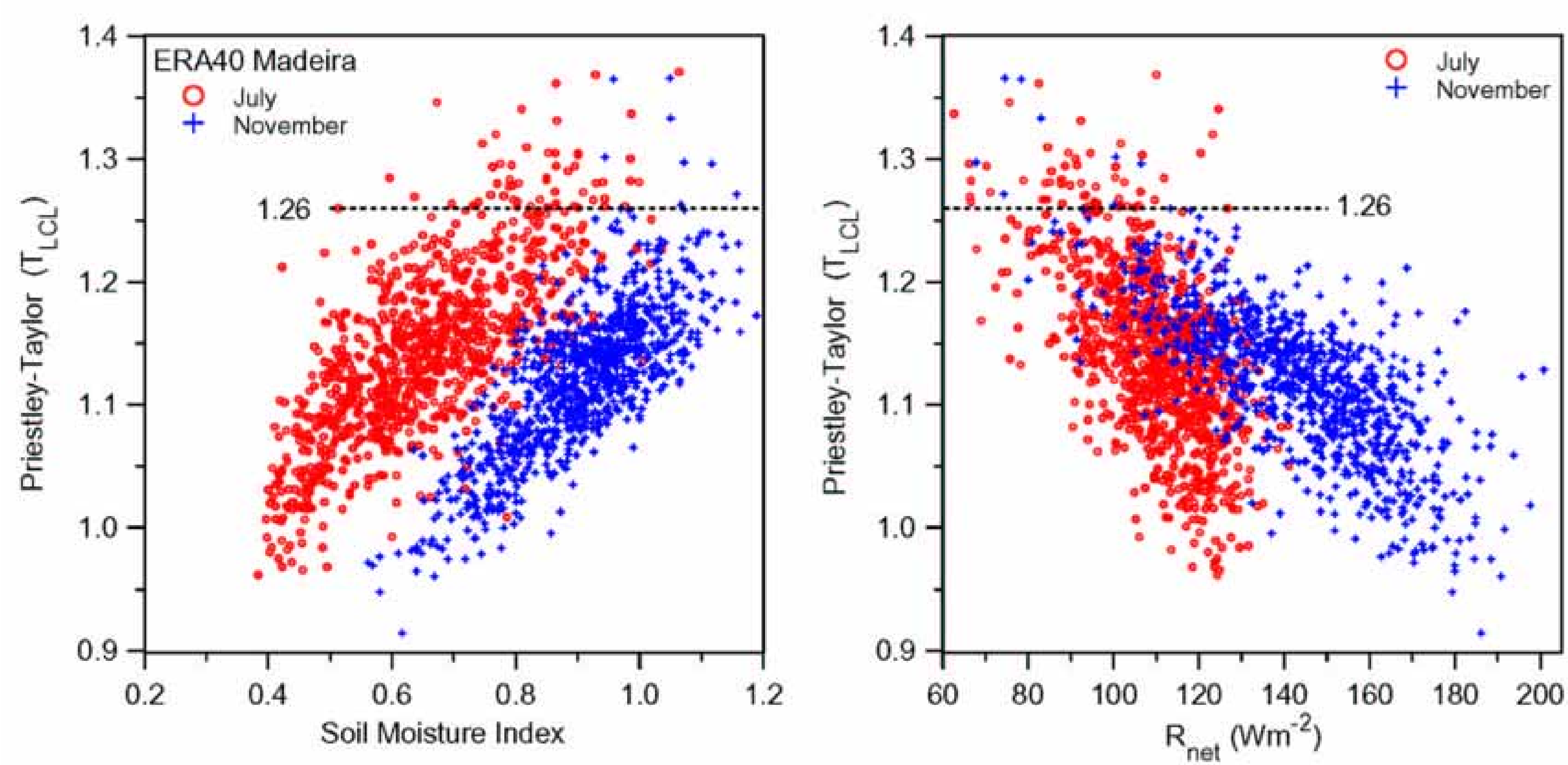


Latent heat flux λE and H

- 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}]



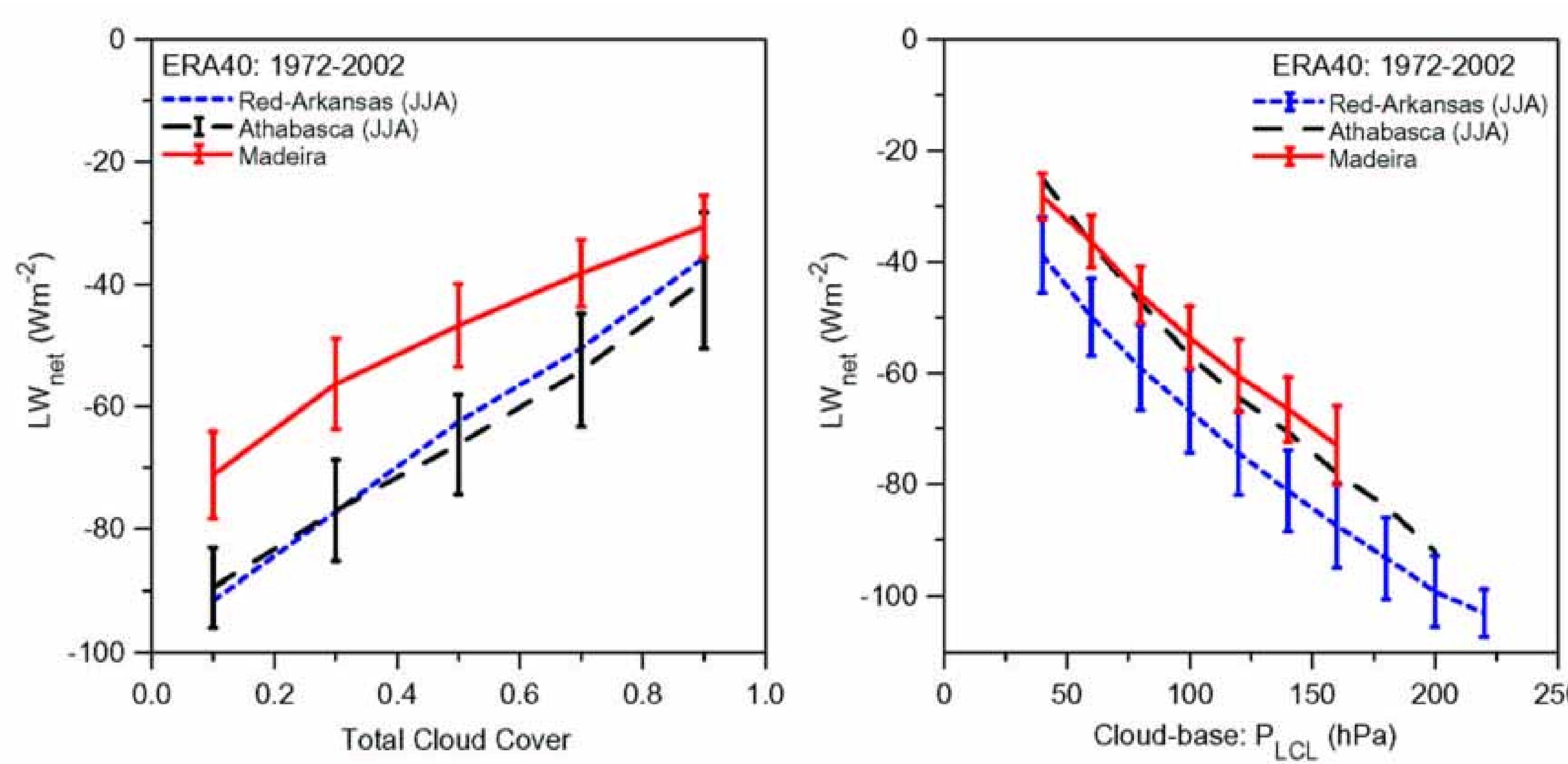
Priestley-Taylor ratio



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

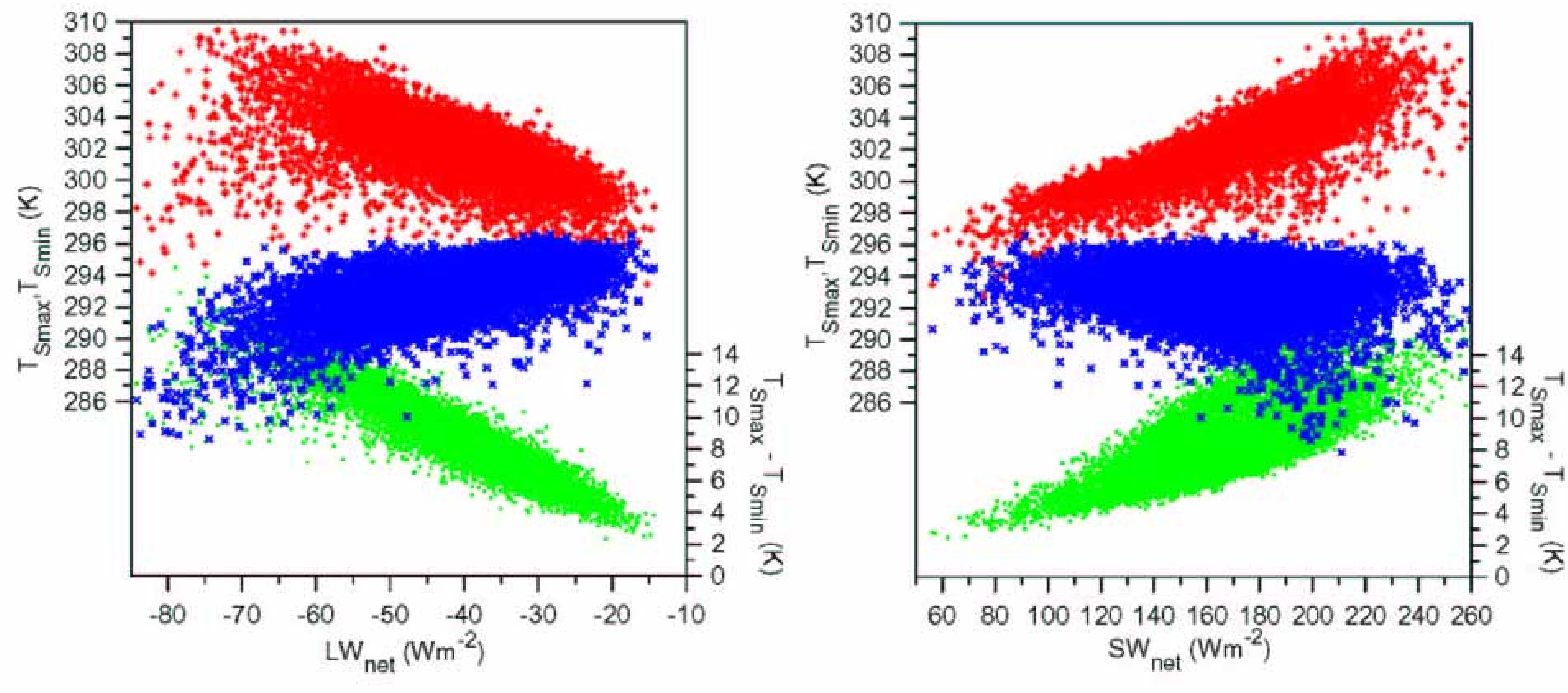
  with upper limit near 1.26

LW coupling for other basins



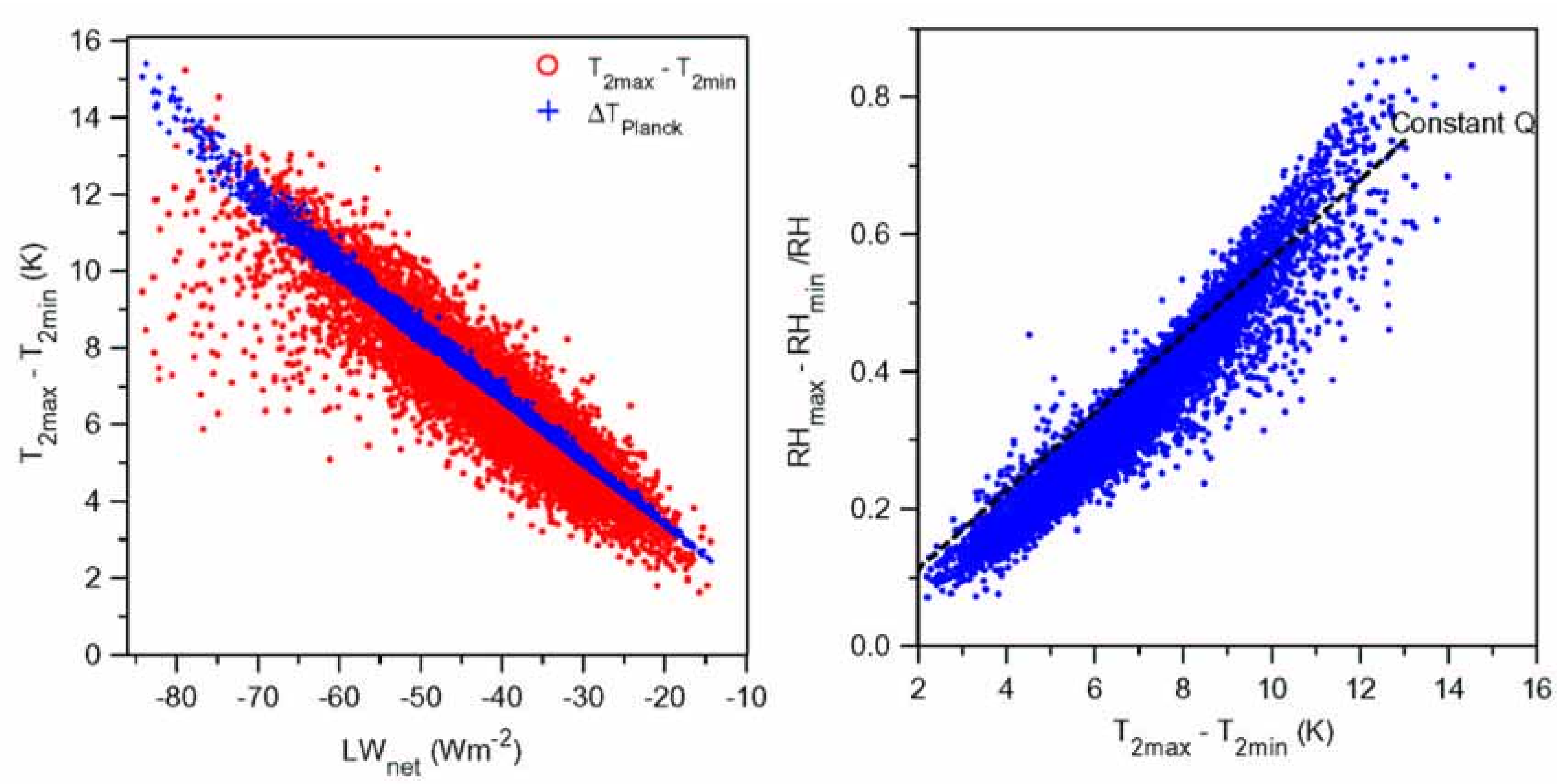
- LW_{net} tightly coupled to cloud cover and cloud-base
- Madeira has 50hPa lower cloud-base
- Red-Arkansas has 0.25 lower cloud cover

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]

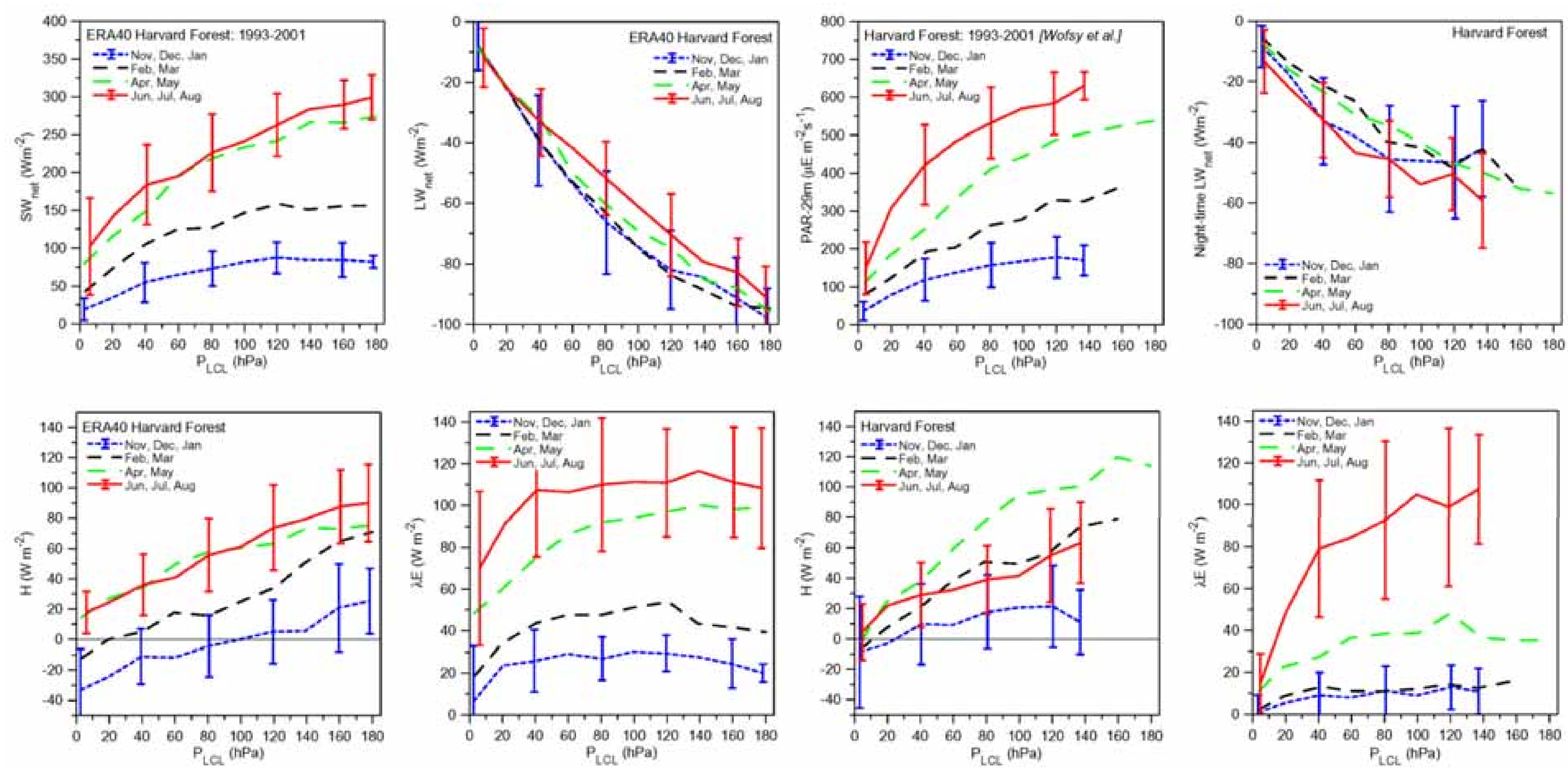
- Surface energy balance and energy partition coupled to cloud-base

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*

Comparisons with data



ERA-40 ‘point’

Harvard forest tower

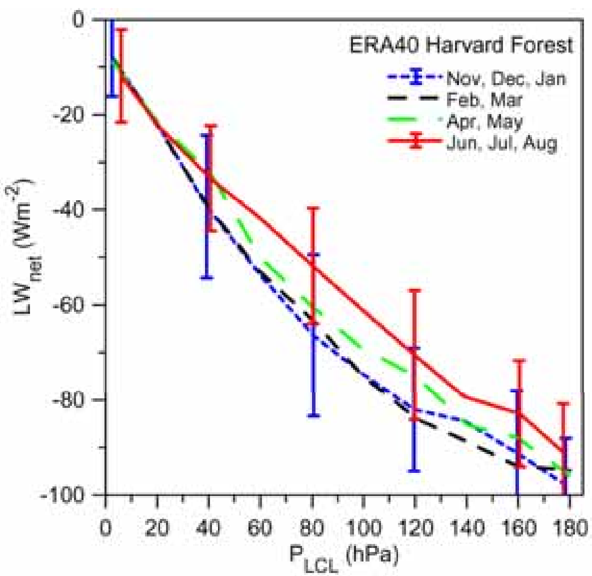
SW-cloud coupling to P_{LCL}

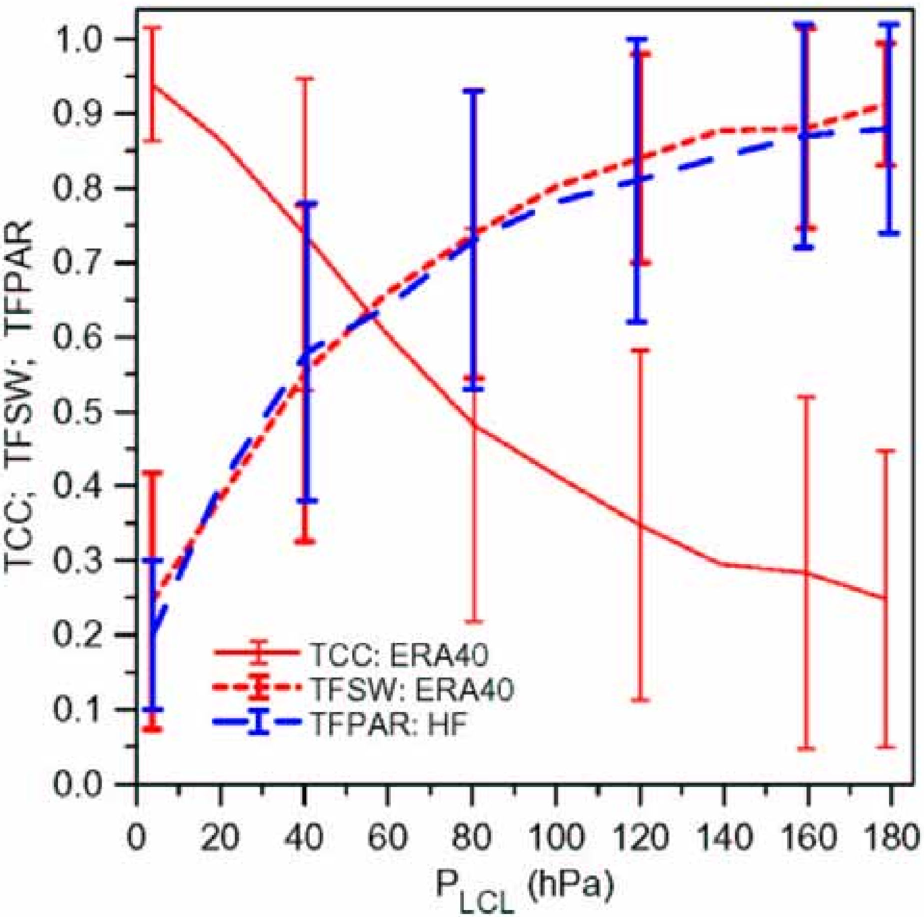
-Total cloud cover: ERA40

-Transmitted fraction SW

-Transmitted fraction PAR

-compare LW coupling





Hydrometeorology and Climate

Alan K. Betts [akbetts@aol.com]

- 1. Understanding Hydrometeorology using global models
- 2. Boundary layer equilibrium
  - oceans and land [FL2-1001Tues.10am]
- 3. River basin budgets from ERA40
  [Mesa-Chapman,Tues.3pm]
- 4. Diurnal cycle over land
  [FL2-Main seminar, Wed. 3.30pm]

AKB office is FL2-3006

ftp://members.aol.com/bettspapers