

The Boundary Layer and Related Phenomena

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The Boundary Layer and Related Phenomena

- Introduction

- Structure and Evolution

- The Nature of Turbulent Fluxes

What is the boundary layer?

Stull (1988):

Planetary boundary layer is the part of troposphere that is directly influenced by the presence of the earth surface and responds to surface forcings with a timescale of about an hour or less.

Sorbjan (2012):

The lowest portion of the atmosphere, which extensively exchanges mass (water), momentum, and heat with the Earth's surface.

What is the boundary layer?

The *boundary layer*, also known as the atmospheric boundary layer (ABL) or planetary boundary layer (PBL), is a disturbance of the lower atmosphere induced by the underlying surface of the Earth.

In other words, the BL is an interfacial layer between the troposphere and the ground.

What is the boundary layer?

The forcings that originate at the surface include:

- ▶ frictional drag
- ▶ evaporation and transpiration
- ▶ heat transfer
- ▶ pollutant emissions
- ▶ terrain-induced flow modifications

What is the boundary layer?

In the lowest few millimeters of the BL, conduction between the air and the ground is important.

This small layer is also known as the *viscous sublayer*.

Above this layer, the effects of molecular diffusion are ignored since they are negligible compared with the mixing effects of turbulent eddies.

What is the boundary layer?

Molecular viscosity does not directly influence BL motions above a few centimeters.

However, the viscous sublayer is crucial in the formation of BL eddies.

In other words, the BL would not exist without an underlying surface.

What is the boundary layer?

Specifically, as a result of molecular viscosity the flow vanishes at the surface (*no-slip boundary condition*).

Consequently, large vertical wind shear is generated near the ground (even with light winds).

This shear leads to the formation of small turbulent eddies that act to transfer momentum, heat, and moisture to the lower BL.

These turbulent motions have spatial and temporal variations at scales much smaller than those resolved by a meteorological observing network.

What is the boundary layer?

BL flow is dominated by these turbulent eddies, as well as by those that result from surface heating.

These eddies are most often ignored in the free atmosphere.

The transfer of momentum, heat, and moisture by these turbulent eddies must be accounted for in the dynamical equations in order to accurately describe the BL evolution of θ and q and the relationship between the ∇p and u .

What is the boundary layer?

In this part of the course, we:

- ▶ focus on a qualitative overview of the BL
- ▶ describe the inclusion of turbulence in the dynamical equations
- ▶ discuss several related phenomena
- ▶ consider applications of boundary layer theory.

The importance of the boundary layer

Overheard across the years in SoM

- ▶ “My eyes are bleeding from all of these equations!”
- ▶ “This s#&! is a waste of time!”
- ▶ “Boundary layer? More like Boring Layer - amirite?!?”

The importance of the boundary layer

Found in the SoM bathroom stall



The importance of the boundary layer

The boundary layer is often perceived as a boring, esoteric topic to meteorology students.

This is likely due to the fact that much of the theory historically stems from fluid mechanics and other engineering-focused areas of research.

In other words, engineers have no souls :)

The importance of the boundary layer

Admittedly, boundary layer theory is laden with long equations and complex parameterizations.

It is understandable why so many students' eyes glaze over when they are introduced to the boundary layer.

We will soon cover why these equations and parameterizations are necessary to properly describe the evolution of mass, momentum, and moisture fields in the lowest portion of the atmosphere.

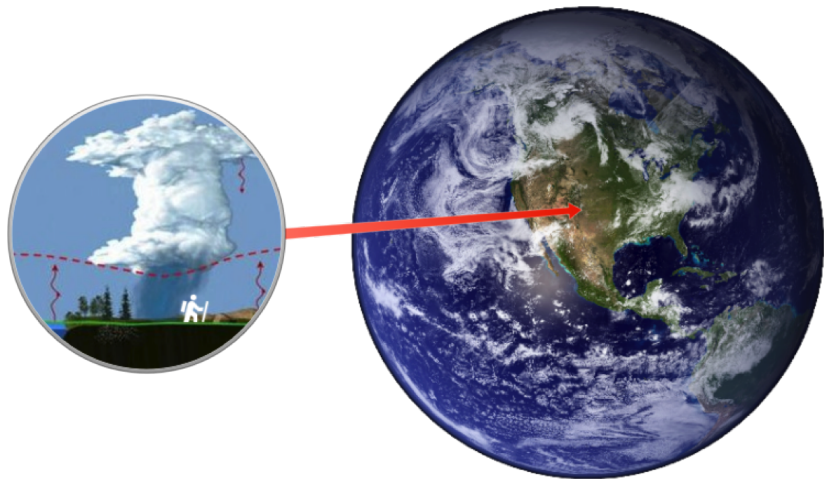
The importance of the boundary layer

First, let us put aside rigorous math exercises and consider real-world examples that illustrate the importance of the boundary layer.

Why should you care about the boundary layer? Let me count the ways.

The importance of the boundary layer

We live there!!!!



The importance of the boundary layer

Some more reasons

- ▶ Forecasts of dew, frost, minimum and maximum temperatures (to name a few) are really boundary layer forecasts.
- ▶ Pollution is trapped and dispersed within the boundary layer.
- ▶ Fog occurs in the boundary layer

The importance of the boundary layer

Some more reasons

- ▶ The primary energy source for the atmosphere is solar radiation, which is generally absorbed by the surface. Boundary layer processes act to transmit this energy to the rest of the atmosphere.
- ▶ $\sim 90\%$ of the net radiation absorbed by oceans causes evaporation. The latent heat stored in water vapor accounts for $\sim 80\%$ of the fuel that drives atmospheric motions!

The importance of the boundary layer

Some more reasons

- ▶ Crops are grown in the boundary layer, where pollen is distributed within.
- ▶ Cloud nuclei are sent into the air from the surface by boundary layer processes.
- ▶ Almost all water vapor that reaches the free atmosphere is transported through the boundary layer by turbulence and advection.

The importance of the boundary layer

Some more reasons

- ▶ Thunderstorm/hurricane evolution is tied to the inflow of moist boundary layer air.
- ▶ Downward turbulent transport of momentum through the boundary layer to the surface is the single most important atmospheric momentum sink.

The importance of the boundary layer

Some more reasons

- ▶ Turbulence and gustiness affect the design of structures.
- ▶ Wind turbines extract energy from boundary layer flows.
- ▶ Wind stress on the ocean surface is the primary energy source for ocean currents.

The importance of the boundary layer

The list is not exhaustive, but it shows several tangible examples in which the boundary layer directly impacts our lives, in addition to indirect effects through its influence on weather.

Comparison of boundary layer and free atmosphere characteristics

Another way to illustrate the importance of the boundary layer is to compare its characteristics with the overlying free atmosphere.

We will now describe these difference that highlight the role of the boundary layer and its importance to the entire atmosphere.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Turbulence	Almost continuously turbulent over its whole depth.	Turbulence in convective clouds and sporadic clear air turbulence in thin layers of large horizontal extent.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Friction	Strong drag against the earth's surface. Large energy dissipation.	Small viscous dissipation.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Dispersion	Rapid turbulent mixing in the vertical and horizontal	Small molecular diffusion. Often rapid horizontal transport by the mean wind.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Winds	Near logarithmic wind speed profile in the surface layer. Sub-geostrophic, cross-isobaric flow is common.	Winds nearly geostrophic.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Vertical transport	Turbulence dominates.	Mean wind and cumulus-scale dominate.

Comparison of boundary layer and free atmosphere characteristics

Table: adapted from Stull (1988)

Property	Boundary Layer	Free Atmosphere
Thickness	Varies between ~ 100 m to 3 km in time and space. Diurnal oscillations over land.	Less variable at 8-18 km. Slow time variations.

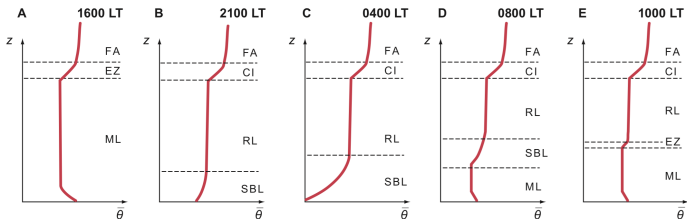
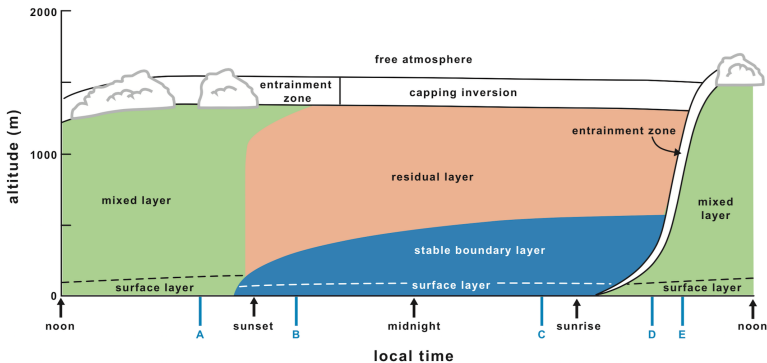
Structure and evolution

The following figure illustrates the typical diurnal cycle of the BL.

This pronounced cycle is one of the defining features of the BL owing to its fast response time to surface forcings.

The diurnal evolution of the BL, as well as the associated structural changes, will be discussed in detail

Structure and evolution



BL depth: dependencies

- ▶ morning atmospheric profile of temperature
- ▶ intensity of turbulent mixing, which itself depends on
 - ▶ the amount of insolation and sensible heat flux (buoyancy-driven turbulence)
 - ▶ mean vertical wind shear (mechanically-driven turbulence)

Structure and evolution

BL depth: variations

- ▶ stable, nighttime conditions
 - ▶ as shallow as a few tens of meters
 - ▶ intermittent turbulence can exist

BL depth: variations

- ▶ unstable, daytime conditions
 - ▶ as deep as several kilometers
 - ▶ layer is typically superadiabatic and dominated by convective motions

Structure and evolution

General BL Evolution

- ▶ After sunrise, the boundary layer is heated by the underlying surface through sensible heat flux.
- ▶ This heating drives the air in contact with the ground toward the dry adiabatic lapse rate ($\partial\bar{\theta}/\partial z = 0$).
- ▶ Within a shallow layer in contact with the ground, superadiabatic conditions induce vertical mixing and turbulence.
- ▶ Mixing promotes homogeneity, which leads to moisture and wind speed profiles that are approximately constant with height.

Structure and evolution

General BL Evolution, continued

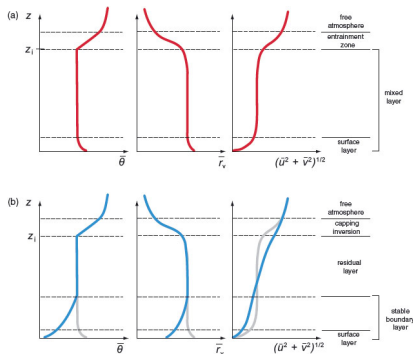
- ▶ Thermals rise and penetrate the stably-stratified atmosphere.
- ▶ This *penetrative convection* induces mixing through an even deeper layer, leading to a deepening of the boundary layer.
- ▶ These overshooting thermals lead to cooling at the top of the mixed layer within the penetrated stable region, which in turn creates a capping inversion.
- ▶ Continued surface heating generates more thermals, deeper mixing, and a growing boundary layer.

General BL Evolution

- ▶ The maximum boundary layer depth is attained near sunset.
- ▶ After sunset the surface sensible heat flux reverses sign.
- ▶ As a result of the negative surface sensible heat flux, cooling starts and a stable region forms near the surface.

Structure and evolution

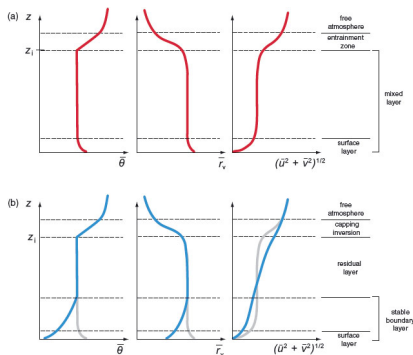
Daytime BL Structure



- ▶ The layer of the daytime boundary layer extending from the surface to the *entrainment zone* (EZ; which tops the boundary layer) is often referred to as the *mixed layer* (ML) or *convective boundary layer* (CBL).

Structure and evolution

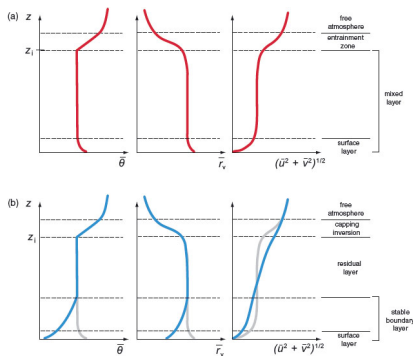
Daytime BL Structure



- ▶ Profiles of potential temperature ($\bar{\theta}$) are approximately constant with height, except within the lowest 10% of the CBL. This layer is called the *surface layer* (SL).
- ▶ Transfer of momentum, mass, and moisture within this layer is able to overcome mixing effects (see Fig. ??).

Structure and evolution

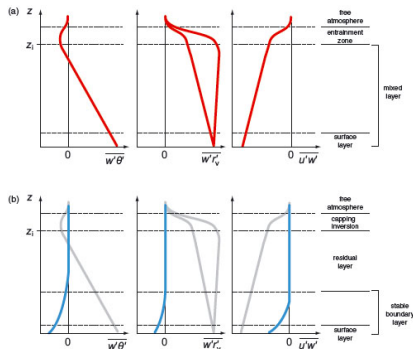
Daytime BL Structure



- ▶ Consequently, $\bar{\theta}$ may decrease by 1-2 K from the ground to the top of the SL (*i.e.*, super-adiabatic conditions). In addition, moisture (\bar{q}) may also decrease with height within this layer, while wind speed (\bar{u}) logarithmically approaches zero from the top of the layer to the ground.

Structure and evolution

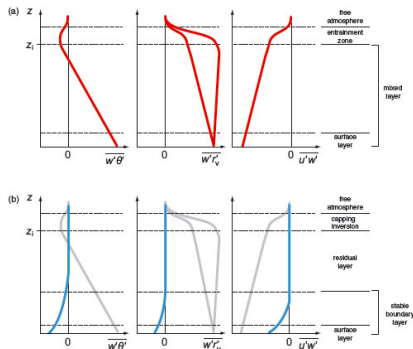
Daytime BL Structure



- Turbulent fluxes generally have their largest magnitude at the surface and decrease in magnitude with height, where they become negligible at the base of the free atmosphere.

Structure and evolution

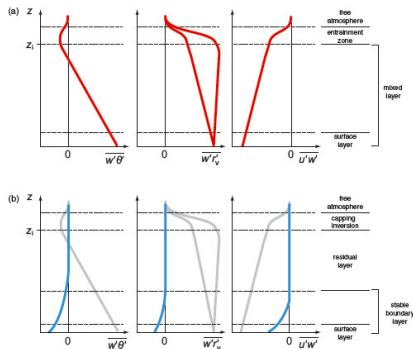
Daytime BL Structure



- An exception to this is the moisture flux ($\overline{w'q'}$), which can have a maximum magnitude at a level significantly above the surface (it is still negligible at the base of the free atmosphere).

Structure and evolution

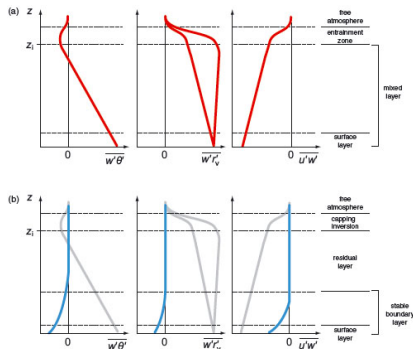
Daytime BL Structure



- ▶ Since (\bar{u}) generally increases with height, the momentum flux $(\overline{w'u'})$ tends to be negative.
- ▶ Thus, rising thermals are associated with negative velocity perturbations as they carry lower momentum upward. Conversely, the downward motions are associated with positive velocity perturbations as they bring higher momentum downward.

Structure and evolution

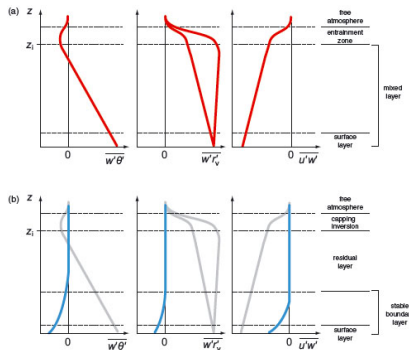
Daytime BL Structure



- ▶ $\overline{w'u'}$ tends to decrease linearly with height from the surface to the top of the CBL. The magnitude decreases rapidly from the base of the CBL to a value near zero at the top of the EZ.

Structure and evolution

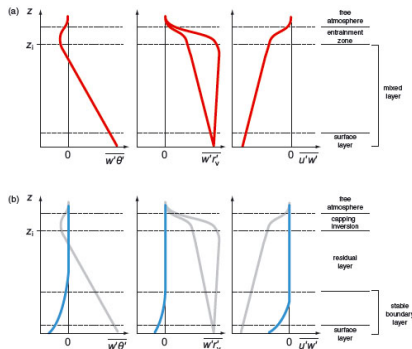
Daytime BL Structure



- ▶ The kinematic heat flux ($\overline{w'\theta'}$) is generally positive in the CBL as a result of rising air being positively buoyant.
- ▶ ($\overline{w'\theta'}$) generally decreases linearly with height from the surface to the top of the CBL.
- ▶ Within the EZ, $\overline{w'\theta'}$ is generally negative and $\sim 10\text{-}20\%$ of its surface magnitude.

Structure and evolution

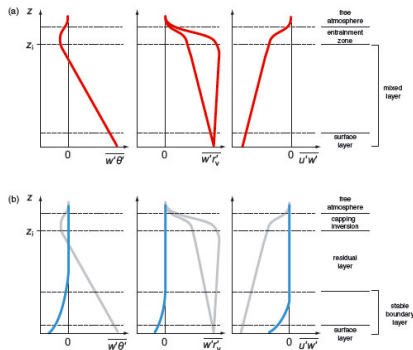
Daytime BL Structure



- ▶ Under these conditions, $\partial(\overline{w'\theta'})/\partial z < 0$ in the CBL, which implies mean warming.
- ▶ Conversely, $\partial(\overline{w'\theta'})/\partial z > 0$ in the EZ, which points to mean cooling. Penetrating thermals are responsible for cooling this layer.

Structure and evolution

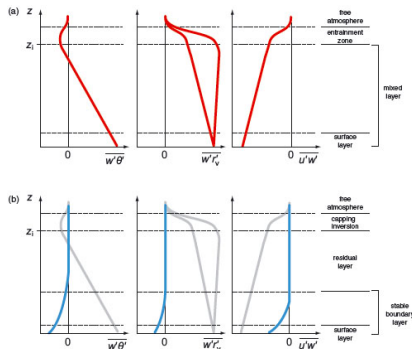
Daytime BL Structure



- ▶ $\overline{w'q'}$ also changes linearly with height, though the change can either be negative or positive depending on whether there is drying or moistening of the CBL.

Structure and evolution

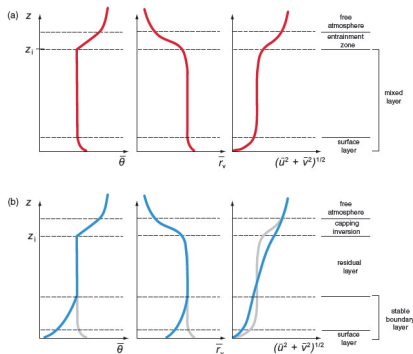
Daytime BL Structure



- ▶ The sign of $\partial(\overline{w'q'})/\partial z$ largely depends on the surface moisture characteristics.
- ▶ $\partial(\overline{w'q'})/\partial z < 0$ in the EZ, which implies net moistening in the layer.

Structure and evolution

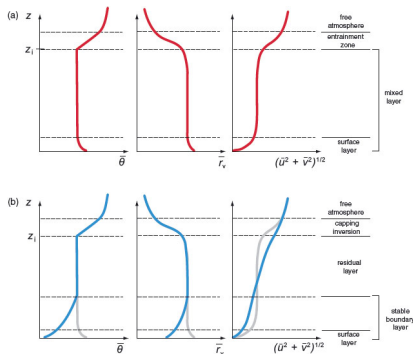
Nighttime BL Structure



- ▶ A shallow inversion layer forms near the surface at night due to heat loss by the ground.
- ▶ This layer is called the *stable boundary layer* (SBL) or *nocturnal boundary layer* (NBL).

Structure and evolution

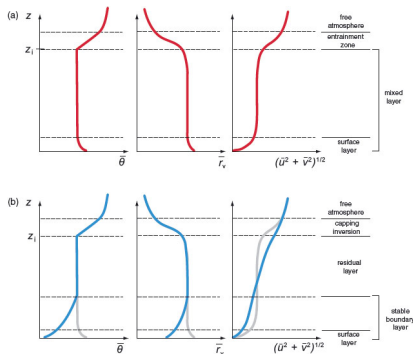
Nighttime BL Structure



- ▶ The SBL becomes *decoupled* from the ML because the inversion inhibits mixing.
- ▶ The decoupled “leftover” ML from the daytime CBL is called the *residual layer* (RL).
- ▶ The RL is characterized by nearly constant $\bar{\theta}$ and \bar{q} .

Structure and evolution

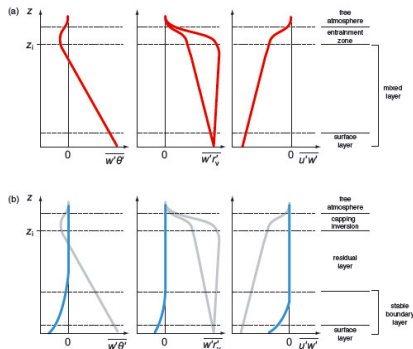
Nighttime BL Structure



- ▶ The daytime's EZ is referred to as the capping inversion at night since there is not much exchange between the free atmosphere and the residual layer.

Structure and evolution

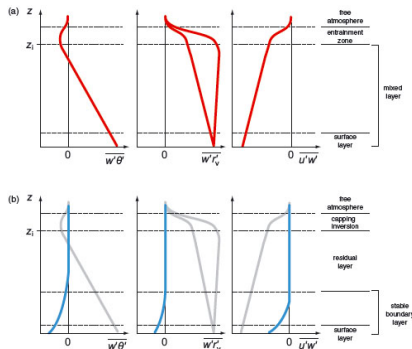
Nighttime BL Structure



- ▶ Turbulent fluxes are generally negative in the SBL.
- ▶ The maximum magnitude of each turbulent flux is located at the surface, while each flux becomes negligible at the top of the layer.

Structure and evolution

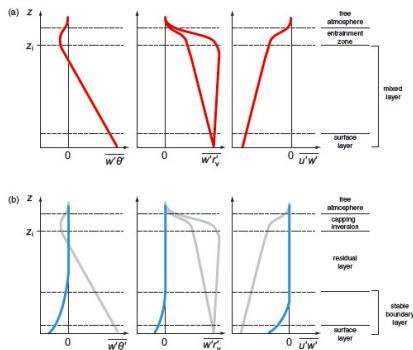
Nighttime BL Structure



- ▶ Put another way, $\partial(\overline{w'u'})/\partial z$, $\partial(\overline{w'\theta'})/\partial z$, and $\partial(\overline{w'q'})/\partial z$ are all > 0 .
- ▶ Thus, the SBL is characterized at night by cooling and drying, while acting as an effective drag on the mean wind.

Structure and evolution

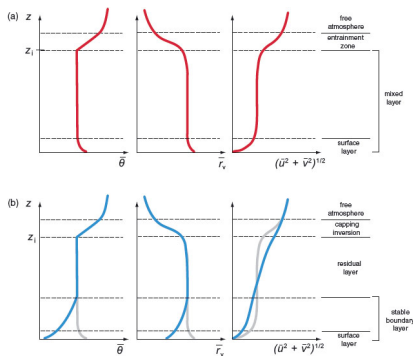
Nighttime BL Structure



- ▶ The shallow inversion layer grows in steps, which are often interrupted by intermittent turbulent events. These events are the result of small, mechanically-generated eddies.
- ▶ These intermittent turbulence events act to deepen the SBL and reduce its stability.

Structure and evolution

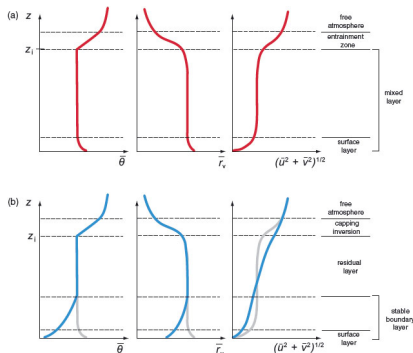
Nighttime BL Structure



- ▶ Relative humidity increases in the SBL, forming dew, which may act to reduce \bar{q} through condensation.
- ▶ Radiational cooling is strongest on nights with weak winds and infrequent turbulence events. On these nights, the inversion is rather strong and shallow, leading to especially low near-surface air temperature.

Structure and evolution

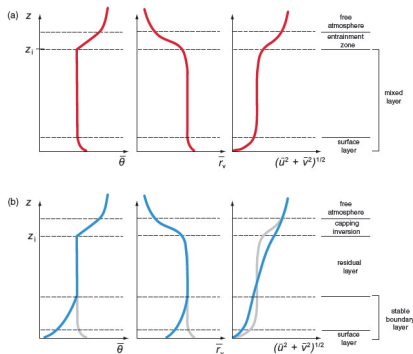
Nighttime BL Structure



- ▶ The depth of the RL compared to the depth of the SBL is largely a function of mean wind shear.
- ▶ The SBL can be as shallow as ~ 10 m on clear nights with minimal winds.
- ▶ Conversely, the SBL depth may be of the same order as the daytime CBL on cloudy nights with strong winds.

Structure and evolution

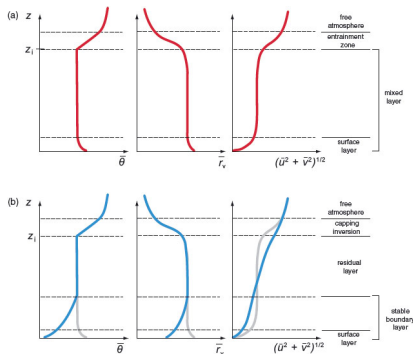
Nighttime BL Structure



- \bar{q} at the surface can either increase or decrease after sunset depending on the degree of dew formation versus the degree to which moisture was reduced in the daytime SL due to mixing.

Structure and evolution

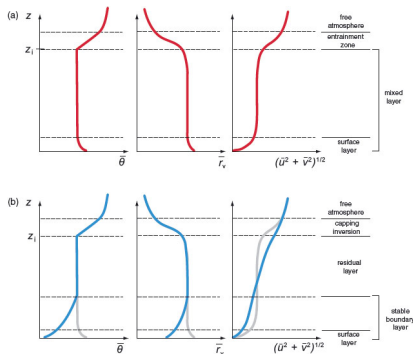
Nighttime BL Structure



- ▶ Winds at the top of the SBL and within the RL accelerate at night as surface drag is effectively eliminated.
- ▶ As a result, a nocturnal low-level wind maximum forms. This is often called the *low-level jet*. We will discuss the dynamics of the low-level jet in an upcoming section.

Structure and evolution

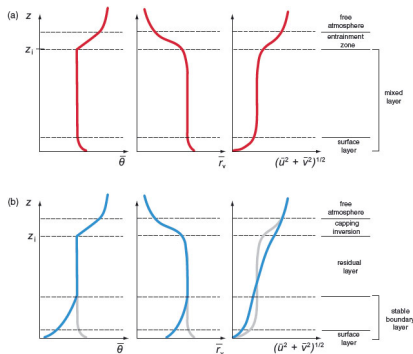
Nighttime BL Structure



- At the surface, negatively buoyant air tends to sink toward lower elevations. This results in so-called *drainage winds*, which are cold-air-runoff winds that are produced when air in contact with terrain surfaces is cooled and flows downslope (katabatic) and/or downvalley.

Structure and evolution

Nighttime BL Structure



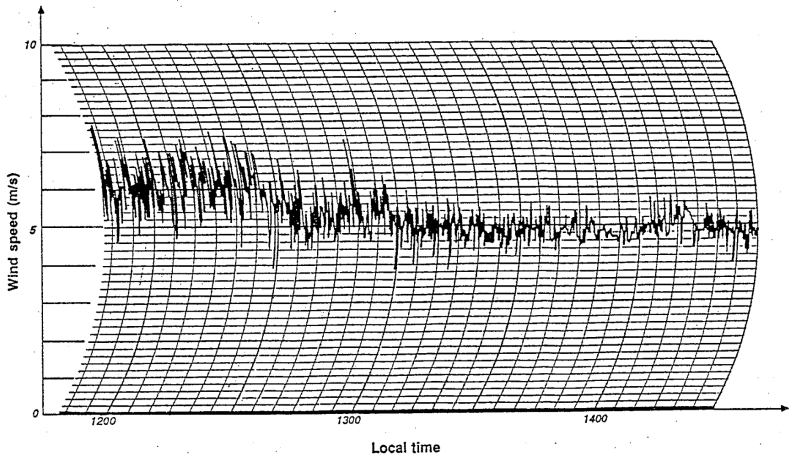
- Drainage winds also refer to gravity winds that drain cold air into frost hollows, river valleys, and other lower-lying terrain.

The nature of turbulent fluxes

Before considering specific boundary layer phenomena, we need to develop a set of equations that properly account for turbulent motions.

Reynolds averaging

Consider the time series plot of the wind speed shown here. The trace contains many high-frequency (fast) fluctuations. Such fluctuations are due to small turbulent eddies, which do not reliably represent the mean flow.



Reynolds averaging

To obtain a wind speed measurement representative of the large-scale flow, one must obtain take an average over a time period long enough to smooth over the fluctuations but still short enough for keep the trend.

Such averaging was first proposed by *Reynolds*, and is therefore named after him.

The End*

* After a math break!