Overview of Tropical Meteorology and Climate Variability

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1 Introduction, Purpose, Scope and Definitions

The purpose of this note is to introduce the reader to the main features and characteristics of the weather and climate in the tropical regions. Here we define the tropics as more-or-less the region bounded by the Tropic of Cancer to the north and Tropic of Capricorn to the south. This discussion will refer mostly to atmospheric processes with some relevant points about the land and ocean. As before, little mathematical detail will be provided (see references), more emphasis is given to physical mechanisms and phenomonology.

Whereas there is no sharp delineation between the tropical region and extra-tropical when considering thermodynamical processes, certain reasonable approximations are often made in text books, such as the relative role of the Corriolis effect and diabatic mechanisms, the reader should be aware that the reality is rather more complex than such simple descriptions as given here. I shall often make comparative statements to the mid-latitudes.

With a globe (or world altas in hand) it is instructive to familiarize oneself with the distribution of land and ocean and the characteristics thereof. Pay particular attention to the distribution of mountain ranges (Andes, Himalaya), the deserts (Atacama, Sahara, Arabian, Kalahari, Gobi and Australian). Also the ocean currents (see for example my earlier post at `http://asl.umbc.edu/pub/chepplew/OceanTD_intro.html`), note the detail of the zonal flow and the actual surface temperatures.

2 Principal Governing Phenomena

Starting with the obvious, as anyone who has spent time in the tropics will know - the length of the day does not vary much throughout the year, the (noon) solar zenith angle is close to 90-deg, and the amplitude of the seasonal temperature cycle is generally (comparatively) small, although there are important regional factors and micro-climates that make exceptions to this observation. See figure 1 . Note, however that depending on location, altitude etc, the amplitude of the diurnal temperature changes can be large, compare for example a desert and a tropical rain forest climate).

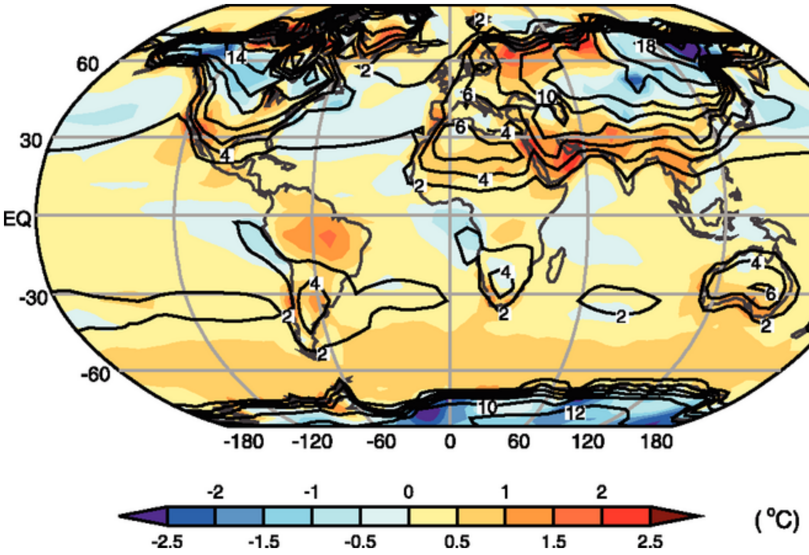

Figure 1: Global map annual temperature cycle

Next, based on a zonal average (key point) there is a net excess of heating into the tropical ocean and atmosphere, which together with a net deficit of heating at higher latitudes results in transport of heat from tropics to the extra-tropics, see figure 2. A portion of the excess radiative heating goes to warming the surface (land and ocean) and evaporation. This leads (in general) to an abundance of atmospheric moisture (excluding the sub-tropical high pressure belts), and so latent heat plays a significant part in the energy cycles in the tropical atmosphere.

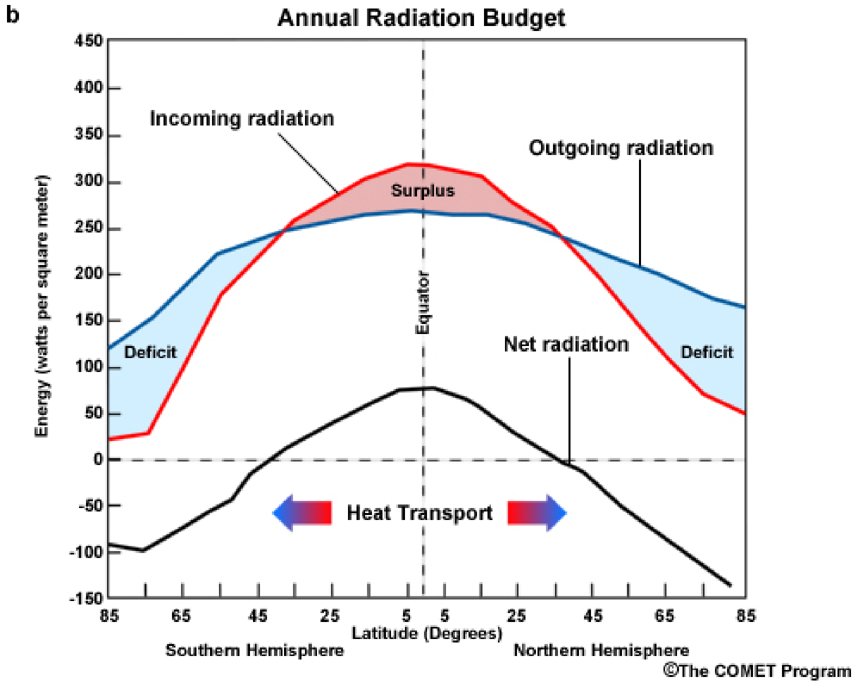

Figure 2: Zonal Average radiation budget

An important consequence of the excess heating at the tropics is the formation of an overturning circulation which tends to form two cells (Hadley cells) north and south of a relatively narrow central region of ascent characterised by excess precipitation (the inter-tropical convergence zone, ITCZ). The release of latent heat strengthens the uplift, and the circulation tightens the convergence zone. The descending arms of the Hadley cells are associated with the sub-tropical high pressure belt and excess evaporation. These are illustrated in figure 3 and figure 4 .

The tropical tropospheric winds tend to be dominated by vertical motion

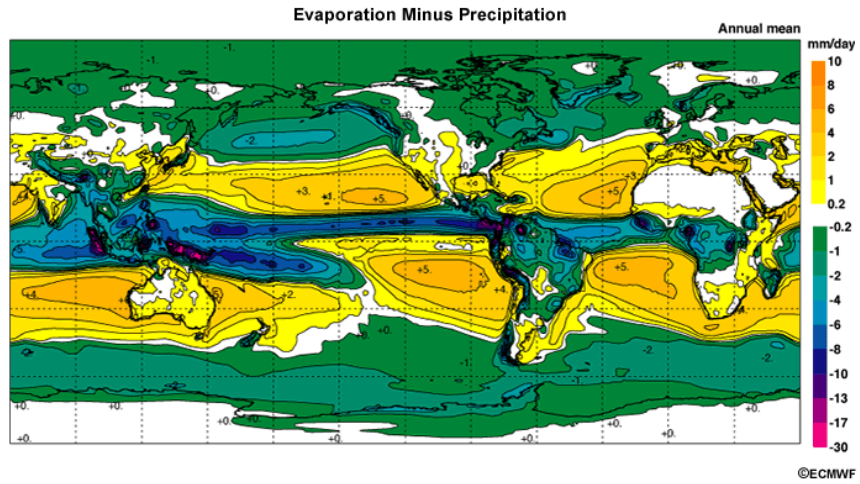

Figure 3: Global mean annual evaporation minus precipitation

and rather weak (on average) zonal winds of an easterly nature. See figure 5. Whereas in the mid-latitudes, a relatively strong pressure gradient can be sustained with strong (geostrophic) winds, in the Tropics, the Coriolis effect is very small, so when there is a pressure gradient the air moves more directly from high to low pressure. Whereas this statement is correct, there can be strong (horizontal) winds in the tropics associated with strong convective systems (squalls and MCS) and the hurricanes (cyclones, typhoons), see next section.

An important concept to appreciate and which is a consequence of the average horizontal motions, is that (on average), since the zonal air flow is slower than the surface of the Earth, momentum is transferred from the Earth to the atmosphere in the Tropics, and the reverse true in mid-latitudes. See figure 6.

Concerning the oceans, the structure of the Pacific, Atlantic and Indian are of interest. In this short overview, we observe the typical equatorial thermal cross-section of the Pacific as shown in figure 7. Note the surface gradient from east to west near the surface, and the near-zero gradient below about 300 m depth. The region of warmest surface waters tend to coincide with the higher annual average precipitation, near Indonesia.

There are important details about the ocean circulation, depth of the mixed layer and upwelling which are beyond the scope of this note. However, roughly speaking the assymetry (warm pool in the west and cooler in the

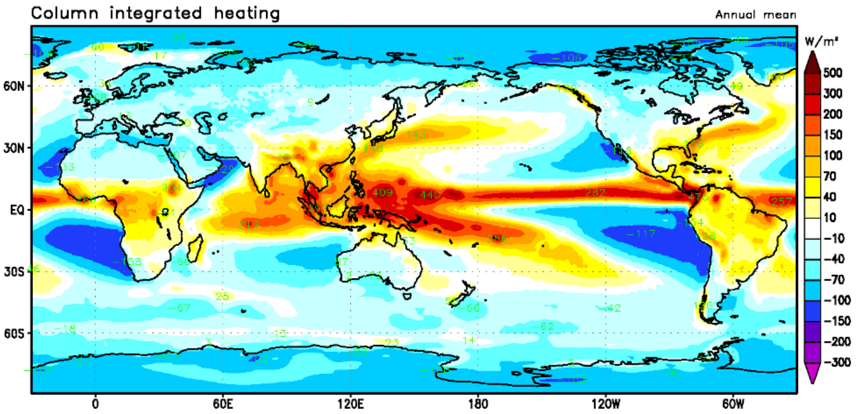

Figure 4: Global mean net diabatic heating

east Pacific) tends to drive a zonal circulation (ascending over the warm pool descending over the east) called the Walker circulation, see figure 8. This has important feedback effects which can cause the surface thermal structure to change and lead to the ENSO, see below.

There are many other salient details of the atmosphere that are characteristic of the tropical region and influence the thermodynamics and weather patterns, which I shalln't go into here.

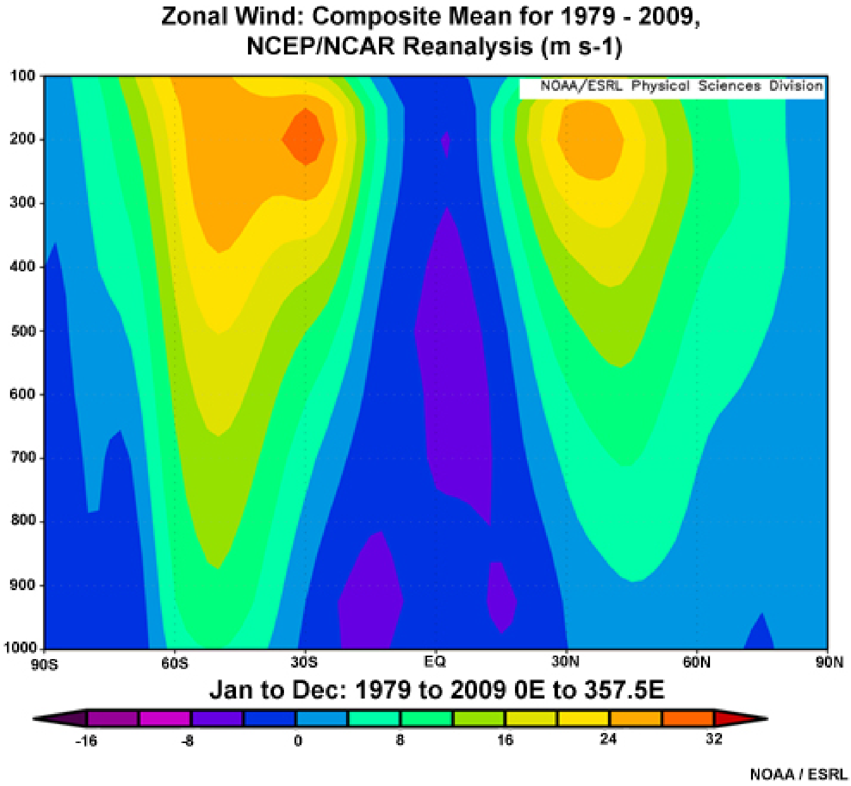

Figure 5: Zonal wind cross section

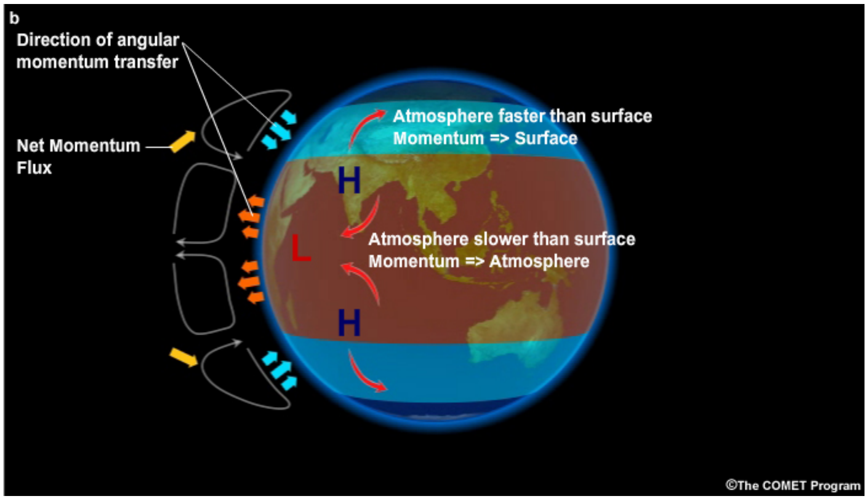

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Figure 6: angular momentum

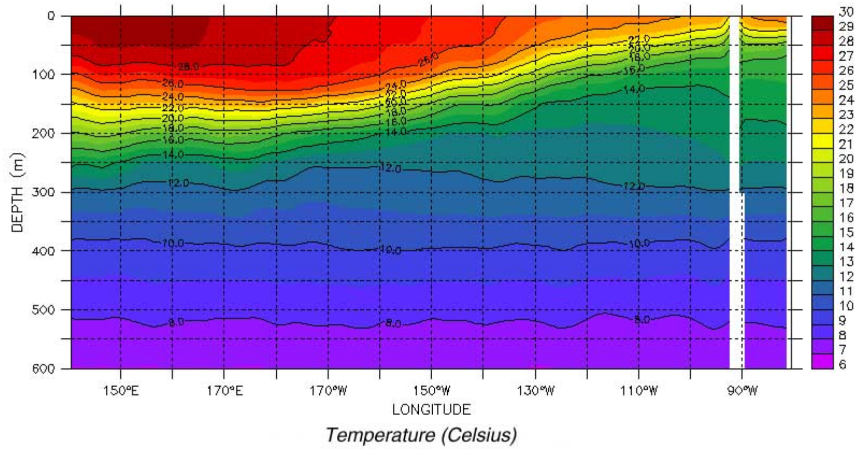


Figure 7: Pacific ocean thermal section

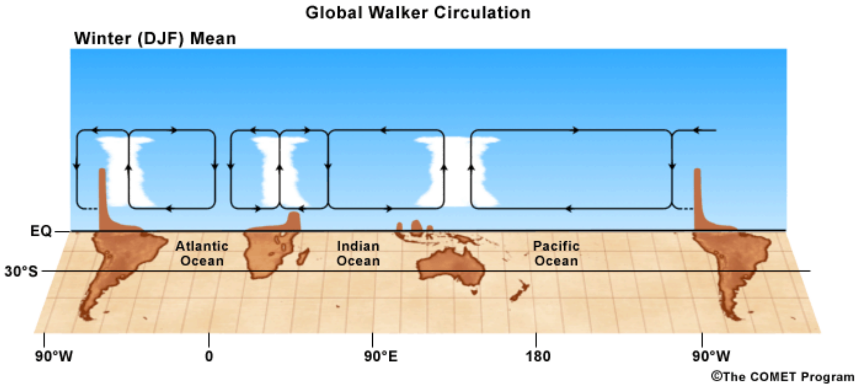


Figure 8: ENSO walker

3 Tropical Variability

Of particular interest to stratospheric processes, and only to mention here, if one considers a slice at constant pressure through figure 5 at near 100 mb (and things get even more interesting at higher altitudes), one sees an oscillation in the strength of the sub-tropical jets and the strength of the tropical easterlies (a reversal), with a nearly 6-month period. This is the quasi-biennial oscillation (QBO) of the tropical middle atmosphere. see figure 9. The QBO is known to affect the transport of aerosols in the lower stratosphere, and has some influence on the strength of tropical cyclones, through the change in vertical shear of the horizontal wind in the upper troposphere, and possibly the monsoons (refs to be added later).

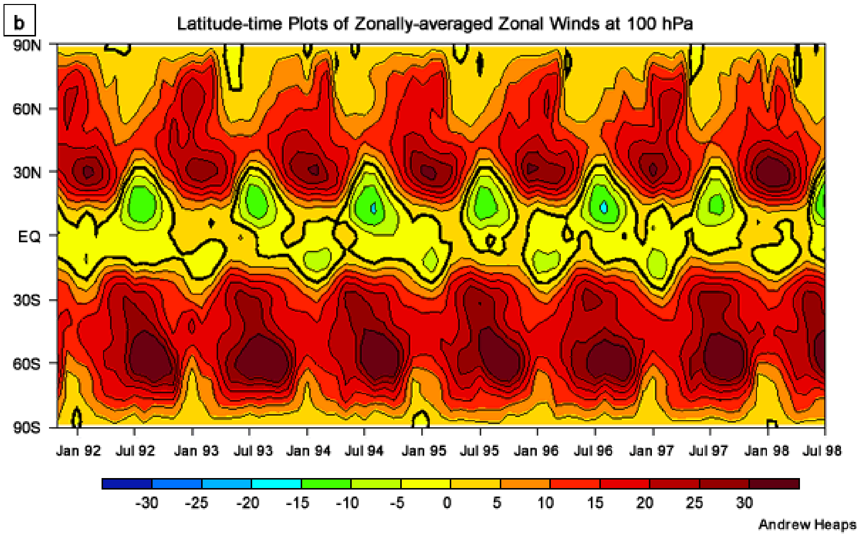


Figure 9: QBO zonal

If there were no land, and the equatorial plane were not inclined to the plane of the ecliptic, then the ITCZ and the Hadley cells might be expected to be rather zonally invariant. In reality the ITCZ tends to follow the annual motion of the sun north and south of the equator. Figure 10 illustrates roughly the most northerly and southerly movement of the ITCZ. Notice how its migration is largest over the Indian Ocean and how restricted is its motion south over the Pacific. The thermal effects of the Pacific and monsoon related land/sea contrasts influence this. Indeed, close examination of precipitation maps over the Pacific reveal a bi-modal (split) pattern extending East from the warm pool.

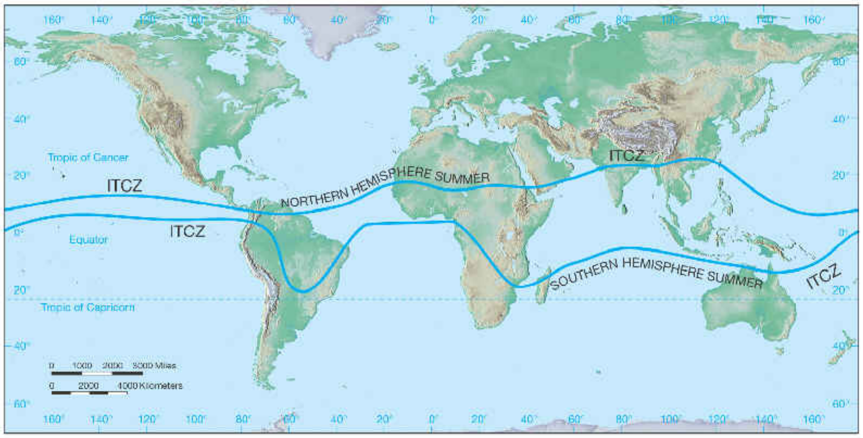
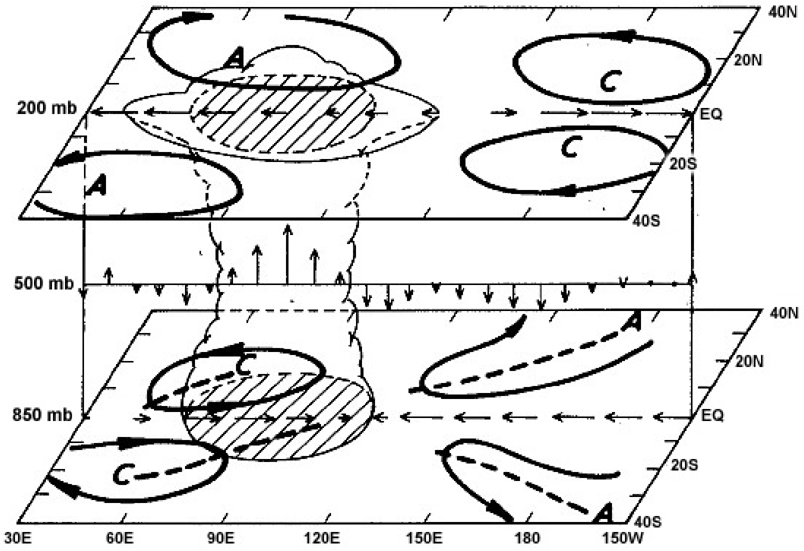


Figure 10: ITCZ annual

The ITCZ is, ofcourse, not a continuous, unbroken line around the Earth and there are regions of enhanced convergence and preciptation over the warmest waters and the tendency for convective systems to organize into clusters. At any given portion of the ITCZ the phase velocity tends to be westward. This is particularly the case later in the northern hemisphere summer from North Africa westward across the Atlantic Ocean. It's instructive to watch the movies at: `http://goes.gsfc.nasa.gov`. There also tends to be enhanced precipitation over the tropical rainforest, as a result of the recycling of moisture through evapotranspiration from plants.

4 Madden Julian Oscillation

A coherent structure of deep convective clouds, enhanced precipitation, surface pressure and wind anomalies were observed in the 1970s with period ranging from 30 to 60 days, propagating eastward across the Indian Ocean and into the western Pacific. The characteristic wavelength is between 12,000 and 20,000 km. A great source for monitoring and news is: `http://www.bom.gov.au/climate/mjo/` There appears to be an ongoing discussion about the detail on how the MJO forms and it's evolution, but it does have a baroclinic structure with upper tropospheric warming and low level cooling during the westerly phase, with westerly anomalies in the lower troposphere. This is consistent with the thermodynamics of deep convection. The maximum in precipitation occurs around the region of enhanced low level convergence (just ahead of the max westerly anomaly). This zonal flow anomaly can be seen in the context of a regionally modified Walker type circulation. There is an associated feedback and response with surface ocean temperature. The MJO tends to be at its strongest in the austral summer (DJF) and in neutral ENSO and tends to be suppressed during either strong El Niño or La Niña events. A schematic representation of the synoptic scale flow and pressure structure are shown in figure 11.


Schematic Depiction of the Large-scale Wind Structure of the MJO

Rui and Wang 1990

Figure 11: MJO wind

And the structure can be tracked by observing the OLR as illustrated in figure 12. There is much debate on the details of the MJO, for example in repsect of the local feedback and impacts and dependencies upon the larger scale motions, the phase of the ENSO and the monsoon circulations.

There has often been observed the tendency for regions of DCC and precipitation to be organised into clusters (MSC), in addition to the MJO, and there are several theories as to how these form. These models are based upon the notion of wave-like strctures forming in the tropical atmosphere, the phase of the wave then resulting in an enhancement or reduction in convergence or uplift, with resultant diabatic response (through latent heat effects). There are eastward propogtaing Kelvin waves and westward propagating Rossby waves. The Kelvin waves, see figure 13 are equatorially trapped gravity waves which may be initiated by excess convection say over Amazonia. The waves tend to propagate eastward and are convectively coupled. We've come across Rossby waves as the dominant planetary wave structure in the mid-latitudes. The restoring force is the gradient of potential vorticity. The solutions to the linearized momentum equations on a beta-plane for the equator provides solutions that are described as westward propogating Rossby waves, see figure 14 . Note that one particular solution provides for the possibility of mixed Rossby-gravity waves, see figure 15. In the case of westward Rossby waves, the structure tends to be symmetric about the equator, for mixed Rossby-gravity then tend to be anti-symmetric about the equator. These waves are also convectively coupled (i.e. diabatic heating influences its evolution) and can influence the mid-latitude atmospheric circulation.

Intriguingly, and for those at the AGU 2014, it is postulated that an eastward propogating MCS associated with the MJO, lead to a growing Rossby wave-type structure that extended north from the tropical waveguide region, resulting in the so-called atmospheric river of moisture, see figure 16. In my opinion it was necessary also to have the interaction with a developing mid-latitude cyclone, or Rossby wave, at the same time and place to advect the tropical air north eastward.

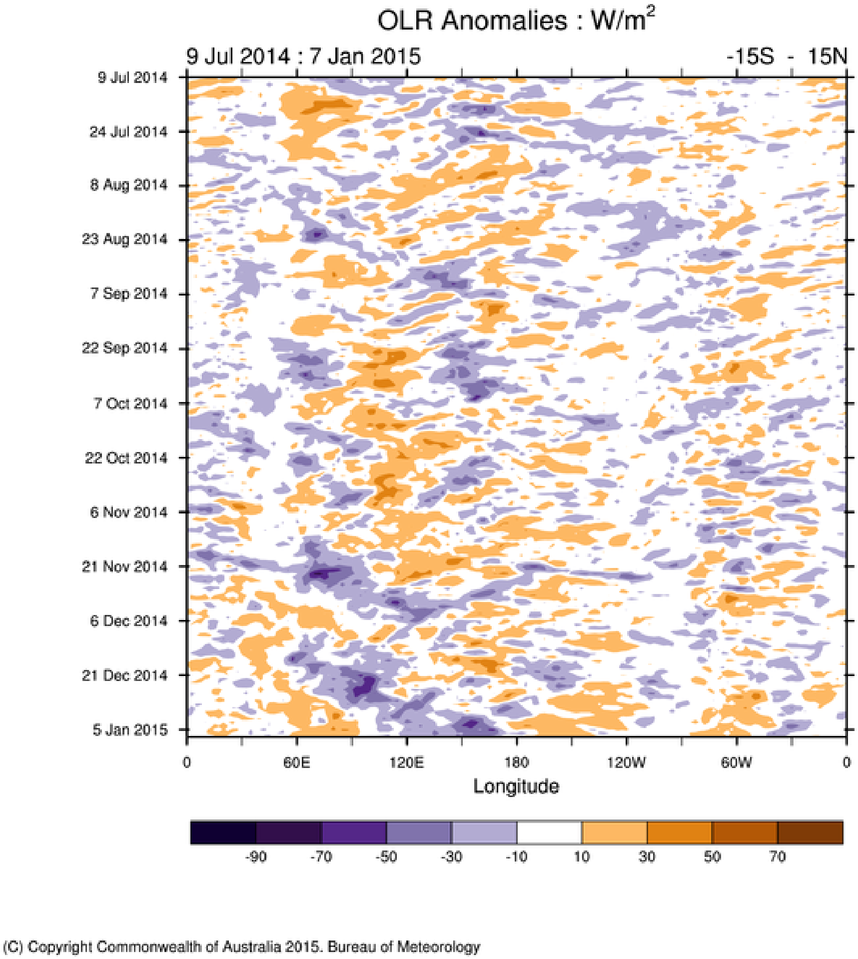


Figure 12: MJO OLR

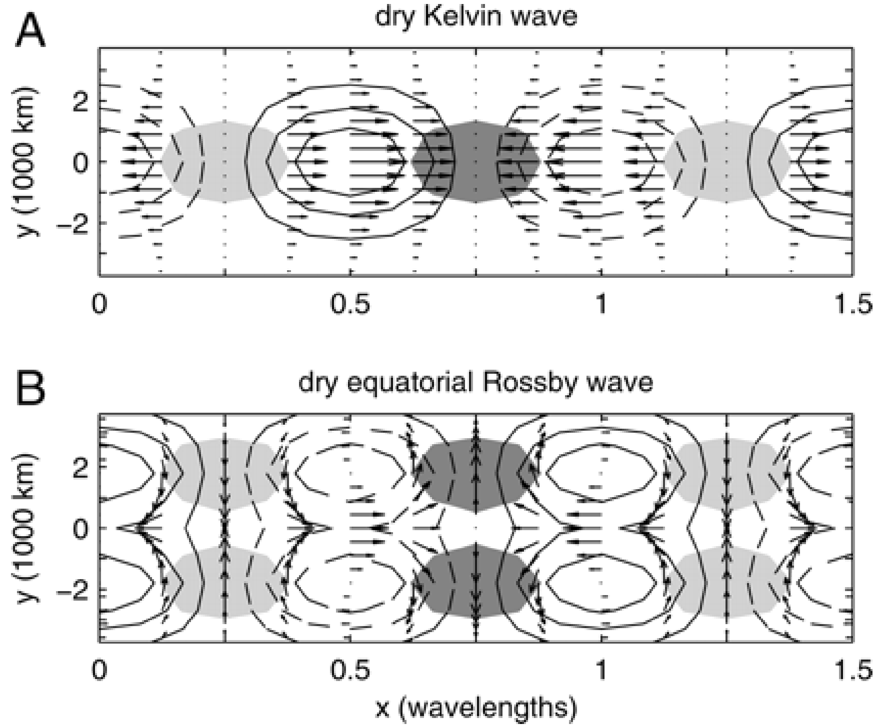
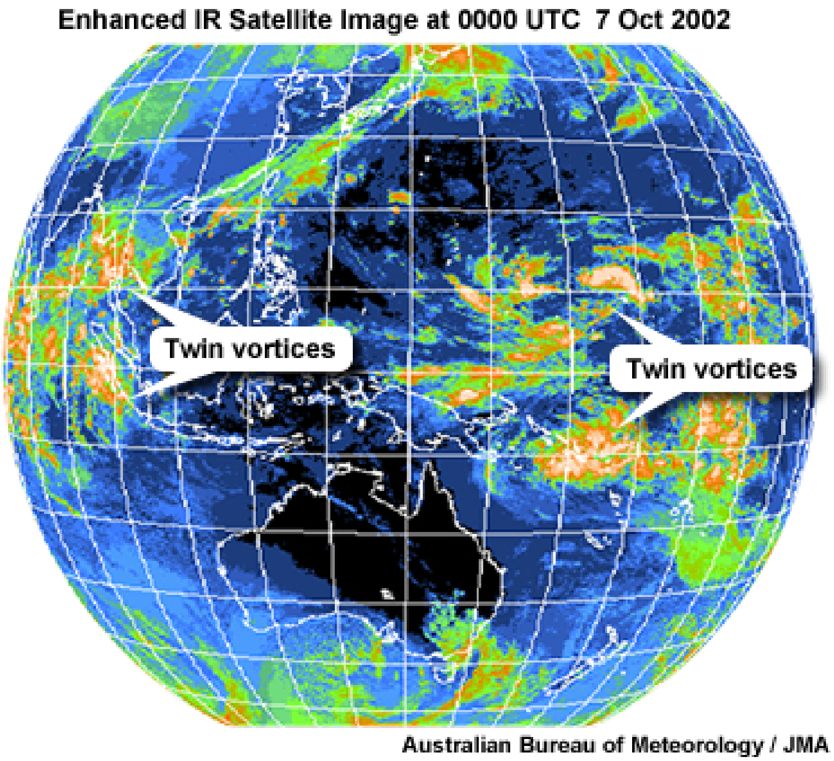


Figure 13: Rossby Kelvin waves



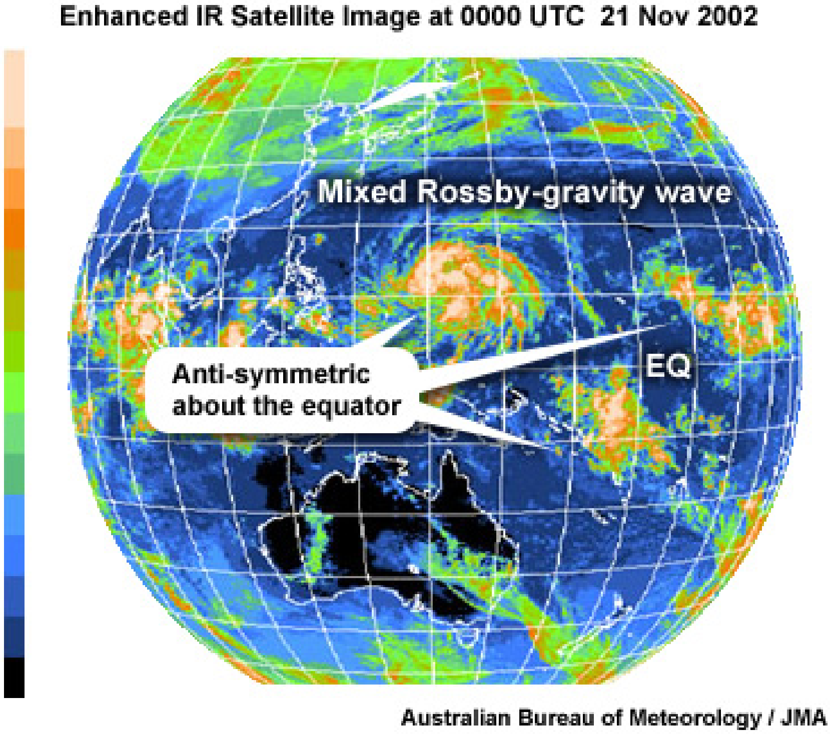
Enhanced IR Satellite Image at 0000 UTC 7 Oct 2002

Twin vortices

Twin vortices

Australian Bureau of Meteorology / JMA

Figure 14: Rossby waves



Enhanced IR Satellite Image at 0000 UTC 21 Nov 2002

Mixed Rossby-gravity wave

Anti-symmetric about the equator

Australian Bureau of Meteorology / JMA

Figure 15: Mixed RG waves

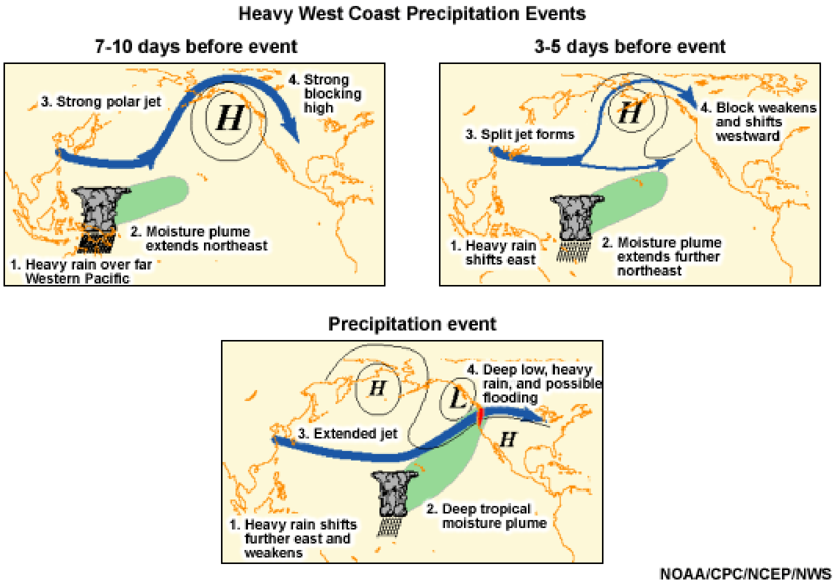


Figure 16: pineapple

5 Tropical Cyclones

Otherwise known as typhoons (Japan and China), hurricanes (Atlantic), these are the most energetic of tropical weather systems. They are most prevelant and at their strongest in the western Pacific, they occur in the northern Atlantic, with far fewer in the southern western Pacific and Indian oceans. They form and grow most quickly when they are close to the equator - but they never cross the equator. They either weaken and dissipate in situ or become abosrbed in to the extra-tropical storm tracks and may transistion into mature extra-tropical disturbances. See figure 17.

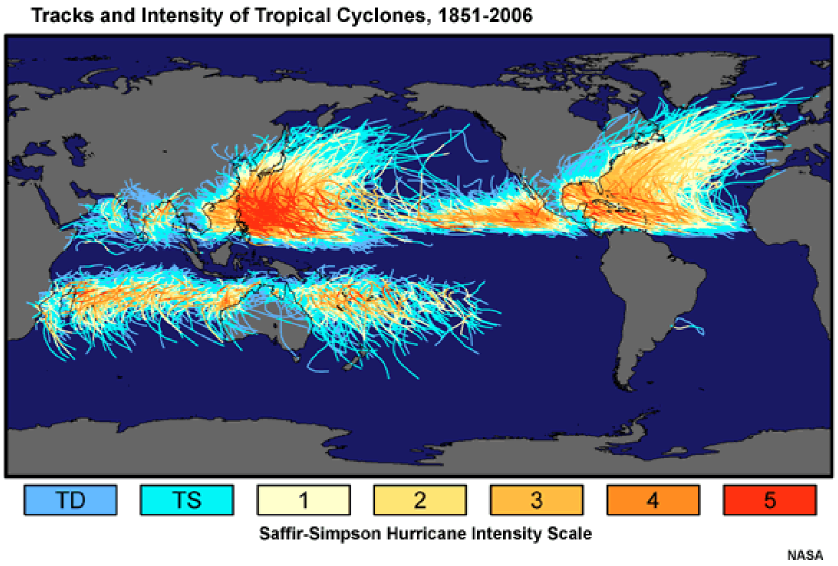


Figure 17: Global TC map

Tropical cyclones develop best if the SST to a depth of tens of meters > 26 C; if there is excess humidity in the low to mid-troposphere; the atmsophere is conditionally (hydrostatically) unstable; there is weak vertical shear of the horizontal winds; and it is at least 5 deg latitude away from the equator. To a first approximation the cyclone is largely driven by conversion of latent heat into kinetic energy.

The initial genesis of the cyclone depends upon local destabilization of the ITCZ (through positive tendency of potential vorticity driven by the overturning in convectove cells), or by quatorial trapped mixed Rossby gravity waves (see above) - the proposed mechanism here is related to the spatial phase of deepest convection relative to convergence (inflow) zone. Concerning Atlantic hurricanes, the westward propogation of easterly waves from north Africa over the warm waters sometimes leads to the generation of cyclones. Notwithstanding, these waves are often associated with MCSs in the tropical Atlantic. If the wave remains coherent as it reaches the warmer waters of the western tropical Atlantic and Gulf, they may have sufficient energy available from the sea to grow. See figure 18 as an example of the movement of an MCS complex as viewed from space and the development into a hurricane.

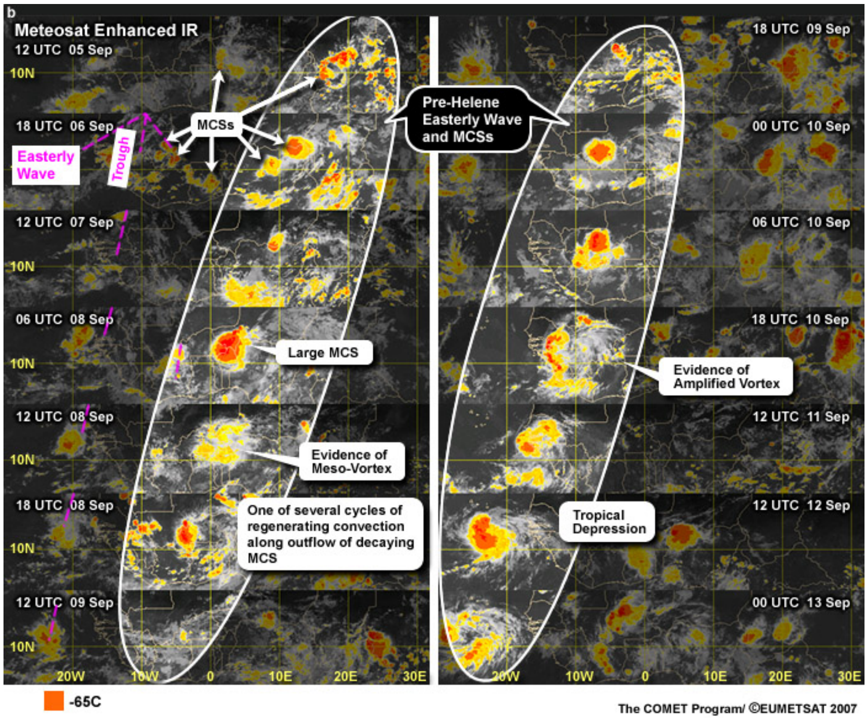


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Figure 18: MCS wave

The frequency of TCs can be measured in various ways, here we look at the number of storms with winds greater than the given threshold averaged over a hundred years and normalized. In figure 19, note how the storm frequency varies between the ocean basins, that the Pacific has had a TC in every month. Also shown are the average number of TC-days between the two thresholds. The solid shading is for winds $>$ 64 knts.

Within a given season, the likelihood of a TC developing (or at least

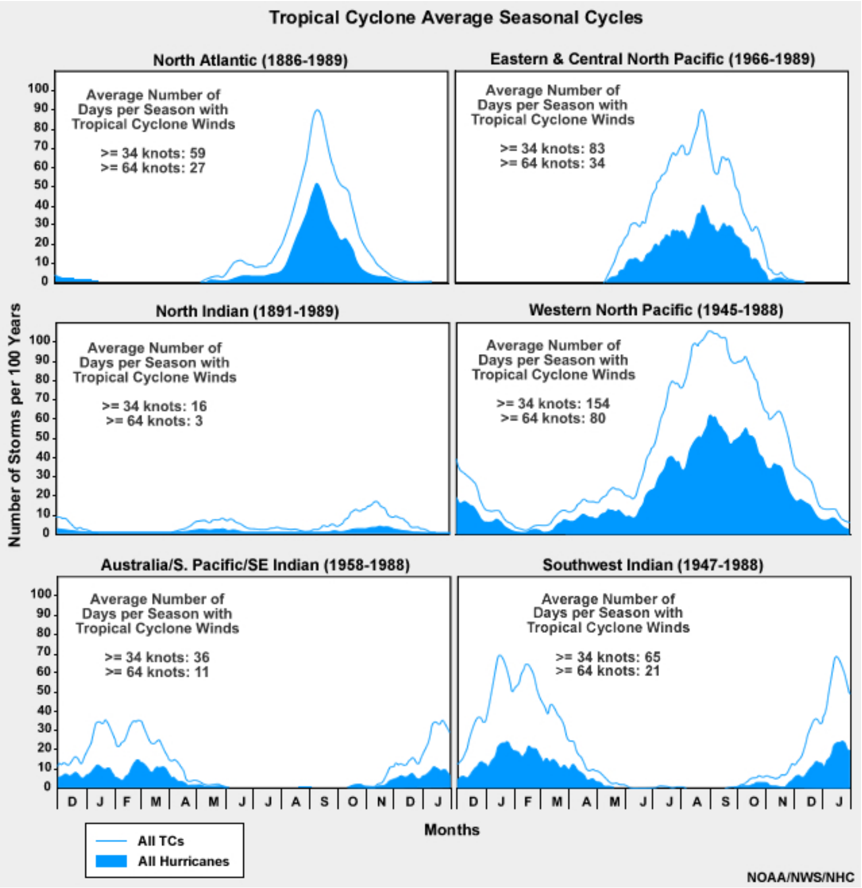
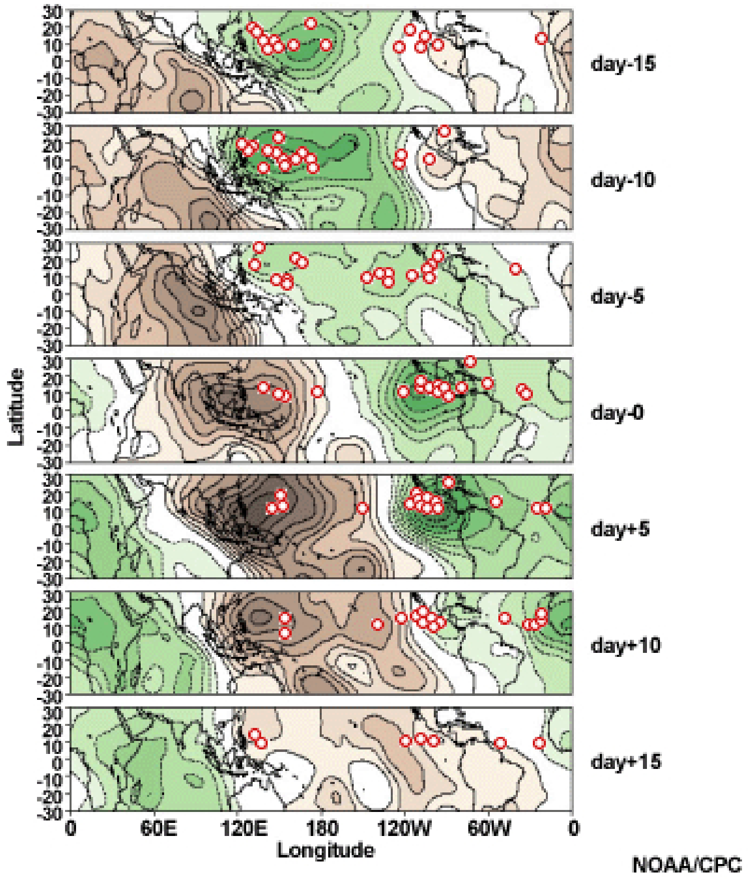


Figure 19: TC annual cycle

gaining strength category 1 or higher) is influenced by the phase of the MJO, more so in the Pacific basin. In general TCs are more likely in the positive phase of the MJO (where convection is enhanced) and less likely - or inhibited - during the negative phase of the MJO. As illustrated in figure 20. The theory is that the deep convection of the +ve MJO maintains a reversal of the PV gradient in the meridional direction (away from the equator), which is conducive to TC spin up. There is also the possibility that if the phase of the MJO and easterly waves coincide TC genesis is more likely.

In the Atlantic basin, there are occasions when low level air flows west from the Sahara during the summer. This is a deep well mixed dry dusty layer of air which mixes with humid maritime air. If this happens when an MCS and easterly African wave form - there can be supression of convection and decrease in the tendency for such distrubances to form TCs.

It is generally accepted that one of the major forcings of the modulation of TC activity is the ENSO. During a positive (El Nino) phase, when deep convection extends east into the central Pacific and extends the Indian ocean zones, there tends to be increase vertical wind shear in the tropical western Pacific and Atlantic basins. The TC genesis zones tend to move east further into the central Pacific during a warm phase. Furthermore, due to increase wind shear TC genesis in the Atlantic basin tends to suppressed. The opposite tends to be true in the negative phase (La Nina). Figure 21 depicts the actual record of Atlantic hurricanes during 14 El Nino cycles, according to the phase of the year relative to the peak ENSO index.



Composite evolution of 200hPa velocity potential anomalies ($10^5 \times m^2/s$) and points of origin of tropical systems that developed into hurricanes/typhoons

Figure 20: TC MJO

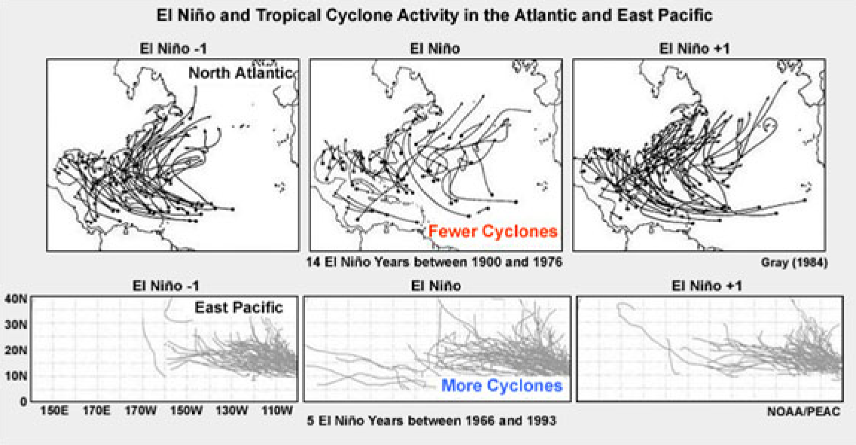


Figure 21: ENSO hurricanes

6 El Nino Southern Oscillation

The El Nino Southern Oscillation (ENSO) of the Pacific basin is perhaps one of the most iconic tropical climate phenomena that has global weather consequences. As you'll know, ENSO is characterized by a eastward shift in the warm pool from Indonesian seas to the central Pacific and warming off the west coast of contiental America. As the easterly trade winds weaken the local sea surface currents change as does the Walker circulation. It has a return period of 3 to 7 years. The southern oscillation (SOI) refers to the swings in surface atmospheric pressure measured between Perth, and Tahiti. The SOI is a proxy for the strength of trade winds, as pressure differences determine wind speed. When there is a smaller pressure difference (low SOI) there are El Niño conditions present; with larger differences (high SOI) and La Niña conditions are present as illustrated in figure 22 .

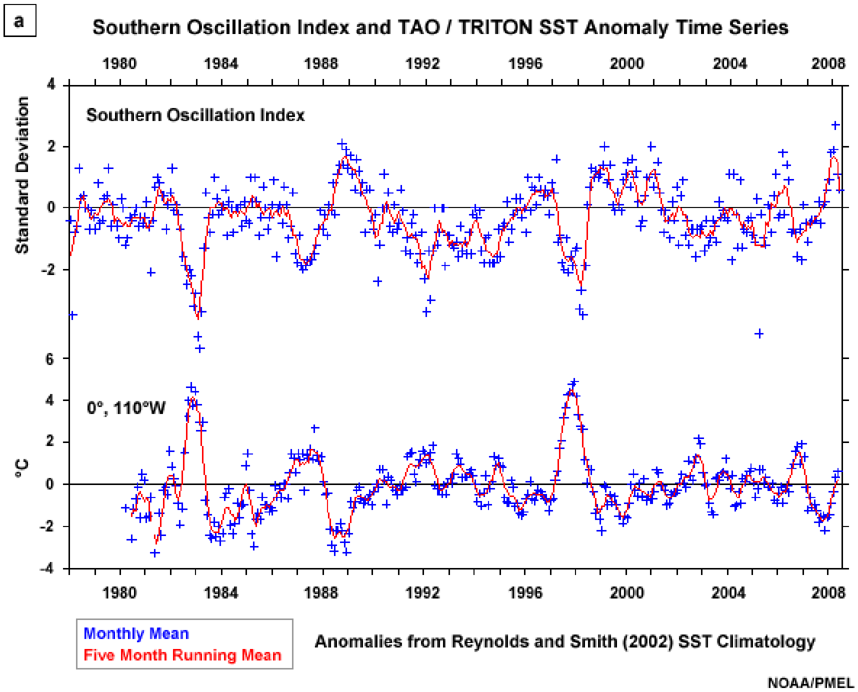


Figure 22: SOI

I shalln't attempt a description of the physical theory of ENSO, sufficient to say that it appears to be a coupled atmosphere-ocean feedback effect due to balance between the slope of the thermohaline and trade winds. The 'normal' balance is illustrated in figure 23.

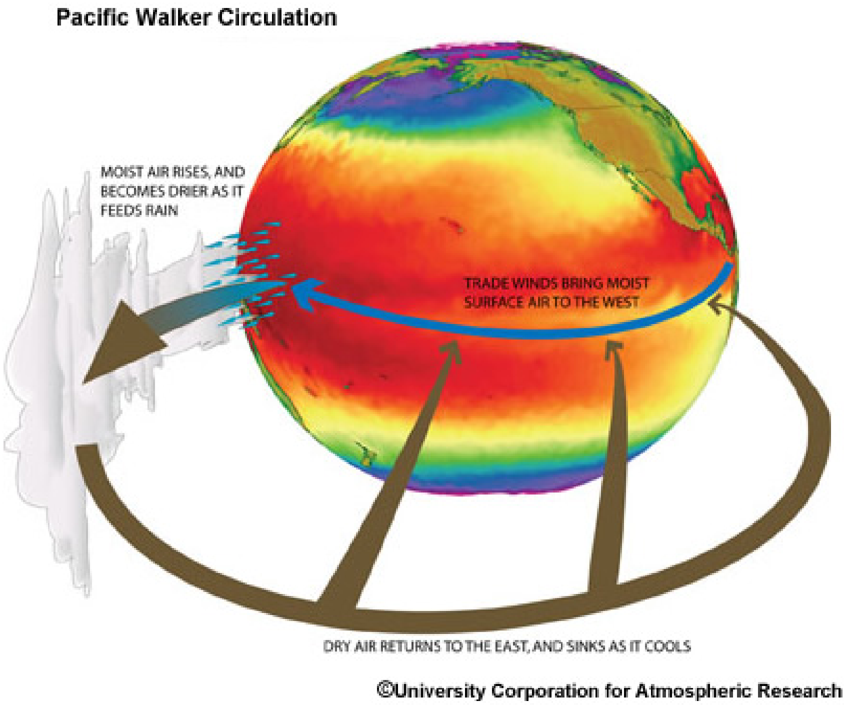
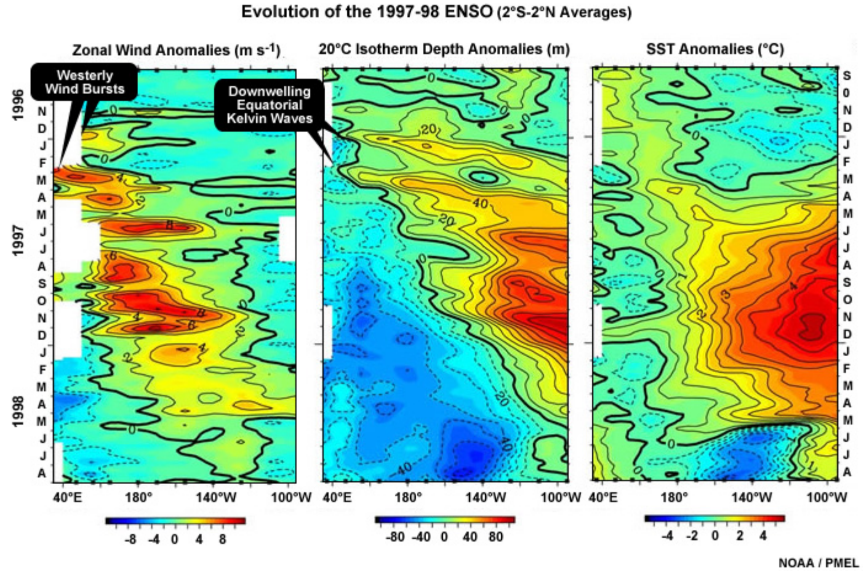


Figure 23: Pacific Walker

When the walker circulation is perturbed, westerly wind bursts occur which generate downwelling Kelvin waves that propogate eastward, setting up local upper ocean currents that advect the warmer water eastward. Figure 24 illustrates the time evolution of these effects. The key appears to be that the westerly wind bursts need to be sustained and strong enough to generate the Kelvin waves. At the eastern boundary, westward equatorially trapped Rosby-type waves in the upper ocean acts to level out the thermocline (think of this simply as a sloshing/seesaw of the upper ocean thermocline). Discussion continues about the role of excess heating in the warm pool and of a "discharge - recharge" process resulting in Sverdrup transport below the Ekman layer (refs).

There is much to learn about the details of precursurs, genesis meachanisms and dissipation (re-normalization), but the point to note that ENSO is not particular periodic and not particularly repeatable. The long-term multivariate ENSO index from 1950 is shown in figure 25.



Evolution of the 1997-98 ENSO (2°S-2°N Averages)

Zonal Wind Anomalies (m s-1)

20°C Isotherm Depth Anomalies (m)

SST Anomalies (°C)

Westerly Wind Bursts

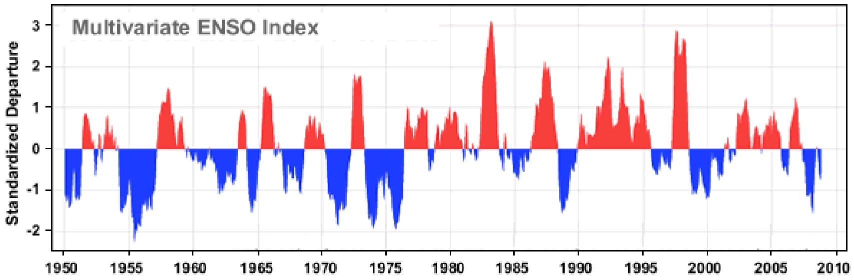
Downwelling Equatorial Kelvin Waves

NOAA / PMEL

Figure 24: Kelvin waves and ENSO

and comparison of six significant El Nino and la Nina events in figure 26 shows that the amplitude of the SST anomalies varies as does the areal exent and 'center of gravity', as shown in figure 27.

ENSO Impacts (TBD).



NOAA / ESRL / Physical Science Division - University of Colorado at Boulder / CIRES / CDC

Figure 25: enso index history

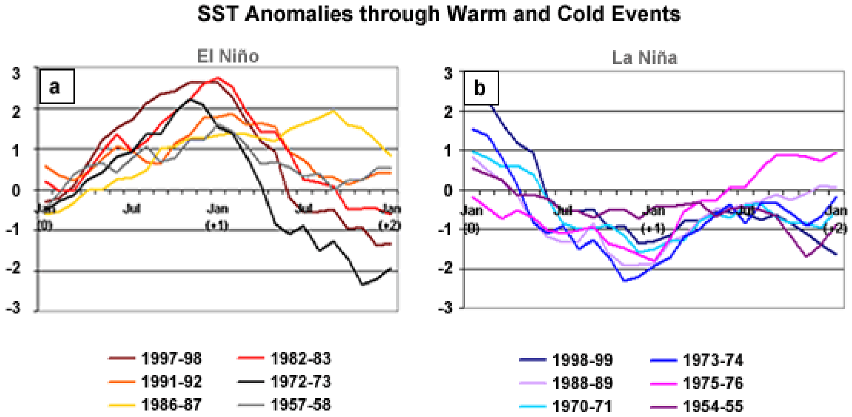


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Figure 26: Graph nino sst

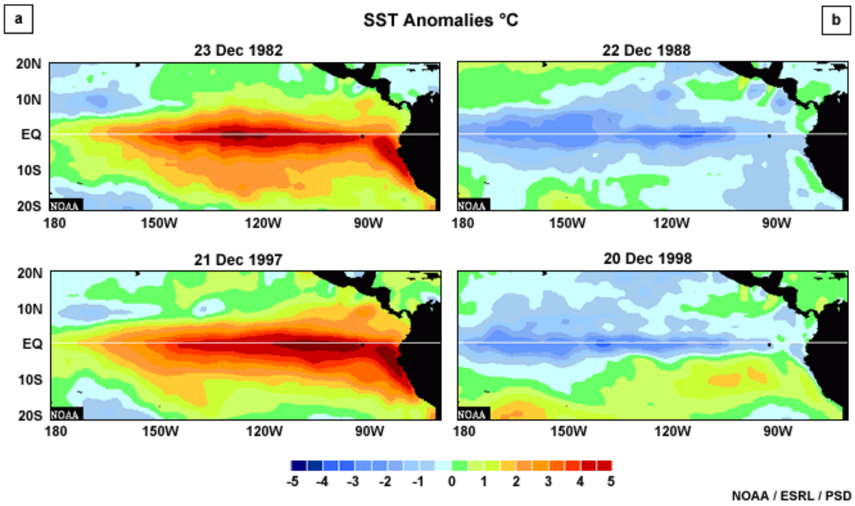
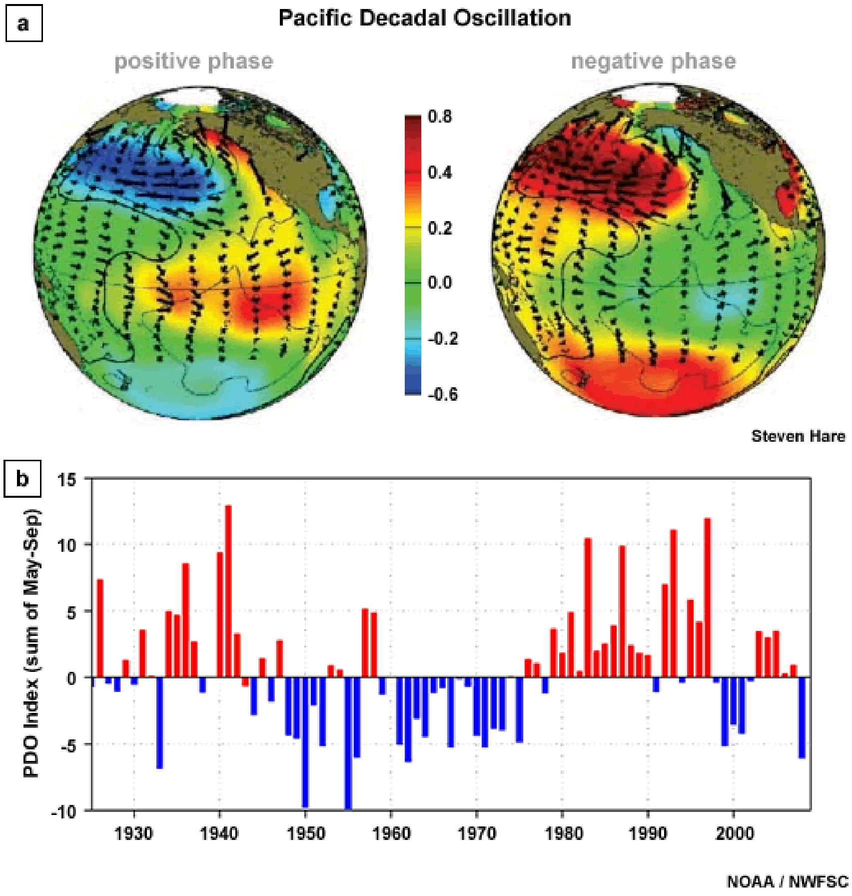


Figure 27: Two strong Ninos

7 Decadal Variability

The Pacific Decadal Oscillation (PDO) is a 20 to 30 year oscillation of north Pacific ocean and atmospheric anomalies. It tends to be correlated with the ENSO in phase in the winter. The PDO signature in the tropics is secondary to its signal in the North Pacific and North America. The PDO signal is more distinct in the northern Pacific (cf PNA) than in the tropics, where ENSO is the dominant signal.

Positive (negative) PDO values are usually associated with wetter (drier) conditions in the Southwestern US. It also influences north Pacific fish populations, see figure 28. Causes of the PDO are not known, and much research is on-going.



Steven Hare

NOAA / NWFSC

Figure 28: PDO

The Atlantic Multi-decadal Oscillation (AMO) is a 20 to 40 year oscillation of the north Atlantic ocean temperature. It appears to be related to the strength of the over-turning circulation (AMOC) and perhaps also the surface Gulf Stream. It appears when the AMOC weakens the north Atlantic surface temperatures cool. Like the PDO the detailed mechanisms are not known and much research is on-going. The AMO appears to influence the strength and extent of the sub-tropical high pressure belts and mid-latitude storm tracks. During a positive (warm) phase less rainfall is likely over north America and more rainfall is likely over Europe. Some research suggests the phase of the AMO influences the hurricane activity. Since the mid-1990s, the AMO has been in a positive phase. Figure 29 shows the AMO SST signal and correlation with gridded SST anomalies over the globe.

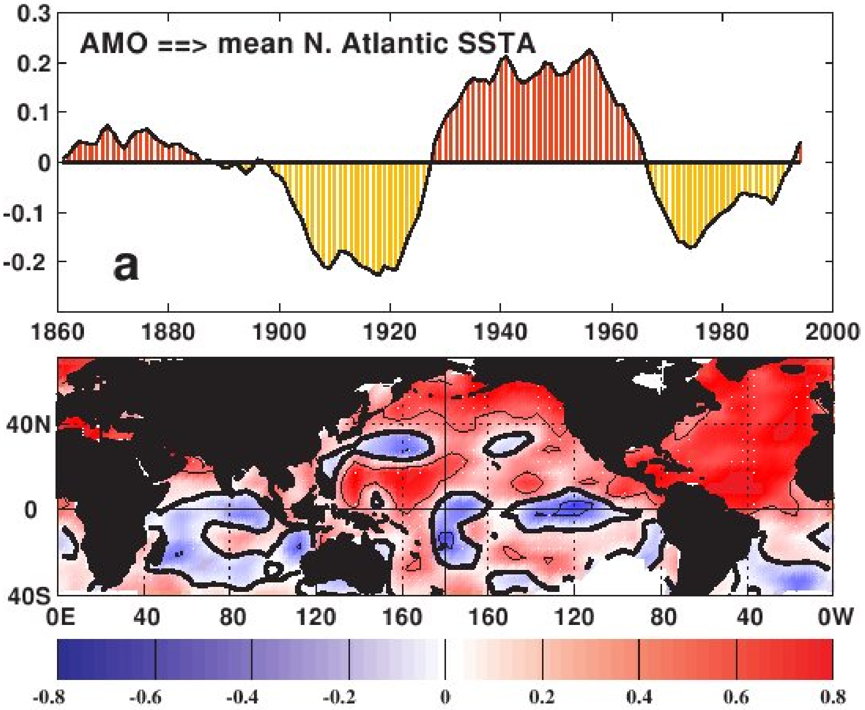


Figure 29: Upper: 10-year running mean detrended north Atlantic SST. Lower: Correlation of AMO index to golbal SST anomaly. Bold line: zero. Thin line: 95% significant.

8 Monsoons

The pattern and variability of rainfall in the tropical regions is a complicated issue and varies depending on location, proximity to ocean etc. Many factors influence rainfall patterns including the diurnal cycle and annual cycles (e.g. over tropical rainforests), the passage and strength of the MJO, the ITCZ, tropical waves and larger scale effects due to the ENSO, PDO. In some regions, such as those boardering deserts and mountain ranges, there is a distinct wet and dry season. One of the seasonal patterns particularly prevelant over the region including India to Northern Australia, and SW USA, is the monsoon. The monsoon can be considered a modulation of the ITCZ caused by the large thermal contrast between ocean and large land mass compared to summer and winter seasons. It is important in describing the physics of the monsoon to include local convective feedback, moisture and rotation of the flow due to planetary motion. Recall, that the main factors required for precipitation are low level convergence (results in upward flow) and moisture supply (latent heating). The areas of the world that are considered to have a monsoon are illustrated in figure 30.

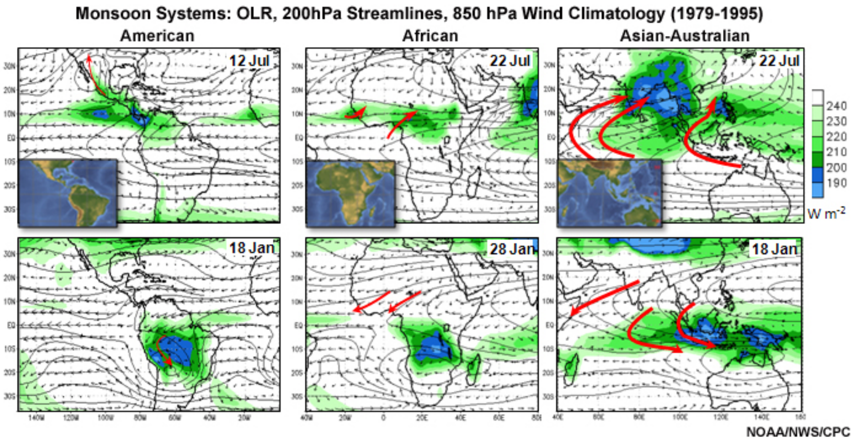


Figure 30: Global monsoons

As the northern summer season progreses, the continent warms up more than the adjacent ocean, resulting in an increasing tendency for the air to rise over the land and trade winds to shift from the ocean. When this coincides with the arrival of the ITCZ trough then enhanced precipitation results. This notion is illustrated in figure 31.

In the case of the Indian sub-continent, most precipitation occurs between

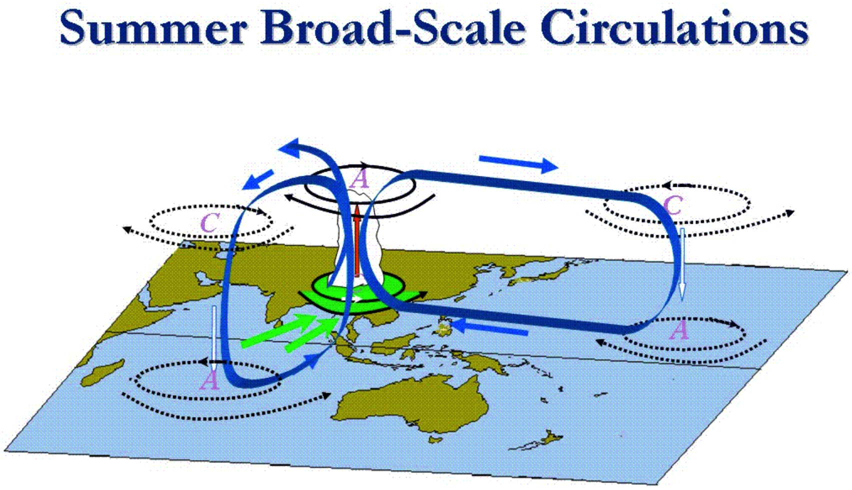


Figure 31: monsoon circulation

May and October peaking around July, see figure 32

Considering the Indian and western Pacific sectors separately and following the rainfall rates, you can clearly see the annual cycle, movement of the ITCZ and enhancement of the monsoon, as shown in figure 33 In the lower pane of this figure you can see that the northern territory of Australia is dry when the Asian monsson is in progress.

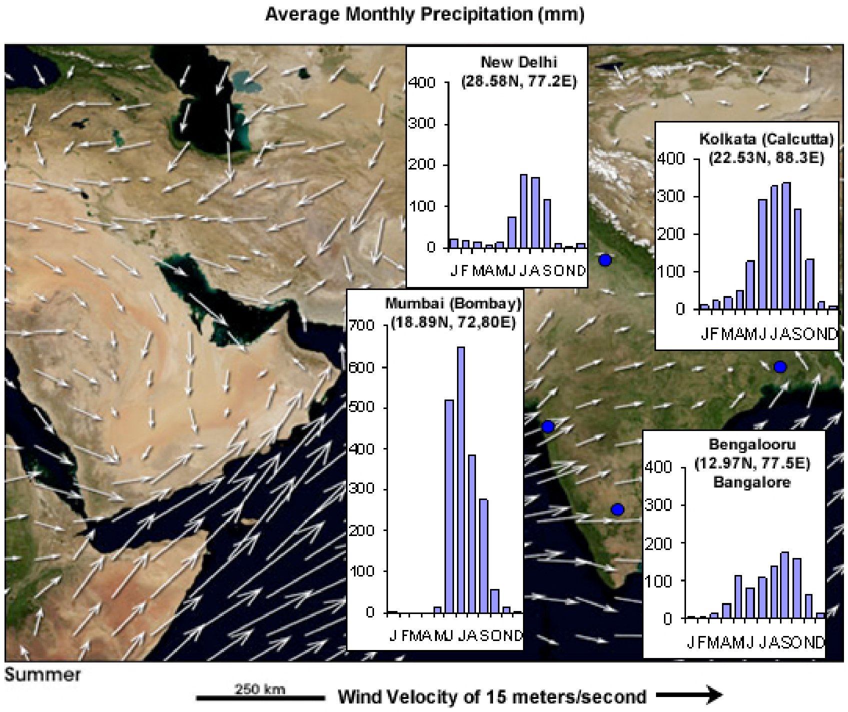


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Figure 32: seasonal rainfall

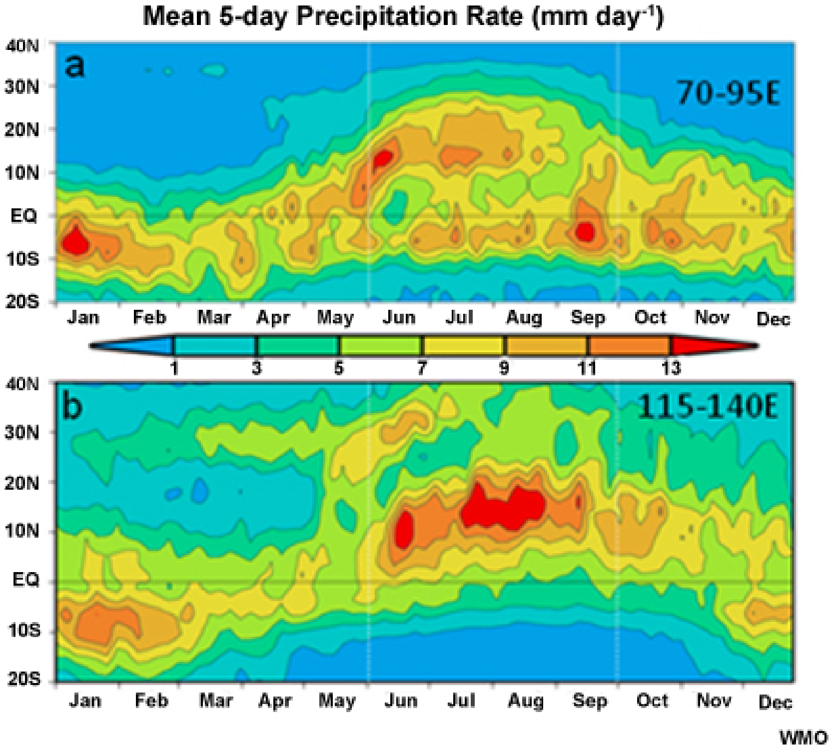

Figure 33: Asian monsoon

9 Conclusions and Points of interest

TBD

10 Acknowledgements

Numerous

11 References

Many