Lecture 4. Boundary Layer Turbulence and Mean BL Profiles

In this lecture…

- Concept of eddy diffusion
- Typical vertical structure of convective and stable ABLs.
- Types of observing systems for the boundary layer
- Large-eddy simulation (3D modeling of turbulent flow)

Mixing length theory and eddy diffusivity

The ensemble averaged hydrodynamic equations involve the divergence of turbulent eddy fluxes. The main goal of turbulence parameterizations in large-scale numerical models is to predict these eddy fluxes in terms of model-predicted variables. The simplest approach, called **downgradient eddy diffusion** or **first-order turbulence closure**, is inspired by **mixing length theory** (Prandtl 1925). We idealize eddies as taking random fluid parcels from some level, and advecting them up or down over some characteristic height or mixing length δz at some characteristic speed V, where the fluid parcel gets homogenized with the other air at that level. Except near the surface, the transport is primarily by eddies whose scale is the boundary layer depth, so we think of V as the large-eddy velocity and δz as proportional to the boundary layer height scale H. Near the surface, a different scaling applies, which we discuss later. At any location, half the time there is an updraft with $w_u' = V$ carrying fluid upward from an average height $z - \delta z/2$, and the other half of the time there is a downdraft with $w_d' = -V$ carrying fluid downward from an average height $z + \delta z/2$. Consider the corresponding vertical flux of some advected quantity a. In updrafts,

$$a_u' = \bar{a}(z - \delta z/2) - \bar{a}(z). \tag{4.1}$$

If we assume that a varies roughly linearly between $z - \delta z/2$ and z, then

$$a_u' = -\frac{\delta z}{2}\frac{d\bar{a}}{dz}. \tag{4.2}$$

Similarly, in downdrafts,

$$a_d' = a(z + \delta z/2) - a(z) = \frac{\delta z}{2}\frac{d\bar{a}}{dz}. \tag{4.3}$$

Hence, taking the ensemble average,

$$\overline{w'a'} = \frac{1}{2}\left(w_u'a_u' + w_d'a_d'\right) \approx -K_a\frac{d\bar{a}}{dz}, \text{ where } K_a = V\delta z/2. \tag{4.4}$$

Thus the eddy flux of a is always down the mean gradient, and acts just like diffusion with an eddy diffusivity K_a. For typical ABL scales $V = 1$ m s^{-1}, $\delta z = 1$ km, mixing length theory would predict $K_a = 500$ m^{2}s^{-1}. Most first order turbulence closure models assume that turbulence acts as an eddy diffusivity, and try to relate V and δz to the profiles of velocity and static stability; we'll disucss this further when we talk about parameterization.

Typical boundary layer profiles

Mixing length theory predicts that vigorous turbulence should strongly diffuse vertical gradients of mean quantities in the BL, resulting in a `well-mixed' BL with only slight residual vertical gradients. How well does turbulence mix up observed boundary layers? For clear unstable (convective) BLs, mixed layer structure is observed in θ, usually in q, and often in u, v (with slight veering of the wind with height).

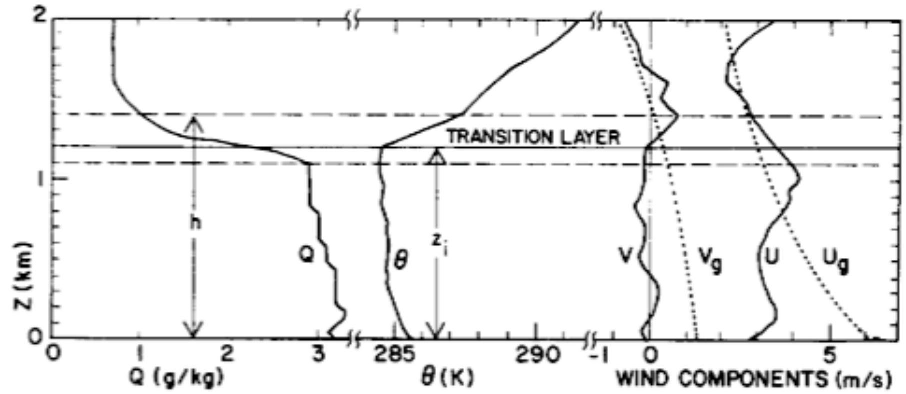

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Fig. 6.5 Measured wind, potential temperature, and specific humidity profiles in the PBL under convective conditions on day 33 of the Wangara Experiment. [From Deardorff (1978).]

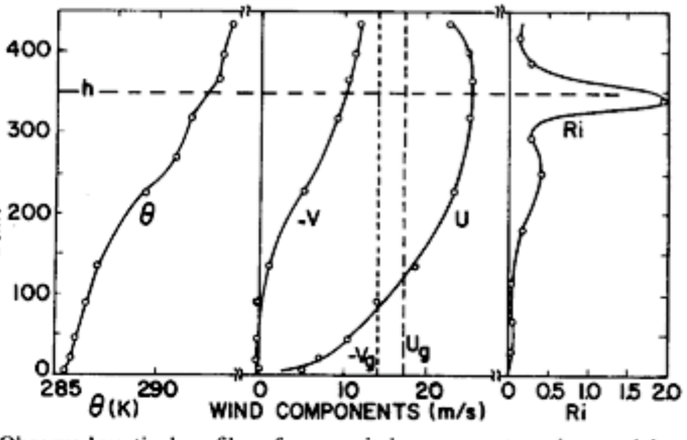

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Fig. 6.7 Observed vertical profiles of mean wind components and potential temperatu and the calculated Ri profile in the nocturnal PBL under moderately stable conditio [From Deardorff (1978); after Izumi and Barad (1963).]

For moderately stable BLs in which turbulence is largely continuous in space and time, the BL is far from well-mixed, but the Richardson number Ri remains less than 1/4 (see figure above). In extremely stable boundary layers, the turbulence is sporadic and the mean Ri can be 1 or more (see below). The low-level veering of the wind with height is much larger in very stable boundary layers, where most of the surface stress is distributed as momentum flux convergence near to the bottom of the BL (see below).

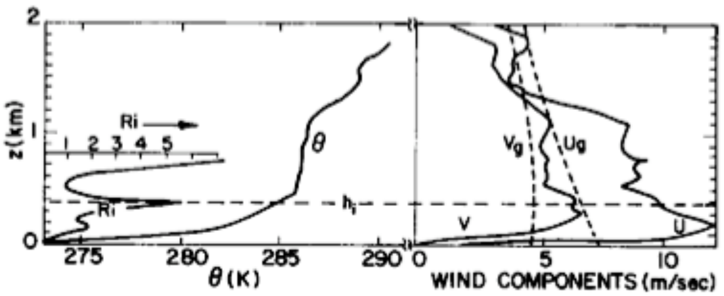

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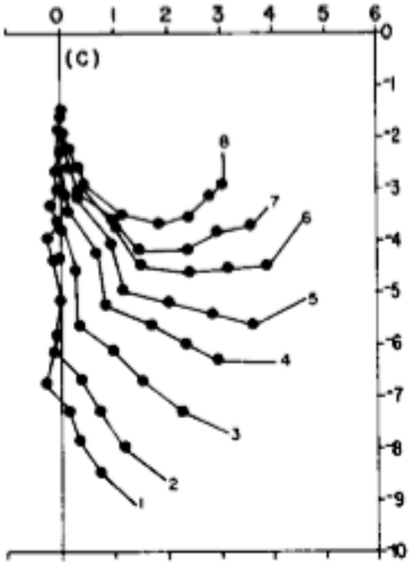
Fig. 6.8 Observed wind and potential temperature profiles under very stable (sporadic turbulence) conditions at night during the Wangara Experiment. [From Deardorff (1978).]



Wind hodograph at South Pole Station. Categories 1-8 correspond to increasingly stable BLs; dots are composites of measurements at 0.5, 1, 2, 4, 8, 12, 16, 20, 24, 32 m; *y*-axis is in the surface wind direction. Note large turning of the wind with height in stable BLs

Observing the BL

The turbulent nature of BL flow presents special challenges for observations and modeling. On the other hand, its nearness to the surface makes surface-based observing systems particularly useful. Chapter 10 of Stull's book (handout) is an excellent summary of sensors (and the principles by which they work), types of measurement and analysis methods for ABL observations. It also has a list of major BL field experiments through early 1987 and describes numerical modelling of boundary layer turbulence. Fast response sensors capable of in-situ measurements of turbulent perturbations in velocity components, temperature, pressure, humidity and some trace gases (such as CO_2) from different platforms, e.g. an airplane, balloon, mast, or surface site are now widely available, and can be used to calculate vertical turbulent fluxes and moments. Due to the sensitivity of the instruments and their high data rate, these measurements are restricted to dedicated field experiments. Remote sensors measure waves generated or modified by the atmosphere at locations distant from the sensor. Active remote sensors generate sound (sodar), light (lidar), or other EM waves (e. g. radar). Passive remote sensors, rely on electromagnetic waves generated by the earth (infrared, microwave), the atmosphere (infrared), or the sun (visible). Remote sensors can often scan over a large volume and are invaluable in characterizing aspects of the vertical structure of the BL, but typically provide poor time and space resolution. However, Doppler lidar (in clear air with some scatterers) and mm-wave radar (in cloud) have proved capable of resolving larger turbulent eddies and characterizing some of the turbulent statistics of the flow, and are particularly useful for characterizing the structure of the entrainment zone at the top of the boundary layer.

Laboratory Experiments

Turbulence is important in many contexts outside atmospheric science, such as aerodynamics, hydraulics, oceanography, astrophysics, etc. Most of our fundamental understanding of turbulence derives from laboratory experiments with these contexts in mind. Convection has been studied, mainly in liquids, in tanks a few cm to a few m in size. Shear flows have been studied in water tunnels or rotating tanks. Salt can be used to produce stratification. Turbulence can be created by stirring or passing moving fluid through a grid. Many sophisticated visualization techniques, using dye, in-situ sensors, laser velocimetry, etc. are used. Many simple models of atmospheric turbulence are `tuned' based on laboratory results.

Large-eddy simulation

Numerical modeling, in particular large-eddy simulation (LES) has also become a formidable tool for understanding BL turbulence. A two or preferably three-dimensional numerical domain somewhat deeper than the anticipated boundary layer depth H, and at least 2-3H wide, is covered by a grid of points. A typical domain size for an ABL simulation might be 5×5×2 km. The grid spacing must be small enough to accurately resolve the larger eddies which are most energetic and transport most of the fluxes. Grid spacings of 100 m in the horizontal and 50 m in the vertical are adequate for a convective boundary layer without a strong capping inversion. Such a simulation might run nearly in real time on a single processor. Higher resolution (10-20 m) is required near strong inversions and for stable, shear-driven BLs, requiring clusters or supercomputers.

The Boussinesq equations or some other approximation to the dynamical equations are discretized on the grid. A subgridscale model is used to parameterize the effects of unresolved eddies on the resolved scale. There is no consensus on the ideal subgridscale model. Luckily, as long as the grid-spacing is fine enough, LES simulations have been found to be relatively insensitive to this. One can understand this as a consequence of the turbulent energy cascade, in which energy fluxes down to small scales in a manner relatively independent of the details of the viscous drain. In an LES, the energy cascade must be terminated at the grid scale, but as long as the grid-scale is in the inertial range and the grid-scale eddies are efficiently damped, this should not affect the statistics of the large eddies.

The simulation is started from an idealized, usually nonturbulent, initial profile, and is forced with realistic surface fluxes, geostrophic winds, etc. Small random perturbations are added to some field such as temperature; these seed shear or convective instability which develops into a quasi-steady turbulent flow, typically within an hour or two of simulated time for ABL simulations. The simulation is run for a few more hours and flow statistics and structures from the quasi-steady period are analyzed. For cloud-topped boundary layers, the LES must also include representations of radiative fluxes and of cloud microphysics.

Intercomparisons between different LES codes and comparisons with data show that for a convective boundary layer without a strong capping inversion, the simulation statistics are largely independent of the LES code used, building confidence in the approach. For stratocumulus-topped boundary layers under a strong capping inversion, different codes agree on the vertical structure of the large eddies within the BL, but predict considerably different rates of entrainment of free-tropospheric air for the same forcing, even when run at vertical resolutions as small as 5-10 m around the inversion. As soon as other physical parameterizations, such as cloud microphysics, radiation, or land-surface models are coupled into the LES, the results are only as good as the weakest parameterization! Thus, LES models of most realistic BLs are illuminating and an extremely useful predictive tool, but must be carefully validated against observations.