Chapter 2. Planetary Boundary Layer and PBL-related Phenomena

In the chapter we will first have a qualitative overview of the PBL. We will then discuss several applications of the boundary layer concepts, including the development of mixed layer as a pre-conditioner of server convection, low-level jet and dryline phenomena. The emphasis is on the applications.

Main references:
Stull, R. B., 1988: *An Introduction to Boundary Layer Meteorology*. Kluwer Academic, 666 pp.

2.1. Planetary boundary layer and its structure

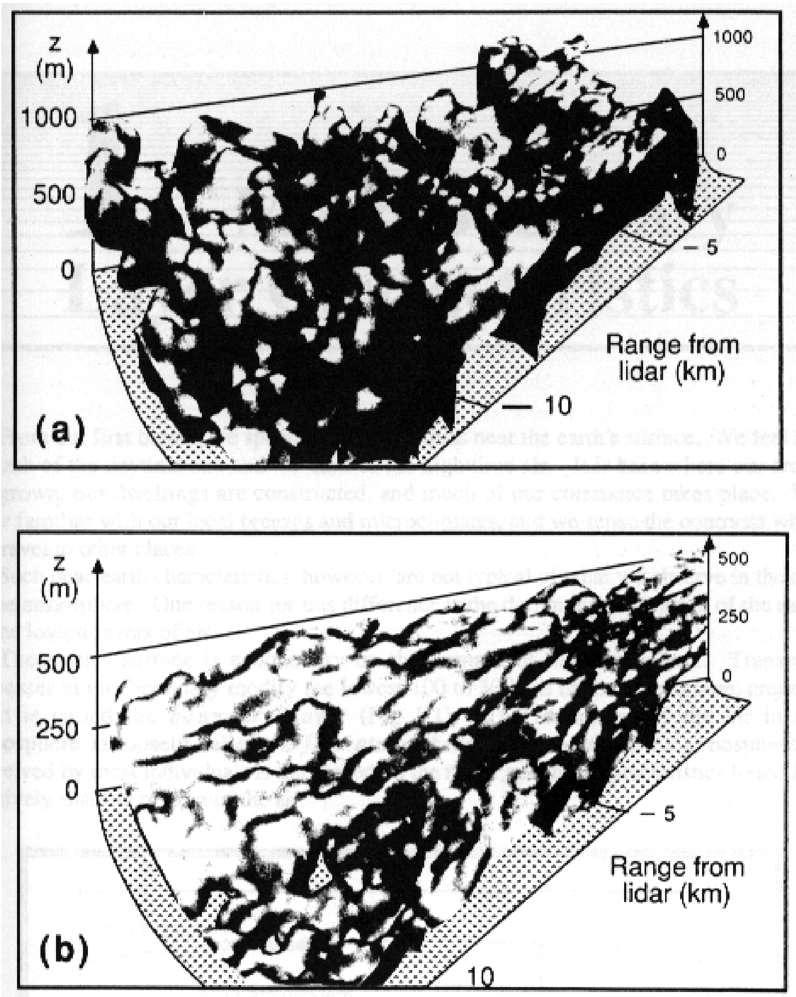
The **planetary boundary layer (PBL)** is defined as the part of the atmosphere that is <u>strongly influenced directly</u> by the presence of the <u>surface of the earth</u>, and responds to surface forcings with a <u>timescale of about an hour or less</u>.

PBL is special because:

- we live in it
- it is where and how most of the solar heating gets into the atmosphere
- it is complicated due to the processes of the ground (boundary)
- boundary layer is very turbulent
- others …

In this section, we discuss some aspects of the planetary boundary layer that are important for the understanding of boundary layer related phenomena such as dryline and nocturnal low-level jet.

Day time boundary layer is usually very turbulent, due to ground-level heating, as illustrated by the following figure.



Lidar images of the aerosol-laden boundary layer, obtained during the FIFE field experiment in Kansas. (a) Convective mixed layer observed at 1030 local time on 1 July 1987, when winds were generally less than 2 m/s. (b) Slightly-stable boundary layer with shear-generated turbulence, observed at 530 local time on 7 July 1987. Winds ranged from 5 m/s near the surface to 15 m/s near the top of the boundary layer. Photographs from the Univ. of Wisconsin lidar are courtesy of E. Eloranta, Boundary Layer Research Team.

The layer above the PBL is referred to as the <u>free atmosphere.</u>

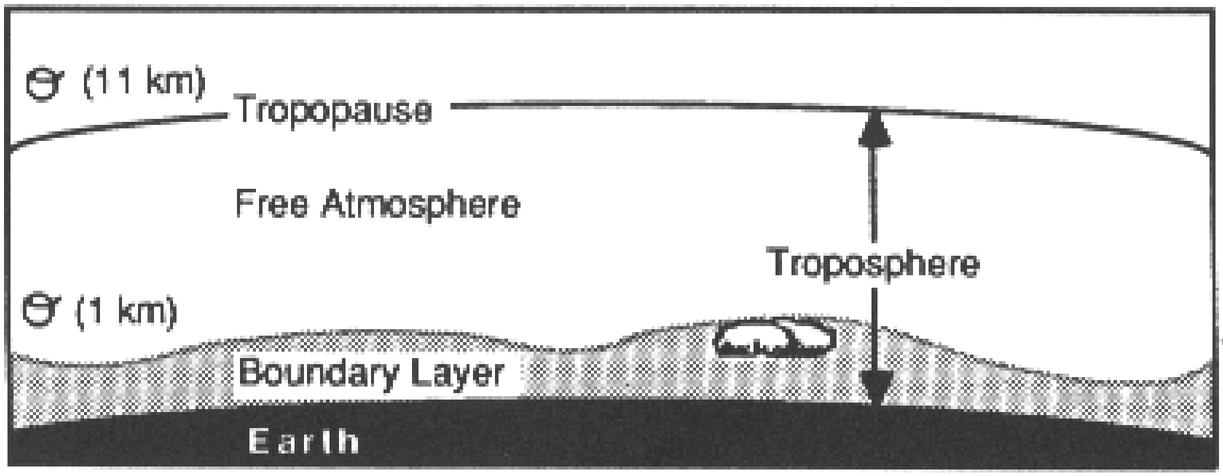


Fig. 1.1 The troposphere can be divided into two parts: a boundary layer (shaded) near the surface and the free atmosphere above it.

- **<u>Comparison of boundary layer and the free atmosphere characteristics</u>**

Table 1-1. Comparison of boundary layer and free atmosphere characteristics.

Property	Boundary Layer	Free Atmosphere
Turbulence	• Almost continuously turbulent over its whole depth.	• Turbulence in convective clouds, and sporadic CAT in thin layers of large horizontal extent.
Friction	• Strong drag against the earth's surface. Large energy dissipation.	• Small viscous dissipation.
Dispersion	• Rapid turbulent mixing in the vertical and horizontal.	• Small molecular diffusion. Often rapid horizontal transport by mean wind.
Winds	• Near logarithmic wind speed profile in the surface layer. Subgeostrophic, cross-isobaric flow common.	• Winds nearly geostrophic.
Vertical Transport	• Turbulence dominates.	• Mean wind and cumulus-scale dominate
Thickness	• Varies between 100 m to 3 km in time and space. Diurnal oscillations over land.	• Less variable. 8-18 km. Slow time variations.

Diurnal evolution of the BL

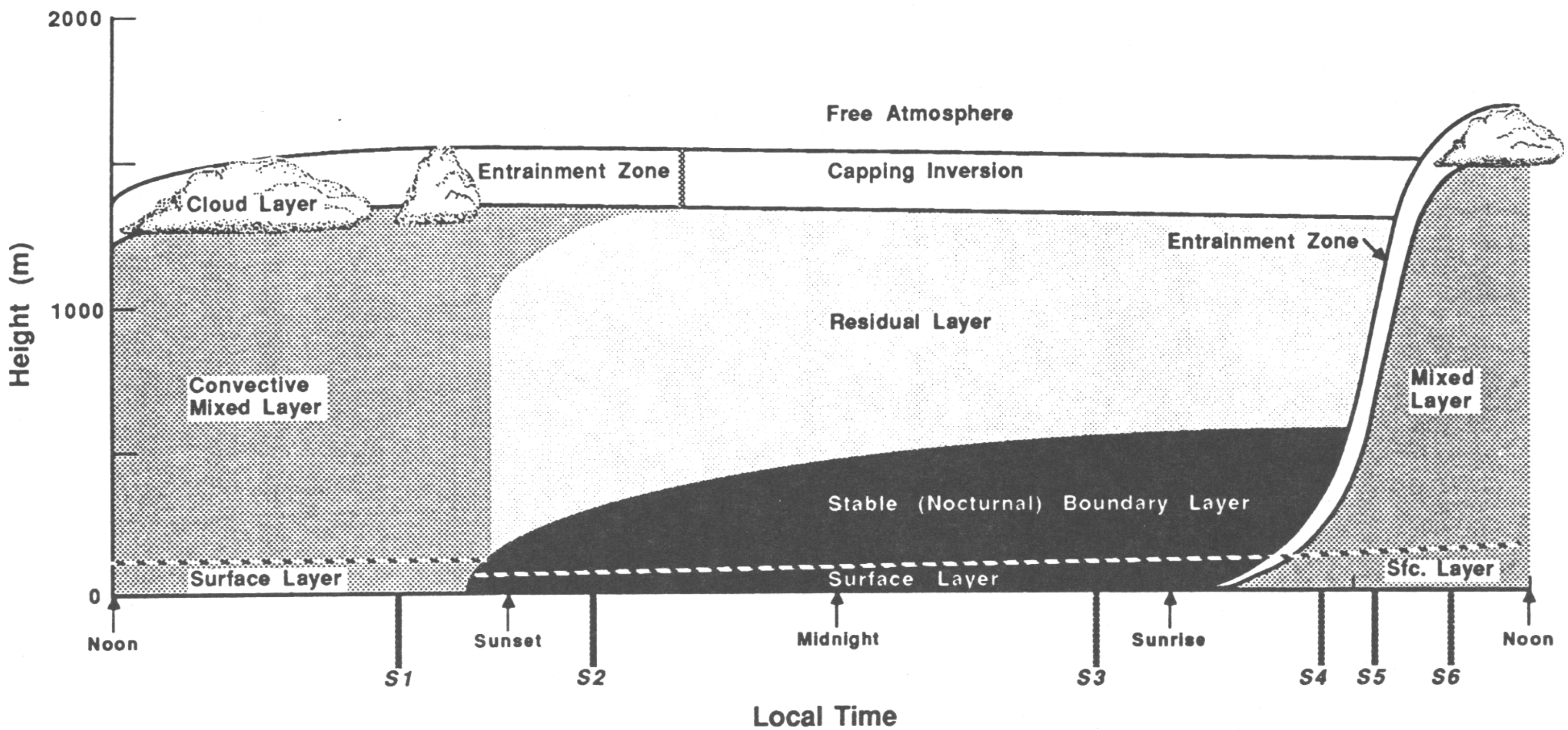


Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer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

- The above figure shows the typical **diurnal evolution of the BL** in high-pressure regions (i.e., without the development of deep cumulus convection and much effect of vertical lifting).

- At and shortly after sunrise, surface heating causes turbulent eddies to develop, producing a **mixed layer** whose depth grows to a maximum depth in late morning. In this mixed layer, potential temperature and water vapor mixing ratio are nearly uniform.

- At the sunset, the deep surface cooling creates a **stable (nocturnal) boundary layer,** above which is a **residual layer**, basically the leftover part of the daytime mixed layer

- At all time, near the surface is a thin **surface layer** in which the vertical fluxes are nearly constant. It is also called **constant-flux layer**.

Mixed layer development

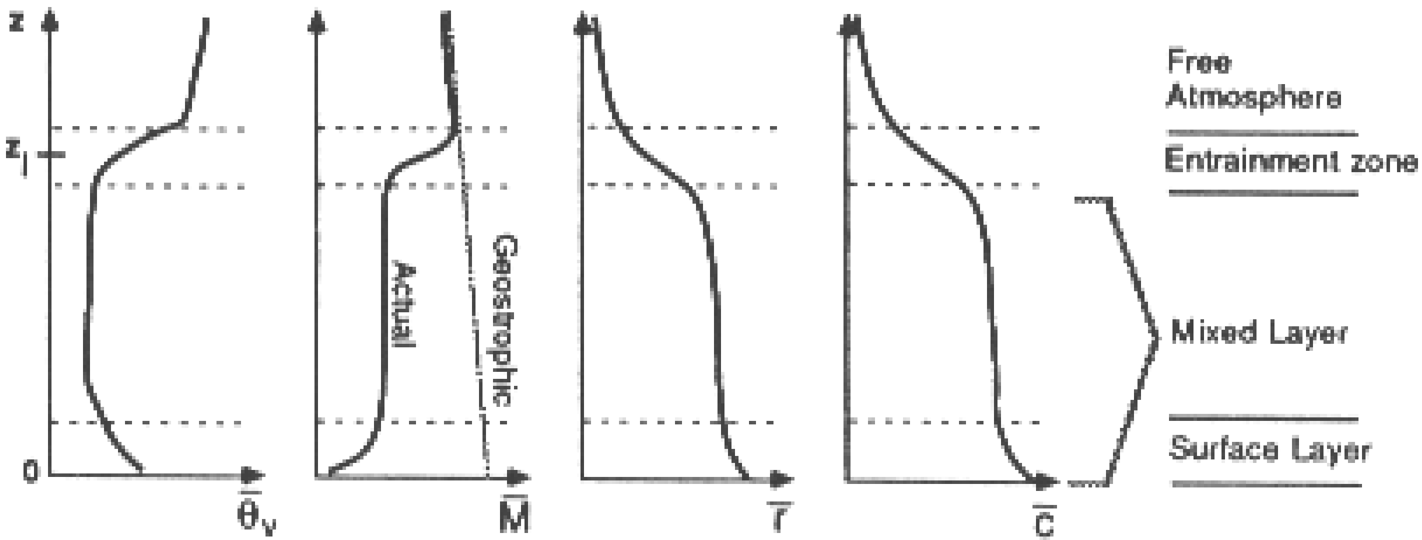


Fig. 1.9 Typical daytime profiles of mean virtual potential temperature $\overline{\theta}_v$, wind speed $\overline{M}$ (where $\overline{M}^2=\overline{u}^2+\overline{v}^2$), water vapor mixing ratio $\overline{r}$, and pollutant concentration $\overline{c}$.

- Turbulence in the mixed layer is usually **convectively driven**, i.e., driven by buoyancy due to instability. Strong wind shear can also generate turbulence, however.

- The virtual potential temperature (it determines the buoyancy) is nearly **adiabatic** (i.e., constant with height) in the middle portion of the mixed layer (ML), and is **super-adiabatic** in the surface layer. At the top of the ML there is usually a stable layer to stop the turbulent eddies from rising further. When the layer is very stable so that the temperature increases with height, it is usually called **capping inversion**. This capping inversion can keep deep convection from developing.

- When the surface heating is sufficient so that the potential temperature of the entire ML is raised above the maximum potential temperature of the capping inversion, convection breaks out (assuming there is sufficient moisture in the BL). This usually occurs in the later afternoon. The best time for tornado chasing.

- The boundary layer wind is usually **sub-geostrophic**, due to surface drag and vertical mixing of momentum.

- The water vapor mixing ratio is nearly constant in the ML.

With a typical diurnal cycle, the PBL (well-mixed layer in particular) grows by a **4-phase process**:

1) Formation of a shallow M.L. (burning off of the nocturnal inversion), ~ 10's to 100's meter deep

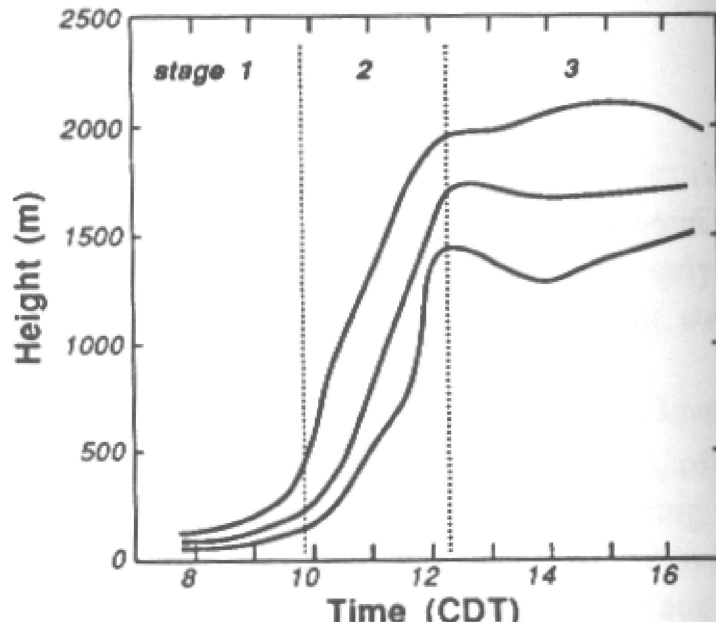
2) Rapid ML growth, surface thermals rises easily to the top of residual layer

3) Deep ML of nearly constant thickness. Growth slows down with the presence of capping inversion.

4) Decay of turbulence at sunset as the layer becomes convectively stable.

The following figure shows an example of the first three phases as measured by a ground-based lidar.

Fig. 11.10
Evolution of the entrainment zone measured by lidar at the BLX83 field site for 15 June 1983. The top and bottom lines represent the top and bottom of the entrainment zone, respectively, while the middle line is the average, mixed layer depth, $\overline{z_i}$. (After Wilde, et al., 1985.)



Stable Boundary Layer

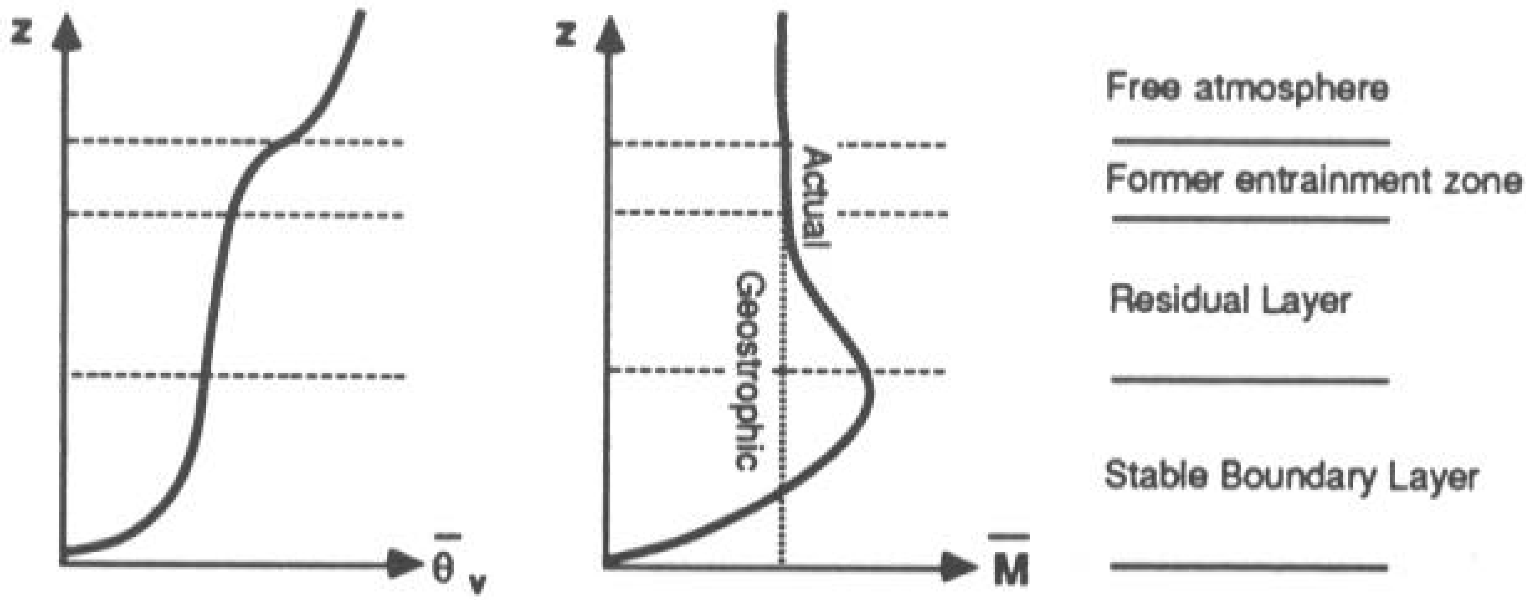


Fig. 1.11 Mean virtual potential temperature, $\overline{\theta}_v$, and wind speed, $\overline{M}$, profiles for an idealized stable boundary layer in a high-pressure region.

- 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 super-geostrophic 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 day time 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.

- **SBLs can also form during the day, as long as the underlying surface is colder than the air**. These situations often occur during warm-air advection over a colder surface, such as after a warm frontal passage or near shorelines.

Virtual Potential Temperature Evolution

(how is virtual temperature defined and what's its significance?)

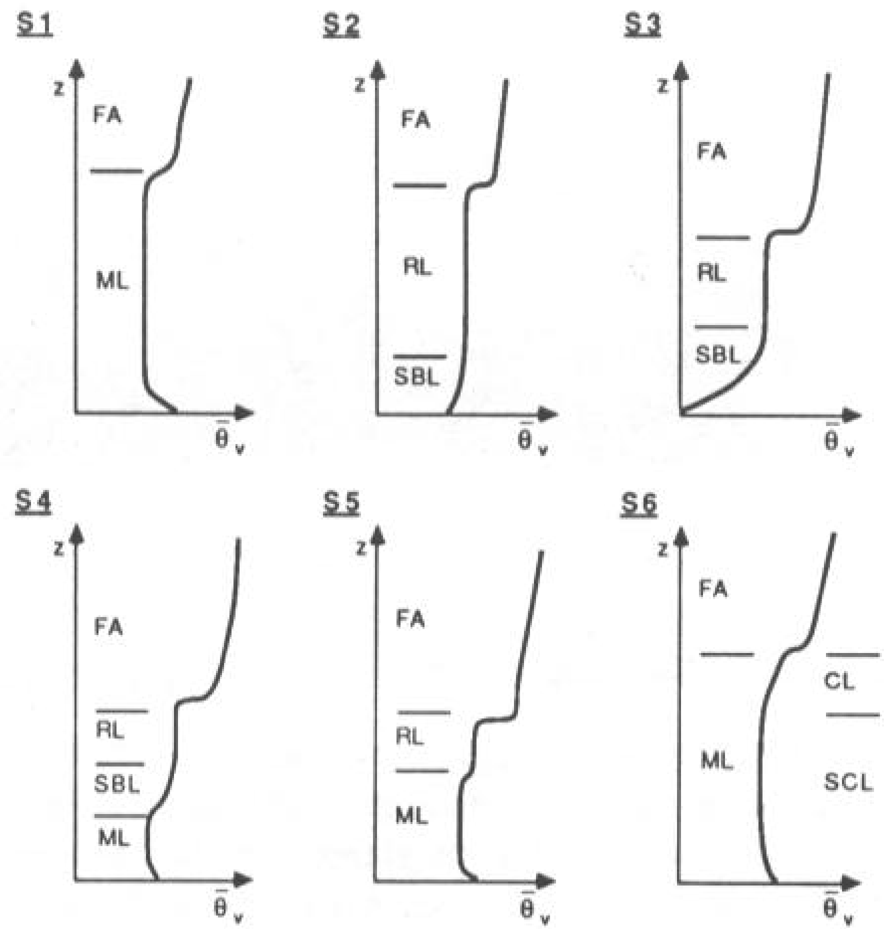


Fig. 1.12 Profiles of mean virtual potential temperature, $\bar{\theta}_v$, showing the boundary-layer evolution during a diurnal cycle starting at about 1600 local time. S1-S6 identify each sounding with an associated launch time indicated in Fig. 1.7.

- Virtual potential temperature profile evolution at time S1 through S6 indicated in Fig.1.7.

- The structure of the BL is clearly evident from these profiles, i.e., **knowledge of the virtual potential temperature lapse rate is usually sufficient for determining the static stability**.

- **An exception to this rule** is evident by comparing the **lapse rate in the middle of the RL with that in the middle of the ML**. Both are adiabatic; yet, the ML corresponds to statically unstable air while the RL contains statically neutral air. One way around this apparent paradox for the classification of adiabatic layers is to note the lapse rate of the air immediately below the adiabatic layer. If the lower air is super-adiabatic, then both that super-adiabatic layer and the overlying adiabatic layer are statically unstable. Otherwise, the adiabatic layer is statically neutral.

<u>An example of a deep well mixing boundary layer in the Front range area of the Rockies, shown in Skew-T diagram.</u>

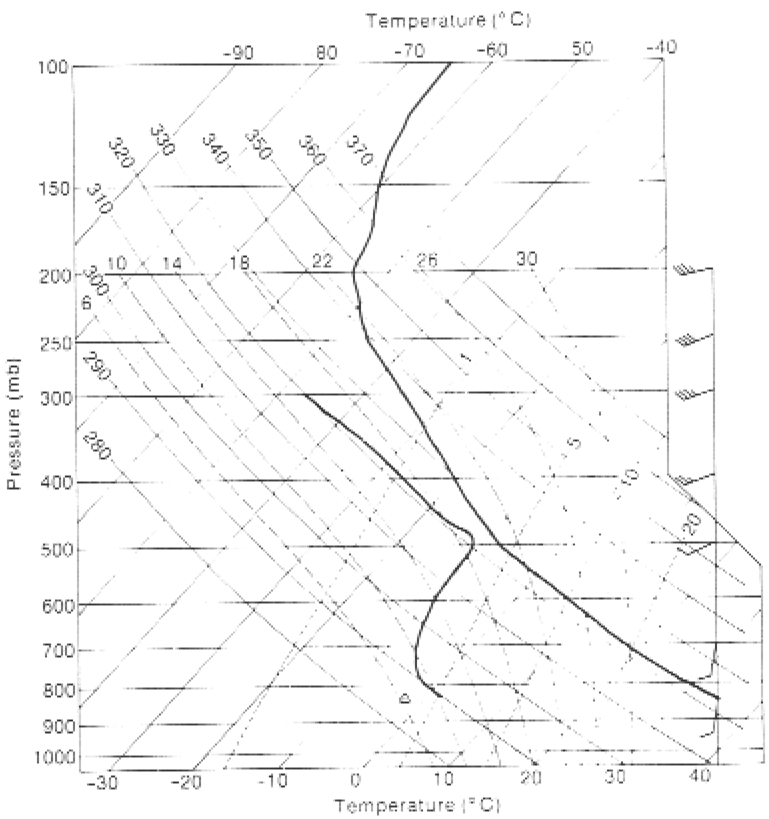


Figure 9a. A composite of five afternoon (0000 UTC) soundings by Brown et al. (1982) for convective events that produced damaging surface winds associated with high-based cumulonimbi in the Front Range area of Colorado. The temperature is represented by the curve on the right, and the dew point temperature by the curve on the left. The sounding is also typical of the type of environment found, during JAWS, to be associated with large numbers of microbursts (Caracena and Flueck, 1988). The sounding shows the characteristic deep, dry mixed layer (with dry adiabatic lapse rate, ~9.8°C km⁻¹) topped by a moist, cloud-bearing layer (low dew point depression).

An example morning sounding showing the surface inversion (stable) layer that developed due to night-time surface cooling. Such a shallow stable layer can usually be quickly removed after sunrise.

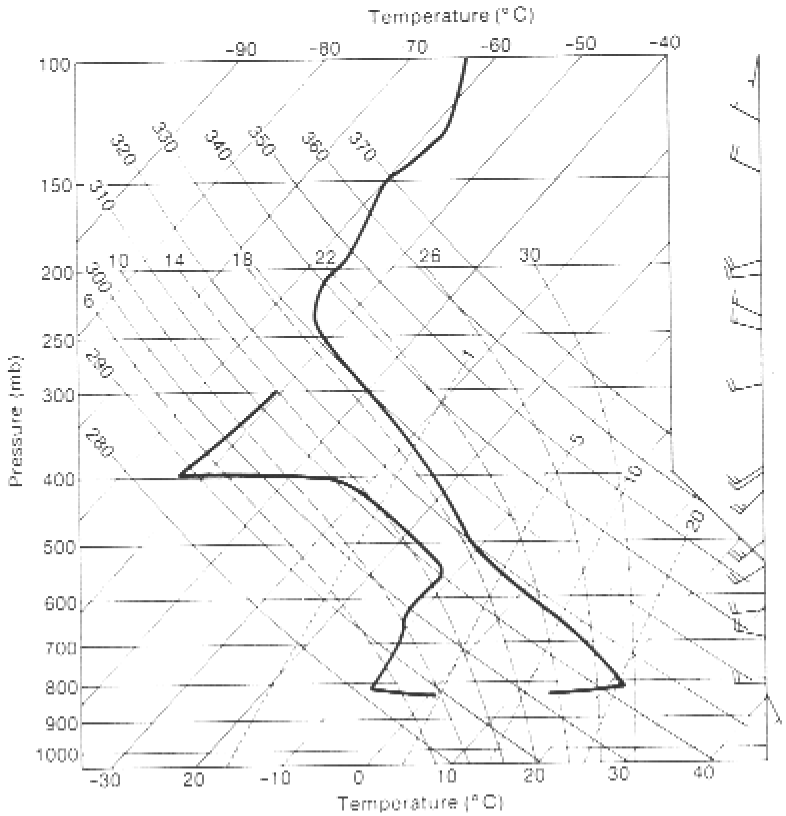


Figure 9b. A dry microburst sounding, as in Fig. 9a, but taken in the morning (1200 UTC) of 31 May 1984, showing the kind of shallow inversion near the surface that usually disappears later in the day to produce a sounding like Fig. 9a, thereby implying a high potential for dry microbursts later in the day. This sounding was taken about 7 hours before a microburst-related near-accident at Stapleton International Airport.