Lecture on Planetary Boundary Layer and Coupling to the Land Surface

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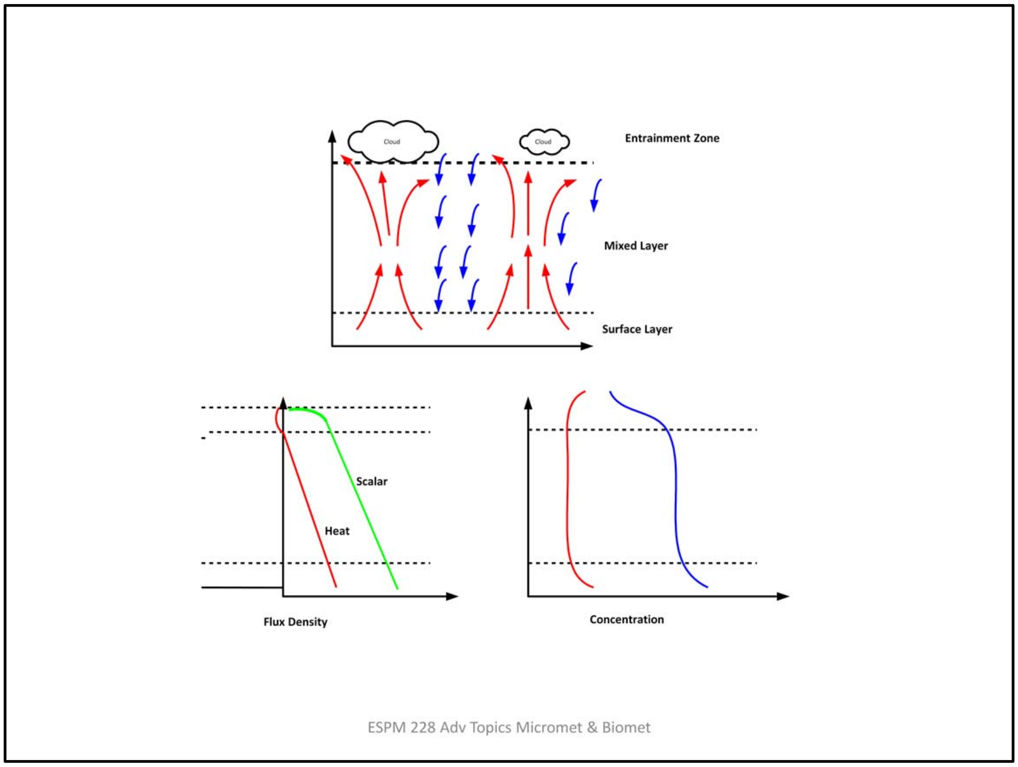
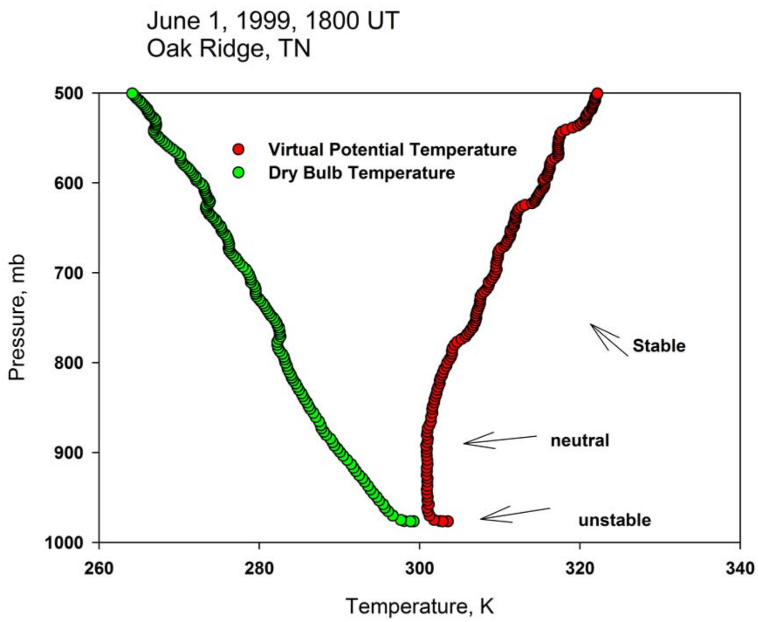
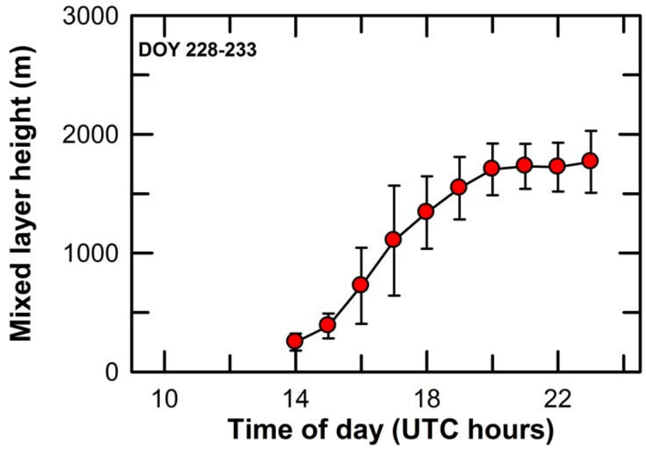
We live in the planetary boundary layer, the layer of the atmosphere affected by the land surface. It is a dynamic layer that can be visualized by the base of convective clouds on a partly cloudy day. Above the boundary layer the sky is clear and blue, below it you see dirt, aerosols, pollution from land activities. There can be greater build ups and withdrawals of biogenic and biotrophic trace gases.



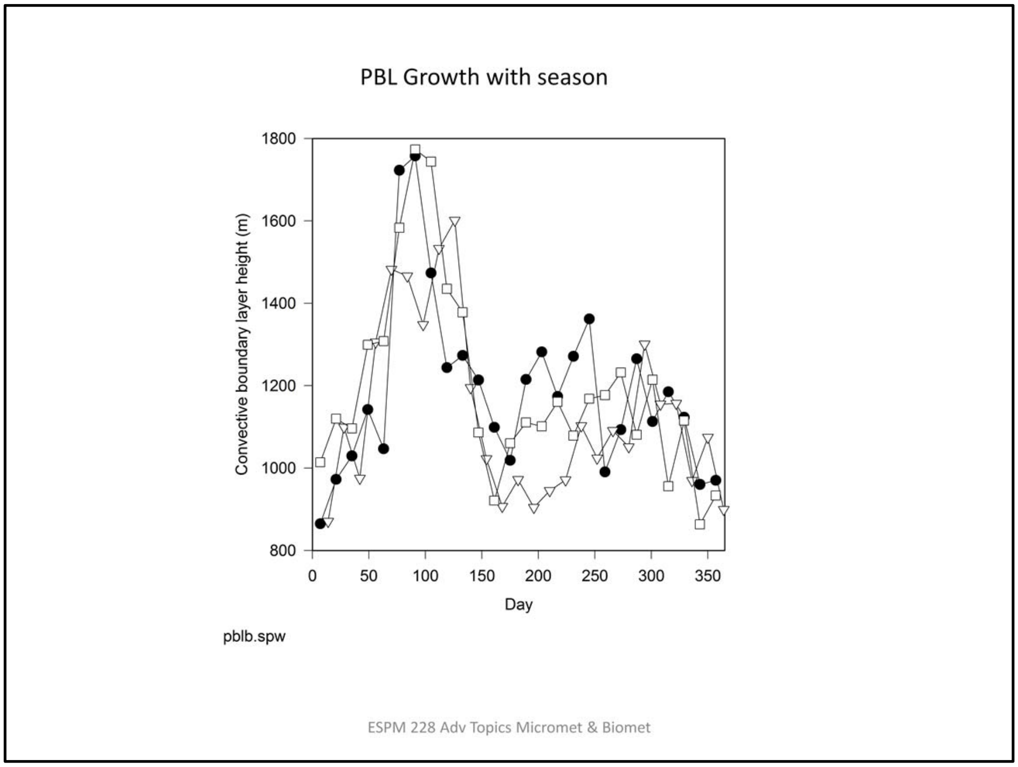
The pbl is dynamic it grows during the day with heat exchange. It has various zones. An entrainment layer, the mixed layer and the surface layer. Fluxes tend to vary linearly with height. Scalar profiles have a strong gradient near the surface, a mixed layeer due to big convective activity, then gradients across the inverted entrainment layer


June 1, 1999, 1800 UT
Oak Ridge, TN
Virtual Potential Temperature
Dry Bulb Temperature
Pressure, mb
500
600
700
800
900
1000
260
280
300
320
340
Temperature, K
Stable
neutral
unstable

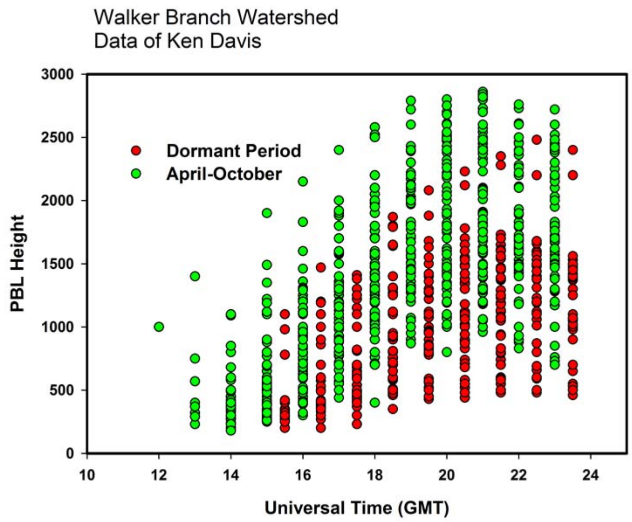
Diurnal Growth of PBL



Data of Baldocchi, Davis, analysis by Fuentes



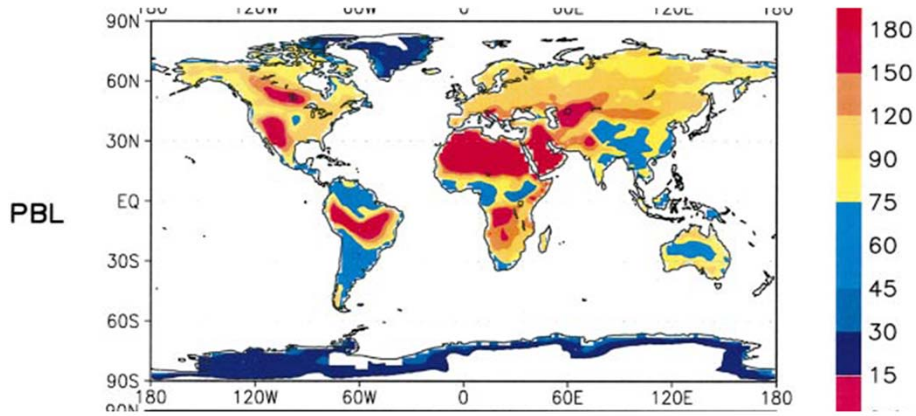
Seasonal trend in pbl growth over Walker Branch Watershed in Oak Ridge, TN



Fuentes, Baldocchi, Davis

Seasonality of the time rate of growth of pbl height over the Walker Branch Forest

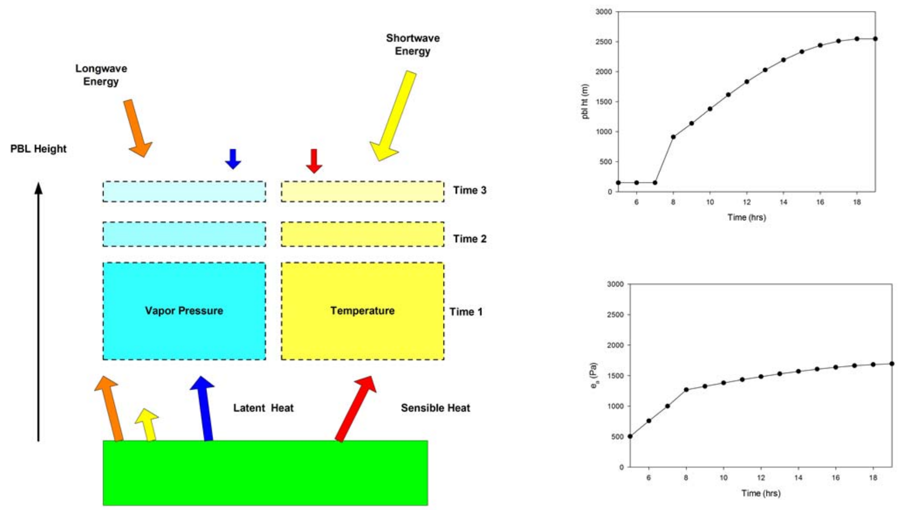
Ht in millibar



Molud et al 2003

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

Conceptual Diagram of PBL Interactions



H and LE: Analytical/Quadratic version of Penman-Monteith Equation

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

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

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

Scale flux at top of pbl with surface flux

$$-(\overline{w'\theta'}_v)_h = \beta_\mathrm{h}\,(\overline{w'\theta'}_v)_s$$

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

$$-(\overline{w'\theta'}_v)_h = \Delta\theta_v\,\mathrm{w_e}$$

Parameterizing the entrainment flux remains the more difficult and poorly known quantity

Entrainment velocity

$$w_e = \frac{\partial h}{\partial t} - \overline{w}_s$$

Pbl growth rate minus subsidence velocity

In some places on earth we have large scale subsidence, like summer over California, so this downward velocity must be added (substracted) from the time rate of change of pbl growth, dh/dt

Mixed Layer Budget Eq.

Flux in from the top

$$\frac{dC_m}{dt} = \frac{F_c}{h} + \frac{C_e - C_m}{h}(\frac{dh}{dt} - W_s)$$

Time rate
Of change

Flux in the
bottom

Growth - subsidence

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Simple box budget model

PBL Budgets w/o subsidence

$$h \frac{\partial \theta_{vm}}{\partial t} = (\overline{w'\theta'_v})_s + \Delta\theta \frac{\partial h}{\partial t}$$

$$\rho C_p h \frac{d\theta_m}{dt} = H + \rho C_p (\theta_T - \theta_m) \frac{dh}{dt}$$

$$\rho h \frac{dq_m}{dt} = E + \rho (q_T - q_m) \frac{dh}{dt}$$

Equations for potential virtual temperature, potential temperature in the mixed layer and specific humidity in the mixed layer

Growth of PBL

$$\frac{\partial \mathrm{h}}{\partial t} = \frac{(\overline{w'\theta'_v})_s}{\gamma_{\theta_v}\, h}$$

$$\frac{dh}{dt} = \frac{(H + 0.07\lambda E / \rho C_p)}{h(d\theta_v, e / dz)}$$

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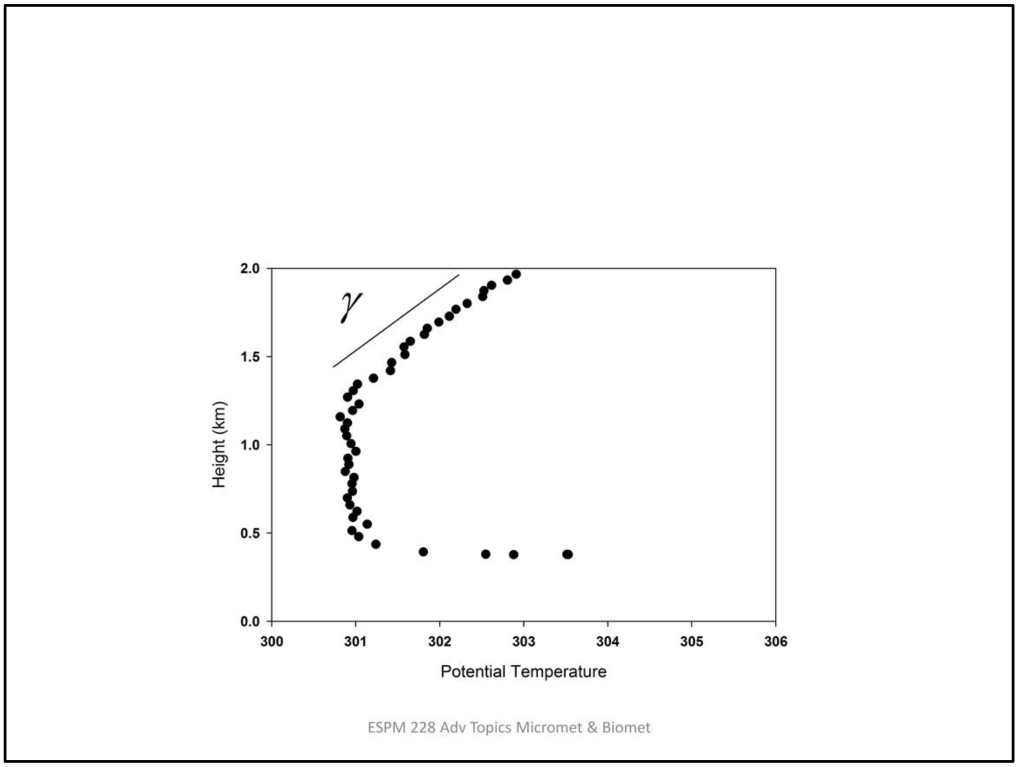
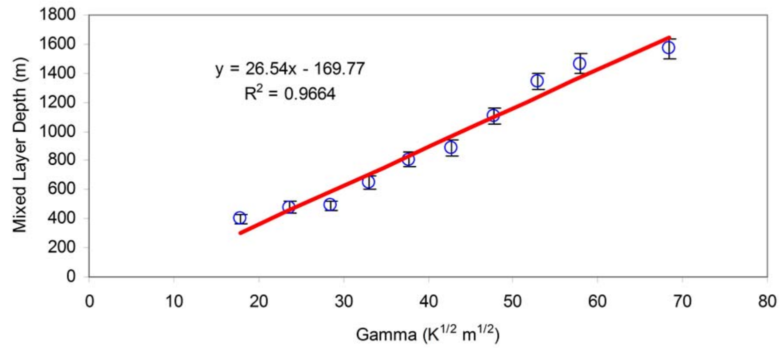
Equations for computing the time rate of change in height of the pbl, by converting virtual potential temperature flux covariance into sensible and latent heat fluxes



Gamma is the slope of the temperature inversion

$$\frac{\partial h}{\partial t} = \frac{(\overline{w'\theta'_v})_s}{\gamma_{\theta_v} h}$$

Wank Brach 1999



Fuentes, Baldocchi, Davis

Fuentes looked at our data from Walker Branch and tested the gamma values with mixed layer height

Date	t_0 (Decimal DOY)	$h(t_0)$ m	$\gamma_{\theta v}$ (K km^{-1})	$\Delta\theta_v$ (K)
09 May (DOY 129)	129.63	380.0	2.9	4.3
16 May (DOY 136)	136.58	500.0	??	??
17 May (DOY 137)	137.58	400.0	13.8	11.0
24 May (DOY 144)	144.54	570.0	7.6	8.0
15 Jun (DOY 166)	166.58	500.0	3.7	7.0
03 Aug (DOY 215)	215.58	400.0	8.4	8.0
04 Aug (DOY 216)	216.63	350.0	3.6	5.0
05 Aug (DOY 217)	217.63	340.0	4.1	6.0
31 Aug (DOY 243)	243.58	300.0	20.0	10.0

Growth of PBL

$$\frac{\partial h}{\partial t} = \frac{\beta_{\mathrm{h}}\,(\overline{w'\theta'_v})_s}{\Delta\theta_v} + \overline{\mathrm{w}}_{\mathrm{s}}$$

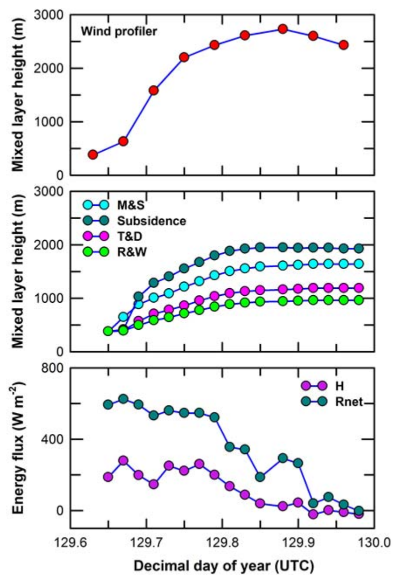
Diedronks and Tennekes

$$\frac{\partial \mathrm{h}}{\partial t} = \frac{0.2\,\mathrm{w}_*^{\,3} + 5\,\mathrm{u}_*^{\,3}}{\frac{g}{\theta_{\mathrm{v0}}}\,\mathrm{h}\,\Delta\theta_{\mathrm{v}}}$$

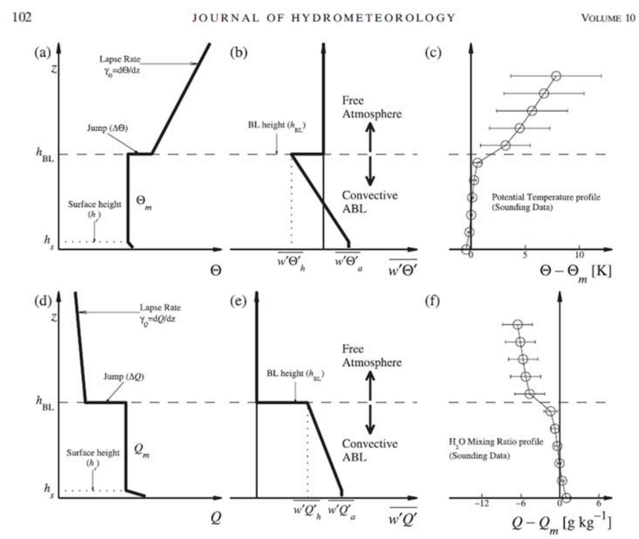
Raupach

$$\frac{\partial \mathrm{h}}{\partial t} = \frac{0.18\,\mathrm{w}_*^{\,3}}{0.8\,\mathrm{w}_*^{\,2} + \frac{\mathrm{g}}{\theta_{\mathrm{v0}}}\,\mathrm{h}\,\Delta\theta_{\mathrm{v}}}$$

Other models for pbl growth



Fuentes, Baldocchi, Davis



Siqueria et al

Role of Lifted Condensation Level
Occurs with Zi intersects with HLCL

$$H_{\mathrm{LCL}} = \frac{R\,T_{\mathrm{a}}}{M_{\mathrm{a}}\,g}\,\log\left(\frac{P_{\mathrm{s}}}{P_{\mathrm{LCL}}}\right),$$

$$P_{\mathrm{LCL}} = P_{\mathrm{s}}\left(\frac{T_{\mathrm{LCL}}}{T_{\mathrm{a}}}\right)^{3.5}, \qquad (7)$$

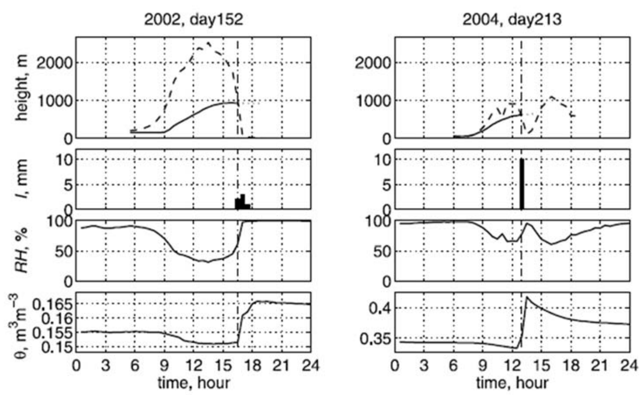
where T_{LCL} (K) is the saturation point temperature at H_{LCL} and can be derived from the Clausius–Clapeyron equation given by (Stull, 1988)

$$T_{\mathrm{LCL}} = \frac{2840}{3.5\ln(T_{\mathrm{a}}) - \ln\left(\frac{P_{\mathrm{s}}r}{0.622+r} - 7.108\right)} + 55, \qquad (8)$$

Juang et al 2007, GCB

Clouds and Precipitation Occur when Zi matches H LCL

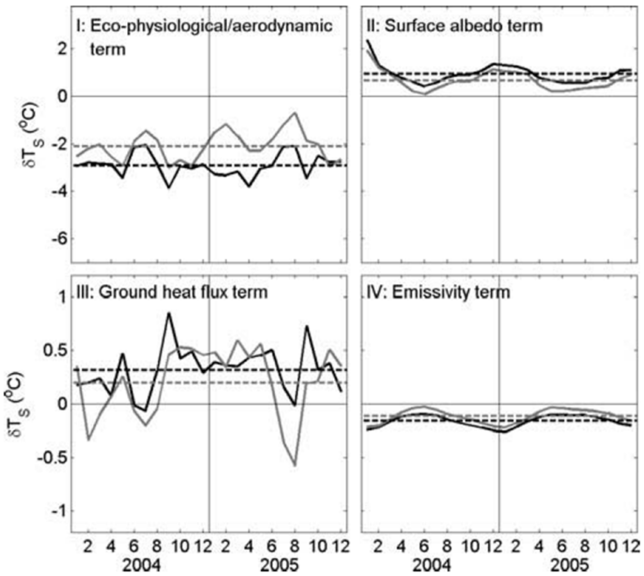
JUANG ET AL.: HYDROLOGIC AND ATMOSPHERIC CONTROLS



igure 4. Modeled z_i (solid line) and H_{LCL} (dashed line) and the corresponding measured precipitation, H and θ, (left) on day 152 of 2002 and (right) on day 213 of 2004.

Juang et al 2007 WRR

Note when the pbl and lifted condensation levels match, precipitation occurs. One should also see a decrease in solar radiation with clouds



Juang et al 2007 GRL

The Physics and Ecology of Carbon Offsets:
Case Study of Energy Exchange over Contrasting Landscapes, a grassland and oak woodland

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2008 NCEAS WorkGroup on 'Linking carbon storage in terrestrial ecosystems with other climate forcing agents'

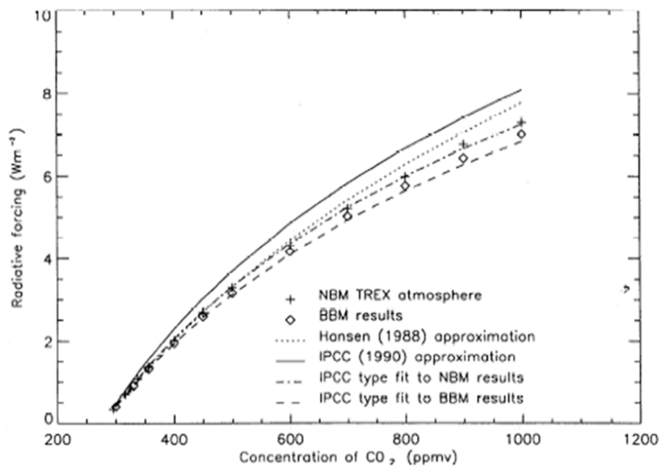
Case study of the roles of PBL growth on interpreting the effects of changing land use on the climate.

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

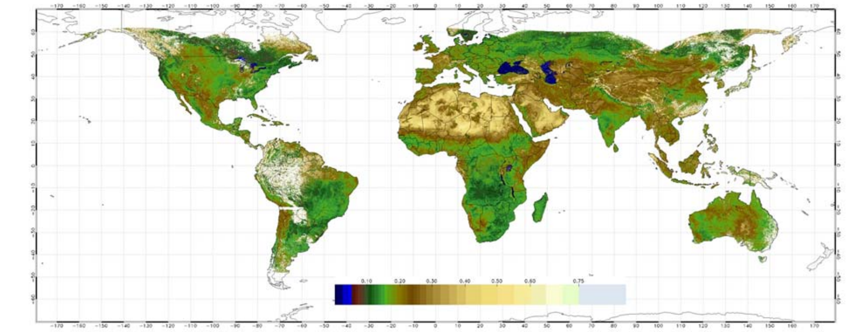
Energetics of Greenhouse Gas Forcing:
Doubling CO_2 provides a 4 Wm^{-2} energy increase, Worldwide



Myhre et al 1998 GRL

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.

Global Albedo

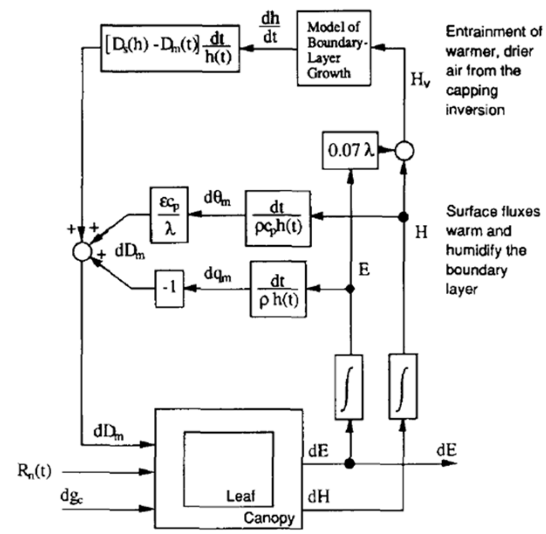


Albedo: Conifer Forests < Deciduous Forests < Grass<Crops

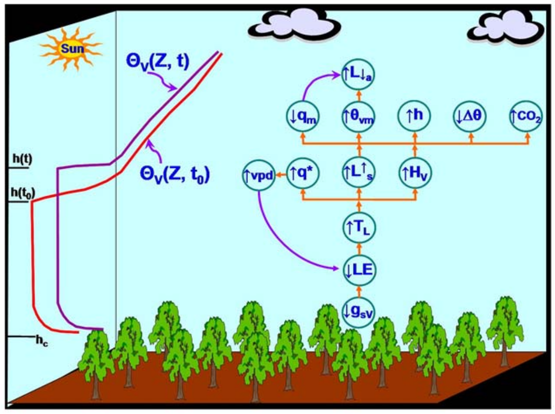
Changing Land from Forests to Grass can Increase Reflectance by 10 - 20 W m^{-2}

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

K.G. McNAUGHTON AND P.G. JARVIS

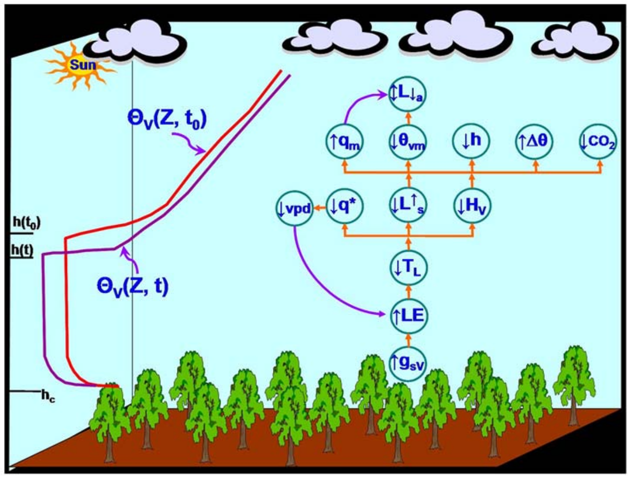


Feedbacks with Growing Boundary Layer

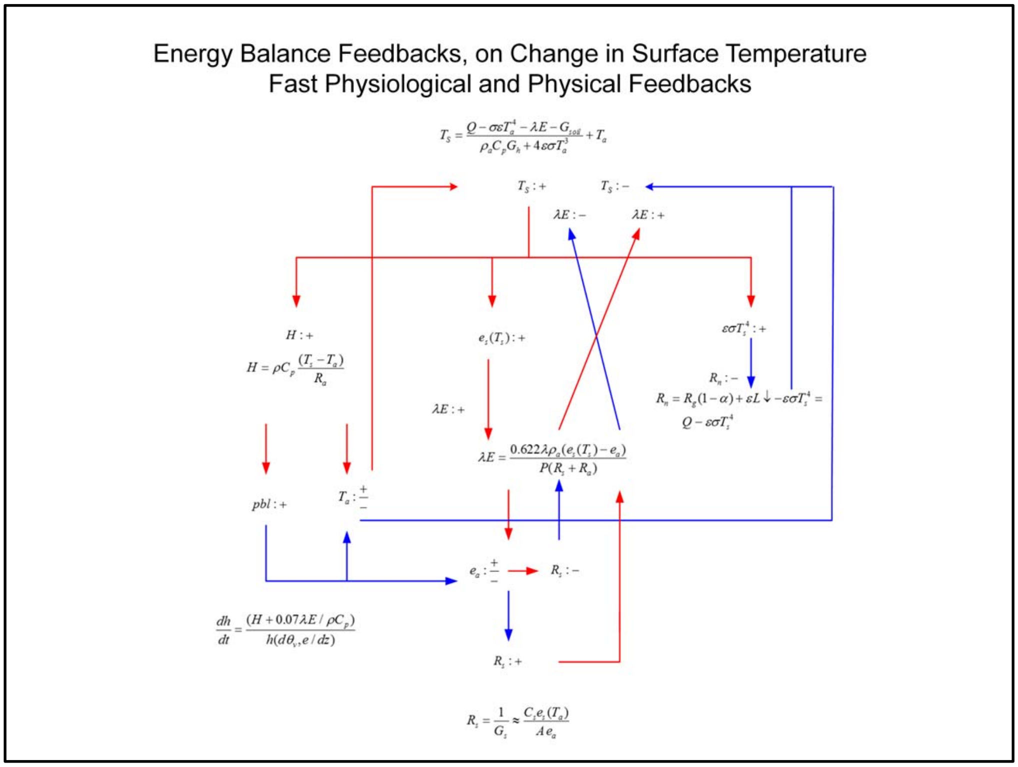


Jose Fuentes

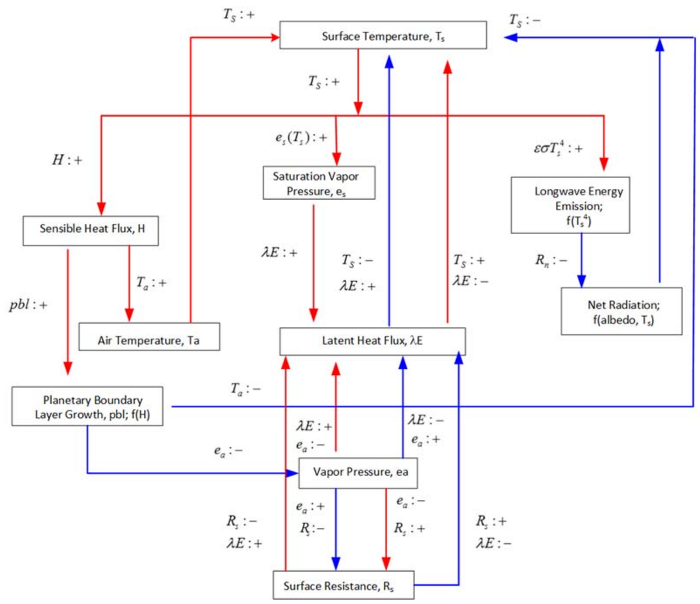
Feedbacks with Collapsing Boundary Layer



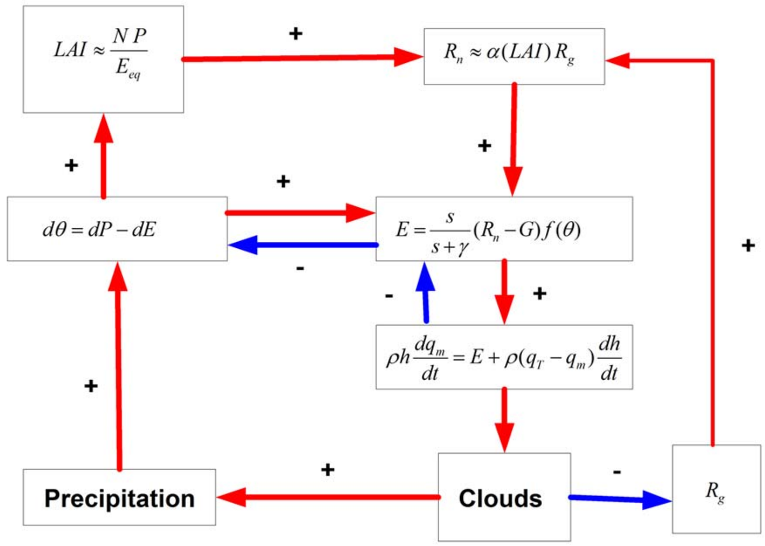
Jose Fuentes



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


Surface Temperature, T_s
$T_S: +$
$T_S: -$
$e_s(T_s): +$
$\varepsilon\sigma T_s^4: +$
$H: +$
Saturation Vapor Pressure, e_s
Longwave Energy Emission; $f(T_s^4)$
Sensible Heat Flux, H
$\lambda E: +$
$T_S: -$
$\lambda E: +$
$T_S: +$
$\lambda E: -$
$R_n: -$
$T_a: +$
$pbl: +$
Net Radiation; f(albedo, T_s)
Air Temperature, Ta
Latent Heat Flux, λE
Planetary Boundary Layer Growth, pbl; f(H)
$T_a: -$
$\lambda E: +$
$e_a: -$
$\lambda E: -$
$e_a: +$
$e_a: -$
Vapor Pressure, ea
$e_a: +$
$R_s: -$
$e_a: -$
$R_s: +$
$R_s: -$
$\lambda E: +$
$R_s: +$
$\lambda E: -$
Surface Resistance, R_s

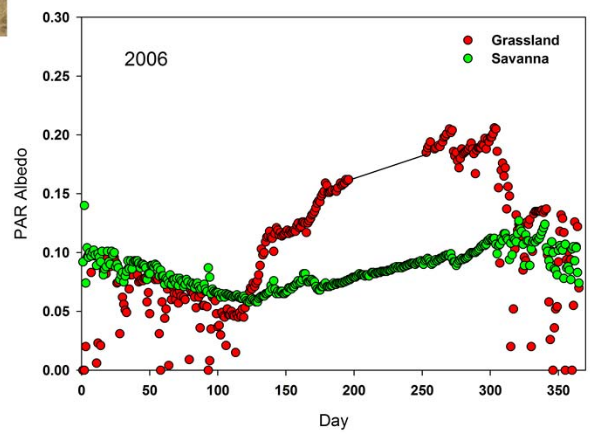
Slower Ecological and Hydrological Feedbacks



Case Study:

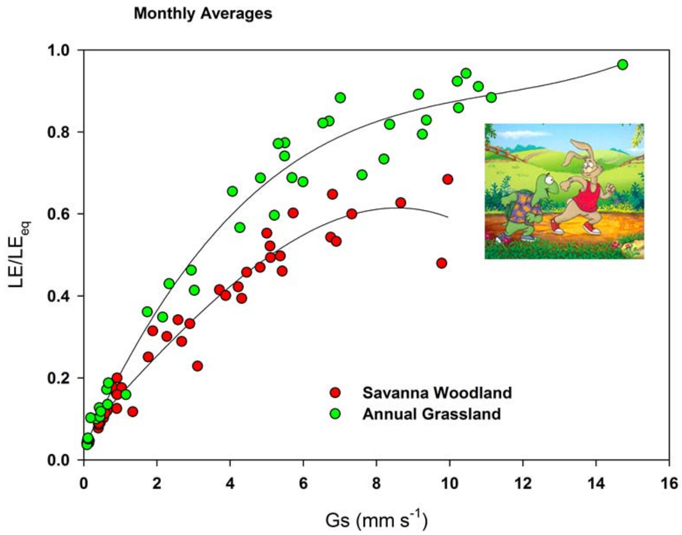
Energetics of a Grassland and Oak Savanna

Measurements and Model



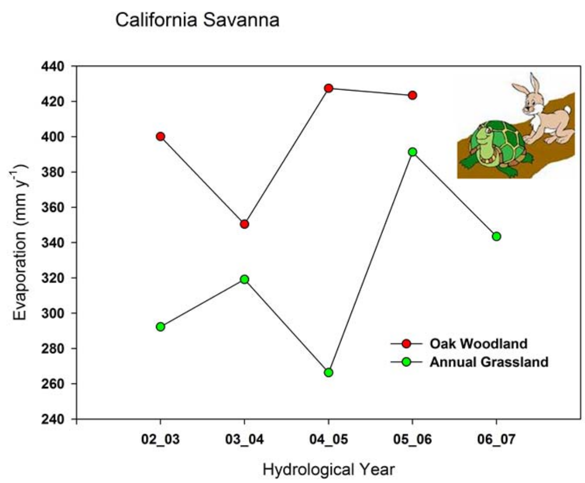
2. Grassland has much great albedo than savanna;

Landscape Differences
On Short Time Scales, Grass ET > Forest ET

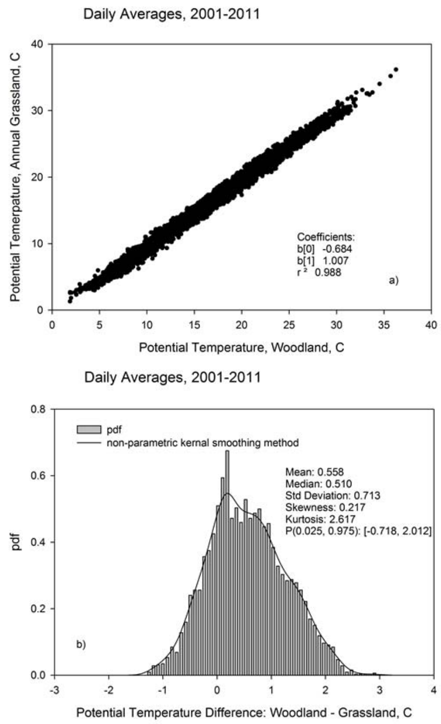


Ryu, Baldocchi, Ma and Hehn, 2009, JGR-Atmos

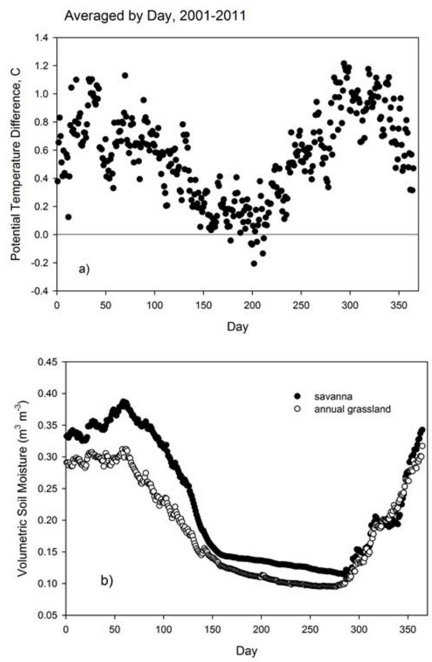
Role of Land Use on ET:
On Annual Time Scale, Forest ET > Grass ET



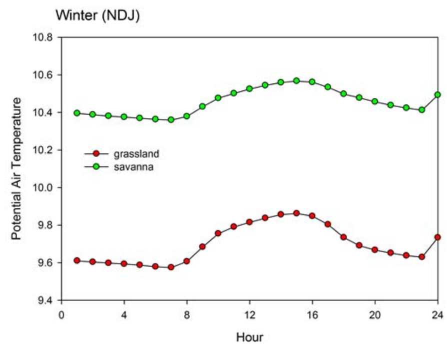
Ryu, Baldocchi, Ma and Hehn, JGR-Atmos, in press

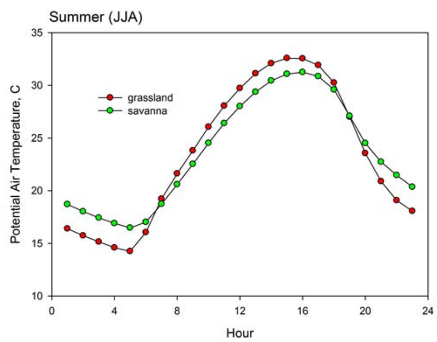


On Average, mean Daily Averaged Potential Temperature Over savanna is warmer than over grassland, Δ = 0.558 C



But Temperature Differences, Tsavanna-Tgrass, Vary by Season



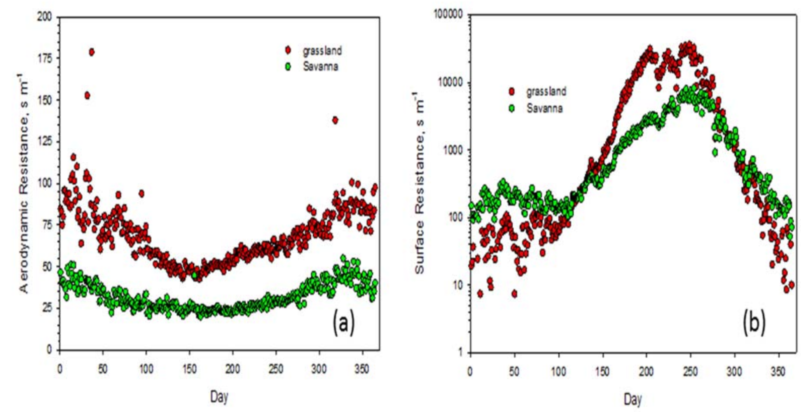


Temperature Differences
Also vary by time of Day

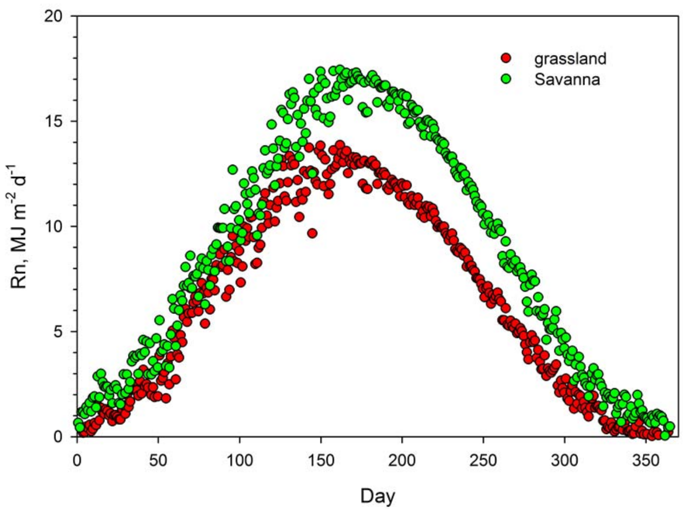
WHY?

le penseur de Rodin, aka the ‘thinker’

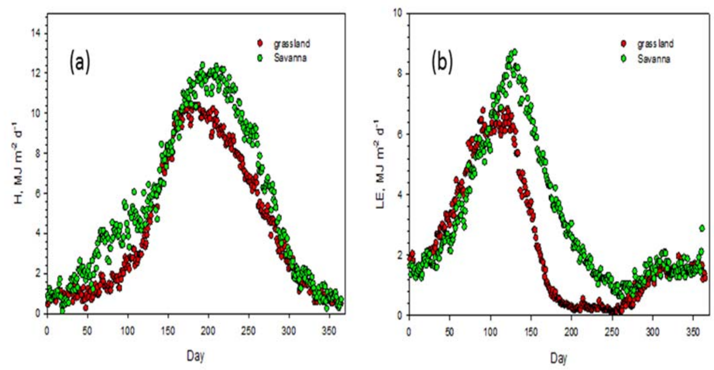
The Savanna is much more Rougher, Aerodynamically
The Savanna experiences a greater Surface Conductance
During the Winter, when deciduous and a Smaller conductance
During the Summer when it is Transpiring and the Grass is Dead



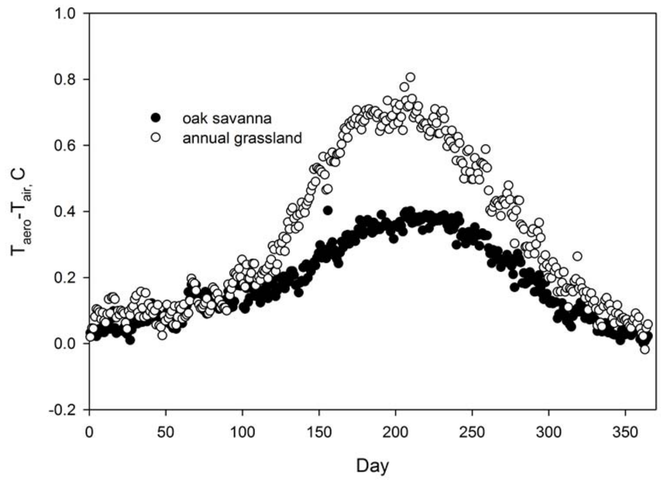
More Net Radiation is absorbed by the Savanna during The Hot, Dry summer, but this is when the Temperature Differences are Smallest



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

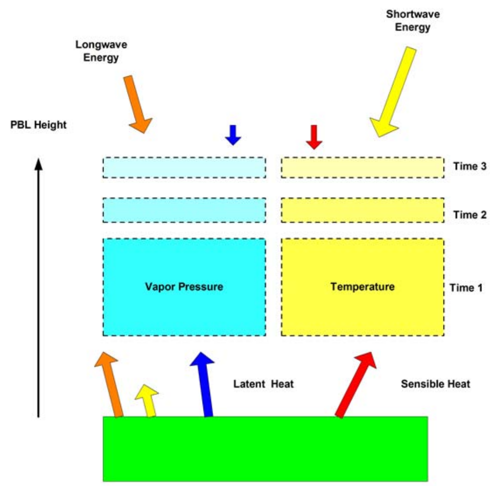
- The greatest differences in potential air temperature occurred during the winter when net radiation fluxes overlapped one another, more sensible heat exchange was lost by the savanna, and more latent heat was lost by the grass.
- Differences in how energy was partition occurred because the grass maintained 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.

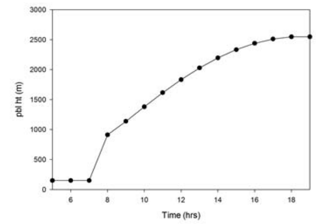
Summary from Data, so far, p2

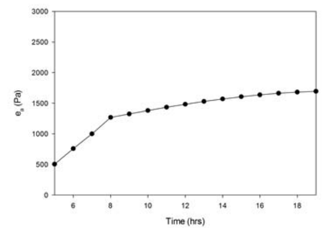
- Smallest differences in potential air temperature during the spring/summer transition despite the fact that the savanna gained much more net radiation and lost much more sensible heat, and, despite the fact that the surface temperature of the grassland was warmer than that of the savanna.
- Greater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

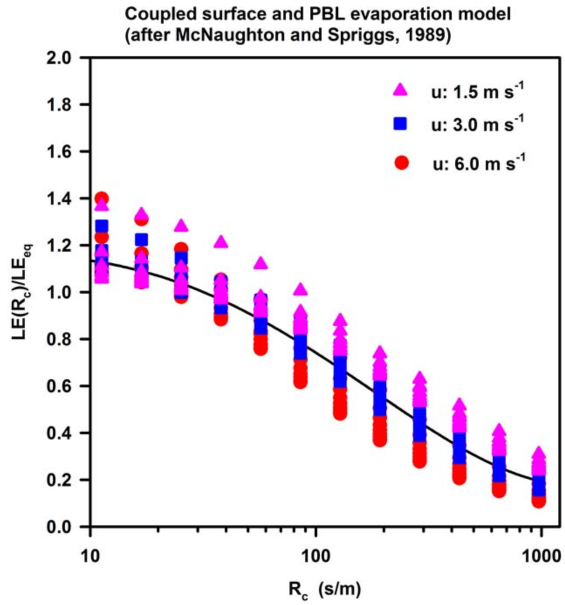
Conceptual Diagram of PBL Interactions



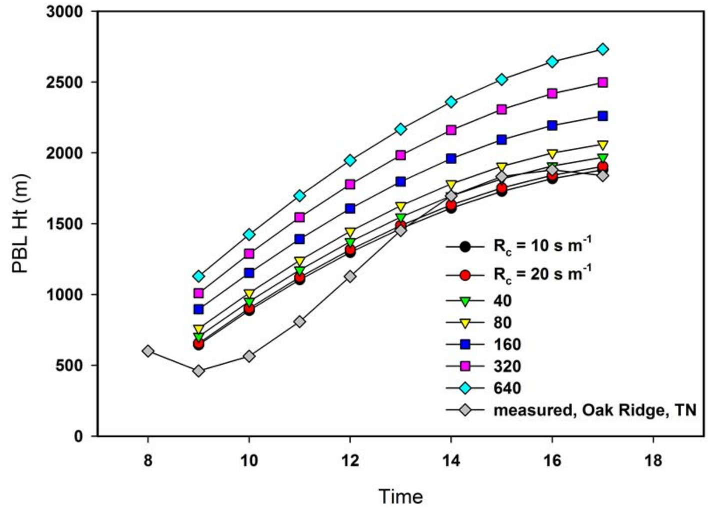




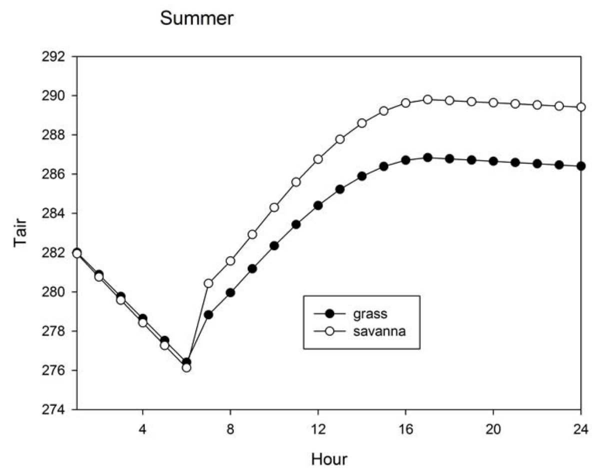
H and LE: Analytical/Quadratic version of Penman-Monteith Equation

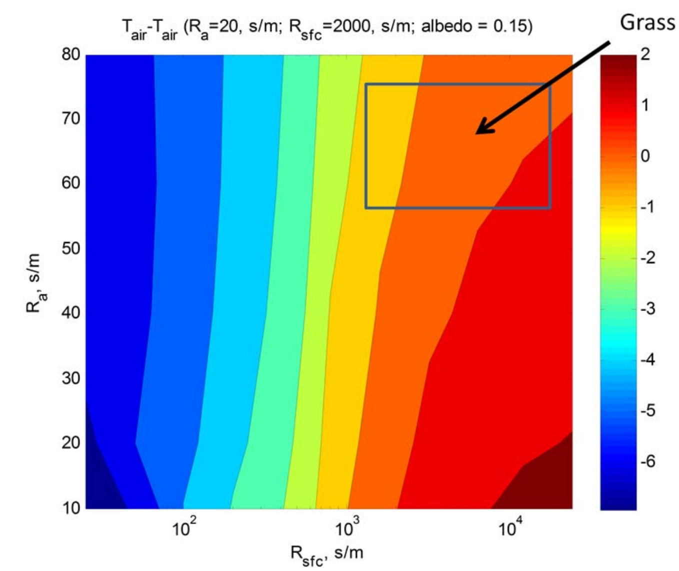


Coupled surface and PBL evaporation model
(after McNaughton and Spriggs, 1989)
u: 1.5 m s-1
u: 3.0 m s-1
u: 6.0 m s-1
LE(Rc)/LEeq
Rc (s/m)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
10
100
1000



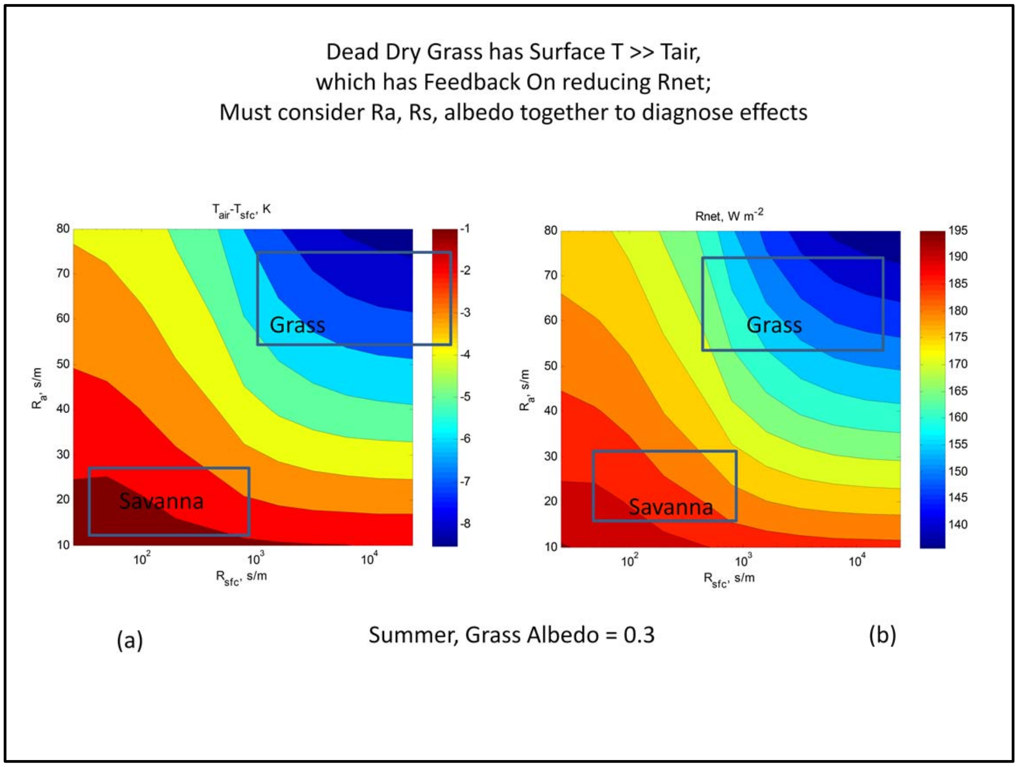
3000
2500
2000
1500
1000
500
0
PBL Ht (m)
8
10
12
14
16
18
Time
R_c = 10 s m^-1
R_c = 20 s m^-1
40
80
160
320
640
measured, Oak Ridge, TN


Summer
Tair
Hour
grass
savanna
292
290
288
286
284
282
280
278
276
274
4
8
12
16
20
24



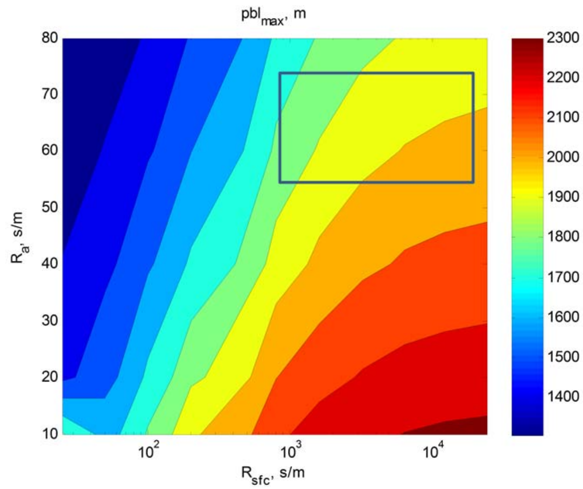
Summer, Grass Albedo = 0.3

Model computations of air temperature, referenced to temperatures above conditions experienced by the savanna (R_a = 20 s m^{-1}; R_{sfc} = 200 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.

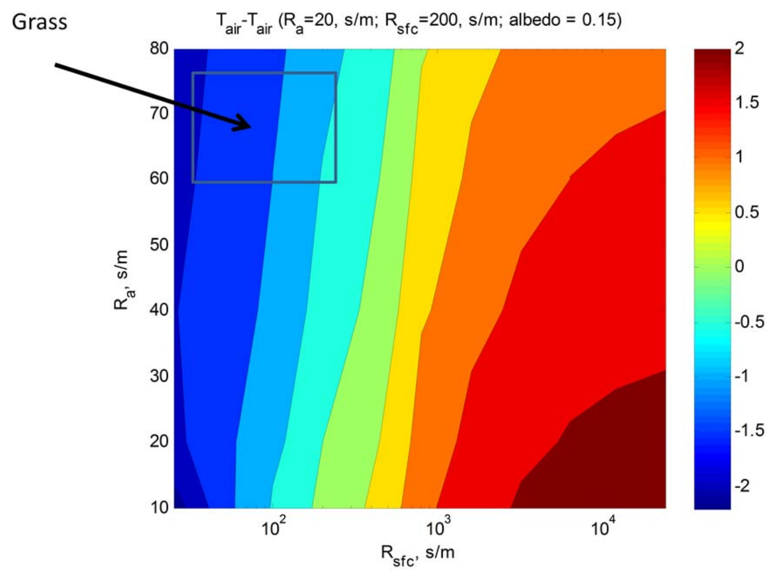


Model computations of air minus radiative surface temperatures, as a function of aerodynamic and surface resistances. B) Model computations of net radiation, as a function of aerodynamic and surface resistances. Computations assumed albedo equaled 0.3 and summer time conditions of temperature and sunlight.

Deep Boundary Layers Form, Buffering change in T with H, dT/dH

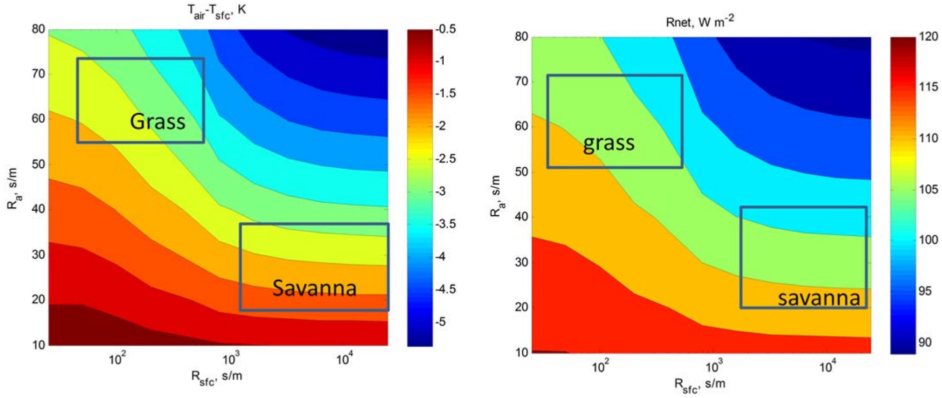


Grass, Summer Albedo = 0.30



winter, Grass Albedo = 0.15

Rn Budgets are about the Same in the Winter

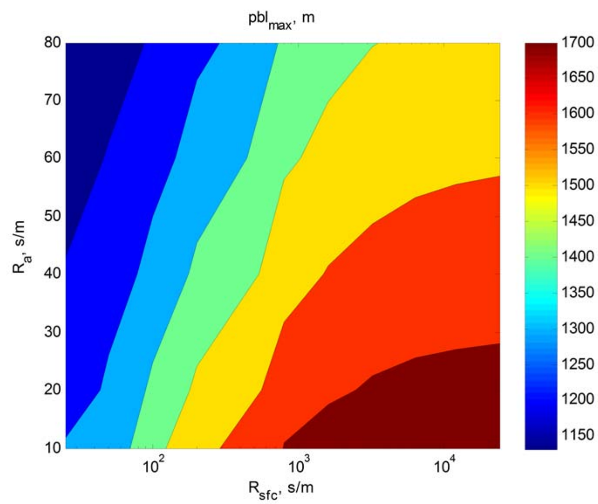


(a)

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:

Rn savanna ~ grass; H savanna >>grass; LE grass > savanna; Rs savanna > grass; Ra grass >> savanna; Tsfc grass ~ savanna

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

Rn savanna >> grass; H savanna >>grass; LE grass > savanna; Rs savanna << grass; Ra grass >> savanna; Tsfc grass >> savanna

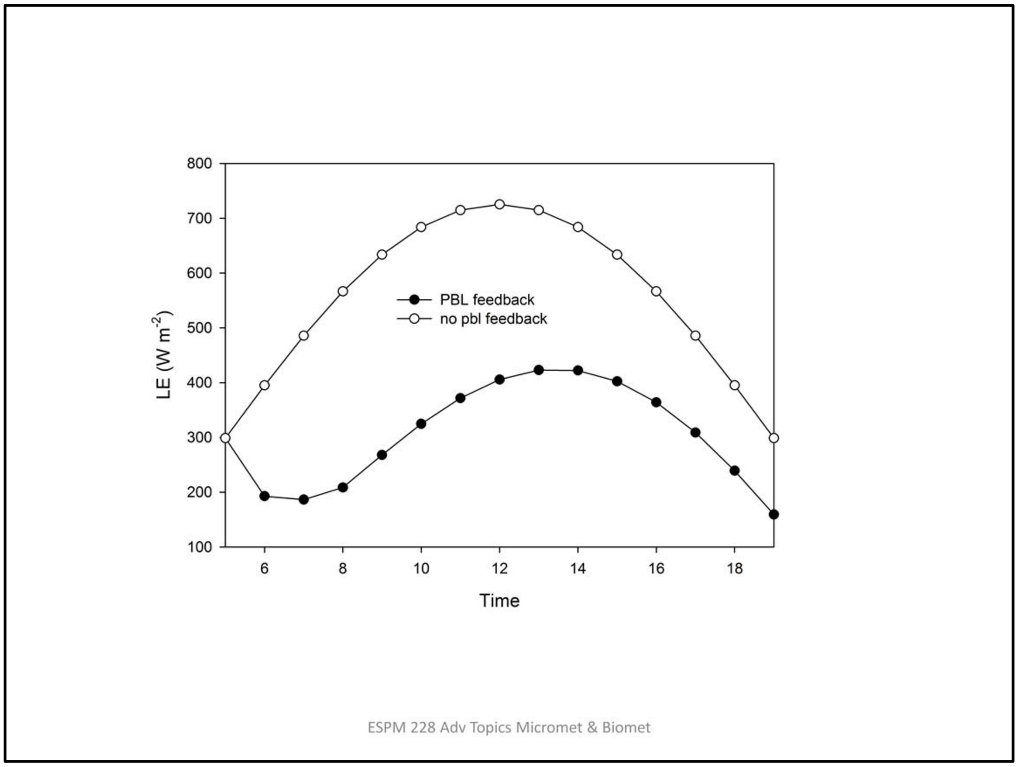
Issues of Concern and Take-Home Message

- Much vegetation operates less than ½ 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

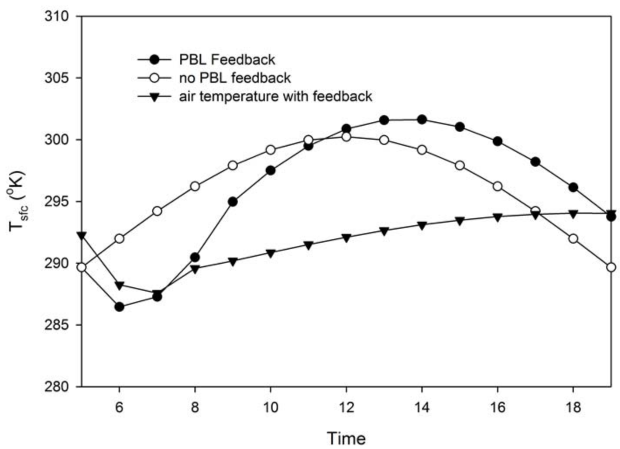
Should we cut down dark forests to Mitigate Global Warming?:
UpScaling Albedo Differences Globally, part 1

- 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



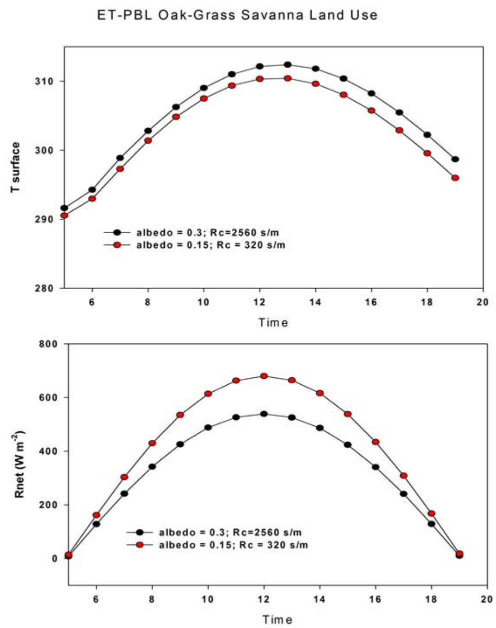
We get different prognostic answers if we consider surface energy balance with or without pbl feedbacks


PBL Feedback
no PBL feedback
air temperature with feedback
T_{sfc} (°K)
Time
310
305
300
295
290
285
280
6
8
10
12
14
16
18

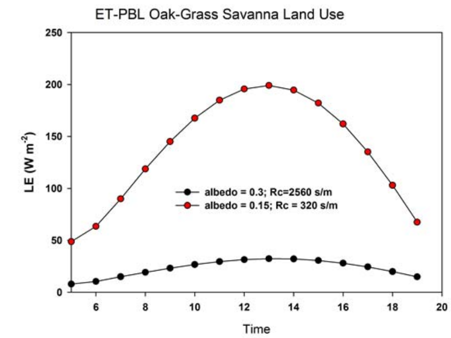
•The Energetics of afforestation/deforestation is complicated

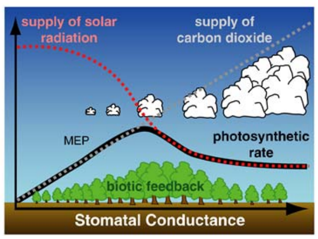
•Forests have a low albedo, are darker and absorb more energy

•But, Ironically the **darker** forest maybe **cooler** (T_{sfc}) than a bright grassland due to evaporative cooling

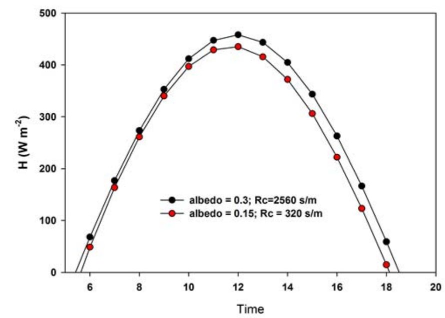


- •Forests Transpire effectively, causing evaporative cooling, which in humid regions may form clouds and increase planetary albedo
- •Due to differences in Available energy, differences in H are smaller than LE

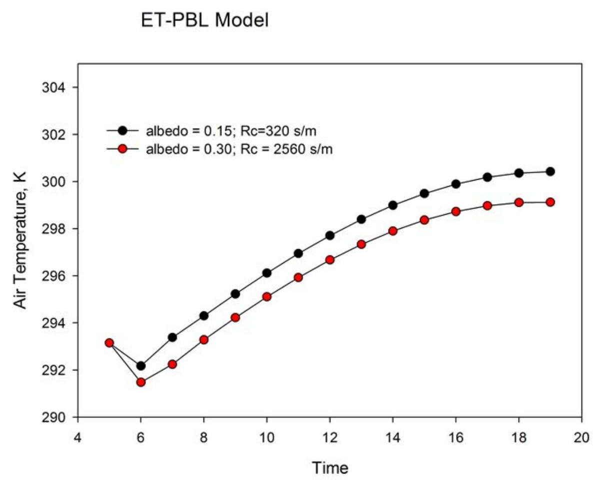




Axel Kleidon

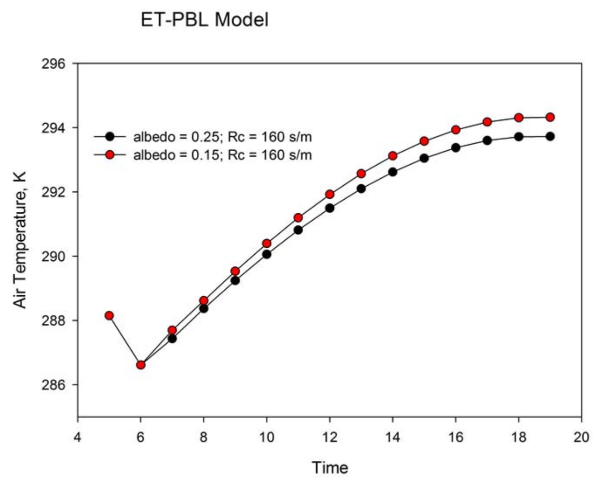


Theoretical Difference in Air Temperature: Grass vs Savanna



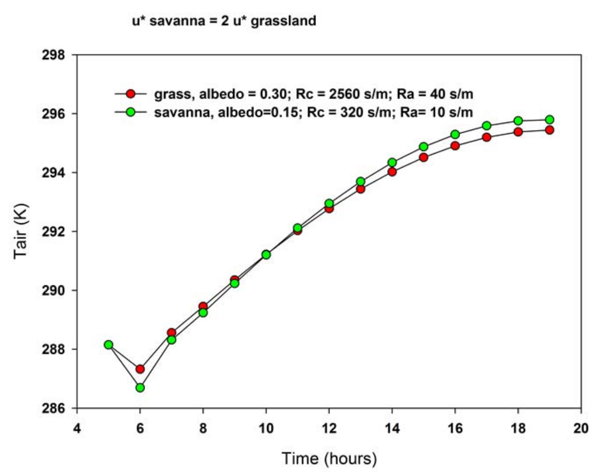
Summer Conditions

Temperature Difference Only Considering Albedo



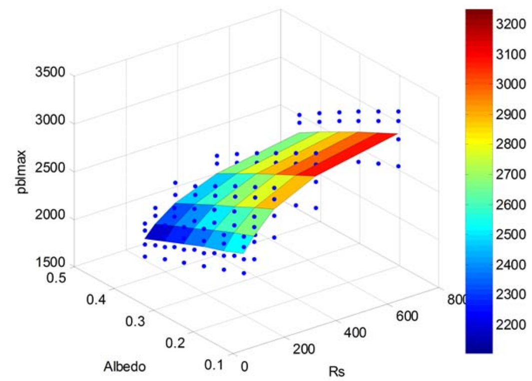
Spring Conditions

And Smaller Temperature Difference considering PBL, R_a and albedo….!!

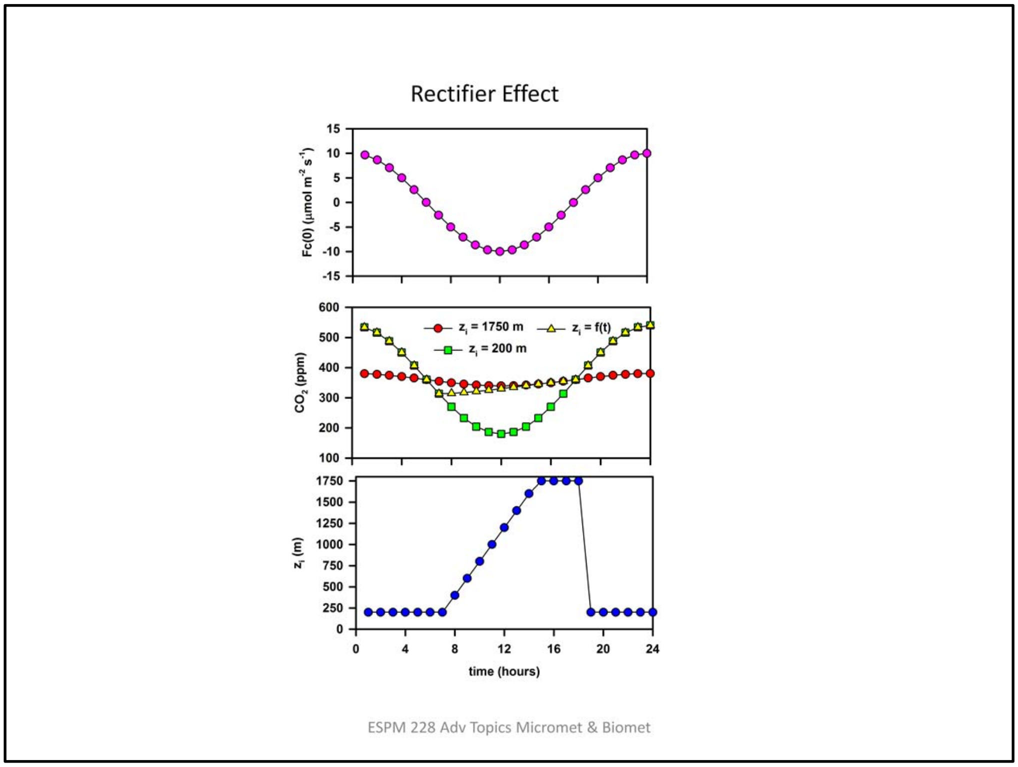


Summer Conditions

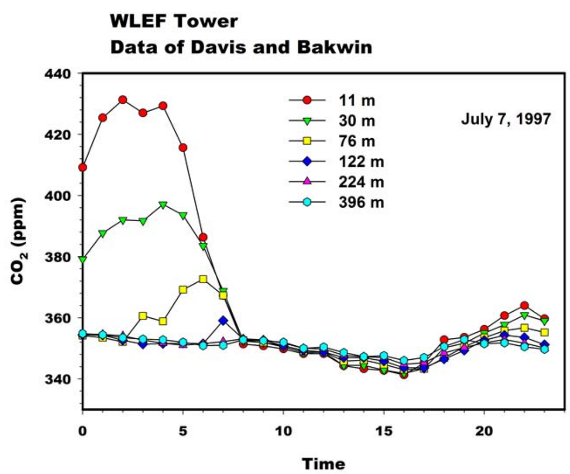
And temperatures are about equal when albedo of the grass is 0.25

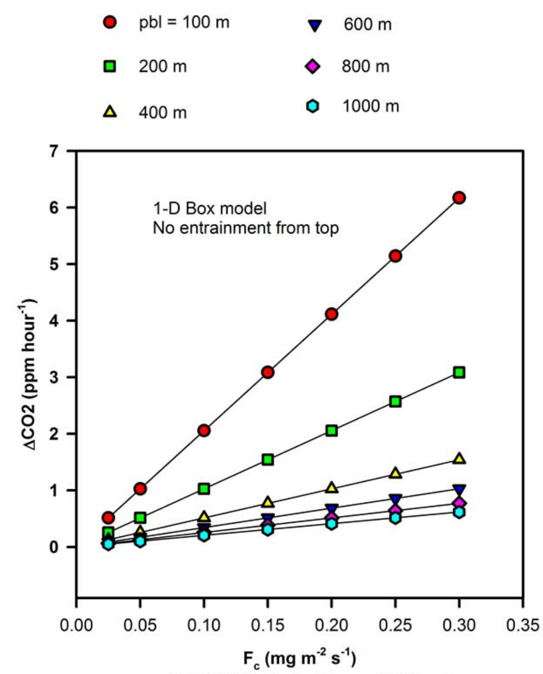


3500
3000
2500
2000
1500
pblmax
0.5
0.4
0.3
0.2
0.1
Albedo
0
200
400
600
800
Rs
3200
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200



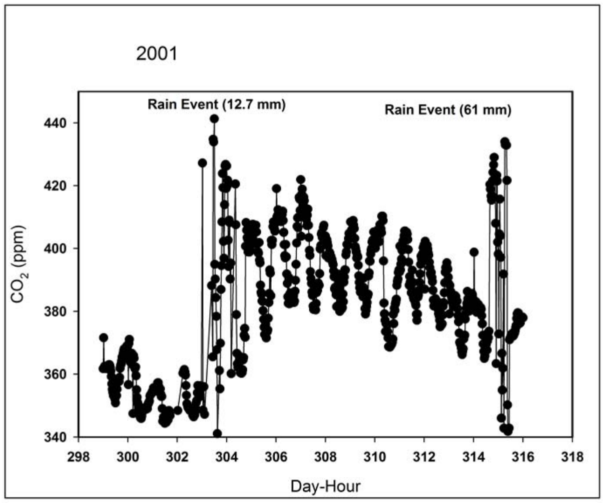
Linkages between the surface fluxes and growth of the boundary layer produces a rectifier effect, that chops off a sine wave. Consideration of this effect is important when inverting concentration time series from the boundary layer to infer large scale fluxes.


WLEF Tower
Data of Davis and Bakwin
11 m
30 m
76 m
122 m
224 m
396 m
July 7, 1997
CO_2 (ppm)
Time
440
420
400
380
360
340
0
5
10
15
20



ESPM 228 Adv Topics Micromet & Biomet

Impact of rain pulse on regional atmospheric CO_2



Coupled PBL-Sfc Energy CO_2 Model: *al a McNaughton-Spriggs*