Lecture 4
Tropical Climates (III): Tropical Cyclones & ENSO and their Influence on Rainfall in the Tropics

KEY QUESTION:

*How does synoptic scale circulations affect rainfall in the tropics?***

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

- Atmospheric and surface conditions necessary for the development of tropical cyclones and resultant effects on rainfall patterns
- The three phases of the El Niño Southern Oscillation (ENSO) and the associated changes in rainfall over tropical Pacific

Note that this key question was also partly addressed in Lect 3 when we studied monsoons. Please connect the content for monsoons and this lecture when revising synoptic scale circulations and their influence on rainfall in the tropics.

Lecture Outline

4.1 Tropical Cyclones

- 4.1.1 The Anatomy of a Topical Cyclone
- 4.1.2 Conditions for Formation and Decay of Tropical Cyclones
- 4.1.3 The Resultant Effects of Tropical Cyclones on Rainfall Patterns
- 4.1.4 The Saffir-Simpson Scale of Tropical Cyclone Intensity

4.2 El Niño-Southern Oscillation (ENSO)

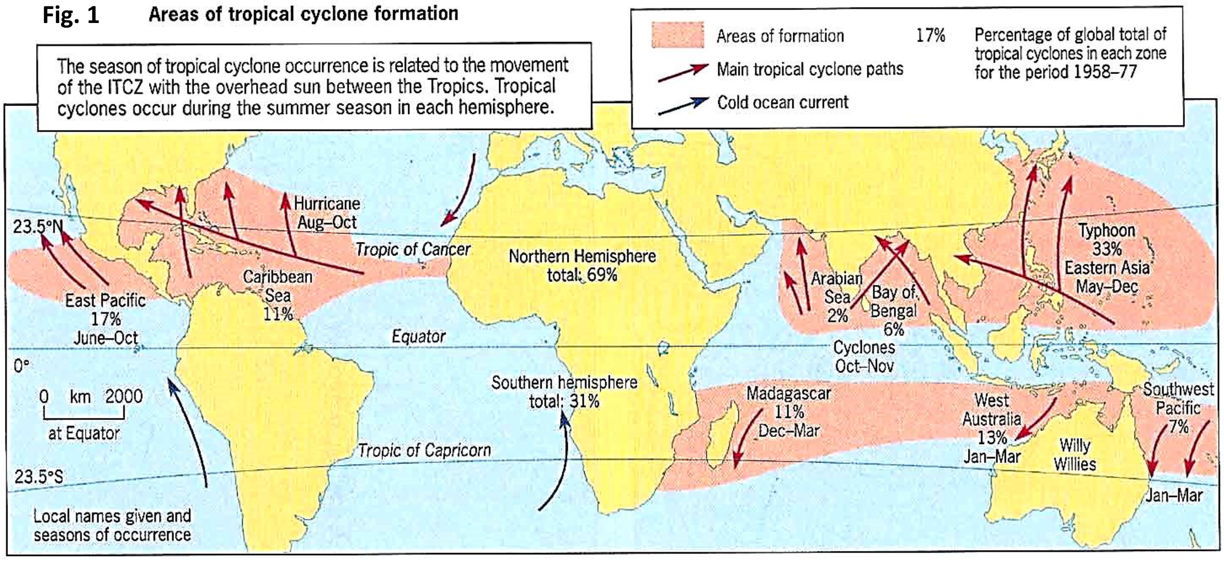
- 4.2.1 The Three Phases of ENSO
  - **(A)** Neutral phase – The Walker Circulation
  - **(B)** La Niña phase
  - **(C)** El Niño phase
- 4.2.2 Changes in rainfall over tropical Pacific due to the El Niño and La Niña

*The Atacama Desert is one of the most arid places on Earth (see **left**), but in selected years, flowers may bloom (see **right**), hardly the norm. This has to do with the location of the desert in South America on the east of the Pacific Ocean. How often do such instances occur, and why?*

4.1 Tropical Cyclones

- By far the most significant atmospheric disturbances in the tropics are tropical cyclones.
- These storms are known by different names in different places: *hurricanes* in North and Central America, *typhoons* in the western North Pacific, and simply *cyclones* in the Indian Ocean. (See **Fig. 1**)
- Whatever the name, these are **intense, revolving, rain-drenched, migratory, destructive storms** that occur erratically in certain regions of the tropics and subtropics.

Fig. 1 Areas of tropical cyclone formation



4.1.1 The Anatomy of a Tropical Cyclone

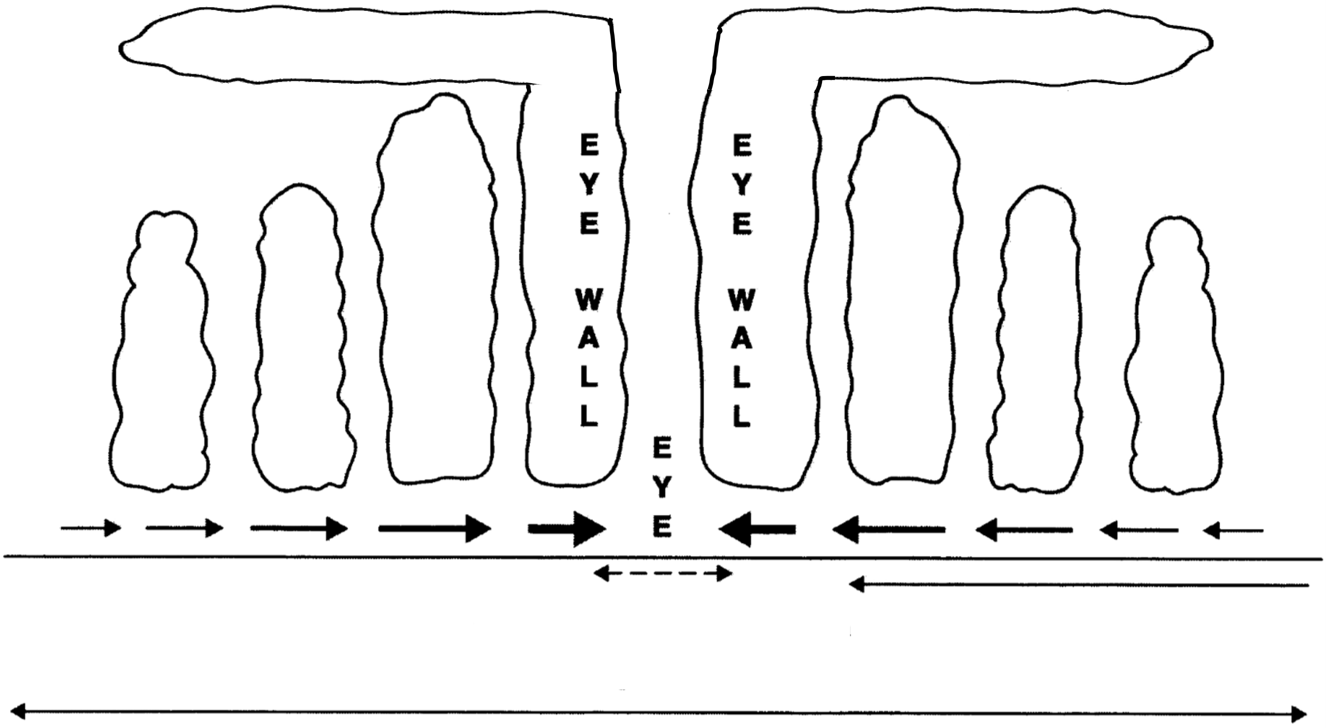


Fig. 2 A Cross Section Through a Tropical Cyclone (Hurricane)

- **An intense tropical cyclone is an almost circular storm centre of extremely low pressure (LP)**. From the outer edge of the tropical cyclone to the centre, the barometric pressure typically drops to 950 mb or lower (see **Figs 2 and 3**).
- **Mature tropical cyclones average about 600 km across**, although they can range in diameter from 150 km up to 1000 km or even more (see **Fig. 2**).
- Because of the very strong pressure gradient (see **Fig. 3**), **winds spiral inward at high speed**. Once sustained wind speeds reach 37 km/h, tropical disturbances become tropical depressions. As wind speed increases to 63 km/h, tropical depressions are upgraded to tropical storms. **Eventually, when wind speed reaches 119 km/h, tropical storms are officially referred to as tropical cyclones.** It can continue to increase to higher speeds (**Section 4.1.4**).
- As the inward rush of warm, moist surface air approaches the LP core of the storm, **it turns upward and ascends in a ring of towering cumulonimbus clouds**.
    - This wall of intense of convective activity is called the **eye wall**, which can exceed 16 km in height. It is here that the greatest wind seeds and **heaviest rainfall occur**.
    - Surrounding the eye wall are curved bands of clouds that trail away on spiral fashion. **Near the top of the tropical cyclone the airflow is outward, carrying the rising air away from the storm centre, thereby providing room for more inward flow at the surface.**
- At the very centre of the storm is the **eye** of the tropical cyclone, in which **air gradually descends and heats by compression**, making it the warmest part of the storm. Here **clear skies and calm winds** prevail. The diameter of the eye can range from 30-50 km.
- The weather pattern within a tropical cyclone is relatively symmetrical around the eye.
    - As the eye passes over a site, calm prevails, and the sky clears. Passage of the eye may take about half an hour, after which the storm strikes with renewed ferocity, but with winds in the opposite direction.

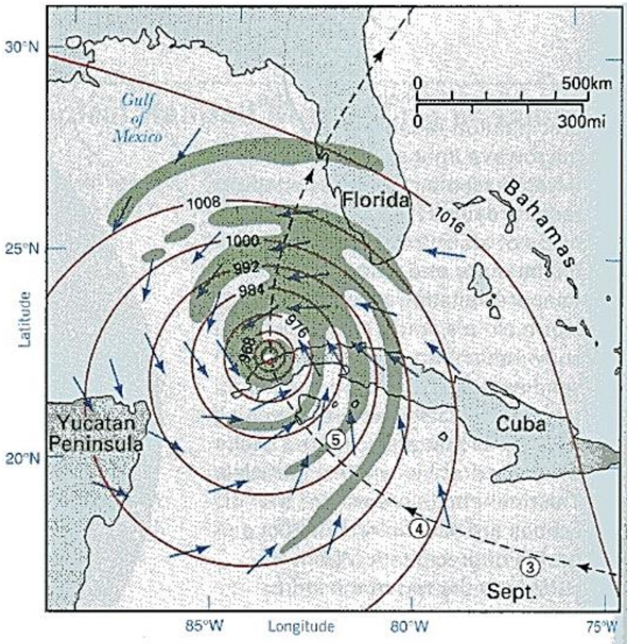


Fig. 3 ***Hurricane weather map*** *A simplified weather map of a hurricane passing over the western tip of Cuba. Daily locations, beginning on September 3, are shown as circled numerals. The recurving path will take the storm over Florida. Shaded areas show dense rain clouds as seen in a satellite image.*

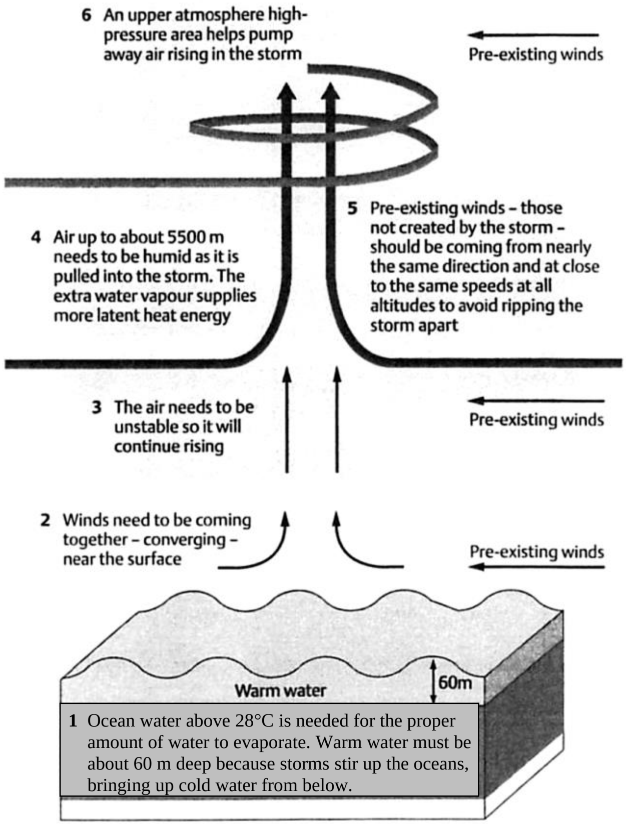


Fig. 4 Conditions supporting the development of tropical cyclones

4.1.2 Conditions for Formation and Decay of Tropical Cyclones

- Tropical cyclones occur only when a set of conditions are available (see **Fig. 4; previous page**). As a result, there are **specific areas and times in a year** in which they form and impacts experienced (see **Section 4.1.3**).

- **Warm sea-surface temperature.**
  - Tropical cyclones develop most often in the late summer when ocean waters have reached temperatures of **26-27°C or higher** and are thus able to provide the necessary heat and moisture to the air. This helps air above the water to be warmed and become unstable, producing the low pressure condition to draw surrounding surface winds in.
  - **Sufficient depth (about 60 m) of warm water** is therefore also necessary because storms are capable of stirring up water from below. If the depth of warm water is insufficient, the supply of warm water will be cut when stirred by the storm, and the formation of the tropical cyclone will be weakened.

- **High humidity and therefore plenty of water vapour.**
  - Tropical cyclones require an enormous supply of energy, which is provided by the **latent heat released when water vapour condenses**. (See **Lect 3 Box 1**)
  - The release of latent heat warms the air and provides buoyancy for its upward flight. The result is to reduce the pressure near the surface, which, in turn, encourages a more rapid inflow of air.
  - To get this 'engine' started, a large quantity of rising warm, moist air is required, and a continuous supply is needed to keep it going.

- **Strong Coriolis effect.**
  - Tropical cyclones usually form only over warm oceans in 8° to 20°N and S latitudes.
  - Although water temperatures are sufficiently high, hurricanes do not form within 5° of the equator because the Coriolis effect is too weak **to initiate the necessary rotary motion** for air to spiral upwards around the LP centre.

- **Light pre-existing winds.**
  - Winds should be light and coming from nearly the same direction (i.e. **little or no wind shear**) so as to allow significant vertical development of the tropical cyclone.

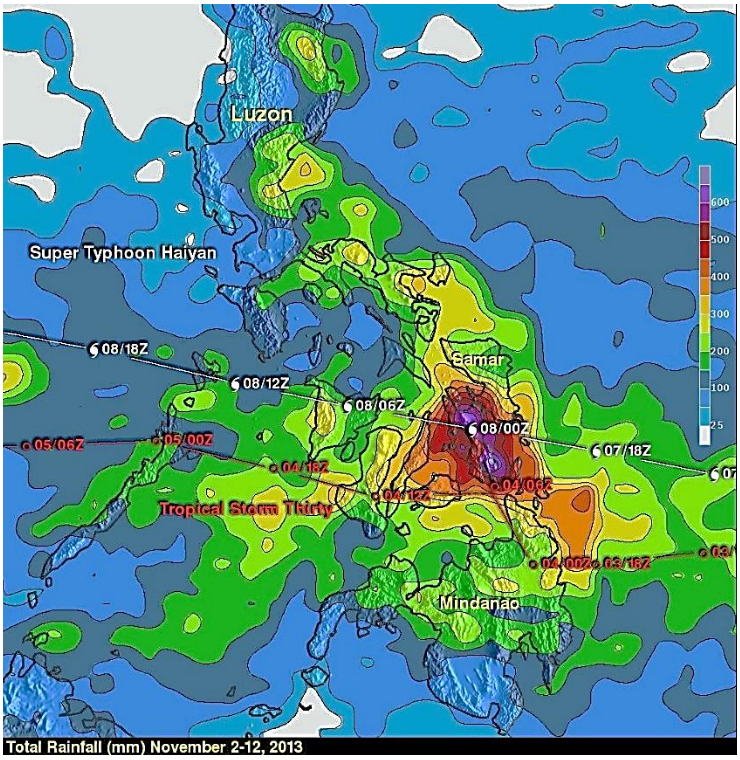
- As a result of the above conditions, tropical cyclones usually last 1-2 weeks (but can be short as a day, and up to 4 weeks!), and diminish in intensity whenever they:
  - move over cooler water that cannot supply warm, moist air;
  - move over land, where it abruptly loses its power source of the warm, surface waters of the ocean; *or*
  - reach a location where the large-scale flow aloft is unfavourable (i.e. either subsiding or where wind shear, i.e. a change in wind speed and/or direction, is strong).

4.1.3 The Resultant Effects of Tropical Cyclones on Rainfall Patterns

- Tropical cyclones cause severe damage to affected areas, through **(1) storm surges** (which gives coastal flooding that goes deep inland), **(2) extremely strong winds**, and **(3) torrential (or high-intensity) rains**. For our purpose, we focus only on **(3)**.
- The effects of (1) storm surges and (2) strong winds are concentrated in coastal areas. However, **(3) heavy rains** may affect places hundreds of kilometres from the coast for several days after the storm.
- Similar to monsoons (see **Lect 3**), tropical cyclones contribute to the total annual rainfall in areas that experience cyclones by adding most rain during the warmer months.

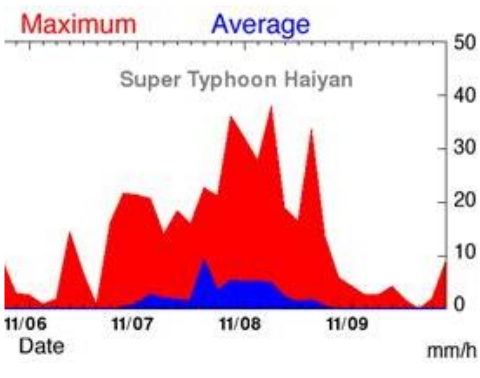
Box 1: Super Typhoon Haiyan

- Typhoon Haiyan – local name Yolanda – was one of the strongest ever-recorded typhoons to hit the Philippines on 8 November 2013. It was classified as a super typhoon with sustained surface winds estimated at 195 mph (~315 kph).
- The impacts of Typhoon Haiyan were severe, with more than 6000 deaths, and many more injured and missing. For comparison purposes, Hurricane Katrina in 2005, considered one of the strongest tropical cyclones to make landfall in the United States, was responsible for 1833 fatalities.
- Within a span of only 10 days, Typhoon Haiyan and two other *earlier* smaller storms, brought copious amounts of rainfall to the central Philippines. Typhoon Haiyan alone generated an average of 400 mm of rainfall.
- The combined rainfall from these tropical cyclones is shown in the map below during the period from November 2-12, 2013. It shows that most of the island of Leyte had rainfall totals greater than 500 mm (~19.7 inches, dark red) with a peak amount of over 685 mm (~27 inches, lighter purple) located over the southeast corner of the island.
- Peak and average rainfall over the central Philippines shows rain intensities (shown in red) and average rainfall (shown in blue) of Haiyan.



Total rainfall from Typhoon Haiyan and two preceding smaller storms, Nov 2-12, 2013

Rainfall intensities and amount of rainfall brought by Typhoon Haiyan



4.1.4 The Saffir-Simpson Scale of Tropical Cyclone Intensity

- By studying past storms, the Simpson-Saffir Scale (see **Table 1**) was established to rank the relative intensities of hurricanes. Predictions of hurricane severity and damage are usually expressed in terms of this scale.
- This scale ranks storms based on the central pressure of the storm, mean wind speed, and height of accompanying storm surge (i.e. water pushed towards the shore by the force of winds, resulting in rise in water level and severe flooding in <u>coastal</u> areas).
- Category assignments are based on observed conditions at a particular stage in the life of a tropical cyclone and are viewed as estimates of the amount of damage a storm would cause if it were to make a landfall without changing size or strength.
- As conditions change, the category of the storm is re-evaluated so that public-safety officials can be kept informed. By using the Simpson-Saffir Scale, the disaster potential of a tropical cyclone can be monitored and appropriate precautions can be planned and implemented.
- Category 1 storms are weak, while Category 5 storms are devastating.

Table 1 The Saffir–Simpson hurricane disaster-potential scale

Scale number	Central pressure (mb)	Wind speed (km/h)	Storm surge (m)	Damage potential. The amount of damage increases exponentially with the scale: a category 5 is likely to cause 250 times more damage than a category 1
1	>980	119-153	1.2–1.6	**Minimal:** Damage to vegetation and poorly anchored mobile homes. Some low-lying coasts flooded. Solid buildings and structures unlikely to be damaged.
2	965–979	154-177	1.7–2.5	**Moderate:** Trees stripped of foliage and some blown down. Major damage to mobile homes. Damage to some roofing materials. Coastal roads and escape routes flooded 2–4 hours before the cyclone centre arrives. Piers damaged and small unprotected craft torn loose. Some evacuation of coastal areas is necessary.
3	945–964	178-209	2.6–3.8	**Extensive:** Foliage stripped from trees and many blown down. Great damage to roofing materials, doors and windows. Some small buildings structurally damaged. Larger structures may be damaged by floating debris. Serious coastal flooding and escape routes cut off 3–5 hours before cyclone centre arrives. Evacuation of coastal residents for several blocks inland may be necessary.
4	920–944	210-250	3.9–5.5	**Extreme:** Trees and signs all blown down. Extensive damage to roofing, doors and windows. Many roofs of smaller buildings ripped off and mobile homes destroyed. Extensive damage to lower floors of buildings near the coast. Evacuation of areas within 500 m of coast may be necessary and low-lying areas up to 10 km inland. Major erosion of beaches.
5	<920	>250	>5.5	**Catastrophic:** Complete roof failure of many residential and industrial buildings. Major damage to lower floors of all structures lower than 3 m above sea level. Evacuation of all residential areas on low ground within 16–24 km of coast likely.

This scale describes the meteorological characteristics of the storm based on the intensity of the low pressure, its disaster potential and the likely damage. This is useful for governments and emergency services in areas at risk.

4.2 El Niño-Southern Oscillation (ENSO)

- El Niño-Southern Oscillation (ENSO) is **the occasional switch in the direction and intensity of winds <u>and</u> ocean currents over the Pacific Ocean** (see **Fig. 6** later).
- ENSO occurs (very roughly) **every 3 to 7 years**, can last for anything from several months to more than a year and is a **switching** (hence, "oscillation") between three different types of climate: the neutral situation (or the Walker Circulation), La Niña and El Niño.
- As we shall see, ENSO is linked to changes in meteorological conditions including storm patterns, and instances of drought (see **Section 4.2.2**). These changes, while originating in the Pacific Ocean, can happen and bring impacts of varying degrees to different parts of the world.

4.2.1 The Three Phases of ENSO

- To understand the El Niño-Southern Oscillation (ENSO), it can be thought of as three phases – neutral conditions (**Fig. 5**), La Niña (**Fig. 6**) and El Niño (**Fig. 7**).
- Apart from the role of trade winds and currents, take note of another important driver, the **thermocline**, the zone that separates warm surface water (above 25°C) and cool deep ocean water (below 15°C).

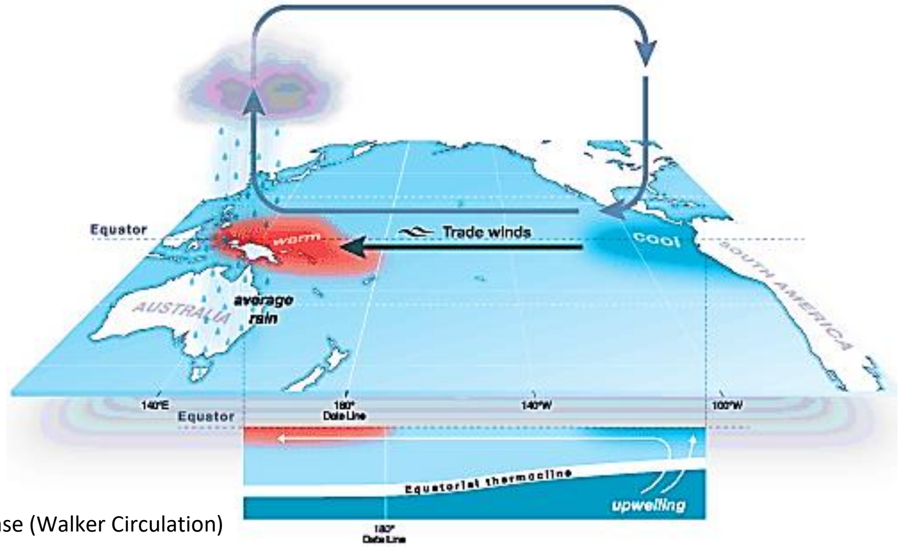


Fig. 5 Neutral phase (Walker Circulation)

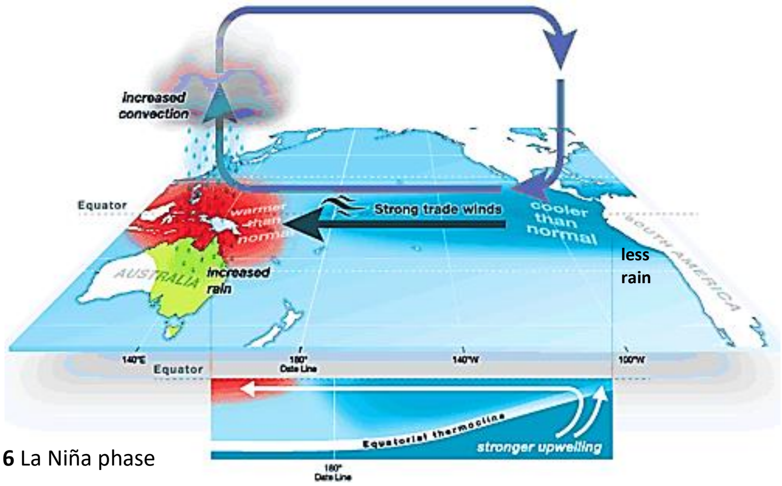


Fig. 6 La Niña phase

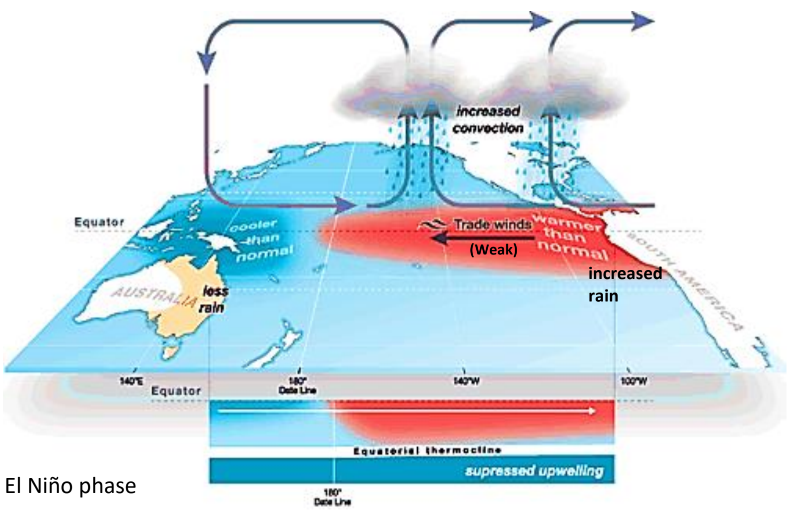


Fig. 7 El Niño phase

(A) Neutral phase – The Walker Circulation

- In tropical Pacific, trade winds generally drive the surface waters **westwards** (see **Figs 5 and 9**). The surface water becomes progressively warmer going westward from South America towards Australia because of its longer exposure to solar heating.
- The warm, moist air and warm surface water driven towards the western Pacific **deepens the thermocline** (**Fig. 5**). This creates warm water at depth and sea level is typically 0.5-1m higher (and about 8°C warmer) on Australia's east coast than on South America's west coast.
- The warm water along Australia's east coast drives atmospheric **convection**, forcing warm moist air upwards to form cumulonimbus clouds that produce rain.
- Once the air has released its moisture, it travels **east** at the upper atmosphere before descending over the cooler eastern Pacific (or South America's west coast). This loop is the neutral phase of the ENSO, also referred to as the **Walker Circulation**.
- In the ocean, the cold Humboldt Current passes northward along the South American coast. Cold water from deep is **drawn up to replace the surface waters that are being driven westward**.

(B) La Niña phase

- To aid our understanding, it is useful to consider the La Niña phase as an **enhanced/strengthened neutral phase of ENSO** (see above, **part A**).
- Typically, a La Niña is preceded by a build-up of **cooler** than normal subsurface waters in the east Pacific (see **Fig. 8**).
- In this phase, the easterly **trade winds strengthen**, cold upwelling off Peru and Ecuador intensifies, and sea-surface temperatures (SSTs) drop below normal (see **Fig. 6**). For example, during the 1988-89 La Niña, SSTs fell to as much as 4°C below normal.

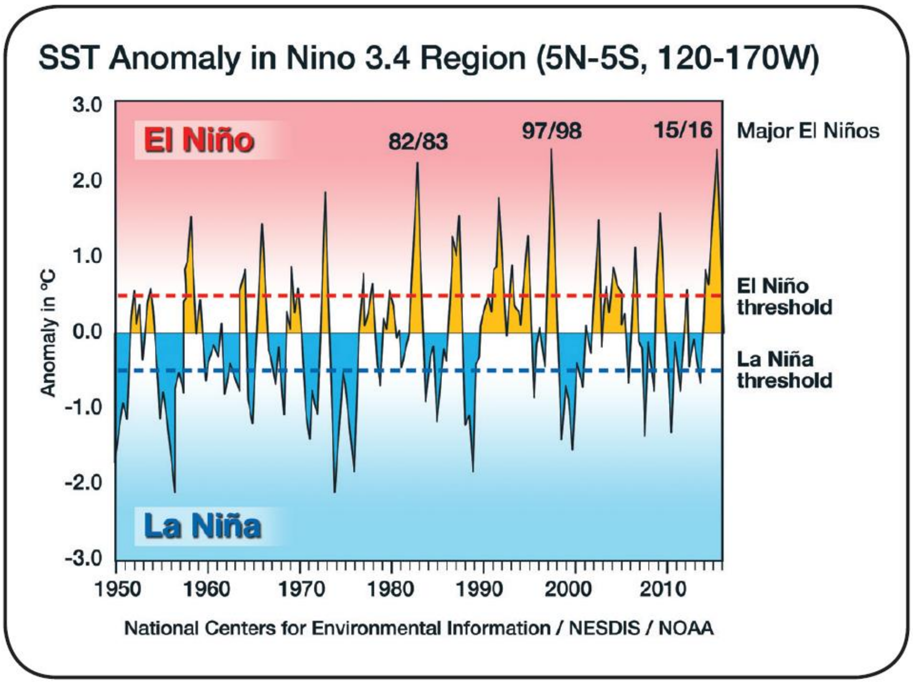


Fig. 8 *ENSO events since 1900*

(C) El Niño phase

- Both La Niña and El Niño refer to large-scale changes in sea-surface temperature across the central and eastern tropical Pacific. Both tend to peak during the Southern Hemisphere summer.
- But they are very different phenomena. In an El Niño year (**Fig. 7**) the **trade winds are weaker** and the water is pushed around less. With less water piled up in the west Pacific, more remains in the east Pacific and not so much cold water gets pulled up from the depths of the ocean.
- In an extreme El Nino year, there is sometimes even a **reverse direction of flow**. The piled up water in the west Pacific, sloshes back east. The result is that the eastern Pacific becomes 6-8°C warmer, and a 30 cm rise in sea level in Peru along the west coast of South America. Thus, compared to the neutral phase, the region of rising air has moved to east Pacific with the associated convectional uplift.
- **Fig. 9** provides a top view of the winds and currents at play under normal conditions; while **Fig. 10** shows what happens during an El Nino event. Notice how the weakening of the NE and SE trade winds allowed the occurrence of a counter current, reversing the usual flow of water in the Pacific.

Fig. 9 *Conditions during the neutral phase*

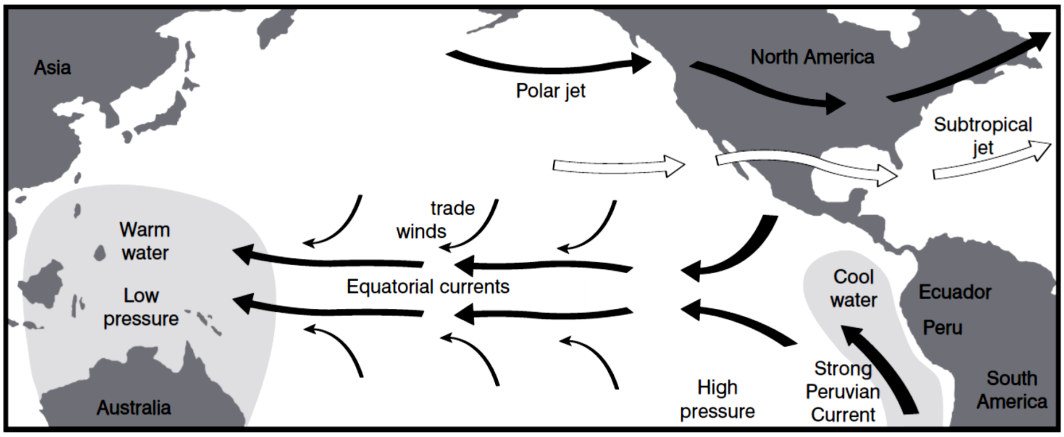
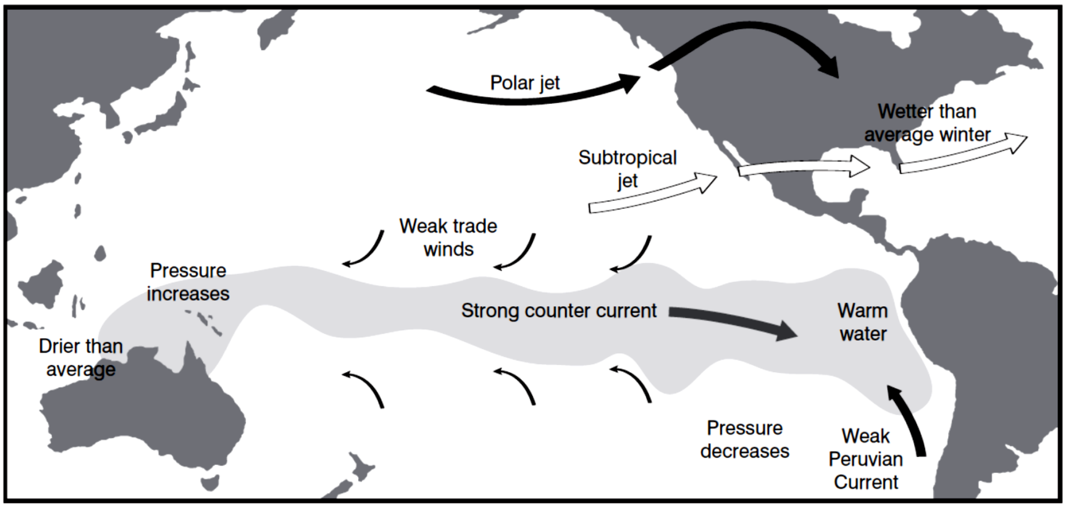


Fig. 10 *Conditions during an El Niño event*



✍ Activity

Figs 5-7 and 9-10 are detailed representations of the processes behind the phases of ENSO. It is however unrealistic for you to reproduce the same when explaining them.

Fig. 11 on the right are simpler versions which you can produce and annotate further.

After which, **practice sketching** all three phases of ENSO on a separate piece of paper.

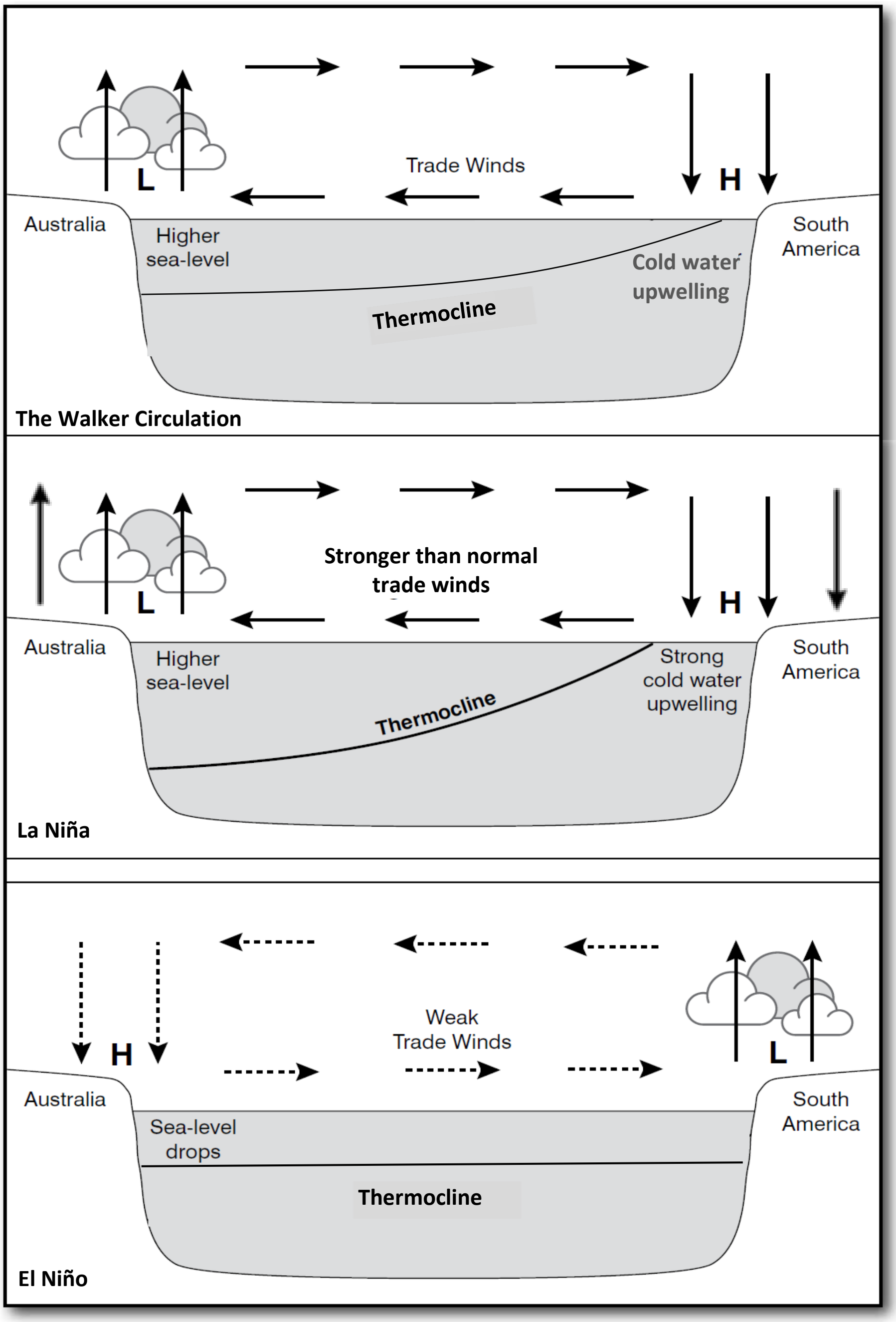


Fig. 11

4.2.2 Changes in rainfall over tropical Pacific due to the El Niño and La Niña

- Both El Niño and La Niña create short-term natural changes in temperature and rainfall conditions (see **Table 2**).
- The most reliable effects of El Niño in the tropical Pacific region are excessive rainfall in south-eastern South America, and southern USA and reduced rainfall over Indonesia, Australia, southern Africa and northern South America (**Fig. 10**). The latter makes these areas more vulnerable to forest fires.
- On the other hand, the La Niña can bring droughts to parts of South America but more rain than usual to parts of Southeast Asia (consider **Fig. 9**, but with effects amplified).

<table>
<tr><th>Table 2</th><th>El Niño</th><th>La Niña</th></tr>
<tr><td>East of the Pacific (e.g. South America)</td><td>More rain than usual
The warm water that builds up off the coast of South America leads to significant increases in evaporation and precipitation.
1982/83 saw one of the most severe El Niños on record: over 2500 mm of rain fell over a six month period in Ecuador and northern Peru, about 300 times the average figure. This led to devastating flooding that swept away people's homes and caused extensive damage to farming.
In the 2015-2016 event, the El Niño exacerbated the summer rains in Paraguay and the worst floods for many decades forced 100,000 people to evacuate their homes.</td><td>Less rain than usual
La Niña is associated with severe drought conditions in coastal areas, as well as decreased temperatures.
During normal years there is a reasonable amount of rain in the mountainous areas of Peru, as a result of the easterly trade wind flow over the Andes. But in 1996 (a La Niña year), there was no rainfall along the coastal regions, unlike the situation during El Niño years.</td></tr>
<tr><td>West of the Pacific (e.g. Australia and SE Asia)</td><td>Less rain than usual
While South America has wetter conditions, Southeast Asia experiences the opposite. The colder water in the western Pacific reduces evaporation, encouraging drier conditions.
Eastern Australia endured one of its worst-ever droughts in 1982/83.
Indonesia also had dry conditions in 1982/83, and many died as a result of crop failure and famine.</td><td>More rain than usual
La Niña can bring some welcome relief to areas that normally experience drier conditions.
Rains in late 2005 and early 2006 brought relief to Australia, which had been gripped by its worst drought in living memory since 2002. Australian farmers benefited from the best rain in 10 years, which fell throughout eastern and southern grain-growing areas towards the end of April, exactly the right time for planting of winter grains crops.
The wetter conditions were welcomed by farmers in Vietnam, the world's largest robusta coffee producer and the second-largest exporter of rice.
Heavy rains associated with La Niña can also bring problems, though.
In late 2005 into early 2006, the Philippines, the world's largest coconut oil shipper, was hit by La Niña and experienced above-average rainfall.</td></tr>
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