ESCI 344 – Tropical Meteorology
Lesson 3 – General Circulation of the Tropics

References: *Forecaster's Guide to Tropical Meteorology* (updated), Ramage
Climate Dynamics of the Tropics, Hastenrath
Tropical Climatology (2nd ed), McGregor and Nieuwolt
Tropical Meteorology, Tarakanov
Climate and Weather in the Tropics, Riehl
General Circulation of the Tropical Atmosphere, Vol II, Newell et al.
"The South Pacific Convergence Zone (SPCZ): A Review", Vincent, *Mon.Wea. Rev.*, 122, 1949-1970, 1994
"The Central Pacific Near-Equatorial Convergence Zone", Ramage, *J. Geophys. Res.*, **86**, 6580-6598

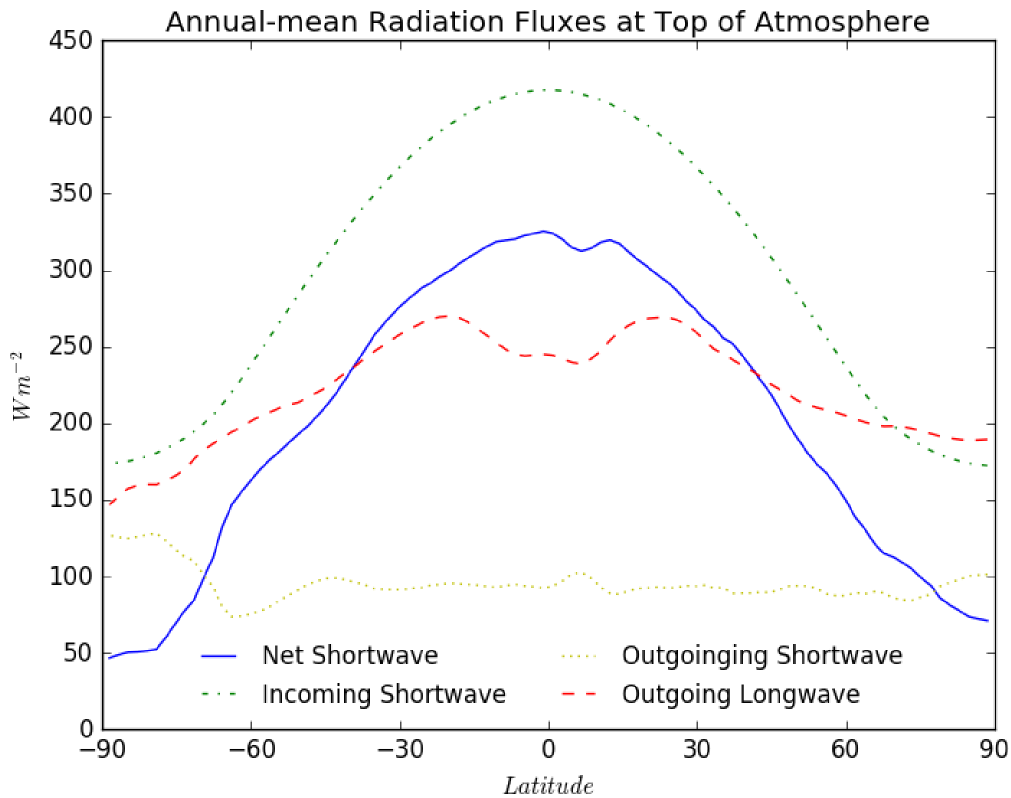
Reading: *Introduction to the Meteorology and Climate of the Tropics*, Chapter 3
Vincent, "The SPCZ: A Review"
Lau and Yang, "Walker Circulation"
James, "Hadley Circulation"
Waliser, "Intertropical Convergence Zones"
Hastenrath, "Tropical Climates"
Madden, "Intraseasonal Oscillation (MJO)"

TERMINOLOGY

- ***Boreal* refers to the Northern Hemisphere**
- ***Austral* refers to the Southern Hemisphere**

LATITUDINAL HEAT IMBALANCE

- ***Net radiation flux* is defined as the difference in incoming radiation flux and outgoing radiation flux.**
    - **A positive net radiation flux indicates a surplus of energy, while a negative net radiation flux indicates a deficit.**
- **This figure shows the longitudinally-averaged, annual-mean radiation fluxes at the top of the atmosphere.**
    - **Outgoing shortwave is due to scattering and reflection.**
    - **Net shortwave is the difference between the incoming and outgoing shortwave radiation.**



- **When the *earth-atmosphere system* is considered as a whole, there is a positive net radiation flux between about 40N and 40S, while there is a negative net radiation flux poleward of 40 in both hemispheres.**
- **In order for a steady-state temperature to be achieved, there must be transport of heat from the earth's surface to the atmosphere, and from the tropics to the polar regions.**
- **It is this *latitudinal heat imbalance* that drives the general circulation of the atmosphere and oceans.**

IMPORTANCE OF LATENT HEAT VERSUS SENSIBLE HEAT

- **The surface provides energy to the atmosphere in two ways:**
  - ***Sensible heat*, which leads directly to an increase in temperature of the atmosphere.**
  - ***Latent heating*, which is essentially energy stored in water vapor. As the water vapor condenses it releases energy to the atmosphere.**
    - **Water vapor in the atmosphere can be thought of as stored energy.**

- **80% of the energy provided by the surface to the atmosphere is via latent heating.**
  - **This underscores the importance of water vapor, and the oceans, on the atmosphere, and is why no meteorologist's education is complete without taking a course in Oceanography. (*Dr. DeCaria's personal opinion*.)**
  - **Half of the latent heat supplied by the ocean to the atmosphere comes from the tropical oceans (between 30N and 30S), and points out why what happens in the tropics is so important to what happens in the non-tropical atmosphere.**
- **The ratio of sensible heat flux to latent heat flux from the surface to the atmosphere is called the *Bowen ratio.***
  - **The lower the Bowen ratio, the greater the contribution from latent heat.**
  - **Typical values of the Bowen ratio (from the *Glossary of Meteorology*) are**

Surface type	Bowen ratio
Semi-arid	5
Grassland and forest	0.5
Irrigated orchard or grass	0.2
Ocean	0.1

  - **The Bowen ratio can actually be negative, which would occur when the air is warmer than the surface, but evaporation is occurring.**

ROLE OF CONVECTION

- **The overwhelming majority of heat transferred to the atmosphere from the surface is in the form of latent heat stored in water vapor.**
- **The heat is released to the atmosphere when the water vapor condenses in convective clouds.**
- **Convection is therefore an extremely important process for the general circulation of the atmosphere, especially in the tropics.**
- **In two papers, Malkus and Riehl estimated that the heat balance of the tropics can be maintained by around 30 synoptic-scale disturbances consisting of a total of several thousand giant cumulonimbus clouds.**

THE HADLEY CIRCULATION

- **The Hadley circulation is a meridional circulation with an ascending branch in the extreme low-latitudes and a sinking branch in the subtropics.**
  - **If the earth were not rotating the Hadley circulation would be expected to reach all the way to the poles.**
- **The ascending branch is associated with the zone of maximum solar heating, and migrates with the seasons.**
- **If the earth's surface was uniform, the mean position of the ascending branch would be at the Equator.**
- **Due to the asymmetric distribution of land between the Northern and Southern Hemispheres, and the very different thermal properties of land versus water, the mean position of the ascending branch of the Hadley cell is at about 5N.**
  - **5N is often referred to as the *Meteorological Equator*.**
- **The ascending branch varies from about 5S to 15N over the course of the year.**
- **In the ascending branch, heat (primarily latent) is transported from the surface to the upper troposphere, where it is then transported poleward.**
- **In each hemisphere, the Hadley cell is strongest in winter, and weakest in summer.**
- **The Hadley cell in the winter hemisphere is stronger than its counterpart in the summer hemisphere.**

ZONAL CIRCULATIONS

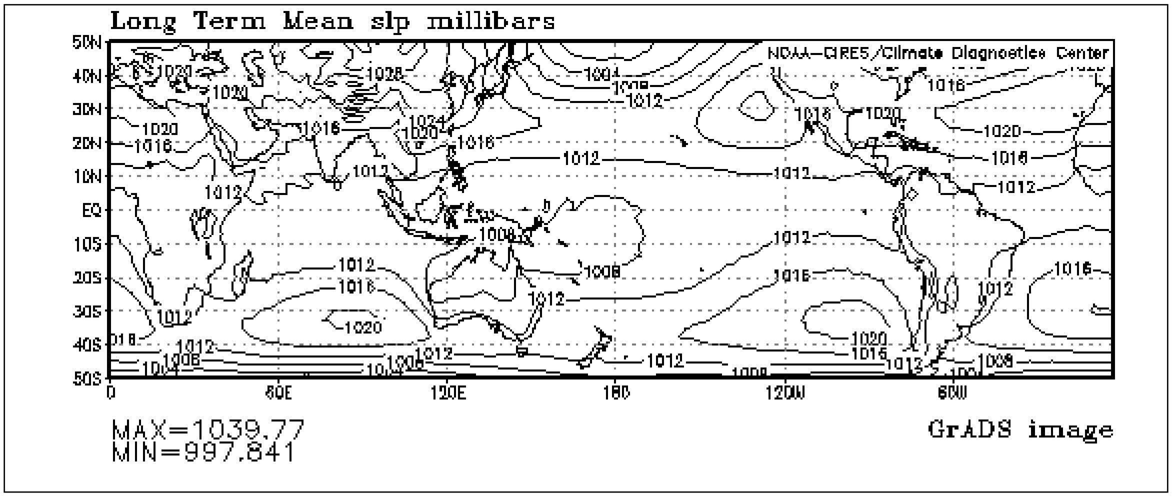
- **In addition to the meridional circulation of the Hadley cell, numerous attempts have been made to establish the existence of large-scale zonal circulations in the Tropics.**
- **There have been several, often contradictory theoretical and observational studies which have attempted to describe and document the structure of these circulations.**
- **These studies differ mainly in the number and locations of the cells. However, the existence of three large cells centered over the Pacific, Atlantic, and Indian Oceans is generally agreed upon.**

- **Krishanmurti's 1971 map of velocity potential and divergence field shows:**
  - **Large upper-level divergence maximum in summer over Bay of Bengal.**
  - **Large upper-level convergence maximum in summer off tip of Baja California.**
- **Pacific Ocean – The largest cell if located over the Pacific, and involves rising motion in the Western Pacific in the vicinity of Indonesia (Indonesia is often referred to as the *Maritime Continent*), with sinking motion in the Eastern Pacific off of South and Central America.**
  - **This circulation is known as the *Walker Circulation*.**
- **Atlantic Ocean – Over the Atlantic there is rising motion in the West, with sinking motion in the East.**
- **Indian Ocean – In the Indian Ocean there is rising motion over Indonesia, with sinking motion off of the east coast of Africa.**

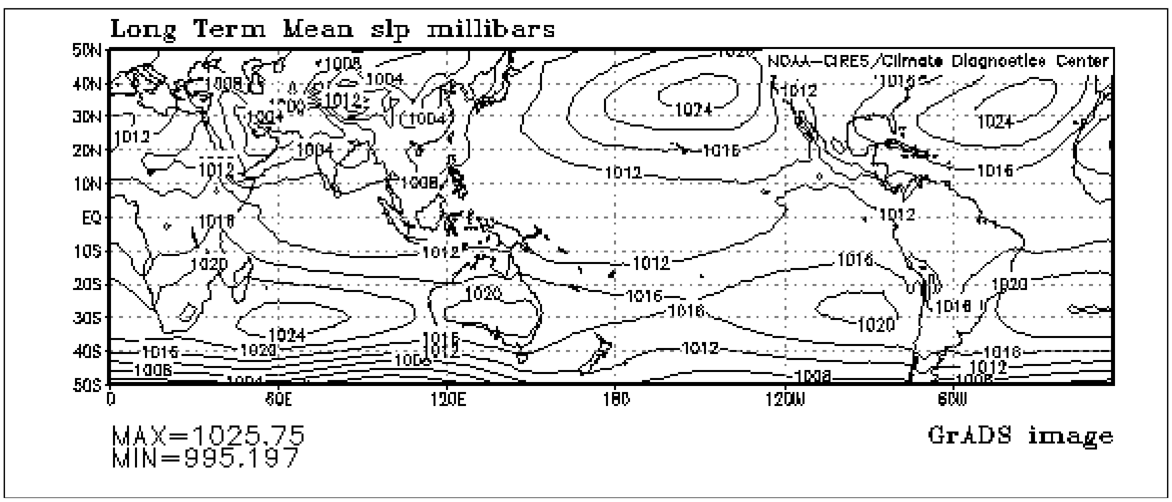
THE SUBTROPICAL HIGHS

- **Found over the oceans.**
- **In both hemispheres they are more intense in July than in January.**
- **In both hemispheres the anticyclones are more westward in July and more eastward in January.**
  - **The exception to the above is the South Pacific high.**
- **Centers are closer to Equator in respective winters, and closer to Poles in respective summers.**

Image provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.



January



July

- **The upper-level high is usually located to the west of the surface high.**
- **Because of the asymmetry in the upper-level versus surface high, as well as the fact that ocean temperatures are generally warmer in the western ocean basins, the weather characteristics associated with the subtropical highs are distributed asymmetrically as follows:**

Characteristic	Western portion	Eastern portion
Vertical motion	**Weak subsidence or rising motion**	**Strong subsidence**
Surface wind	**From Equator**	**From Pole**
Advection	**Warm**	**Cold**
Temperature	**Warmer**	**Colder**
Dew point	**Higher**	**Lower**
Stability	**Weakly stable**	**Strongly stable**
Clouds	**Open-cell**	**Clear or closed-cell**

- **The longitudinal axis of the high can often be inferred from satellite imagery based on the transition from open-cell to closed-cell convection.**
- **Formation and maintenance of the subtropical highs is complex, and is likely the result of a combination of dynamic and thermal processes. Possible important processes are:**
  - **Poleward moving air in the upper-branch of the Hadley cell experiences upper-level convergence in the subtropics, resulting in higher surface pressure.**
    - **This process by itself could not produce the subtropical highs because the resulting subsidence would cause adiabatic warming, which would push the lower-level pressure surfaces downward and work against creating of a ridge (recall the *hypsometric* equation).**
    - **If diabatic cooling of the air were added to the above process, it could offset the adiabatic warming during descent. Two sources of diabatic cooling are:**
      - **Long-wave radiational cooling of the upper atmosphere.**
      - **Cooling of lower atmosphere from cold ocean currents or wintertime continents.**
  - **Another possible dynamic process is the *non-linear Beta effect*. This effect results in Polar anticyclones moving equatorward, providing mass to maintain the subtropical highs.**

THE TRADE WINDS

- **The trade winds result from the flow on the equatorial side of the subtropical highs.**
- **The trades blow generally from ENE in the NH and from ESE in the SH.**
- **The trades extend over about 20° of latitude in the summer hemisphere, and about 30° of latitude in the winter hemisphere.**
- **They blow more toward the equator in winter than in summer.**
- **Mean velocities are 3.6 – 7.2 m/s, and are stronger in winter than in summer.**
- **The trades are very steady, though there is large inter-annual variability.**
- **The trades have a 3-layer vertical structure:**
  - ***Sub-cloud layer* – The layer below the cloud bases.**
  - ***Cloud layer***
  - ***Inversion layer* – Characterized by negative lapse rate, and therefore, the tops of the convective clouds.**
- **The trade-wind inversion is a subsidence inversion.**
- **The inversion height and strength vary spatially as follows:**

	Zonally	***Meridionally***
Height	**Increases toward the west**	**Increases toward the Equator**
Strength	**Decreases toward the west**	**Decreases toward the Equator**

- **As the inversion height and strength vary, so do the type and height of the clouds, with small cumulus or stratocumulus prevailing in the east, while taller cumulus clouds become more prevalent toward the west, or toward the Equator.**
- **The spatial variation of the inversion is explained by the fact that subsidence is strongest, and convection weakest, to the east of the subtropical high, resulting in a low, strong inversion in that region.**
- **As the air embedded in the trades moves westward and equatorward it encounters less subsidence, as well as enhanced convection (since it is picking up latent and sensible heat from the ocean surface.) This results in a weaker, higher inversion toward the Equator, or toward the west.**

- **The warming of the air as it moves westward helps to maintain the trade winds by resulting in a lowering of surface pressure to the west (recall again the hypsometric equation).**
- **The maximum wind in the trades is usually found near the bottom of the cloud layer.**
  - **Friction causes the wind to increase with height.**
  - **Thermal wind is westerly, so causes trades to decrease with height.**
  - **Result of these two effects is a wind max near the bottom of the cloud layer.**
- **This vertical shear causes the trade-wind cumulus clouds to have their characteristic appearance of leaning upstream.**

THE INTERTROPICAL CONVERGENCE ZONE

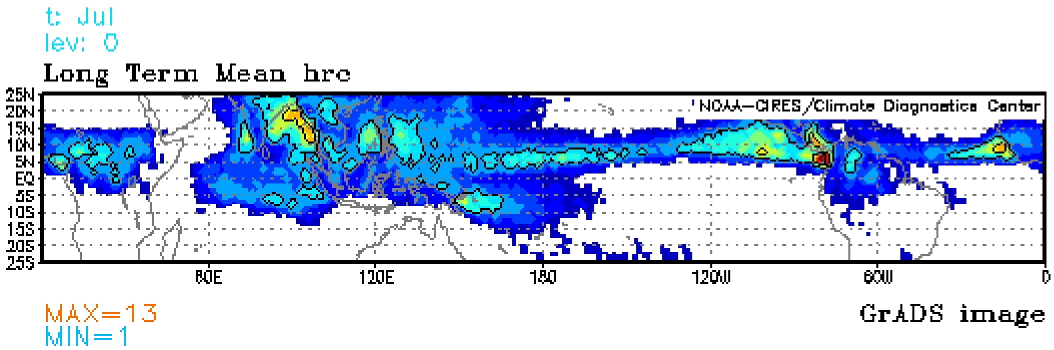
- **The region where the trades from each hemisphere converge is commonly known as the *inter-tropical convergence zone (ITCZ)*.**
- **Other names sometimes used for all or some of the ITCZ are *equatorial trough*, *monsoon trough*, or *meteorological equator*.**
- **The trough associated with the ITCZ is a *thermal trough*.**
- **The ITCZ has a complex structure.**
  - **The zone of lowest pressure, highest temperature, and maximum wind confluence is separated by 300 - 1000 km from the zone of maximum cloudiness, rainfall, and convergence.**
  - **The convergence maximum is equatorward of the confluent zone in the wind field.**
- **A somewhat simplistic explanation for the equatorward position of the region of maximum convergence is as follows:**
  - **As cross-equatorial flow from the winter hemisphere enters the summer hemisphere and moves away from the Equator, Coriolis acceleration begins to curve it anticyclonically.**
  - **In the region of maximum anticyclonic curvature the flow will be faster than it is downstream, when it becomes more straight-line.**

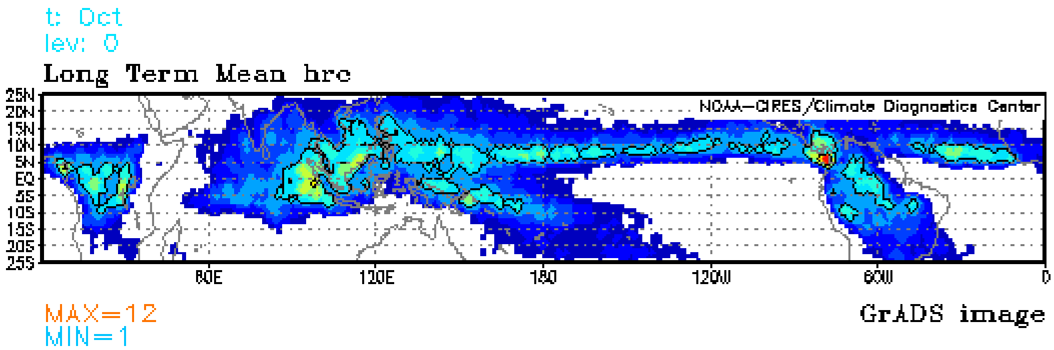
- **The deceleration of the flow downstream from the region of maximum anticyclonic curvature (but before reaching the equatorial trough) results in convergence.**

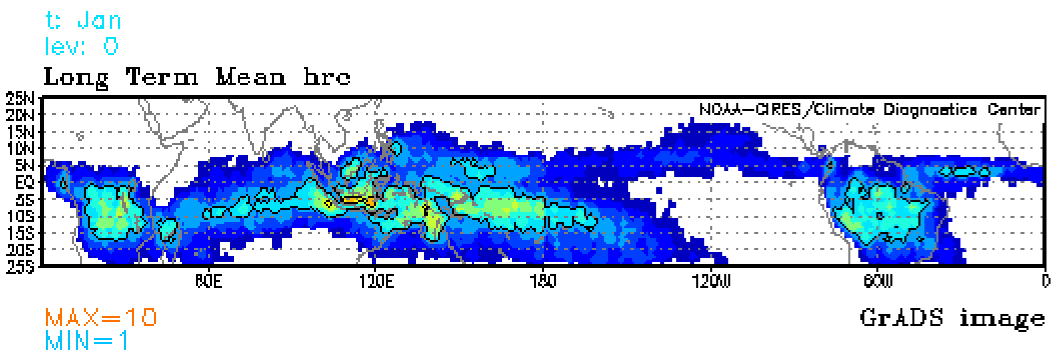
- **The separation of the regions of maximum cloudiness and minimum pressure is necessary to maintain the thermal trough.**
    - **If the max cloudiness were directly over the thermal trough, the solar energy at the surface would be decreased, which would be a negative feedback for maintaining the thermal trough and maximum in surface temperature.**
- **The role of the sea-surface temperature (SST) maximum is not completely clear.**
    - **Some argue that SST maximum directly contributes to the formation of the equatorial trough.**
    - **Others (e.g., Ramage) argue that the SST maximum is caused by the convergence of the ocean surface waters from the converging trades, and is therefore an artifact, rather than a cause, of the trough.**
- **There is a positive feedback mechanism between the upper ocean and the atmosphere that also aids in the formation of the equatorial trough.**
    - **Where the surface winds are strong there is more mixing of the upper ocean, resulting in cooler surface temperatures.**
    - **In the region of the trough the surface winds are lighter, resulting in less ocean mixing and warmer ocean temperatures, which result in warmer atmospheric temperatures and lower surface pressure.**
- **If the earth's surface were uniform the position of the ITCZ would be oriented along the lines of latitude, and its annual migration would be symmetric with respect to the Equator.**
- **Because of the land-water contrasts, the ITCZ is not oriented exactly zonally, but meanders north and south.**
- **The ITCZ takes its largest poleward excursions in the summer hemisphere over large land masses.**
- **Because the NH has much more land than the SH, the ITCZ is closer to the poles in boreal summer than in austral summer.**
    - **Mean position of ITCZ**
        - **15 N in boreal summer**

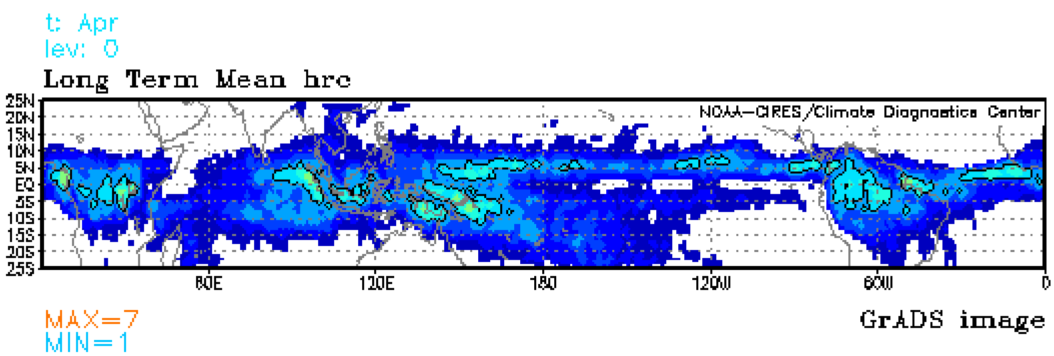
- **5 S in austral summer**

- **Maps of highly reflective clouds gives an idea of the location of the ITCZ. Below are monthly means (***Image provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/.*)

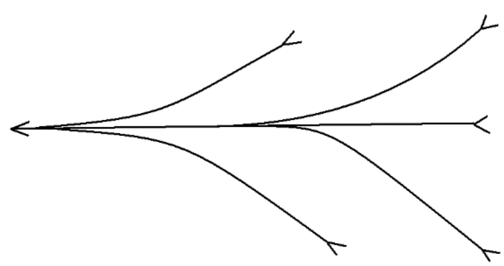








- **There are two general types of circulations associated with the equatorial trough.**
  - **A *trade-wind trough* occurs when there is a confluence of the trade winds from each hemisphere, with no directional shear across the trough.**
    - **The trade-wind trough occurs over the open ocean areas of the North Atlantic, and over the Northeast and North Central Pacific.**
  - **A *monsoon trough* occurs when the trades from the winter hemisphere recurve as they cross the Equator, and so there is a westerly flow on the equatorial side of the trough.**
    - **The monsoon trough occurs near large continental areas, and is prevalent in the Western Pacific and Indian Oceans.**
- **A region where the cross-equatorial winds recurve from easterly to westerly is referred to as a *near-equatorial buffer zone*.**
  - **Since the buffer zone is so close to the Equator, and Coriolis is negligible in this region, terms such as cyclonic or anticyclonic have rather nebulous meaning when applied to circulations in the buffer zone.**



Trade-wind trough

Monsoon Trough and Buffer Zone

- **The cloudiness associated with the ITCZ varies.**
  - **Generally narrow band of clouds over Atlantic and Eastern Pacific associated with a trade-wind trough.**
  - **Broader over Western Pacific and Indian Ocean associated with the monsoon trough.**

THE SOUTH PACIFIC CONVERGENCE ZONE

- **Region of persistent convection in South Pacific.**
- **Generally oriented east-southeastward.**
  - **More zonally oriented in the western portion, and diagonally oriented in the eastern portion.**
- **Present year round, but more active in austral summer.**
- **Several theories for origin and maintenance.**
  - **SST gradients – Gradients in SST lead to moisture convergence in the low-levels, with enhanced convection. Most applicable to zonal portion.**
  - **Land-sea distribution.**
  - **Equatorial/midlatitude wave dynamics, interaction, and energy convergence.**
  - **Tropical/mid-latitude interaction – Most applicable to diagonal portion.**
- **The strength and location of the diagonal portion appears related to the subtropical jet.**

EL NINO, LA NINA, AND THE SOUTHERN OSCILLATION

- **Under "normal" conditions the easterly winds in the Tropics result in an elevation of the thermocline (and cold surface waters) in the eastern tropical Pacific ocean, and a lowering of the thermocline (with warm surface waters) in the western tropical Pacific.**
- **During an El Nino event the trade winds weaken or even reverse direction. We've already seen that the tropical oceans adjust relatively quickly to changes in equilibrium. The response during El Nino is a progressive lowering of the thermocline from west to east.**
  - **The lowering of the thermocline is believed to be in part the result of an equatorially trapped Kelvin wave traveling along the thermocline from west to east.**
- **El Nino occurs in conjunction with the *Southern Oscillation*, a shift in the pressure patterns between the eastern and western tropical Pacific.**
- **El Nino and the Southern Oscillation are closely linked. This is why the phenomenon is often abbreviated and referred to as *ENSO*.**

- **ENSO really isn't an abnormal phenomenon. It can be thought of as just one of several stable global climate modes. For reasons not completely understood, the general circulation of the ocean/atmosphere system switches periodically between modes.**
- **The question then becomes, "Why aren't the shifts regular and predictable"?**
  - **The reason is because "weather" is superimposed upon these climate modes. The entire system is non-linear (perhaps chaotic?), so the response to "weather" cannot be predicted.**

MADDEN-JULIAN OSCILLATION (MJO)

- **This is a shorter-period (30-50 day) oscillation.**
- **The oscillation is manifest as enhanced convection in the Indian Ocean which then moves eastward into the Pacific.**
- **The theory behind the MJO is not fully developed, but it is believed to be partially explained by equatorial Kelvin-Rossby waves.**