CHAPTER ONE

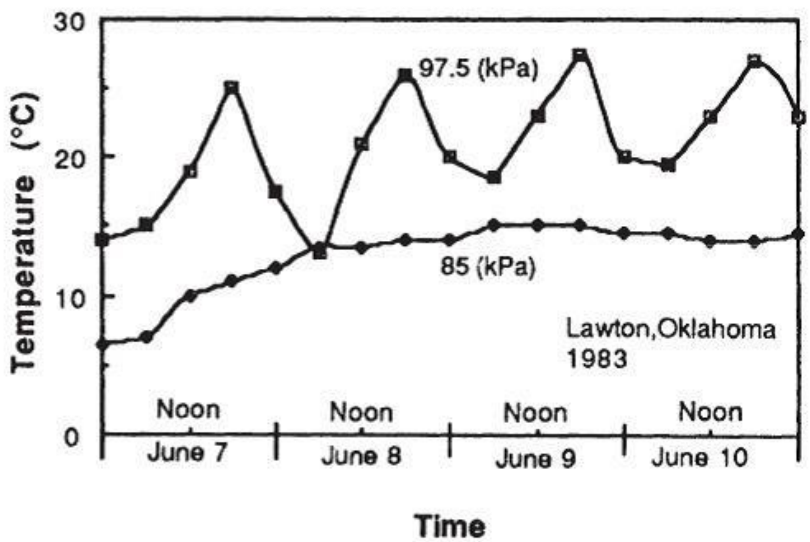
MEAN CHARACTERISTIC OF BOUNDARY LAYER

1- Boundary-Layer Definition

We can define the boundary layer as that part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcing with a timescale of about an hour or less. These forcings include frictional drag, evaporation and transpiration, heat transfer, pollutant emission, and terrain induced flow modification.

An example of temperature variations in the lower troposphere is shown in Fig 1.2. They show a *diurnal variation* of temperature near the ground that is not evident at greater altitudes.

Fig. 1
Evolution of temperatures measured near the ground (97.5 kPa) and at a height of roughly 1100 m above ground (85 kPa). Based on rawinsonde lauches from Ft. Sill, OK.

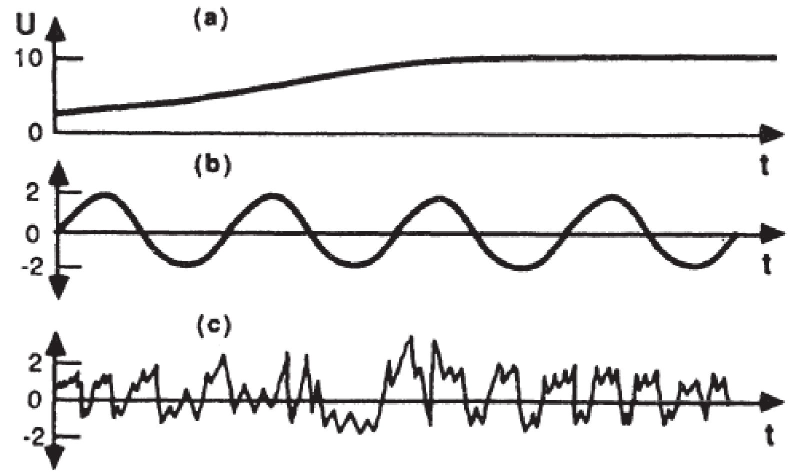


This diurnal variation is not caused by direct forcing of solar radiation on the boundary layer. Little solar radiation is absorbed in the boundary layer; most is transmitted to the ground where typical absorptivities on the order of 90% result in absorption of much of the solar energy. It is the ground that warms and cools in response to the radiation, which in turn forces changes in the boundary layer via transport processes. *Turbulence* is one of the important transport processes, and is sometimes also used to define the boundary layer.

2. Wind and Flow

Air flow, or wind can be divided into three broad categories: ***mean wind***, ***turbulence***, and ***waves*** (Fig 2). Each can exist separately, or in the presence of any of the others. Each can exist in the boundary layer, where transport of quantities such as moisture, heat, momentum. And pollutants is dominated in the horizontal by the mean wind, and in the vertical by turbulence. The relatively high frequency of occurrence of turbulence near the ground is one of the characteristics that makes the boundary layer different from the rest of the atmosphere. Outside of the boundary layer, turbulence is primarily found in convective clouds, and near the jet stream where strong wind

Fig. 2 Idealization of (a) Mean wind alone, (b) waves alone, and (c) turbulence alone. In reality waves or turbulence are often superimposed on a mean wind. U is the component of wind in the x-direction.



Shears can create clear air turbulence (CAT). Sometimes atmospheric waves may enhance the wind shears in localized regions, causing turbulence to form. Thus, wave phenomena can be associated with the turbulent transport of heat and pollutants, although waves without turbulence would not be as effective.

3. Turbulent Transport

Turbulence, the gustiness superimposed on the mean wind, can be visualized as consisting of irregular swirls of motion called *eddies.* Usually turbulence consists of many different size eddies superimposed on each other. The relative strengths of these different scale eddies define the ***turbulence spectrum***. Much of the boundary layer turbulence is generated by forcing from the ground. For example, *solar heating* of the ground during sunny days causes *thermals* of warmer air to rise. These thermals are just large eddies.

Frictional drag on the air flowing over the ground causes ***wind shears*** to develop, which frequently become turbulent. ***Obstacles*** like trees and buildings deflect the flow, causing ***turbulent wakes*** adjacent to, and downwind of the obstacle. Smaller size eddies are apparent in the swirls of leaves and in the wavy motions of the grass. These eddies feed on the larger ones. The smallest eddies, on the order of a few millimeters in size, are very weak because of the dissipating effects of molecular viscosity.

4. Boundary Layer Depth and Structure

Over oceans, the boundary layer depth varies relatively slowly in space and time. The sea surface temperature changes little over a diurnal cycle because of the tremendous mixing within the top of the ocean. Also, water has a large heat capacity, meaning that it can absorb large amounts of heat from the sun with relatively little temperature change. Thus, a slowly varying sea surface temperature means a slowly varying forcing into the bottom of the boundary layer. Over both land

and oceans, the general nature of the boundary layer is to be thinner in high-pressure regions than in low-pressure regions (Fig 3). The subsidence and low level horizontal divergence associated with synoptic high pressure moves boundary layer air out of the high towards lower pressure regions. The shallower depths are often associated with cloud-free regions. If clouds are present, they are often cumulus or stratocumulus clouds.

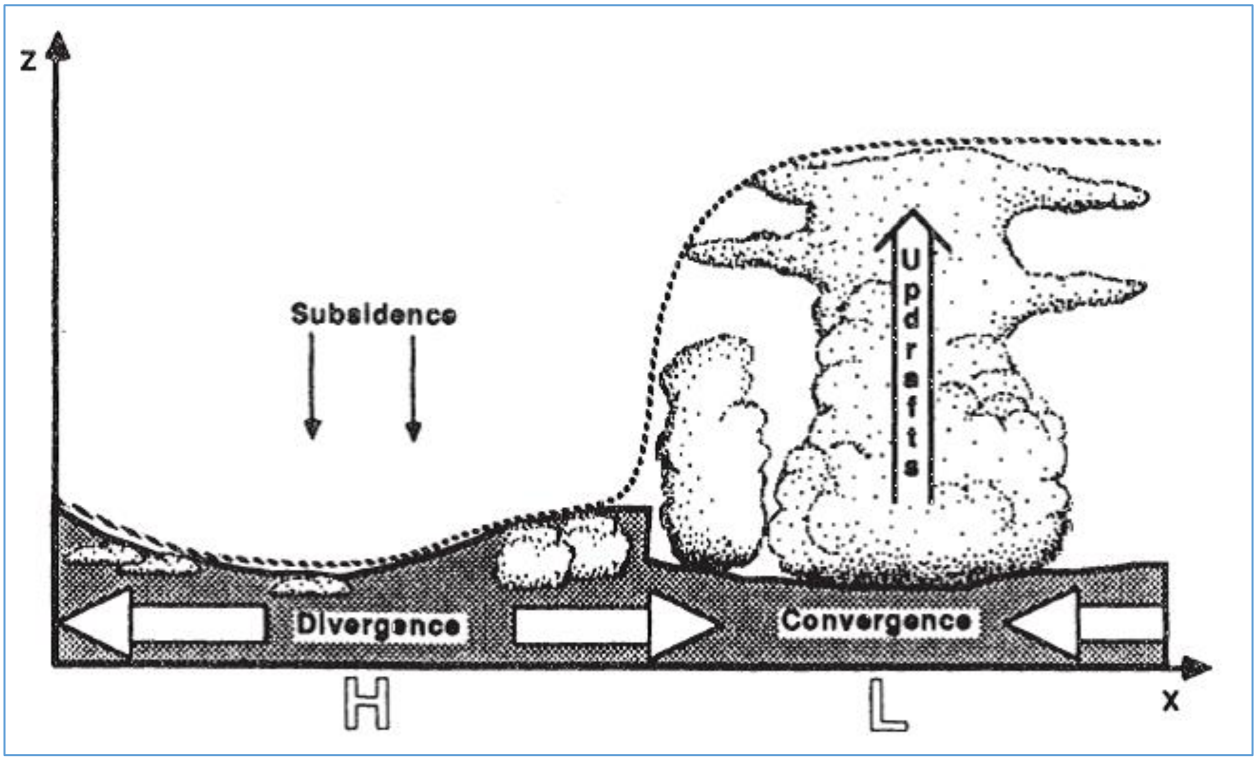


Figure (3): Schematic of synoptic - scale variation of boundary layer depth between centers of surface high (H) and low (L) pressure. The dotted line shows the maximum height reached by surface modified air during a one-hour period. The solid line encloses the shaded region, which is most studied by Boudary-Iayer Meteonogists.

Over land surfaces in high pressure regions the boundary layer has a well-defined structure that evolves with the diurnal cycle (Fig 4). The three major components of this structure are the *mixed layer,* the *residual layer,* and the *stable boundary layer.* When clouds are present in the mixed layer, it is further subdivided into a *cloud layer* 'and a sub cloud layer.

The *surface layer* is the region at the bottom of the boundary layer where turbulent fluxes and stress vary by less than 10% of their magnitude. Thus, the bottom 10% of the boundary layer is called the surface layer, regardless of whether it is part of a mixed layer or stable boundary layer. Finally, a thin layer called a microlayer or interfacial layer has been identified in the lowest few centimeters of air, where molecular transport dominates over turbulent transport.

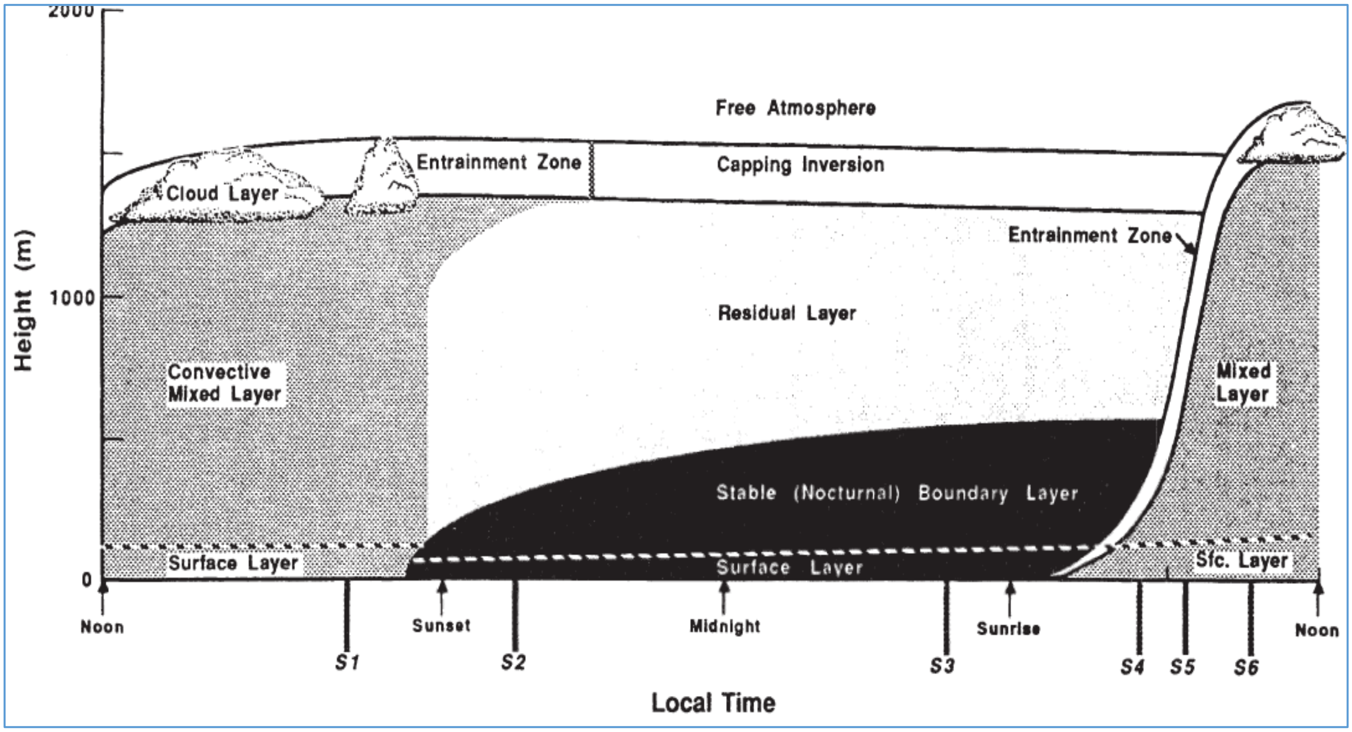


Fig.4: The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a sub cloud layer.

5. Mixed Layer (ML)

The turbulence in the mixed layer is usually *convectively driven,* although a nearly well-mixed layer can form in regions of strong winds. Convective sources include heat transfer from a warm ground surface, and radiative cooling from the top of the cloud layer. Even when convection is the dominant mechanism, there is usually *wind shear* across the top of the ML that contributes to the turbulence generation. This free-shear situation is more akin to CAT, and is thought to be associated with the formation and breakdown of waves in the air known as *Kelvin-Helmholtz* waves. ML growth is tied to solar heating of the ground. Starting about a half hour after sunrise, a turbulent ML begins to grow in depth. This ML is characterized by intense mixing in a statically unstable situation where thermals of warm air rise from the ground (Fig 1.7). The ML reaches its maximum depth in late afternoon. It grows by *entraining,* or mixing down into it, the less turbulent air from above.

The resulting turbulence tends to mix heat, moisture, and momentum uniformly in the vertical. *Virtual potential temperature* profiles are nearly *adiabatic* in the middle portion of the ML. In the surface layer one often finds a *superadiabatic* layer adjacent to the ground. A stable layer at the top of the ML acts as a lid to the rising thermals, thus limiting the domain of turbulence. It is called the ***entrainment zone*** because entrainment into the ML occurs there. At times this capping stable layer is strong enough to be classified as a temperature inversion; that is, the absolute temperature increases with height. In fact, it is frequently called an *inversion layer* regardless of the magnitude of the stability. The most common symbol for ML depth is z_i' which represents the average height of the inversion base.

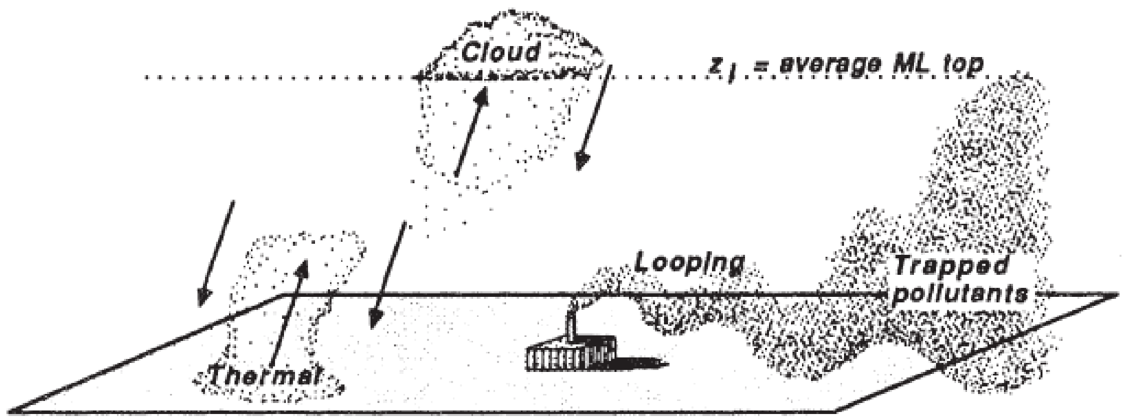


Fig. 5 : Idealization of thermals in a mixed layer. Smoke plumes loop up and down in the mixed layer eventually becoming uniformly distributed.

Wind speeds are *subgeostrophic* throughout the ML, with wind directions *crossing the isobars* at a small angle towards low pressure. The middle portion of the ML frequently has nearly constant wind speed and direction. Wind speeds decrease towards zero near the ground. Resulting in a wind speed profile that is nearly *logarithmic* with height in the surface layer. Wind directions cross the isobars at Increasingly large angles as the ground is approached, with 45 degree angles not uncommon near the surface. Mixing ratios tend to decrease with height, even within the center portion of the ML. This reflects the evaporation of soil and plant moisture from below, and the entrainment of drier air from above.

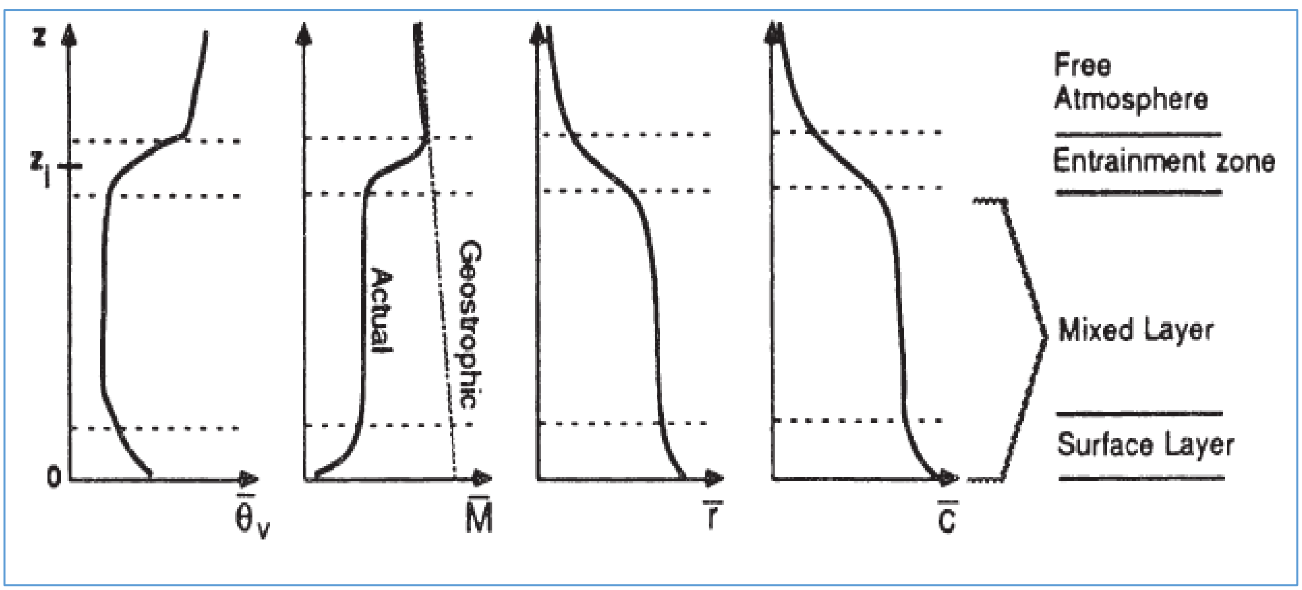


Fig. 6: Typical daytime profiles of mean virtual potential temperature θ_v , wind speed M (where $\overline{M^2} = \overline{U^2} + \overline{V^2}$). water vapor mixing ratio $\bar{r}$, and pollutant concentration C.

The moisture decrease across the top of the ML is very pronounced, and is often used together with potential temperature profiles to identify the ML top from rawinsonde soundings.
Most pollutant sources are near the earth's surface. Thus, pollutant concentrations can build up in the ML while FA concentrations remain relatively low. Pollutants are transported by eddies such as thermals; therefore, the inability of thermals to penetrate very far into the stable layer means that the stable layer acts as a lid to the pollutants too.

6. Residual Layer

About a half hour before sunset the thermals cease to form (in the absence of cold air advection), allowing turbulence to decay in the formerly well-mixed layer. The resulting layer of air is sometimes called the residual layer because its initial mean state variables and concentration variables are the same as those of the recently-decayed mixed layer. For example, in the absence of advection, passive tracers dispersed into the daytime, mixed layer will remain aloft in the RL during the night. The RL is neutrally stratified, resulting in turbulence that is nearly of equal intensity in all directions. As a result, smoke plumes emitted into the RL tend to disperse at equal rates in the vertical and lateral directions, creating a cone-shaped plume. Figure 7 shows a sketch of ***coning***.

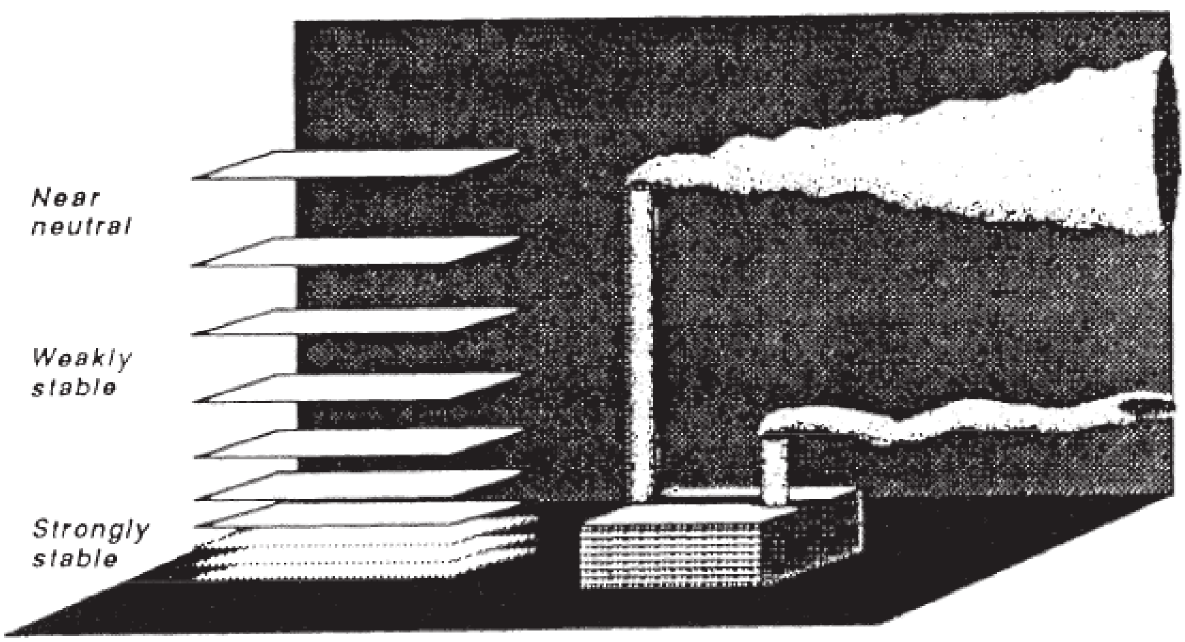


Figure 7 : The static stability decreases with height in the nocturnal boundary layer. Gradually blending into the neutrally-stratified residual layer aloft, as indicated by the isentropic surfaces sketched on the left. Smoke emissions into the stable air fan out in the horizontal with little vertical dispersion other than wavelike OScillations. Smoke emissions in the neutral residual-layer air spread with an almost equal rate in the vertical and horizontal, allowing the smoke plume to assume a cone-like shape.

Nonpassive pollutants may react with other constituents during the night to create compounds that were not originally emitted from the ground. Sometimes gaseous chemicals may react to form aerosols or particulates which can precipitate out. The RL often exists for a while in the mornings before being entrained into the new ML. During this time solar radiation may trigger photochemical reactions among the constituents in the RL. Moisture often behaves as a passive tracer. Each day, more moisture may be evaporated into the ML and will be retained in the RL. During succeeding days, the re-entrainment of the moist air into the ML might allow cloud formation to occur where it otherwise might not.

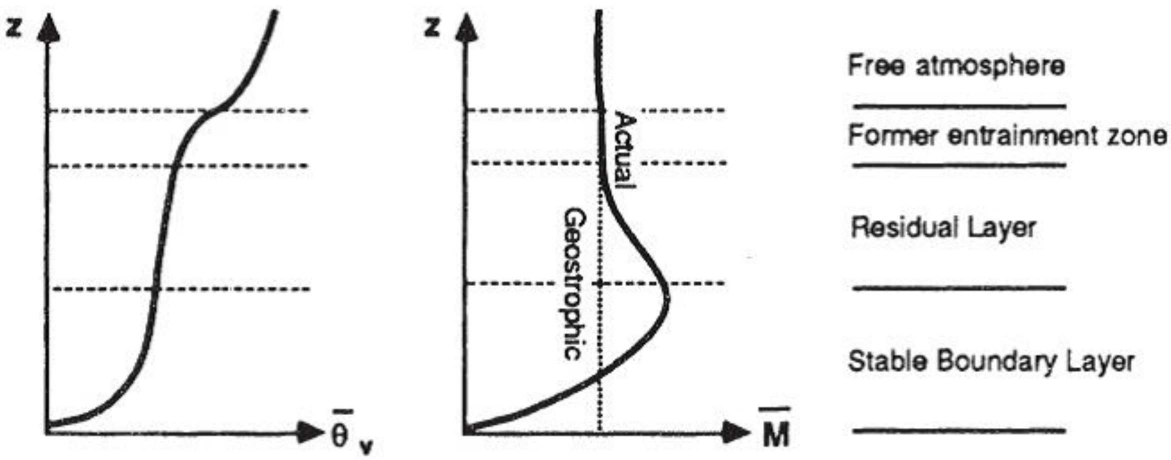


Fig. 8 Mean virtual potential temperature, $\overline{\theta}_v$, and wind speed, $\overline{M}$, profiles for an idealized stable boundary layer in a high-pressure region.

7. Stable Boundary Layer:

As the night progresses, the bottom portion of the residual layer is transformed by its contact with the ground into a stable boundary layer. This is characterized by statically stable air with weaker, sporadic turbulence. Although the wind at ground level frequently becomes lighter or calm at night, the winds aloft may accelerate to ***supergeostrophic*** *speeds* in a phenomenon that is called the ***low-level jet*** or ***nocturnal jet***. The statically stable air tends to suppress turbulence, while the developing nocturnal jet enhances wind shears that tend to generate turbulence. As a result, turbulence sometimes occurs in relatively short bursts that can cause mixing throughout the **SBL**. During the non-turbulent periods, the flow becomes essentially decoupled from the surface. As opposed to the daytime ML which has a clearly defined top, the SBL has a poorly defined top that smoothly blends into the RL above (Fig 1.10 and 1.11). The top of the ML is defined as the base of the stable layer, while the SBL top is defined as the top of the stable layer or the height where turbulence intensity is a small fraction of its surface value. Pollutants emitted into the stable layer disperse relatively little in the vertical. They disperse more rapidly, or "fan out", in the horizontal. This behavior is *called/fanning,* and is sketched as the bottom smoke plume in Fig 7. Sometimes at night when winds are lighter, the effluent *meanders* left and right as it drifts downwind. Wave motions are a frequent occurrence in the SBL. The strongly stable NBL not only supports gravity waves, but it can trap many of the higher-frequency waves near the ground. Vertical wave displacements of 100 m have been observed, although the associated wind and temperature oscillations are relatively small and difficult to observe without sensitive instruments. SBLs can also form during the day, as long as the underlying surface is colder than the air.