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

- **Variation in Space**
  - Wind in the Surface Boundary Layer: Concepts and Principles
    - Boundary Layers
      - Planetary Boundary Layer
      - Surface Boundary Layer
      - Internal Boundary Layer (constant flux layer)
      - Flux footprints
      - Nocturnal Boundary Layer
    - Logarithmic Wind Profiles

Last lecture we were introduced to boundary layers. Today we will focus on atmospheric boundary layers

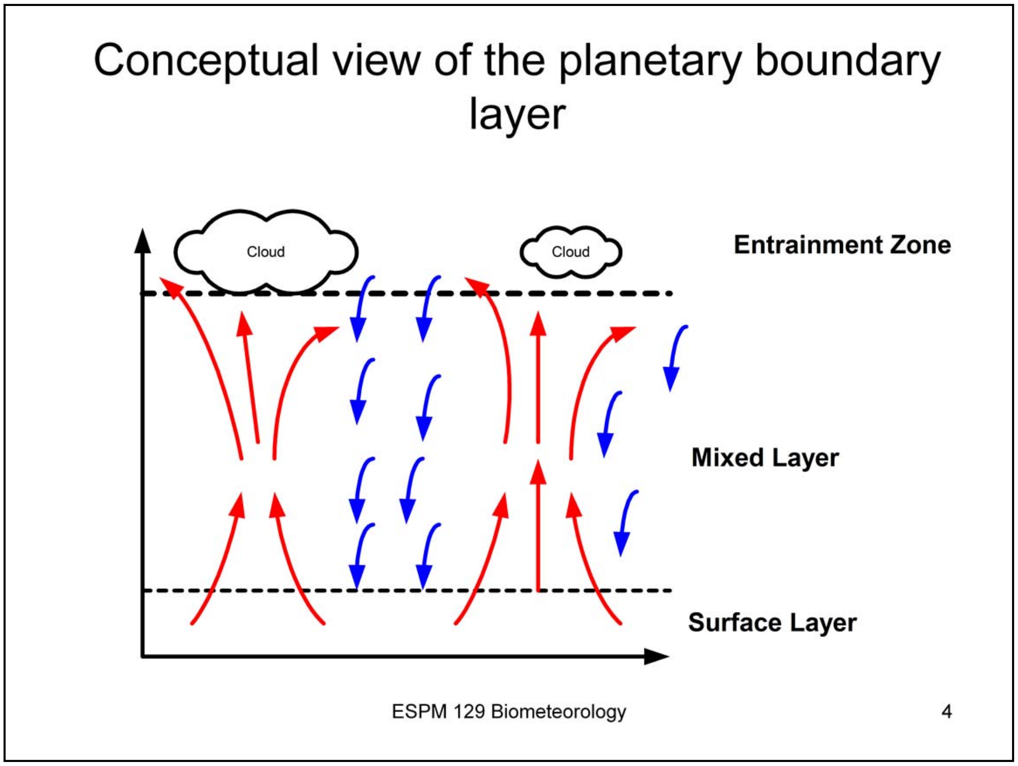
Boundary Layers

- Planetary boundary layer
  - Region where friction forces by the surface are evident
  - Air possesses characteristics of underlying surface
- Surface Layer
  - Lower 10% of planetary boundary layer
  - Region of strong gradients in u, T, q
  - Coriolis force is nil
- Internal Boundary Layer
  - Constant flux layer
- Roughness Sublayer
  - Zone between 1.5 to 2 h
  - Region of non-local transport
- Nocturnal, Stable Boundary Layer
  - Intermittent, sporatic
  - Wind jet aloft

There are a number of boundary layers that are of interest and importance

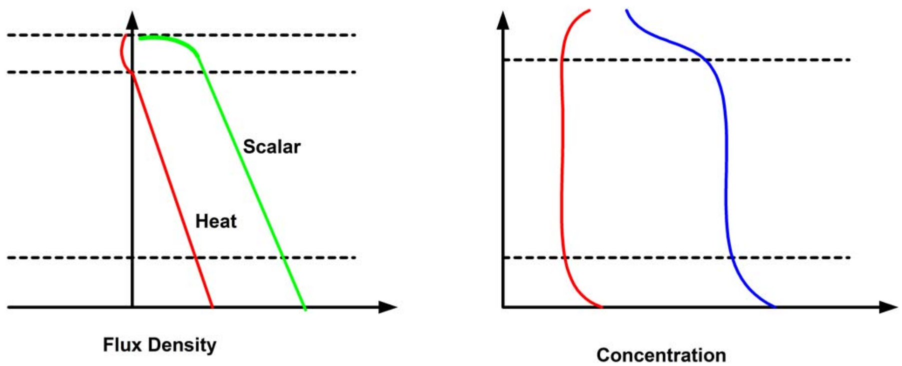
Planetary Boundary Layer

The base of fair weather convective clouds is often a visual cue of the top of the planetary boundary layer



The pbl consists of a surface layer, where gradients are strongest, a mixed layer that is mixed well by large scale convective eddies and is capped by an inversion layer. Growth of the pbl with daytime heating causes entrainment from above.

Conceptual view of the planetary boundary layer



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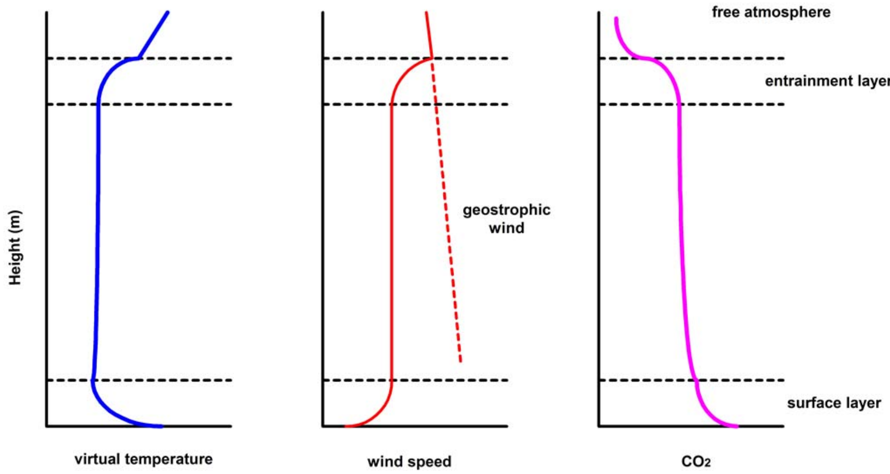
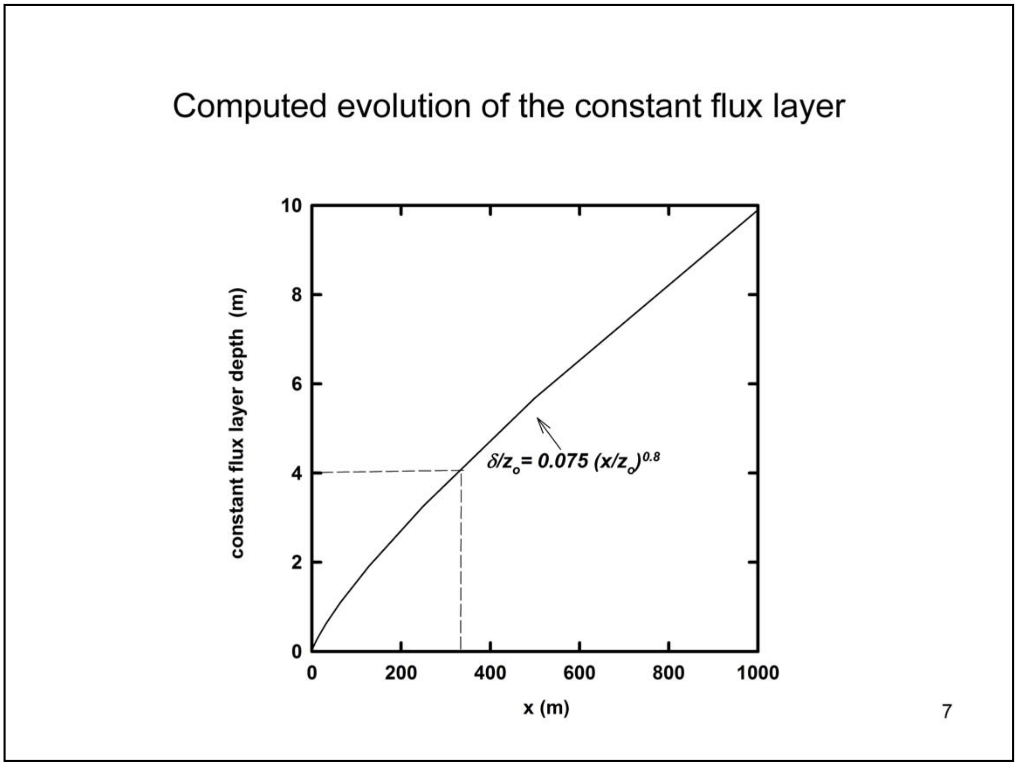
Profiles of fluxes of heat and scalar and the scalar and temperature

Conceptual profiles of temperature and wind in the surface, mixed and entrainment boundary layers

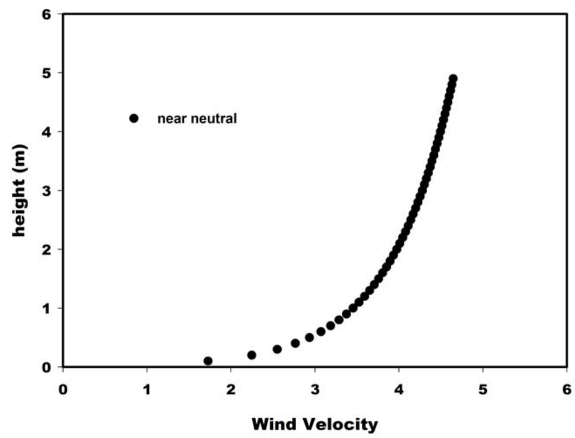


Virtual temperature, wind speed and CO2 all have distinct profiles

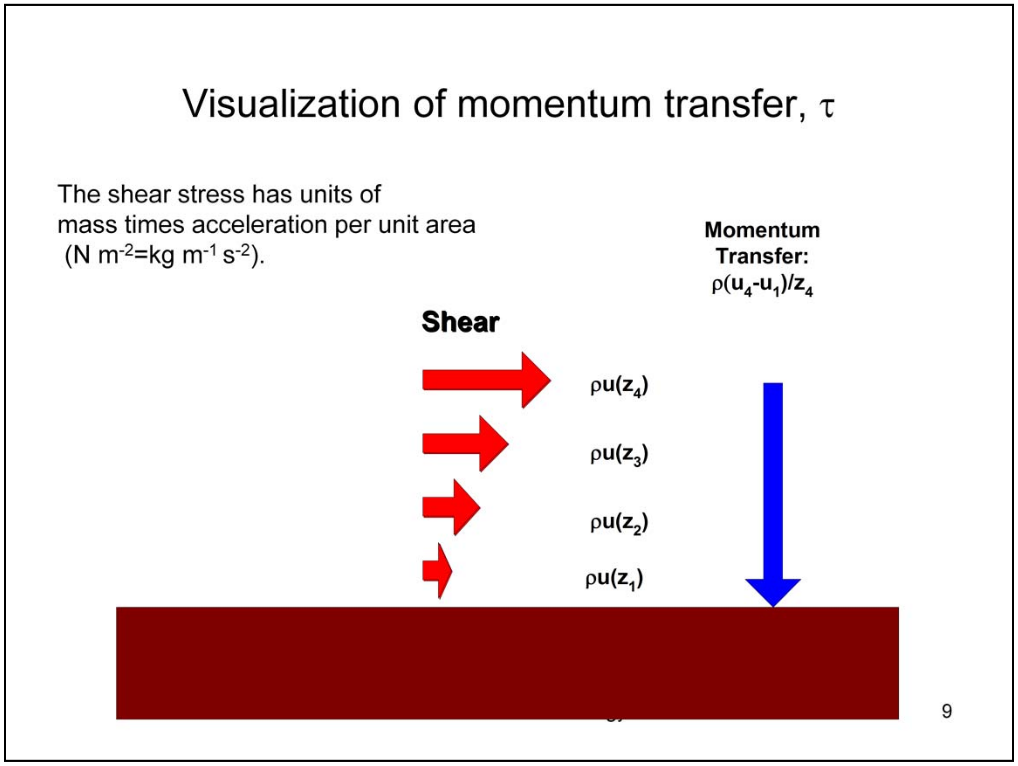


Within the surface layer is the constant flux layer. Here we need enough fetch for the wind to blow over a uniform extended surface to gain the properties of that surface. Rule of thumb is a 100:1 fetch to height ratio. Within the layer fluxes tend to be constant with height as advection is nill.

Logarithmic Wind Profile in the Surface Boundary Layer

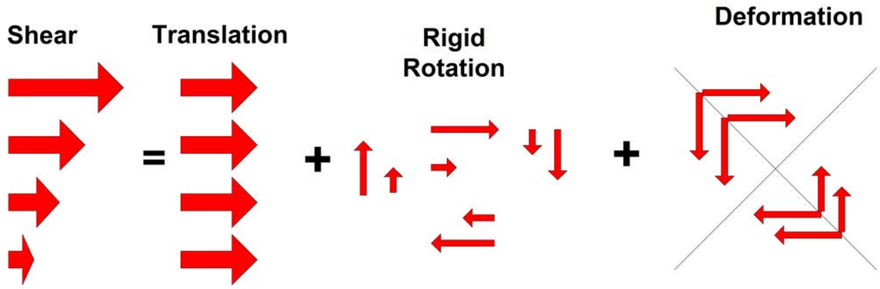


Next we will focus on the wind profile in the surface boundary layer, and with the assumption of a constant flux layer of momentum we really are addressing wind profiles in the constant flux layer



Like the example of air flow over a plate or leaf, in the last lecture, we expect to experience a gradient in shear across the land-air interface. This will produce a gradient in momemtum (mass times velocity) and yield a flux density of momentum to the surface

Conceptual diagram of shear and its contributors



Adapted from Blackadar

Shear in the atmosphere is associated with complex fluid motions, translation, rotation and deformation

Wind speed gradients are a function of momentum stress (τ), air density (ρ) and height (z)

$$\frac{du}{dz} = f(\tau, \rho, z)$$

$$\frac{du}{dz} \propto \frac{\tau}{z} \propto \frac{u_*}{z} \qquad (s^{-1})$$

u*, friction velocity, m s^{-1}

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Here we start to put our ‘engineer’ hat on and think about dimensional scaling. What drives wind gradients and shear. From first principles they are a function of the shear stress (the flux density of momentum transfer to the surface, tau, the density of the fluid, rho, and the height about the surface

Define Friction Velocity, u*, from Reynolds Shear Stress, τ

$$\tau = \rho \overline{w' u'} = \rho u_*^2$$

$$u_* = \left| \overline{w' u'} \right|^{1/2}$$

momentum shear stress (τ)
air density (ρ)
height (z)
u, horizontal wind velocity
w, vertical wind velocity
‘, fluctuation from mean
Overbar, time average

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We can measure the shear stress in terms of the covariance between vertical velocity and horizontal velocity fluctuations. We also use this equation to define a new quantity, the friction velocity, u*.

Wind Shear Equation, Near Neutral Conditions

$$\frac{du}{dz} = \frac{u_*}{kz}$$

k is von Karman's constant, 0.40

From dimensional arguments the wind velocity gradient, du/duz, is proportional to the ratio between friction velocity, u*, and height. A non dimensional constant is applied from many fluid flow studies. It is the von Karman constant and has a value near 0.40.

Momentum Transfer via:
Eddy Covariance, Flux Gradient and Ohm’s law

$$\tau = \rho \overline{w'u'} = -\rho u_*^2 \approx -\rho K_m \frac{\partial u}{\partial z} = -\rho \frac{u}{R_{a,m}}$$

It is important to know how to measure and infer fluxes of momentum. The eddy covariance method enables us to measure <w’u’> directly with a sonic anemometer, sampling at 10 Hz and averaging over 30 to 60 minutes. Prior to the ubiquity of sonic anemometers, we had to infer momentum fluxes using gradient measurements of wind speed. Now we had to define an eddy diffusivity (Km) or a resistance Ra,m

Momentum Transfer via Flux Gradient

$$\tau = -\rho u_*^2 \approx -\rho K_m \frac{\partial u}{\partial z} \qquad \frac{du}{dz} = \frac{u_*}{kz}$$

Solve for Km

$$K_m = u_* kz = \frac{\partial u}{\partial z} kzkz = k^2 z^2 \frac{\partial u}{\partial z} \qquad (\mathrm{m^2\ s^{-1}})$$

$$\tau = -\rho k^2 z^2 (\frac{\partial u}{\partial z})^2$$

Eddy exchange coefficient

Using the gradient expression for wind we can solve for Km and apply to assess tau.

Momentum Transfer via Ohm's law

$$\tau = \rho u_*^2 \approx \rho \frac{u}{R_{a,m}}$$

$$R_{a,m} = \int_{z_0}^{z} \frac{dz}{K_m}$$

$$R_{a,m} = \frac{u}{u_*^2} \qquad (\mathrm{s\ m^{-1}})$$

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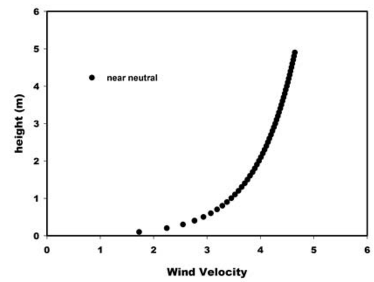
We consider Ohm's law and can define the boundary layer resistance in terms of the integral between height and the roughness length, z0, where wind velocity extrapolates to zero.

Logarithmic Wind Law



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

z_0, is the **roughness parameter,**

Conceptually it is the height where u goes to 0.

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If we integrate du/dz with respect to height we arrive at the famous logarithm wind law. Remember this is for near neutral thermal stratification. We define a new parameter, z0, the roughness length, the height at u extrapolates to zero.

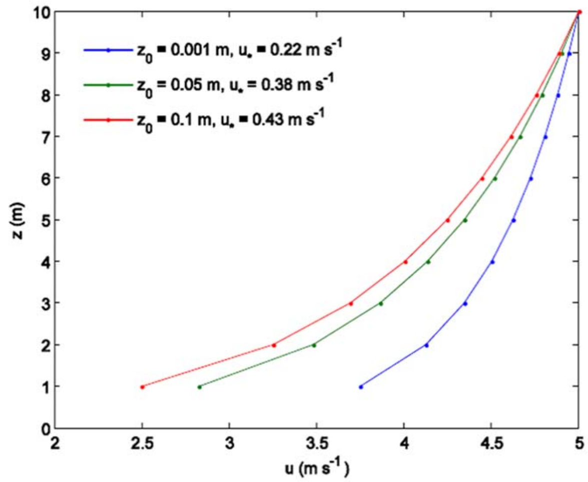
Derivation

$$\frac{\partial u}{\partial z} = \frac{u_*}{k\,z}$$

$$\int_0^U \partial u = \frac{u_*}{k}\int_{z_0}^{Z}\frac{\partial z}{z}$$

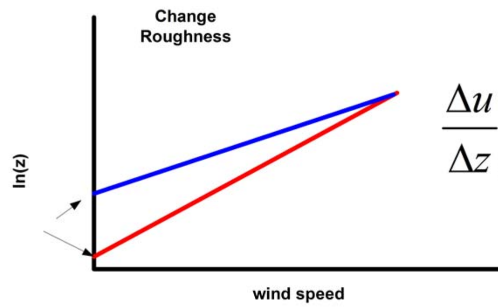
$$U(Z) = \frac{u_*}{k}\ln\frac{Z}{z_0}$$

Simple derivation of the log wind law



Different roughnesses yield different wind profiles. Rougher surfaces have greater z0 and for the same wind speed aloft produce greater shear and more momentum transfer to the surface in terms of increasing u*..Important principle.

How z_0 varies with canopy roughness, e.g. shear



$$\frac{\Delta u}{\Delta z}_{Blue} > \frac{\Delta u}{\Delta z}_{Red}$$

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It may be counter intuitive that a steeper slope produces more shear and greater u* because we tend to plot the wind profile upside down, putting the independent variable, z, on the y axis, and the dependent variable u on the x axis. So visually a flatter line is really a steeper slope of du/dz. This figure is really important for you to understand and think about what happens when you change vegetation, like afforestation or deforestation.

Roughness length, z_0

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

Computing Wind Speed at other Heights

$$u(z_2) = u(z_1)\ln(\frac{z_2}{z_0}) / \ln(\frac{z_1}{z_0})$$

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Wind speed extrapolation to other reference heights

Summary points

- Momentum transfer is related to the covariance between vertical velocity and horizontal velocity fluctuations. It can also be estimated using flux-gradient theory:
- Friction velocity is a scaling velocity that is related to momentum transfer
- The eddy exchange coefficient for momentum transfer can be estimated with measurements of wind profiles:
- (m^2 s^{-1})
- Wind velocity profiles in the surface boundary layer is a logarithmic function of height. The slope of the log profile for wind velocity is a function of friction velocity and the zero intercept is a function of the roughness length (z_0); k is von Karman's constant (0.4):
- For a similar wind velocity at height z (u(z)), friction velocity increases with increasing surface roughness, eg z_0

Prandtl Mixing Layer Theory

$$u' = \overline{u}(z-l) - \overline{u}(z) = -l\frac{\partial u}{\partial z}$$

$$w' \sim -u'$$

$$l \approx z$$

$$l = kz$$ l, Prandtl mixing length

$$\overline{w'u'} \sim -\overline{l^2}(\frac{\partial \overline{u}}{\partial z})^2$$

k is von Karman's constant, 0.40
u, horizontal wind velocity
w, vertical wind velocity
', fluctuation from mean
Overbar, time average