Lecture 13. Stable and nocturnal BLs

In this lecture…

- The nocturnal boundary layer
- Stable BLs due to katabatic flow
- Nocturnal jets

Introduction

The stable nocturnal BL (NBL) has proved one of the more difficult types of BL to understand and model. The boundary layer tends to be only 50-300 m deep. Turbulence tends to be intermittent and gravity-wave like motions are often intermingled with turbulence, especially in the upper part of the boundary layer. Radiative cooling in the air often has a comparable effect on the stratification to the turbulence itself, reaching 1 K hr^{-1} or more in the lowest 50-100 m (by comparison, a downward heat flux of H_0 = -10 W m^{-2} out of a NBL h = 100 m would cool it at a rate $dq/dt|_{turb} = H/\rho c_p h = 10^{-4}$ K s^{-1} = 0.3 K hr^{-1}. Even the largest turbulent eddies do not span the entire BL, so there is a tendency to layering of chemicals and aerosols within the BL, especially in the upper part of the BL where turbulence is weakest. Wind profiles are much less well-mixed at night than during the daytime convective BL.

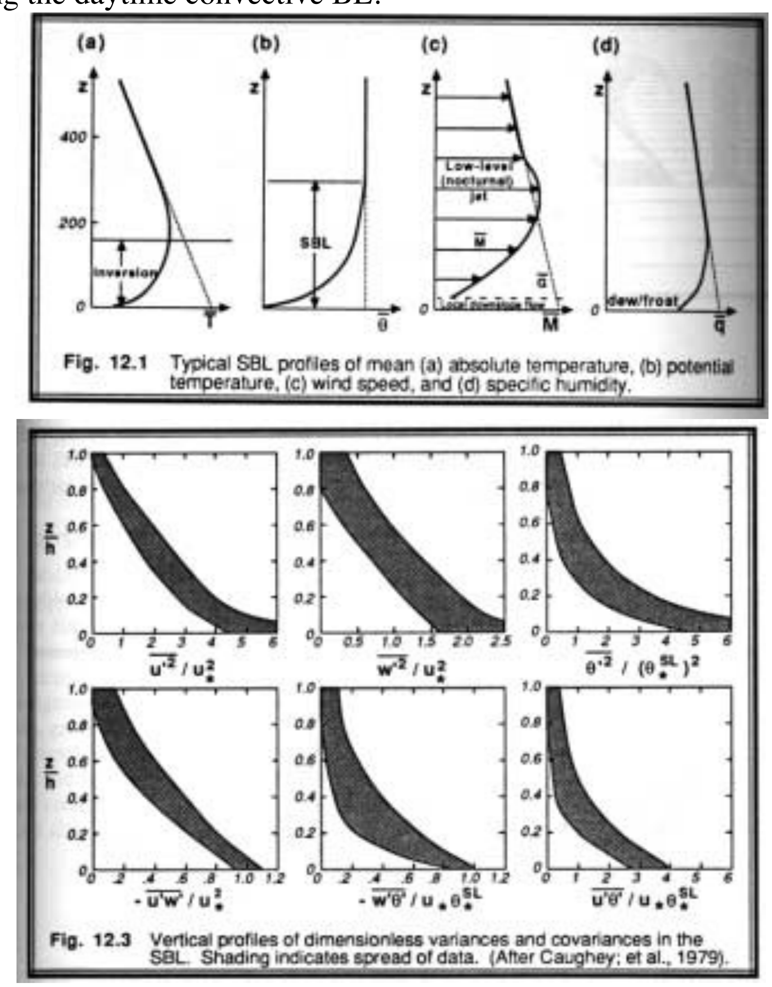


Fig. 13.1: In a stable BL, turbulence decreases sharply with height (Stull book)

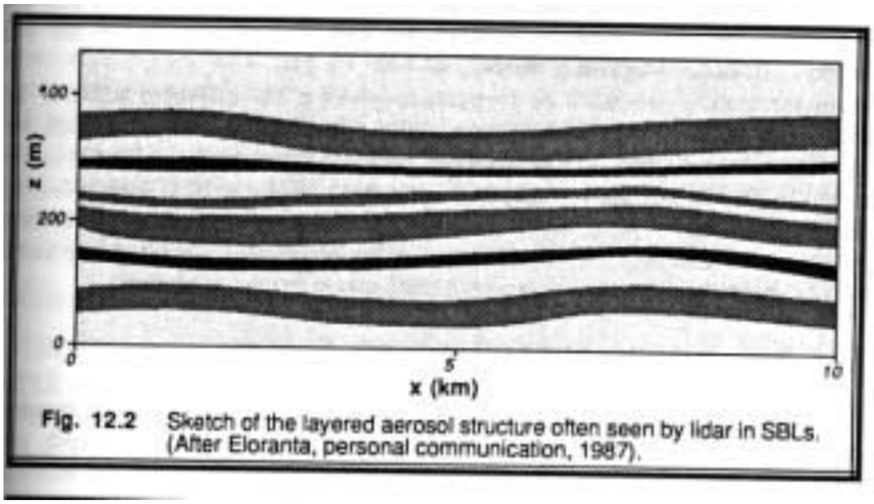


Fig. 12.2 Sketch of the layered aerosol structure often seen by lidar in SBLs. (After Eloranta, personal communication, 1987).

Fig. 13.2: Layered NBL with gravity wave undulations that can modulate local shear, stratification, and hence turbulence (Stull).

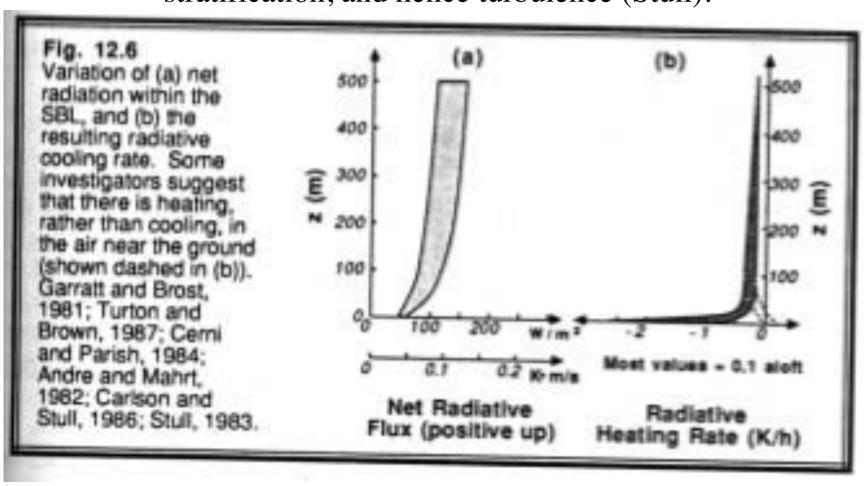


Fig. 12.6 Variation of (a) net radiation within the SBL, and (b) the resulting radiative cooling rate. Some investigators suggest that there is heating, rather than cooling, in the air near the ground (shown dashed in (b)). Garratt and Brost, 1981; Turton and Brown, 1987; Cerni and Parish, 1984; Andre and Mahrt, 1982; Carlson and Stull, 1986; Stull, 1983.

Fig. 13.3: Near a cold surface, radiative cooling can be surprisingly fast and helps maintain a stable stratification (Stull).

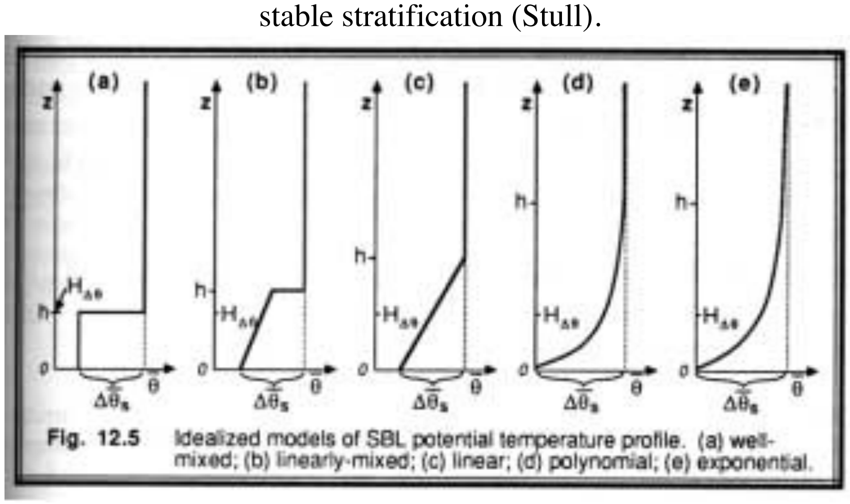


Fig. 12.5 Idealized models of SBL potential temperature profile. (a) well-mixed; (b) linearly-mixed; (c) linear; (d) polynomial; (e) exponential.

Fig. 13.4: (b) typifies strong-wind NBL, (d) a weak-wind NBL under clear sky (Stull).

Katabatic Flows

Sloping terrain has a large influence on stable boundary layers. The cold dense air near the surface is now accelerated by the downslope component $b \sin \alpha$ of its buoyant acceleration (α is the slope angle and $b < 0$ is the buoyancy of air within the BL relative to above-BL air at the same height). Viewed in terrain-parallel coordinates, $b \sin \alpha$ is like an effective pressure gradient force, which is strongest near the ground where b is most negative. In this sense, the slope acts similar to a thermal wind (which would also be associated with a height dependent PGF) . Slopes of as little as 2 in 1000 can have an impact on the BL scaling.

As the slope increases, or BL stability increases, the velocity profile is increasingly determined by drag created by turbulent mixing with air above rather than surface drag. The resulting BL is typically 10s of m thick over glaciers or 100 m or more thick over large ice sheets. Over glaciers, katabatic winds often occur during the day as well as during the night, since the net radiation balance of a high-albedo surface is negative even during much of the day, and evaporative cooling due to surface snowmelt can also stabilize the air near the surface. On the coast of Antarctica, persistent katabatic flows down from the interior icecap can produce surface winds in excess of 50 m s^{-1}.

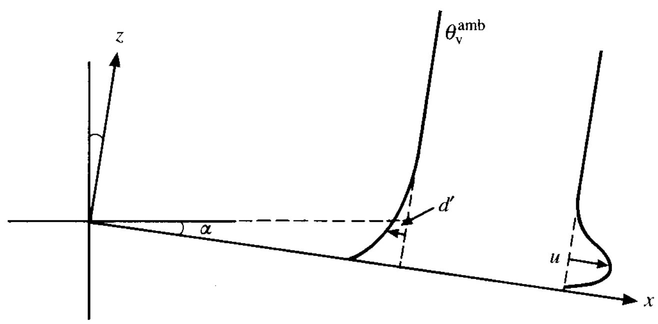


Fig. 6.22 Schematic representation of the downslope flow typical of night-time flow under light wind, clear sky conditions. Here, α is the slope angle and d' is the θ deficit of the flow relative to the ambient field.

Fig. 13.5: Katabatic flow (Garratt)

The nocturnal jet

As turbulence dies down in the residual layer in late afternoon, it decouples from the BL. The momentum flux convergence that was helping to reduce and turn the wind during the day suddenly disappears, leaving a wind profile in which there is an imbalance between the two main horizontal forces, Coriolis force and pressure gradient force. Fig. 13.6 shows the resulting evolution of the wind during one night of the Wangara experiment (which took place over flat ground). During the night a strong jet develops above the nocturnal BL. In the bottom panel is another example in which the geostrophic wind is also plotted. During the daytime, the wind component along the geostrophic wind direction is subgeostrophic, but at night it is supergeostrophic.

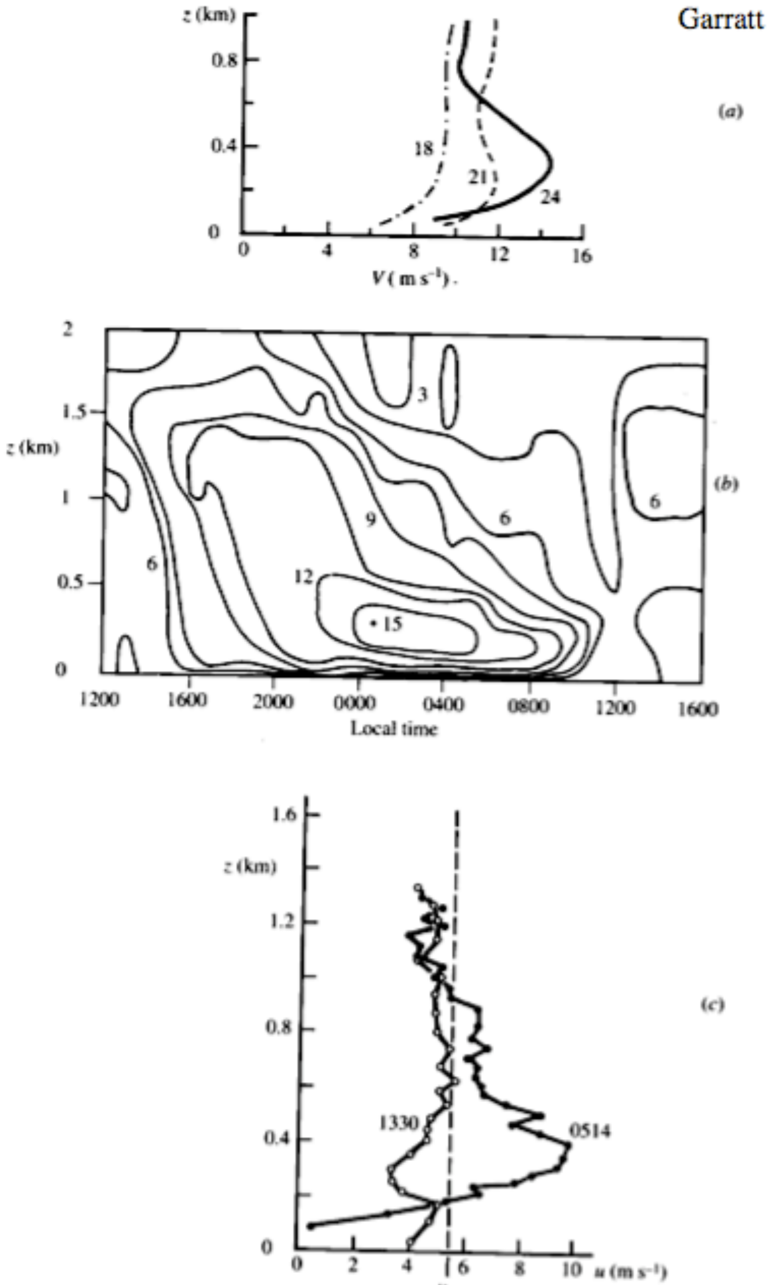
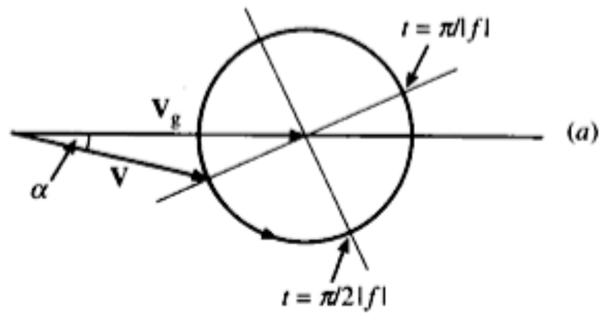


Fig. 6.18 Observations illustrating the formation of the nocturnal jet. (*a*) Wind-speed profiles on day 13 of WANGARA, local times indicated. (*b*) Height–time cross-section of wind speed (in $\mathrm{m\,s^{-1}}$) on days 13/14 at WANGARA. Isopleths of wind speed are drawn at $1.5\,\mathrm{m\,s^{-1}}$ intervals. (*c*) Profiles of the u-component of the wind velocity, with the x-axis along the geostrophic wind direction, for mid-afternoon (1330 UT, 6 August, 1974) and early morning (0514, 7 August, 1974) near Ascot, England. After Thorpe and Guymer (1977), *Quarterly Journal of the Royal Meteorological Society*.

Fig. 13.6: Observations of nocturnal jets

This is one of the cleanest atmospheric examples of an inertial oscillation. The pressure gradient is horizontally uniform, so the ageostrophic wind $\mathbf{u}_a = \mathbf{u} - \mathbf{u}_g$ rotates clockwise with the Coriolis period $2\pi/f$, which at mid-latitudes is somewhat less than a day. Supergeostrophic winds ensue during the night, as shown in Figure 13.7. In the morning, the convective mixed layer deepens into the residual layer, so the wind profile becomes frictionally coupled again. The Great Plains nocturnal southerly jet, prominent during the springtime when it can achieve speeds of 30 m s^{-1} less than 1 km above the surface, partially owes its origin to this mechanism. In this region, climatological southerly geostrophic flow occurs due to a thermal low over the elevated terrain to the west (i. e. the Rockies). The strong enhancement of low-level southerlies during the night help pump humid air northward, where it can help fuel severe thunderstorms and mesoscale convective systems through the night.



Garratt

Fig. 13.7: Formation of a nocturnal jet via an inertial oscillation (f <0; Southern Hemisphere!).