Lecture 3
Tropical Climates (II*b*): Rainfall Patterns in the Tropics

KEY QUESTIONS:

How does global atmospheric circulation affect rainfall in the tropics?
How does synoptic scale circulation affect rainfall in the tropics?

With the completion of this lecture, attached readings and tutorial, you should be able to understand the:

- Influence of atmospheric circulation in the Hadley cells on rainfall patterns in the tropics
- Influence of seasonal migration of the Hadley cells on rainfall patterns in the tropics
- Influence of distribution of heat over land and sea on summer and winter monsoon circulations in humid tropical Asia, and the resultant effects on rainfall patterns

Lecture Outline

3.1 Introduction: Rainfall and the Tropics

3.2 Some basics to Understanding Rain Formation

3.2.1 Atmospheric Stability and Instability

3.2.2 Condensation, Clouds and Rain

Box 1: Latent Heat

3.3 Influence of Hadley cells on Rainfall Patterns in the Tropics

3.3.1 Influence of Hadley cells on rainfall patterns of Af climates

3.3.2 Influence of Hadley cells on rainfall patterns of BWh and BSh climates

3.3.3 Influence of seasonal migration of Hadley cells on rainfall patterns of Am/Aw climates

3.4 Influence of distribution of heat over land and sea in humid tropical climates

3.5 Summary

All these photographs are of places in the tropics.

*Why are some places in the tropics so wet all year round (**top left**), some dry all year round (**right**), and others seasonally wet and dry (**bottom left**)?*

3.1 Introduction: Rainfall and the Tropics

- Recall from **Lect 1** that the Tropics may be described as…

> **A climatic region of <u>solar radiation surplus</u> delimited by boundaries fluctuating between 30° and 35° north and south latitudes. <u>Common to all areas in this region</u> (at sea level) is <u>high temperature</u>. Significant variations in the <u>amount and pattern of rainfall differentiate these areas</u> into different tropical climate zones, primarily the humid tropics and the arid tropics.**

- While mean annual temperature in the Tropics is generally high everywhere (as we saw in **Lect 1 and 2**), the definition provided above reminds us that rainfall in the Tropics is not as simple to explain. Indeed, as we shall see in thus lecture, the Tropics can be further categorised into different climatic regions, by virtue of **how much rainfall they receive <u>and</u> how that varies over time and space**.
- In this lecture, we first focus on the basic conditions for rainfall to occur so that we can understand the role of Hadley Cells in influencing rainfall in this part of the world. For this, we must begin with the concepts of **atmospheric stability** and **instability**.

3.2 Some Basics to Understanding Rain Formation

This section explains concepts that will not be explicitly assessed, but an understanding of it is assumed when learning content for this lecture as well as subsequent lectures.

3.2.1 Atmospheric Stability and Instability

- An air parcel is defined as **a quantity of air in which there is no exchanges of mass and energy between its interior and exterior;** that is, there is no (or negligible) mixing of parcel air with surrounding air. It is an object with *imagined boundaries*, invented to aid understanding of atmospheric processes.
- Suppose the air parcel is a physical object, and the surrounding air is fluid. Just as an object will rise or sink as a result of the density differences between itself and the fluid, this air parcel will also seek its own level. This means that **a parcel of air moves <u>vertically</u> until it reaches a level at which the surrounding air is of equal density**.
- If an air parcel were to rise away from the Earth's surface, it would **expand in volume** (since atmospheric pressure acting on the parcel would drop), and in the process, **reduces its density** and also its temperature (that is, **it cools**).
- The important observation to make here is how different the temperature and density of this air parcel are compared to its surrounding air. (See **Fig. 1**)
    - If the parcel of air is **cooler**, and therefore **denser** than the surrounding air, it tends to either **sink** or at least to **resist uplift**. This parcel of air is said to be **stable**. The sinking movement of air creates high pressure areas, hence **high pressure areas are associated with stable conditions**. (See **Section 3.3.2** later)
    - If the parcel of air is **warmer**, and thus **less dense** than the surrounding air, it tends to **rise on its own**. Thus, warm air is said to be **unstable**. With the upward movement of air, **low pressure areas are created, hence low pressure areas are also associated with unstable conditions**. (See **Section 3.3.1** later)

- In summary, stability is a property of air that describes its tendency to resist uplift (stable), or to rise (unstable).

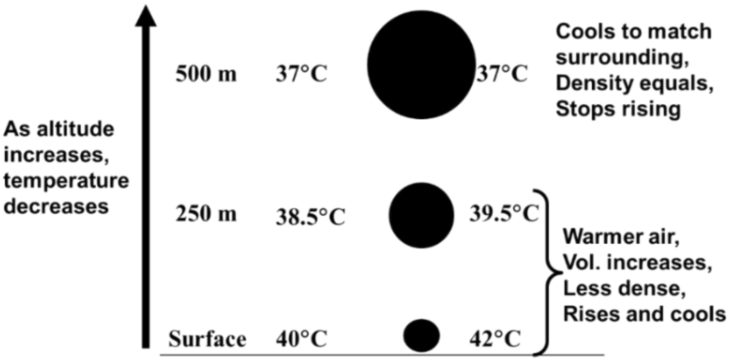


Fig. 1

Assume that ELR = 6°C per 1000 m (left side) and the air parcel cools at 10°C per 1000 m (right side).

Stability occurs when a ***rising parcel of air cools <u>more rapidly</u>*** than the air surrounding it. As it rises, it becomes colder and denser than its surroundings and therefore will sink back to its starting point.

Instability occurs when a ***rising air parcel cools <u>more slowly</u>*** than the atmosphere and thus remains warmer and lighter

3.2.2 Condensation, Clouds and Rain

- When a parcel of air is heated enough so that it is warmer than the surrounding air, it becomes unstable (see **Fig. 1**). This is a typical condition on a warm summer afternoon. The air parcel rises until it reaches an altitude where the surrounding air has similar temperature and density. **While ascending, it will be cooled**.
- For an ascending air parcel that contains water vapour, it will reach a height where it will be cooled to its **dew point temperature**, when **saturation** is reached and this water vapour will begin to **condense** (that is, water vapour is converted to liquid water). This height in the atmosphere is known as the **condensation level**.
- During condensation, **latent heat** (see **Box 1**) is released. The parcel of air becomes warmer than the surrounding air. This **enhances atmospheric instability** and causes the air parcel to rise further on its own, which in turn leads to further cooling and condensation.
- The collection of minute droplets of water is called **clouds**. The condensation level is therefore also the cloud base – the point at which the rising parcels of air become visible as clouds.
- Not all clouds give rain, but **all rain comes from clouds**. In other words, if there are no clouds, it would not be possible to have rain.

<u>Box 1</u>: Latent Heat

- Even as heat is added, the temperature of water does not increase while it is undergoing a phase change. The energy exchanged during a phase change is called **latent heat**.
- When water vapour condenses back to liquid water, the highly agitated water vapour molecules must give up some of their internal structural energy in order to revert to a less agitated liquid state. The energy released during condensation is called the **latent heat of condensation**.
- Because latent heat must be released during condensation, condensation is, in effect, a warming process. Water vapour represents a "reservoir" of heat – whenever and wherever condensation takes place, this heat is added back to the atmosphere. The release of latent heat during condensation fuels **atmospheric instability** when air that is heated up rises.

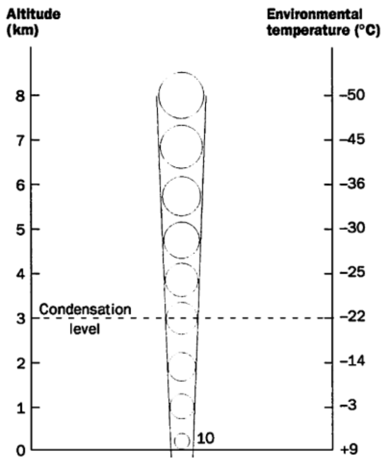
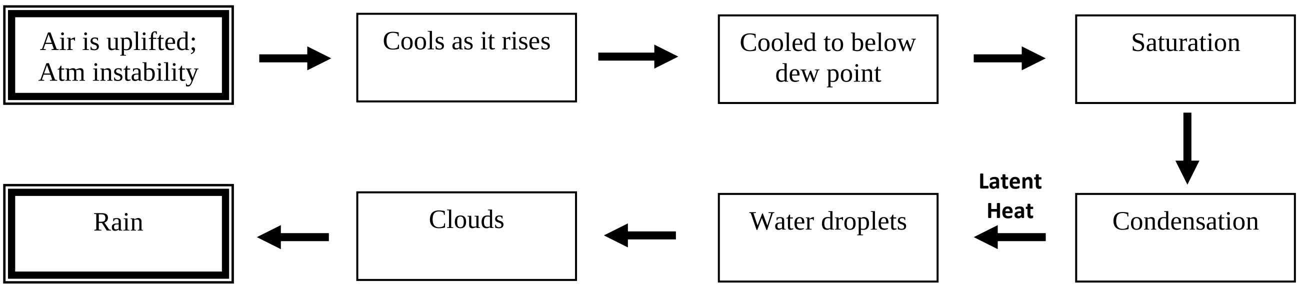


Fig. 2 Assume that the air parcel remains warmer than its surrounding, and that dew point is reached when at 3 km altitude. *How should the cloud formation be represented?*

A Summary for Section 3.2 …

By linking Sections 3.2.1 and 3.2.2 together, we come to a conclusion about rainfall formation. **Uplifting of air is a necessary condition**.

Air parcels must be uplifted. They may be cooled slower than their surrounding as they continue to rise, and if they reach dew point, clouds form, and rain is possible result. ***In other words, no uplifting of air means no occurrence of rain. If there is rain, lifting of air must have occurred.***



3.3 Influence of Hadley Cells on Rainfall Patterns in the Tropics

- Influence of Hadley cells on the rainfall patterns depend mainly on the positions of ITCZ and STH respectively. By "positions", we consider both where they are most often found, as well as where they migrate to at different times of the year. (**Fig. 3** below is reproduced from Lect 2)

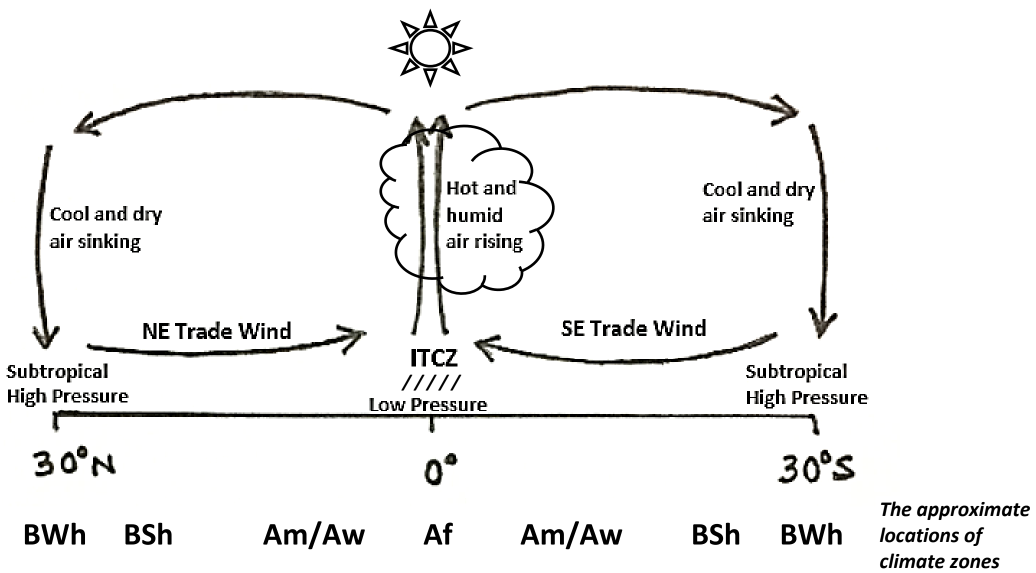


Fig. 3
The Hadley Cells

3.3.1 Influence of Hadley cells on rainfall patterns of Af climates

- Recall from **Lect 1**, Af climates characteristically occur within 5° to 10°N and S of the equator. The region experiences the most heat surplus, especially so in March and September (see **Box 1 in Lect 1 for an account of the shifting location of the overhead sun**).
- Surplus equatorial heating heats up the air. As the air expands, the density of the heated air drops, and so the air parcel rises in a typical convective situation.
- This **convective lifting** of hot and humid air results in low pressure at the Earth's surface forming the **Equatorial Low Pressure Belt** in this region. 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 contributes to heavy rainfall in Af climates.
- At the same time, NE and SE trade winds converge at the equator at the **Intertropical Convergence Zone** or **ITCZ** (see **Figs 3 and 4**) and the converging air rises by **convergent lifting**. As the air is forced to rise, it cools, condenses and forms cumulonimbus clouds and causes heavy rainfall in Af climates.
- Thus, the high rainfall pattern in the Af climates is due to **both** convective and convergent lifting.

*<u>Note</u>: From the above, **the Equatorial Low Pressure Belt and the ITCZ both follow the location of the overhead sun.** (It is wrong to say the overhead sun follows the ITCZ)*

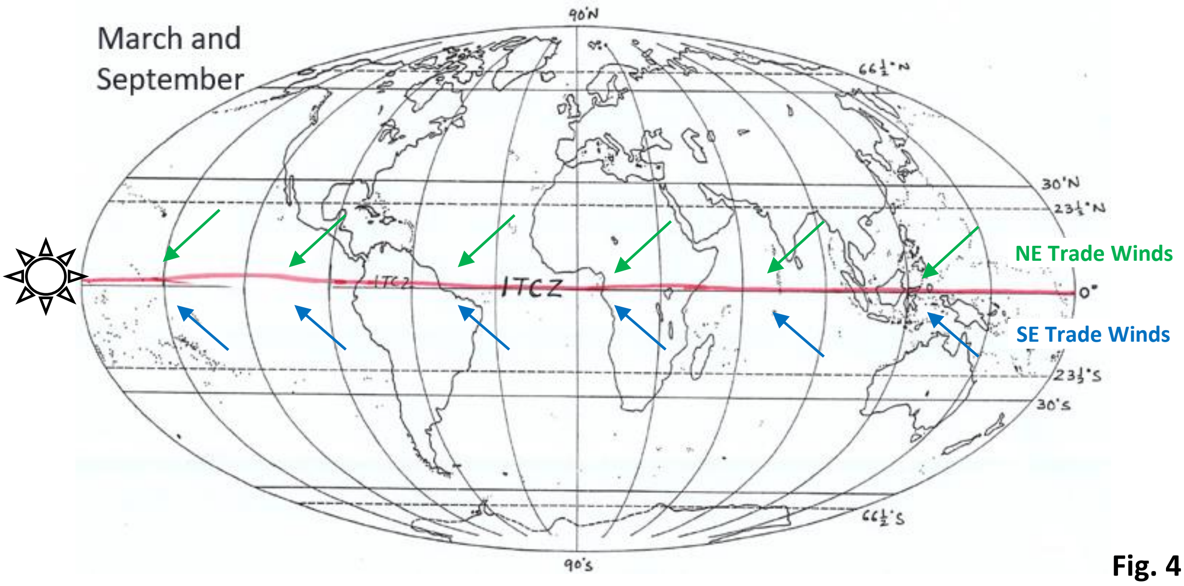
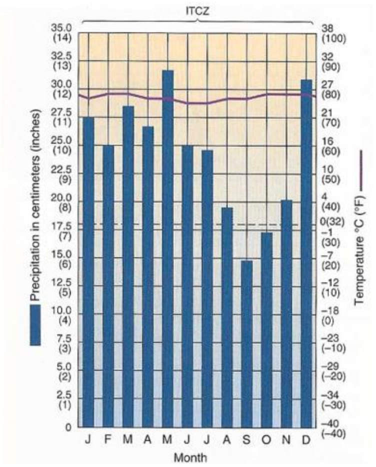


Fig. 4

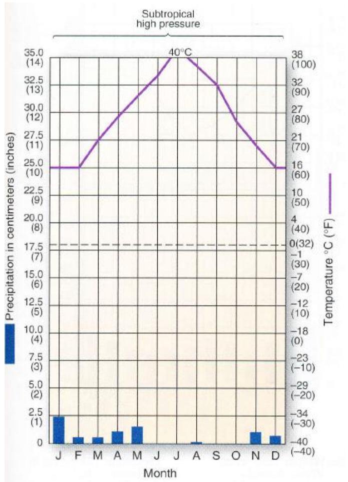
3.3.2 Influence of Hadley cells on rainfall patterns of BWh and BSh climates

- Recall from **Lect 1**, BWh climates usually occur within 25° to 35°N and S of the equator, and the BSh climates characteristically surround BWh climates.
- Their locations coincide with the **Subtropical High Pressure Belts** or **STH** (see **Fig. 3**). The STH is a zone of atmospheric stability and sinking arm of the Hadley cells. The sinking air is cold and dry. Cold air is denser and thus sinks. This discourages cloud formation and thus B climates receive very low rainfall. Also, as cold air is dry it does not contain enough moisture, thus discouraging cloud formation and rain.
- So overall, BWh and BSh climates being under the dominance of STH, receive low to very low rainfall throughout the year.

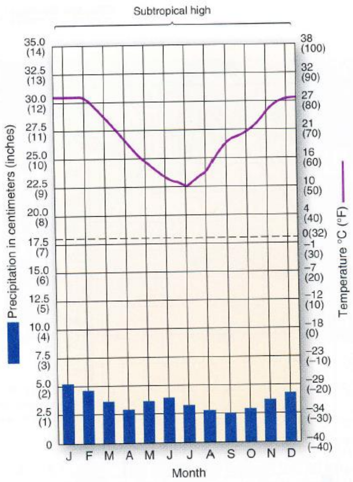
Uaupes, Brazil, 0° lat
[Af]



Riyadh, Saudi Arabia, 24°N
[BWh]



Walgett, NSW, Australia 30°S
[BSh]

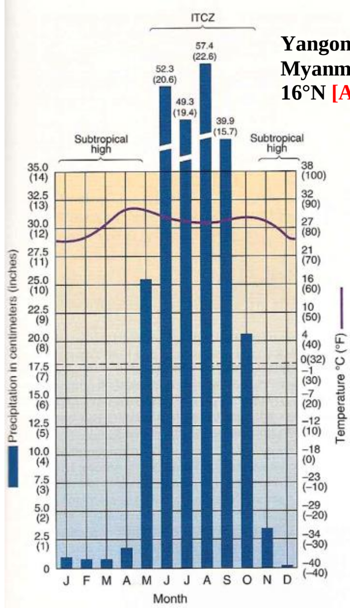


Af, BWh and BSh are climates dependent on the dominance of the ITCZ and STH pressure belts. But the wet and dry seasons seen in Am and Aw are a result of the migration of these belts.

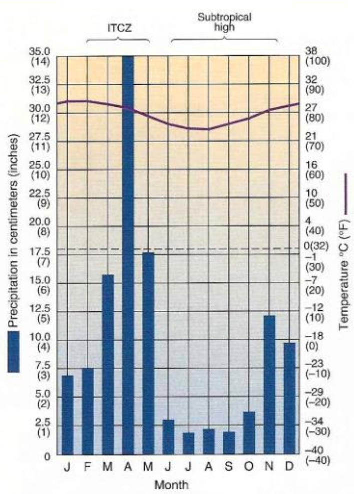
3.3.3 Influence of seasonal migration of the Hadley cells on rainfall patterns of Am/Aw climates

- Am and Aw climates receive seasonal rainfall with **wet summers** and **dry winters**.
- The occurrence of a dry and wet season is mainly because of the **migration** of the Hadley cells. As was hinted in **Section 3.3.1**, the Hadley cells (along with ITCZ and STH) migrate *because* of the migration of the overhead sun.
- Recall from **Lect 1 Box 1** that the location of maximum solar heating on Earth's surface is not fixed because the position of the overhead sun relative to the Earth's surface shifts throughout the year. (See **next page** for the corresponding ITCZ locations.)
  - In June, the overhead sun is in the NH. (See **Figs 5A and 5B**)
  - In December, it is in the SH. (See **Figs 6A and 6B**)
- This creates pressure differences over the Earth's surface, causing major impact on the wind systems in the affected regions (see **Lect 2 Box 1**). The resultant movement of the ITCZ and STH create a reversing wind pattern in Asia known as the **monsoon** (derived from the Arabic "mawsim", meaning "season") and has come to mean a **seasonal reversal of winds**.
- Both the Am and the Aw climates are affected by the monsoons, but to different extent. There are some key differences:
  - The wet seasons of Am are usually longer than the wet seasons of Aw, hence making the amount of total annual rainfall in Am more than Am.
  - The dry seasons of Am are shorter than the dry seasons of Aw.

Yangon, Myanmar, 16°N [Am]



Arusha, Tanzania, 3°S [Aw]



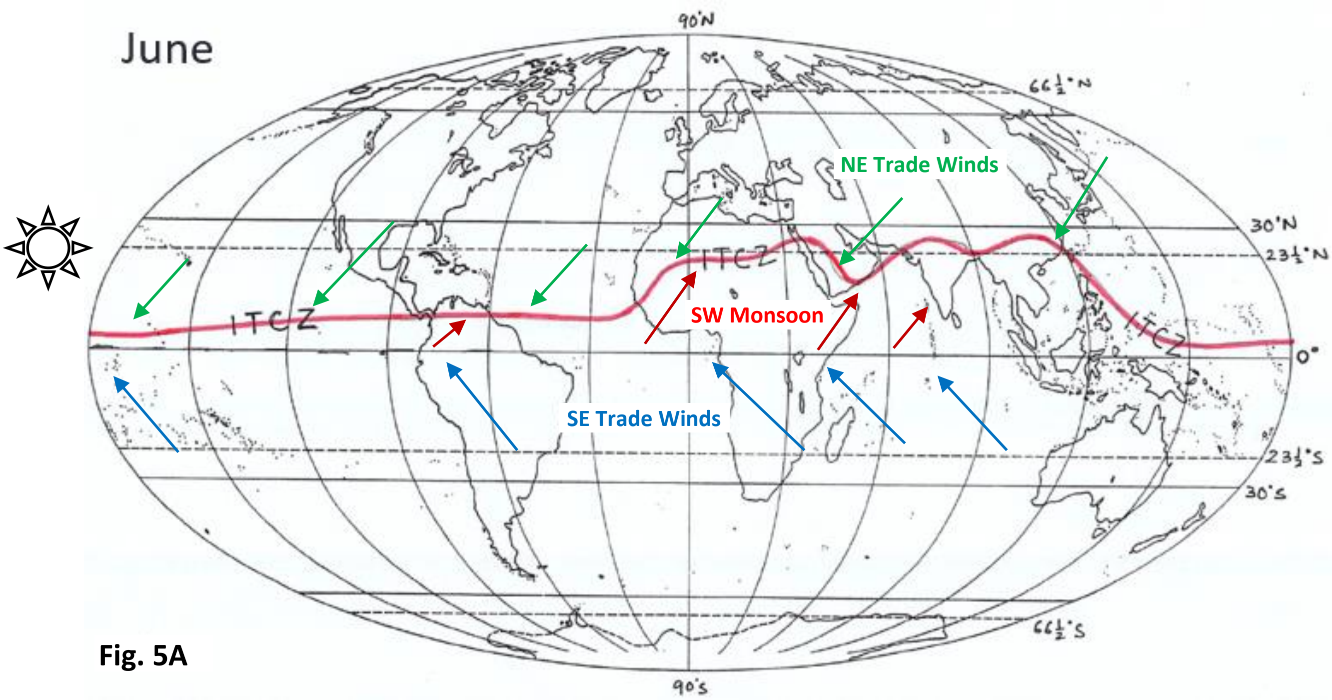


Fig. 5A

NE trade winds SE trade winds SW monsoon NW monsoon

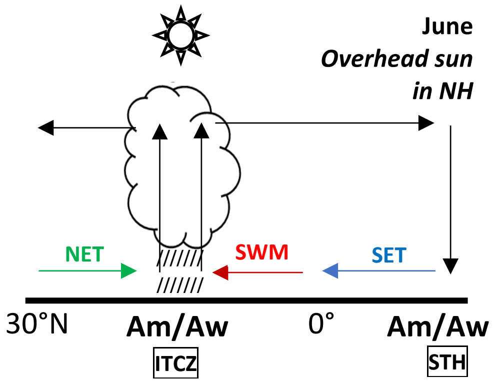
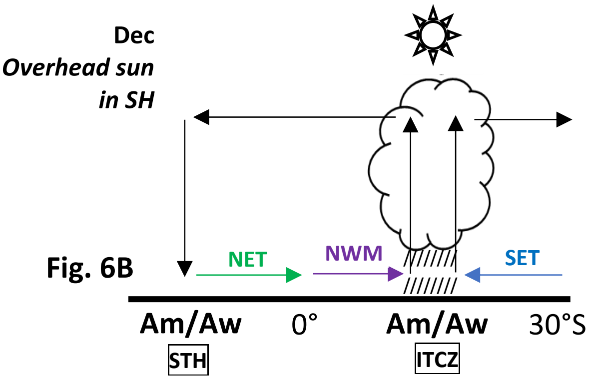


Fig. 5B

Fig. 6B



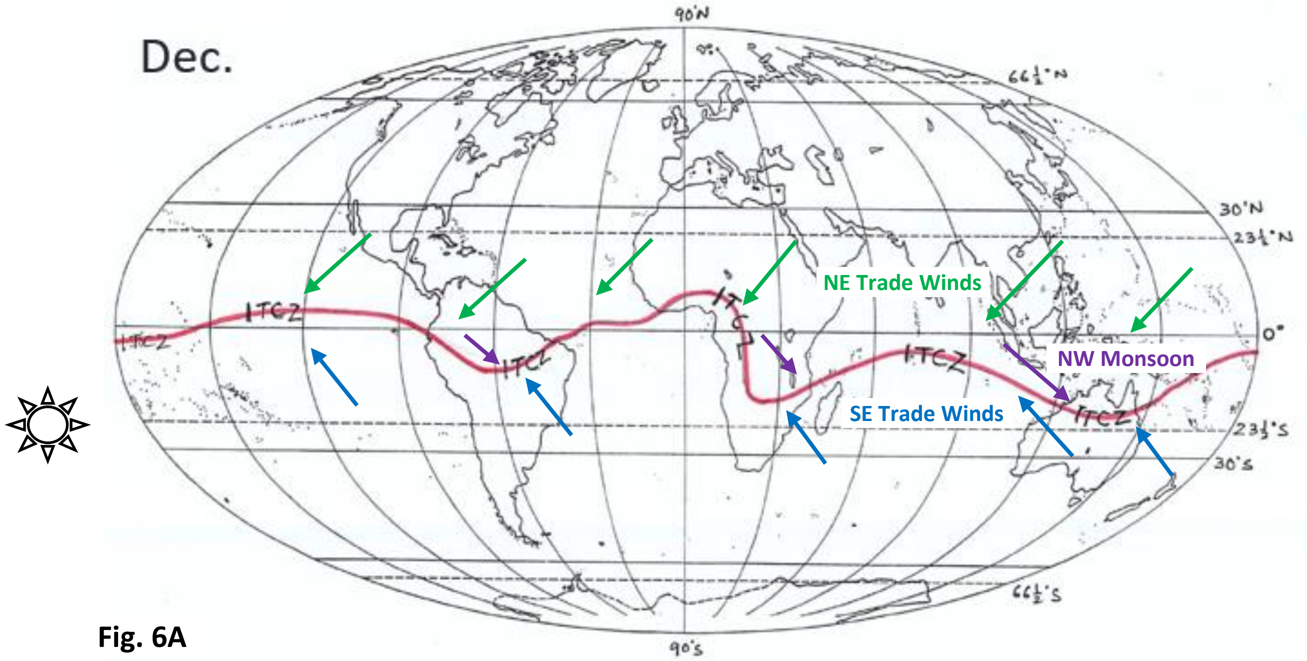


Fig. 6A

- In March and September, when the overhead sun is above the equator, the Hadley cells and the position of the ITCZ and STH is reflected as such. Take note of where the NE/SE trades winds are (see **Fig. 4**).
- In June, intense heating takes place in the NH as the overhead sun is there.
  - **Wet season in NH.** Low pressure cells develop over the continents in the NH as compared to the equatorial low, reversing the pressure gradient seen in March. This pulls the ITCZ northwards over the NH landmasses, causing the SE trade winds from the SH to cross the equator, deflected to its right in the NH due to Coriolis force and blow as SW monsoon winds (see **Figs 5A and 5B**). This monsoon winds absorb lots of moisture from over the oceans and causes high rainfall in summer over the NH landmasses. (For Am climates, it is not unusual to have more than 750 mm of rain in the 2-3 of the summer months. The wet season in Aw climates, on the other hand, do not receive as much.)
  - **Dry season in NH.** In the SH, however, STH conditions dominate. Cold dry sinking air meant the lack of uplifting mechanism for air, giving clear skies and no rain. The dry season results.
- In December, the overhead sun shifts its location to the SH.
  - **Wet season in SH.** Intense heating here allows low pressure cells develop in the SH, pulling the ITCZ southwards, causing the NE trade winds from the NH to cross the equator, deflected to its left in the SH, and blow as NW monsoon winds (see **Figs 6A and 6B**). This too generates intense rainfall events to wherever it blows to.
  - **Dry season in NH.** In the NH, dry conditions result under STH conditions.

Challenge

Both Am and Aw experience wet and dry seasons, but with key differences.

- The wet seasons of Am are longer than the wet seasons of Aw.
- The dry seasons of Am are shorter than the dry seasons of Aw.

With the help of the map in **Fig. 7**, and what you have learnt so far, **explain why**.

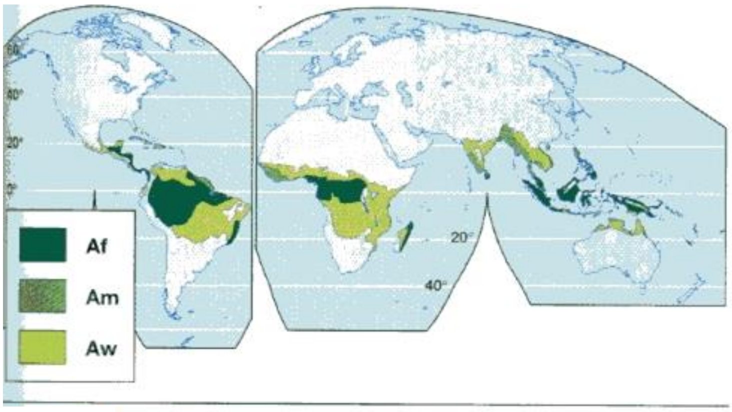


Fig. 7 Distribution of A climates.

We shall consider this question more carefully in Tutorial.

3.4 Influence of distribution of heat over land and sea in humid tropical climates

- While Section 3.3.3 helps explain monsoons at the **global scale**, there exist circulations at the **synoptic scale** that is responsible for monsoons as well. Synoptic scale circulations are "smaller" than global scale circulations such as Hadley cells, but still have areas on the order of hundreds or thousands of square kilometres. For example, in this section, we focus on high pressure and low pressure patterns that occur over large parts of continents.
- Summer and winter monsoon circulations in humid tropical climates (that is, **A climates**) can also occur on the basis of the **unequal warming of land and sea**.

- In June, when the overhead sun is in the NH (hence summer), the warm surface there enables a strong LP cell formed over the continental landmass (see **Fig 8**). This attracts oceanic air onshore (ocean to land) as compared to land, the sea heats up more slowly so the pressure over its surface remains higher than over land. Thus, warm, humid air from the Indian Ocean and the southwestern Pacific moves northward and northeastward into Asia, passing over India and China. This airflow contributes to the SW monsoon (see **Section 3.3.3**) and is also known as the **summer monsoon,** accompanied by heavy rainfall in SE Asia.
- Similarly, in December, when it is winter in NH, a prominent HP cell develops over the continent produces an offshore (land to ocean) wind. A strong outflow of dry, continental air from the north across China, SE Asia, India and the Middle East. During this **winter monsoon**, dry conditions prevail over NH landmasses. (See again, **Fig 8**)

- It is clear that these thermally induced pressure differences contribute to the origin of monsoon winds, but to fully explain monsoons, the seasonal migration of the Hadley cells (see **Section 3.3.3**) must be considered.

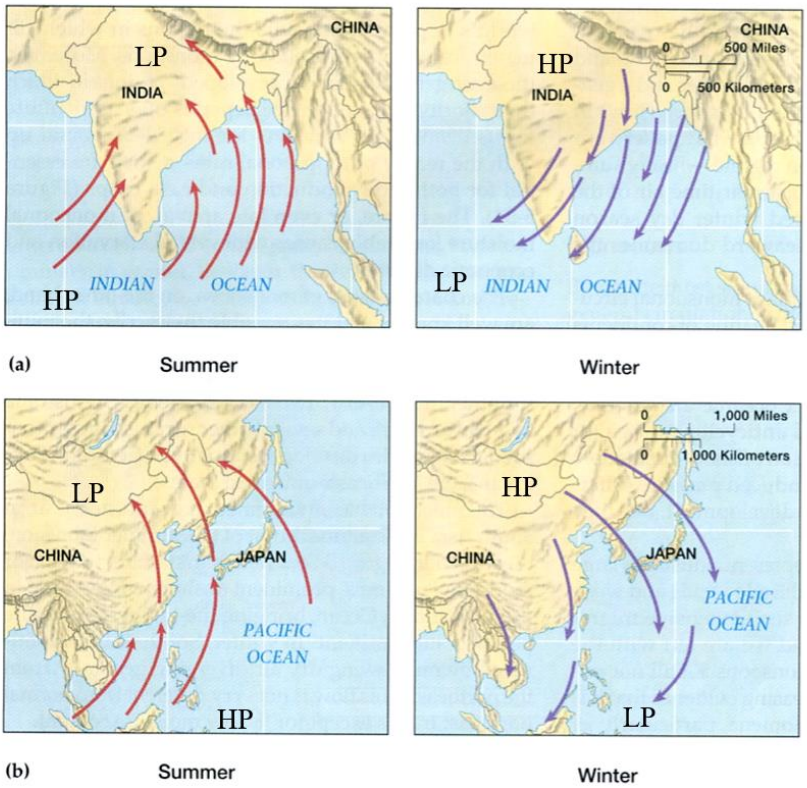


Fig. 8 The two major monsoonal systems. (a) The South Asian monsoon is characterized by a strong onshore flow in summer and a somewhat less pronounced offshore flow in winter. (b) In East Asia, the outblowing winter monsoon is stronger than the inblowing summer monsoon.

3.5 Summary

- Atmospheric stability and instability that contributes to rainfall. The guiding principle is that rainfall can always be traced to the **uplifting of air** (atmospheric instability), and lack of rainfall explained by the **lack of uplifting of air** (atmospheric stability).
- Significant variations in the pattern and amount of rainfall differentiate the Tropics into various climate zones. These are due to the effects of the Hadley cells, particularly the dominance of ITCZ and STH in different parts of the Tropics.
- Monsoons can be explained using circulations at both the global (i.e. Hadley cells) and synoptic (i.e. distribution of heat over land and sea) scales.