Wind and Turbulence, Surface Boundary Layer: Theory and Principles Part III

- Wind over Tall Vegetation
  - Zero plane displacement and Roughness Length
    - Variations of z_o and d with LAI
  - Role of stability on wind profiles
  - Monin Obuhkov theory
  - Richardson number
- Eddy Exchange Coefficients
  - Influence of Scalar
  - Stability
  - Roughness Sublayer

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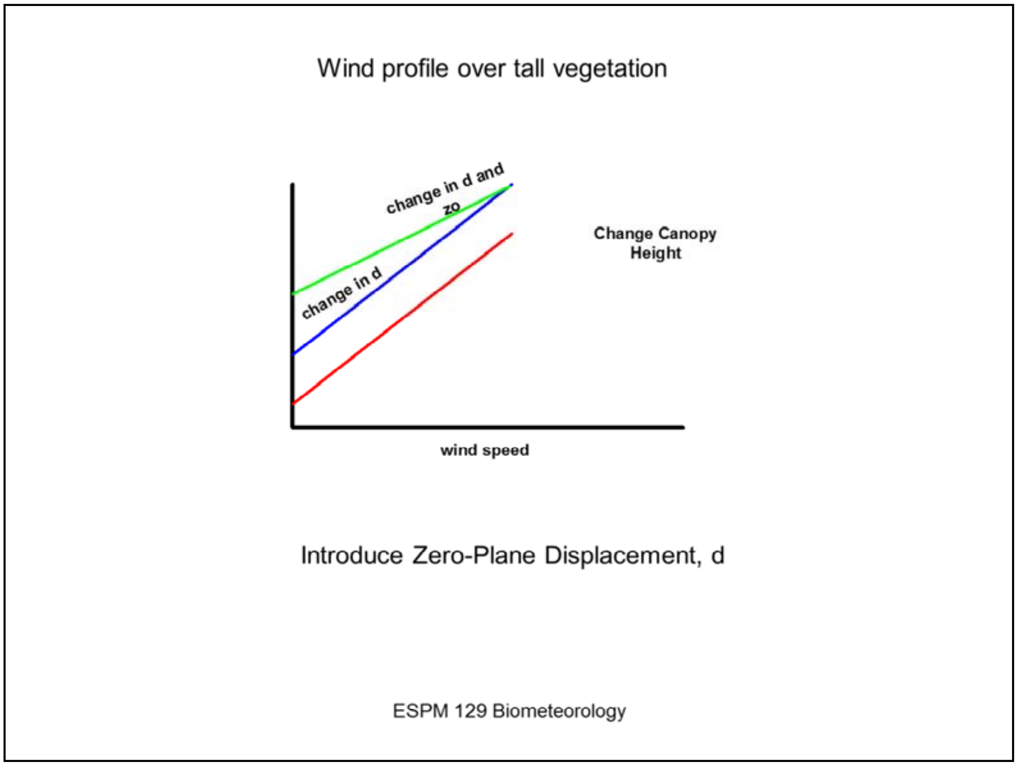
In this lecture we focus on how wind profiles vary over canopies of different heights and roughnesses. We also explore the effect of thermal stratification on wind profiles



With tall vegetation we have to introduce a zero plane displacement, a lifting of the log profile with respect to the mean height in a tall canopy where momentum is absorbed. This makes the wind gradient steeper and the surface rougher, causing it to experience greater u* values for the same wind speed at a reference height. This cartoon provides an illustration of important concepts to be extracted from this lecture.

Wind Profile over Tall Vegetation

Integrate from z_0 +d to z

$$\int_0^u du = \int_{z_0+d}^{z} \frac{u_*}{k(z-d)} dz$$

$$u(z) = \frac{u_*}{k} ln(\frac{z-d}{z_0})$$

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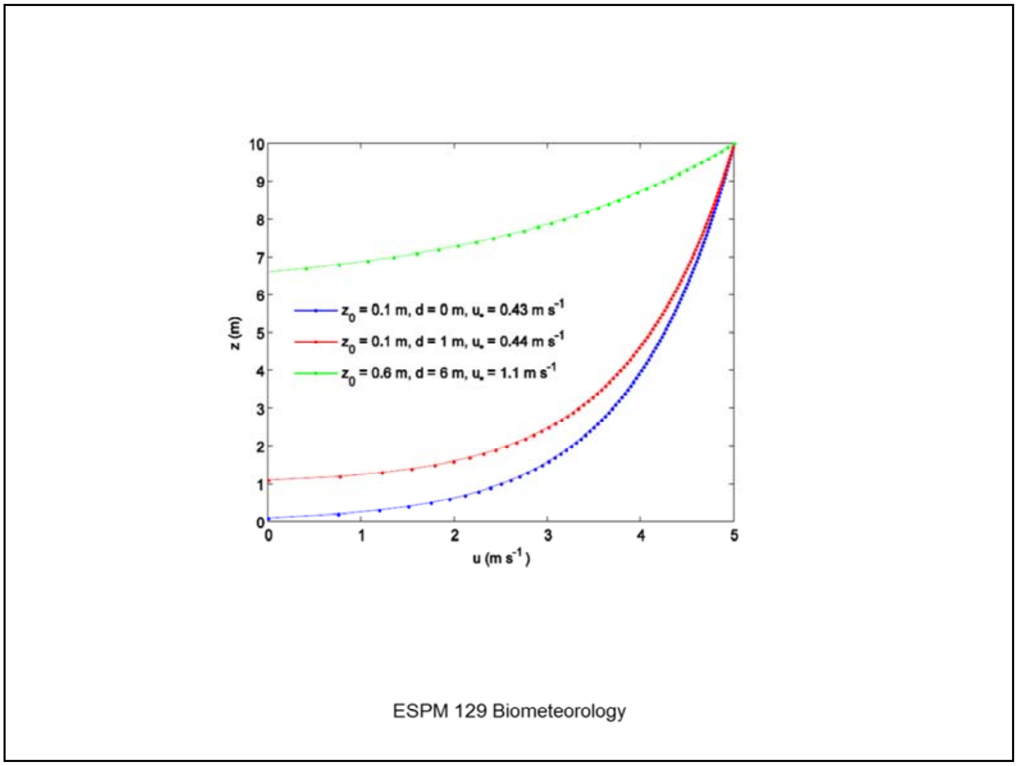
Here is the derivation of the log profile with a zero plane displacement, It shows how the zero plane displacement gets incorporated into the log wind law.



See how different roughness lengths and d values yield a rougher canopy and greater u* all with the same wind speed aloft. So more shear promotes greater u*

Zero plane displacement

- the mean level where momentum is absorbed by a canopy
  - Thom (1975)

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Simple definition of zero plane displacement.

Rules of Thumb for z_o and d

$$z_0 \approx 0.1h$$

$$d \approx 0.6h$$

h, canopy height

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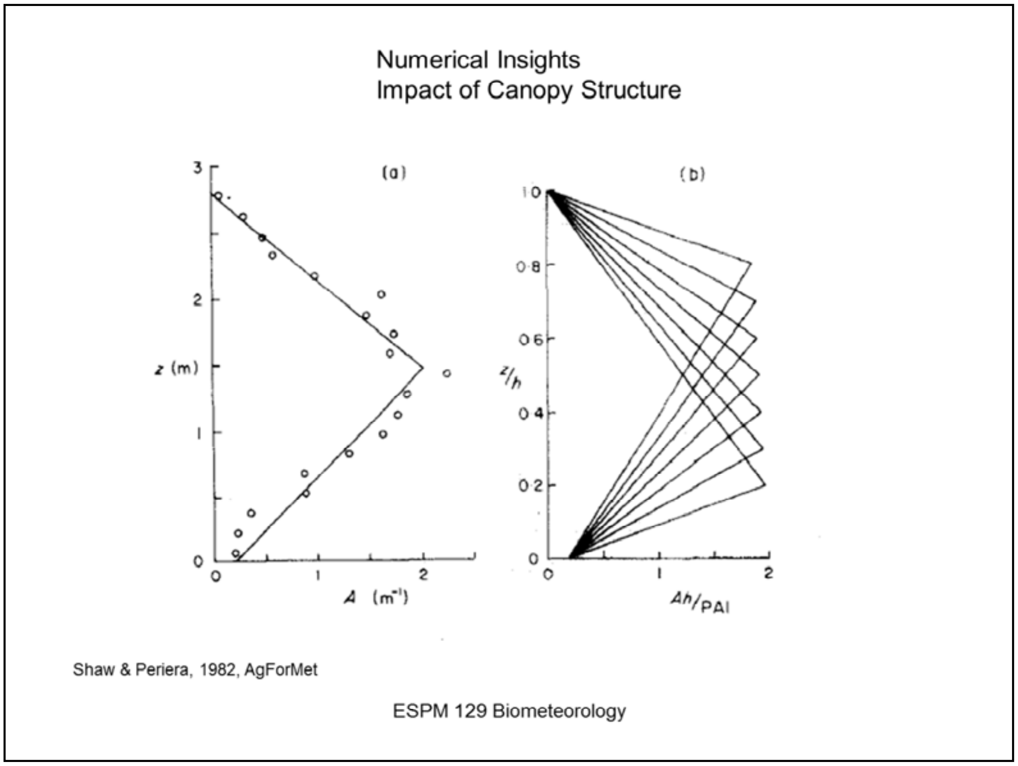
Good and useful rules of thumb

Survey of z_0 and d values

surface	roughness length (m)	zero plane displacement (m)
water	$0.1 - 10^{-4}$	na
ice		na
snow		na
sand	0.0003	na
soil	0.001-0.01	na
grass, short	0.001-0.003	< 0.07
grass, tall	0.04-0.1	< 0.66
crops	0.04-0.2	<3
orchards	0.5-1	<4
deciduous forest	1-6	< 20
conifer forests	1-6	< 30

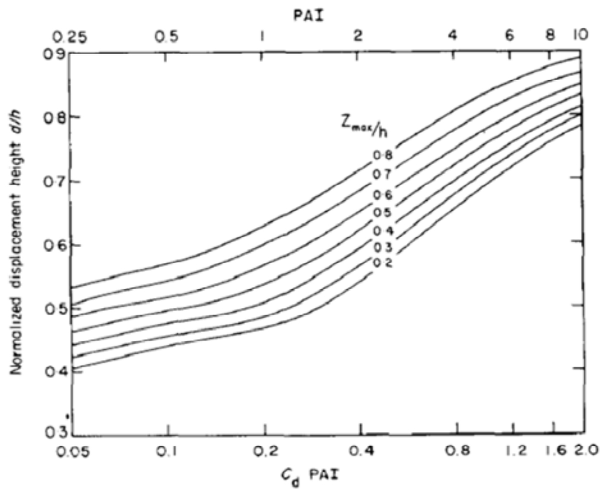
Monteith and Unsworth, 1990

Examples of data



Real canopies have a distribution of LAI that will alter d and zo in a systematic way

Zero Plane Displacement



Shaw & Periera, 1982, AgForMet

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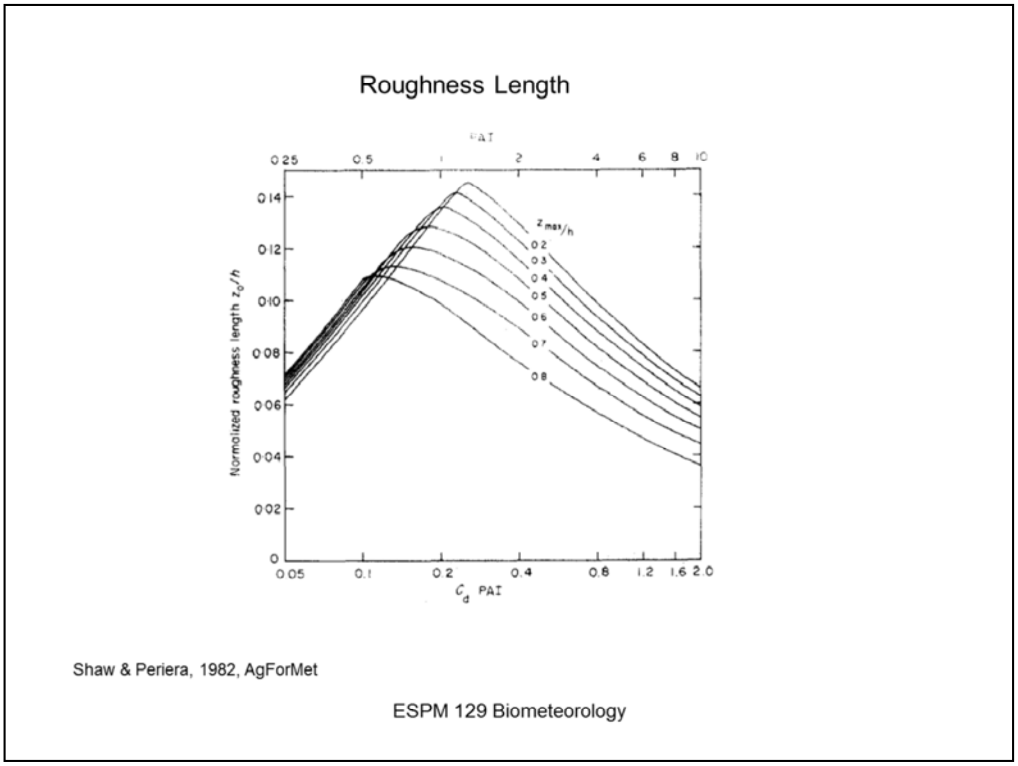
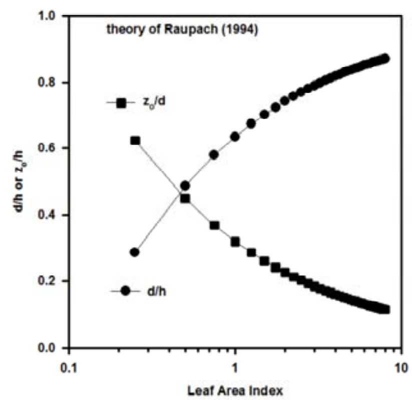
Model work by Shaw showed the deviation between the rule of thumb with different lai and distribution of lai



Zo is a non linear function of lai. Low lai, sparse canopy, low zo. Medium lai, roughest. High LAI, smooth again

$$1-\frac{d}{h}=\frac{1-\exp(-\sqrt{aL})}{\sqrt{aL}}$$

$$\frac{z_o}{h}=(1-\frac{d}{h})\exp(-k\cdot u_h/u_*-\Psi_h)$$



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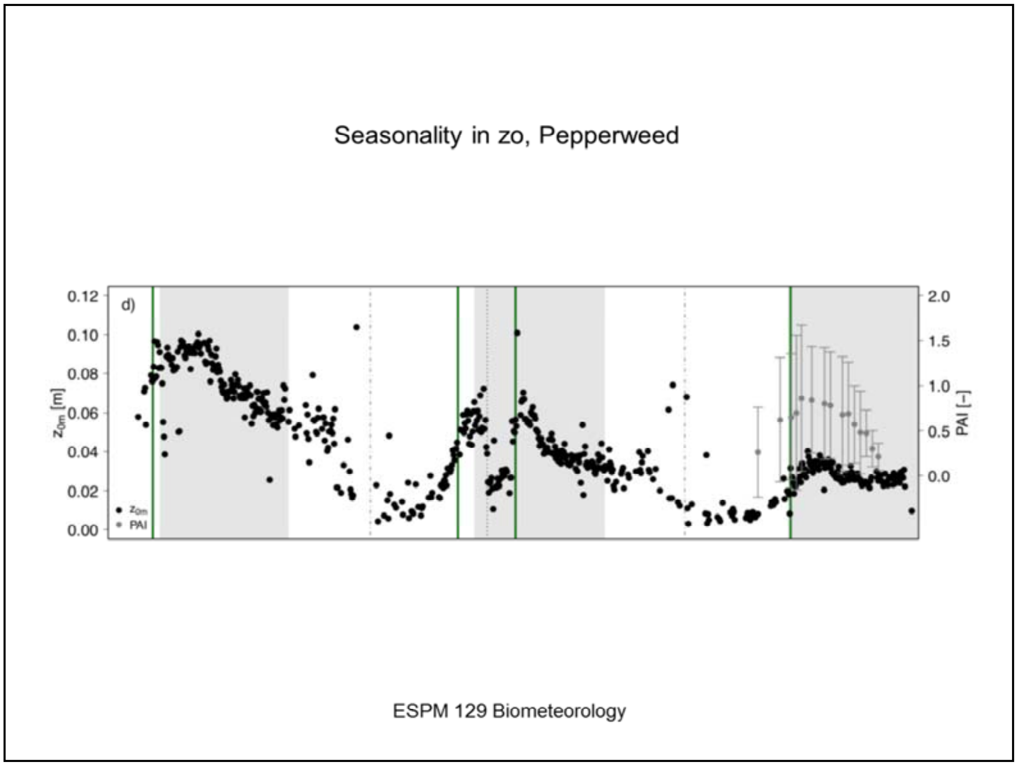
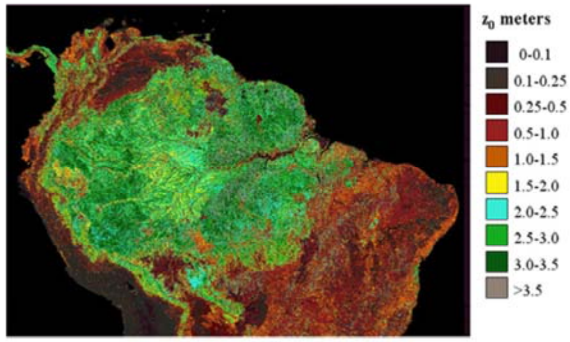
Other simple models to put structure and function into wind profile calculations. Too often ignored in climate models. Here L is leaf area index and a is a model parameter fit to the data.



Phenology can cause seasonality in wind profiles

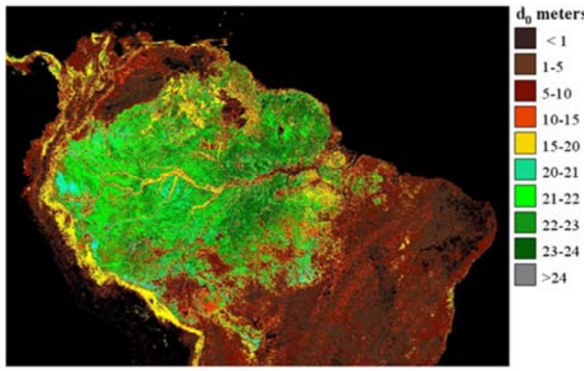
Sonnentag, O., M. Detto, R. Vargas, Y. Ryu, B. R. K. Runkle, M. Kelly, and D. D. Baldocchi. 2011. Tracking the structural and functional development of a perennial pepperweed (Lepidium latifolium L.) infestation using a multi-year archive of webcam imagery and eddy covariance measurements. Agricultural and Forest Meteorology **151**:916-926.

Map of Aerodynamic Roughness Length



www-radar.jpl.nasa.gov/carbon/ab/ar.htm

Map of Zero Plane Displacement Height



www-radar.jpl.nasa.gov/carbon/ab/ar.htm

What Happens to Wind when you Cut Down the Forest?

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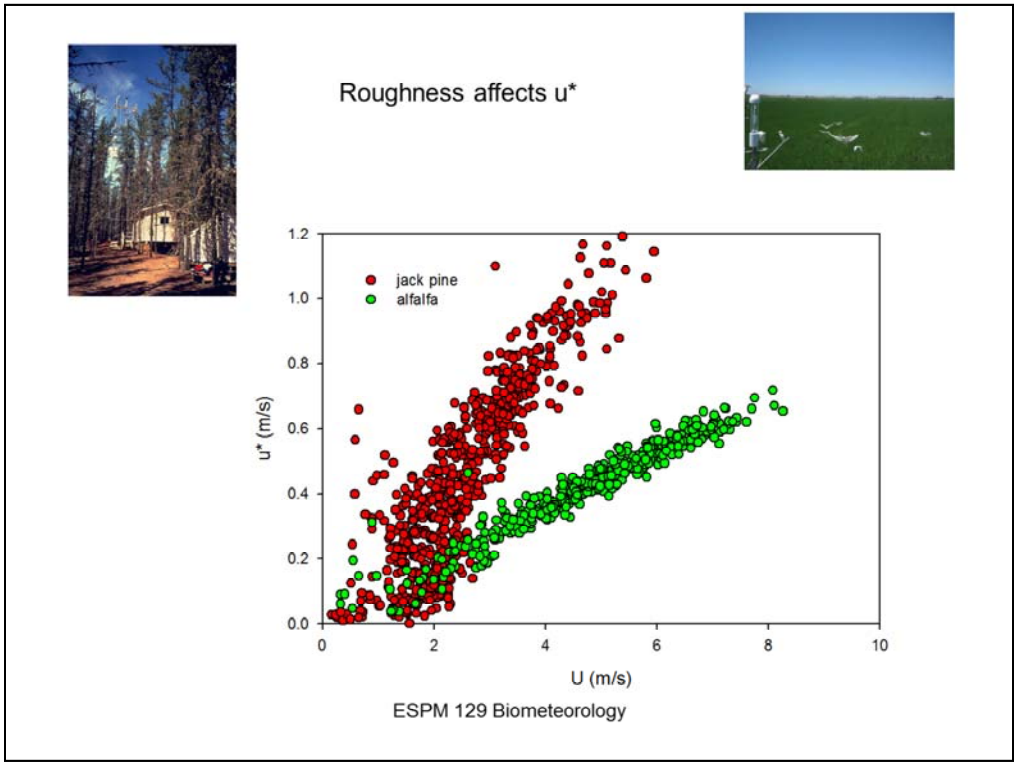
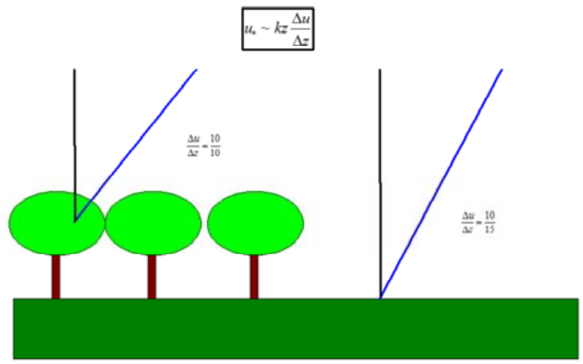
One of the lessons is to think about wind profiles with changes in forest cover



Comparison of u* vs U over a rough jack pine forest and an alfalfa field is a good case study for how deforestation may affect wind fields. Notice that at the same wind velocities u* is almost 3x greater over the jack pine than alfalfa (1.2 vs 0.4 m/s) Yet, maximum wind velocities are much greater over the alfalfa (8 vs 5 m/s)

Changes in roughness and displacement with Canopy Height



Assume Common Regional Wind Speed at Blending Height, aloft

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You should be able to apply first principles and tell us how the wind varies over a forest vs smoother and shorter vegetation

What happens to wind if you remove vegetation?

$$\frac{u(z)_{grass}}{u(z)_{forest}} = \frac{u_{*grass}}{u_{*,forest}}\left[\ln(\frac{z-d_{grass}}{z_{0|grass}})/\ln(\frac{z-d_{forest}}{z_{0|forest}})\right] = \frac{u_{*grass}}{u_{*,forest}}3.39$$

$$\frac{u(z)_{grass}}{u(z)_{forest}} = \frac{u_{*grass}}{u_{*,forest}}\left[\ln(\frac{40-0.3}{0.05})/\ln(\frac{40-18}{3})\right] = \frac{u_{*grass}}{u_{*,forest}}3.39$$

At Reference Height

$$\frac{u(z)_{grass}}{u(z)_{forest}} = 1$$

$$\frac{u_{*,forest}}{u_{*grass}} = 3.39$$

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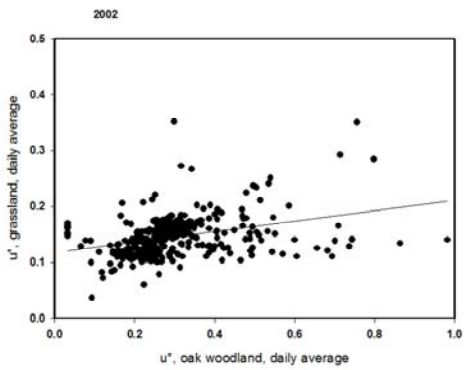
What happens to wind if you remove vegetation??

U* of tall, rough Savanna > short, smooth Grassland



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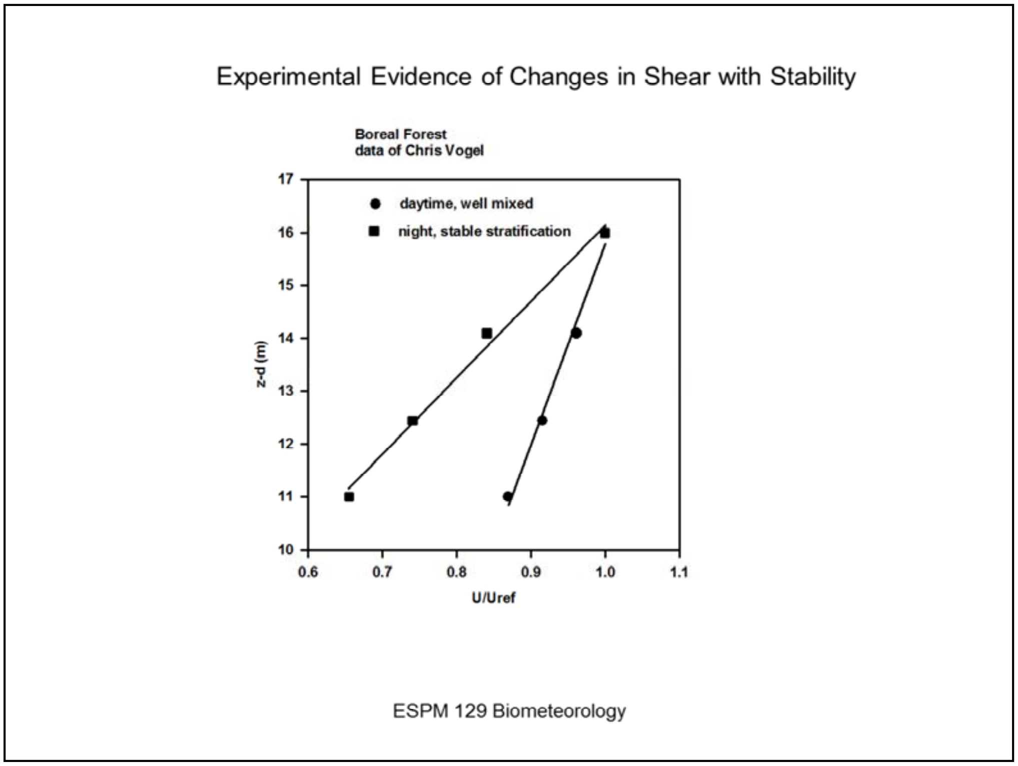
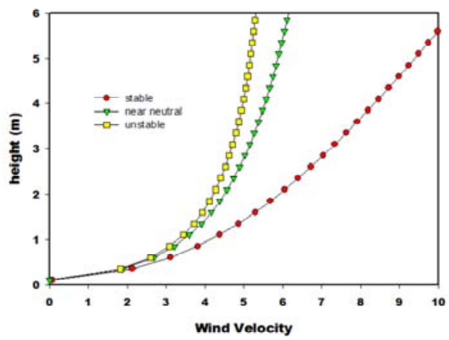
Real data testing the ideas.. Here it is clear that u* is greater over the forest than the grass, a site less than 2 km away and experiencing the same regional wind speeds.



Next we will study how thermal stratification affects wind profiles. The effect is profound, as you can see from these measurements we made. Here is a condition when the reference wind is similar but the profiles are much different. Note more shear at night (du/dz) with stable stratification. We will explain why in the following slides and theory

Effect of Stability on Wind Shear Starting with Same Upper Boundary, Onwards toward Monin-Obukhov Similarity Theory



$$\frac{\partial u}{\partial z} = \frac{u_*}{k\,z}\varphi_m\left(\frac{z}{L}\right)$$

Note: Changes in Shear with transition from unstable to stable Thermal stratification $\frac{\Delta u}{\Delta z}$

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Monin Obukhov similarity theory is the foundation for studying the effects of stabilty on wind. We introduce the non dimensional phi flunction which is a function of z over L, where L is the Scale length

Wind Velocity Gradients over Tall Vegetation,
And Varying Thermal Stratification

$$\frac{\partial u}{\partial z} = \frac{u_*}{k(z-d)}\varphi_m(\frac{(z-d)}{L})$$

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Slight change with tall vegetation

Monin-Obukhov Similarity Theory and Non-Dimensional Wind Shear

Figure 2. (a) A.S. Monin (source: Russian Academy of Science: http://hp.itp.ru/ger/pers.ac.htm). (b) A.M. Obukhov (source: Yaglom, 1990).

(from Foken, 2006, BLM)

$$\varphi_m\left(\frac{z}{L}\right) = \frac{kz}{u_*}\frac{\partial u}{\partial z}$$

L is the Monin-Obukhov length scale

$$L = -\frac{u_*^3\,\theta_v}{k\,g\,\overline{w'\theta_v'}}$$

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Monin and Obukhov developed the widely used similarity theory to describe wind profiles over vegetation for different thermal stratification. Phi is non dimensional wind shear. L is the MO length scale, a function of heat flux, gravity and friction velocity

Monin-Obukhov length scale

$$L = -\frac{u_*^3\,\theta_v}{k\,g\,\overline{w'\theta_v'}}$$

u*, friction velocity, m s^{-1}
k, von Karman's constant, 0.4
g, acceleration due to gravity, 9.8 m s^{-2}
θ_v, virtual temperature
$w'\theta_v'$, virtual heat flux

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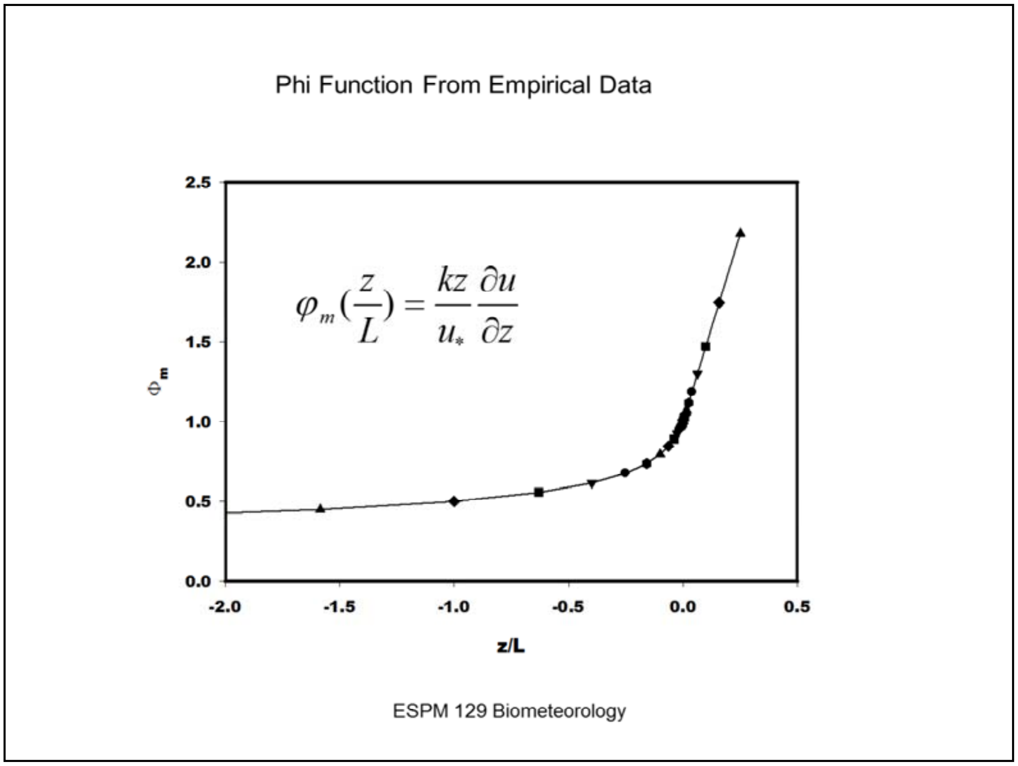
Definition of L



Functional dependence of Phi with z/L. Pay attention to values and limits.

The 'phi' function has 3 asymptotic limits

- Under neutral conditions z/L approaches zero and Phi approaches 1.
- Under unstable conditions z/L approaches negative infinity and Phi is < 1.
  - At the extreme case wind speeds are very light and free convection occurs. In this situation friction velocity is not the appropriate scaling velocity. Instead, a convective scaling velocity (w*) relevant
- Under stable conditions, z/L is greater than 0 and Phi is Greater than 1
  - At Extremes, these dimensionless groups are independent of height.
  - decoupling between turbulent flow at various layers

Know these limits

Unstable Thermal Stratification, z/L < 0

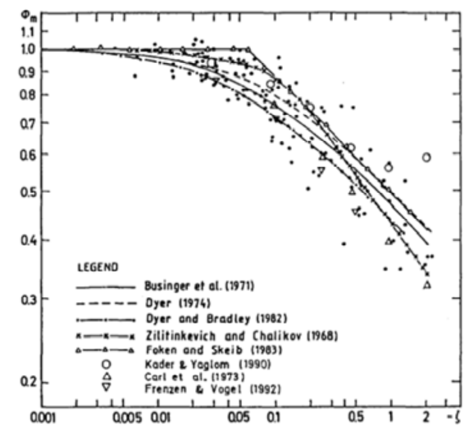


Figure 3. Plot of ϕ_m against $(z - d)/L$ in log–log representation for unstable stratification. The small dots are data from Högström (1988). The other symbols have been derived from modified expressions from the sources listed in the legend.

Hogstrom, 1996, BLM

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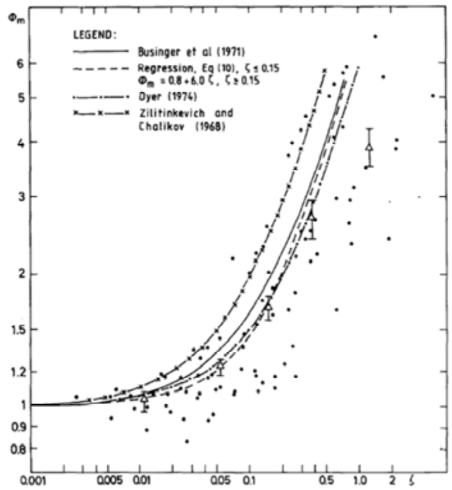
Real data and functional forms

Stable Thermal Stratification, z/L > 0



Hogstrom, 1988, BLM

The Kansas Experiment

$$\phi(z / L) = (1 - \gamma z / L)^{\beta}$$

Unstable

Citation	k	γ	β
Businger (1971)	0.35	-15	-1/4
Dyer (1974)	0.41	-16	-1/4
Dyer and Bradley (1982)	0.40	-28	-1/4
Hogstrom (1996): ave	0.40	-19	-1/4

Stable

Citation	k	γ	β
Businger (1971)	0.35	4.7	1
Dyer (1974)	0.41	5	1
Hogstrom (1996): ave	0.40	5.3	1

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Functional values for application…'Micrometeorologists are like Dorothy in the Wizard of Oz..they always want to go back to Kansas'..attributed to David Fitzjarrald, SUNY-Albany

Buckingham pi Theory:
Dimensionless Group Analysis for Deriving MO Theory

- Four Parameters to define $kz/u_* \, du/dz$
  - Bouyancy, g/T
  - Height, z
  - Momentum flux, $u^* = (w'u')^{1/2}$
  - Kinematic Heat flux density, $w'T' = H/\rho C_p$

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Background on dimensionless theory

production of turbulent kinetic energy, v2.0

shear and buoyant production of tke
must equal the rate at which energy
is **dissipated into heat by viscous processes**

$$-\overline{w'u'}\frac{\partial \bar{u}}{\partial z} + \frac{g}{\theta_v}\overline{w'\theta_v} = \varepsilon$$

g, acceleration of gravity
θ_v, virtual potential temperature

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Another way to think about z/L is via the budget for turbulent kinetic energy

z/L

Ratio between of the buoyant production of turbulent kinetic energy, TKE

$$\frac{-g\overline{w'\theta_v'}}{\overline{\theta_v}}$$ Buoyant Production of TKE

$$\overline{w'u'}\frac{\partial \bar{u}}{\partial z}$$ Shear Production of TKE

$$-\overline{w'u'}\frac{\partial \bar{u}}{\partial z}+\frac{g}{\theta_v}\overline{w'\theta_v}=\varepsilon$$ TKE Budget: Production = Dissipation

Evaluate Dissipation Rate

TKE Budget $$-\overline{w'u'}\frac{\partial \bar{u}}{\partial z}+\frac{g}{\theta_v}\overline{w'\theta_v}=\varepsilon$$

Normalize by Shear Production $$1+z/L=\varepsilon kz/u_*^3$$

Neutral Conditions, z/L=0,
solve for dissipation rate $$\varepsilon=\frac{u_*^3}{kz}$$

Richardson Number, Gradient-Based Stability Index

$$Ri = \frac{\frac{g}{\overline{\theta_v}} \frac{\partial \overline{\theta_v}}{\partial z}}{(\frac{\partial \overline{u}}{\partial z})^2}$$

u, wind velocity, m s^{-1}
g, acceleration due to gravity, 9.8 m s^{-2}
θ_v, virtual temperature

Integrated Form of Log Wind Law for Diabatic Conditions

$$u(z) = \frac{u_*}{k}(\ln(\frac{z-d}{z_0}) - \Psi_m(\frac{z-d}{L}) + \Psi_m(\frac{z_0}{L})$$

Psi-Functions

Stable

$$\psi_m(\frac{z}{L}) = -4.7\frac{z}{L}$$

Unstable

$$\psi(\frac{z}{L}) = \ln[(\frac{1+x}{2})^2(\frac{1+x^2}{2})] - 2\tan^{-1}(x) + \frac{\pi}{2}$$

$$x = (1-15\frac{z}{L})^{1/4}$$

Arya, 1988

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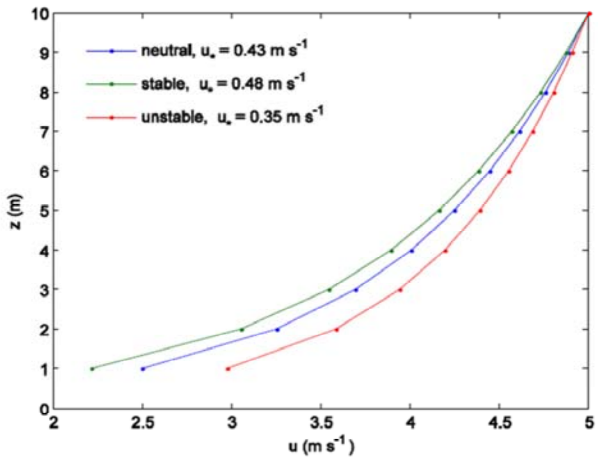
Integrated form of log wind law..



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Re-Visit K Theory

$$F_c = \rho_a K_c \frac{\Delta C}{\Delta z}$$

Reynolds Analogy

$$K_m = K_v = K_h = K_c = K_x$$

$$K_m \neq K_v = K_h = K_c = K_x$$

Momentum transfer is affected by pressures forces, which do not play a role in mass transfer, so turbulent Prandtl number (K_m/K_h) does not equal 1

Eddy Exchange Coefficient for Momentum, K_m, over Tall Vegetation

$$K_m = u_* k (z - d)$$

$m^2 s^{-1}$

K is a Function of Thermal Stratification, too

$$K_m = k\, u_* (z-d) / \phi_m (z/L)$$

$$K_h = k\, u_* (z-d) / \phi_h (z/L)$$

$$\phi_h = \frac{kz}{\theta_*} \frac{\partial \theta}{\partial z} \qquad \theta_* = \frac{-\overline{w' \theta_v'}}{u_*}$$

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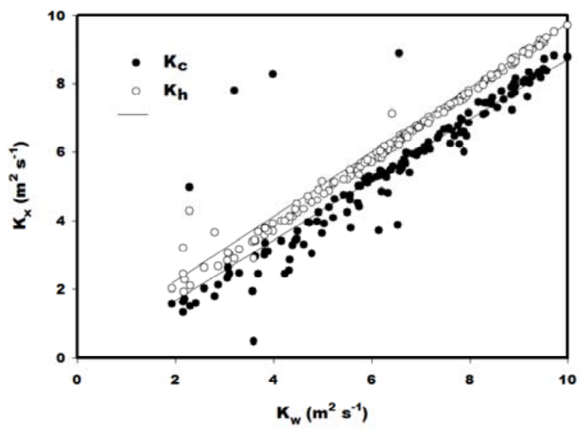
Km is the eddy exchange coefficient for momentum; Kh is the eddy exchange coefficient for heat, k is von Karman's constant, u* is friction velocity

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1 - Ri)^{0.25}$$

$$\frac{K_h}{K_m} \approx \frac{K_w}{K_m} = (1 - 16|z / L|)^{0.25}$$

Role of Different Sources and Sinks on K



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Here are computations I made with a Lagrangian transport model. Heat (Kh) and water (Kw) sources are co-located in the upper vegetation so these Ks are similar. CO2 exchange is bidirectional with a sink co-located with Kh and Kw, but also with a source at the ground. This causes Kc < Kw~Kh

Breakdown in MO theory in Roughness Sublayer

$$\gamma_e = \frac{K_{obs}}{K_{mo}} = \frac{\phi(z/L)_{mo}}{\varphi_{obs}}$$

height	unstable	Near neutral	Stable
1.9-2.2h	0.92	1.18	1.18
1.6-1.9h	1.23	1.27	1.52
1.4-1.6h	1.64	1.31	1.49
1.2-1.4h	1.60	1.57	1.66

Simpson et al. 1998

Counter Gradient Transfer, a New Paradigm

K Theory Fails in the Roughness Sub-layer of Tall Vegetation and Forests,
And within Vegetated Canopies

Strong Shear at the Canopy-Atmosphere Interface
Causes Non-Local Transport, A Scale Emergent Property

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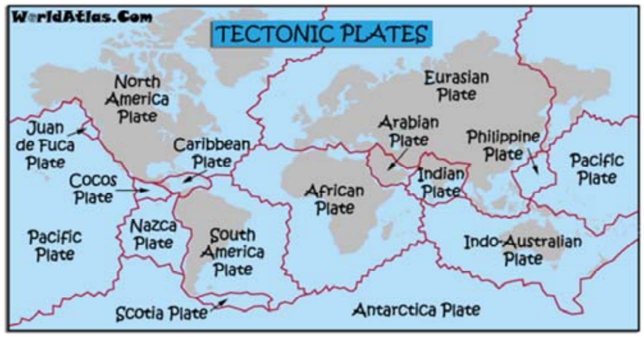
The Discovery of Counter Gradient Fluxes can be viewed
As radical and paradigm shifting as Plate Tectonics



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Understanding Roughness Sublayer with Flux Covariance Budget Equation

$$\frac{\partial \overline{w'c'}}{\partial t} = 0 = -\overline{w'^2}\,\frac{\partial \bar{c}}{\partial z} - \frac{\partial \overline{w'w'c'}}{\partial z} - \overline{c'\,\frac{\partial p'}{\partial z}} + g\,\frac{\overline{\theta'c'}}{\theta}$$

I II III IV

I. Shear Production
II. Non-Local Transport
III. Pressure Interations
IV. Bouyancy Production

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P is pressure, theta is potential temperature, c is concentration, w is vertical velocity

Non-Local Transport Causes MO Theory to Breakdown

$$\frac{\partial \overline{w'c'}}{\partial t} = 0 = -\overline{w'^2}\frac{\partial \bar{c}}{\partial z} - \frac{\partial \overline{w'w'c'}}{\partial z} - \overline{c'\frac{\partial p'}{\partial z}} + g\frac{\overline{\theta' c'}}{\theta}$$

$$\overline{c'\frac{\partial p'}{\partial z}} = \frac{\overline{w'c'}}{\tau}$$

$$\overline{w'c'} = \frac{-\overline{w'^2}}{\tau}\frac{\partial \bar{c}}{\partial z} - \frac{\partial \overline{w'w'c'}}{\tau \partial z}$$

$$\overline{w'c'} = K\frac{\partial \bar{c}}{\partial z} - \frac{\partial \overline{w'w'c'}}{\tau \partial z}$$

Non-Local Transport augments K theory in the Roughness Sublayer!

$$\overline{w'c'} = -K\frac{\partial \bar{c}}{\partial z} - \frac{\partial \overline{w'w'c'}}{\tau\,\partial z}$$

Summary Points

- Over tall vegetation the logarithmic wind profile is adjusted by incorporation of the zero plane displacement, d.
- The zero plane displacement represents the 'center of pressure' or the mean height of momentum absorption by a tall canopy.
  - As a rule of thumb d is about 60% of canopy height, but will very with leaf area index and the vertical profile of leaf area index.
- The roughness length is about 10% of canopy height
- Momentum transfer is greater over tall rough vegetation than short smooth vegetation, given the same wind speeds aloft.
- Stable and unstable thermal stratification will alter the wind gradient relationship
- A non-dimensional shear function has been defined empirically and is a function of the Monin Obuhukov scale length.
- The non-dimensional Monin-Obhukov length scale is defined as the ratio between buoyant and shear production of turbulent kinetic energy. It can also be defined with non-dimensional analysis using Buckingham pi theory.
- Non-dimensional wind shear is greater than one when thermal statification is stable; wind shear must increase to transfer momentum to the surface. Non-dimensional wind shear is less than one when thermal stratification is unstable. Non-dimensional wind shear equalsone when thermal stratification is neutral.
- Eddy exchange coefficients are enhanced in the roughness sublayer (~1 to 1.5 h) due to large scale transport of momentum. Monin-Obuhkov scaling theory fails in this region.
- Reynolds analogy assumes the eddy exchange coefficients for heat, water and momentum are equal. In practice this is not true as momentum transfer is affected by pressure fluctuations and the other scalars are not.

Homework

- Base: Wind at 10 m = 5 m/s, zo=0.1, d=0
  - Compute profile at 10,7,5,3,2,1 m for base and zo=0.001 and z0=0.05 m, d=0
  - Compute u profile for d=6, z0=0.1m
  - Compute u profile for Base conditions, but
    - z/L=0.1
    - z/l=-3