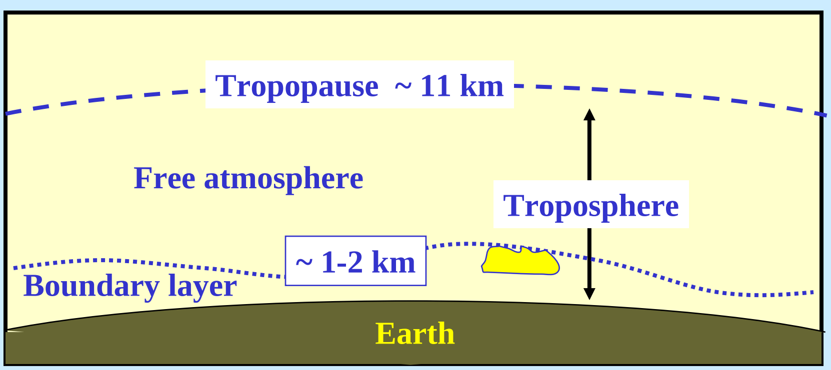
Boundary Layer Meteorology

Roger K. Smith

Contents

Literature

- J. R. Garratt **The atmospheric boundary layer** Cambridge University Press, 1992
- R. B. Stull **An introduction to boundary layer meteorology** Kluwer Academic Publishers, Dordrecht, 1988
- A comprehensive list of textbooks is given by Garratt (see pp12-13)



- Often only the lowest 2 km are directly modified by the boundary layer (BL).
- The **boundary layer** is 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.

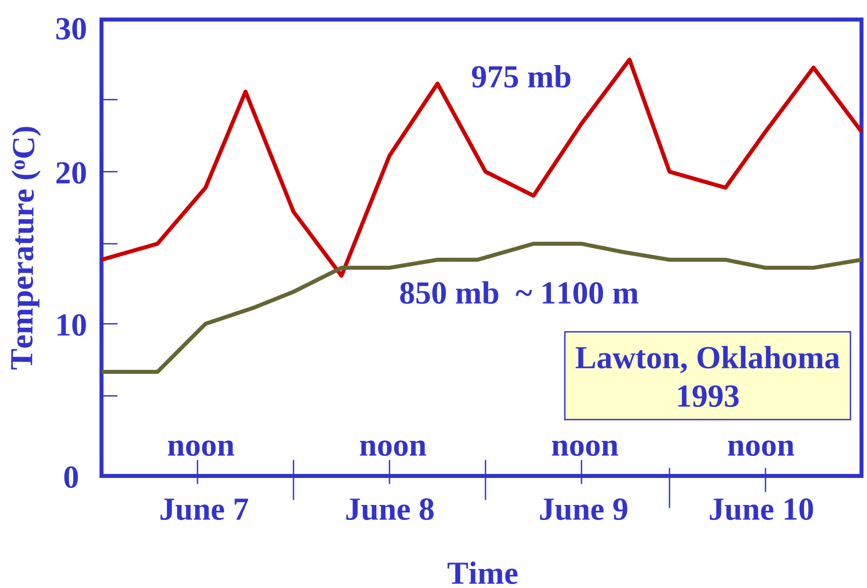
BL processes

BL processes include:

- ❖Frictional drag
- ❖Evaporation and transpiration
- ❖Heat transfer
- ❖Pollution emission
- ❖Terrain induced flow modification

The BL thickness is quite variable in time and space, ranging from hundreds of metres to a few km.

Temperature variations in the lower atmosphere



- **The diurnal variation is not caused by direct forcing of radiation on the boundary layer.**
- **Little solar radiation is absorbed in the BL; most is transmitted to the ground where typical absorptivities on the order of 90% result in the absorption of much of the solar energy.**
- **The ground that warms and cools in response to the radiation, which in turn forces changes in the BL via transport processes.**
- **Turbulence is one of the important transport processes, and is sometimes used to define the BL.**
- **Indirectly the whole troposphere can change in response to surface characteristics, but this response is relatively slow outside the boundary layer.**

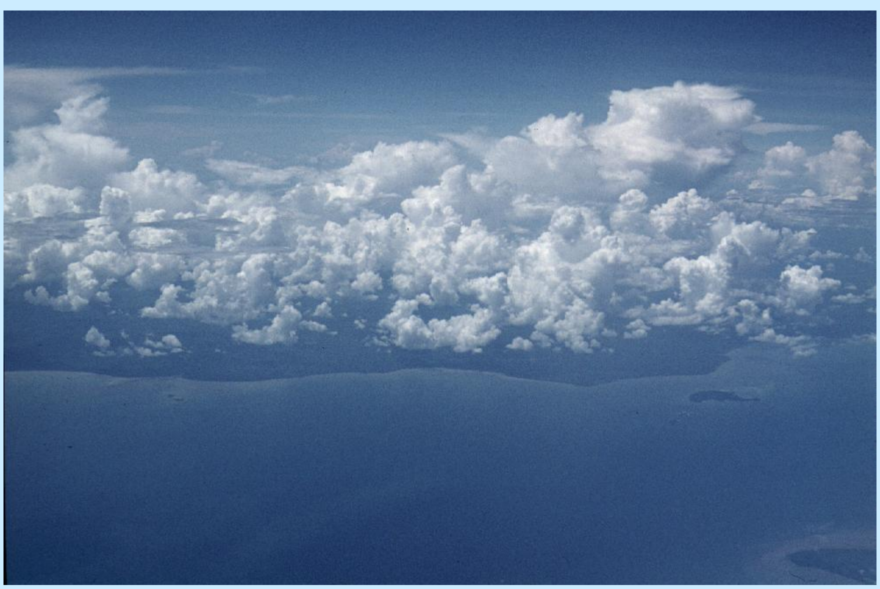
- **Two types of clouds are often included in boundary layer studies:**
  - **Fair-weather cumulus,**
  - **Stratocumulus.**
- **Fair-weather cumulus is so closely tied to thermals in the BL that it is difficult to study the dynamics of this cloud type without focusing on BL triggering mechanisms.**
- **Stratocumulus cloud fills the upper portion of a well-mixed humid BL where cooler temperatures allow condensation of water vapour.**
- **Fog, a stratocumulus cloud that touches the ground, is also a BL phenomenon.**

Fair weather cumulus

Stratocumulus

- **Thunderstorms**, while not a surface forcing mechanism, can modify the BL in a matter of minutes by drawing up BL air into the cloud, or by laying down a carpet of cold downdraught air.
- While thunderstorms are not normally thought of as BL phenomena, I shall review later their interaction with the BL.

Convection over land



Applications of boundary layer theory

- The atmospheric (or planetary) boundary layer plays an important role in many fields:
  - air pollution
  - agricultural meteorology
  - hydrology
  - aeronautical meteorology
  - mesoscale meteorology
  - weather forecasting and climate
  - urban meteorology

Application to urban meteorology

- Urban meteorology is associated with the low-level urban environment and air pollution, including air pollution episodes involving photochemical smog and accidental releases of dangerous gases.
- The dispersal of smog and low-level pollutants depends strongly on meteorological conditions.
- Of particular importance is information on the likely growth of the shallow mixed layer resulting from surface heating, and on the factors controlling the erosion and ultimate breakdown of the surface inversion.

Los Angeles Smog

The control and management of air quality

- is closely associated with the transport and dispersal of atmospheric pollutants, including industrial plumes.
- Processes of concern include turbulent mixing in the atmospheric BL, particularly the role of convection, photochemistry and dry and wet deposition to the surface.
- In this general area, research on atmospheric turbulence has a very important practical application, and local meteorology, including the role of mesoscale circulations (sea breezes, slope winds, valley flows) and the phenomenon of decoupling of the low-level flow and the large-scale upper flow, is of major relevance also.

Mount Isa Mines, Central Queensland, Australia

Aeronautical meteorology

- Is concerned with BL phenomena such as low cloud, low-level jets and intense wind shear leading to high-intensity turbulence, of particular interest for aircraft landing and taking off.
- In the case of low clouds and low-level jets, factors affecting their formation, maintenance and dissipation are of great importance.

Agricultural meteorology and hydrology

- Are concerned with processes such as the dry deposition of natural gases and pollutants to crops; evaporation, dewfall and frost formation.
- The last three are intimately associated with the state of the atmospheric BL, with the intensity of turbulence and with the energy balance at the surface.

Numerical weather prediction and climate simulation

- **These are based on dynamical models of the atmosphere and depend on the realistic representation of the Earth's surface and the major physical processes occurring in the atmosphere.**
- **No general circulation model is conceptually complete without a sufficiently accurate inclusion of BL effects, and no weather prediction model can succeed without a sufficiently accurate inclusion of the influence of the boundary.**
- **The BL affects both the dynamics and thermodynamics of the atmosphere.**

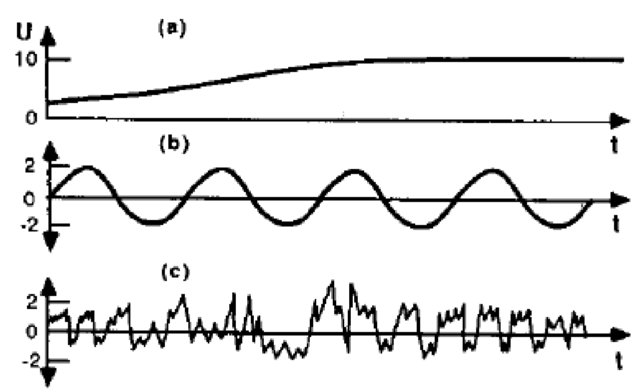
- **There is a variety of dynamical effects:**
  - **more than half of the atmosphere's KE loss occurs in the BL.**
  - **BL friction produces cross-isobar flow in the lower atmosphere and the vertical motion induced at the top of the BL causes vorticity changes in the free atmosphere above.**
- **Thermodynamical effects**
  - **all water vapour entering the atmosphere by evaporation from the surface must enter through the BL.**
- **The oceans gain most of their momentum through the boundary layer and this affects the ocean circulation.**

- From both climate and local weather perspectives, the most important BL processes that need to be parameterized in numerical models of the atmosphere are vertical mixing and the formation, maintenance and dissipation of clouds.
- Those land-surface properties that are potentially crucial to accurate climate simulation include albedo, roughness, moisture content and vegetation cover.

Mean wind, waves and turbulence

Air flow, or wind, can be divided into three broad categories: **mean wind, turbulence and waves:**

Fig. 1.3 Idealization of (a) Mean wind alone, (b) waves alone, and (c) turbulence alone. In reality waves or turbulence are often super-imposed on a mean wind. U is the component of wind in the x-direction.



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Mean winds

- Mean wind is responsible for very rapid horizontal transport, or **advection**. Horizontal winds on the order of 2 – 10 m/sec are common in the BL.
- Friction causes the mean wind speed to be slowest near the surface.
- Vertical mean winds are very much smaller, usually on the order of mm/sec to cm/sec near the surface.

Waves

- Waves are frequently observed in the nighttime boundary layer.
- Waves transport little heat, moisture, or pollutants, but they are effective in transporting momentum and energy.
- Waves can be generated locally by mean-wind shears and by mean flow over obstacles.
- Waves can propagate some distance from their source.

Turbulence

- The relatively high frequency of occurrence of turbulence near the ground is one of the characteristics that makes the BL different from the rest of the atmosphere.
- Outside of the BL, turbulence is primarily found in convective clouds, and near the jet stream where strong wind shears can create clear air turbulence (CAT).
- Sometimes atmospheric waves may enhance the wind shears in localized regions, causing turbulence. Thus wave phenomena can be associated with the turbulent transport of heat and pollutants, although waves without turbulence would not be so effective.

Decomposition of the wind

- A common approach for studying either turbulence or waves is to split the variables such as temperature and wind into a mean part and a perturbation part (e.g. $T = \overline{T} + T'$).
- The perturbation part can represent either the wave effect or the turbulence effect that is superimposed on the mean wind.
- When inserted into the equations of motion, new terms are created involving perturbation quantities.

Turbulence versus waves

- Products of perturbation quantities describe **nonlinear interactions** and are primarily associated with **turbulence** (these are usually neglected when wave motions are of primary interest).
- Other terms, containing only one perturbation variable, describe linear motions that are associated with waves (these are neglected when turbulence is emphasized).

Turbulence

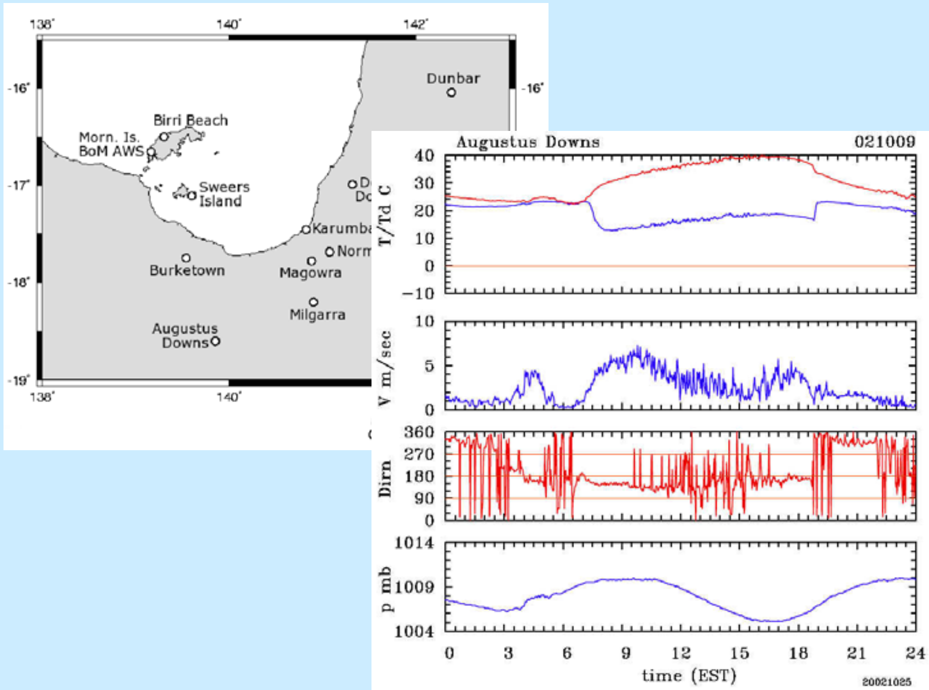
- Turbulence, the gustiness superimposed on the mean wind, can be visualized as consisting of irregular swirls of motion called **eddies**.
- Usually it consists of many different size eddies super-imposed on each other. The relative strengths of these different scale eddies define the **turbulence spectrum**.
- Much of the BL turbulence has its source at the ground:
  - **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.

Turbulent eddies

- The largest BL eddies **scale to** (i.e. have sizes roughly equal to) the depth of the BL; i.e. 100 to 3000 m in diameter.
- These are the most intense eddies.
- 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 mm in size, are very weak because of the **dissipating effects** of molecular viscosity.

Evidence of large BL eddies: cloud streets

Cloud streets



Taylor's hypothesis

- **We often need information on the size of eddies and on the scale of motion in the BL.**
- **It is difficult to create a snapshot picture of the BL.**
- **Instead of observing a large region of space at an instant of time, it is easier to make measurements at one point in space over a long period of time (e.g. instruments mounted on a tower can give a time record of the BL as it blows past them).**
- **In 1938, G. I. Taylor suggested that in certain circumstances, turbulence might be considered to be frozen as it advects past a sensor $\Rightarrow$ the wind speed measurements could be used to convert turbulence measurements as a function of time to their corresponding measurements in space.**

Applicability of Taylor's hypothesis

- Of course, turbulence is not really frozen ⇒ Taylor's assumption is useful only in cases where turbulent eddies evolve with a timescale longer than the time it takes for an eddy to be advected past a sensor.

Example

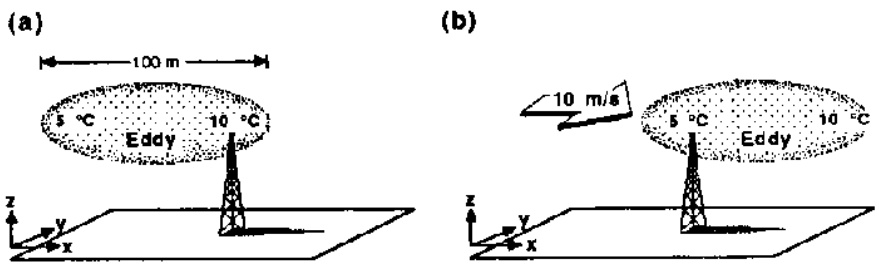


Fig. 1.4 Illustration of Taylor's hypothesis. (a) An eddy that is 100 m in diameter has a 5 ° C temperature difference across it. (b) The same eddy 10 seconds later is blown downwind at a wind speed of 10 m/s.

Temperature measured varies with time as the eddy advects past.

$$\frac{\partial T}{\partial x} = 0.05\ \mathrm{K/m} \qquad \frac{\partial T}{\partial t} = -0.5\ \mathrm{K/s} \quad \Rightarrow \quad \frac{\partial T}{\partial t} = -U\frac{\partial T}{\partial x}$$

Taylor's hypothesis for one dimension

Taylor's hypothesis

- **For any variable ξ, Taylor's hypothesis states that turbulence is frozen when**

$$\frac{D\xi}{Dt} = \frac{\partial \xi}{\partial t} + U\frac{\partial \xi}{\partial x} + V\frac{\partial \xi}{\partial y} + W\frac{\partial \xi}{\partial z} = 0$$

i.e.

$$\frac{\partial \xi}{\partial t} = -U\frac{\partial \xi}{\partial x} - V\frac{\partial \xi}{\partial y} - W\frac{\partial \xi}{\partial z}$$

This hypothesis can be stated also in terms of a wavenumber κ, and frequency, ν:

$$\kappa = f/U$$

$\kappa = 2\pi/\lambda$ → $\kappa = f/U$ ← $f = 2\pi/T$

λ = **wavelength** T = **period**

Taylor's hypothesis

- **To satisfy the requirements that the eddy undergoes negligible change as it advects past a sensor, Willis and Deardorff (1976)* suggest that $\sigma_M < 0.5U$, where σ_M, the standard deviation of the wind speed, is a measure of the intensity of the turbulence.**
- **Thus Taylor's hypothesis should be satisfactory when the turbulence intensity is small compared with the mean wind speed.**

*** Willis, G. E., and J. W. Deardorff, 1976: On the use of Taylor's translation hypothesis for diffusion in the mixed layer. QJ, 102, 817-822.**

Use of Taylor's hypothesis

- The validity of Taylor's hypothesis allows, for example, a frequency spectrum measured at a fixed point in space to be interpreted as the wavenumber spectrum measured at a point in time, and for aircraft data to be compatible with data obtained on a tower.

Boundary layer depth and structure

- Over oceans, the BL 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 layers of the ocean and the large heat capacity of water.
- A slowly varying SST means a slowly varying forcing of the atmospheric BL.
- Most changes in BL depth over oceans are caused by the advection of different air masses over the sea surface, and changes in vertical motion, associated with synoptic and mesoscale processes.
- An air mass with a near-surface temperature different from the SST will undergo modification until equilibration occurs.

- Once equilibration is reached, the resulting BL depth might vary by only 10% over a horizontal distance of 1000 km.
- Exceptions can occur near the borders between two ocean currents of different temperatures.
- Over both land and oceans, the BL tends to be thinner in high pressure regions than in low pressure regions.
- The subsidence and low-level 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 fair-weather cumulus or stratocumulus clouds.

- In low pressure regions the upward motions carry BL air away from the ground to large altitudes throughout the troposphere. It is difficult to define a BL top in these situations.
- Cloud base is often used as an arbitrary cut-off for BL studies in these cases.

Figure

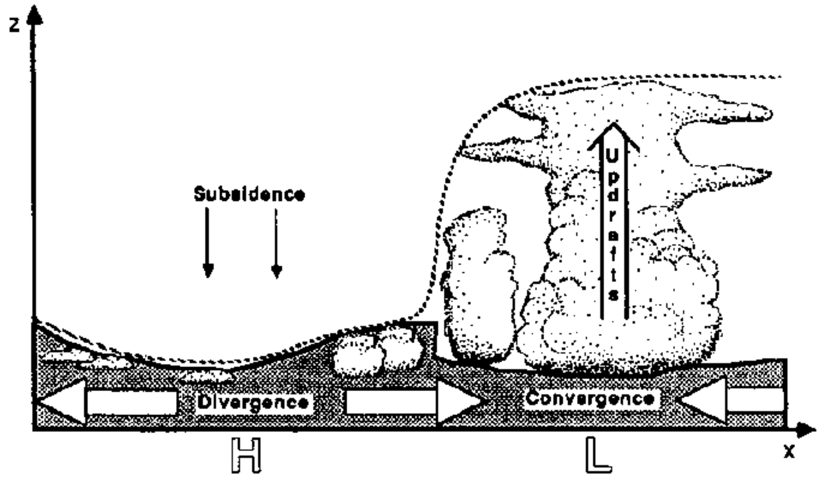
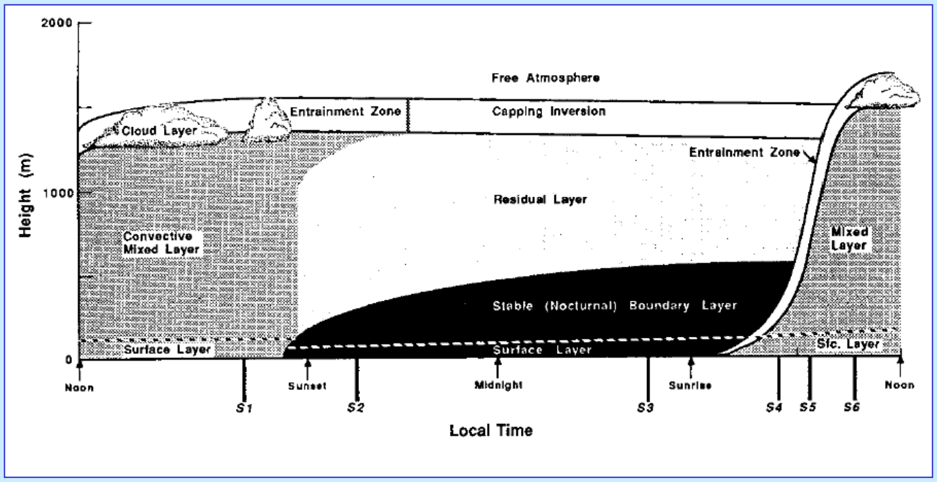


Fig. 1.6 Schematic of synoptic - scale variation of boundary layer depth between centers of surface high (H) and low (L) pressure. The dotted line shows the maximum height reached by surface modified air during a one-hour period. The solid line encloses the shaded region, which is most studied by boudary-layer meteorlogists.

- **Over land surfaces in high pressure regions, the BL has a well-defined structure that evolves with the diurnal cycle.**
- **The three major components of this structure are: the mixed layer, the residual layer, and the stable BL.**
- **When clouds are present in the mixed layer, it is further subdivided into a cloud layer and a subcloud layer.**
- **The surface layer is the region at the bottom of the BL where the turbulent fluxes and stress vary by less than** 10% **of their magnitude. Thus the bottom** 10% **of the BL is called the surface layer, regardless of whether it is part of a mixed layer or stable boundary layer.**
- **A thin layer, called a microlayer or interfacial layer, has been identified in the lowest few cm of air, where molecular transport dominates over turbulent transport.**



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.

The mixed layer

- **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, radiative cooling from the top of the cloud layer, and cooling associated with the evaporation of clouds.**
- **The first situation creates thermals of warm air rising from the ground, while the second and third create thermals of cool air sinking from cloud top, or from the region of evaporation.**
- **These mechanisms can occur simultaneously, the first two especially when a cool stratocumulus topped mixed layer is advected over warmer ground.**

- Even when convection is the dominant mechanism, there is usually **wind shear** across the top of the mixed layer and this contributes to turbulence generation.
- This free shear situation is akin to that which produces **CAT** and is believed to be associated with the formation and breakdown of **Kelvin-Helmholtz waves**.
- On initially cloud-free days, mixed layer growth is tied to solar heating of the ground. Starting about half an hour after sunrise, a turbulent mixed layer begins to deepen.
- This mixed layer is characterized by intense mixing in a statically unstable situation where thermals of warm air rise from the ground.
- The mixed layer reaches its maximum depth in the 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.
- Pollutants emitted from smoke stacks exhibit a characteristic looping as the portions of effluent emitted into warm thermals begins to rise.
- The resulting profiles of virtual potential temperature, mixing ratio, pollutant concentration, and wind speed are frequently as sketched in the next figure.

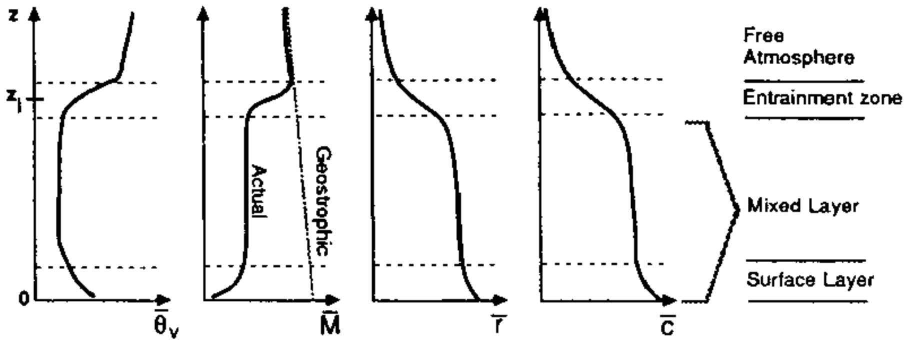


Fig. 1.9 Typical daytime profiles of mean virtual potential temperature $\bar{\theta}_v$, wind speed $\bar{M}$ (where $\bar{M}^2 = \bar{u}^2 + \bar{v}^2$), water vapor mixing ratio $\bar{r}$, and pollutant concentration $\bar{c}$.

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- **Most pollutant sources are near the earth's surface.**
- **Thus pollutant concentrations can build up in the mixed layer while free atmosphere 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.**
- **Trapping of pollutants below such an "inversion layer" is common in high pressure regions, and sometimes leads to pollution alerts in large urban communities.**

Boundary layer clouds

- As the tops of the highest thermals reach greater and greater depths during the course of the day, the highest thermals might reach their **lifting condensation level** (LCL) if sufficient moisture is present.
- The resulting fair-weather clouds are often targets for soaring birds and glider pilots, who seek the updraughts of thermals.
- High or middle level overcast can the insolation at ground level, thereby, reducing the intensity of thermals. On these days the mixed layer may exhibit slower growth, and may even become nonturbulent or neutrally stratified if the clouds are thick enough.

- If the ground is very wet, much of the insolation goes into evaporating water and again the intensity of thermals is reduced.
- Thus deep mixed layers are features of arid desert regions.

Trade wind cumulus

The residual layer

- About half an 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 residual layer during the night.

- The residual layer is neutrally stratified, resulting in turbulence that is nearly of equal intensity in all directions. As a result, smoke plumes emitted into the layer tend to disperse at equal rates in the vertical and lateral directions, creating a **cone-shaped plume**.

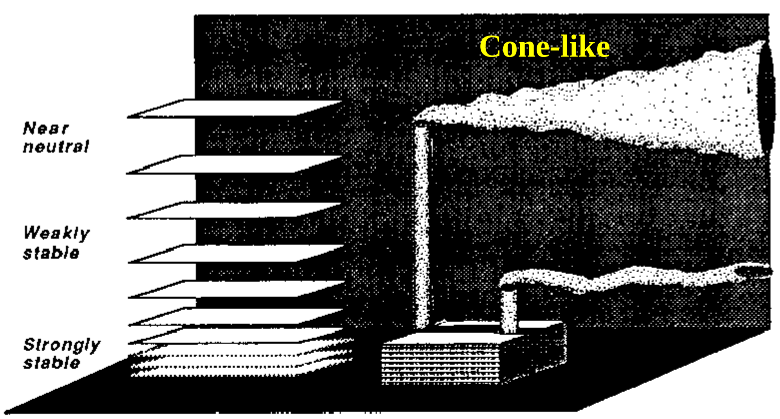


Fig. 1.10 The static stability decreases with height in the nocturnal boundary layer, gradually blending into the neutrally-stratified residual layer aloft, as indicated by the isentropic surfaces sketched on the left. Smoke emissions into the stable air fan out in the horizontal with little vertical 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.

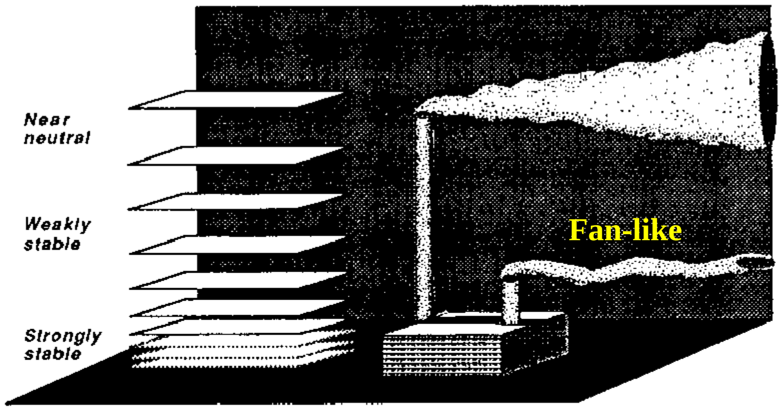
- Nonpassive pollutants may react with other constituents during the night to create compounds that were not originally emitted from the ground.
- Sometimes gaseous chemicals may react to form aerosols or particulates that can precipitate out.
- The residual layer often exists for a while in the mornings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

- Variables such as virtual potential temperature usually decrease slowly during the night because of radiative cooling.
- The cooling rate is on the order of $1^{o}C$ per day and is more-or-less uniform throughout the depth of the residual layer, thereby allowing the potential temperature profile to remain nearly adiabatic.
- When the top of the next day's mixed layer reaches the base of the residual layer, the mixed layer grows very rapidly.
- The residual layer does not have direct contact with the ground. During the night, the nocturnal stable layer gradually increases in thickness by modifying the bottom of the residual layer. Thus the remainder of the residual layer is not affected by turbulent transport of surface-related properties and hence does not really fall within our definition of a boundary layer.

The stable boundary layer

- As the night progresses, the bottom of the residual layer is transformed by its contact with the ground into a stable BL.
- 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 known as the **low-level jet** or **nocturnal jet**.
- The statically stable air tends to suppress turbulence, while the developing nocturnal jet enhances the vertical wind shear that tends to generate turbulence. As a result, turbulence sometimes occurs in relatively short bursts that can cause mixing throughout the stable BL.

- During nonturbulent periods, the flow becomes essentially decoupled from the surface.
- As opposed to the daytime mixed layer, which has a clearly-defined top, the stable BL has a poorly-defined top that blends smoothly into the residual layer above.
- The top of the mixed layer is defined as the base of the stable layer, while the top of the stable BL is defined as the top of the stable layer.
- Pollutants emitted into the stable layer disperse relatively little in the vertical. They disperse more rapidly, or **fan out**, in the horizontal. This behaviour is called **fanning**.
- Sometimes at night when winds are lighter, the effluent **meanders** left and right as it rifts downwind.



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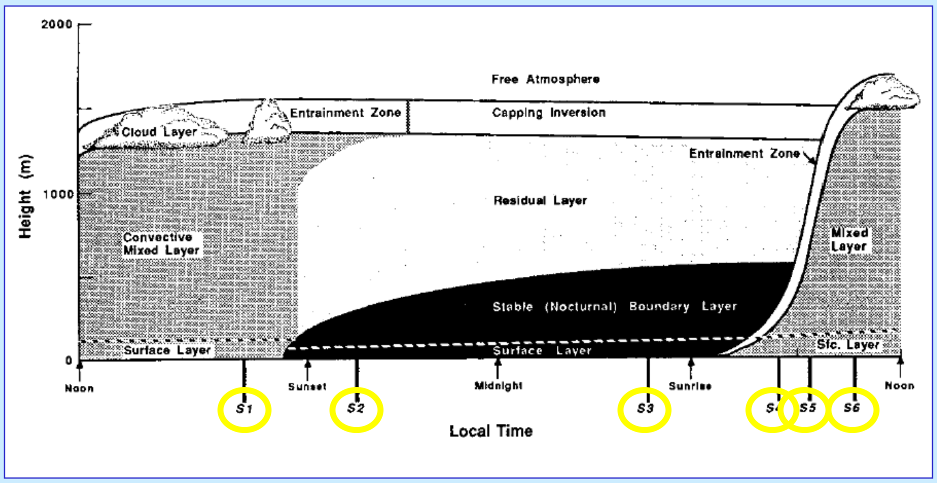
- **Winds exhibit a very complex behaviour at night.**
- **Just above ground level the wind speed often becomes light or even calm.**
- **At altitudes on the order of** 200 **m above the ground, the wind may reach** 10-30 **m** s^{-1} **in the nocturnal jet.**
- **Another few hundred metres above that, the wind speed is smaller and closer to its geostrophic value.**
- **The strong shears below the jet are accompanied by a rapid change in wind direction, where the lower level winds are directed across the isobars towards low pressure.**
- **Touching the ground, however, is a thin (order of a few metres) layer of katabatic or drainage winds. These are caused by the colder air, adjacent to the ground, flowing downhill under the influence of gravity.**

- Winds speeds of 1 m s^{-1} at a height of 1 m are possible.
- This cold air collects in the valleys and depressions and stagnates there.
- Unfortunately, many weather stations are located in or near valleys, where the observed surface winds bear little relationship to the broadscale flow at night.
- **Wave motions** are a frequent occurrence in the stable BL.
- The strongly-stable nocturnal boundary layer not only supports gravity waves, but it can trap many of the higher-frequency (acoustic) waves near the ground.
- Stable BLs can form also during the day, as long as the underlying surface is colder than the air. These situations occur during warm air advection over a colder surface, such as after a warm frontal passage or near shorelines.



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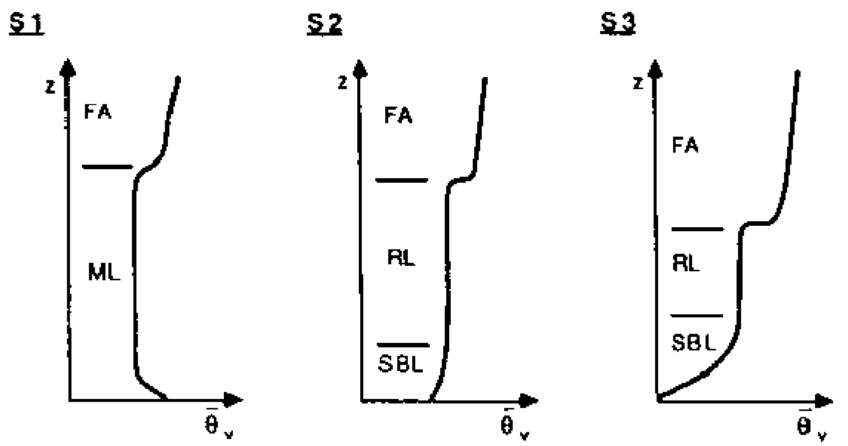
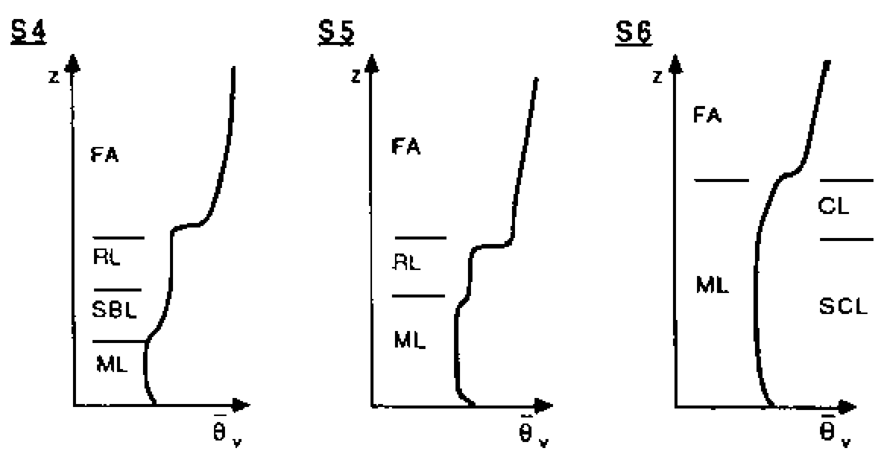
Evolution of virtual potential temperature



Late afternoon | After sunset | Before sunrise

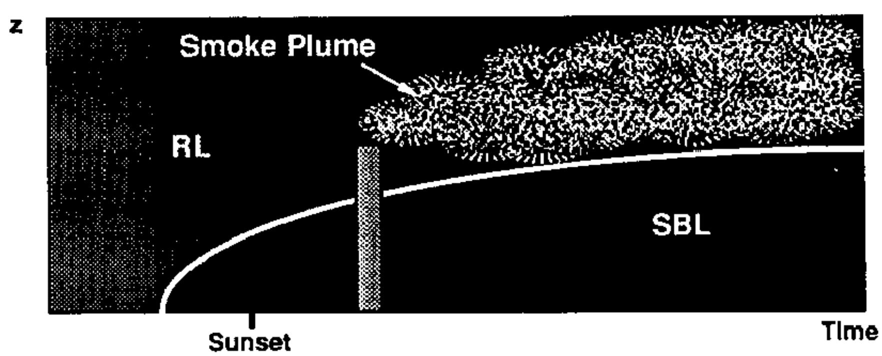
Evolution of virtual potential temperature



After sunrise | A little later | Before noon

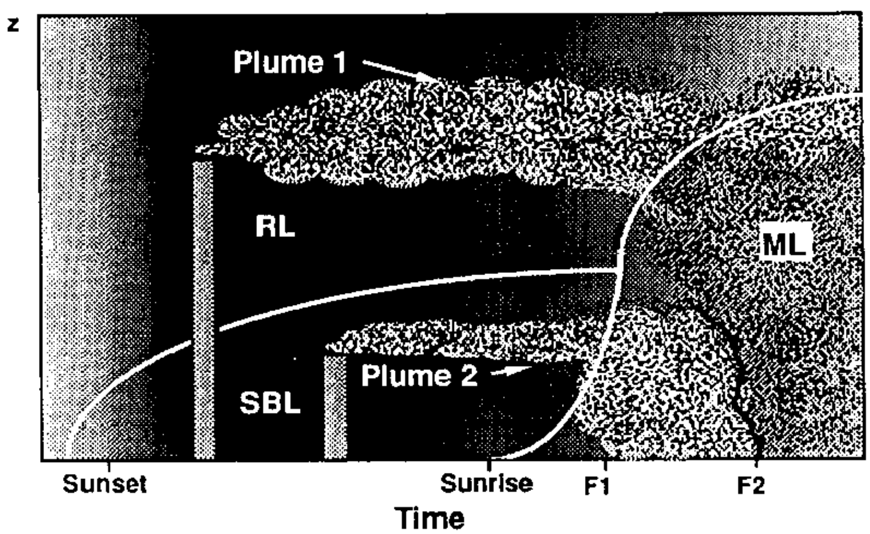
Evolution of smoke plumes

- As the virtual potential temperature profile evolved with time, so must the behaviour of smoke plumes.
- For example, smoke emitted into the top of the nocturnal BL or into the residual layer is rarely dispersed down to the ground during the night because of the limited turbulence. These smoke plumes can be advected hundreds of kilometres downwind from the source during the night.
- Smoke plumes in the residual layer may disperse to the point where the bottom of the plume hits the top of the nocturnal BL. The strong static stability and frequent reduction in turbulence reduces the downward mixing into the nocturnal BL. The top of the smoke plume can sometimes continue to rise into the neutral air. This is called lofting.

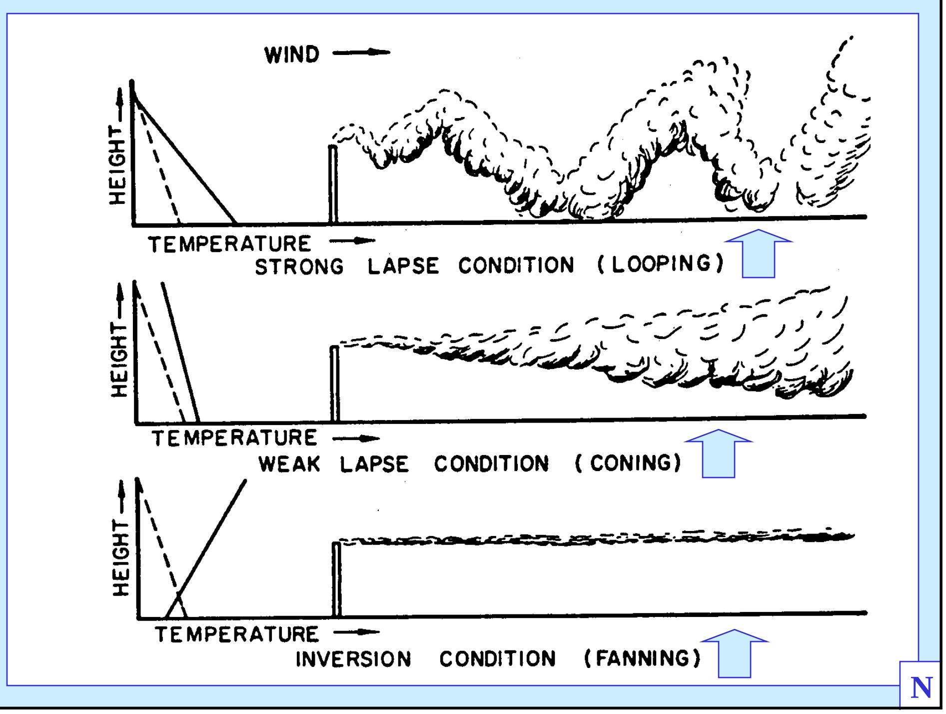


Lofting of a smoke plume occurs when the top of the plume grows upward into a neutral layer of air while the bottom is stopped by a stable layer.

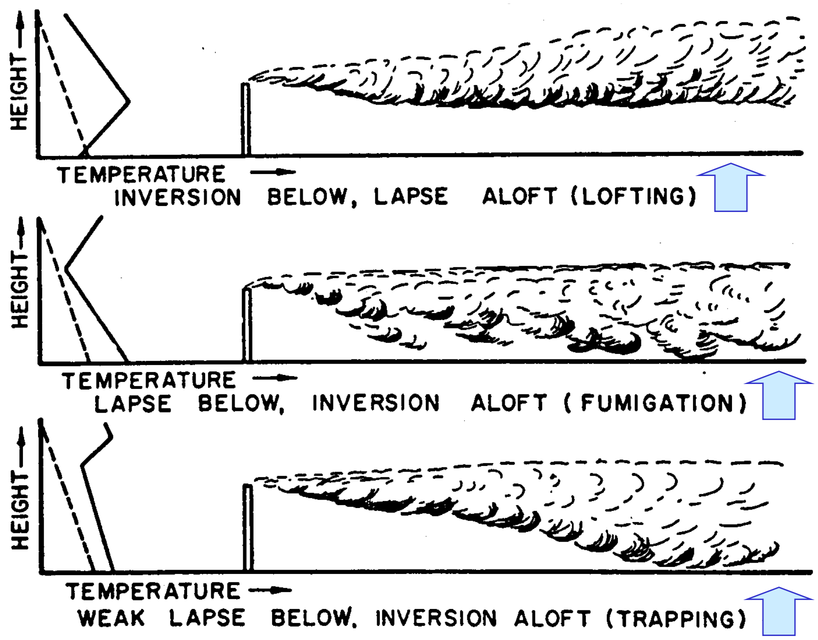
- After sunrise a new mixed layer begins to grow, eventually reaching the height of the elevated smoke plume from the previous night.
- At this time, the elevated pollutants are mixed down to the ground by mixed layer entrainment and turbulence in a process called fumigation.
- An analogous process is often observed near shorelines, where elevated smoke plumes in stable or neutral air upstream of the shoreline are continuously fumigated downstream of the shoreline after advecting over a warmer bottom boundary that supports mixed-layer growth.



Sketch of the fumigation process, where a growing mixed layer mixes elevated smoke plumes down to the ground. Smoke plume 1 is fumigated at time F1, while plume 2 is fumigated at time F2.



WIND
HEIGHT
TEMPERATURE
STRONG LAPSE CONDITION (LOOPING)
HEIGHT
TEMPERATURE
WEAK LAPSE CONDITION (CONING)
HEIGHT
TEMPERATURE
INVERSION CONDITION (FANNING)
N



Time and space scales for micro and mesoscales

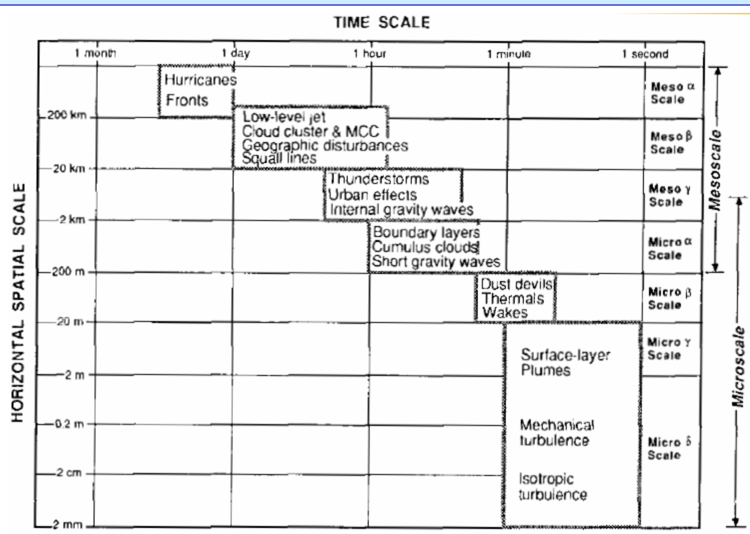


Fig. 1.15 Typical time and space orders-of-magnitude for micro and mesoscales. (After Orlanski, 1975.)

Microscale and Micrometeorology

- Compared with the other scales of meteorological motions, turbulence is on the small end.
- Phenomena such as turbulence with space scales smaller than about 3 km and time scales less than about an hour are classified as microscale.
- Micrometeorology is the study of such small scale phenomena.
- The study of the BL involves the study of microscale phenomena and BL Meteorology and Micrometeorology are virtually synonymous.

Methods of micrometeorology

- Because the BL is mostly turbulent, a deterministic approach is not possible.
- As a result,micrometeorologists have developed three primary avenues for exploring their subject:
  - Stochastic methods
  - Similarity theory
  - Phenomenological classifications
- Stochastic methods deal with the average statistical effects of turbulence.
- Similarity theory involves the apparent common-behaviour exhibited by many empirically-observed phenomena, when properly scaled.

- In **phenomenological methods**, the largest size structures such as thermals are classified and sometimes approached in a partly deterministic manner.

Boundary Layer Experiments

- Micrometeorology has relied heavily on field experiments to learn more about the BL.
- Unfortunately, the large variety of scales involved and the large variability in the vertical require a large array of sensors including airborne platforms and remote sensors.
- There has been a few famous BL experiments:
  - Wangara, Hay, NSW, Australia, 1967
  - Kansas Experiments, 1968
  - BOMEX, Carribean, 1969
  - Koorin, Daly Waters, NT, Australia, 1974
  - AMTEX, East China Sea, 1974, 1975
- A more complete list is given by Stull (p418-419)

- Alternative studies have used **numerical** and **laboratory simulations**.
- Much of the turbulence work has been performed in laboratory tanks, usually using liquids such as water as the working medium.
- There have been many successful laboratory studies of small-scale turbulence, but only a few simulations of larger phenomena such as thermals.
- Wind tunnel studies have been used to observe the flow of the neutral BLs over complex terrain and buildings.
- Because of the difficulty of stratifying the air has meant that typical daytime and nighttime BLs have not been adequately simulated.