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 CO₂ world?

- Strategy 1: Fully coupled Earth system model sensitivity tests with ensembles of models
  - **Large inter-model variation** - vegetation-CO₂-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

Cloud-layer

\[ \theta_{\text{mid}}, \quad \text{RH}_{\text{mid}}, \quad \text{CO}_2_{\text{mid}} \]

\[ \text{Ps} - 350 = 650 \text{ hPa} : \text{specified} \]

\[ \rho_b \text{W}_{\text{sub}} \]

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

Entrainment fluxes linked to jumps and \( \rho_b(W_{\text{sub}} + W_{\text{clld}}) \)

Mixed layer balance

\[ \theta_m, \quad q_m, \quad \text{CO}_2_{\text{m}} \]

Constant mass divergence

Surface fluxes

\[ P_{\text{LCL}} : \text{RH}_m, \quad T_m, \quad q_m, \quad \text{CO}_2_{\text{m}} \]

P_{\text{s}} : \text{surface pressure}

Vegetation model

Cloud forcing

\[ \text{RH}_{\text{sf}}, \quad T_{\text{sf}}, \quad q_s(T_{\text{sf}}), \quad \text{CO}_2_{\text{L}} \]

Soil moisture specified
Mid-tropospheric boundary conditions

- **Above cloud-base to 650 hPa**

  \[ \theta(p) = \theta_{00} + \Gamma_w(950-p) \]

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

  \[ \theta_{cld} = \theta_{00} + \Gamma_w(P_{ML} - 50) \quad \text{for } Ps = 1000 \]

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

- \( RH_{mid} = 40\% \) gives \( q_{mid} \); \( CO_{2mid} = 380, 760 \) ppm

- Set ‘Oceanic’ reference \( \theta_{00} = (297, 299K) \) for the present and doubled \( CO_2 \) climates
Surface radiation & cloud forcing

- $SW_{\text{net}}(\text{clear}) = 250$ Wm$^{-2}$ [mid-lat. summer]
- $LW_{\text{net}}(\text{clear}) = -117 + 0.175(300-P_{ML})$ Wm$^{-2}$
- $SWCF = -0.4*250 \left( \frac{\rho_b W_{\text{cld}}}{\rho_b W_{40}} \right)$
- $LWCF = 20 \left( \frac{\rho_b W_{\text{cld}}}{\rho_b W_{40}} \right)$
- $ML_{\text{cool}} = -3 \left[ 1 - 0.4 \left( \frac{\rho_b W_{\text{cld}}}{\rho_b W_{40}} \right) \right] K \text{ day}^{-1}$

Cloud mass flux $\quad$ 40% eff. cloud albedo
Surface & ML Budget equations

Surface Energy balance

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

ML Water balance

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

  Transpiration    Subsidence          cloud-base flux

ML Heat balance

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

  Sensible    Radiation          cloud-base flux

ML CO$_2$ balance

• $\text{NEE} = A \rho_b W_{\text{sub}}(\text{CO}_2m - \text{CO}_2\text{mid}) = A(\rho_b W_{\text{sub}} + \rho_b W_{\text{clld}})(\text{CO}_2m - \text{CO}_2\text{clld})$

  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: $\theta_{oo}$

- Cloud decreases, $T_{air}$, $R_{net}$, $\lambda E$ increase, ML a little shallower, small increase of EF
Sensitivity studies: CO$_2$

- Canopy conductance drops
- EF falls a lot, Cloud decreases, $R_{\text{net}}$ flat, $T_{\text{air}}$ increases & $q_m$ decreases, ML deepens a lot
Sensitivity studies: subsidence

- $q_m$ falls, ML deepens, cloud decreases, $R_{\text{net}}$ increases, $T_{\text{air}}$ 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 $\theta_{oo}$ +2K

[very approx. A1B scenario; AR4-WG1, Ch 11]
Changes in ML equilibrium & cloud-base

- $T_{\text{air}}$
- RH
- $P_{LCL}$
- $P_{ML}$
- $Q$
- $\theta_E$

Soil water index
Changes in Surface energy fluxes

$R_{\text{net}}$

Cloud mass flux & Albedo

$H$

$\lambda E$

Soil water index

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\(_{\text{veg}}\)

![Graphs showing changes in CO\(_2\) fluxes](image)
Changes with ML depth-2

- EF falls as $P_{ML}$ deepens
  - Upper boundary conditions disappear
- Cloud mass flux $\rightarrow 0$ as $P_{ML}$ increases