ICAO

# INTERNATIONAL CIVIL AVIATION ORGANIZATION

A UN SPECIALIZED AGENCY

# Vertical Motion and Convection, Cyclogenesis and Cyclone Types

José Manuel Gálvez

Researcher and Instructor

Axiom for WPC International Desks/NWS/NOAA

ICAO

# Overview

01 Mechanisms that induce vertical motions and implications

02 Cyclogenesis: Upper jets, troughs and other processes

03 Extratropical Cyclones

04 Tropical Cyclones

05 Subtropical Cyclones

# 01

# Mechanisms that induce vertical motions and implications

# Types of induced vertical motions

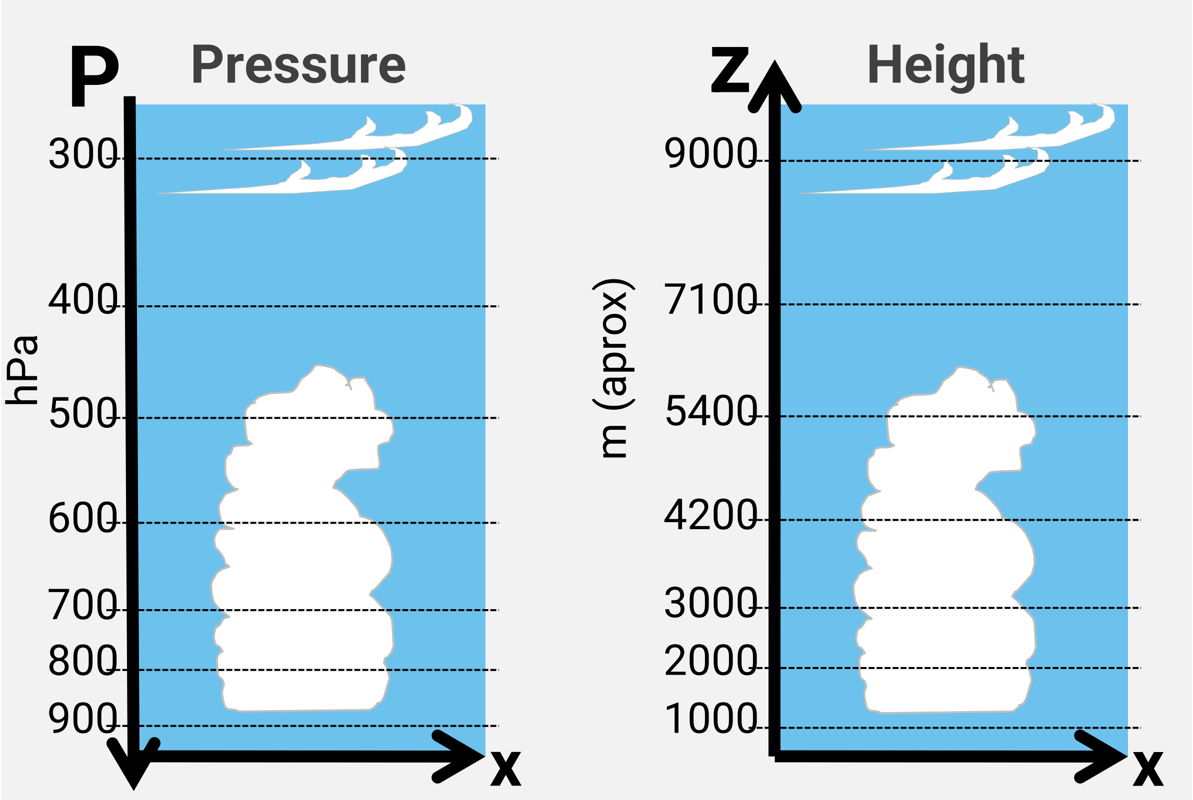
Vertical motions can be induced by:

1) thermodynamically (by the distribution of stability in the column)
2) dynamically (by features in the atmospheric flow)
3) mechanically (by flow interactions with terrain).

This section will focus on dynamically-induced vertical motion. Examples: Convergence/Divergence in low and upper levels; vorticity and advection, and role of upper jets.

# Vertical Coordinates for assessing motion

- Pressure decreases with height logarithmically.
- Pressure coordinates are most commonly used.
- Vertical motion is expressed as the change of pressure with time (dP/dt) or as the change of elevation with time (dz/dt). Their signs will be different.



# Vertical motion expressed in pressure and height coordinates

**P**

Omega→ **ω = dP/dt**

Change of pressure with time:

ω > 0 = descent (pressure increases)

ω < 0 = ascent (pressure increases)

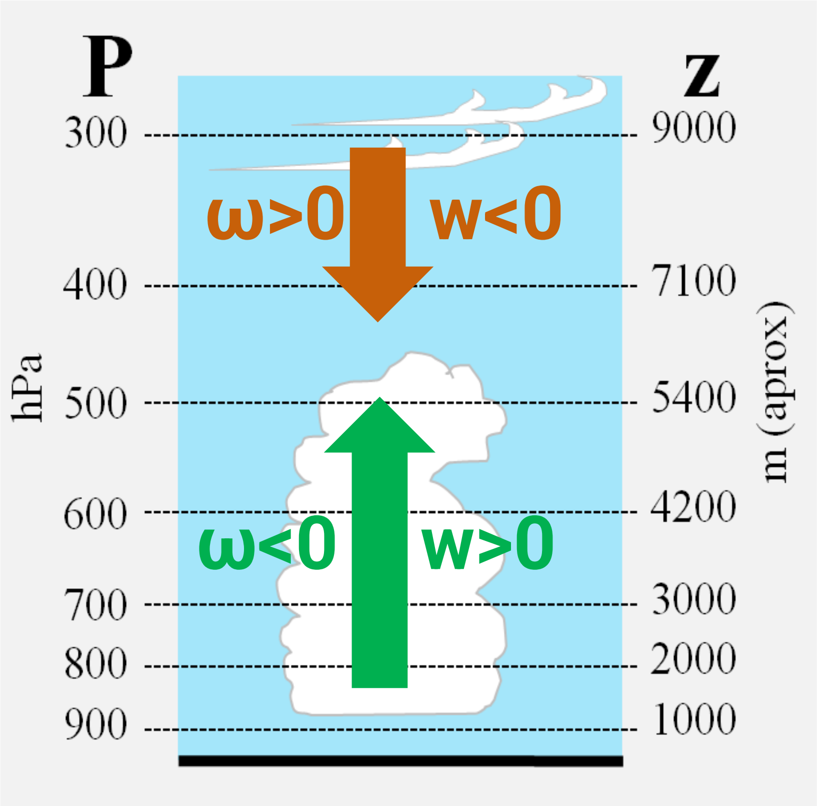
**Z**

**w = dz/dt**

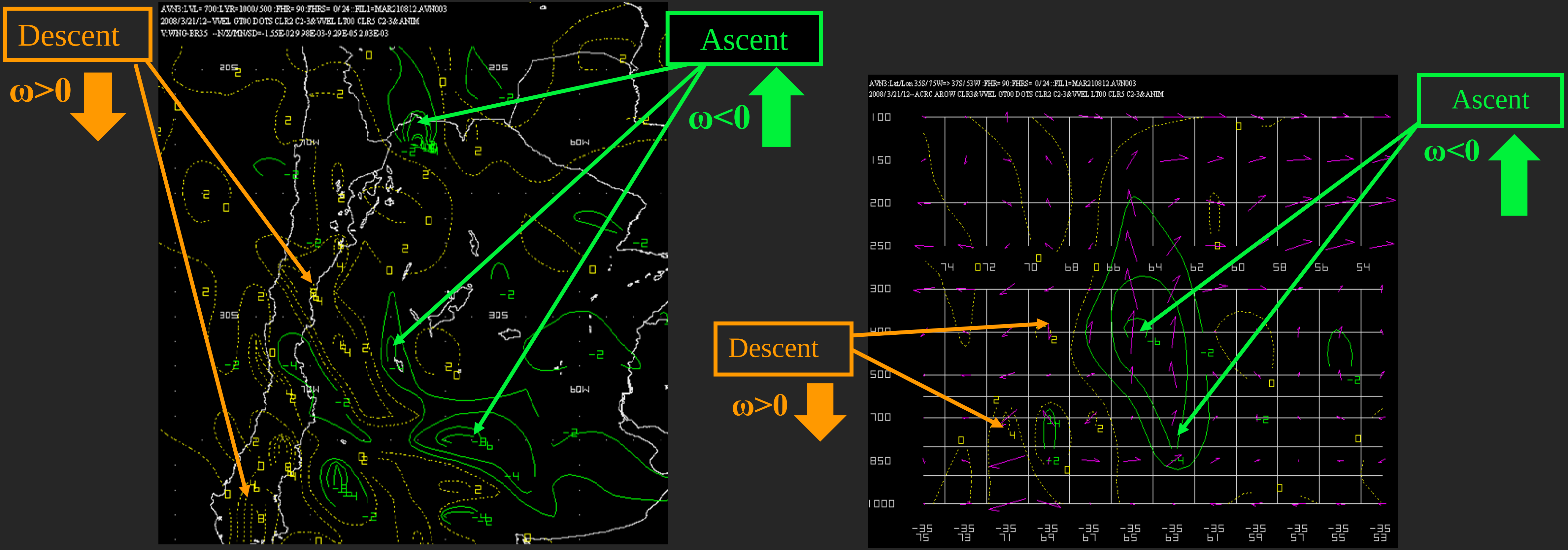
Change of elevation with time:

w < 0 = descent (elevation decreases)

w > 0 = ascent (elevation increases)



# Vertical Velocity (Omegas) in the GFS Model

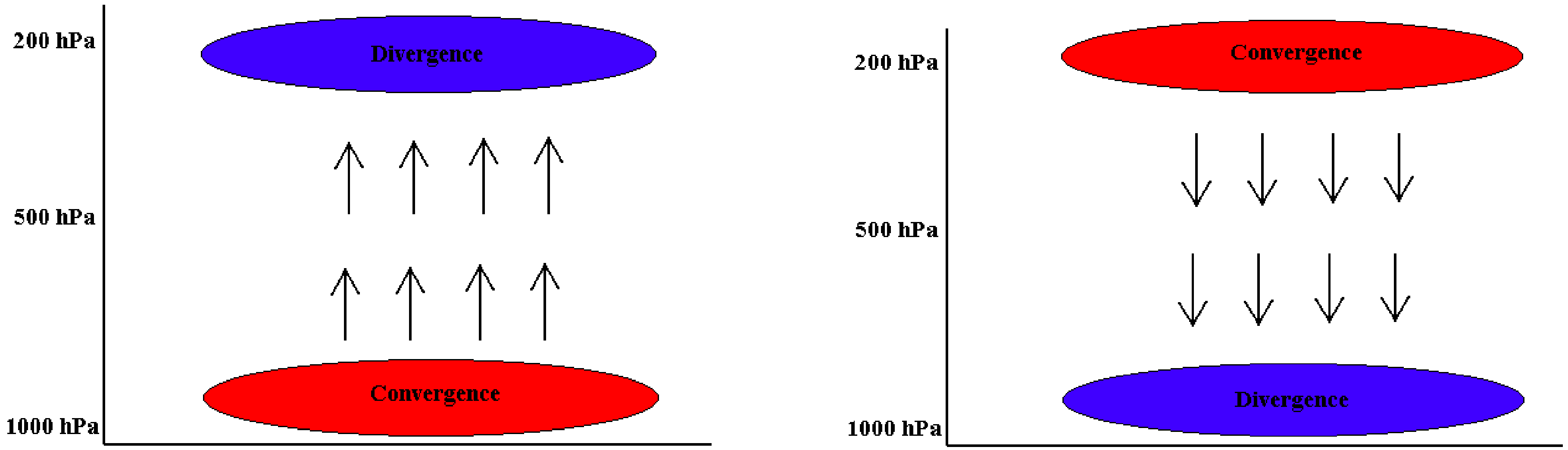


# Mechanisms that induce vertical motions dynamically

- Dynamically means induced by the flow.
- Most common mechanisms for inducing ascent:
    - Upper divergence and low-level convergence
    - Vorticity advection increasing with height
    - Geopotential height/pressure falls (decreases)
    - Ageostrophic circulations induced by upper jets
    - Approaching upper trough or easterly wave
    - Warm advection below, cold advection aloft (they induce a thermodynamic response by enhancing instability)

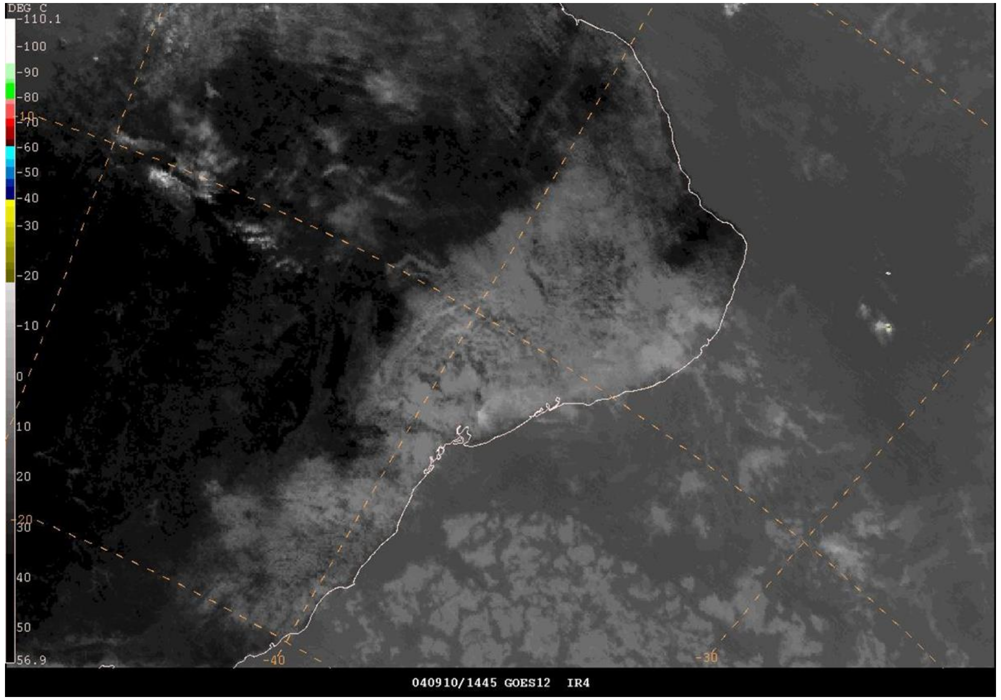
# Role of divergence and convergence in inducing vertical motions

## Deep layer ascent and descent

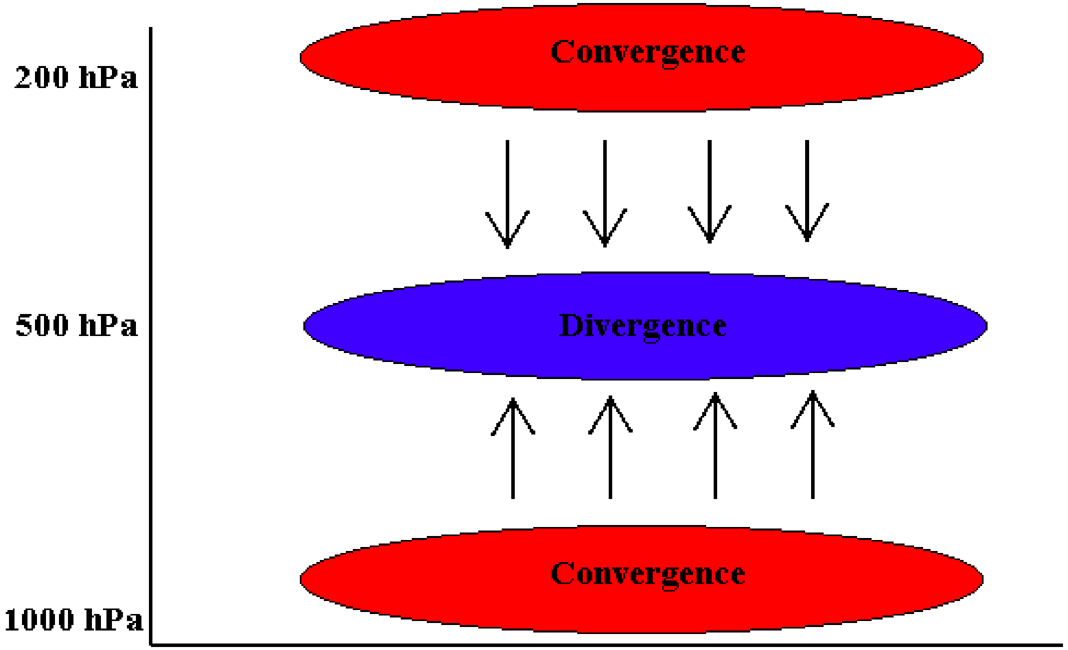


# Shallow Convection

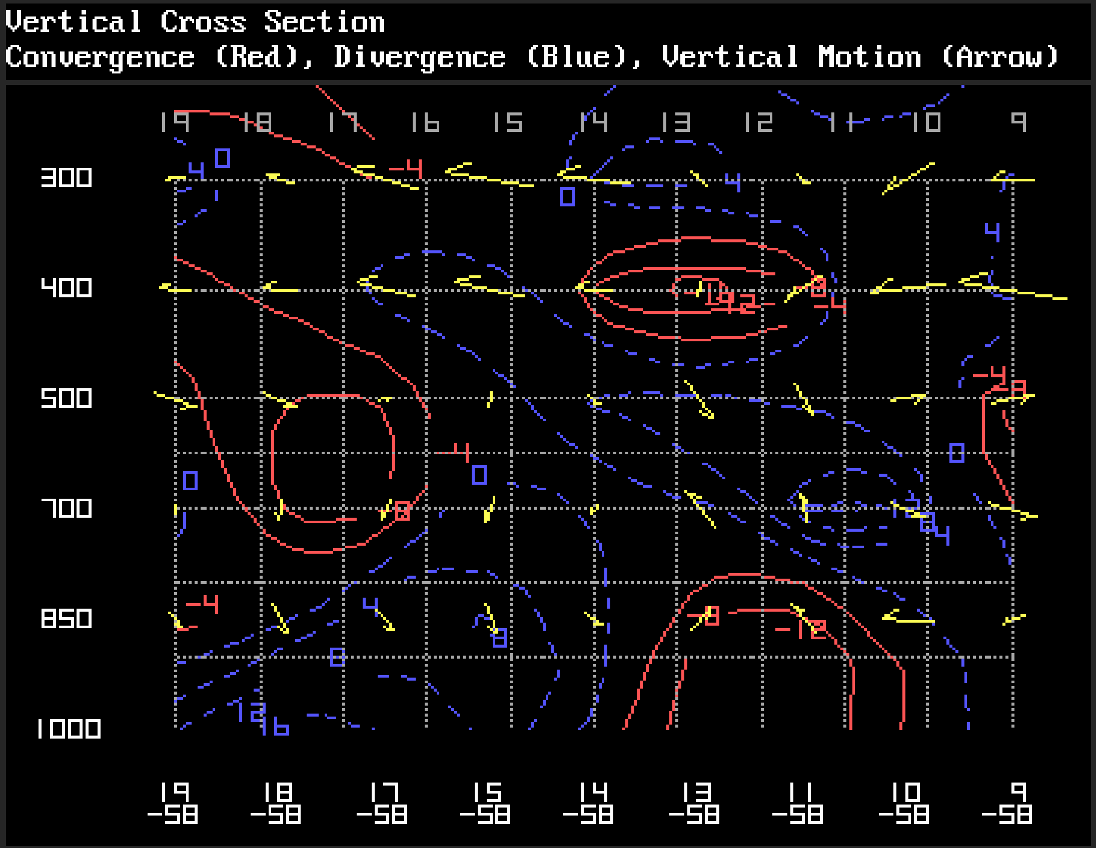
Shallow convection in northeast Brazil

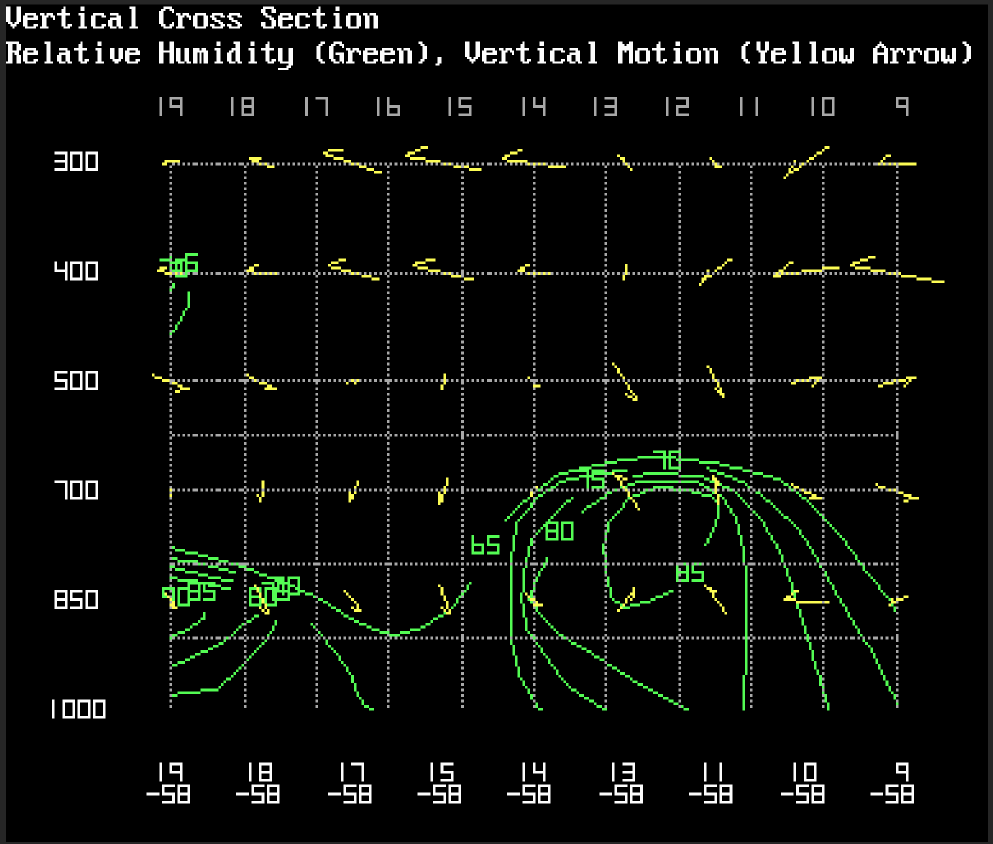



Vertical distribucion of divergence and convergence during shallow convection



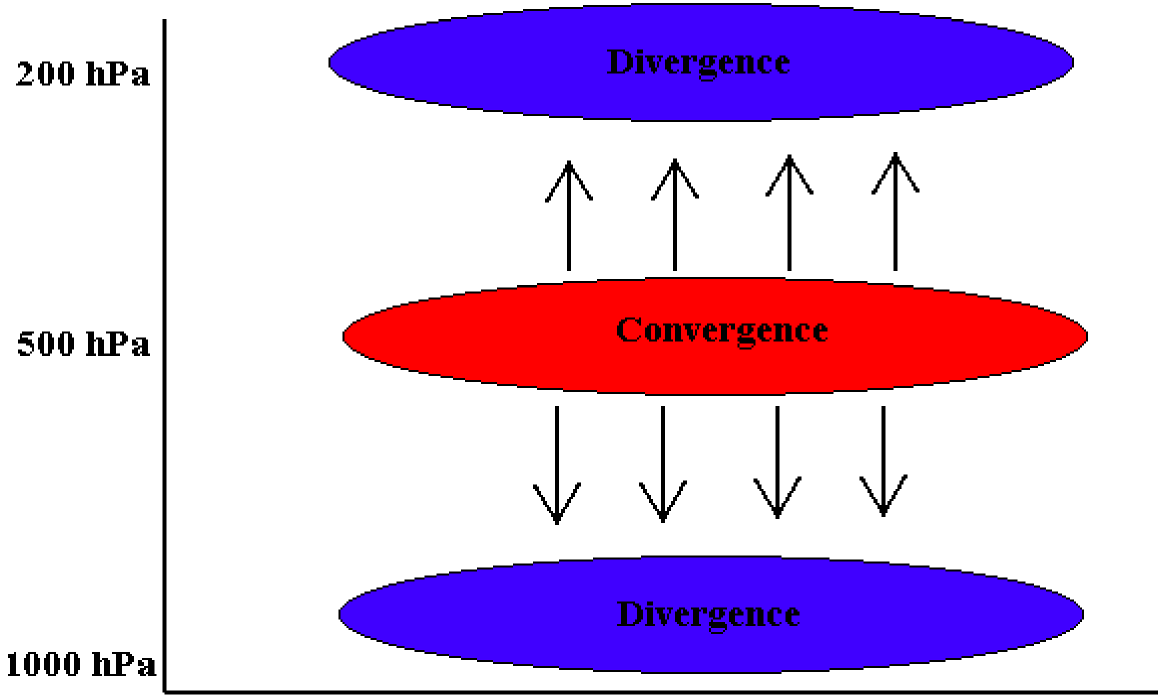
# Numerical Representation of Shallow Convection



# Subsidence in the low troposphere

- Enhanced convergence in the mid-troposphere favors subsidence in the low troposphere.
- Thie favor fair weather and minimizes the potential for convection and precipitation.
- It is very favorable for aviation as it tends to minimize turbulence.
- It can, however, favor low clouds and stratus decks, including fog. Fog can be a problem for landing and aircraft.

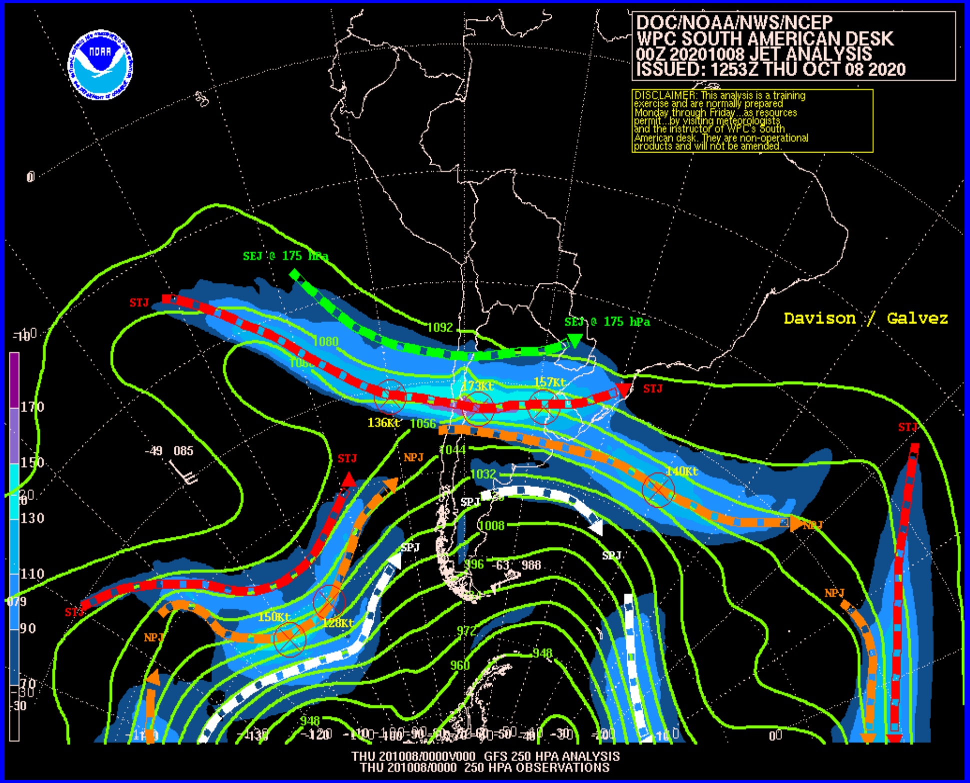


# 02

# Upper jet dynamics and cyclogenesis

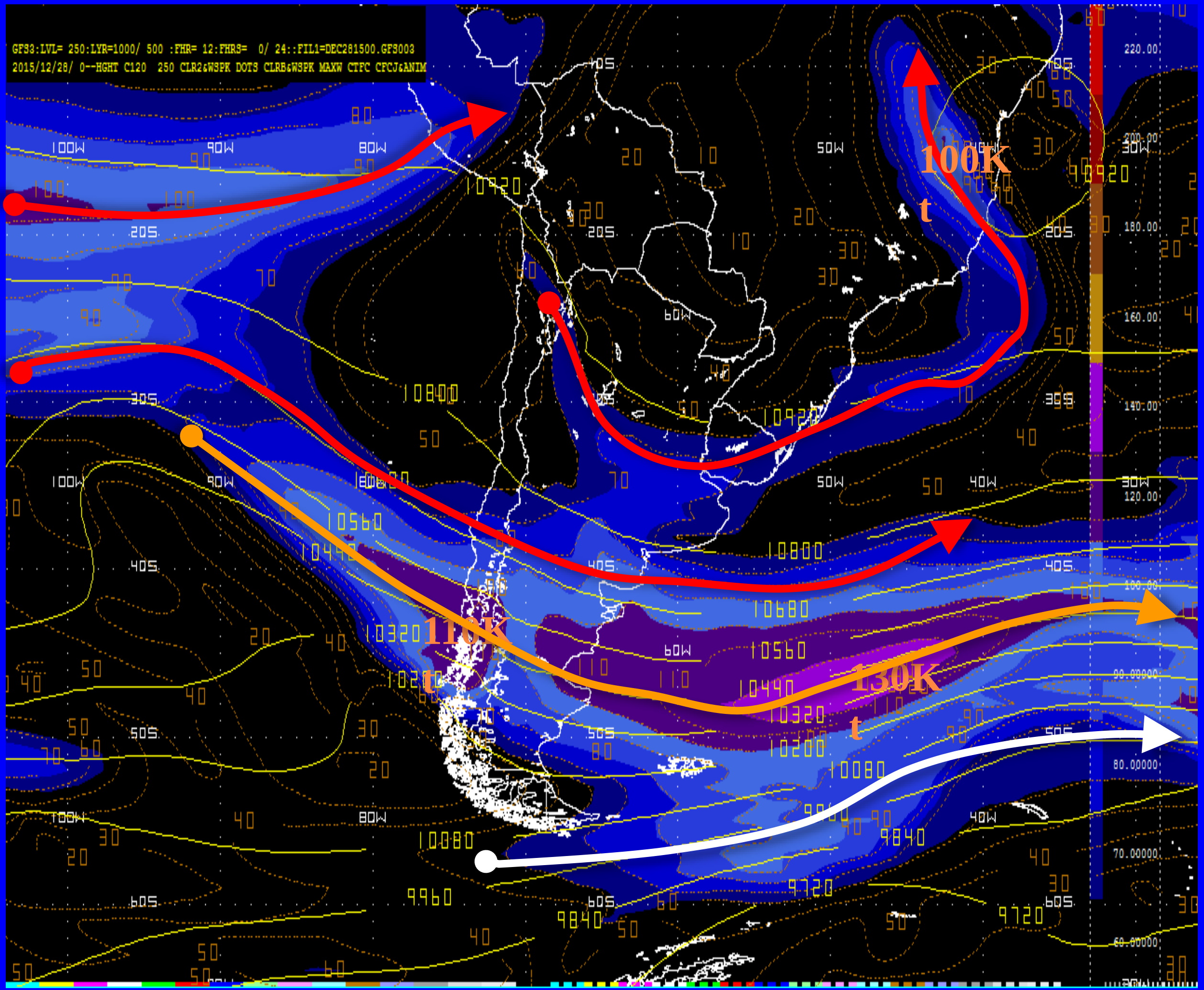
# Upper Jets: Definition

- Strong currents in the upper troposphere that respond to underlying termal, and associate with a sharp change in tropopause height (higher tropopause in the warmer side of the jet).
- **Official definition (ICAO):** strong currents that develop in the upper troposphere (250-150 hpa) with winds >70kt, and a máximum of >90kt is present. Separation between currents needs to be at least 5° of latitude.
- Operationally, however, the impacts can be felt when speeds exceed 35kt, especially in the Tropics where moisture and instability are higher.



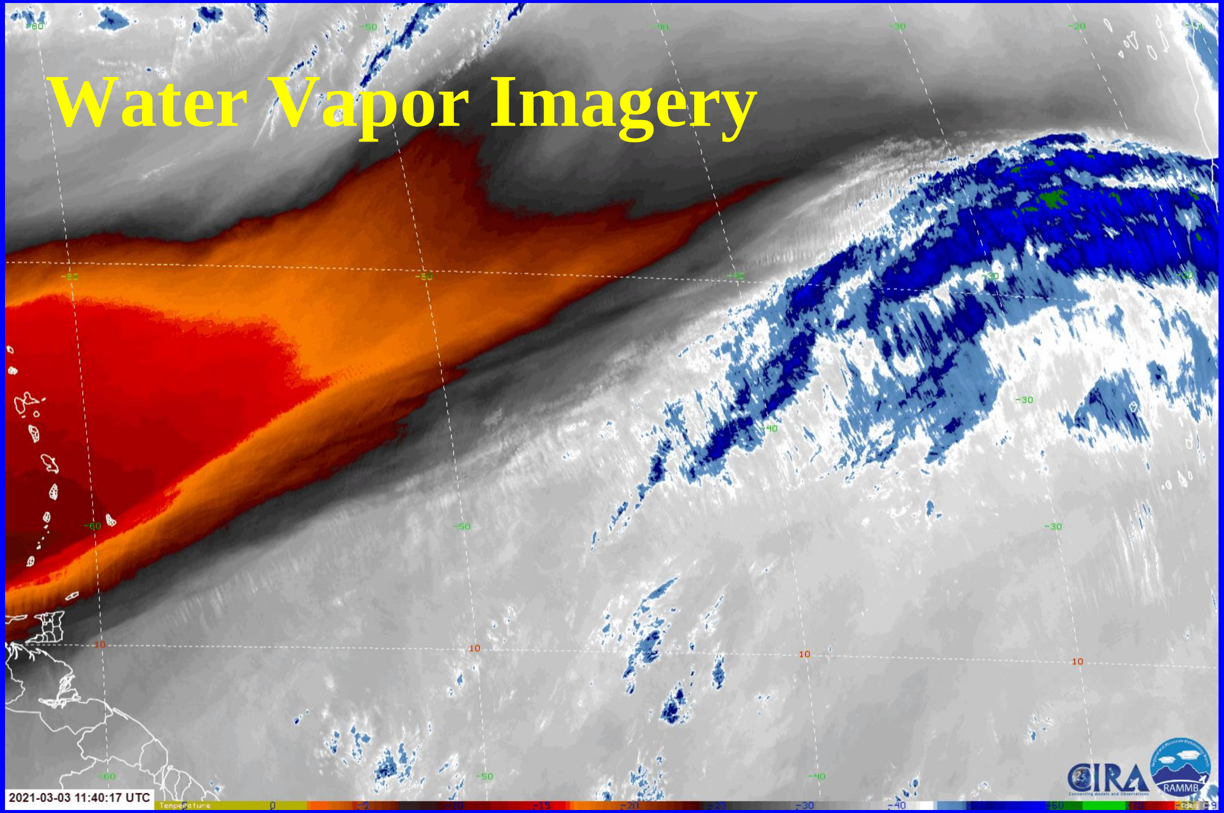
# Upper Jets in the Southern Hemisphere

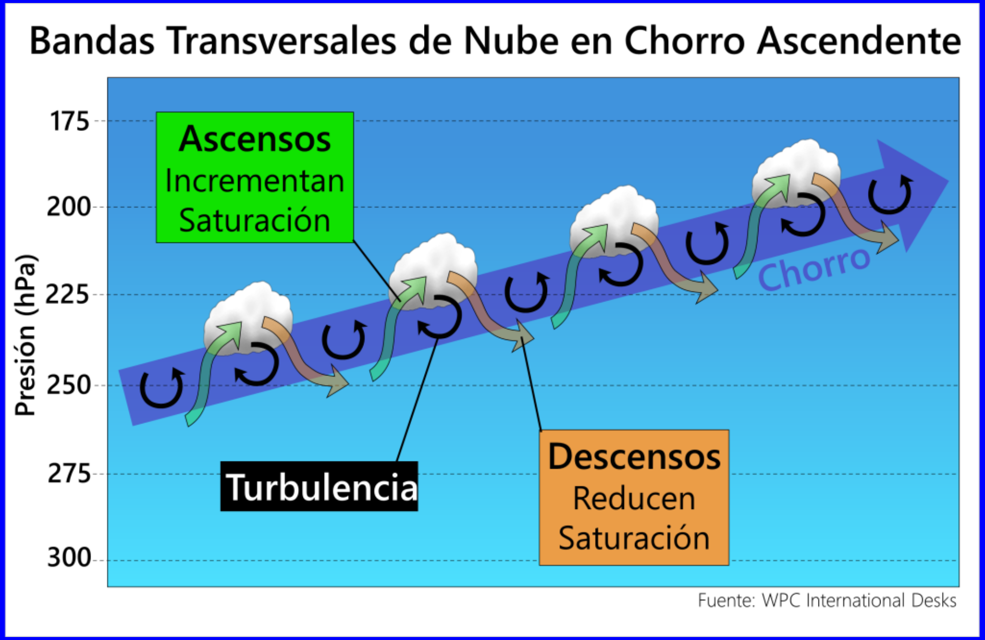
- 3 branches. South Hemisphere: subtropical jet (red), north polar jet (orange) and south polar jet (white).
- Subtropical (northernmost): 200-250 hPa.
- North Polar: 250 hPa.
- South Polar: 300-250 hPa.



# Transverse Bands

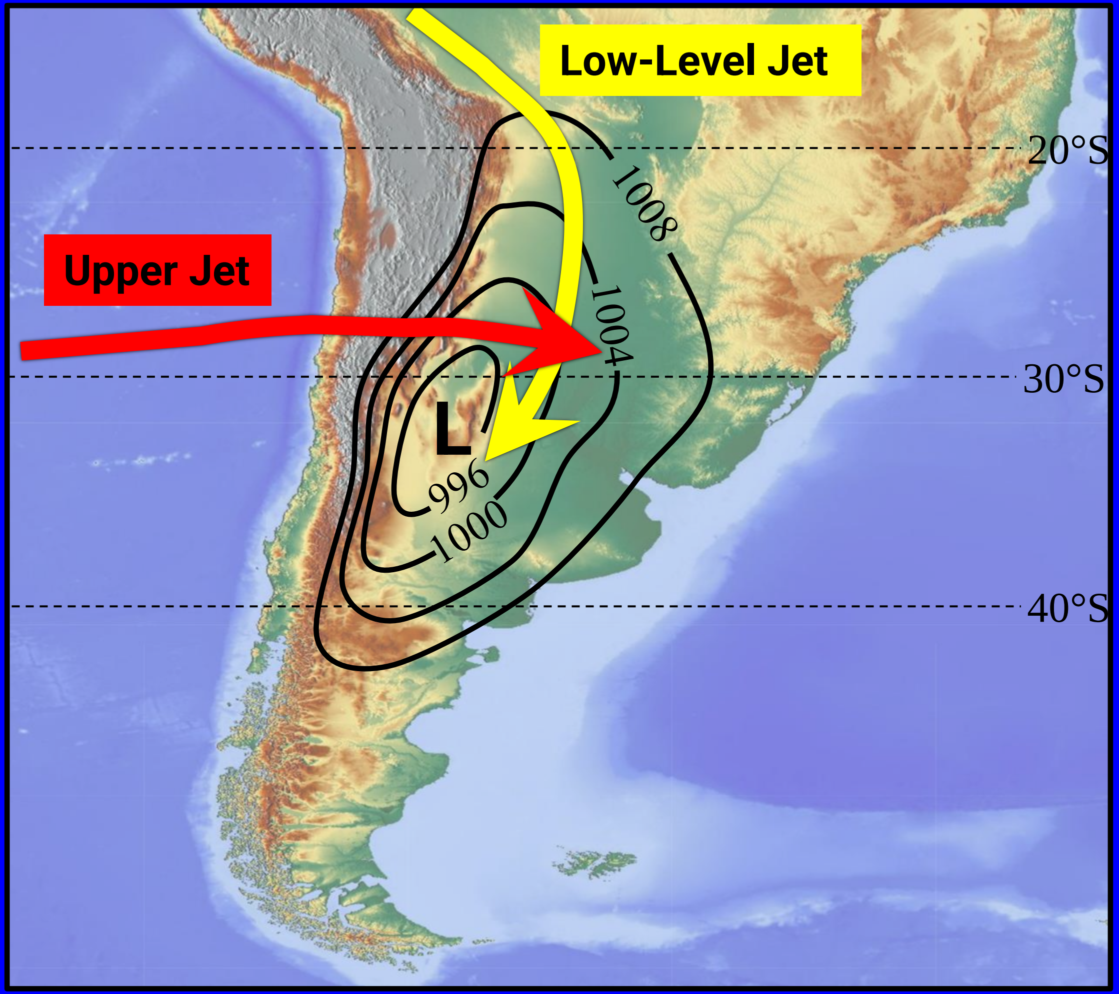
## Ascending Jet in a moist environment



# Impact of Jets in Lee Surface Pressure

- Jets crossing the Andes enhance adiabatic compression on the lee side, strengthening the Surface low.
- Similar to lee cyclogenesis east of the Rocky Mountains in the United States.
- Stronger jets result in lower Surface pressures. This strengthens the low-level jet fro the north, which transports moist air from the Amazon basin into Central Argentina.

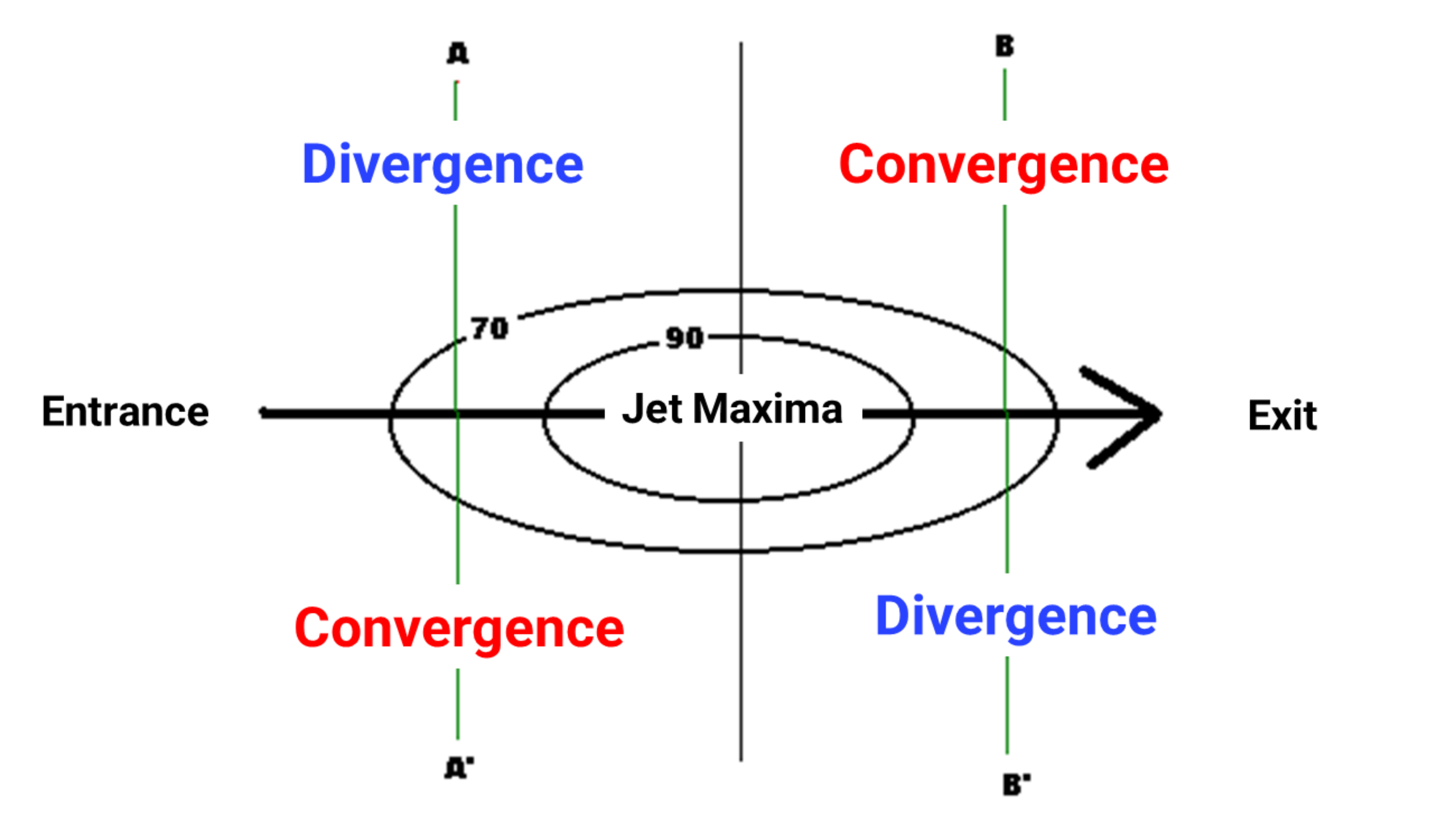


# Jet streaks

Induced circulations and cyclogenesis

# Conceptual Model of a Jet Maxima or "Jet Streak"

- The effects of Coriolis organize 2 regions of enhanced Upper divergence: in the warm side of the entrance and in the cool side of the exit.
- These are favorable for stronger ascent and processes such as cyclogenesis and frontogenesis.

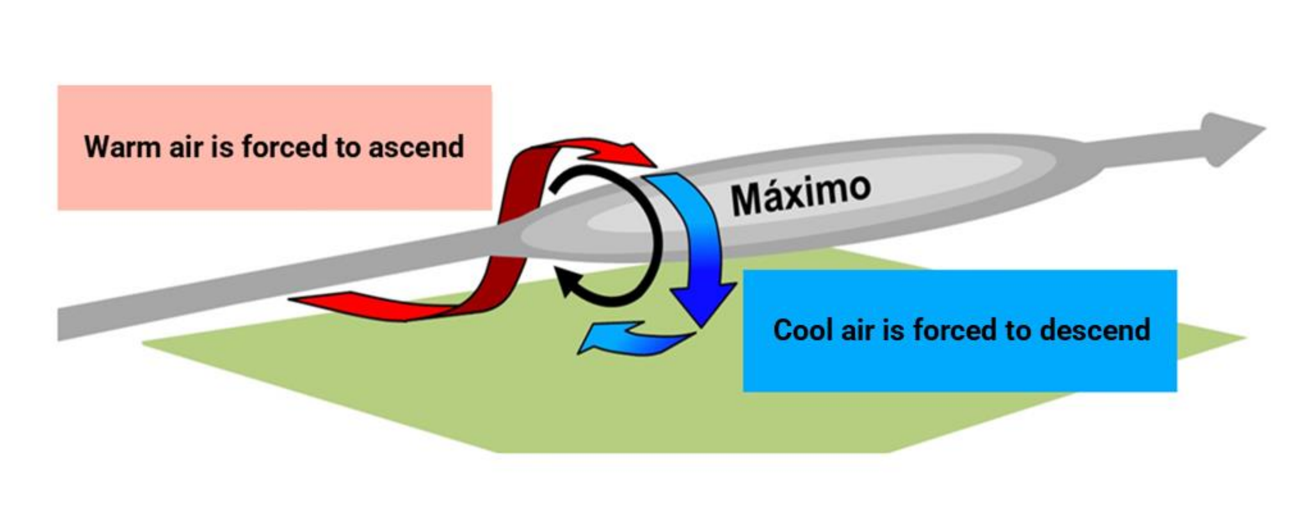


# Circulations in the entrance of a jet streak

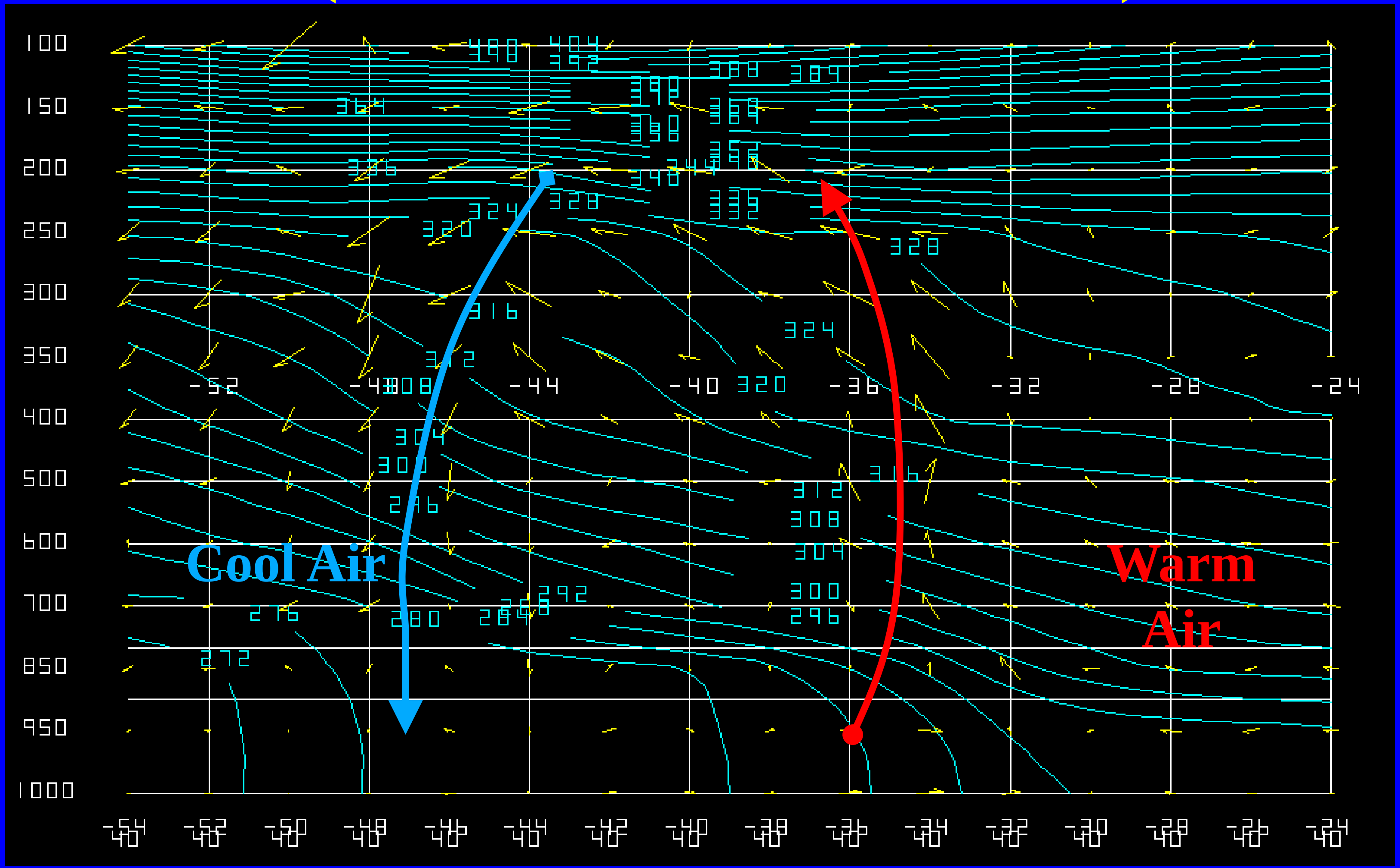
- Upper divergence in the warm side forces warm air to ascend.

- Upper convergence in the cool side forces cool air to descend.

- This is a “Direct Circulation” = light air ascends and dense air descends. Role: Restore baroclinicity or reduce thermal gradients.



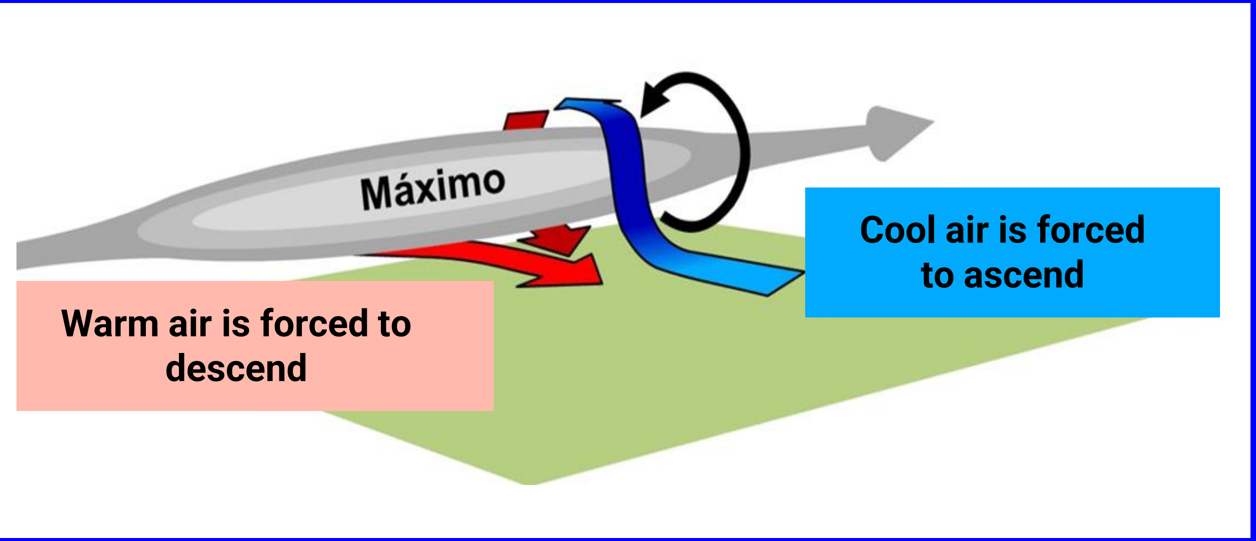
# Direct Ageostrophic Circulation
# (Jet Streak Entrance)



# Circulations in the exit of the jet streak

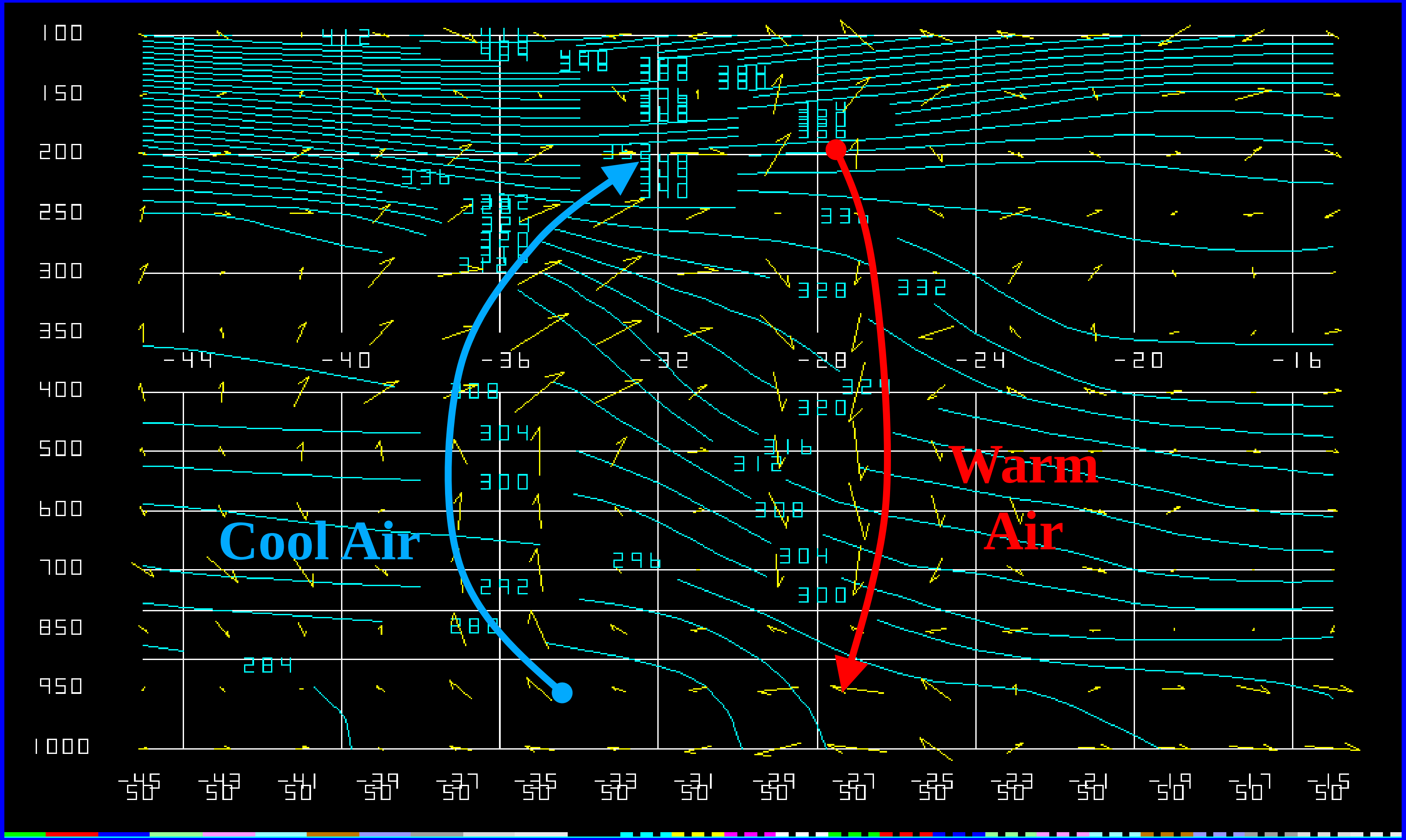
- In the exit region, upper divergence is positioned over the cool air mass, forcing cold air to ascend. Upper convergence on the warm side forces warm air to descend.

- This is an indirect circulation: denser air rises and lighter air sinks. This enhances baroclinicity = tightens temperature gradients.

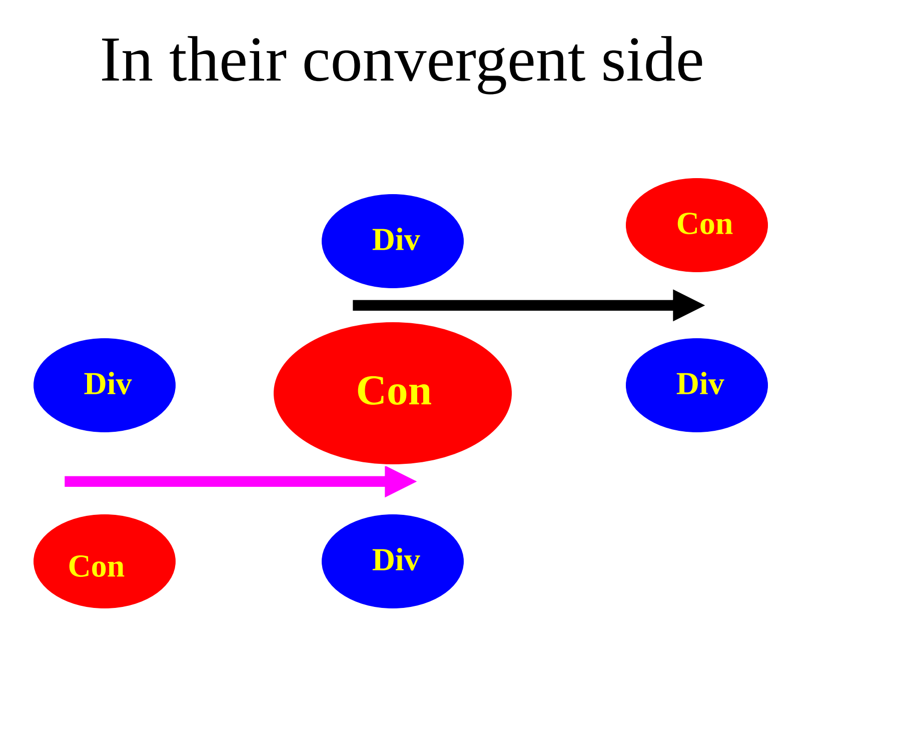


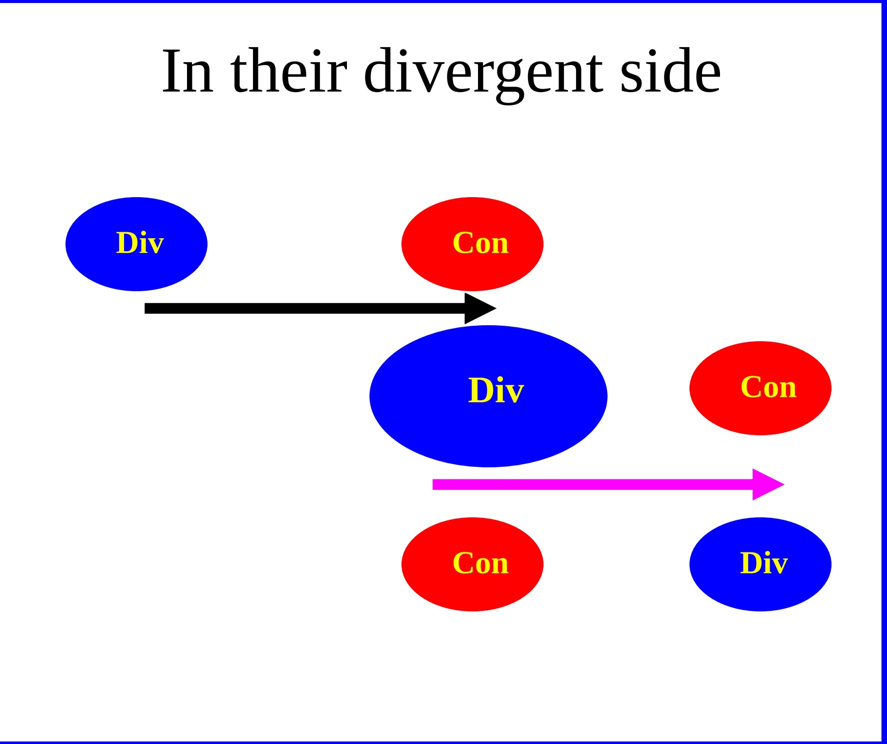

- The cool exit region is the most favorable for the strongest cyclogenesis and frontogenesis.

# Direct Ageostrophic Circulation
# (Jet Streak Exit)



# Coupled Upper Jets

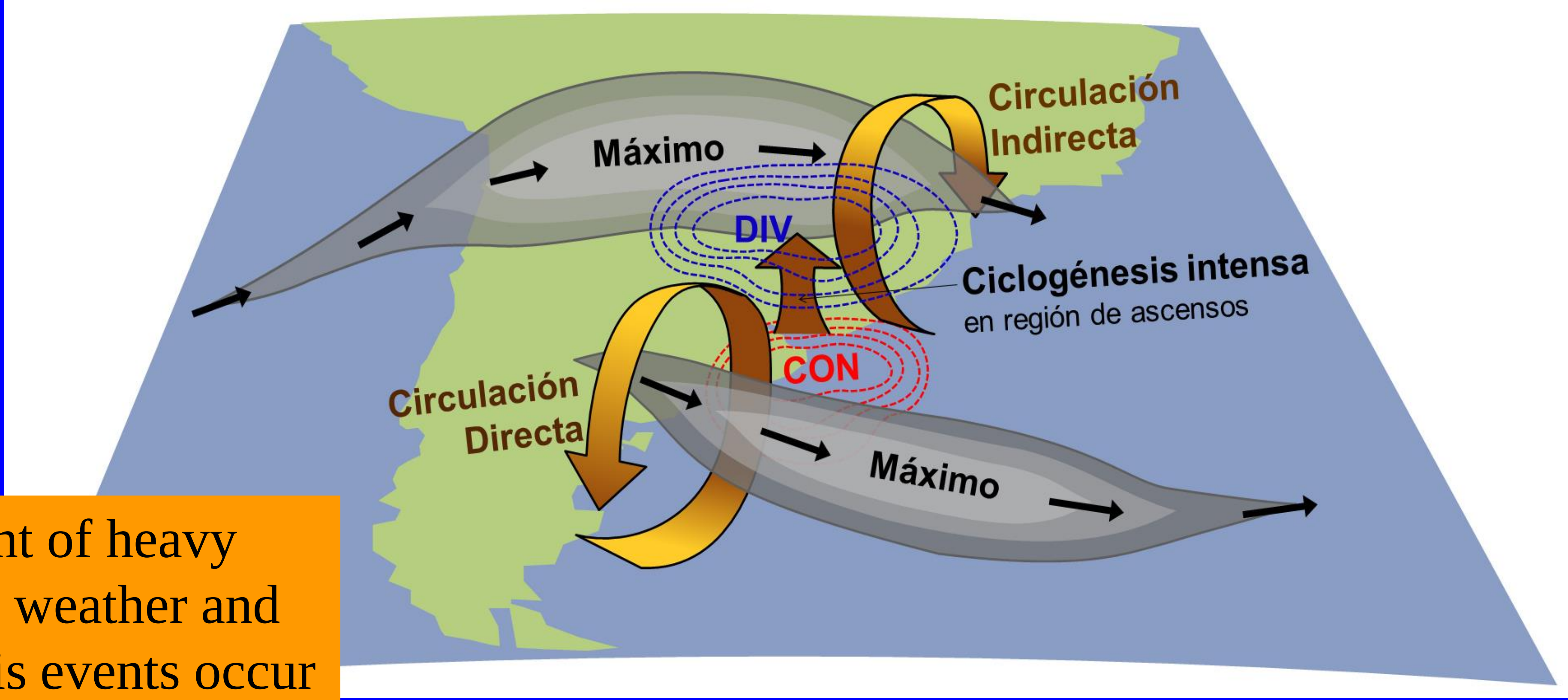



Ideal for strong descent (subsidence) in synoptic scale.

Ideal for strong ascent which favors strong deep convection, cyclogenesis and/or frontogenesis.

# Conceptual model of cyclogenesis in the south atlantic from coupled jets

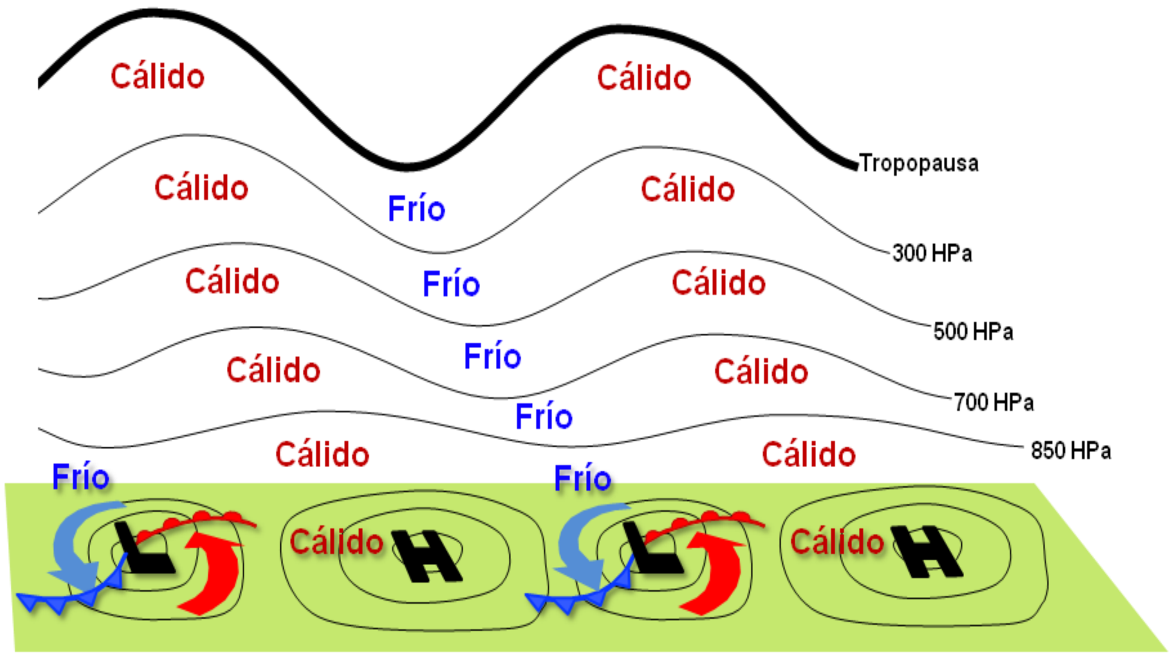



A large percent of heavy Rainfall, severe weather and rapid cyclogenesis events occur during coupled jet situations.

# Upper Troughs and Cyclogenesis

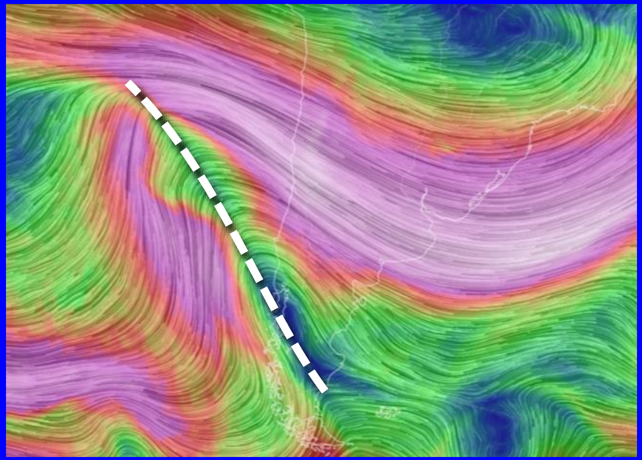
**Upper troughs in the westerlies induce surface lows downstream. Several processes stimulate cyclogenesis:**

- Geopotential height falls as the system approaches
- Enhanced Upper divergence ahead (east) of the approaching trough
- Cyclonic vorticity advection in the Upper troposphere
- Differential termal advection in the lower troposphere
- Diabatic heating processes.

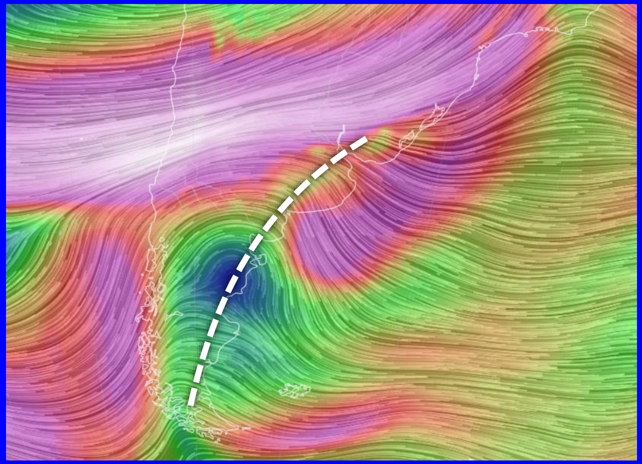


# Negatively tilted vs Positively Tilted Upper Troughs

- Positive: Warm side trails behind the cold side
- Negative: Warm side ahead (east) of cold side
- Negative Troughs are more dangerous:
  - They associate with Upper jets coupled on their divergent side = enhanced cyclogenesis = more ascent
  - Moisture wraps around system favoring more instability and enhancement by diabatic (latent heat release enhancing) processes.
  - More moisture = more precipitation



**Positively Tilted**

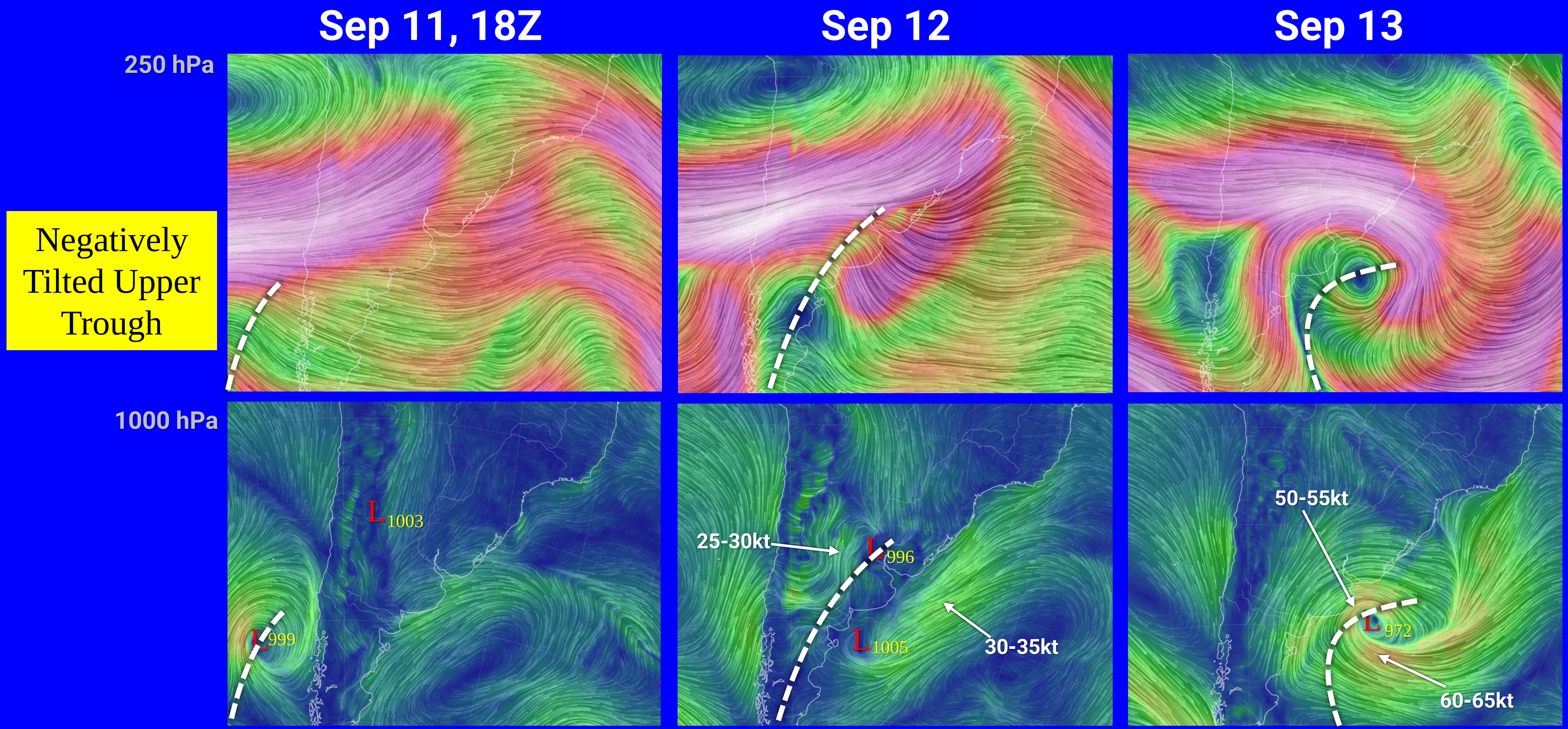


**Negatively Tilted**

# Cyclogenesis: Negatively Tilted Upper Trough

September 2016

# Cyclogenesis in Argentina, September 2016



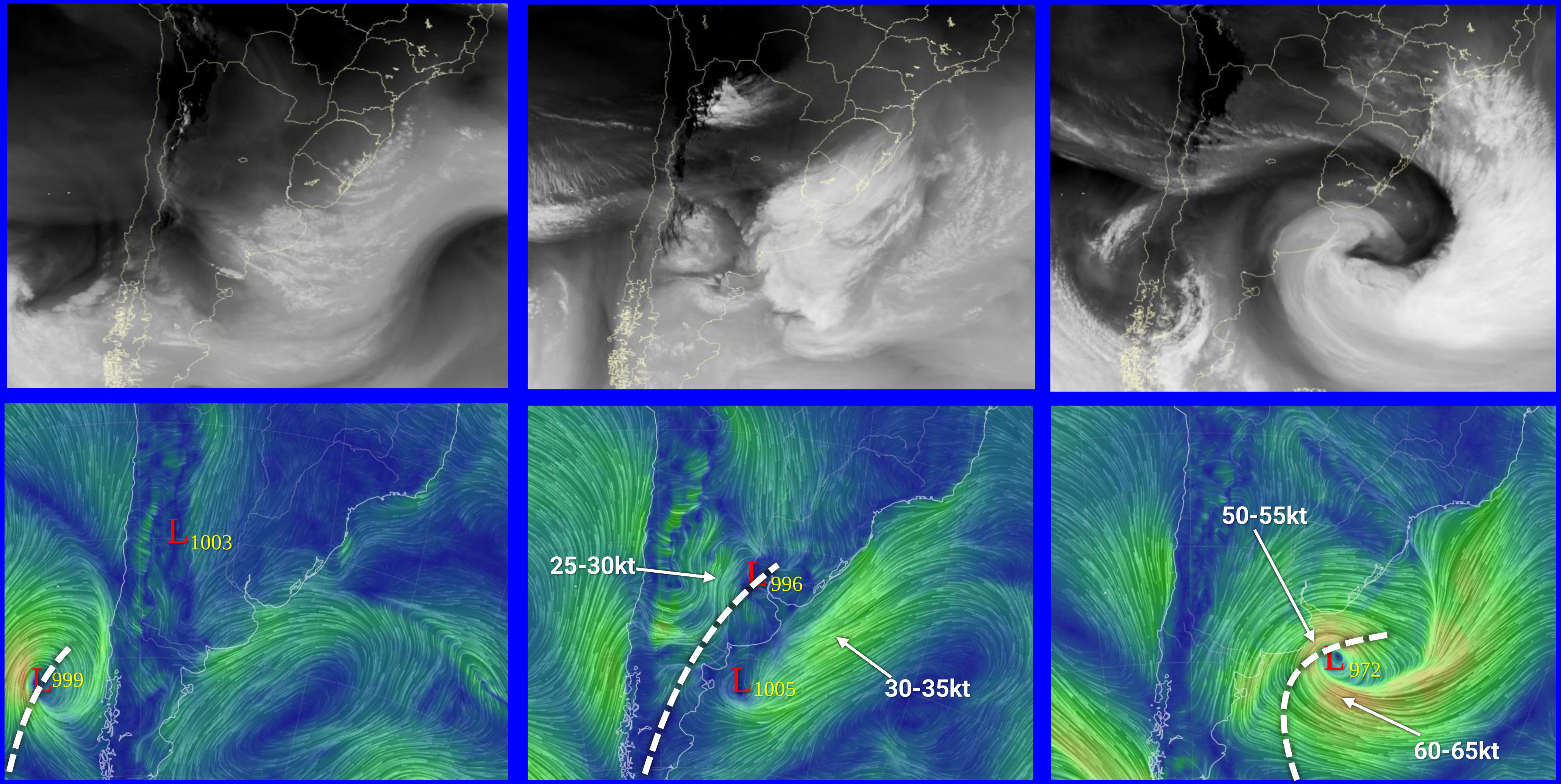
# Cyclogenesis in Argentina, September 2016

Sep 11, 18Z | Sep 12 | Sep 13

250 hPa

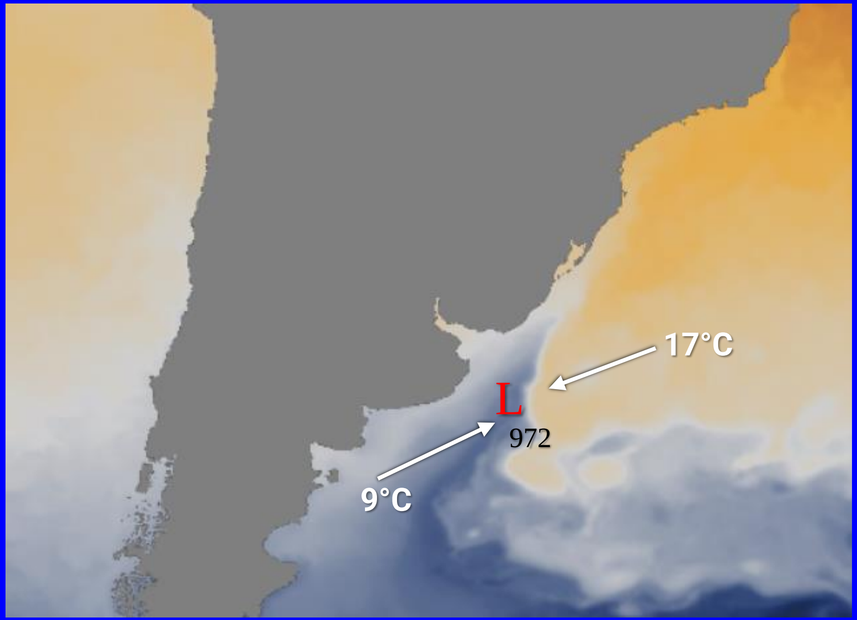
1000 hPa

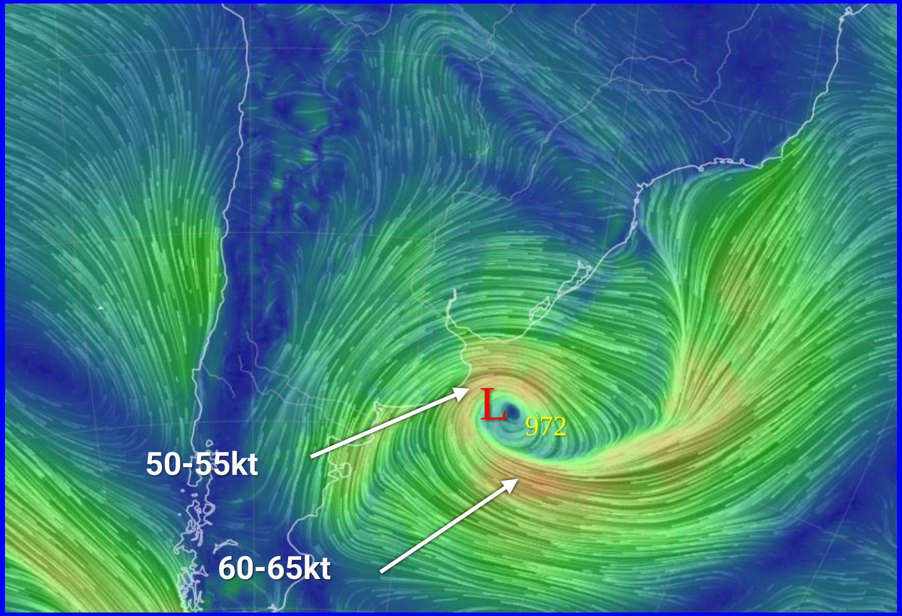
Negatively Tilted Upper Trough



# Cyclogenesis in Argentina, September 2016

- Sharp SST gradients where the Malvinas current (Cold) encounters the Brazil current (warm) favor strong cyclogenesis due to enhanced differencial temperature advection.
- Enhances low-level warm advection east, and cold advection west of the center = more baroclinicity and a stronger system.

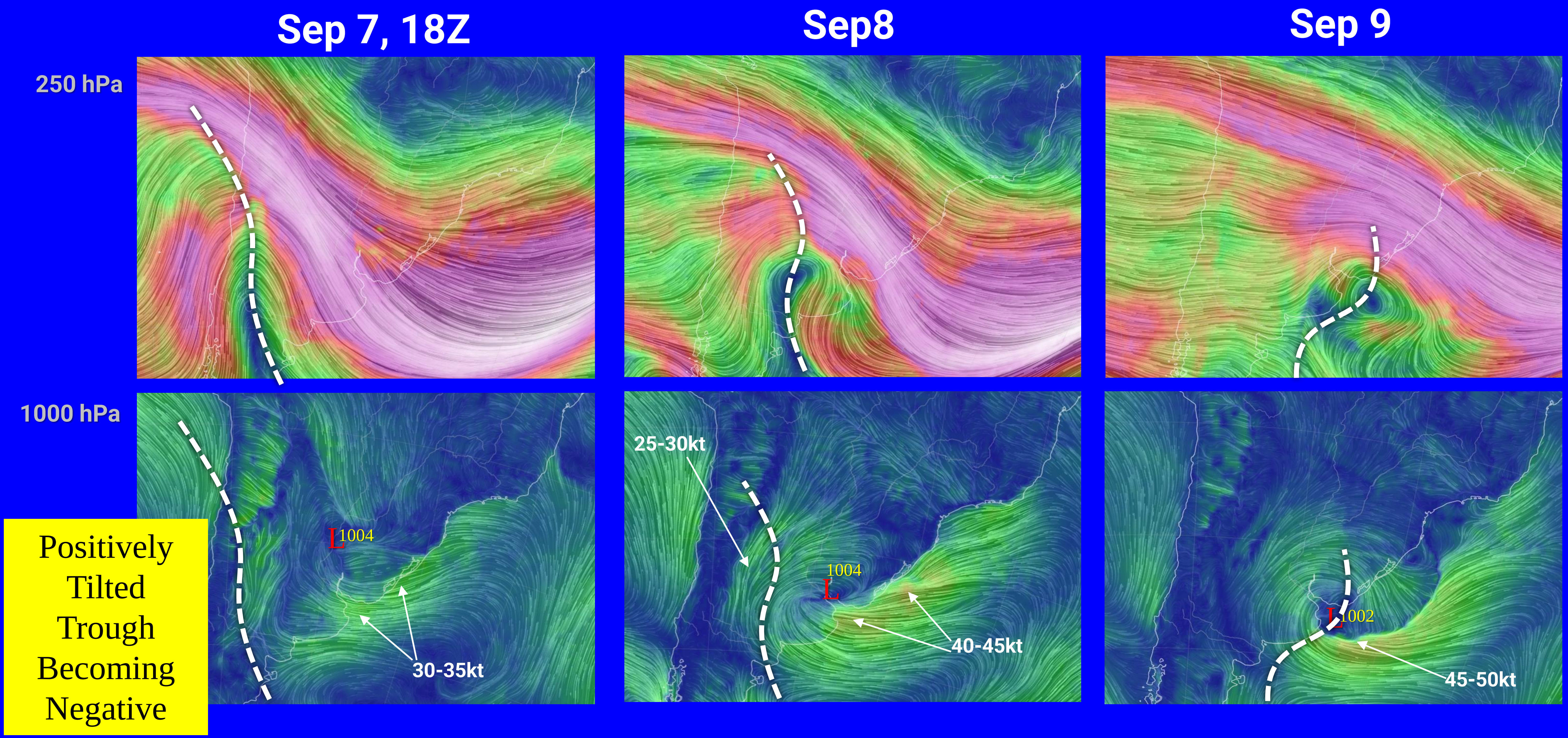


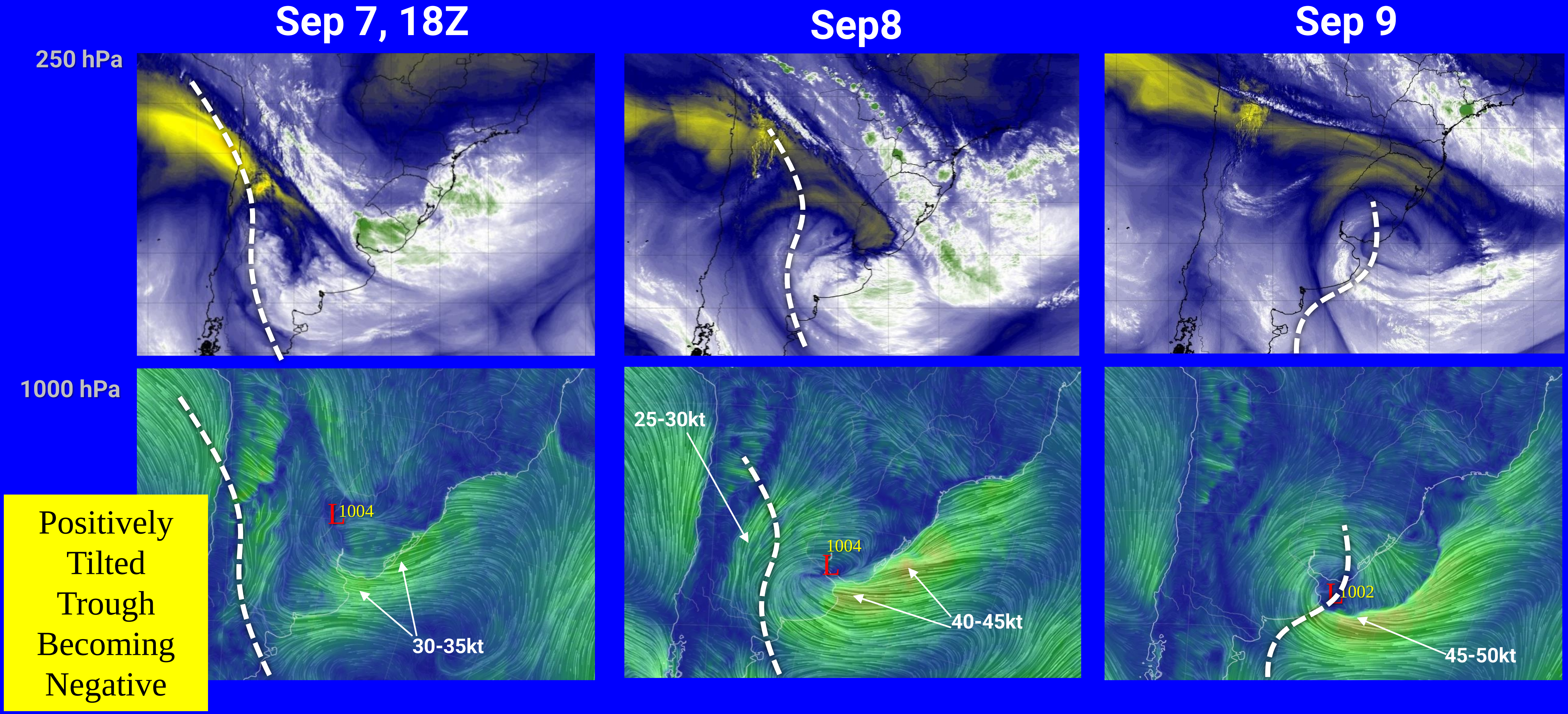
# Cyclogenesis: Positively Tilted Upper Trough

September 2016

# Cyclogenesis in Argentina, September 2021



# Cyclogenesis in Argentina, September 2021



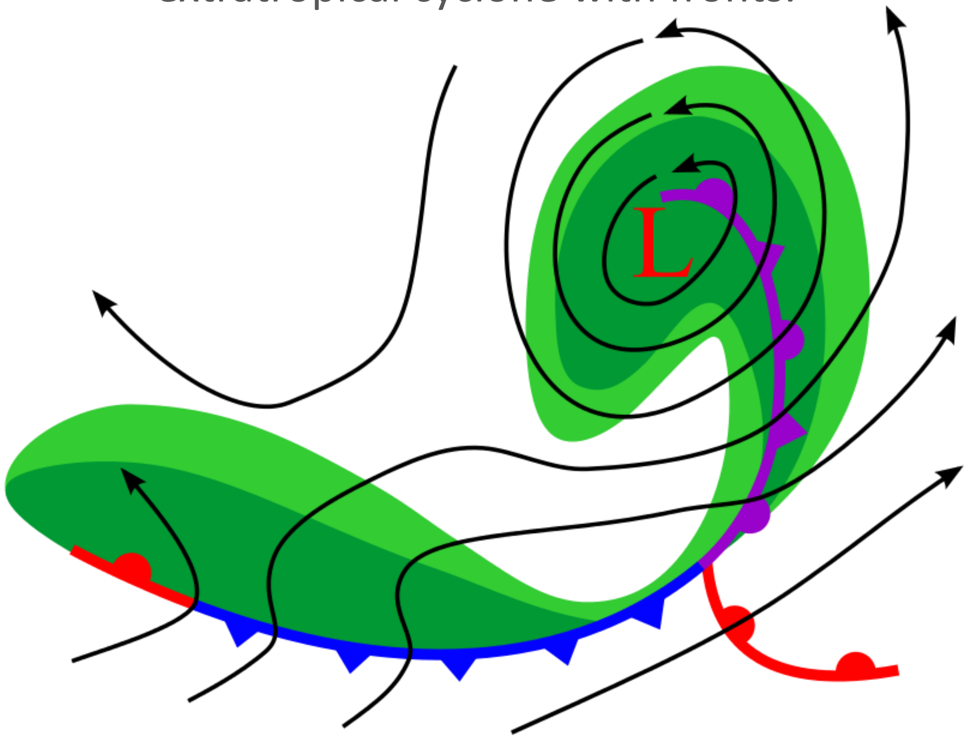
# 03

# Extratropical Cyclones

# Extratropical Tropical Cyclone

- Large cyclone that forms in the extratropics, associated with cold upper troughs located upstream, and associated with temperature gradients, thus it often develops fronts.
- Energy source: Temperature gradient (potential energy) and associated thermal advection, which stimulates vertical motions when interacting with the upper structures.
- Maintenance: Enhanced temperature gradients or baroclinicity.

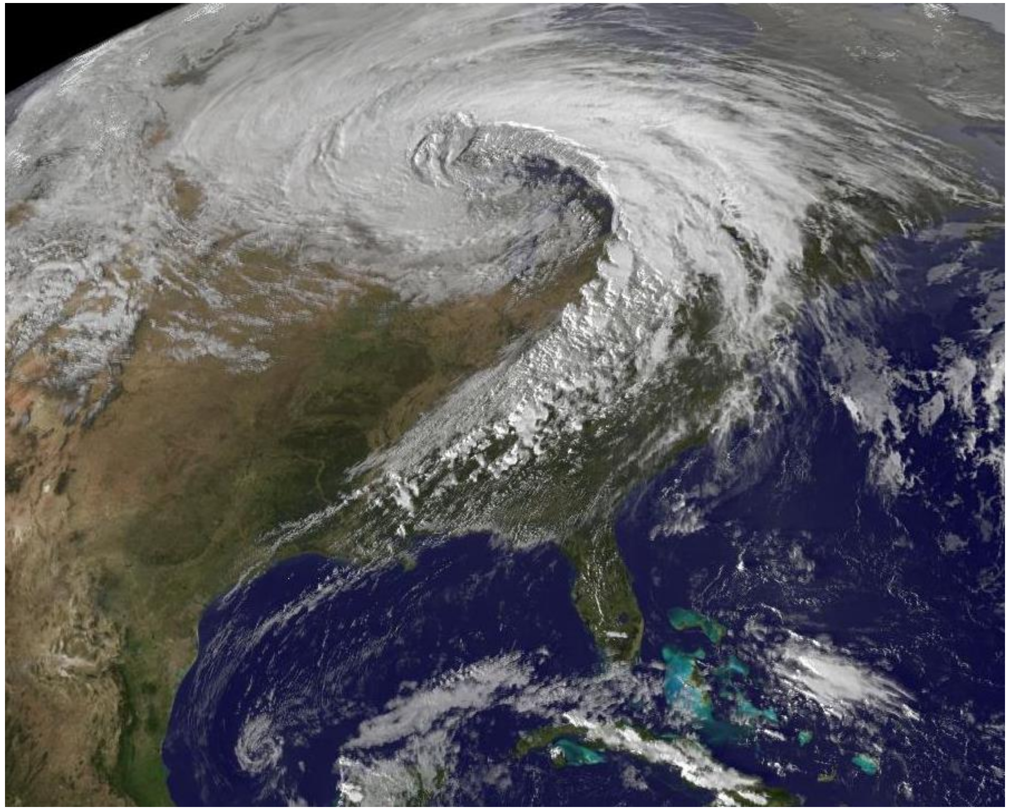
North Hemisphere surface analysis of an extratropical cyclone with fronts.



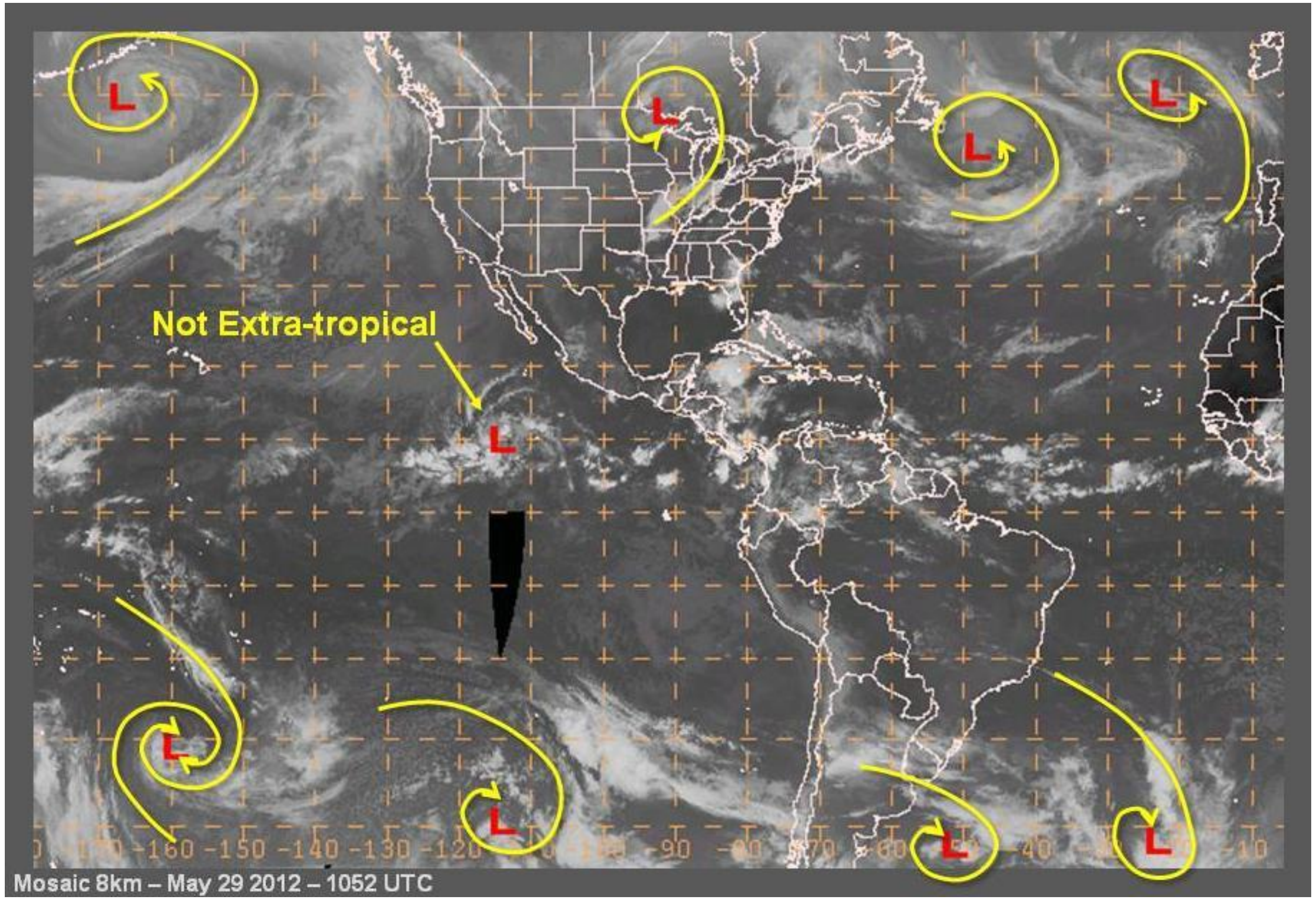

http://pressbooks-dev.oer.hawaii.edu/atmo/chapter/chapter-13-extratropical-cyclones/

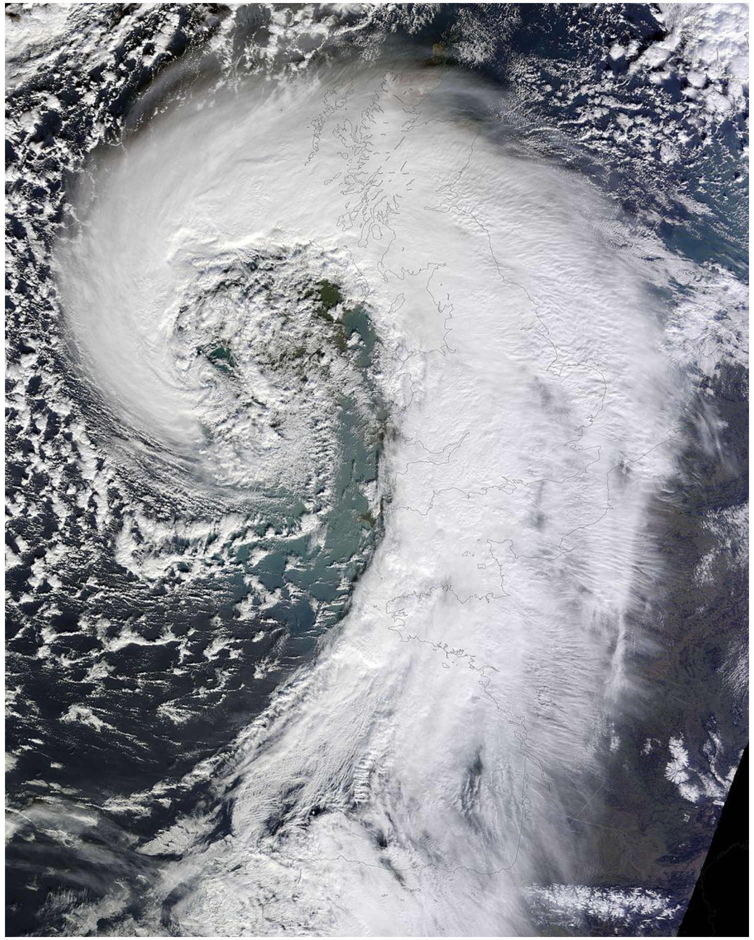
# Extratropical Tropical Cyclone Characteristics

- Tropospheric system, from the surface to the stratosphere.
- They can be very large, on occasions larger than 2000km (20°).
- Cold core aloft as it associates with an upper trough, and assymetric core in the lower levels from temperature gradients between air masses.
- Vorticity: Becomes more cyclonic with height.
- Lower tropopause.
- Baroclinicity: Prevalent temperature advection processes generally develop fronts.



# Extratropical Tropical Cyclone



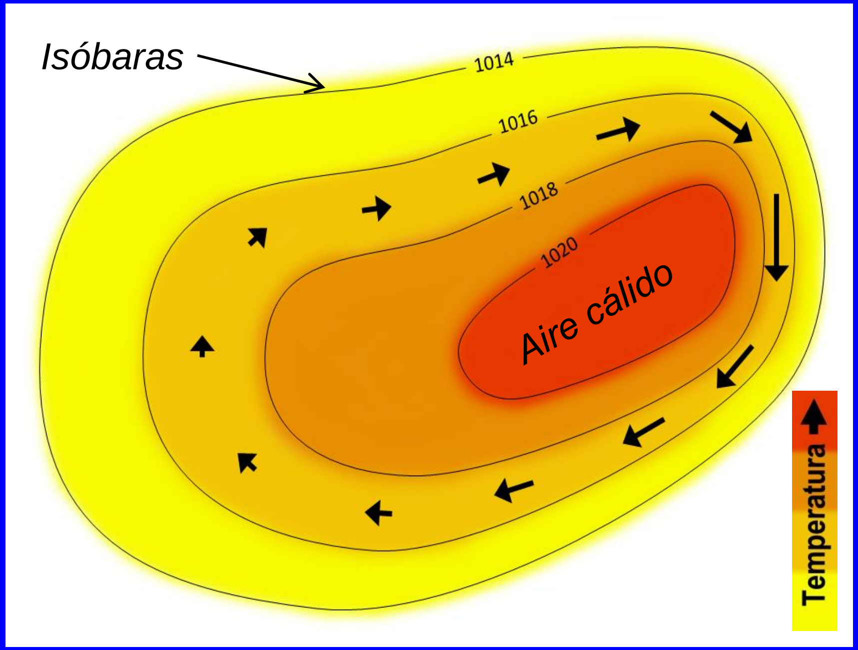



# Barotrópico vs Baroclínico

Baroclinicidad implica advección de temperatura.

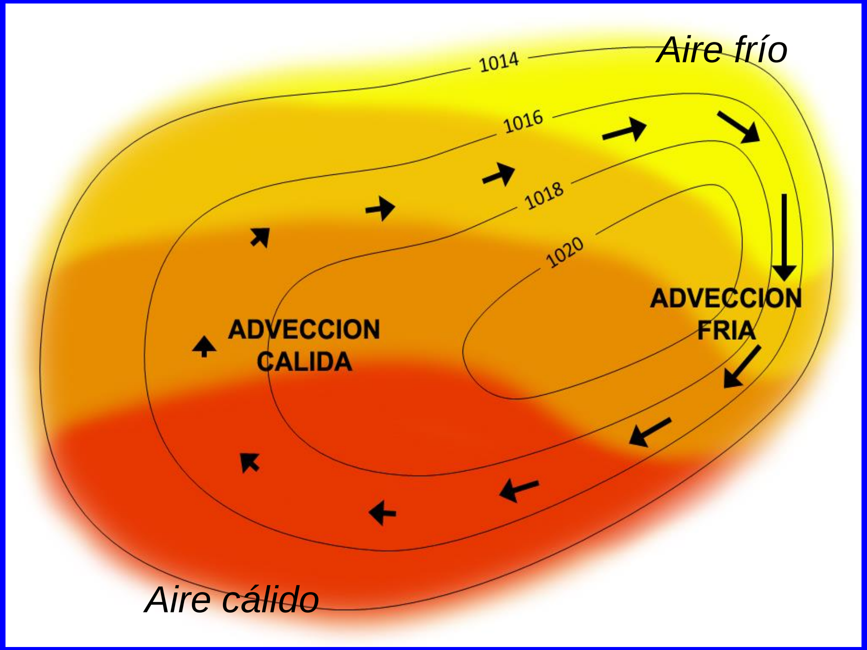
**Ejemplo:**

SISTEMA BAROTROPICO




-**NO** hay advección de temperatura.
-Isóbaras son paralelas a isotermas.

SISTEMA BAROCLINICO

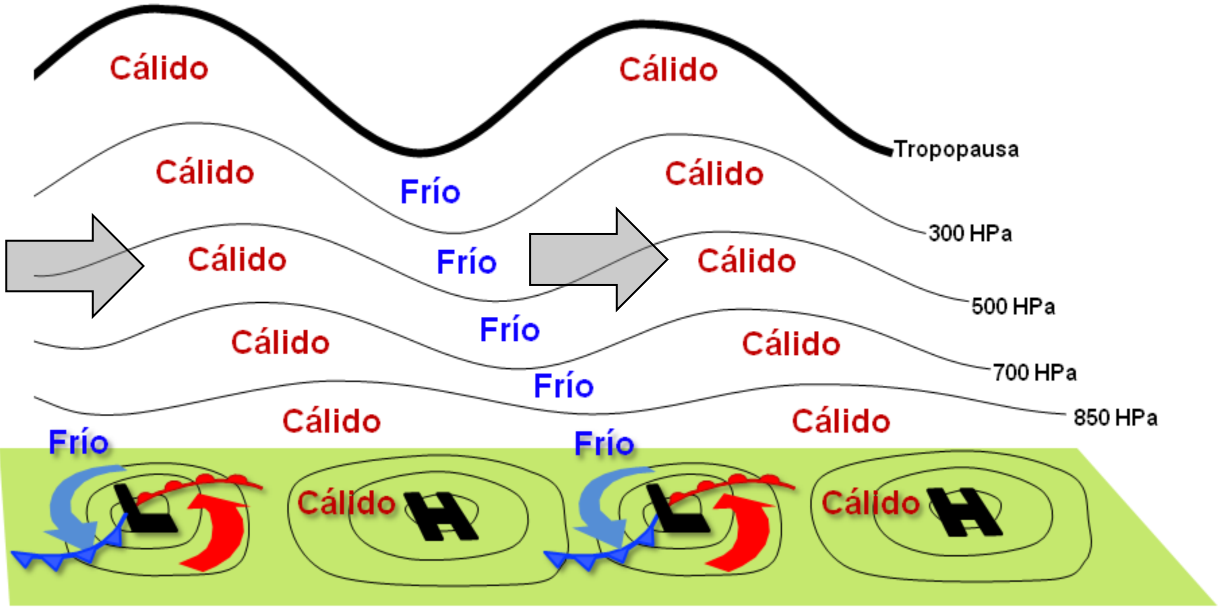



-Hay advección de temperatura.
-Isóbaras **NO** son paralelas a isotermas.

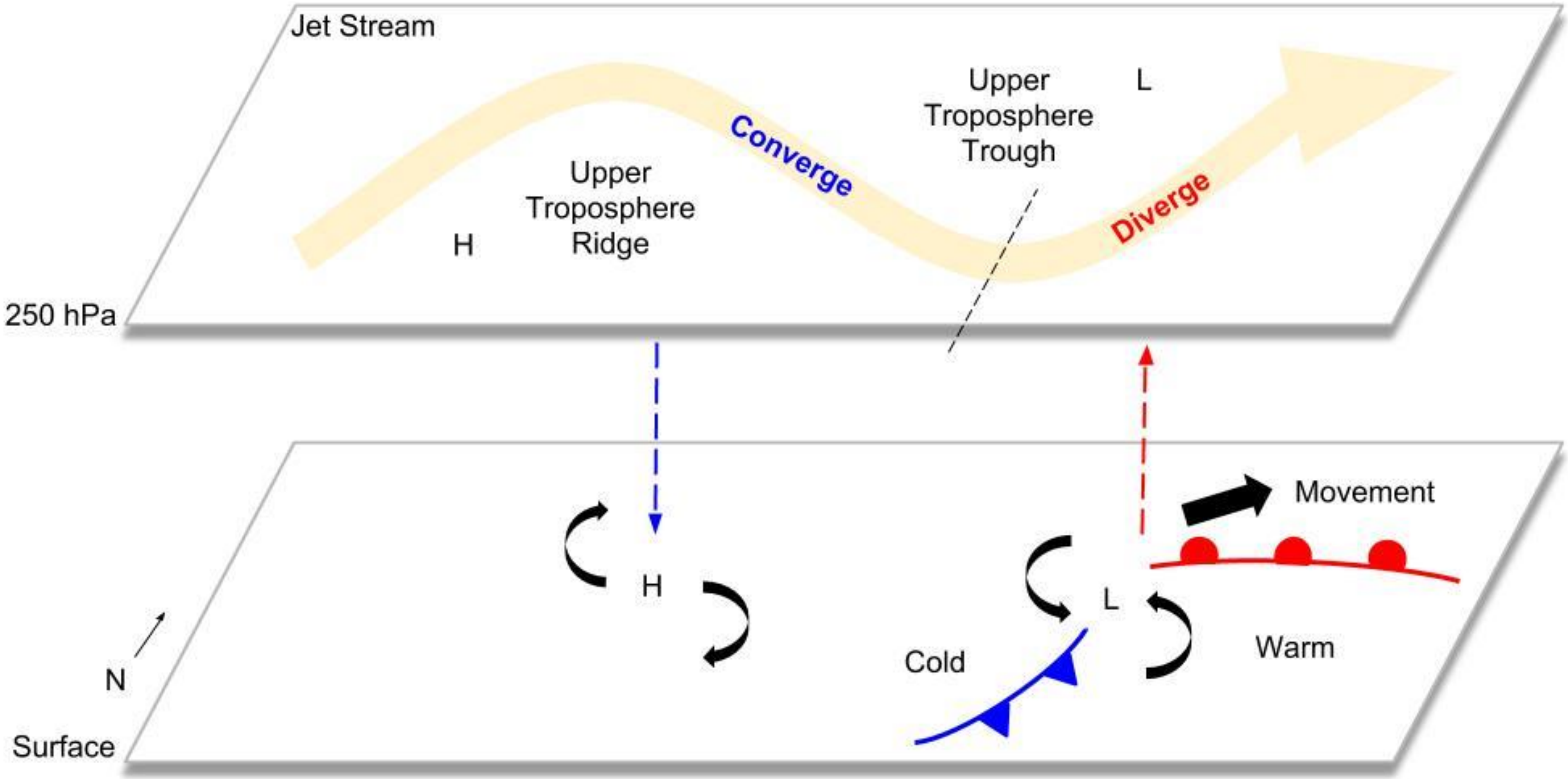
# Baroclinic Wave

Migrating disturbance that associates with large values of baroclinicity (temperature advection processes).

It is characterized by extratropical troughs slanted with height and áreas of enhanced vertical wind shear.



# Baroclinic Wave



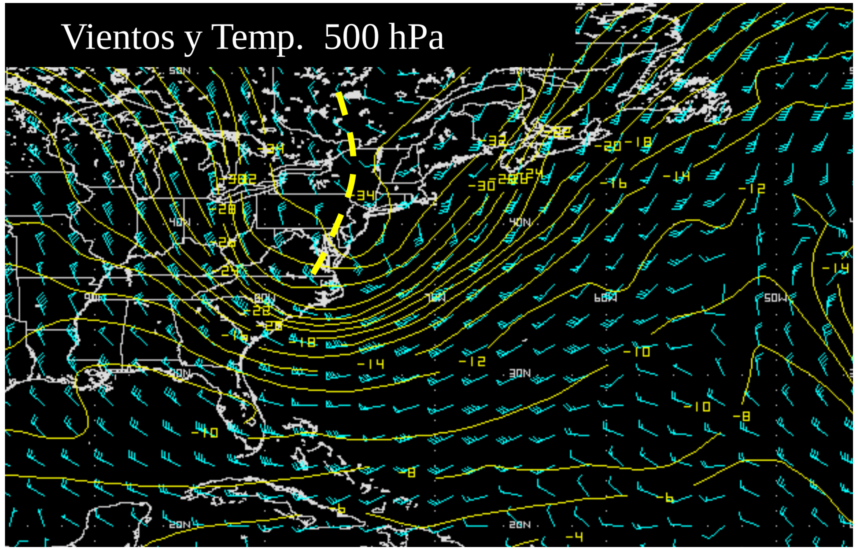
# Baroclinic Disturbance

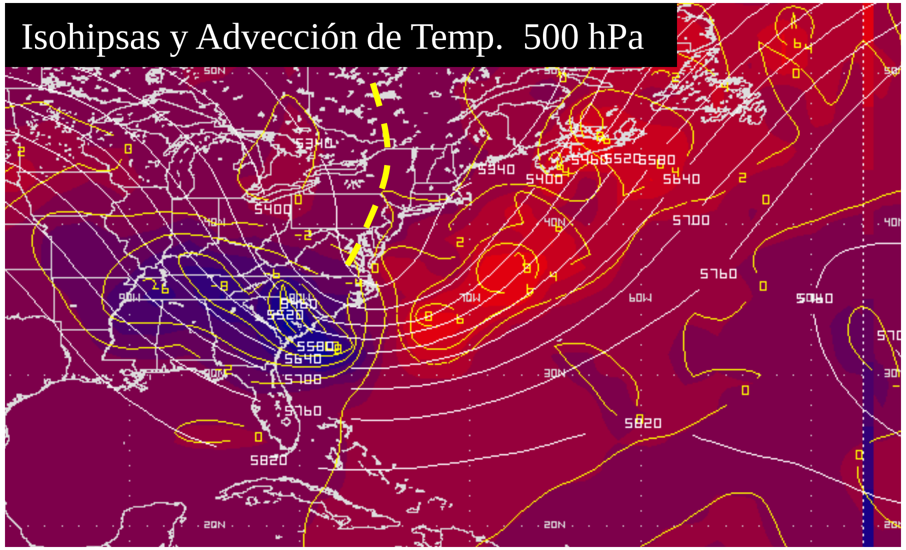
- Plays a role in redistributing energy in the atmosphere.
- Potential energy is converted into kinetic energy.
- Winds and vorticity vary with height.

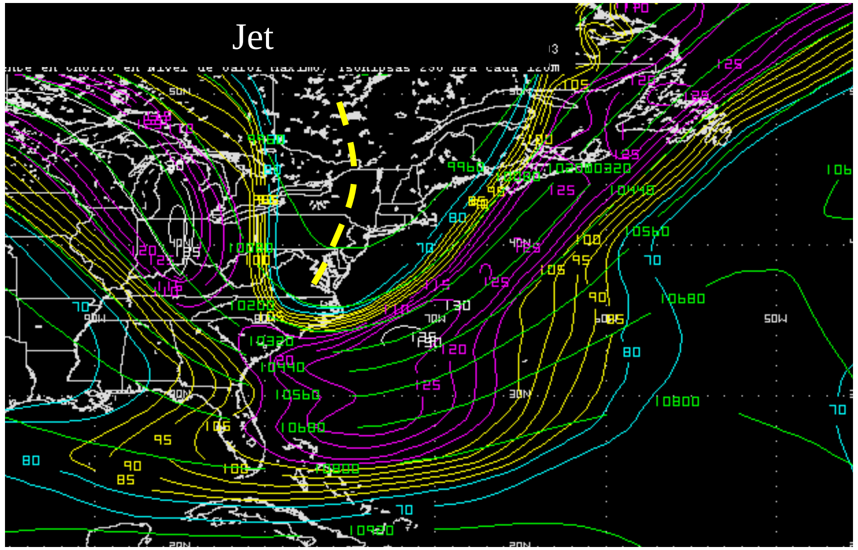
**How to recognize it in analyses?**

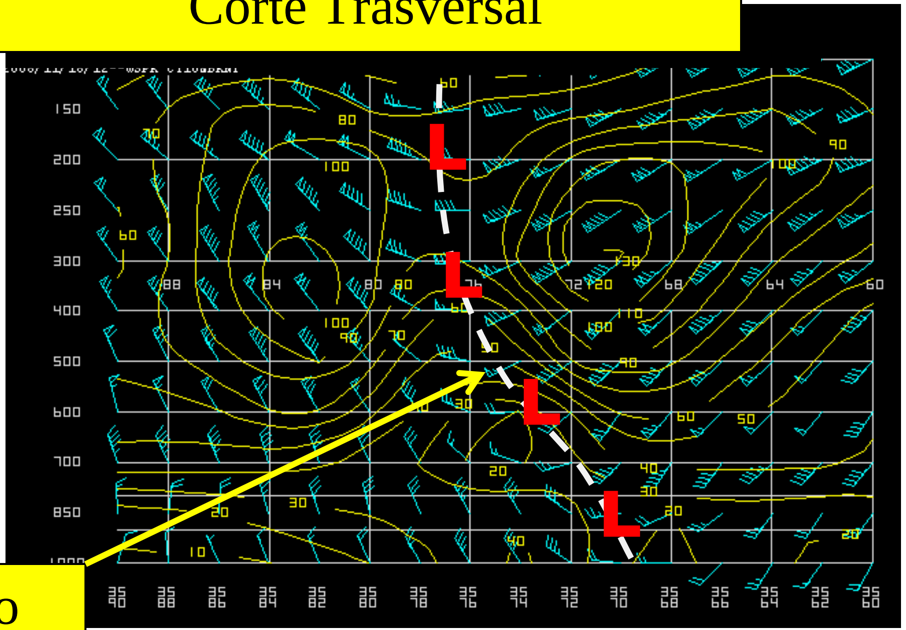
-Looking at temperature/thickness gradients and evaluating termal advection.

# Baroclinic Disturbance (North Hemisphere)



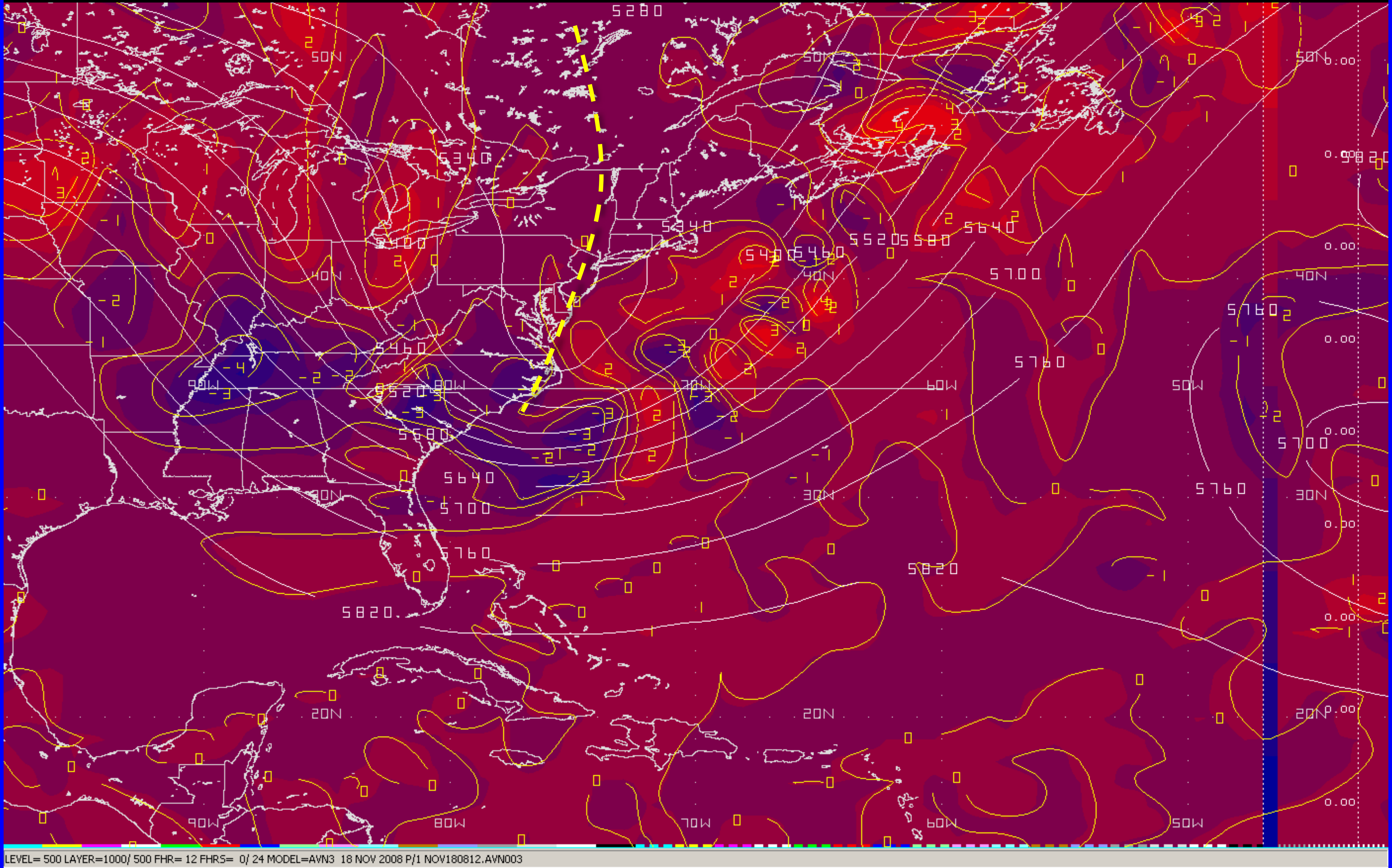



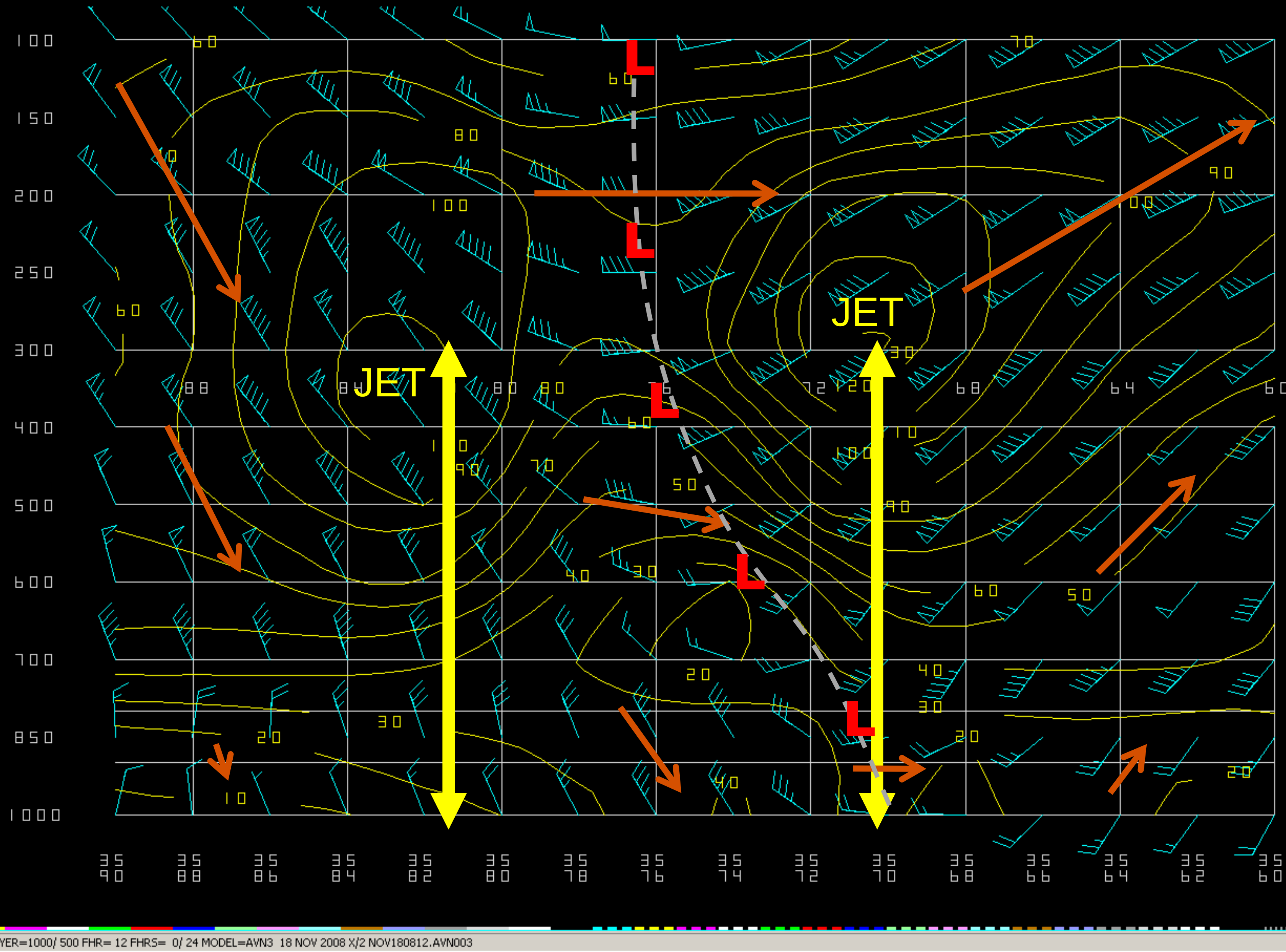
# Baroclinic Disturbance (North Hemisphere)

## Height contours and temperature advection at 500 hPa

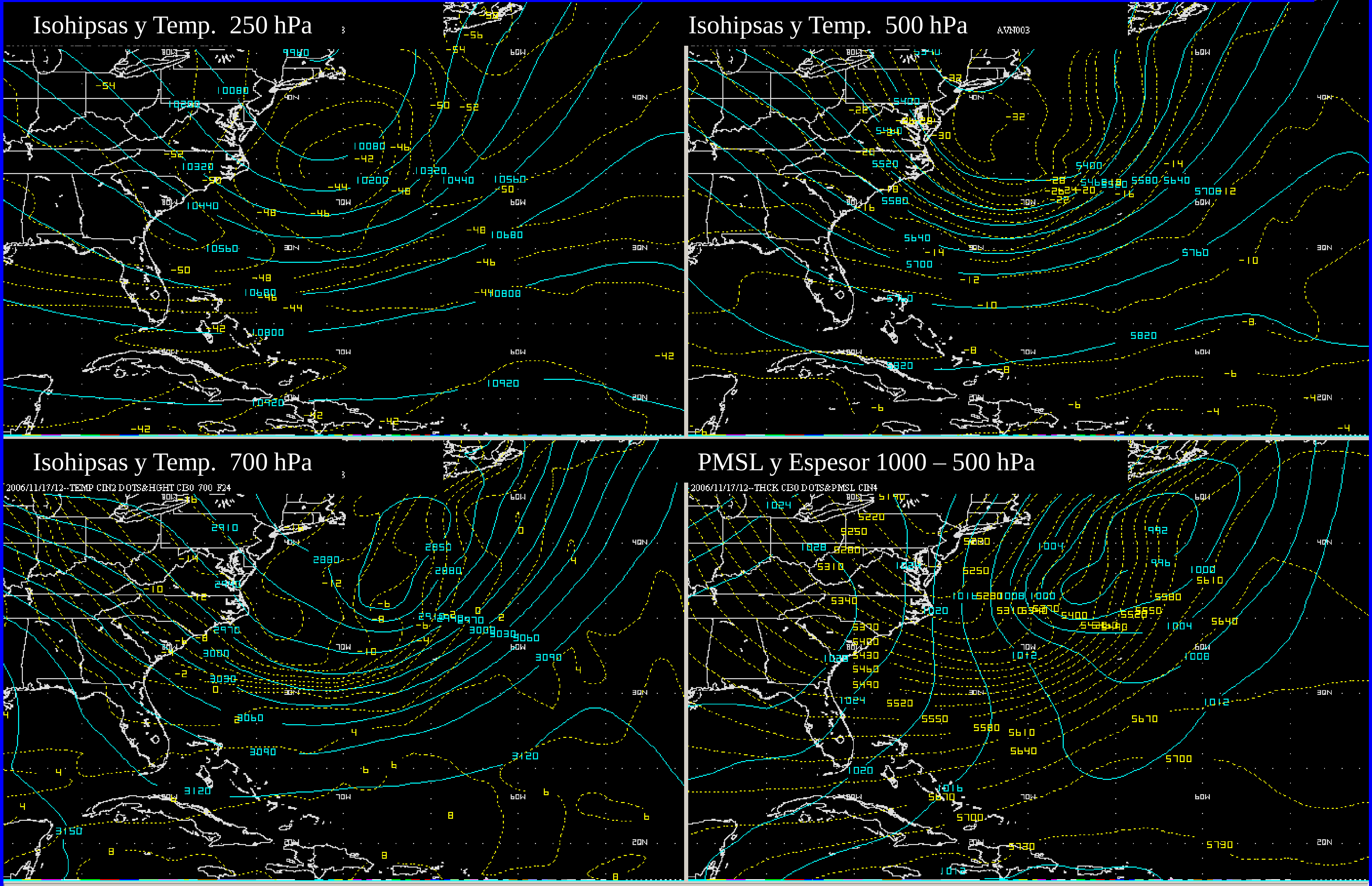


# Baroclinic Disturbance (North Hemisphere) Corte

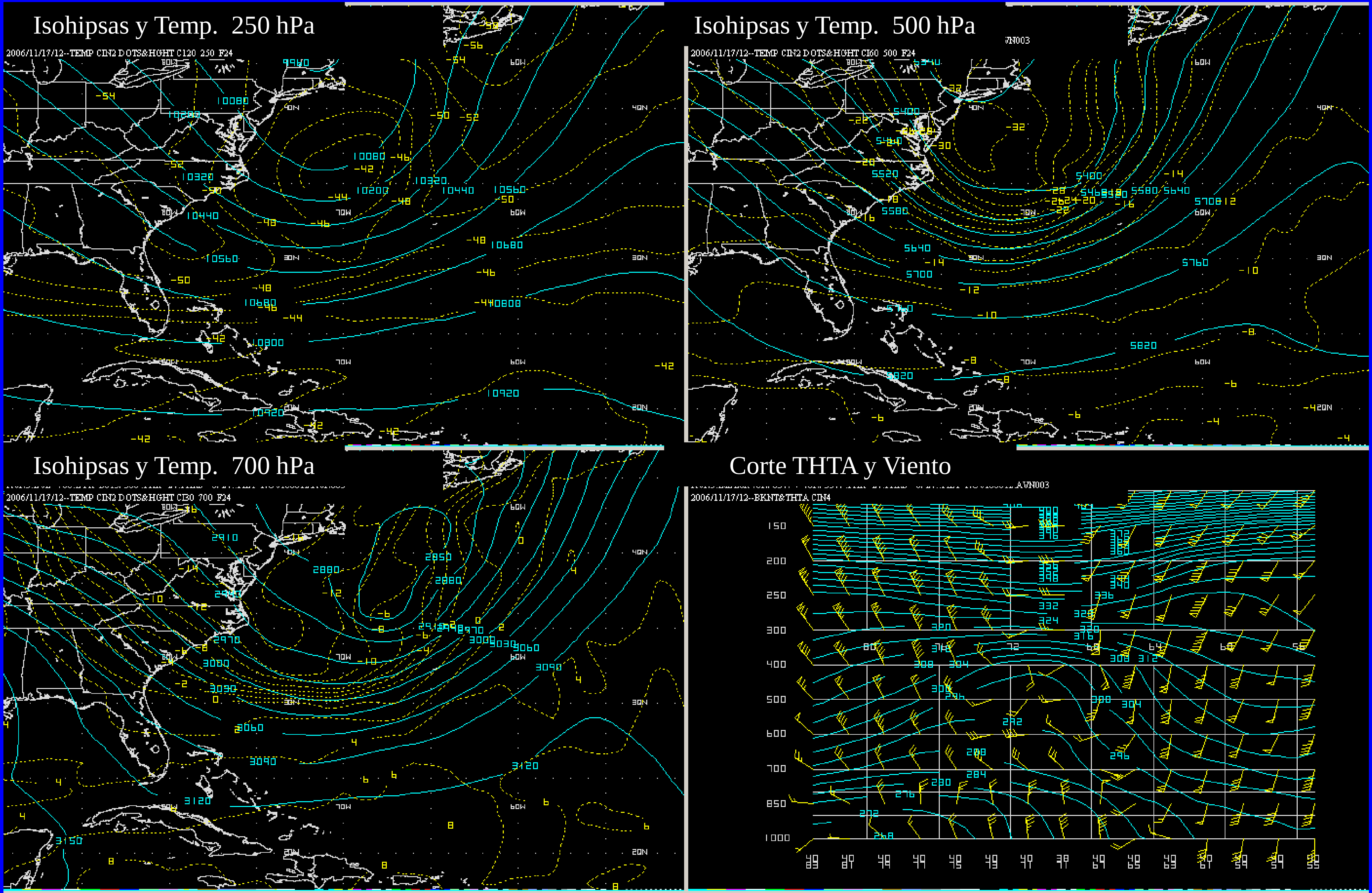
## Cross Section of winds



# Cold trough (NH)



# Cold Trough (NH)



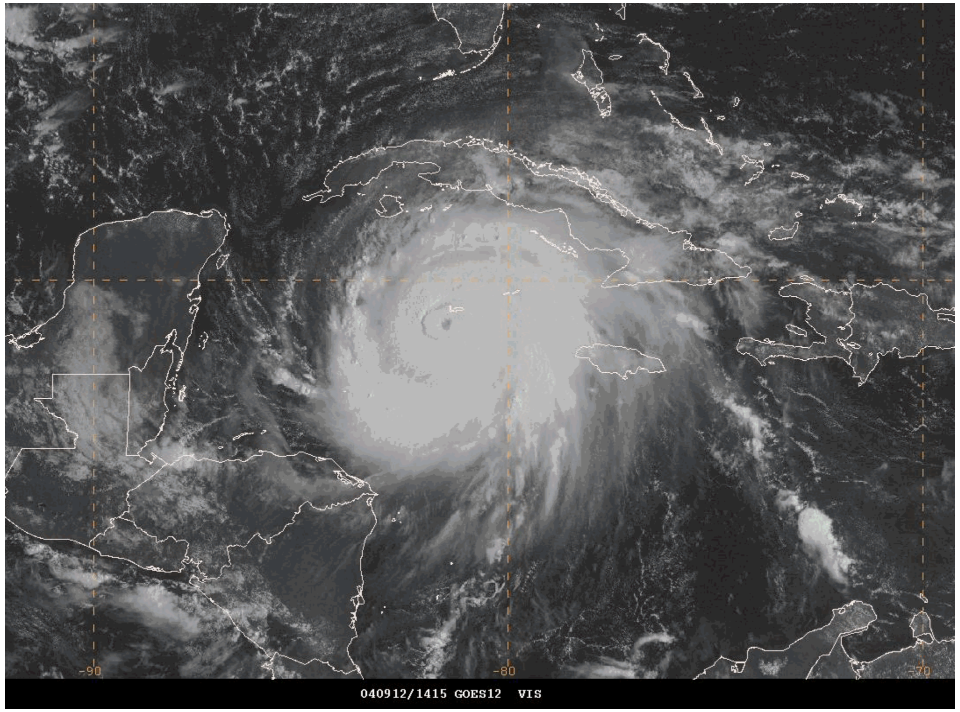
# 04

# Tropical Cyclones

# Tropical Cyclone

- 100-1000km cyclone that forms over warm tropical oceans (>27°C) and develops a deep-layer symmetric warm core up to the tropopause.
- Energy source: heat extracted from the ocean by the winds, released into the atmosphere by rapid condensation.
- Maintenance: It sustains itself based on the latent heat-stronger winds-more heat extraction positive feecback mechanism. Also by controlling its environment (generates its own upper ridge controlling shear).

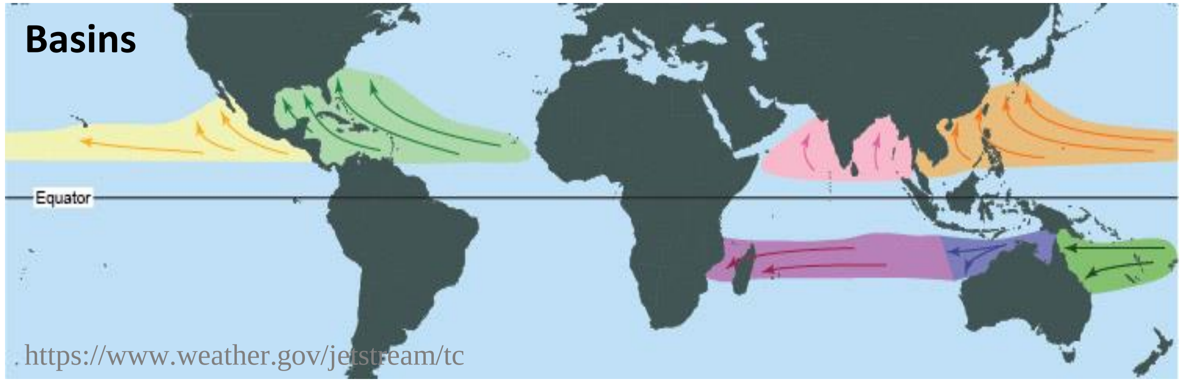
Hurricane Ivan in 2004

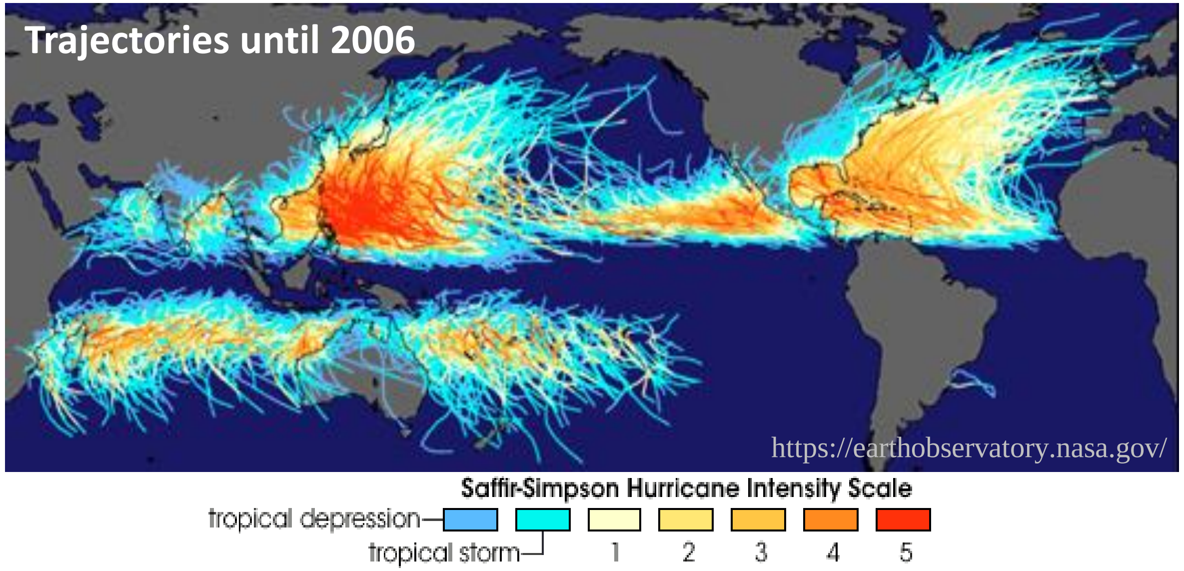



**Difference from other cyclones: the warm core in the entire column. Shows very well in theta and thera-e cross sections.**

# Requirements for Tropical Cyclone formation

- **Warm SST:** > 27°C through a depth of ~50m.
- **Coriolis Force:** Minimum distance of ~500km (~5°) away from the equator.
- **Low Vertical Wind Shear:** Low values (< 20kt) between the surface and the upper troposphere.
- **High Moisture:** Moist up to the mid-levels. The moister the better.
- **Conditional Stability:** Unstable if moist convection develops.
- **Preexisting Perturbation:** MCS, Easterly Wave, ITCZ Low, induced perturbation, etc.

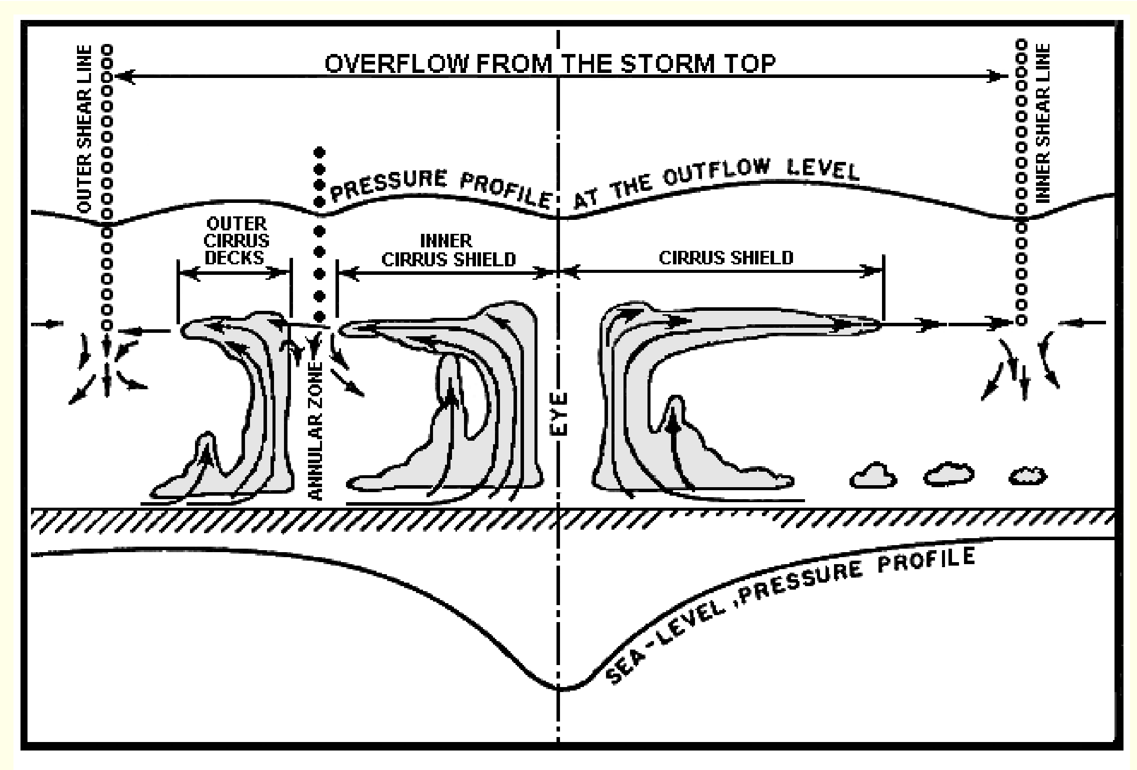


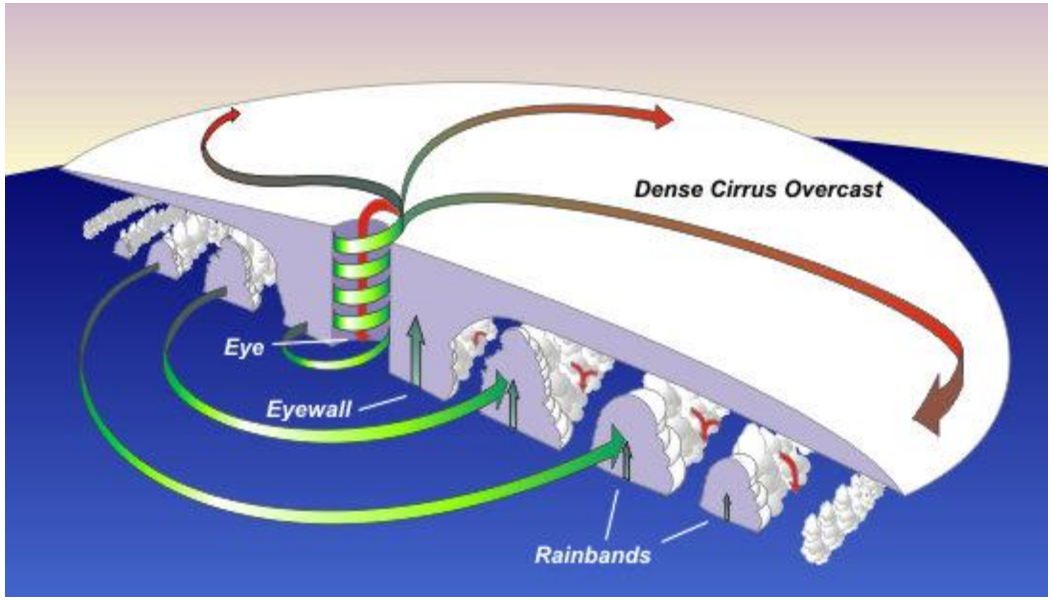



# Tropical Cyclone Triggers

- **Easterly Waves, especially African Easterly Waves**
  - They associate with enhanced environmental rotation, but also moist environments and ongoing latent heat release by convection.
- **Mesoscale Convective Complexes (MCC)**
  - Organized circular complex of thunderstorms can develop rotation and start sustaining itself.
- **TUTT**
  - Induced Trough develops a closed circulation. Deep Convection gradually warms up the column. The system transitions from subtropical (cold air aloft) to tropical (warm air in the entire column)
- **West African Disturbance Line (WADL):**
  - Line of convection (similar to a squall line) which forms over West Africa and moves into the Atlantic Ocean.

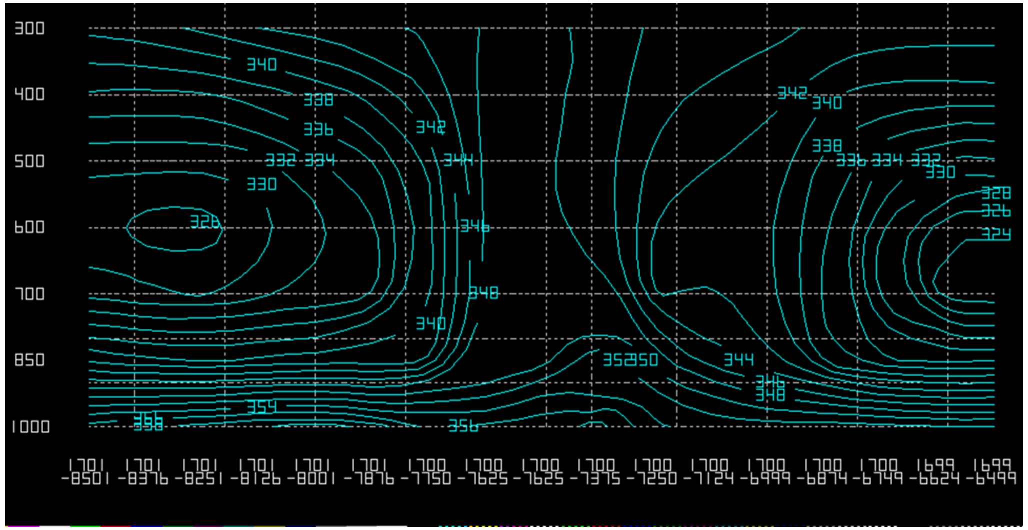
# Tropical Cyclone Vertical Structure

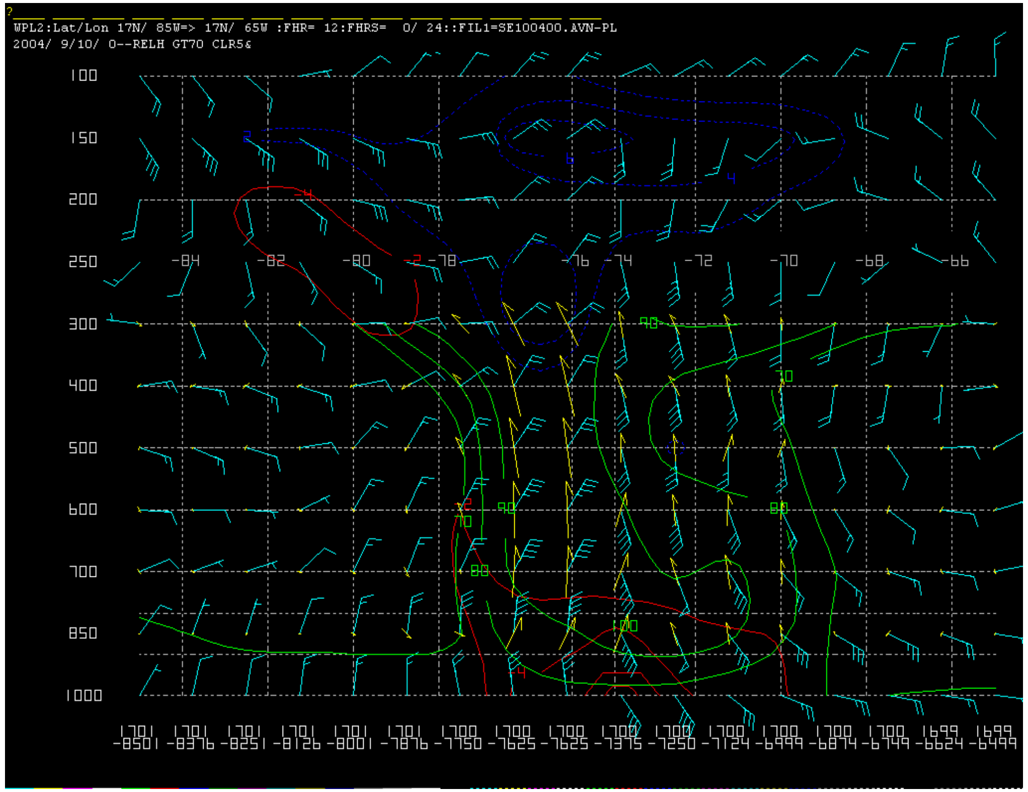


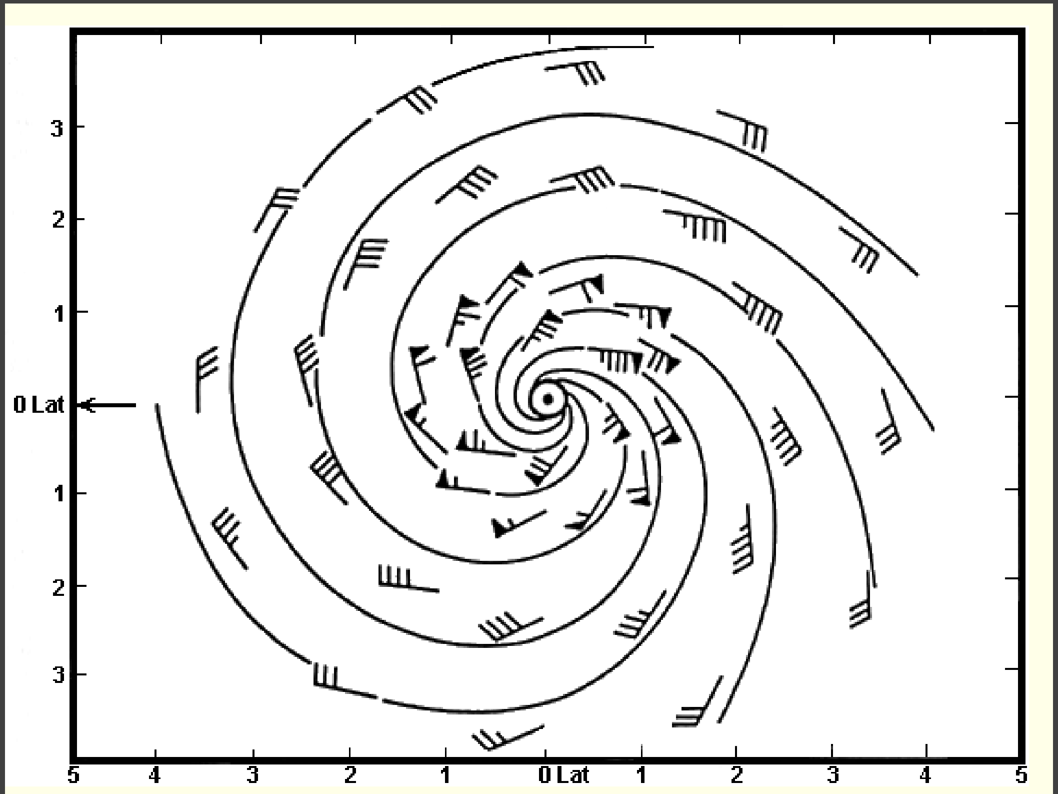
# Structure of the cyclone thermal core

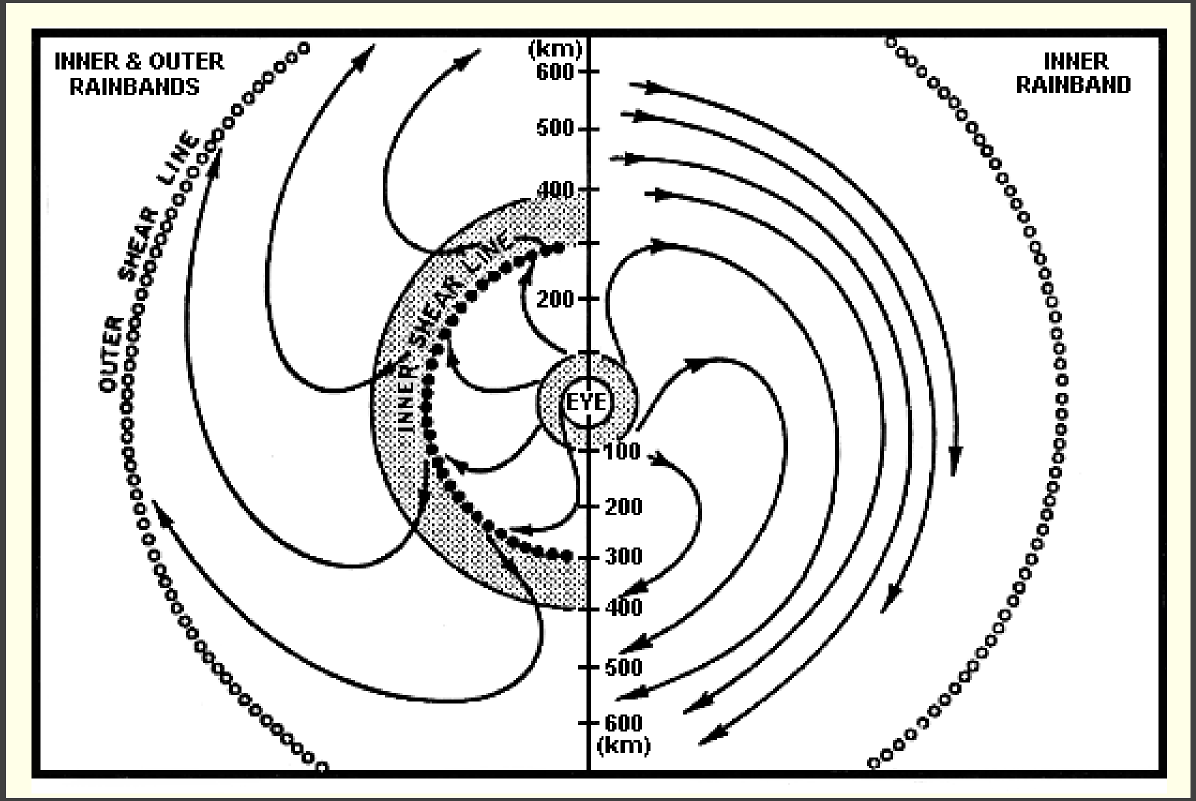
Column of large values of equivalent potential temperature



# Low and Upper Level Structure



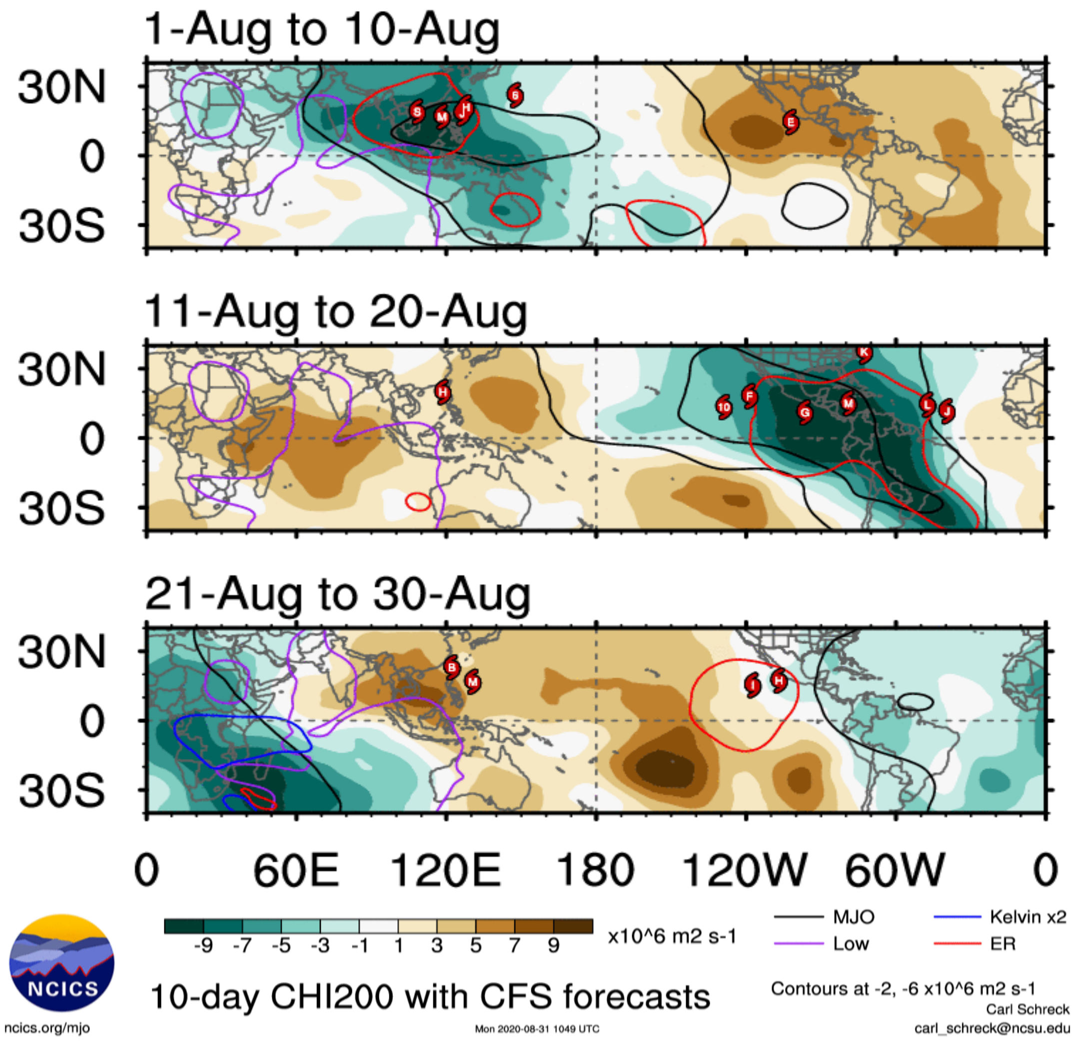



# Inside a Hurricane

Huracán Jeanne

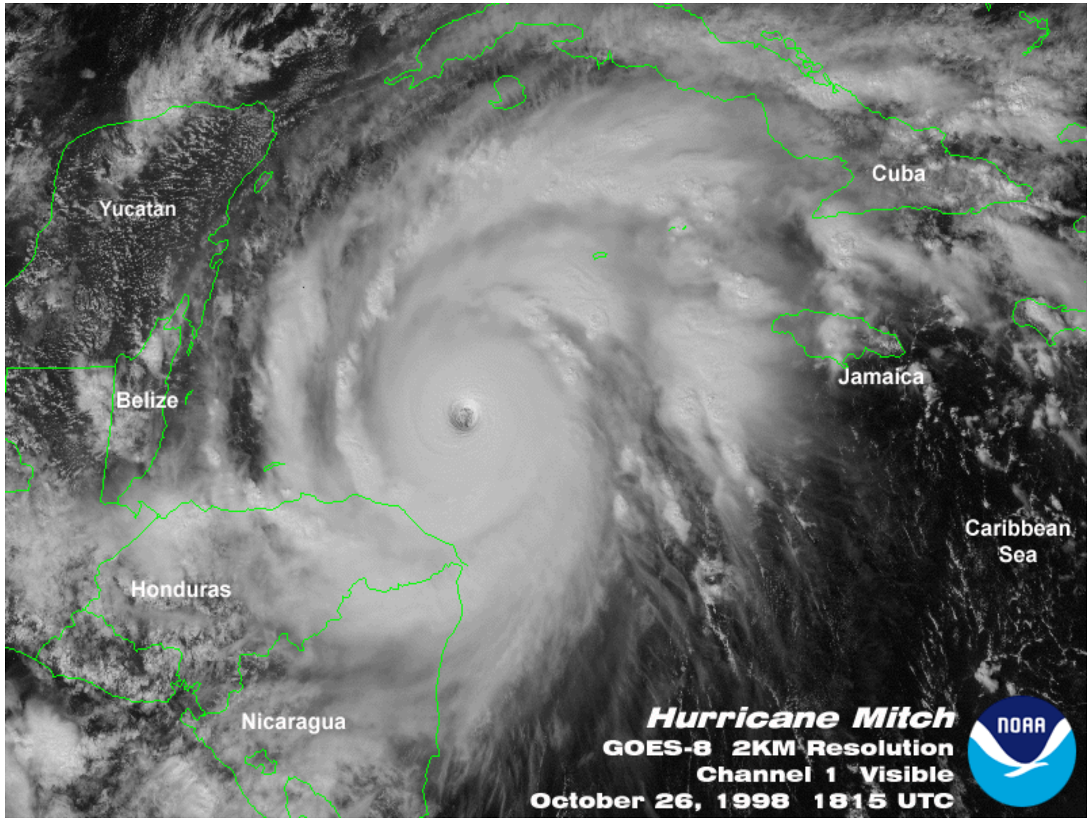
# MJO and Tropical Cyclones

- MJO (Phases 1 and 8) stimulate Tropical Cyclogenesis by enhancing upper divergence and low-level westerlies and divergence and stimulating rotation. However, a favorable environment needs to be in place: Warm and very moist airmass over warm SSTs and a perturbation.
- Figure: velocity potential (green for upper divergent) during August 2020, and the cyclones that formed during those periods.

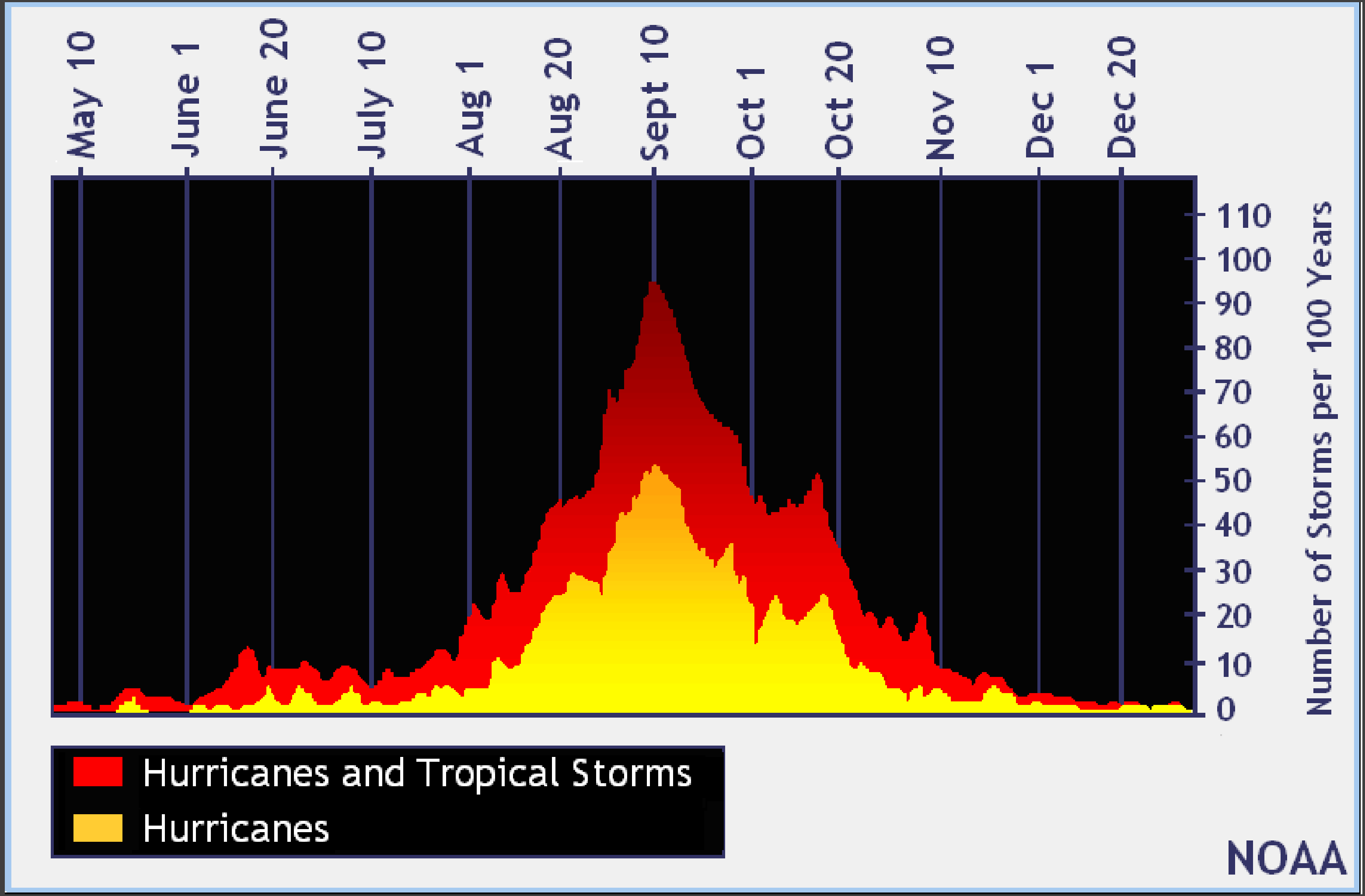


# Classification of Tropical Cyclones

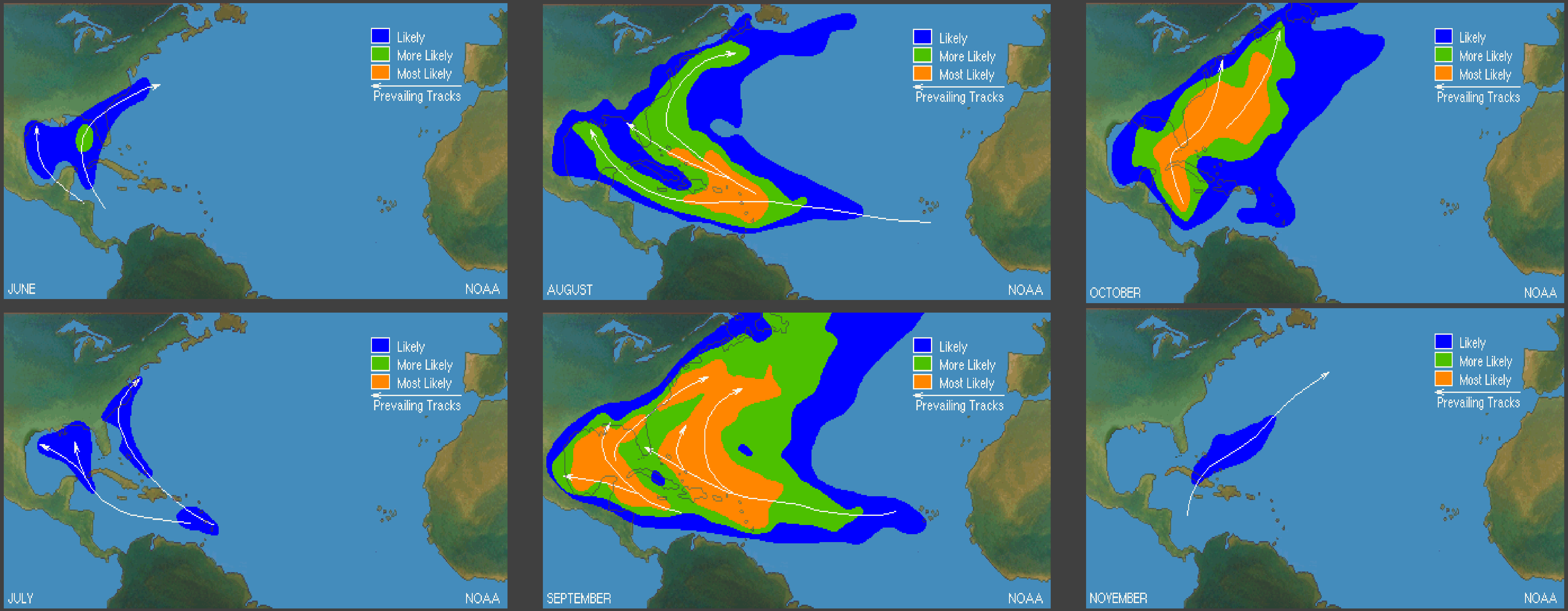
- Tropical Depressions: Winds < 34kt
- Tropical Storms: Winds of 35-64kt
- Hurricanes and Typhoons: Winds > 64kt



# Seasonality in the Caribbean

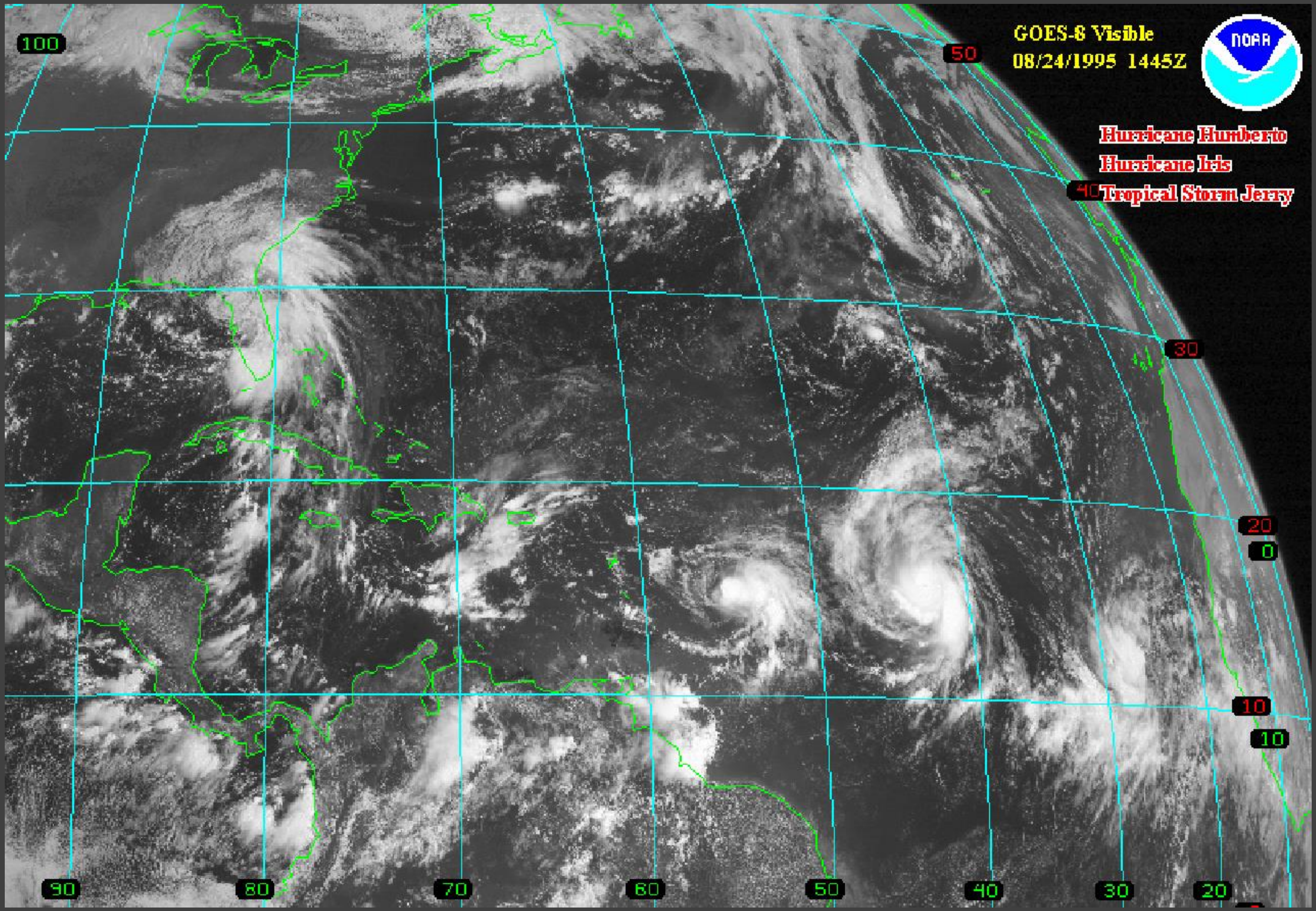


# Tropical Cyclone Genesis Areas by Month



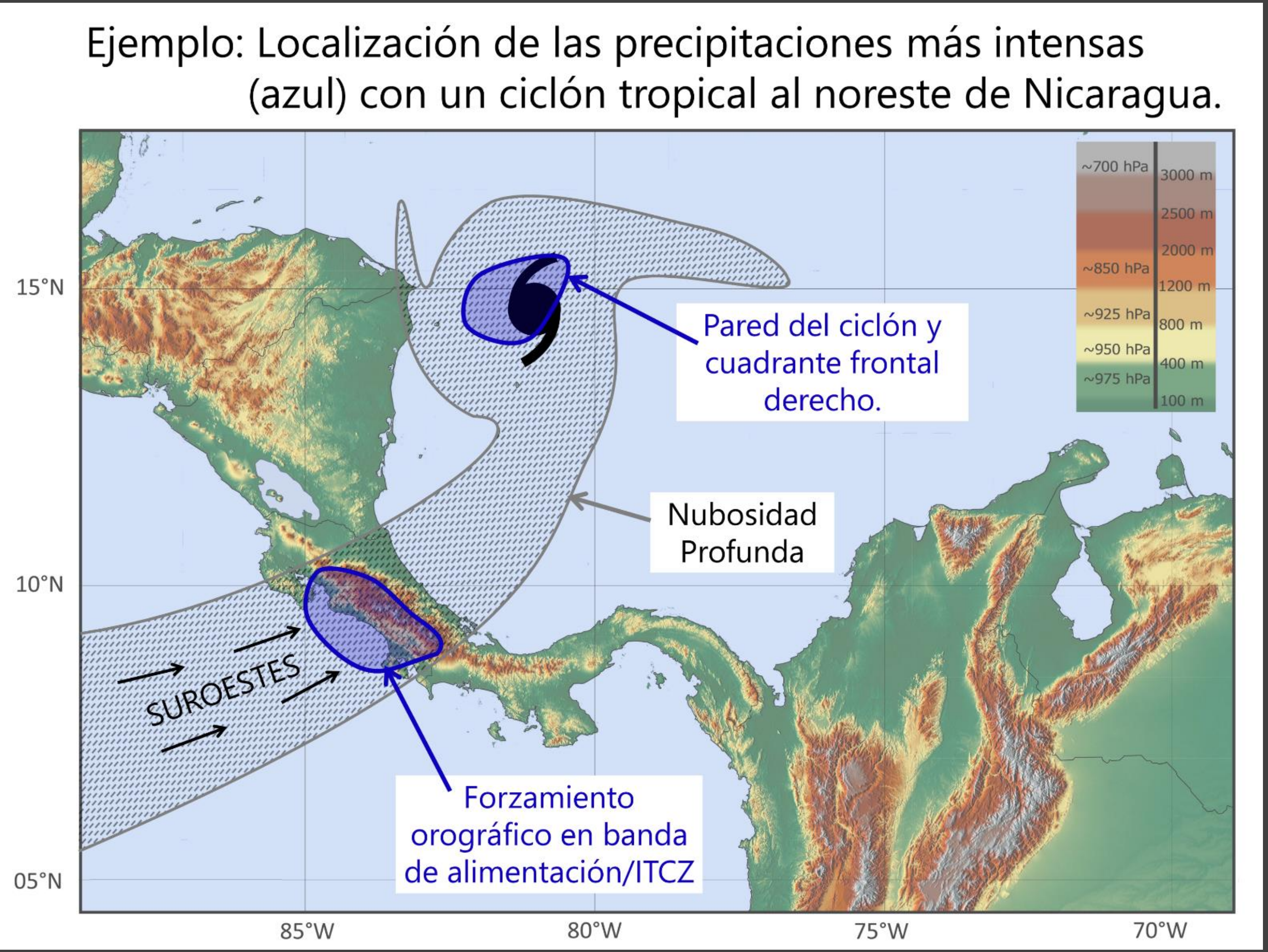
# Storm Families

- Storms can form one after the other, in environments that characterize by very warm SST, abundant moisture, disturbed flow (weak shear, enhanced rotation) and ventilation.
- A strong wet MJO between August and October can generate this, if the moisture and disturbed flow are in place.



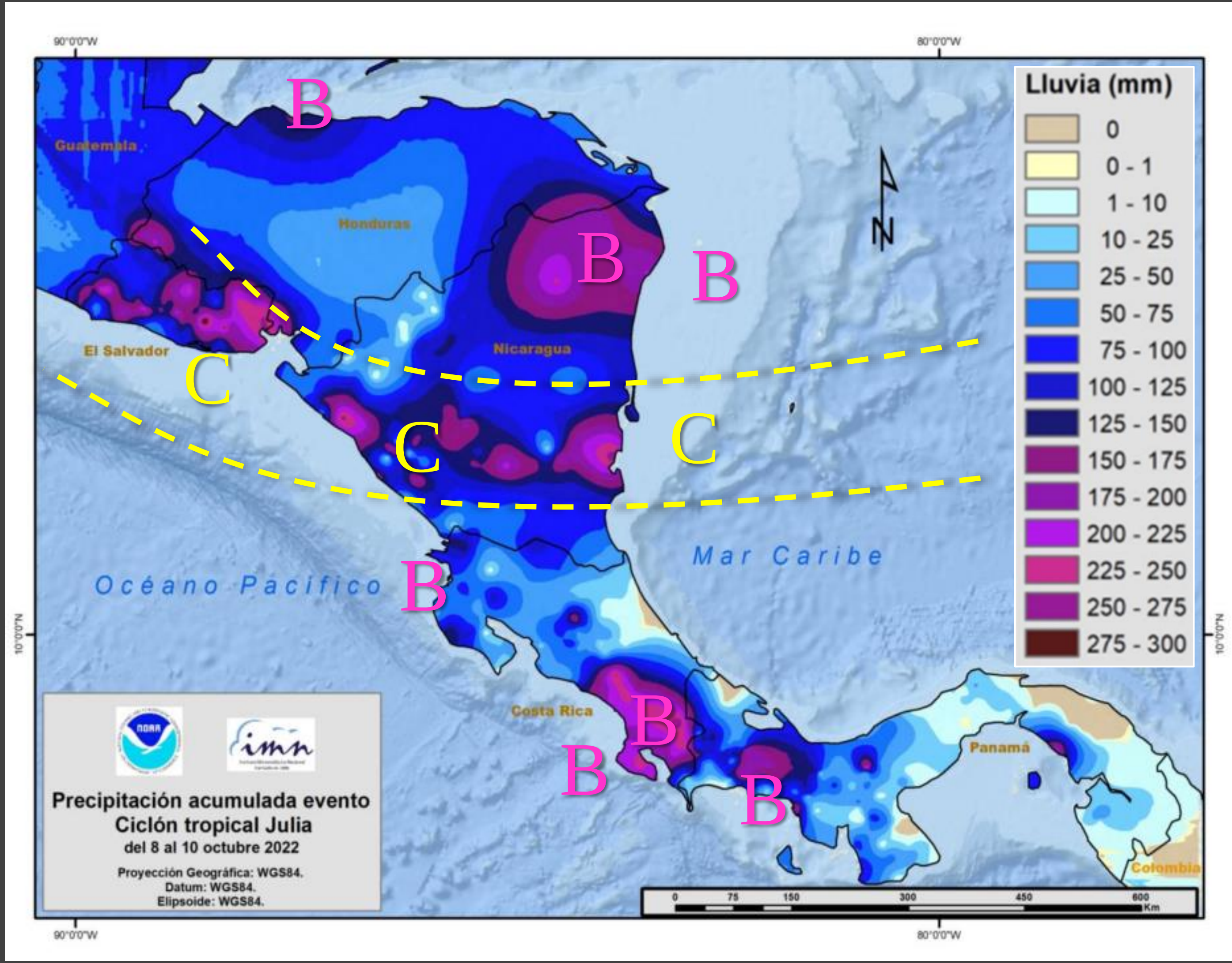
# Feeder Band Impacts in remote locations

- Feeder bands generate low-level convergence and moisture in remote locations.
- These can generate heavy Rainfall, especially when interacting with orography.
- Sometimes, a cyclone in the Caribbean interacts with the ITCZ and the latter acts as a feeder band. This is a problem in southwestern basins of Central America.

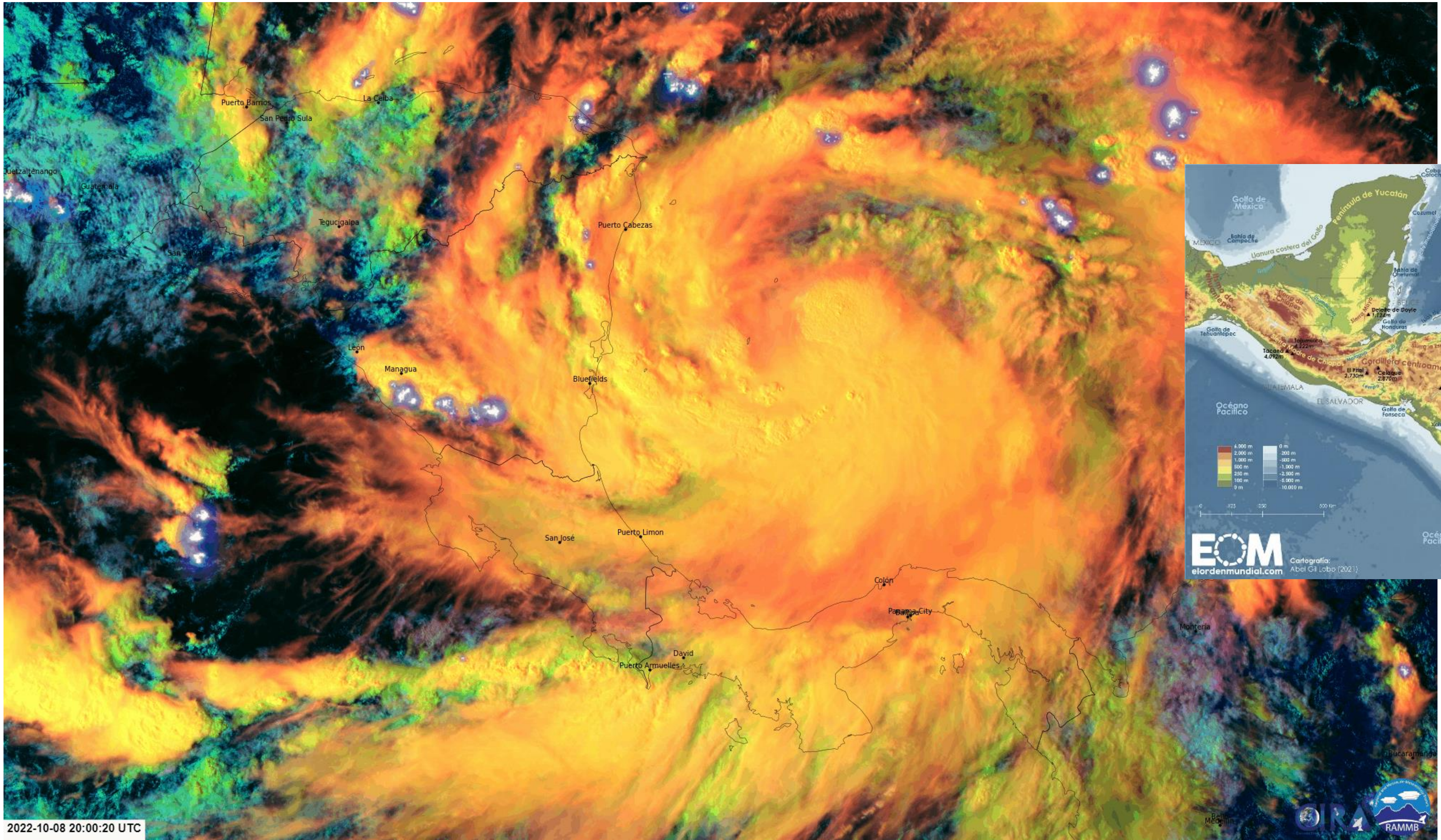


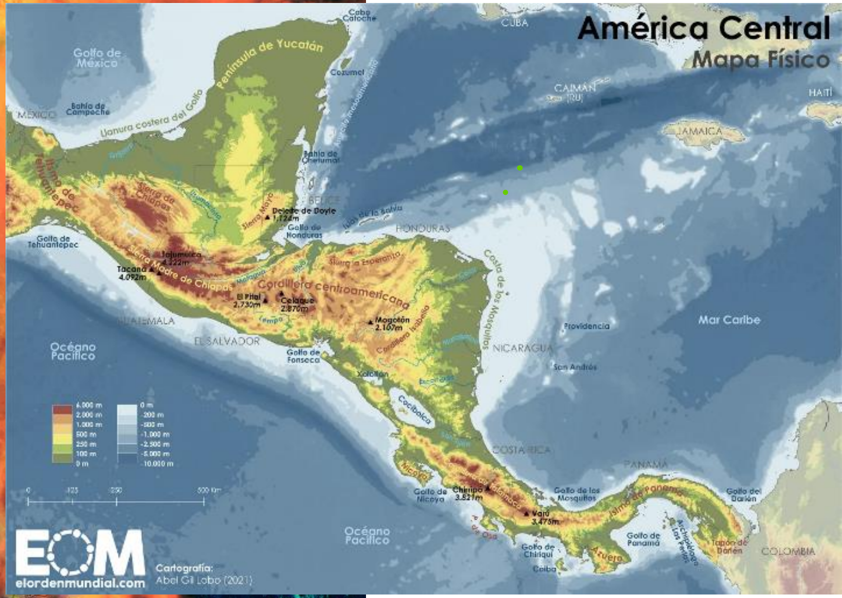
# Feeder Band Impacts in remote locations

- Rainfall field from Hurricane Julia (2022) from raingauges in Central America.
- Feeder band impacts are indicated with B, while Rainfall associated with the center of the Cyclone is indicated with C.
- The rains in Southern Costa Rica were as excessive as those produced by the center, since the ITCZ acted as a feeder band.



# Satélite – Day Cloud Phase Distinction



# 05

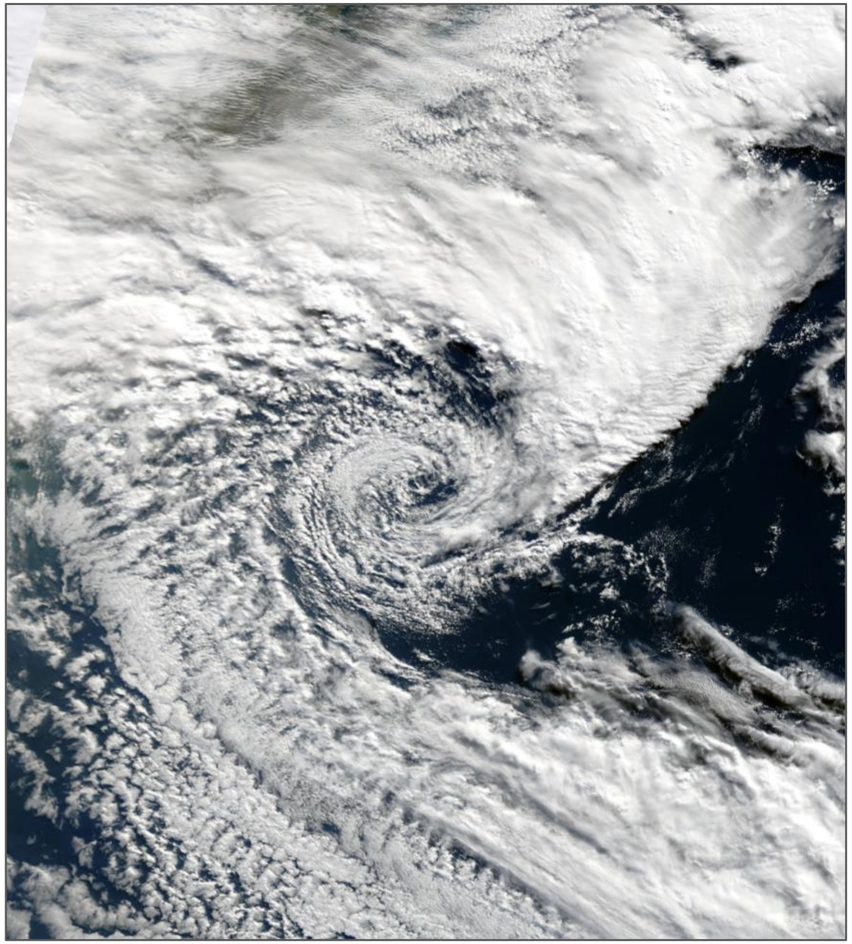
# Subtropical Cyclones

# Subtropical Cyclone

- A cyclone that forms in subtropical locations, that has the characteristics of a tropical cyclone in the lower levels and of an extratropical cyclone aloft.
- It develops a warm core, but underlying a cold core associated with an upper trough.
- They are non-frontal.  They behave more like tropical cyclones at the surface, but temperatures tend to be lower.

**What defines a subtropical cyclone:**
**A warm core underlying a cold core.**

Subtropical Storm Yakecan, off the coast of Uruguay and Brazil in 2022



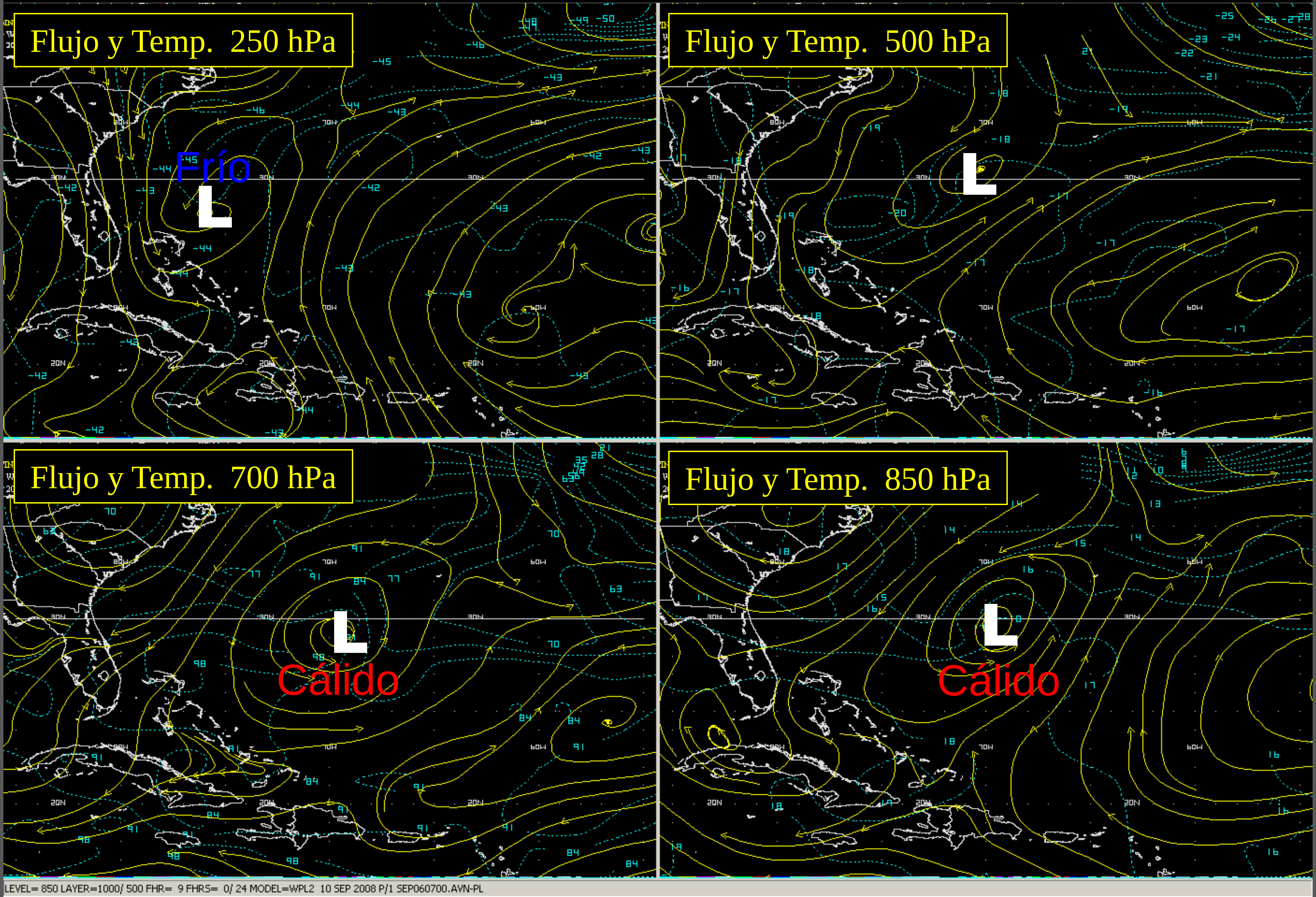
# Sources of energy and evolution

- Initially the thermal gradient/potential energy is the main source of energy. They often transition from the occluded low inside an extratropical cyclone.
- They usually develop in regions of weak to moderate temperature gradients.
- The transition is favored when moving over warm SSTs while active deep convection is occurring. This deep convection is favored by enhanced instability provided by the cold air of the upper trough.
- Eventually, the main source of energy becomes the heat from the ocean and latent heat processes dominate, but the low and mid-troposphere only.

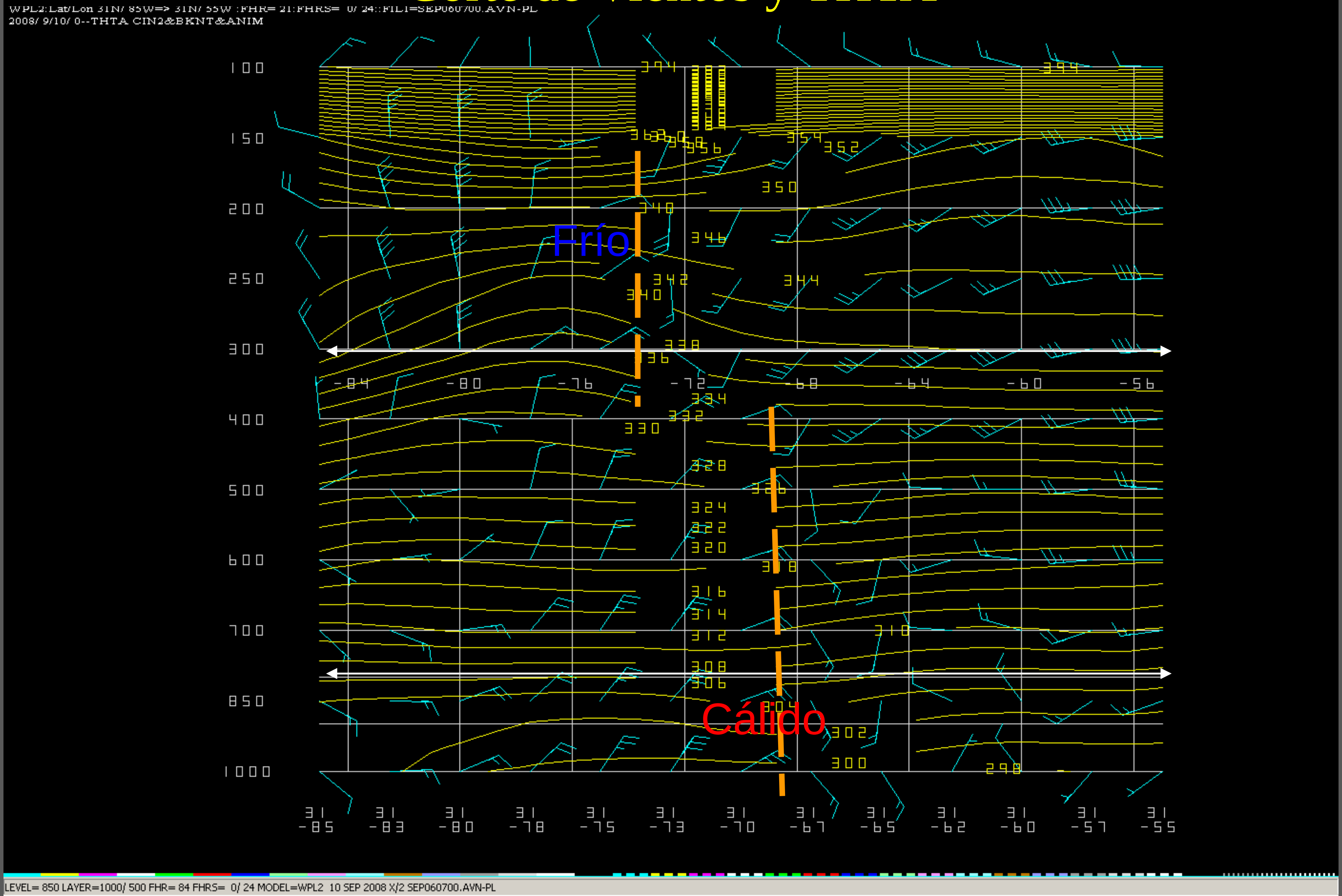
# Characteristics of subtropical cyclones

- Synoptic-scale cyclones with a cold core aloft and warm core in the low levels.
- Lower tropopause, associated with the upper trough.
- Vorticity: maxima in the lower levels and another maxima aloft.
- Radius of maximum winds larger than tropical cyclones.
- Winds have not been observed to exceed 64kt (Cat 1 hurricane)
- SST generally > 23°C

# Subtropical Cyclone in the North Hemisphere

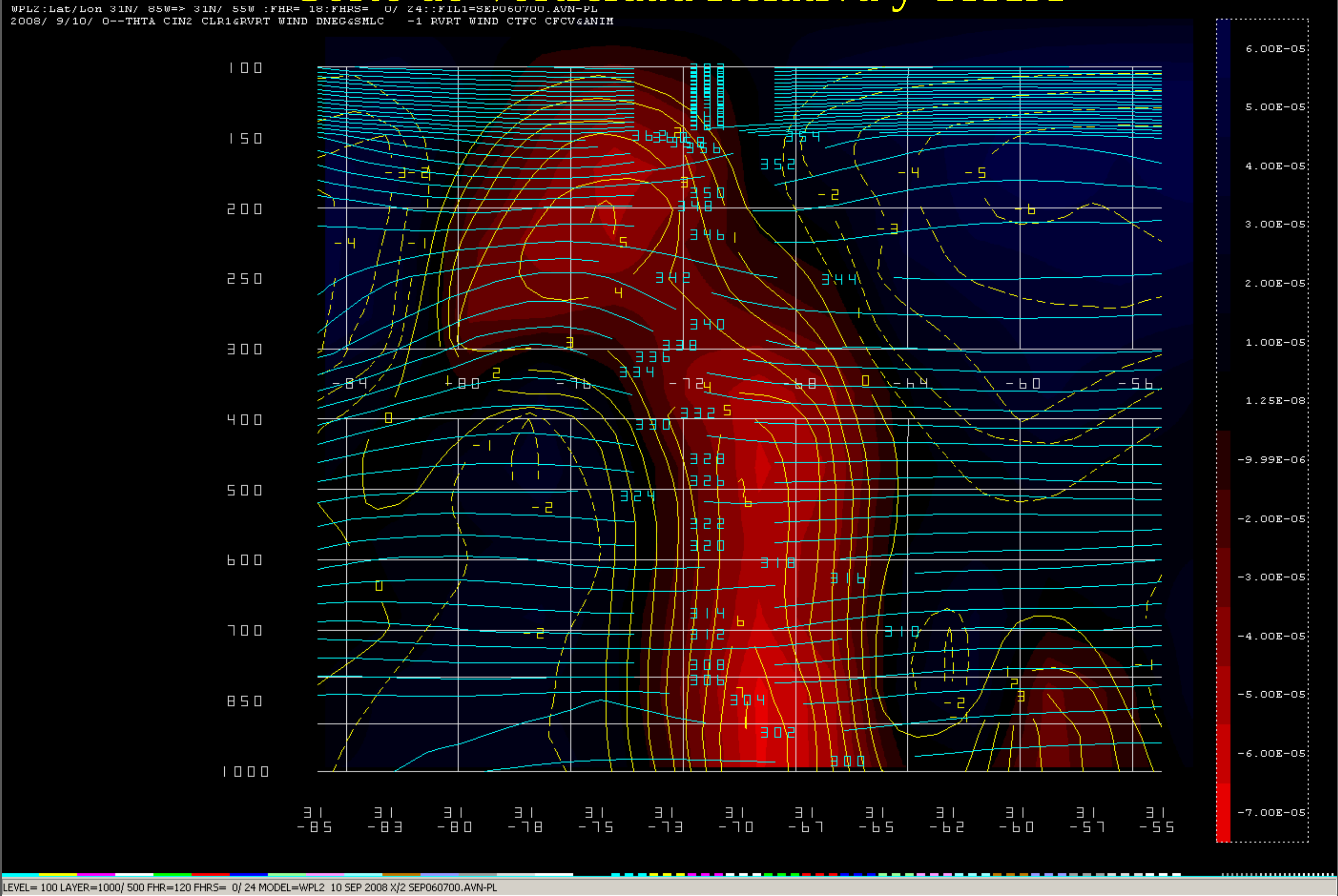


# Ciclón Subtropical (HN)
# Corte de Vientos y THTA



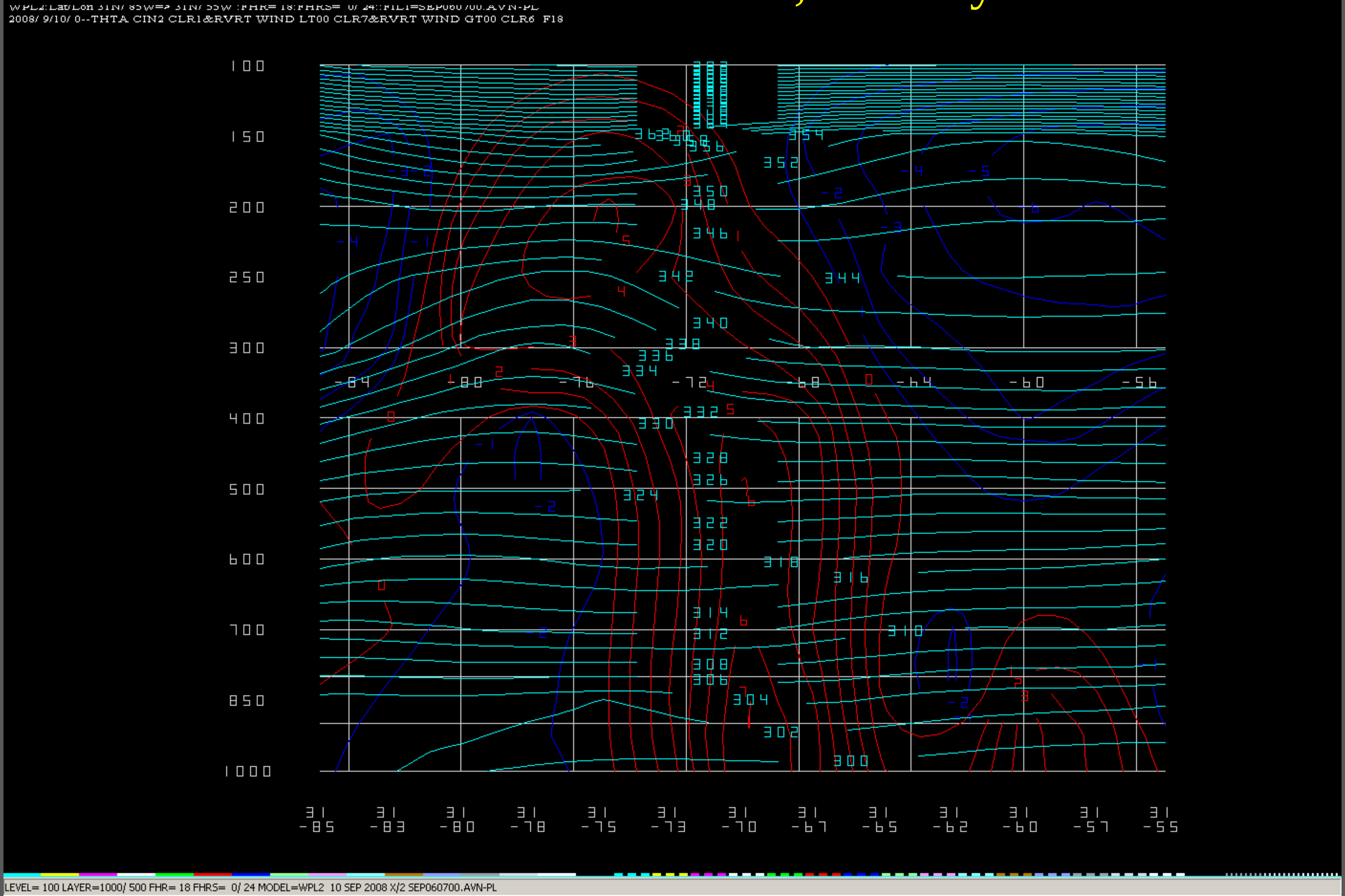
# Ciclón Subtropical (HN)

# Corte de Vorticidad Relativa y THTA

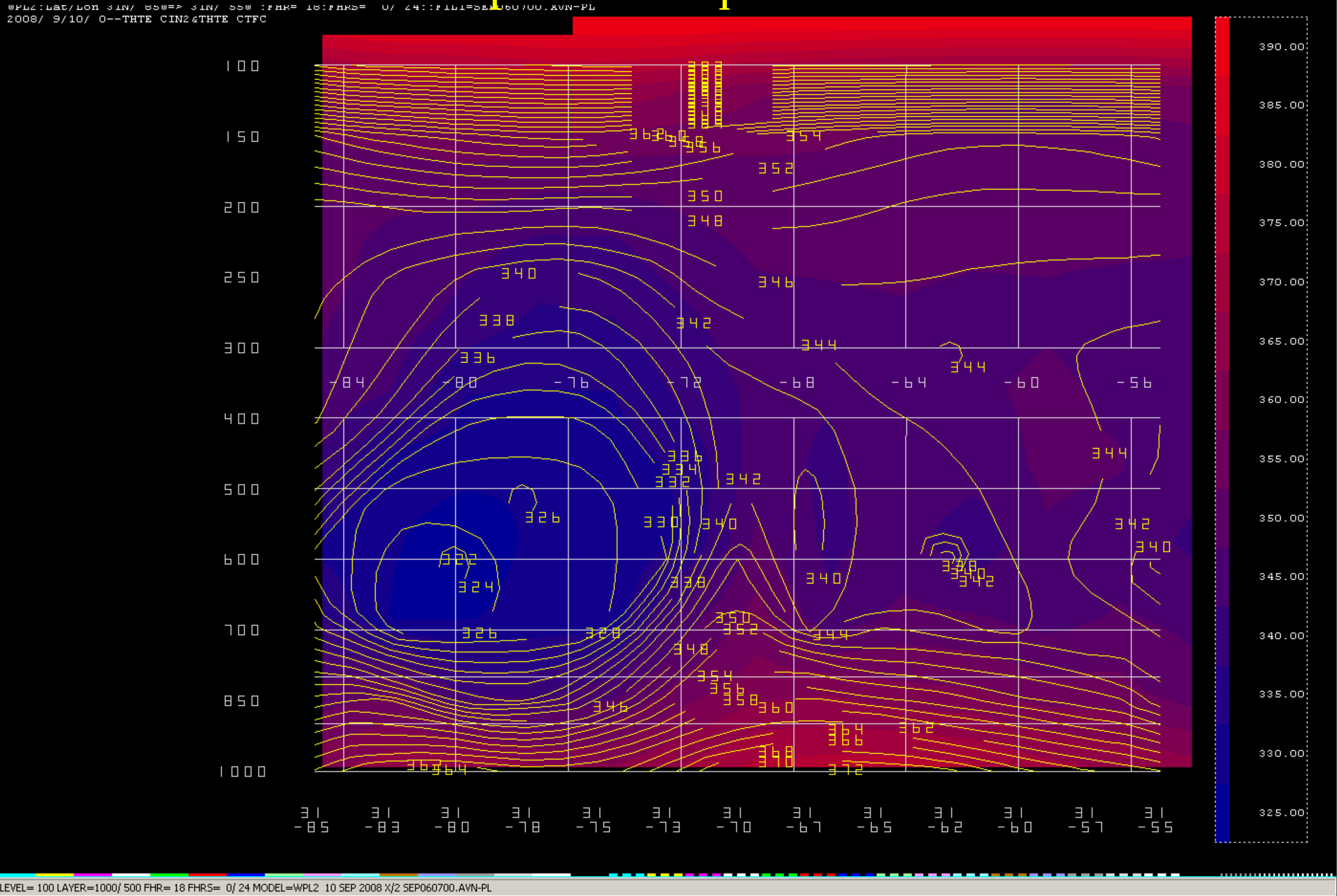


# Ciclón Subtropical (HN)

## Corte de Vorticidad Relativa, Viento y THTA



# Ciclón Subtropical (HN)
## Corte de Temperatura Equivalente Potencial



# Classification of a Subtropical Cyclone

## Evans and Guishard, 2009

1. The system attains gale-force winds (>17 m $s^{-1}$ or **35kt** ) at 925 hPa, which need to be sustained for at least three consecutive 12-hourly model analyses (equivalent to 36 h). The time of first onset of gales is defined as the ST formation time, T;

2. the hybrid structure also persists for at least 36 h (i.e., more than one diurnal cycle). This hybrid structure criterion is determined using the CPS parameters (Hart 2003);

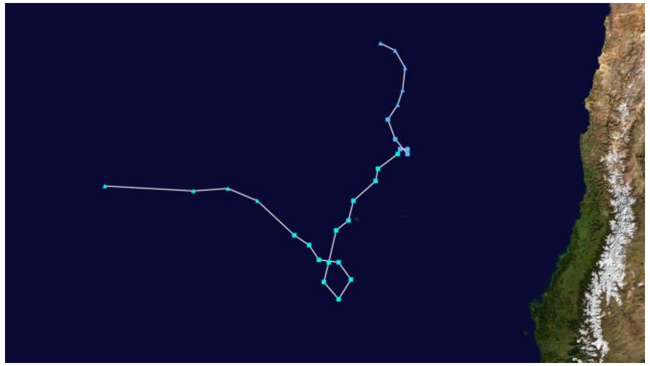
3. only storms that form (i.e., attain gales) between 20° and 40° are retained;

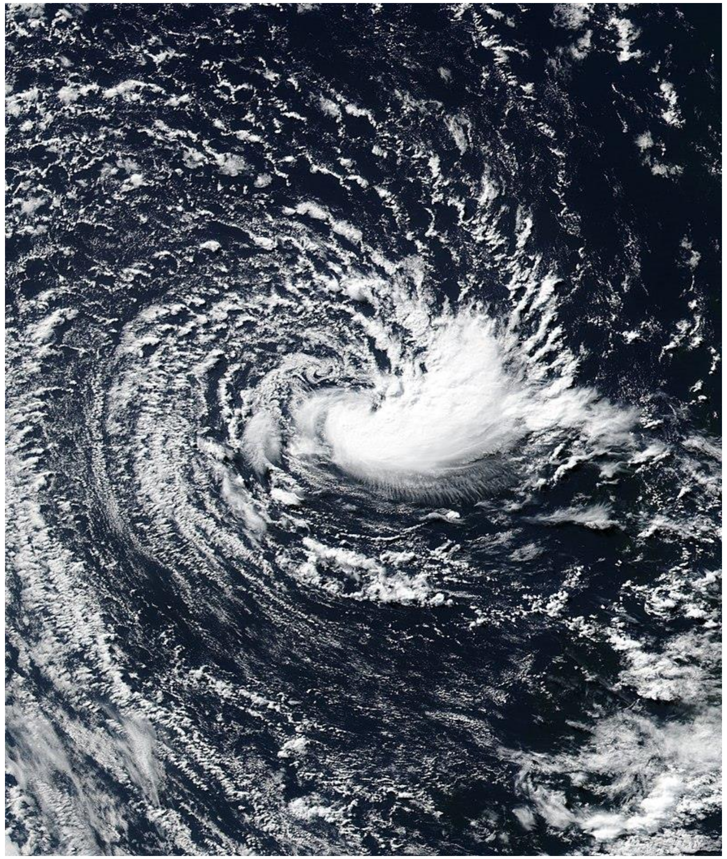
4. the cyclone should not have been tracked as either a purely cold- or warm-cored structure for more than 24 h prior to attaining hybrid structure; and

5. only storms located over the ocean from the first instance of a closed low through all instances of hybrid characteristics and the first occurrence of gales are considered.

# Subtropical Storm Lexi, Chile, May 2018

- Rare Subtropical Cyclone that formed off the coast of Chile in 2017.

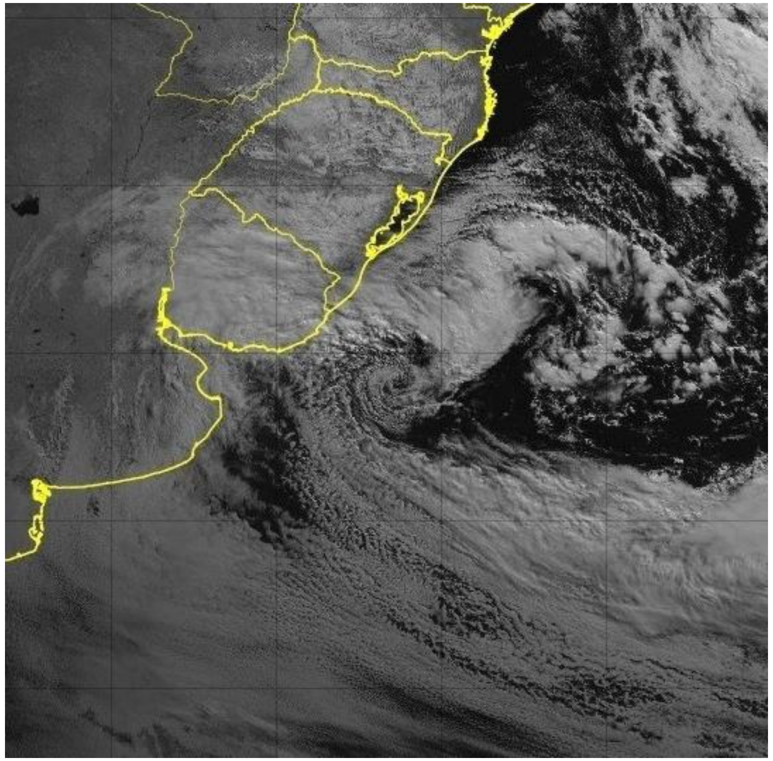




# Subtropical Storm Yakecan, Uruguay/Argentina/Brazil, May 2022

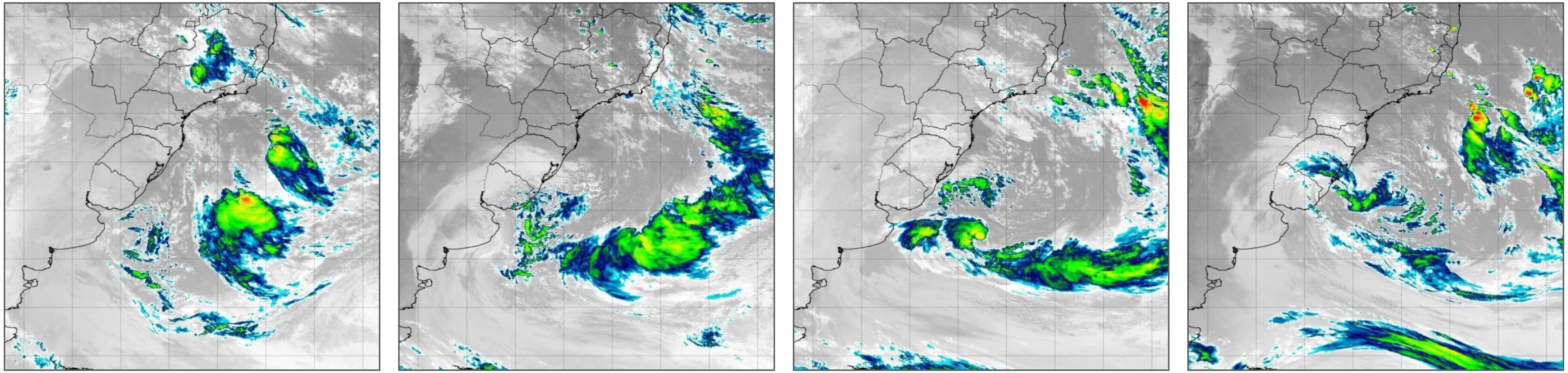
- Subtropical Cyclone that formed off the coast of Uruguay in May 2022, producing ~60kt winds when its right front quadrant entered in the morning of May 17.
- It then moved into southern Brazil where it produced severe impacts including 2 fatalities.

Coastal Flooding in Uruguay



0.84um Satellite Image during 17 May 2022 at 13 UTC, showing the left front quadrant of the cyclone entering Uruguay.

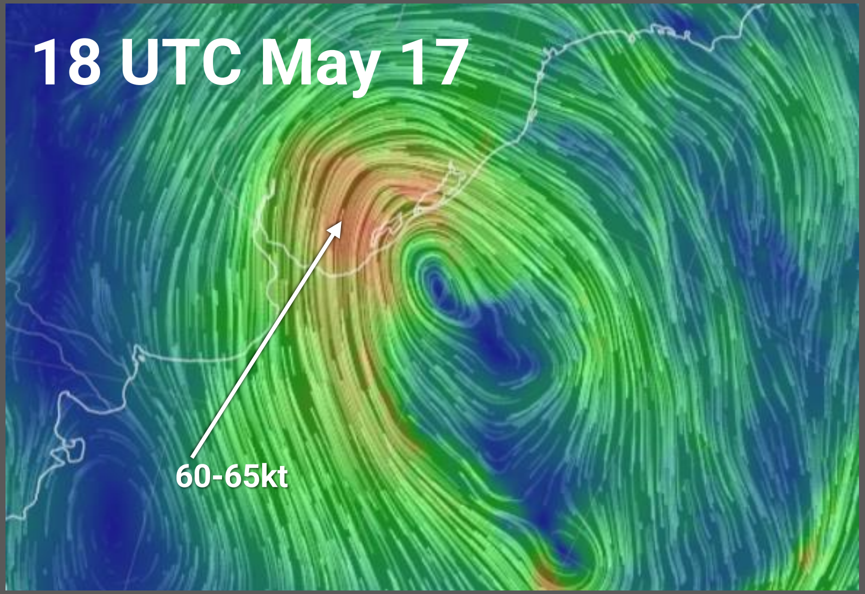
# Evolution of Subtropical Storm Yakecan on Satellite

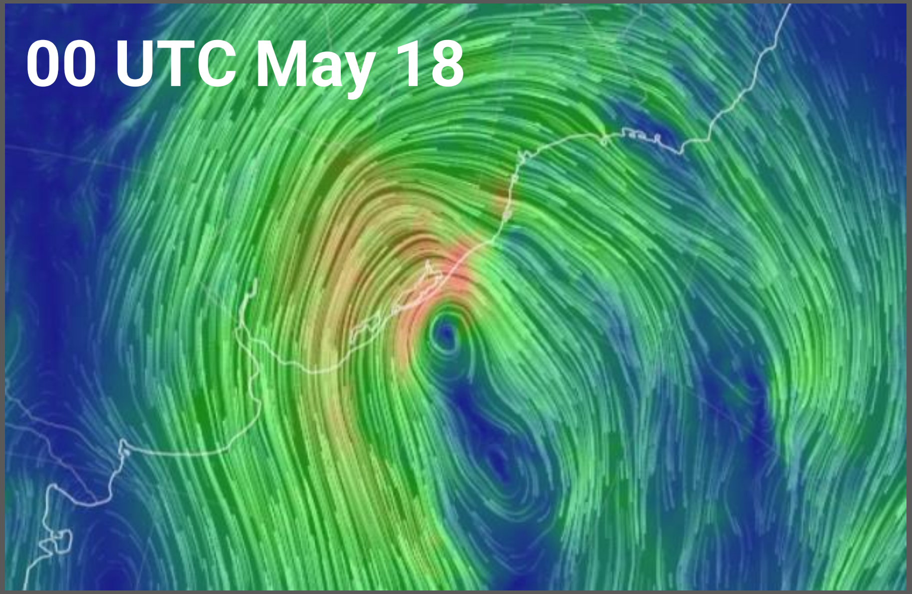


16May 06Z | 16May 18Z | 17May 06Z | 17May 18Z

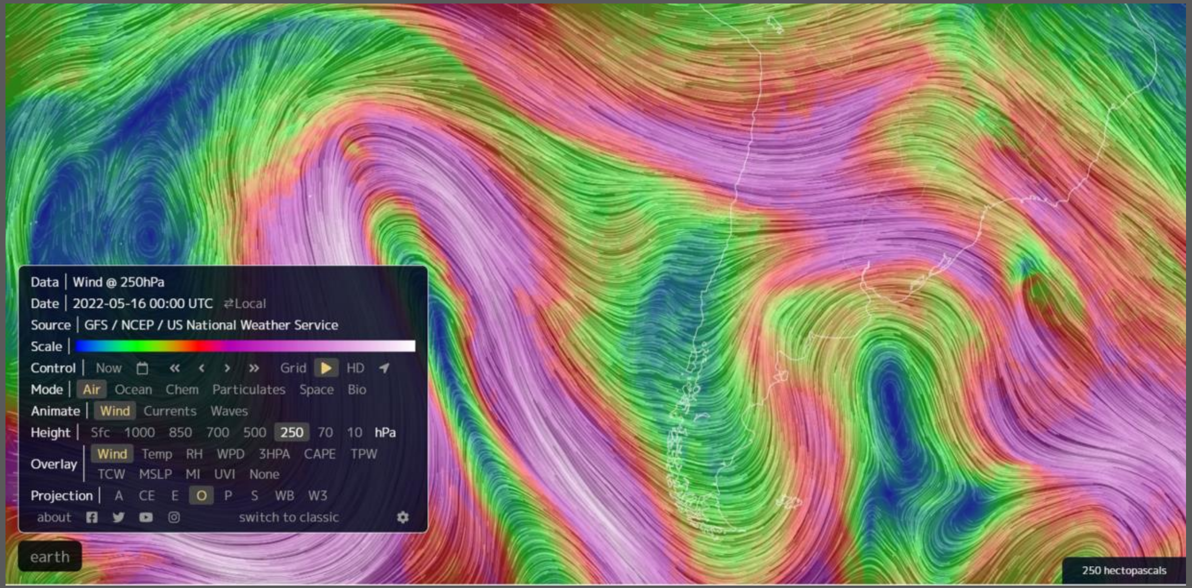
The sequence shows a disorganized subtropical cyclone evolving from an occluded low evident on panel 1. The cyclone then makes landfall in Uruguay in the morning of 17 May.

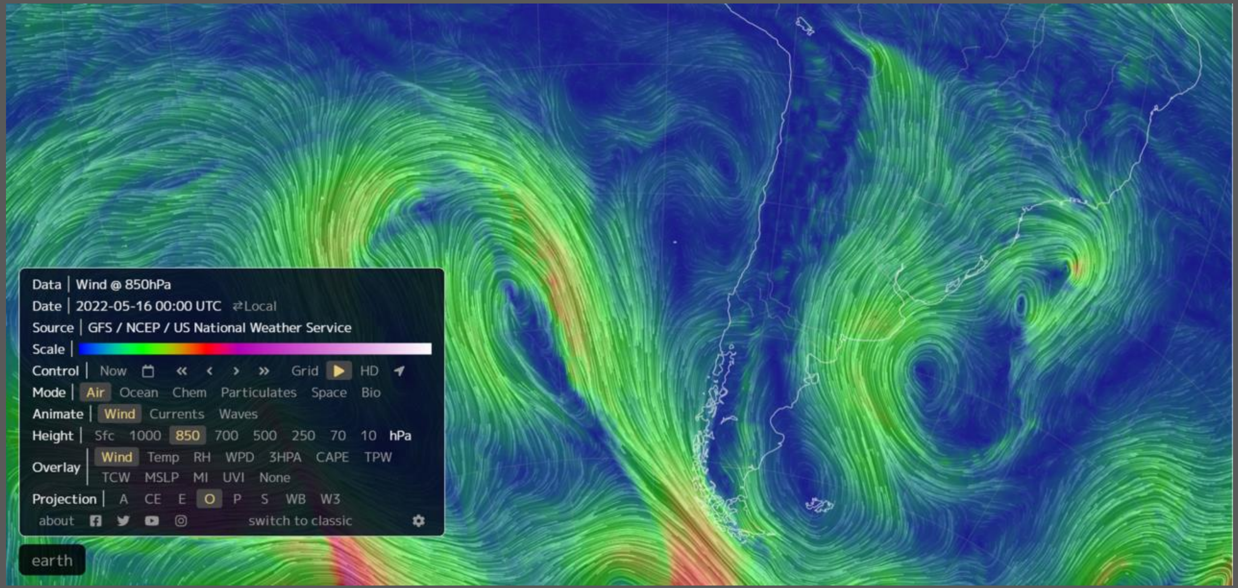
# Subtropical Cyclone in Argentina and Uruguay and Southern Brasil, May 2022



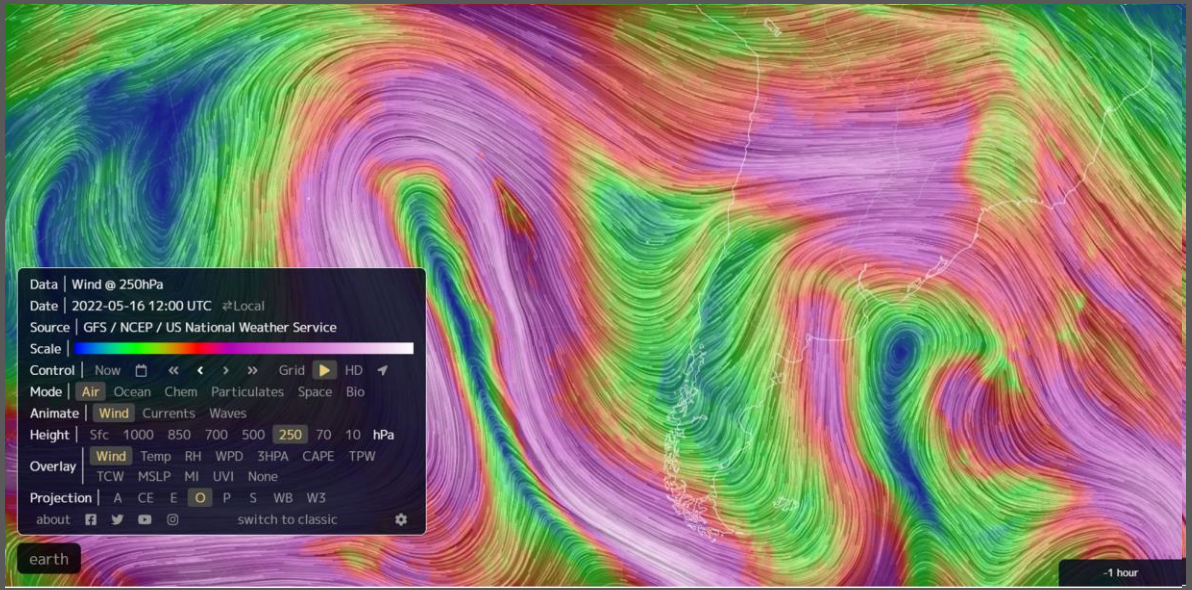



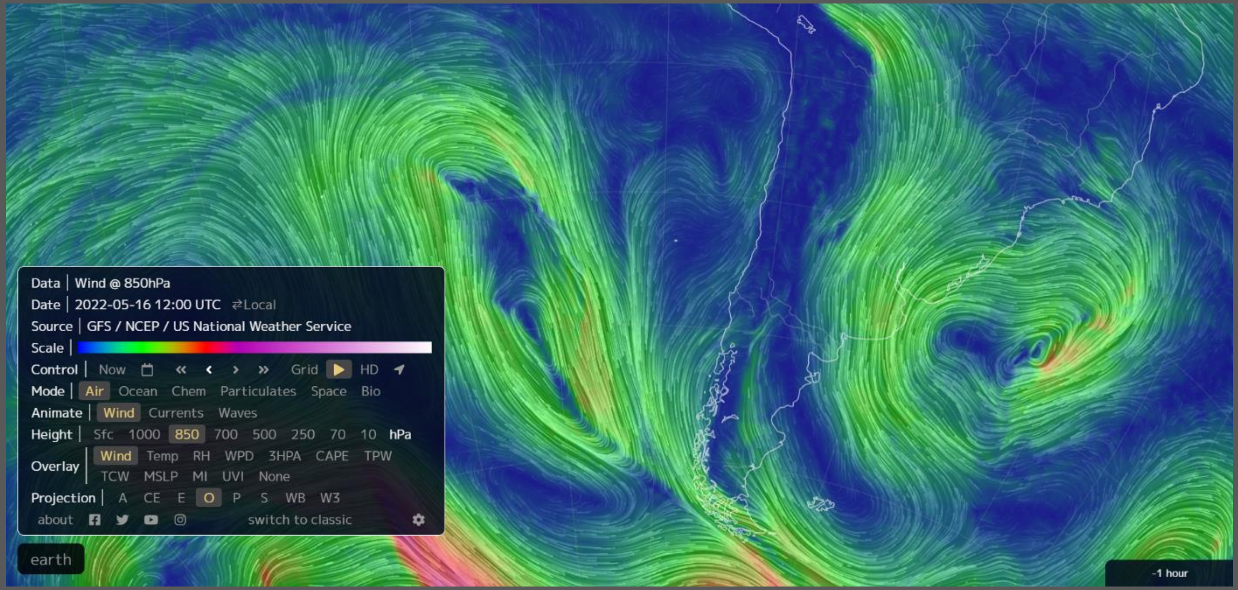
# Subtropical Cyclone in Argentina and Uruguay and Southern Brasil, May 2022



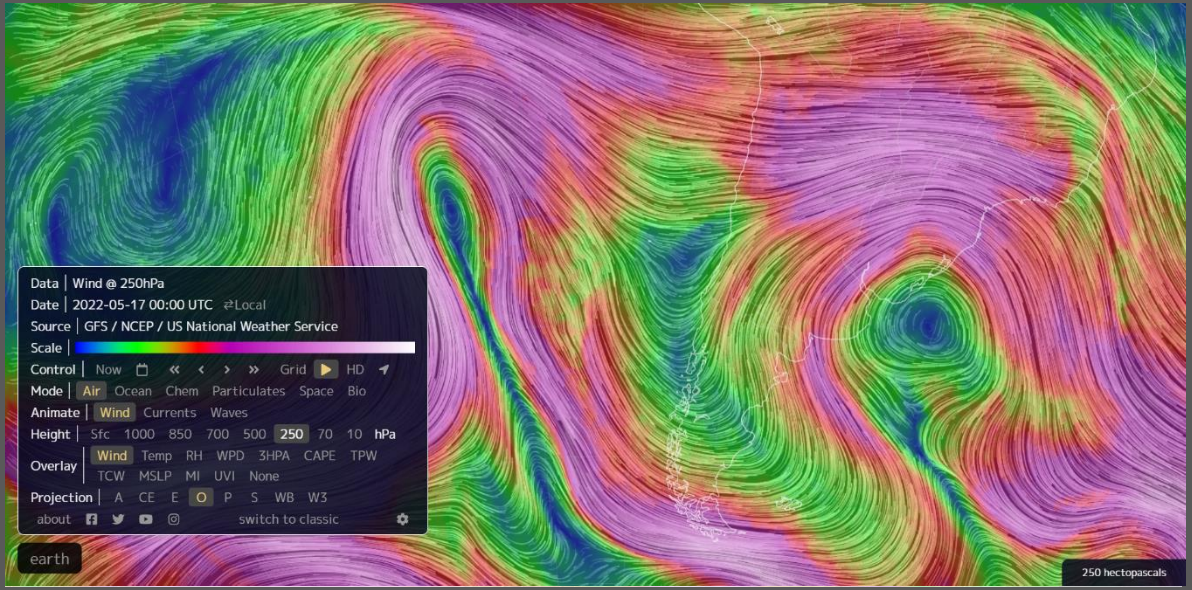



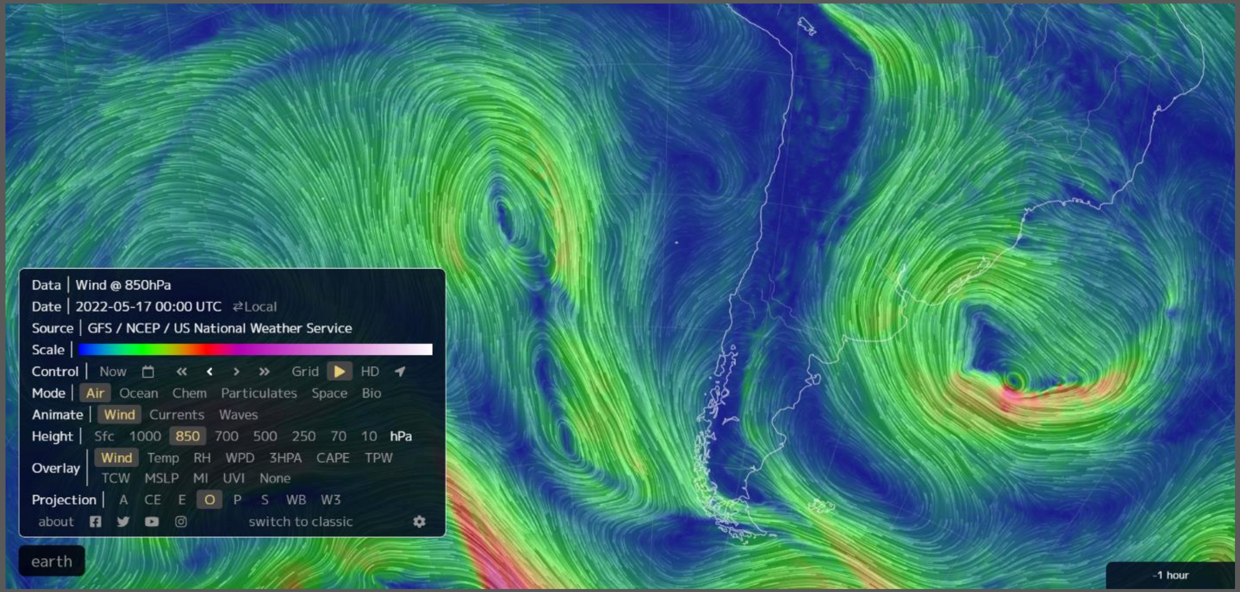
# Subtropical Cyclone in Argentina and Uruguay and Southern Brasil, May 2022



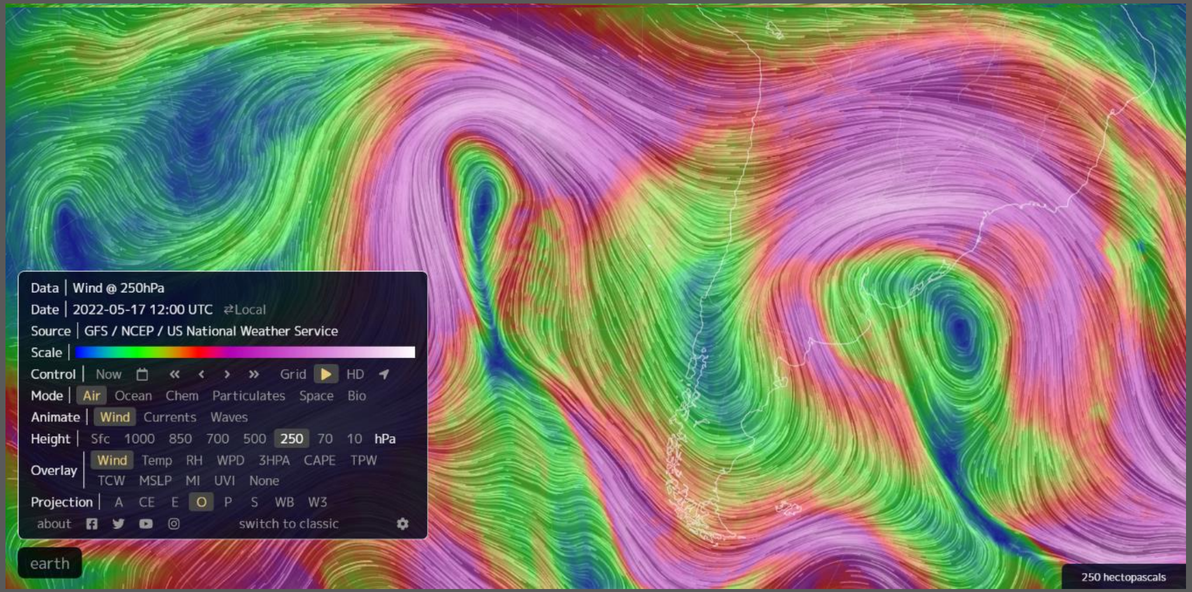



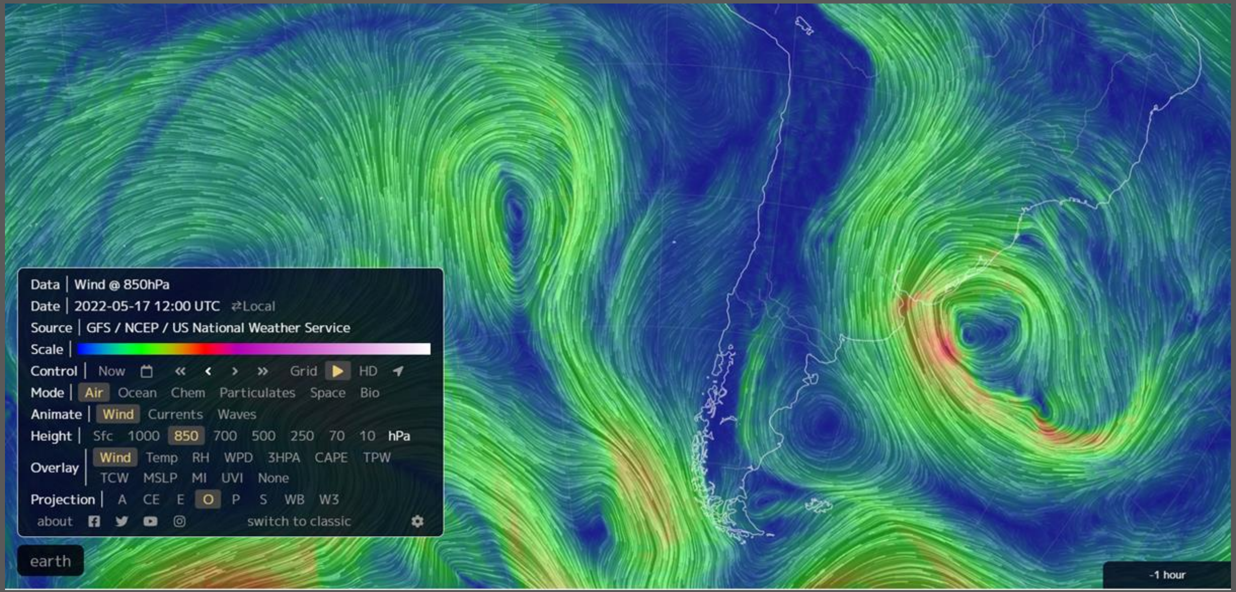
# Subtropical Cyclone in Argentina and Uruguay and Southern Brasil, May 2022



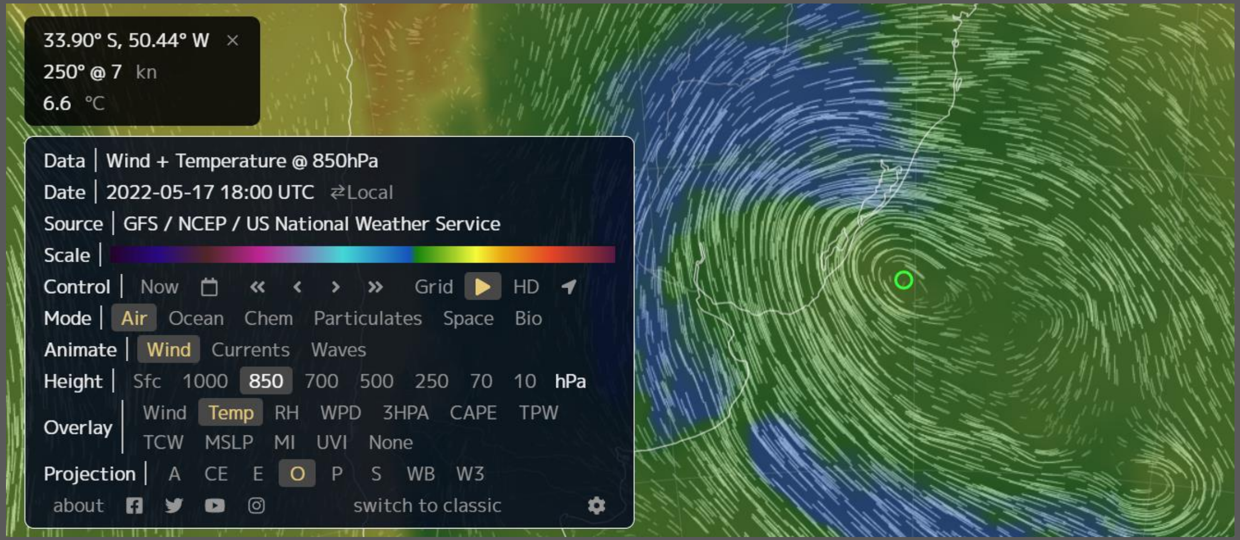



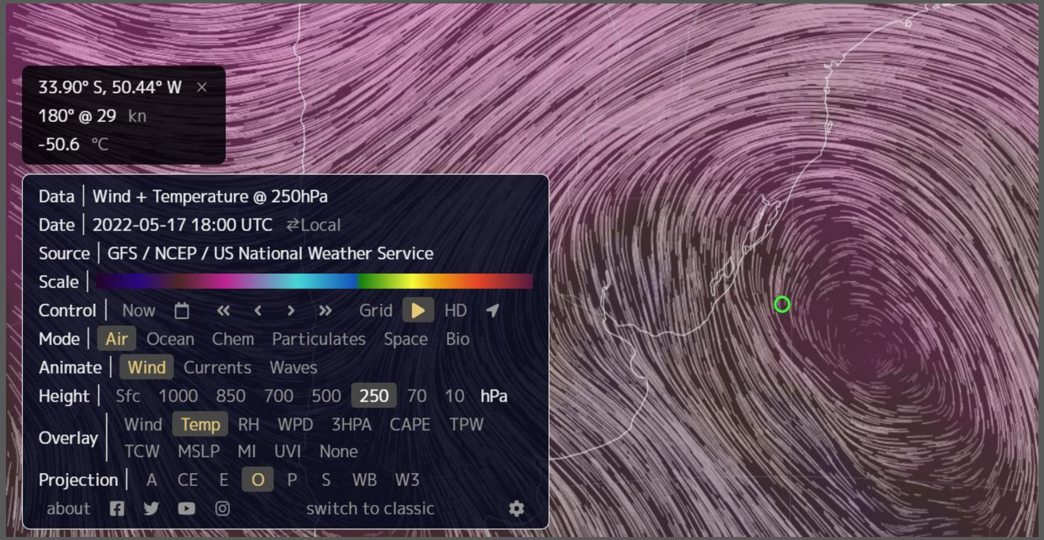
# Subtropical Cyclone in Argentina and Uruguay and Southern Brasil, May 2022

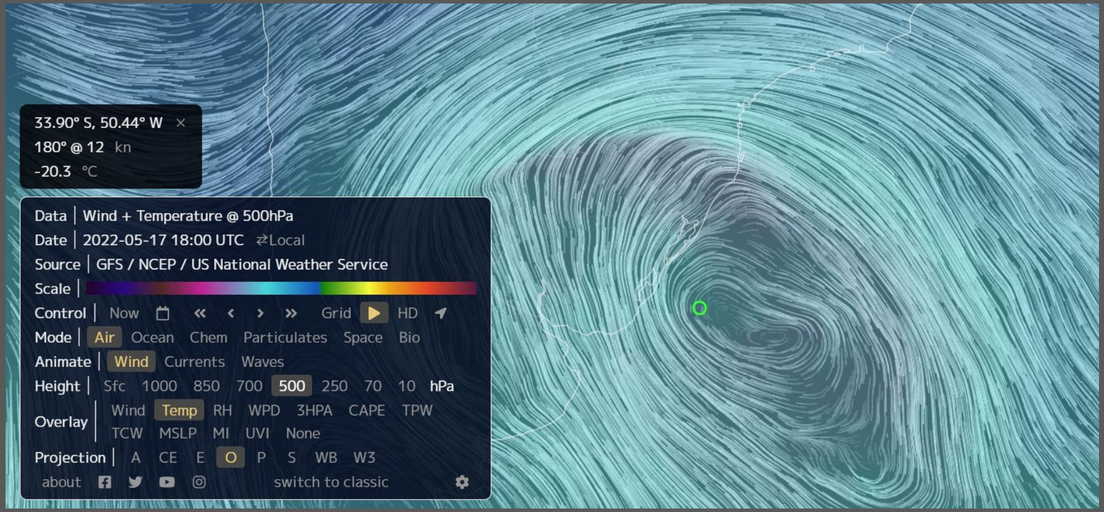


# Thermal Structure of Subtropical Cyclone Yakecan




ICAO Headquarters
Montréal
European and North Atlantic (EUR/NAT) Office
Paris
Asia and Pacific (APAC) Sub-office
Beijing
Middle East (MID) Office
Cairo
Western and Central African (WACAF) Office
Dakar
North American Central American and Caribbean (NACC) Office
Mexico City
Asia and Pacific (APAC) Office
Bangkok
Eastern and Southern African (ESAF) Office
Nairobi
South American (SAM) Office
Lima

# Thank You!