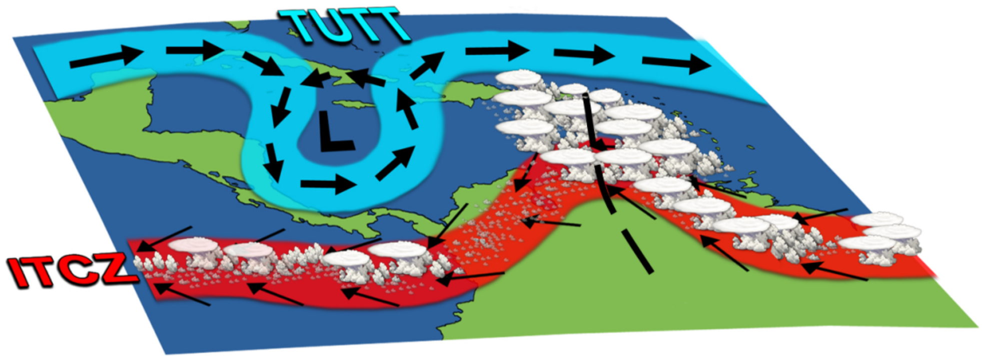
Atlantic/Caribbean Basin Tropical Waves and TUTT Induced Inverted Troughs



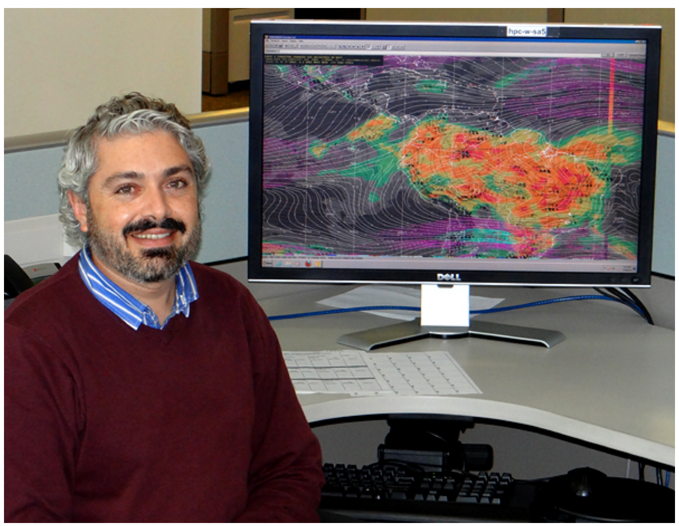
Mike Davison, Chief, International Desks
Dr. José Gálvez, International Desks Researcher
Reviewed by **Dr. Arlene Laing**, CMO

June 2020

Part 1: Concepts

NATIONAL WEATHER SERVICE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Mike Davison, WPC



Jose Galvez, WPC

Kathy-Ann Caesar, CIMH

Dr. Bernadette "Bernie" Connell
CSU/CIRA-RAMMB

Facilitator, moderator, technical support, communications, the heart and soul of the VISIT program

Rules

- Your participation is required
  - Partake of the poll questions to assess your understanding of the material
- Questions??
  - Use the chat box to send a text message(s)
  - Bernie, Jose and Kathy will be monitoring
    - They will answer and/or identify questions of common interest.

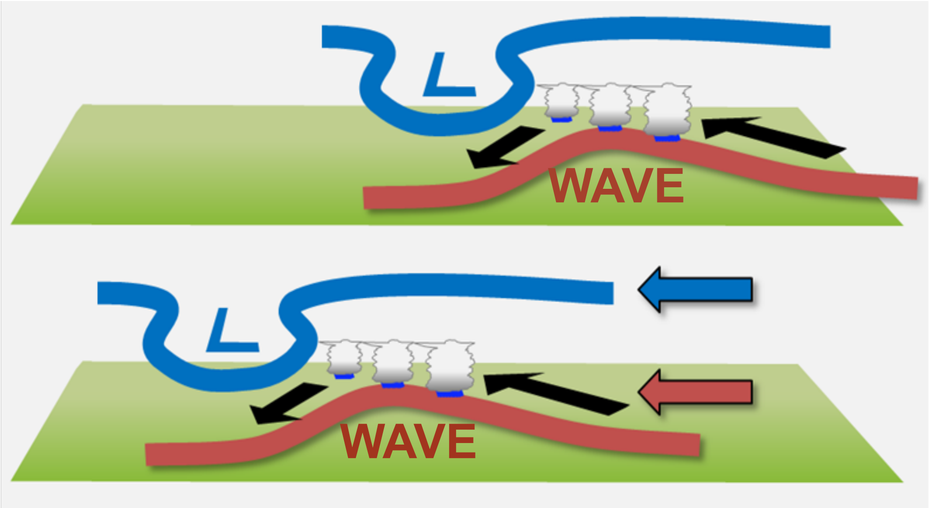
Tropical waves or TUTT-induced troughs…

Why is this important??

- Commonalities
  - Both can produce significant persistent precipitation (rain/rain showers and deep convection)
  - Both can develop into Tropical Cyclones
- TUTT induced waves, however, can remain stationary
  - Resulting in higher potential to produce persistent precipitation and potential flash flooding
- Positive Scale Interaction
  - Tropical wave might interact (phase) with an upper TUTT to result in areas of heavy/potentially severe convection.

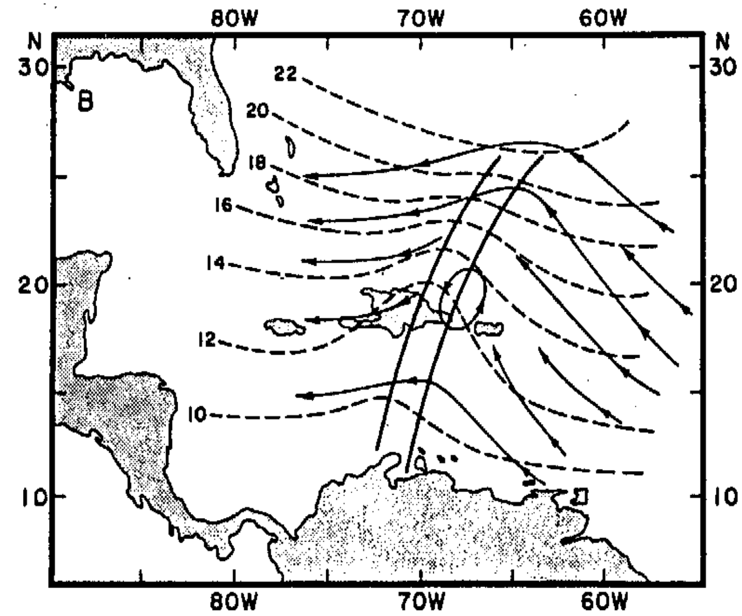
Source of confusion

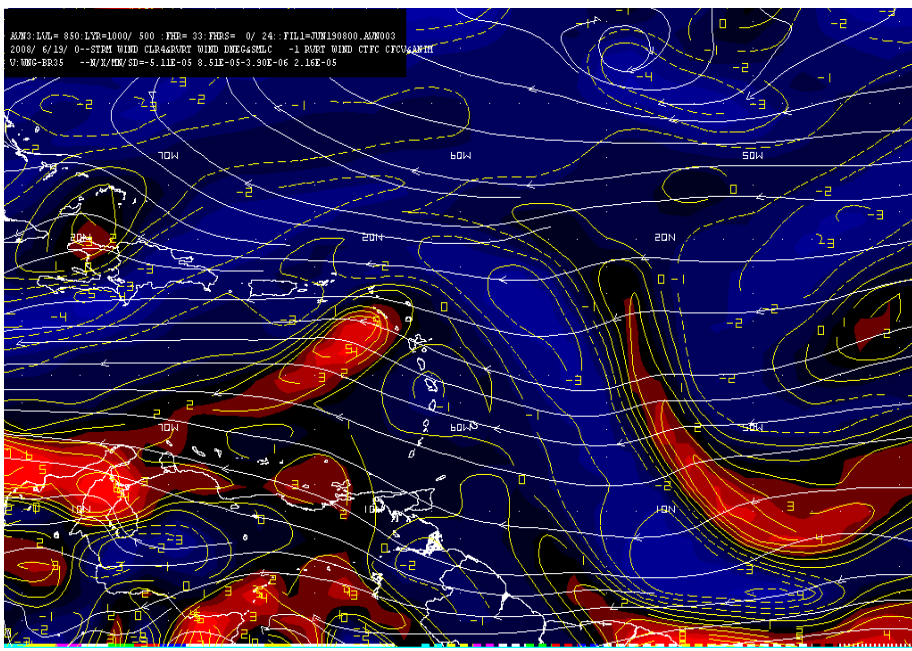
A retrogressing, westward moving, TUTT can induce a trough at low levels that will also propagate west following the TUTT.

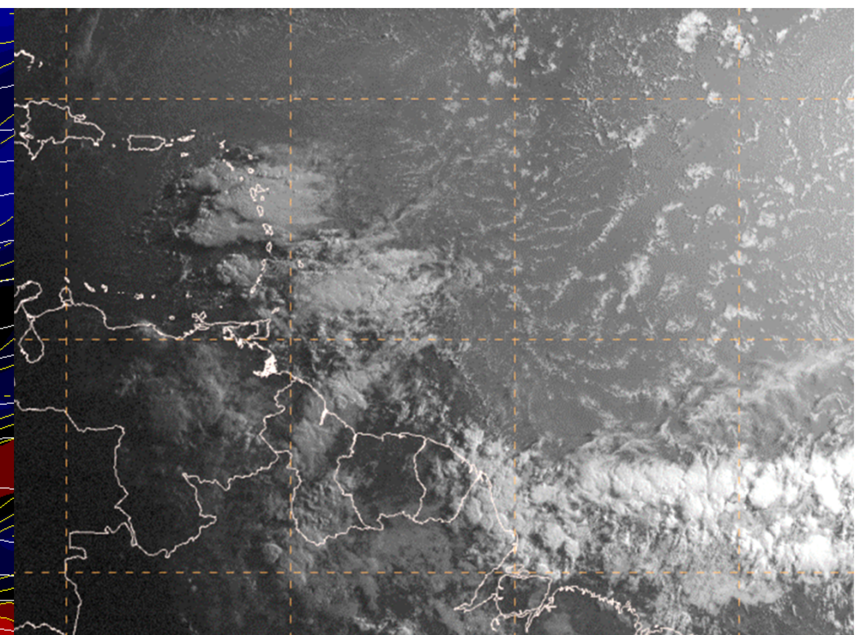


- The satellite signature and westward propagation of the induced trough will mimic that of an easterly/tropical wave.
  - *The **astute** forecaster, through careful analysis and interpretation, will be able to tell the difference.*

Tropical Waves







Tropical Waves

- **Conceptual Model**
  - Riehl (1945) : -Inverted “**V**”
  - Burpee (1972): -Origin in North Equatorial Africa
    -Instability along Mid-Level African Easterly Jet
  - Thorncroft (2008) -Aid of latent heat release in organized deep convection
- **Characteristics**
  - Wave amplitude: Varies between 10-30 degrees
  - Typically from the surface up to **850-700 hPa (1.5 - 3 km)**
- **Propagation**
  - Westward or from the east (“Easterly Waves”)
  - Propagation speed → 10-15 kt
- **Frequency:** Period of 3-4 days between waves.
- **Seasonality**: April through November

Characteristics Typical Tropical Wave

- **Core:** Cold at low levels/warm above.
- **Sustained by** latent heat released by condensation.
- **Vorticity:** Due to low level cold core and upper warm core, the cyclonic vorticity increases from surface to 850/800 hPa, then decreases with height.
- **Effects of Vertical Wind Shear on convection**
  Weak→ Enhances convection. Strong→ Inhibits convection.

Characteristics Typical Tropical Wave

- **Associated weather**

  - Fair weather usually ahead of the wave.
    - +Upper convergence / Low-level divergence.
    - +Dry/Subsident pattern.

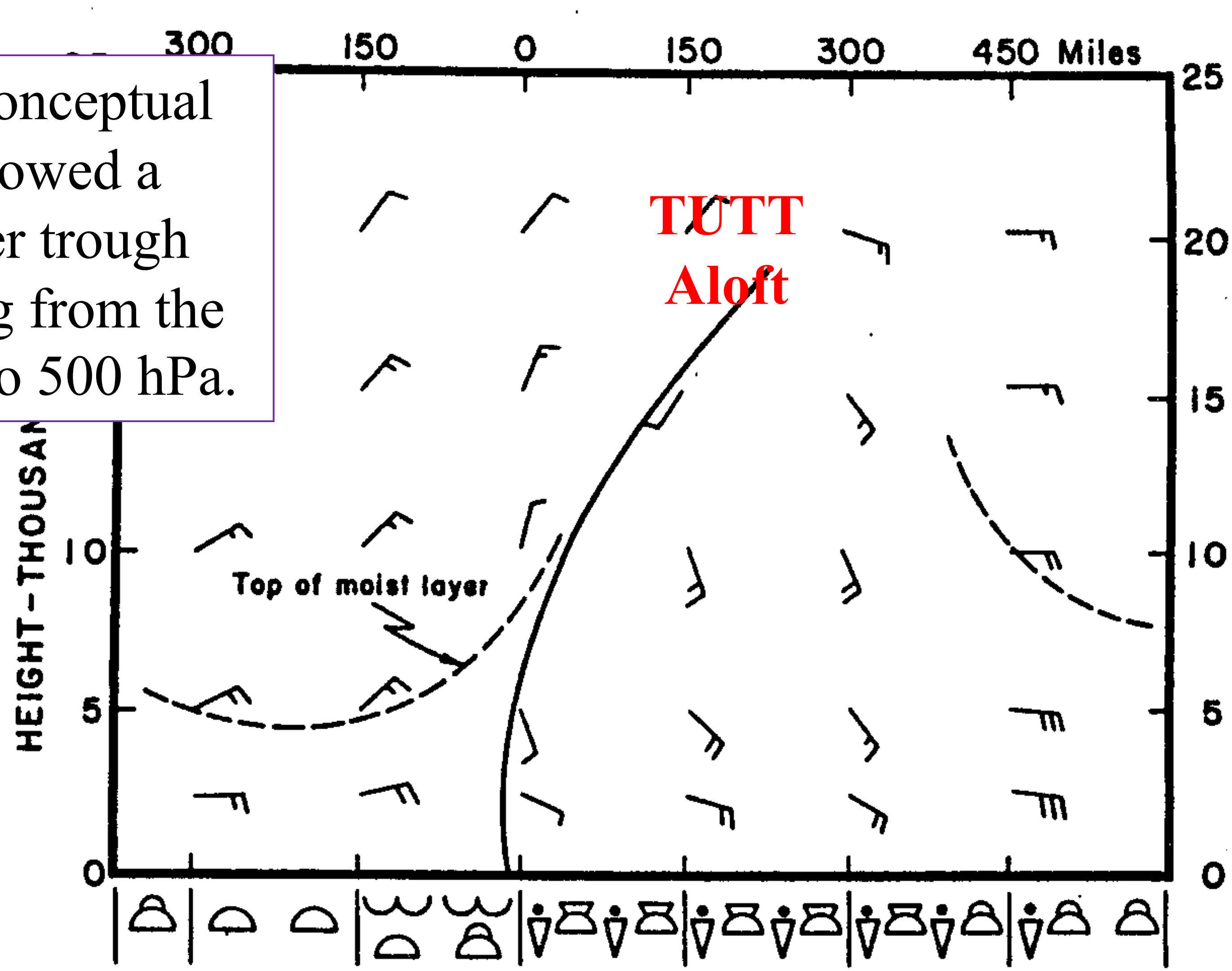
  - Inclement weather with wave passage and to the east.
    - + Upper divergence / Low-level convergence.
    - + Deeper moist layer.

  - Diurnal cycle of convective instability enhances nocturnal convection when over water. Over land, diurnal heating of the surface enhances afternoon convection.

Riehl's Conceptual Model

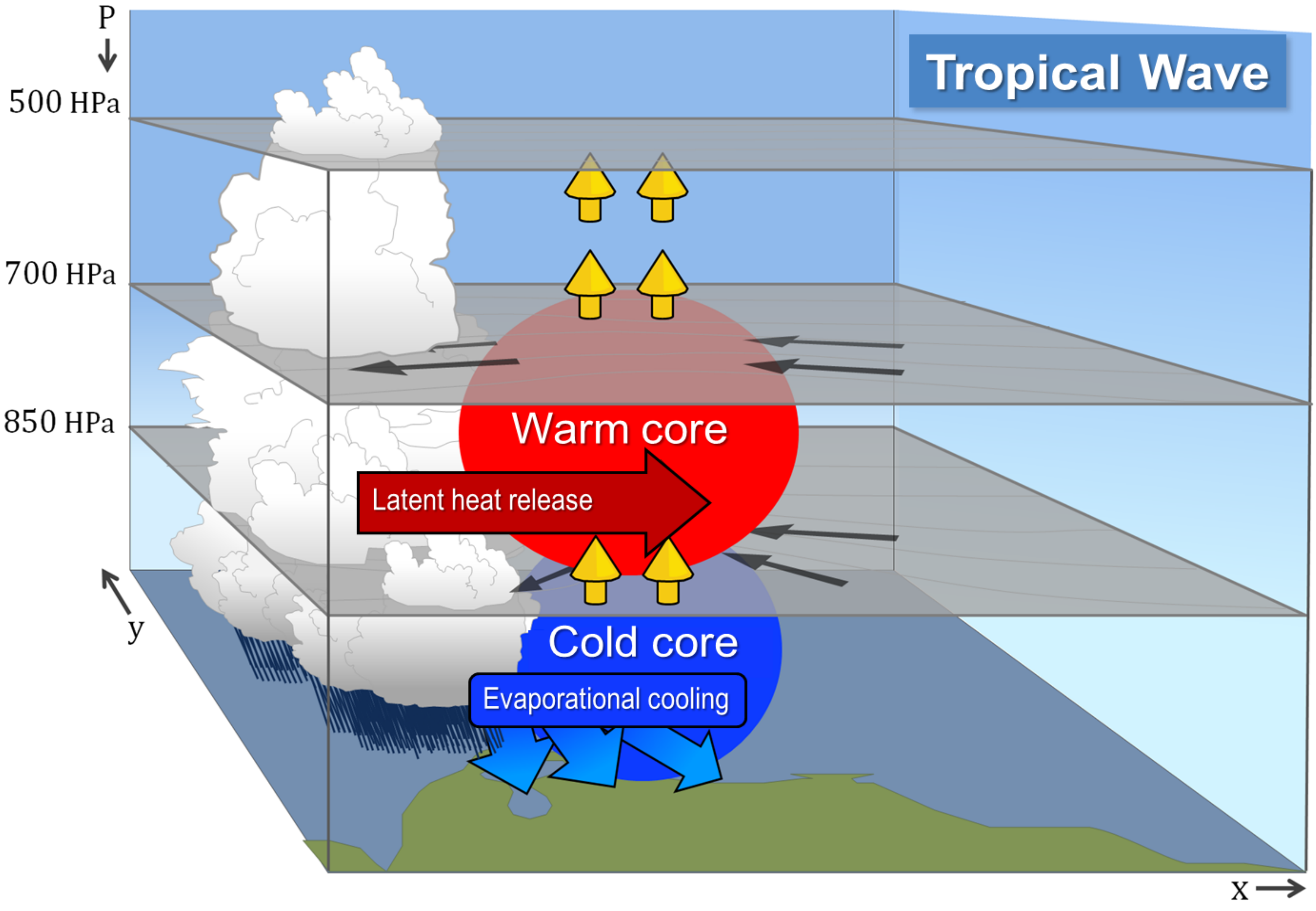
Vertical cross section

Riehl's conceptual model showed a deep layer trough extending from the Surface to 500 hPa.



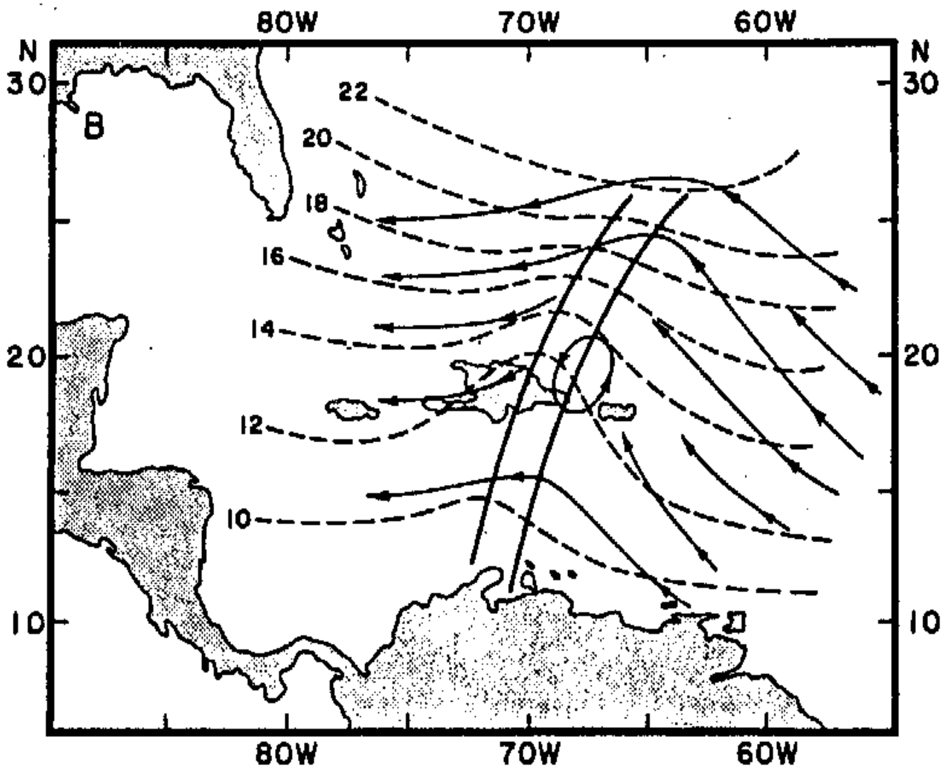
USAFETAC/TN-89/003, The Caribbean Basin, A Climatological Study, December 1989

Tropical Waves: Characteristics

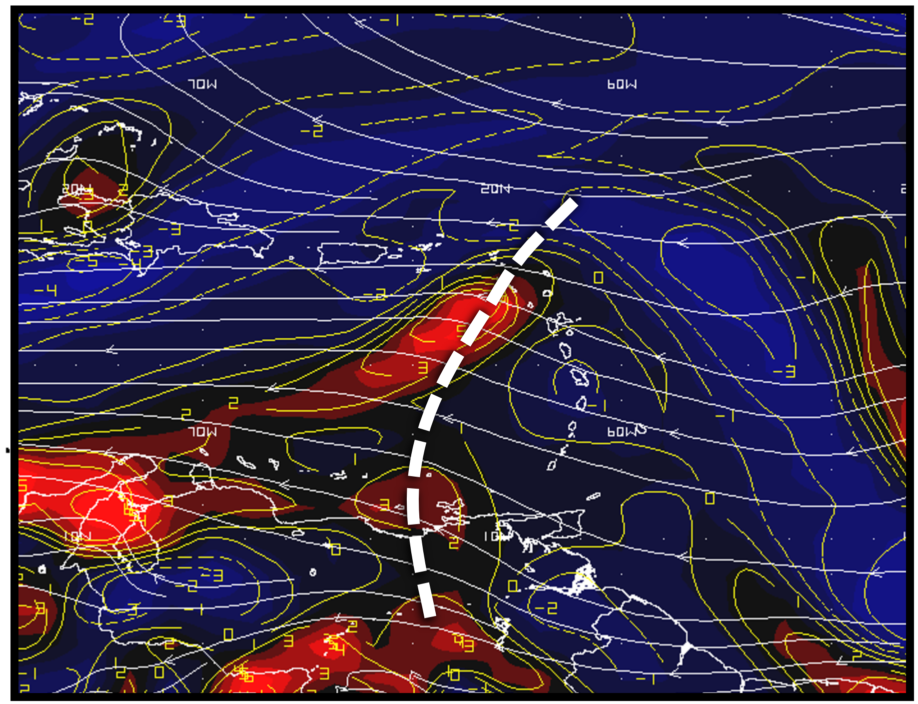


Tropical Waves
Application of the Conceptual Model

Tropical Wave: Horizontal View



Riehl's Conceptual Model

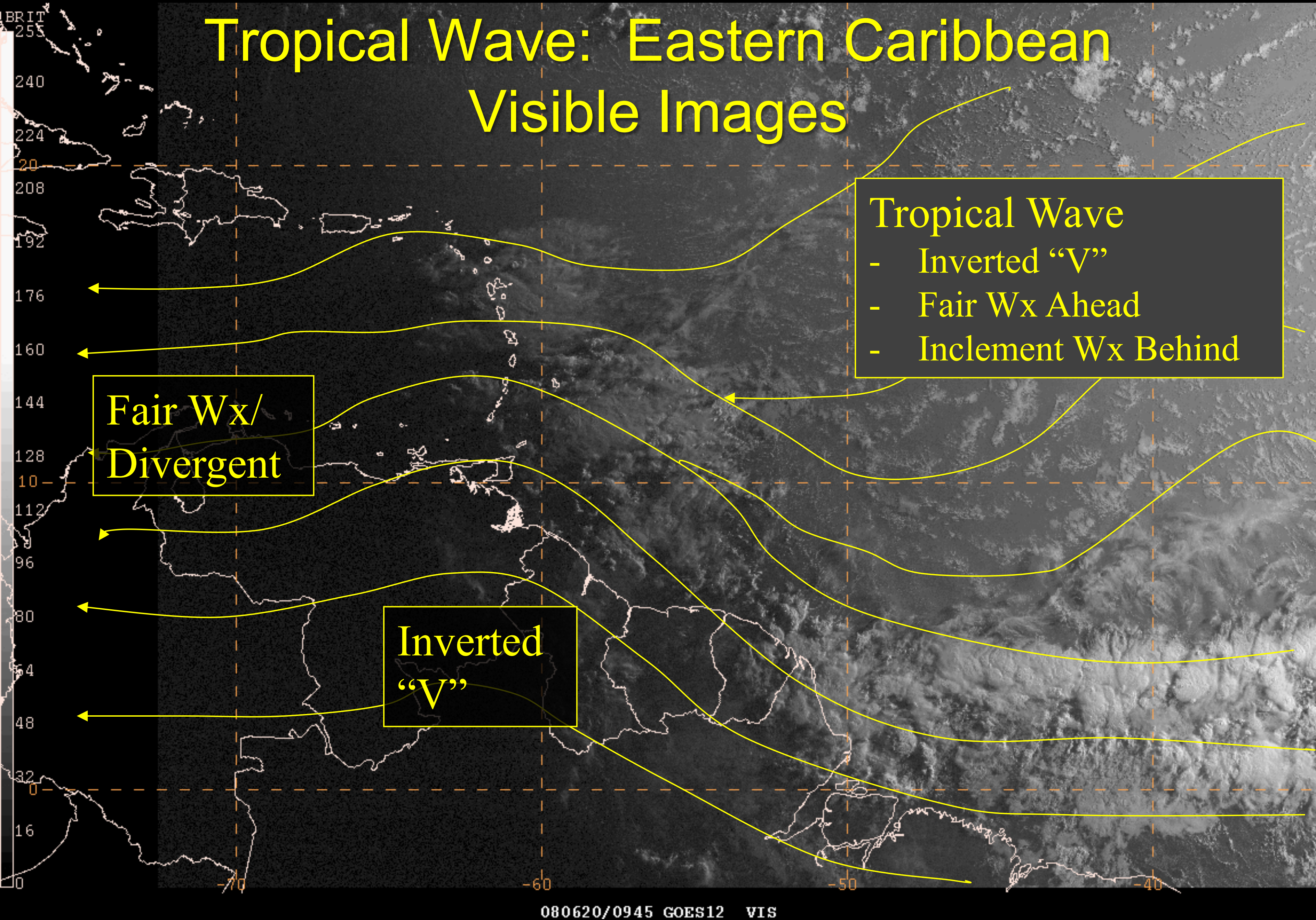


GFS Model (850 hPa)

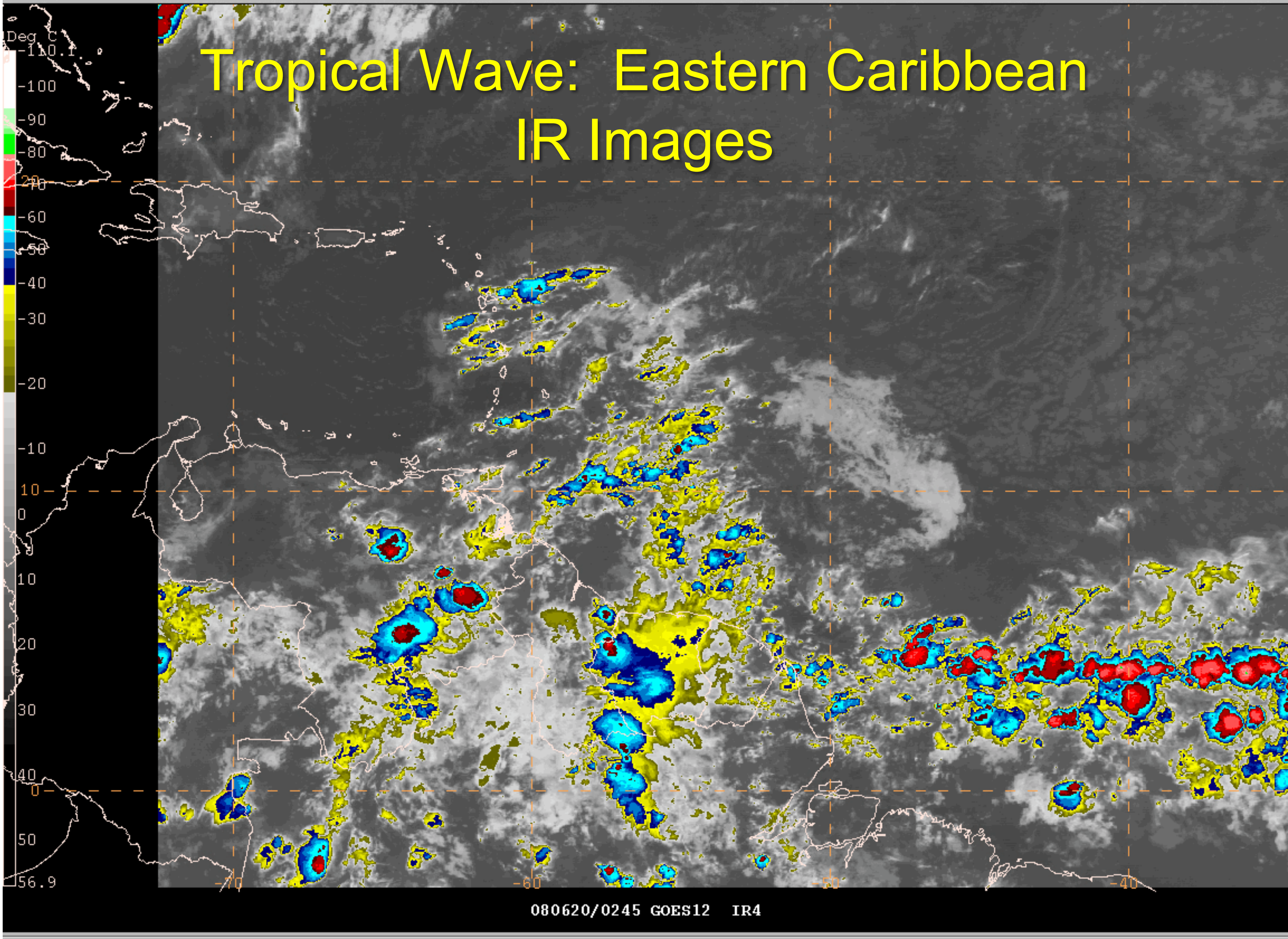
- - - - - Sea level pressure
⟵ Low Level Streamlines

Cyclonic Vort.
AC Vorticity
⟵ Streamlines

Tropical Wave: Eastern Caribbean Visible Images



Tropical Wave: Eastern Caribbean IR Images



Tropical Wave:
Terminology

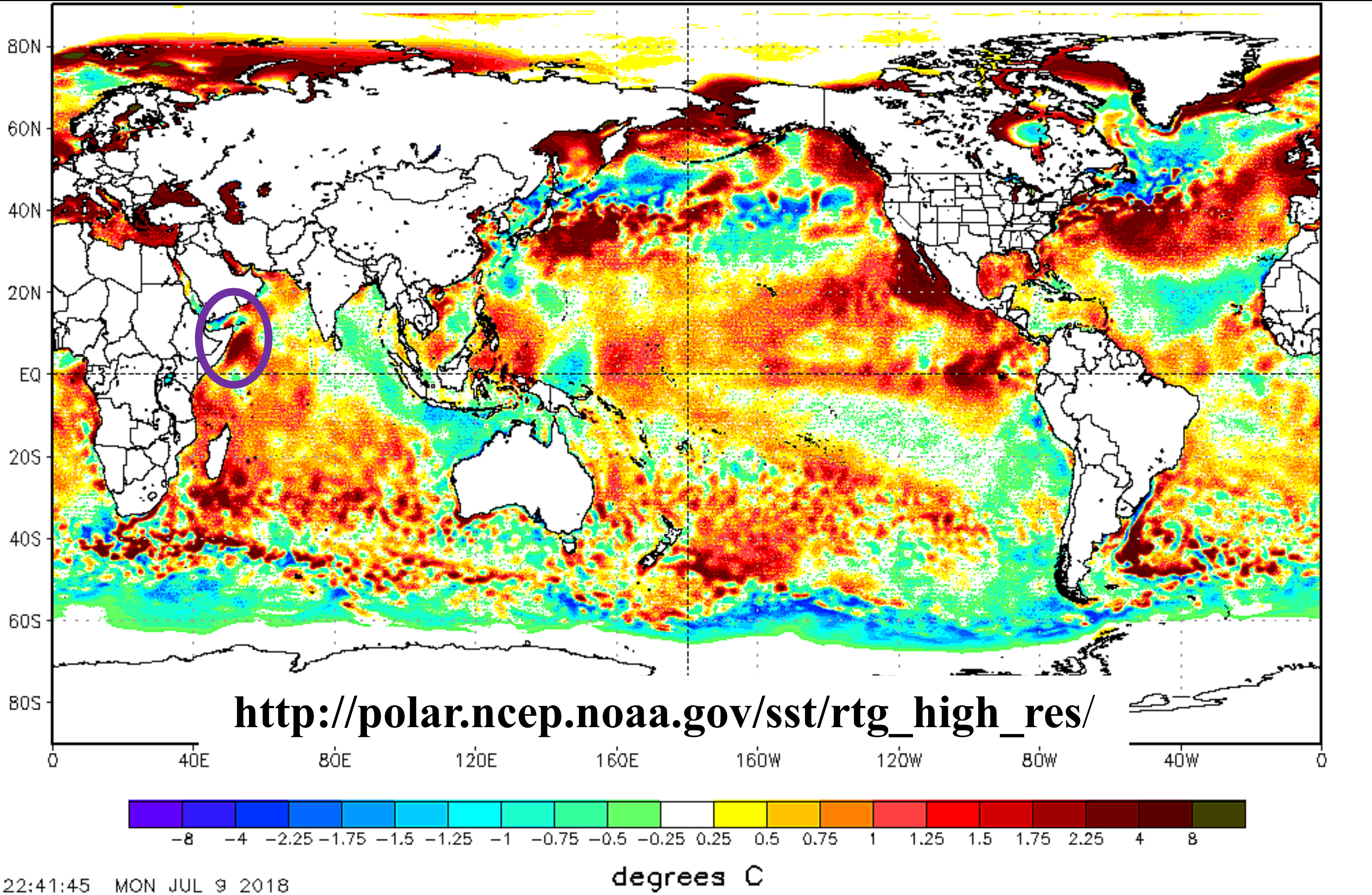
"**Easterly Wave**", conceptual model by Riehl (**1945**) - Synoptic disturbance in tropical easterlies - observations in the Caribbean

African Easterly Wave (*AEW*) – Dominant synoptic-scale wave propagating westward across tropical Africa, tropical Atlantic, Caribbean, and East Pacific in the warm season

Tropical Wave – Since waves in the easterlies may have other origins, the National Hurricane Center defined a **generic term**: "**Tropical Wave** – A trough or cyclonic curvature maximum in the trade wind easterlies or equatorial westerlies. The wave may reach maximum amplitude in the lower middle troposphere, or may be the reflection of an upper-troposphere cold low or equatorial extension of a mid-latitude trough." *(Hurricane Committee Operational Plan)*

African Easterly Waves (AEW)

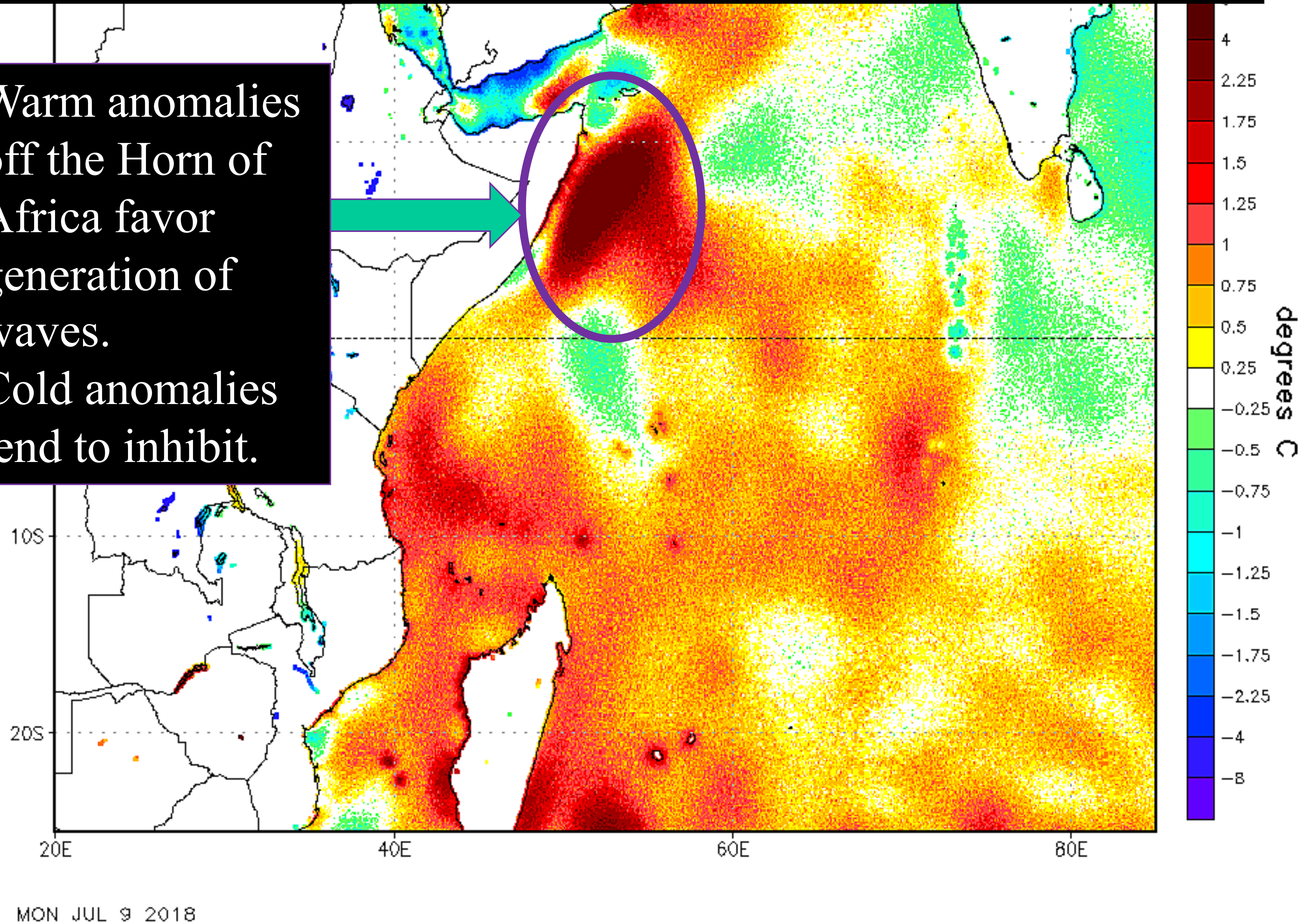
Maritime Influence in the Formation of AEW (Sea Surface Temperature Anomalies)



http://polar.ncep.noaa.gov/sst/rtg_high_res/

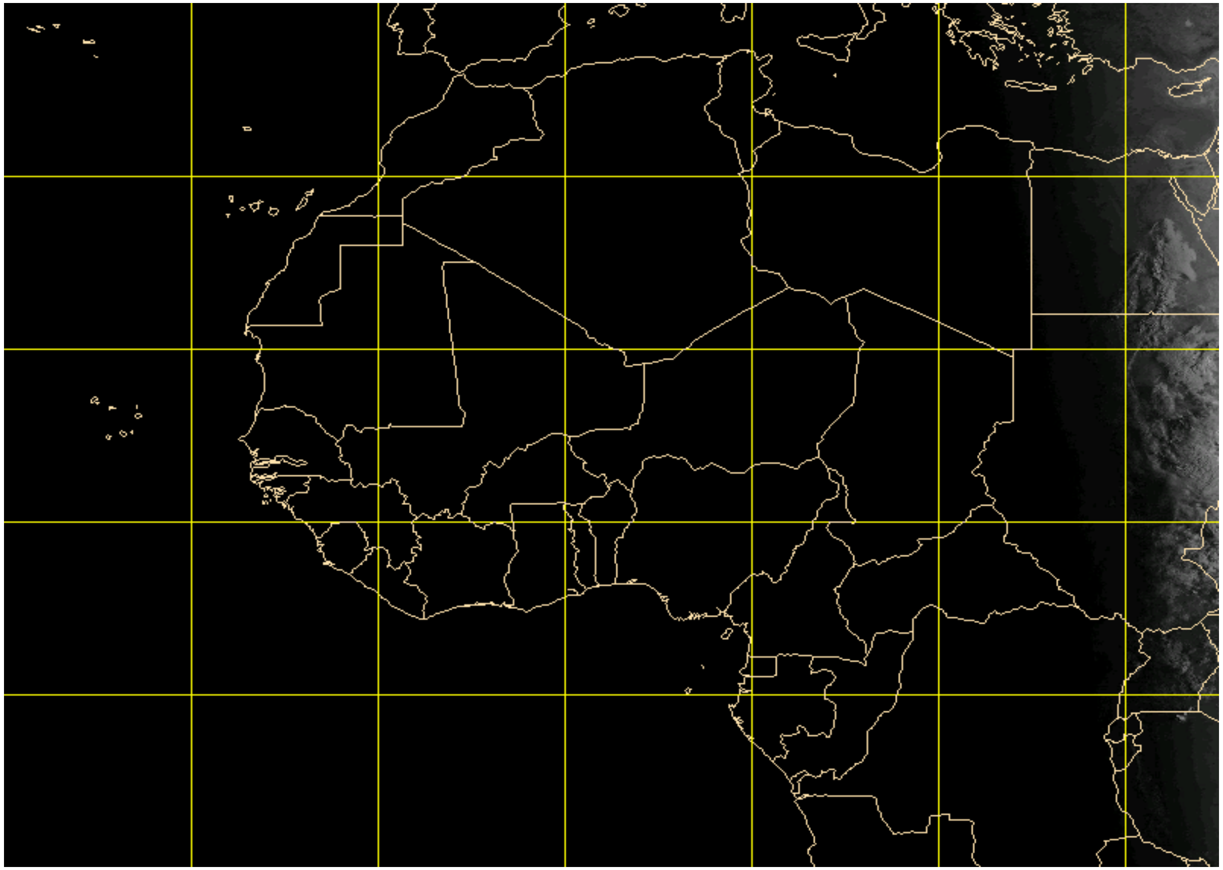
Maritime Influence in the Formation of AEW (Sea Surface Temperature Anomalies)

- Warm anomalies off the Horn of Africa favor generation of waves.
- Cold anomalies tend to inhibit.

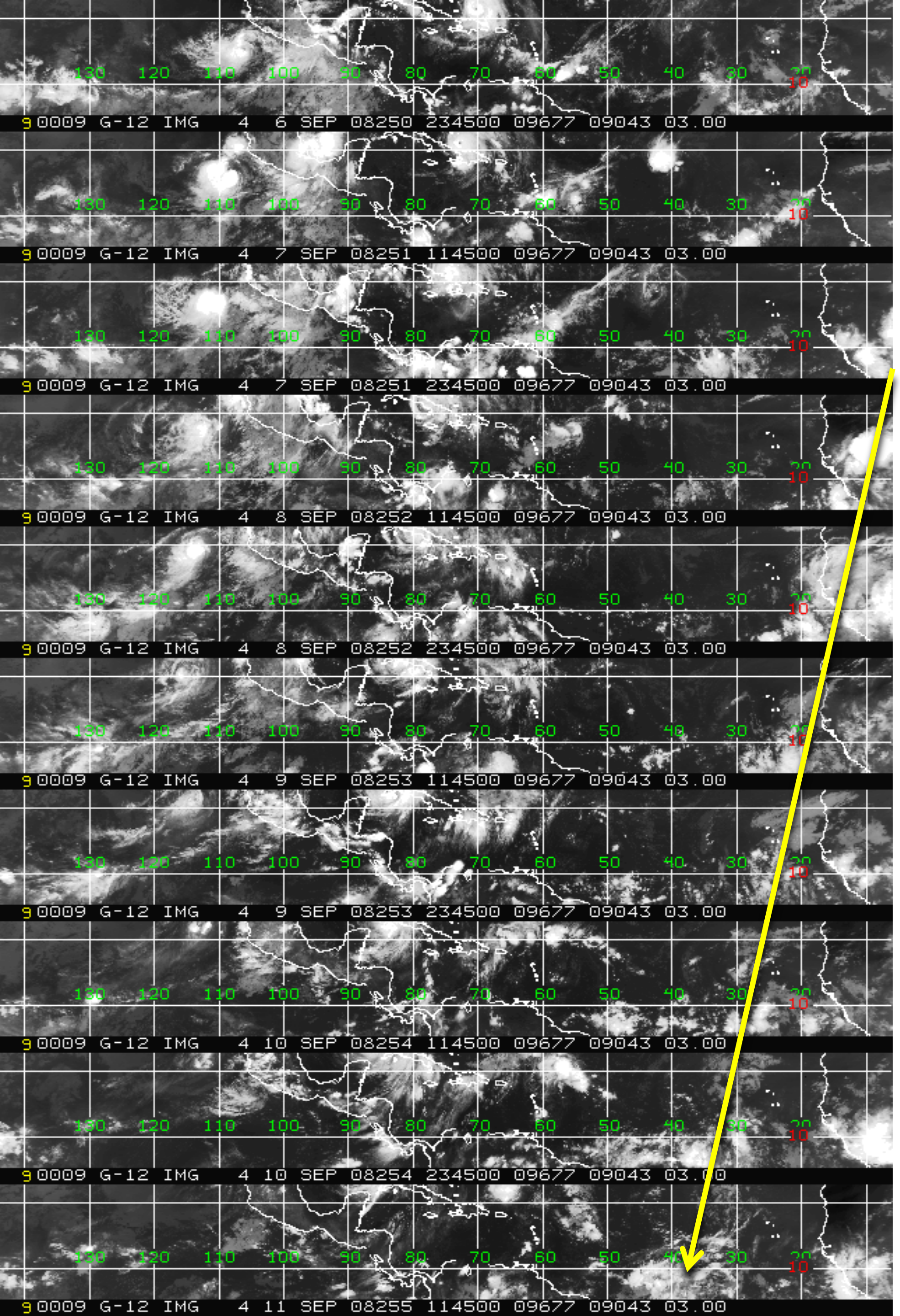


Tropical Wave Origin

Northern Tropical Africa



Hovmöller Diagram

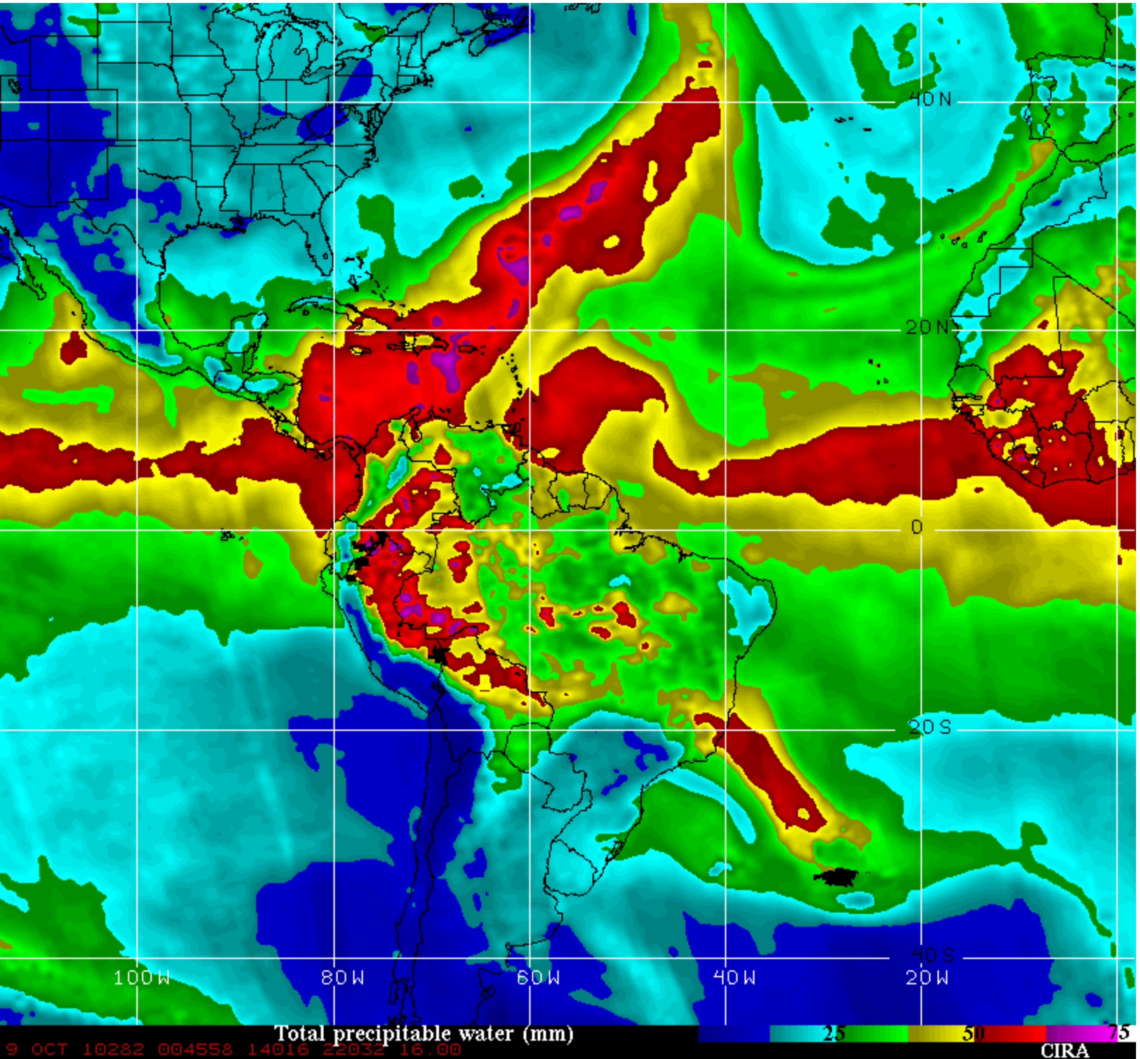


http://www.nhc.noaa.gov/analysis_tools.shtml

The Hovmöller Diagram allows us to determine the origin of an easterly wave, and whether it originated over Africa or if it formed in-situ.

Time

Satellite Derived TPW Analysis



The TPW analysis is another tool we can use to monitor easterly waves, and where they originated.

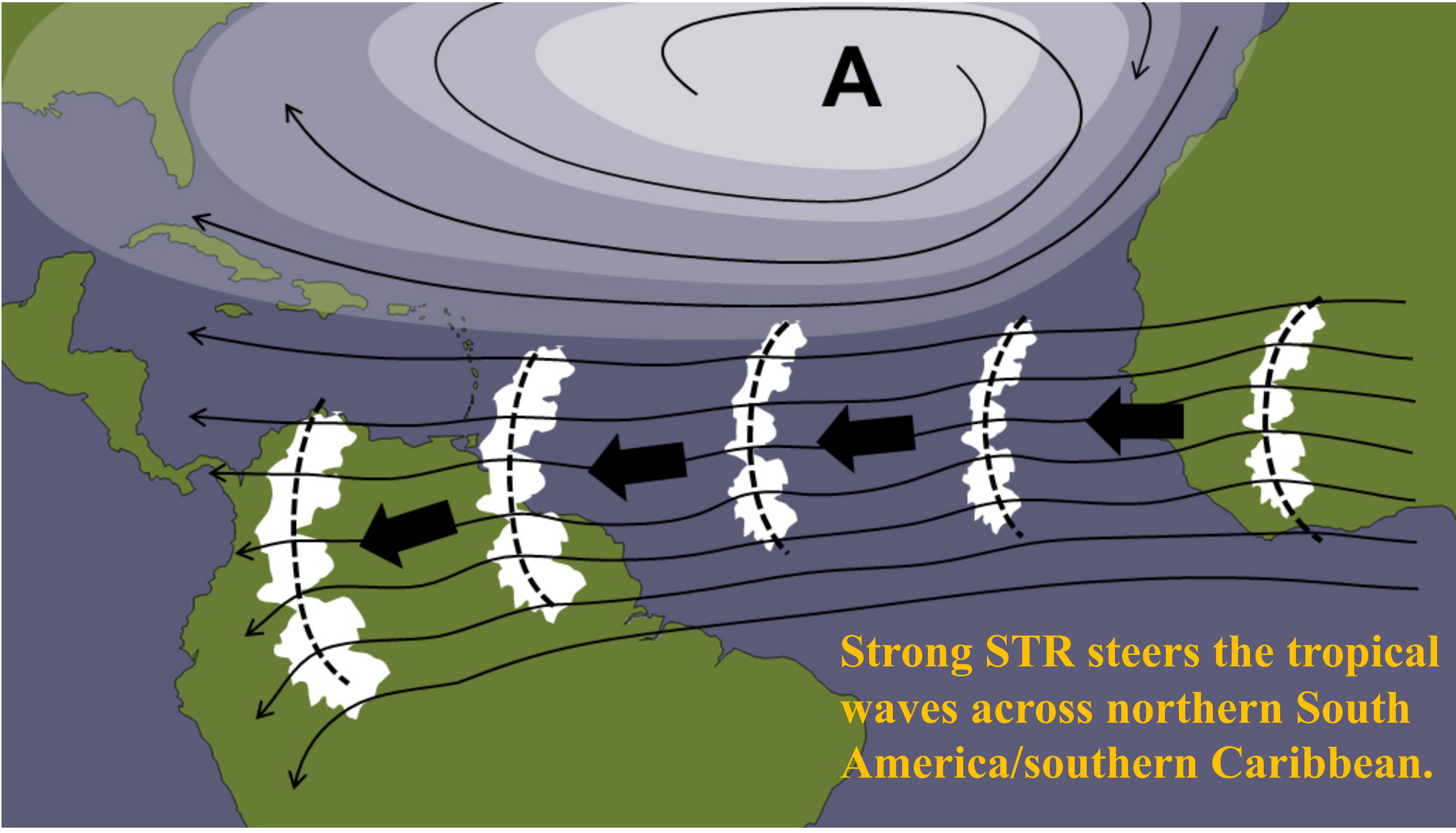
- In this example you can see one exiting Africa as another enters the eastern Caribbean.

Propagation

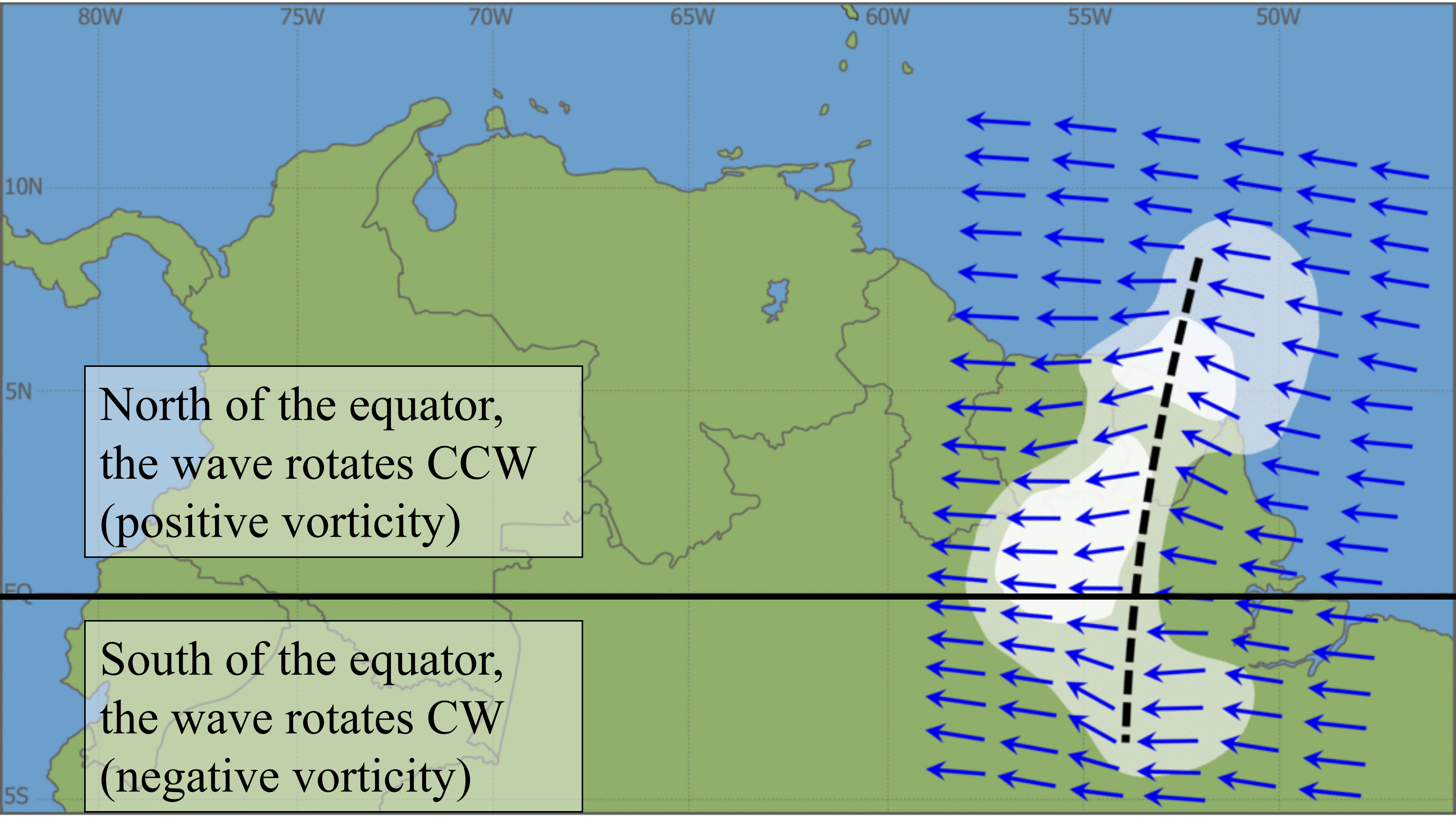
- The track the waves follow, amplitude and speed of propagation across the Atlantic and Caribbean basin are a function of the position/intensity of the subtropical ridge.
- **Strong Ridge**: Lower amplitude wave/faster propagation
- **Weaker Ridge**: Higher amplitude wave/slower propagation

Typical Evolution: April – June

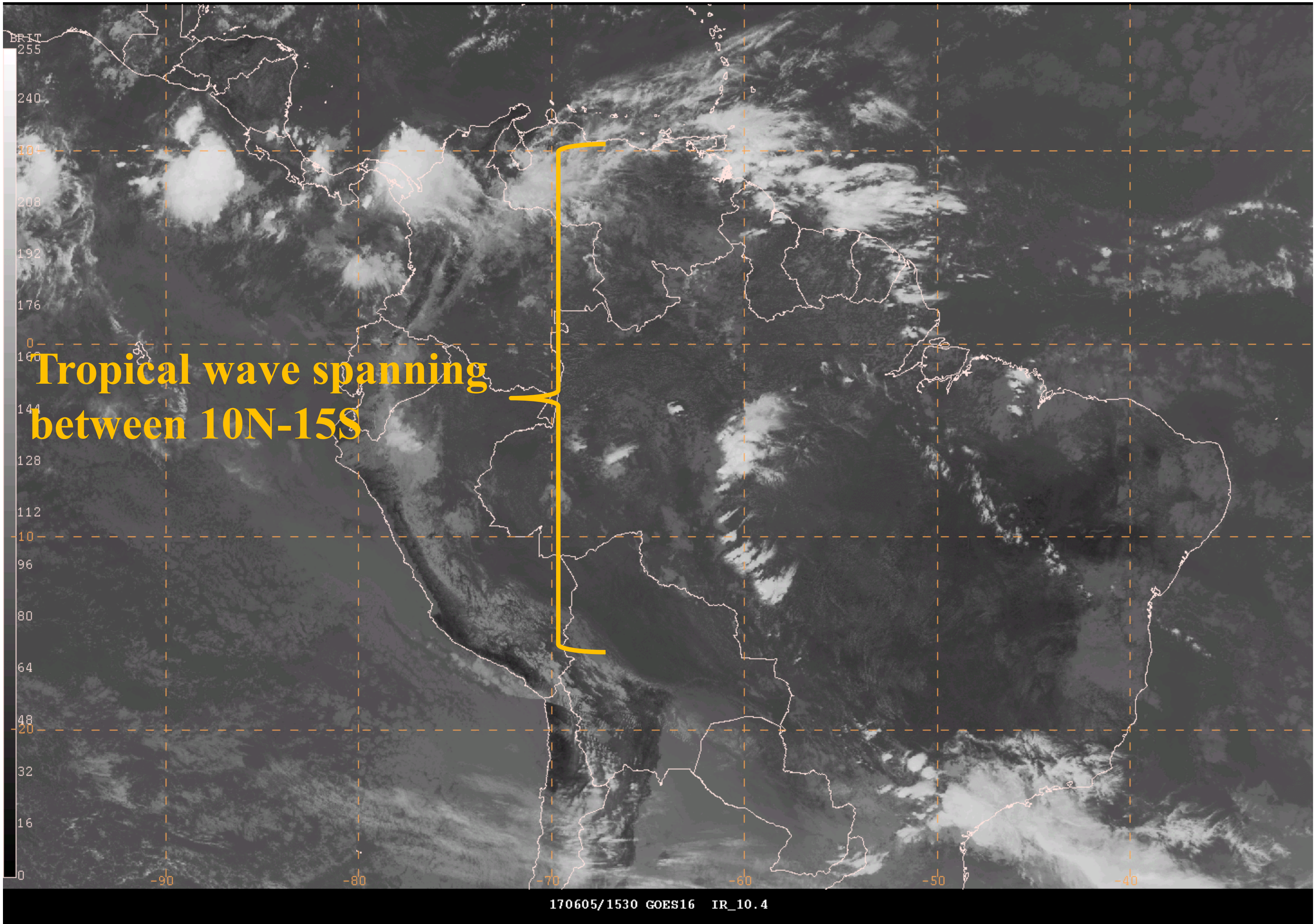
Strong Subtropical Ridge



Wave's Rotation over Equatorial South America

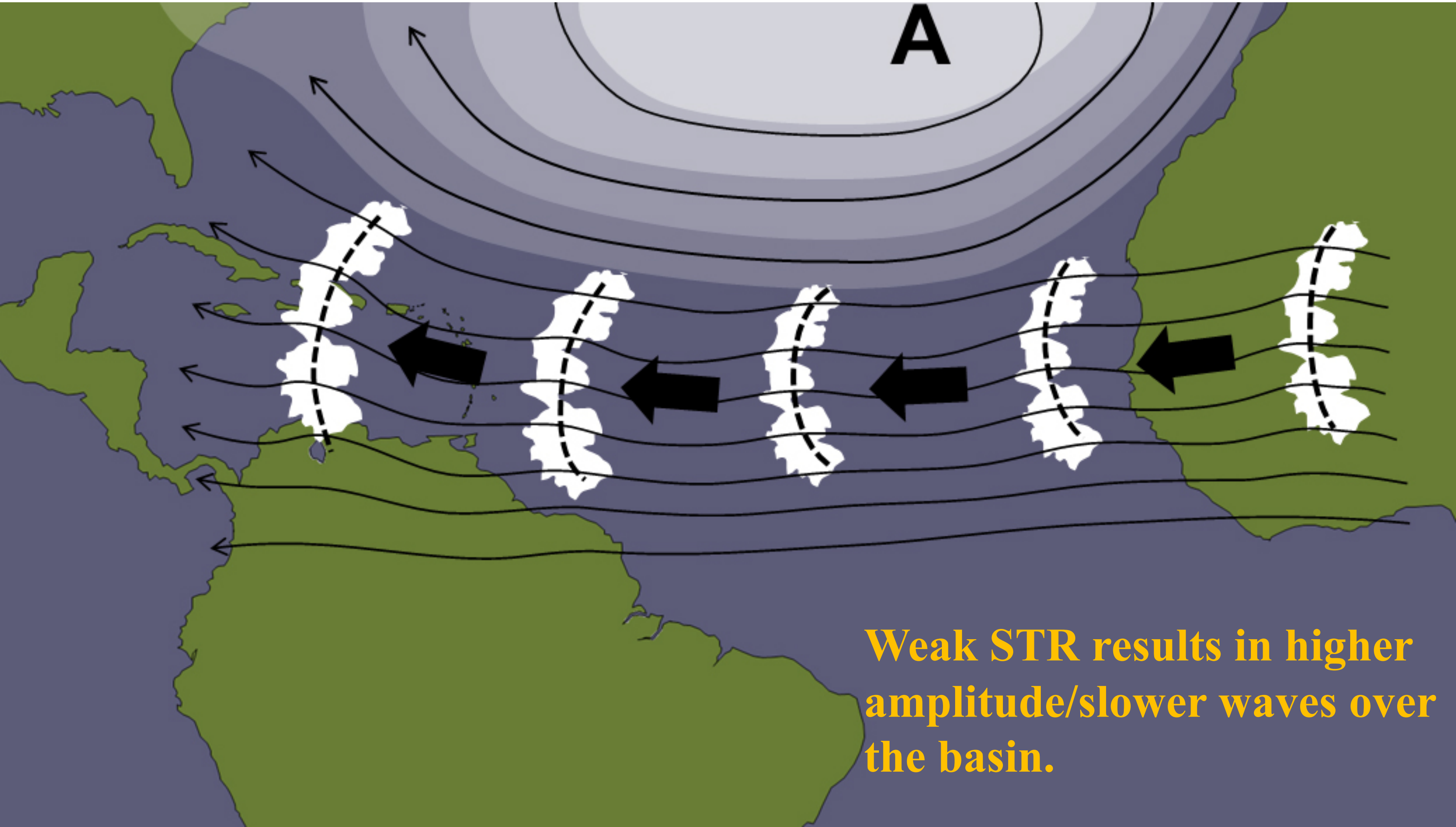


Early Season Tropical Wave



Typical Evolution: July – October

Weak Subtropical Ridge

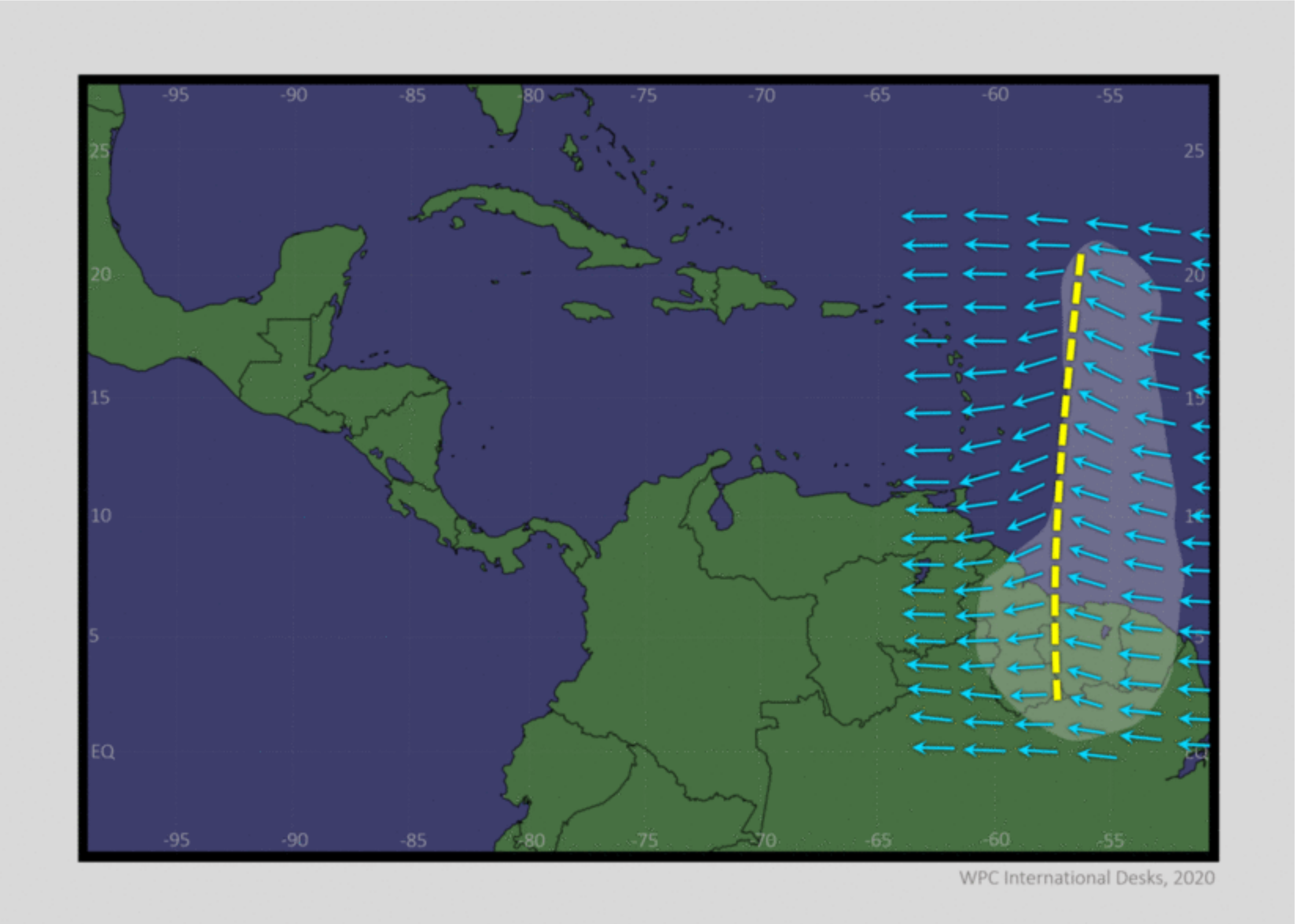


Weak STR results in higher amplitude/slower waves over the basin.

Tropical Wave (Wave Amplitude)

- The amplitude of a Tropical Wave is not constant.
- Interaction with the Subtropical Ridge, terrain over South America and the ITCZ
  - Tropical Atlantic-northern South America
    - 2,000-3,000Km (Synoptic)
  - Central America/Western Caribbean-Mexico
    - 800-1,500Km (Meso-**α)**

Wave Amplitude



Poll Question #1 (Select all that apply)

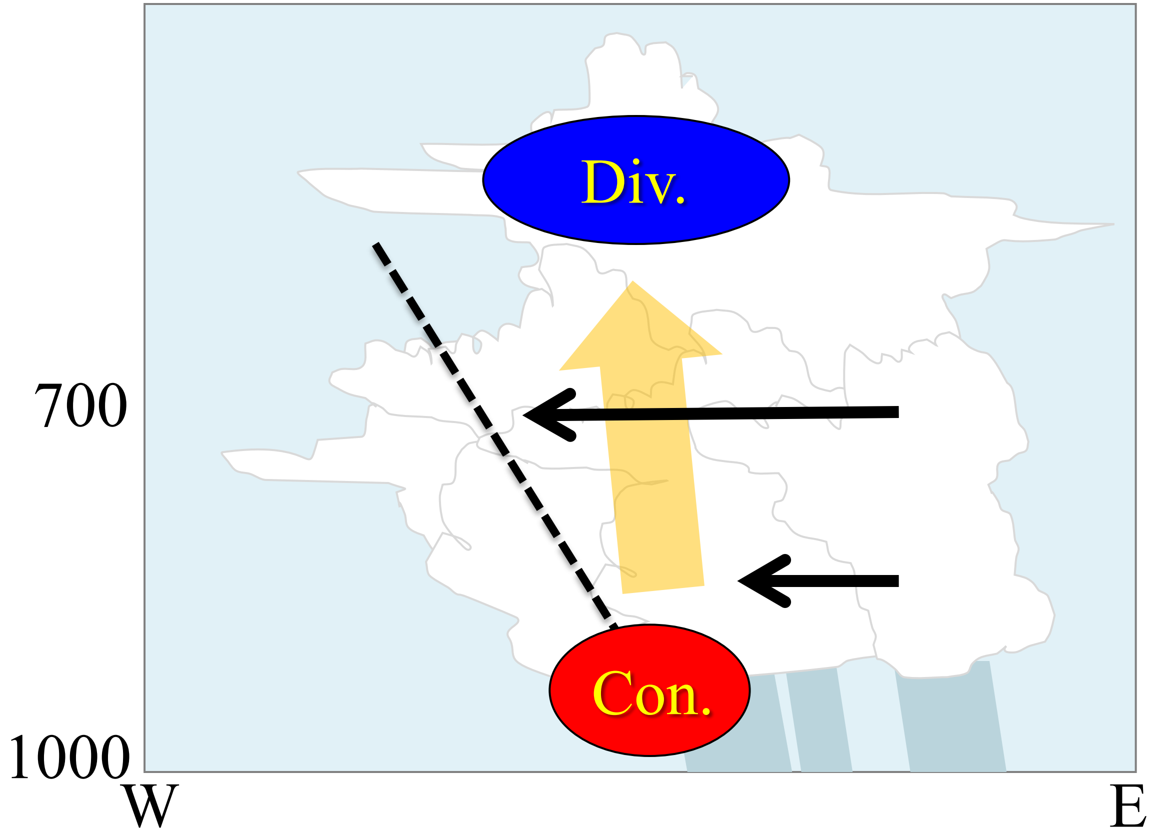
- All easterly waves are tropical waves
- Tropical waves span between the sfc-500 hPa
- Tropical waves confine to lower atmosphere below 700 hPa
- Tropical waves are dual core, cold below 800 hPa/warm above

Positive vs. Negative Tilted Waves

Vertical Structure

Positively Tilted

- The most common type and affect the entire basin.
- Observed when wind speed **<u>increases</u>** with height.
  - 700 hPa winds stronger than 850 hPa winds.



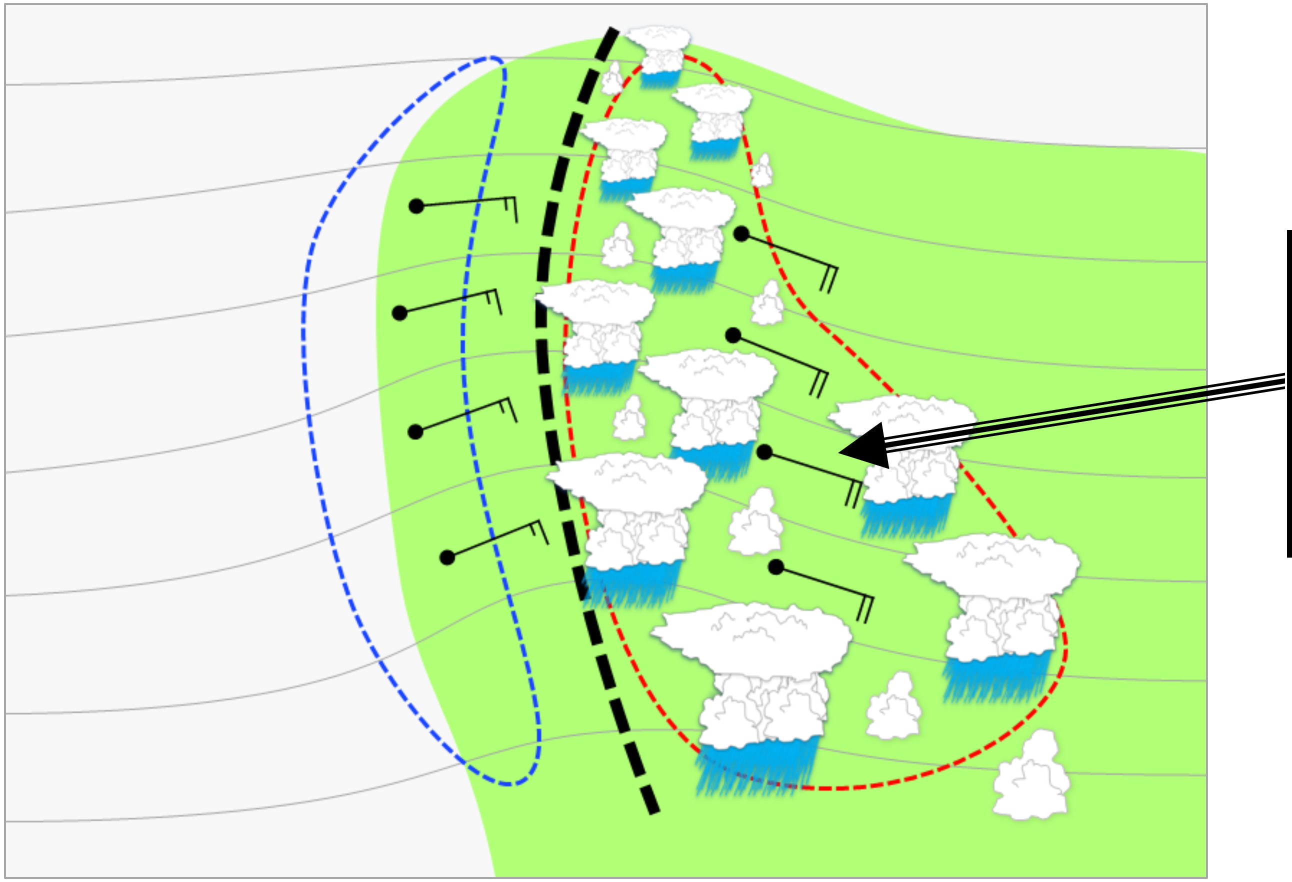
Accordingly, vertical axis tilts westward with height.

Convergence dominates along and behind (***<u>east of</u>***) the wave.

Positively Tilted
Characteristics

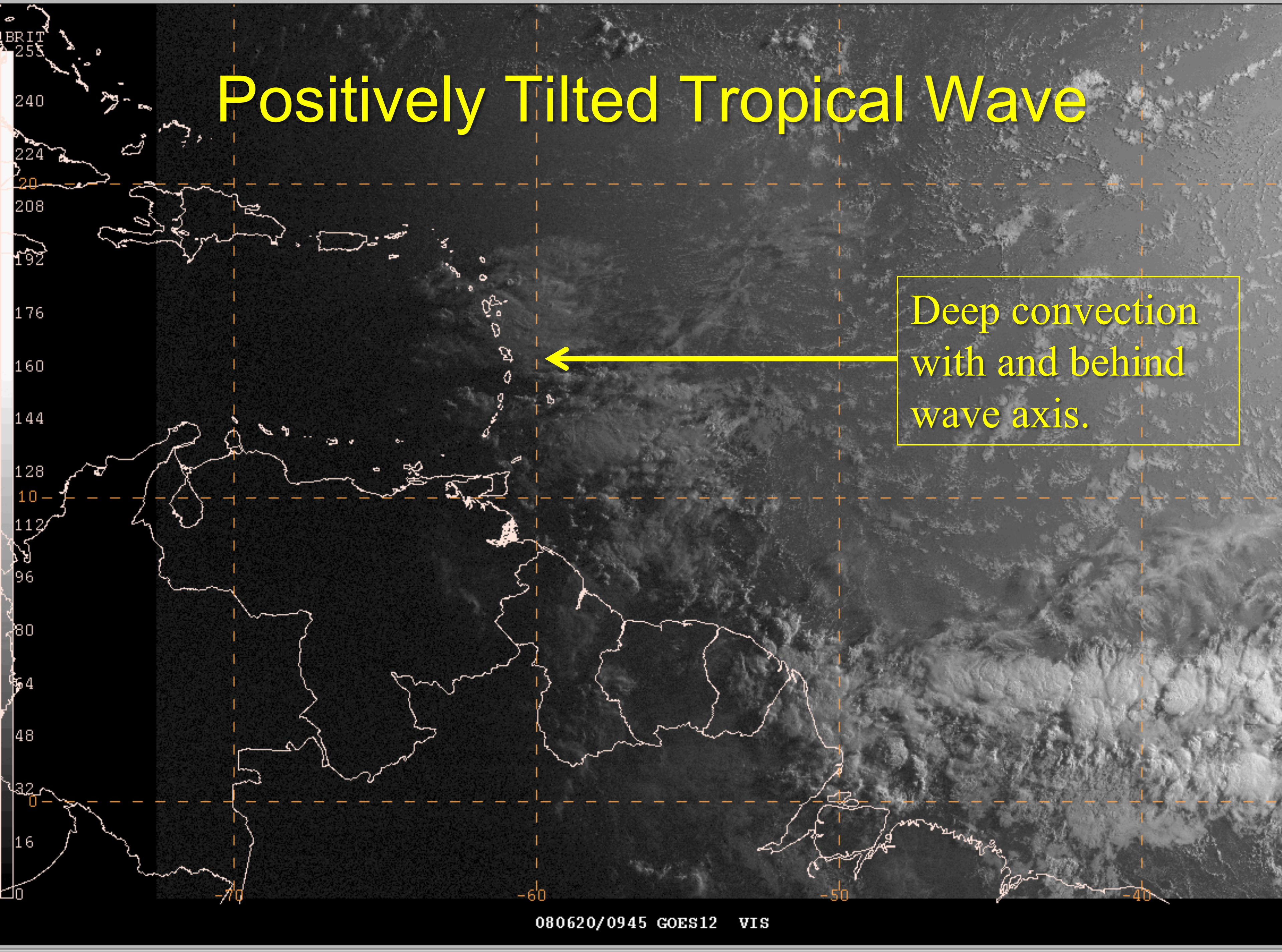
- Propagation speed: 10-15kt
- Fair weather precedes the wave
- Moist convection with and behind the wave
- Moist convection can last 6-9 hours

Positively Tilted
Plan View



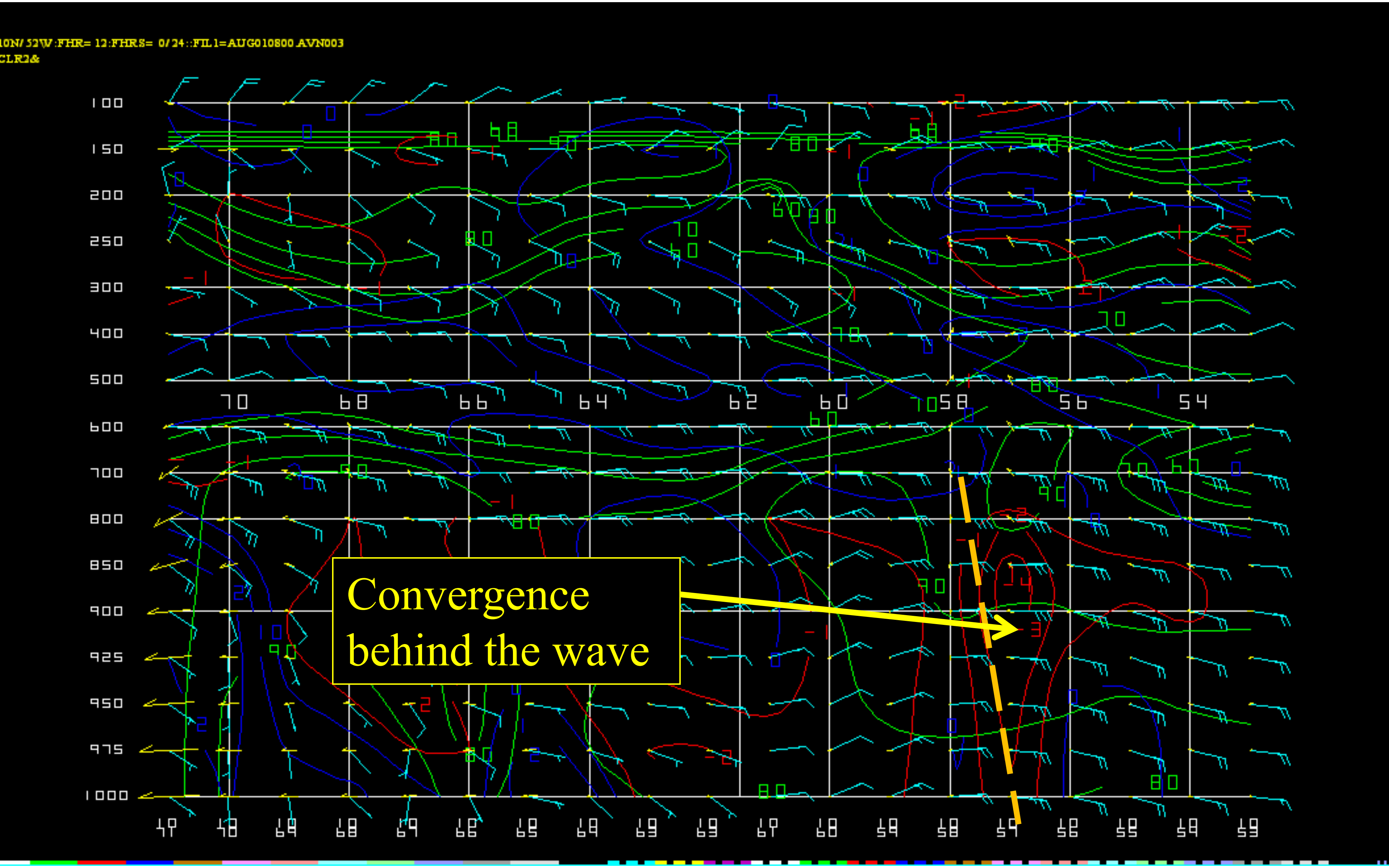
Moist plume and low-level convergence are in phase

Positively Tilted Tropical Wave



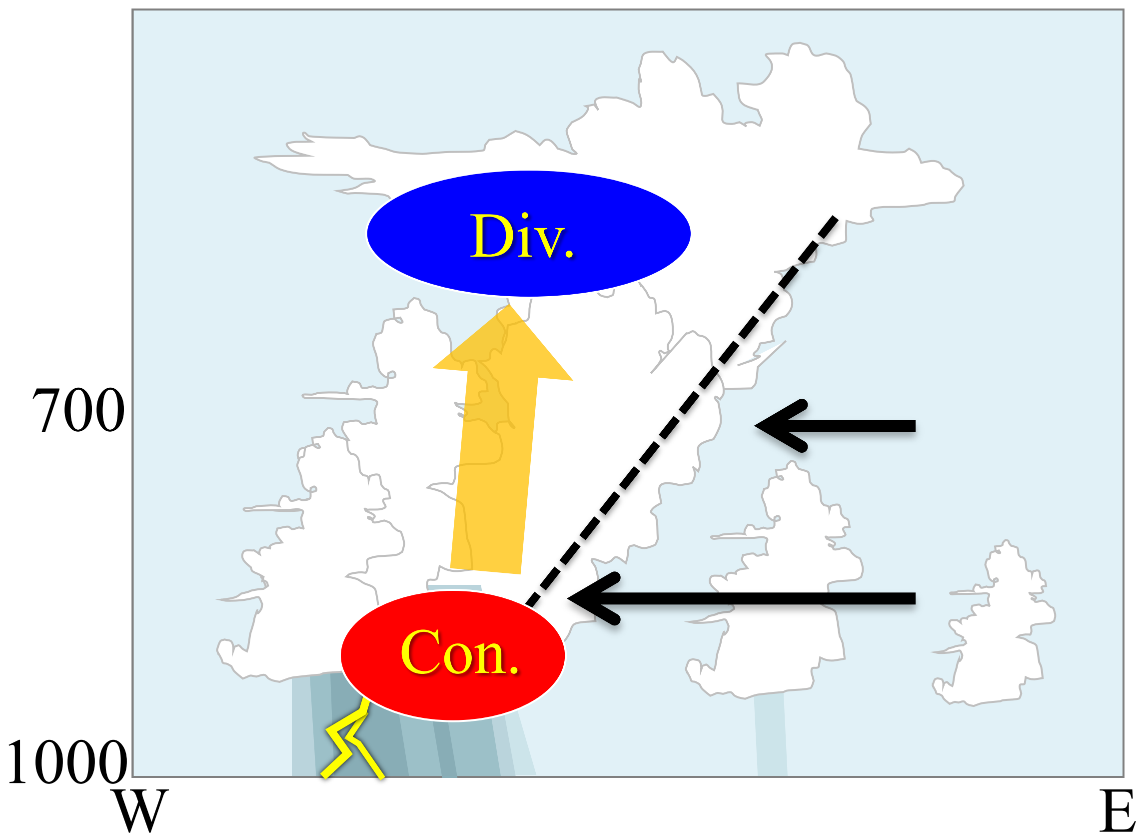
Positive Wave Cross Section (GFS Model)

(Convergence in Red)



Negatively Tilted Wave

- Less common/frequent.
- Mostly in Tropical Atlantic and Eastern Caribbean.
- Observed when wind speed **decreases** with height.
  - 850 hPa winds stronger than at 700 hPa.



Thus, the axis tilts towards the east with height.

Convergence ahead of (***west of***) wave axis.

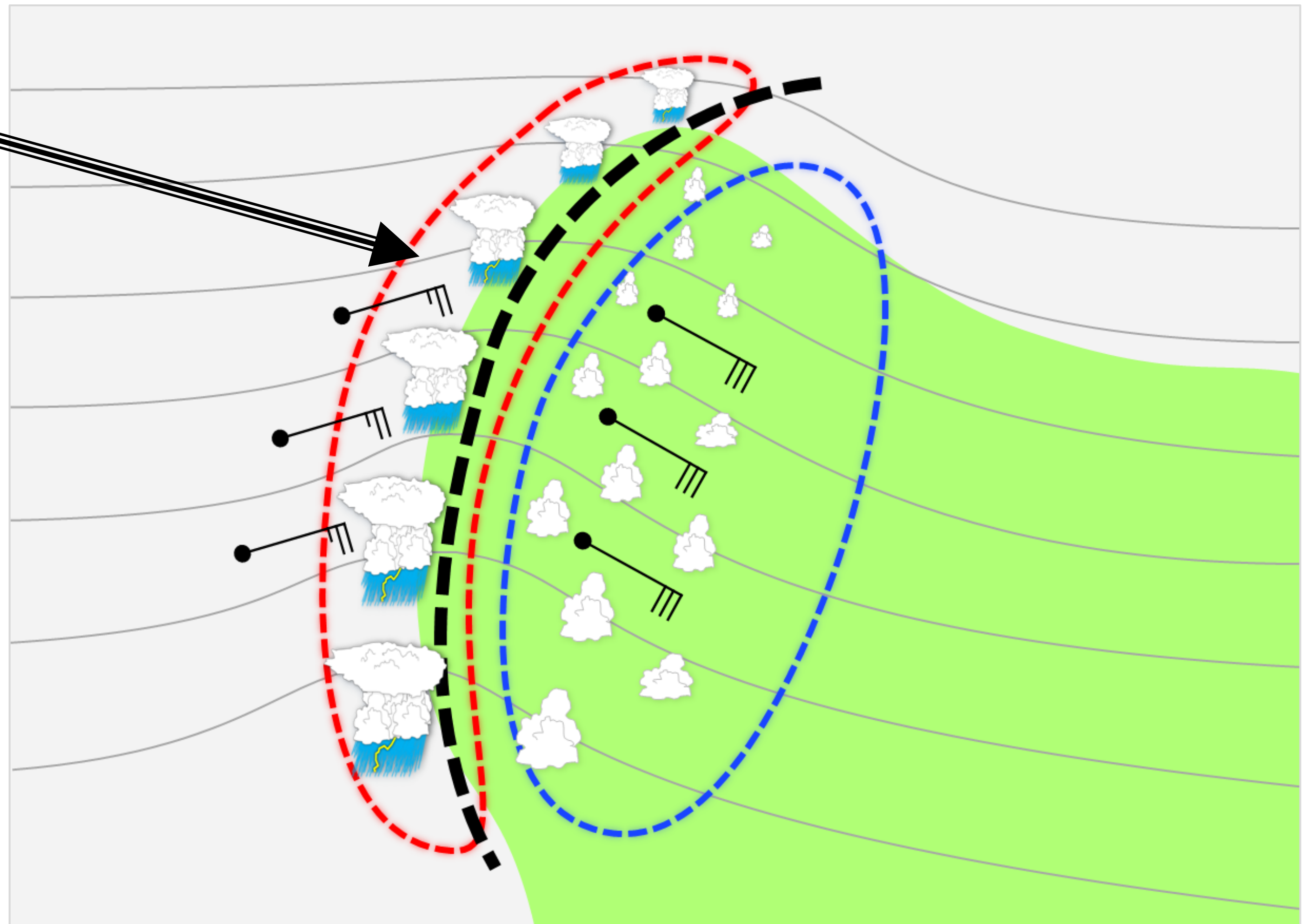
Negatively Tilted
Characteristics

- Active convection ahead of wave axis.
  - Propagation speed: 25-30kt, can induce squall line.
  - Squally Weather
    - Potential for Severe Convection / Waterspouts.
  - Usually more violent/damaging than positive wave.
  - Screaming Eagle cloud signature
- Convection usually lasts 3-6 hours.

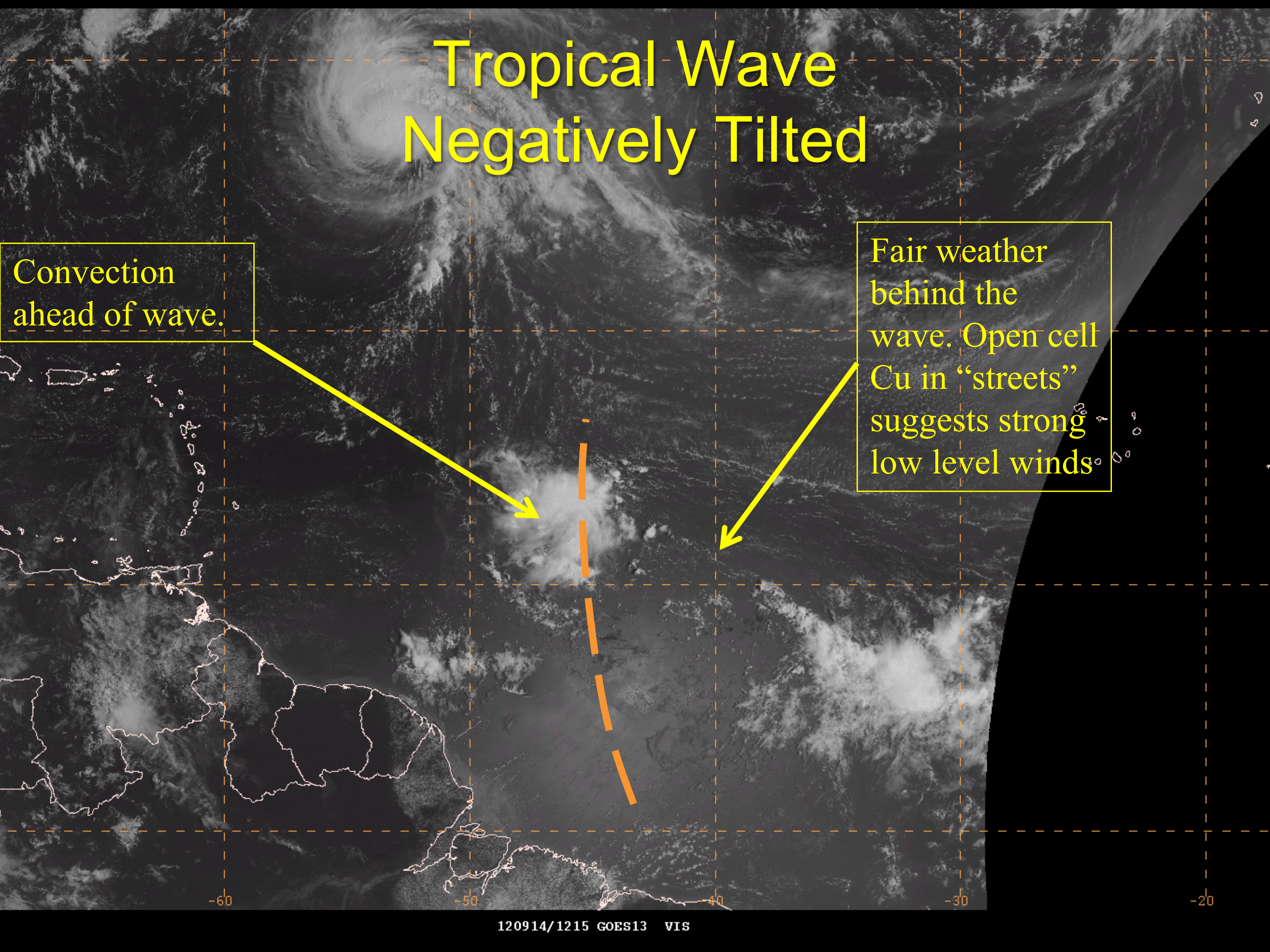
Negatively Tilted

Horizontal View

Moist plume and low level convergence are **<u>NOT</u>** in phase.

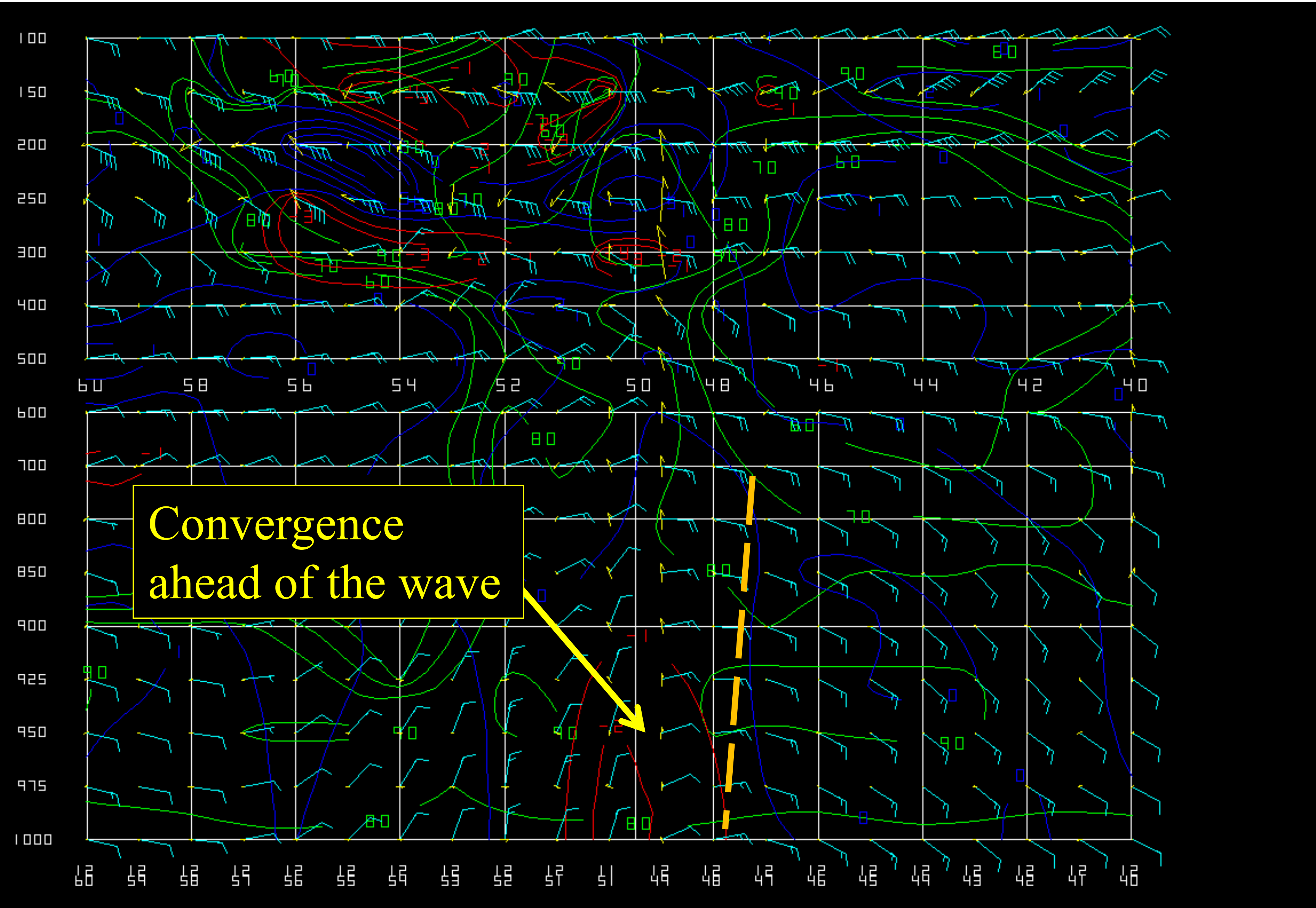


Tropical Wave Negatively Tilted



Negative Wave Cross Section (GFS Model)

(Convergence in Red)



Tropical Waves and the ITCZ

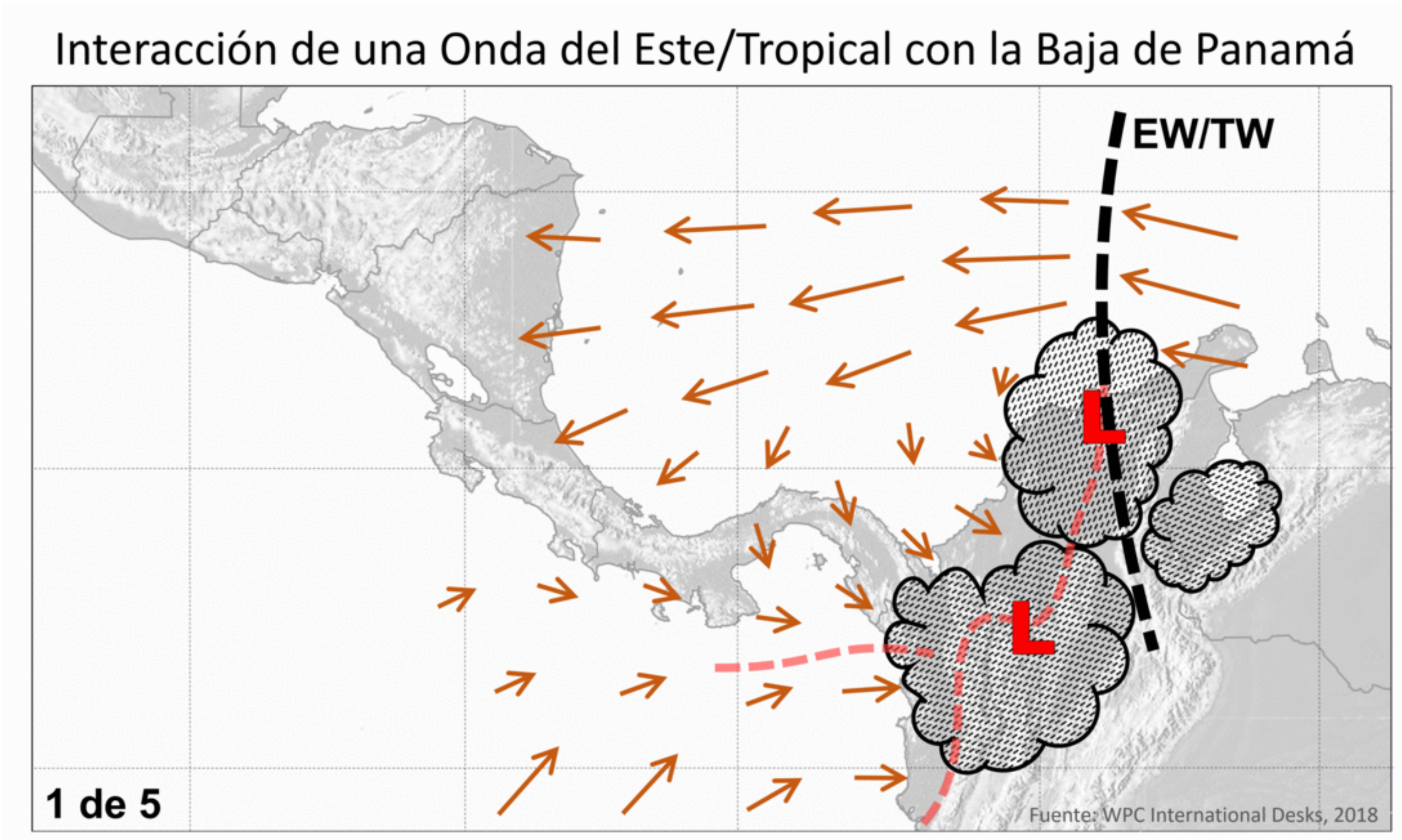
They interact positively with the near equatorial trough/ITCZ

- Enhancement of convection, especially across:
  - Lake Maracaibo
  - Gulf of Urabá
  - Gulf of Honduras
  - Gulf of Fonseca
  - Gulf of Tehuantepec

- Enhancement of the Panamanian Low
  - Gulf of Panama

- Modulation of the ITCZ
  - Strong wave can modulate the ITCZ to the north/south
    - The ITCZ could migrate as much as 3-5 degrees to the north/south of its climatological position following wave passage
    - It can take the ITCZ 2-3 days to return to its climatological position.

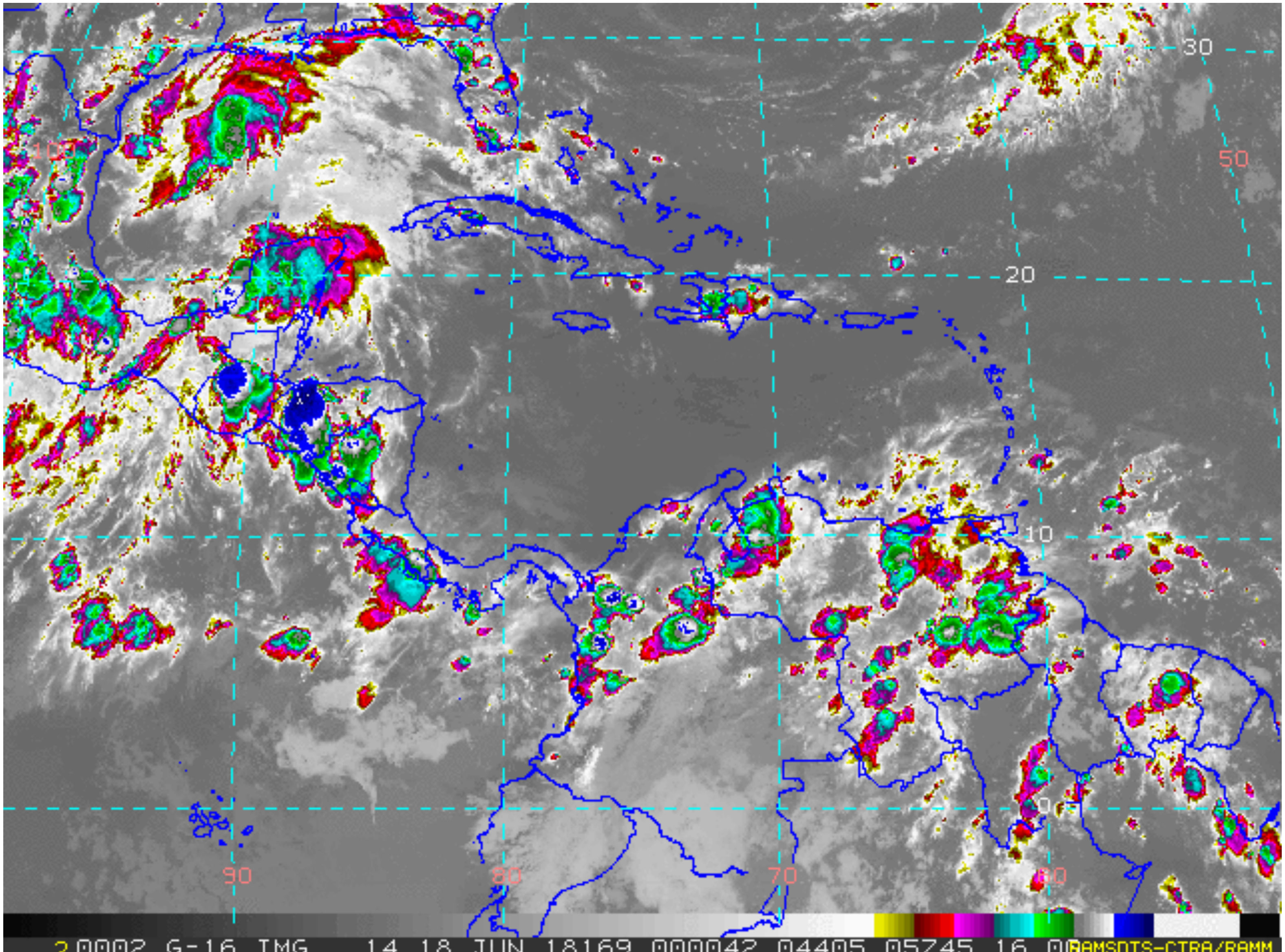
Wave Interaction with the Panamanian Low/Trough



As the wave approaches, the Panamanian low deepens and the convection intensifies.

IR (10.3um): 18-20 June, 2018

Two Waves: One crossing Colombia and the other entering the Eastern Caribbean.



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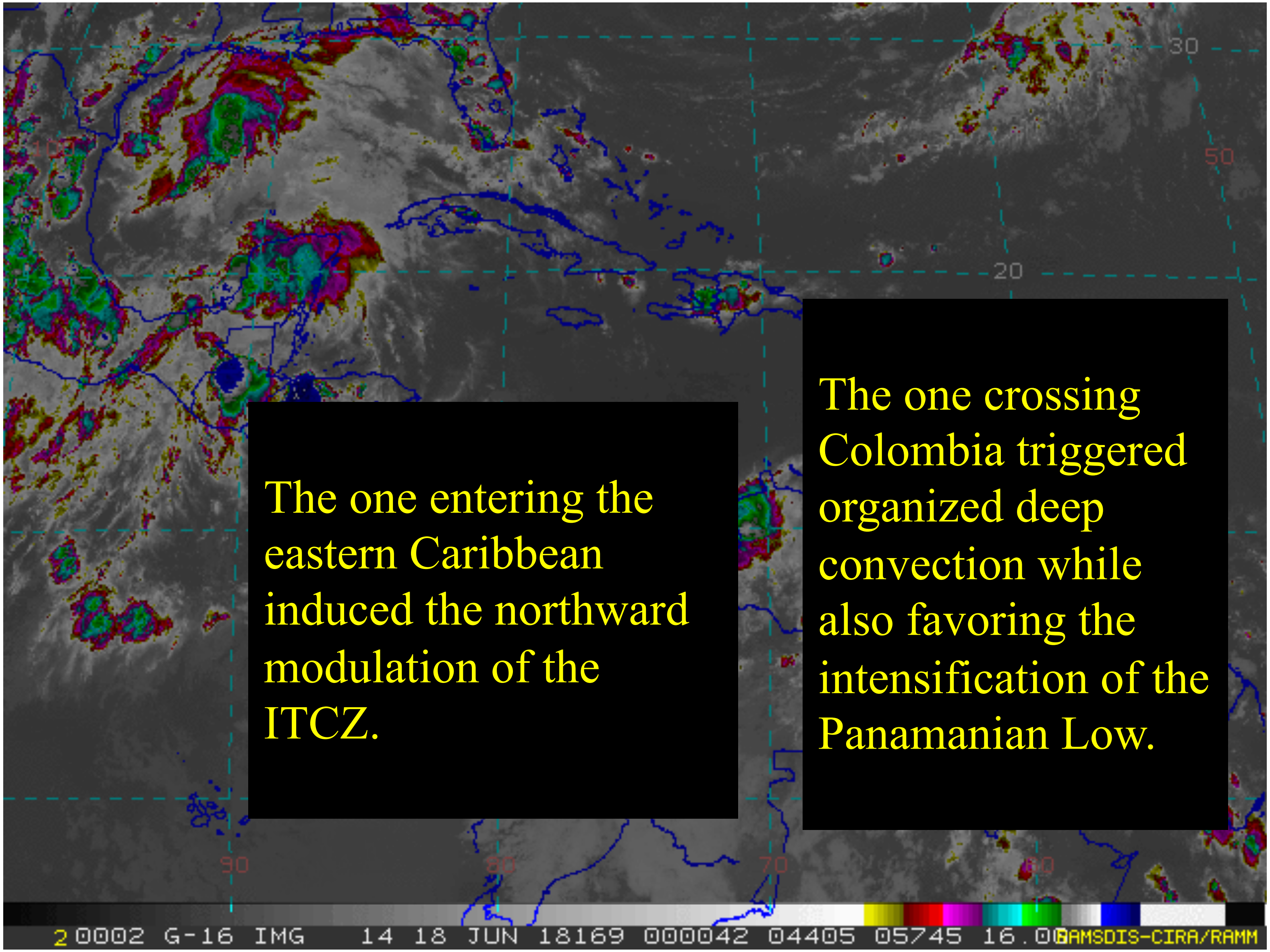


Poll Question #2
(Select all that apply)

Question: **Negatively** tilted waves are typically:

- Slower/weaker than positively tilted
- Convection follows wave passage
- Can sustain squally/severe convection
- Tilts west with height (stronger winds at 700 hPa)
- Tilts east with height (stronger winds at 850 hPa)

Tropical Waves
in Numerical Models

Global Model Limitations: Initialization and Forecast of Tropical Waves

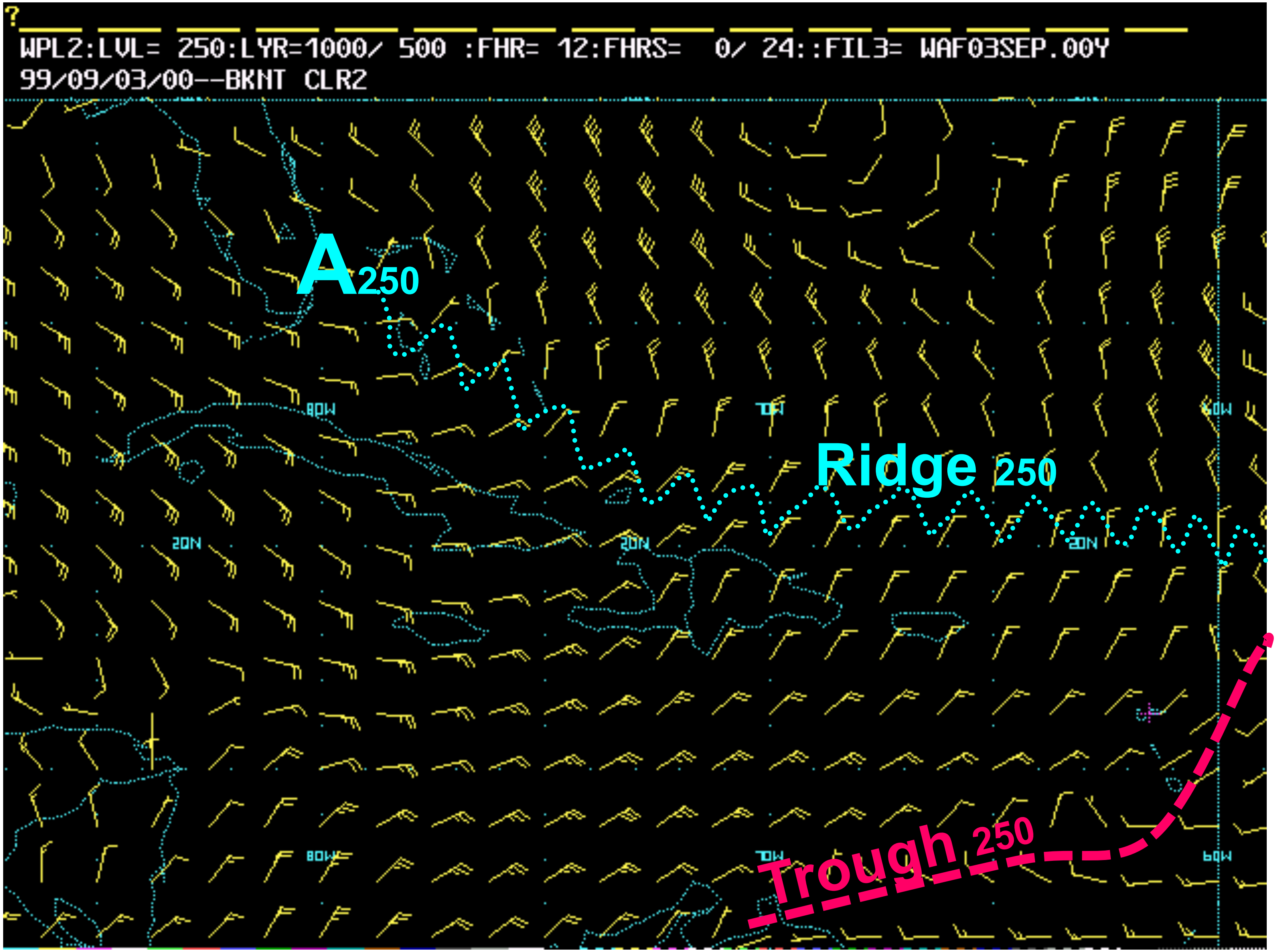
- **Wave Amplitude**: Varies depending on interaction with terrain over South America and the Subtropical Ridge
  - The proper initialization and forecast depend on model resolution and the amplitude of the wave.

- **Problem Area:** Over the central/tropical Atlantic, observations are quite sparse/lacking. More weight given to satellite images and the ***previous forecast***.
  - Due to lack of data, spurious perturbations are sometimes initialized.
    - Once a spurious perturbation is initialized by the models, it can take several model cycles/runs before it gets filtered out.

Numerical Modeling of A Tropical Wave

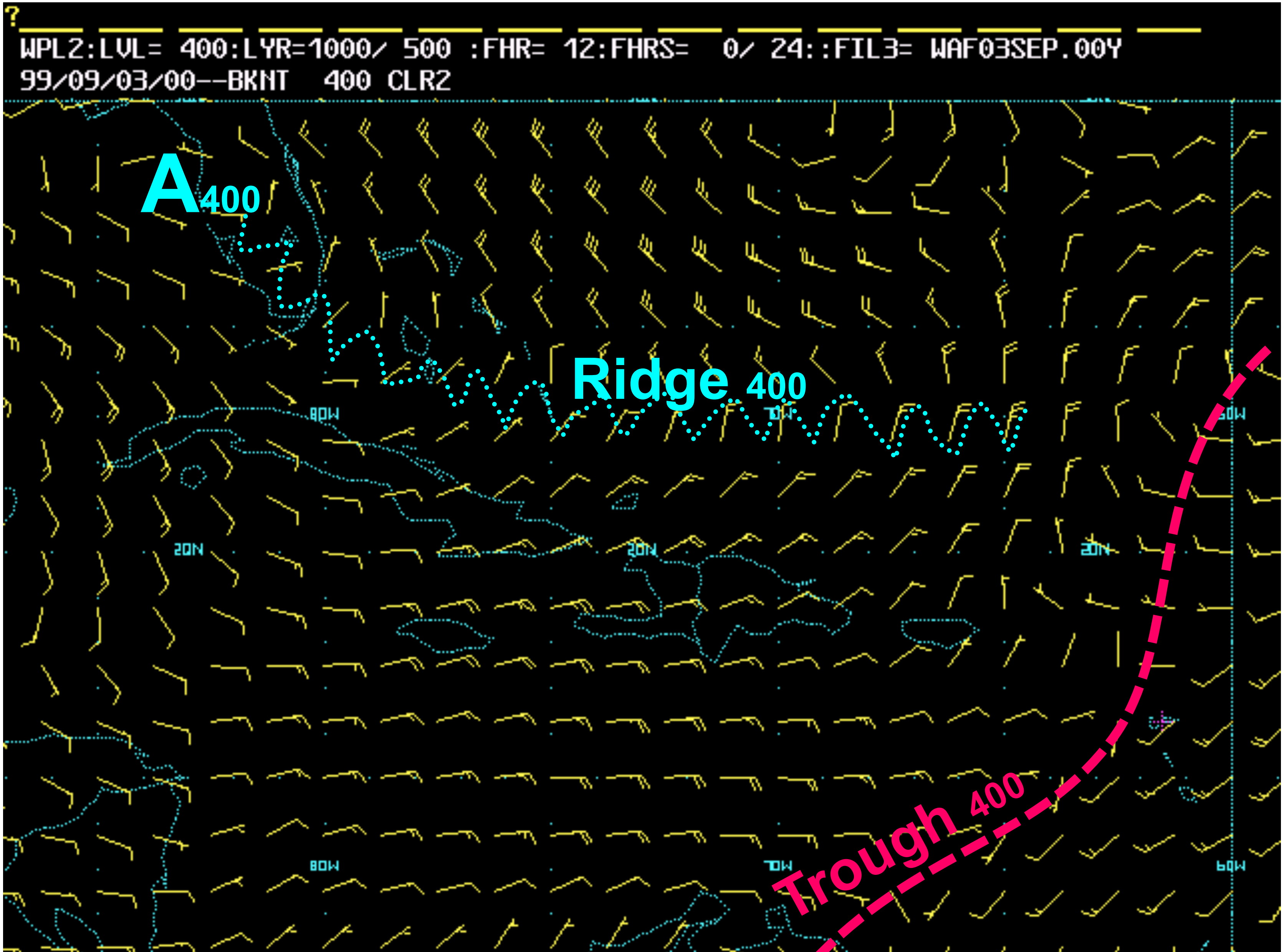
250 hPa Winds

(The wave is not evident)

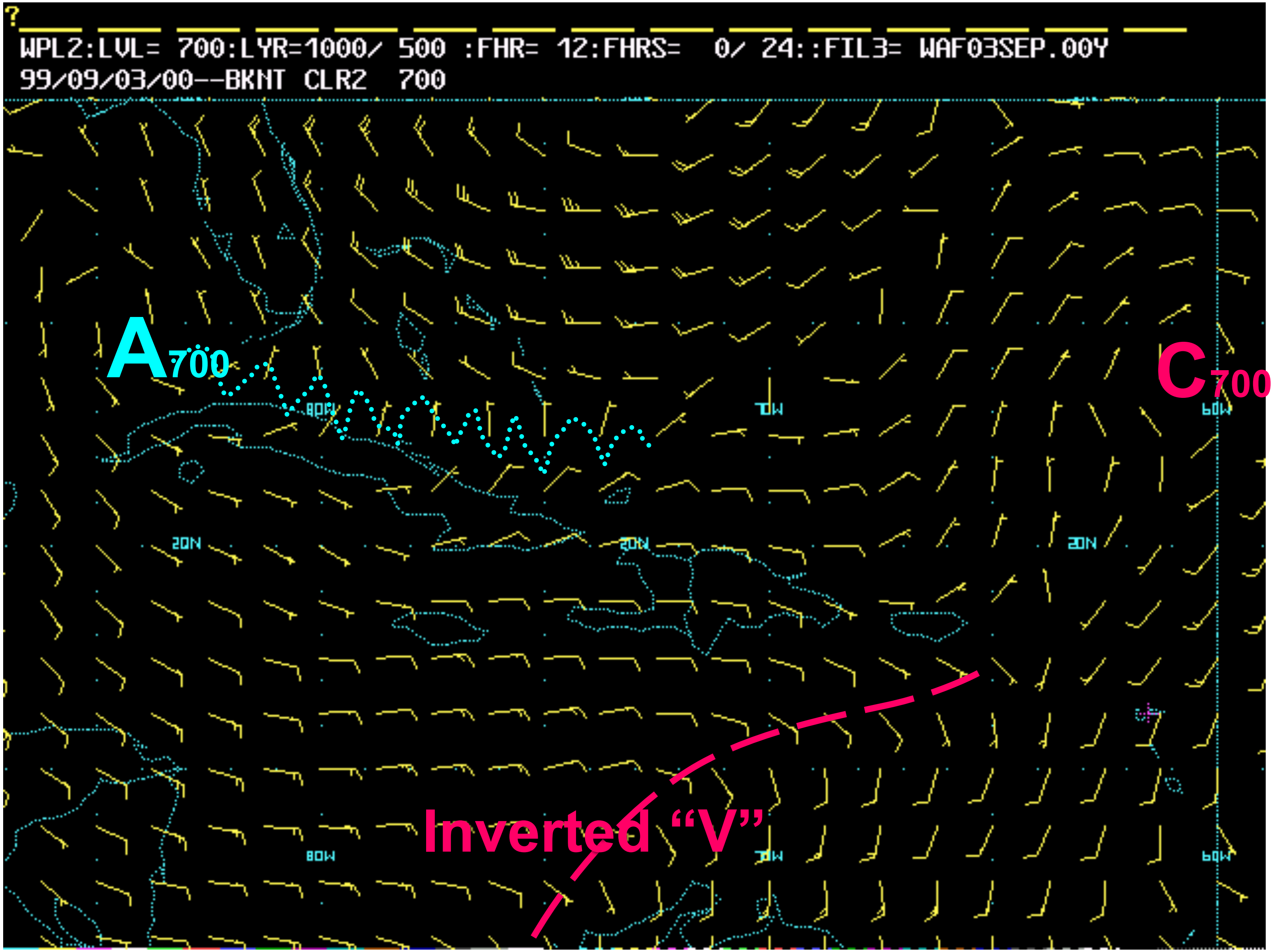


400 hPa Winds

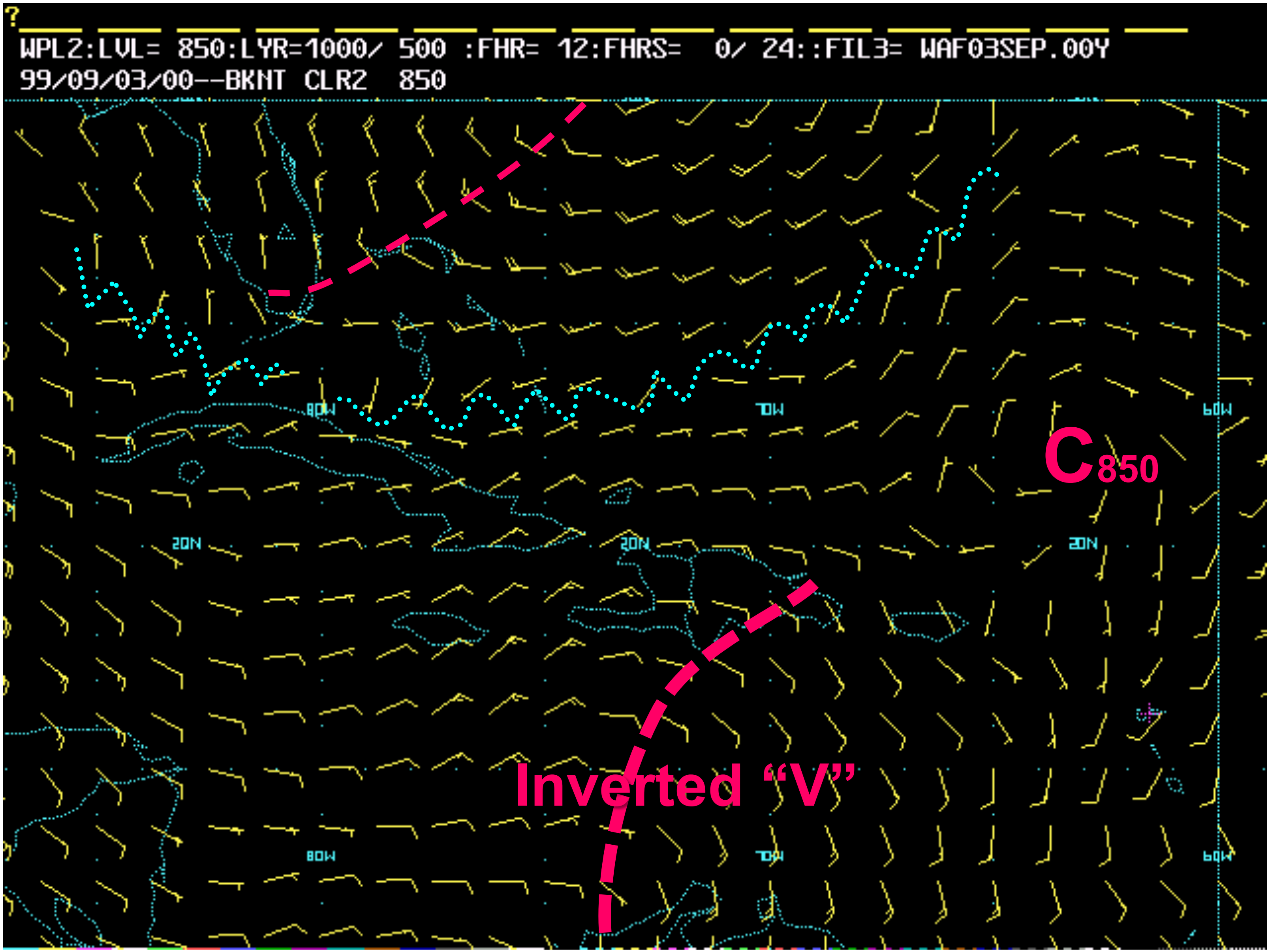
(The wave is not evident)



700 hPa Winds
(The wave is evident!)

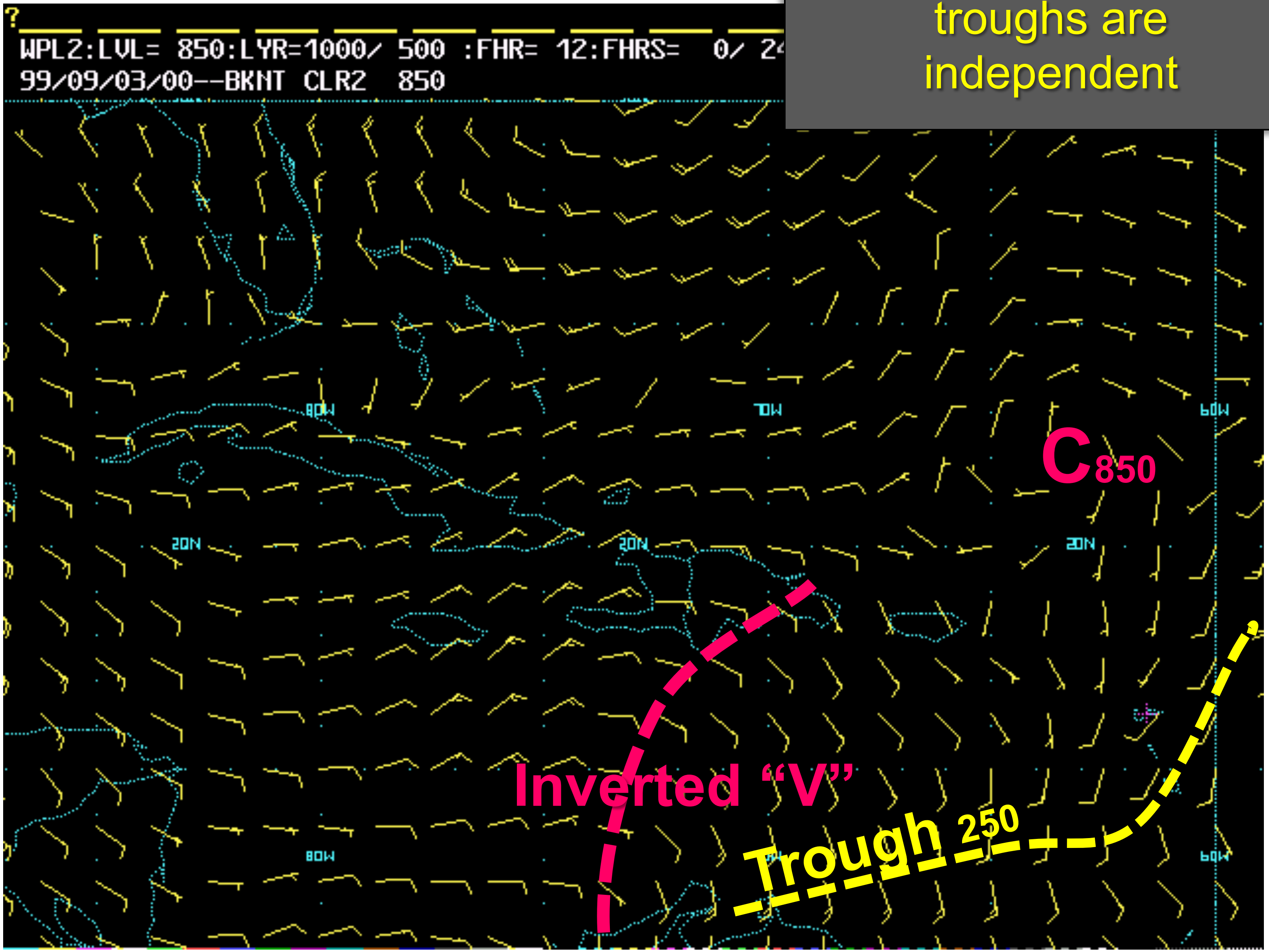


850 hPa Winds
(The wave is evident!)

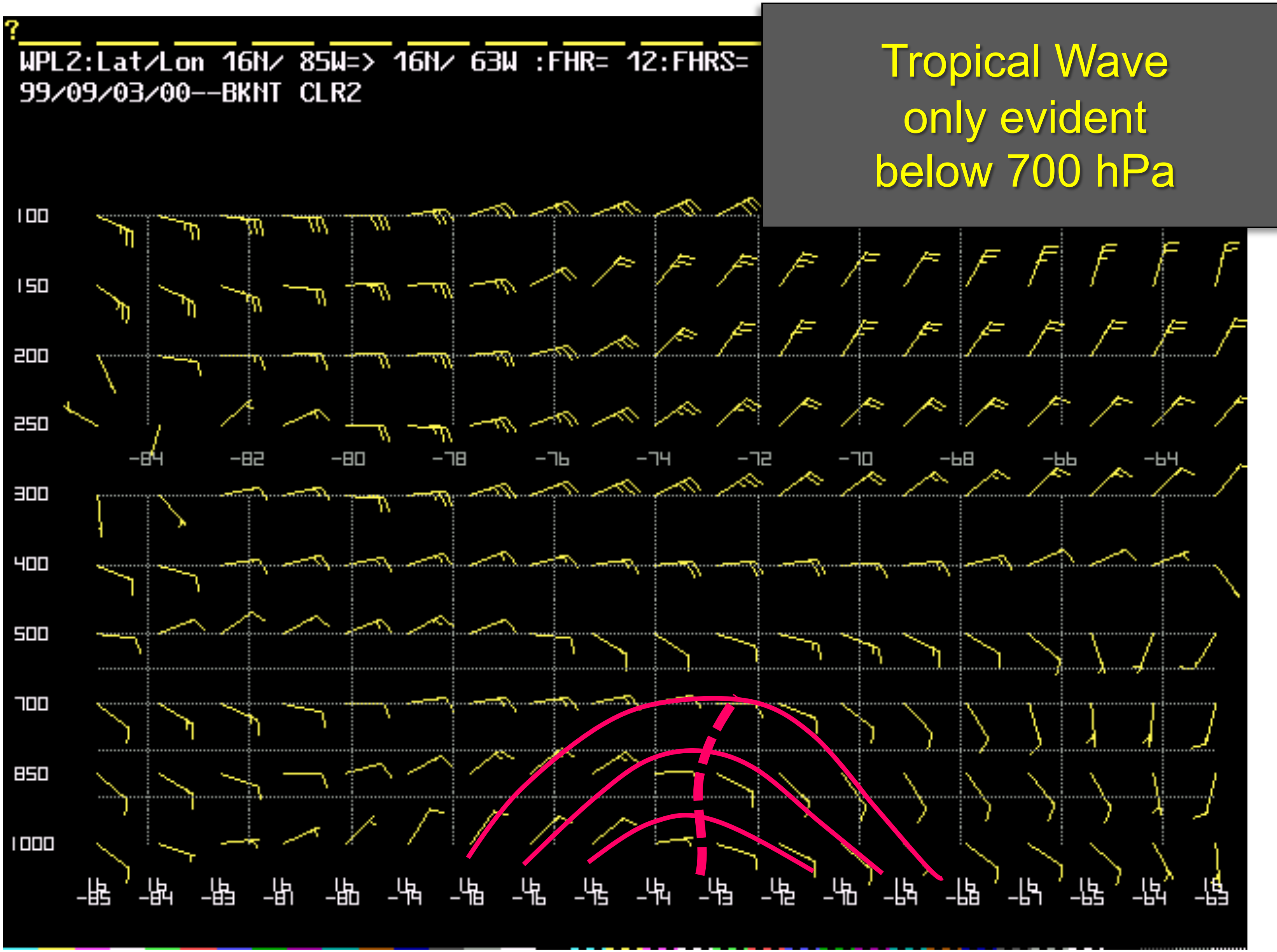


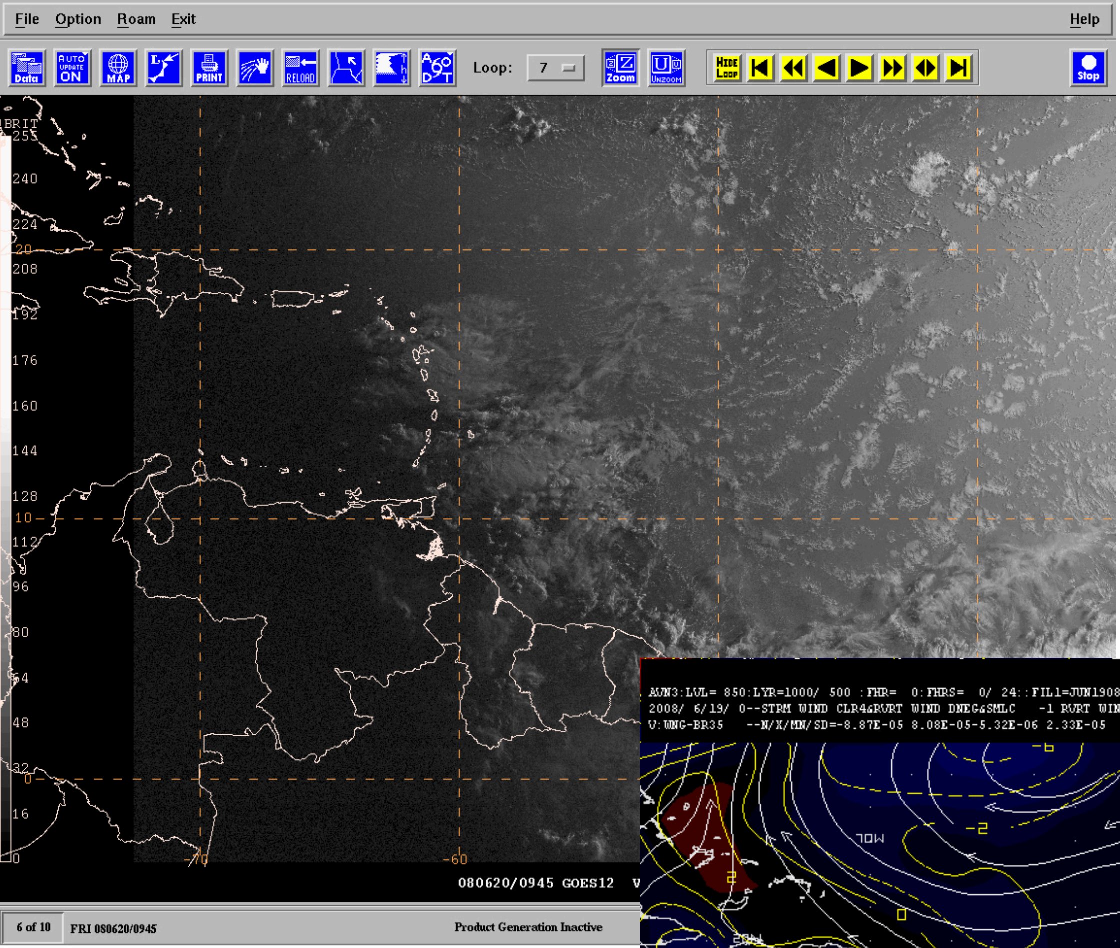
850 hPa Winds

Upper and low-level troughs are independent

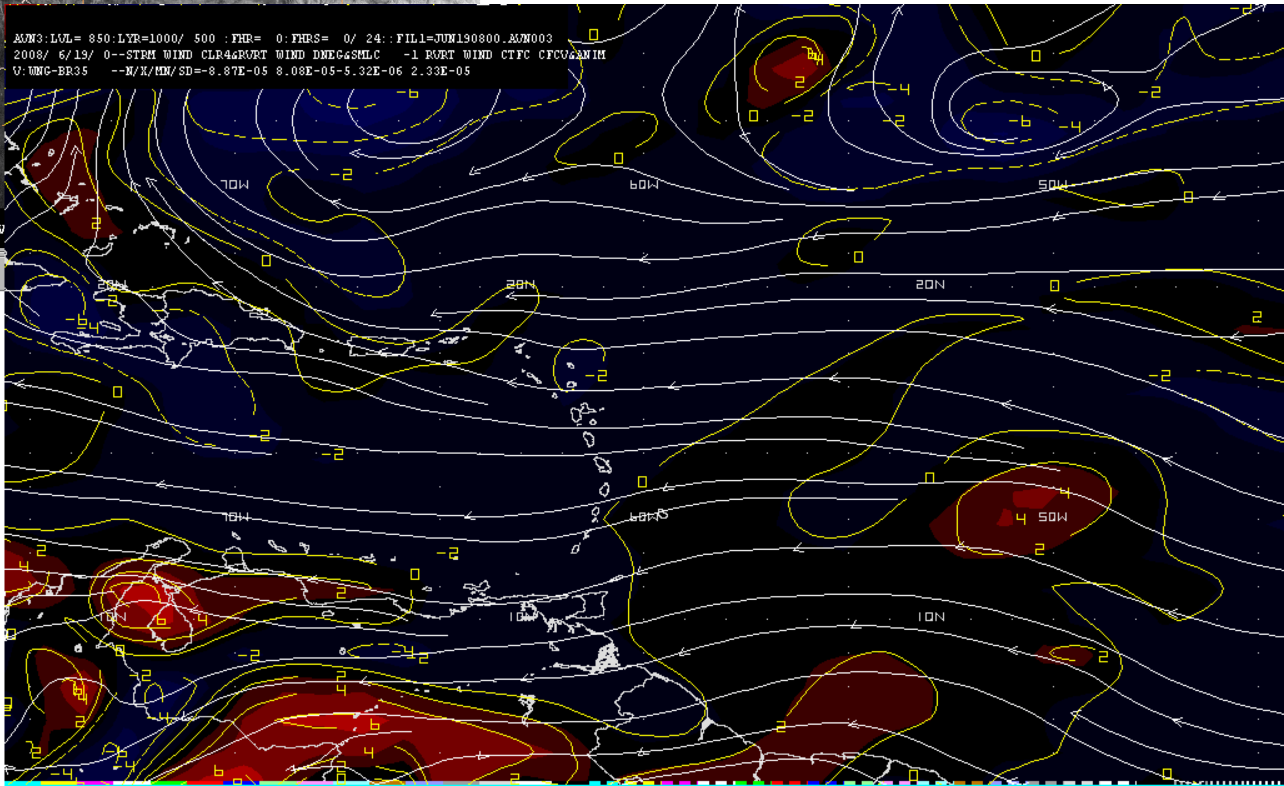


Vertical Cross Section of a Tropical Wave





The GFS forecast of vorticity and streamlines, as verified by corresponding Vis Images, shows good initialization and forecast of a tropical wave entering the Lesser Antilles.



Tropical Upper Tropospheric Trough (TUTT)

TUTT and TUTT Lows

- **Mid-Upper atmospheric** feature that separates the subtropical ridge from the subequatorial ridge.
  - ***600/500 hPa and above***.
  - They can retrogress, move westward, along the periphery of the subtropical ridge as it lies to the west and north.
- Seasonality: most frequent from **May-September**.
  (Best defined during July-early September).
- Cold core system (center is colder than surroundings).
- Circulation: **cyclonic vorticity strengthens with height**.
  - ***Maximum cyclonic rotation near the tropopause.***
- Source of Energy: **potential energy**.
  - Conversion of potential to kinetic energy.
  - Requires ***inflow*** of cold air, if not it tends to dissipate.

TUTT and TUTT Lows

- Formation of cloud complexes depends on heat and moisture available:
  - Most significant systems tend to form to the south of trough axis.

- **Main function: supply outflow channels while venting deep convection**.

- TUTT location/orientation has an important role on the secondary formation of tropical cyclones over the Western Caribbean.
  - Subtropical cyclones

- **Interaction with the ITCZ**
  - Can induce the northward modulation
  - Can induce perturbations/inverted trough along the convergence zone

- ***Trigger Severe Weather and Flooding***

Mean 300 hPa Flow

July - October

Figure 2-18. Mean 300-millibar Flow, July.

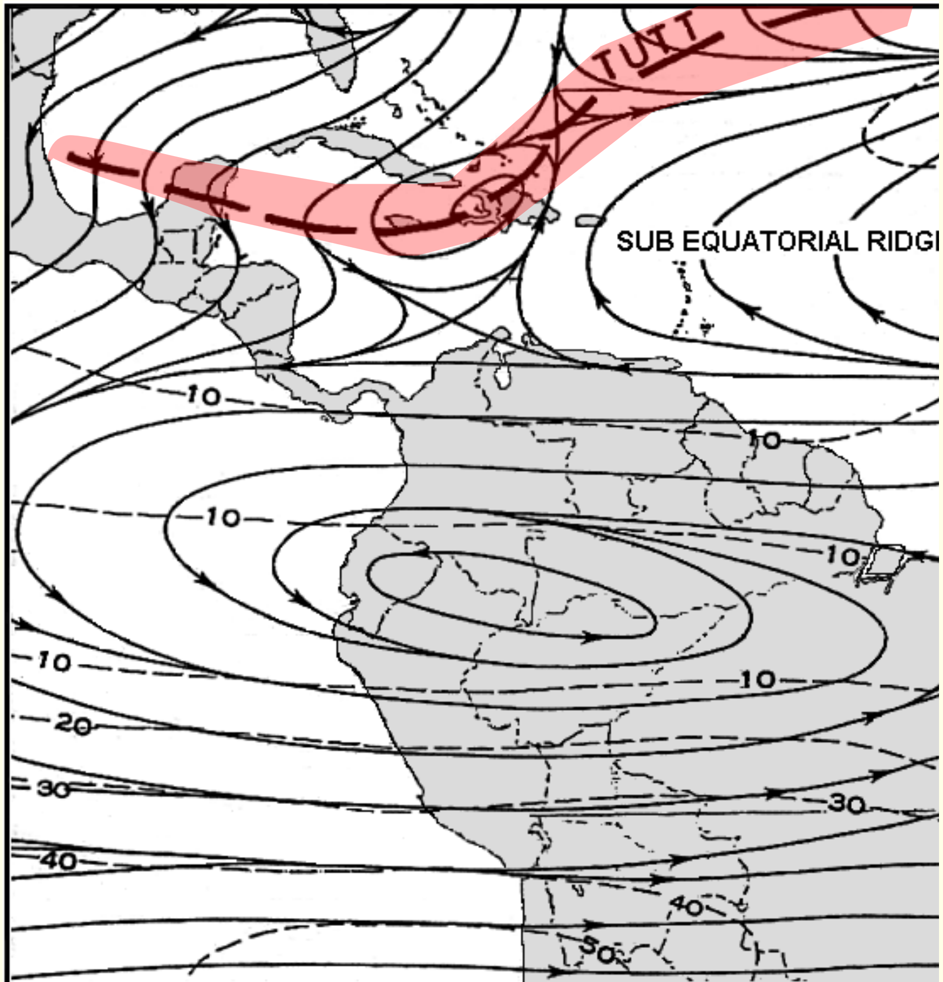
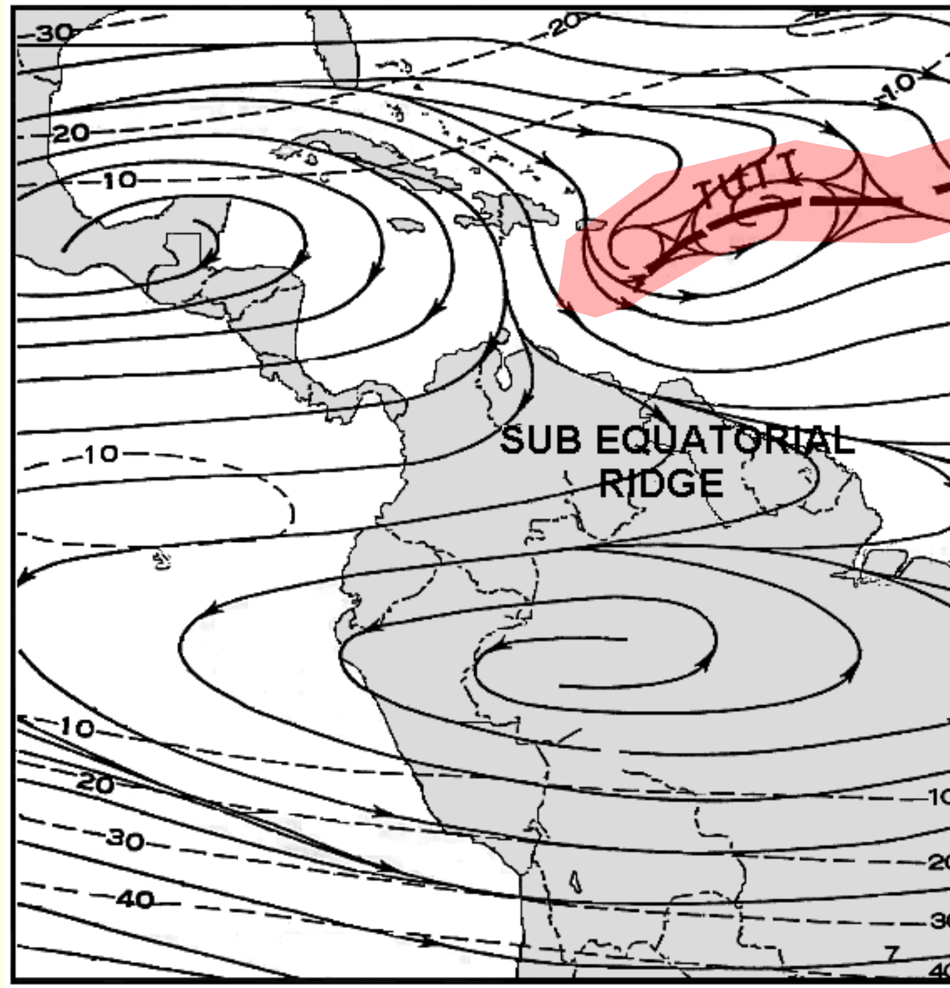


Figure 2-19. Mean 300-millibar Flow, October.



USAFETAC/TN-89/003, The Caribbean Basin, A Climatological Study, December 1989

Vertical Circulations across a TUTT Low

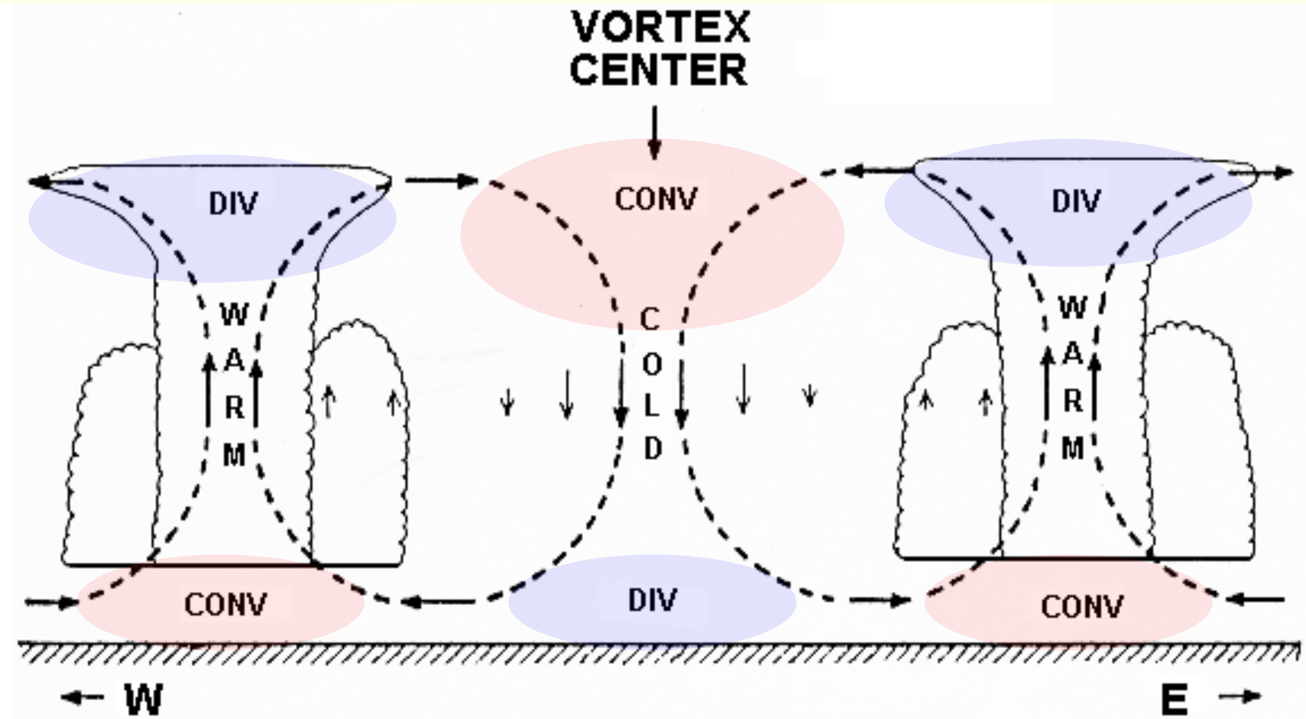
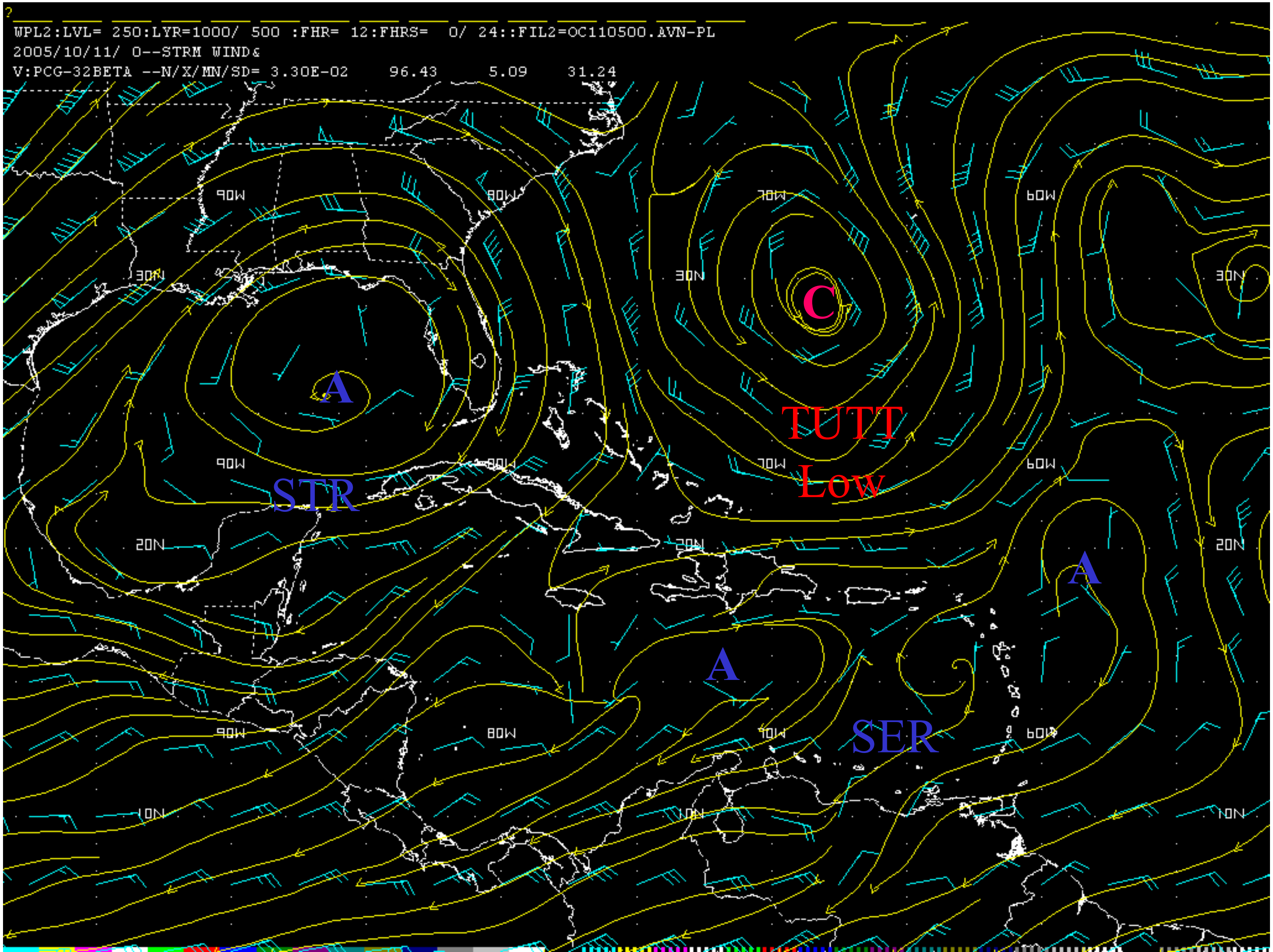


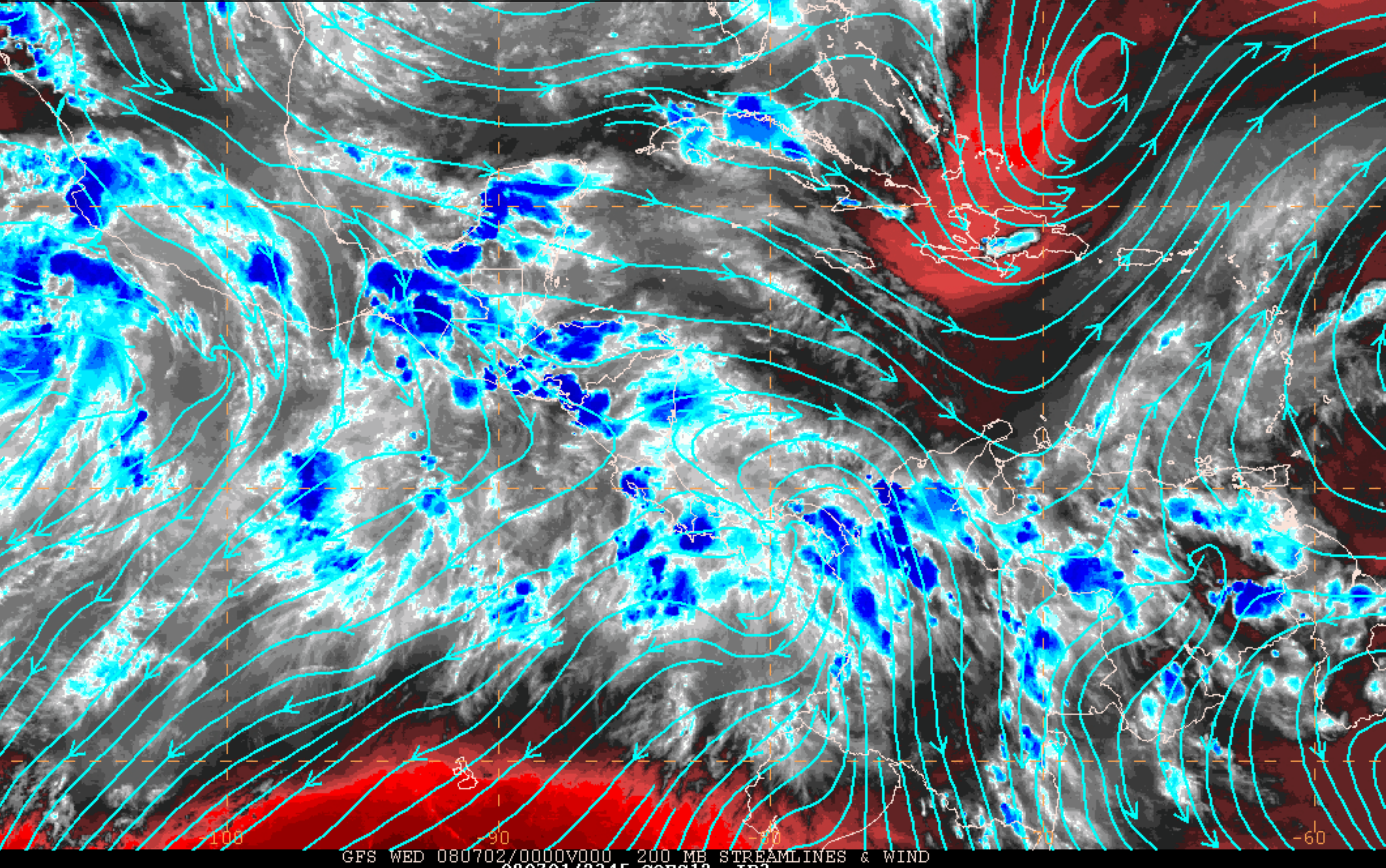
Figure 2-41. Vertical Cross Section Through an Upper-Troposheric Cyclonic System

AFCC Theater Climatic File CD. Volume 4: South America, South of the Amazon River, Ver. 1.0 June 1998.

GFS Analysis of a TUTT



TUTT over the Caribbean (Water Vapor)



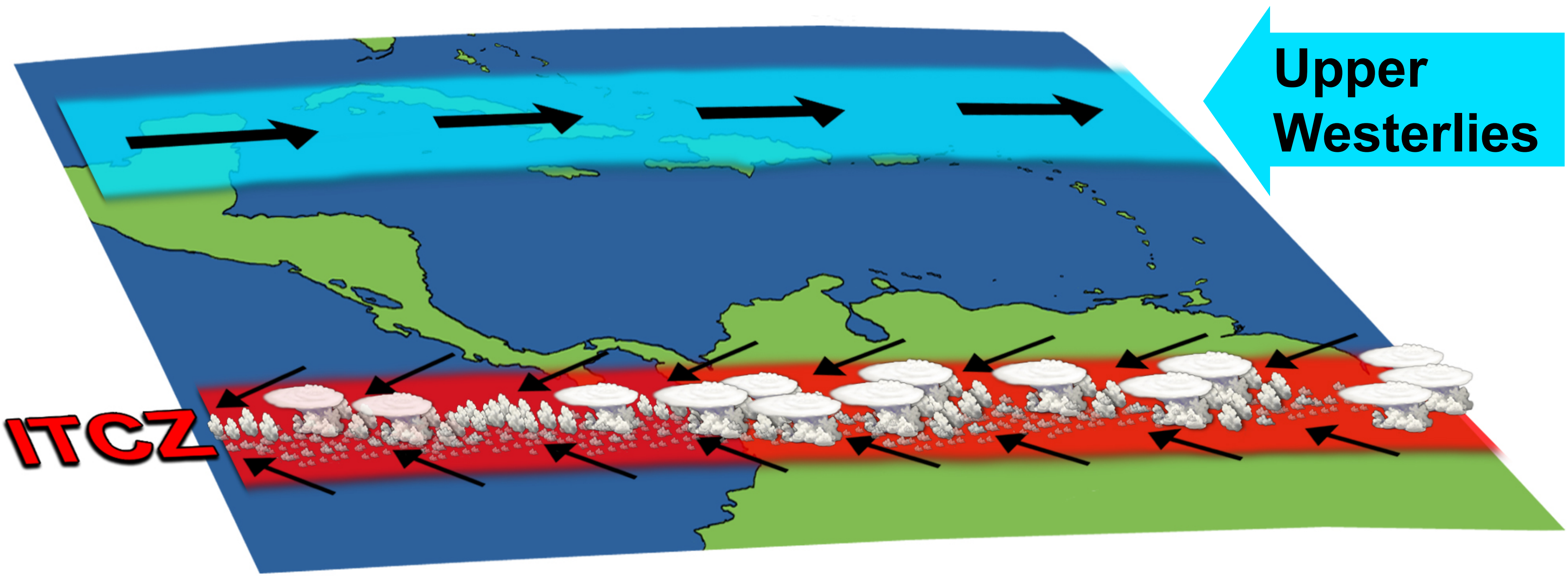
TUTT Interaction with the ITCZ

Generation of an Induced Trough

How does a TUTT induces an inverted trough in the low levels easterlies?

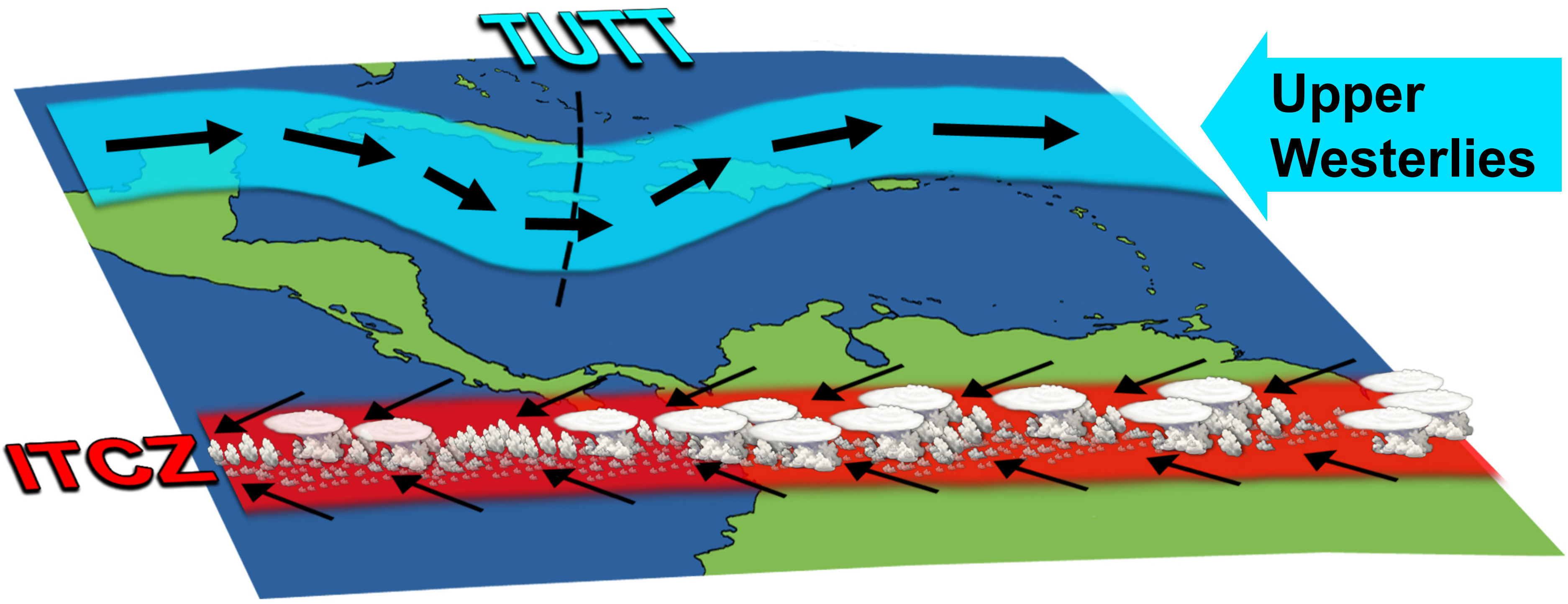
Genesis of a TUTT-Induced Trough

(1) Starts with zonal flow



Genesis of a TUTT-Induced Trough

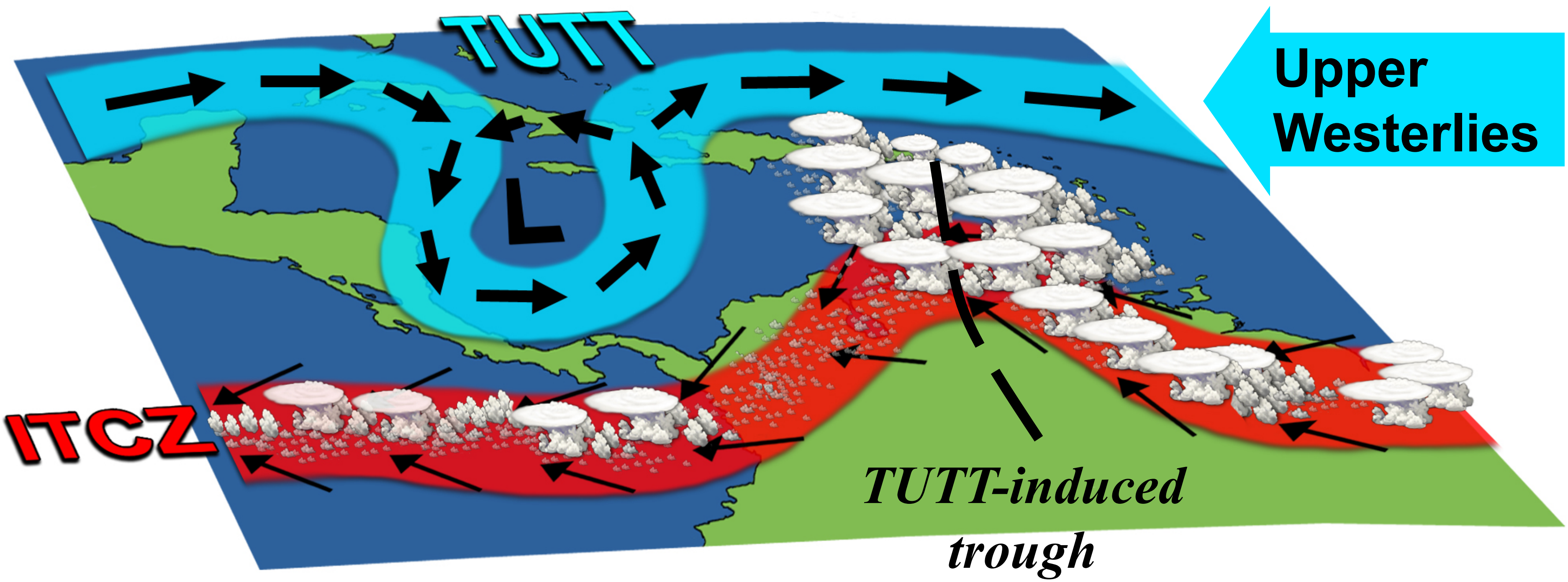
(2) Perturbation in upper westerlies forms



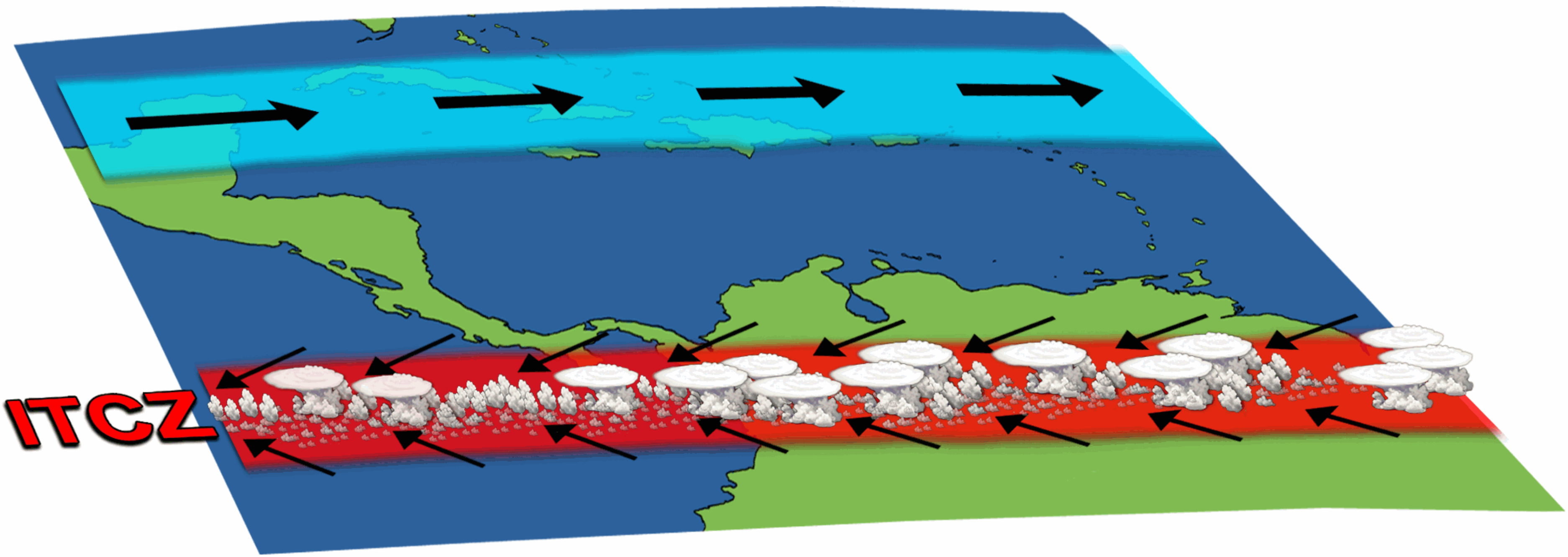
Genesis of a TUTT-Induced Trough

(3) Lower flow responds to upper forcing.

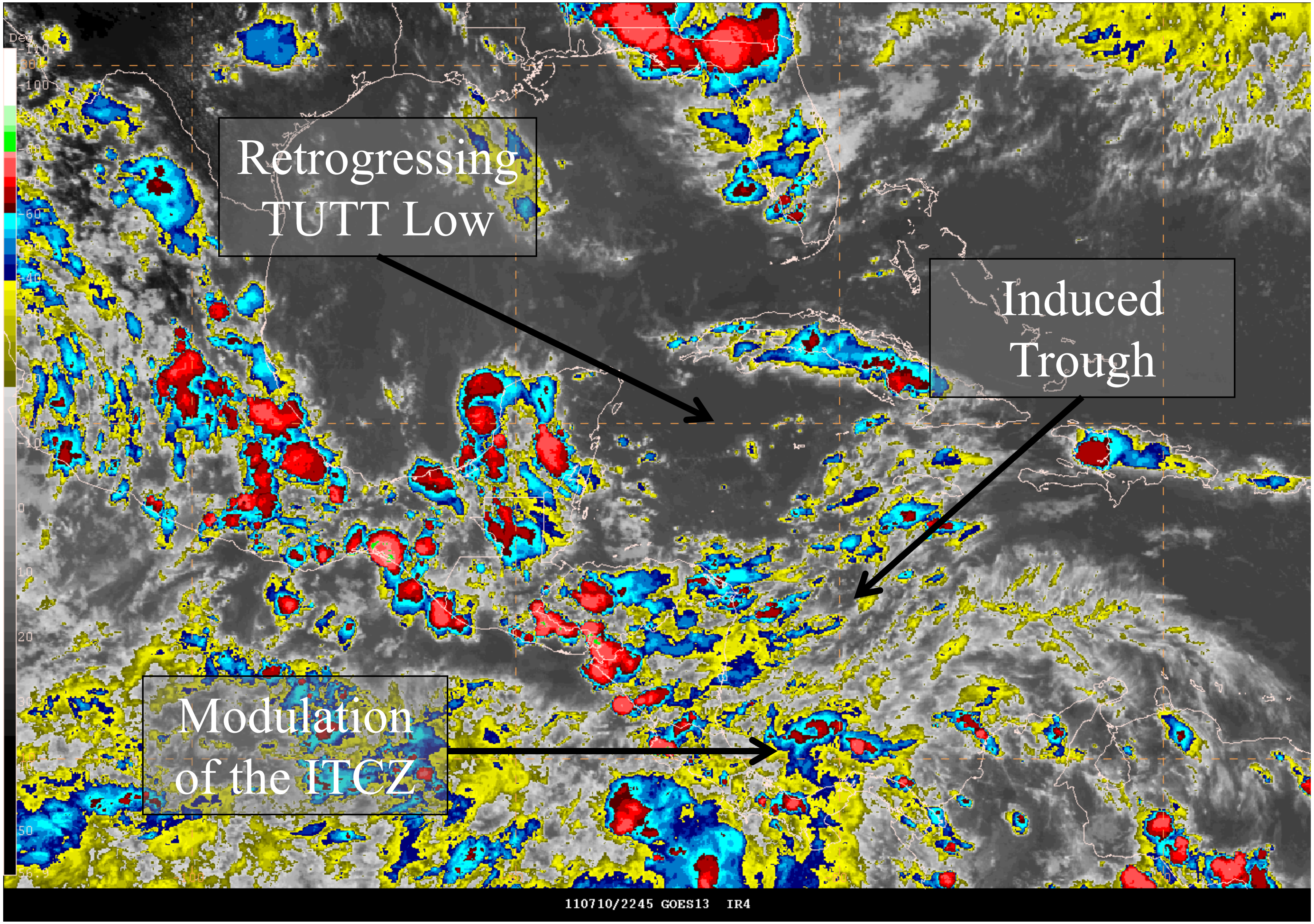
- TUTT induces height falls at lower levels.
- This induces the northward modulation of the ITCZ
- Inverted "V" forms, flow/shape similar to that of a Tropical Wave.



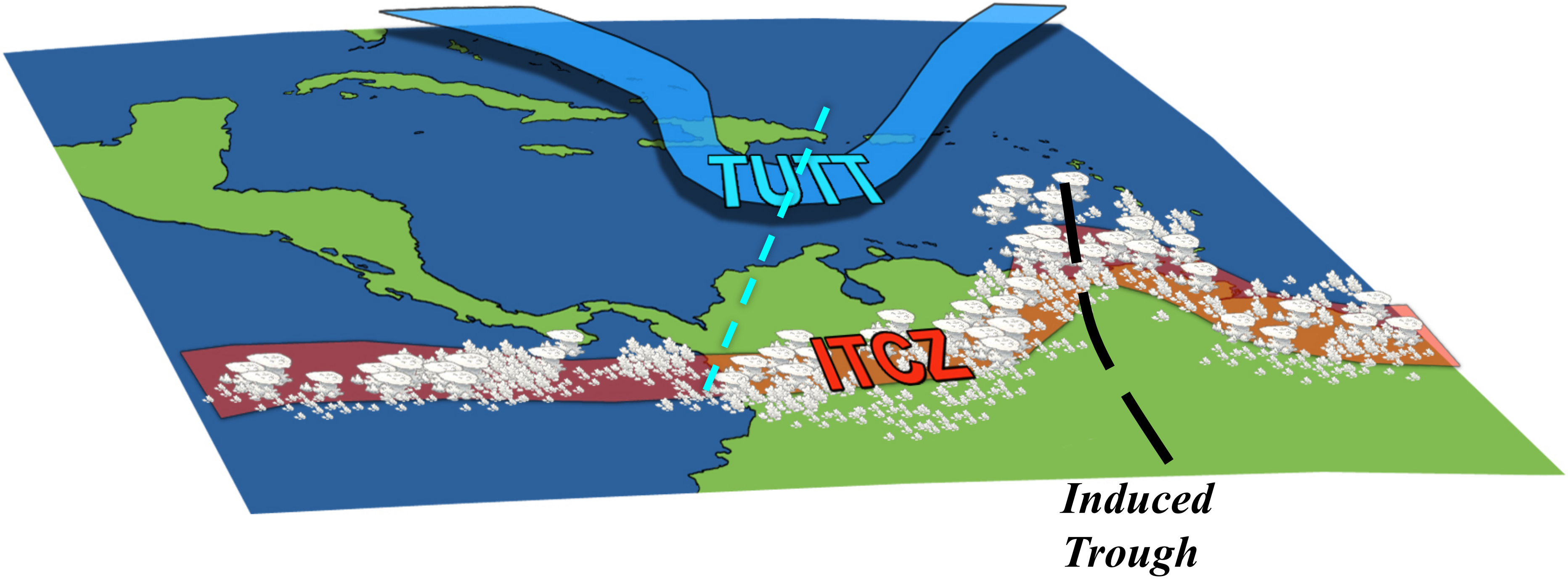
Animation of a TUTT Induced/Inverted Trough in the low level Easterly Trades



Modulation of the ITCZ by a TUTT



Conceptual Model of Induced Trough

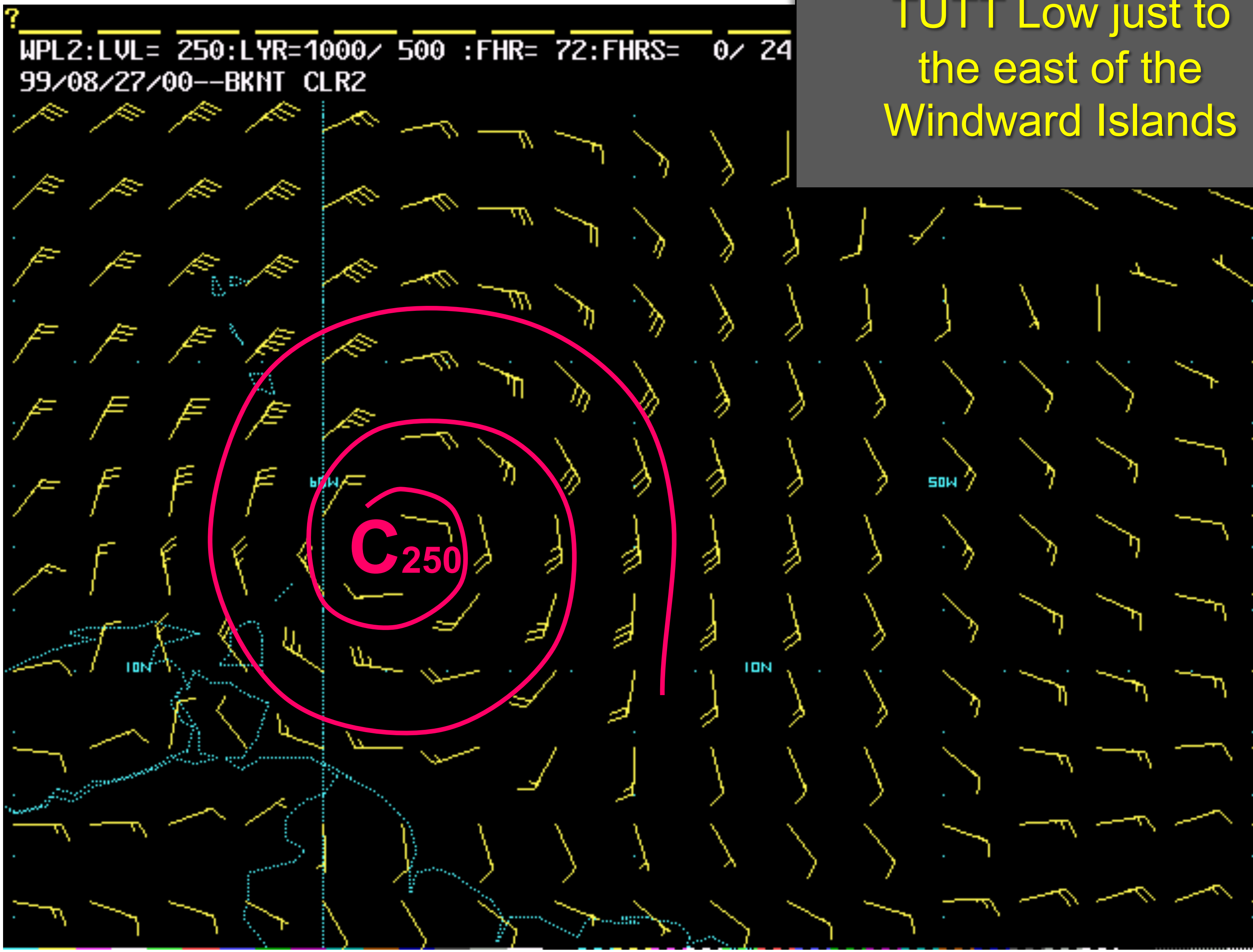


- Note: For a TUTT to induce a perturbation in the low level easterlies it must reflect at mid-levels of the troposphere as well.

- When a TUTT ***limits to levels above 300 hPa***, it is less likely to induce a perturbation in the easterlies.
- Once the wave forms, it can decouple from the upper trough and propagate as an Easterly Wave. But tends to weaken with time.

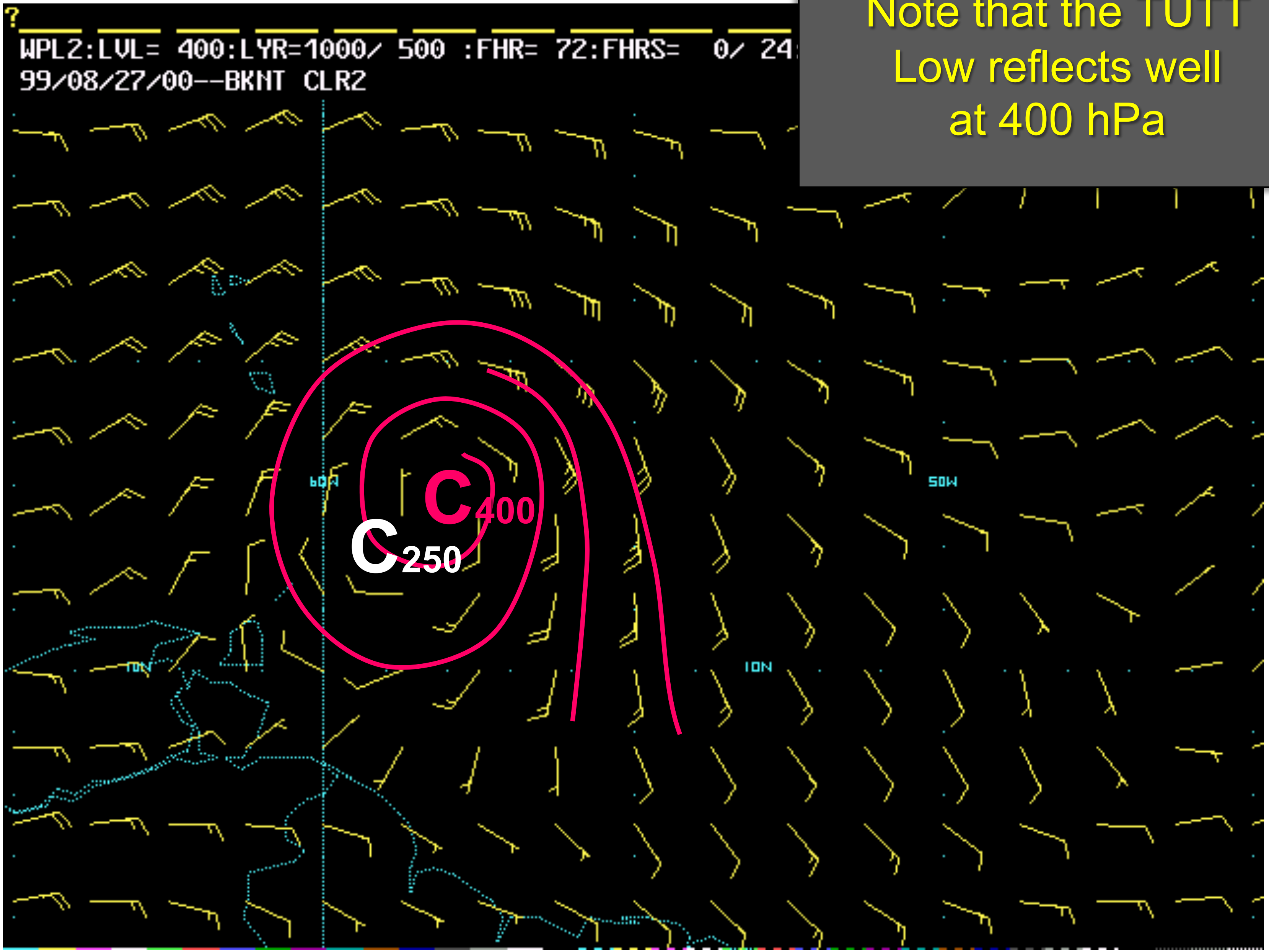
Numerical Modeling of a TUTT and Associated Induced Trough

250 hPa TUTT Low



TUTT Low just to the east of the Windward Islands

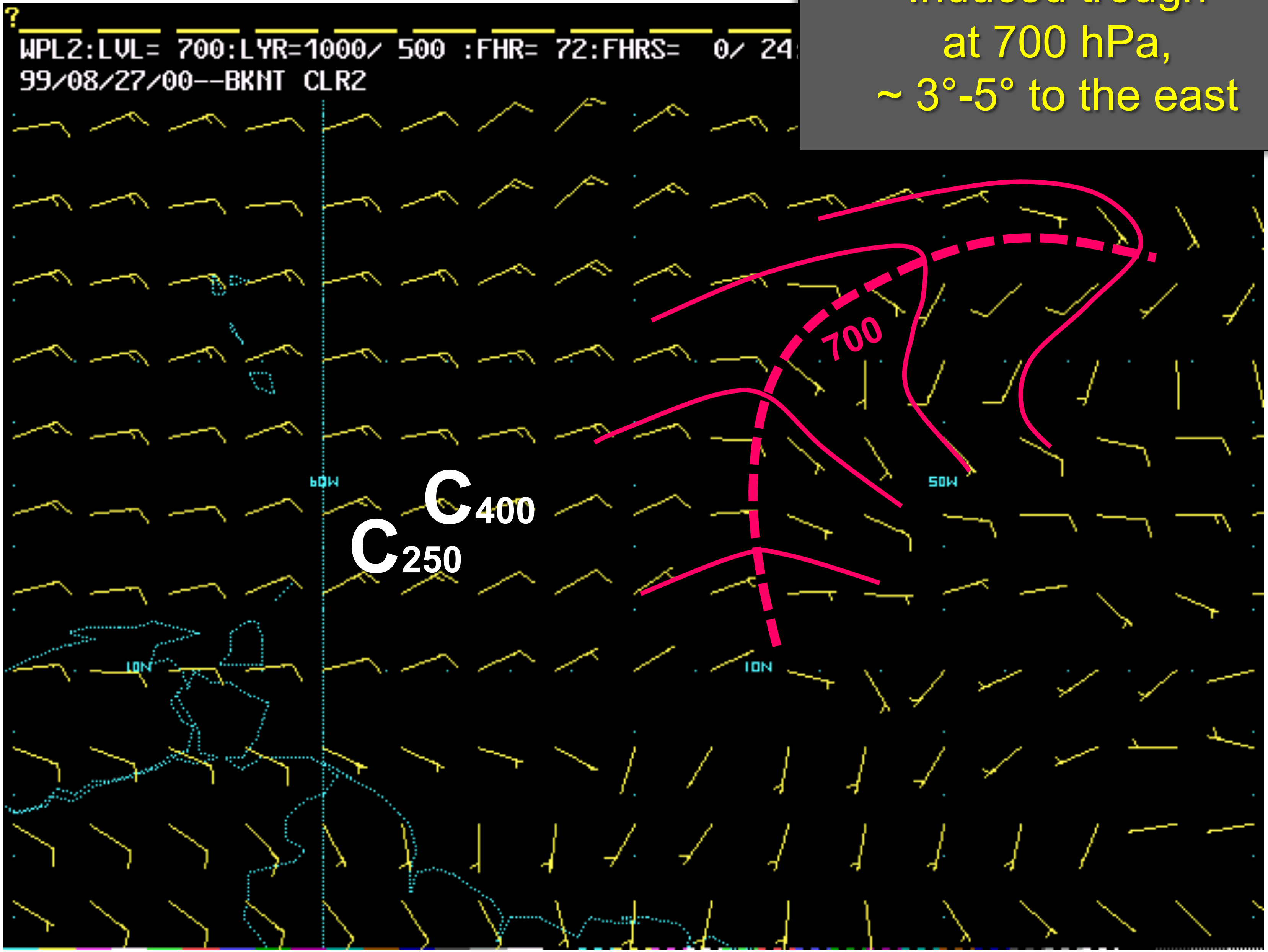
TUTT Low at 400 hPa



Note that the TUTT Low reflects well at 400 hPa

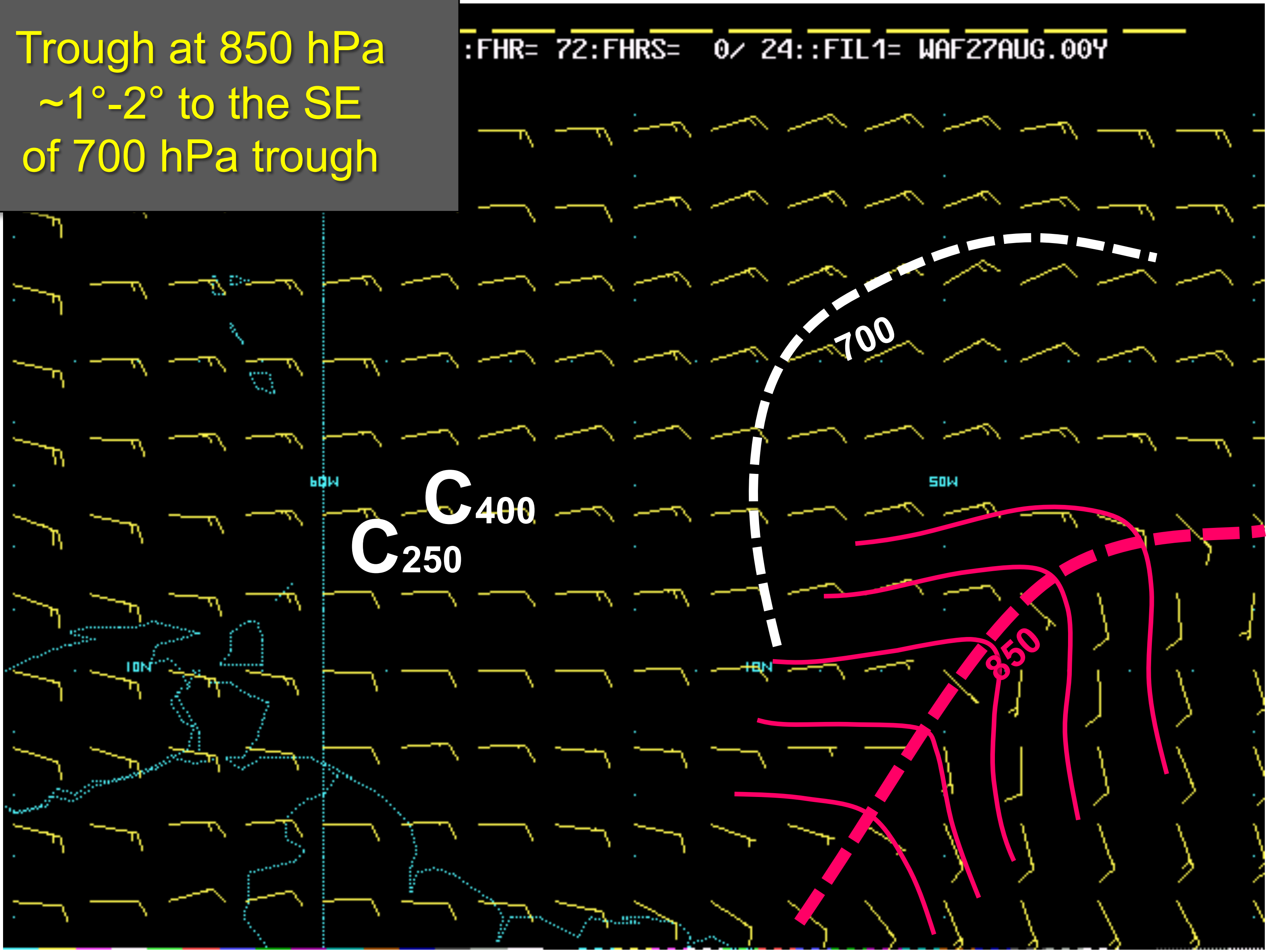
Open Trough at 700 hPa

Induced trough at 700 hPa, ~ 3°-5° to the east

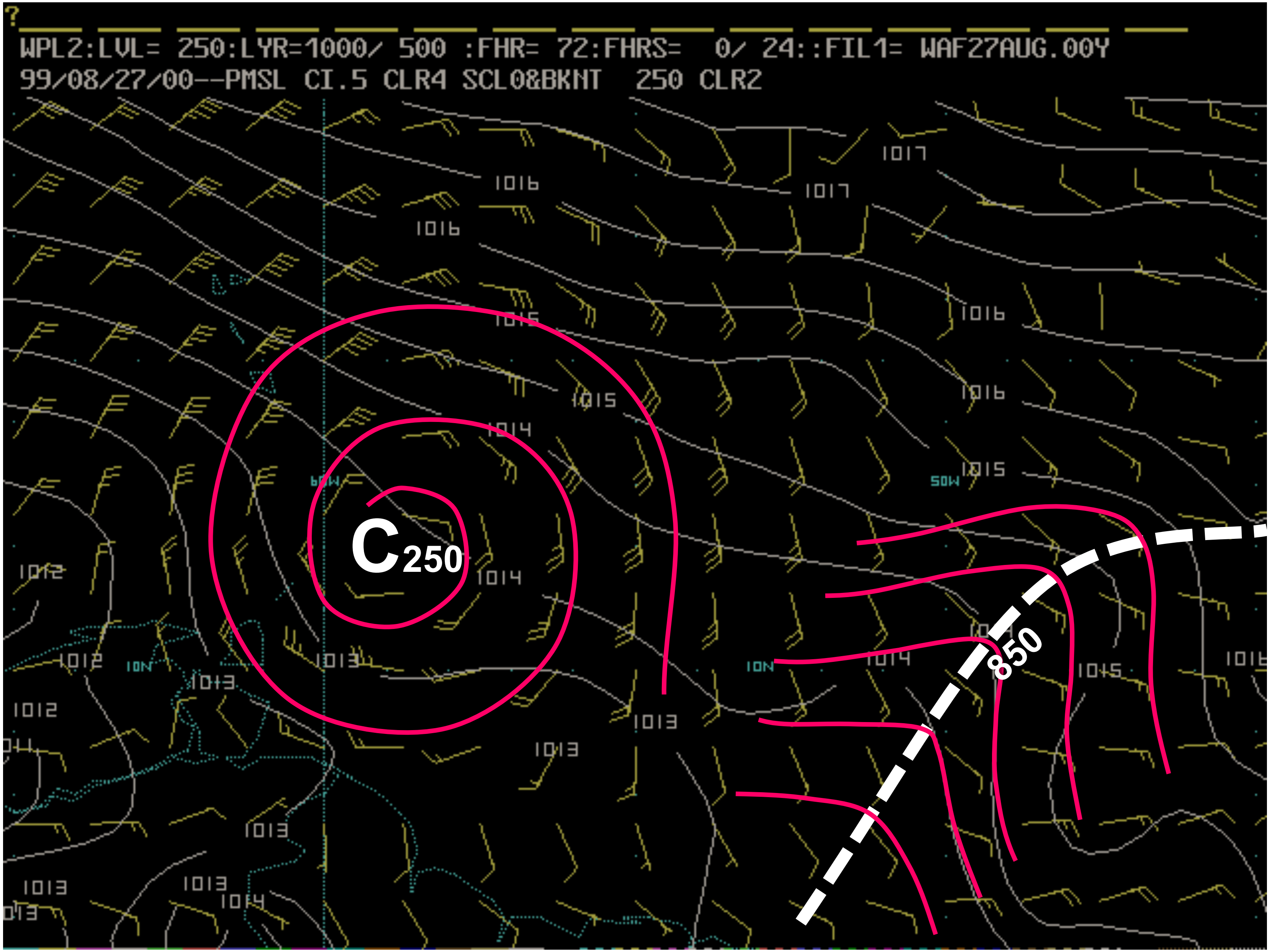


Induced Inverted Trough at 850 hPa

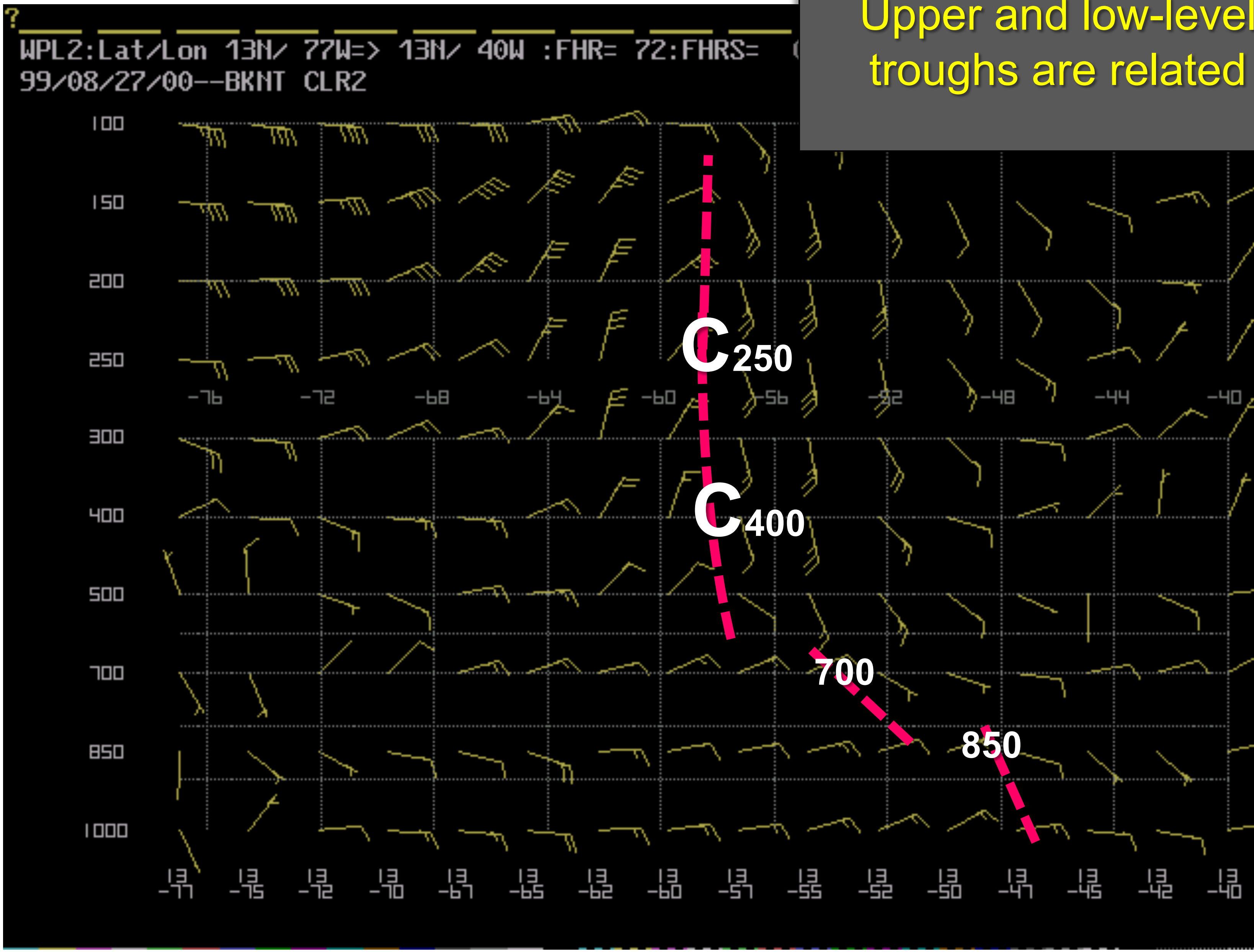
Trough at 850 hPa
~1°-2° to the SE
of 700 hPa trough



TUTT at 250 hPa and Low-Level Induced Trough

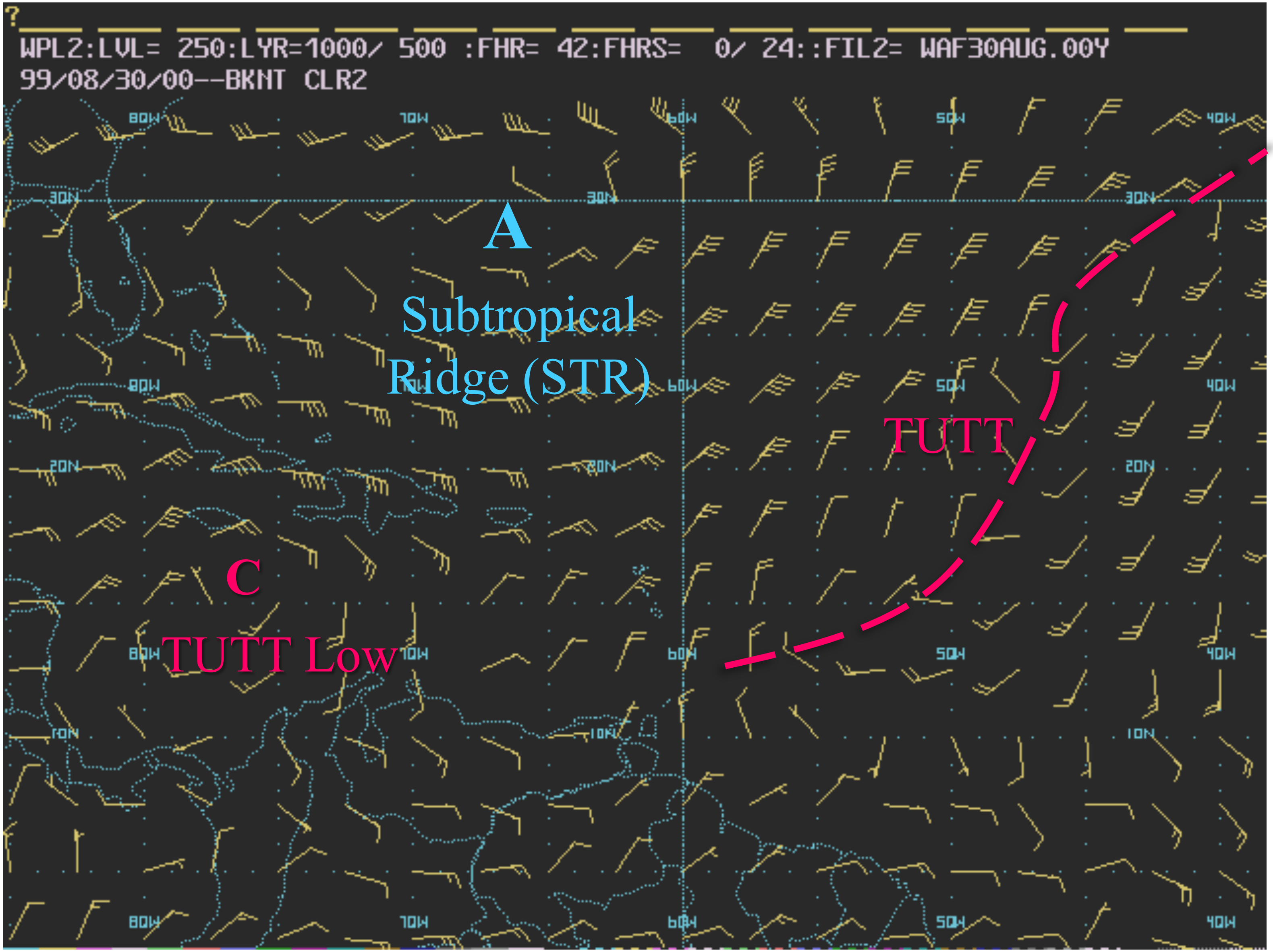


Vertical Cross Section

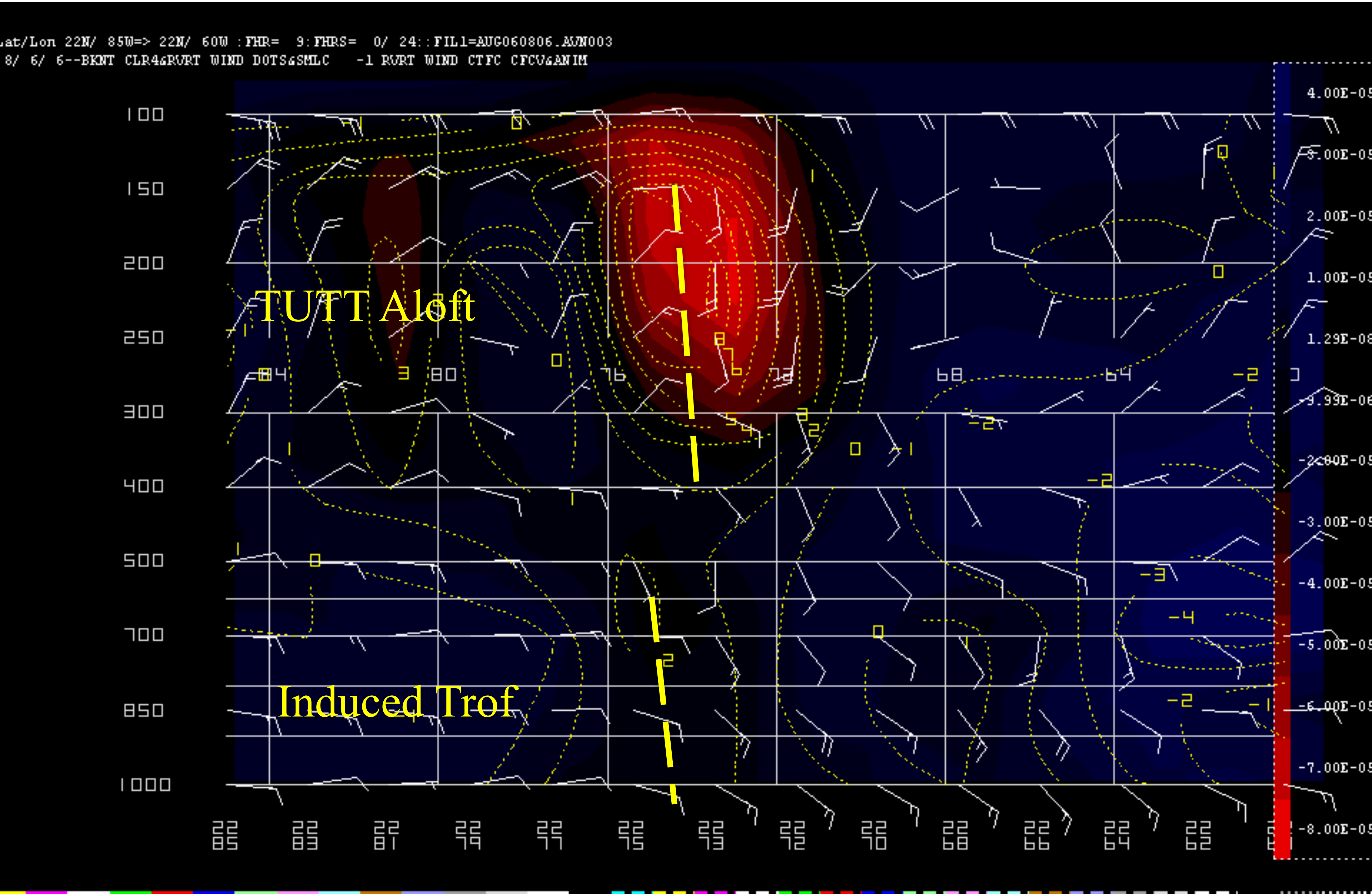


Upper and low-level troughs are related

Another example: 250 hPa Winds



Cross section: Vorticity and Winds



Evaluating the Vertical Structure and Depth of a TUTT

Water Vapor Channels

GOES-16

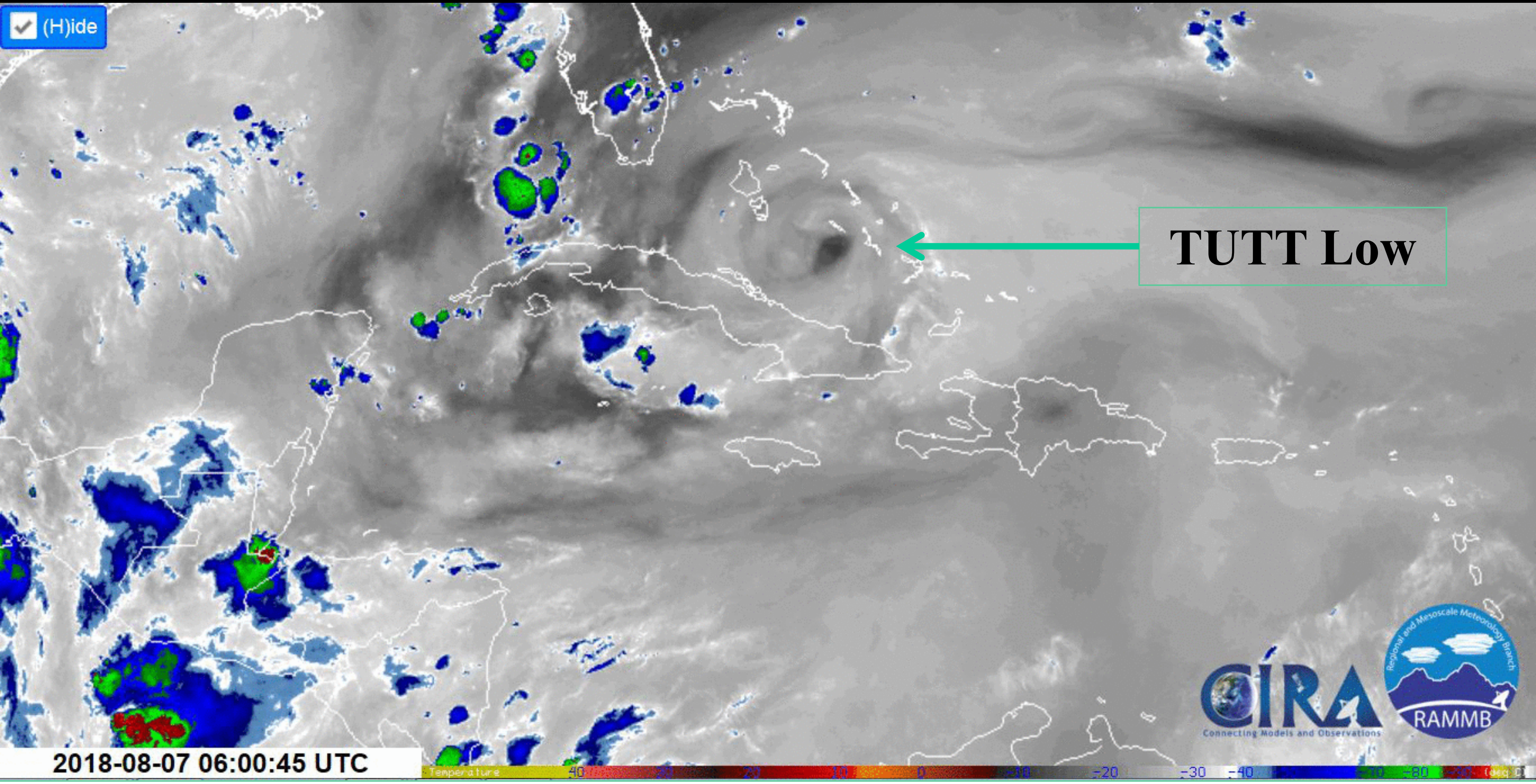
Evaluating the Vertical Structure and Depth of a TUTT

- GOES-16 has three moisture channels
  - **6.2** micron monitors **upper levels atmosphere**
  - **6.9** micron monitors **mid levels atmosphere**
  - **7.3** micron monitors the **mid/lower levels**.

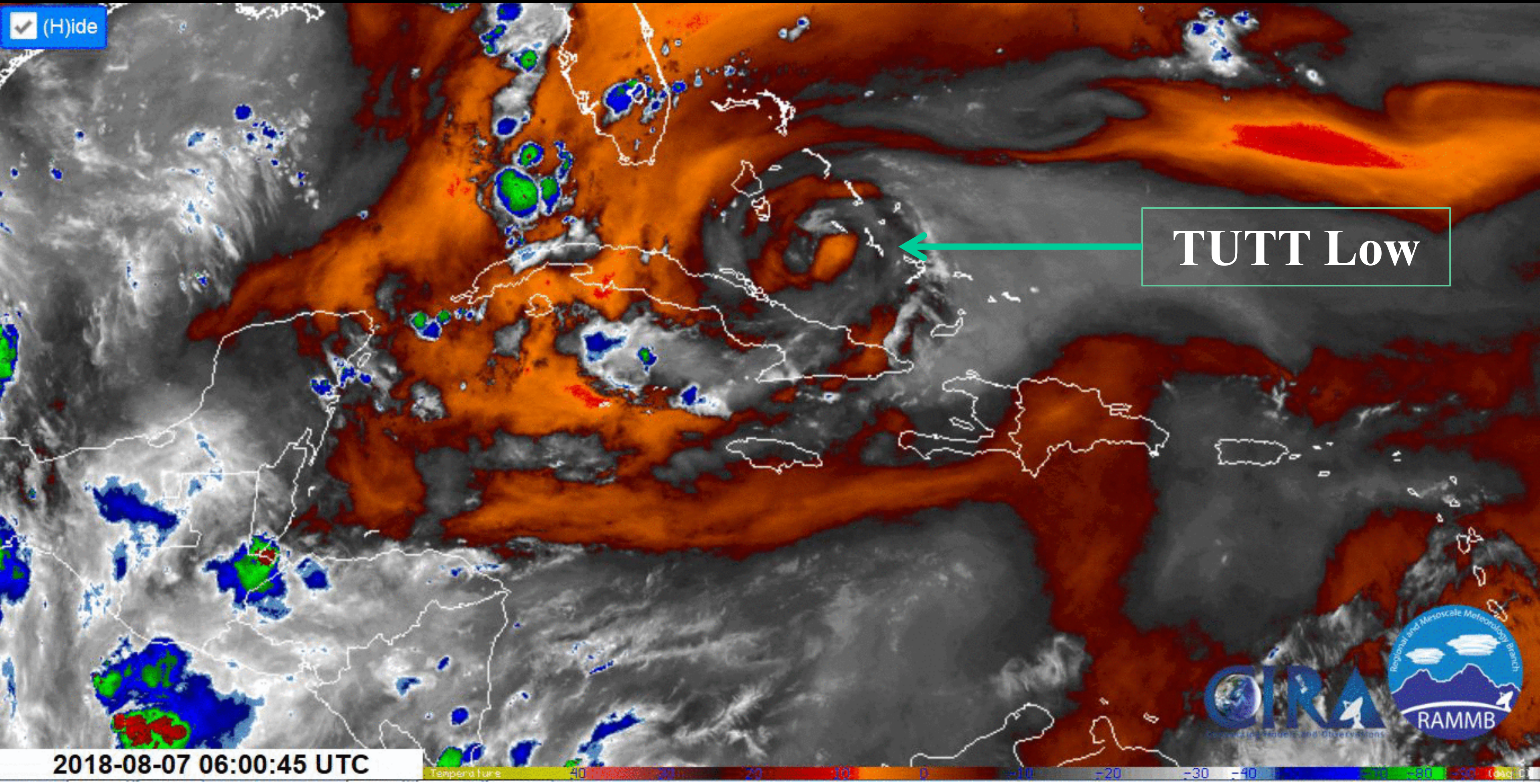
Evaluating the Vertical Structure and Depth of a TUTT

- If the trough, or low, is evident on all ***three moisture channels***, we can infer that it has a deep vertical structure.
  - This is deep enough that it can induce a perturbation in the easterly trades.
- If the trough, or low, is only evident on the **6.2 micron** channel, it confines to the upper levels.
  - It cannot induce a trough in the easterly trades

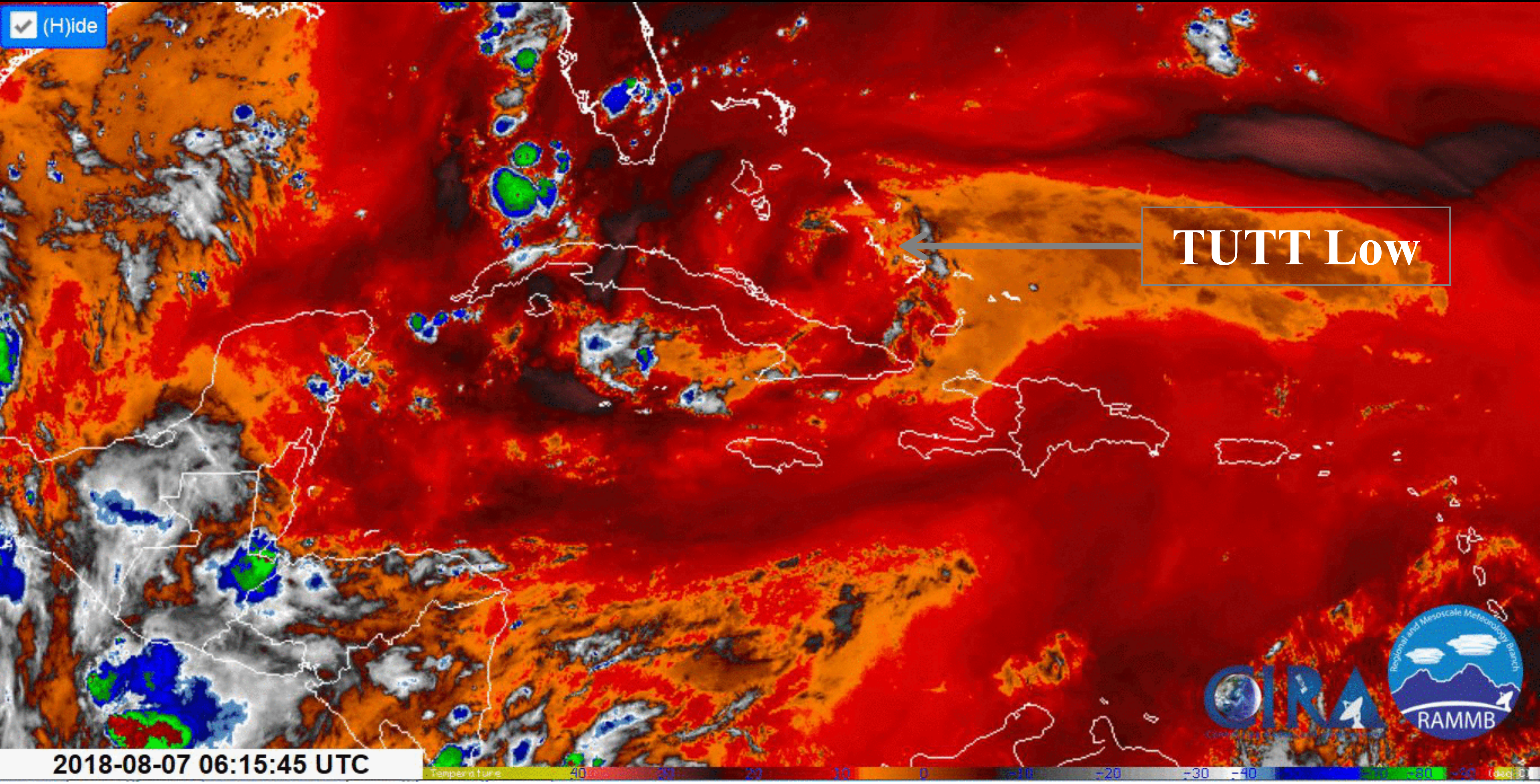
6.2 Micron Images



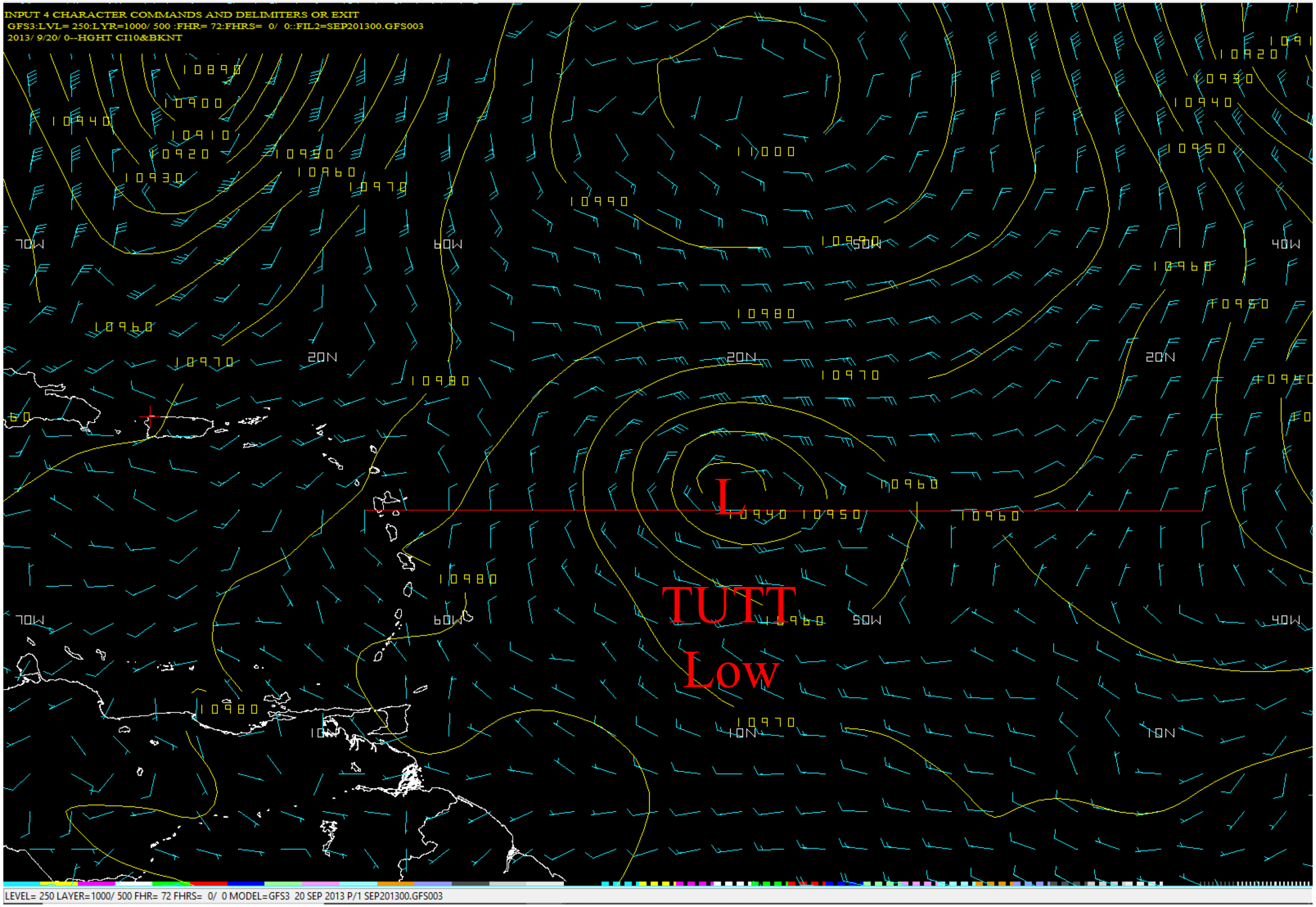
6.9 Micron Images



7.3 Micron Images

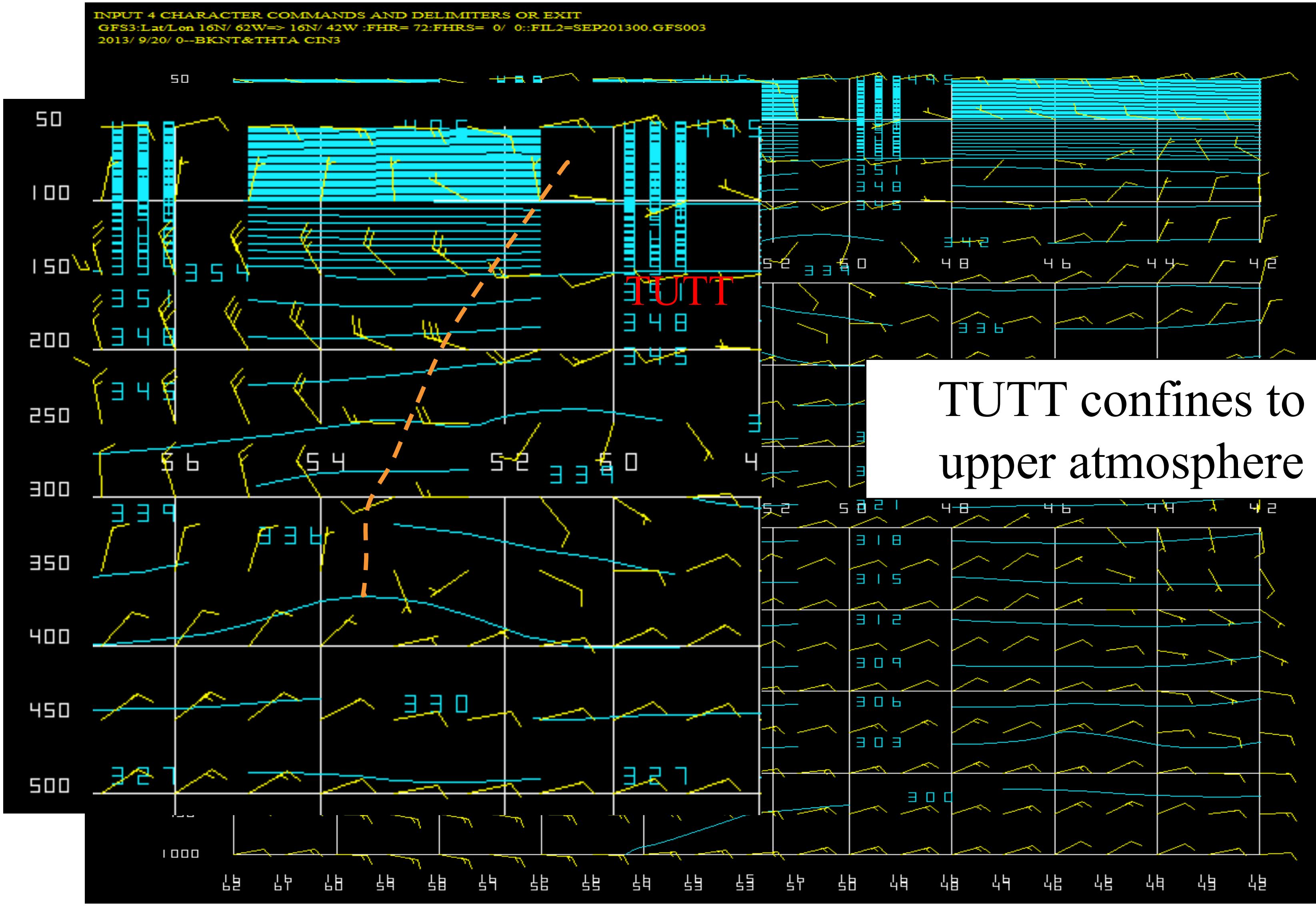


TUTT Low at 250hPa



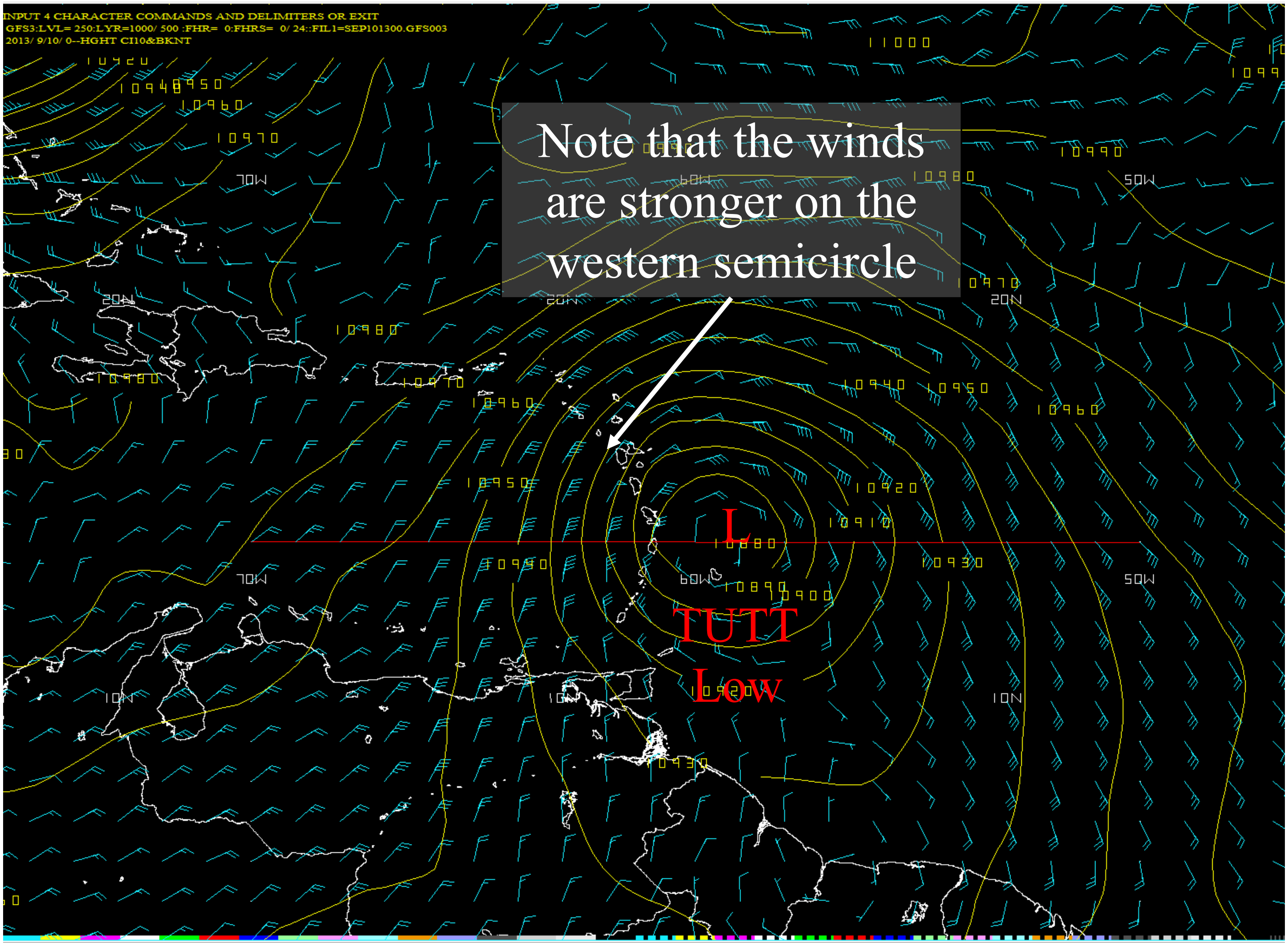
Vertical Cross Section – THTA and Winds

Shallow Layer: Unlikely to induce a low level trough



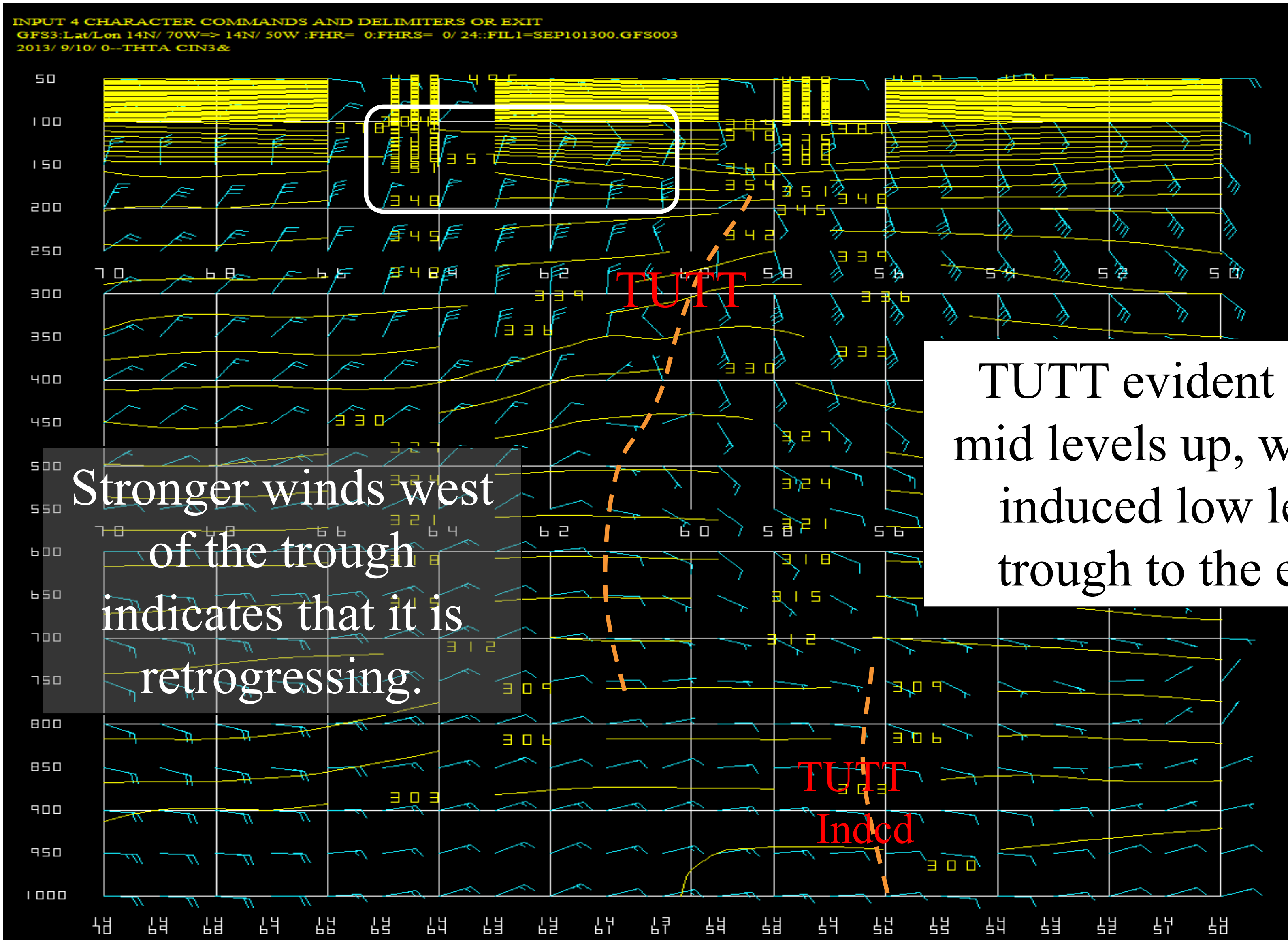
TUTT confines to upper atmosphere

TUTT Low at 250 hPa



Vertical Cross Section – THTA and Winds

Deep Layer TUTT: Likely to induce a low level trough



TUTT evident from mid levels up, with an induced low level trough to the east.

Divergence/Convergence Associated with a TUTT

Areas of Upper Divergence and/or Convergence in Relation with a TUTT?

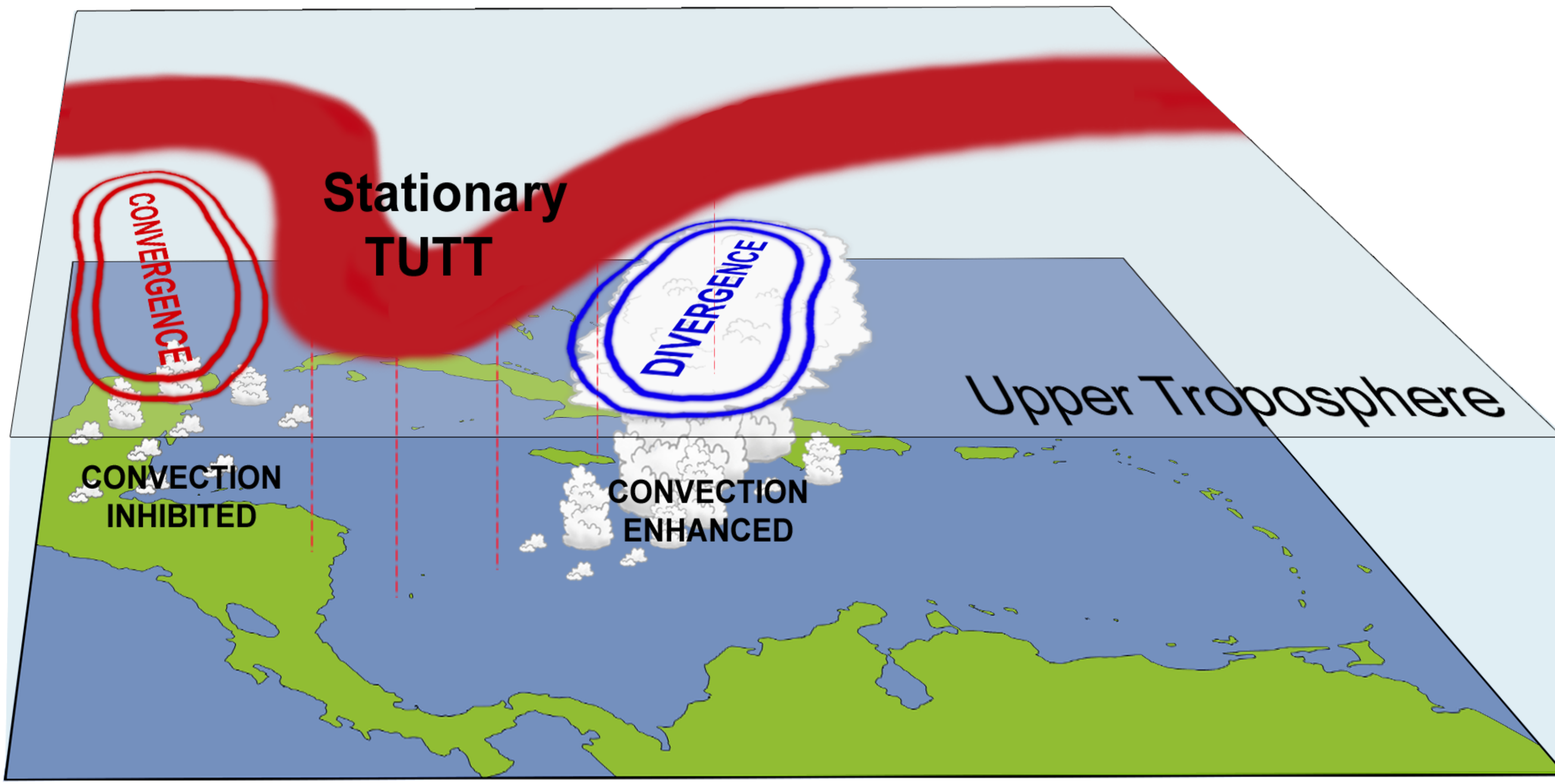
- Depends upon whether….
  - TUTT is stationary
  - TUTT is retrograding
  - Upper Jet Dynamics

Stationary TUTT

-In a ***neutral to positively tilted*** trough axis with height, the best upper divergence lies east of the trough axis.

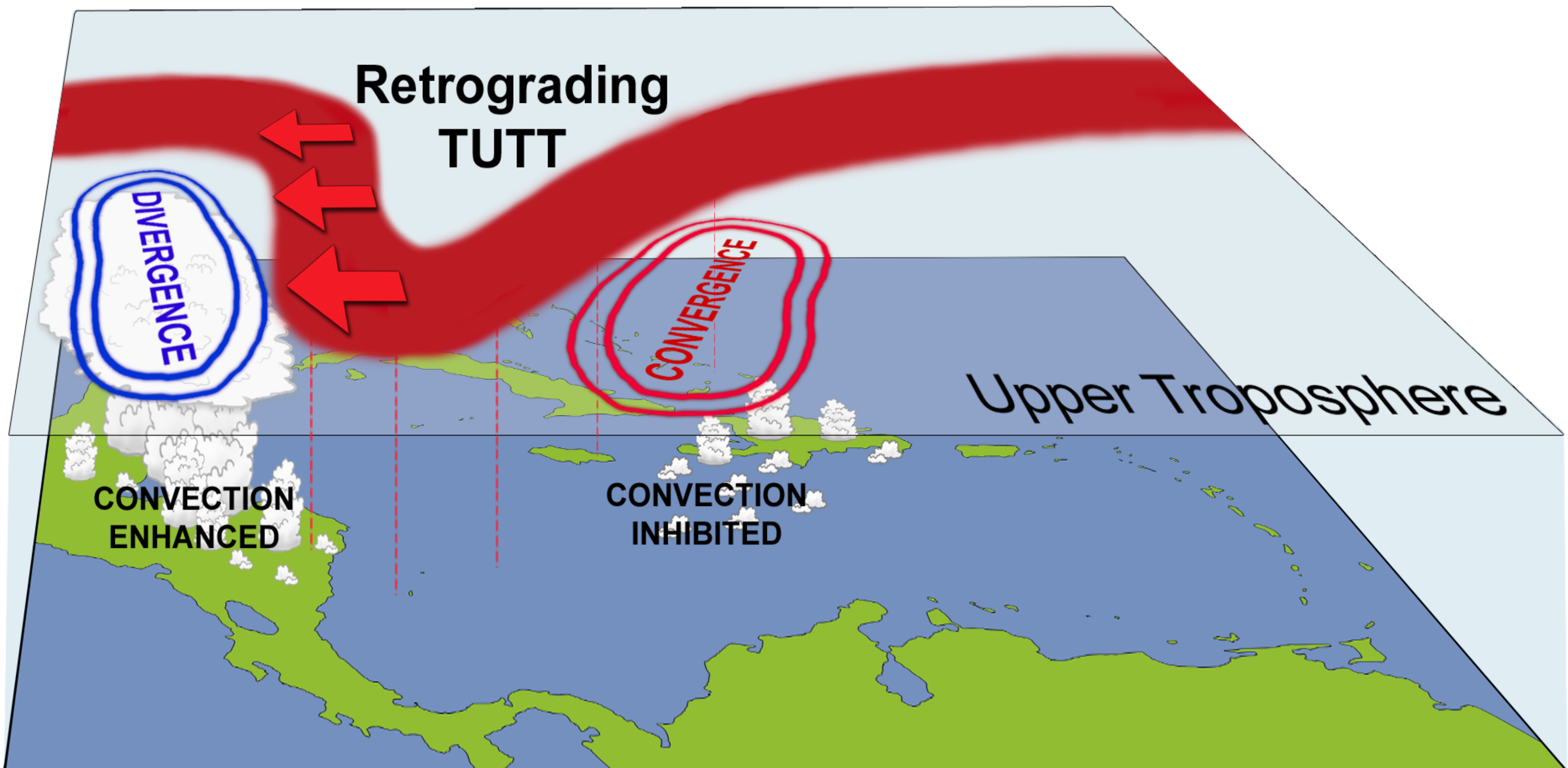
-Upper convergence west of axis.

-Some upper convergence also along the trough axis.



Retrograding TUTT

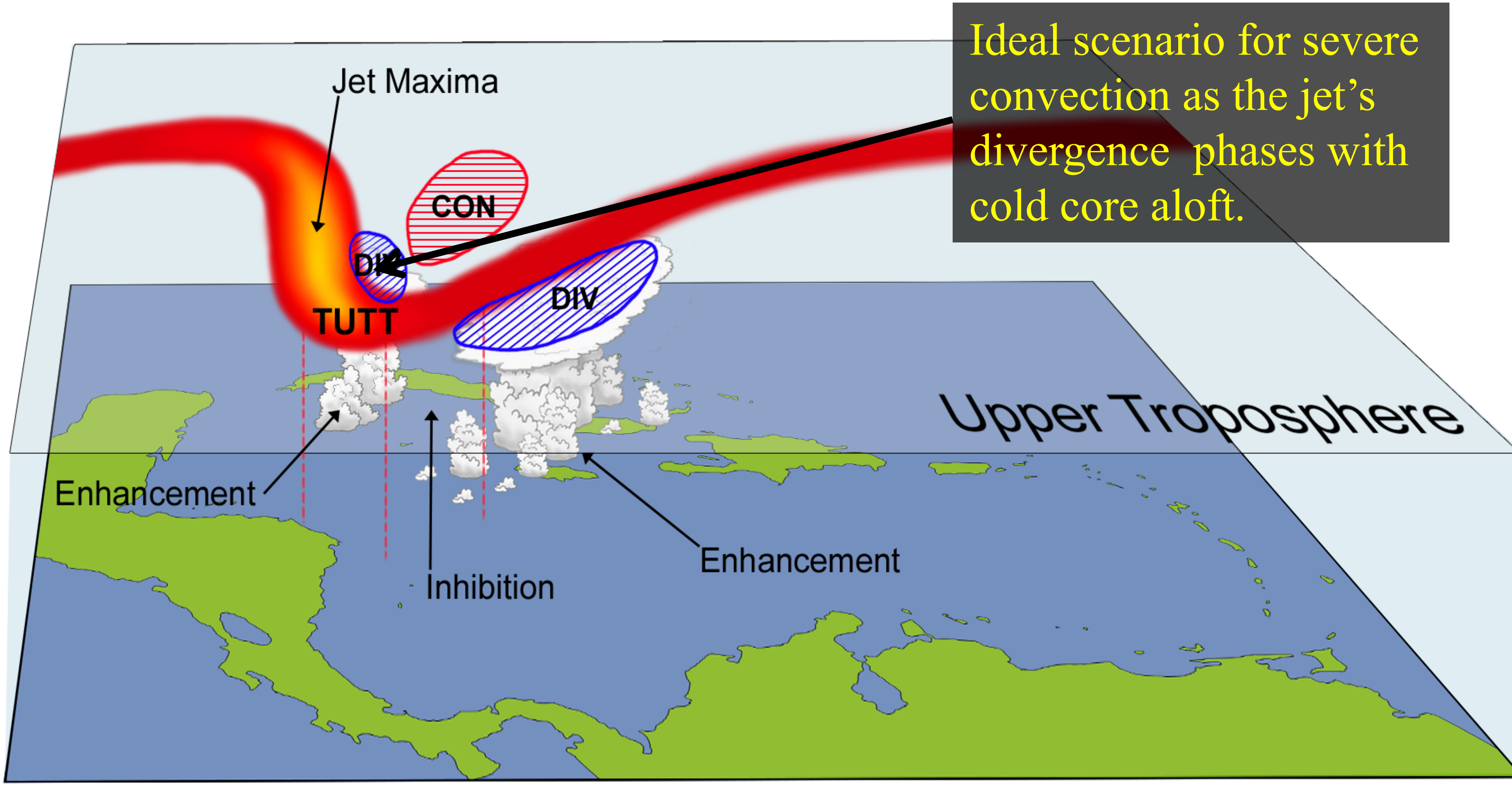
- In a ***negatively tilted*** trough axis with height, best upper divergence lies to the west of main axis.
- Upper convergence to the east of main axis.
- Some areas of upper convergence along its axis.



Jet Rounding a TUTT

Jet Maxima Upstream (to the west)

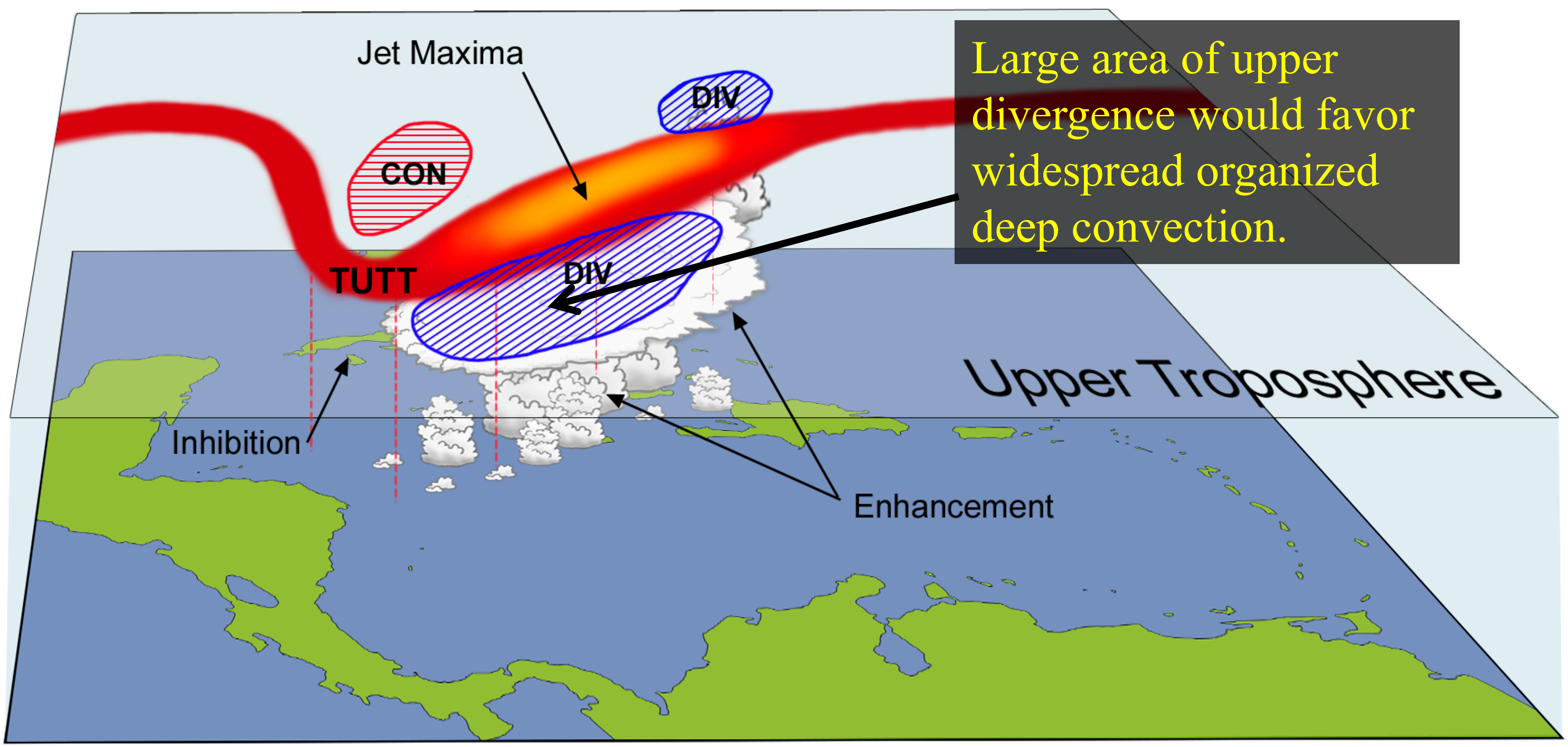
- Best upper divergence to the southeast of TUTT.
- Some upper divergence on upper jet's left exit.
- Upper convergence along TUTT's axis.



Jet Rounding Base of the TUTT

Jet Maxima Downstream (to the east)

-Upper divergence **boosted** to the southeast of TUTT.
-Some upper divergence on upper jet's left exit.
-Upper convergence along TUTT's axis.



Scale Interactions

Tropical Wave Interacting with a TUTT

TUTT-Tropical Wave Interactions

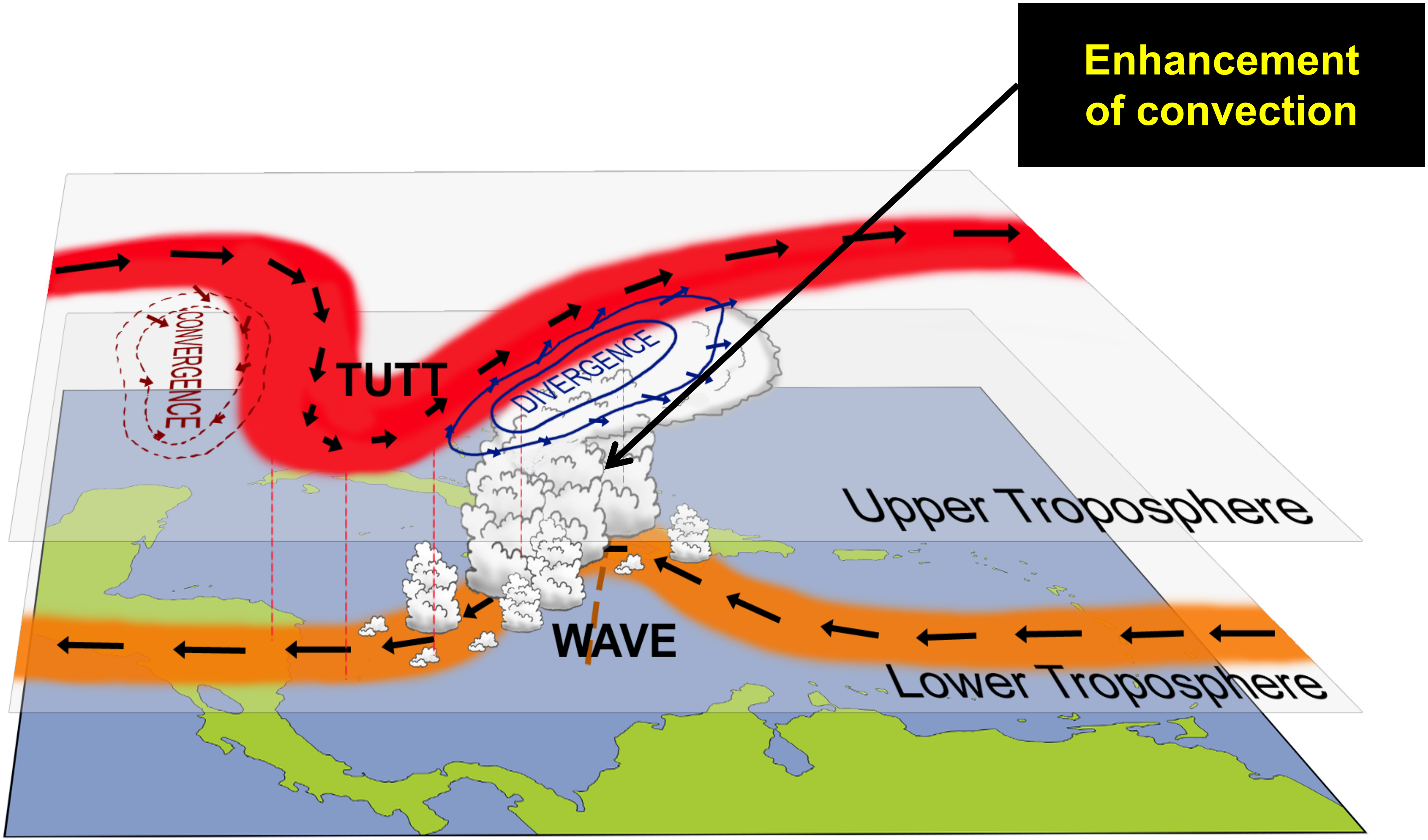
- TUTTs and tropical (easterly) waves are meso-synoptic systems.
- What happens when a tropical wave propagates underneath a TUTT?

TUTT-Tropical Wave Interactions

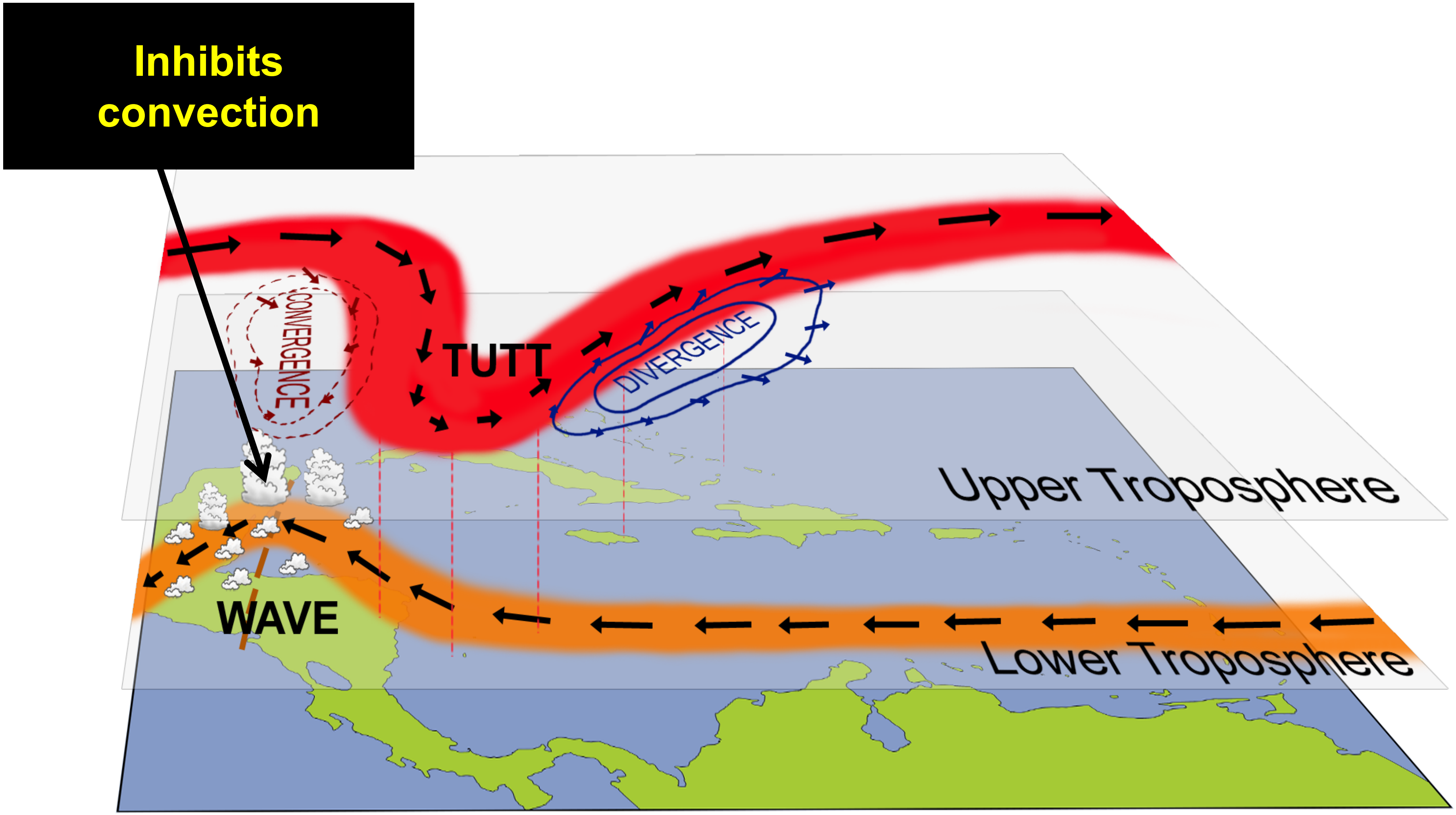
Both positive or negative interactions are possible. It depends upon the relative position of the systems.

- **Positive interactions**: when region of convection associated with the tropical wave phases with upper divergent region of TUTT.
- **Negative interactions**: when region of upper convergence associated with the tropical wave phases with upper convergent region of TUTT.
  - Also, when the tropical wave enters region of large vertical shear associated with TUTT.

Positive Interaction



Negative Interaction



How to differentiate between an induced trough from a tropical wave?

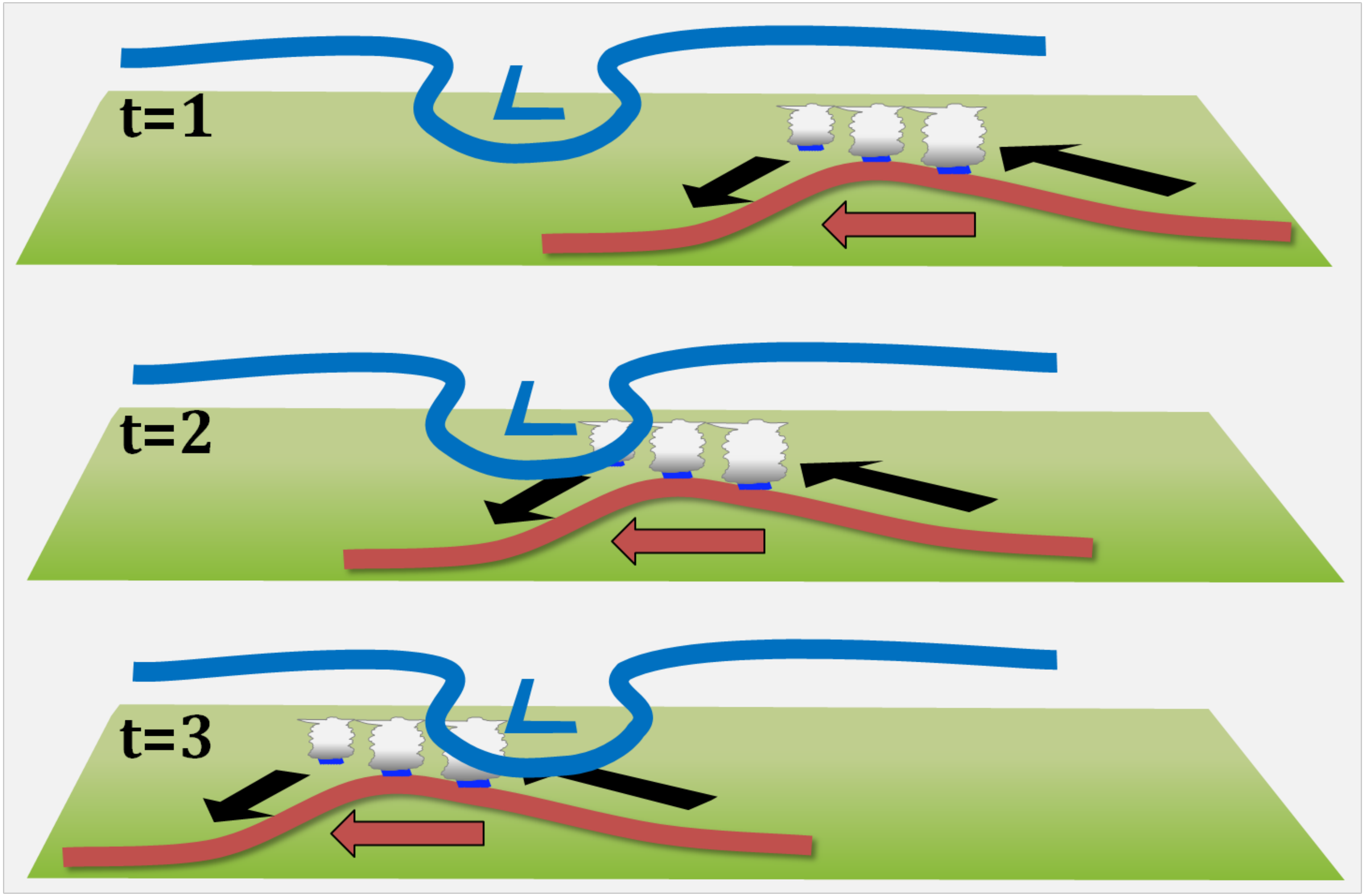
By analyzing the movement and origin of the system!

- If a trough in the low-level easterlies is ***moving independently from mid/upper tropospheric systems***, it is a Tropical Wave.

- If a trough in the low-level easterlies ***moves in-tandem*** with a TUTT it is likely that it is an induced trough.
  - But, as the upper trough weakens, and the low level trough decouples, it can evolve into an easterly wave.

- However, occasionally a tropical wave and a TUTT can enter in phase and will appear to move in unison. This is why it is important to determine the origin of each system.

Tropical Wave: Moving *Independently*

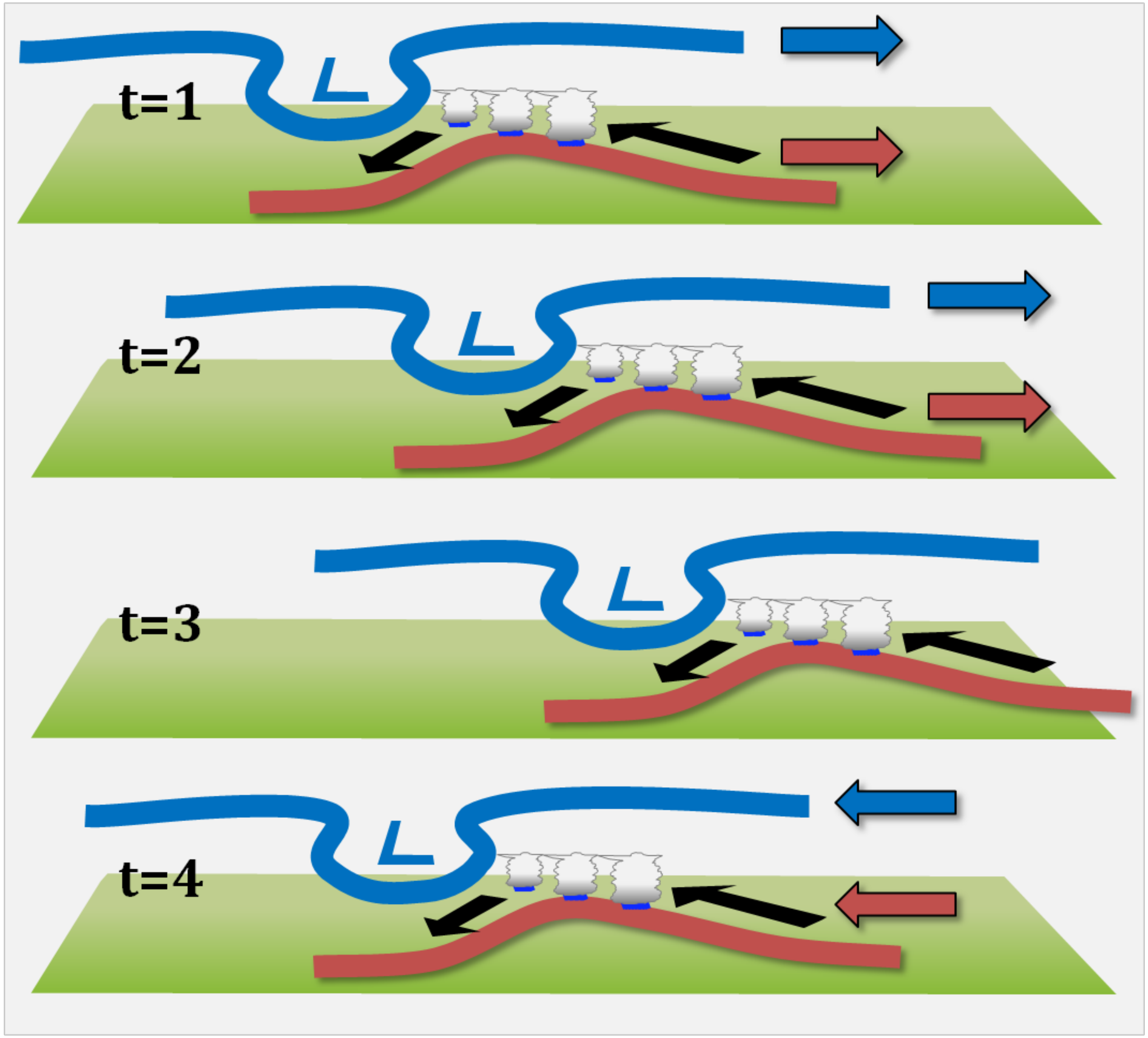


The TUTT aloft is stationary, wave in the trades is moving west

Induced Trough: In-Tandem with TUTT

TUTT and the induced trough moving to the East

TUTT and the induced trough retrogressing to the West



Summary of Characteristics

TUTT Induced Trough	Tropical Wave
•Cold core dominates ○ Cannot evolve directly into a Tropical cyclone (warm core system). ○ Could first evolve into a subtropical cyclone (hybrid system)	•Combination of warm/cold core. ○ Could directly evolve into a tropical cyclone (is the seed).
Movement: Controlled by upper flow.	Movement: Controlled by the lower troposphere.
Origin: Induced by a trough generally to its northwest	Origin: **Instability along on the African Easterly Jet and latent heat release in organized deep convection and also monsoon trough of Tropical North Africa**

Tools to differentiate wave type

	Induced Trough	Tropical Wave
Water Vapor Image	Best tool to assess the presence and depth of an upper cyclone (TUTT).	Determine sources of upper level ventilation, or the lack of.
IR and Visible Images	• Good to find inverted "V" troughs in low-level cloud fields. • Ci/Cs might hint presence of upper trough..	Good to find inverted "V" troughs in low-level cloud fields.
Flow analysis	500-200 hPa for upper trough, 850-700 hPa for low level trof.	850-700 hPa
Movement of low-level trough	• It moves **in-tandem** with upper trough. • Could remain stationary or , if the TUTT is retrogressing, progress at 05-15 kt.	• Low-level trough moves **independent** from upper systems. • They move at 10-20 kt. •Negatively tilted tend to be faster.

Poll Question #3
(Select all that are true)

- A TUTT is a deep layer/tropospheric trough
- For a TUTT to induce and EW, **it must** reflect at mid levels
- Divergence with a TUTT is always found on the east side
- A TUTT induced trough in the easterly trades is a tropical wave

Questions?

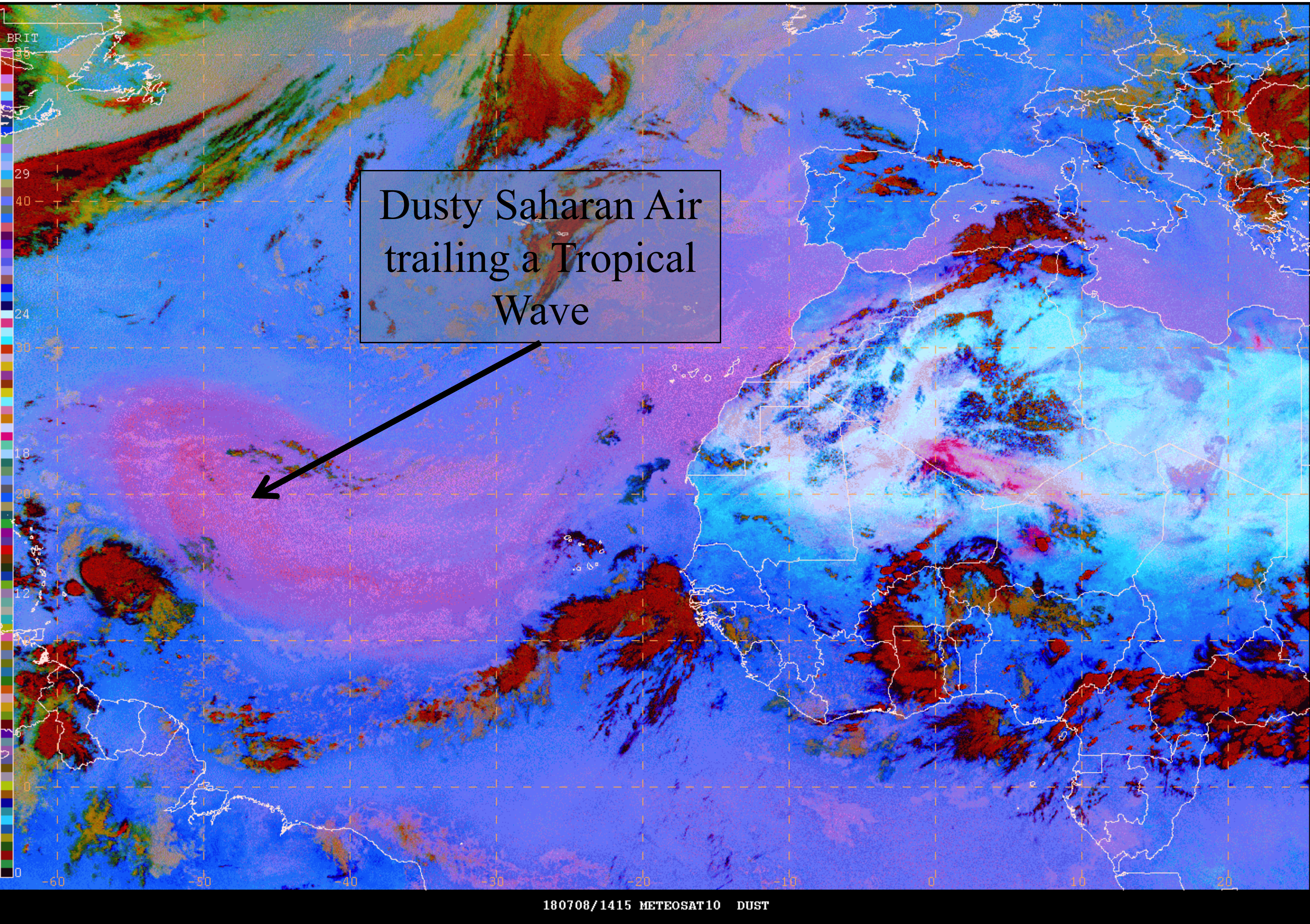
Saharan Air Layer and Trade Wind Surges

Other Perturbations in the Easterly Trades

Trade Wind Surges
Saharan Air Layer (SAL)

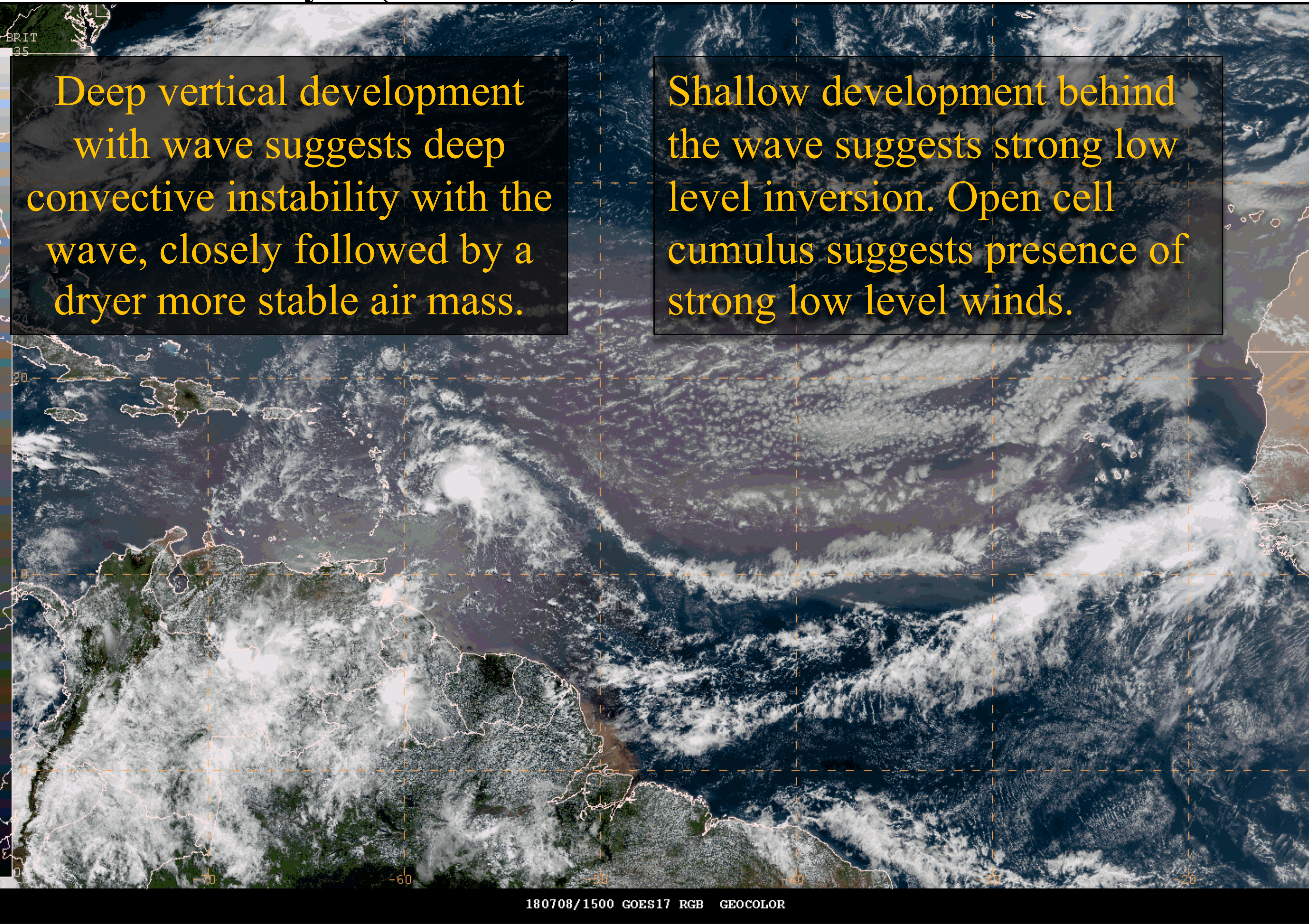
- Wind surges over Africa can trigger dust storms.
- In a shallow and stable layer, the dust spreads across the Tropical Atlantic to the Caribbean
  - As the gradient slackens, and the winds weaken, the dust gradually settles.

Saharan Air Layer (MSG Dust Product)

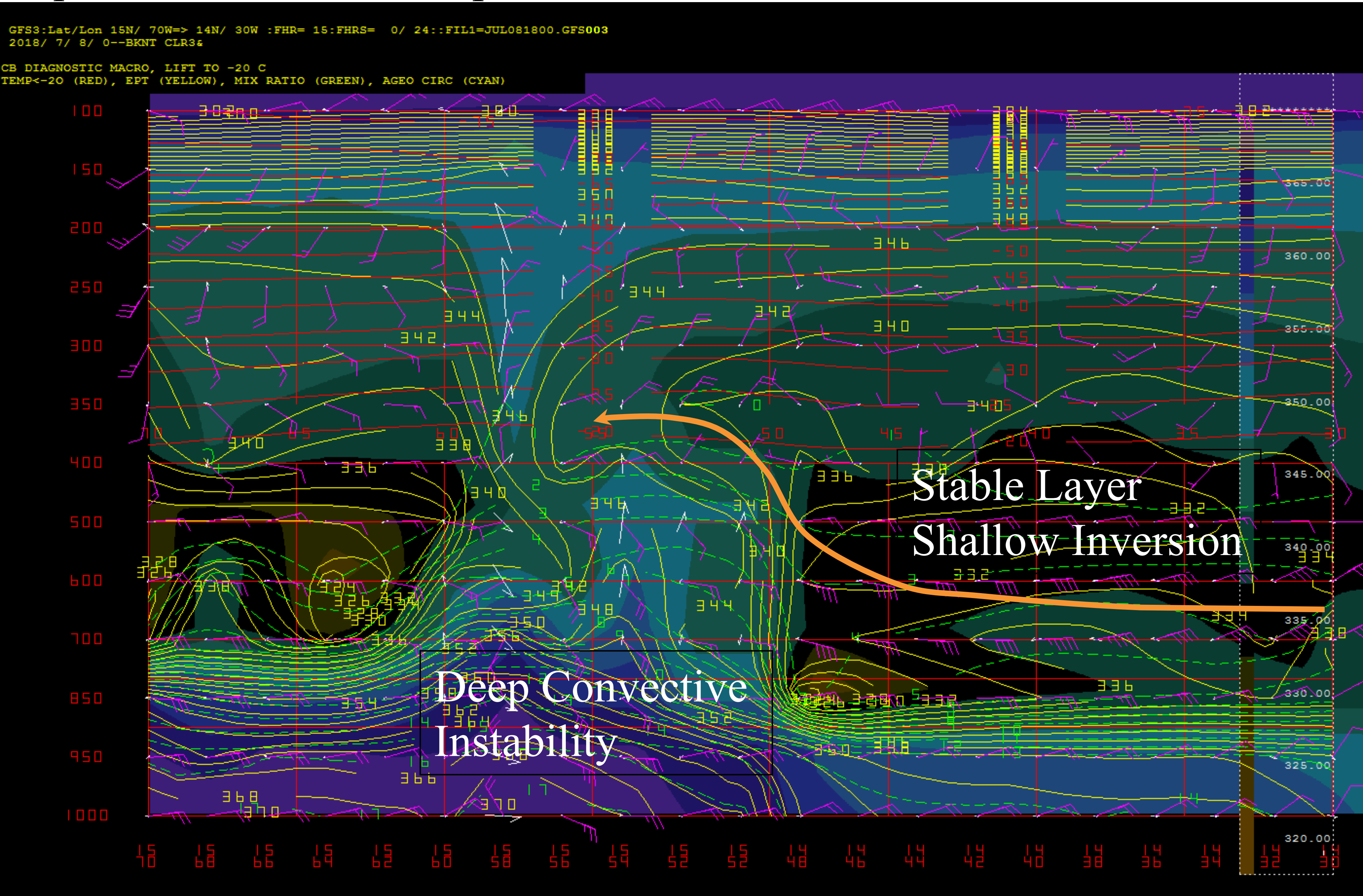


Saharan Air Layer (GOES-16, Geocolor Image

Saharan Air Layer (GOES-16, Geocolor

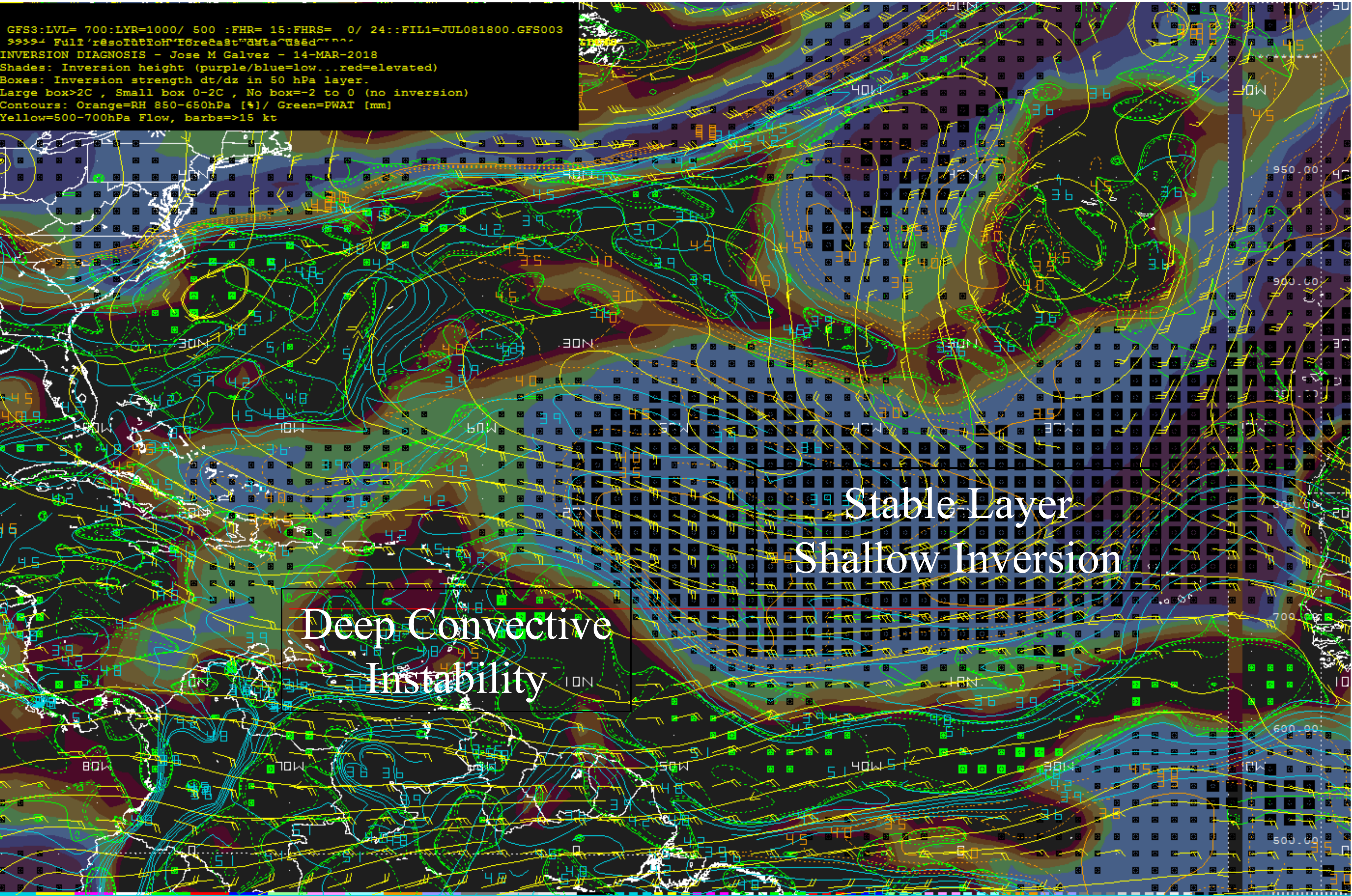


Vertical Cross Section
Equivalent Potential Temperature

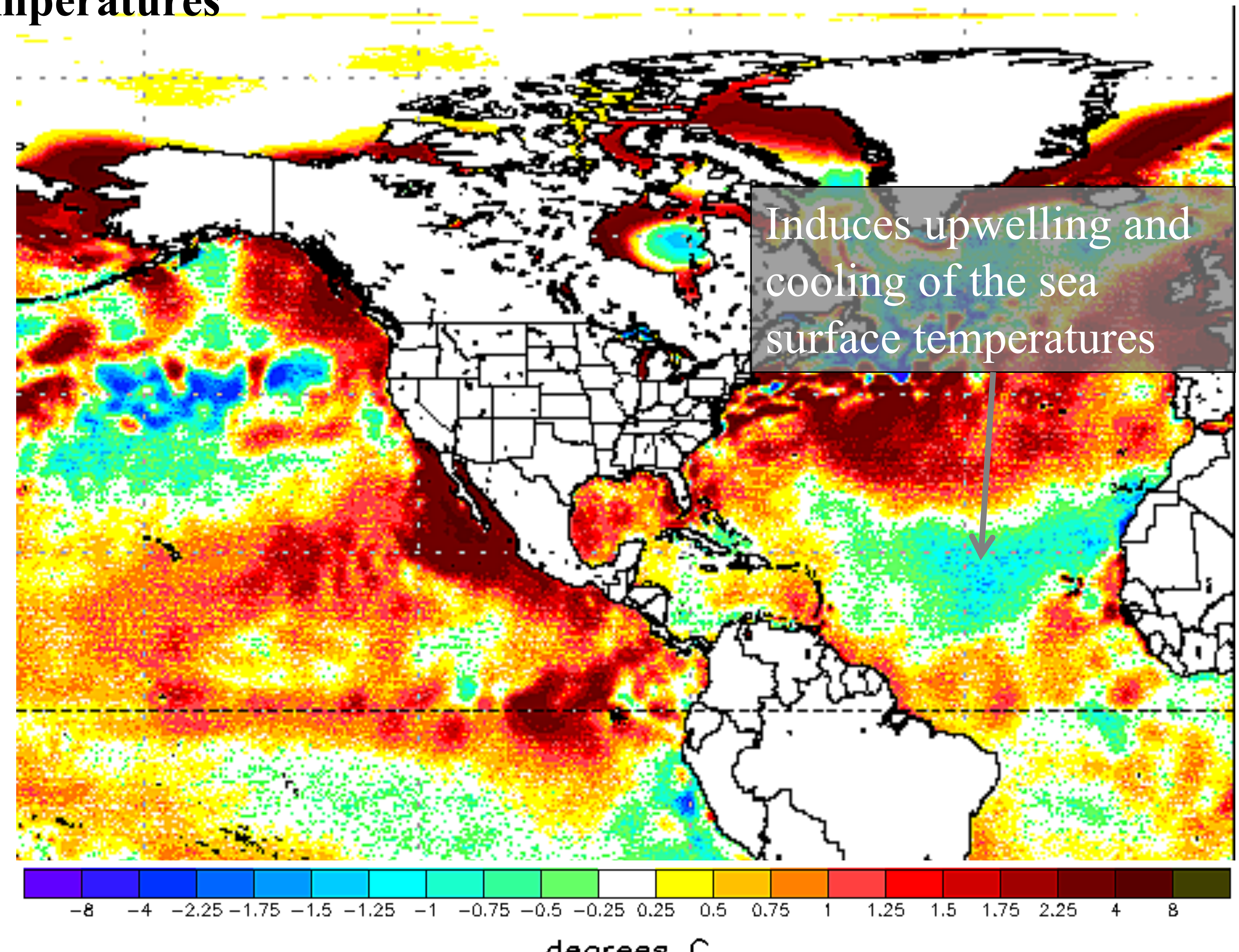


Trade Wind Inversion (TWIN.)

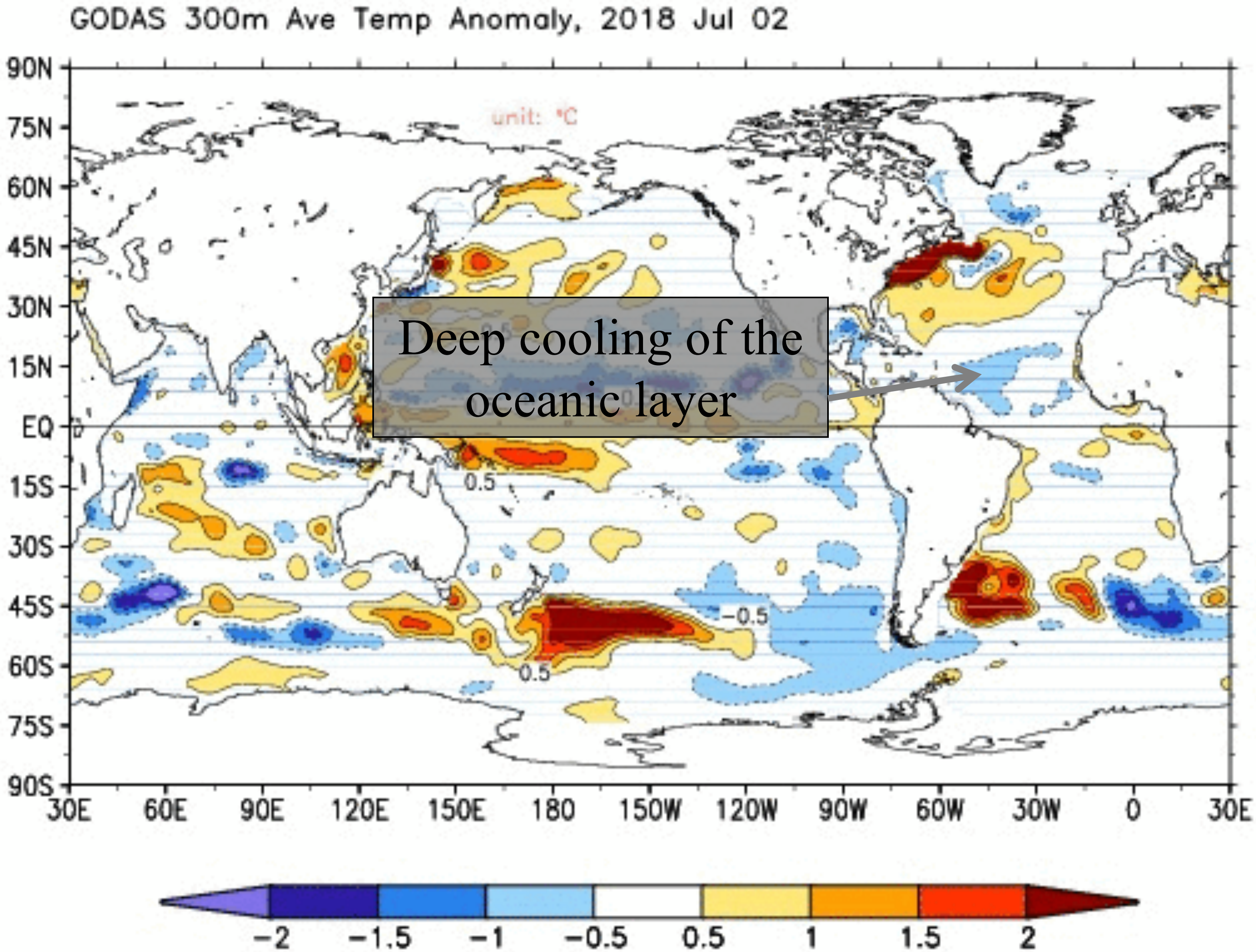
https://www.wpc.ncep.noaa.gov/international/wng/04_CAR/index.shtml



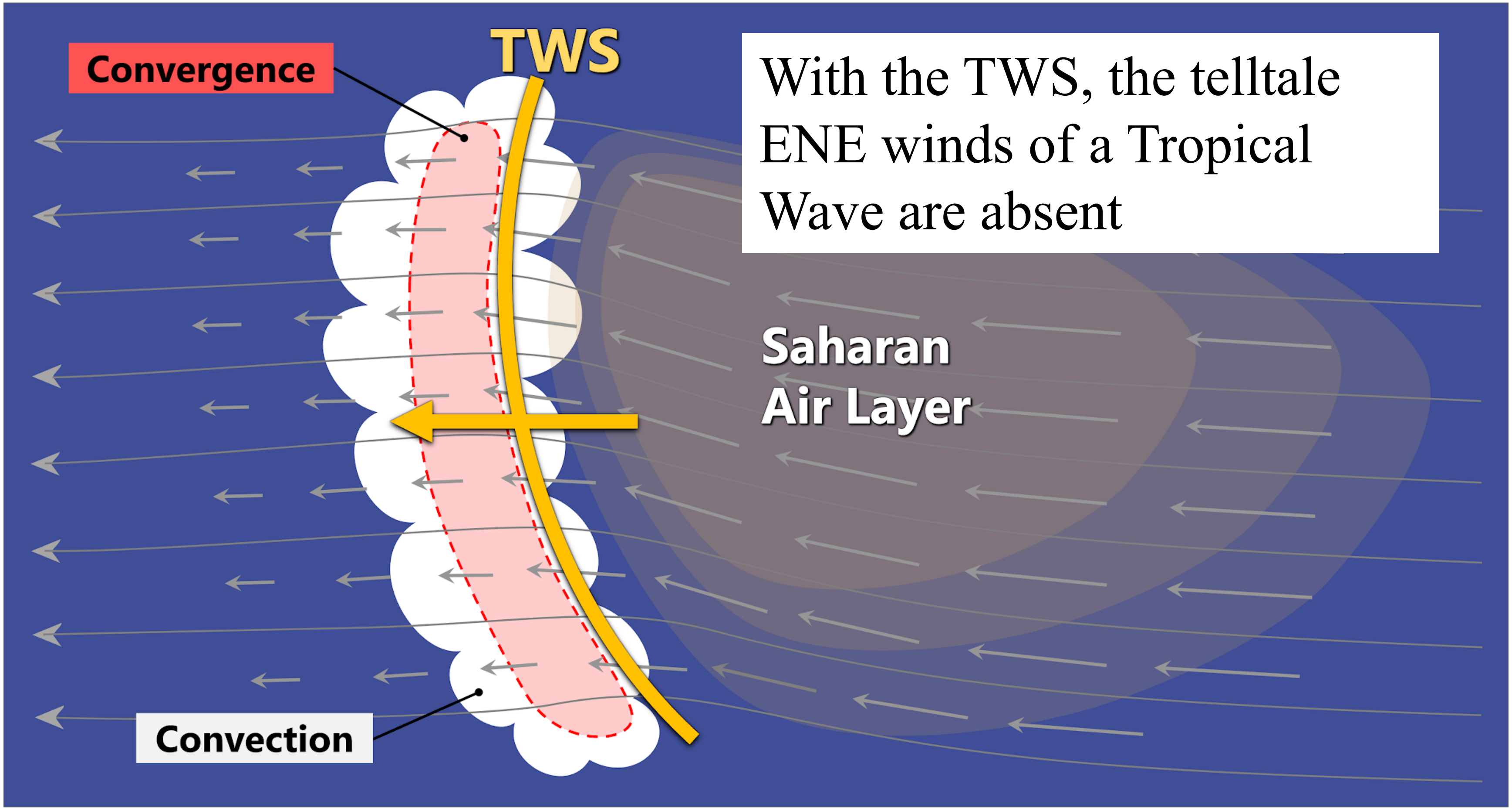
Impact of Trade Wind Surges on Sea Surface Temperatures



Average Sea Temperature Anomalies between SFC-300m



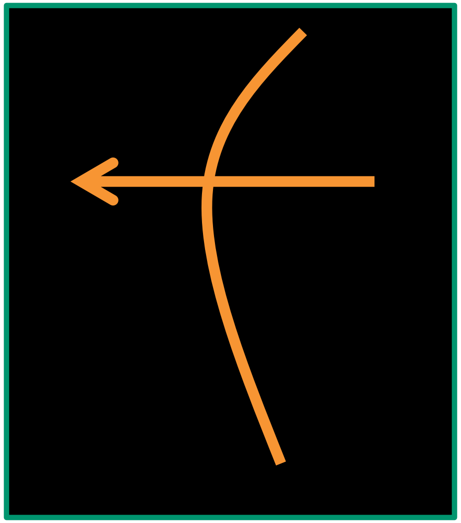
SAL with Trade Winds Surges (TWS)



Easterlies and convection typically precede the TWS, with winds shifting to the ESE following passage

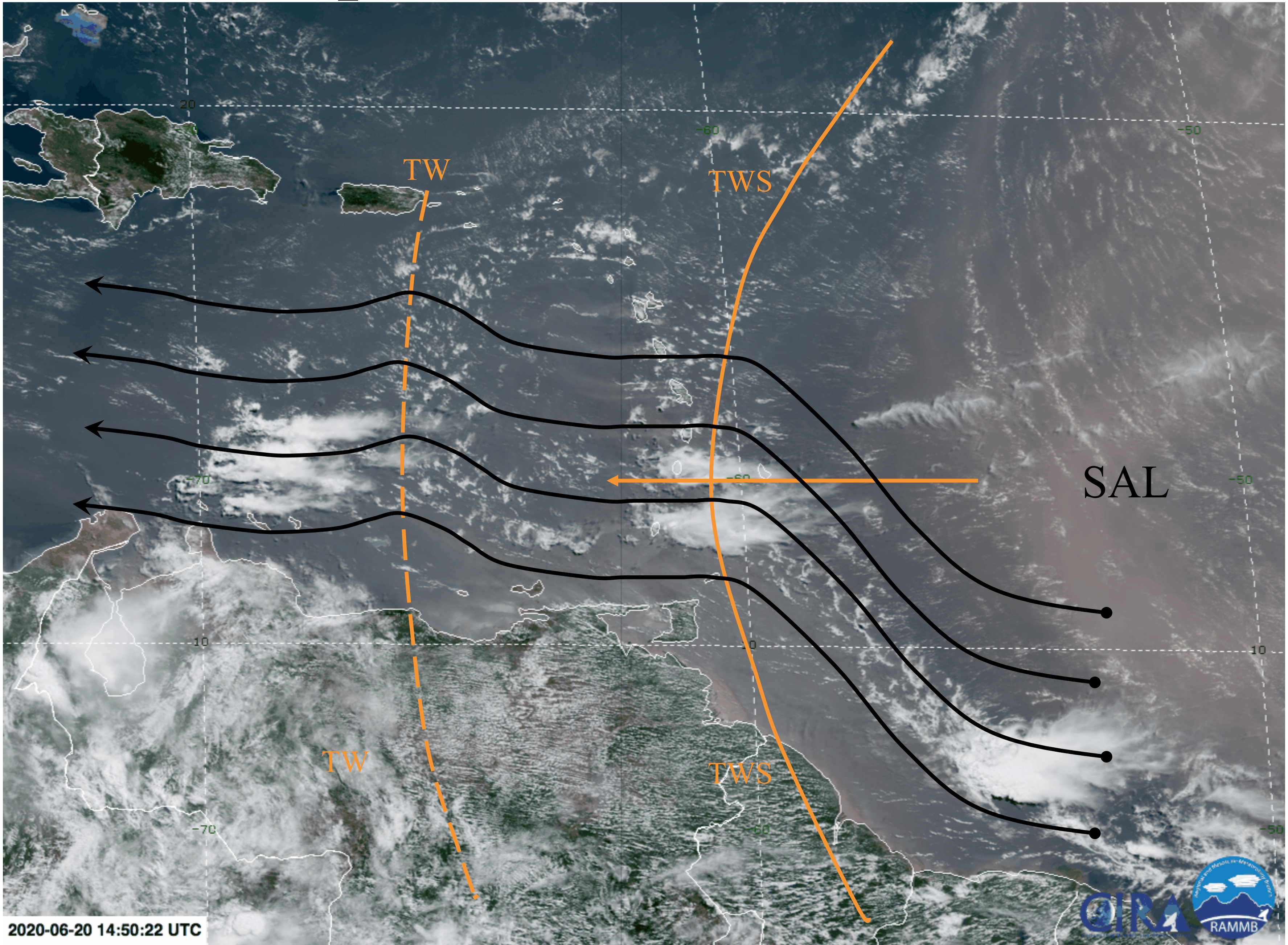
Trade Wind Surges

- Squally weather often precedes the wind surges
- Fair weather, windy and reduced visibilities follow.

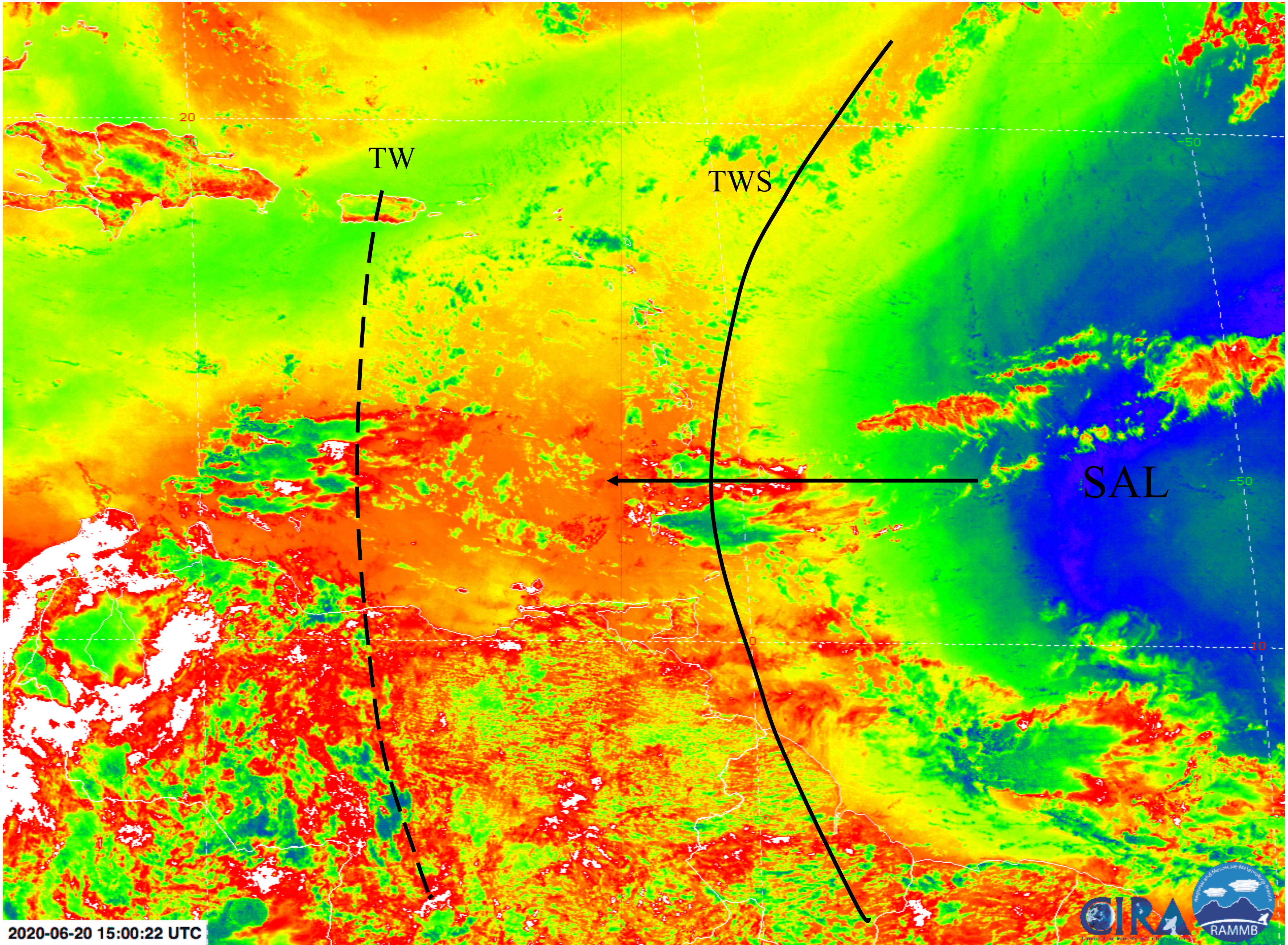


- The Bow and Arrow symbol was proposed to represent trade wind surges

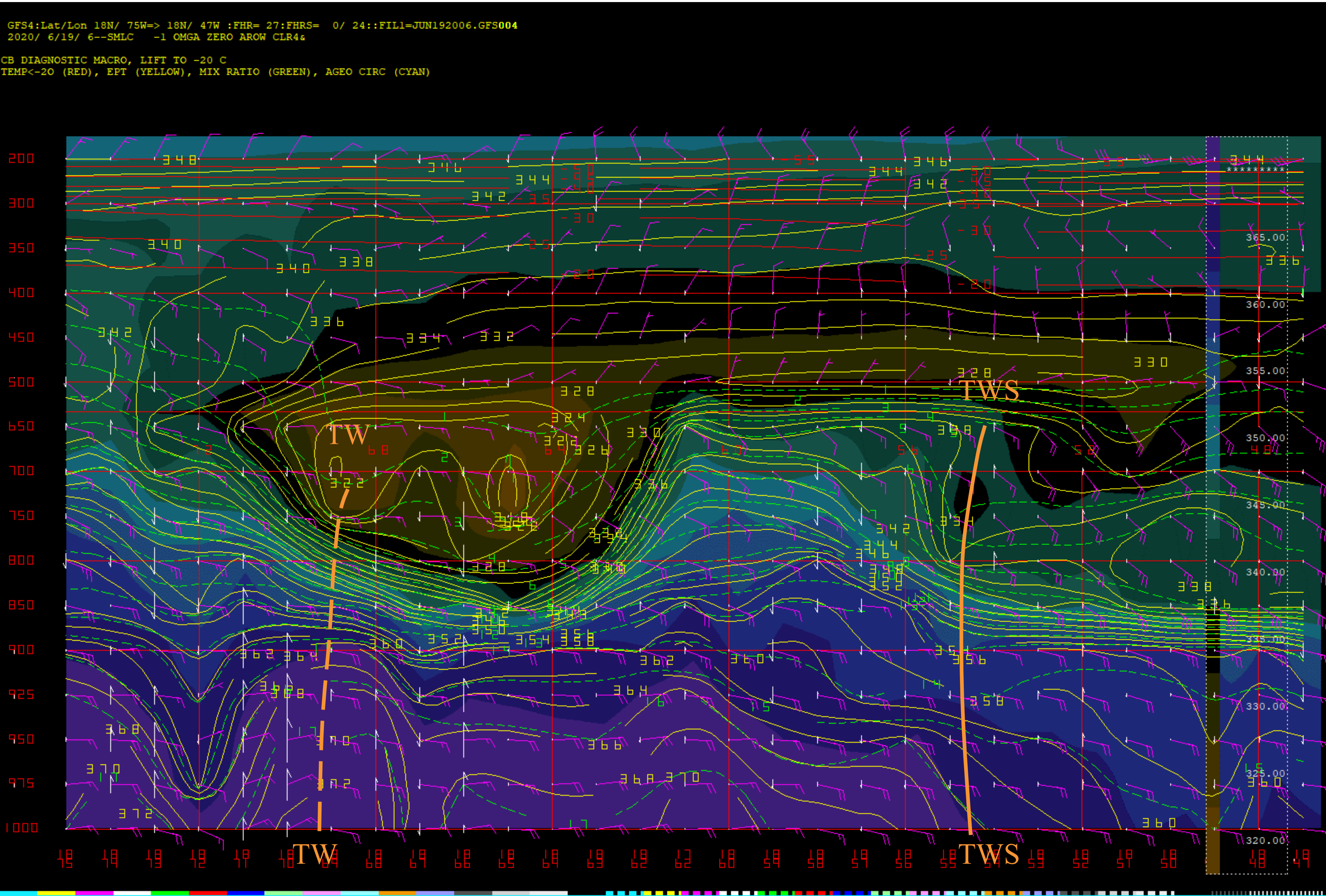
Tropical Wave or TWS?



GOES-16 Split Window (10.3-12.3 um)



Cross Section THTE



Dust Storm

Arabian Peninsula?

Trinidad & Tobago, June 20, 2020.
Courtesy Met Service