Land-surface-BL-cloud coupling as climate changes

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Outline of Talk

- **Land-surface, BL & cloud coupling**
- **Idealized equilibrium model:**
  - forest and grassland; double CO_2
  - impact on BL cloud, temperature and NEE
- *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.* [Note: published paper extends radiative coupling, but considers only grassland]

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

Land surface climate

- **Highly coupled system: mean state + diurnal cycle**
  - **Surface processes**: evaporation & carbon exchange
  - **Atmospheric processes**: clouds, precip. & ω
- Clouds have radiative impact on SEB in both shortwave and longwave
- **Surface, BL and BL-clouds tightly coupled**
- *[Precip. modifies RH, LCL and soilwater]*

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 Model Structure

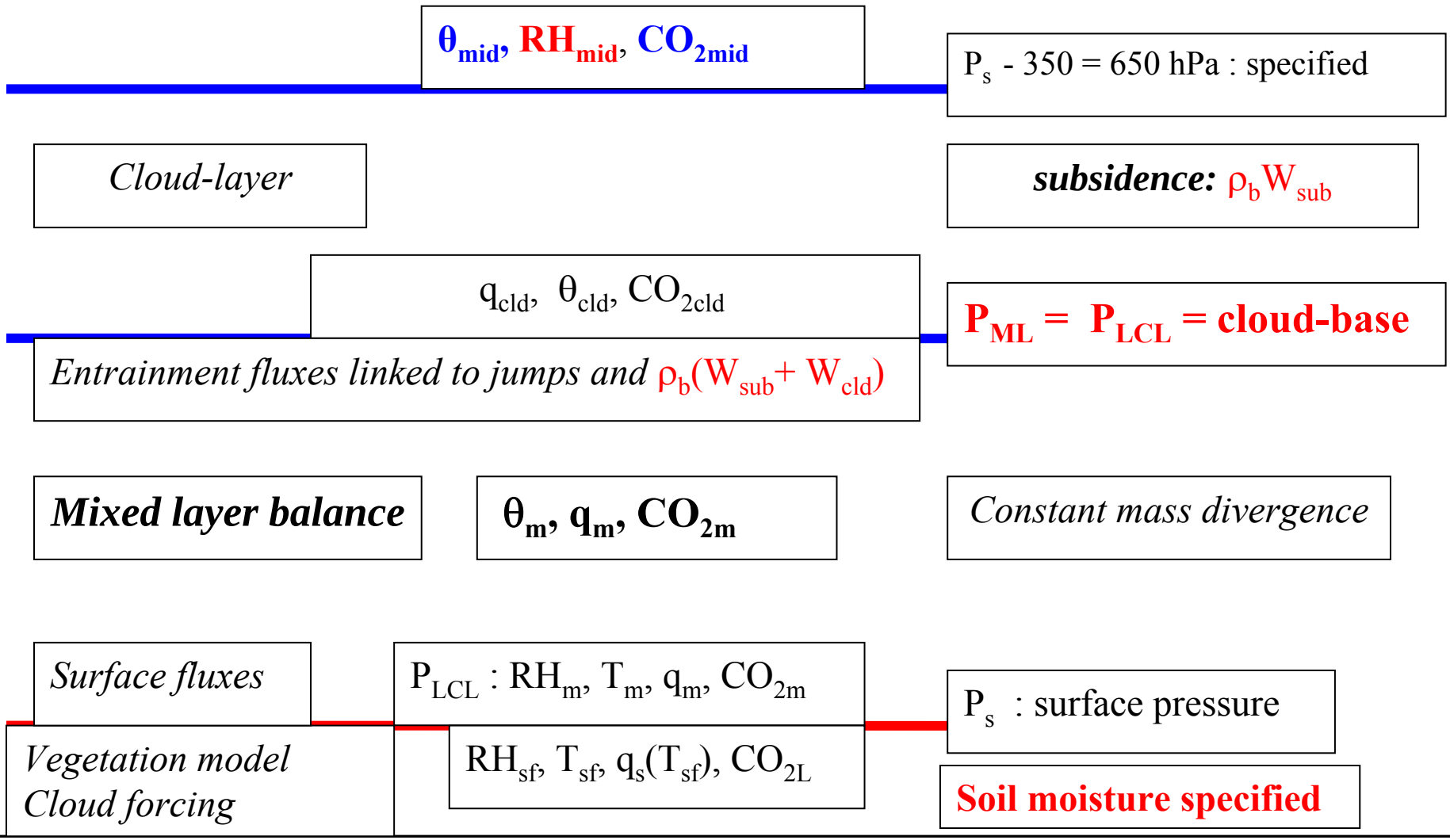
- External variables: soil moisture index; mid-tropospheric CO_2, RH, lapse-rate [coupled to moist adiabat]; Clear-sky SW_{net} radiation
- SW_{net}, LW_{net}, R_{net} and ML cooling coupled to cloud-base mass flux ['**cloud forcing**']
- Canopy photosynthesis model: *[Collatz et al, 1991]*

  [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**

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

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

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

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

- 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

- $SW_{net}(clear) = \quad 250\ Wm^{-2}$ [mid-lat. summer]
- $LW_{net}(clear) = -\ 117 + 0.175(300-P_{ML})\ Wm^{-2}$
- $SWCF = -\ 0.4*250\ (\rho_b W_{cld})/(\rho_b W_{40})$

Cloud mass flux *40% eff. cloud albedo*

- $LWCF = 20\ (\rho_b W_{cld})/(\rho_b W_{40})$
- $ML_{cool} = -3[1 - 0.4\ (\rho_b W_{cld})/(\rho_b W_{40})]\ \ K\ day^{-1}$

Surface & ML Budget equations

Surface Energy balance

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

ML Water balance

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

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

ML Heat balance

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

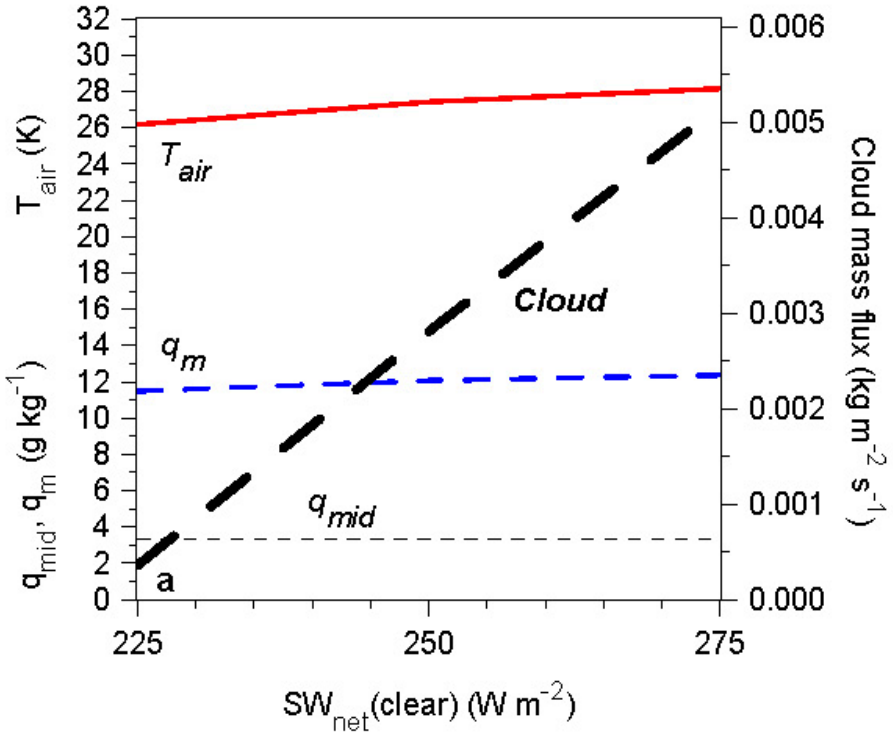
Sensible ***Radiation*** ***cloud-base flux***

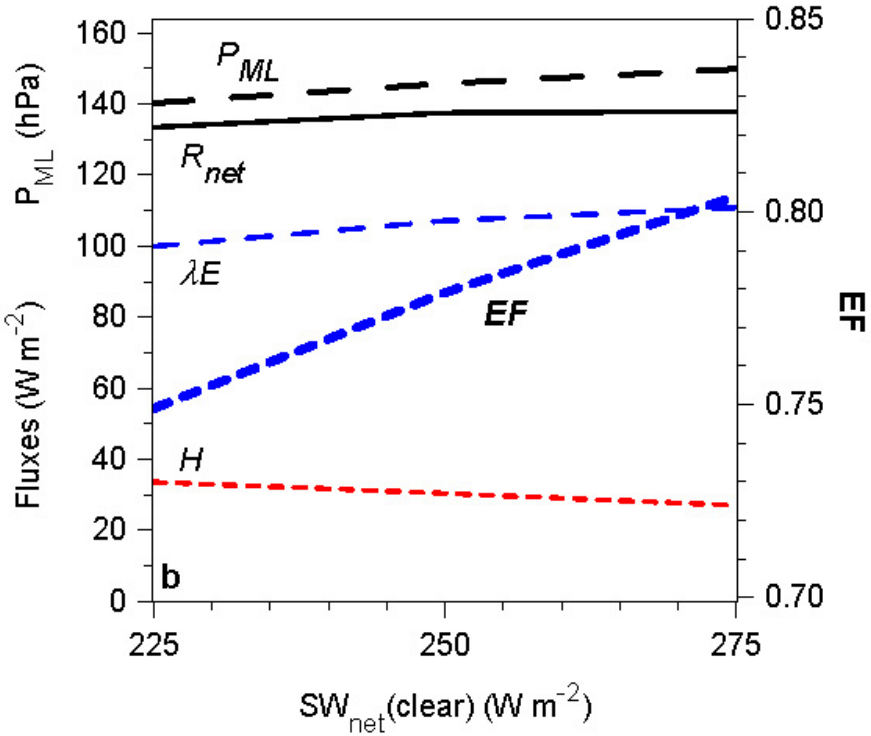
ML CO_2 balance

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

where $A = 287/8.314 = 34.52$

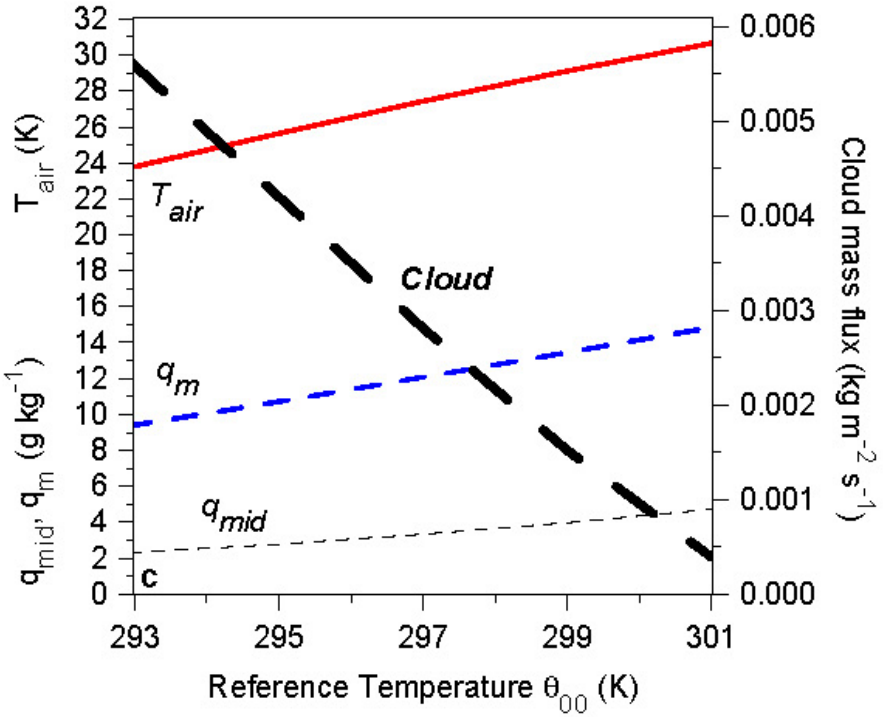
Sensitivity studies: SW_{net}(clear)

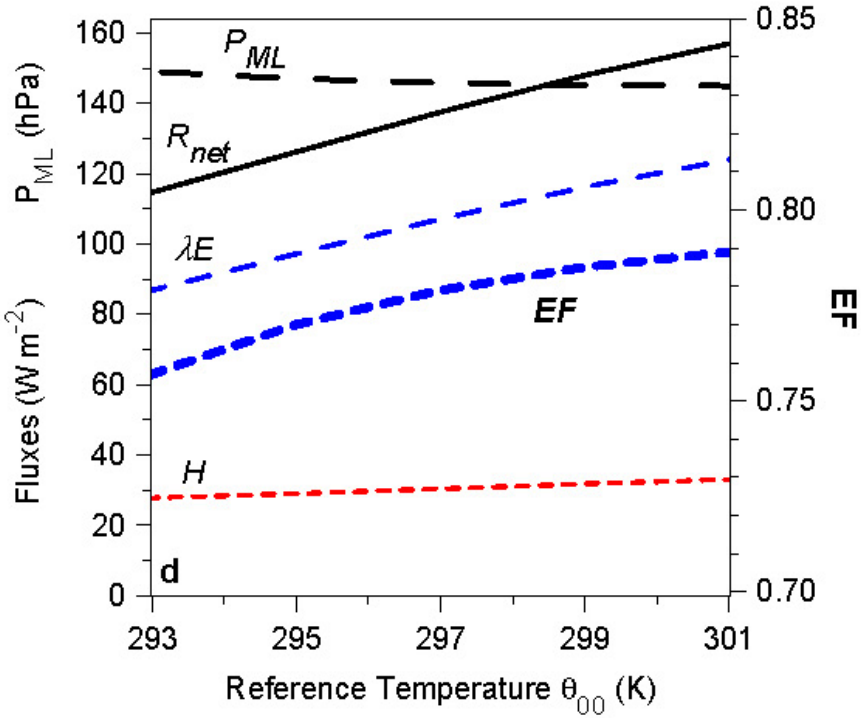




- Cloud increases, R_{net}, T_{air}, ML depth barely rise; small increase of EF

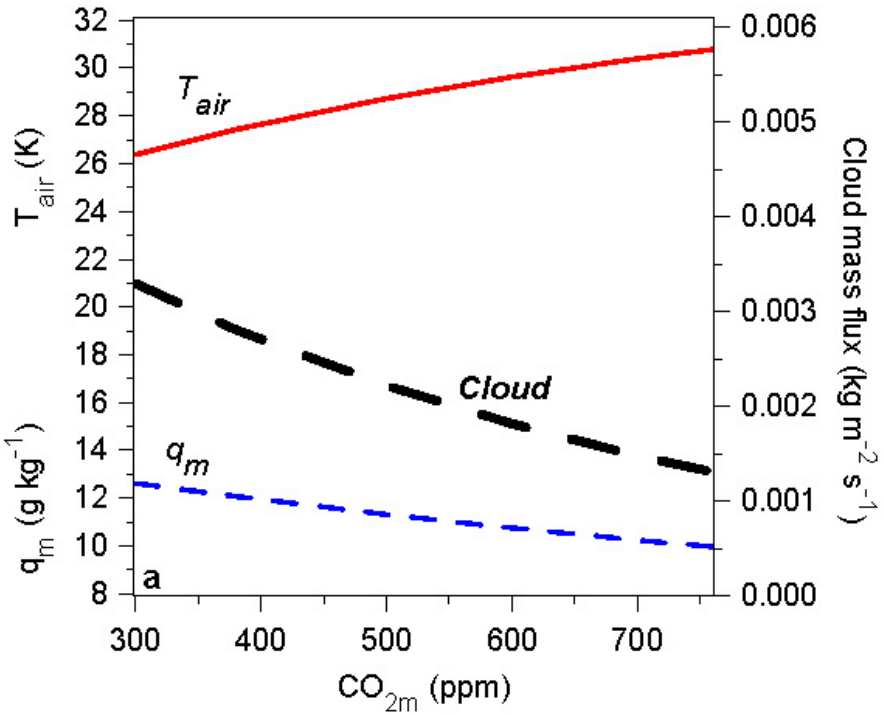
Sensitivity studies: θ_{oo}

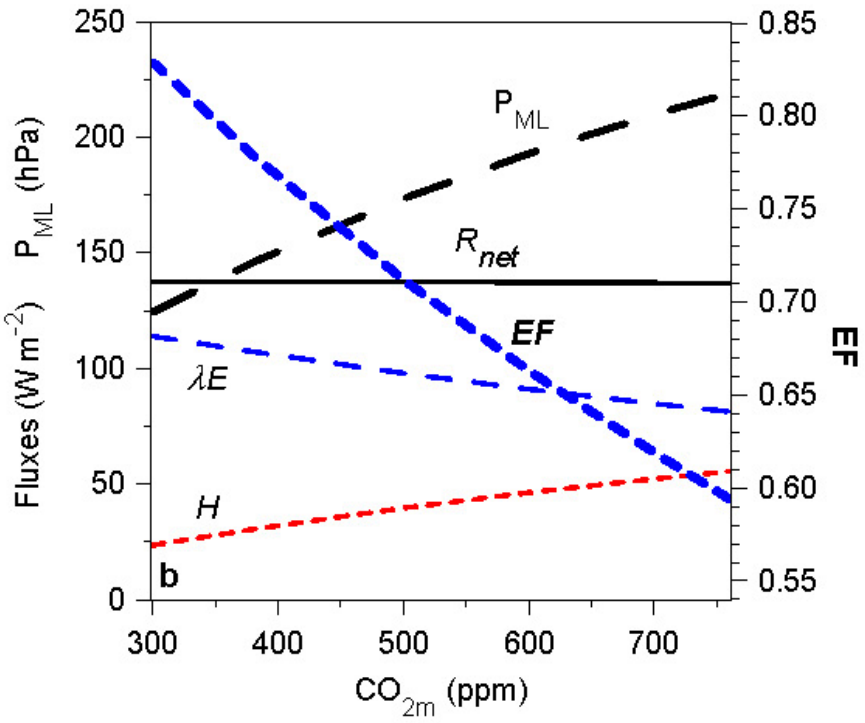




- Cloud decreases, T_{air}, R_{net} , λE increase, ML a little shallower, small increase of EF

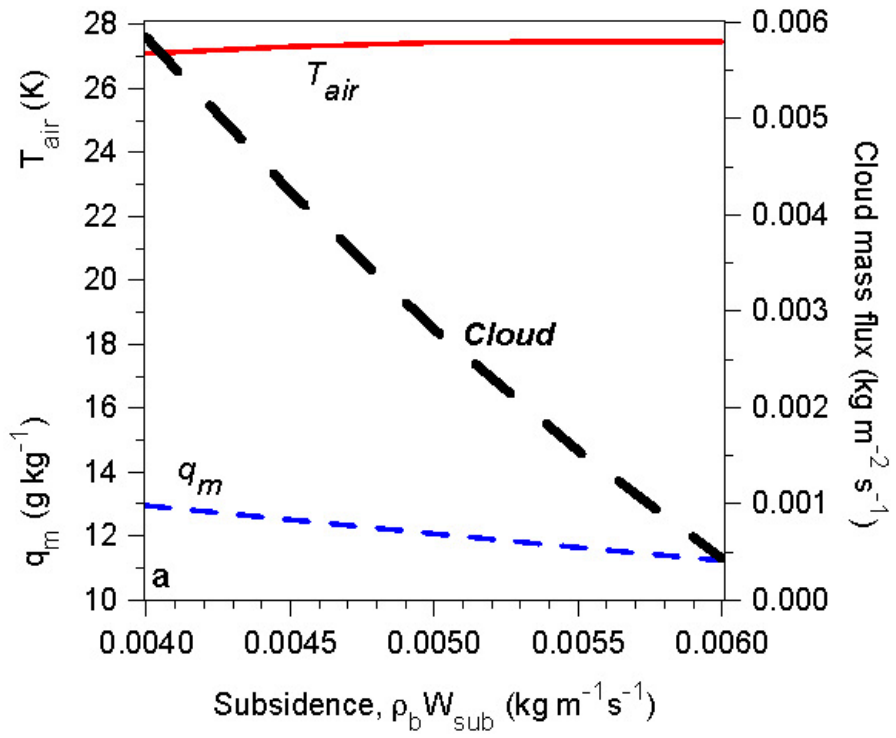
Sensitivity studies: CO_2

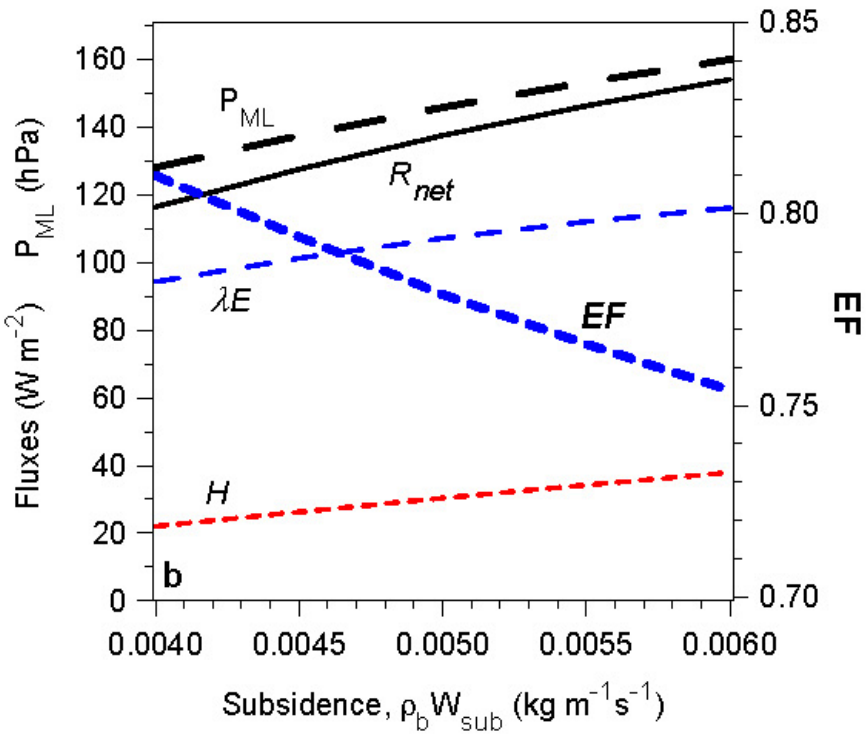




- Canopy conductance drops
- EF falls a lot, Cloud decreases, R_{net} flat, T_{air} increases & q_m decreases, ML deepens a lot

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

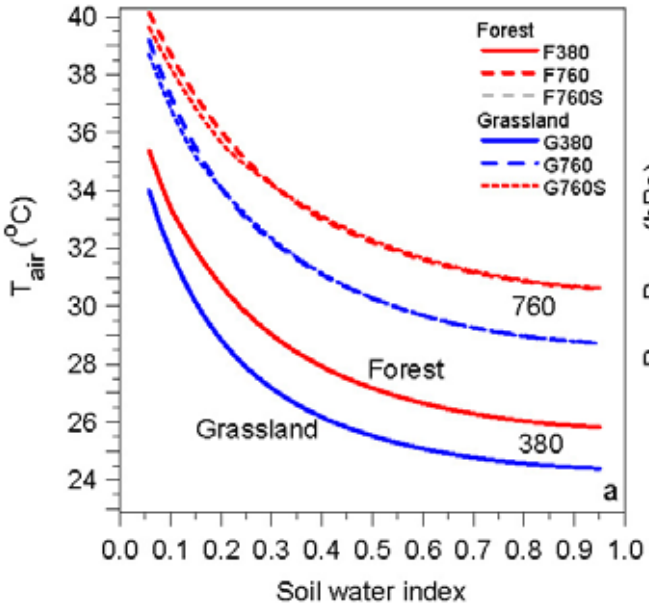
  & moist adiabat tropospheric reference T:

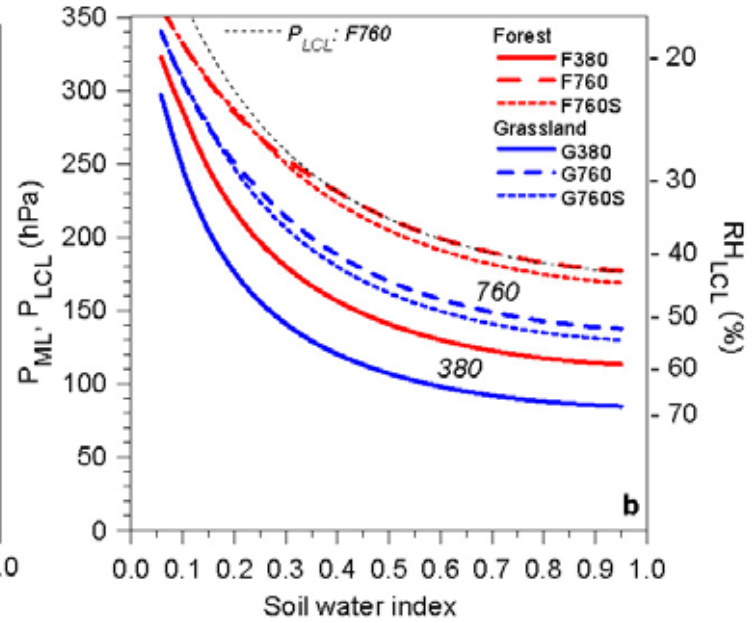
  tied to SST increase of $\boldsymbol{\theta_{oo}}$ +2K

  [very approx. A1B scenario; AR4-WG1, Ch 11]

Changes in ML equilibrium & cloud-base

T_{air}



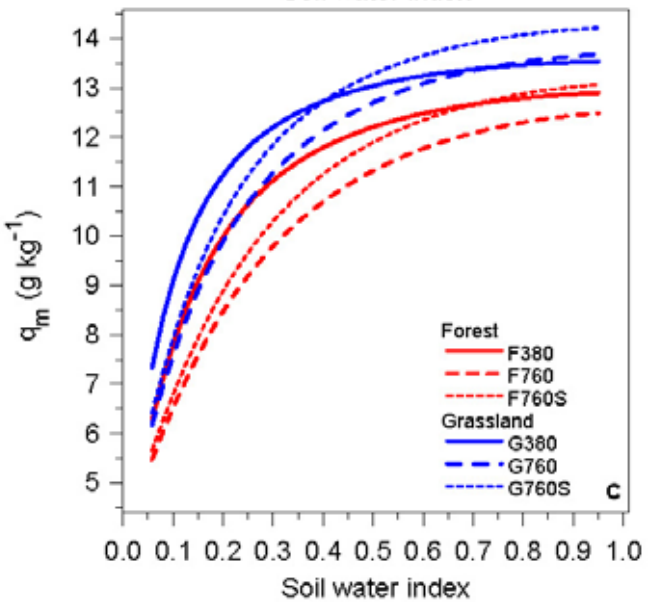


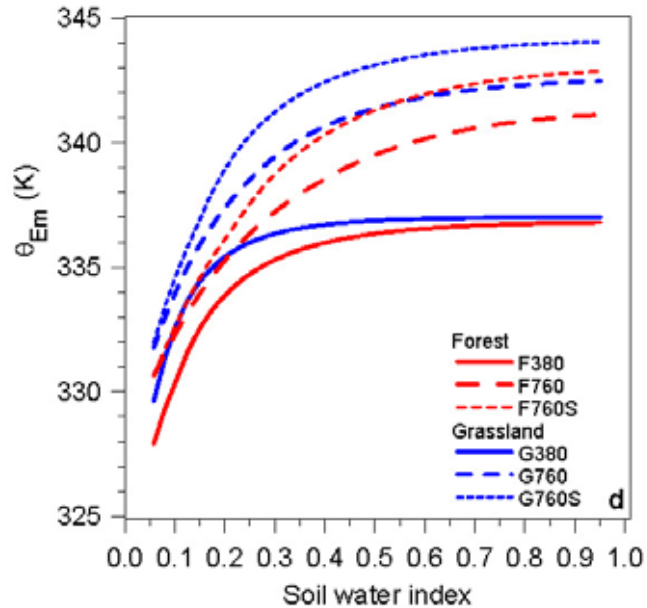
RH

P_{LCL}

P_{ML}

Q



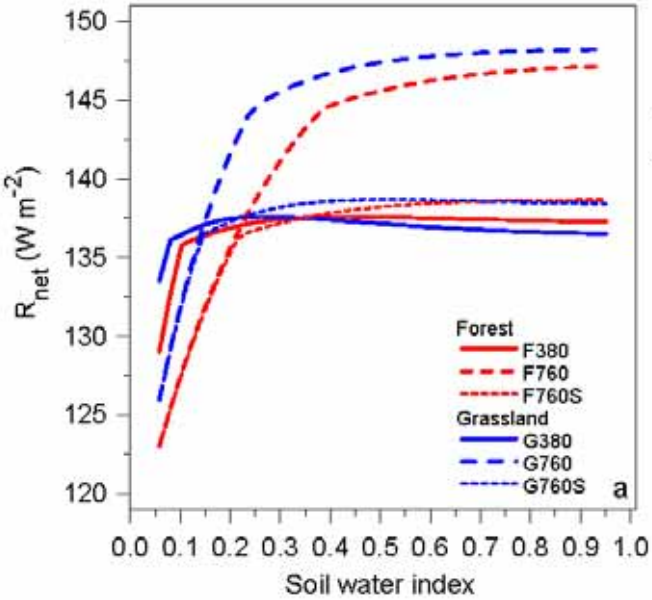


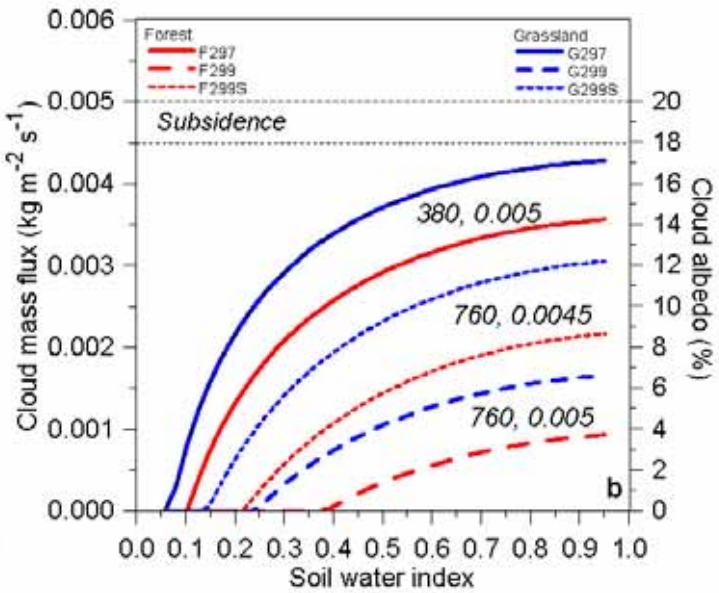
θ_E

Soil water index

Changes in Surface energy fluxes

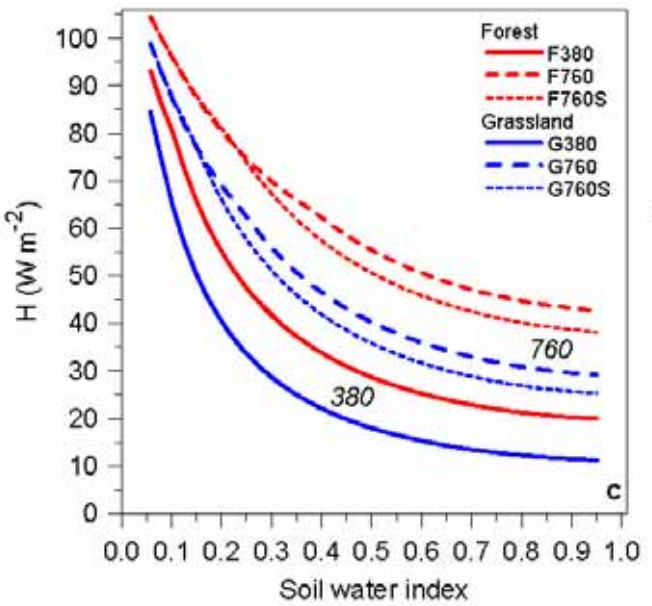
R_{net}

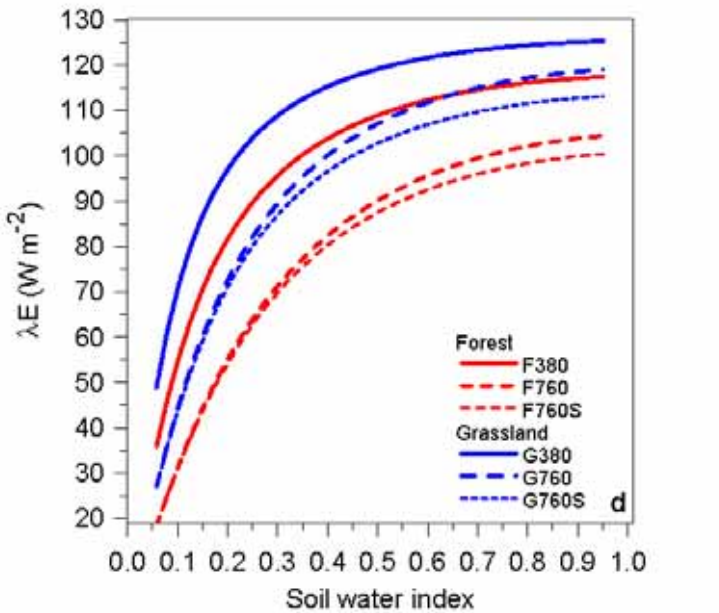




Cloud mass flux & Albedo

H

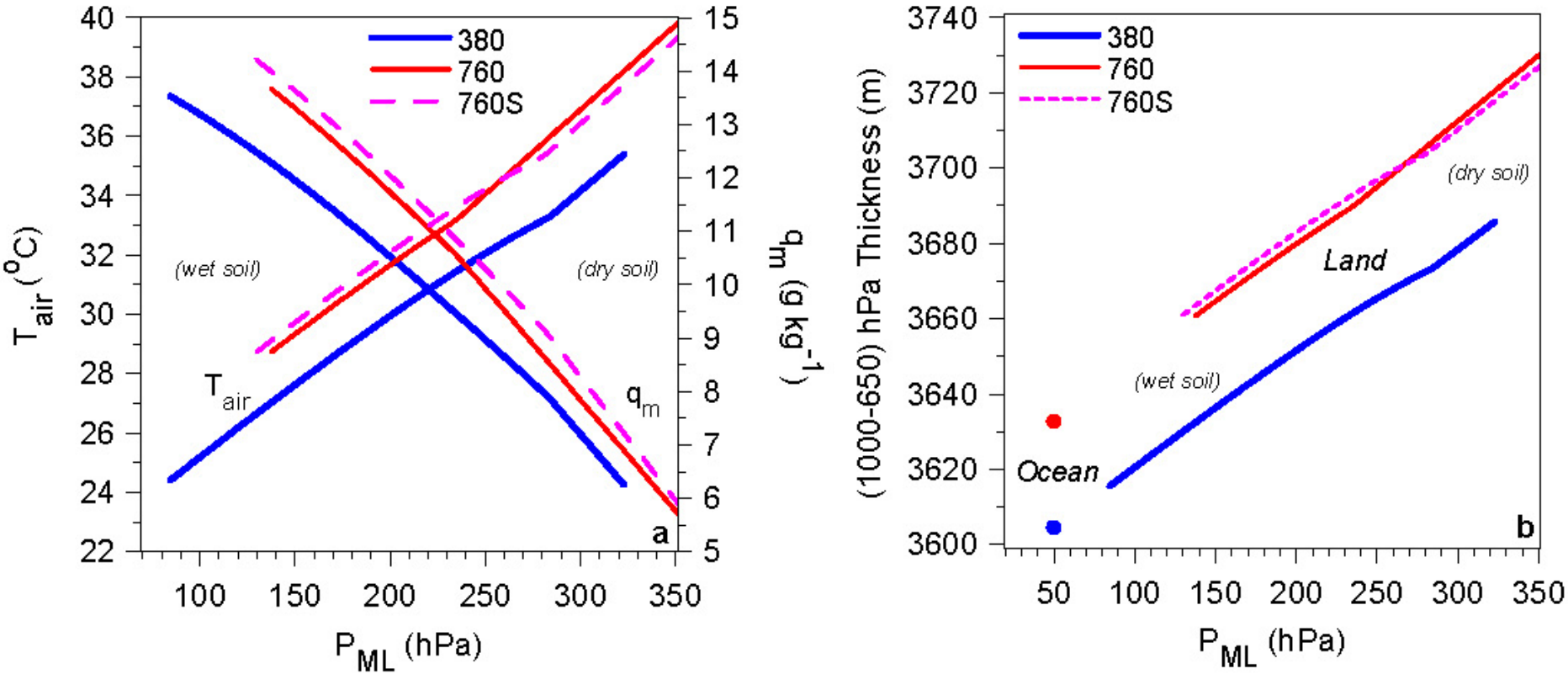




λE

Soil water index

Changes with ML depth



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

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]

- ***Caveats: soil-water & subsidence changes unknown; partial radiative coupling***

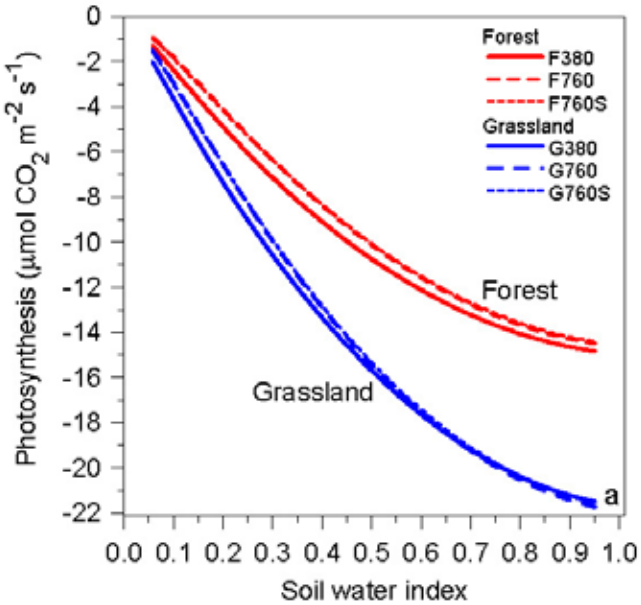
Conclusions

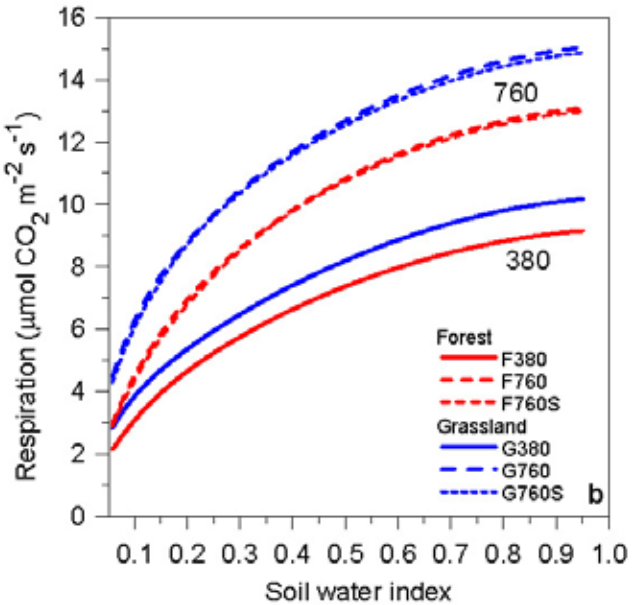
- **Simplified model shows changes in BL-cloud over land with vegetation change and warmer high CO_2 climate**

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

Changes in CO_2 fluxes

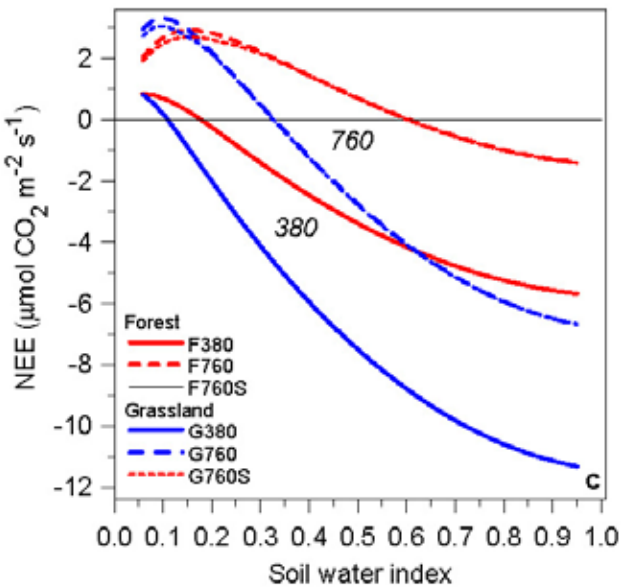
PH

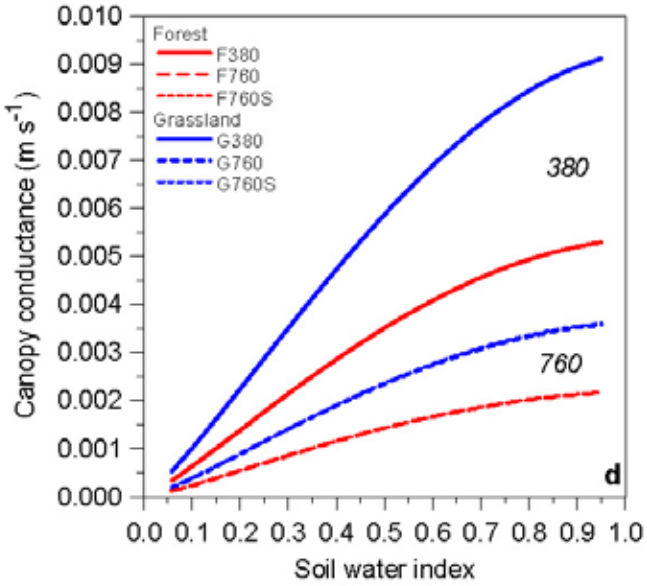




Resp

NEE

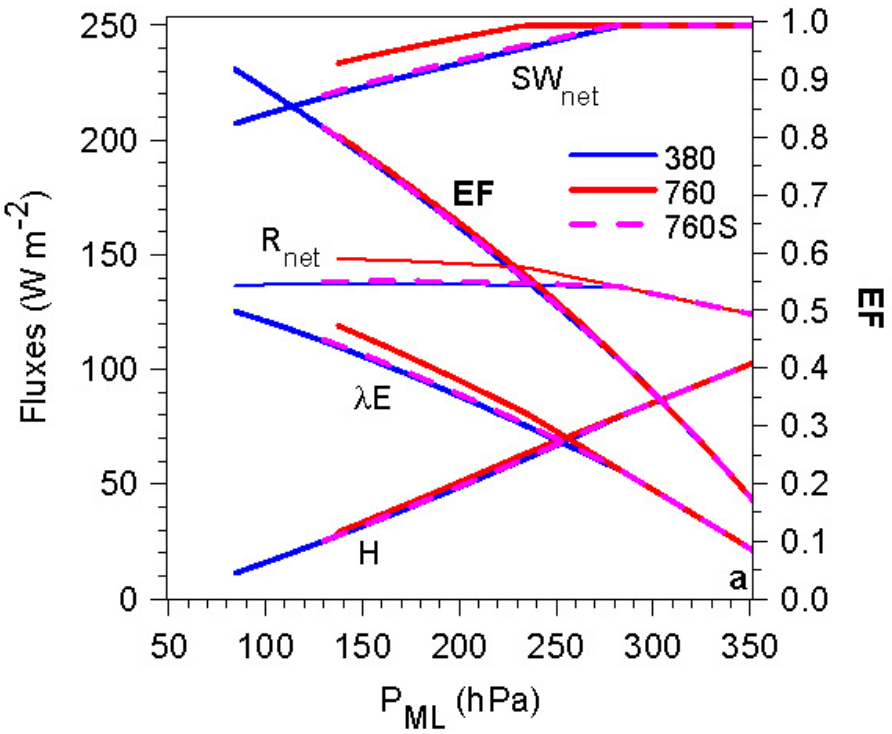


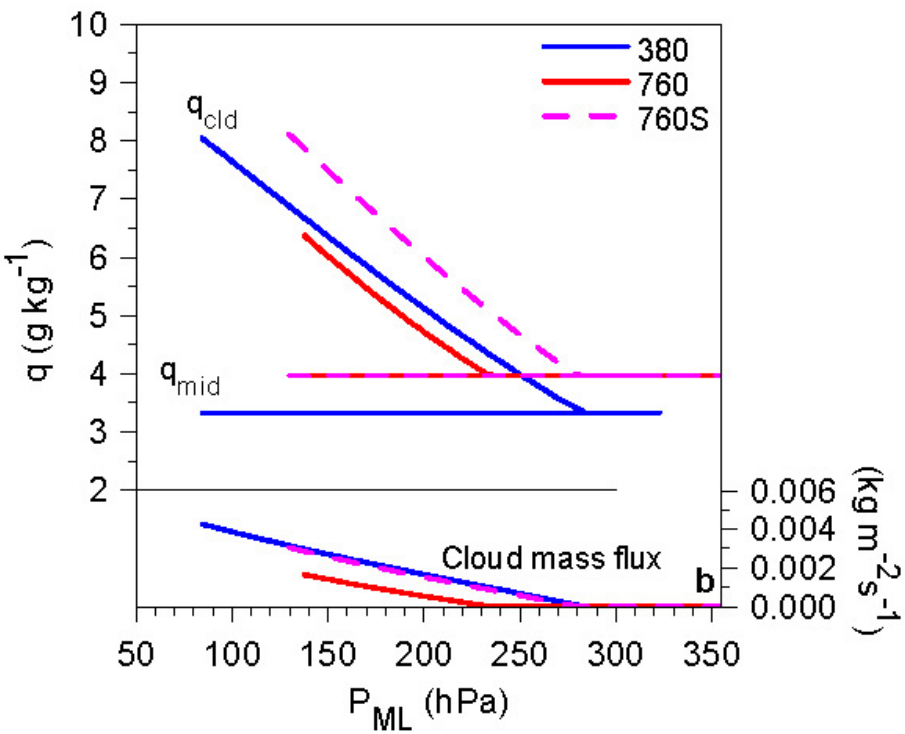


g_{veg}

Soil water index

Changes with ML depth-2





- **EF falls as P_{ML} deepens**
  - *Upper boundary conditions disappear*
- Cloud mass flux ⟶ 0 as P_{ML} increases