LECTURE OBJECTIVES

1. Explain how the Hadley Cell affect tropical climates through the Convergence of Trade Winds at the Intertropical Convergence Zone (ITCZ), and the resultant effects on atmospheric stability and rain formation

2. Explain why seasonal variations in wind direction occur through understanding of Asian and African Monsoons

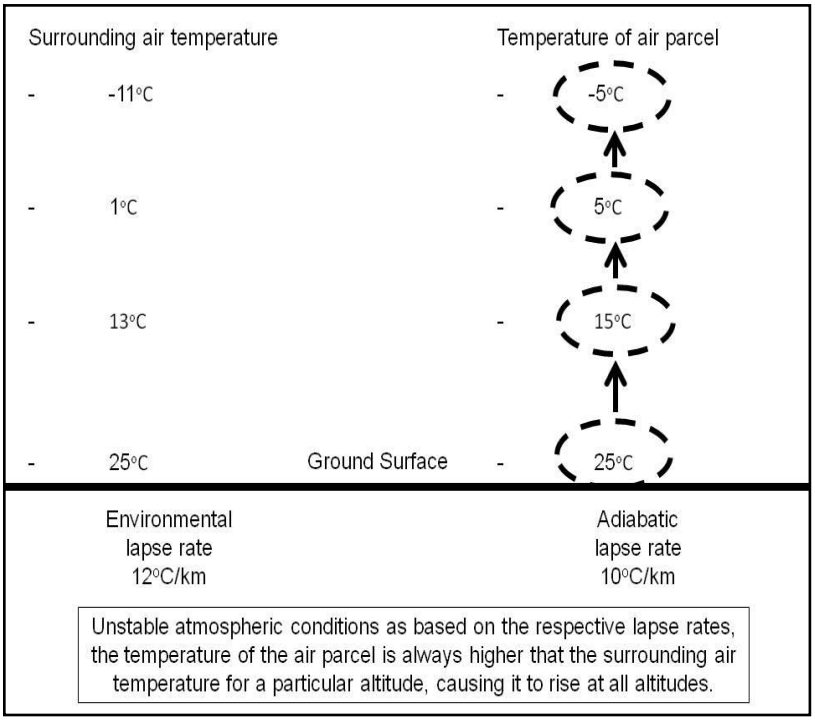
3. Explain how weakening of the Walker Circulation and the El Nino Southern Oscillation (ENSO) phenomenon affect Tropical Climates

INTRODUCTION

Atmospheric stability refers to the tendency of an air mass to either remain in place or change its vertical position by ascending or descending.

An air mass is **stable** and will sink if it is cooler *(and hence denser)* than the surrounding air. Hence, a stable air mass resists replacement upwards or when disturbed, tends to return to its original position.

An air mass is **unstable** and will rise if it is warmer *(and hence less dense)* than the surrounding air. An unstable air mass has the tendency to continue rising until it reaches an altitude where the surrounding air has a density similar to its own.



(A) HOW DOES RAINFALL OCCUR?

1. Rainfall formation starts when an air mass containing moisture undergoes uplift.

2. The uplift of the air mass can occur in various ways such as: a) convectional uplift, b) orographic uplift, or c) convergent uplift.

3. The rising air mass will dynamically expand due to a decrease in pressure of surrounding air and result in ***adiabatic cooling***[1] of the air mass (Fig. 1).

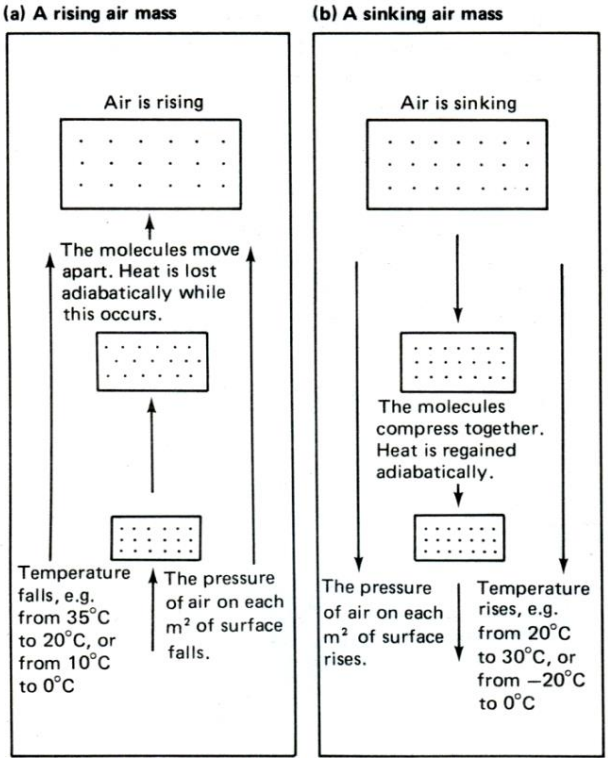


Fig. 1: Dynamic expansion / contraction of air mass causing adiabatic cooling / heating

4. When the air mass containing water vapour is cooled to its **dew point**[2], it becomes **saturated**[3] (**relative humidity**[4] of 100%).

5. Further cooling below the dew point causes the water vapour to condense and form small water droplets which become clouds. However, condensation can only take place if there are particles such as dust, pollen, smoke and ash in the air to act as nuclei for condensation. Thus, in order for clouds to form, (i) air must be cooled below its dew point, and (ii) cloud condensation nuclei must be present.

6. Water droplets in clouds coalesce over time to become larger. When the larger water droplets become too heavy to remain suspended by the rising air, they fall down from the atmosphere in the form of precipitation such as rain.

[1] Adiabatic cooling refers to the reduction in temperature without the addition of heat energy.
[2] The temperature at which air is saturated with water vapour.
[3] The air is holding the maximum amount of moisture it can hold. The maximum amount of moisture air can hold increases with its temperature.
[4] The amount of moisture contained in the air mass compared to the maximum amount of moisture that the air mass can hold, measured in terms of percentage.

(B) WHAT ARE THE DIFFERENT TYPES OF RAINFALL?

The types of rainfall commonly found in the tropics include:

a. Convectional rainfall (uplift)
b. Orographic (relief) rainfall (uplift)
c. Convergent rainfall (uplift)

Convectional rainfall (Fig. 2) occurs when the air layer near the ground or sea surface is heated by conduction and long wavelength radiation. (Temperature driven)

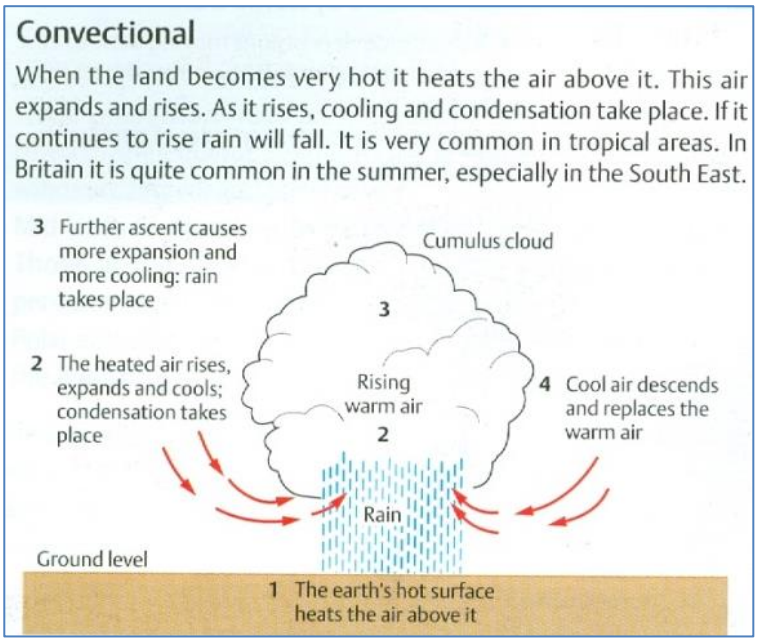


Fig. 2: Formation of Convectional Rainfall

a. Air in contact with the ground warms and expands (Thermal expansion). Consequently, being lighter than the surrounding air, it becomes unstable and rises.

b. The rising air mass will expand dynamically due to the decrease in surrounding air pressure with increasing altitude. As a result, adiabatic cooling occurs.

c. When the air mass containing water vapour is cooled to its dew point, the air mass becomes saturated, and its relative humidity reaches 100%. Cooling below dew point causes the water vapour to condense and form small water droplets on condensation nuclei such as dust, pollen and ash[5].

d. Water droplets in clouds coalesce over time to become larger. When the larger water droplets become too heavy to remain suspended by the rising air, they fall down from the atmosphere in the form of precipitation such as rain.

e. Convectional rain usually occurs in the early afternoon when the surface temperatures are high due to intense insolation present. It brings short-lived

[5] Tall and towering clouds such as cumulonimbus clouds may form due to the rapid uprising of moisture-laden air, forming raindrops of considerable sizes.

showers which last for minutes. Convectional rainfall thus commonly occurs in warmed or heated areas such as tropical lands and oceans.

f. It is less frequent but can also occur in tropical desert regions and the interior of continents in the summer.

2. **Orographic or relief rainfall** (Fig. 3) occurs when moist air is forced to undergo uplift when meeting mountain barrier. This is known as orographic uplift.

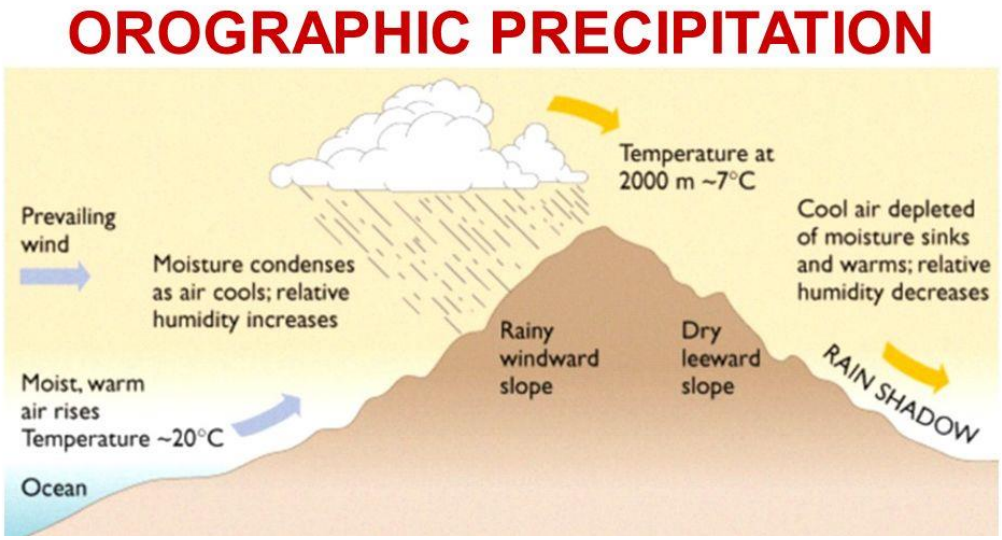


Fig. 3: Formation of Orographic/Relief Rainfall

a. The rising air mass will expand dynamically due to a decrease in pressure of surrounding air with increasing altitude. As a result, adiabatic cooling occurs.

b. When the moist air mass is cooled to its dew point, the air mass becomes saturated, and its relative humidity reaches 100%.

c. Further cooling below the dew point causes the water vapour, in the presence of condensation nuclei, to condense and form small water droplets.

d. When the larger water droplets become too heavy to remain suspended in the air, they fall down from the atmosphere as orographic rainfall. The side of the mountain on which rainfall occurs on is known as the windward slope.

e. If the mountain is very high, air currents which are now dry continue to rise because they are pushed upward by continual air movement from below. After crossing the mountain, the descending dry air is compressed and becomes warmed adiabatically, making condensation and precipitation less likely to occur. This side of the mountain is known as the leeward slope.

f. The descending air forms a warm dry wind called föhn wind or chinook wind, and brings very little moisture. The leeward side of mountain forms a rain shadow area, experiencing very little rainfall. This may result in the formation of a rain shadow desert.

3. **Convergent rainfall** (Fig. 4) occurs when surface winds converge and air masses are forced to rise as a result. For example, this occurs at the Inter-tropical Convergence Zone (ITCZ) when trade winds from the northern and southern hemisphere converge together.

    a. As the surface winds converge, the respective air masses are forced to undergo uplift. The rising air mass will dynamically expand due to a decrease in pressure of surrounding air with increasing altitude. As a result, adiabatic cooling occurs.

    b. When the air mass containing water vapour is cooled to its dew point, the air mass becomes saturated, and its relative humidity reaches 100%.

    c. Further cooling below the dew point causes the water vapour, in the presence of condensation nuclei, to condense and form small water droplets.

    d. When the larger water droplets become too heavy to remain suspended in the air, they fall down from the atmosphere and are known as convergent rainfall.

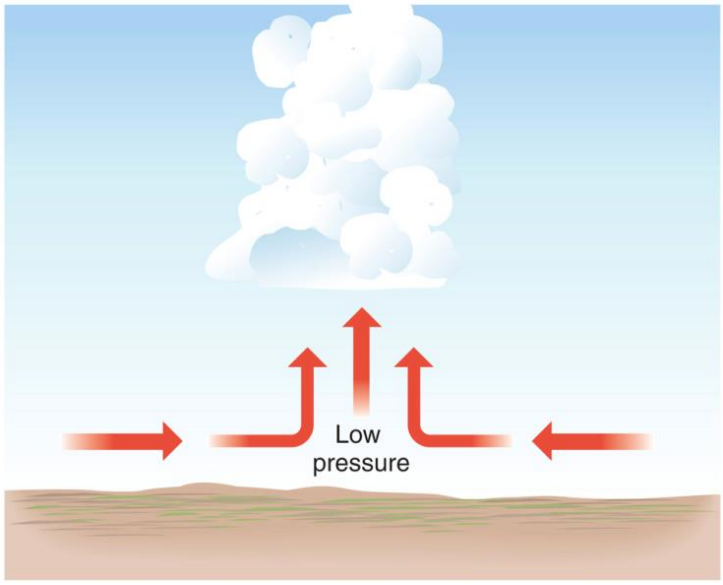


Fig. 4: Formation of Convergent Rainfall

(C) WHAT ARE THE FACTORS INFLUENCING THE RAINFALL PATTERNS OF CLIMATE ZONES IN THE TROPICS?

The various factors influencing rainfall patterns of climate zones in the tropics include:

Factor	How it affects rainfall
Presence and Migration of Pressure Belts	Total rainfall, seasonality of rainfall
Offshore Oceanic current	Total rainfall
Monsoon Winds	Total rainfall, seasonality of rainfall
El Nino Southern Oscillation	Total rainfall, seasonality of rainfall

1. Presence and Migration of Pressure Belts

a. The main pressure belts which play a major influence on the rainfall patterns of climate zones in the tropics are the Inter Tropical Convergence Zone (ITCZ) as well as the subtropical high (STH) pressure belts. These pressure belts are part of the Hadley Cells (Fig. 5).

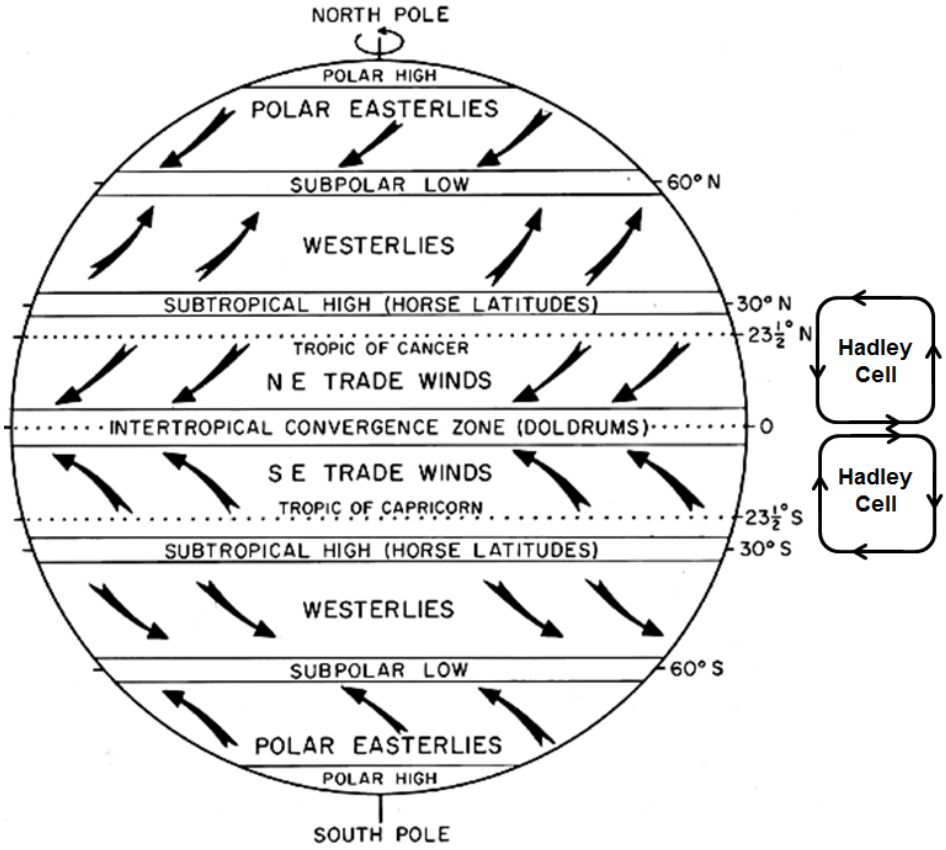


Fig. 5: Hadley cells, surface winds and the pressure belts

b. The presence and migration of pressure belts influence the total rainfall and the seasonality of rainfall, as the pressure belts influences the stability of the air (whether or not air masses will be uplifted to form clouds and eventually rainfall).

c. Locations under the influence of the ITCZ generally experience consistent convectional and convergent rainfall due to uplift of air masses, while locations under the influence of the STH generally experience minimal rainfall due to sinking of air masses.

i. A **Hadley Cell** is a <u>thermally-direct cell</u> found between the equator and 30^0 north and south of the equator in both the northern and southern hemisphere.

ii. The Hadley Cell is thermally direct because its formation is triggered by heat energy.

    1. Along the thermal equator (region with the highest average temperature), concentrated insolation received due to the low latitude cause air masses to be heated and to rise. This creates a zone of low pressure at the equator called the Inter Tropical Convergence Zone (ITCZ).

    2. The rising air at the ITCZ then start moving polewards as upper atmospheric winds, before sinking at around 30°N and S as the falling limb of the Hadley Cell, forming the Sub Tropical High Pressure Belt (STHPB) and then moving back to the ITCZ as surface winds, completing the cell.

iii. The ITCZ is thus a <u>broad zone of low pressure</u> caused by <u>high temperatures</u> present at the equator. Due to the low pressure present, there are also <u>surface winds converging</u> towards the ITCZ, in the form of trade winds. Lastly, the ITCZ is marked by <u>high rates of uplift of air and rainfall formation</u>, in the form of **<u>convectional rainfall</u>** due to the intense heating present at the ITCZ as well as convergent rainfall due to the convergence of surface winds at the ITCZ.

iv. Furthermore, at the ITCZ, the constant uplift of air that dominates the region favours the formation of torrential rainfall, particularly in the afternoon. Many locations in the ITCZ record more than 200 days of rain each year.

v. In contrast, locations which are under the influence of the STH tend to experience minimal rainfall due to the descending air masses in the zone. The descending air masses dynamically contract and experience adiabatic heating, suppressing the formation of clouds and rainfall.

vi. Due to the **axial tilt of the earth along with the earth revolution around the sun**, it has to be noted that the location of the ITCZ, STH and thus the Hadley cells are **not constant but move northwards and southwards** due to the change in the position of the overhead sun (Fig. 6).

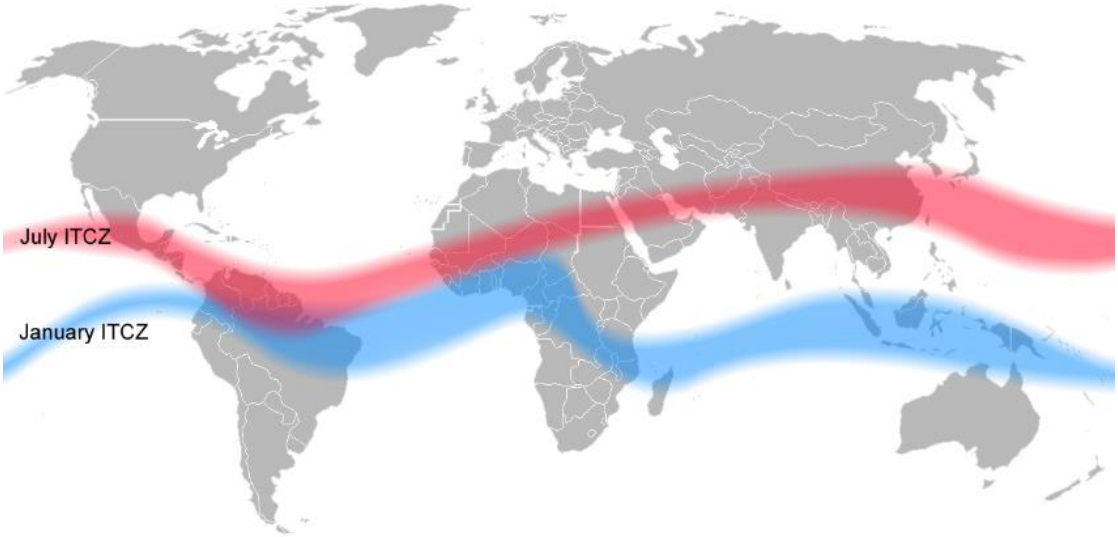


Fig. 6: Locations of the ITCZ in different months of the year

d. Hence, the presence of the pressure belt in the form of the ITCZ explains why the tropical rainforest (Af) climate has a high total annual rainfall and there is an absence of seasonality as total precipitation for each month exceeds 60mm. This is because locations with tropical rainforest climate are constantly under the influence of the ITCZ throughout the year, despite the migration of the pressure belts.

e. On the other hand, hot low latitude desert (BWh) climate has a low total annual rainfall with an absence of seasonality as total monthly precipitation for each month is below 60mm. This is because locations with hot low latitude desert climate are constantly under the influence of the STH throughout the year, despite the migration of the pressure belts (Fig. 11).

f. For the tropical monsoon (Am), tropical savanna (Aw) and sub-tropical steppe (BSh) climates, they have a seasonality of rainfall across months due to the migration of the ITCZ and STH over the locations over the course of the year, resulting in wet and dry seasons.

2. Offshore Cold Ocean currents

a. The nature of the offshore oceanic currents also affect the propensity for uplift and evaporation, resulting in variations in precipitation. Cold currents inhibit evaporation and uplift, causing stable conditions and low precipitation levels. This explains why the major deserts of the world tend be found in areas fringing cold currents. (see Fig 11)

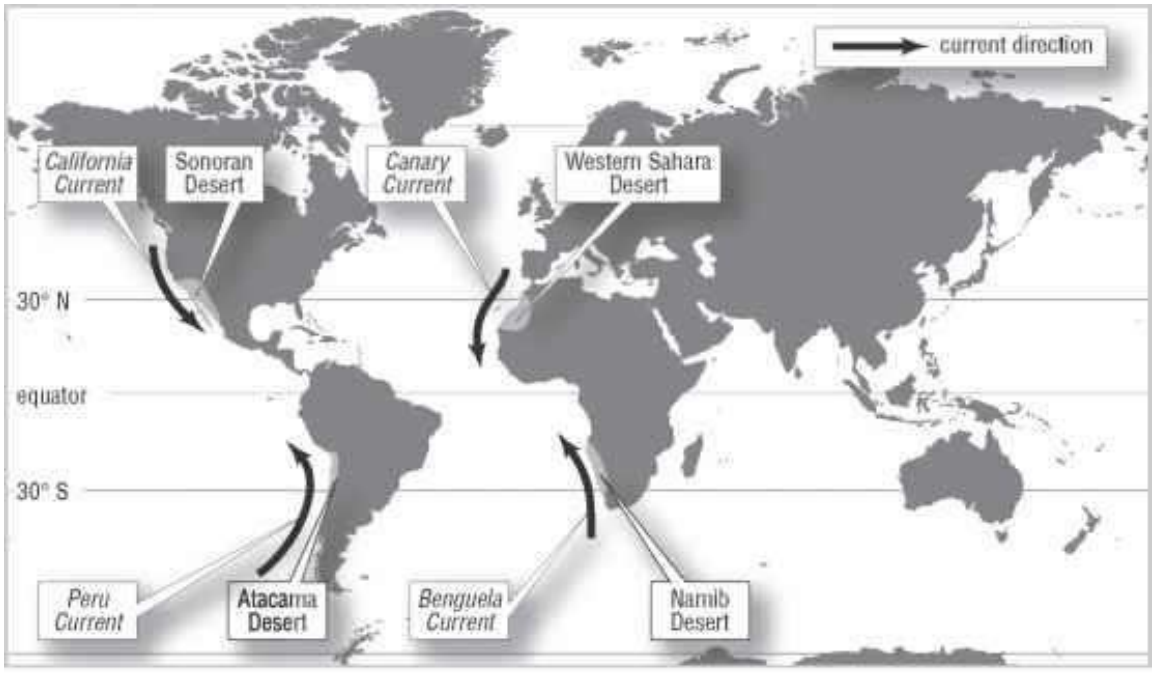


Fig. 11: The influence of the STH and ocean currents on precipitation

3. Continentality

a. In part of the world, the inland generally receives lesser amounts of rainfall than the coast.

b. Continentality contributes to aridity because areas that are a considerable distance from the oceans are not as influenced by moisture-bearing weather systems (i.e. rain). By the time air masses from coastal areas reach the interior, they have lost all their moisture.

c. Continentality is a major cause of dryland conditions in the interior of North America and Central Asia. They can form inland deserts such as the Gobi Desert, in China and Mongolia.

Figure 12: Formation of Gobi Desert due to continentality

4. Monsoon

Monsoon winds are large-scale seasonal winds generated due to differences in temperature and pressure over land and ocean bodies.

Locations affected by monsoon winds such as those with the tropical monsoon (Am) climate will experience marked dry and wet seasons due to the influence of the monsoon winds.

Examples of monsoon winds include the South Asian monsoon and the African monsoon.

3.1 Asian Monsoon

The **Asian monsoon** consists of both the south-west monsoon in the summer and the north-east monsoon in the winter.

3.1.1 Asian Summer Monsoon (June to September)

For the case of the south-west monsoon (June to September):

In the months of June to September, the sun is overhead in the Northern Hemisphere. The higher temperatures in the northern hemisphere during the season results in air masses over continental south Asia such as northern India, Pakistan and central Asia to be heated and rise. This rising air creates a large area of low pressure over central Asia (Fig. 12). [**ITCZ shift north over central Asia**].

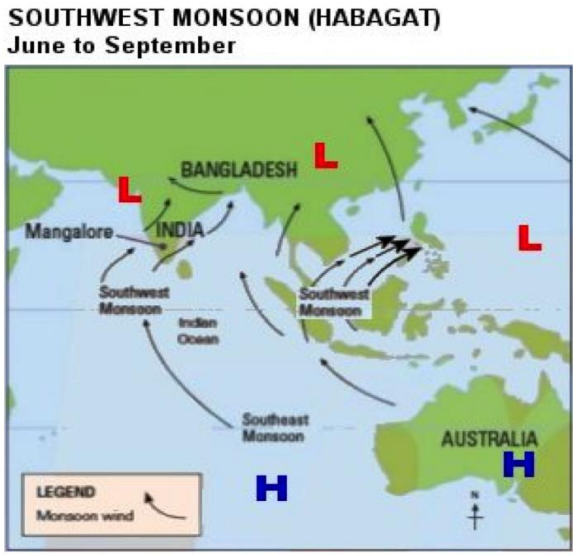


Fig. 12: South-west monsoon in the summer

Understand the monsoon!

1. Which hemisphere is experiencing winter/summer?
2. Which direction is the ITCZ shifting towards?
3. Where are the winds coming from?
4. What is the impact on precipitation?

Australia in the Southern Hemisphere is experiencing winter as it is further away from the sun. Cold air sinks over Australia, creating an area of high pressure. Due to difference in pressure gradient (air moves from high to low pressure), the air mass would move from Australia towards Central Asia. Due to the location in the southern hemisphere, the air is deflected to the left by the Coriolis force and blows as a south-easterly wind. As it moves it blows across the Indian Ocean, the air mass picks up moisture (increasing the relative humidity of the wind).

Once the wind crosses the equator, the Coriolis effect reverses and the wind is deflected right, causing the wind to become a south westerly. It also "splits" into two branches, the Arabian Sea Branch and the Bay of Bengal Branch.

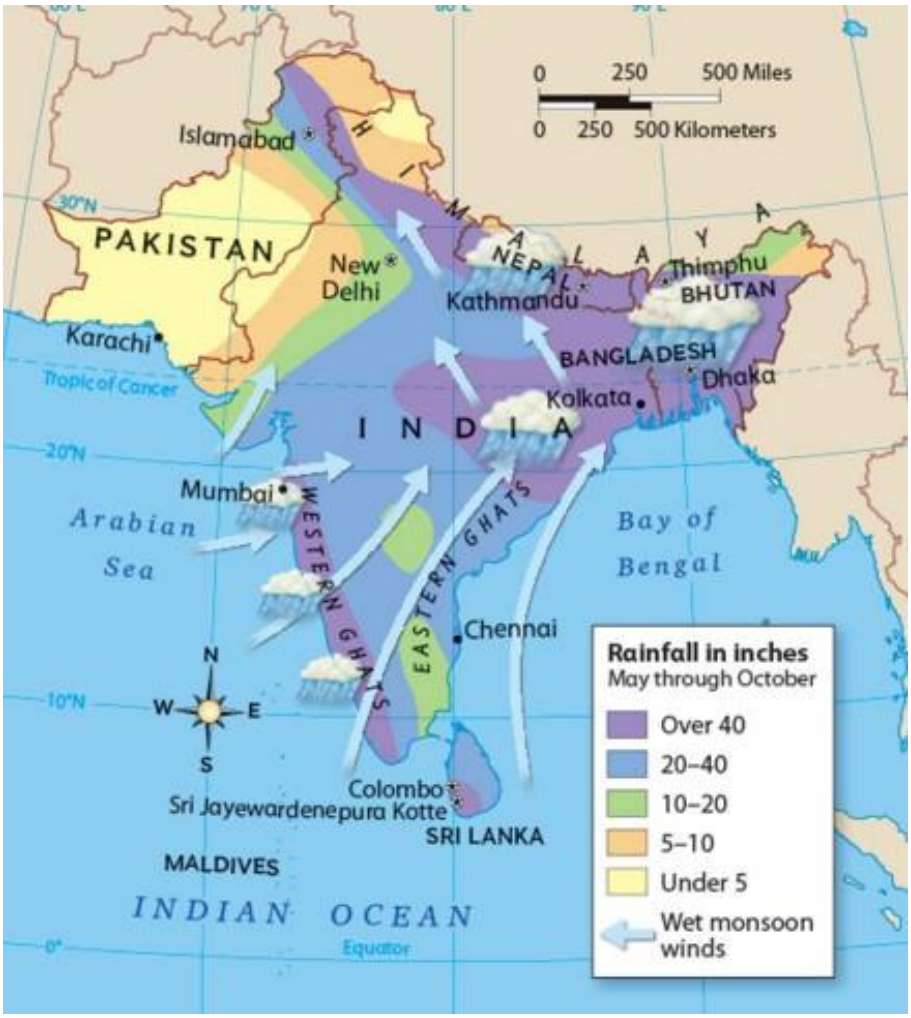
The ***Arabian Sea Branch of the SW Monsoon*** first hits the Western Ghats (a mountain range on the Western side of the Indian Peninsula) of the coastal state of Kerala, India and hence Kerala is the first state in India to receive rain from the South-West Monsoon.

The ***Bay of Bengal Branch of the SW Monsoon*** flows over the Bay of Bengal heading towards North-Eastern India and Bengal, picking up more moisture from the Bay of Bengal. Its hits the Eastern Himalayas, where it undergoes orographic uplift, and provides high precipitation to the regions of North-East India, Bangladesh and West Bengal.

After striking the Eastern Himalayas it turns towards the West, travels over the Indo-Gangetic Plain, at a rate of roughly 1-2 weeks per state, pouring rain all along its way. This is because, when these moisture-laden winds are drawn towards the Himalayas, the Himalayas acts like a high wall and do not allow the winds to pass into Central Asia, forcing them to rise.

With the gain in altitude of the clouds, the temperature drops and precipitation occurs. Some areas of the subcontinent receive up to 10,000 mm of rain, and the monsoon accounts for 80 percent of the rainfall in the country.

Furthermore, due to the higher specific heat capacity of the Indian Ocean, the ocean is cooler than the Indian Sub-continent, this means that air over the Indian ocean will cool and sink, creating an area of high pressure which will moves towards the Indian Sub-continent, an area of low pressure, bringing about additional monsoon rain.



3.2 Winter Monsoon (Nov to Jan)

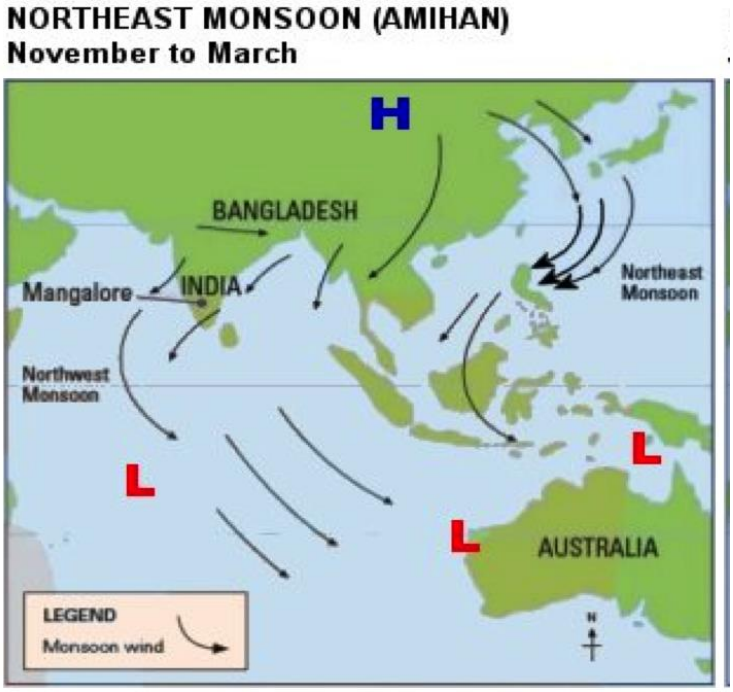
During the northern winter, from **November to February,** the sun is overhead in the southern hemisphere. Temperatures fall over Central, Southern and Eastern Asia, reaching less than 25°C as the ITCZ shifts south past the equator.

N.hemisphere having winter, southern hemisphere (Australia) experiencing summer**.**

Winter = High Pressure as cold air sinks; Summer = Low Pressure as warm air rises

This brings about the winter season in the northern hemisphere as temperature falls creating a zone of high pressure there. **Northeasterly winds** are generated as a result, **and blows from the high pressure continental land masses and North Pacific Ocean to the equatorial low-pressure zones** that develops over South-East Asia and **Australasia** (monsoon trough).

These winds are analogous to the **trade winds** and are known in South Asia as the **northeast (or winter) monsoon, and they** affect **Southern and Southeast Asia**.



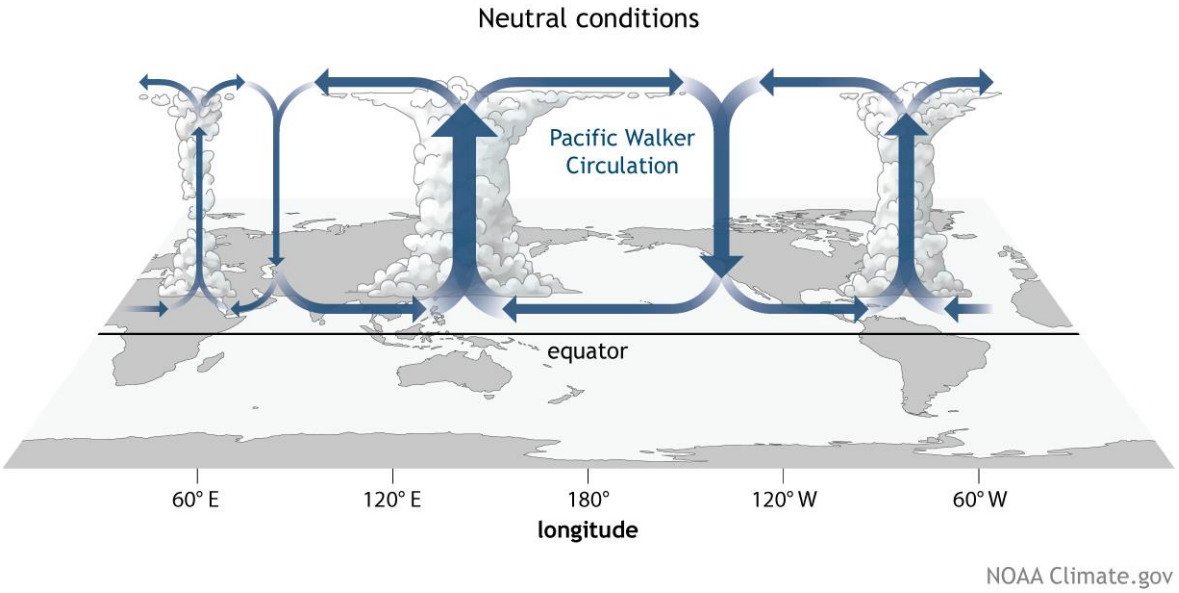
- Due to their continental origin from the Himalayas and Indo-Gangetic Plain, the winds are cold and dry as they blow towards the Indian Ocean. This is known as the **North-East Monsoon or Retreating Monsoon**.
- While traveling towards the Indian Ocean, the dry cold wind picks up some moisture from the Bay of Bengal and pours it over peninsular India. Cities like Chennai, which get less rain from the South-West Monsoon, receives rain from the Retreating Monsoon. About 50% - 60% of the rain received by the state of Tamil Nadu is from the North-East Monsoon.

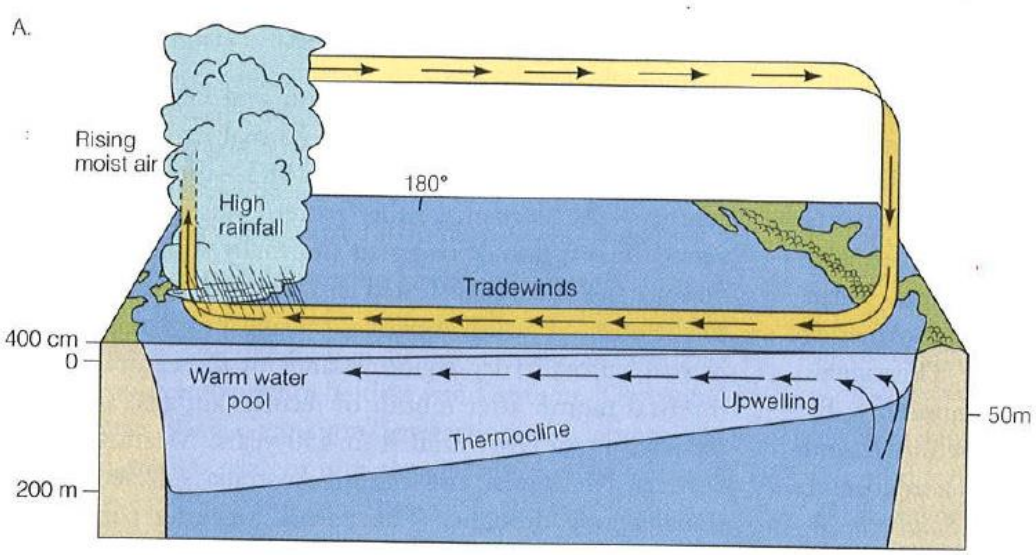
It is also worth noting that North-East Monsoon (or the Retreating Monsoon) is not able to bring as much rain as the South-West Monsoon.

- As it crosses the equator, it is deflected left again due to the Coriolis force. It then flows towards the low pressure zone in Australia and brings rain there.

4. El Nino Southern Oscillation (ENSO)

Besides the Hadley Circulation cell, the **Walker Circulation** cell also operates over the Tropics. El Nino events refer to changes in the Walker Circulation, which can lead to changes in rainfall patterns in tropical climates. There is a weather system over the Pacific Ocean known as the Walker Circulation. The Walker Circulation occurs because of the interaction between the atmosphere and the ocean currents.



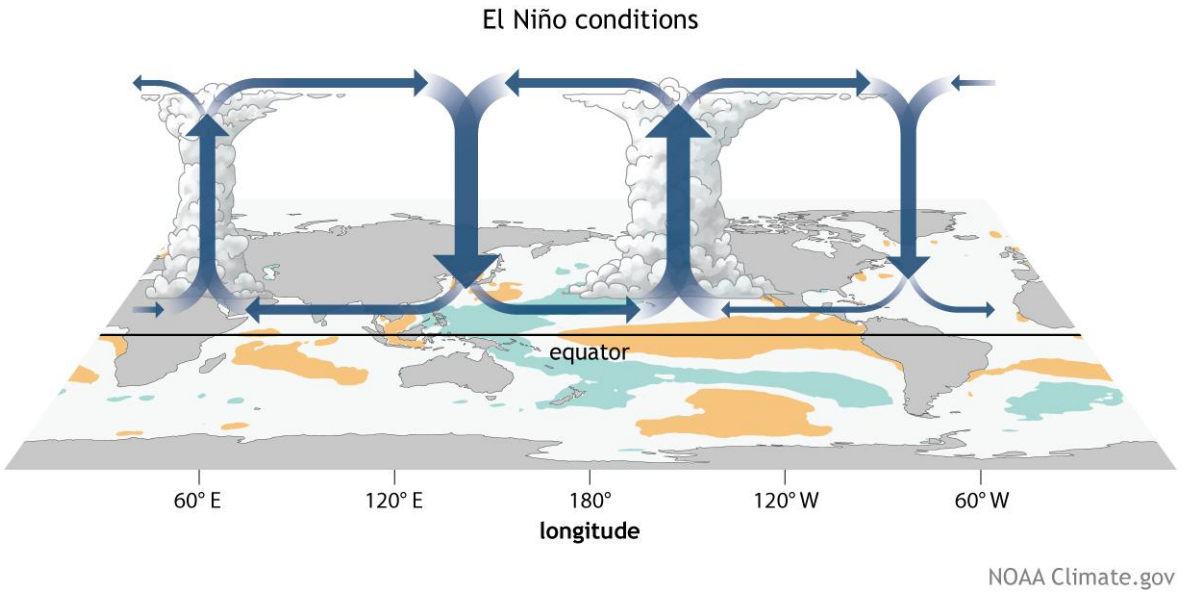


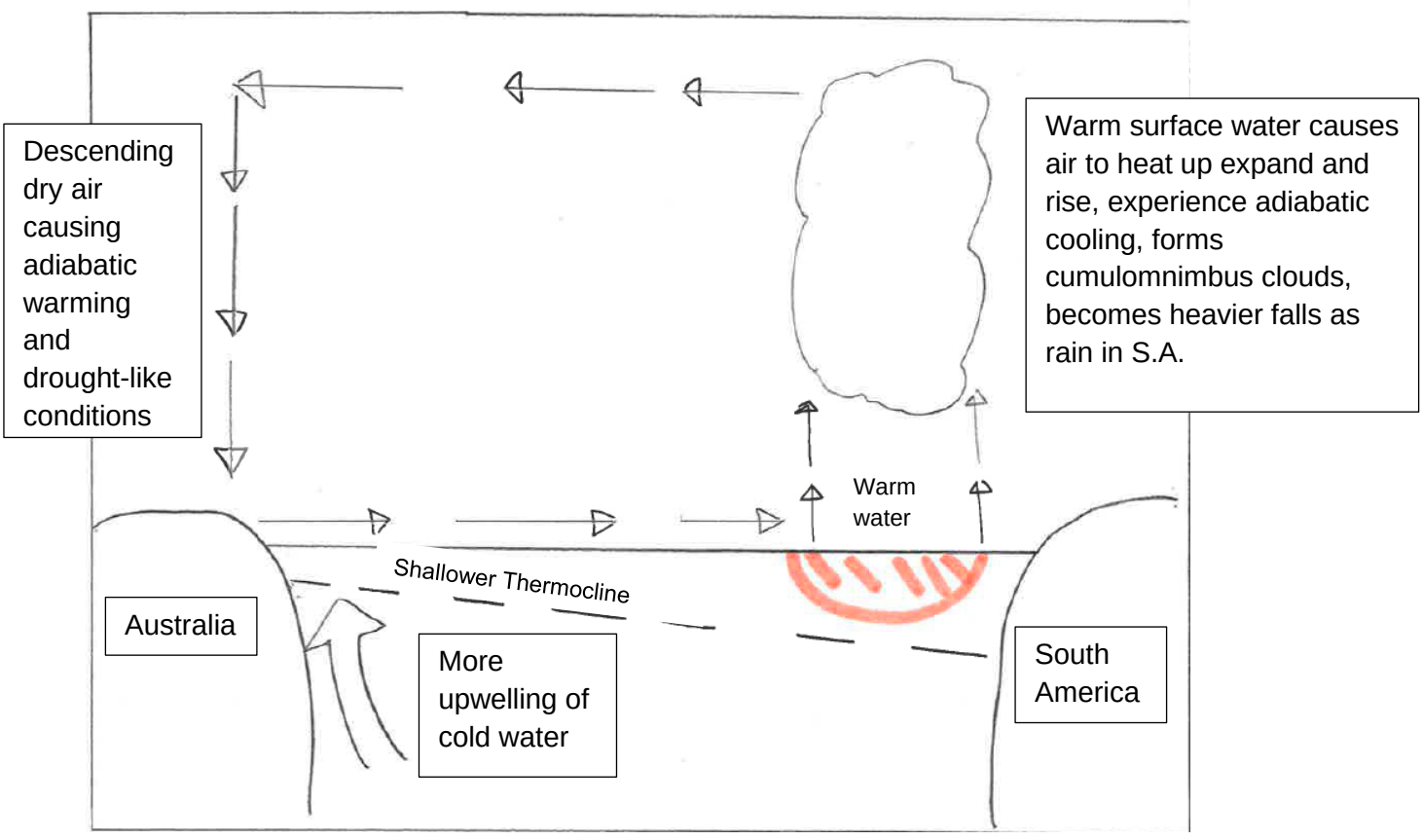
(ENSO Neutral Phase) Walker Circulation:

- Easterly trade winds push water in the Pacific Ocean westward. Winds blow from South America towards Southeast Asia. Sea level in Australia and the Philippines is normally 60cm higher than in Peru (in South America).
- The westward flow of water is known as the Equatorial Current. Water in this current remains in the surface, and gradually heats up to as high as 28°C.
- The warm ocean waters in the heat up the atmosphere above it. This causes convectional uplift to occur. Warm, moist air over Asia and Australia rises, cools, and condenses, forming rain clouds (cumulonimbus clouds).

- The pushing of ocean water westward causes the South Pacific thermocline to be shallow. As a result, cold deep water is allowed to *upwell*.
- The cool water causes air to sink, creating a high pressure zone over the west coast South America, causing aridity, contributing to the formation of the Atacama Desert.

During El-Nino Events





An El Nino event is an irregularly occurring and complex series of climatic changes affecting the equatorial pacific region. It is characterized by the appearance of **unusually warm, nutrient poor water off northern Peru and Ecuador**.

Causes of El Nino:

- The trade winds weaken or die over the Western Pacific.
- Less water is pushed from South America to Asia, so sea levels fall in Asia and Australia, and rise over the South American coast.
- Warm water occurs further east, and due to the deeper thermocline, less cold water upwells near the Peruvian coast.
- Convectional uplift occurs over the Pacific Ocean instead of over Asia and Australia, causing wetter conditions to island nations in the Pacific. Uplift also occurs on the Western Coast of North and South America, causing an increase in rainfall in those areas.

The weakened trade winds delay the arrival of the monsoons in Asia, causing drought. The cooler waters over Southeast Asia and Australia may also **suppress the formation of clouds and rain**, leading to droughts.

Effects of El Niño on weather patterns

- El Niño events are closely related to significant changes in weather patterns around the world.
    - In Southeast Asia (e.g. Indonesia, Philippines) and Australia, normally humid and rainy conditions are replaced by hotter, drier drought conditions, and a fall in average sea levels.
    - In South America (e.g. Peru, Chile) the cold Peruvian current is replaced by warmer waters, sea levels tend to be higher. This can lead to greater atmospheric instability and torrential rains, leading to floods.
    - In the central Pacific islands, unstable weather conditions can lead to heavy torrential rains.
- The changes in weather patterns can also lead to changes in other regions around the world. A change in regional wind patterns can alter local and global wind patterns, which has subsequent impacts on rainfall and temperature. Remember, the atmospheric system is made of multiple *nested* and *interdependent* systems. Changes to one system can lead to significant impacts and feedback mechanisms in others.
- One of the strongest El Niño events occurred in 2015 and only started to weaken in January 2016 and had far-reaching impacts (see attached articles on El Nino).

Socio-economic impact of El Nino

The changes of the weather can also have severe impacts on ecosystems, agriculture, water supply and health.

- Natural ecosystems may be damaged by droughts and floods, and the reproductive patterns of fauna may be disrupted by changing weather patterns.
- Droughts and floods can destroy crops, leading to famine and starvation.
- Higher temperatures can increase the spread of malaria, dengue and the Zika virus.

The loss of water supply can also lead to disruptions to industrial and other economic activity and financial losses associated with the destruction of property.

La Niña

La Niña conditions are the reverse of El Niño. While El Niño refers to weakening or reversal of the Walker Circulation, during La Niña, the Walker Circulation is strengthened.

- During La Niña, the trade winds strengthen and push even more water westward, causing higher sea levels in Southeast Asia and Australia and lower sea levels on the South American coast.
- This enhances the upwelling of cold water off the Peruvian coast, which cools the air over the eastern Pacific region.
- The low pressure over the western Pacific (Asia and Australia) becomes even lower, and the high pressure over the eastern Pacific (South America) becomes even higher.
- Hotter and wetter conditions are found over the western Pacific, while cooler and drier conditions are found in the eastern Pacific.

i. compared to the eastern Pacific countries, which may lead to droughts occurring.

b. Thus, as the ENSO occurs every 3 to 7 years and lasts up 12 to 18 months, it may significantly influence the climate patterns of affected areas when it occurs, disrupting the typical climates experienced at such locations.

WHAT ARE LINKS BETWEEN THE FACTORS INFLUENCING THE PRECIPITATION AND THE CHARACTERISTICS OF THE 5 CLIMATE ZONES IN THE TROPICS?

Climatic Zones Summary Table					
Climate	**Tropical Rainforest**	**Tropical Monsoon**	**Tropical Savanna**	**Sub-Tropical Steppe**	**Hot Low Latitude Desert**
Köppen classification	Af	Am	Aw	BSh	BWh
	Total annual rainfall: More than 1500mm **→ Due to constant influence of the ITCZ**	**Total annual rainfall:** More than 1500mm **→ Due to varying influence of the ITCZ** **→ Due to influence of monsoon winds**	**Total annual rainfall:** 1500-500mm **→ Due to varying influence of the ITCZ**	**Total annual rainfall:** Between 250mm to 500mm **→ Due to influence of the** ITCZ **and STH**	**Total annual rainfall:** Less than 250mm **→ Due to constant influence of the STH**
	Seasonality of rainfall: Absent. Even distribution of precipitation. Total precipitation for each month exceeds 60mm, no month is considered deficient of rainfall. Rainfall is mainly in the form of convectional rainfall in the late afternoons. **→ Due to constant influence of the ITCZ**	**Seasonality of rainfall:** Present, with a marked short dry season with one or more months receiving less than 60mm. Rainy season is excessively wet. Large amounts of rainfall fall mainly during the wet season. **→ Due to influence of the ITCZ** **→ Due to influence of monsoon winds**	**Seasonality of rainfall:** Present, with monthly precipitation totals dropping below 60mm for 4 to 6 months during the dry season. Rainfall concentrated in the wet season. Heavy convectional rainfall during wet season in summer can give 80% of the total annual rainfall in four or five months. **→ Due to varying influence of the ITCZ**	**Seasonality of rainfall:** Present, with some monthly precipitation totals at above 60mm. Precipitation may occur due to short incursions of the ITCZ or from occasional mid-latitude cyclones. **→ Due to varying influence of the** ITCZ **and STH**	**Seasonality of rainfall:** Absent, with all monthly precipitation totals below 60mm. Precipitation is irregular and unreliable, usually in the form of convectional rainfall during summer. **→ Due to constant influence of the STH**

[Note: Bear in mind the relief, ocean currents and ENSO in influencing rainfall patterns for Data Response Questions & Structured Essay Questions.]