

- Necessary conditions for tropical cyclone formation
- Leading theories of tropical cyclogenesis
- Sources of “incipient” disturbances
- Extratropical transition

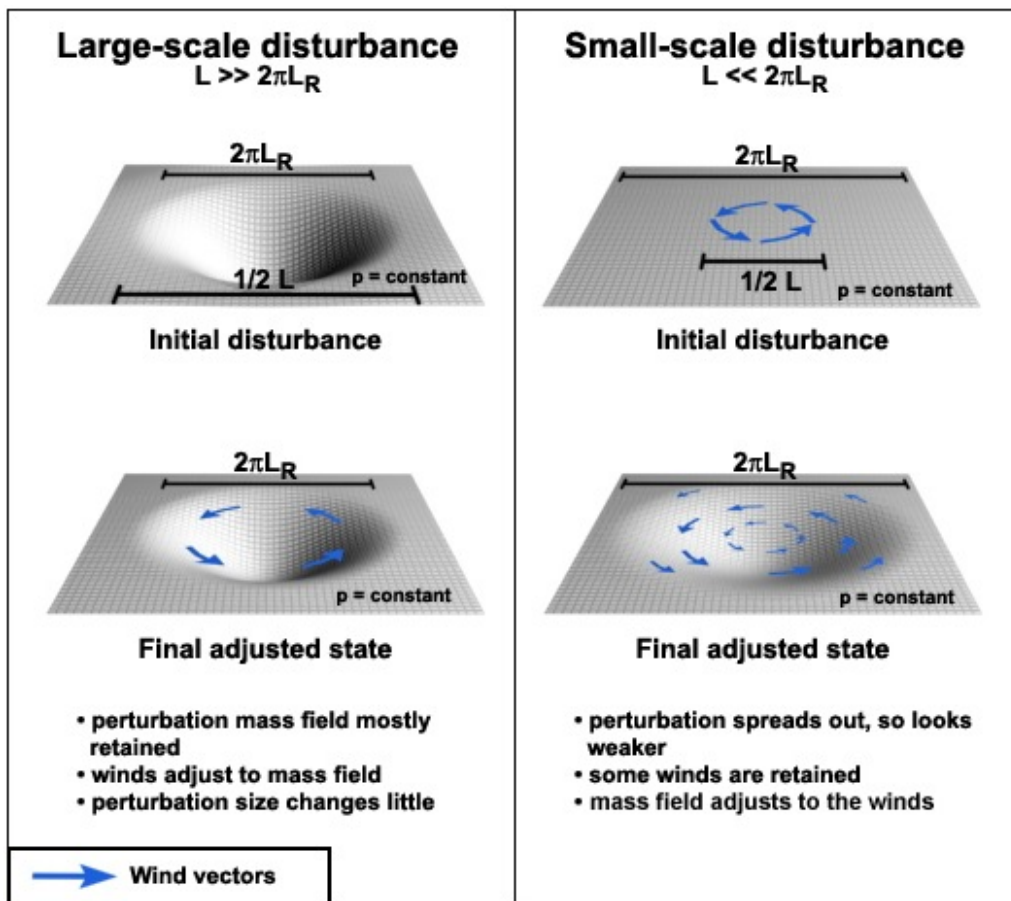
*Goal: Understand the conditions and causes of tropical cyclogenesis and cyclolysis*

# Conditions required for tropical cyclogenesis

- Latitudes poleward of  $\sim 5^\circ$
- Adequate ocean thermal energy
  - SST  $> 26^\circ$  extending to a depth of 60m
- Moist troposphere
- Enhanced lower troposphere relative vorticity
- Weak vertical shear

# Rossby radius of deformation

The Rossby radius of deformation,  $L_R$ , defines the scale at which rotation becomes comparable to the buoyancy force: 
$$L_R = \frac{NH}{\zeta + f}$$



The COMET Program

- $L_R$  is a measure of the distance traveled by gravity waves in an inertial period
- Perturbations (e.g., a diabatic heating anomaly) smaller than  $L_R$  are simply dissipated via gravity waves
- Features larger than  $L_R$  are governed by Rossby wave dynamics
- One can also think of  $L_R$  in terms of partitioning between (potential) vorticity and static stability or potential and kinetic energies

–e.g., the “adjusted” state of a large scale disturbance reflects in temperature/height, thus appears in the mass field (potential energy)

# Theories of tropical cyclogenesis

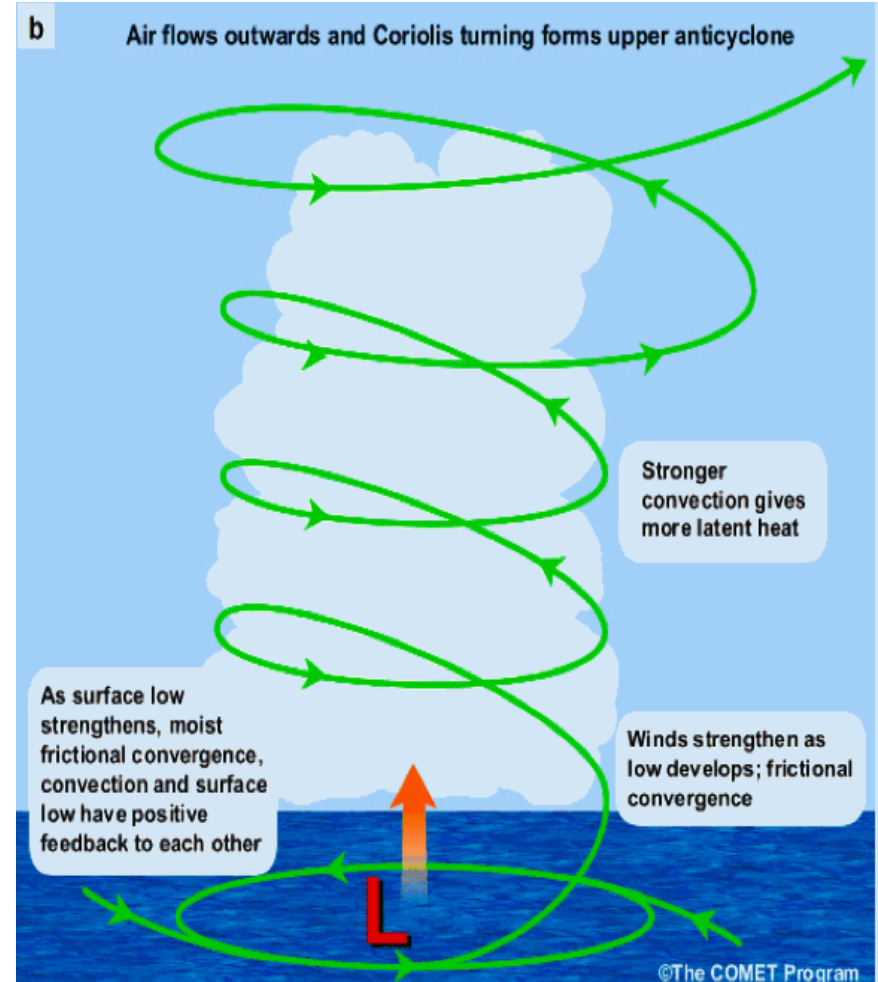
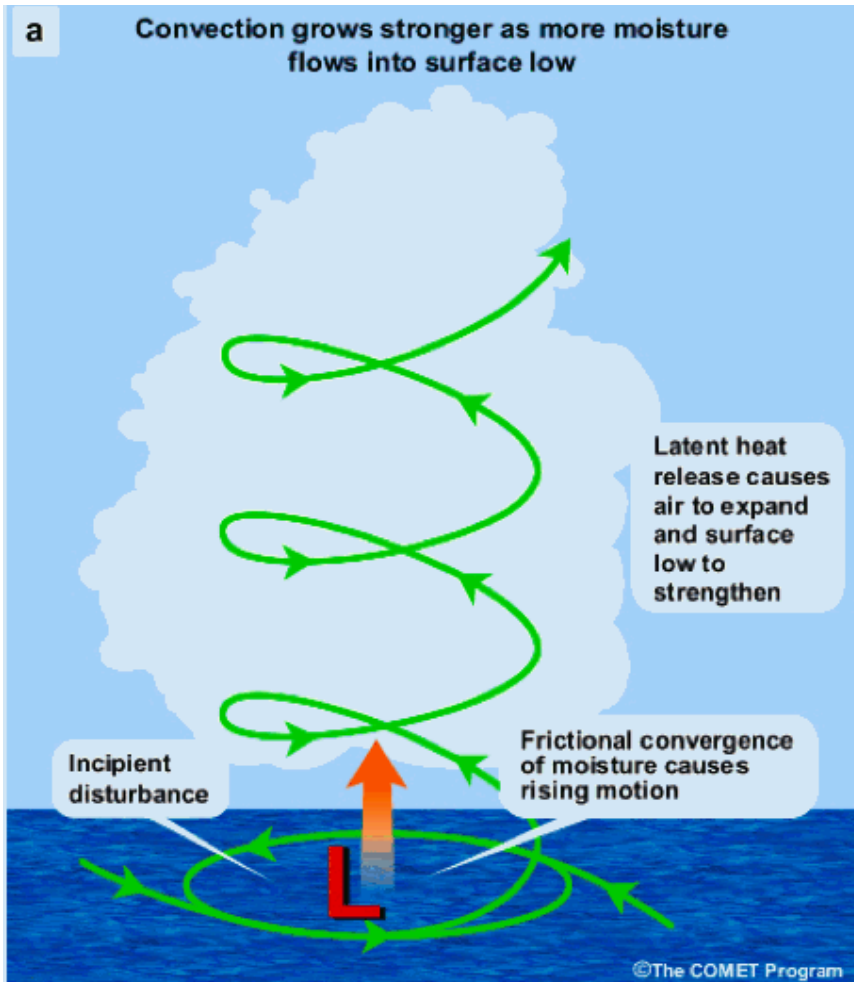
- Conditional instability of the 2nd Kind (CISK)
- Wind-induced surface heat exchange (WISHE)\*

*\*Essentially the Carnot framework.*

# Overview of CISK

- Prior: Miller's model (1958)
  - Maximum intensity related to storm center SST, surface relative humidity, environmental lapse rate, and top-of-the-storm potential temperature and height
- CISK proposed in the 1960s [Charney and Eliassen, 1964] consistent with the Miller model
  - The motivating question was: *How do cyclones form when the tropical environment appears to favor small-scale convection?*
- The basic idea underlying CISK is cooperation between small scale convection and the larger-scale circulation (positive feedback)
  - Frictional convergence of high ABL  $\theta_e$  (warm & moist) air produces vertical motion (Ekman pumping) [Note: friction decelerates surface winds, which causes the low level convergence]
  - In the vertical ascent region, release of latent heat occurs that drives a secondary circulation that increases inflow
  - Also, vertical “vortex stretching” increases surface cyclonic motion (vorticity), leading to more Ekman pumping
- When latent heat release balances surface frictional dissipation, cyclone maintains its intensity

# CISK Schematic



# WISHE

- In the lecture on convective QE, we discussed issues that argue against CISK
  - In particular, CISK requires widespread conditional instability, although the tropical atmosphere is observed to be close to neutral stability
- Emanuel et al. 1994 outlined the argument for WISHE-induced tropical cyclogenesis
  - An incipient disturbance generates vertical motion that leads to downdrafts of low  $\theta_e$  air
  - However, stratiform precipitation moistens the subcloud layer, which offsets the low  $\theta_e$  air
  - Latent heating from the wind-induced evaporation dominates, heating the core and allowing the vortex to grow
- Thus, WISHE creates instability through energy extraction from the underlying ocean

# WISHE Schematic

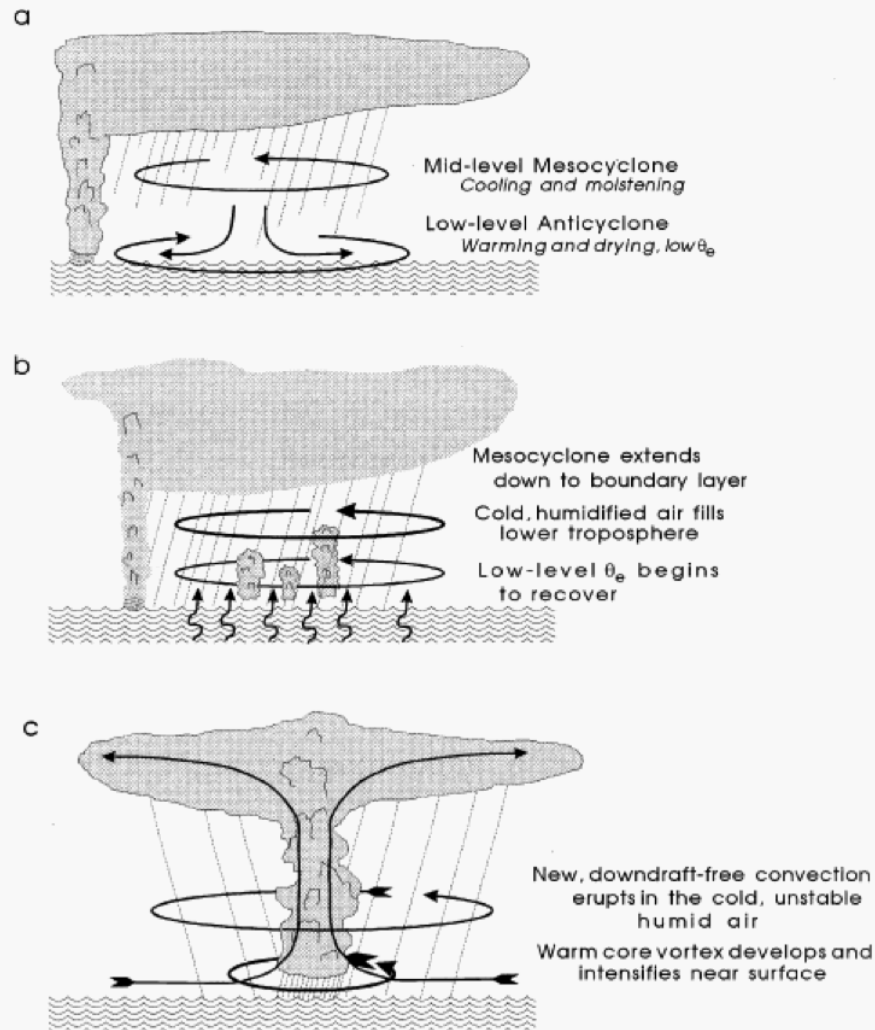


Figure 8. Conceptual model of tropical cyclogenesis from a preexisting MCS. (a) Evaporation of stratiform precipitation cools and moistens the upper part of the lower troposphere; forced subsidence leads to warming and drying of the lower part. (b) After several hours there is a cold and relatively moist anomaly in the whole lower troposphere. (c) After some recovery of the boundary layer  $\theta_e$ , convection redevelops (From Bister and Emanuel 1997, Copyright American Meteorological Society).

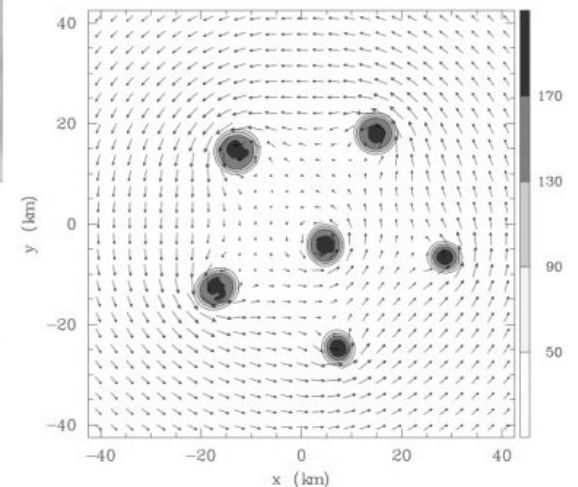
# Core dynamics: mesoscale vortices



DMSP image of Isabel on 12 September



Vorticity and wind vectors from the numerical experiment



# Eyewall replacement cycles

- Concentric eyewalls may be observed during periods of strengthening or weakening of intense tropical cyclones
- Eyewalls contract as the tropical cyclone intensify. If an outer eyewall begins to form, moisture and momentum are extracted from the existing eyewall, leading to dissipation of the inner eyewall
- The outer eyewall then intensifies and contracts
- Eyewall replacement cycles may last 12-18 hours to several days

# Hurricane Ivan double eyewalls

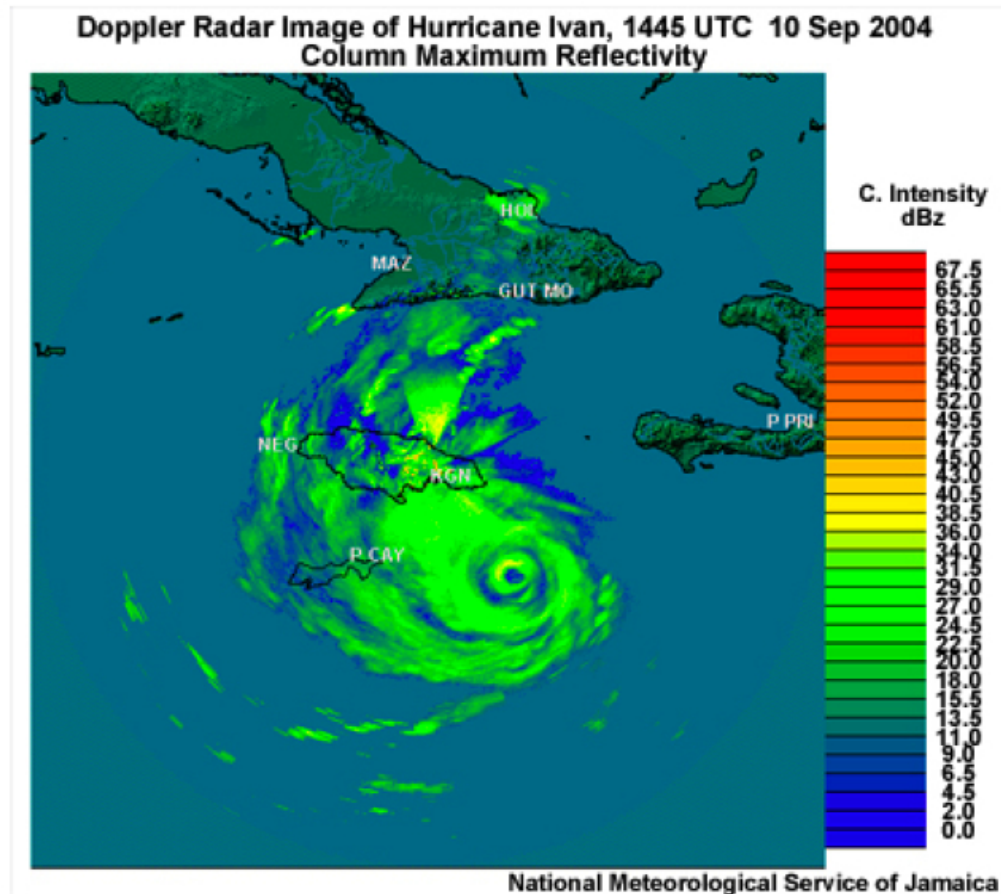


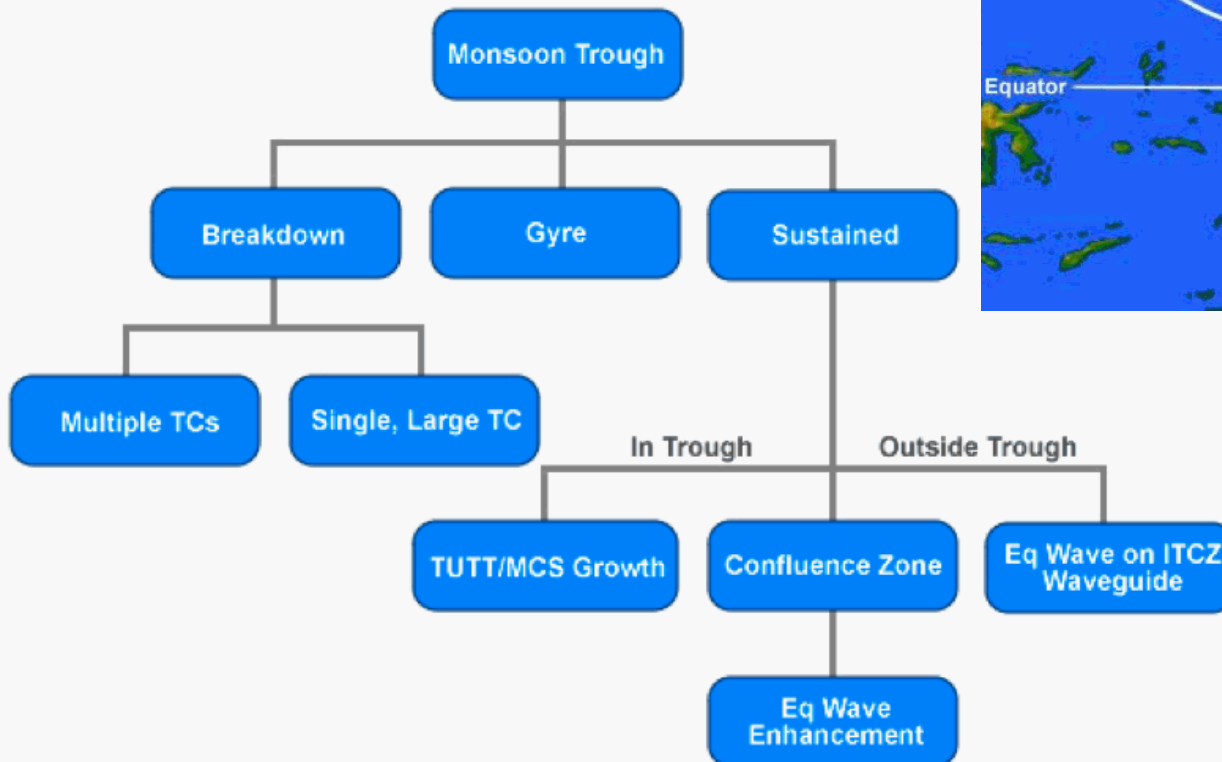
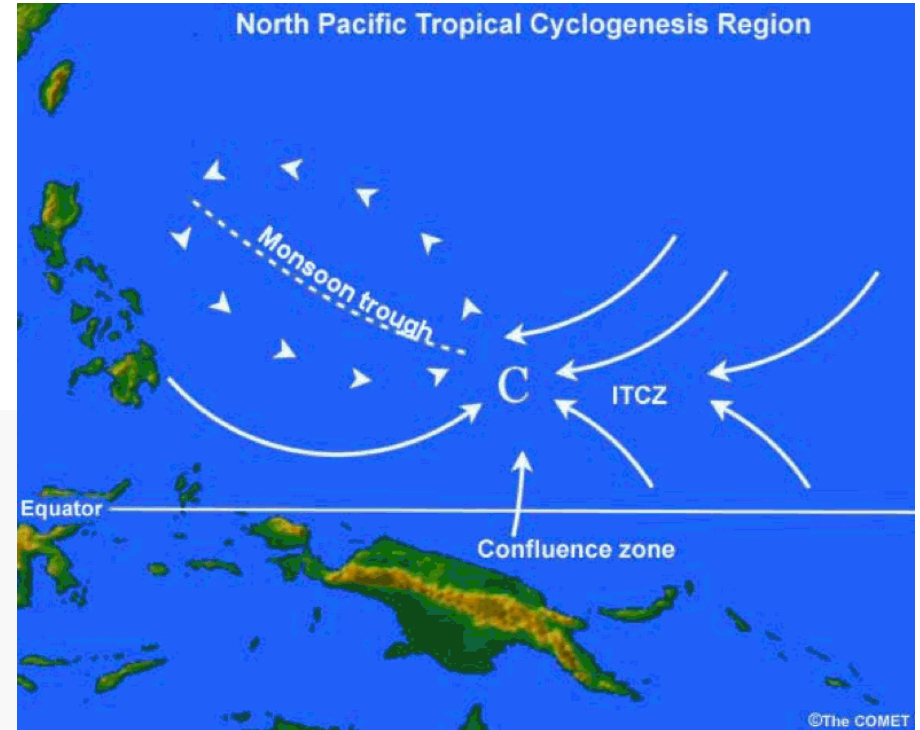
Fig. 10.60. Radar reflectivity image from Kingston, Jamaica at 1445 UTC 10 Sep 2004. Note the two concentric eyewalls that were likely the cause of short term weakening in Ivan. At this time, Ivan had weakened from category 5 to category 4 with sustained winds of  $65 \text{ m s}^{-1}$  (125 knots; image courtesy of the National Meteorological Service of Jamaica).

# Sources of incipient disturbances

- Recall the first step in tropical cyclone development is a “tropical disturbance.” What are the sources of such disturbances?
- Mechanisms:
  - Monsoon trough
  - ITCZ breakdown
  - Equatorial waves [Rossby, mixed Rossby-gravity]
  - Easterly waves
  - Mesoscale convective complexes
  - Subtropical storms
- Note that not all incipient disturbances in regions of favorable conditions develop into tropical cyclones: e.g., ~100 disturbances per hurricane season in the Atlantic, of which ~15 become tropical cyclones

# Monsoon trough

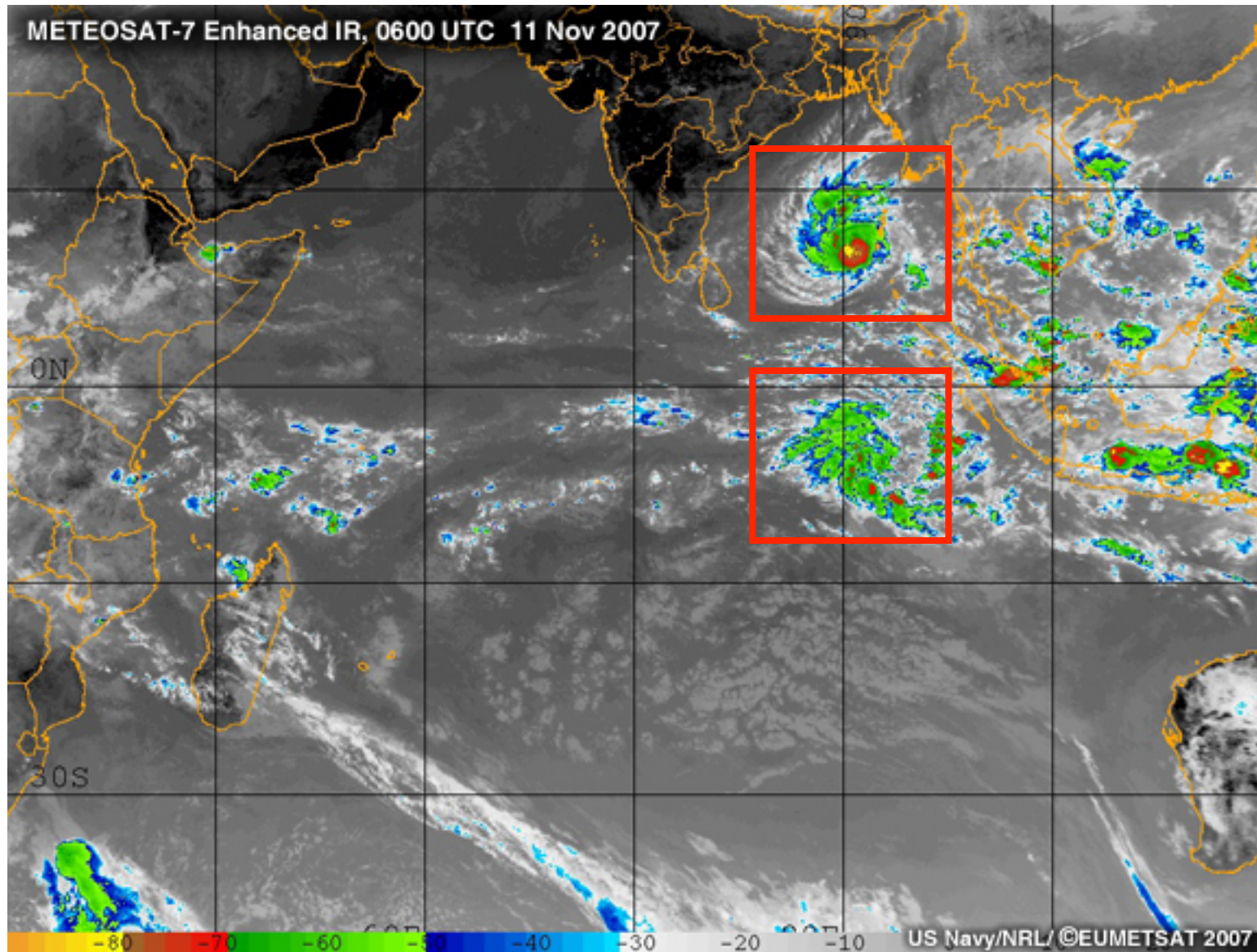
*Summary of mechanisms of disturbance generation associated with the monsoon trough*



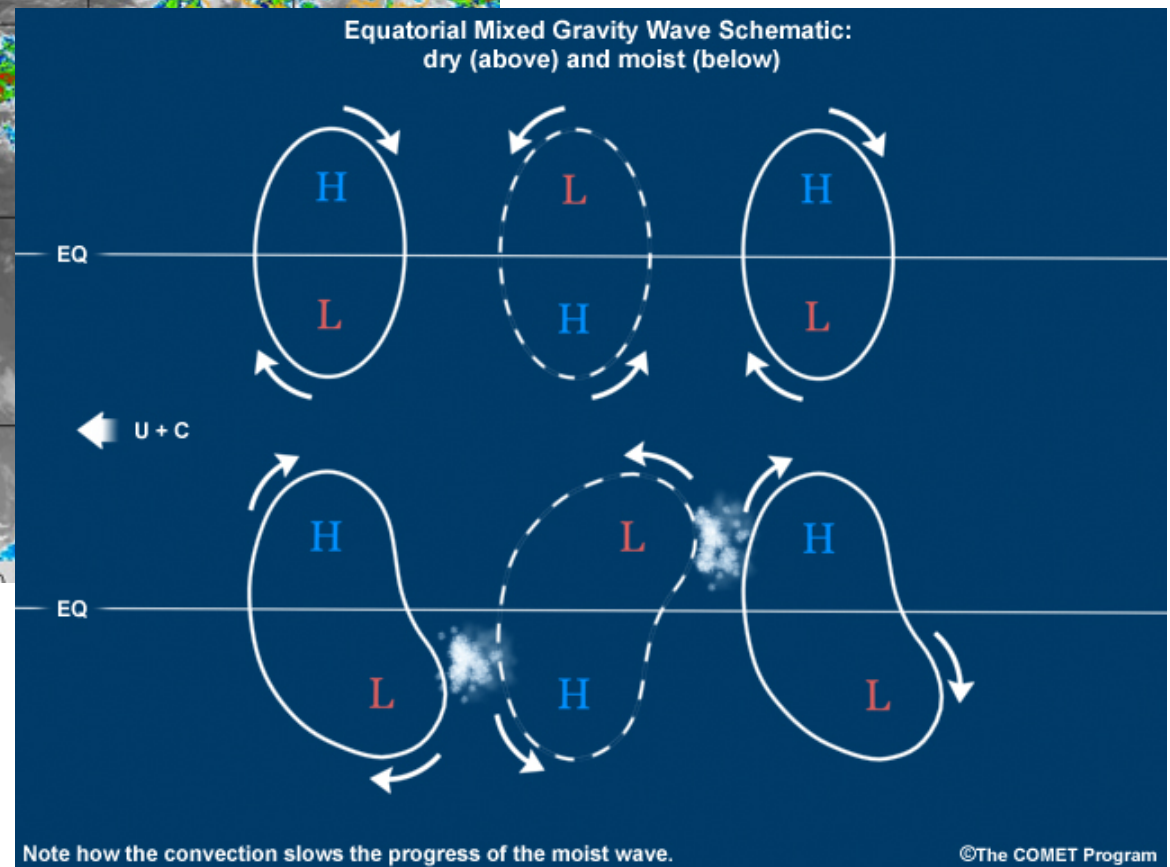
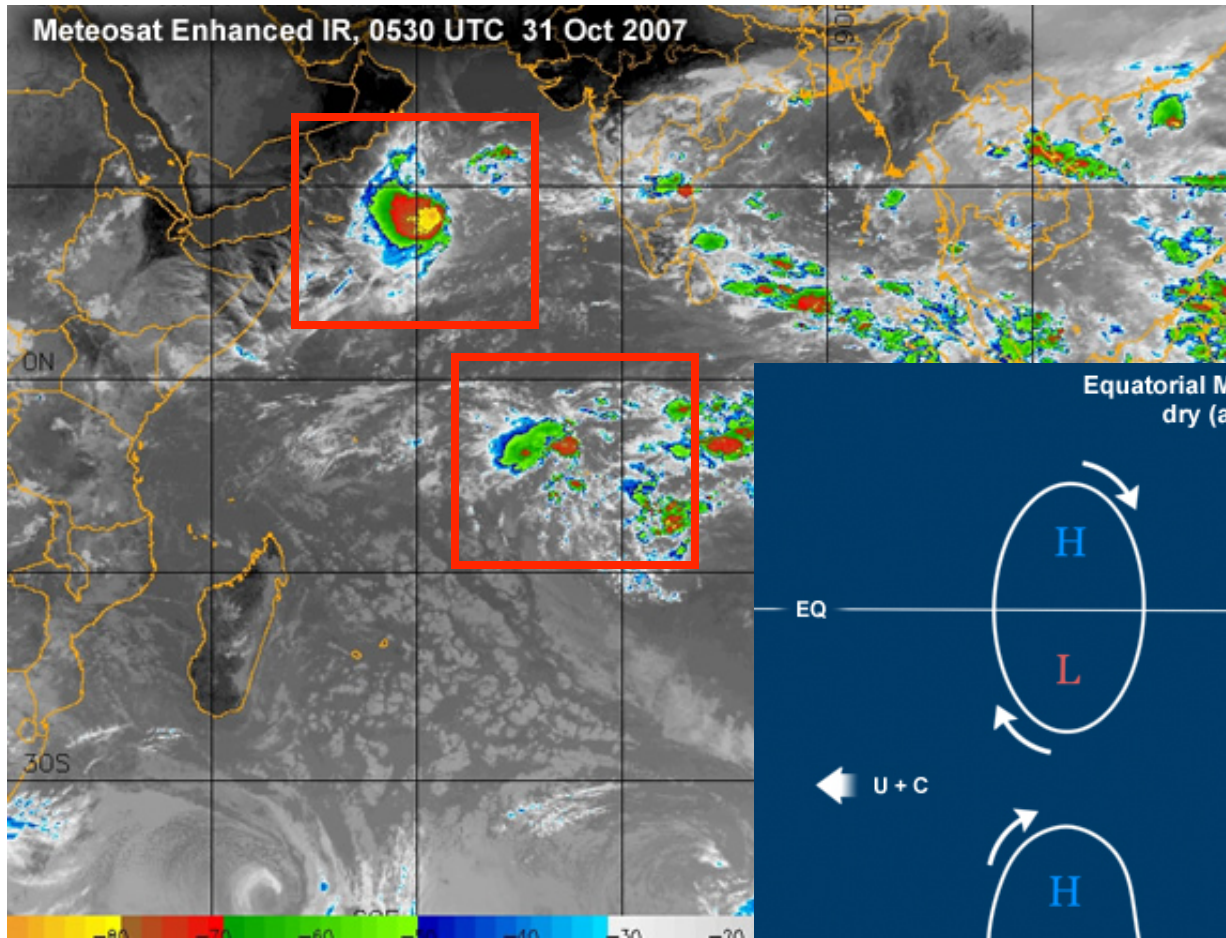
# Monsoon trough mechanisms

- **Tropical Upper Troposphere Trough (TUTT):** meso- to synoptic-scale upper tropospheric cold low
  - Interactions of easterly waves with the TUTT may enhance low-level convergence, leading to favorable conditions for cyclogenesis.
- **Monsoon gyre:** closed, symmetric circulation at ~850 mb extending over ~25° latitude
- **ITCZ or monsoon trough breakdown:** convection within the ITCZ leads to destabilization and breakdown via both barotropic and baroclinic instability
  - Breakdown may form groups of tropical cyclones or a single large one

# Equatorial Rossby wave pair



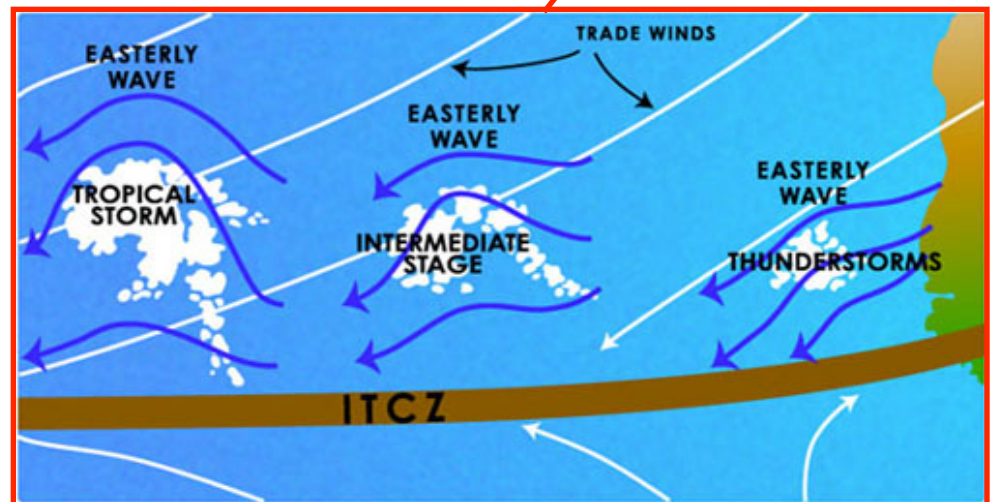
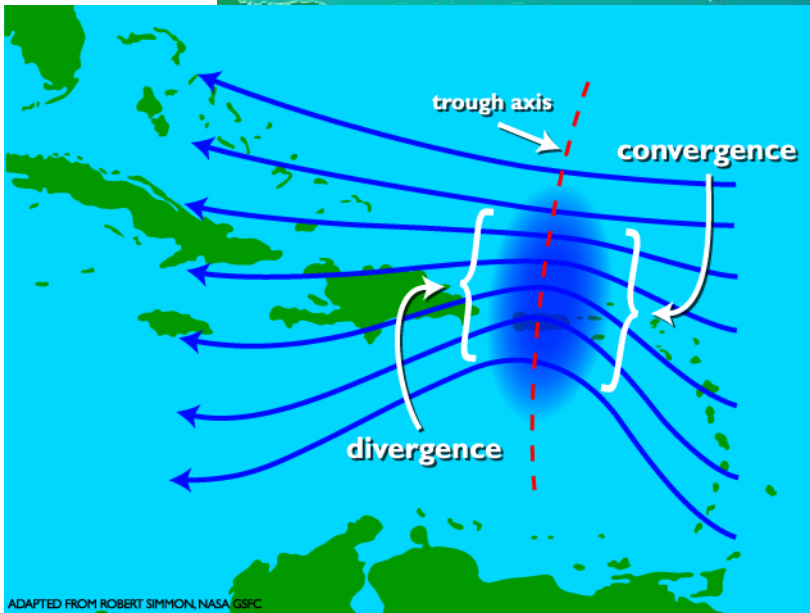
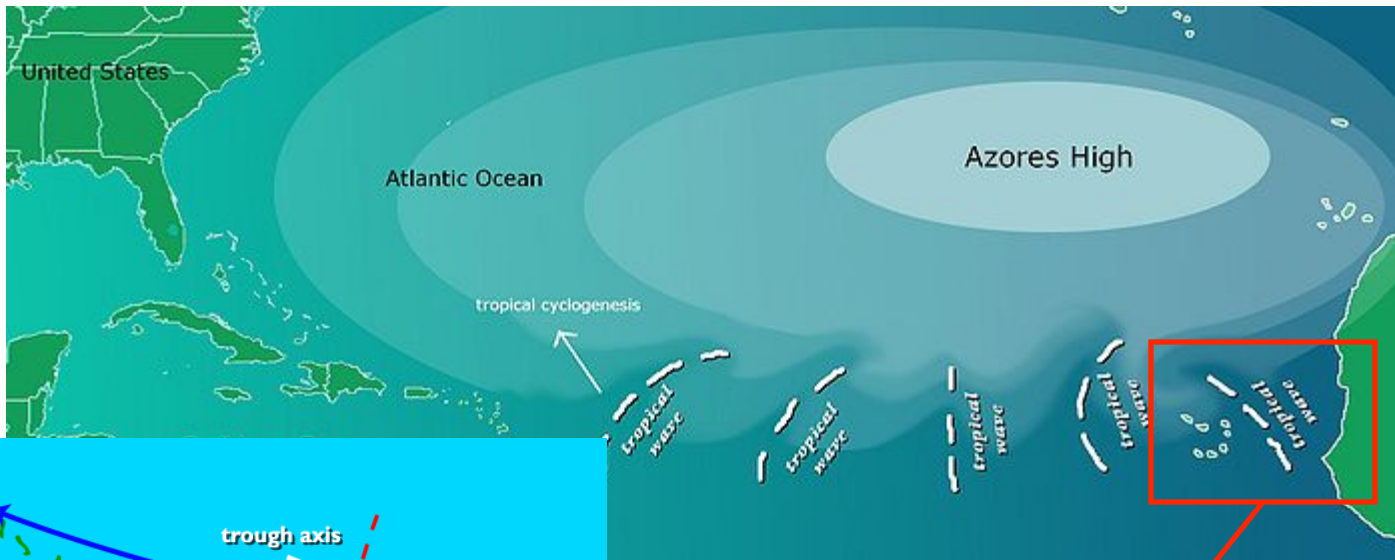
# Mixed Rossby-gravity wave



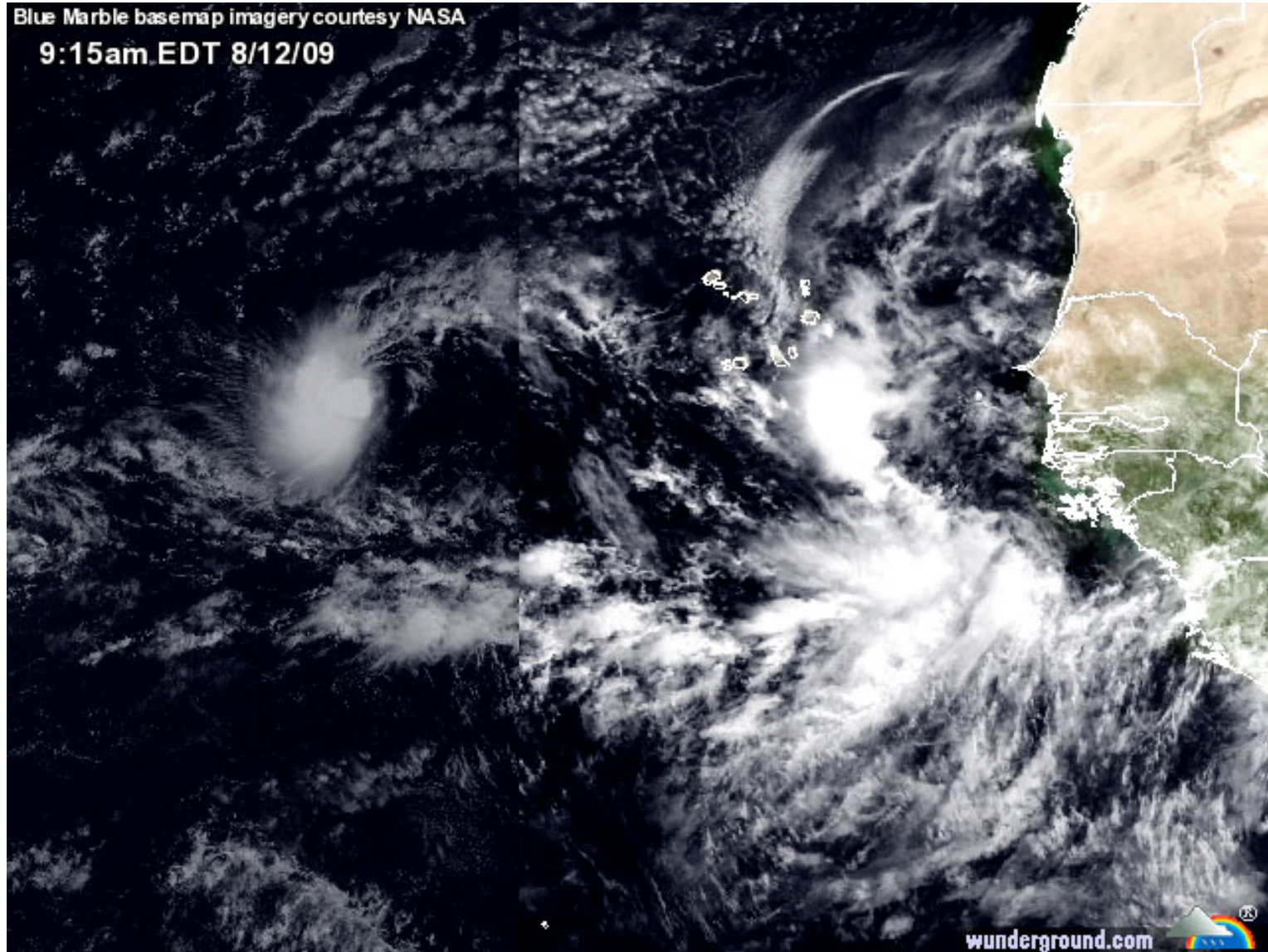
# African Easterly Waves (AEWs)

- Easterly waves that form over the African continent during the monsoon season may initiate cyclones over both the Atlantic and Pacific
  - ~60% of Atlantic hurricanes, and ~85% of major hurricanes, develop from AEWs
- These waves form as a result of instability in the African Easterly Jet.
- They have periods of roughly 3-5 days, have spatial scales of ~1000 km, and move at speeds of 7-8 ms<sup>-1</sup>.
- MCSs embedded within the AEWs may provide additional vorticity for initiating tropical cyclones.

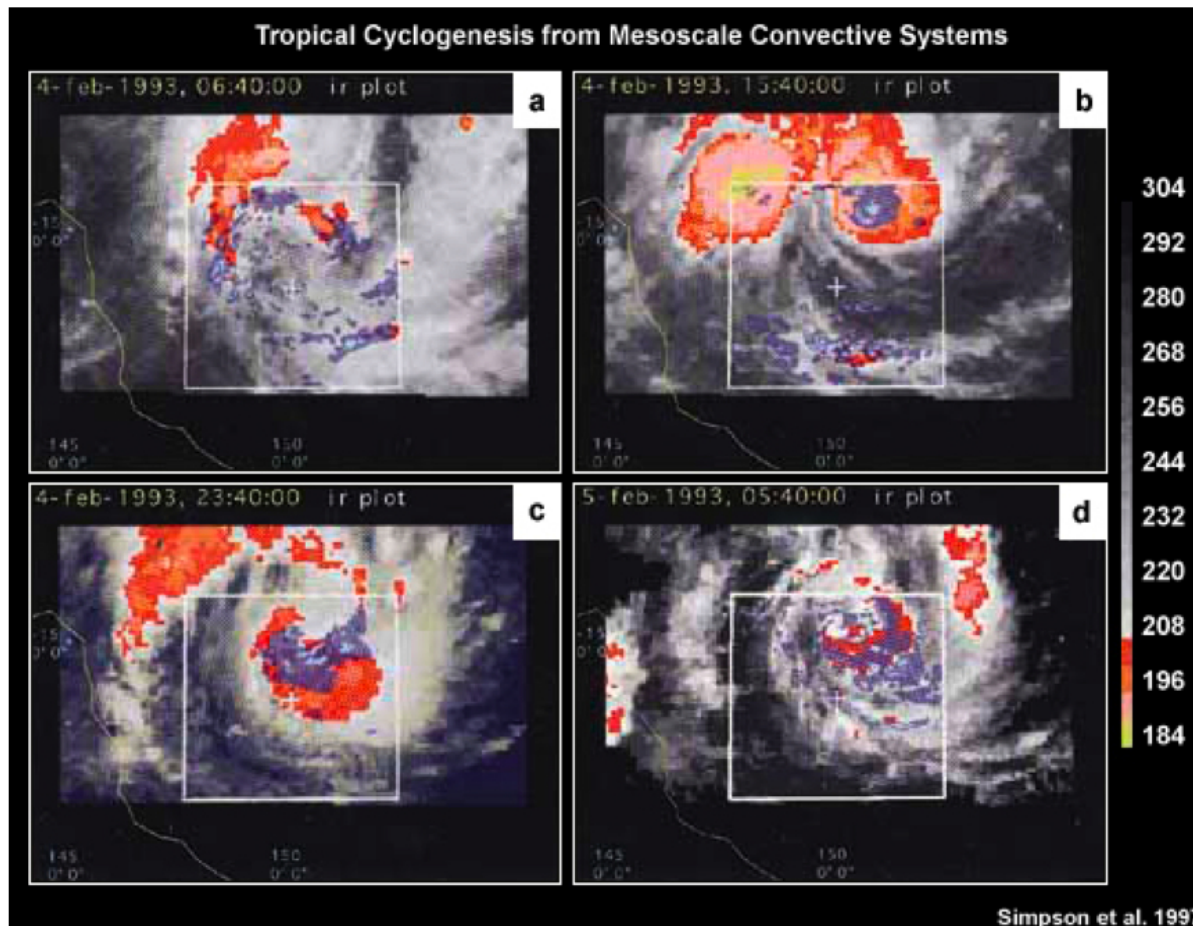
# African Easterly Waves (AEW)



# African Easterly Wave



# Hurricane Oliver (1993): Formation from merger of 2 MCSs



a. Initial cluster of weak mesoscale vortices

b. Two MCSs develop from these vortices

c. The MCS on the right in b. develops an eye-like feature

d. This strengthened MCS shears the other, which becomes a spiral rainband

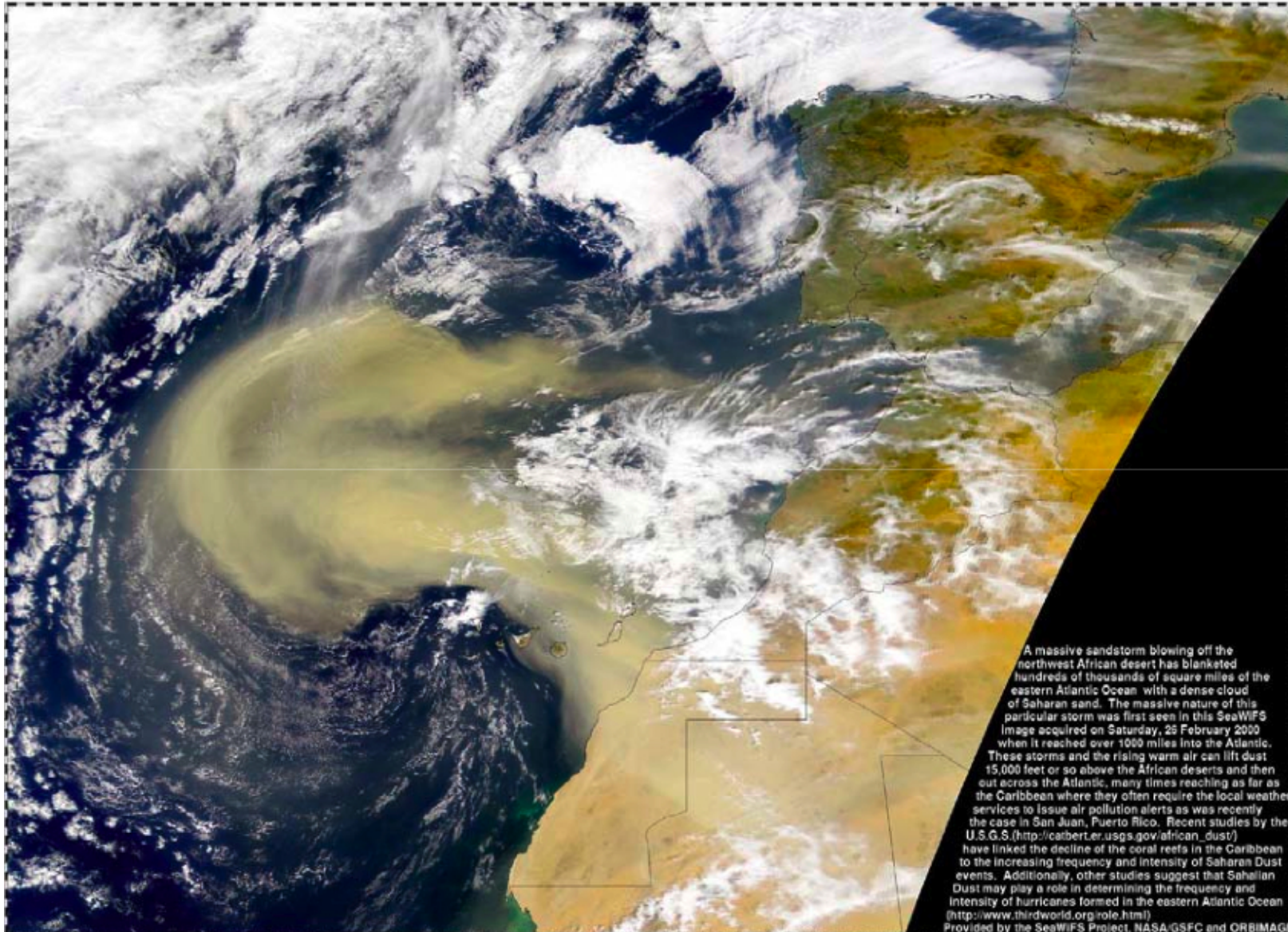
The above occurred in the process of the large-scale monsoon trough environment developing enhanced low-level vorticity, decreasing the local Rossby radius of deformation

# Factors limiting tropical cyclone development

***Essentially, conditions opposite to the necessary conditions for tropical cyclogenesis:***

- *Inadequate* ocean thermal energy
- *Dry* troposphere
- *Diminished* lower troposphere relative vorticity
- *Strong* vertical shear
- Also: Landfall

# Saharan Air Layer



A massive sandstorm blowing off the northwest African desert has blanketed hundreds of thousands of square miles of the eastern Atlantic Ocean with a dense cloud of Saharan sand. The massive nature of this particular storm was first seen in this SeaWiFS image acquired on Saturday, 25 February 2000 when it reached over 1000 miles into the Atlantic. These storms and the rising warm air can lift dust 15,000 feet or so above the African deserts and then out across the Atlantic, many times reaching as far as the Caribbean where they often require the local weather services to issue air pollution alerts as was recently the case in San Juan, Puerto Rico. Recent studies by the U.S.G.S. ([http://catbert.er.usgs.gov/african\\_dust/](http://catbert.er.usgs.gov/african_dust/)) have linked the decline of the coral reefs in the Caribbean to the increasing frequency and intensity of Saharan Dust events. Additionally, other studies suggest that Sahelian Dust may play a role in determining the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean (<http://www.thirdworld.org/role.html>)  
Provided by the SeaWiFS Project, NASA/GSFC and ORBIMAGE

# Extratropical Transition

- Tropical cyclones entering midlatitudes encounter conditions unfavorable to their maintenance which lead to decay: however, *extratropical transition* is the process by which tropical cyclones become extratropical in nature
- Although they may weaken prior to transition [as they experience recurvature, namely a change in direction from westward-poleward to eastward-poleward], transitioning systems can reintensify
- The transitioning system can also provide thermal contrasts for subsequent midlatitude cyclogenesis; the energetics can also interact with the pattern of midlatitude planetary waves, thereby exciting cyclogenesis remote from the transitioning system
- The likelihood of extratropical transition depends on the structure and intensity of the tropical cyclone, its thermodynamic environment, and the characteristics of the midlatitude trough

# Extratropical transition of Typhoon Tokage

