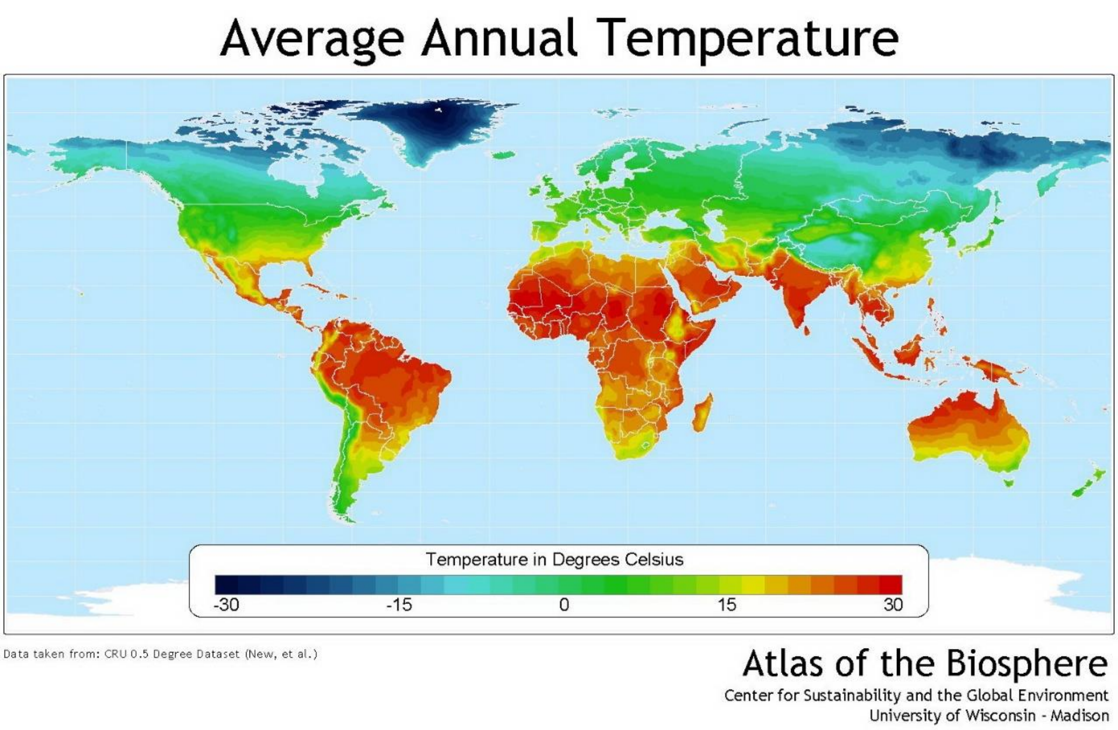
Lecture 2
Tropical Climates (IIa): Hadley Cells

KEY QUESTION:

How does global atmospheric circulation affect rainfall in the tropics?

With the completion of this lecture, attached readings and tutorial, you should be able to understand the:
- Effect of high angle of incidence on surplus heat and temperature in the tropics
- Role of surplus heat in driving atmospheric circulation in the Hadley Cells

Lecture Outline



*This is a map with data calculated by averaging daily temperatures for the years **1961–1990**. There are clearly spatial variations in temperature. Why are the tropics warmer than other regions?*

2.1 Introduction

- In our previous lecture we saw that average annual temperature is high everywhere in the tropics, but rainfall amount and pattern vary. To understand why the rainfall characteristics are so, we have to understand the concepts of surplus heat in the tropics and formation of atmospheric circulation at the global (see **this lecture**) and synoptic (see **Lect 3**) scales.
- In this lecture, we focus our attention on the formation of a global atmospheric circulation called the Hadley cells, and its role in influencing rainfall patterns in the tropics. But, before we can do so, we must become familiar with some basic processes which are responsible for surplus heat in the tropics (see **Section 2.2**) and how such heating results in the formation of the Hadley cells (see **Section 2.3**).

2.2 Surplus Heat and High Temperatures in the Tropics

2.2.1 How the Earth is heated up

- The sun is the only source of energy on earth. Atmospheric temperature is determined by the balance between **insolation received** by the earth and **terrestrial radiation released** by the earth into the atmosphere.
  - The term **"insolation"** refers to **incoming solar radiation**. This input of **shortwave** solar radiation heats up only the earth's surface.
  - The earth's surface releases the heat in the form of **longwave terrestrial radiation**. Terrestrial radiation heats up the atmosphere as **greenhouse gases** like water vapour, carbon dioxide, methane, nitrous oxides **absorb the heat** (greenhouse effect; see **Fig. 1**). This increases the temperature of the atmosphere.
  - The atmosphere gets heated by a number of processes (see **Fig. 2**), before the energy returns to space as output. The difference between the input and output of energy is referred to as the *energy balance* (see **Section 2.2.2**).

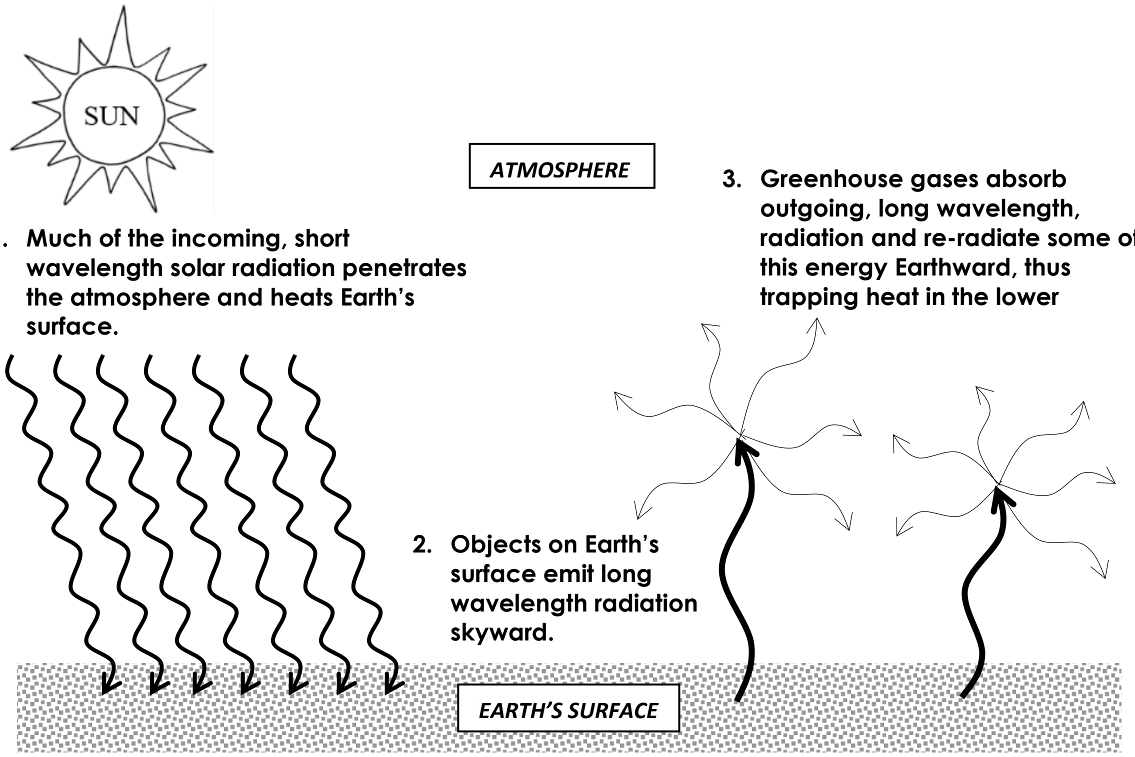


Fig. 1 The (natural) greenhouse effect

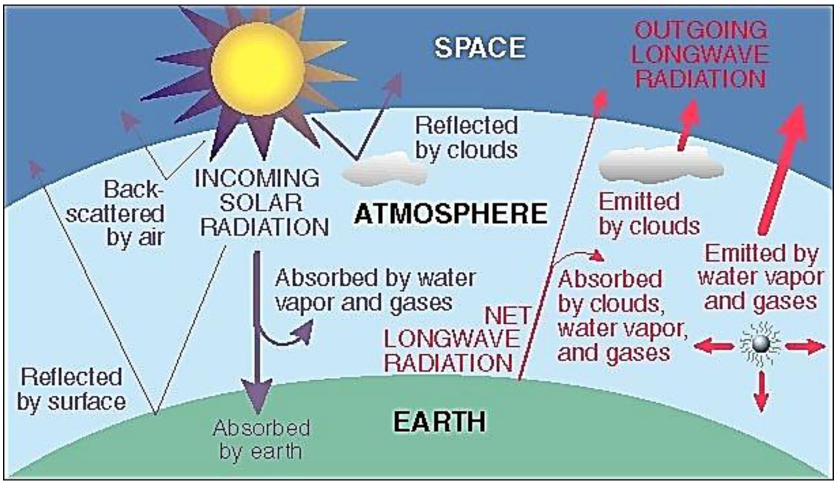


Fig. 2
The energy balance

2.2.2 Surplus heat in the Tropics

- The distribution of heat energy is **uneven** across the Earth.
  - Fig. 3 shows the amount of radiation reaching and lost at the different latitudes.
  - It suggests that there is a radiation **surplus** in the tropics (0° to 30°N and S), and this decreases towards the higher latitudes (30° to 90°N and S), resulting in a radiation **deficit** (or shortage) at and near the poles.

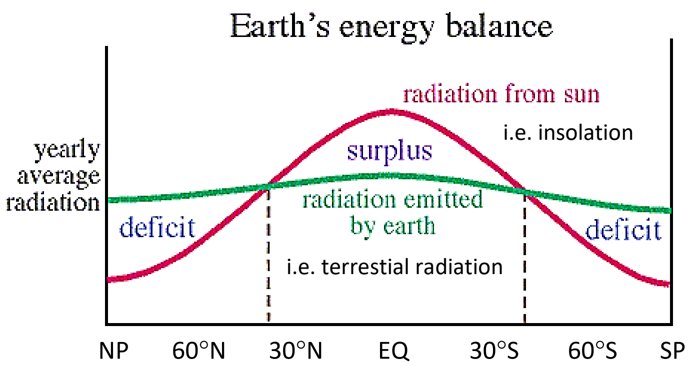


Fig. 3: The amount of radiation reaching and lost at different latitudes

  - Average annual temperature is high everywhere within the tropics. Here, the region delimited by boundaries fluctuating about 30-35° N/S receives **higher insolation** and thus gives out more heat as terrestrial radiation and thus experiences higher temperature than say, the polar region (again, see **Fig. 3**). The variation can be attributed to the angle of incidence (see **Section 2.2.3).**

2.2.3 Effect of Angle of Incidence on Surplus Heat and Temperature in the Tropics

- The angle at which rays from the Sun strike Earth is called the **angle of incidence**. Low latitudes experiences high angle of incidence where insolation falls vertically (90°) on the earth.
- The higher the angle of incidence, the more concentrated the solar radiation that reaches the surface which results in higher terrestrial radiation which heats the atmosphere more causing high average annual temperature at the tropics. Thus, there is **surplus heat at the low latitudes**.
- However, places in the high latitudes experience lower angle of incidence, the insolation that reaches the surface is more spread out and less intense. Thus, higher latitudes experience lower

average annual temperature and are cooler as the oblique rays of the sun spread over a larger area and heat gets distributed. Thus, there is deficit heat in the high latitudes.

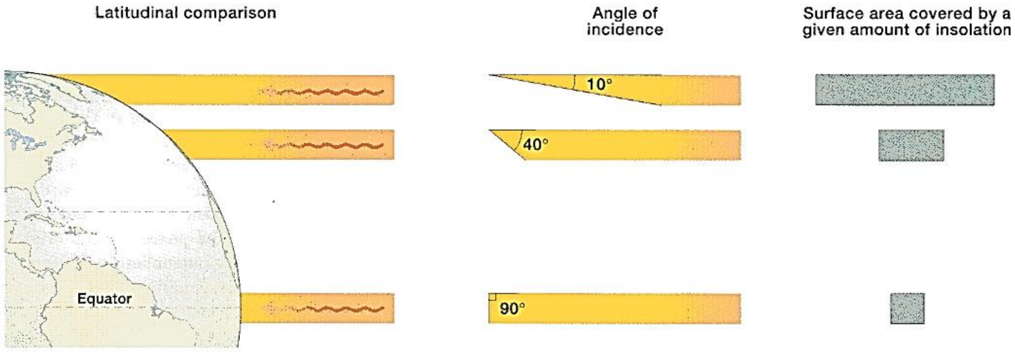


Fig. 4 The angle at which solar rays hit Earth's surface varies with latitude. The larger the angle, the more concentrated the energy and therefore the more effective the heating.

- There is therefore a need for the **redistribution of energy** from areas of surplus to areas of deficit. The details of which will be examined in **Section 2.3**.

2.3 Atmospheric Circulation in the Tropics: The Hadley Cells

- From Section 2.2.3, we can deduce that if there were no mechanisms of moving heat poleward in both hemispheres, the equatorial region would become progressively warmer, and the polar region would become progressively colder.
- Such temperature trends <u>do not occur</u> because there is **a persistent shifting of warmth toward the high latitudes and the consequent cooling of the low latitudes**, thereby making both those latitude zones more habitable than they would otherwise be. One such means is through **atmospheric circulation** (the other is oceanic circulation, which is not our syllabus' emphasis).
- Over the major parts of the Earth's surface, there are large-scale atmospheric circulations present (see **Fig. 5**). The global circulation can be described as the world-wide system of winds which serves as a general framework for **transferring warm air poleward and cool air equatorward**, and in so doing, redistributes the surplus heat from the lower latitudes towards the regions of deficit heat in the higher latitudes. However, the observed impacts are not merely on temperature, as the rainfall patterns will also be heavily dependent on such circulations.

- For our syllabus, we shall only be focusing on the Hadley Cell, (see this section) that is key in influencing rainfall in the Tropics (see **Lect 3**).

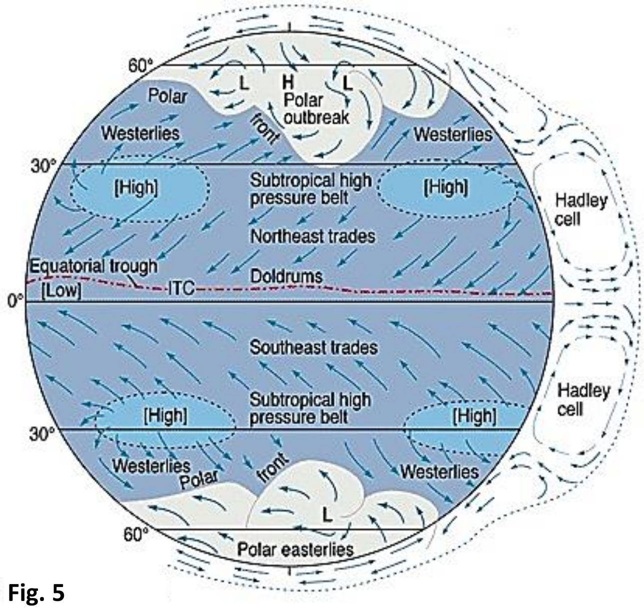
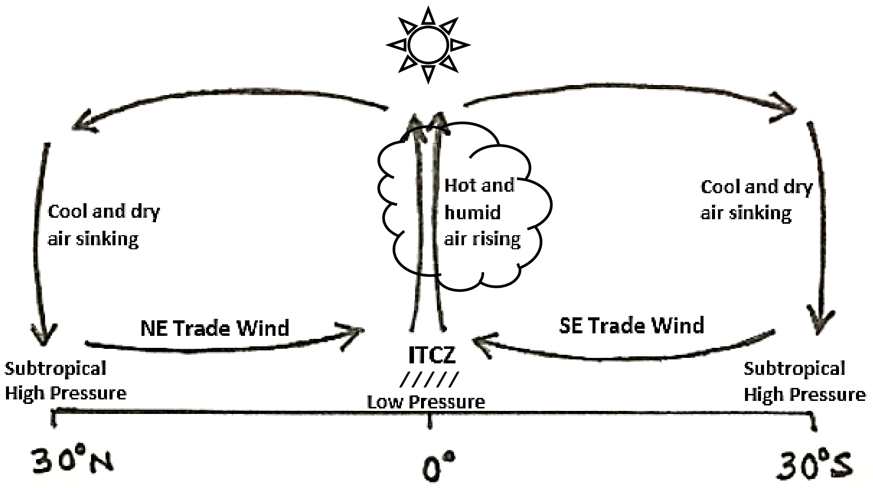


Fig. 5

2.3.1 Equatorial Low and Subtropical High



BWh BSh Am/Aw Af Am/Aw BSh BWh *The approximate locations of climate zones*

Latitude	Pressure Belts
0°- 10°N & S	Equatorial Low Pressure Belt, or Intertropical Convergence Zone (ITCZ)
30°- 35°N & S	Subtropical High Pressure Belts (STH)

Fig. 6
The Hadley Cells

- The Hadley cells are global atmospheric circulations which dissipates heat from the equator (0°) to higher latitudes (**Fig. 6**) in the tropics.
- Surplus equatorial heating causes hot and humid air to rise, resulting in low pressure at the Earth's surface forming the **Equatorial Low Pressure Belt** within 5° to 10°N and S of the equator. The rising air forms the rising arm of the Hadley cells and carries substantial amounts of moisture, which upon cooling and condensing result in high "towers" of cumulonimbus clouds and heavy rainfall (see **Lect 3**).
- The rising air spreads polewards in both the hemispheres. While spreading, the air gets cooler and heavier and sinks to the subtropics at about 30°N and S latitudes in both the hemispheres, forming the sinking arms of the Hadley Cell. Here the cold and dry air sinks or subsides and results in high pressure at the Earth's surface, forming the **Subtropical High Pressure Belts** or STH. The sinking arm of the Hadley cell or STH is associated with dry conditions and minimal rainfall as there is lack of mechanism to uplift air (again, more on this in **Lect 3**).

2.3.2 Trade Winds and the Inter-Tropical Convergence Zone

- The descending air diverges at the STH (see **Fig. 6**). At the low atmospheric levels, a large and steady movement of air called **trade winds** blow from the subtropical highs (STHs) towards the equatorial low pressure thus closing the circulation.
- Trade winds are **easterly** winds as they blow *from* the east *towards* the west. Thus, they are known as **NE trade winds** in the northern hemisphere and **SE trade winds** in the southern hemisphere. These winds cover most of the Earth between about latitude 30°N and 30°S (see **Fig. 7**). (For an explanation for wind direction, see **Box 1**)

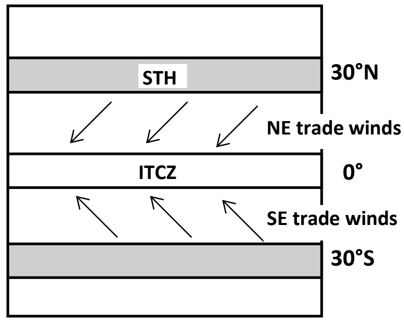


Fig. 7

- The trade winds originate from the STHs. As they move towards the warmer equatorial low, they become warmer as well, capable of holding an enormous amount of moisture, which they do as they blow across the tropical oceans. Hence they have tremendous potential for storminess and precipitation (more on this in **Lect 3**).
- The NE trades and the SE trades converge at the area of **equatorial low pressure belt**, forming the **Inter-Tropical Convergence Zone (ITCZ)**. Here, they are forced to rise, forming the ascending arm of Hadley cells (see again, **Fig. 6**). As we shall learn in **Lect 3**, this promotes rainfall.
  This converging trade winds are extremely moist and full of latent heat energy.

***Box 1** provides a conceptual review, especially useful for students unfamiliar with them. The content will not be explicitly assessed, but an understanding of it is assumed for subsequent lectures.*

Box 1: Some basics – Atmospheric Pressure and Wind

3.1 Atmospheric Pressure

- The Earth's land surface is actually located at the bottom of a vast ocean of air – the Earth's atmosphere. Like the water in the ocean, the air in the atmosphere is constantly pressing on the solid or liquid surface beneath it. This pressure is exerted in all directions.
- Air molecules have mass and are constantly being pulled toward the Earth by gravity. Hence **atmospheric pressure is the force that is produced by the weight of a column of air above a unit area of surface**.

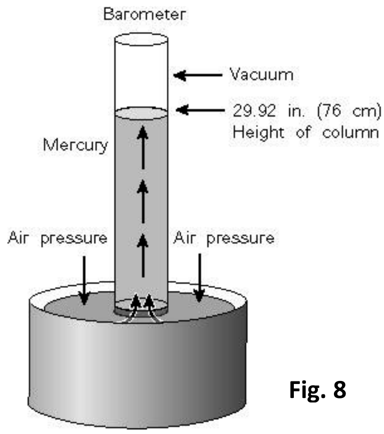


Fig. 8

- Pressure is traditionally measured by a barometer (**Fig. 8**). Many atmospheric pressure measurements are based on the **millibar** (mb) where 1000 mb = 1 kg/km^2.
- At sea level, the force is the weight of about 1 kg of mass of air that lies above each cm^2 of surface (1 kg/cm^2). Standard sea-level pressure is 1013.2 mb.

3.1.1 The Relationship between Atmospheric Pressure and Temperature

- The pressure of a gas is proportional to its density and temperature. However the relationship among these three variables is complex, and will not be discussed here. Nevertheless, some useful generalisations can be made regarding surface pressure conditions:
  - **High temperature** heats up the air. As hot air is light it rises up resulting in **low pressure** at the surface (a thermal low).
  - **Low temperature** cools the air. As cold air is heavy it accumulates near the surface resulting in **high pressure** at the surface (a thermal high).
  - **Strongly rising air** often produces **low pressure** at the surface (a dynamic low).
  - **Strongly descending air** often produces **high pressure** at the surface (a dynamic high).

3.1.2 Representing and Mapping Atmospheric Pressure

- Weather stations normally record atmospheric pressure, either continuously or periodically.
- Once pressure is plotted on a weather map, it is then possible to draw isolines of equal pressure called **isobars** (see **Fig. 9**). The pattern of the isobars reveals the horizontal distribution of pressure in the region under consideration.
- Prominent on such maps are roughly circular or oval areas characterised as being either "high pressure" or "low pressure".
- These highs and lows represent *relative* conditions – pressure that is higher or lower than that of the surrounding areas.
- It is important to keep the relative nature of pressure measurement in mind.
  - For example, a pressure reading of 1005 mb could be either "how" or "low" depending on the pressure of the adjoining areas.

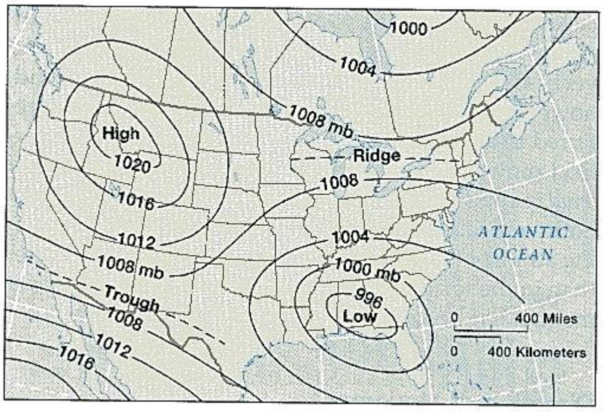
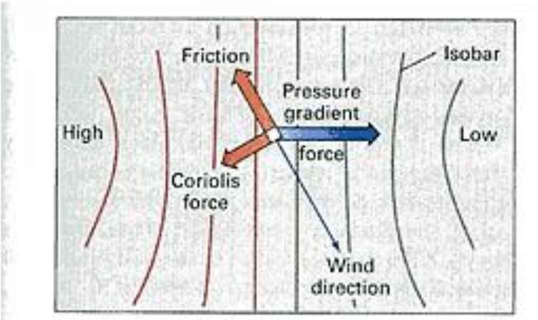


Fig. 9 Isobars are lines connecting points of equal atmospheric pressure. When they have been sketched on a weather map, it is easy to determine the location of high-pressure and low-pressure centers. This simplified weather map shows pressure in millibars.

3.2 Forces influencing Wind Movement

- Wind is defined as **the horizontal air motion with respect to the Earth's surface**, from areas of high pressure to low pressure. In this section, we examine the forces influencing the occurrences of winds, and their speed and direction.
- Note that winds are named according to the direction **from which they originate**. For example, winds blowing from the *southwest towards the northeast* are called *southwest winds*.
- Near the Earth's surface, wind movements are affected by three forces **acting together** (see **Fig. 10**), namely i) *pressure-gradient force* (PGF), ii) *Coriolis force* (CF) and iii) *friction*.



7.13 Balance of forces on a parcel of surface air
...gh the pressure gradient will push a parcel of air ... low pressure, it will be deflected by the Coriolis force and slowed by friction with the surface. The wind direction will be the result of the three forces acting together.

Fig. 10

3.2.1 Pressure-Gradient Force (PGF)

- **Insolation** is the ultimate cause of wind movement because all winds originate from the same basic sequence of events.
  - **Unequal heating of different parts of Earth's surface** brings about **temperature differences** that generate **pressure difference**. (See **Section 3.1.1**)
  - Such differences can be reflected on an isobar map (see **Fig. 9**). The relative closeness of isobars indicates the horizontal rate of pressure change, or **pressure gradient**. The gradient can be thought of as representing the "steepness" of the pressure slope, a characteristic that has a direct influence on the speed of the wind. (See **Fig. 10**)
  - In practice, we say that these pressure differences establish a **pressure gradient force (PGF)**.

- A number of characteristics of the PGF worth noting:
  - the PGF is always directed at **right angles** to the isobars; and
  - the **greater the pressure difference** between the two locations, the **greater this force will be** and **the stronger the wind**. Hence, closely spaced isobars indicate a steep pressure gradient and strong winds; widely spaced isobars indicate a weak pressure gradient and light winds.

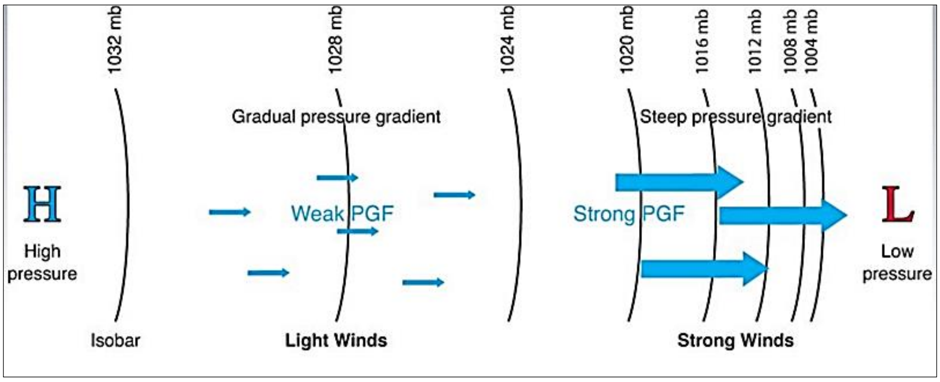


Fig. 10 Pressure-Gradient Force

3.2.2 Coriolis Force

- The Coriolis force is a result of the Earth's **rotation**. Through the Coriolis force, an object in motion on the Earth's surface always appears to be deflected away from its course (**Fig. 11**).
- The object moves as though *a force were pulling it sideward*. The apparent deflection is **to the right in the Northern Hemisphere** and **to the left in the Southern Hemisphere**.
- All free moving objects over long distances, including wind and ocean currents, are affected by the Coriolis force.
- In essence, the Coriolis force:
  - is always **directed at right angles** to the direction of airflow (note: *can be any direction*);
  - **affects only wind direction**, not wind speed;
  - is **affected by wind speed** (the stronger the wind, the greater the deflecting force); and
  - is **strongest at the poles** and **weakens equatorward**, becoming nonexistent at the equator.

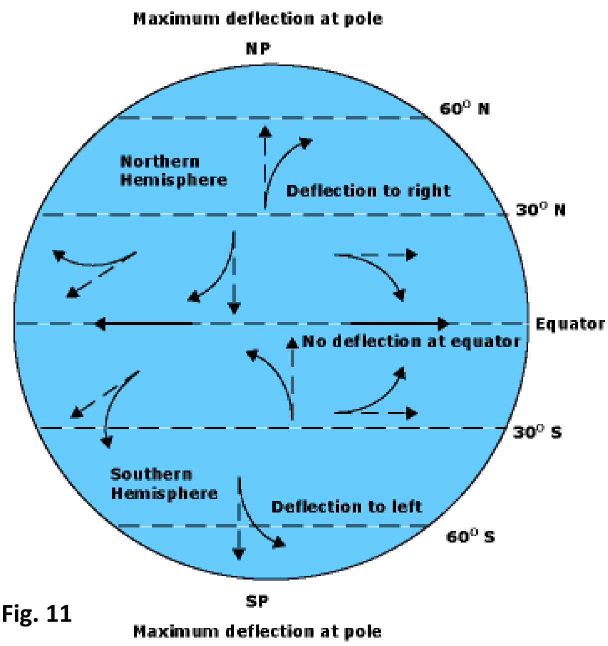


Fig. 11

3.2.3 Friction

- Winds near the ground are affected by a third force – friction (see **Fig. 12**). Acting opposite to the direction of motion, the frictional drag of Earth's surface acts both to **slow down wind movement** and to **modify its direction**.
- Instead of blowing perpendicular to the isobars (in response to the pressure gradient) or parallel to them (in response to the Coriolis effect), **the wind takes an intermediate course between the two and crosses the isobars at some angle that is larger than 0° but less than 90°** (see again, Fig. 3).

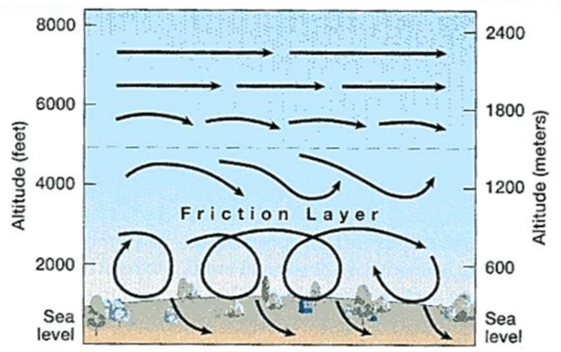


Fig. 12 A vertical cross section of the atmosphere to show wind movement. Near Earth's surface, friction causes wind flow to be turbulent and irregular. At higher altitudes, where there is less friction, the lines of wind flow are much straighter.

- As a general rule, this effect is greater over land (as it is more uneven and hence more friction) than over the ocean, and less with increasing altitude. As Fig. 12 shows, its effect is negligible above a height of a 1500 m. Higher than that, most winds will only be affected by PGF and Coriolis force.

A Summary for Box 1

Air in motion near the surface is subjected to three forces.

1. The pressure-gradient force (PGF) that pushes the parcel toward low pressure.
2. The Coriolis force, which always acts at right angles to the direction of motion.
3. A frictional force exerted by the ground surface, which is proportional to the wind speed and always acts in the opposite direction to the direction of motion.

The sum of these three forces produces a direction of motion that is toward low pressure but at an angle to the pressure gradient. (See **Fig. 13**)

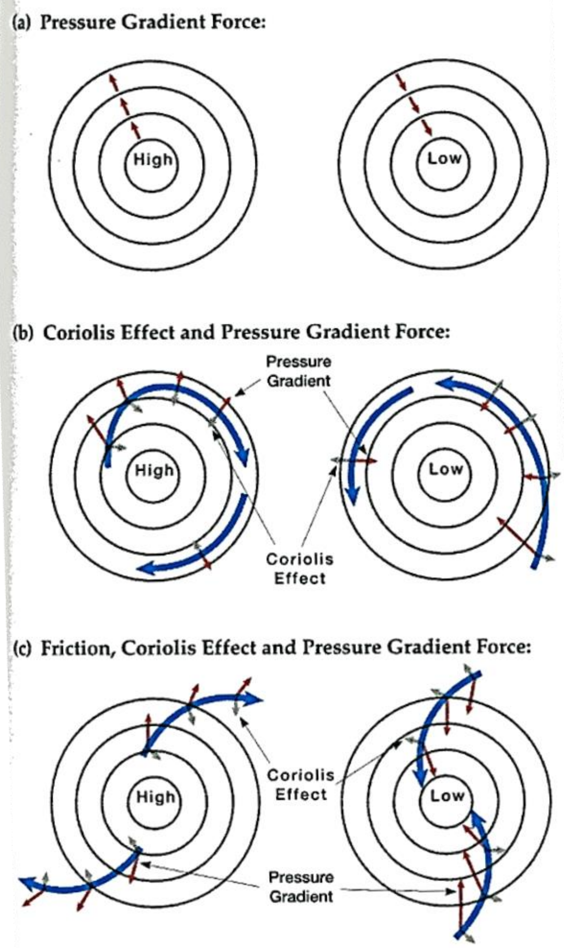


Fig. 13 The direction of wind flow is determined by a combination of three factors. The pressure gradient (a) dictates that movement is perpendicular to the isobars. The Coriolis effect (b) causes movement parallel to the isobars. Friction (c) dictates that an intermediate course is followed, so that the direction of movement is across the isobars at some angle between 0° and 90°.