METR 130: Lecture 1

- ABL depth
- Definitions, Terminology, Conventions

Spring Semester 2011

February 1 & 3, 2011

Reading

- Arya, Chapter 1
- Seidel et al. JGR paper, "Estimating PBL heights from radiosonde observations …" (will use for Assignment #1)
- Prandtl "Physics Today" article
(for your interest only … not required)
- See reference to various other sections in Arya in ensuing slides …

What is the ABL? (1)
(see also handout from first day of class)

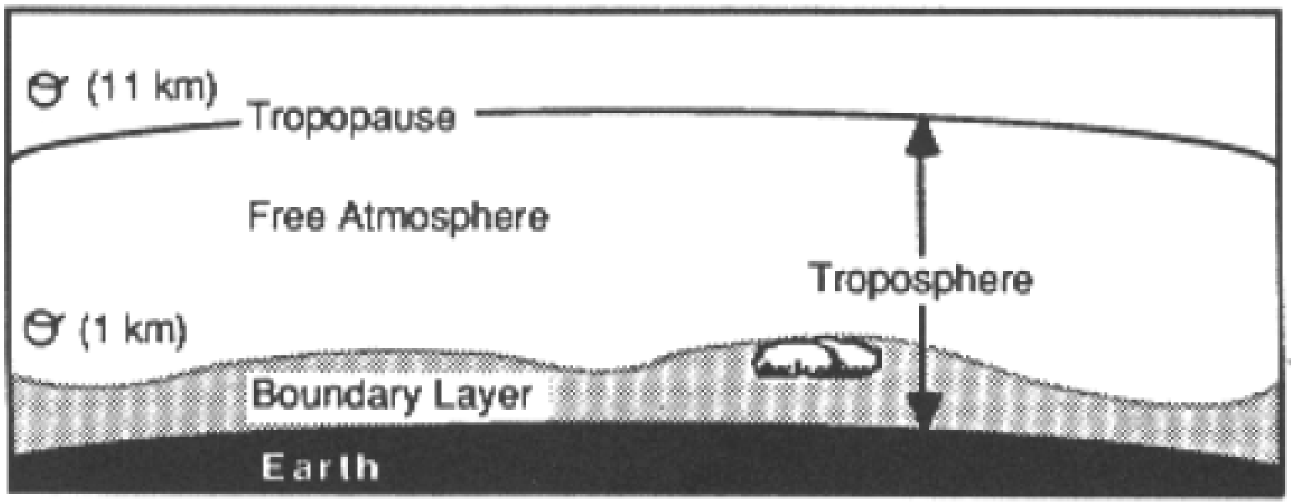


Fig. 1.1 The troposphere can be divided into two parts: a boundary layer (shaded) near the surface and the free atmosphere above it.

What is the ABL? (2)
(see also handout from first day of class)

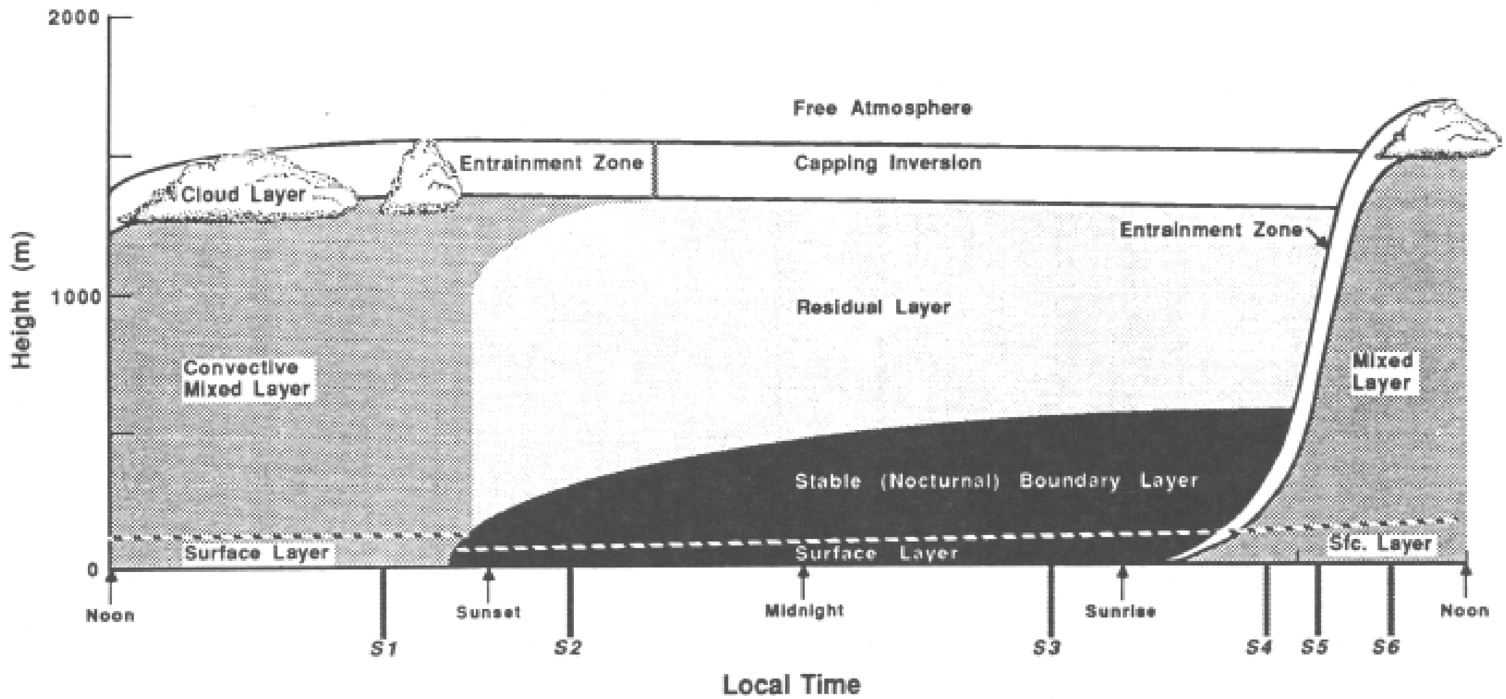


Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

Stull Diagram on Previous Slide Illustrates the Stratified (Unstable or Stable) ABL over Land

- Driven by diurnal heating & cooling of the surface.
- Most common during fair weather conditions.
- This is a **turbulent** boundary layer
  - Coupling of ABL to surface is due to turbulence (a form of convection)
  - As opposed to a **laminar** boundary layer (due to conduction)
- **Sub-Regions** of diurnal ABL over land …
  - Convective Mixed/Boundary Layer (CML or CBL)
  - Stable Boundary Layer (SBL)
  - Residual Layer (RL)
  - Surface Layer (SL)
  - Elevated (Capping) Inversion Layer
  - Entrainment Zone
- See Seidel et al paper for typical values for heights of these ABLs, and manner by which determined

ABLs can also be Non-Stratified, i.e. Neutral or "Barotropic"

(Constant potential temperature in ABL, no heating or cooling of surface)

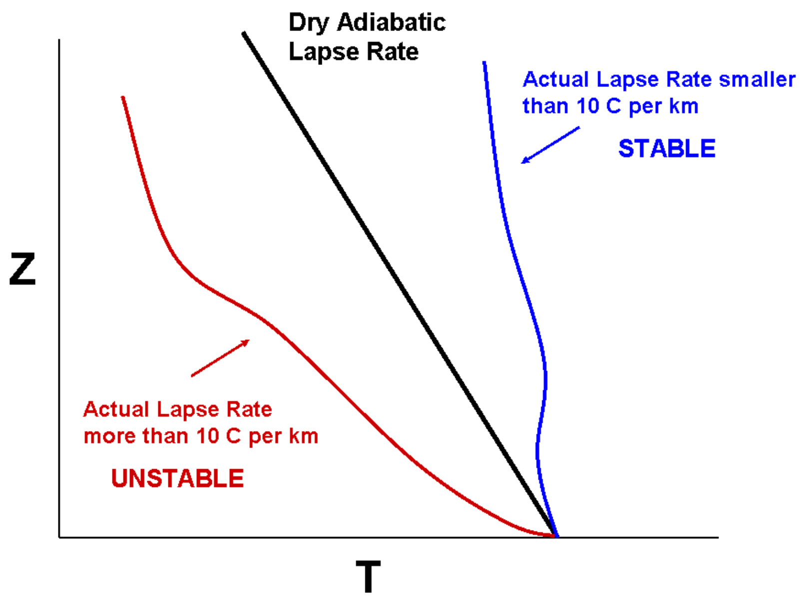
We will now briefly look at neutral boundary layers for two main reasons …

1. To introduce some basic concepts involved in studying boundary layers.
2. Because near-neutral ABLs do occur in nature.
3. Because stratified ABLs are essentially a stability modification to the neutral ABL.

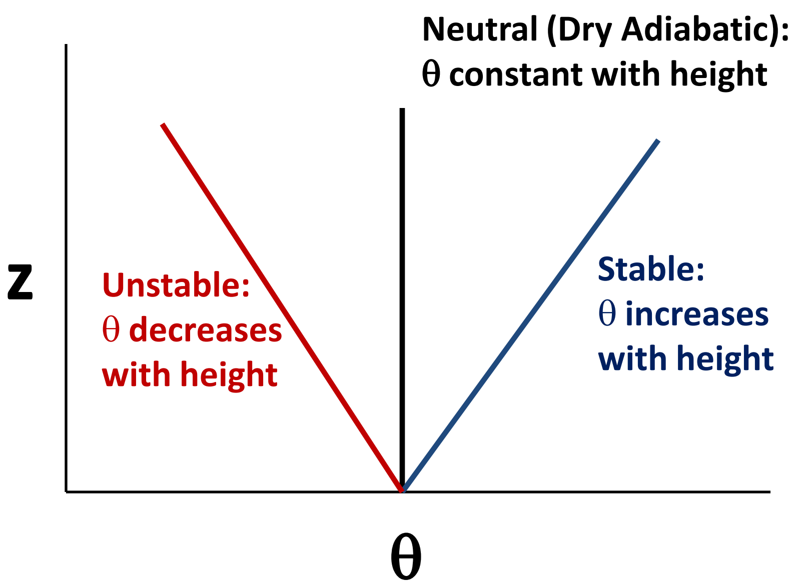
Where near-neutral ABLs are common …

- Over oceans and large water bodies, where diurnal surface heating & cooling is small
- During strong synoptic storms, during which stratification is largely mixed out
- During cloudy conditions (weaker diurnal cycle due clouds effects on radiation).
- Never <u>completely</u> neutral since such conditions are rare in nature.

Atmospheric Stability: Review



In terms of **temperature**



In terms of **potential temperature**

Typical θ & V Profile: Neutral ABL

Typical θ & V Profile: Stable ABL

(Stable Boundary Layer, SBL)

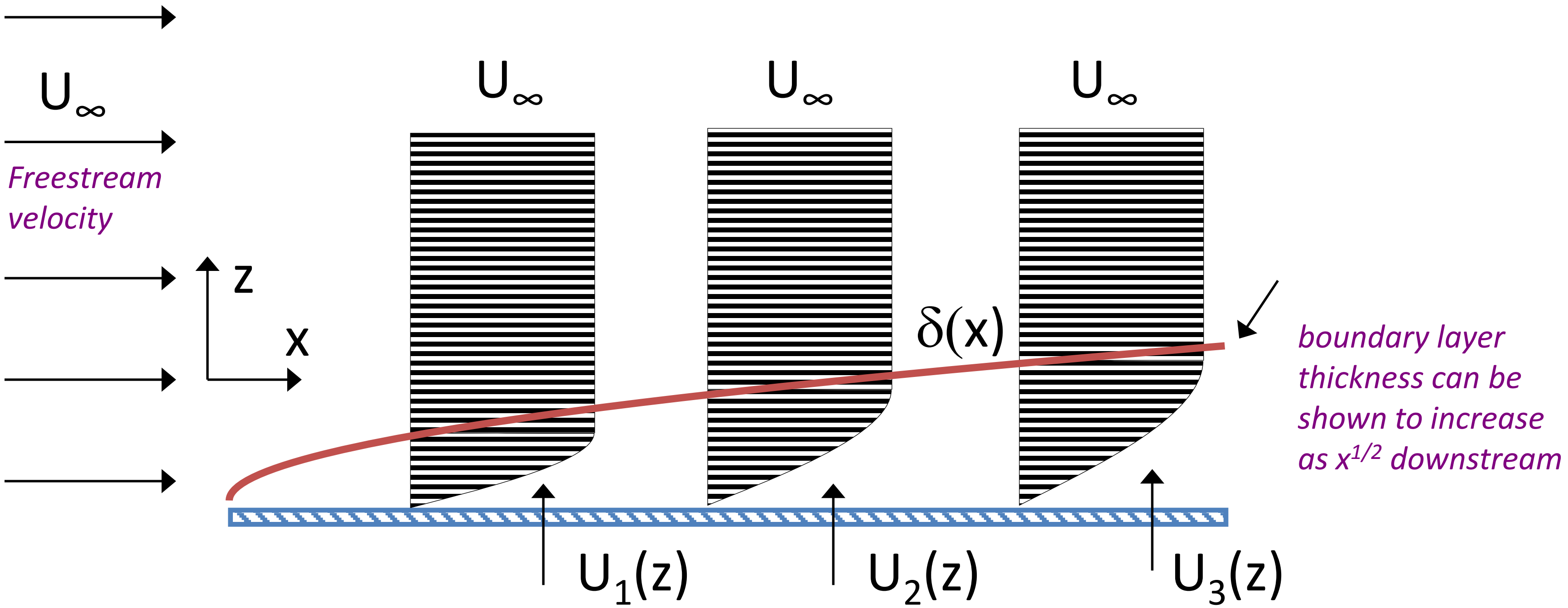
Typical θ & V Profile: Unstable ABL

(Convective Boundary or Mixed Layer, CBL or CML)

Neutral Boundary Layers …

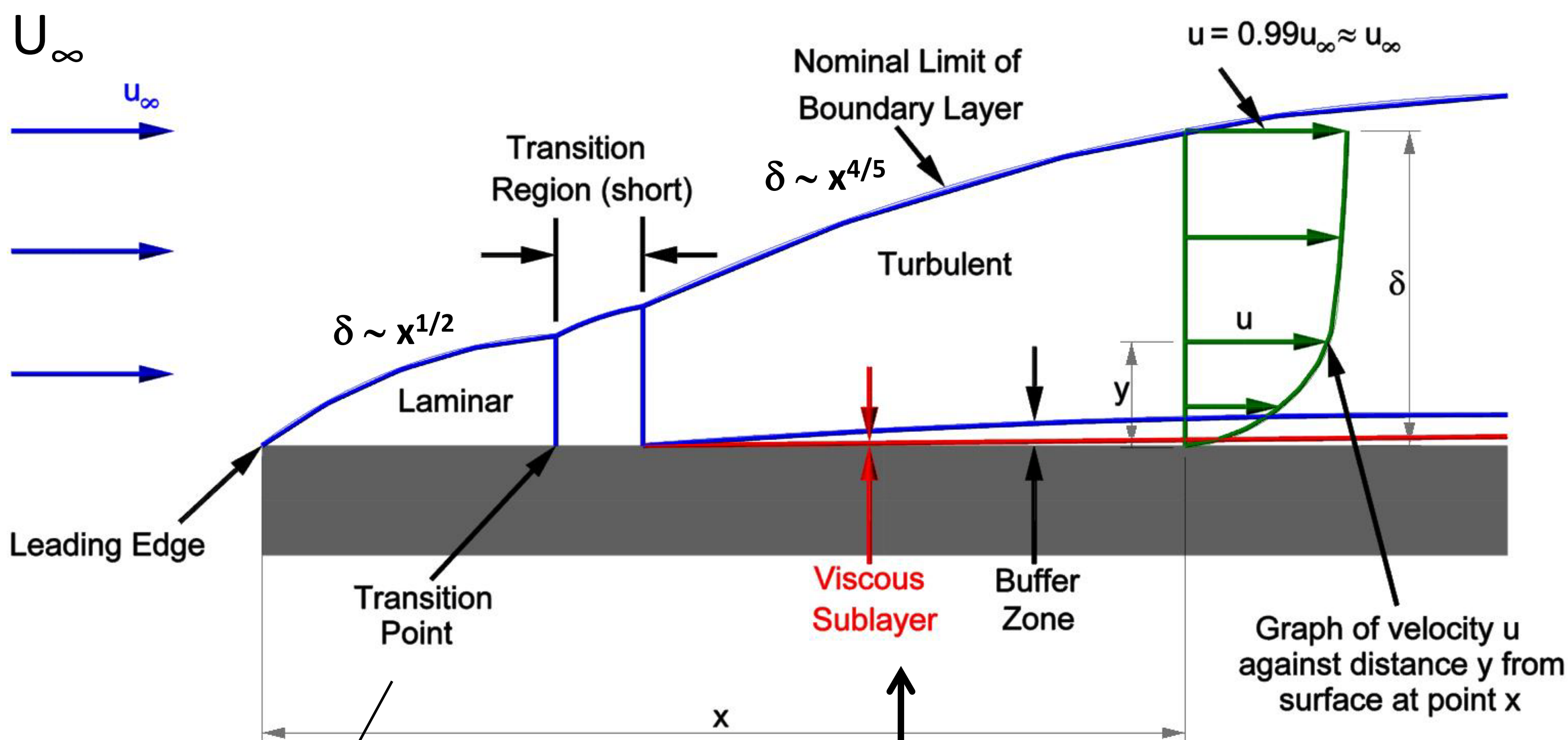
- Laminar Flat-Plate Boundary Layer (LFPBL)
- Neutral ABL (NABL)
- Key concepts introduced along the way …

Laminar Flat Plate Boundary Layer
(LFPBL, Arya 7.6 for further details)



- *Evolving flow profile at different points 1,2 and 3 downstream*
- *Non-zero shear in boundary layer due to frictional slowing of flow from surface drag and ensuing shear stress on flow.*
- *Shear zone transfers vertically deeper and deeper into fluid with downstream distance due to viscous effects (i.e. "laminar" flow)*
- *Flow is not turbulent, rather it stays organized and layered ("laminar")*
- *Rate of vertical transfer controlled by "**molecular viscosity**" (υ, dimensions L^2/T)*

Transition to Turbulence …



Still a very, very shallow laminar layer near surface …

Transition to turbulence occurs when
Reynolds Number (Re) exceeds critical value,
where $Re \equiv U_\infty \delta/\upsilon$ or $Re \equiv U_\infty x/\upsilon$ (has been defined either way in literature for this topic)

Short Video …

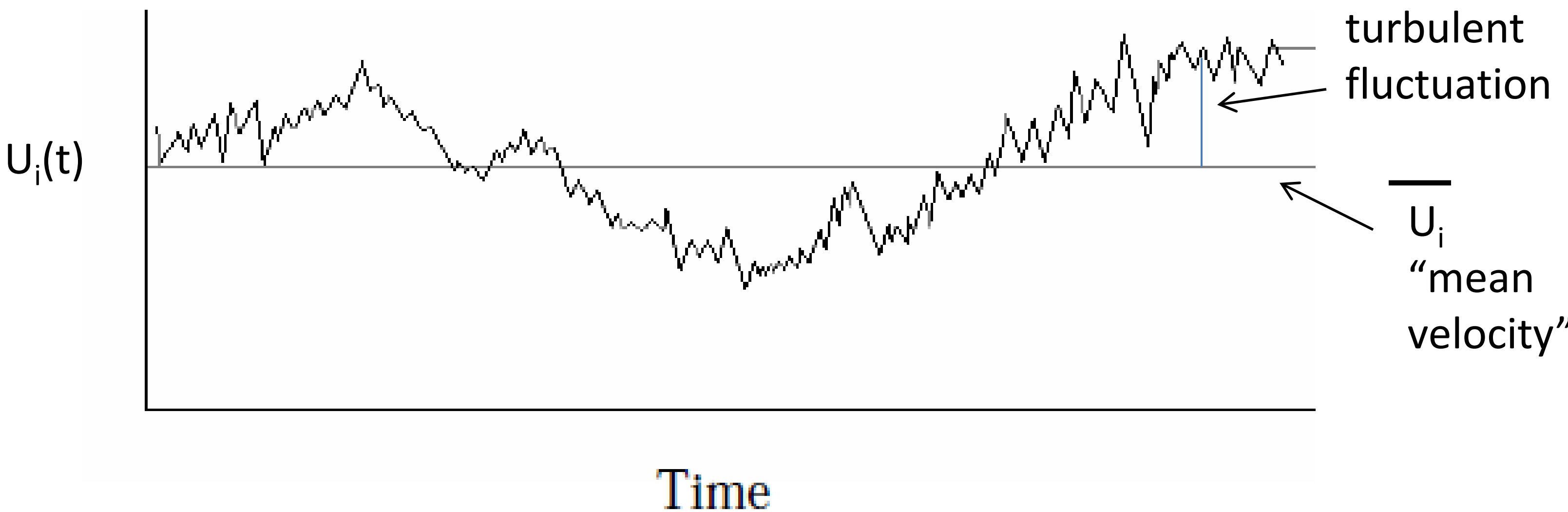
http://www.iahrmedialibrary.net/db/i1/i1_fluid%20mechanics.htm

See about halfway down page ‘**Introduction to the turbulent flows characteristics - Characteristics of the Laminar and Turbulent Flows**’

Turbulence Decomposition of Velocity

(See also 8.4 of Arya) …

$$U_i(t) \equiv \overline{U_i} + u_i(t).$$



Similar decomposition for other variables …

1) Potential Temperature
2) Specific Humidity
3) Species Concentration
4) Pressure
5) Density (although, can relate to P & T through IGL)

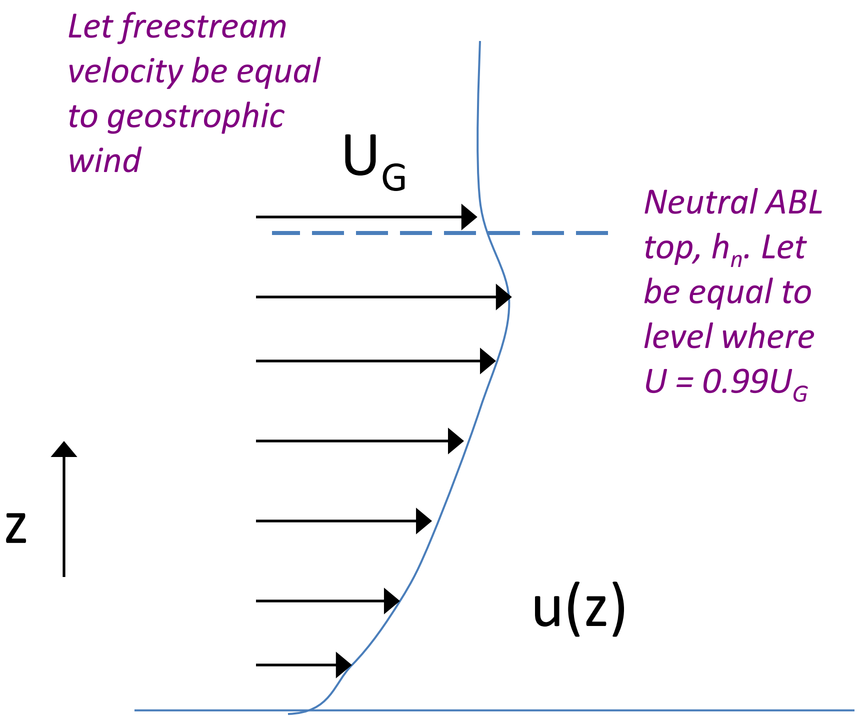
Tensor Notation & Coordinate System
(Chalkboard)

$U_i = (U_1, U_2, U_3) = (u,v,w) = \overrightarrow{V}$
$x_i = (x_1, x_2, x_3) = (x,y,z) = \overrightarrow{x}$

where we will generally take:
x: the direction of the freestream (geostrophic) flow
y: horizontally perpendicular to x
z: vertically upward

Neutral Atmospheric Boundary Layer

(One-Dimensional, Horizontally Homogeneous)

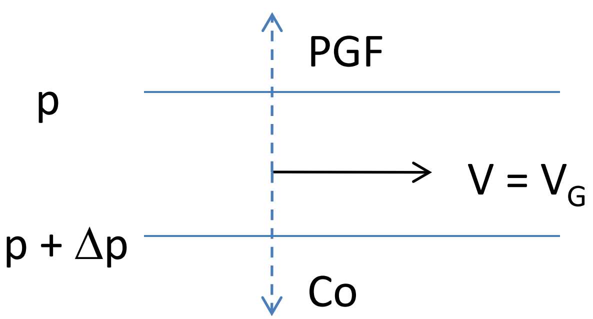


- Assume $\vec{V}_G = (U_G, 0)$
- Figure on left is for u component
- Can also have for v component (not shown)

What we already know

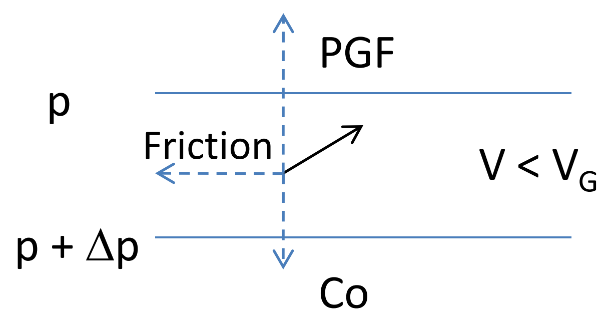
(Also see Arya, Chapter 6)

Above the boundary layer



Wind is geogrophic …
(or perhaps “gradient flow”
or something in between);
main point: no friction, wind
parallel to isobars

Near the surface



… Wind slowed due to friction.
Wind flow at angle α_0 to isobars
(“cross isobaric flow angle”)

Momentum Equations: Neutral ABL (1)

$$f(v - v_g) + \frac{d}{dz}\left(\frac{\tau_x}{\rho}\right) = 0,$$

$$-f(u - u_g) + \frac{d}{dz}\left(\frac{\tau_y}{\rho}\right) = 0.$$

Equations for **mean** velocity

Divergence of vertical **turbulent shear stress** per unit mass,
where τ_x = x-component of vertical turbulent shear stress
and τ_y = y-component of vertical turbulent shear stress.

- These are the "F" terms used in MET121 for the friction force.
- Magnitude of shear stress = $(\tau_x^2 + \tau_y^2)^{1/2} \equiv \tau$
- Surface value $\tau(z=0)/\rho = \tau_0/\rho = u_*^2$
- The implied key velocity scale u_* is called the "**friction velocity**"

Momentum Equations: Neutral ABL (2)

$$\left.\begin{aligned} f(v-v_g)+\frac{d}{dz}\left(\frac{\tau_x}{\rho}\right)&=0, \\ -f(u-u_g)+\frac{d}{dz}\left(\frac{\tau_y}{\rho}\right)&=0. \end{aligned}\right\}$$

Equations for **mean** velocity

Can be shown that neutral ABL depth for the above case can be expressed as $\mathbf{h_n = cu_*/f}$, where ‘c’ is a constant. Recent computer experiments, which can specify exactly neutral conditions, suggest $c \approx 0.6$.

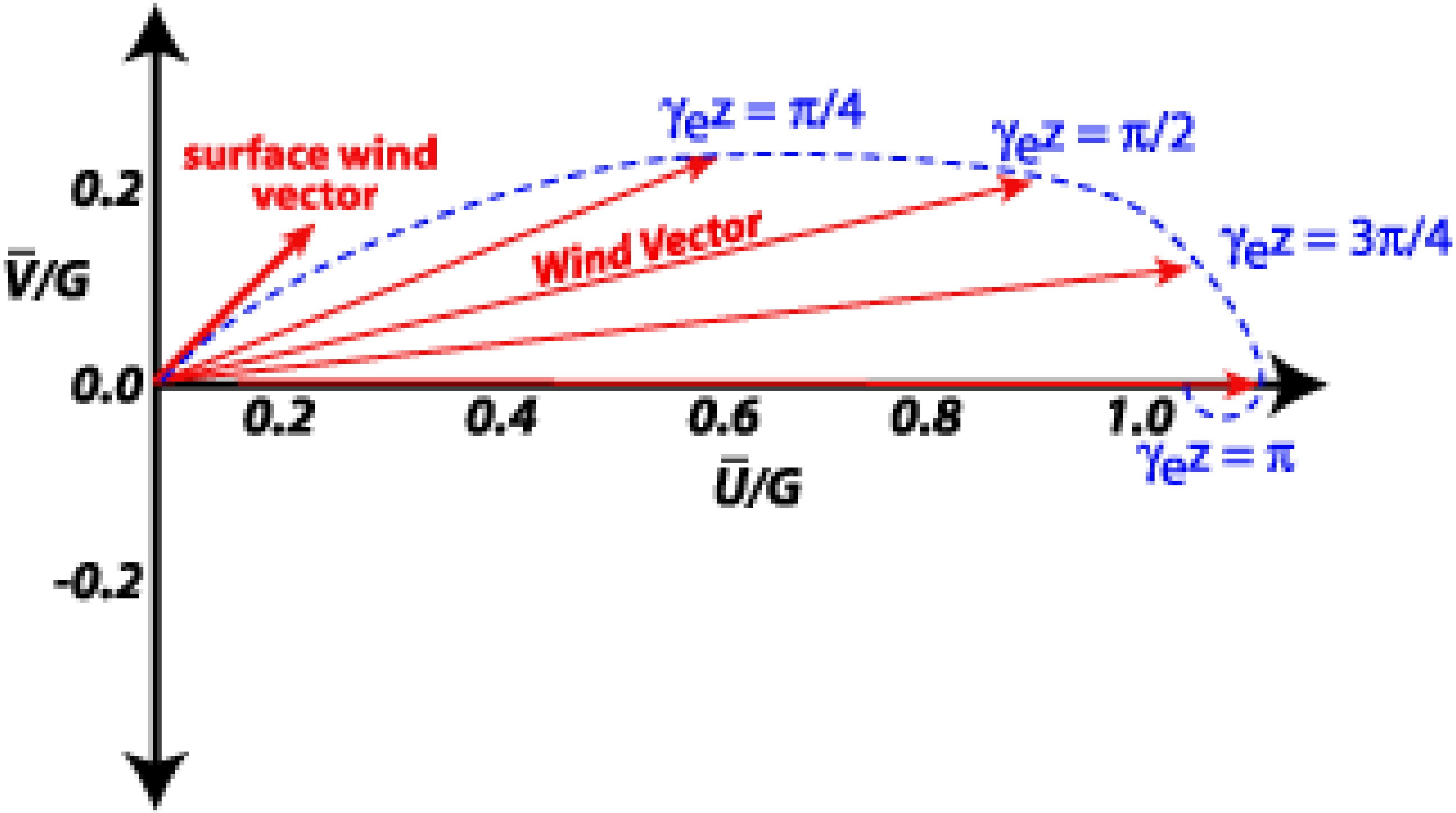
Solving these equations …

To solve the neutral ABL equations, we need some way of representing τ as f(z). We will see various ways of doing this throughout semester. However, one way is through the expression $<\tau_x, \tau_y> = -K_m \partial<u,v>/\partial z$, where K_m is the **turbulent ("eddy") viscosity**. Assuming K_m is a constant ($\neq$ f(z)) leads to the famous "**Ekman**" solution, also called the "Ekman Spiral".
In this case, the flow profile is called an **Ekman Layer**.
Ekman was the name of the famous oceanographer credited for pioneering this theoretical work.

Arya Section 7.5 presents the Ekman Layer for the laminar case (i.e. replacing K_m with υ). The Wikipedia page on "Ekman Layer" is also quite good for further reading. See also http://amsglossary.allenpress.com/glossary/search?id=ekman-spiral1.

However, the Ekman solution predicts a 45° cross-isobaric flow angle (α_0), which is larger than observed in nature for neutral boundary layers in the atmosphere and ocean. The assumption of constant K_m is therefore not good it turns out. Can we do better? Stay tuned for later in semester …

EKMAN SPIRAL



Why are capping stable layers & inversions so common above ABL?