Boundary layer equilibrium – oceans and land [2004]

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Based on:

Betts, A.K., 1997: Trade Cumulus: Observations and Modeling. Chapter 4 (pp 99-126) in *“The Physics and Parameterization of Moist Atmospheric Convection*, Ed. R. K. Smith, NATO ASI Series C: Vol. **505**, Kluwer Academic Publishers, Dordrecht, 498pp.

Betts, A. K., and B. A. Albrecht, 1987: Conserved variable analysis of boundary layer thermodynamic structure over the tropical oceans. *J. Atmos. Sci.*, **44**, 83-99.

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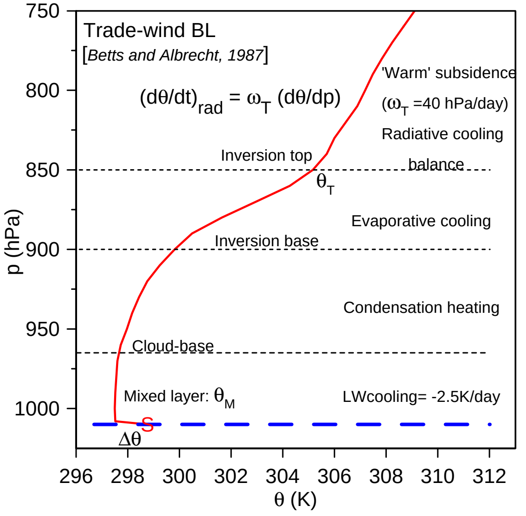
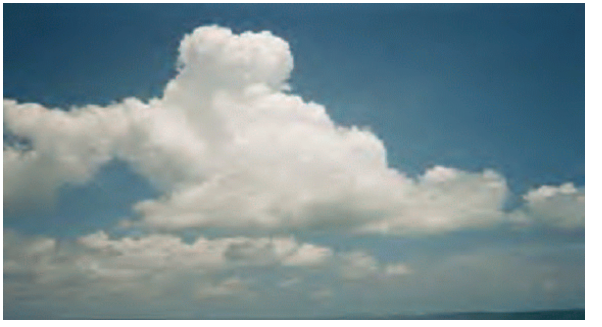
Betts, A.K. and W. L. Ridgway, 1989: Climatic equilibrium of the atmospheric convective boundary layer over a tropical ocean. *J. Atmos. Sci.*, **46**, 2621-2641.

Betts, A. K., 2000: Idealized model for equilibrium boundary layer over land. *J. Hydrometeorol.*,**1**, 507-523.

Betts, A. K., B. Helliker and J. Berry, 2004, Coupling between CO_2, water vapor, temperature and radon and their fluxes in an idealized equilibrium boundary layer over land. *J. Geophys. Res.* (In revision).





Why is mixed layer cooler than the ocean SST?

LW cooling = -2.5 K/day

Clouds redistribute heat and water and modify radiative balance

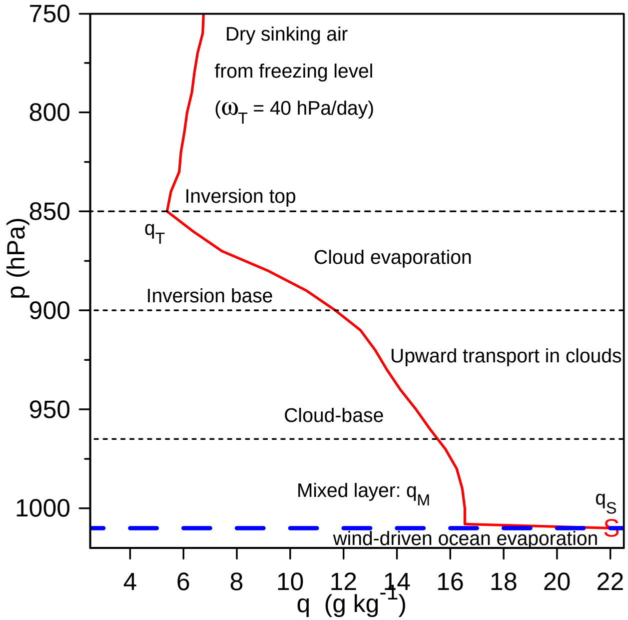
Equilibrium for whole layer:

$$0 = (g/C_p)\,\Delta R_{net} + \omega_0\,\Delta\theta + \omega_T\,(\theta_T - \theta_M)$$

-40	+10	+30 W m^{-2}
cooling	surface flux	subsidence

Surface velocity scale: $\omega_0 = \rho V_0\, C_D \approx$ 90hPa/day

Subsidence: $\omega_T \approx$ 40 hPa/day



Why is the mixed layer not saturated, as the air blows over ocean? Evaporation from ocean is balanced by subsidence of dry air above.

$$0 = \omega_0 \,(q_S(SST) - q_M) + \omega_T \,(q_T - q_M)$$

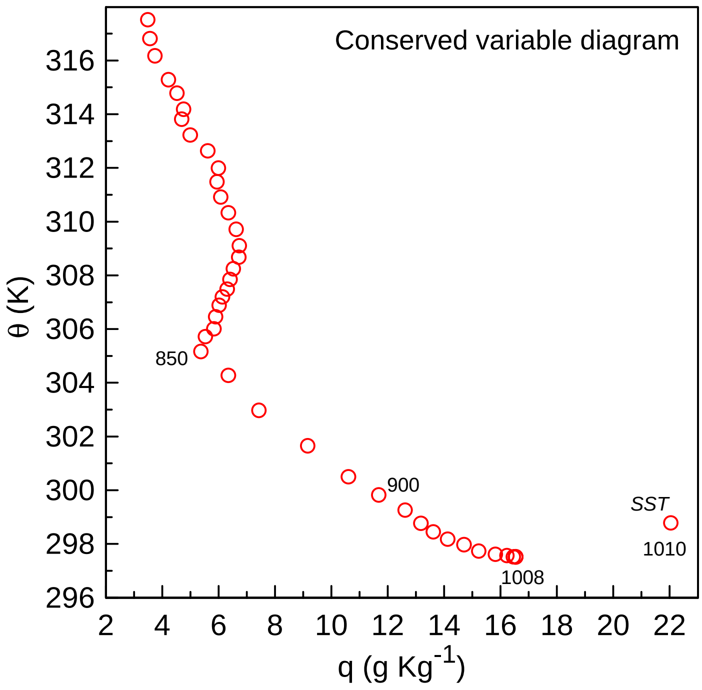
$$q_M = [\omega_0 \, q_S(SST) + \omega_T \, q_T]/(\omega_0 + \omega_T)$$

A weighted average

q_M = [90*22 +40*5]/130 = 16.7 g/kg

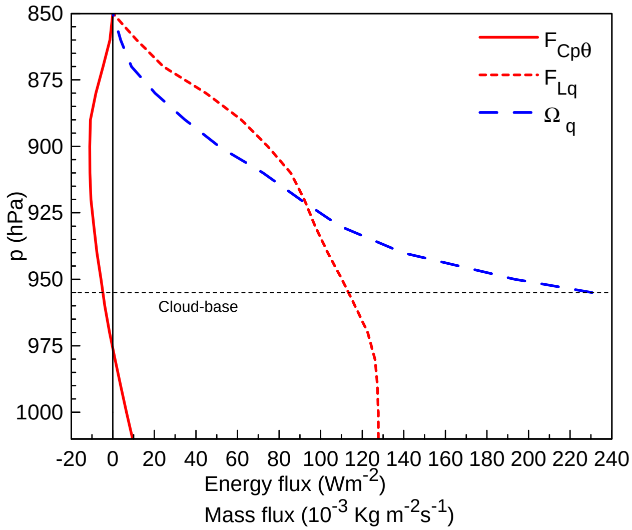
so $\theta_{EM} \approx 346$K

cloud-base ≈ 960hPa



Can think of the two balances on a ‘conserved parameter’ diagram: “Mixing” of surface point and 850hPa point, modified by radiation.

Relate equilibrium structure to convective fluxes: F_q, F_θ [illustration]



Assume ω = 40hPa/day in cloud layer, below cloud-base decreases linearly to zero at surface.
Assume radiative cooling $\partial\theta_{Rad}/\partial t$ = -2.4 K/day

Equilibrium means steady state
[assume horizontally homogeneous]

$0 = \partial F_q/\partial p + \omega\, \partial \overline{q}/\partial p$
$0 = \partial F_\theta/\partial p + \omega\, \partial \overline{\theta}/\partial p + \partial\theta_{Rad}/\partial t$

[where F_q and F_θ represent the convective fluxes of total water and 'liquid water potential temperature' above cloud-base]

Integrate to give fluxes from ω, θ and q profiles, and $\partial\theta_{Rad}/\partial t$.
This gives *equilibrium fluxes* [in units of W m^{-2}] *from profiles*

Simple mass-flux model [illustration]
Can couple fluxes with a *mass flux transport model* for shallow convection

$F_q = \Omega_q\,(q_c - q)$ with $q_c = q_B$ a cloud-base value of 16.54 gkg^{-1}

and compute the Ω_q shown in the figure.

Shallow Cumulus

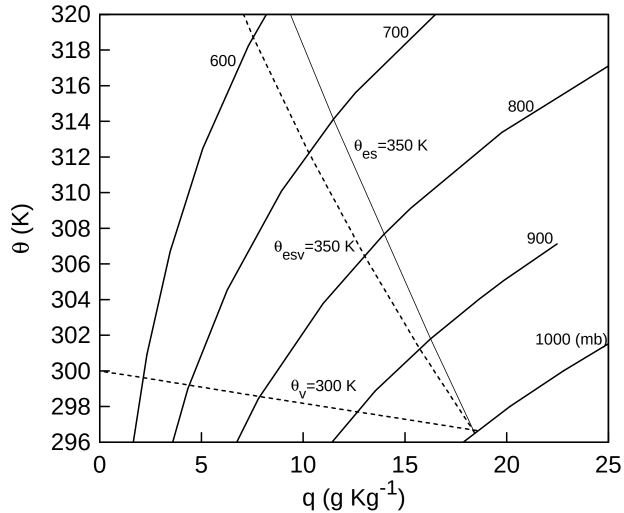
– non-precipitating
– net LH = 0
– but transport heat because condense water, advect it upward and reevaporate it [a “refrigerator”]
– buoyant, because of condensation but still ‘cold’, because of liquid
– conserved variables:

$$\theta_E = \theta + Lq/C_p$$
$$\theta_L = \theta - L\ell/C_p$$
$$q_T = q + \ell$$

– represent by mass transport of air with sub-cloud properties to higher levels
– equilibrium structure over ocean is balance of convective transports, subsidence, and radiative flux divergence (cooling)

Conserved Variable diagram – 2

– Similar to other thermodynamic diagrams; just θ, q as axes



Dry virtual potential temperature

$\theta_v = \theta(1+.608*q/1000)$

– vapor is less dense

– SP of equal density

– Slopes 1K every 6g kg^{-1}

[Could use as axis]

Wet virtual potential temperature

– if parcels carry liquid .. Denser; $\Delta\ell$=2 g kg^{-1}/100hPa

– $\theta_v = \theta(1+.608*q/1000 - \ell/1000)$

– line of equal density

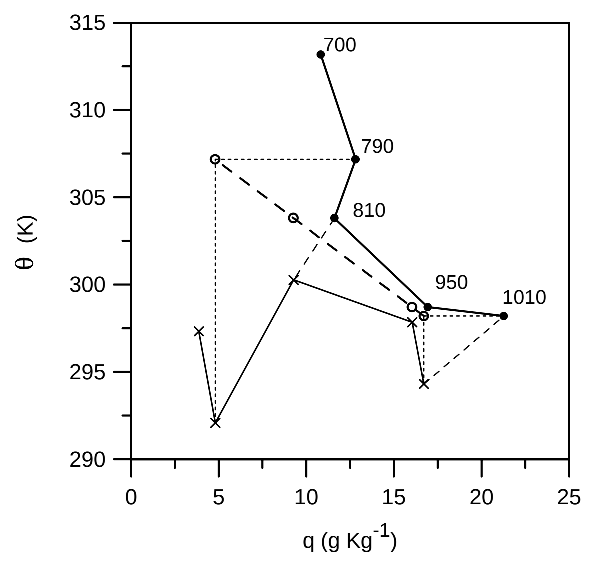
$(\partial\theta/\partial p)_{\theta esv} \approx 0.9\ (\partial\theta/\partial p)_{\theta es}$

Parameterizing shallow convection with a mixing line representation

– parameterize a cloud field: what do these simple diagnostic studies tell us?
– two approaches:

a) parameterize fluxes, and their gradients:
eg with mass flux model; say cloud-base q-flux = surface q flux
[Problem from a ‘climate perspective is that system may drift to either dry or cloudy state]

b) parameterize structure: eg ‘mixed layer’ or ‘mixing line’.



Single mixing line can represent whole BL structure of both clear and cloudy air.

Unsaturated air: find T, T_d at p by drawing lines of constant θ and q
Cloudy air: find T, T_d [for total water] at p by drawing lines of constant θ_{es} and q

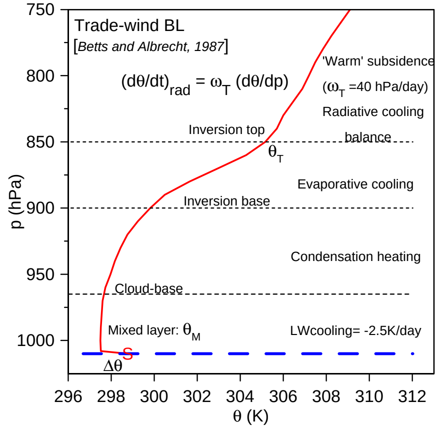
A type of convective adjustment.

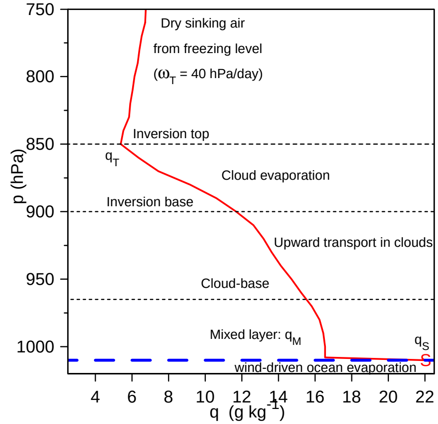
[example: advanced students read paper/Betts and Ridgway,1989]

How does ocean BL and land differ?

Radiative cooling
SH, subsidence

Evaporation and
subsidence





Stays a little cooler than ocean and sub-saturated:
surface wind and subsidence control evaporation
[ocean store suns heat; diurnal cycle small]

LAND: what are the essential differences??

Sun heats surface and drives large diurnal cycle; daytime unstable;
cools radiatively at night; at night stable BL
Surface not saturated.. Except inside leaves.
Sun drives evaporation through photosynthesis
[coupled to CO_2 uptake]
Subsidence of dry air still plays key role, averaged over 24hrs.

Need to understand mean state and diurnal cycle

Coupling of CO_2 and water vapor through the BL

BOREAS Northern Study area [Thompson, Manitoba]

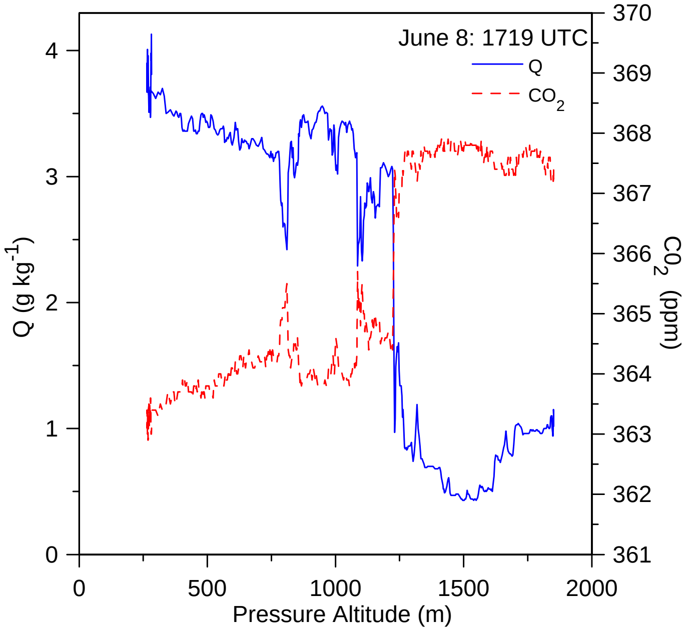


Figure 1 Coupling of CO2 and water vapor profiles of June 8 at 1719 UTC (LST=UTC-6h)

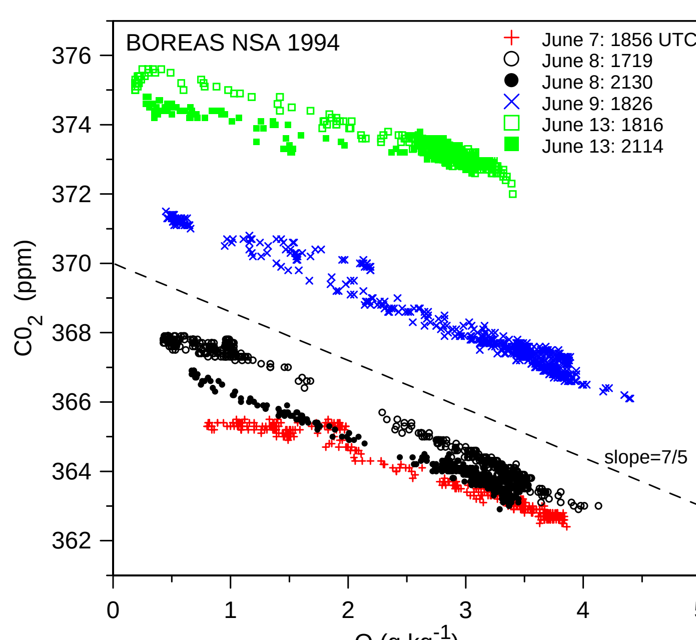


Figure 2. Profiles through the mixed layer on four days in June, showing tight coupling between water vapor and CO_2 structure. Illustrative slope of 7 ppm CO_2 to 5 g kg^{-1} is shown.

RH, LCL and pressure height of cloud-base are fundamental BL quantities

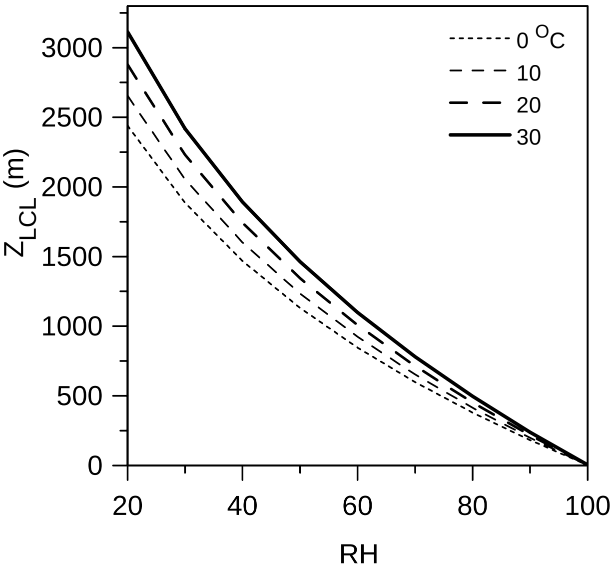


Fig. 19a.. Relation between height of cloudbase and RH as surface temperature varies.
[Note independent of surface pressure]

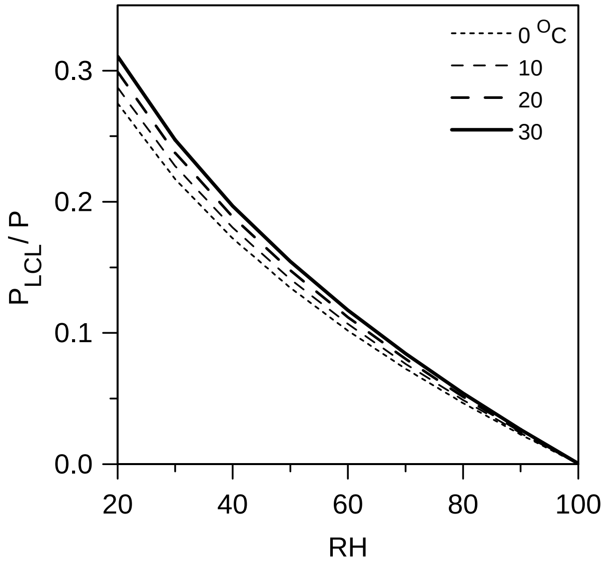


Fig.19b. As Fig. 4a for ratio of P_{LCL} to surface pressure p
[Note dependence on T is weak]

– Over land, there is link to evaporative resistance

Dry soils ➔ large resistance to evaporation

Extra resistance produces drop of saturation from inside leaf to outside leaf

Reduces relative humidity (RH) and increases BL depth

We can create an “equilibrium model” by averaging over 24hour cycle

– how does mean BL depth and fluxes depend on soilwater and solar forcing?

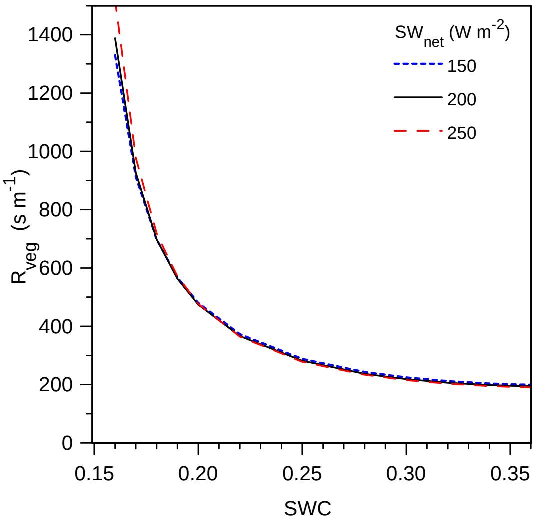


Figure 20. Dependence of stomatal resistance on SWC, and SW_{net}

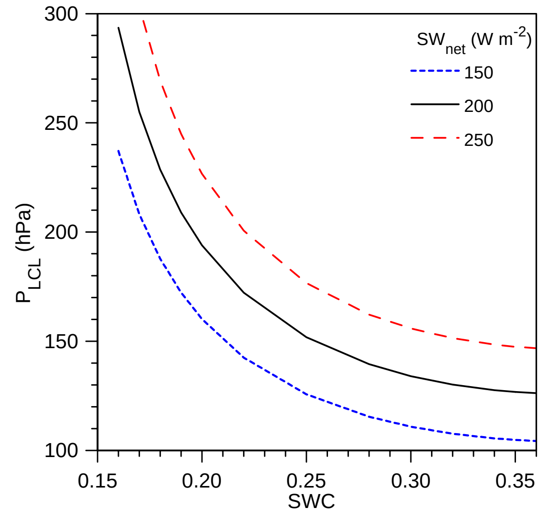


Figure 21. Dependence of BL depth on SWC and SW_{net}

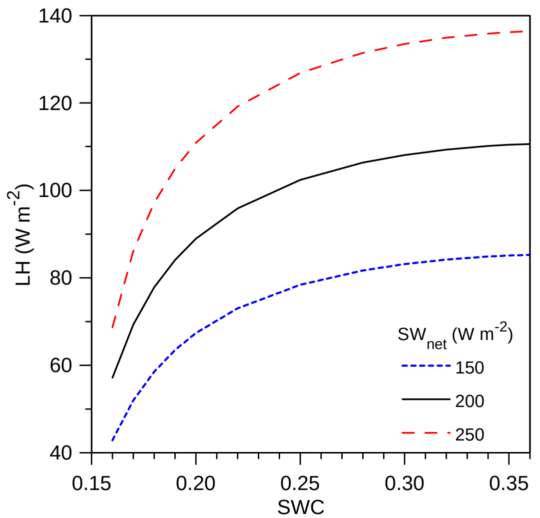


Figure 22. Latent heat on BL depth

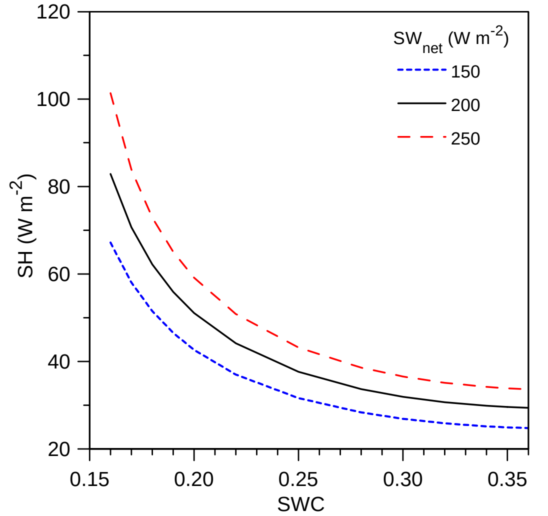
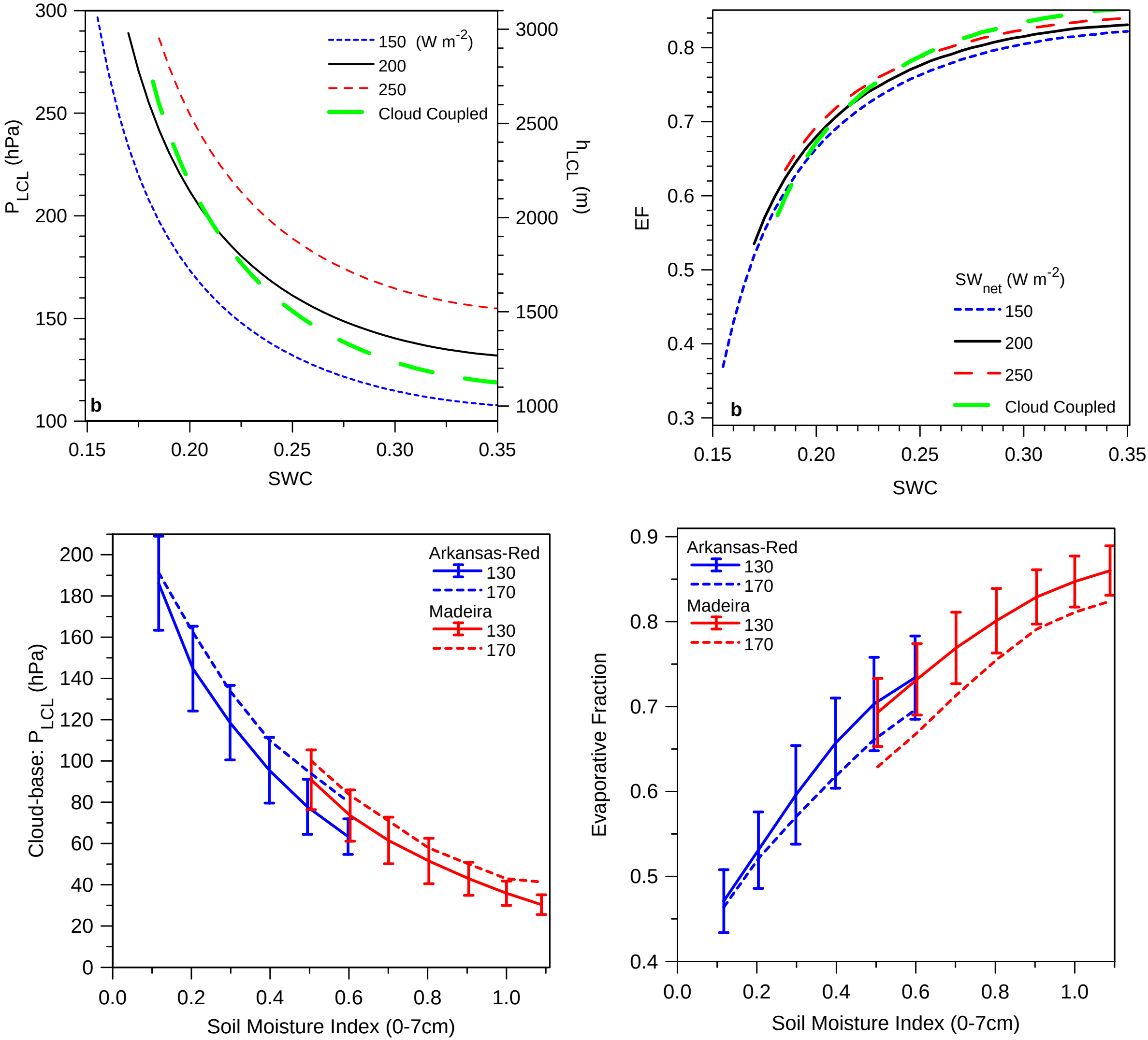


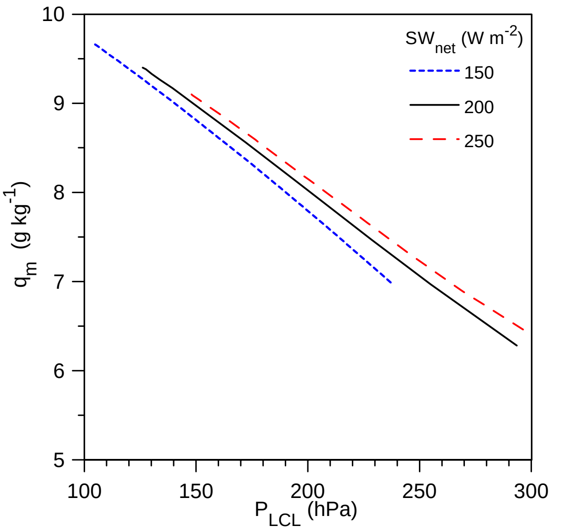
Figure 23. Sensible heat on BL depth

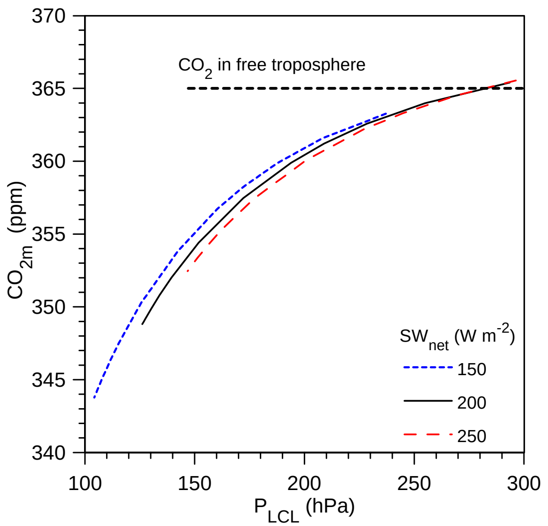
[see Betts: *J. Hydrometeorol*. 2000]

Compare idealized model and diurnally averaged ERA40

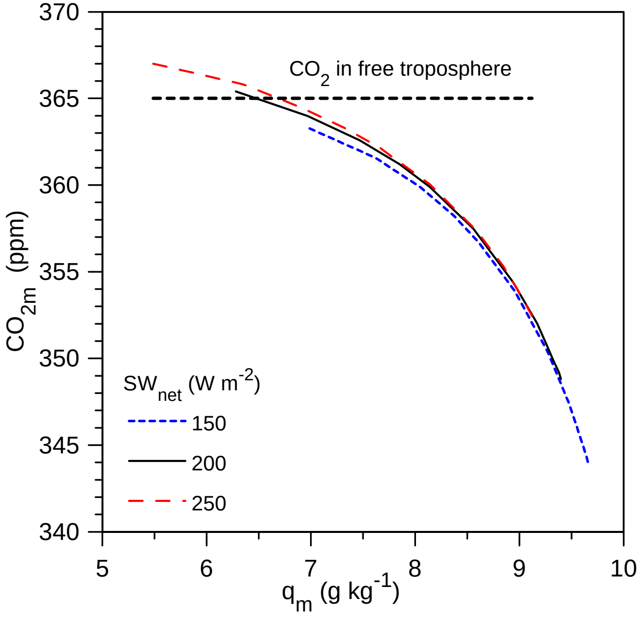


Evaporation and photosynthesis are linked to *same* vegetative resistance





q and CO_2 at equilibrium are functions of BL depth



CO_2 and water vapor are tightly coupled

Coupling between CO_2, water vapor, temperature and radon and their fluxes in an idealized equilibrium boundary layer over land.

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- Brent Helliker and Joe Berry

  Carnegie Inst. of Washington, Stanford, CA

[*J. Geophys. Res*. in revision]

Idealized equilibrium boundary layer over land

- Extension of Betts (2000) in *J. Hydromet*.
- Idealization is to average over diurnal cycle
- Extensions

  - add vegetation model
  - CBL and ML equilibrium
  - Simple coupling of radiation to clouds

Purpose

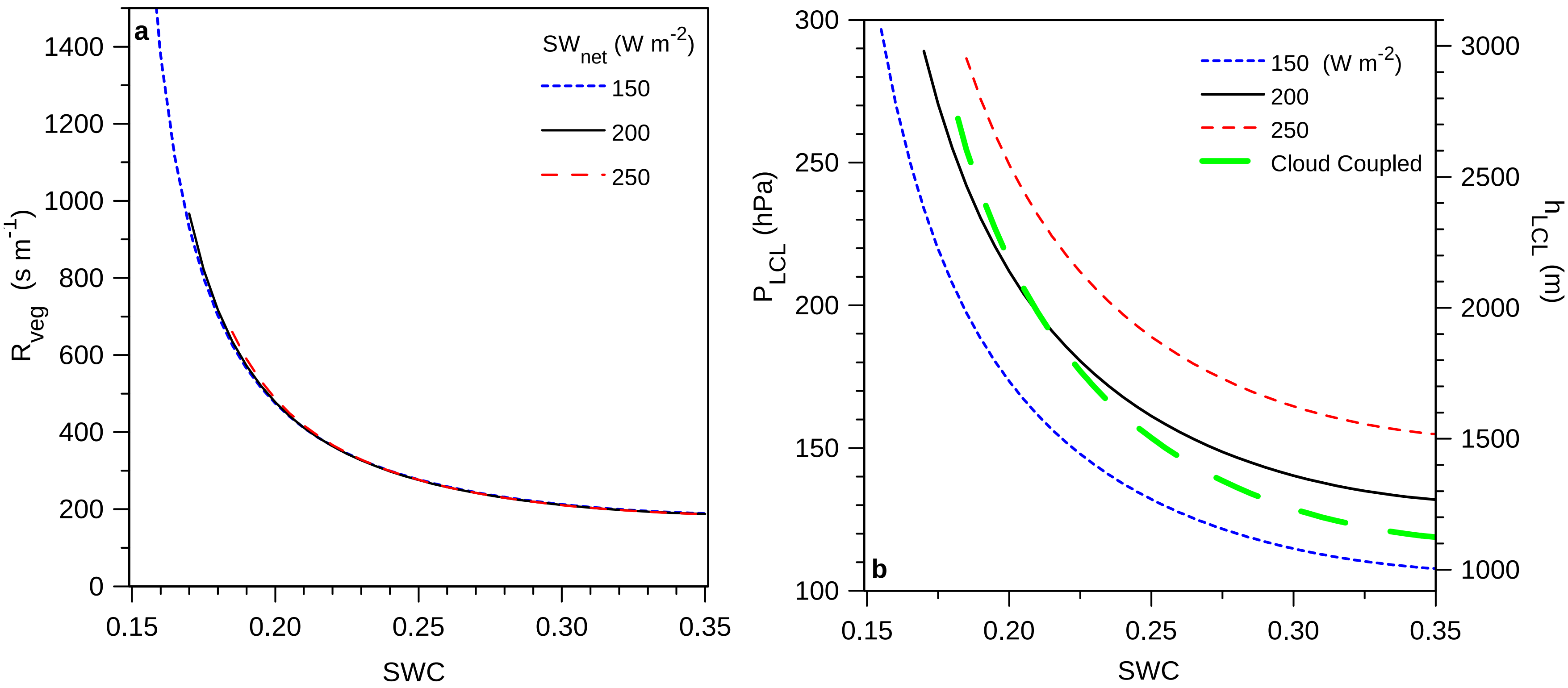
- Couple mixed layer 'equilibrium' of potential temperature, water vapor, CO_2 (and radon) with the surface energy and water budgets and net ecosystem exchange (and surface radon flux)
- Suggest that regional ML budgets may give useful constraints on regional carbon budgets.

Idealized equilibrium model

- Surface energy budget: diurnal mean
- Radiative fluxes coupled through cloud cover
- Photosynthetic controlled evaporation, linked to stomatal resistance, calculated from Ball-Berry model, fitted to Wisconsin tall tower data.
- ML and CBL equilibrium

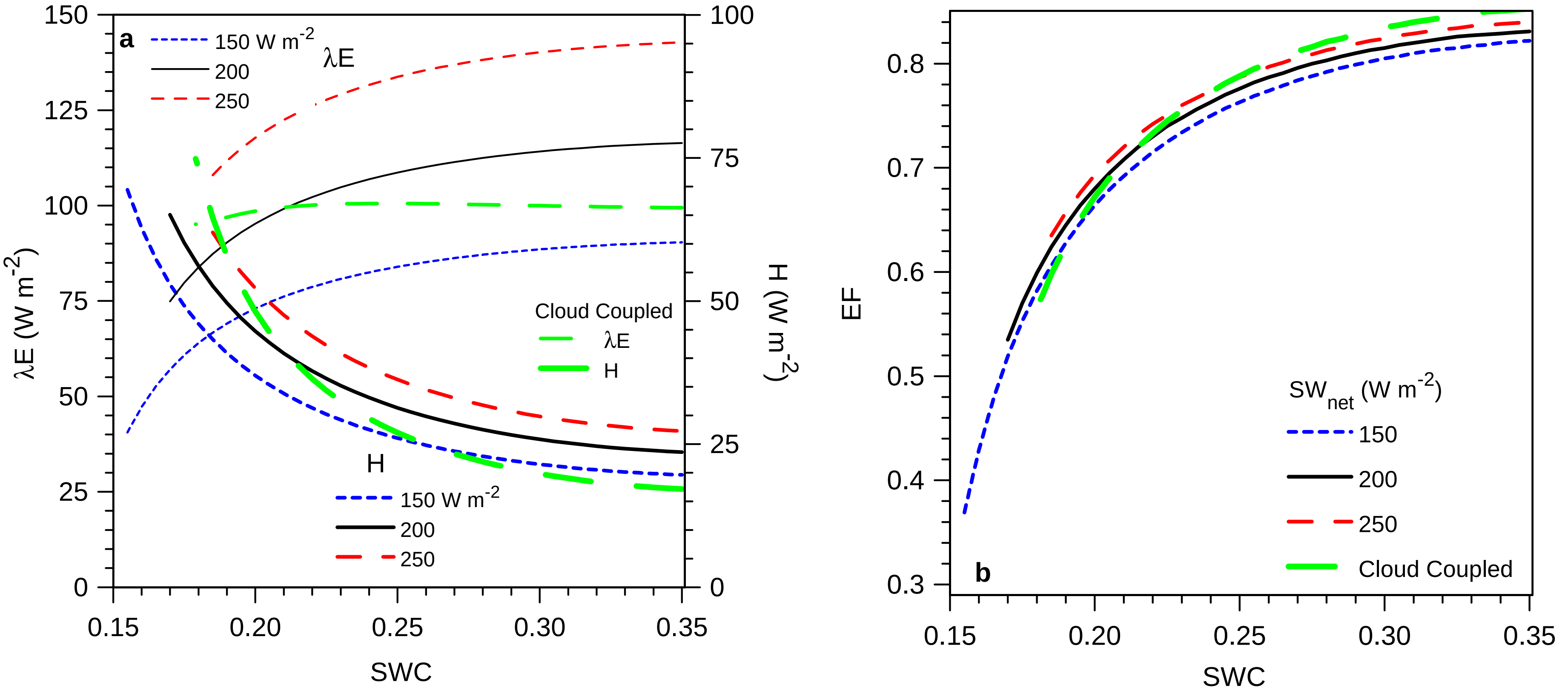
- 45 equations … read the paper

Equilibrium solutions



- *Sensitivity of vegetative resistance and ML depth to soil water and net short-wave*

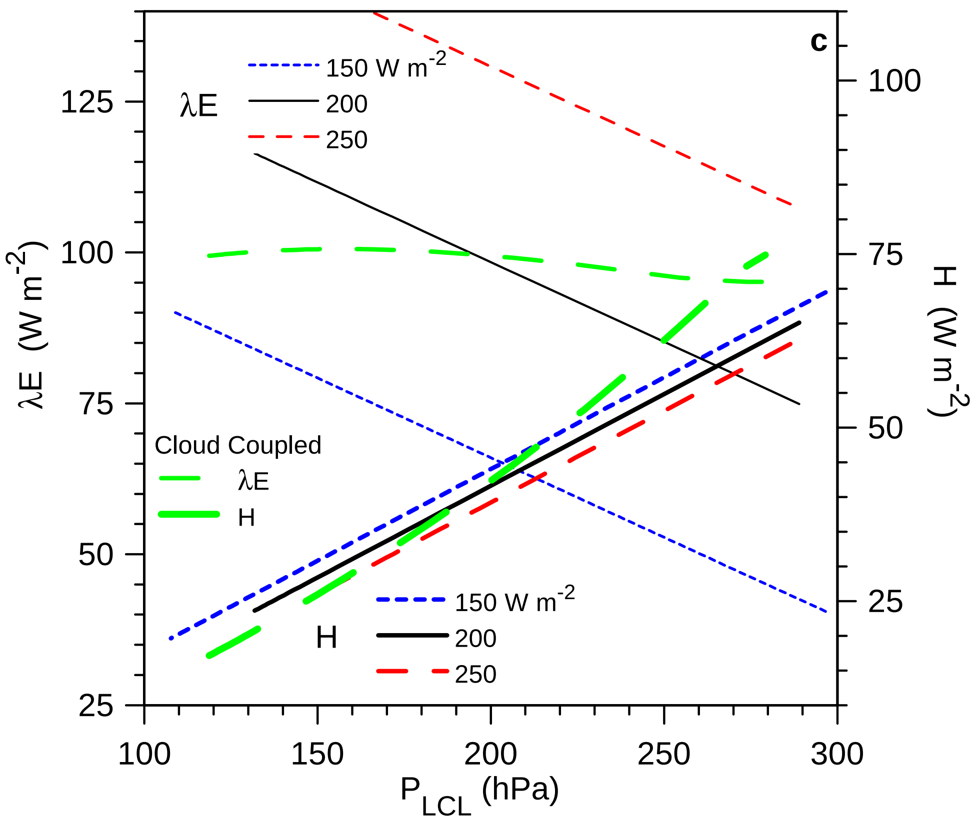
Surface energy fluxes and EF as a function of soil water content



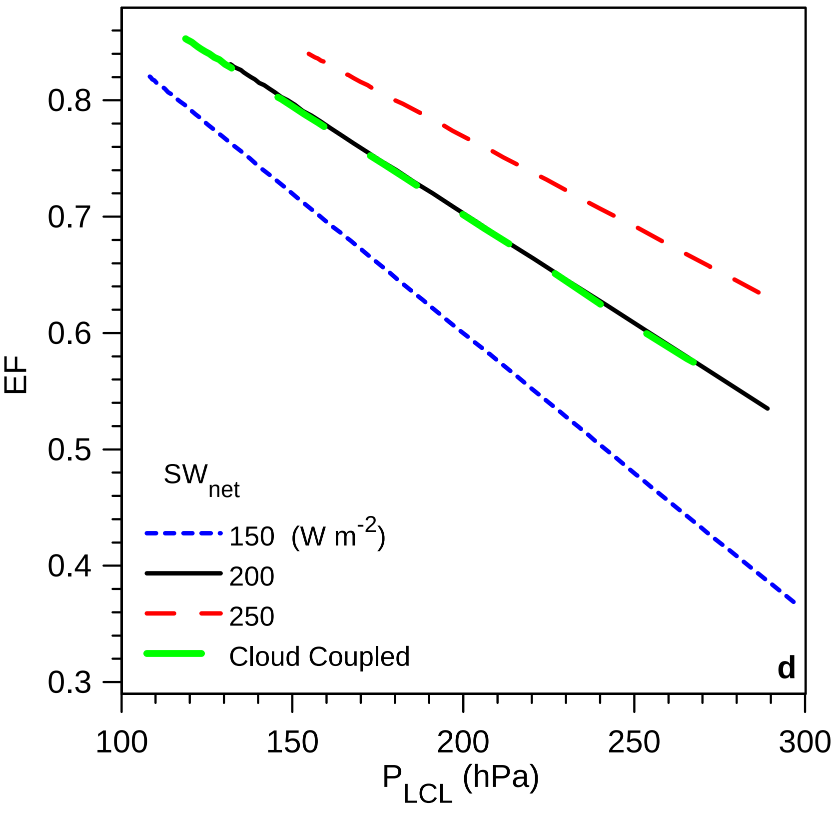
Latent and sensible heat fluxes

Evaporative fraction

Surface energy fluxes and EF as a function of ML depth: P_{LCL}

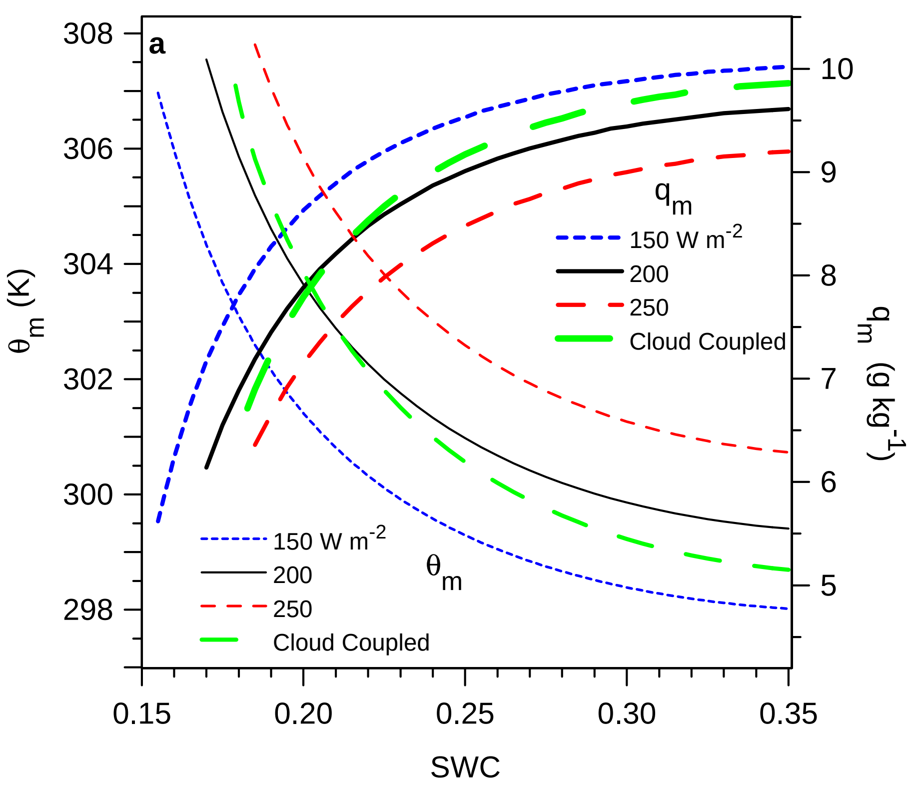


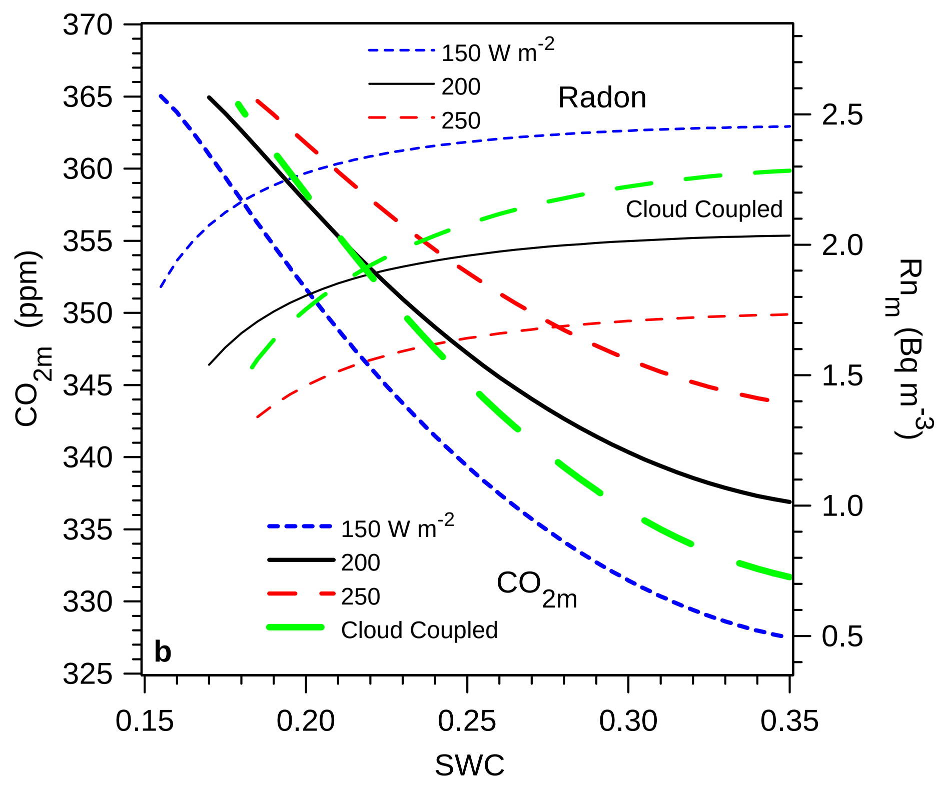
Latent and sensible heat fluxes



Evaporative fraction

ML properties as a function of soil water content

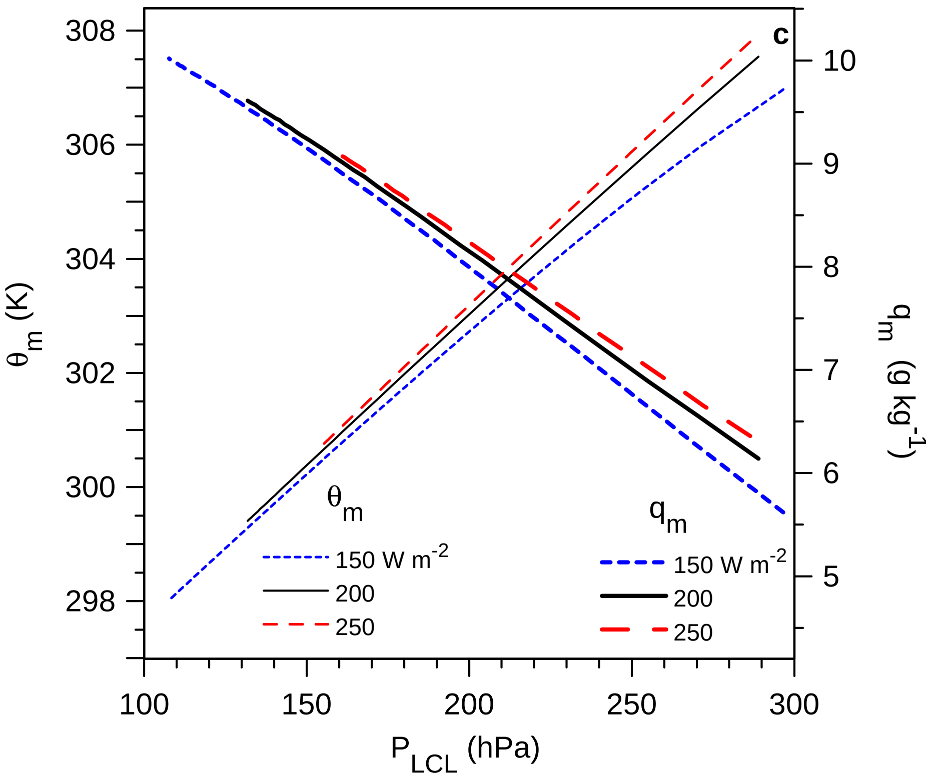




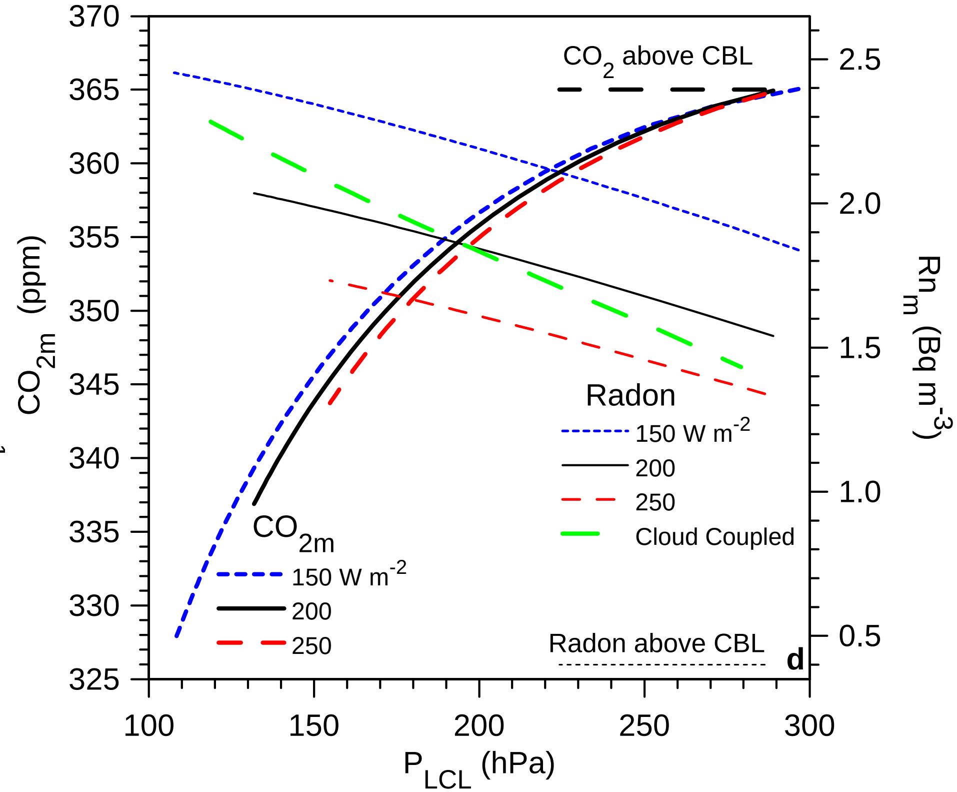
ML potential temperature and mixing ratio

ML CO_2 and radon

ML properties as a function of ML depth: P_{LCL}

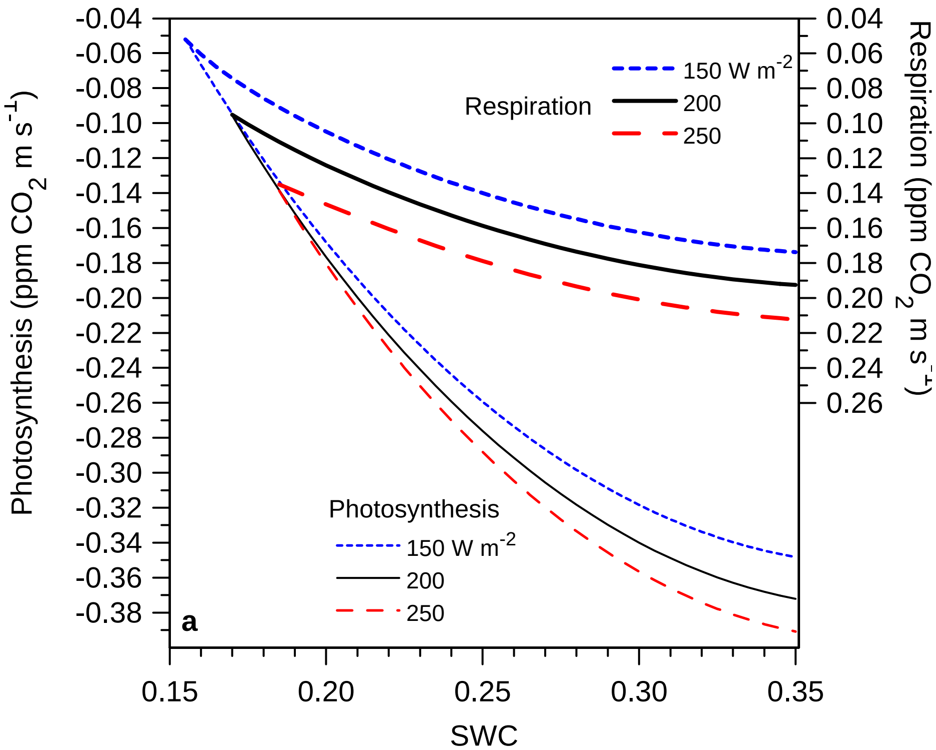


ML potential temperature and mixing ratio

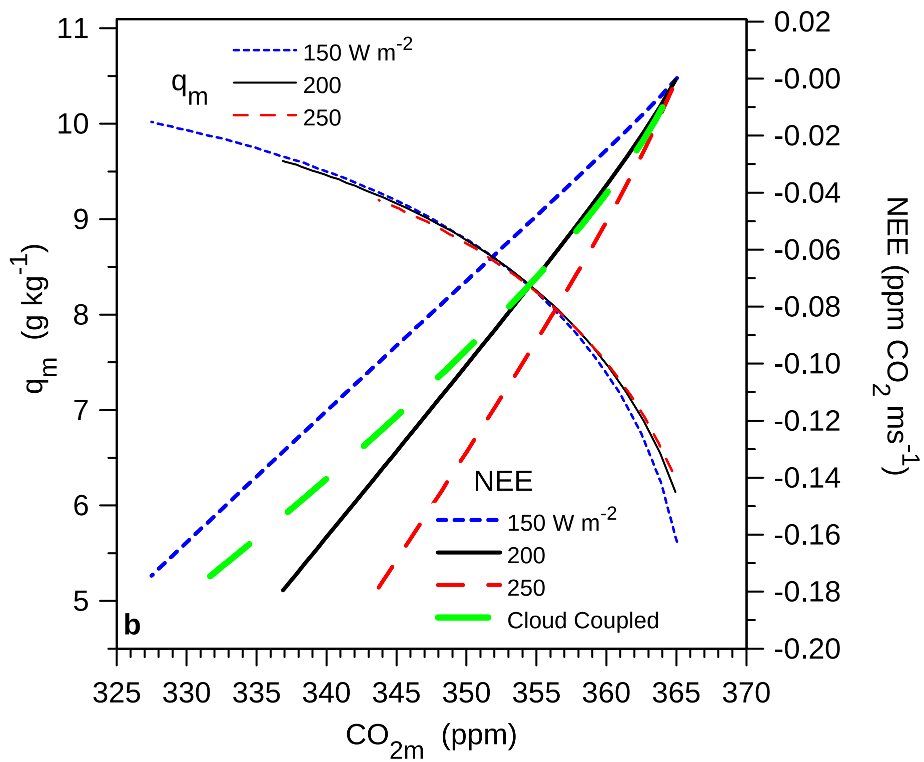


ML CO_2 and radon

Photosynthesis and respiration Coupling of CO_{2m} to q_m and NEE



Photosynthesis; respiration



CO_{2m} against q_m and NEE

Conclusions-1

- SWC is primary control on NEE and on evaporation through stomatal resistance
- Dry soil: equilibrium depth of the ML increases sharply, as reduced evaporation leads to a warmer drier equilibrium
- LCL is powerful constraint on ML depth
- Radiative impact of clouds on equilibrium

Conclusions-2

- Two different perspectives:
  - as a function of SWC
  - as function of cloud-base height
- Important coupling between ML q and CO_2, and between NEE exchange and CO_2

  - useful for carbon budget estimates

Preprint at ftp://members.aol.com/bettspapers/BHB_JGR.pdf

Take away these ideas

Ocean equilibrium: balance of radiative cooling, subsidence and surface fluxes

giving a typical tradewind BL with cloud-base 50hPa above surface and a 150hPa deep shallow cumulus layer....
[Solar heating absorbed in deep ocean mixed layer]

Land diurnal cycle driven by solar heating, but *equilibrium* similar to ocean, except a drier mean state because additional ‘vegetative’ resistance to evaporation at surface.

CO_2 and water vapor coupled in BL over vegetation.