Lecture on Planetary Boundary Layer and Coupling to the Land Surface

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We live in the planetary boundary layer, the layer of the atmosphere affected by the land surface. It is a dynamic layer that can be visualized by the base of convective clouds on a partly cloudy day. Above the boundary layer the sky is clear and blue, below it you see dirt, aerosols, pollution from land activities. There can be greater build ups and withdrawals of biogenic and biotrophic trace gases.
The pbl is dynamic it grows during the day with heat exchange. It has various zones. An entrainment layer, the mixed layer and the surface layer. Fluxes tend to vary linearly with height. Scalar profiles have a strong gradient near the surface, a mixed layeer due to big convective activity, then gradients across the inverted entrainment layer.
Diurnal Growth of PBL

Mixed layer height (m)

Time of day (UTC hours)

DOY 228-233

Data of Baldocchi, Davis, analysis by Fuentes

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Seasonal trend in pbl growth over Walker Branch Watershed in Oak Ridge, TN
Seasonality of the time rate of growth of pbl height over the Walker Branch Forest
Paper on depth of pbl growth across the world. We found much deeper boundary layers in the boreal forest of Canada, than over Siberia. Ours were as deep as the deserts of the Middle East
Conceptually you can see the interactions with rate of growth of the pbl and the fluxes into and volume from below and above
Time rate of change of virtual potential temperature
Is a function of heat flux at the bottom and top of the
Boundary layer

\[ h \frac{\partial \theta_{vm}}{\partial t} = (w' \theta'_v)_s - (w' \theta'_v)_h \]
Parameterizing the entrainment flux remains the more difficult and poorly known quantity

\[ h \frac{\partial \theta_{vm}}{\partial t} = (\overline{w' \theta'_v})_s - (\overline{w' \theta'_v})_h \]

Scale flux at top of pbl with surface flux

\[-(\overline{w' \theta'_v})_h = \beta_h (\overline{w' \theta'_v})_s \]

Scale flux at top of pbl as a function of the jump
Temperature and the entrainment velocity

\[-(\overline{w' \theta'_v})_h = \Delta \theta_v w_e \]
In some places on earth we have large scale subsidence, like summer over California, so this downward velocity must be added (subtracted) from the time rate of change of pbl growth, $dh/dt$
Mixed Layer Budget Eq.

\[
\frac{dC_m}{dt} = \frac{F_c}{h} + \frac{C_e - C_m}{h} \left( \frac{dh}{dt} - W_s \right)
\]

Flux in from the top

Time rate of change

Flux in the bottom

Growth - subsidence

Simple box budget model
Equations for potential virtual temperature, potential temperature in the mixed layer and specific humidity in the mixed layer.
Equations for computing the time rate of change in height of the pbl, by converting virtual potential temperature flux covariance into sensible and latent heat fluxes.
Gamma is the slope of the temperature inversion
Fuentes looked at our data from Walker Branch and tested the gamma values with mixed layer height.
<table>
<thead>
<tr>
<th>Date</th>
<th>Ld (Decimal DOY)</th>
<th>N−1 m</th>
<th>x_{m} (K km^{-1})</th>
<th>ΔH (K)</th>
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<td>123.63</td>
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</table>
Other models for pbl growth

\[
\frac{\partial h}{\partial t} = \frac{\beta_h (w' \theta'_v)_v}{\Delta \theta_v} + \frac{w_s}{\Delta \theta_v}
\]

Diedranks and Tennekes

\[
\frac{\partial h}{\partial t} = \frac{0.2 w_*^3 + 5 u_*^3}{\frac{g}{\theta_{v0}} h \Delta \theta_v}
\]

Raupach

\[
\frac{\partial h}{\partial t} = \frac{0.18 w_*^3}{0.8 w_*^2 + \frac{g}{\theta_{v0}} h \Delta \theta_v}
\]
Fuentes, Baldocchi, Davis

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Siqueria et al

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Role of Lifted Condensation Level
Occurs with ZI intersects with HLCL

\[ H_{LCL} = \frac{R T_a}{M_a g} \log \left( \frac{P_s}{P_{LCL}} \right), \]

\[ P_{LCL} = P_s \left( \frac{T_{LCL}}{T_a} \right)^{3.5}, \quad (7) \]

where \( T_{LCL} \) (K) is the saturation point temperature at \( H_{LCL} \) and can be derived from the Clausius–Clapeyron equation given by (Stull, 1988)

\[ T_{LCL} = \frac{2840}{3.5 \ln(T_a) - \ln \left( \frac{P_s}{0.622 t r} - 7.108 \right)} + 55, \quad (8) \]

Juang et al 2007, GCB

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Note when the pbl and lifted condensation levels match, precipitation occurs. One should also see a decrease in solar radiation with clouds.
Case study of the roles of PBL growth on interpreting the effects of changing land use on the climate.
If Papal Indulgences can save us from burning in Hell: Can Carbon Indulgences Save us from Global Warming?
Working Hypotheses

- **H1: Forests have a negative feedback on Global Warming**
  - Forests are effective and long-term Carbon Sinks
  - Landuse change (more forests) can help offset greenhouse gas emissions and mitigate global warming
- **H2: Forests have a positive feedback on Global Warming**
  - Forests are optically dark and Absorb more Energy
  - Forests have a relatively large Bowen ratio (H/LE) and convect more sensible heat into the atmosphere
  - Landuse change (more forests) can help promote global warming
To consider changing the surface energy budget, we need to think about the magnitude of the fluxes in context to greenhouse warming. A doubling of CO2 will increase the IR flux to the surface by about 6 W m\(^{-2}\). But this is everywhere on earth.
Albedo effects are on the order of 10s W m⁻² squared, assuming about 161 W m⁻² input averaged over the planet and the year, by changing land use, snow fields etc. But land is only 30% of the Earth’s surface.
Feedbacks with Growing Boundary Layer

Jose Fuentes

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Feedbacks with Collapsing Boundary Layer

Jose Fuentes
The knobs we turn to affect the surface and air temperature of the planet include factors like the surface and aerodynamic resistance, albedo and pbl growth.
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Case Study:

Energetics of a Grassland and Oak Savanna

Measurements and Model
2. Grassland has much greater albedo than savanna.
Landscape Differences
On Short Time Scales, Grass ET > Forest ET

Monthly Averages

\[ \frac{LE}{LE_{\text{md}}}, Gs (\text{mm s}^{-1}) \]

- Savanna Woodland
- Annual Grassland

Ryu, Baldocchi, Ma and Hehn, 2000, JGR-Atmos
Role of Land Use on ET:  
On Annual Time Scale, Forest ET > Grass ET

California Savanna

![Graph showing evaporation (mm y⁻¹) over different hydrological years for Oak Woodland and Annual Grassland, with the conclusion that Forest ET is greater than Grass ET.]
On average, mean daily averaged potential temperature over savanna is warmer than over grassland, $\Delta = 0.558 \, ^\circ C$. 

- Coefficients: 
  - $1.050 \times 0.558$ 
  - $0.000 \times 0.558$ 
  - $0.000 \times 0.558$
But Temperature Differences, Tsavanna-Tgrass, Vary by Season
Temperature Differences
Also vary by time of Day
WHY?

le penseur de Rodin, aka the ‘thinker’
The Savanna is much more Rougher, Aerodynamically
The Savanna experiences a greater Surface Conductance
During the Winter, when deciduous and a Smaller conductance
During the Summer when it is Transpiring and the Grass is Dead
More Net Radiation is absorbed by the Savanna during the Hot, Dry summer, but this is when the Temperature Differences are Smallest.
The Savanna Injects more Sensible Heat into the Atmosphere During the Winter and Summer; This can partly Explain T differences in the Winter
But the surface of the Grass is Much Hotter than the Savanna;  
Why does this Not Translate into Warmer Air Temperatures over  
The Grass During the Summer?
Summary from Data, so far, p1

- The greatest differences in potential air temperature occurred during the winter when net radiation fluxes overlapped one another, more sensible heat exchange was lost by the savanna, and more latent heat was lost by the grass.
- Differences in how energy was partition occurred because the grass maintained a lower surface resistance, while the woodland established a smaller aerodynamic resistance, thereby enabling the woodland to inject more sensible heat into the atmosphere and warm the air more.
Summary from Data, so far, p2

- Smallest differences in potential air temperature during the spring/summer transition despite the fact that the savanna gained much more net radiation and lost much more sensible heat, and, despite the fact that the surface temperature of the grassland was warmer than that of the savanna.

- Greater latent heat exchange by the savanna and more long-wave energy lost by the grassland diminished the potential air temperature differences between the two sites.

- Yet, a complete explanation for these temperature differences remains unresolved with our measurements, alone.

- To complete our analysis we apply a coupled energy balance/planetary boundary layer model to this problem.
Landscape Modification of Energy Exchange in Semi-Arid Regions: Theoretical Analysis with a couple Surface Energy Balance-PBL Model
Conceptual Diagram of PBL Interactions

H and LE: Analytical/Quadratic version of Penman-Monteith Equation
Model computations of air temperature, referenced to temperatures above conditions experienced by the savanna ($R_a = 20 \text{ s m}^{-1}$; $R_{sfc} = 200 \text{ s m}^{-1}$; albedo = 0.15), for summer-like weather. The model was run for a range of values in the aerodynamic and surface resistances. We assumed the albedo of the grass was 0.3.
Model computations of air minus radiative surface temperatures, as a function of aerodynamic and surface resistances. B) Model computations of net radiation, as a function of aerodynamic and surface resistances. Computations assumed albedo equaled 0.3 and summer time conditions of temperature and sunlight.
Deep Boundary Layers Form, Buffering change in T with H, dT/dH

Grass, Summer Albedo = 0.30
Grass

\[ T_{atm} - T_{eff} \ (R_s = 20 \text{ s/m}; \ R_{ref} = 200 \text{ s/m}; \ \text{albedo} = 0.15) \]

\[ R_s \text{ s/m} \]

\[ R_{ref} \text{ s/m} \]

winter, Grass Albedo = 0.15
Rn Budgets are about the Same in the Winter

(a) winter, Grass Albedo = 0.15

(b)
PBL is shallow in Winter, so differences in H can Translate into Greater differences in air temperature

winter, Grass Albedo = 0.15
Greatest temperature differences were observed during winter period:

$R_n$ savanna $\sim$ grass; $H$ savanna $\gg$ grass; $LE$ grass $> \text{savanna}; R_s$ savanna $> \text{grass}; Ra$ grass $\gg \text{savanna}; T_{sfc}$ grass $\sim$ savanna

Smallest temperature differences were observed during the spring/summer transition when

$R_n$ savanna $\gg$ grass; $H$ savanna $\gg$ grass; $LE$ grass $> \text{savanna}; R_s$ savanna $< \text{grass}; Ra$ grass $\gg \text{savanna}; T_{sfc}$ grass $\gg$ savanna
Issues of Concern and Take-Home Message

- Much vegetation operates less than 1/3 of the year and is a solar collector with less than 2% efficiency
  - Solar panels work 365 days per year and have an efficiency of 20%+
- Ecological Scaling Laws are associated with Planting Trees
  - Self-Thinning Occurs with Time
  - Mass scales with the -4/3 power of tree density
- Available Land and Water
  - Best Land is Vegetated and New Land needs to take up More Carbon than current land
  - You need more than 500 mm of rain per year to grow Trees
- The Ability of Forests to sequester Carbon declines with stand age
- Energetic and Environmental Costs to soil, water, air by land use change
  - Forests are Darker than Grasslands, so they Absorb More Energy
  - Changes in Surface Roughness and Conductance and PBL Feedbacks on Energy Exchange and Evaporative cooling may Dampen Albedo Effects
  - Forest Albedo changes with stand age
  - Forests Emit volatile organic carbon compounds, ozone precursors
  - Forests reduce Watershed Runoff and Soil Erosion
- Societal/Ethical Costs and Issues
  - Land for Food vs for Carbon and Energy
  - Energy is needed to produce, transport and transform biomass into energy
Should we cut down dark forests to Mitigate Global Warming?:
UpScaling Albedo Differences Globally, part 1

• Average Solar Radiation varies with Latitude: ~95 to 190 W m\(^{-2}\)
• Land area: ~30% of Earth’s Surface
• Tropical, Temperate and Boreal Forests: 40% of land
• Forest albedo (10 to 15%) to Grassland Albedo (20%)
  • Area-weighted change in incoming Solar Radiation: 0.8 W m\(^{-2}\)
    – Smaller than the 4 W m\(^{-2}\) forcing by 2x CO\(_2\)
    – Ignores role of forests on planetary albedo, as conduits of water vapor that
      form clouds and reflect light

We must Consider Magnitude of Energy Forcing x Spatial Scale
We get different prognostic answers if we consider surface energy balance with or without pbl feedbacks.
• The Energetics of afforestation/deforestation is complicated

• Forests have a low albedo, are darker and absorb more energy

• But, Ironically the darker forest maybe cooler ($T_{sk}$) than a bright grassland due to evaporative cooling
• Forests Transpire effectively, causing evaporative cooling, which in humid regions may form clouds and increase planetary albedo
• Due to differences in Available energy, differences in H are smaller than LE
Theoretical Difference in Air Temperature: Grass vs Savanna

ET-PBL Model

Summer Conditions
Temperature Difference Only Considering Albedo

ET-PBL Model

Spring Conditions
And temperatures are about equal when albedo of the grass is 0.25
Linkages between the surface fluxes and growth of the boundary layer produces a rectifier effect, that chops off a sine wave. Consideration of this effect is important when inverting concentration time series from the boundary layer to infer large scale fluxes.
1-D Box model
No entrainment from top

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Impact of rain pulse on regional atmospheric CO$_2$
Coupled PBL-Sfc Energy CO₂ Model:
al a McNaughton-Spriggs

![Graph showing CO₂ (ppm) against time]

- Points (R₀)
- Rimp after ppt
- Upwind a m s⁻¹
- F₀ = 10 μmol m⁻² s⁻¹