Lecture Notes on Boundary Layer Meteorology

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Abstract
Notes of Lectures and addional information from books:
An introduction to boundary layer meteorology([1]).

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1. Lecture 1 09/01/2025

1.1 Introduction to Boundary Layer

The Boundary Layer can be defined as part of the troposphere that is directly influenced by the presence of the Earth's surface and responds to surface forcings with a time scale of about an hour or less.

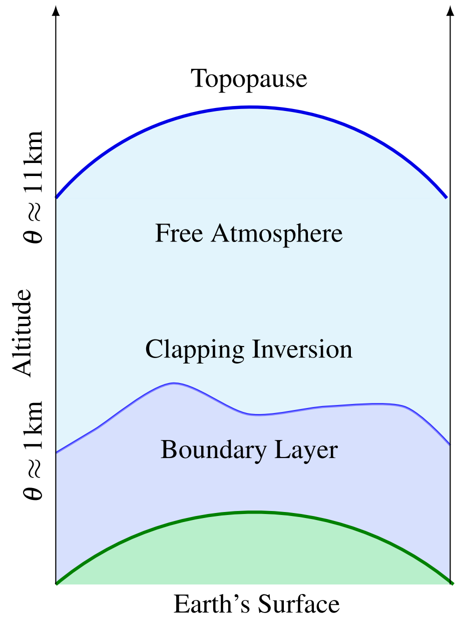


Figure 1. Atmosphere can be divided into 2 parts: boundary layer near surface and free atmosphere above it.

1.2 Boundary layer forcing mecchanism

What physical process modify boundary layer air parcel?

1. Heat transfer to.from the ground.
2. Frictional drag.
3. Evaporation/transpiration.
4. Terrain-induced flow modification.
5. Pollution emission.

1.3 Types of air flow or wind

Air flow or wind can be decomposed into following 3 types:

1. **Mean Wind** $(\bar{u}, \bar{v}, \bar{w})$: Represents the average wind components in the horizontal $(\bar{u}, \bar{v})$ and vertical $(\bar{w})$ directions. It is important for the horizontal transport of quantities such as moisture, heat, momentum, and pollutants, a process known as advection.
2. **Waves**: Atmospheric waves, such as gravity waves, occur mostly at night in the nocturnal boundary layer (NBL). They can influence the structure of the boundary layer and the transport of energy.
3. **Turbulence**: The vertical transport of moisture, heat, momentum, and pollutants is primarily dominated by turbulence, which is characterized by chaotic and irregular motion.

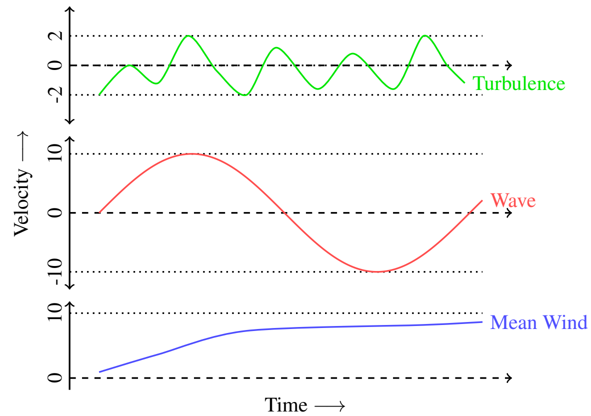


Figure 2. Plot showing profiles of Mean, Wave and Turbulent winds

1.4 Eddies

Eddies are formed due to the interaction of currents with obstacles like coastlines, underwater topography, or other currents, as well as from the instability of larger current systems. Eddies exhibit a rotational flow pattern, either clockwise or counterclockwise. Eddies can vary from size 100 to 3000 metres and also can exists as small as few millimetres. Small eddies might last for seconds to minutes, while larger oceanic eddies can persist for weeks, months, or even years.

1.5 Turbulence Generation Mechanisms

- **Solar Heating**: Solar heating generates thermals, which are essentially larger eddies that drive turbulence in the atmospheric boundary layer.
- **Wind Shear**: Variations in wind speed or direction with height create wind shear, which is a significant source of turbulence.
- **Obstacle-Induced Flow**: Deflected flow around obstacles such as trees, buildings, or other structures generates turbulent eddies downstream of these obstacles, creating turbulent wakes.

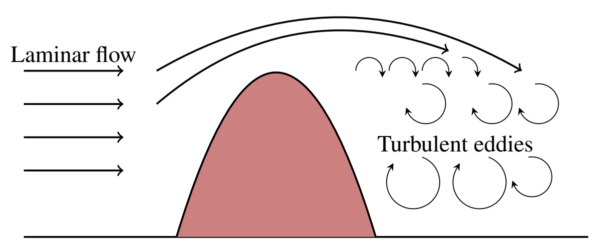


Figure 3. Eddy formation due to Turbulence caused by an obstacle

Large eddies will break into smaller eddies after which small eddies dissipates from K.E. to thermal energy.

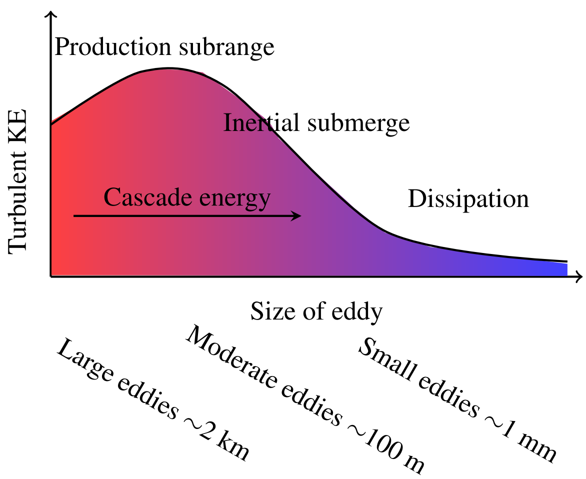


Figure 4. Variation of Turbulent Kinetic energy with change in Size of eddies

Todo:
1. BLD figure

2. Leture 2 15/01/2025

2.1 Taylor's Hypothesis

- When studying atmospheric boundary layer (ABL), It is not easy to create a snapshot of turbulence in the Atmosphere.
- Hence it is easier and cheaper to make measurements of point in the atmoshpere for a longer time, then an instantaneous snapshot.
- So we just consider the atmoshpere is frozen.
- ***Taylor suggested that turbulence can be considered frozen as it advects past sensor.***

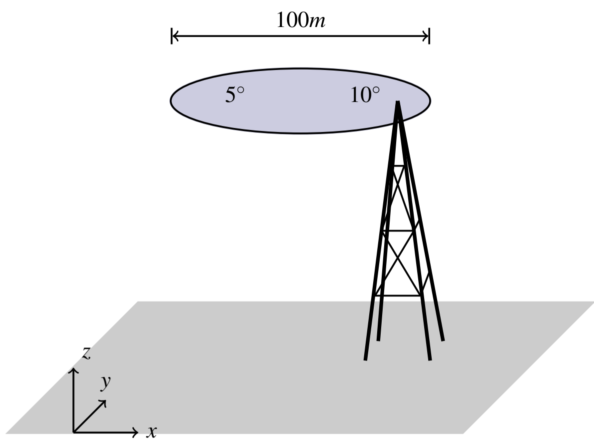


Figure 5. Eddy propagation

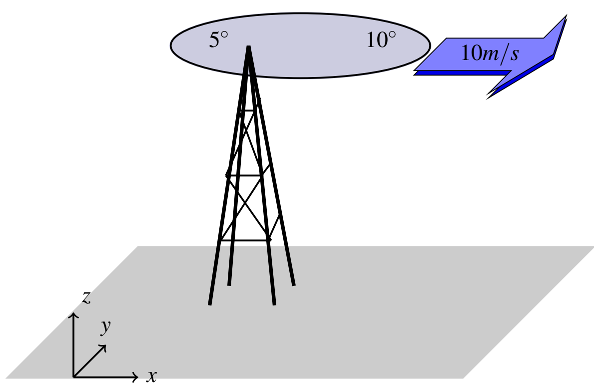


Figure 6. Eddy passing by the sensor mounted on tower

$$\frac{\partial T}{\partial x} = 0.05\text{K/m}, \quad \frac{\partial T}{\partial t} = -0.5\text{K/s}$$

$$\underbrace{\cancel{\frac{DT}{Dt}}}_{\substack{\text{Total derivative = 0}\\ \text{(Taylor's hypothesis)}}} = \underbrace{\frac{\partial T}{\partial t}}_{\text{Local derivative}} + \underbrace{u\frac{\partial T}{\partial x}}_{\text{Advective term}}$$

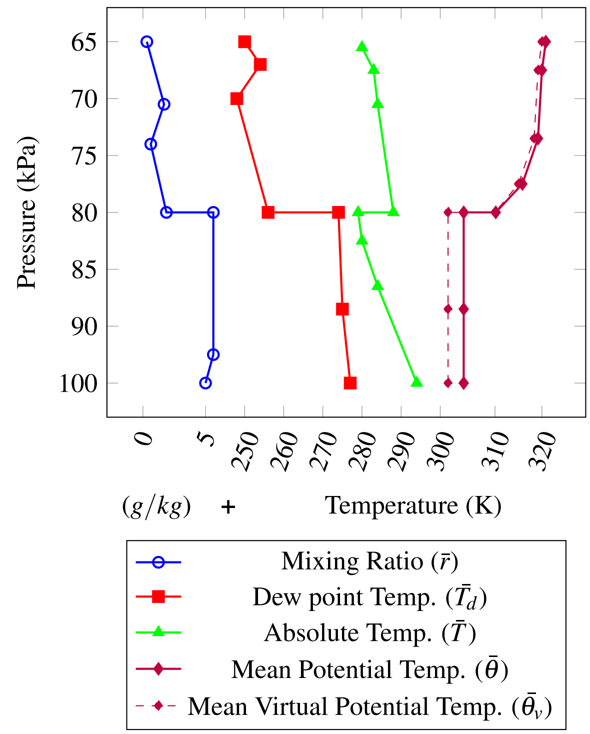
2.2 Virtual Potential Temperature

Virtual potential temperature:

$$\theta_v = \theta(1+0.61r) \tag{1}$$

Virtual temperature:

$$T_v = T(1+0.61r) \tag{2}$$



Question 2.1:

Given 25°C termperature, mixing ratio $\bar{r}$ is $20g/kg$, measured Pressurere at $900hPa$, find virtual potential temperature.

Answer 2.1:

Solution:

$$\begin{aligned}
\theta &= T \times \left(\frac{1000}{P}\right)^{0.286} \\
&= 298 \times \left(\frac{1000}{900}\right)^{0.286} \\
&= 332.222K \\
\theta_v &= \theta \times \left(1 + 0.61r\right) \\
&= 332.22 \times \left(1 + 0.61 \times 0.025\right) \\
&= 336.273K \\
\theta_v - \theta &\approx 4.05K
\end{aligned}$$

2.3 Boundary Layer Depth and Structure

- Mixed layer

- Residual layer
- Stable Boundary layer
- Capping Inversion
- Nauturnal Boundary layer

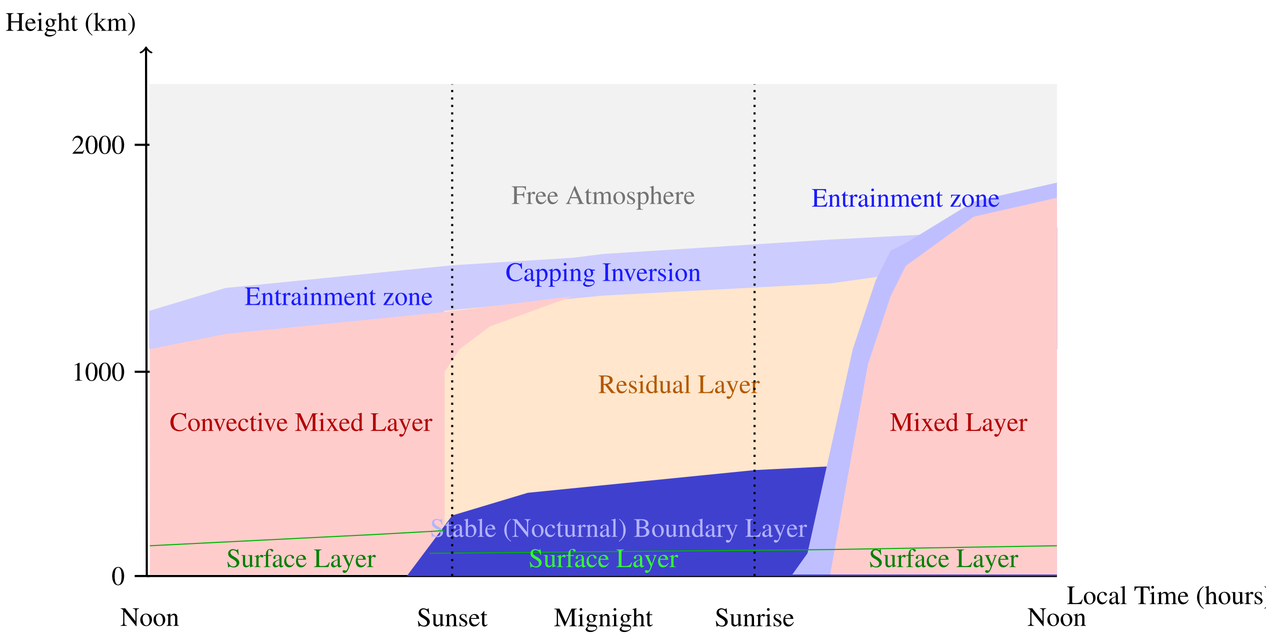


Figure 7. Height vs Local Time Diagram of Atmospheric Boundary Layers.

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Ocean: Variations are minimal, with only 10% changes observed over 1000 km. Significant variations occur primarily during weather phenomena.
Land: Day-to-day and diurnal variations are prominent, with distinct boundary layer structures:

1. **Convective Mixed Layer:** Thermodynamically unstable with intense vertical mixing.
2. **Residual Layer:** Neutral stratification with turbulence of equal intensity in all directions.
3. **Stable Boundary Layer (Nocturnal B.L.):**
   - Neutral stratification with nocturnal jets (30 m/s, 200 m width).
   - Sporadic turbulence and internal gravity waves transporting air parcels vertically.
4. **Capping Inversion:** Found at altitudes between 1.5–3 km, acting as a barrier to upward mixing.
5. **Entrainment Zone:** Transition region from stable to unstable conditions, facilitating energy and mass exchange.

3.1 Stability and Plume Behaviour

1. **Looping plumes:** Looping plumes occur in highly unstable atmospheric conditions, often during the day when strong surface heating creates significant vertical mixing. In this scenario, warm air rising from the surface interacts turbulently with the cooler surrounding air, resulting in an oscillatory motion where the plume alternately rises and descends. This turbulence promotes widespread dispersion of pollutants in multiple directions and is commonly observed in arid or desert-like regions with intense solar heating.

2. **Fanning plumes:** Fanning plumes are characteristic of stable atmospheric conditions, especially during nighttime when surface radiational cooling leads to temperature inversions. Under these conditions, vertical mixing is suppressed, and the plume spreads laterally, forming a horizontal ”fan” near the ground. This behavior often results in pollutants being dispersed over a larger horizontal area but concentrated closer to the surface, posing significant air quality concerns in urban or industrial areas.

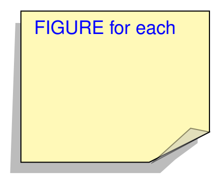
3. **Coning plumes:** Coning plumes emerge under neutral atmospheric conditions, where vertical mixing is moderate. The plume exhibits a cone-like shape as it rises and spreads symmetrically in both vertical and horizontal directions. These plumes are typically observed during overcast days or in the early morning and late evening when temperature gradients are minimal, and turbulence levels are balanced.

4. **Lofting plumes:** Lofting plumes occur under conditions where the atmosphere is stable below the emission source and unstable above it. In this case, the pollutants rise and disperse above the stable layer, avoiding significant downward mixing. Lofting is advantageous for minimizing ground-level pollution, as the emissions remain elevated and do not contribute significantly to surface concentrations.

5. **Fumigation plumes:** Fumigation occurs when pollutants emitted into a stable layer above an unstable surface layer are entrained downward due to rising turbulence during the day. This results in high concentrations of pollutants at the surface, posing significant risks to air quality and human health, especially in industrial regions.

6. **Sigmoidal plumes:** Sigmoidal plumes form when the plume rises and bends due to wind shear or changing atmospheric stability with height. This creates an S-shaped dispersion pattern often observed in areas with layered winds or transitions in stability, such as near mountain ranges.

7. **Eruptive plumes:** Eruptive plumes are associated with highly energetic sources like volcanic eruptions, wildfires, or explosions. These plumes rise rapidly and explosively, often penetrating through the atmosphere's stable layers and dispersing pollutants at higher altitudes, leading to long-range transport.



3.2 Importance of Boundary Layer

The boundary layer plays a critical role in regulating interactions between the Earth's surface and the atmosphere. Its study is important in various fields, including:

1. **Agricultural meteorology:** Understanding microclimates within the boundary layer aids in crop management, irrigation planning, and predicting the effects of extreme weather on agriculture.

2. **Air pollution meteorology:** Dispersion and concentration of pollutants are governed by boundary layer processes, making it crucial for air quality monitoring and pollution control strategies.

3. **Cloud nuclei meteorology:** The boundary layer provides a reservoir of aerosols and moisture that act as cloud condensation nuclei, influencing cloud formation, precipitation, and local weather patterns.

4. **Thunderstorms and hurricanes physics:** The exchange of heat, moisture, and momentum in the boundary layer drives the development and intensity of thunderstorms and hurricanes, making it essential for improving weather prediction models.

5. **Urban meteorology:** The boundary layer's interactions with urban landscapes affect local climate, energy balance, and pollutant dispersion, aiding in city planning and sustainability efforts.

6. **Renewable energy:** Wind energy potential and efficiency are heavily dependent on boundary layer dynamics, which dictate wind speed profiles and turbulence levels near the surface.

Incomplete

References

[1] R. B. Stull. *An Introduction to Boundary Layer Meteorology*. Atmospheric Sciences Library. Kluwer Academic Publishers, 1988.