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.

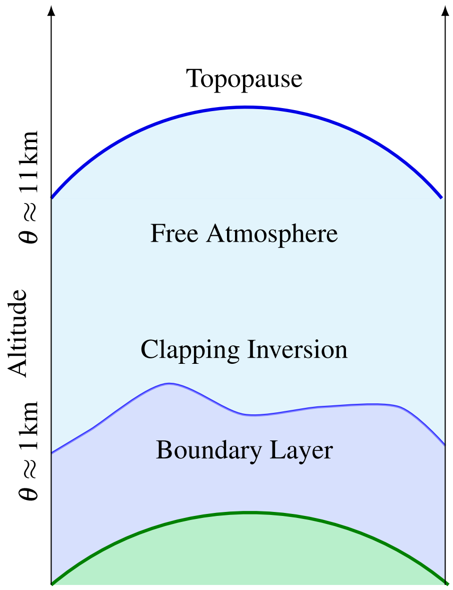


Figure 1. Atmosphere can be divided into 2 parts: boundary layer near surface and free atmosphere above it.

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.

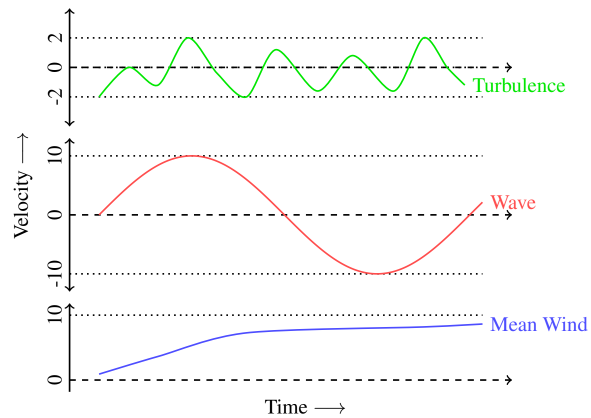


Figure 2. Plot showing profiles of Mean, Wave and Turbulent winds

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.

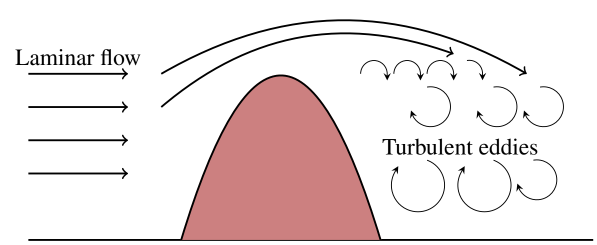


Figure 3. Eddy formation due to Turbulence caused by an obstacle

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

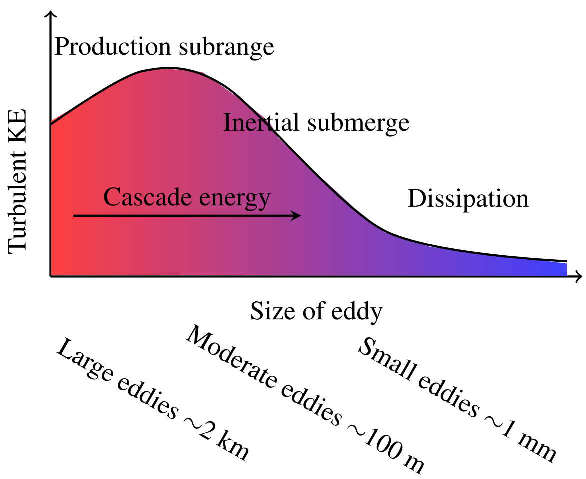


Figure 4. Variation of Turbulent Kinetic energy with change in Size of eddies

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.***

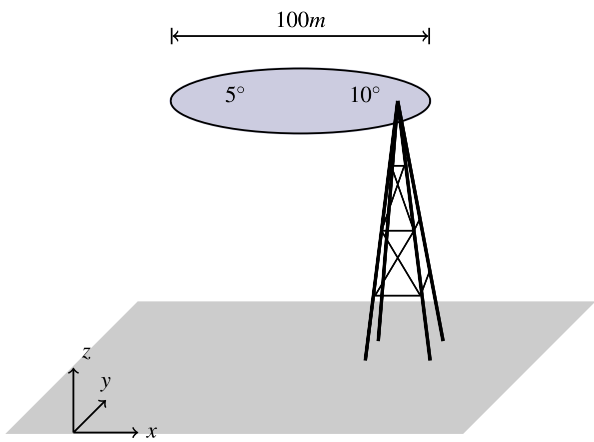


Figure 5. Eddy propagation

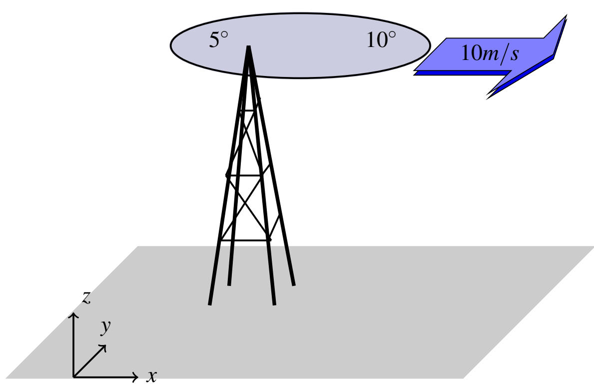


Figure 6. Eddy passing by the sensor mounted on tower

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

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

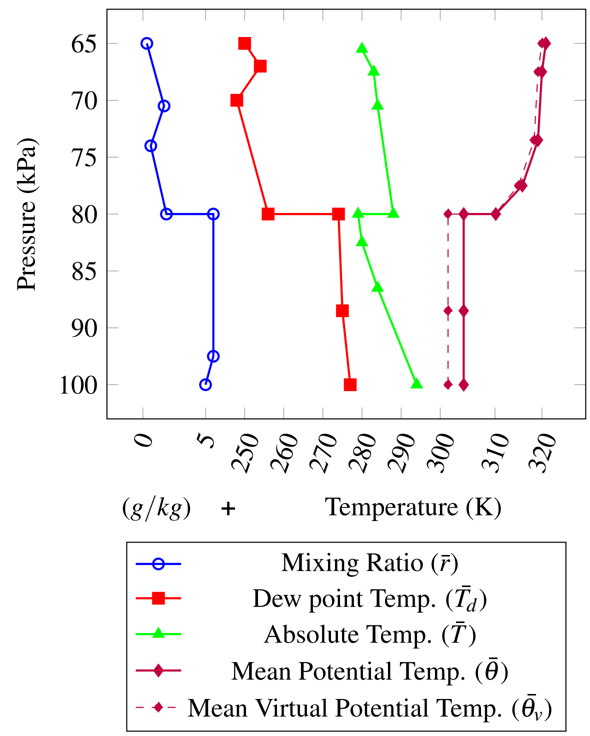
2.2 Virtual Potential Temperature

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.

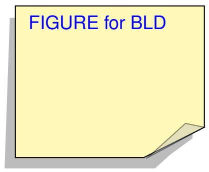
Answer 2.1:

Solution:

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

2.3 Boundary Layer Depth and Structure

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



2.4 Stability and Pluming Behaviour

1. **Looping plumes** occurs in highly unstable conditions and results in the formation of turbulence caused by the rapid mixing of warm air rising from the source and cooler surrounding air. This leads to a vertical development of the plume, with the plume rising and descending intermittently. It is typically seen in conditions where the surface heating is strong, such as during the day in a hot, dry environment. Looping plumes indicate turbulent mixing, which can lead to the dispersion of pollutants in all directions.

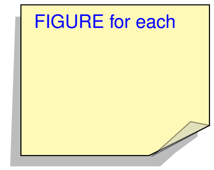
2. **Fanning plumes** occur under stable atmospheric conditions, especially during the nighttime when the temperature of the air near the ground is cooler than the air higher up (due to radiational cooling). In these conditions, the plume spreads horizontally as the rising air is restrained from mixing vertically. This results in a plume that fans out, typically staying near the ground and dispersing pollutants over a wide area. Fanning plumes are more commonly observed in the nocturnal layer, where the surface inversion traps the plume's dispersion.

3. **Coning plumes** occur in neutral atmospheric conditions, where the plume rises vertically but begins to spread out in a cone shape due to moderate turbulence. This behavior is observed under typical daytime conditions with moderate mixing.

4. **Sigmoidal plumes** form an S-shape when the plume initially rises and then bends or loops due to wind shear or changing atmospheric conditions, leading to a sigmoidal dispersion pattern.

5. **Rising plumes** occur in extremely unstable conditions, where the plume rises vertically without much lateral spreading. This is seen in convective systems like strong daytime heating or thunderstorms.

6. **Eruptive plumes** are associated with high-energy sources like volcanic eruptions, where the plume rises rapidly and explosively due to intense heat or pressure, leading to rapid dispersion at higher altitudes.



References

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