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Anjugramam - Kanyakumari Main Road, Palkulam, Variyoor P.O. - 629 401, Kanyakumari District.

CAI 335 : SOLAR AND WIND ENERGY SYSTEMS

UNIT 3

WIND MAPPING ANALYSIS AND CHARACTERISTICS OF WIND

Prepared by:

Mr.Arunpandian.N.

Assistant Professor

Department of Agricultural Engineering

Nature of Wind: Wind Structure and Measurement

Wind is the movement of air from areas of high pressure to areas of low pressure, driven by the uneven heating of the Earth's surface by the Sun. The nature and behavior of wind depend on several factors, including temperature, geography, atmospheric pressure, and the rotation of the Earth. Understanding the structure of wind and how to measure it is crucial in fields such as meteorology, renewable energy (wind power), aviation, and environmental science.

1. Nature of Wind

a. What is Wind?

Wind is essentially air in motion relative to the Earth's surface. It is a natural phenomenon that occurs due to the Earth's uneven heating by the Sun, which leads to differences in air pressure. Wind flows from regions of **high pressure to low pressure**, and the Earth's rotation (Coriolis effect) causes wind patterns to be deflected, further influencing wind behavior.

b. Factors Influencing Wind

Several key factors influence the speed, direction, and nature of wind:

- **Temperature Differences:** The Sun heats different parts of the Earth's surface at varying rates, creating areas of high and low temperatures. These temperature differences cause air to expand and rise in warmer regions (creating low pressure) and cool and sink in colder regions (creating high pressure). This movement of air from high to low pressure is what we perceive as wind.
- **Atmospheric Pressure:** The difference in atmospheric pressure between two regions is one of the primary drivers of wind. Wind flows from areas of high pressure to areas of low pressure to equalize the pressure differences.
- **Coriolis Effect:** Because the Earth rotates, moving air (wind) is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This deflection modifies the wind's direction and plays a critical role in the global wind patterns, such as trade winds, westerlies, and polar easterlies.
- **Friction:** Wind interacts with the surface of the Earth, which causes friction. This friction slows the wind down, particularly near the ground, and can alter its direction. In areas with rough terrain or urban settings, the effect of friction on wind speed and direction is more noticeable.
- **Topography:** Mountains, valleys, and bodies of water can significantly affect wind patterns. For instance, winds can be funneled through valleys or deflected by mountains, leading to changes in wind speed and direction. Large bodies of water like oceans or lakes can also moderate temperature differences and influence regional wind patterns.

c. Wind as an Energy Source

Wind has been harnessed for human use for centuries, most notably through windmills and now with modern wind turbines. Wind power is a renewable energy source, and its variability depends on local wind conditions, such as the average wind speed, the frequency of gusts, and the direction of wind over time.

2. Wind Structure

Wind exhibits a structured pattern influenced by the Earth's rotation, the differential heating of the Earth's surface, and the physical characteristics of the environment. Wind structure can be understood by examining its distribution across different levels of the atmosphere and the forces acting upon it.

a. Vertical Wind Structure

The structure of wind changes as you move from the Earth's surface to higher altitudes in the atmosphere. Some of the key layers and structures include:

- **Boundary Layer (Surface Layer):**
 - The **boundary layer** is the lowest layer of the atmosphere, extending from the Earth's surface up to about 1-2 kilometers (about 3,000-6,000 feet). This is where friction between the air and the Earth's surface affects wind speed and direction.
 - In this layer, the wind is slower due to the frictional forces acting on it, and the wind direction can change due to the influence of local geography, such as mountains, forests, and buildings.
- **Free Atmosphere:**
 - Above the boundary layer lies the **free atmosphere**, where friction is minimal and wind speed increases with altitude. In this region, wind patterns are influenced more by the pressure differences and the Coriolis effect.
 - Wind direction in the free atmosphere tends to be more consistent and can follow large-scale circulation patterns, such as the westerlies or trade winds.
- **Jet Stream:**
 - At higher altitudes (about 8-15 km or 5-9 miles), the **jet stream** exists as narrow bands of high-speed wind that flow from west to east in both hemispheres. These strong winds at high altitudes are influenced by temperature differences between polar and tropical air masses and the Earth's rotation.

b. Horizontal Wind Structure

Wind also exhibits horizontal structures, and its patterns vary based on geographic location, the time of year, and atmospheric pressure systems. Some significant horizontal wind patterns include:

- **Global Wind Circulation:**

- The Earth's wind patterns are driven by the combination of the **Coriolis effect** and **differential heating** of the Earth's surface.
- **Trade Winds:** These winds blow from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere. They are found in the tropics, between the equator and about 30 degrees latitude.
- **Westerlies:** Winds that blow from the west towards the east in the mid-latitudes (30 to 60 degrees latitude). They are responsible for much of the weather systems in temperate regions.
- **Polar Easterlies:** Winds that blow from east to west near the poles.
- **Local Wind Systems:** In addition to global wind patterns, local winds, such as **sea breezes**, **land breezes**, and **mountain/valley winds**, develop due to local temperature differences. These wind patterns are more temporary and can vary based on time of day and geographical features.

3. Measuring Wind

Wind measurement is crucial for understanding local weather patterns, forecasting, and harnessing wind energy. Several instruments are used to measure the speed, direction, and other characteristics of wind.

a. Wind Speed Measurement

Wind speed is typically measured using:

- **Anemometer:**
 - The most common instrument for measuring wind speed, it can be mechanical (cup or vane type) or electronic (ultrasonic or hot-wire anemometers).
 - **Cup Anemometer:** Consists of three or four cups mounted on horizontal arms. As the wind blows, it rotates the cups, and the speed of rotation is proportional to the wind speed.
 - **Vane Anemometer:** A small fan that spins in the wind, with the speed of the spin corresponding to wind speed.
 - **Hot-wire Anemometer:** Measures wind speed based on the cooling effect of the wind on a heated wire. It is highly sensitive and used in more precise applications.

b. Wind Direction Measurement

- **Wind Vane:** A wind vane is a simple instrument used to measure the direction of the wind. It is usually shaped like an arrow and points in the direction from which the wind is blowing. A wind vane is often mounted on a rotating spindle to allow it to turn freely and align with the wind.
- **Weather Vane:** A specific type of wind vane used in meteorological stations to indicate wind direction. It can be designed to rotate freely to ensure it accurately tracks changes in wind direction.

c. Wind Pressure Measurement

- **Pitot Tube:** This instrument is used to measure the wind pressure, which is often used in calculating wind velocity in different contexts. The Pitot tube measures the difference in pressure between a stagnant air pocket and the moving air.
- **Barometers:** While not directly measuring wind, barometers measure atmospheric pressure, which can be correlated with wind patterns. Low-pressure systems generally correlate with stronger winds, particularly when high-pressure systems are nearby.

d. Wind Profiler

- **Wind Profilers** use radar or other methods to measure wind speed and direction at various heights in the atmosphere, providing a vertical profile of wind that is essential for weather forecasting and understanding atmospheric behavior.

e. Data Collection and Weather Stations

- Automated weather stations (AWS) are commonly used to monitor wind speed, direction, and other atmospheric parameters in real time. These stations typically include an anemometer, wind vane, barometer, thermometer, and hygrometer to collect data on wind and other weather variables.

f. LIDAR and SODAR

- **LIDAR (Light Detection and Ranging):** LIDAR is a remote sensing method that uses laser beams to measure wind speed and direction at different heights in the atmosphere.
- **SODAR (Sonic Detection and Ranging):** This method uses sound waves to determine wind speed and direction in the lower atmosphere.

4. Applications of Wind Measurement

Wind measurements are essential for several applications:

- **Weather Forecasting:** Understanding wind patterns helps meteorologists predict weather conditions, including storms, temperature changes, and precipitation.
- **Wind Energy:** Wind speed and direction are critical factors in determining the viability of wind power generation at a particular location. Wind turbines require consistent wind speeds to produce energy efficiently.
- **Aviation:** Wind measurements are essential for flight planning, particularly for takeoff, landing, and navigation, as wind affects aircraft performance and fuel consumption.
- **Environmental Science:** Wind measurements help in understanding pollution dispersion, forest fires, and other environmental phenomena, as wind plays a critical role in the movement of airborne particles and gases.

Conclusion

Wind is a dynamic and complex natural phenomenon that significantly impacts weather patterns, energy production, and human activities. Its nature is determined by factors such as temperature, pressure, Earth's rotation, and local geographic conditions. Understanding wind structure, both vertically and horizontally, is crucial for accurate forecasting, energy generation, and environmental management. Advanced wind measurement technologies enable precise data collection, supporting industries from meteorology to renewable energy.