

**ESCI 344 – Tropical Meteorology**  
**Lesson 8 – Tropical Weather Systems**

- References:** *Tropical Climatology (2<sup>nd</sup> Ed.)*, McGregor and Nieuwolt  
*Climate and Weather in the Tropics*, Riehl  
*Climate Dynamics of the Tropics*, Hastenrath  
*Forecaster's Guide to Tropical Meteorology (AWS TR 240 Updated)*,  
Ramage  
“Conceptual Models of Tropical Waves,” Burton and Burton (online MetEd module), <https://www.meted.ucar.edu/meteoforum/tropwaves/>  
African Easter Waves, (online MetEd module),  
[https://www.meted.ucar.edu/tropical/synoptic/Afr\\_E\\_Waves](https://www.meted.ucar.edu/tropical/synoptic/Afr_E_Waves)  
“The origin and structure of easterly waves in the lower troposphere of North Africa,” Burpee, *J. Atmos. Sci.*, **29**, 77-90, 1972  
“Three dimensional structure and dynamics of the African easterly waves, Part II: Dynamical models,” Hall et al., *J. Atmos. Sci.*, **63**, 2231-2245, 2006  
“African easterly wave variability and its relationship to Atlantic tropical cyclone activity,” Thorncroft and Hodges, *J. of Climate*, **14**, 1166-1179, 2001

- Reading:** *Introduction to the Meteorology and Climate of the Tropics*, Chapter 10  
“African easterly wave variability and its relationship to Atlantic tropical cyclone activity,” Thorncroft and Hodges  
“Conceptual Models of Tropical Waves,” Burton and Burton (online MetEd module), <https://www.meted.ucar.edu/meteoforum/tropwaves/>  
African Easter Waves, (online MetEd module),  
[https://www.meted.ucar.edu/tropical/synoptic/Afr\\_E\\_Waves](https://www.meted.ucar.edu/tropical/synoptic/Afr_E_Waves)

**GENERAL**

- **Deep convection in Tropics tied generally to where there is upper-level divergence and outflow, not so much on static stability.**
- **Tropical weather systems are typically divided into three categories:**
  - **Waves**
  - **Vortexes**
  - **Linear disturbances**
- **Observational studies of tropical weather systems find that often the lowest observed relative humidities are actually located in the region of highest precipitation!**
  - **This is due to the fact that even in the areas of greatest precipitation and convection, compensating subsidence occupies most of the area, and so statistically the observations will be taken in subsiding (dry) regions.**

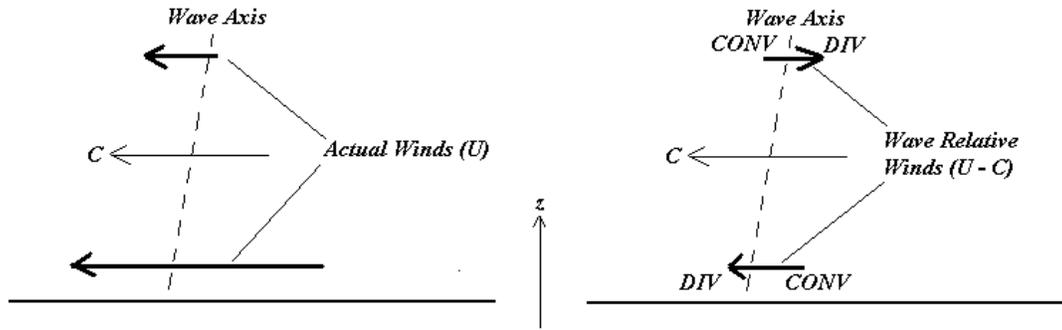
## WAVES IN THE EASTERLIES

- There is lots of different nomenclature with waves. Common terms you will see in the literature are:
  - Easterly waves
  - Waves in the easterlies
  - African waves
  - Equatorial waves
  - Tropical waves
- Not all waves are formed the same way, or have similar dynamics.
  - Some are surface manifestations of upper-level lows, while others are low-level phenomenon.
- The National Hurricane Center uses the generic term *tropical wave* to refer to wave-like features, regardless of their dynamics.
  - They define a tropical wave as “*a trough or area of cyclonic curvature in the trade winds or equatorial westerlies.*”
- The remainder of this section deals only with those waves that are not manifestations of upper-level lows or associated with shear lines, but instead are embedded in the trade-wind easterlies. We will refer to these as *waves in the easterlies*.
- There are several conceptual models for waves in the easterlies. These are:
  - *Riehl’s classical model* – Applies mainly to Caribbean waves
  - *Frank’s inverted “V” model* – Applies to eastern and mid-Atlantic waves
  - *African wave model* – Applies to waves over Equatorial Africa and the western coast of Africa.
- These are only conceptual models, meant to help explain and categorize different waves. This doesn’t mean the every wave fits into one of these categories, or that a wave cannot transition between categories as it propagates.
- Waves in the Easterlies are primarily a Northern Hemisphere phenomena

- This is because they need deep, easterly current to form an propagate, and these are more prevalent in the Northern Hemisphere versus the Southern Hemisphere.

## WAVES OVER THE NORTH ATLANTIC AND CARIBBEAN

- Riehl and Frank models generally apply
- Persist for 1 – 2 weeks
- Vorticity maximum is near 700 mb.
- Cold-core in the low levels, warm-core aloft
- Associated trough tilts upstream with height.
  - This is due to hypsometric considerations, since air is cooler behind the wave.
- The relative magnitudes of the mean wind velocity,  $U$ , versus the propagation speed of the wave,  $C$  is important in explaining the divergence/convergence pattern associated with waves.
  - For any case, as parcels approach the wave axis from whichever relative direction they are coming from, they must acquire positive absolute vorticity, which can only occur through convergence as shown by the vorticity equation
 
$$\frac{D\eta}{Dt} = -\eta \nabla \cdot \vec{V}$$
  - If the wave is moving slower than the mean wind speed ( $U - C > 0$ ), then the air parcels approach the wave axis from the East, and the convergence will lie behind (to the East) of the wave axis.
  - If the wave is moving faster than the mean wind speed ( $U - C < 0$ ), then the air parcels approach the wave axis from the West, and the convergence will lie ahead of the wave axis.
- In most cases the winds in the lower troposphere are faster than the wave speed, while winds in the mid and upper levels are slower than the wave speed. The simplified divergence/convergence pattern would look like the figure below.



*Wind and divergence/convergence pattern associated with conceptual model of a wave in the easterlies*

- **This pattern of convergence/divergence is associated with upward motion and cloudiness behind the wave axis, with subsidence and clearing ahead.**
- **The wave needs anticyclonic outflow aloft for maintenance of the convection.**
- **Convection often amplifies as the waves approach the eastern Caribbean Sea.**
  - **This is due to the presence of the TUTT, which can enhance the upper-level outflow from the convection.**
- **Waves in the easterlies are usually thought to be a North Atlantic phenomenon. There is considerable differences of opinions among researchers and operational meteorologists as to whether or not there are true waves in the easterlies in the Western Pacific, or to whether or not Atlantic waves actually traverse Central and South America and maintain their form into the Eastern Pacific.**

## **BAROTROPIC INSTABILITY**

One form of hydrodynamic instability that can occur in the atmosphere is barotropic instability. The derivation of the condition for barotropic instability is beyond the scope of this course. But, the condition for barotropic instability involves the horizontal shear of the mean wind. The necessary condition for barotropic instability to occur is that, somewhere within the flow, the following condition must be true:

$$\frac{d^2 \bar{u}}{dy^2} - \beta = 0. \quad (1)$$

This means that for barotropic instability to occur that the second derivative of the mean zonal wind must be equal to  $\beta$  somewhere in the flow. Condition (1) can also be written as

$$\frac{d}{dy} \left( \frac{d\bar{u}}{dy} - f \right) = 0 \quad (2)$$

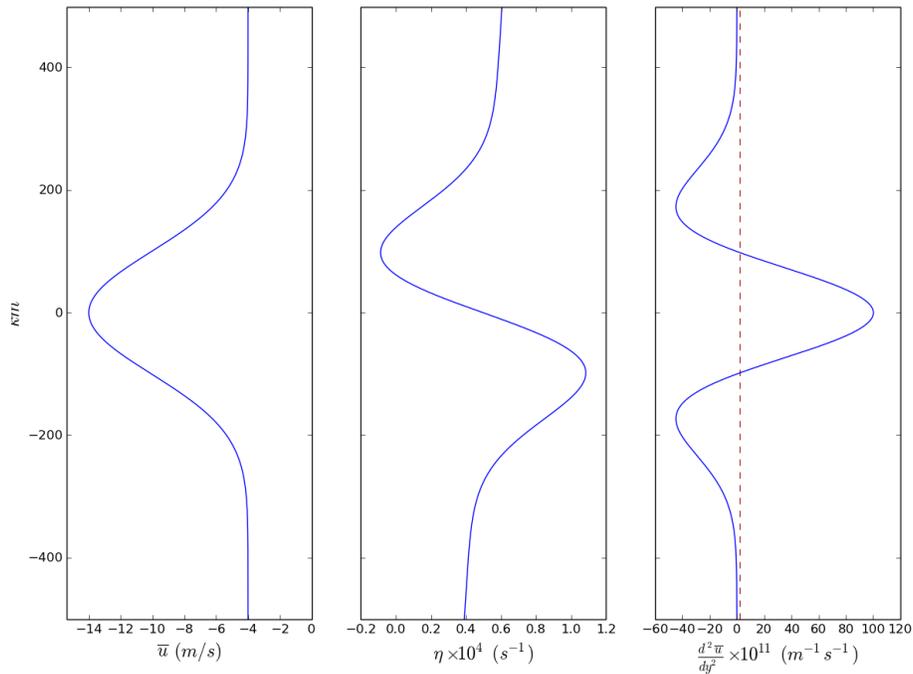
or

$$\frac{d\eta}{dy} = 0. \quad (3)$$

We can interpret this to mean that the absolute vorticity must have a minimum or maximum value somewhere in the flow in order for barotropic instability to occur.

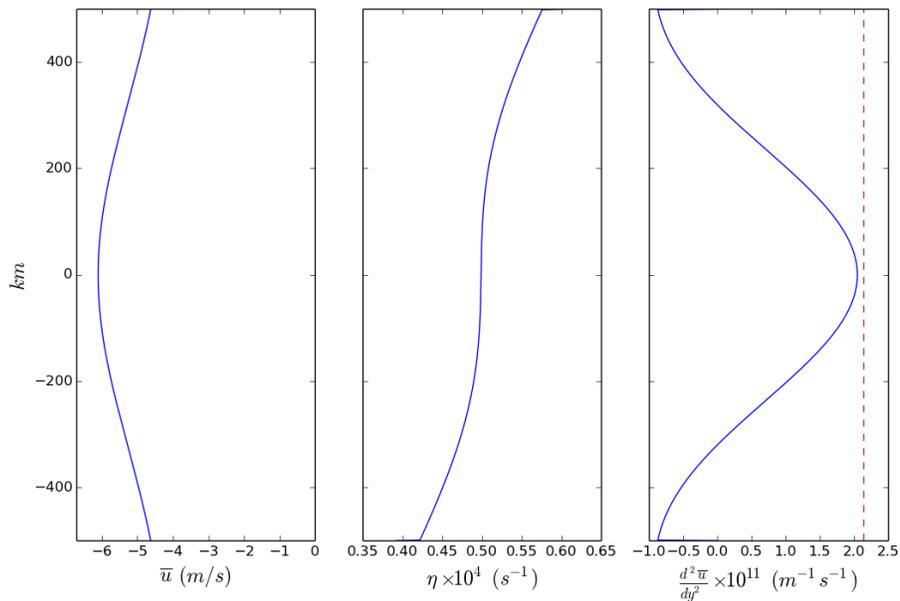
### BAROTROPIC INSTABILITY IN AN EASTERLY JET STREAM

Barotropic instability is dependent upon horizontal shear of the mean flow. To examine if barotropic instability is possible, the horizontal profile of the absolute vorticity must be examined. The plot below shows the zonal velocity, absolute vorticity, and the second derivative of the velocity for an idealized easterly jet stream on the beta plane. The dashed line on the third diagram is the value of beta.



There are absolute vorticity minima and maxima on both flanks of the jet, near the locations of the inflection points in the velocity profile. Thus, the condition for barotropic instability is met in these two regions.

However, the presence of an inflection point does not automatically mean that there is a minimum or maximum in the absolute vorticity. If beta is large compared to the second derivative of the velocity, such as for a broad, weak jet at low latitudes, as shown below, then there will not be any maxima or minima in vorticity, even though there are inflection points in the velocity profile. Thus, beta acts as stabilizing influence against barotropic instability.



## ENERGETICS OF BAROTROPIC DISTURBANCES

Barotropic disturbances derive their energy from the mean flow. Energy considerations show that **for a barotropic disturbance to grow it must tilt opposite to  $d\bar{u}/dy$ .**<sup>1</sup> Since midlatitude disturbances tend to tilt in the same direction as  $d\bar{u}/dy$ , they actually lose energy back to the mean flow due to barotropic instability. Thus, barotropic instability is not a viable way for midlatitude disturbances to form and grow. However, interestingly enough, **since midlatitude disturbance decay due to barotropic instability, they give up energy to the mean flow and help maintain the mean flow against friction.** Thus, barotropic instability is somewhat important for the maintenance of the mean flow in the midlatitudes.

## AFRICAN WAVES

- **Western Africa is major source of waves in the easterlies.**
- **Their dynamics appears to be a combination of both barotropic and baroclinic instability associated with the West African mid-level (easterly) jet.**
  - **Convection may play a role acting as a forcing mechanism to create a perturbation in the flow from which the disturbance can grow into a wave.**
- **Wave axis generally tilted from southwest to northeast, and is opposite to horizontal shear south of the jet.**

<sup>1</sup> See Haltiner and Williams, pp.74-75.

- When tilt and shear are opposite, barotropic instability removes energy from the jet and puts it into the perturbation (wave).
- Thus, growth due to barotropic instability will mainly be south of the jet core.
- Often have multiple vorticity centers, with southern one at around 600 mb and south of the jet axis, and the northern one nearer to 850 mb and north of the jet axis.
  - Thorncroft and Hodges found that those 850 mb vorticity centers that are found over the ocean are not continuations of the 850 mb over the land. Instead, it appears that as the 600 mb vorticity center passes the coast that development occurs downward, possibly influenced by latent heating, so that a new 850 mb vorticity center is formed while the previous, northerly 850 mb vorticity center dissipates.
- These waves are preferentially formed in the half-year associated with the Boreal summer.
- Waves increase in amplitude as they approach the west coast of Africa, and weaken as they head out to sea.
- Divergence/convergence pattern opposite of waves over the North Atlantic.
  - Low-level convergence, clouds and rain ahead of wave axis, rather than behind.
- Waves in the Easterlies account for the majority of all North Atlantic tropical cyclones.
- An increased number of waves means an increased number of tropical cyclones.
- Meteorological factors in the wave formation region over Africa impact the Atlantic tropical cyclone season.

#### UPPER-LEVEL CYCLONES

- Most intense in the 200 – 300 mb level.
- Many don't even show up on the 700 mb chart.
- Associated with upper-level convergence and suppressed convection.
- Often surrounded by rings of thin cirrus.

- Occasionally convection fires in center of low since cool upper-levels are associated with static instability.
  - Convection usually short-lived due to:
    - upper-level convergence
    - entrainment of dry air
- Upper-level lows rarely transform directly into warm-core surface lows, though they can interact with surface features to form new surface lows to the east of the upper-level cyclone.

### **TROPICAL UPPER-TROPOSPHERIC TROUGHS**

- The tropical upper-tropospheric trough (TUTT) is a persistent feature in the North Pacific and North Atlantic during the summer months.
- A mid-latitude short-wave trough passing poleward of the TUTT can sometimes result in a surge of cold air wrapping around the TUTT and forming a cut-off low at the Equatorward end of the TUTT (called a *TUTT cell*).
- The region to the east of the TUTT cell is one of enhanced upper-level divergence, and Sadler has documented cases where this has led to the generation of a tropical cyclone to the southeast of the TUTT cell.

### **SQUALL LINES**

- Non-frontal lines of active thunderstorms.
- Can be hundreds of miles in length
- Persists much longer than lifetime of individual cells that make up line.
  - Usually last for 3 – 15 hours
  - May last for several days in West Africa
- Occur in northern Australia, northwestern India, Bangladesh, Malaysia, Indonesia, South America/Caribbean, and West Africa
- Most frequently occur in mid to late afternoon.
- Require moist low levels with relatively dry mid levels.
- Tropical squall lines have trailing anvil, while mid-latitude squall lines have preceding anvil.

- **Leading edge of gust front sparks new development and propagates line.**

### **SUMATRA**

- **Form during SW monsoon over Straits of Malacca**
- **Usually form at night**
- **Last 1 to 2 hours**
- **Three main factors**
  - **Daytime heating over Sumatra followed by nighttime radiative cooling over the Straits of Malacca**
  - **Orographic lifting over Malaysia**
  - **Converging land breezes from Malaysia and Sumatra**

### **SHEAR LINES**

- **Equatorward extension of a midlatitude cold front**
- **No large temperature or humidity shift**
- **Zone of convergence**
- **Characterized by stratiform clouds with embedded convection**
- **Can stall out and cause low ceilings and rain for extended periods.**

### **COLD SURGES**

- **Surge of cold air from midlatitudes into Tropics.**
- **Surge from winter hemisphere can enhance Equatorial westerlies in summer hemisphere, and increase cyclonic vorticity.**
  - **Can result in development of tropical cyclones in monsoon trough.**