Ecosystem-land-surface-BL-cloud coupling as climate changes

Alan K. Betts

Atmospheric Research,
akbetts@aol.com

CMMAP

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Outline of Talk

- **Land-surface climate:**
  - surface, BL & cloud coupling

1) LBA data: Jaru forest & Rondonia pasture
   - BL-cloud-radiative flux coupling

2) Idealized equilibrium model:
   - forest and grassland; double CO_2
   - impact on BL cloud, NEE and temperature

References

- Betts, A. K. (2007), Coupling of water vapor convergence, clouds, precipitation, and land-surface processes, *J. Geophys. Res., 112*, D10108, doi:10.1029/2006JD008191.
- Betts, A. K. (2009), Land-surface-atmosphere coupling in observations and models. *J. Adv. Model Earth Syst., Vol. 1, Art. #4*, 18 pp., doi: 10.3894/JAMES.2009.1.4 http://adv-model-earth-syst.org/index.php/JAMES/article/view/v1n4/JAMES.2009.1.4
- Betts, A. K. (2009), Idealized model for changes in equilibrium temperature, mixed layer depth and boundary layer cloud over land in a doubled CO_2 climate. *J. Geophys. Res.* (submitted), 2009JD012888

Land surface climate

- **Highly coupled system: mean state + diurnal cycle**
  - **Surface processes**: evaporation & carbon exchange
  - **Atmospheric processes**: clouds & precipitation; ω
- Clouds have radiative impact on SEB in both shortwave and longwave
- Precipitation affects RH and LCL
- Clouds are **“observable”,** but are **poorly modeled**
- **Quantify by scaling shortwave cloud forcing as an “effective cloud albedo”**

"Cloud Albedo"

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

- *surface albedo*

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

- *effective cloud albedo*
  - a **scaled surface short-wave cloud forcing, SWCF**

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

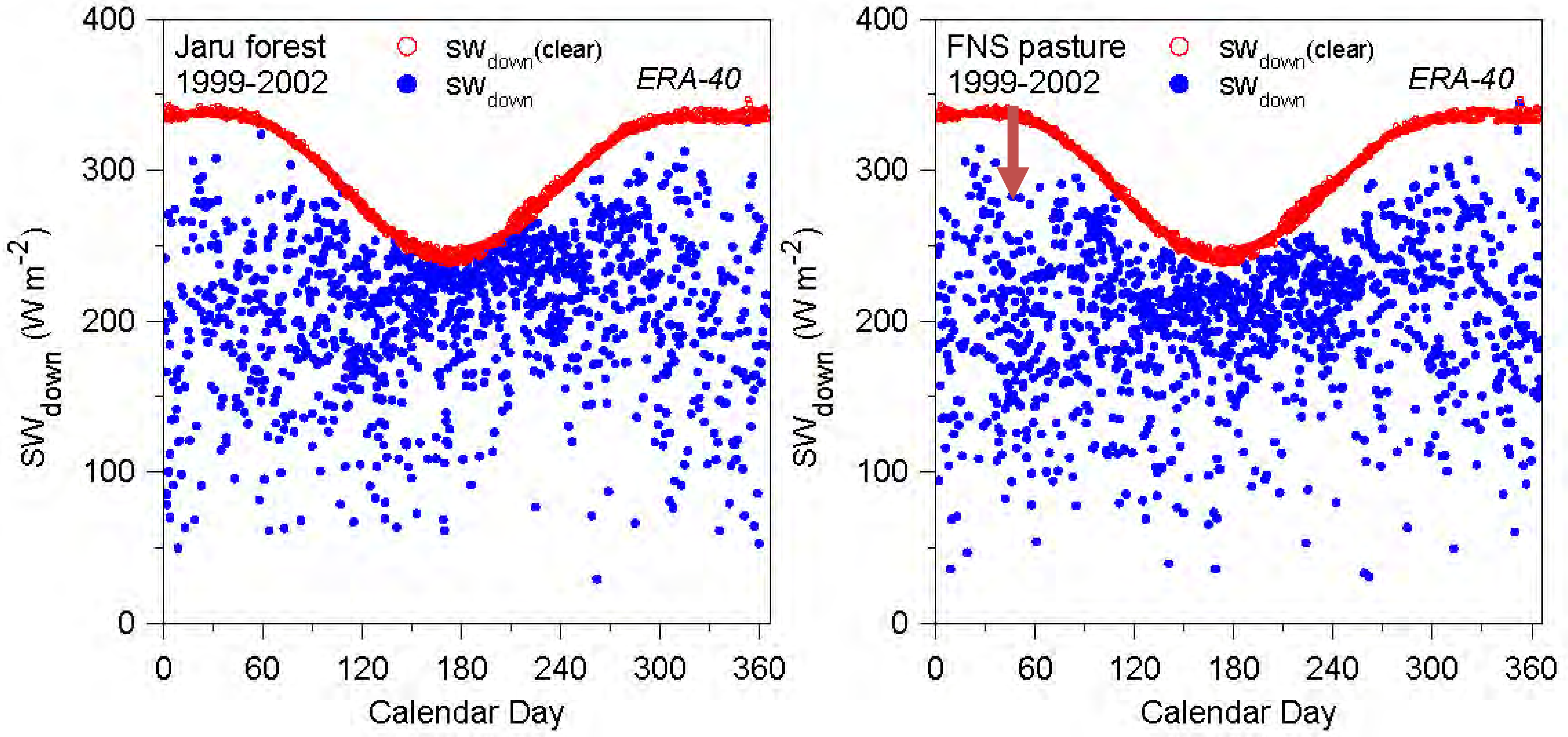
where

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

[Betts and Viterbo, 2005; Betts, 2007]

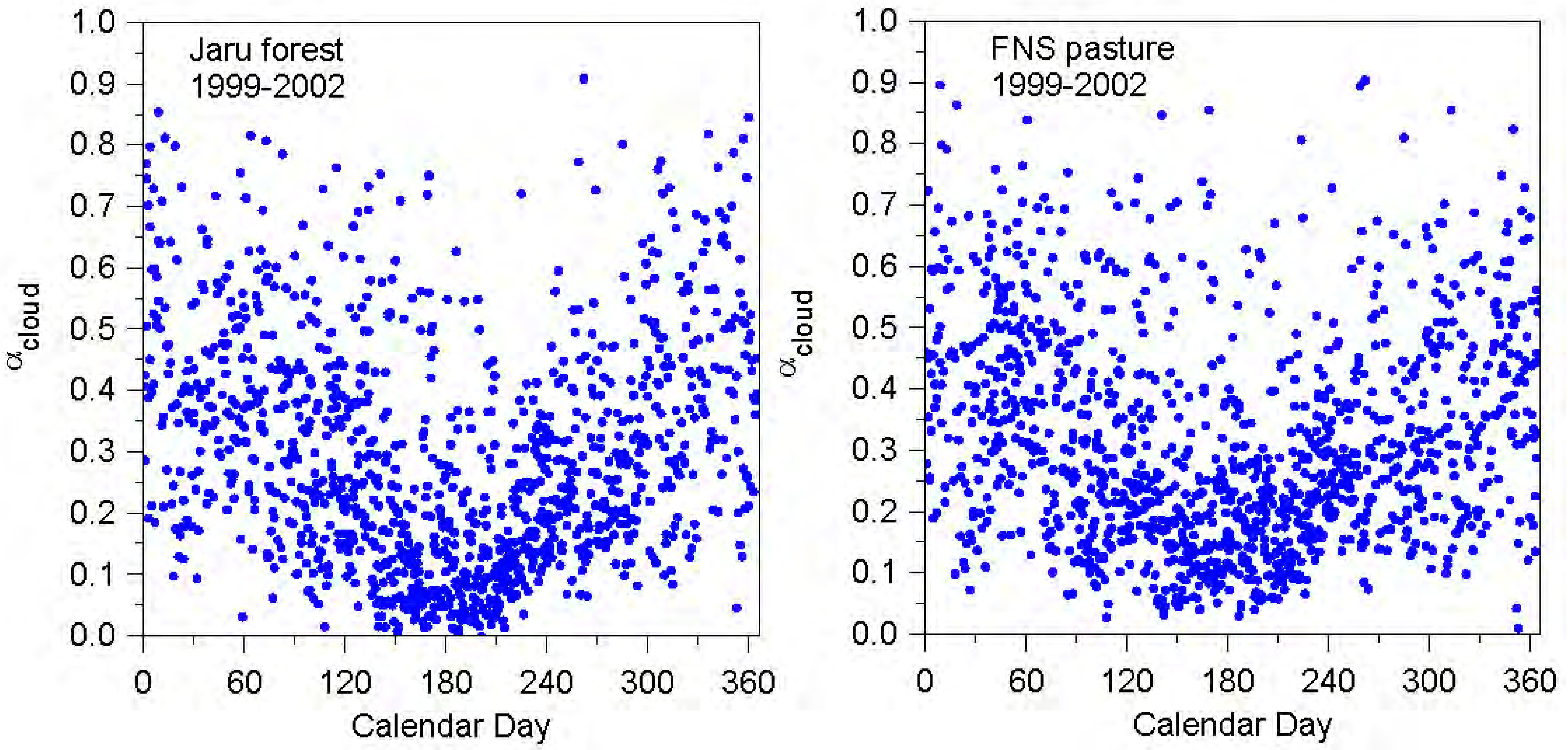
Jaru forest & Rondonia pasture : SWCF

[daily mean data: von Randow et al 2004]



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

Jaru forest & Rondonia pasture - transformation to α_{cloud}



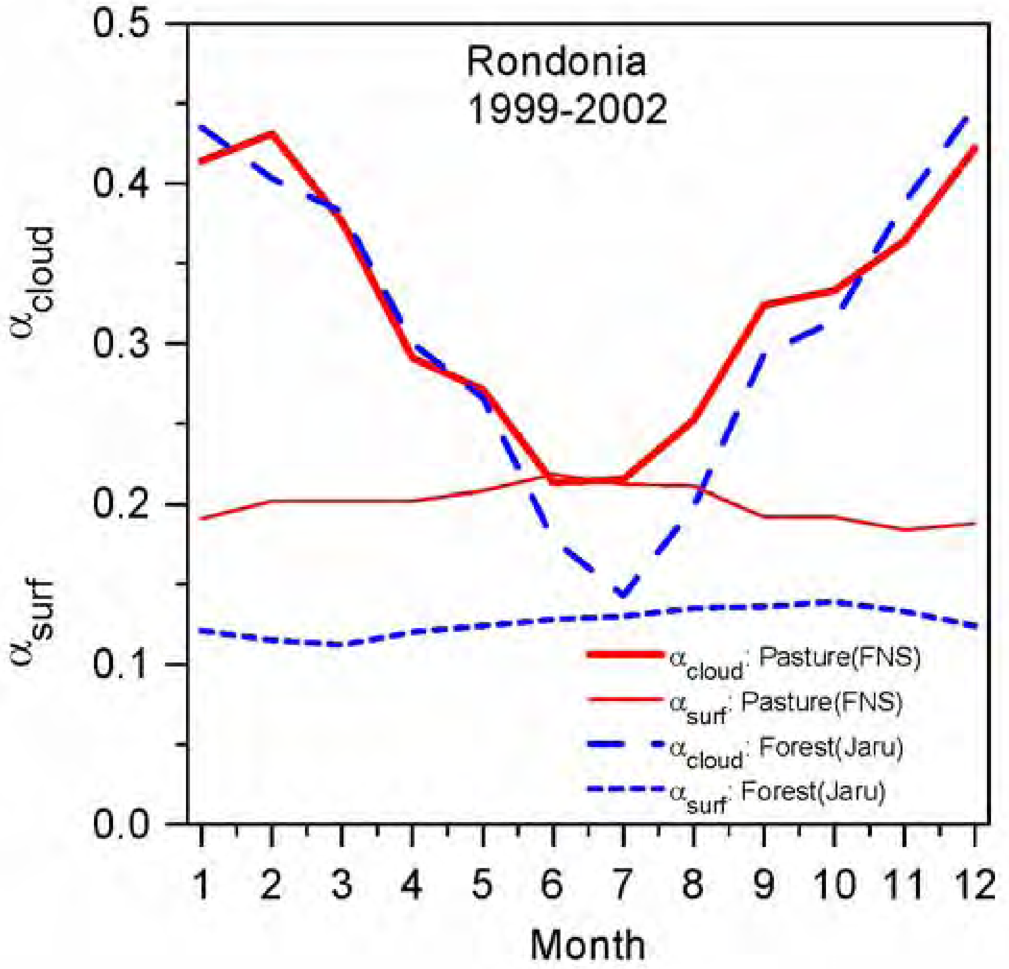
- More cloud over pasture in dry season

SW energy balance: forest and pasture

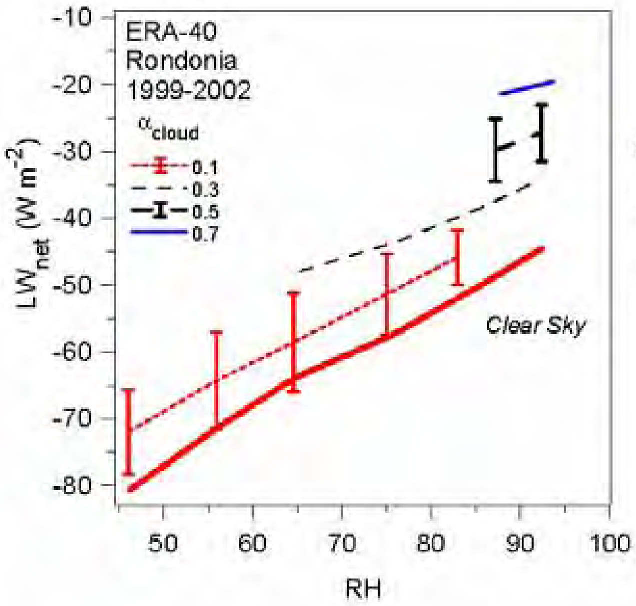
- Pasture in July, has

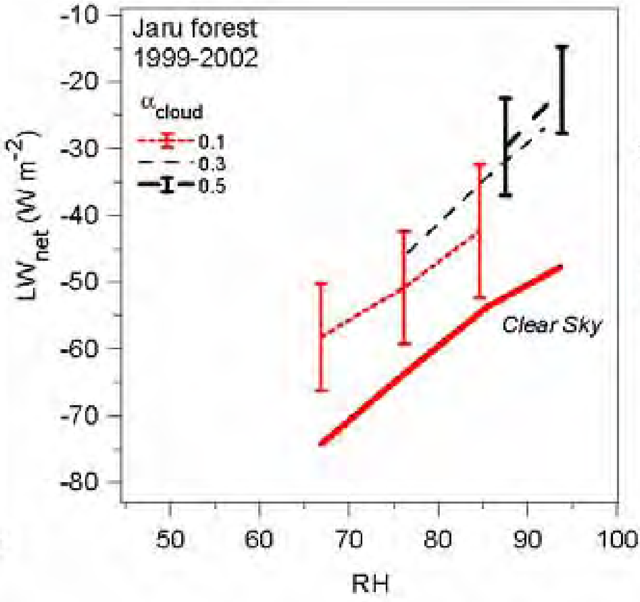
  +8% surface albedo

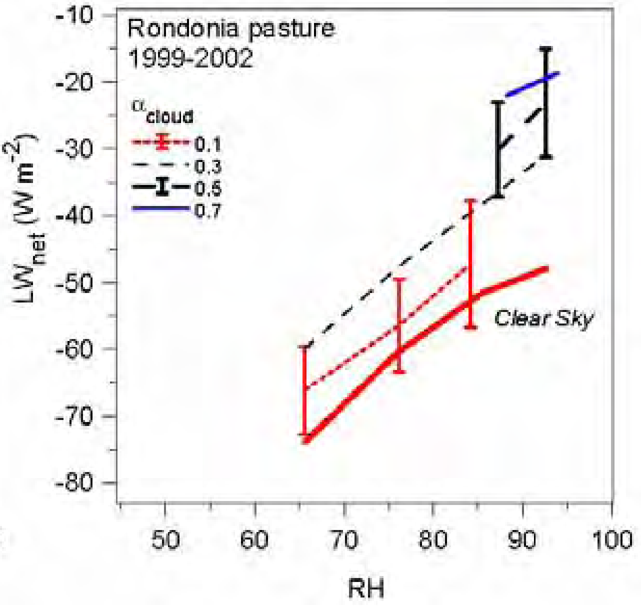
  +7% cloud albedo



RH & cloud → LW_{net}



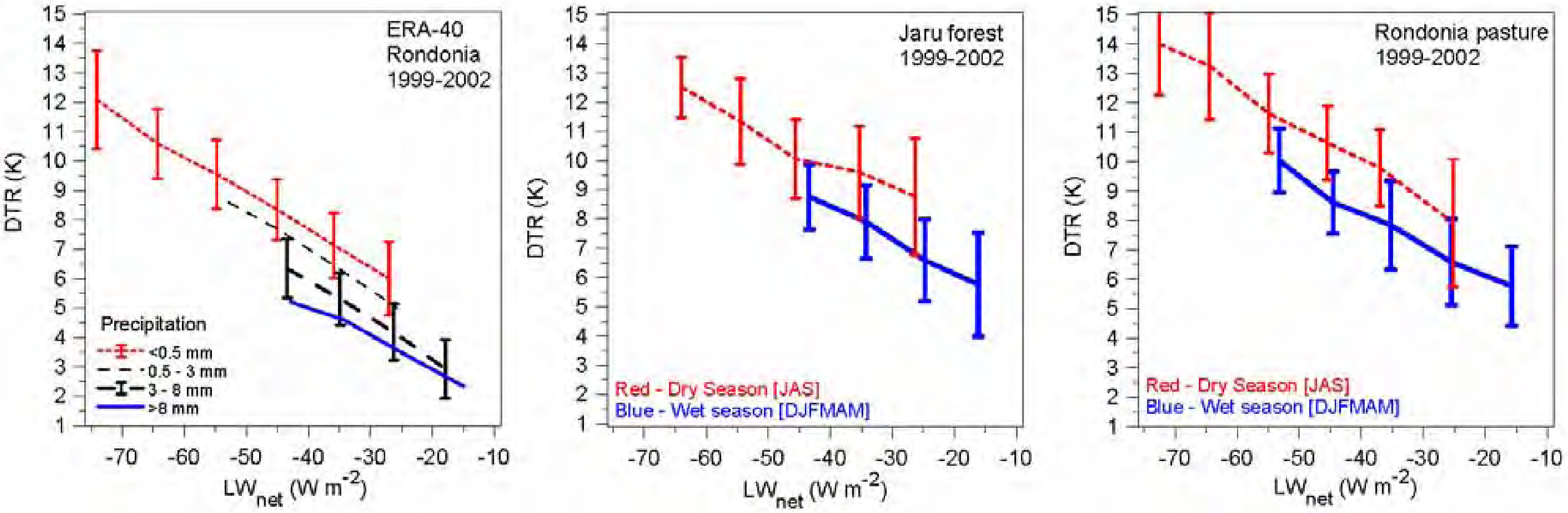




- ERA40 “point”; Jaru tower & Rondonia pasture
- Broadly similar [ERA-40 has ‘drier’ data]
- Humidity and cloud greenhouse effects

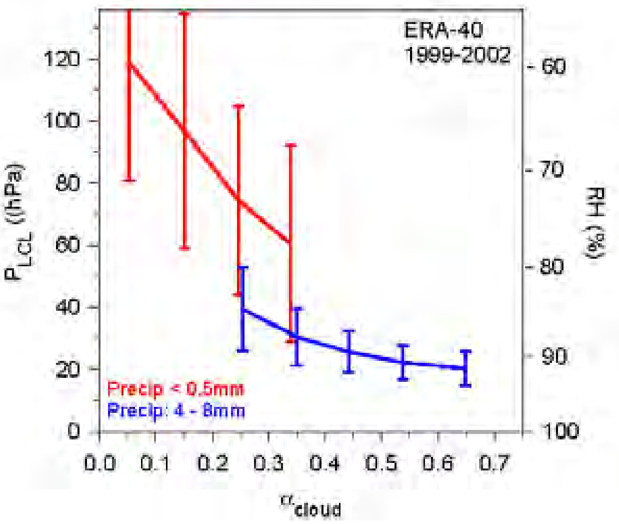
[ERA-40 calculations for clear sky]

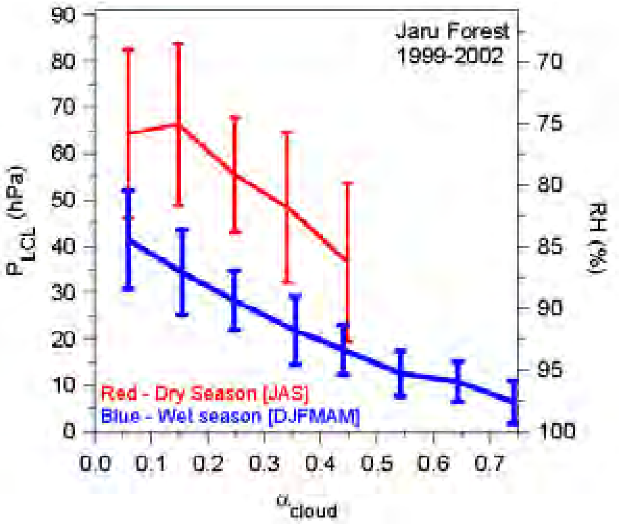
$\mathrm{LW}_{\mathrm{net}}$ → Diurnal Temp. Range

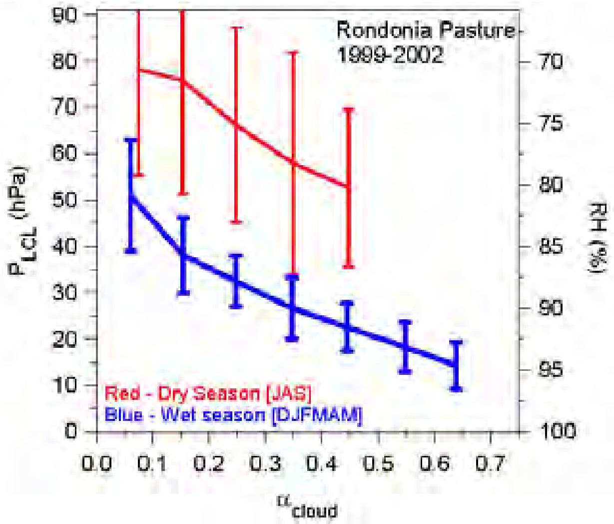


- **DTR quasi-linear with $\mathrm{LW}_{\mathrm{net}}$**
- ERA40 has steeper slope than observations
- Precipitation reduces DTR

Organize by α_{cloud} [*observable*]



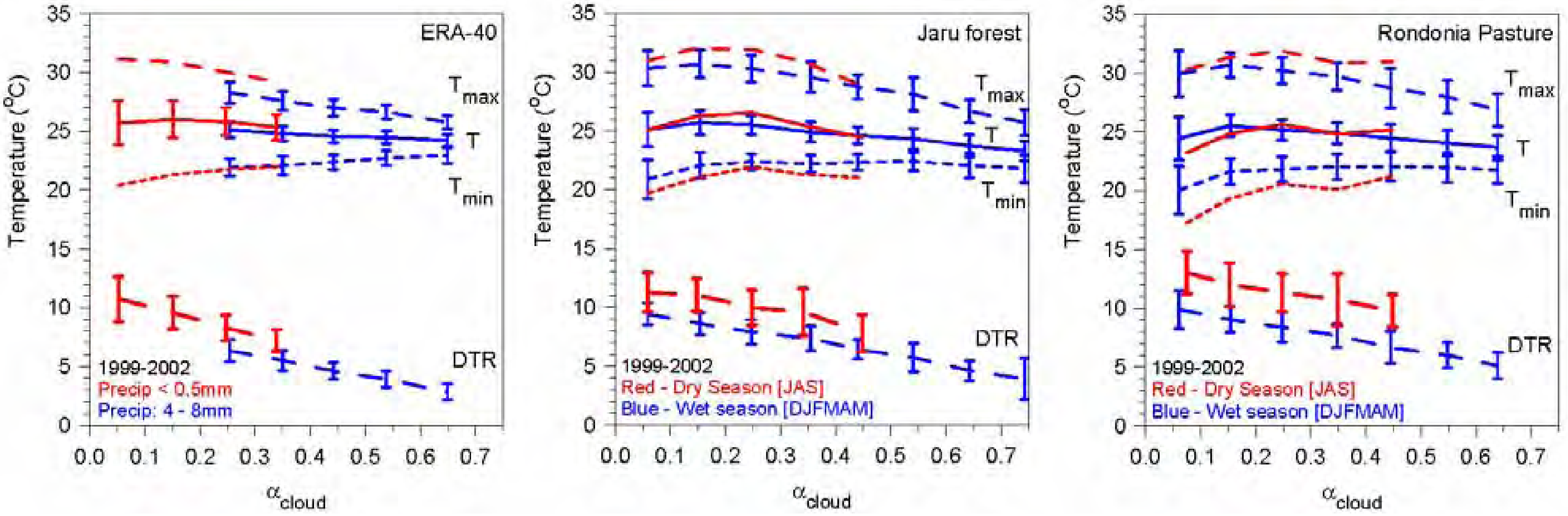




- **α_{cloud} , LCL & RH linked**
- Relation tight in rainy season;

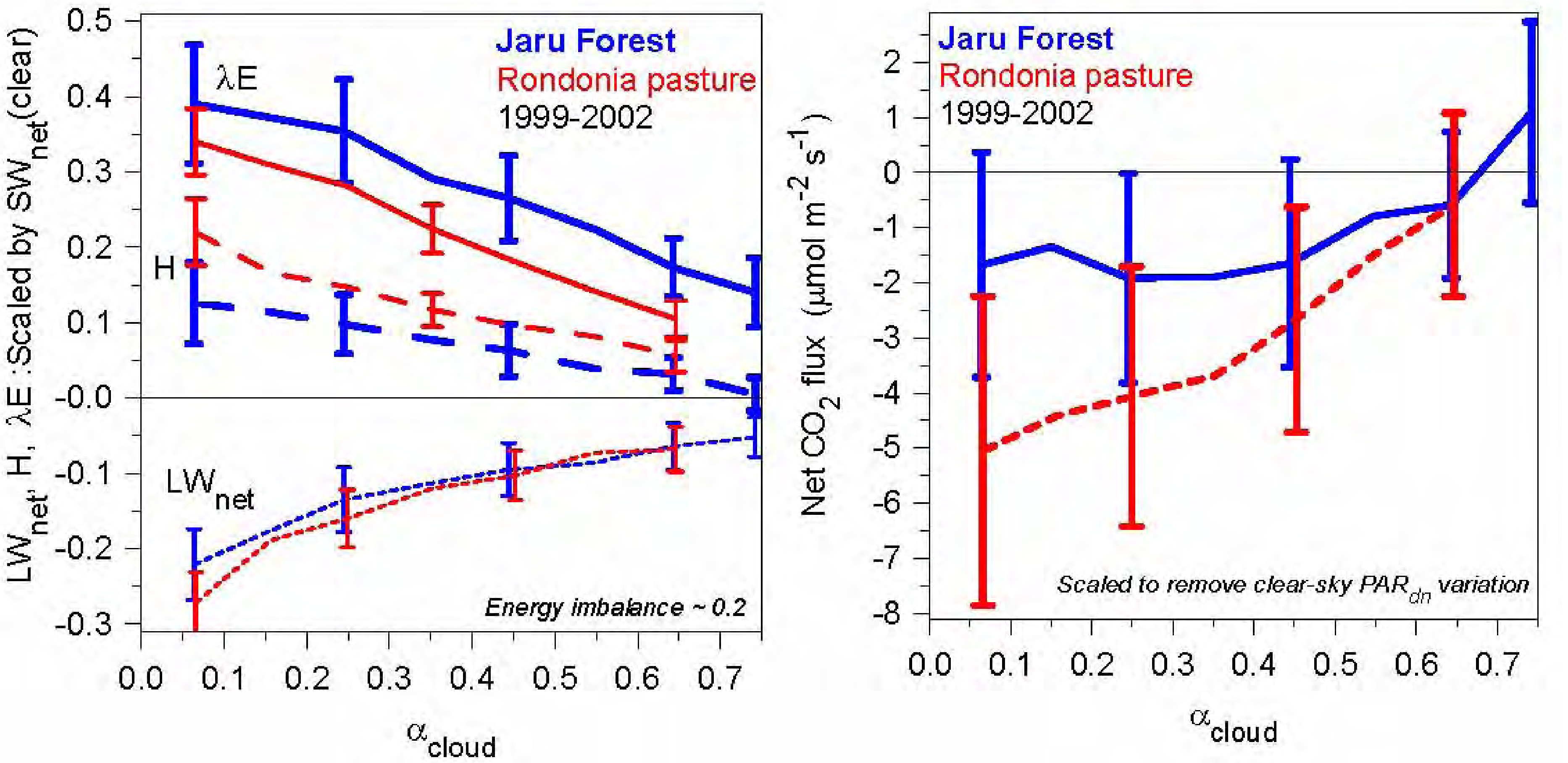
  - poor in dry season

T_{max}, T_{min}, DTR with α_{cloud}



- **DTR and α_{cloud} linked**
- ERA-40: T_{max} decreases & T_{min} increases
- Data: Wet season: T_{max} decreases: T_{min} flat

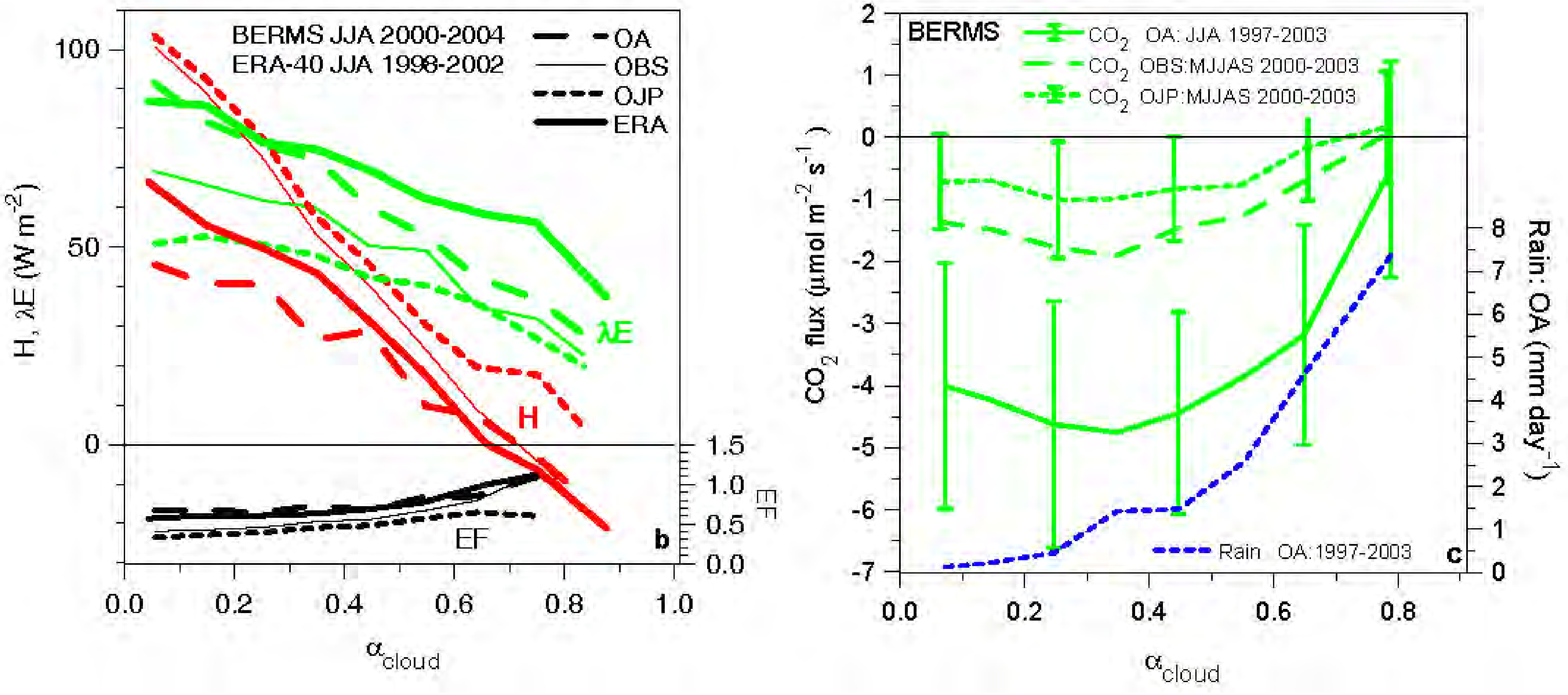
Organize fluxes by α_{cloud}



- Energy fluxes: quasi-linear
- Jaru forest carbon flux ‘flat’ at low α_{cloud}

Summer Boreal forest: Saskatchewan

[Betts et al. 2006]



- Similar dependency on α_{cloud}
- Net CO_2 flux peaks at $\alpha_{cloud} \sim 0.35$

Conclusion -1

- **Land-surface climate [T, RH, LCL, DTR, fluxes] & cloud are tightly coupled**

- **Organize data by α_{cloud}**

Part 2: How will T, RH, cloud-base, BL clouds and surface fluxes change in a warmer, high CO_2 world?

- Strategy 1: Fully coupled Earth system model sensitivity tests with ensembles of models

  - ***Large inter-model variation -*** *vegetation-CO_2-λE-BL-cloud coupling may have significant errors?*

- Strategy 2: Use **idealized model to *understand*** coupled BL- cloud system

  - with specified mid-tropospheric forcing

  - with SWCF and LWCF for BL clouds

Idealized Equilibrium BL model

Betts, A. K. (2009), Idealized model for changes in equilibrium temperature, mixed layer depth and boundary layer cloud over land in a doubled CO_2 climate. *J. Geophys. Res.* (submitted), 2009JD012888

[extension of *Betts, Helliker and Berry, JGR 2004]*

- Vegetation model, *equilibrium* BL model **[24-h mean]** with BL-cloud radiative forcing

Model Structure

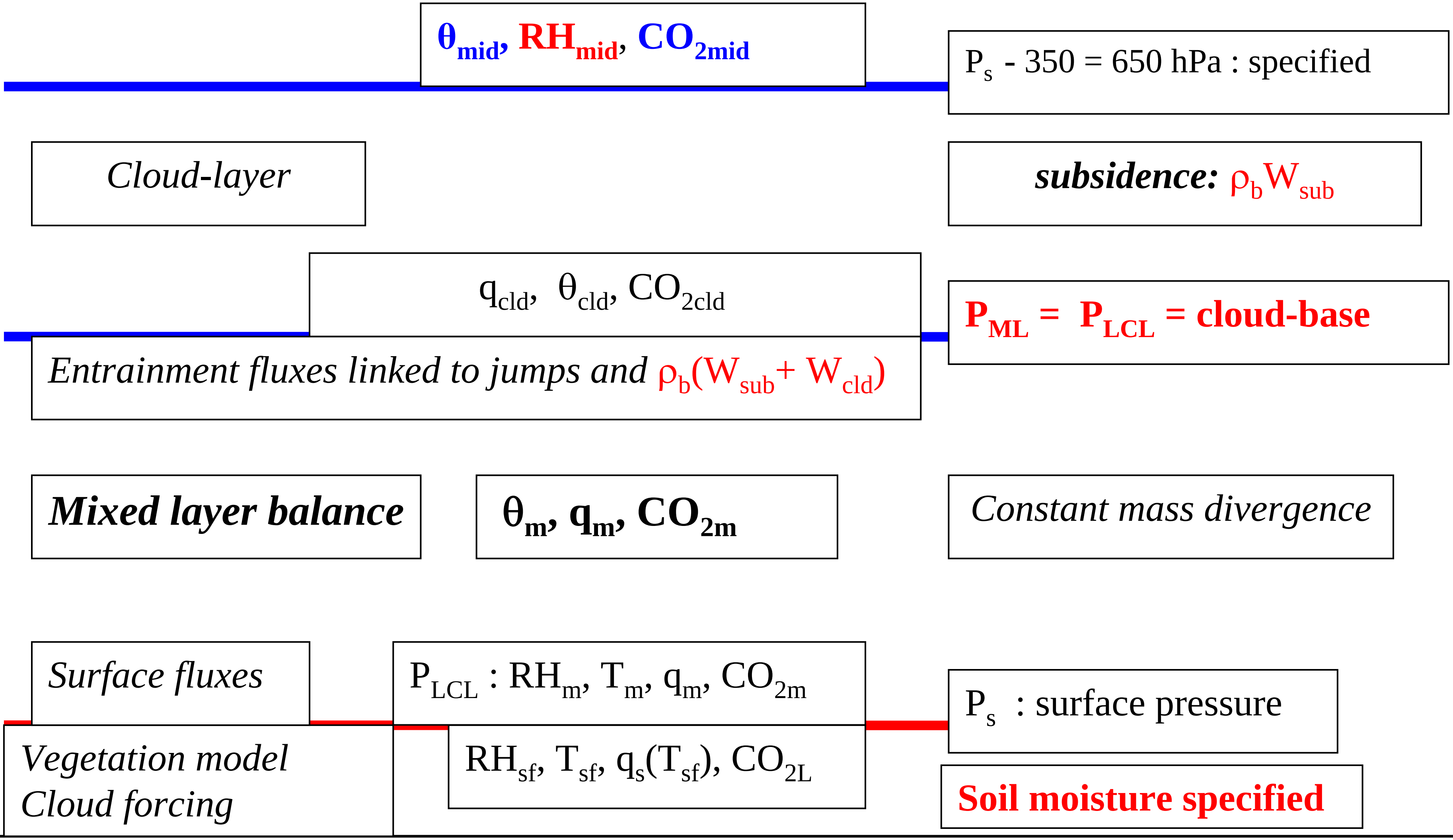
- External variables: soil moisture index; mid-tropospheric CO_2, RH, lapse-rate [coupled to moist adiabat]; Clear-sky SW_{net} radiation
- SW_{net}, LW_{net}, R_{net} and ML cooling coupled to cloud-base mass flux [‘cloud forcing’]
- Canopy photosynthesis model: *[Collatz et al, 1991]*

  [LAI, E_{veg}, Q_{10}] = [5, 6, 1.9] for forest *[Wisconsin]*

  = [3, 10, 2.1] for grassland

  - Temperature and soil water stress factors

Schematic



θ_{mid}, RH_{mid}, CO_{2mid}

P_s - 350 = 650 hPa : specified

Cloud-layer

subsidence: $\rho_b W_{sub}$

q_{cld}, θ_{cld}, CO_{2cld}

P_{ML} = P_{LCL} = cloud-base

Entrainment fluxes linked to jumps and $\rho_b(W_{sub} + W_{cld})$

Mixed layer balance

θ_m, q_m, CO_{2m}

Constant mass divergence

Surface fluxes

P_{LCL} : RH_m, T_m, q_m, CO_{2m}

P_s : surface pressure

Vegetation model
Cloud forcing

RH_{sf}, T_{sf}, $q_s(T_{sf})$, CO_{2L}

Soil moisture specified

Mid-tropospheric boundary conditions

- Above cloud-base to 650 hPa

$$\theta(p) = \theta_{00} + \Gamma_w(950\text{-}p)$$

with $\Gamma_w = -d\theta_w/dp$, moist adiabat thru $(\theta_{00}, 950)$.

$$\theta_{cld} = \theta_{00} + \Gamma_w(P_{ML} - 50) \quad \textit{for } P_s = 1000$$

$$\theta_{mid} = \theta_{00} + \Gamma_w(300)$$

- RH_{mid} = 40% gives q_{mid}; CO_{2mid} = 380, 760 ppm
- Set ‘Oceanic’ reference θ_{00} = (297, 299K) for the present and doubled CO_2 climates

Surface radiation & Cloud forcing

- $SW_{net}(\mathrm{clear}) = \quad 250\ \mathrm{Wm}^{-2}$ [mid-lat. summer]
- $LW_{net}(\mathrm{clear}) = -\ 117 + 0.175(300\text{-}P_{ML})\ \mathrm{Wm}^{-2}$

- $SWCF = -\ 0.4{*}250\ (\rho_b W_{cld})/(\rho_b W_{40})$

Cloud mass flux *40% cloud albedo*

- $LWCF = 20\ (\rho_b W_{cld})/(\rho_b W_{40})$

- $ML_{cool} = -3[1 - 0.4\ (\rho_b W_{cld})/(\rho_b W_{40})]\ \ K\ day^{-1}$

ML Budget equations

Surface energy balance

- $\lambda E + H = R_{net} = SW_{net}(\text{clear}) + SWCF + LW_{net}(\text{clear}) + LWCF$
  - $EF = \lambda E / (\lambda E + H)$

Water balance

- $\lambda E = L\, \rho_b W_{sub}\, (q_m - q_{mid}) = L(\rho_b W_{sub} + \rho_b W_{cld})(q_m - q_{cld})$

Transpiration ***Subsidence*** ***cloud-base flux***

Heat balance

- $H = -\,(C_p/g)\, ML_{cool}\, P_{ML} + C_p(\rho_b W_{sub} + \rho_b W_{cld})\, (\theta_m - \theta_{cld})$

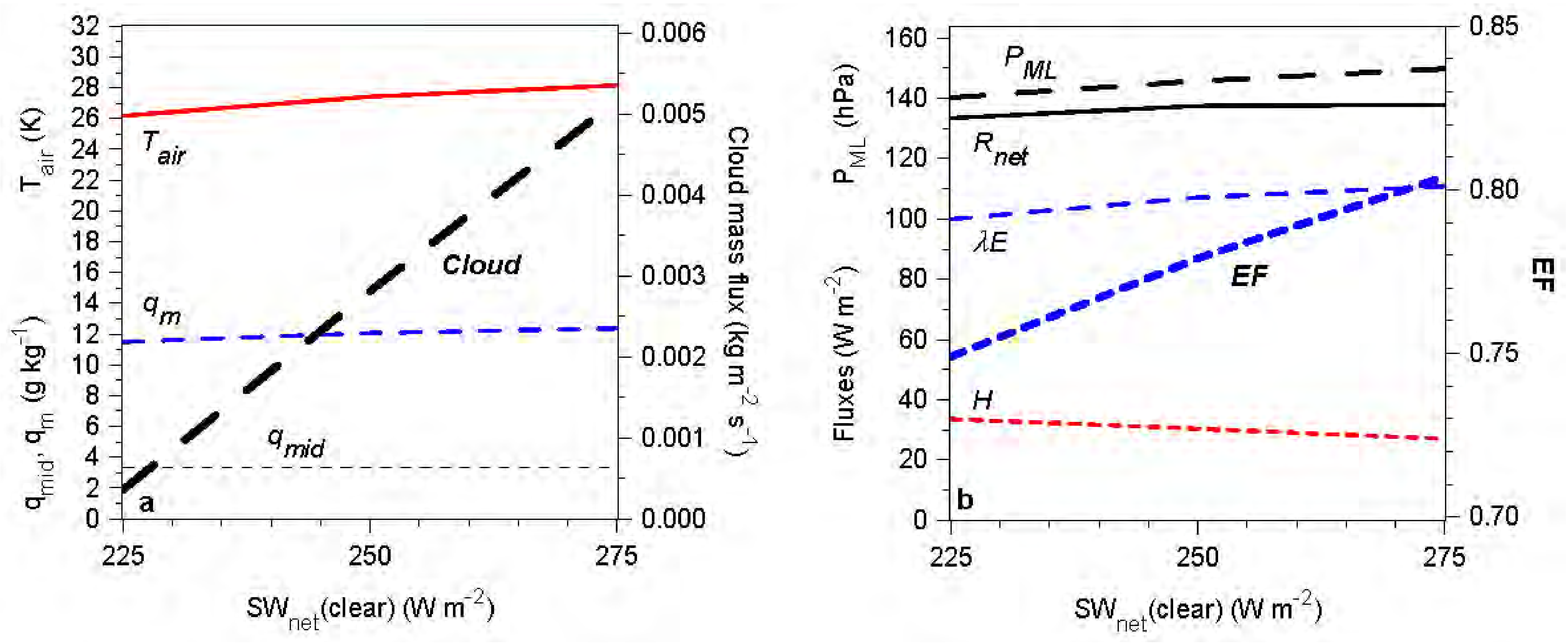
Sensible ***Radiation*** ***cloud-base flux***

CO_2 balance

- $NEE = A\, \rho_b W_{sub}(CO_{2m} - CO_{2mid}) = A(\rho_b W_{sub} + \rho_b W_{cld})(CO_{2m} - CO_{2cld})$

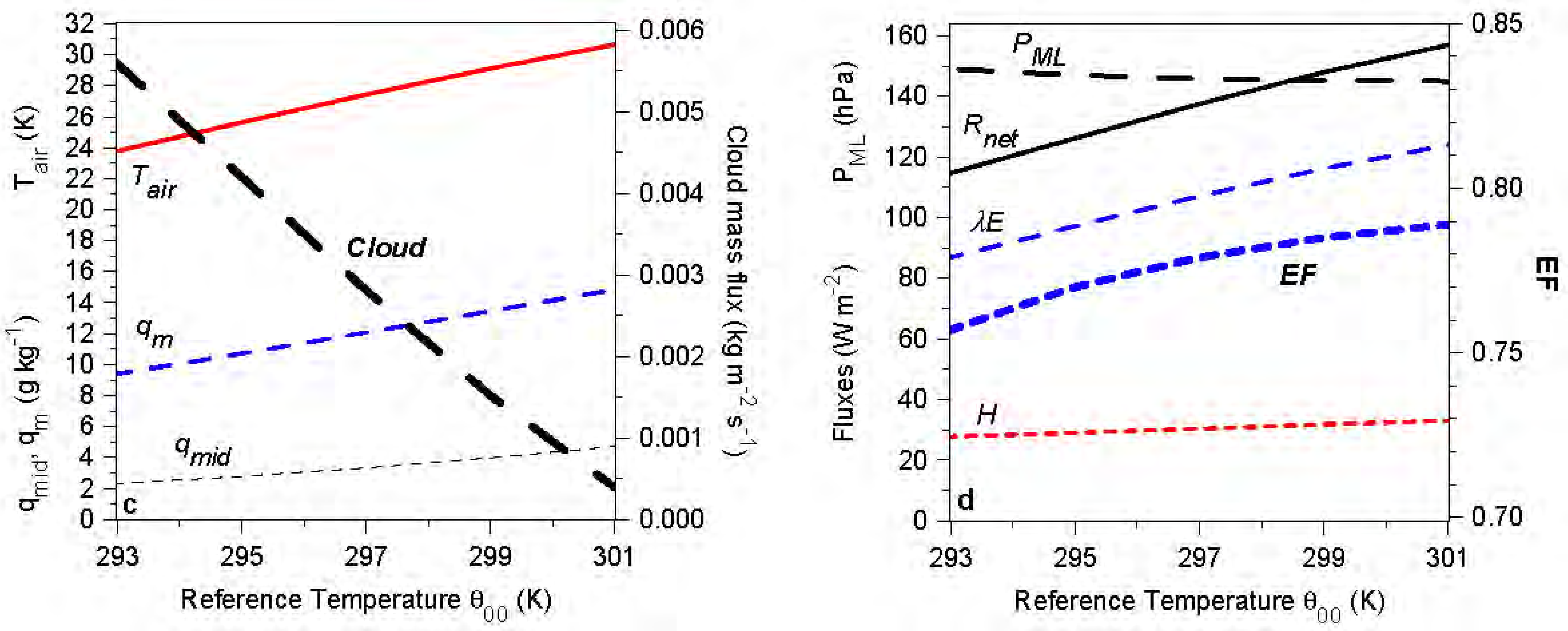
where $A = 287/8.314 = 34.52$

Sensitivity studies: SW_{net}(clear)



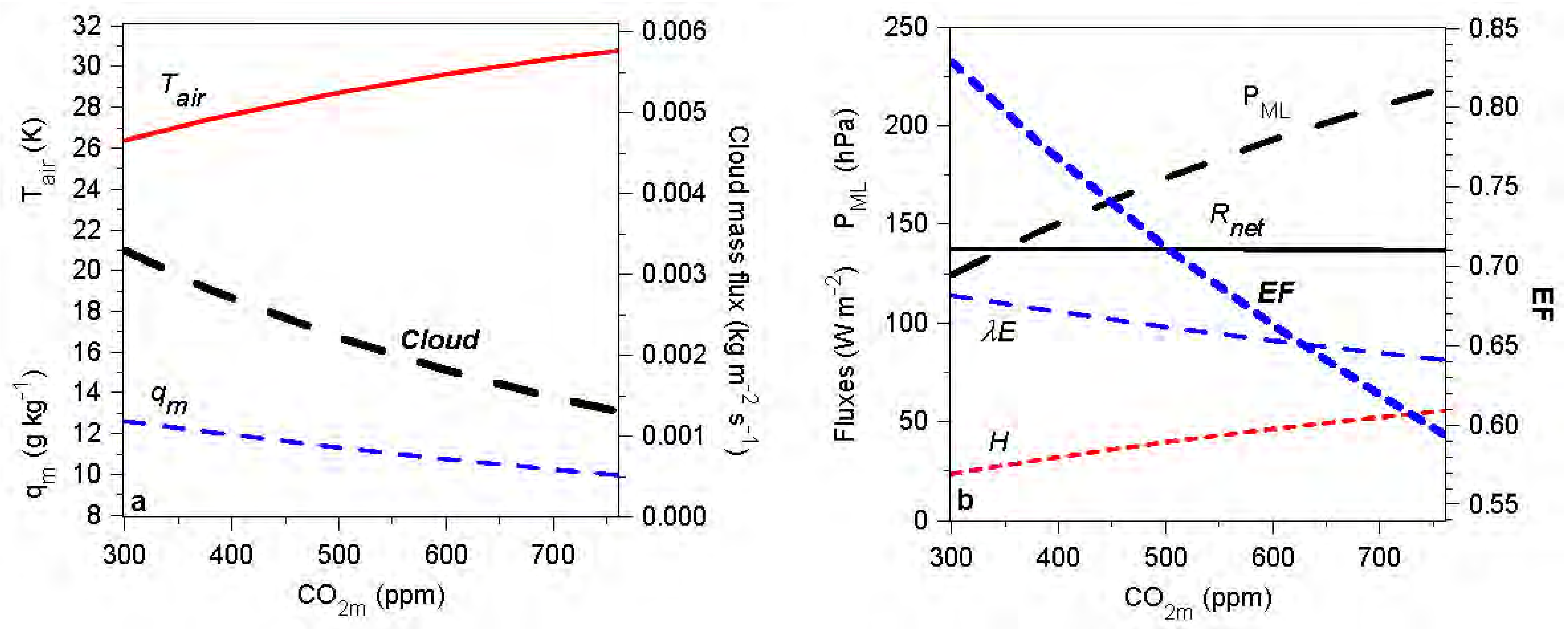
- Cloud increases, R_{net}, T_{air}, ML depth barely rise; small increase of EF

Sensitivity studies: θ_{oo}



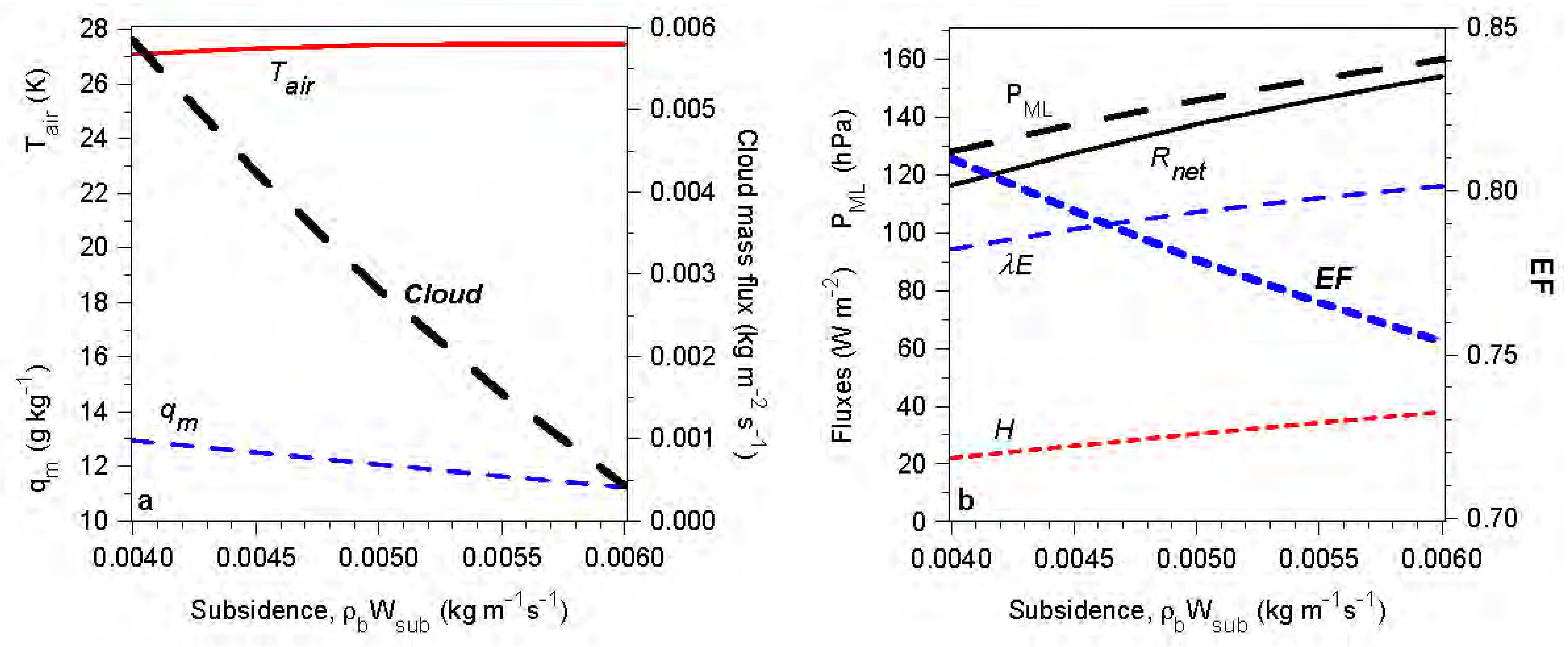
- Cloud decreases, T_{air}, R_{net} , λE increase, ML a little shallower, small increase of EF

Sensitivity studies: CO_2



- Canopy conductance drops
- EF falls a lot, Cloud decreases, R_{net} flat, T_{air} increases & q_m decreases, ML deepens a lot

Sensitivity studies: subsidence



- q_m falls, ML deepens, cloud decreases, R_{net} increases, T_{air} flat, EF falls a little

Climate Change Equilibrium solutions for forest and grassland

- Current climate: 380 ppm CO_2

- 2100 climate: 760 ppm CO_2
  & moist adiabat tropospheric reference T:
  tied to SST increase of $\boldsymbol{\theta}_{\mathbf{oo}}$ +2K
  [very approx. A1B scenario; AR4-WG1, Ch 11]

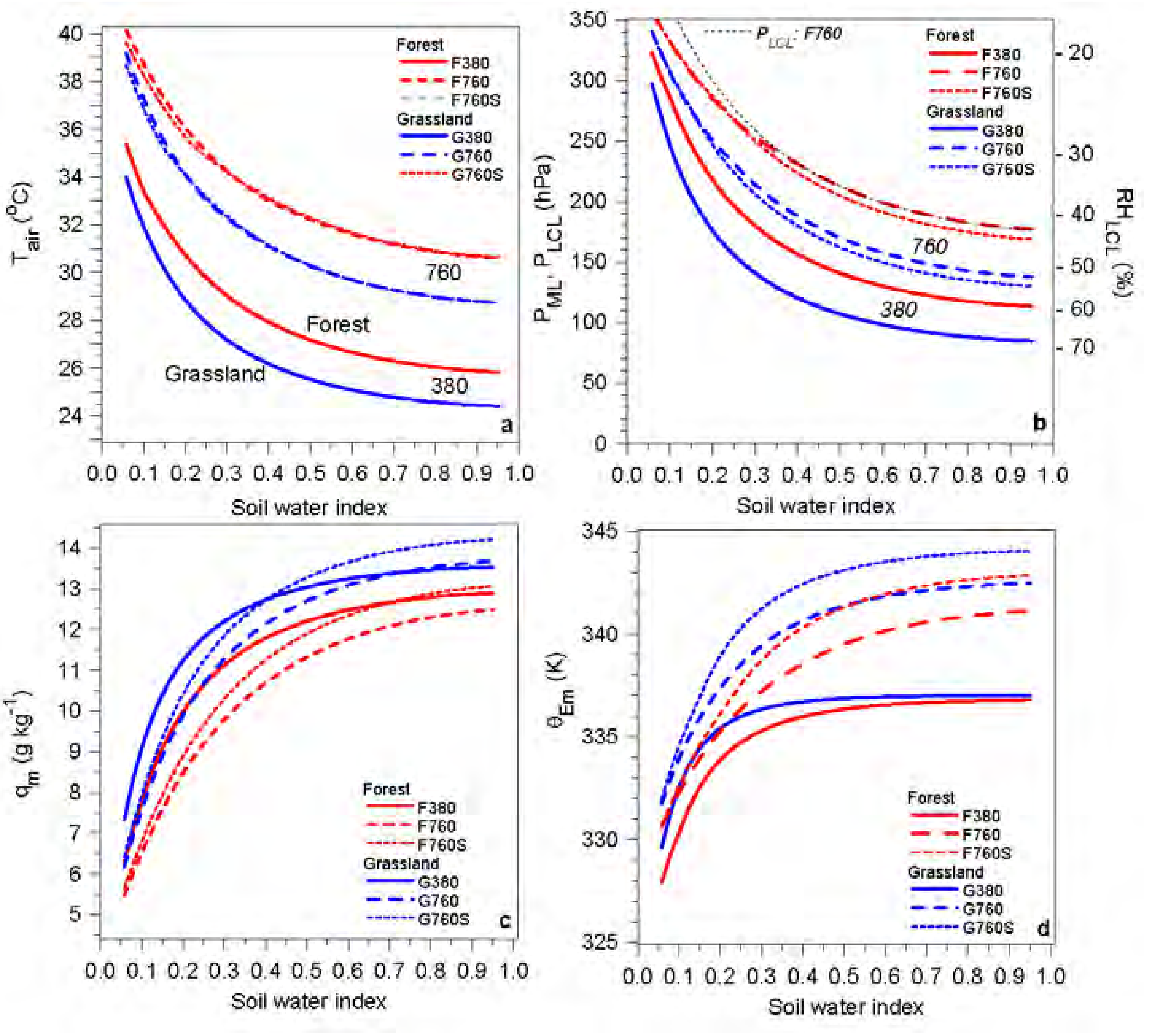
Changes in ML equilibrium & cloud-base

T_{air}

RH

P_{LCL}

P_{ML}

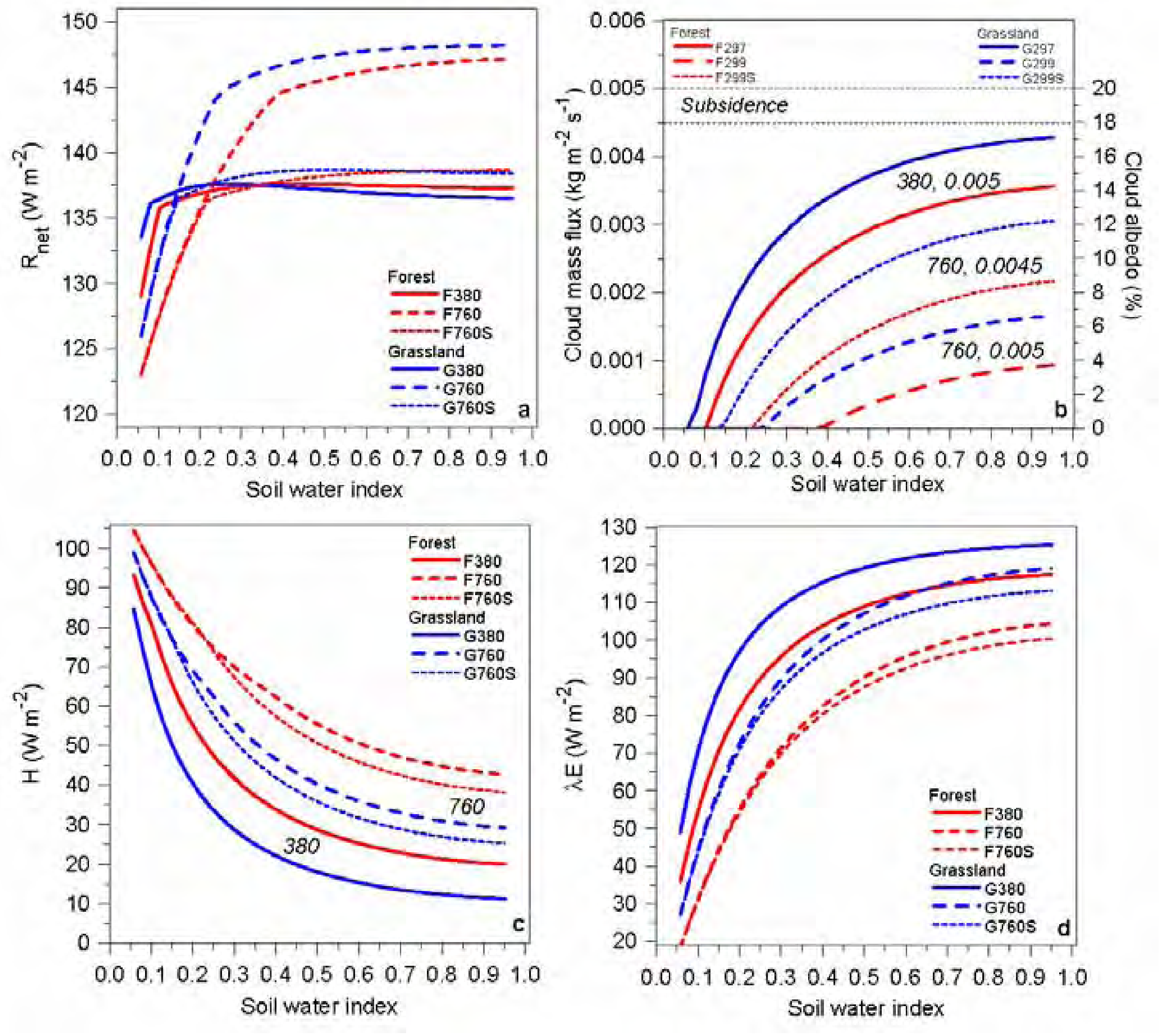


Q

θ_E

Soil water index

Changes in Surface energy fluxes



R_{net}

Cloud mass flux

&

Albedo

H

λE

Soil water index

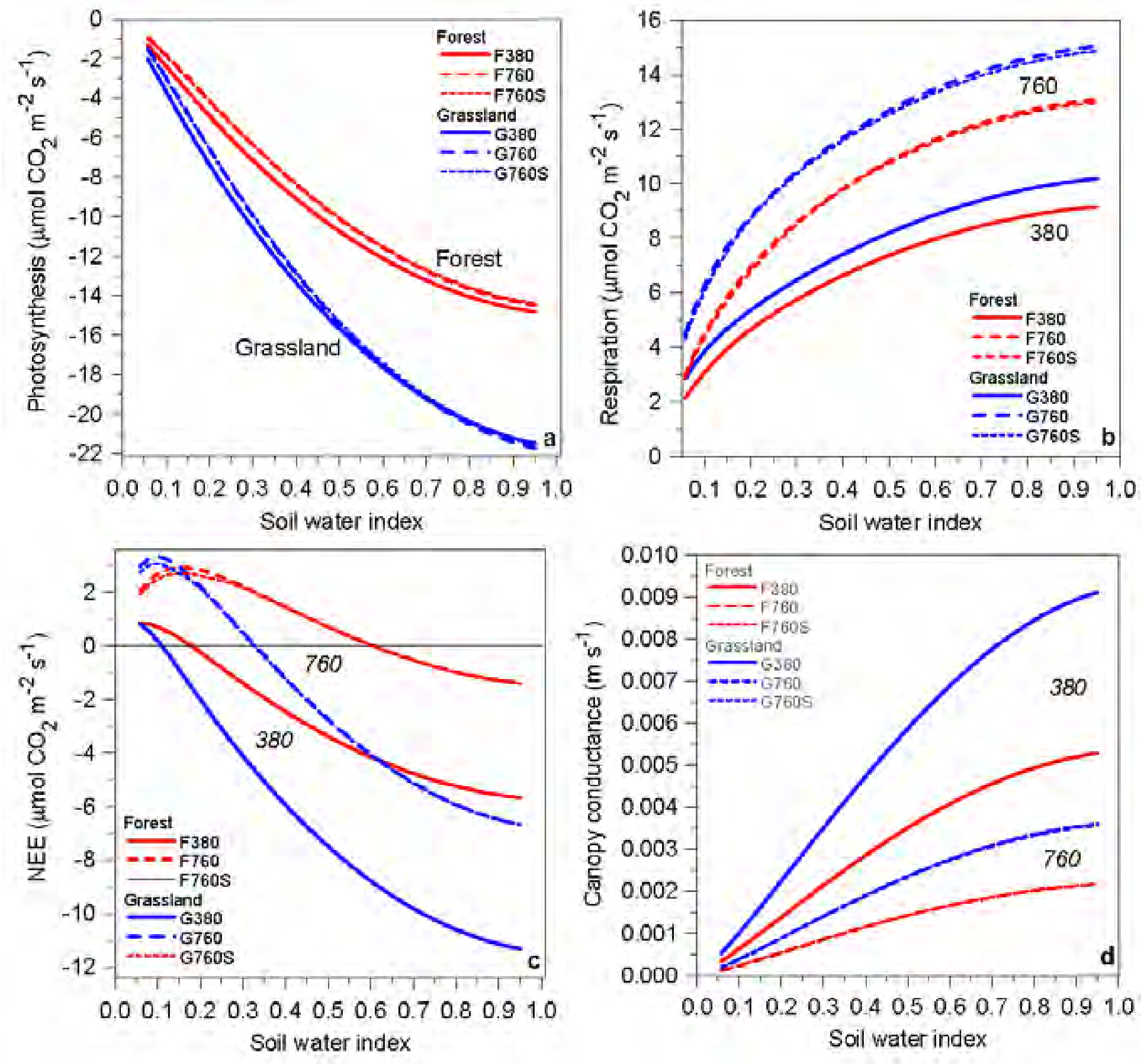
Changes in CO_2 fluxes

PH

Resp

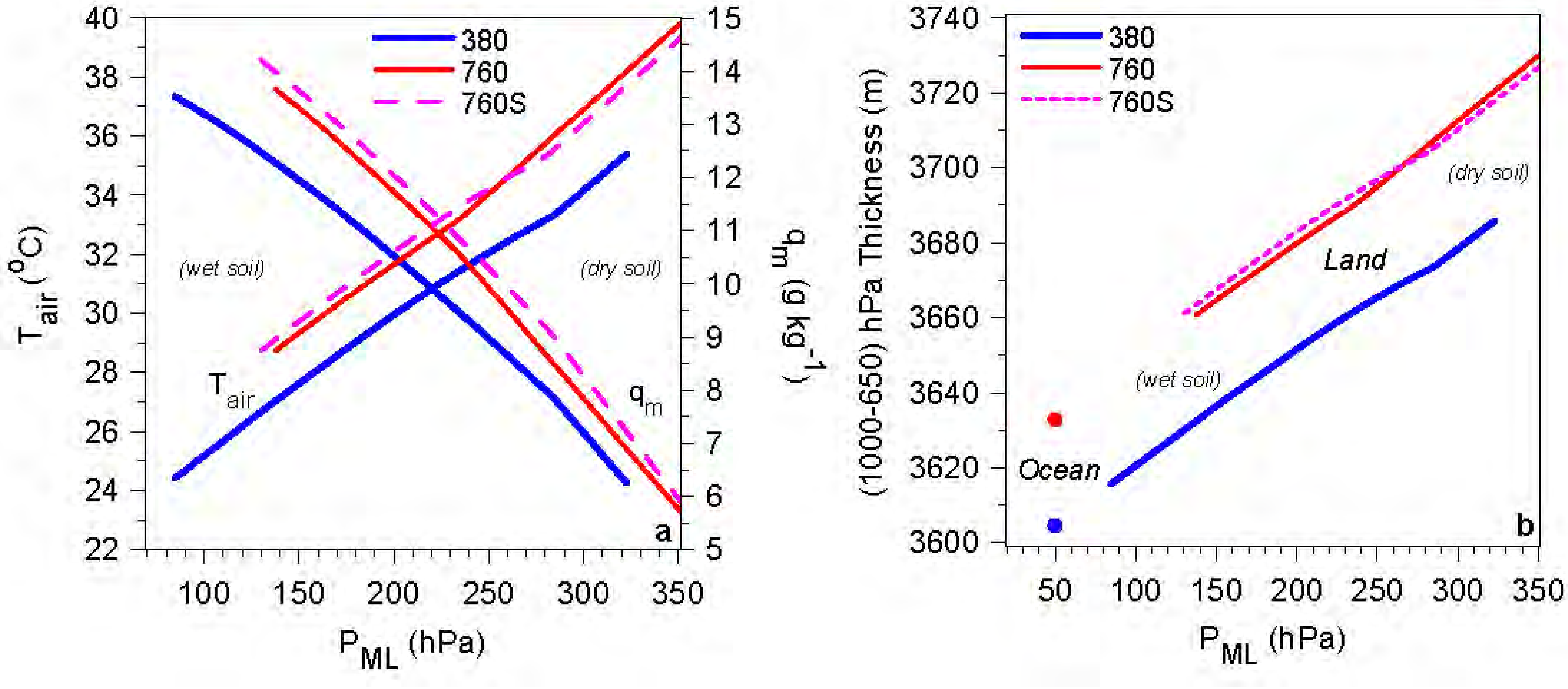
NEE

g_{veg}



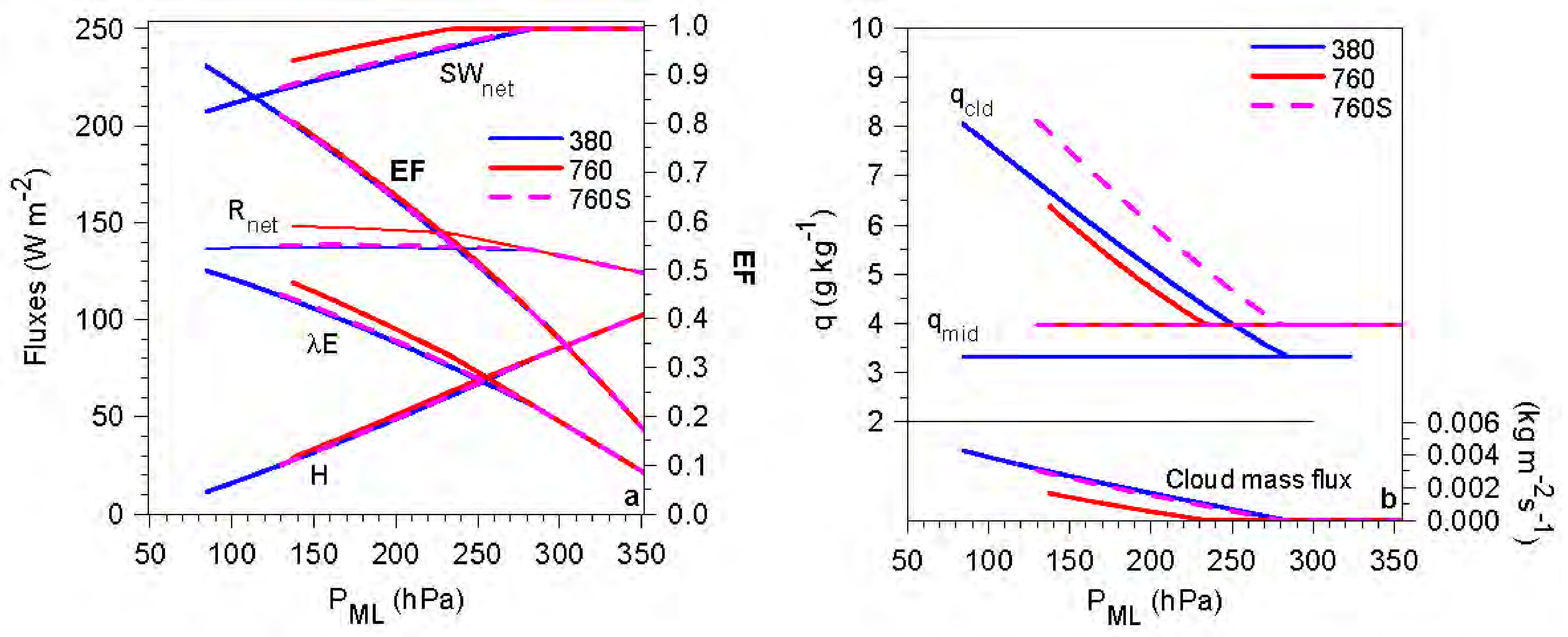
Soil water index

Changes with ML depth



- *Forest & grassland data merge*
- **Warms and dries as P_{ML} deepens**
- 1000-650 hPa thickness increases

Changes with ML depth-2

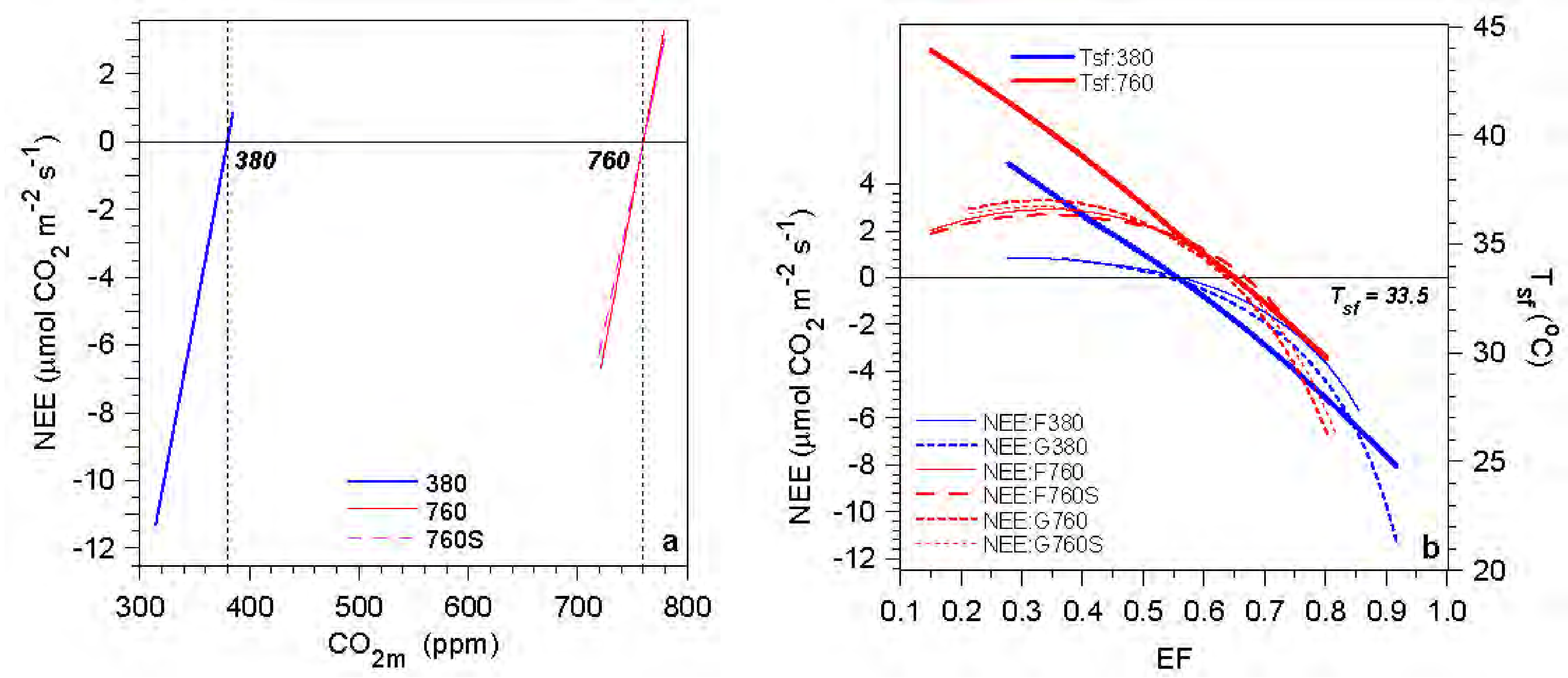


- **EF falls as P_{ML} deepens**

  - *Upper boundary conditions disappear*

- Cloud mass flux ⟶ 0 as P_{ML} increases

Coupling of NEE, CO_2 and EF



- **NEE, subsidence and CO_{2m} linked**
- **NEE, EF and surface temperature linked**
- *NEE > 0 for T_{sf} > 33.5°C for both climates*

Equilibrium model conclusions

- **ML-depth, BL-clouds, energy and water balance, CO_2 budget and transpiration are a tightly coupled system**
- Mid-lat. forest to grassland conversion **increases** BL cloud albedo by +3% and lowers cloud-base by 25 hPa
- Doubling CO_2 +2K background warming **reduces** transpiration, RH (-15%) and BL cloud albedo (-10%), deepens ML (60hPa)
- This **amplifies surface warming over land**

  From +2K over ocean to +5K at 2-m over land
- EF and P_{ML} tightly coupled
- NEE and CO_{2m} tightly coupled
- NEE >0 for $T_{sf} > 33.5^{o}C$

- *[Caveats: soil-water & subsidence changes unknown]*

Conclusions

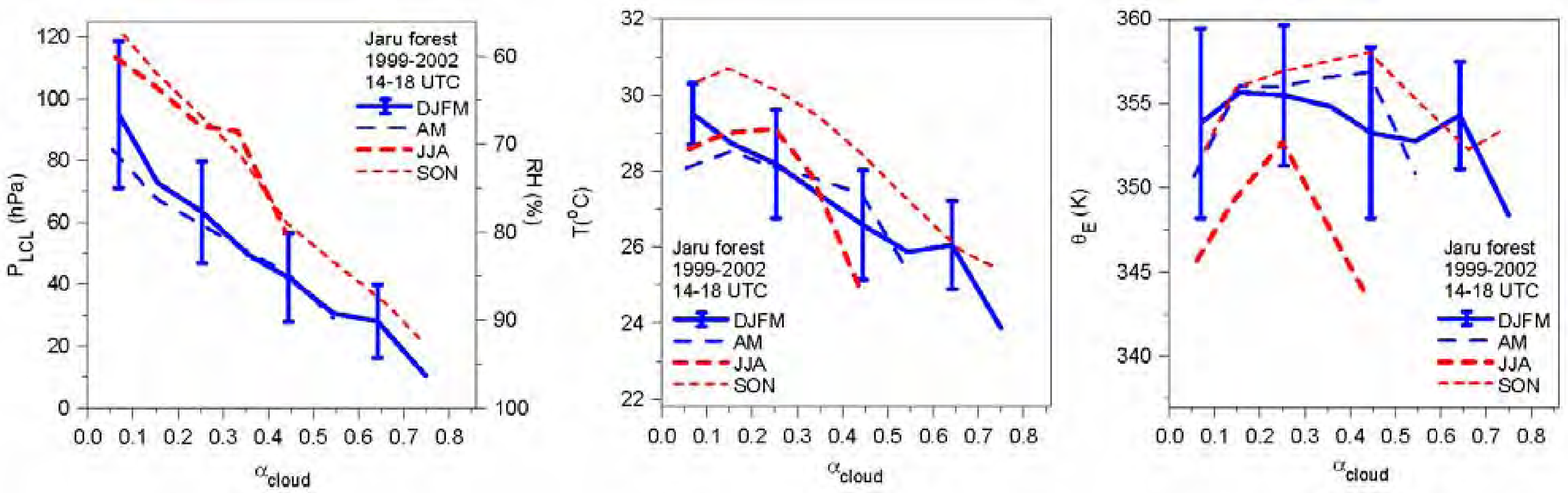
- **Simplified model shows large changes in BL-cloud over land with vegetation change and warmer high CO_2 climate**

  - *qualitative agreement with Hadley model*

- **GCM vegetation models should be tested offline in coupled BL mode to separate cloud forcing and carbon sink issues**

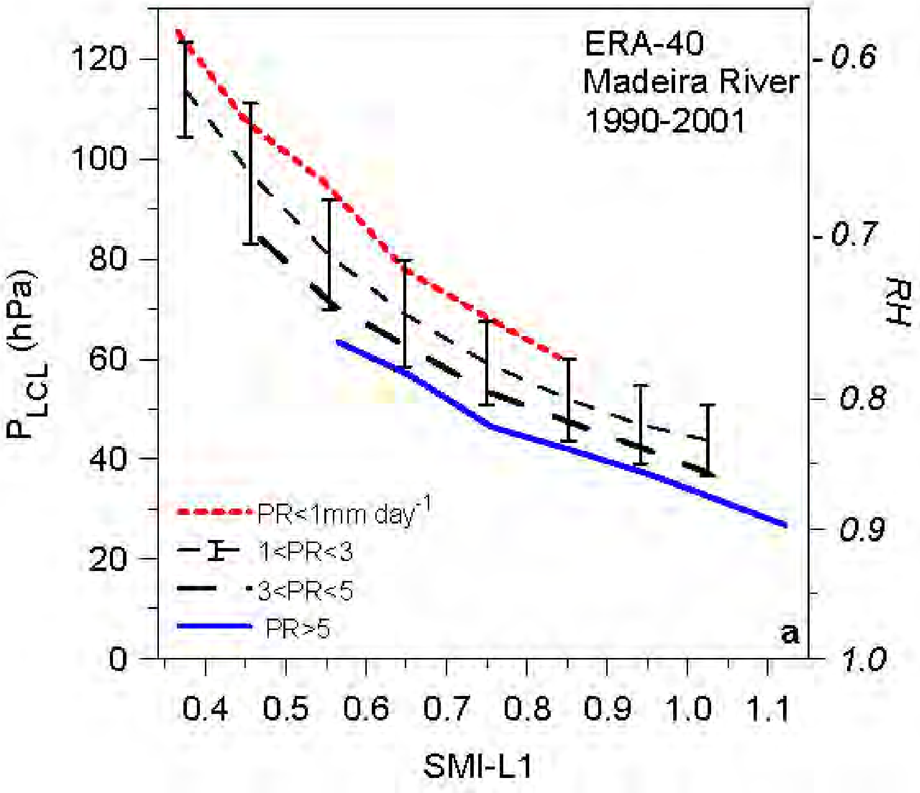
Cloud - BL coupling

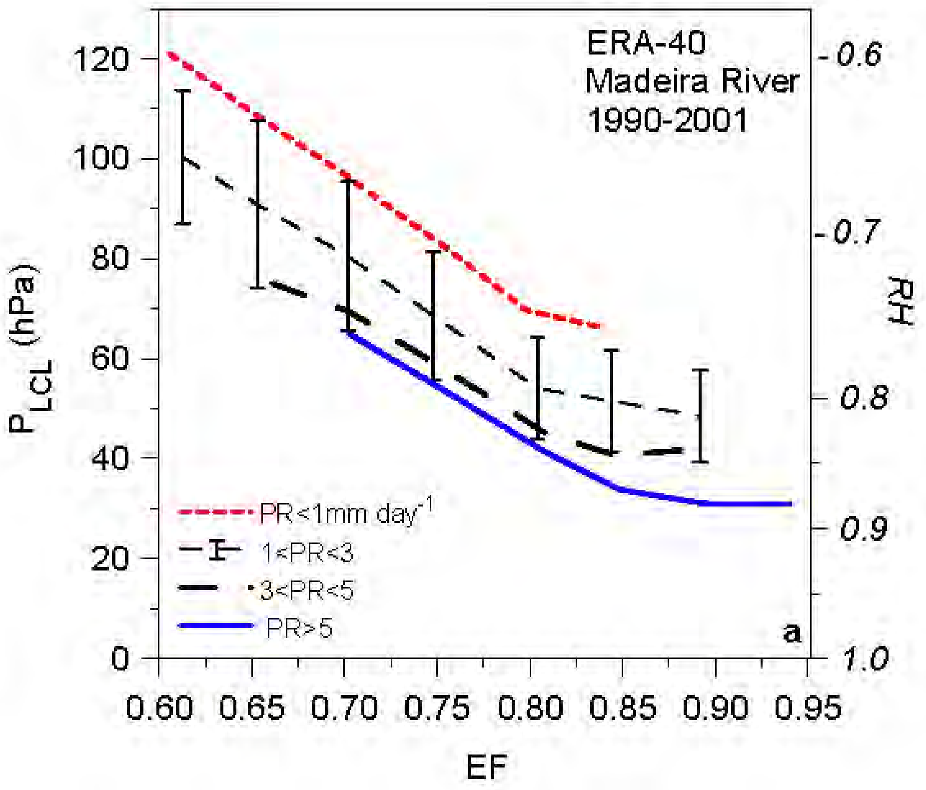
Jaru forest – Noon ±2h



- Cloud amount coupled to cloud-base & RH
- Temperature decreases as cloud increases
- θ_E is flat: regulated by cloud transports

Land-surface-BL Coupling





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