***General Circulation of the Tropics***

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**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.

- 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.

**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

**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.