Land-surface-BL-cloud coupling & the diurnal cycle

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FASTER annual meeting

NASA-GISS, NYC

August 23, 2012

References – see http://alanbetts.com

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Diurnal Cycle

- The surface diurnal cycle over land is the "climate signal" that is important to us
- T_{max}, T_{min} and DTR = T_{max} - T_{min}
- Surely we understand it? Surely we can model it? We observe it every day and forecast centers work hard to reduce their biases!
- As climate warms, some evidence T_{min} increasing faster than T_{max}
- Result of fully coupled system: soil, surface layer, BL, clouds, precipitation…

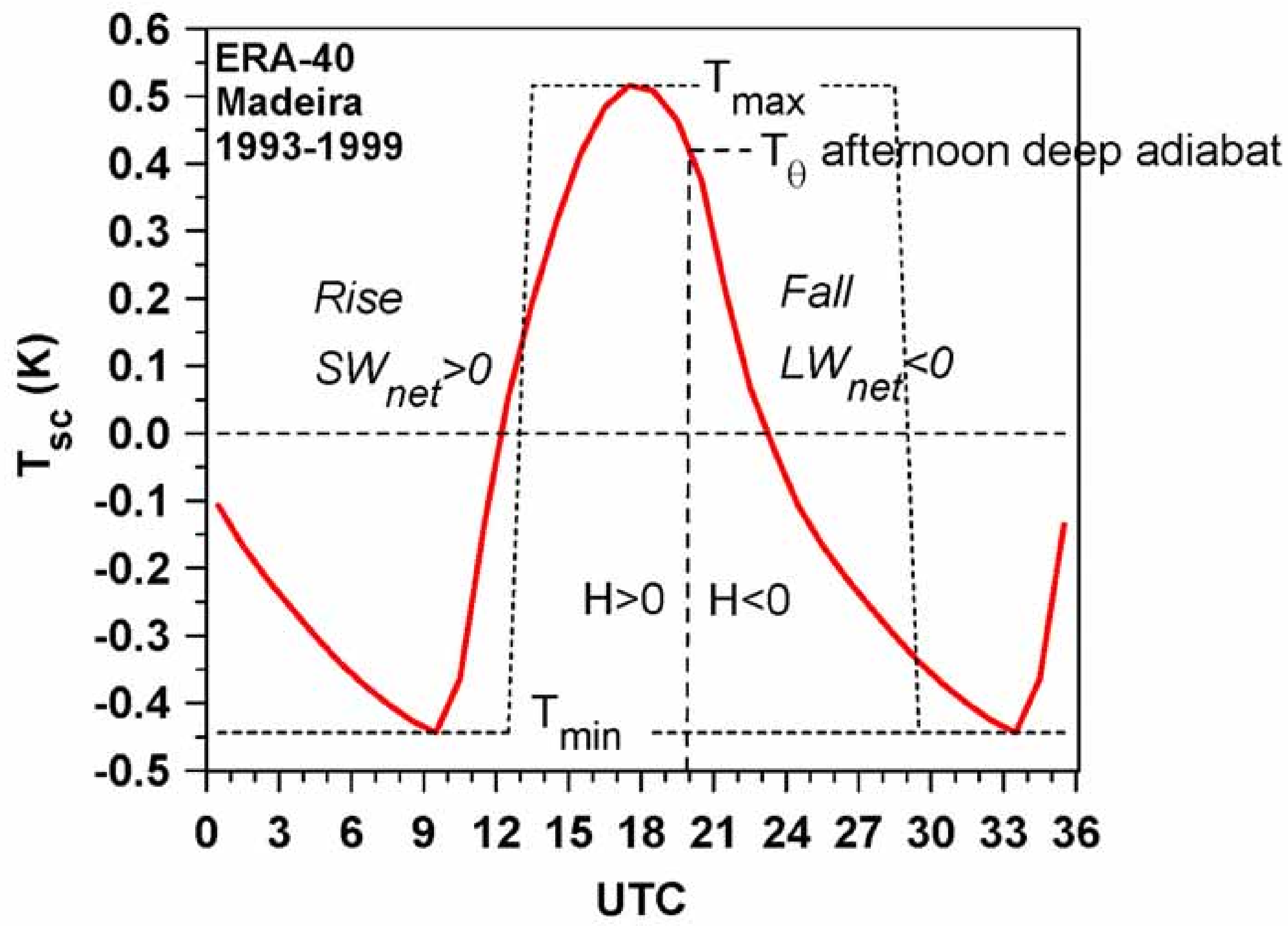
State of our Models: CMIP5

“The diurnal temperature range is found to vary substantially between different CMIP5 models, in particular in the subtropics, and is in general underestimated by the models. In future projections with the high emission scenario, the models disagree on both sign and the magnitude of the change of the diurnal temperature range over land.”

[Lindvall and Svensson, 2012, submitted]

Diurnal Cycle: ERA40

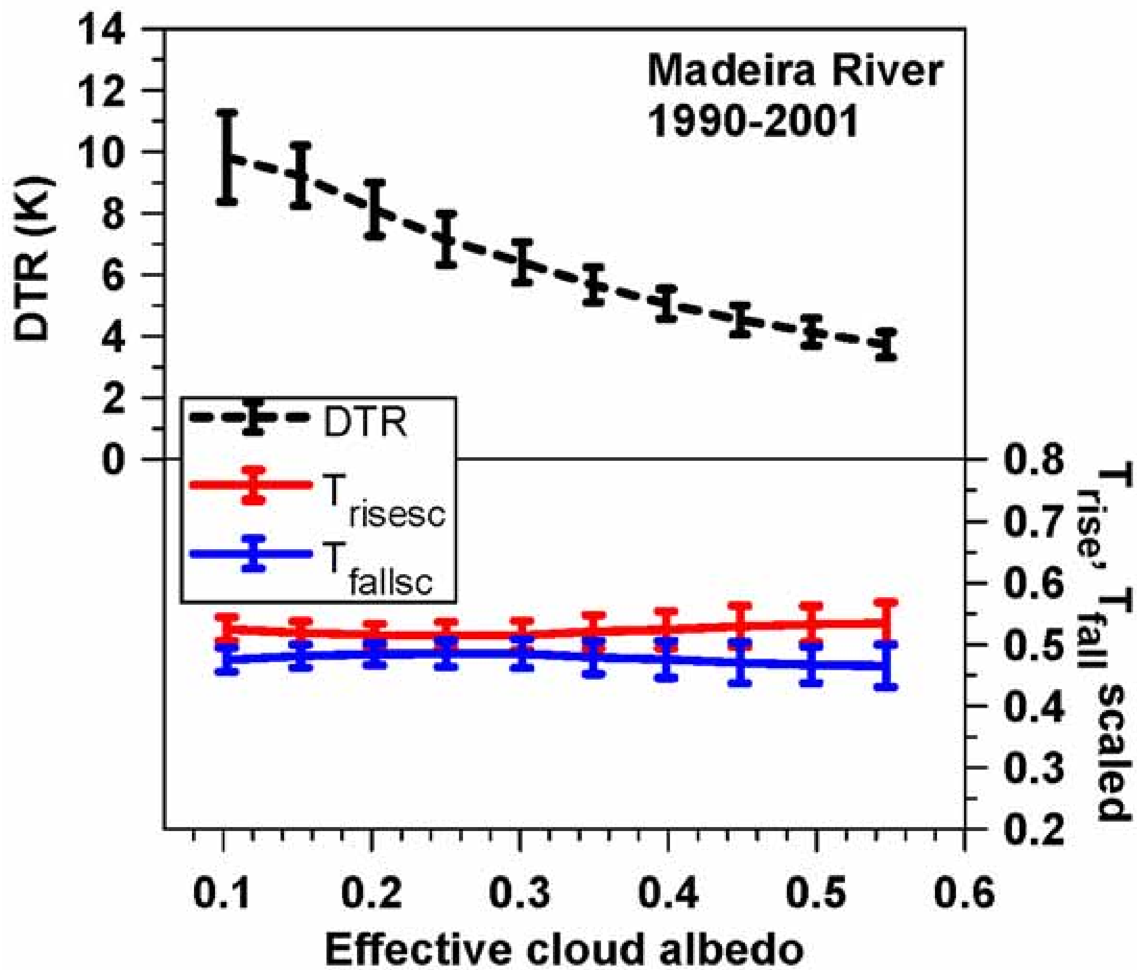
- T_{sc}: scaled by $LW_{net24}/4\sigma T^3$
- Rise: SW_{net} & Bowen Ratio
- Fall: LW_{net}
- Asymmetry
- Both satisfied in coupled system?



Betts (JGR 2006)

Diurnal Temperature Range

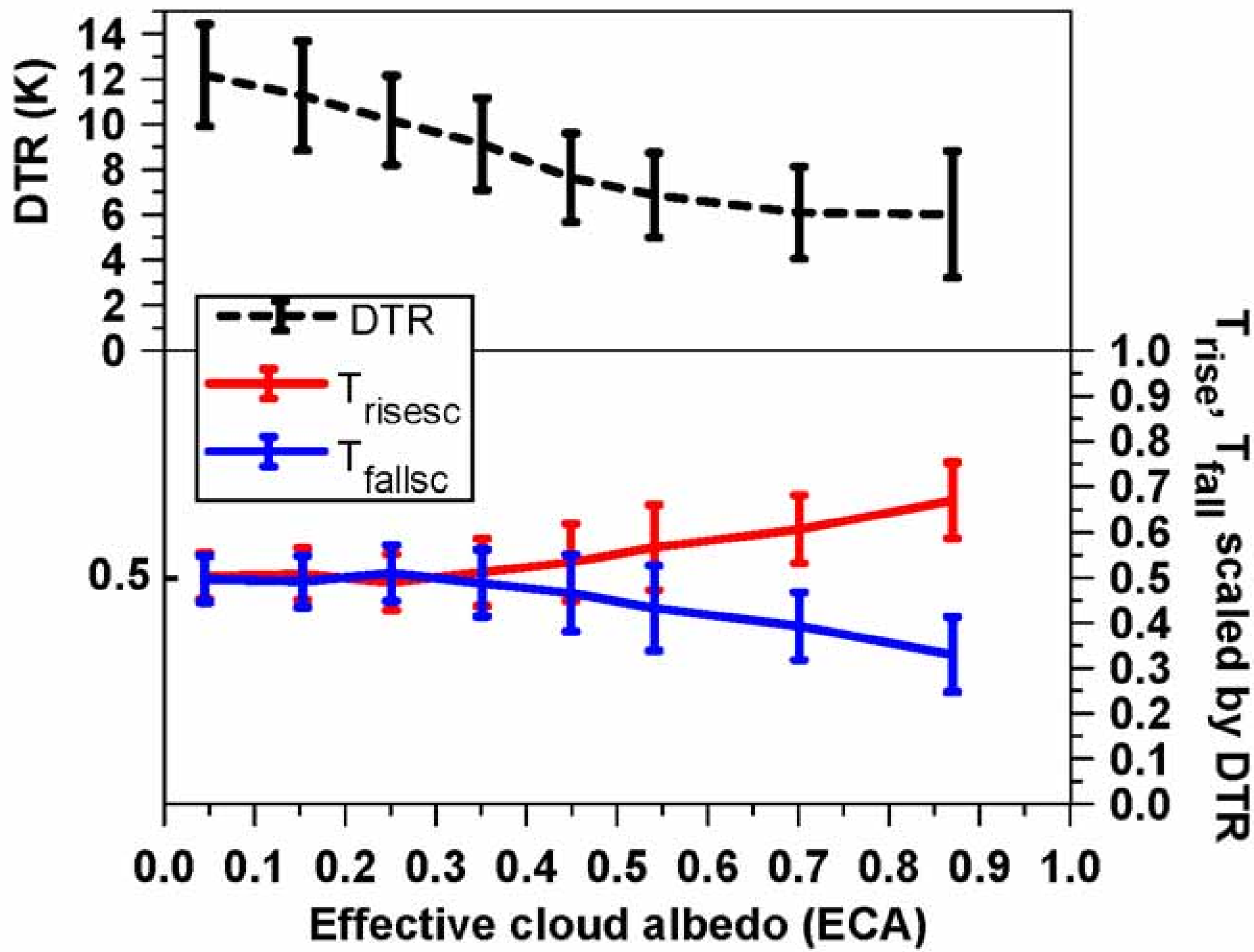
- ***Increasing cloud*: DTR falls**
- $T_{rise} > T_{fall}$ *(DTR Scaled)*
- $T_{mean} < (T_{max} + T_{min})/2$
- *(Zeng & Wang, 2012)*



ERA-40 Madeira River basin

Diurnal Temperature Range

- *Increasing cloud*: DTR falls
- T_{rise} and T_{fall} from T_{mean} become asymmetric
- Scaled $T_{rise} > T_{fall}$



ERA-40 JJA BERMS-SK site

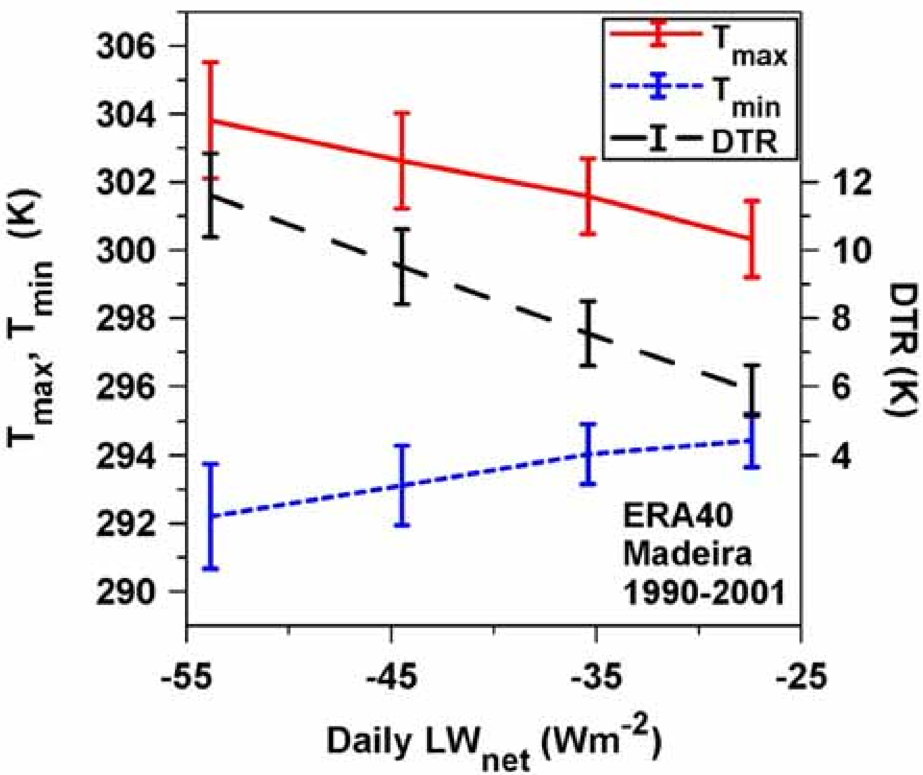
Surface Energy Balance

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

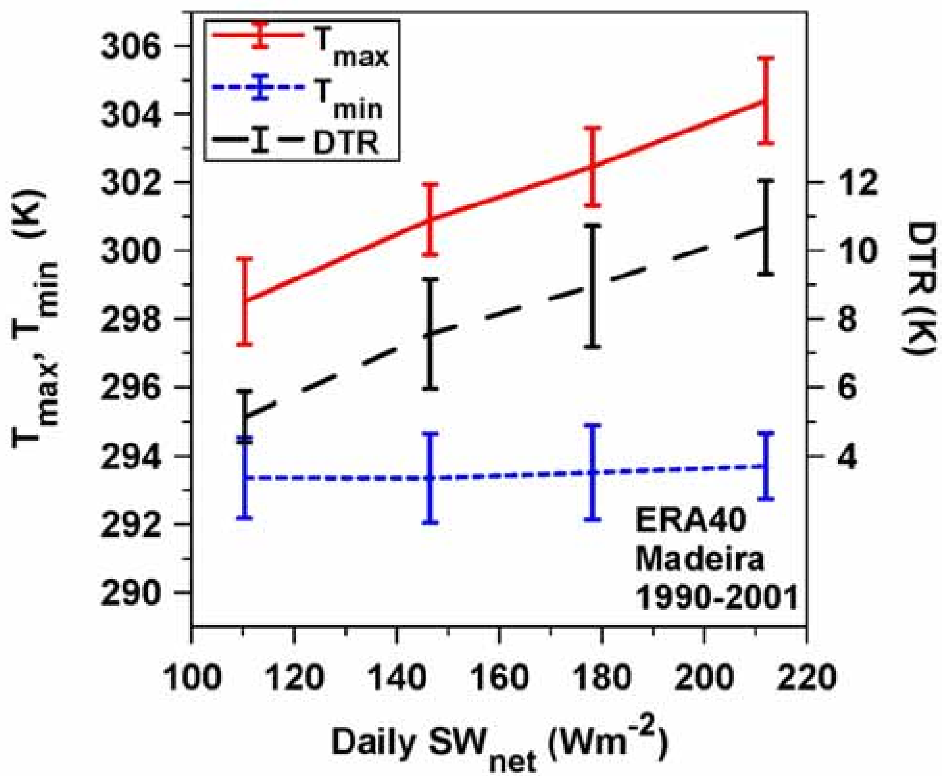
- Surface processes and atmospheric processes
- SW (day) and LW (night) dominate
- Partition between clear-sky and cloud processes in the atmosphere ['cloud forcing']
- Partition of the surface R_{net} into H and λE: availability of water for evapotranspiration

ERA40: T_{max}, T_{min}, DTR

"Night"



"Day"

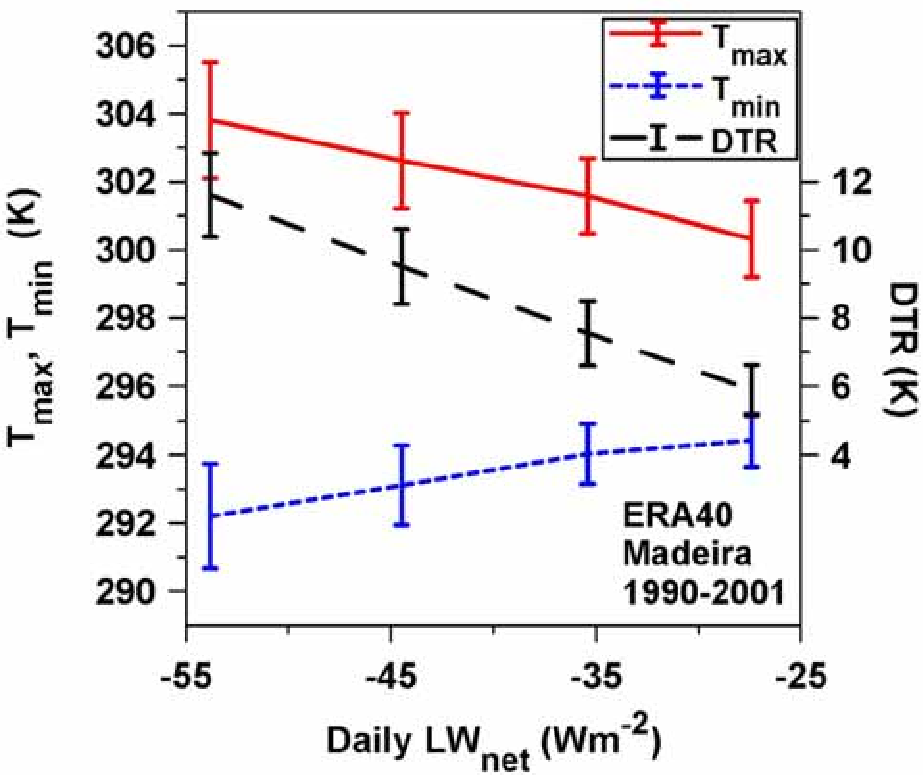


- T_{max}, DTR decrease as LW_{net} gets smaller (moist, cloudy)
- T_{min} increases

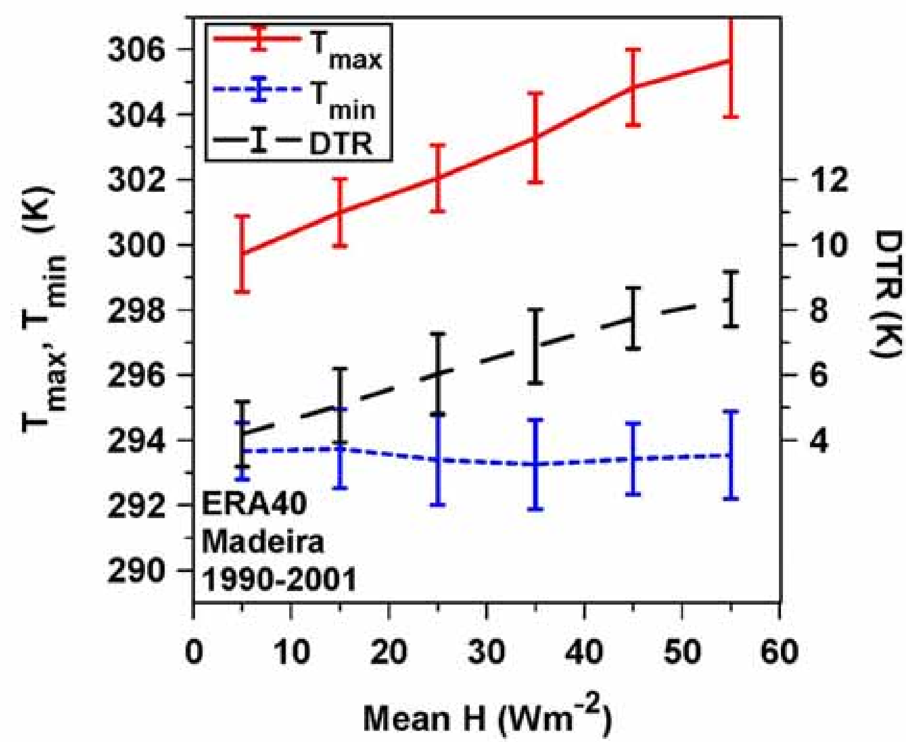
- T_{max}, DTR increase with SW_{net} (dry, sunny)
- T_{min} flat

ERA40: T_{max}, T_{min}, DTR

"Night"



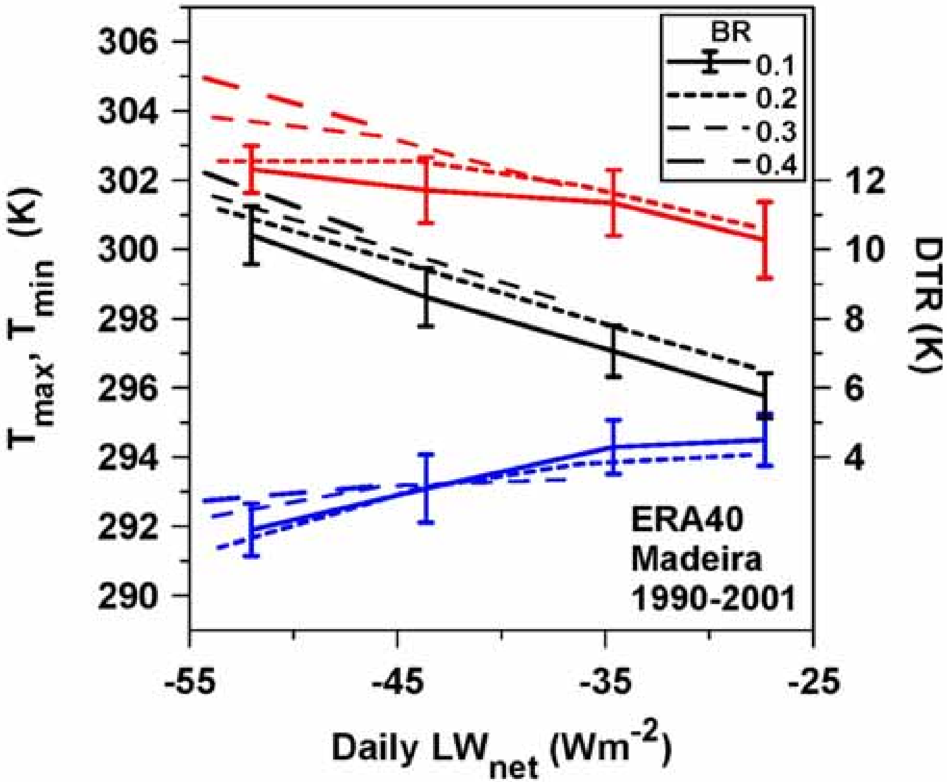
"Day"

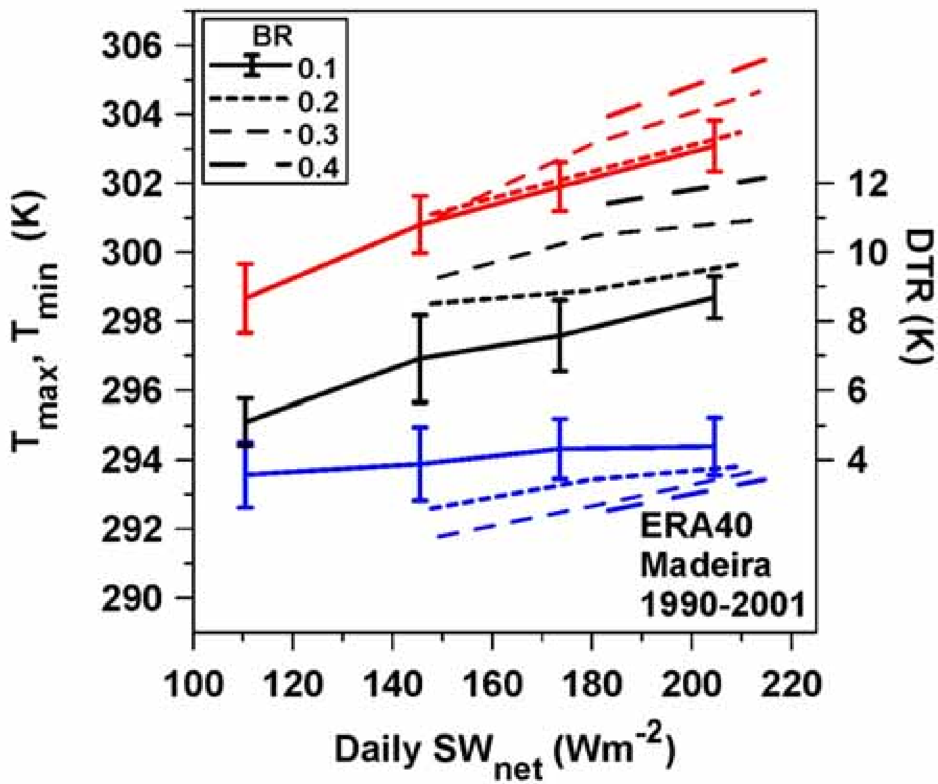


- T_{max}, DTR decrease as LW_{net} gets smaller (moist, cloudy)
- T_{min} increases

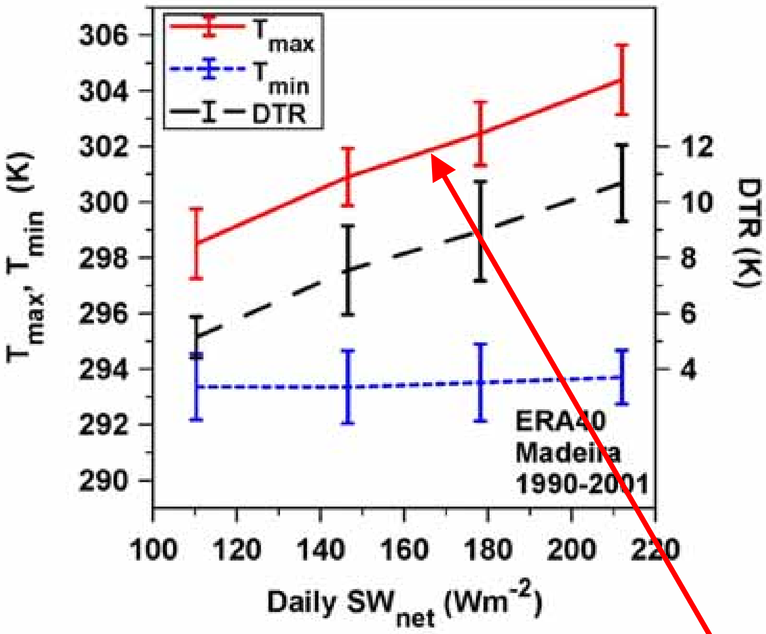
- T_{max}, DTR increase with H (dry, sunny)
- T_{min} flat

Partition by BR = H/λE





- BR impacts T_{max} most
- BR impacts T_{max}, T_{min} and DTR most



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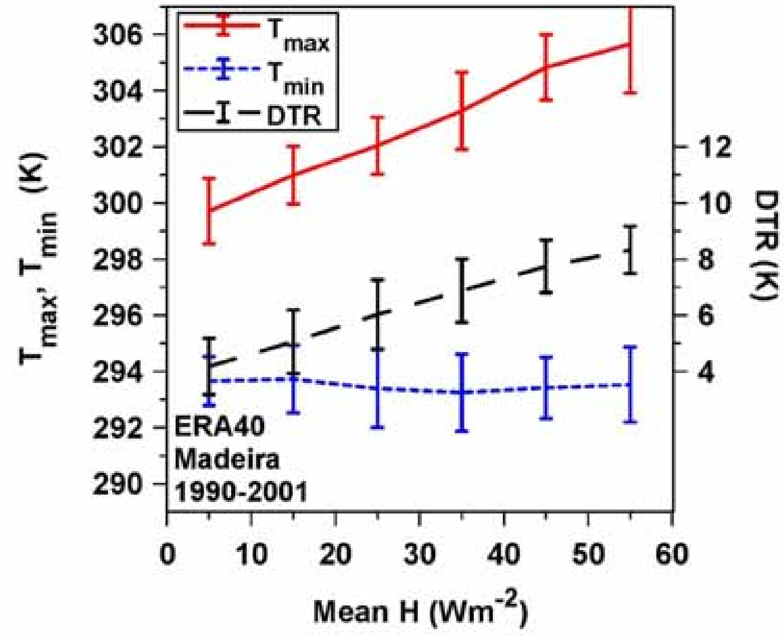
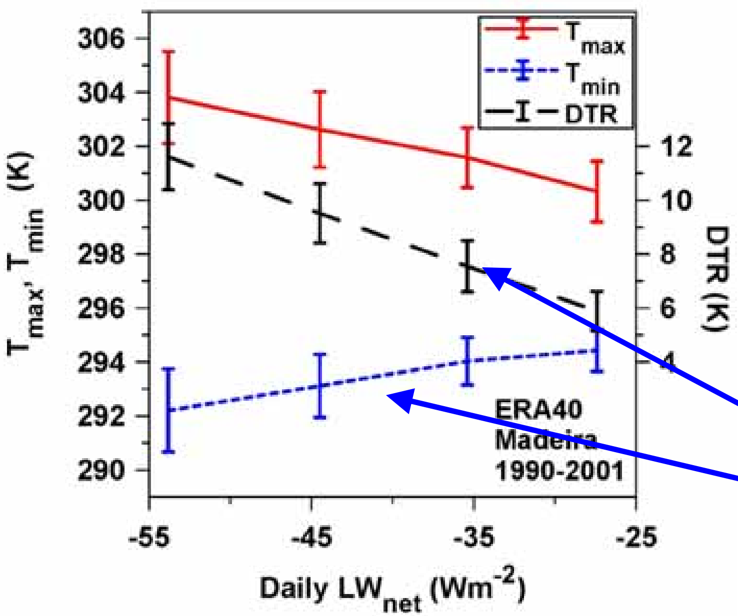




My view of SEB

SW_{net} (or H) dominates T_{max}

LW_{net} dominates DTR, T_{min}

Clouds & Surface SW_{net}

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

Drives T_{max}

- ***surface albedo***

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

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

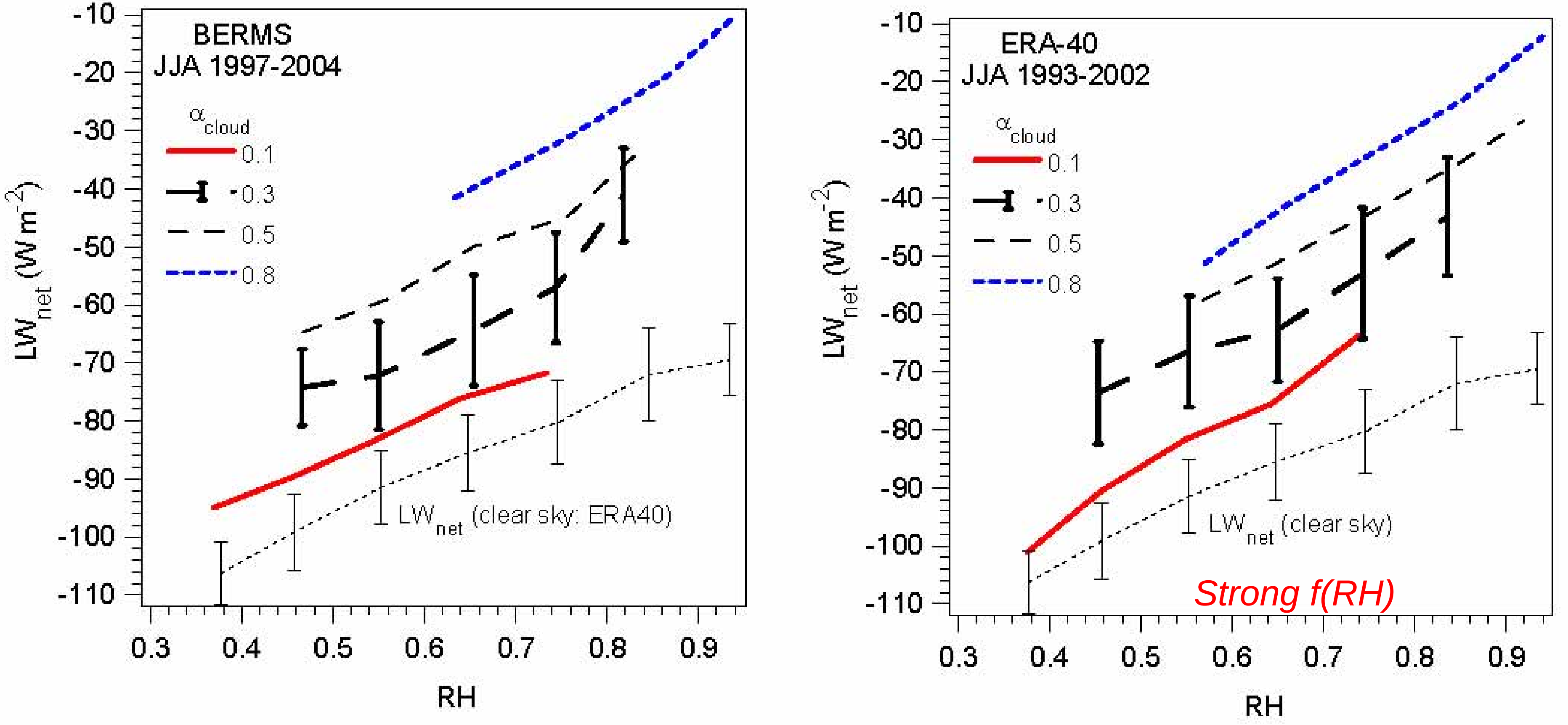
  - scaled surface **short-wave cloud forcing, SWCF**

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

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

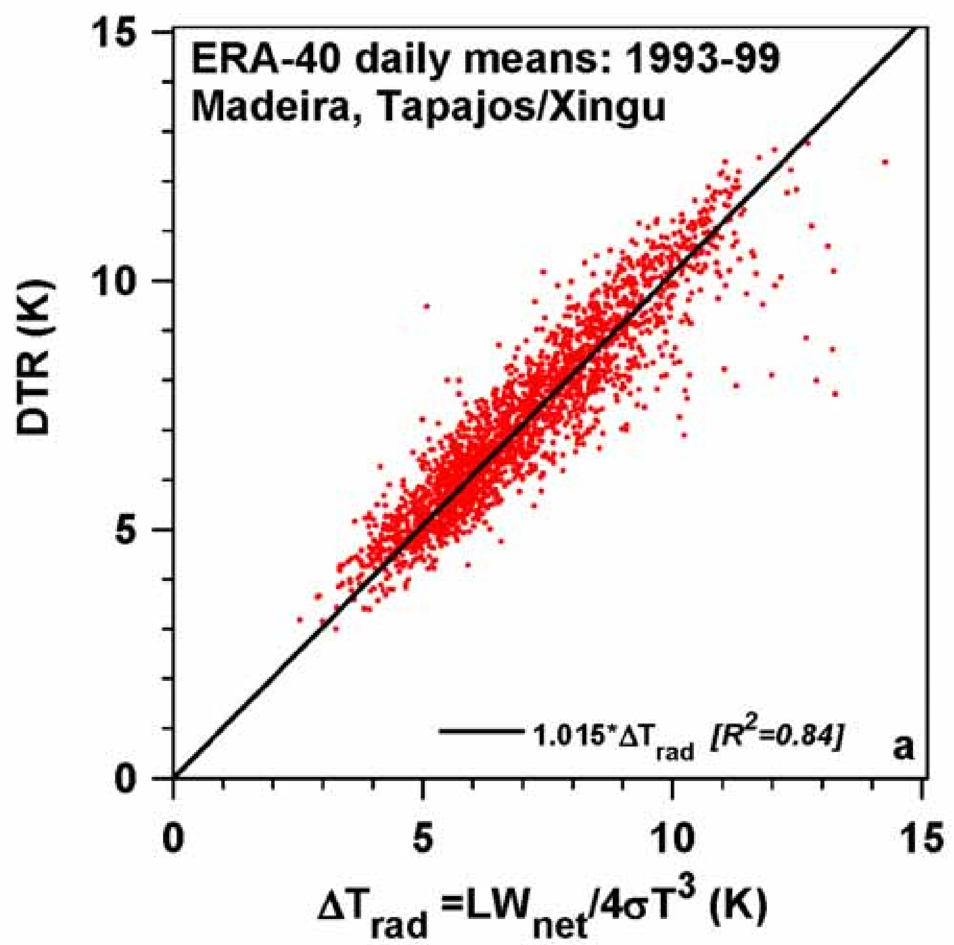
[Betts and Viterbo, 2005; Betts, 2007]

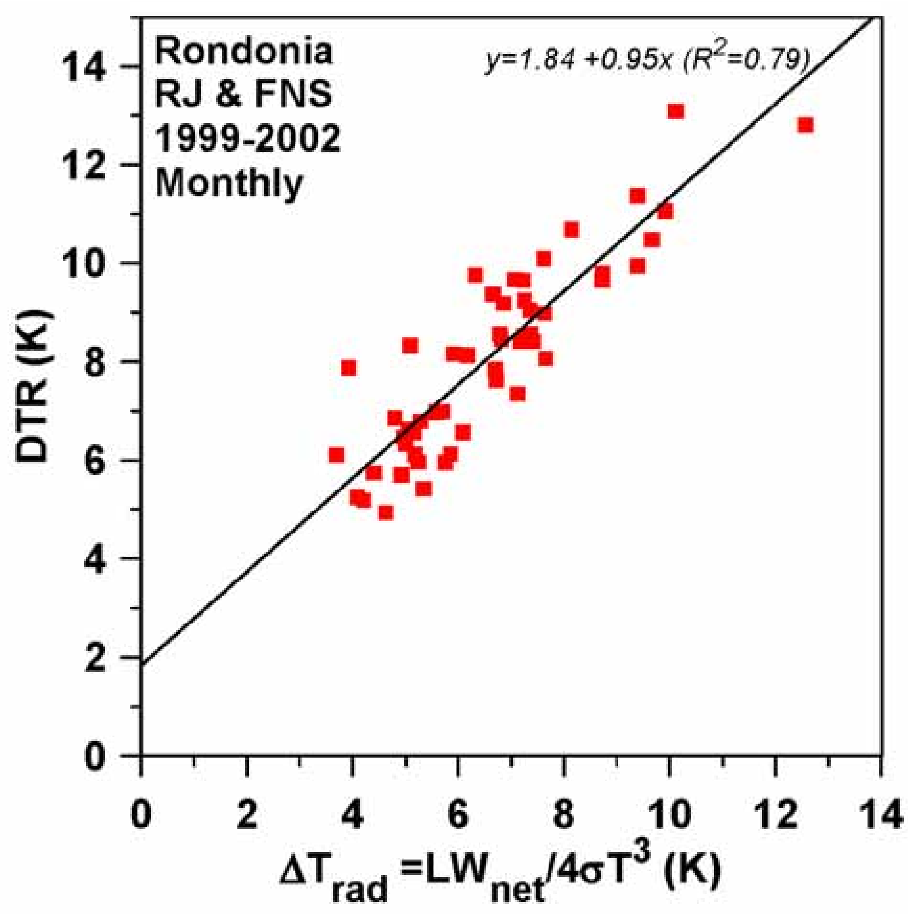
Surface LW_{net}



- **Point comparison: stratified by RH (LCL) & α_{cloud} (ECA)**
- **Quasilinear clear-sky and cloud greenhouse effects**
- **Drives DTR and T_{min}**

LW_{net} - Diurnal Temperature Range ERA-40 & Monthly Flux Tower data



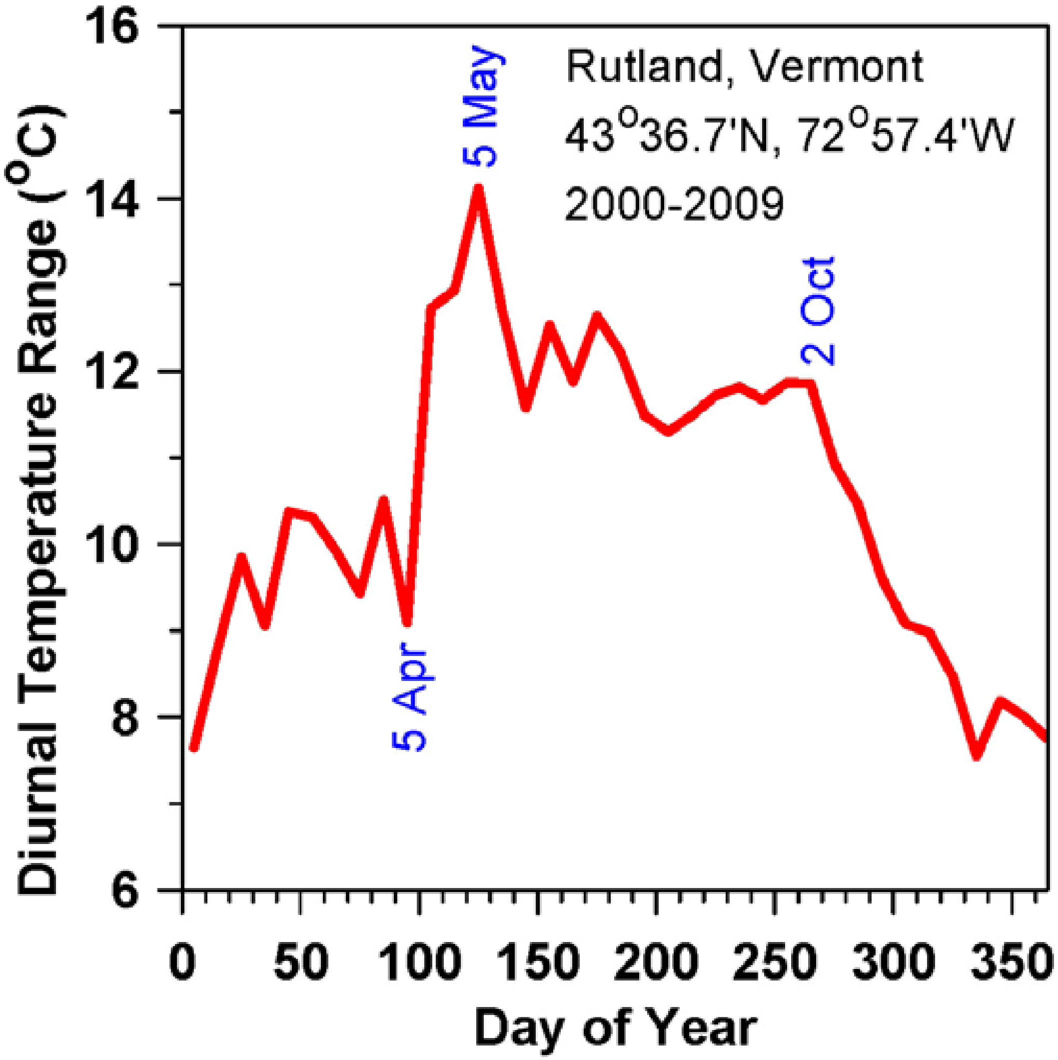


- **Mean LW_{net}, DTR well correlated**

[Betts: JGR, 2006; Betts and Silva Dias, 2010]

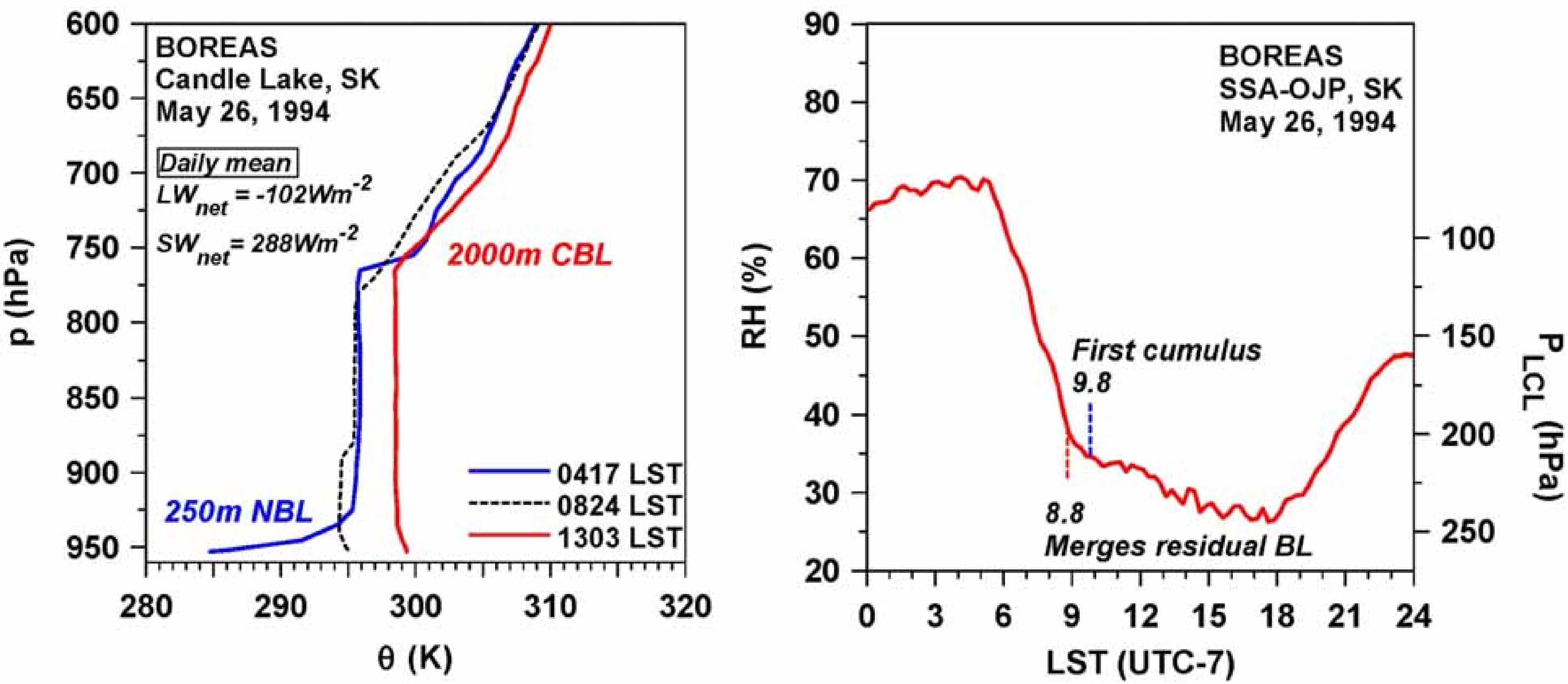
Seasonal cycle of Diurnal Temperature Range (DTR)

- DTR linked to phenology and transpiration
- 5 April: melt, BR high, RH low, clear sky, DTR ↑
- 5 May: forest leaf-out, transpiration, RH, cloud ↑, DTR ↓
- 2 Oct: frost signals forest senescence



[Betts, 2010]

Coupling of RH, ML, LCL, LW_{net}



- **H warms NBL, merges residual BL, forms first cumulus**
- **Shallow cloud transports lock LCL to ML depth**
- **Deep dry BL, large LW cooling gives large DTR (& NBL)**
- **LW cooling of ML balances surface H over 24h**

[Betts, 2003]

Modeling Issues

- **Fully coupled system**
- **Must solve over sequential diurnal cycles with coupled radiation clouds and BL**
- **Even non-precipitating case poorly modeled**
- **Critical measurable parameters are cloud-base, f(θ,q), and cloud-fraction/optical depth, which determine SWCF/ECA**

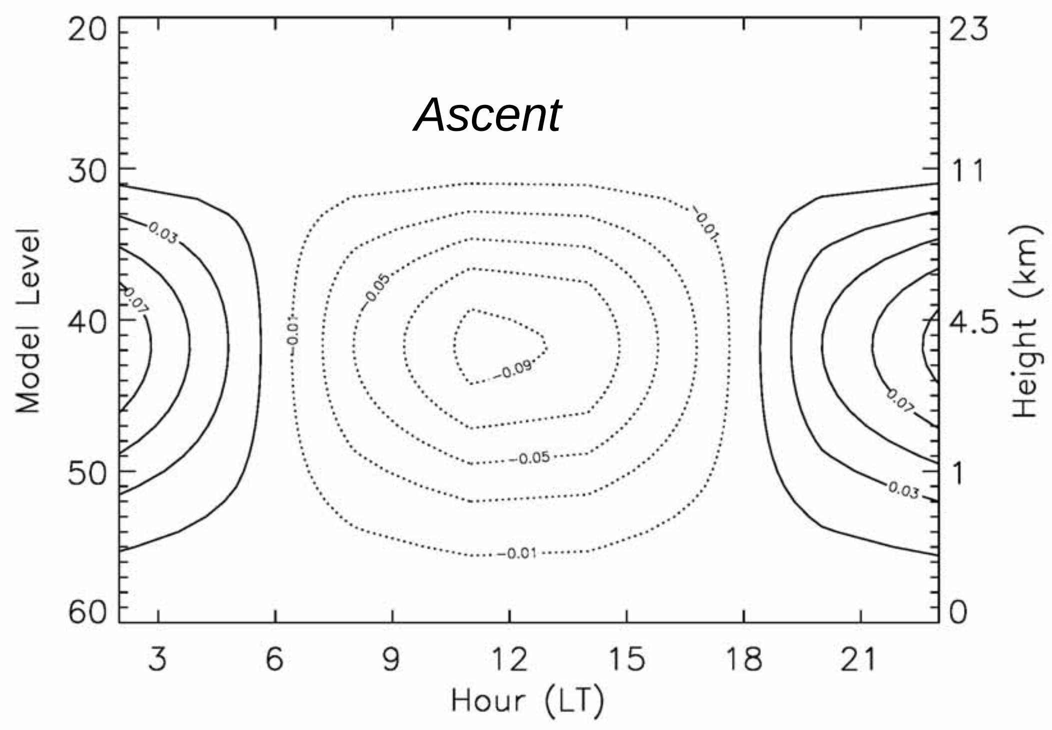
Forced SCM – All Model Physics (Amazon)

ECMWF SCM

Initial conditions:
Grid-point in Rondônia
Forcing
Idealized Diurnal Omega, single tropospheric mode

Φ=0 : subsidence at midnight
M=0 : zero mean ascent
A=2 : 2x 0.05 Pa/sec

Forced SCM run of 15 days
Average day 2-15
Quasi-equilibrium diurnal cycle, all model processes, specified vertical advection, no horizontal advection



[Betts and Jakob, JGR 2002b]

14-day Coupling: Fluxes and Precip.

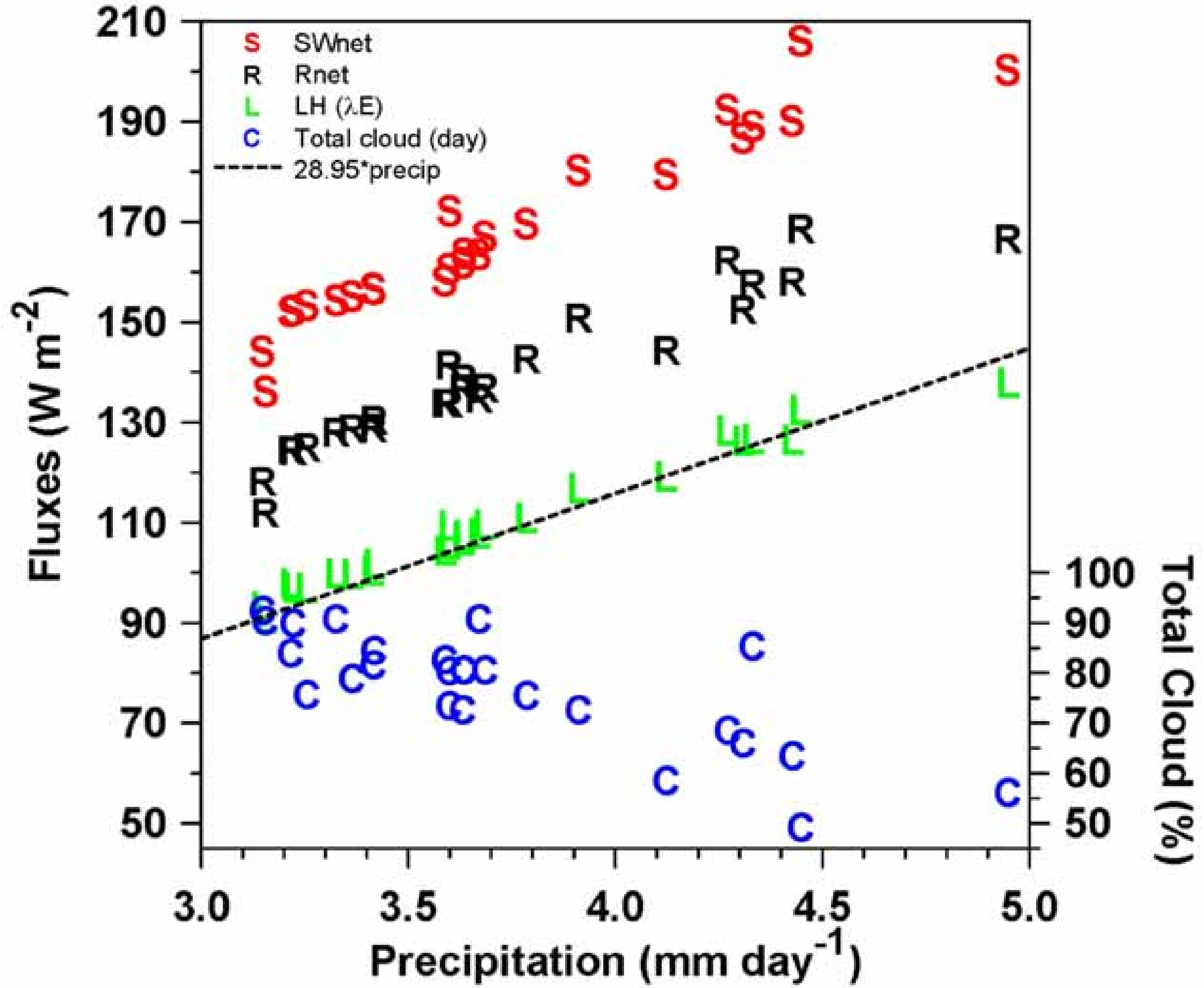
14-day mean fluxes and cloud cover against precipitation

For M=0 (no mean ascent)
Amplitude A=0, 1, 2, 4
Phase Φ from 0 to 21

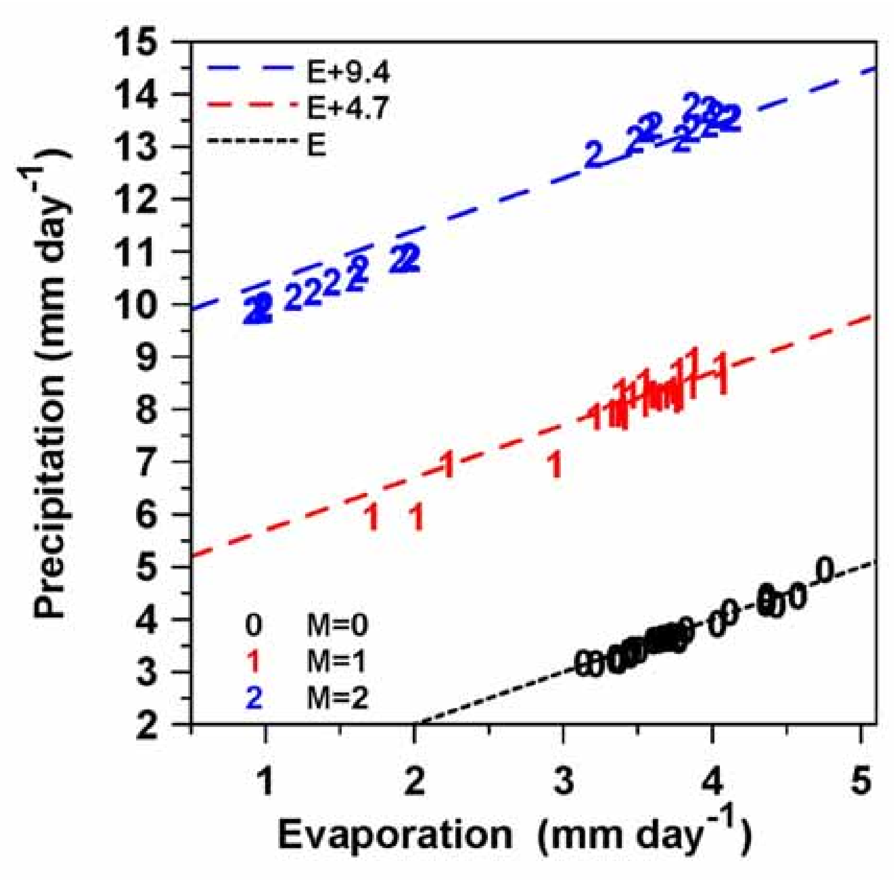
LH (λE) determines precip - 1:1 line shown

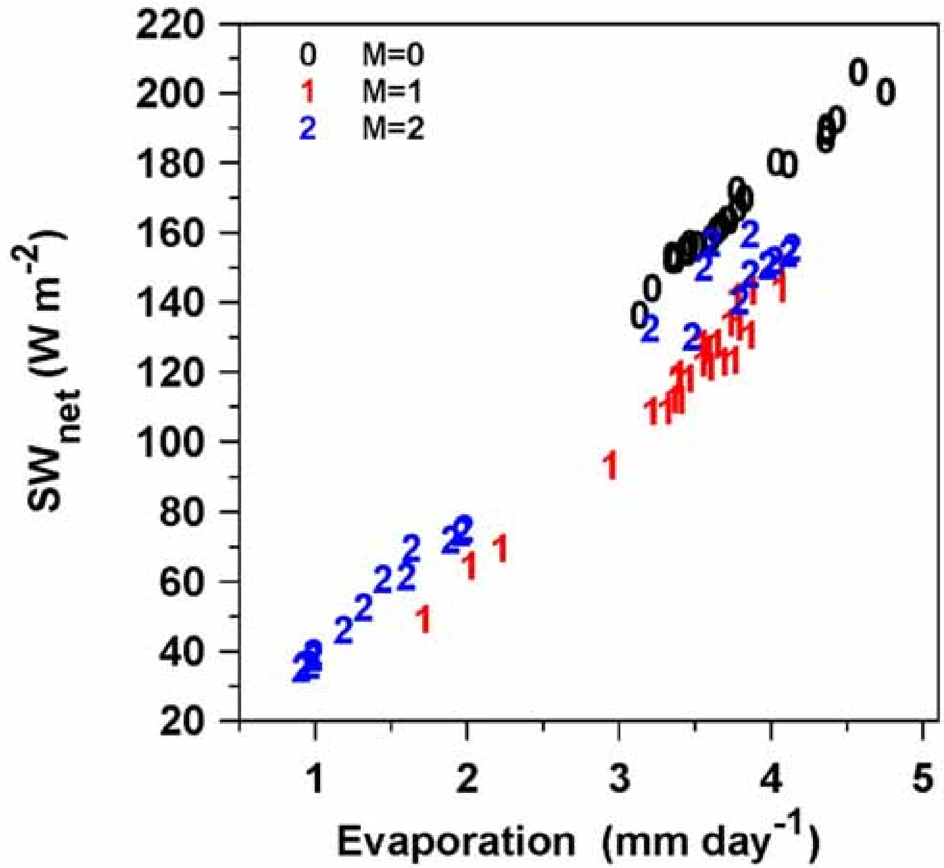
Cloud cover determines SW_{net}, R_{net} and LH

Diurnal phase of omega forcing determines SW cloud forcing



Impose Mean Ascent





Banded data as mean ascent forcing M = 0,1, 2 increases

For M=2, split modes

-daytime ascent gives stratiform precipitation, high cloud cover

-daytime subsidence gives convective precipitation, low cloud cover

Split Modes - Phase of Forcing

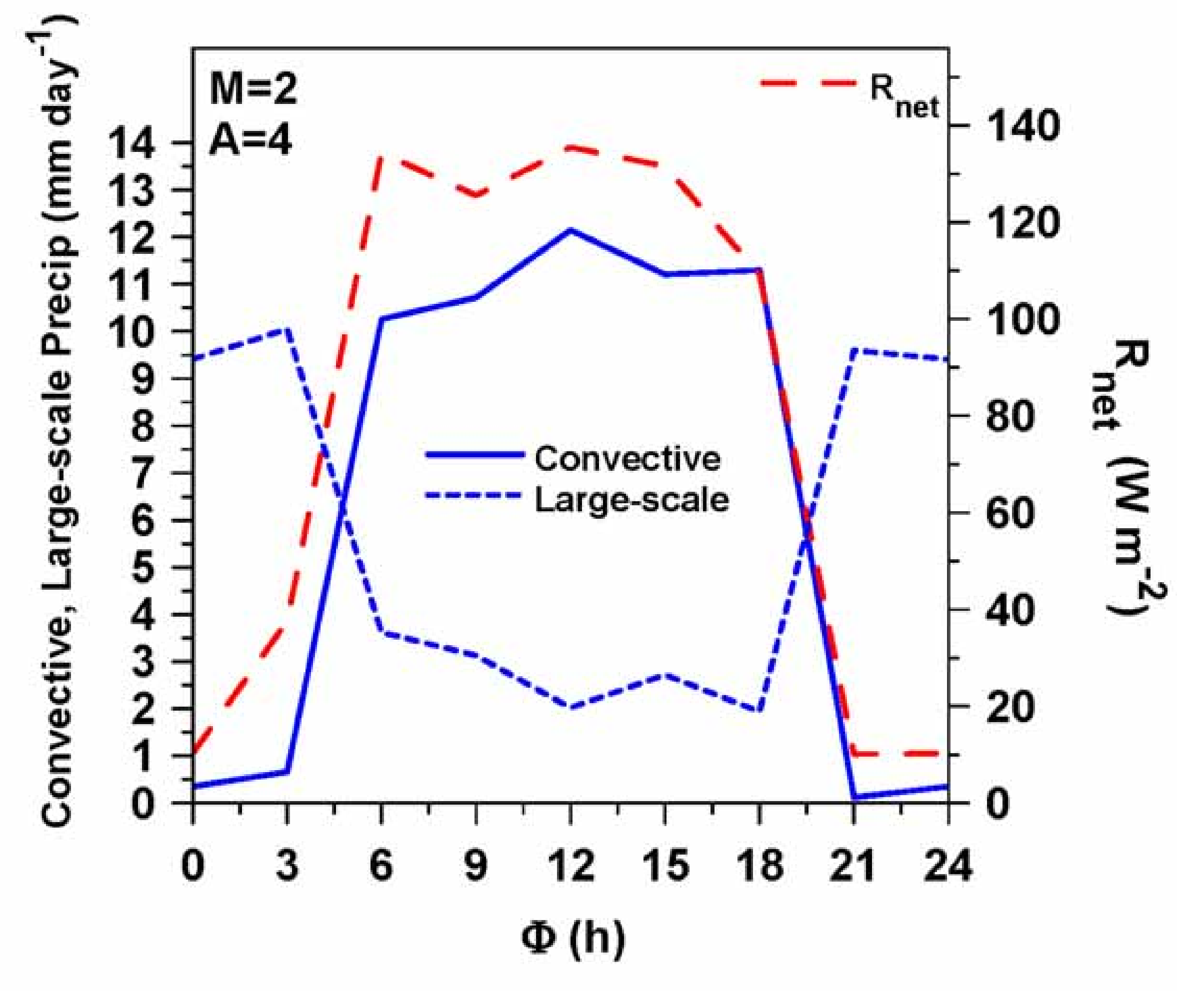
Daily Means:
M=2, A=4

Daytime subsidence:

Φ= 6 to 18 gives
High R_{net} and
Daytime convective rain

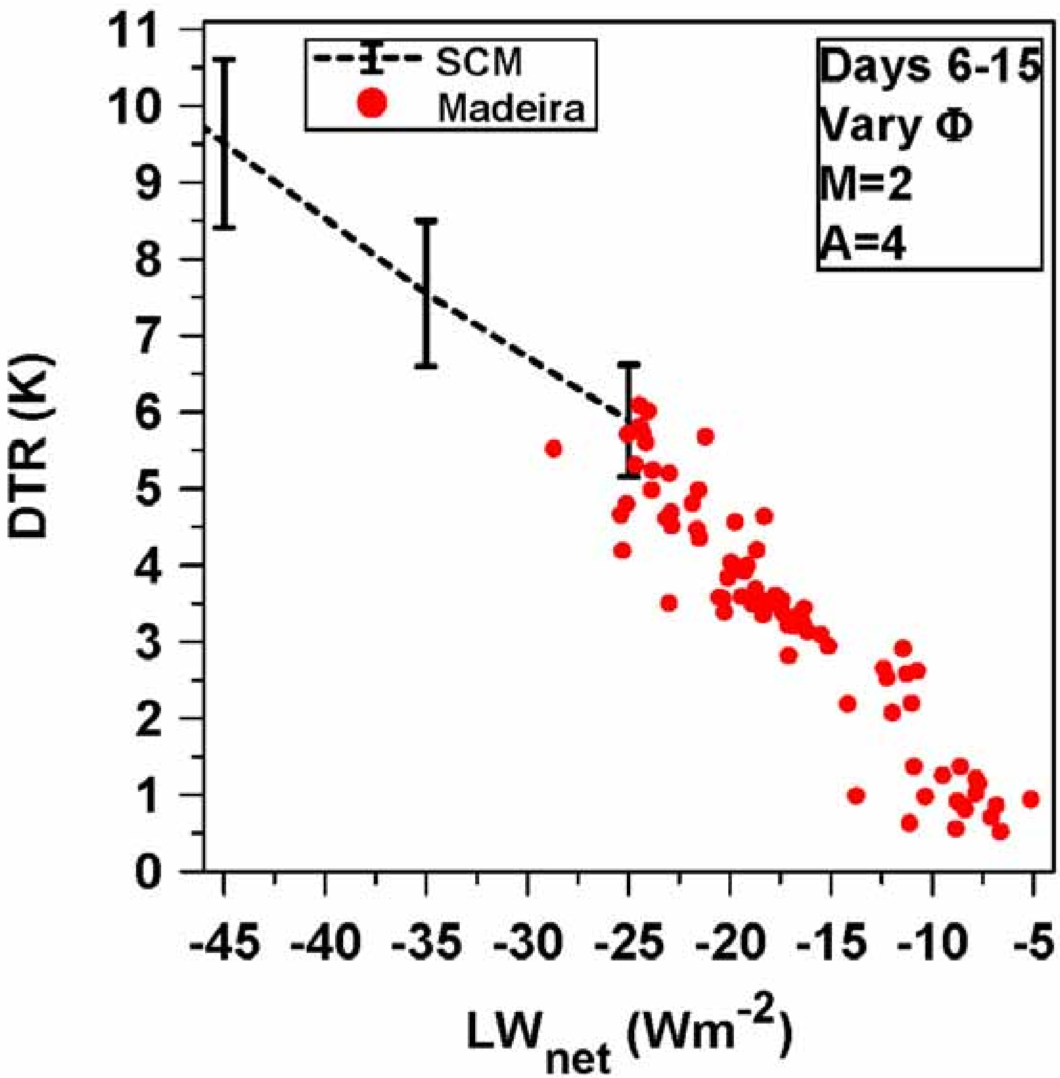
Daytime ascent:

Φ= 21, 0 and 3 gives
Low R_{net} and
Daytime stratiform rain

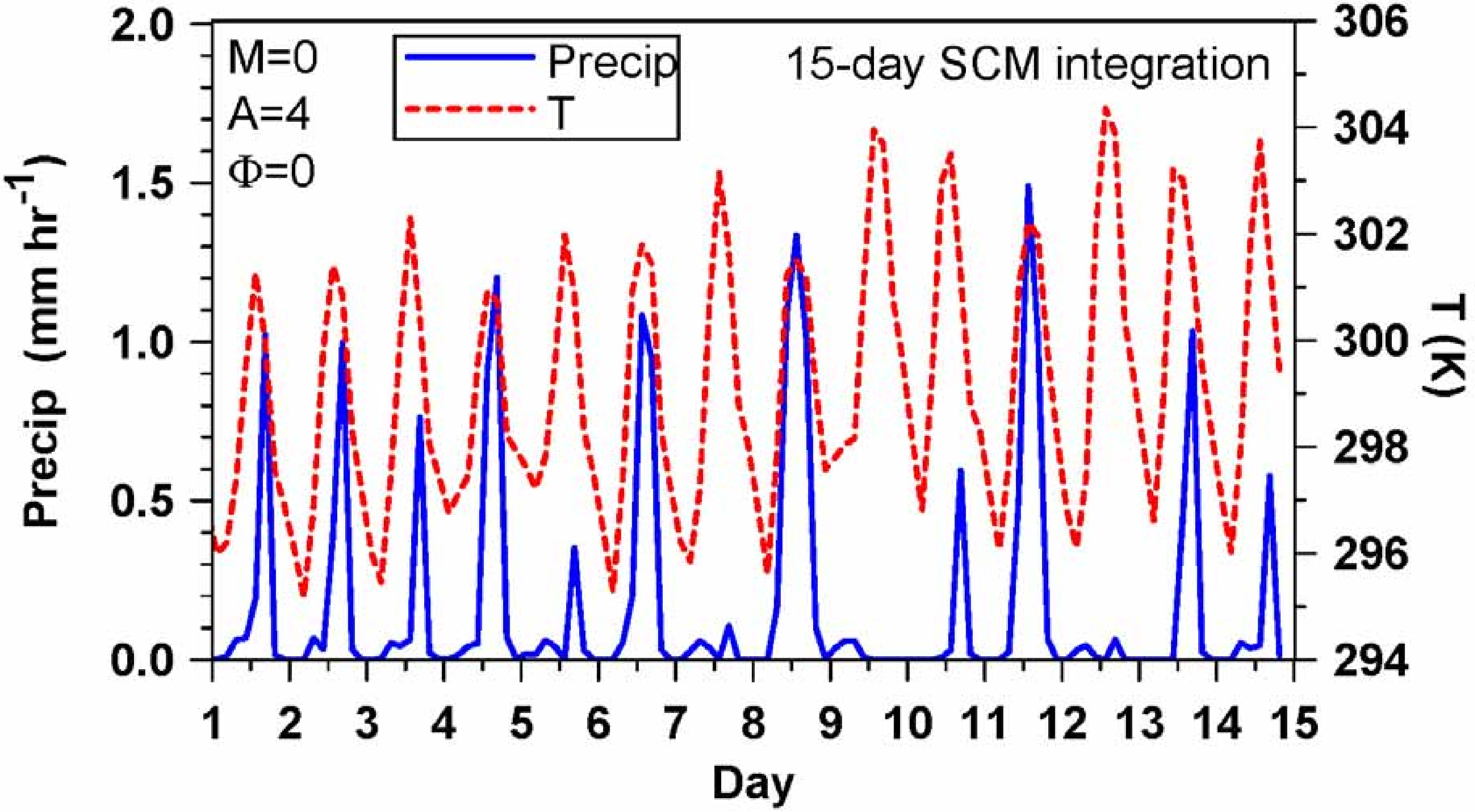


DTR on LW_{net}

- ERA-40 basin means
- Non-equil. SCM



Complex Diurnal Modes



- **Quasi-2day precipitation modes reflected in DTR (and other variables)** ***[for M=Φ=0; A=4]***

Modeling Issues

- **Fully coupled system**
- **Must solve over sequential diurnal cycles with coupled radiation, clouds and microphysics**
- **Precipitation, cloud and surface radiation sensitive to forcing and its phase**
- **Critical measurable parameters are cloud-base, cloud-fraction, cloud forcing, incoming radiation and precipitation**
- **"CMIP5 models disagree on both sign and the magnitude of the change of the diurnal temperature range over land"**