LECTURE 28

The Planetary Boundary Layer

The planetary boundary layer (PBL) [also known as atmospheric boundary layer (ABL)] is the lower part of the atmosphere in which **the flow is strongly influenced by interactions with the earth's surface.** Above the PBL is the **free atmosphere**.

Understanding the structure and dynamics of the PBL is important in:

- Air pollution meteorology (transport and mixing of pollutants)
- Agricultural and forest meteorology (prediction of surface temperatures and frost conditions, guidance for aerial spraying and fire-fighting operations).
- Urban meteorology (heat island, air quality, electrical usage)
- Coastal meteorology (development of sea-breezes and land-breezes)
- Mountain meteorology (katabatic and anabatic flows)
- Wind energy (guidance for siting wind farms and designing turbines)
- Numerical weather prediction (parameterization of physical processes in the PBL)

We will consider the PBL in mid-latitudes under typical synoptic-scale conditions under fair weather conditions (not looking at tropical boundary layers or rainy or cloudy boundary layers).

PBL height (sometimes called depth) can vary from ~30 m under strongly statically stable conditions (strong cooling with very weak winds) to ~3 km under strong daytime surface heating or windy conditions. Typical PBL depth is ~1 km.

The existence of the PBL (region influenced by interactions with the earth's surface) is due to **molecular effects** associated with **molecular viscosity** (kinematic viscosity ν) and **molecular diffusivity** (thermal diffusivity κ). Here is what they do:

- Molecular viscosity causes air to "stick" to lower boundary: so u and v go to 0 at the ground (this is the **no-slip condition**).

- Molecular viscosity also tries to **"slow down" the flow right above the no-slip ground**. It succeeds, but only in a very thin layer called the **viscous sublayer**, which is just a few millimeters deep. So, wind goes from 0 to a few m/s over a few mm – get a huge vertical gradient of $\vec{u}$. Must keep the viscous term $\nu\nabla^2\vec{u}$ (also called friction term) in the equation of motion in the viscous sublayer.

- Molecular diffusivity communicates thermal state of the ground to the atmosphere through **molecular conduction of heat through the air**. Conduction takes place across the viscous sublayer. Get huge vertical gradient of T in the air near the surface.

- In the rest of the PBL (i.e., above the viscous sublayer) molecular diffusion converts the kinetic energy of the smallest eddies (a few mm in radius) into heat. This is called **dissipation**.

So, molecular processes give rise to the viscous sublayer, which contains large gradients of heat and momentum, and the rest of the PBL has to deal with it. **The response is the development of turbulent motion**. Get over-turning motions associated with the strong low-level shear (**mechanical generation of turbulence**), and over-turning motions associated with static instability during daytime heating (**buoyant generation of turbulence**).

Turbulence transfers momentum, heat, and moisture much more effectively than can be done by molecular viscosity/diffusivity. Molecular viscosity/diffusivity did the groundwork (literally, in the viscous sublayer) and set the stage for turbulence to step in and dominate the dynamical processes in the rest of the PBL.

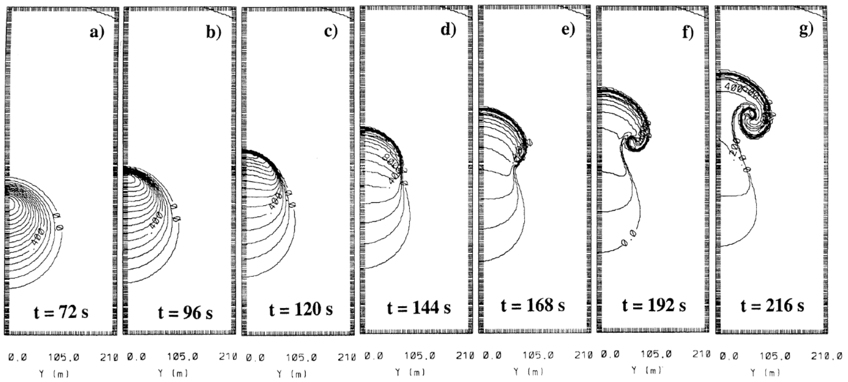
Characteristics of turbulence in the PBL:

- it's **dissipative** (kinetic energy turned into heat)

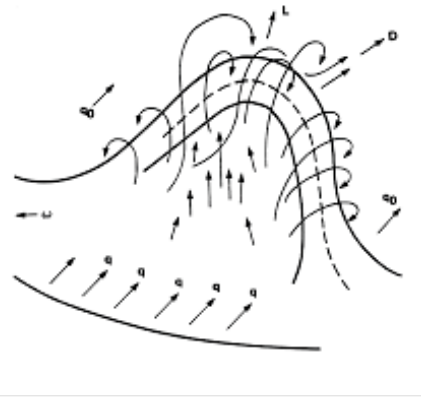
- it's **irregular** (unpredictable in detail)

- it **mixes**. Nearby air parcels move apart from each other, and thus mix properties such as momentum and heat (the final stage of mixing though is mediated by viscosity and diffusivity). Large gradients get smoothed out.

- it's **vortical**. Lots of vorticity and lots of vortices (eddies). Vorticity is generated baroclinically (edges of plumes) and by friction at the surface. Once generated, it can be transported, stretched and tilted. Eddies of a variety of sizes are evident in turbulent flows. Their horizontal and vertical length scales are similar (L ~ H). Sizes range from ~1km (PBL depth) down to a few mm (smallest allowed by viscosity).



vertical slice through a rising buoyant plume



hairpin vortex near surface

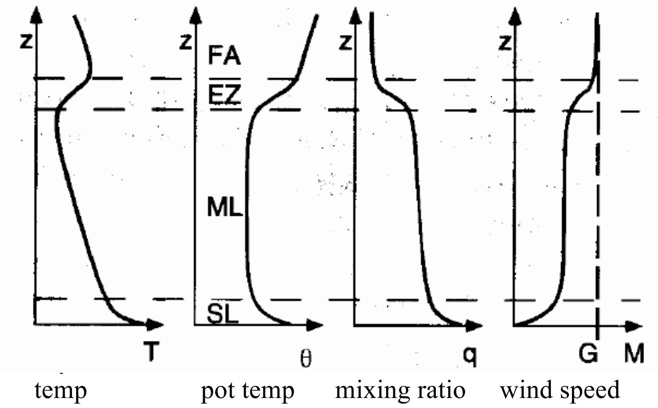
- it's **three dimensional**. No way to study it or make any sense of it without considering 3D dynamics. In particular, vorticity stretching and tilting are important processes in the turbulent PBL and these are 3D processes (they vanish in 2D flows).

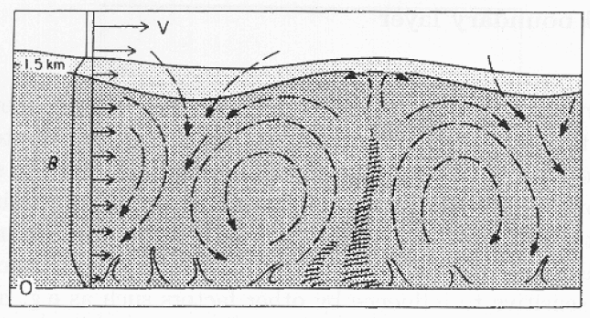
The PBL poses a dilemma for numerical weather prediction (NWP) models (especially climate models). The bulk of the momentum and heat transport between surface and free atmosphere occurs by eddies with length scales ranging from ~ 1 km to a few mm. In contrast, most NWP models run over continents or the globe have horizontal grid spacings of 10km or greater – too coarse to resolve PBL eddies. Need procedures to account for effects of PBL turbulence in numerical models. A first step is to modify (average) the dynamical equations of motion (done in next few classes).

Diurnal cycle and vertical structure of the PBL

During the day the sun heats the earth's surface. Heat is conducted from surface to air. Get hotter (lighter) air underlying cooler (heavier) air. This is an unstable top-heavy arrangement – get thermal instability. Plumes carry hot air upwards.

Schematic of PBL structure and profiles of meteorological variables during the day:





FA: **Free atmosphere**. Potential temperature increases gradually with height. Wind is largely geostrophic (G).

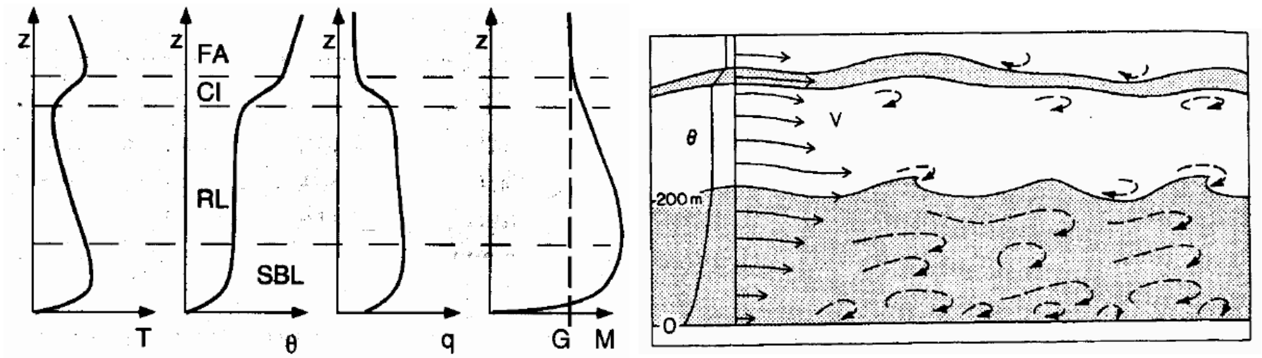
EZ: **Entrainment Zone**. It's an inversion. Large (positive) change in temperature and potential temperature moving upward across it.

ML: **Mixed Layer** [also known as the **convective boundary layer (CBL)**]. Fairly uniform potential temperature and wind profiles.

SL: **Surface Layer**. The bottom 10% of the PBL. Temperature and potential temperature decrease rapidly with height. Wind speed increases rapidly with height.

During the night there's no solar radiation but longwave radiation from surface continues (day and night). Net energy loss, therefore cooling of surface. Production of plumes ceases rapidly around sunset. Turbulent mixing becomes very weak.

Schematic of PBL structure and profiles of meteorological variables during the night:



temp pot temp mixing ratio wind speed

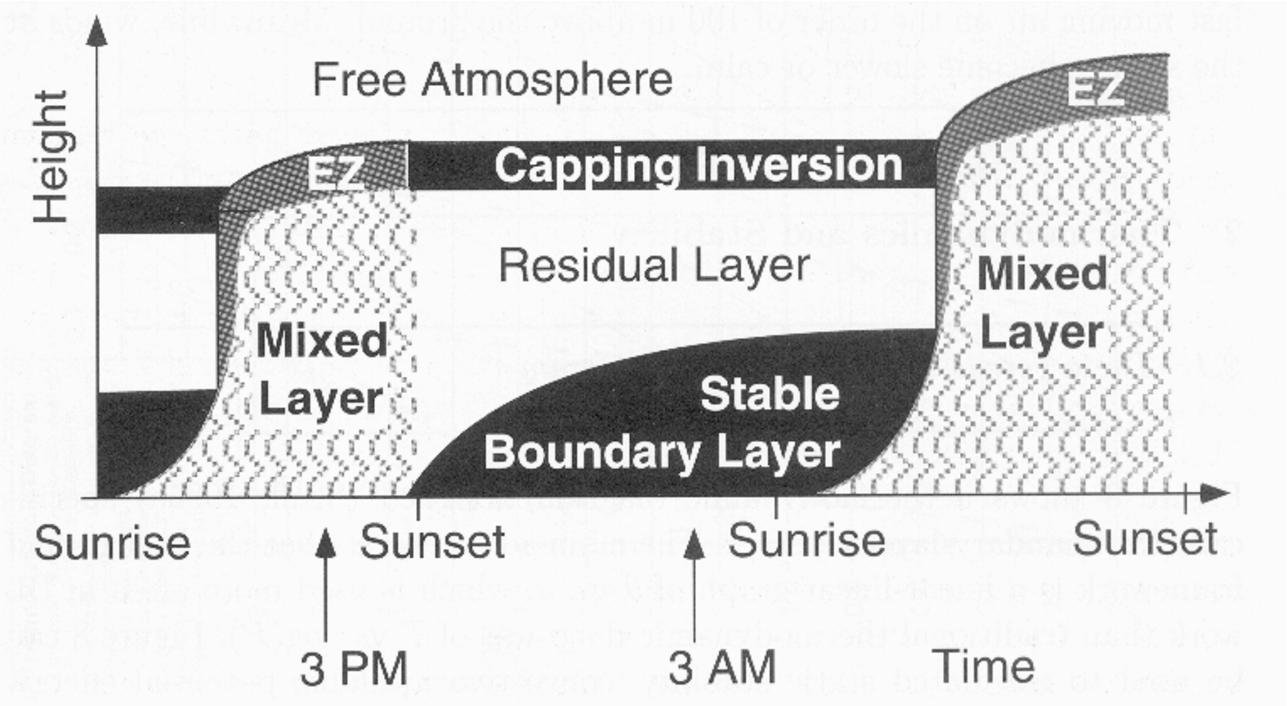
CI: **Capping Inversion.** An extension of the daytime entrainment zone. So Large (positive) change in temperature and potential temperature moving upward across it.

RL: **Residual Layer**. It's the leftovers of the ML from the day before. It's well-mixed but is no longer mixing (at least not nearly as much as during the day).

SBL: **Stable Boundary Layer** [also known as the **Nocturnal Boundary Layer (NBL)**]. It's an inversion. Sometimes called a radiation inversion (unrelated to Capping Inversion). Associated with radiative cooling of the surface (followed by cooling of the air via conduction) and also radiative cooling of the air near the surface. SBL grows from < 10 m to ~ 200 m during the night.

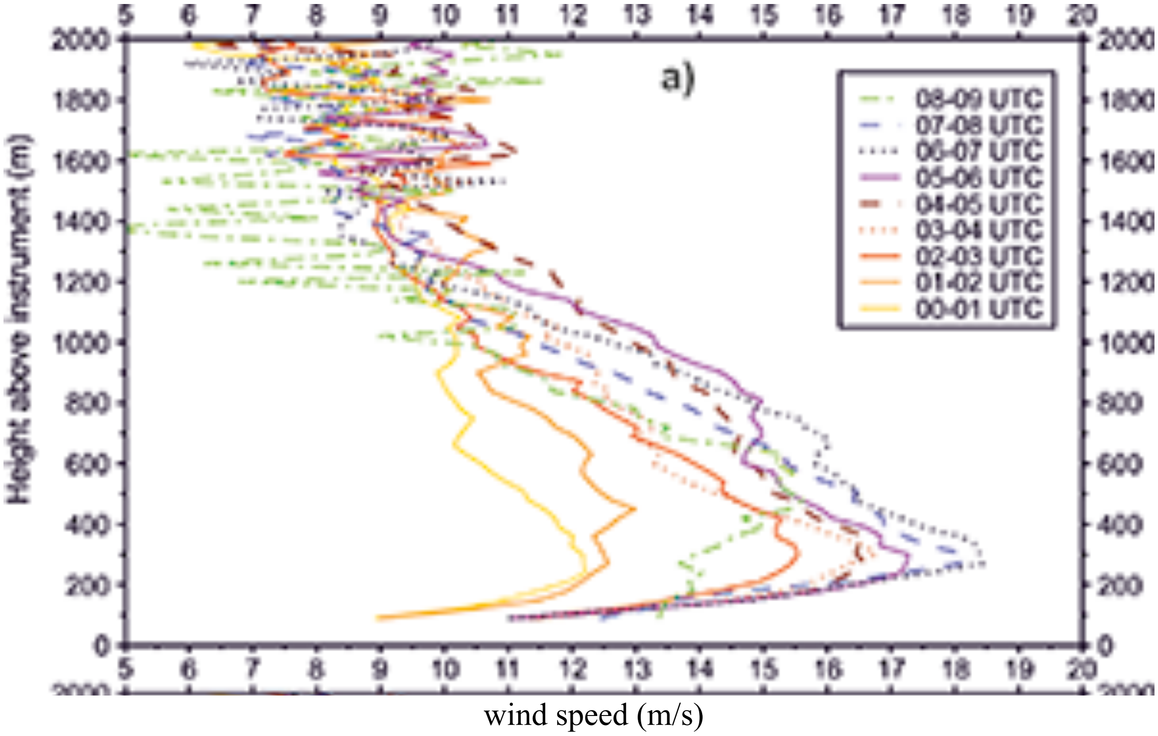
The figure on the right also depicts a **nocturnal low-level jet (LLJ)**. These frequently develop in the SBL and RL at night over the Great Plains and other locations worldwide.

Classical Stull diagram summarizing the diurnal cycle of the PBL:

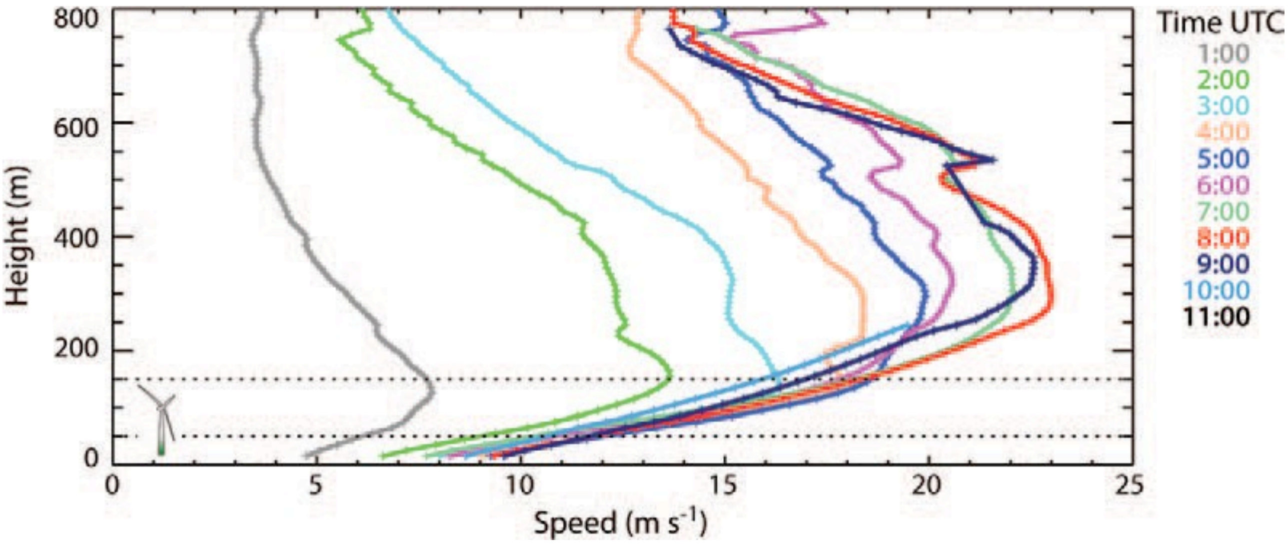


But the Stull diagram doesn't show the LLJ. Here are some figures of the LLJ. That's right, the LLJ is very cool:

A nocturnal LLJ over the Sahara:



A nocturnal LLJ over Lamar, Colorado:



A nocturnal LLJ over north-central Oklahoma: