Useful Forecast Guidance for the **Birth**, **Transition**, and **Afterlife** Stages of Tropical Cyclones

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WMO2019 30 April 2019

Part 1: The Genesis Problem and Calibrated Model Probabilities as One Solution

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One Timeline of TC Genesis in Operational Models

- Through mid 1990s: Operational numerical models were too coarse in grid spacing to produce TCs from nothing
- Late 1990s: Operational grid spacing decreased sufficiently that TCs were now possible to form during the forecast… however..…it appears that the physics in the models hadn't yet been sufficiently calibrated to the improved grid spacing because….
- 1999: Jack Beven documents the "boguscane" problem – the MRF/AVN was seemingly on steroids regarding TC Genesis in the Atlantic culminating in 1998/1999 (this is a bigger problem than just too many TCs!)
- Early 2000s: The boguscane problem was greatly reduced with improvements in physics in the models
- Mid 2000s: Operational models began to have some reliability with TC formation, although with very idiosyncratic behavior
- 2010s: Idiosyncratic behavior reduced some (but remained), leading to the possibility for the first time of statistical guidance on TC formation that exploited this biased, but repeatable, behavior.

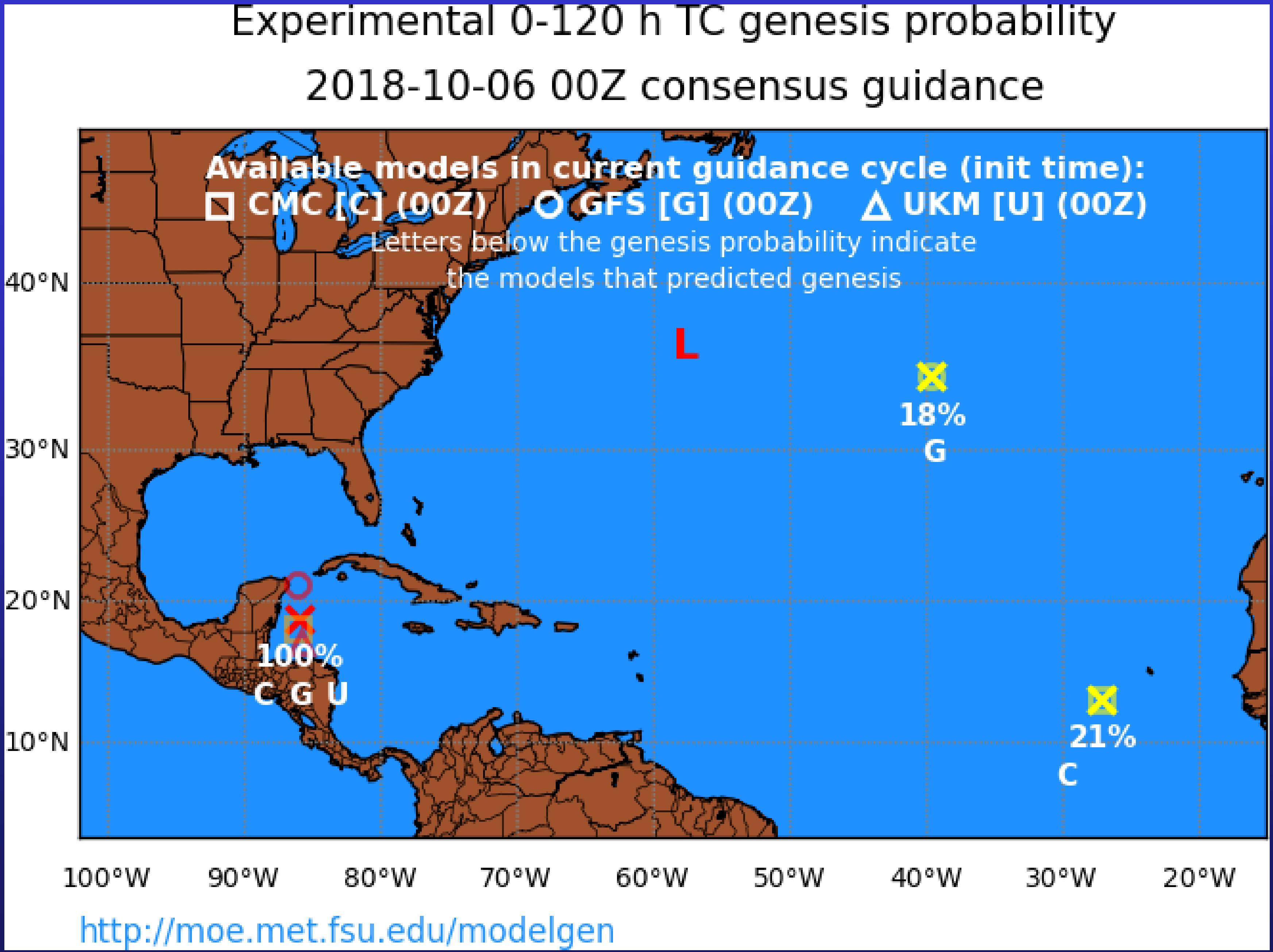
What to look for in the models for genesis?

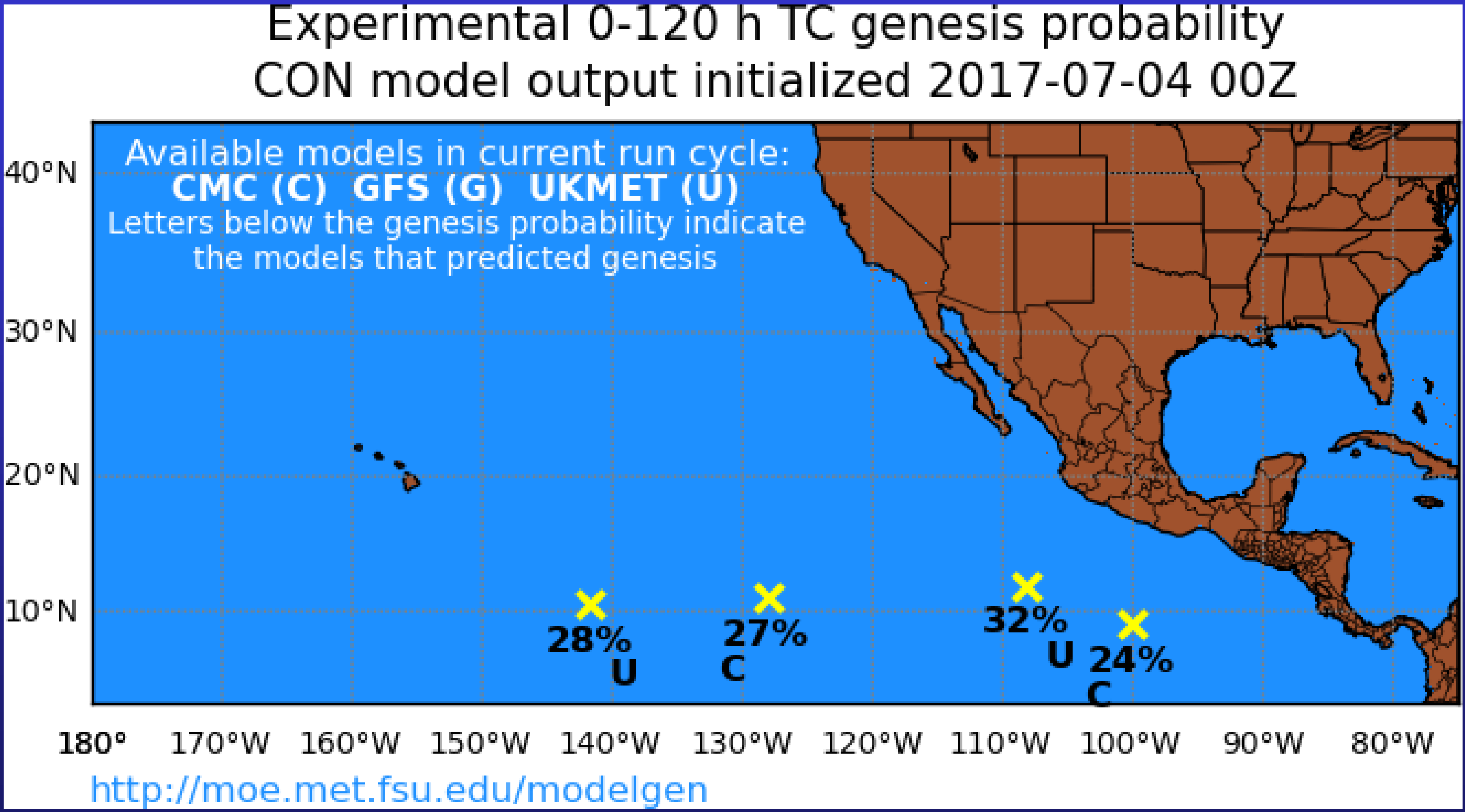
- Although operational models today may not capture all known and unknown key processes for genesis, often there is a broader scale reflection if a TC is forming in the model. Key thresholds on the broader scale of:
  - SLP minima, SLP gradient
  - Low-mid level wind field, Low-mid level vorticity
  - CAPE
  - Thickness, etc.

- So, it makes sense to compare various thresholds of the above to the probability of a known TC forming in a model or group of models

- Based on the idiosyncrasies mentioned earlier, each model would likely have different thresholds or even different key predictive variables.
  - Just because a model may have a bias regarding genesis frequency doesn't mean that it is not useful statistically. In fact those can be the most useful models statistically.

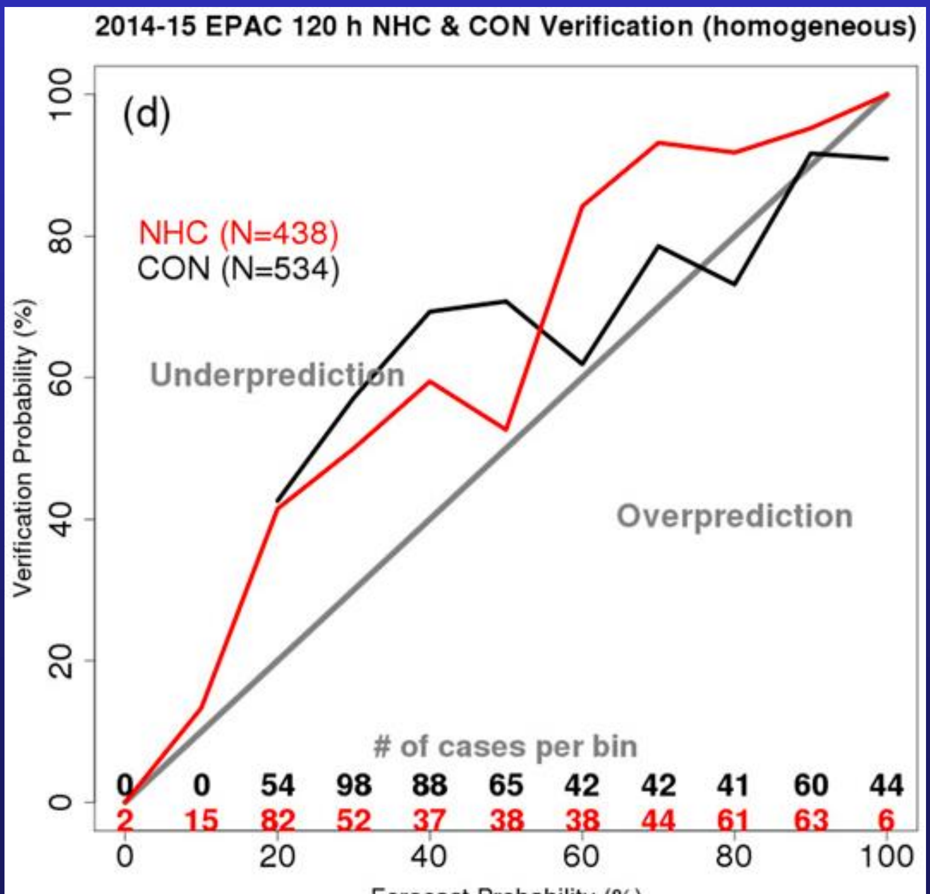
- Produce logisitic regression equations that provide well-calibrated probabilities of TC formation using those model fields.
  - Further improve the guidance by intercomparing multiple models

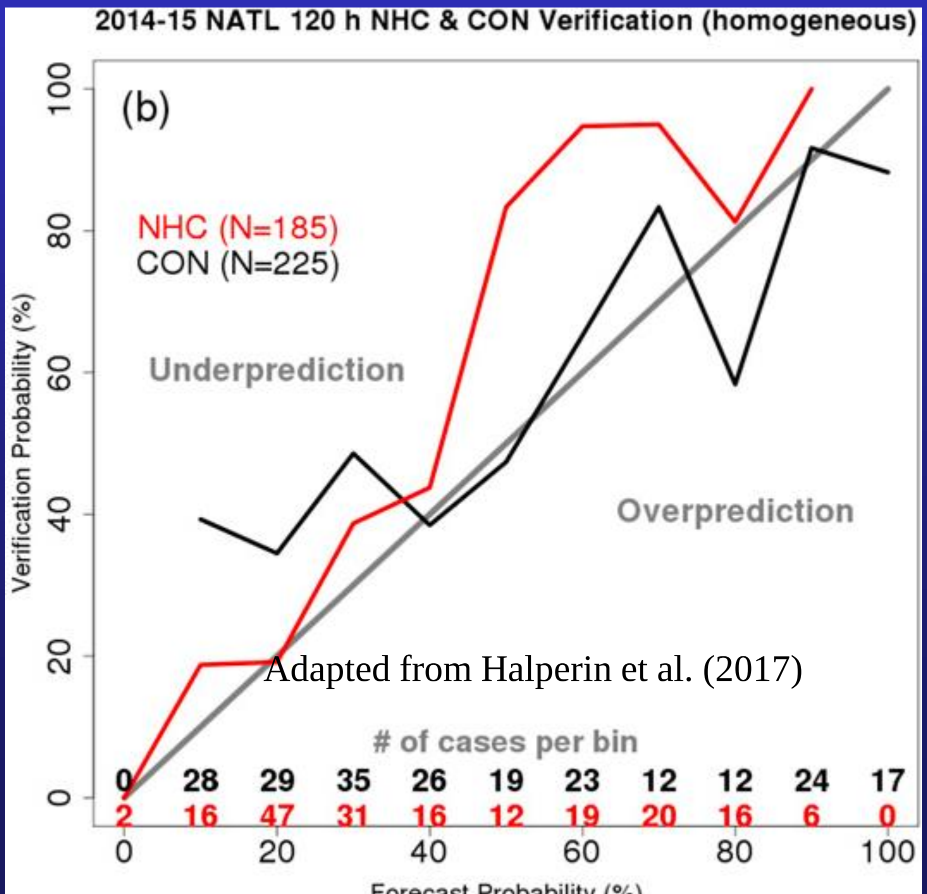

Experimental 0-120 h TC genesis probability
2018-10-06 00Z consensus guidance
Available models in current guidance cycle (init time):
CMC [C] (00Z)
GFS [G] (00Z)
UKM [U] (00Z)
Letters below the genesis probability indicate
the models that predicted genesis
L
18%
G
100%
C G U
21%
C
40°N
30°N
20°N
10°N
100°W
90°W
80°W
70°W
60°W
50°W
40°W
30°W
20°W
http://moe.met.fsu.edu/modelgen


Experimental 0-120 h TC genesis probability
CON model output initialized 2017-07-04 00Z
Available models in current run cycle:
CMC (C) GFS (G) UKMET (U)
Letters below the genesis probability indicate
the models that predicted genesis
40°N
30°N
20°N
10°N
28%
U
27%
C
32%
U
24%
C
180°
170°W
160°W
150°W
140°W
130°W
120°W
110°W
100°W
90°W
80°W
http://moe.met.fsu.edu/modelgen

Genesis Prob. Performance

- Verification revealed well-calibrated forecasts in forecast probability intervals > 50%.





Adapted from Halperin et al. (2017)

Summary

- Resulting JHT-funded Guidance: Tropical Cyclone Logistical Guidance for Genesis (TCLOGG)

- Well-calibrated probabilities for the CP, EP, and ATL basins

- Things can go awry when there are major changes in a given model, or if a specific model disappears (e.g. NOGAPS changes to NAVGEM and GFS changes to FV3-GFS).

- Real-time web page for these probabilities are available using the CMC, GFS, (soon) NAVGEM, and UKMET raw output

  http://moe.met.fsu.edu/modelgen

- Probability equations are updated every year, and use between 5 and 9 years of model output.

- New developments coming in the next 2-3 years

Part 2: The Analysis and Prediction of Hybrid Cyclones and Structural Transition

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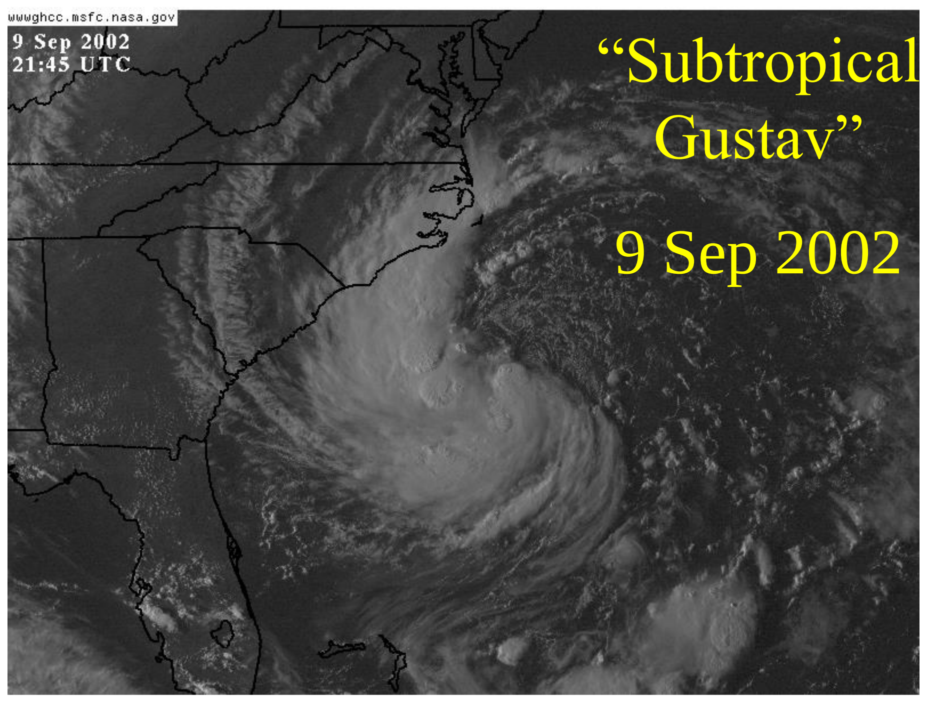

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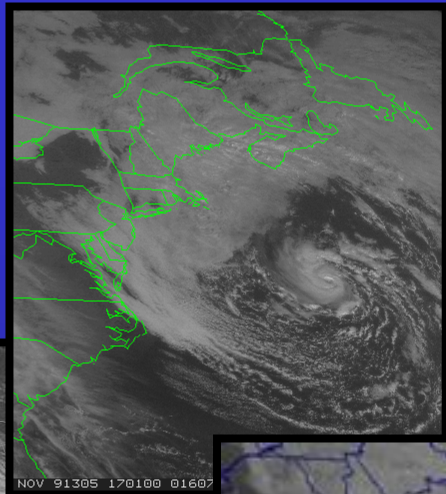
We are taught in class about two mutually exclusive cyclone “worlds”

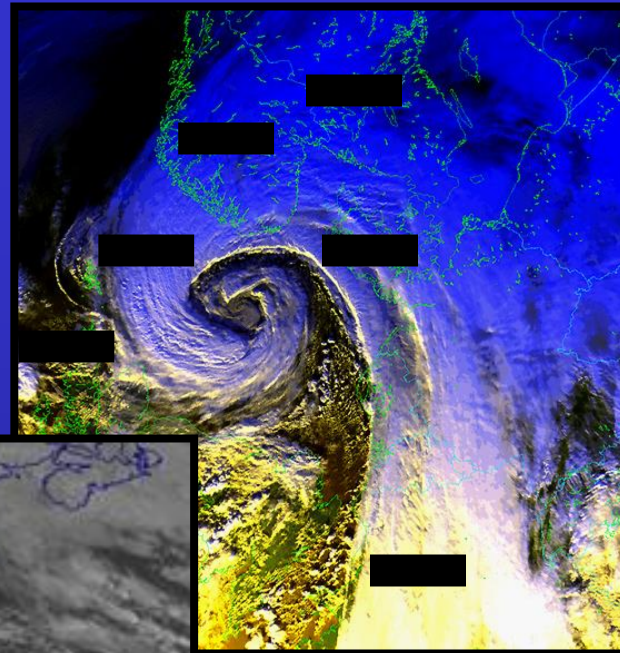
- Extratropical cyclones
  - Exist in the midlatitudes to polar latitudes
  - Form through the interaction of upper level disturbances with surface fronts/lows
  - Intensify through baroclinic instability (e.g. QG Height tendency)
  - Flow is to first order is on isentropic surfaces
  - Convert APE to EKE
  - Minimal role of diabatics at least conventionally
  - Shear is essential to structure through thermal wind balance

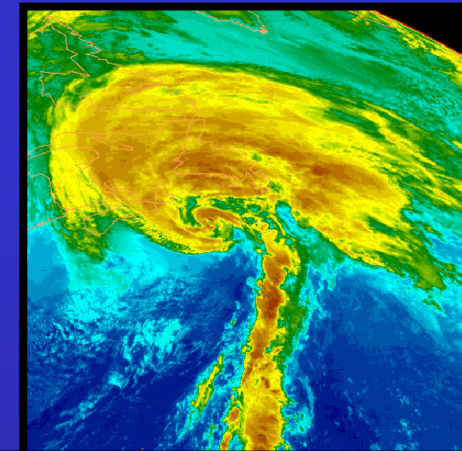
- Tropical Cyclones
  - Generally exist in the tropics to subtropics
  - Form through potentially various methods of organizing convection
  - Intensify through flux induced latent and sensible heat release
  - Flow is to first order isothermal at low levels and then angular-momentum conserving in eyewall and anticyclone
  - Convert diabatic heating to PE and KE
  - Shear is destructive given the barotropic, generally axisymmetric nature of vortex

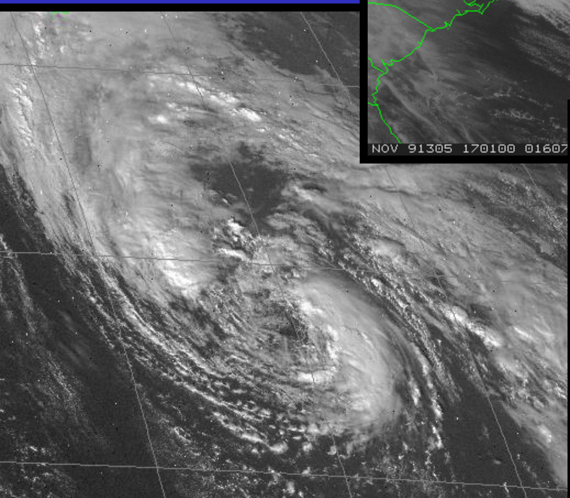
Quiz: Separate the 5 tropical cyclones from the 5 extratropical.

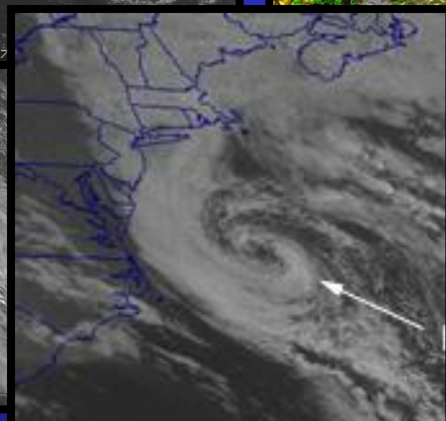
Images courtesy NCDC

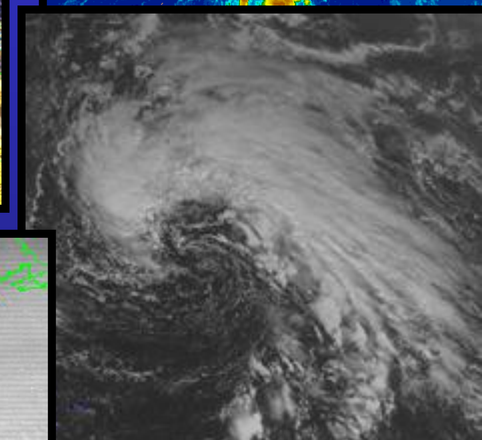


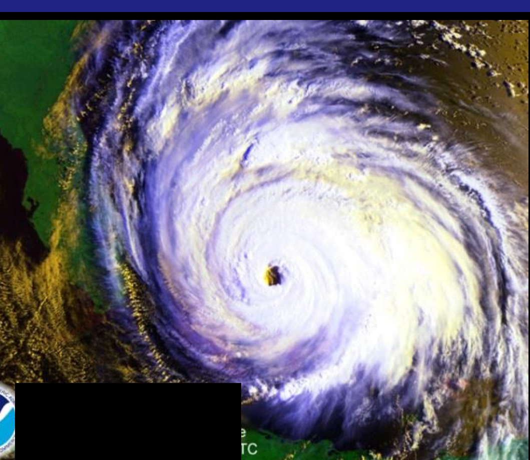


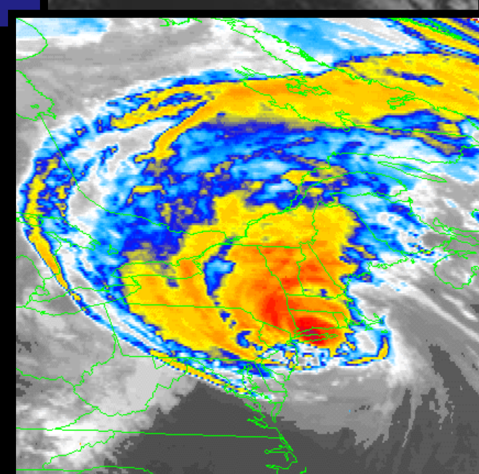


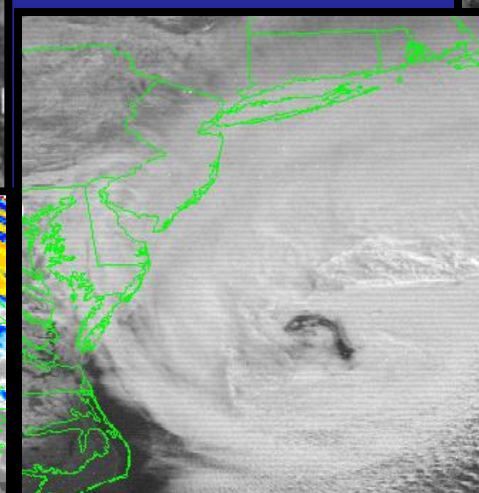


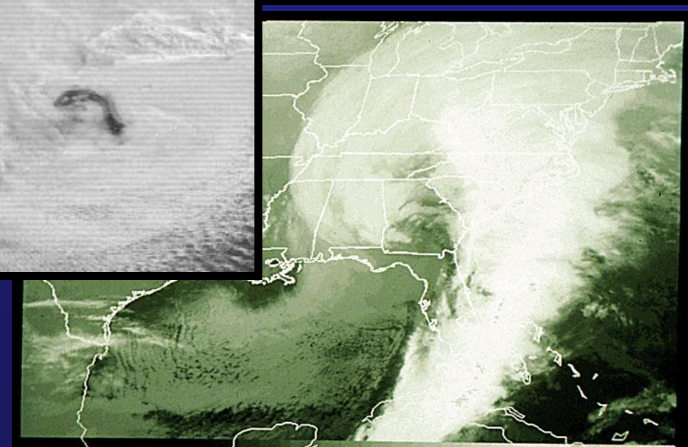




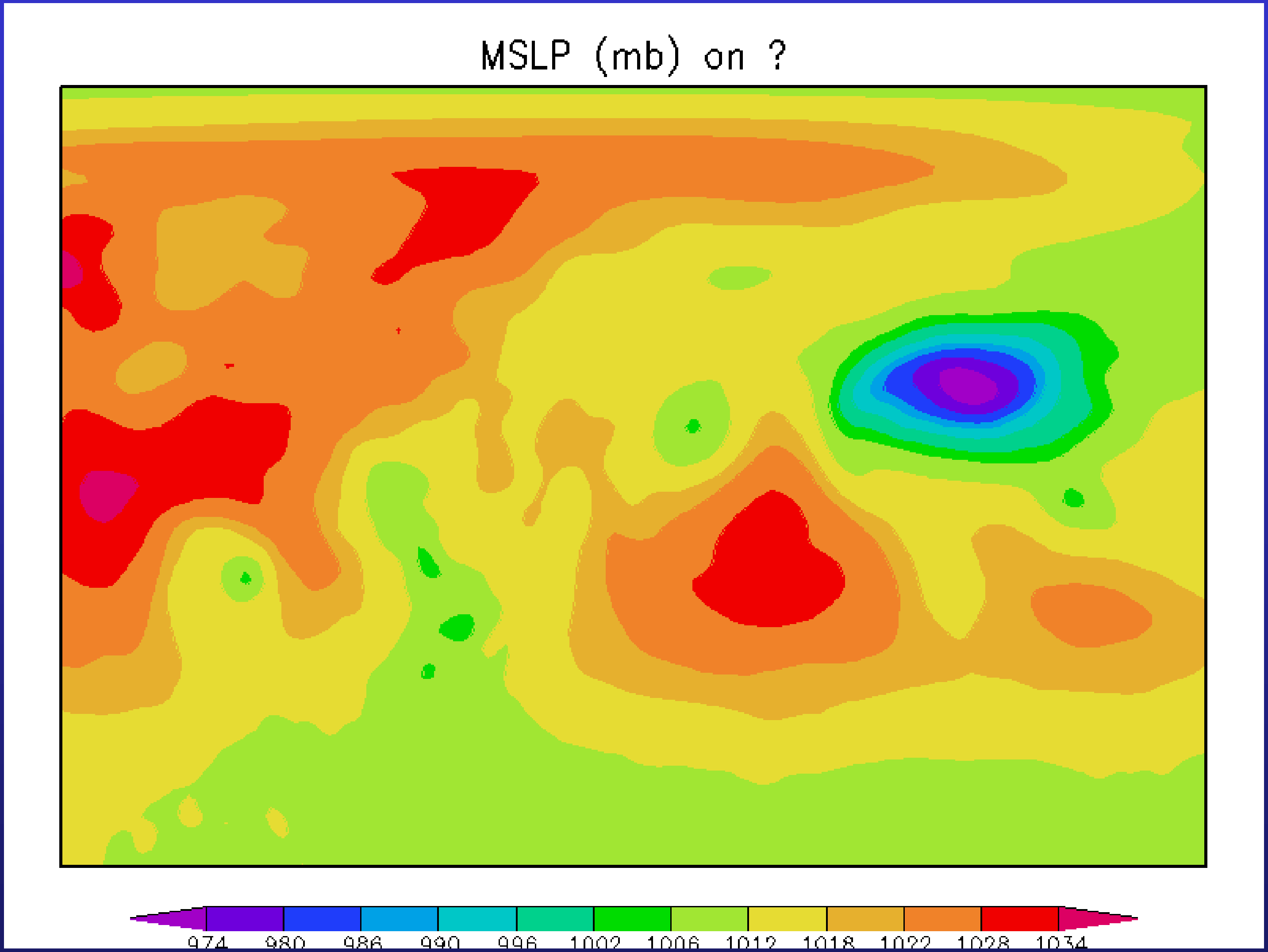




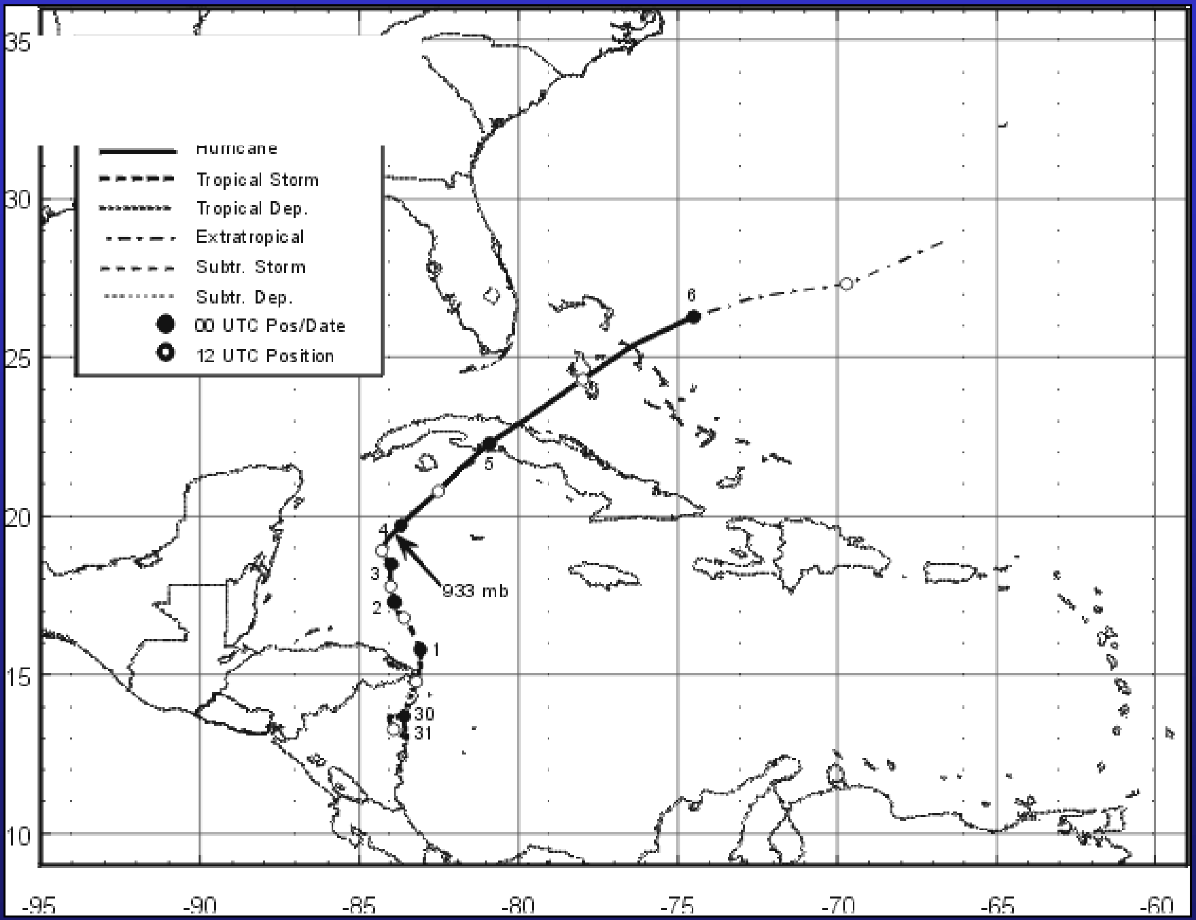




Quiz 2: The sometimes helpful, sometimes perilous reliance on time of year, geography, and SST for assuming structure

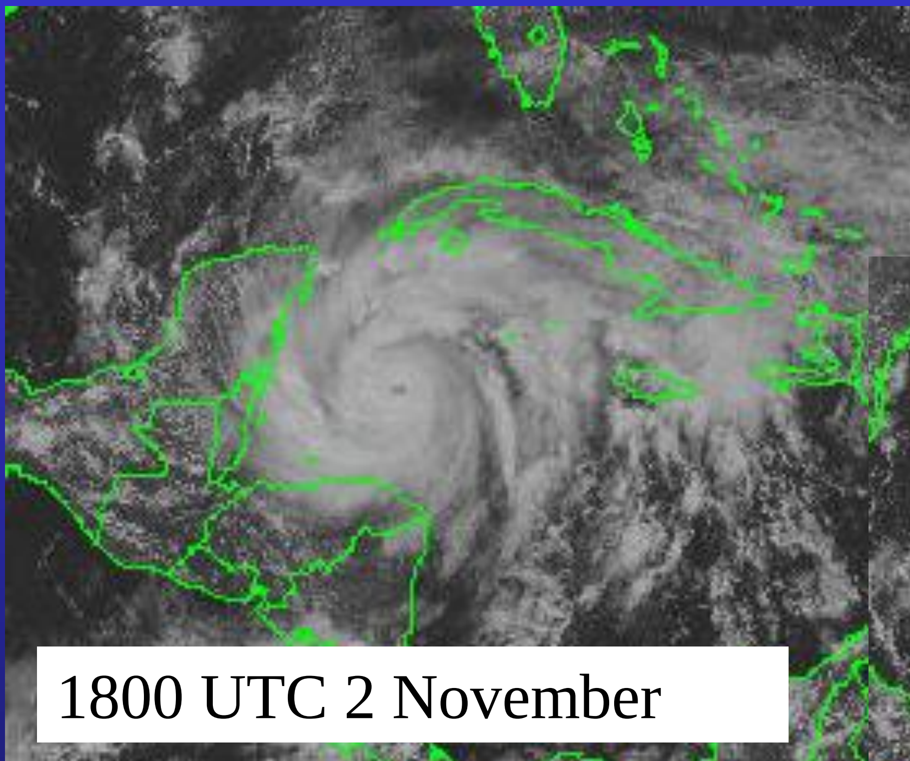


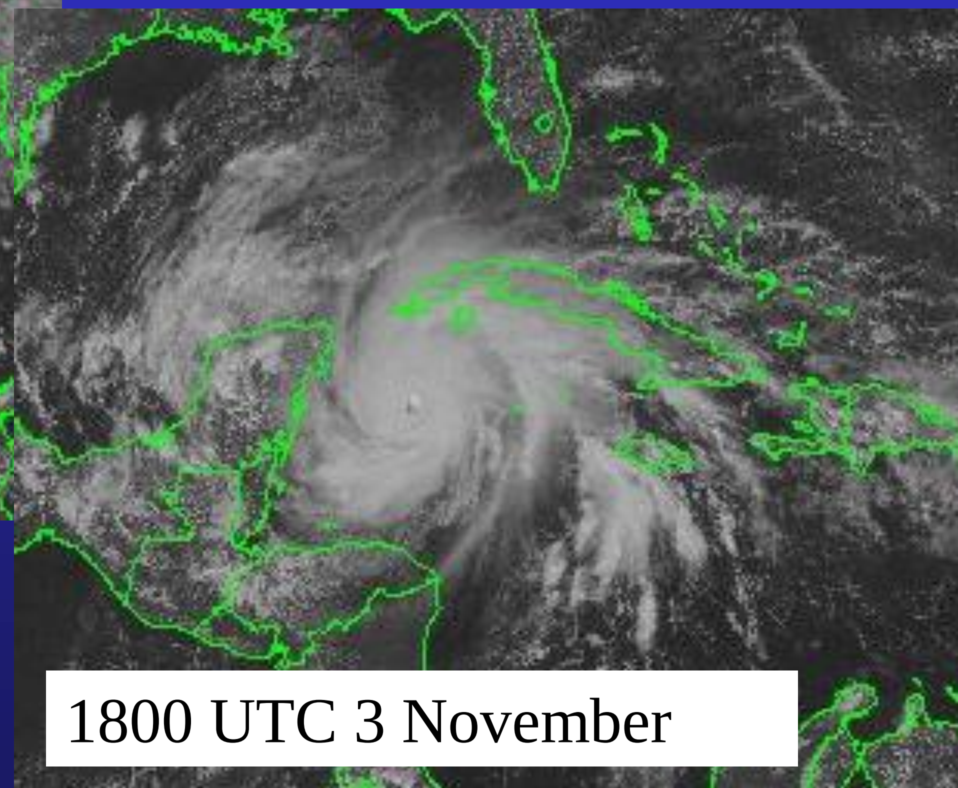
Example of misleading geography:



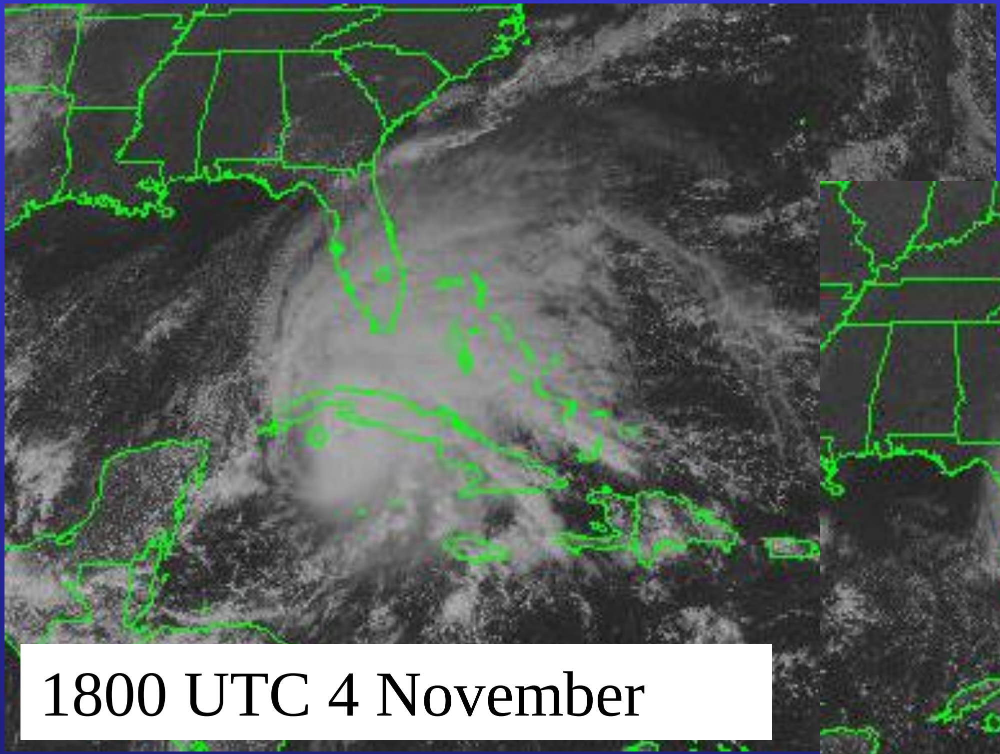
NHC Best Track from Beven (2001)

Hurricane Michelle (2001): GOES-8 Visible Imagery

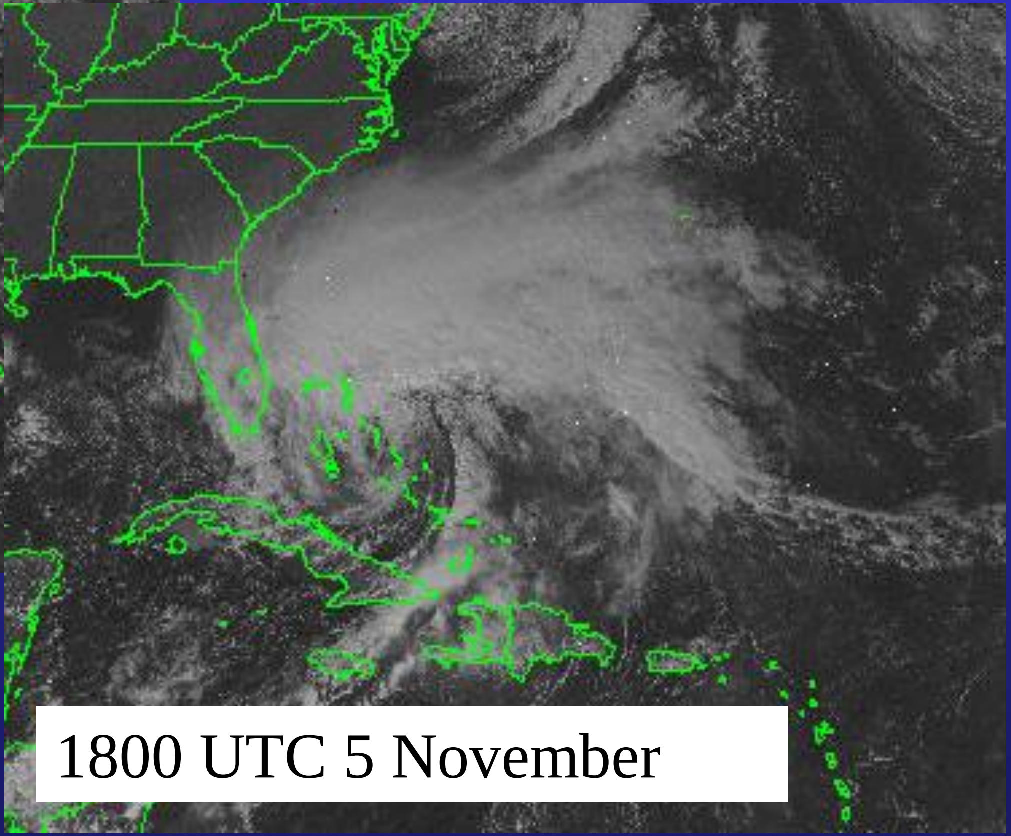




Hurricane Michelle (2001): GOES-8 Visible Imagery

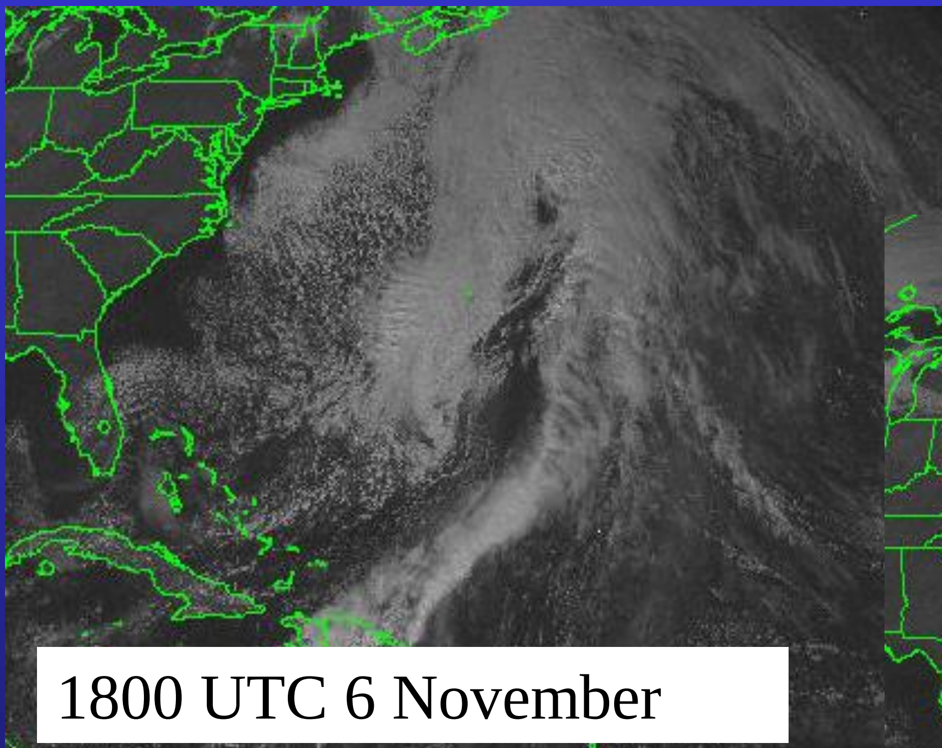


1800 UTC 4 November

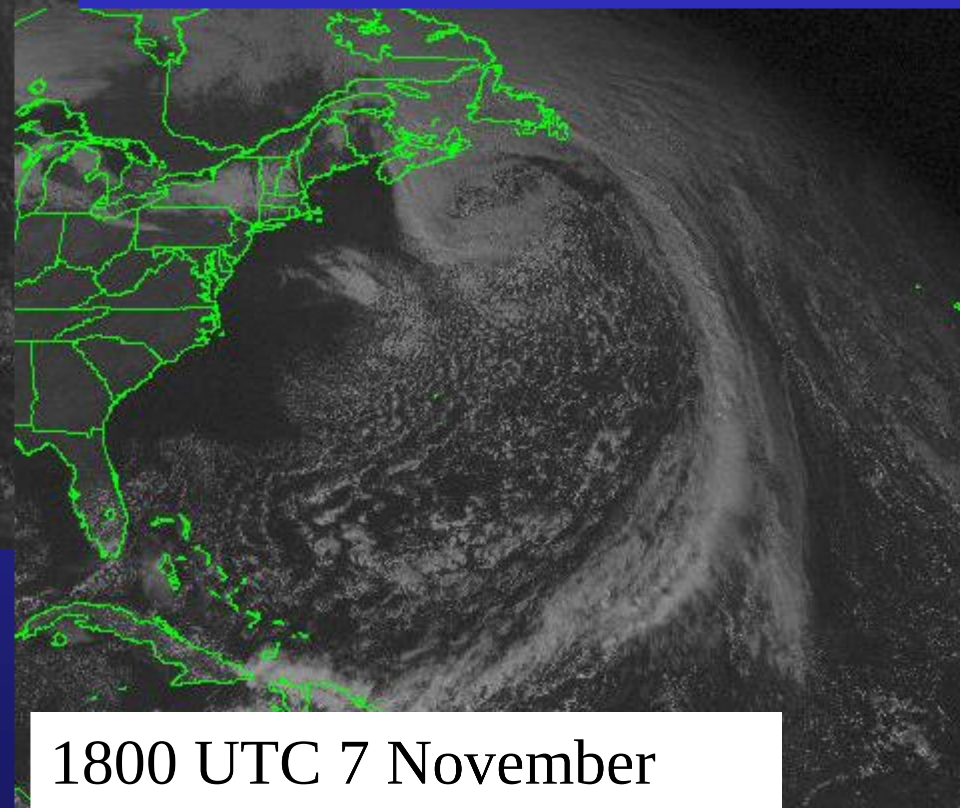


1800 UTC 5 November

Hurricane Michelle (2001): GOES-8 Visible Imagery



1800 UTC 6 November



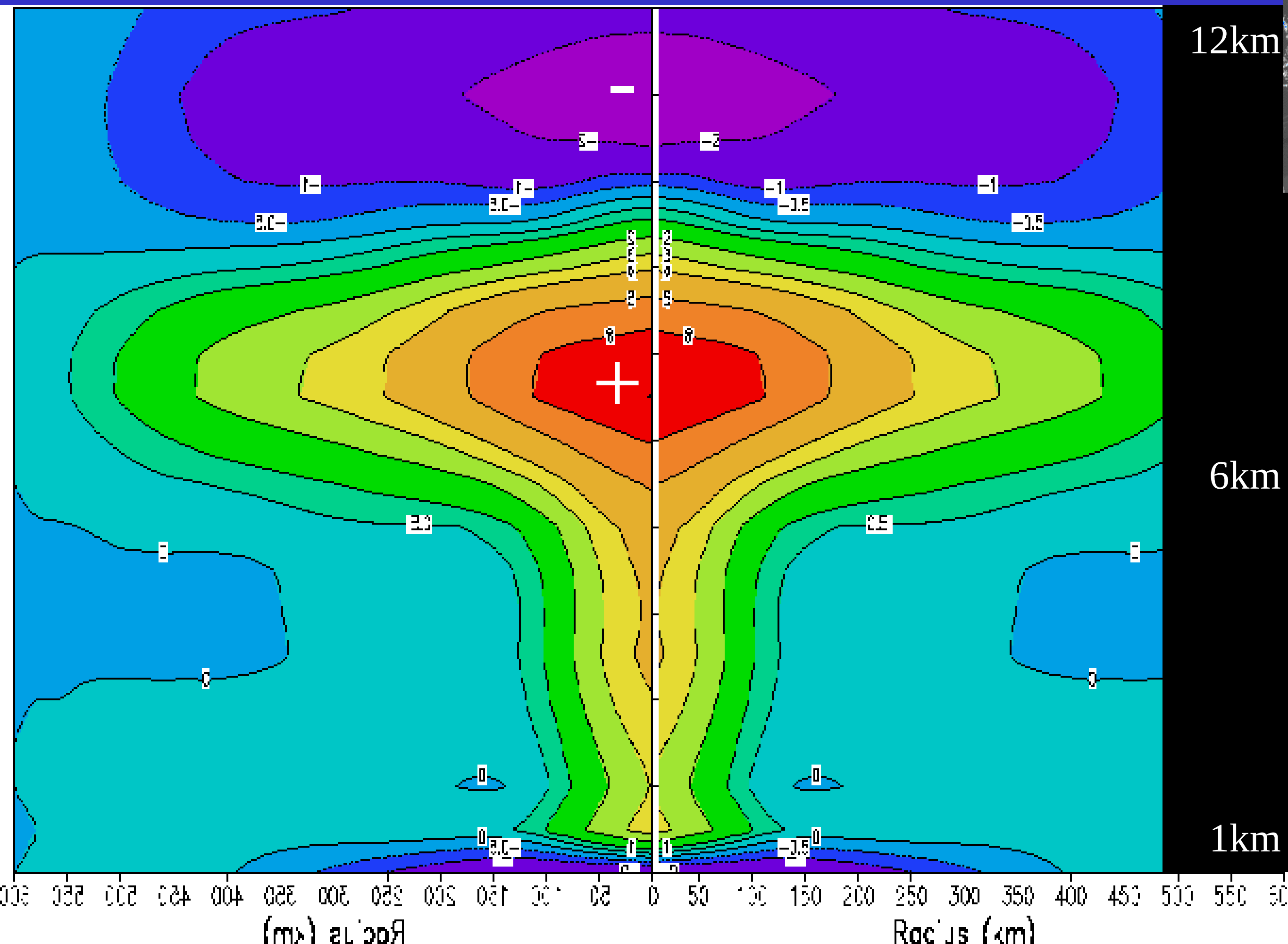
1800 UTC 7 November

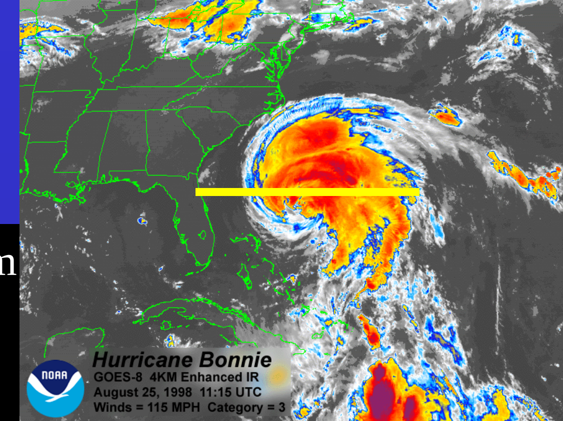
Some relevant questions…

- What makes a cyclone warm or cold-core?
- If all low pressure areas result from a column of air that is on average warmer than its environment, how can there be cold-core cyclones?
- What are the hydrostatic consequences of this thermodynamic structure & the resulting profile of cyclone “strength”?
- What about existence of mixed phase cyclones?
- Why the fuss? 60 knots is 60 knots!
- Let’s first take a step back and reexamine the textbook structures

Classic warm-core cyclone: TC

Hurricane Bonnie (1998) Temperature Anomaly



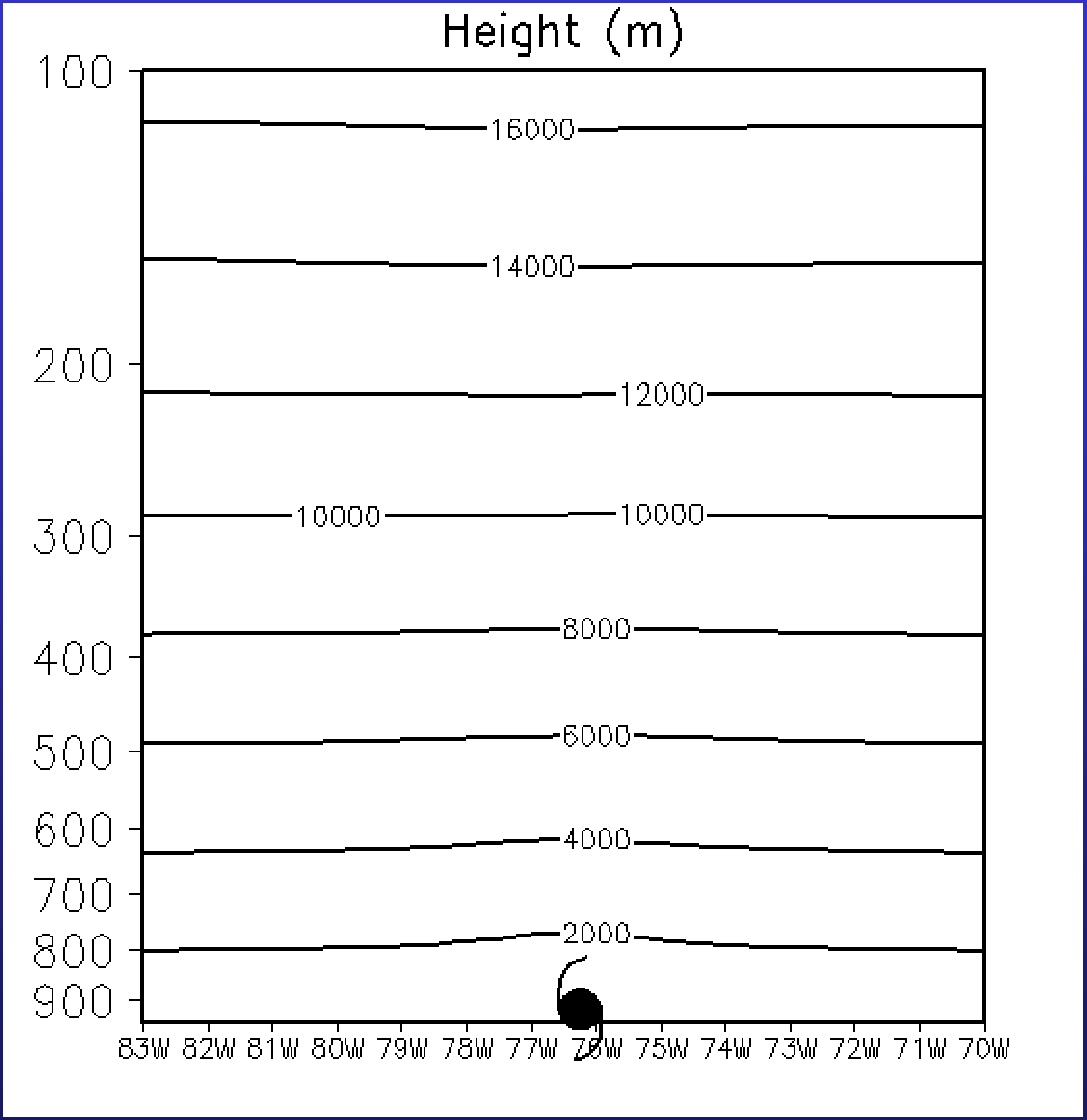


Low pressure results from column of air on average warmer than environment, with the anomalous warmth in the troposphere

Source:
Advanced Microwave Sounder (AMSU) Temperature Anomaly

Image courtesy Mark DeMaria, CIRA/CSU
www.cira.colostate.edu/ramm/tropic/amsustrm.asp

Classic warm-core cyclone: TC

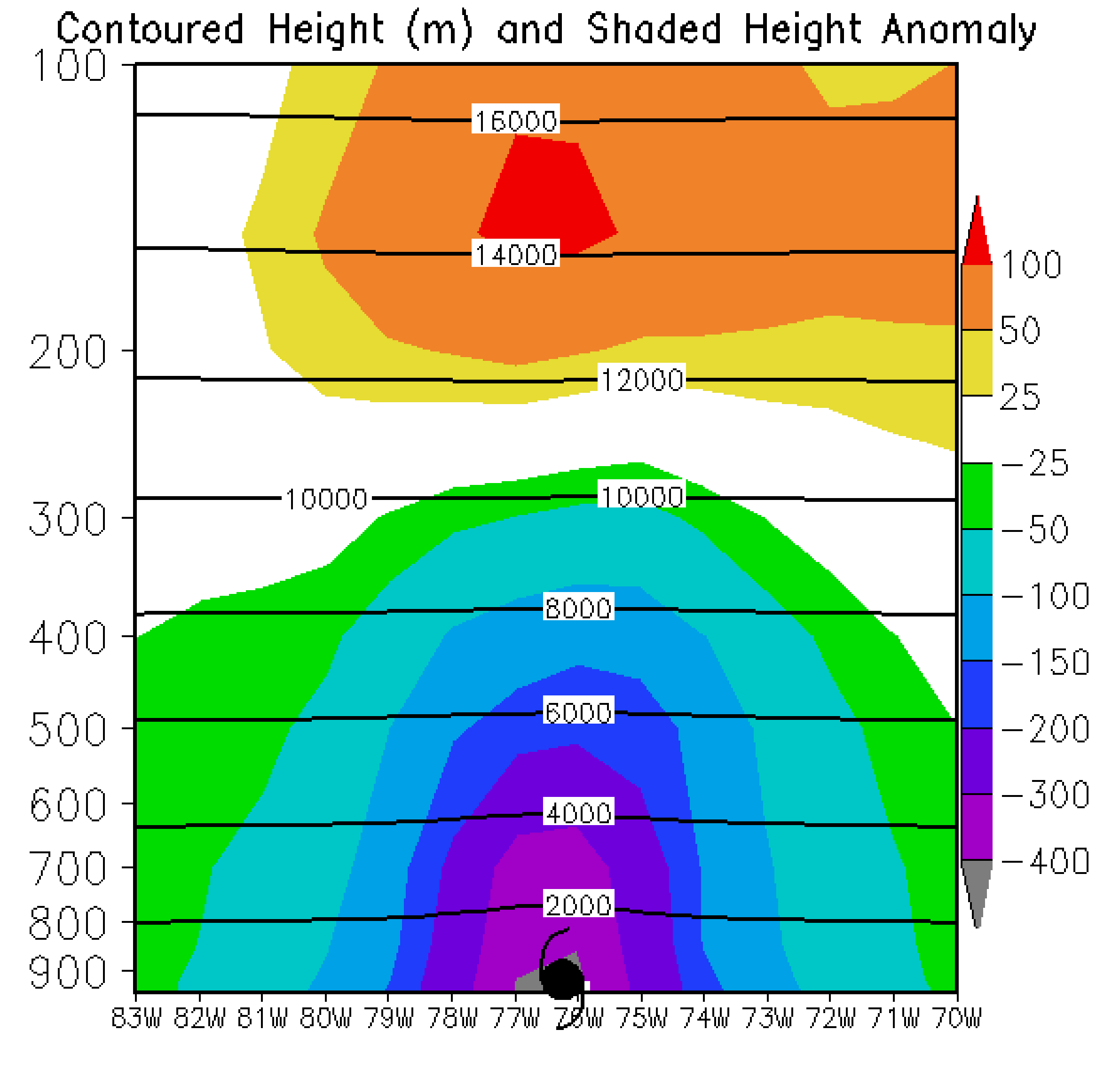


TC Height Field (m) from hydrostatic balance

Warm: expansion of surfaces

Cold: contraction of height surface

Classic warm-core cyclone: TC



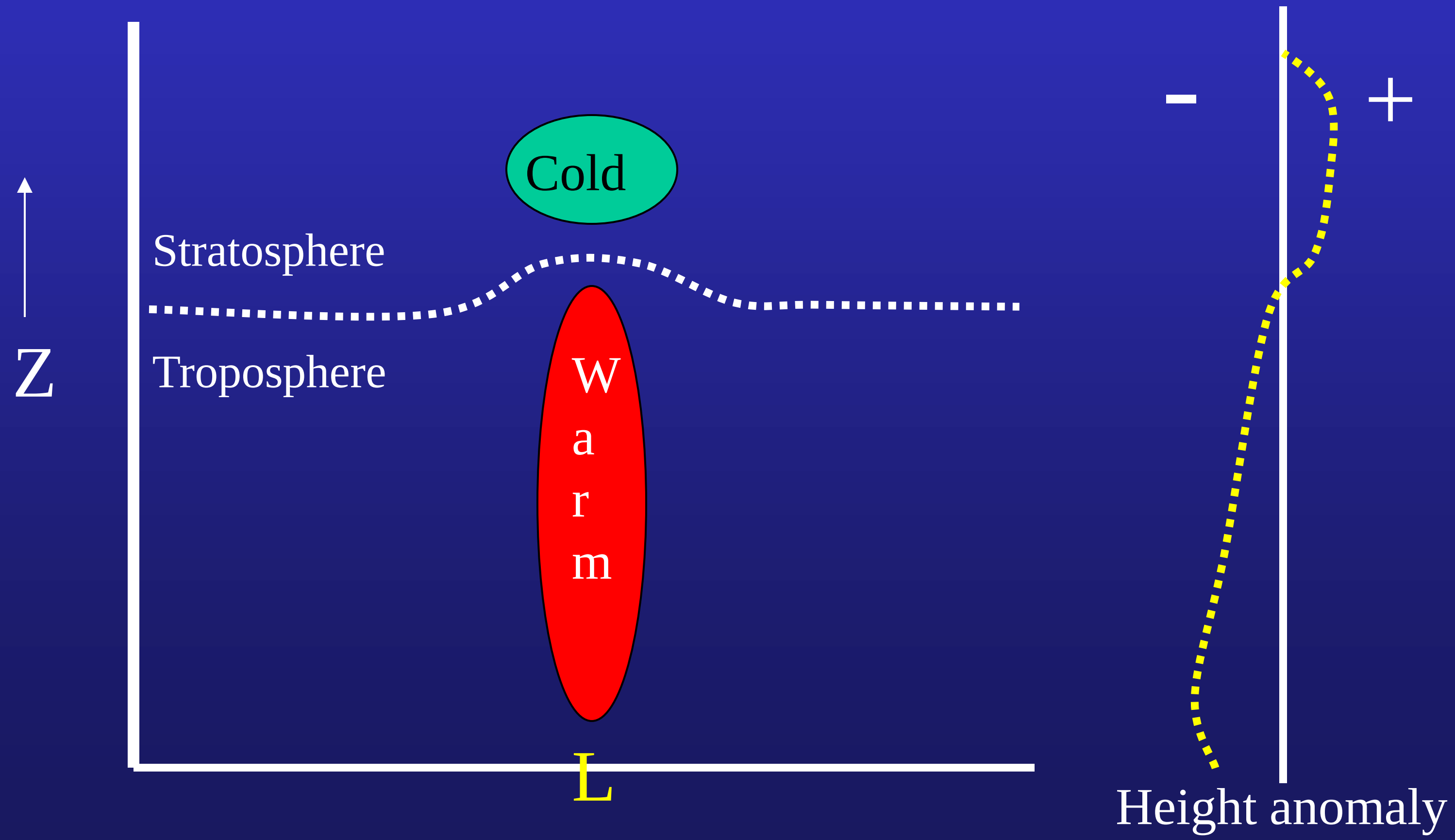
Height anomaly from zonal mean shaded

Height anomaly increases with altitude in troposphere

Classic warm-core cyclone: TC

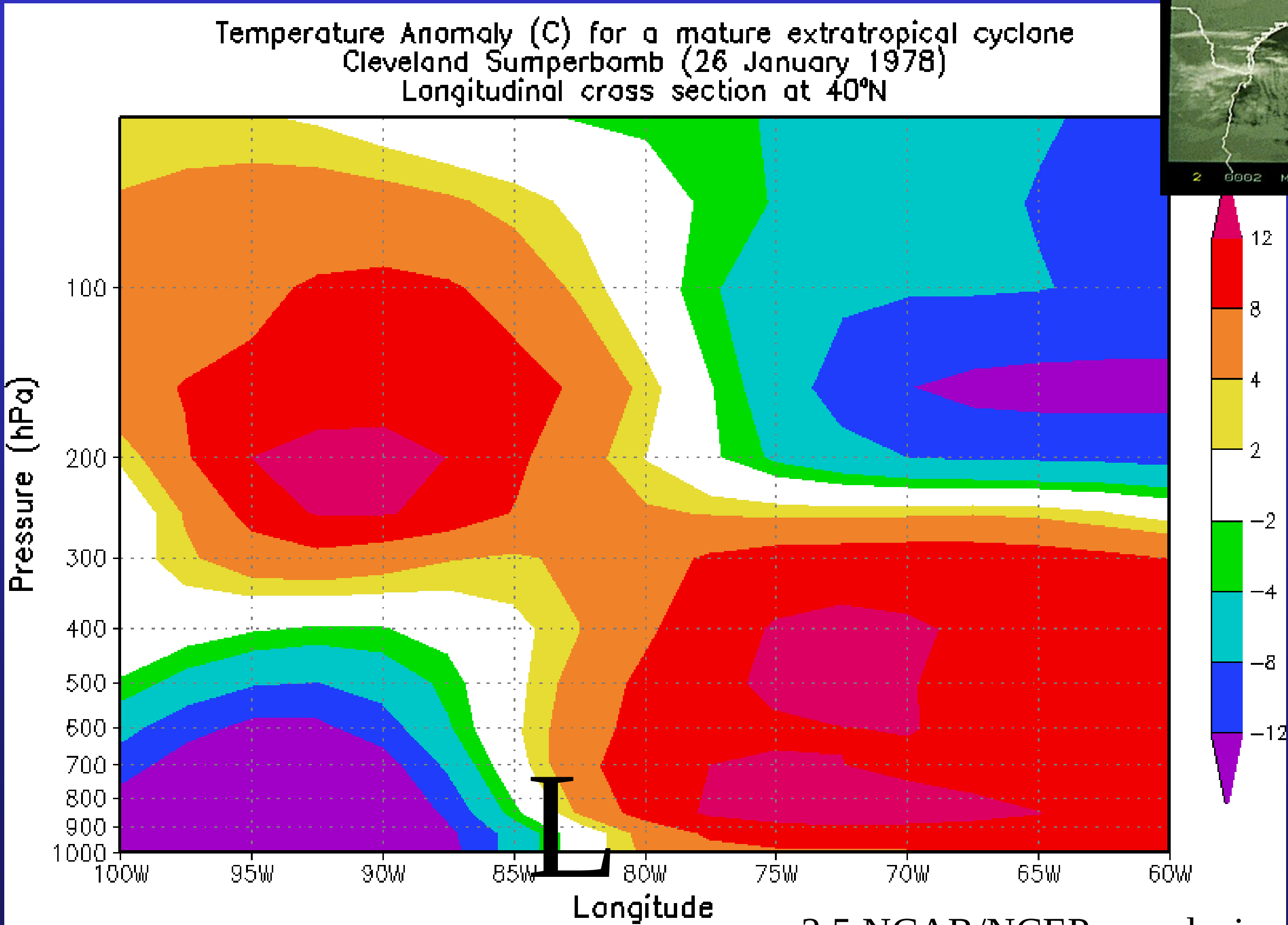
- Intensifies through: sustained convection, surface fluxes.
- Cyclone strength greatest near the top of the PBL

$\Rightarrow$ *Gradient wind balance in a convective environ.*

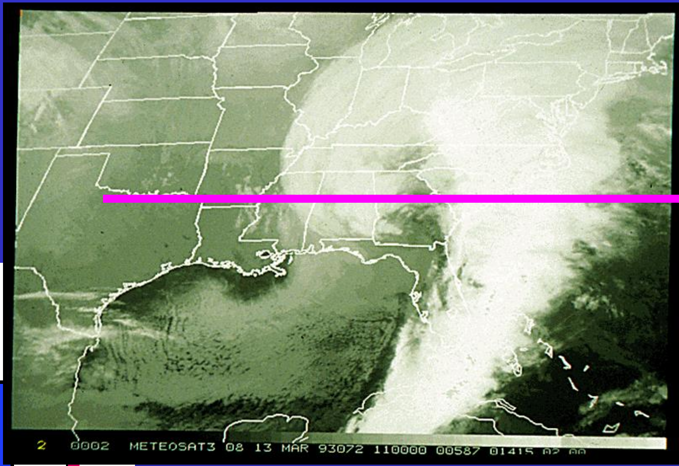


Classic cold-core cyclone: Extratropical

Cleveland Superbomb Temperature Anomaly

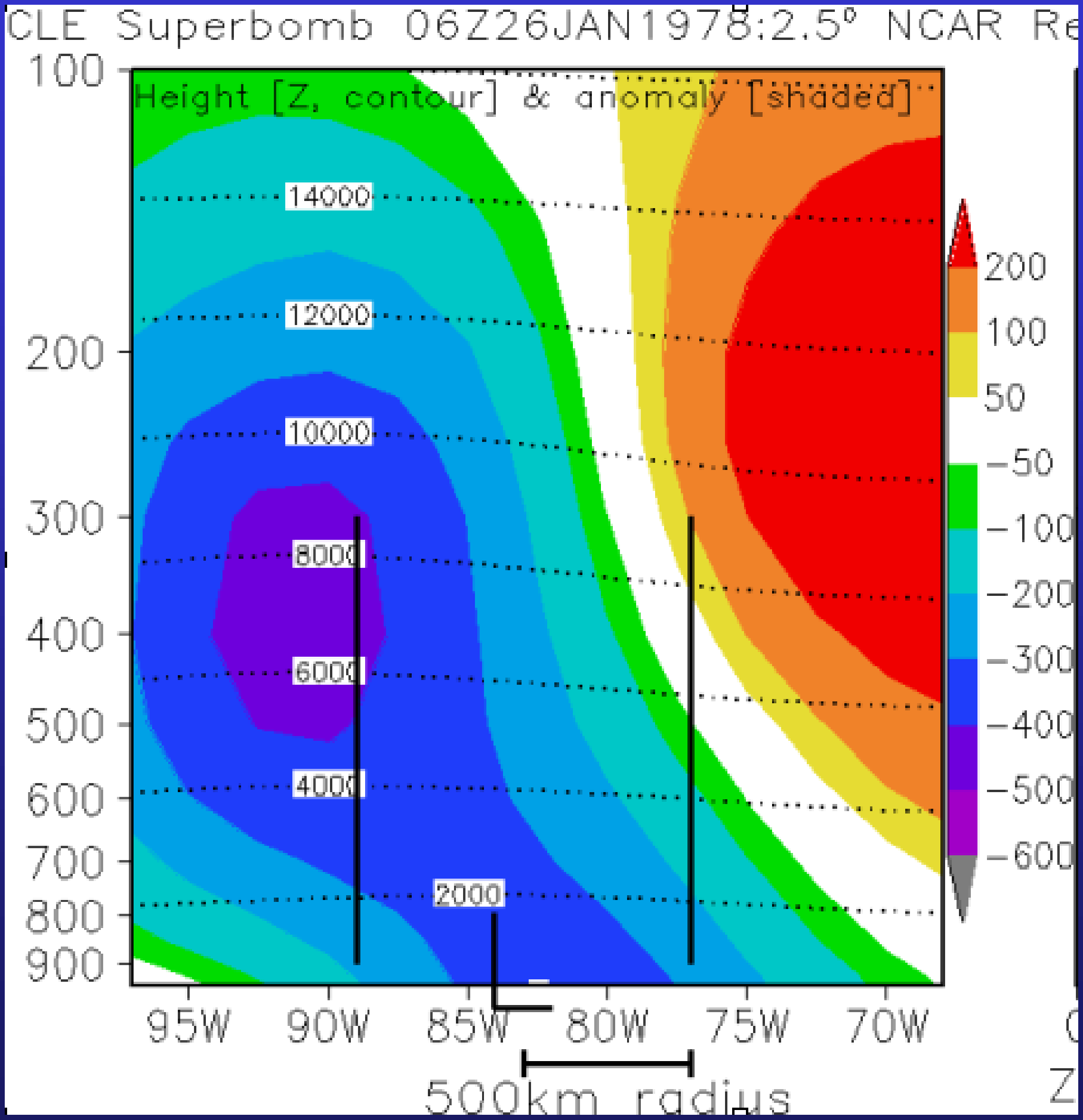


2.5 NCAR/NCEP reanalysis



Low pressure results from column of air on average warmer than environment, with the anomalous warmth in the stratosphere

Classic cold-core cyclone: Extratropical



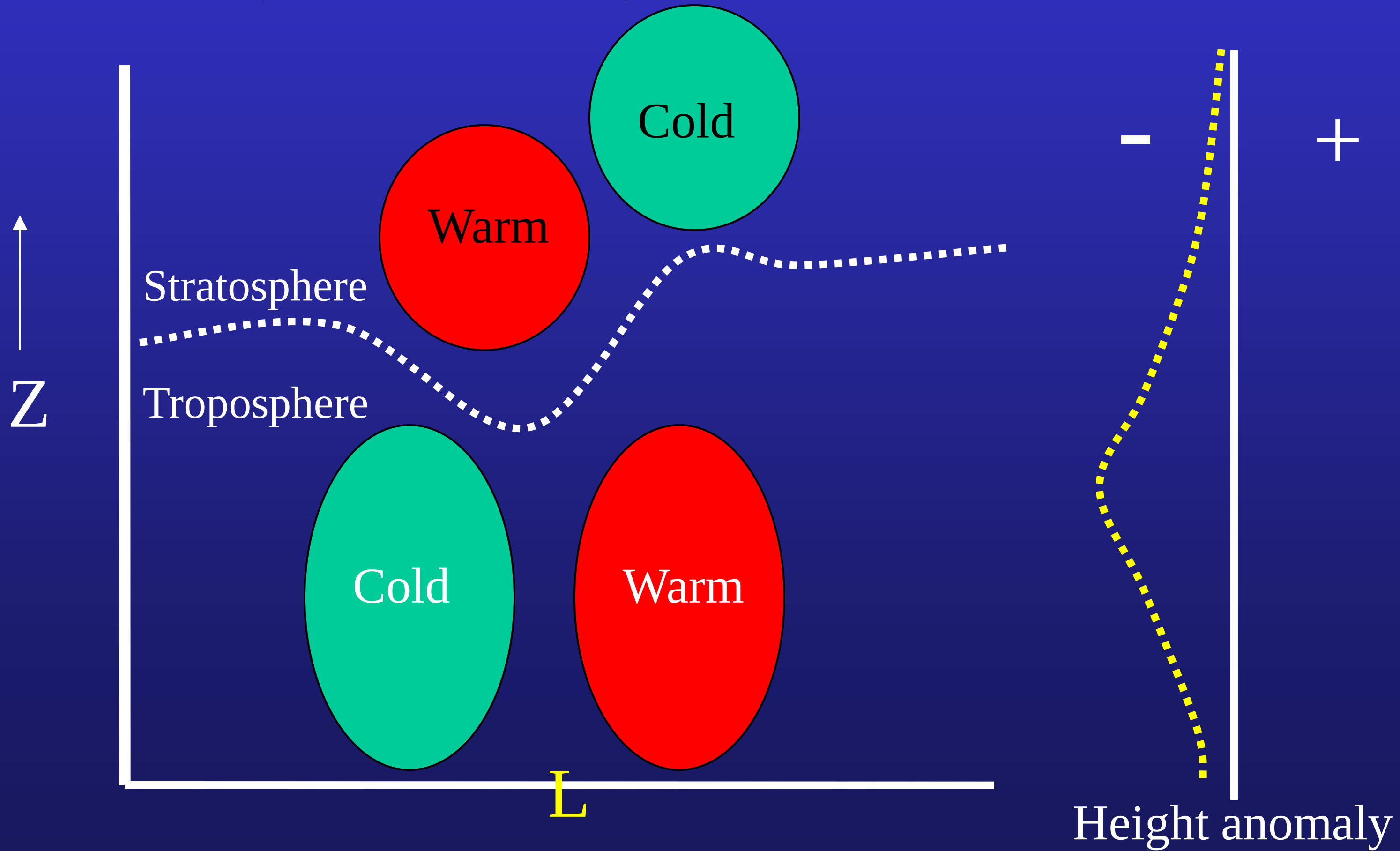
Height anomaly from zonal mean shaded

Height anomaly decreases with altitude in troposphere

Classic cold-core cyclone: Extratropical

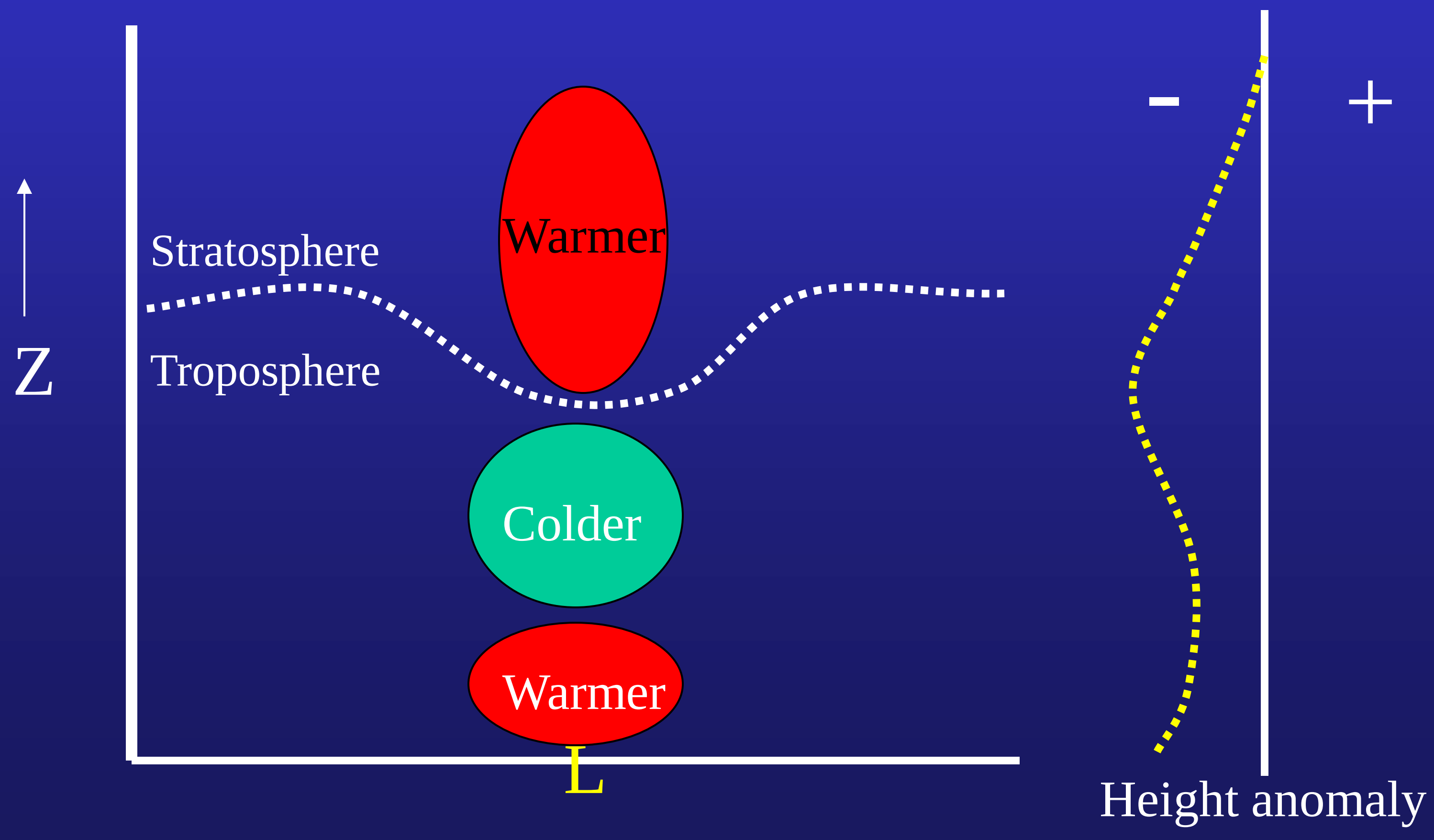
- Intensifies through: baroclinic development, tropopause lowering.
- Cyclone strength greatest near tropopause

⇒ *QG theory in a minimally convective environ*



Hybrid (non-conventional) cyclone

What if an occluded extratropical cyclone moves over warm water?
Characteristics of tropical and extratropical cyclones.

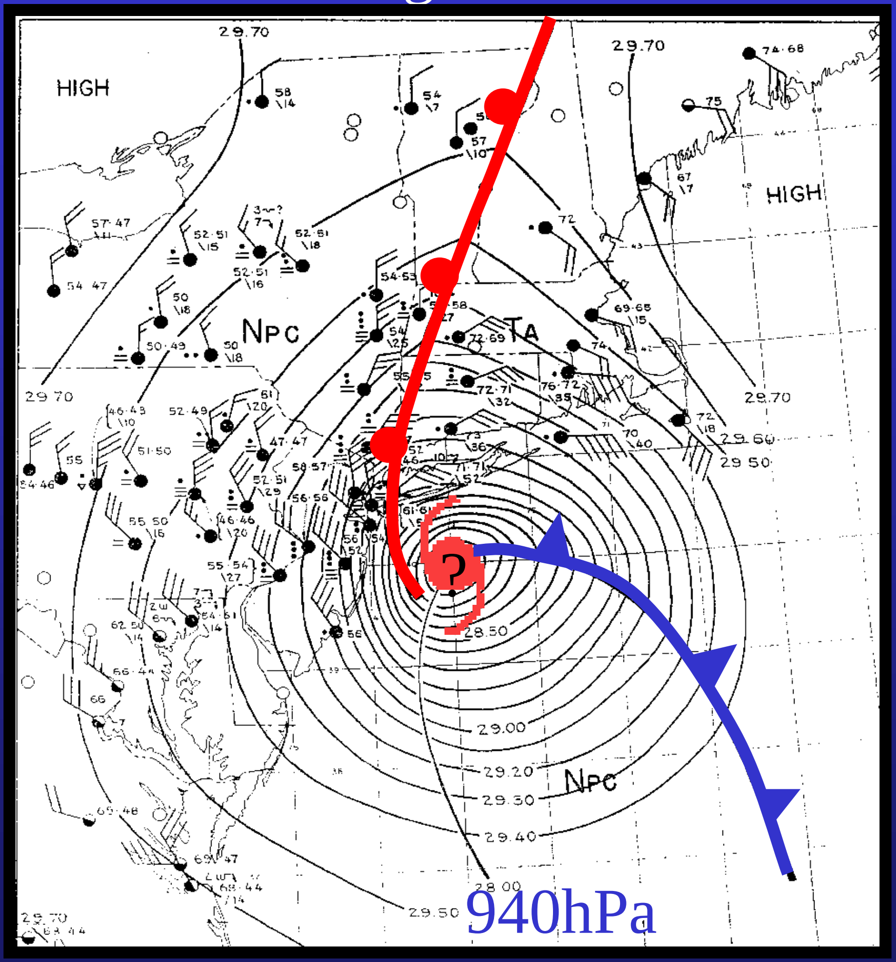


Examples of nonconventional cyclones: Past research

Tannehill (1938):	1938 New England Hurricane
Pierce (1939):	1938 New England Hurricane
Knox (1955):	Hurricane Hazel
Palmén (1958):	Hurricane Hazel
Simpson (1972):	“Neutercanes”
Hebert & Poteat (1975):	Subtropical cyclones
Kornegay & Vincent (1976):	T.C. Candy
Bosart (1981):	President’s Day Snowstorm
DiMego & Bosart (1982):	Hurricane Agnes
Gyakum (1983):	QE2 Storm
Shapiro & Keyser (1990):	Warm seclusion extratropical
Bosart & Lackmann (1995):	Hurricane David
Beven (1997):	Cyclone diagram, Hybrid cyclones, Mediterranean
Miner et al. (2000):	Hurricane “Huron”
Thorncroft & Jones (2000):	Hurricanes Iris & Felix

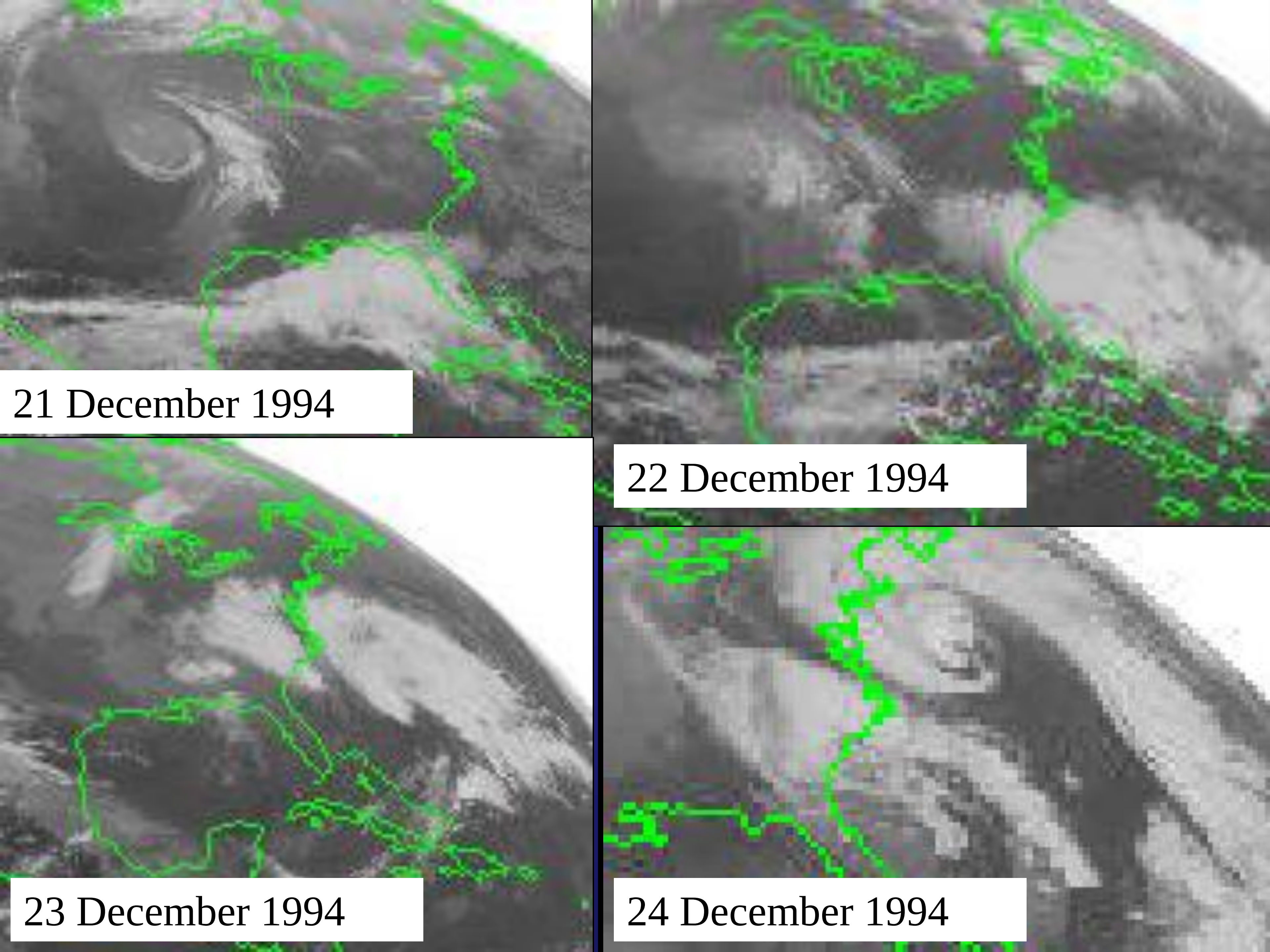
Non-conventional cyclones: Examples

1938 New England Hurricane



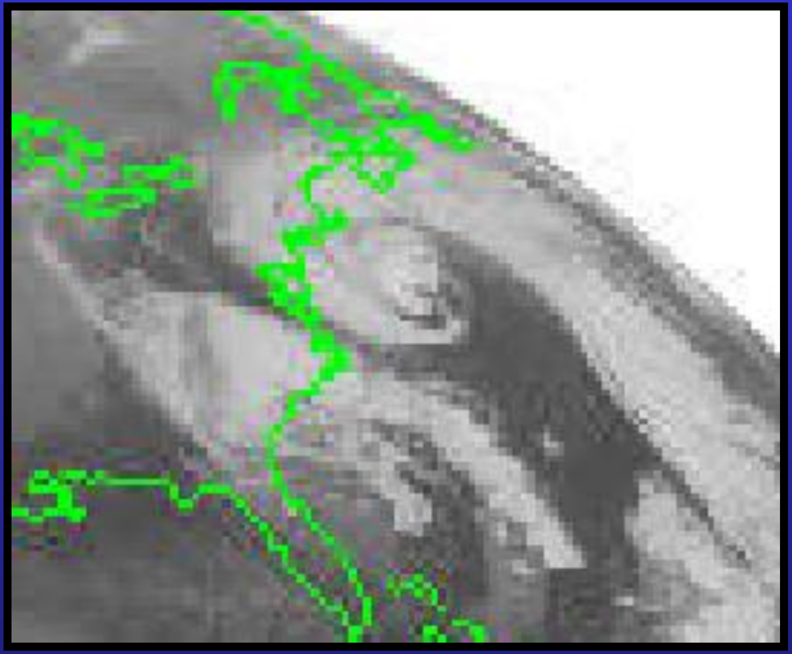
Pierce 1939

- Began as intense tropical cyclone
- Rapid transformation into an intense hybrid cyclone over New England (left)
- Enormous damage ($3.5 billion adjusted to 1990). 10% of trees downed in New England. 600+ lives lost.
- Basic theories do not explain a frontal hurricane


21 December 1994
22 December 1994
23 December 1994
24 December 1994

Non-conventional cyclones: Examples

Christmas 1994
Hybrid New England Storm



NCDC

- Classic (prior to Sandy) example of how track, structure, intensity and eventual impacts are related.

  Gulf of Mexico extratropical cyclone that acquired partial tropical characteristics

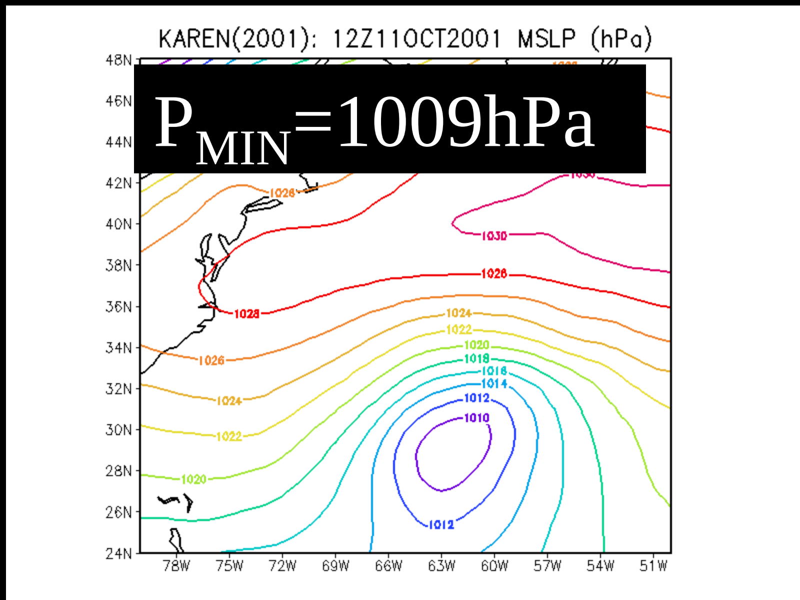
  A partial eye was observed when the cyclone was just east of Long Island

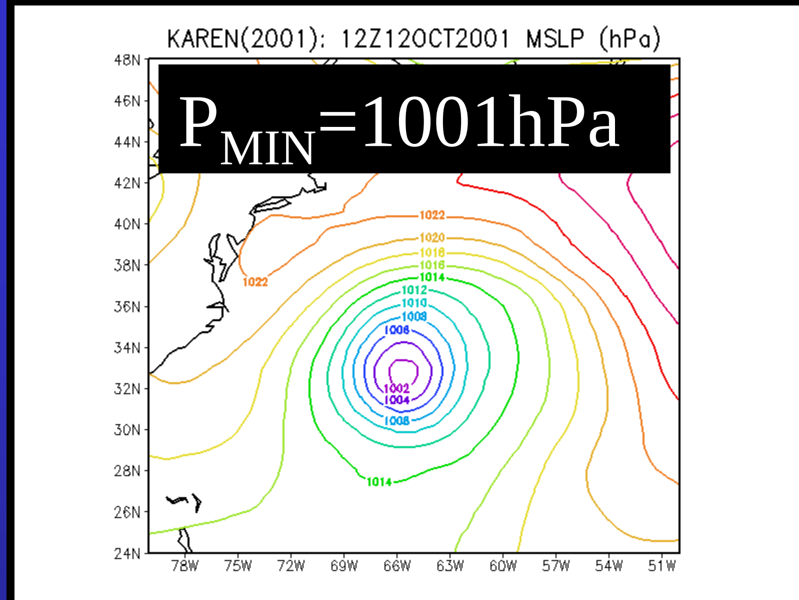
  Wind gusts of 50-100mph observed across southern New England

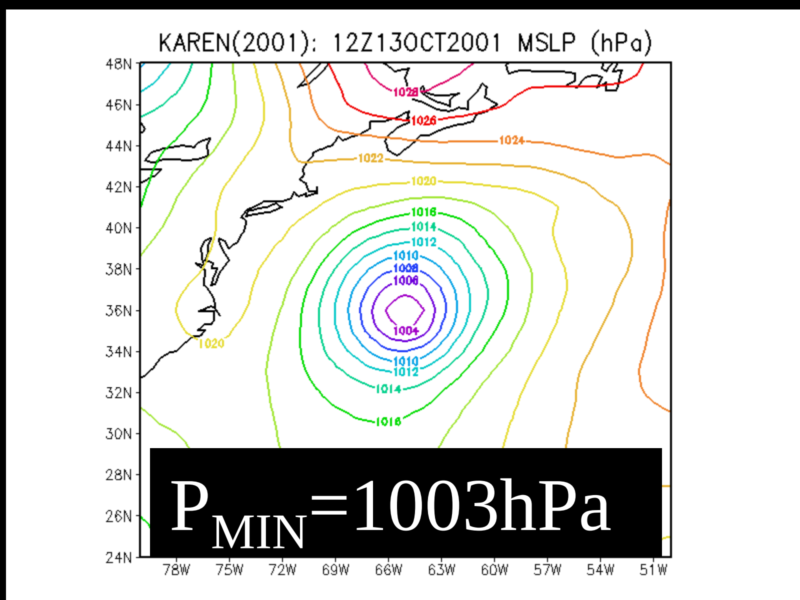
- Largest U.S. power outage (350,000) since Andrew in 1992

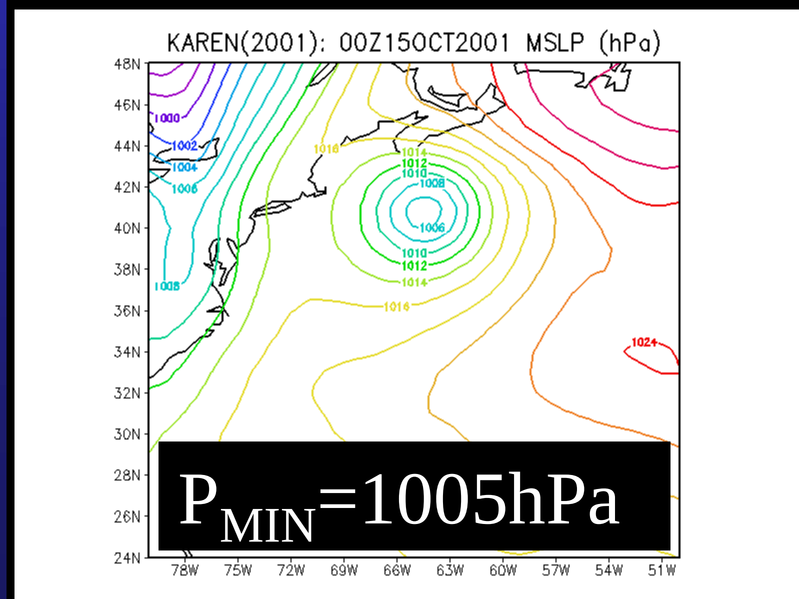
- Forecast 6hr earlier: chance of light rain, winds of 5-15mph.

Model interpretation: What type of development?



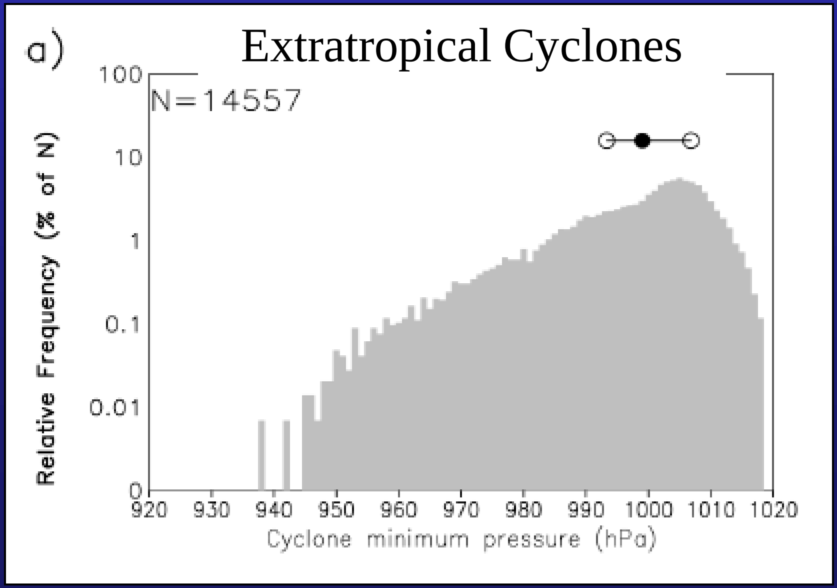


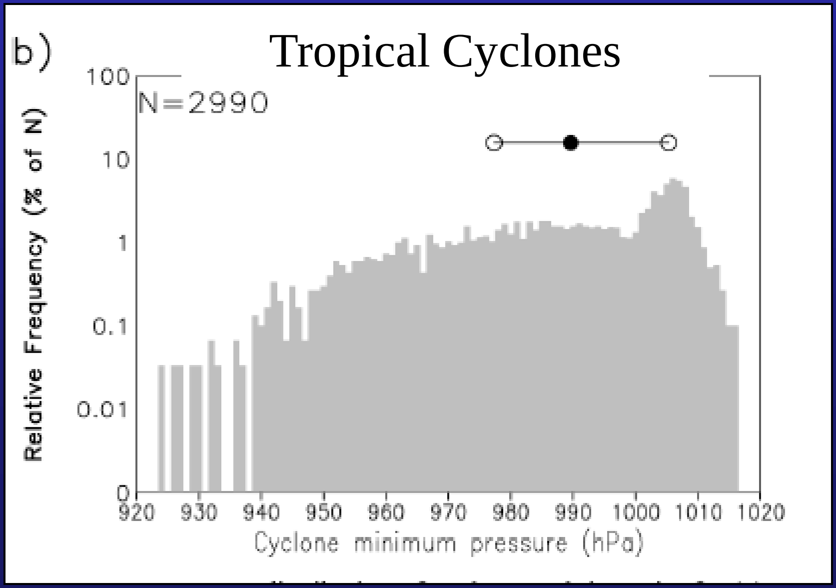




Why is the structure of a cyclone important?

- Predictability is a function of structure
- Model interpretation/trust is a function of structure
- It is often not at first apparent what the model is forecasting, or the nature of cyclone development
- Potential intensity is a function of structure





Impact is a function of structural evolution and interaction

Fran (1996):No transition

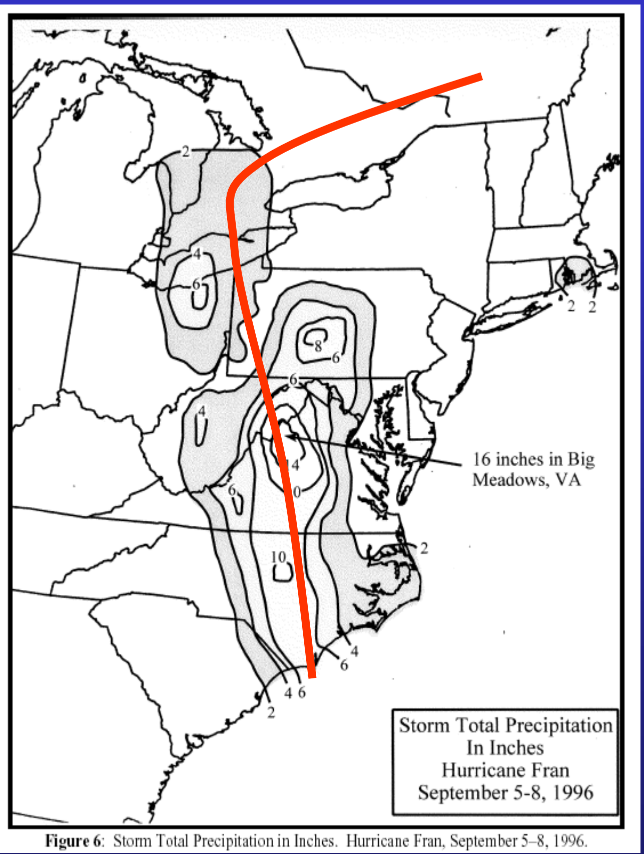
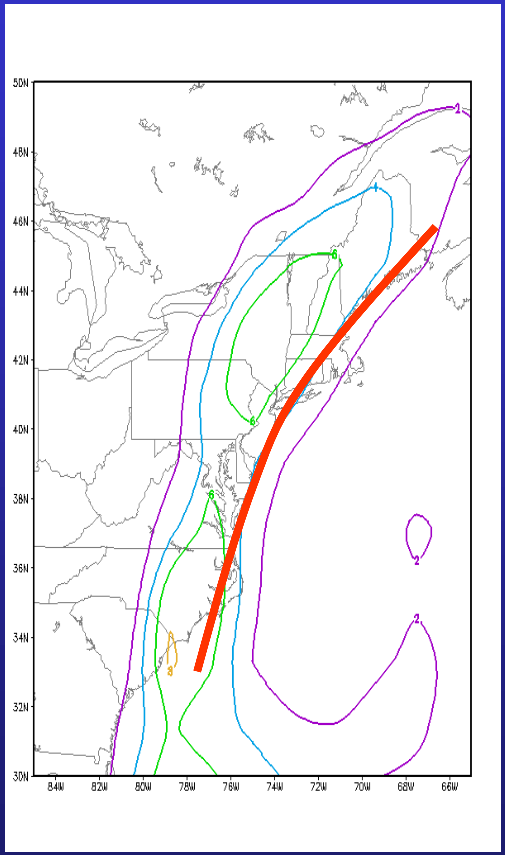


Figure 6: Storm Total Precipitation in Inches. Hurricane Fran, September 5–8, 1996.

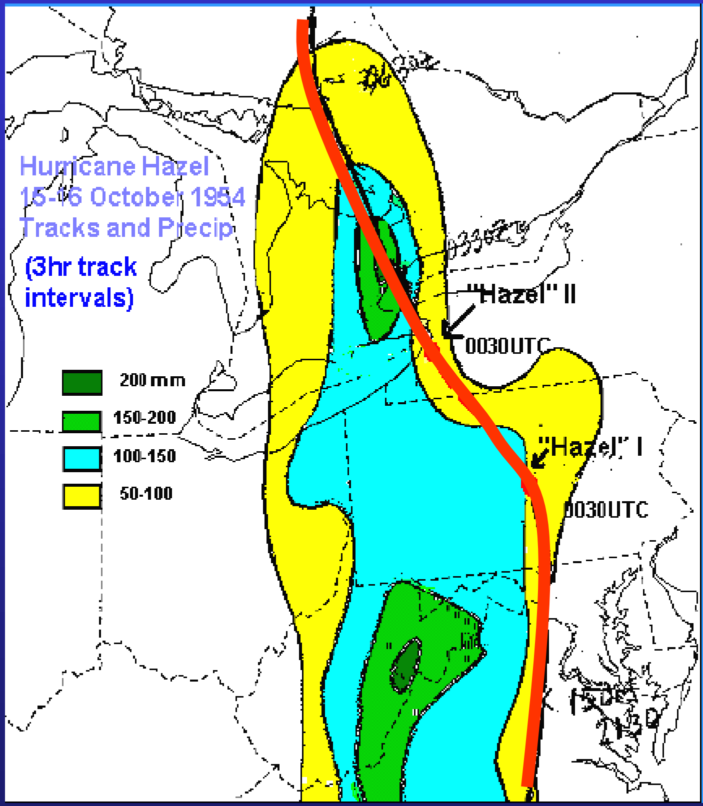
Analysis courtesy NOAA/NWS/NHC

Floyd (1999): Transition from pos. tilt trough



Analysis courtesy NCAR/NCEP Reanalysis-2

Hazel (1954): Transition from a neg. tilt trough



Analysis courtesy Jim Abraham, CHC

Significance:

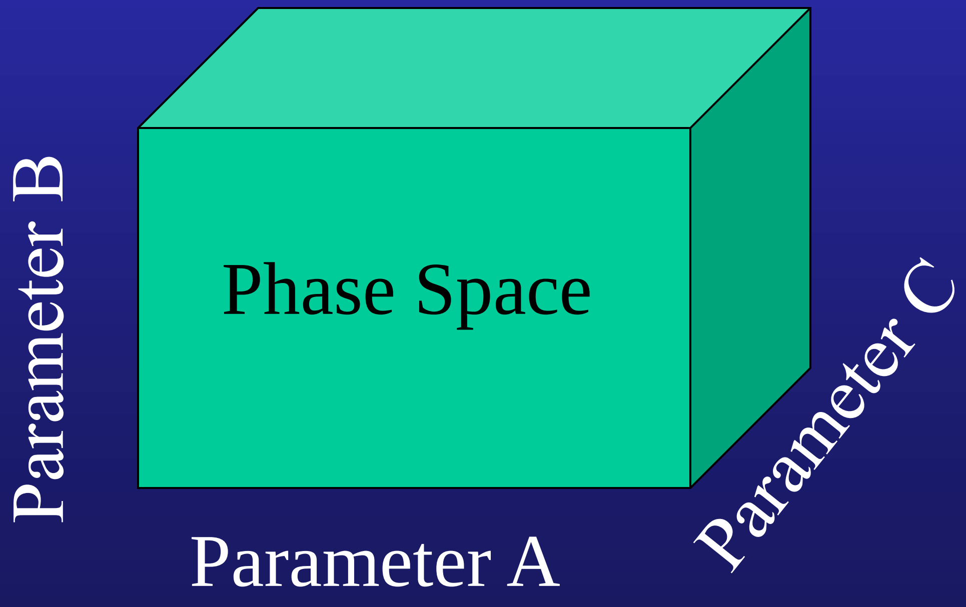
- Classification
- Better understanding of the current state
- Applying conceptual models or designing new ones
- The type/extent of expected impact/damage
- Quantifying potential for intensity change and its uncertainty
  - Scales of motion dependence
  - Maximum intensity
- How can intensity change be forecast if there is great structural uncertainty?
- Amount of intrinsic (mis)trust of numerical model forecasts

$\Rightarrow$ Need a diagnosis of basic cyclone structure that is more flexible than only tropical or extratropical

Goal:

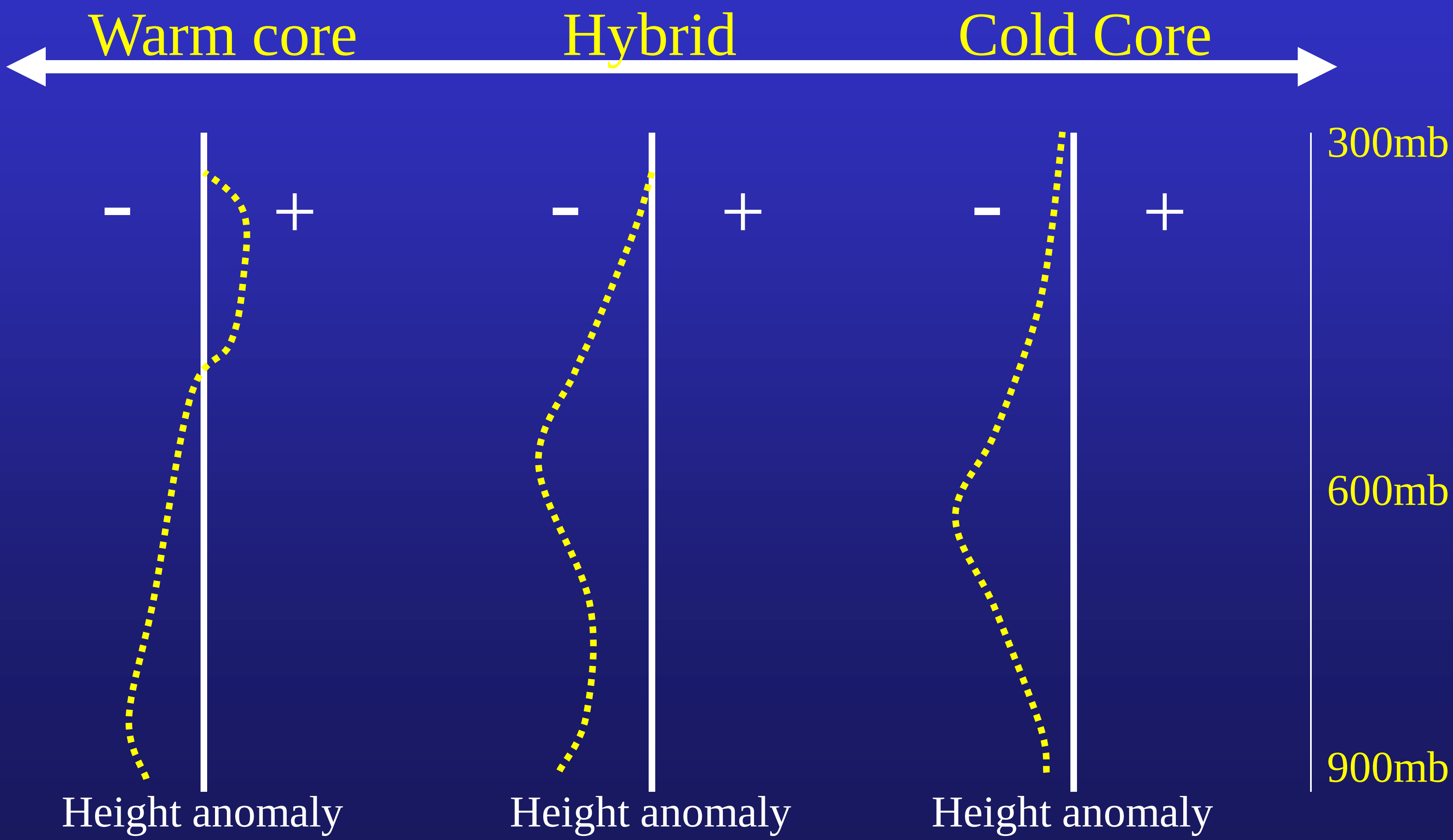
A more flexible approach to cyclone characterization

⇒To describe the basic structure of tropical, extratropical, and hybrid cyclones simultaneously using a cyclone phase space.



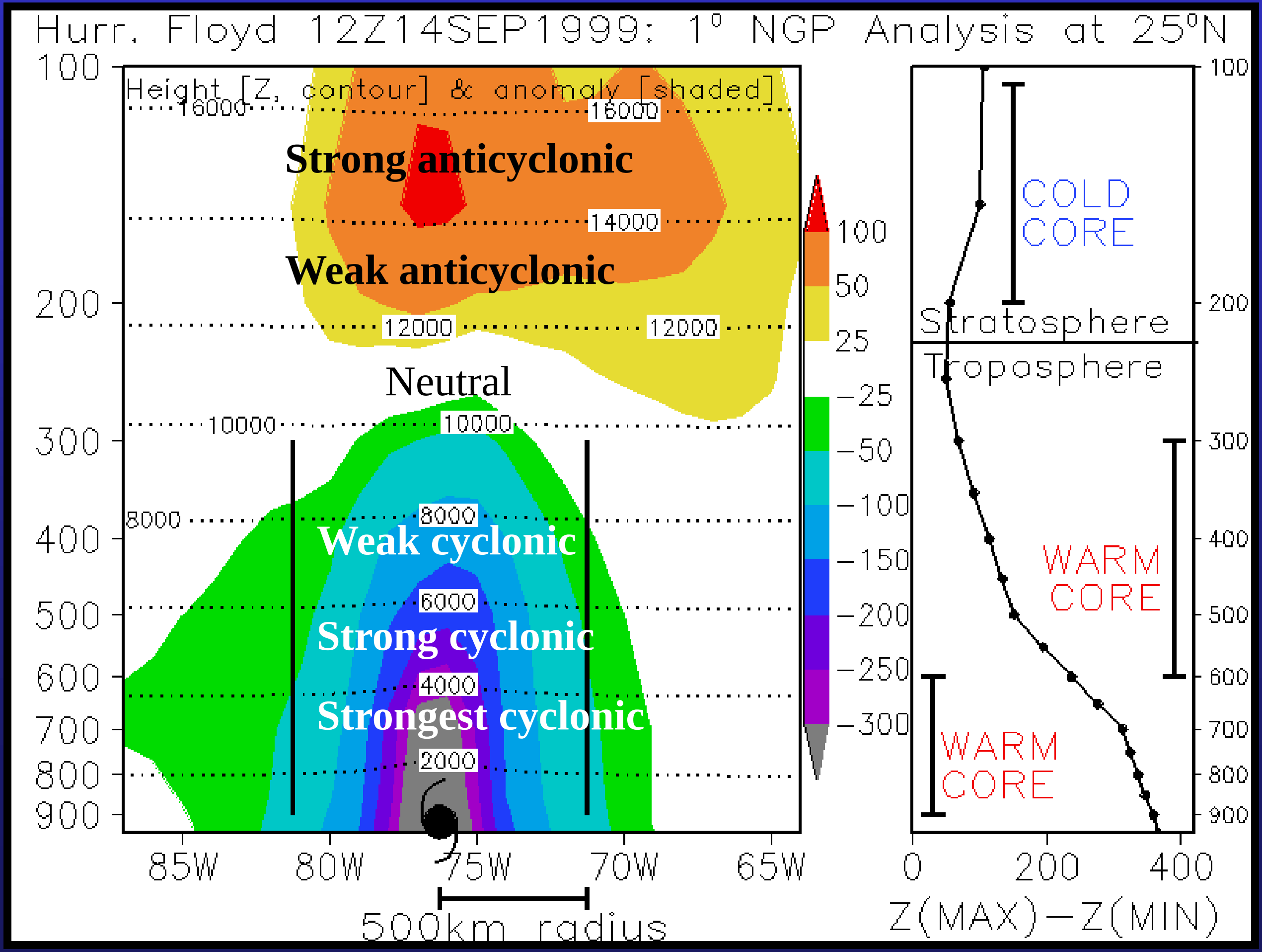
Cyclone Parameter 1: Vertical structure

$-V_T$: Thermal Wind [Warm vs. Cold Core]



Cyclone Parameter $-V_T$: Thermal Wind

Warm-core example:
Hurricane Floyd 14 Sep 1999



Vertical profile of Z_{MAX}-Z_{MIN} is proportional to thermal wind (V_T).

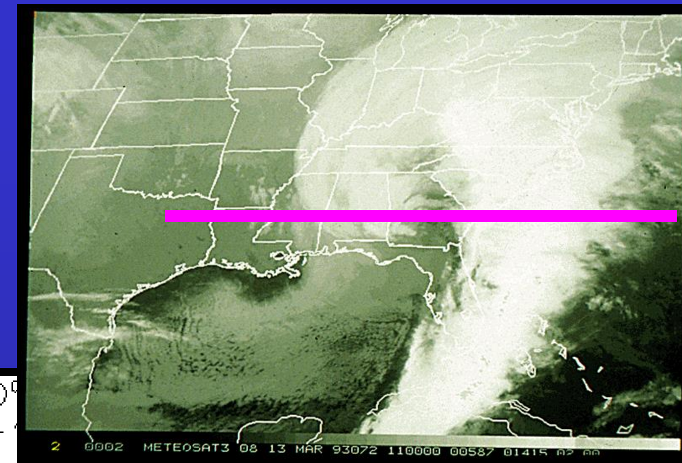
$$\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln p} = -|V_T|$$

Two layers of interest

$$\left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln p}\right|_{600hPa}^{300hPa} = -|V_T^U|$$

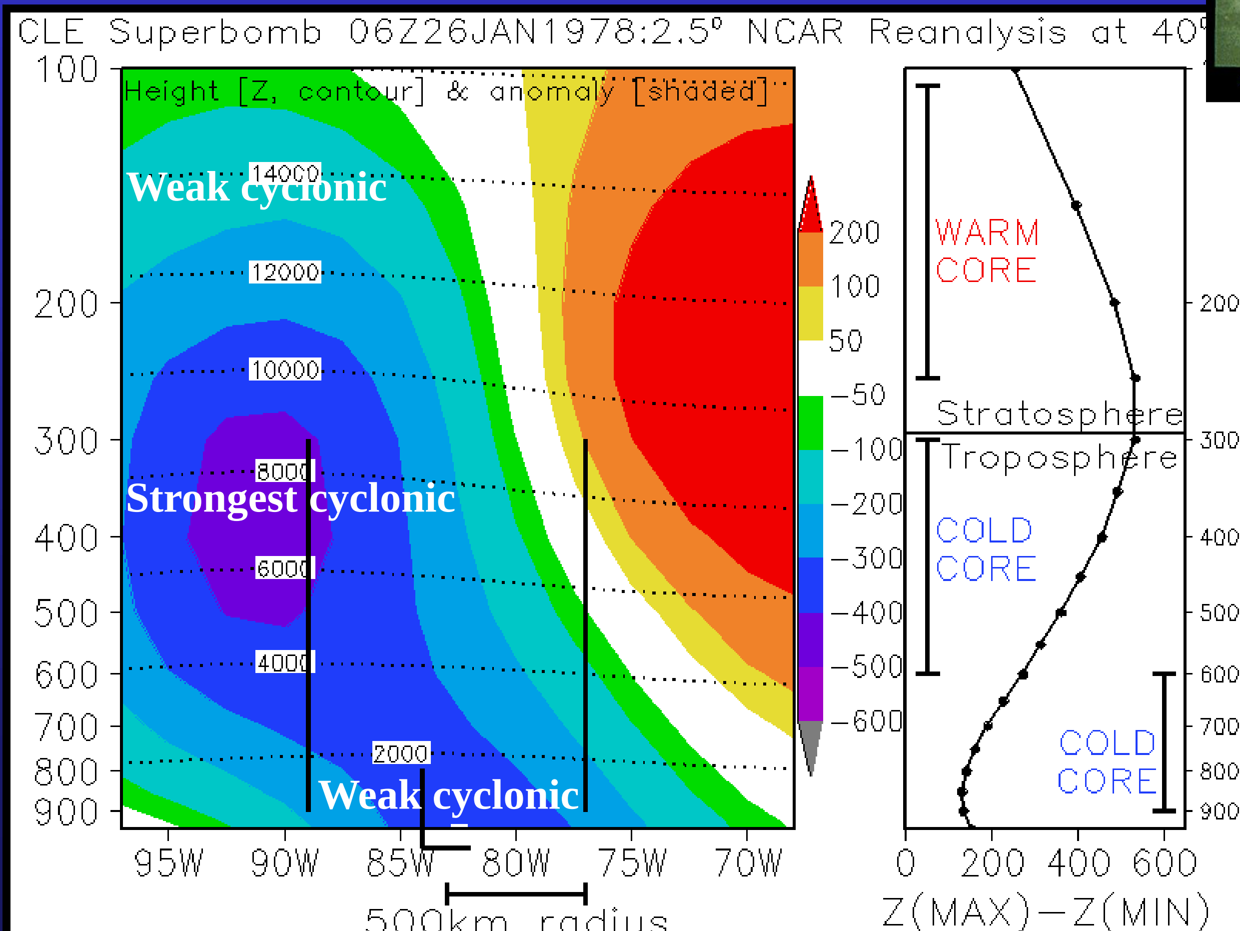
$$\left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln p}\right|_{900hPa}^{600hPa} = -|V_T^L|$$

Cyclone Parameter -V_T: Thermal Wind



Cold-core example:

Cleveland Superbomb 26 Jan 1978



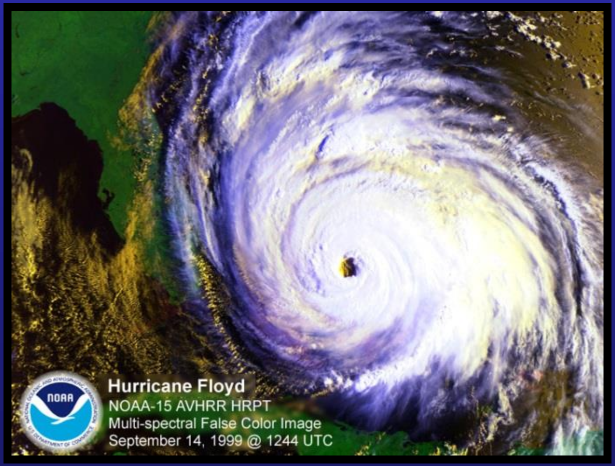
$$\left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln\ p}\right|_{600hPa}^{300hPa} = -|V_T^U|$$

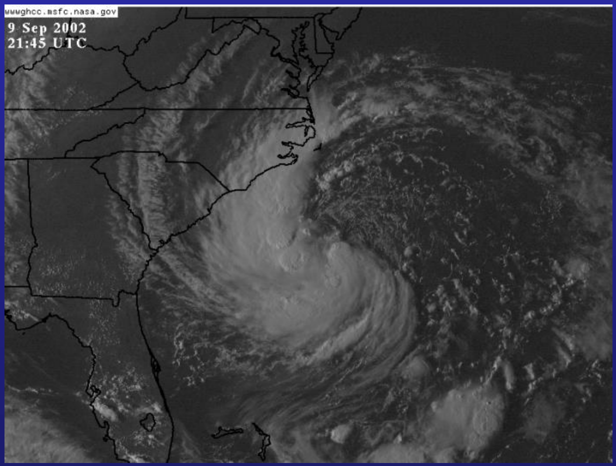
$$\left.\frac{\partial(Z_{MAX} - Z_{MIN})}{\partial \ln\ p}\right|_{900hPa}^{600hPa} = -|V_T^L|$$

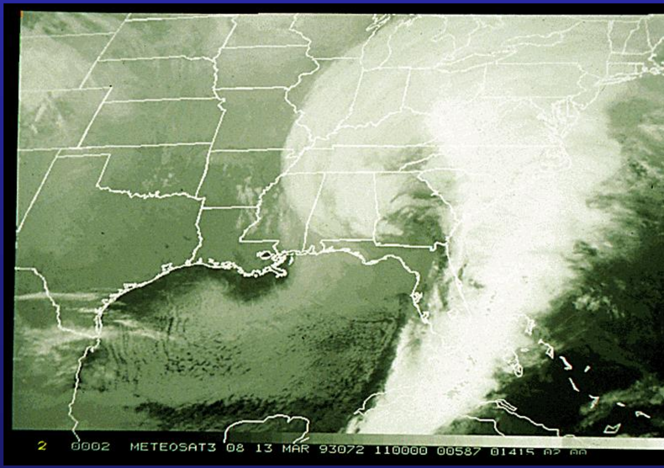
Cyclone Parameter 2: Horizontal structure

B: Thermal Asymmetry

Symmetric   Hybrid   Asymmetric



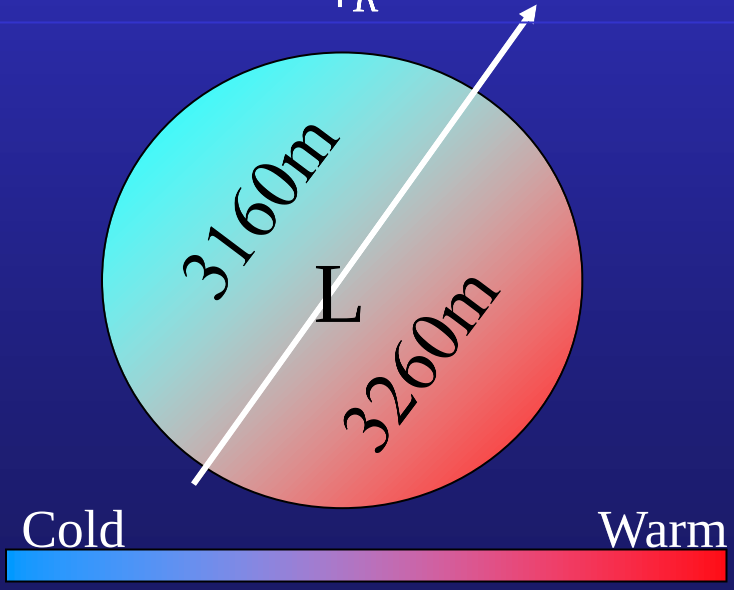




Cyclone Parameter B: Thermal Asymmetry

- Defined using storm-relative 900-600hPa mean thickness field (shaded) asymmetry within 500km radius:

$$B = \left.\overline{Z_{600hPa} - Z_{900hPa}}\right|_R - \left.\overline{Z_{600hPa} - Z_{900hPa}}\right|_L$$

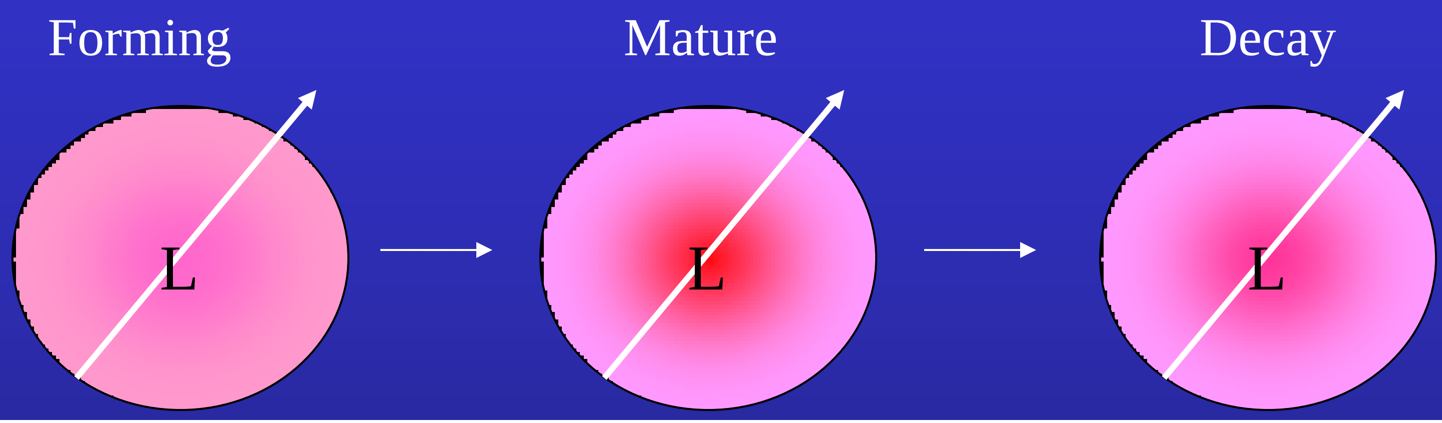


B >> 0: Frontal

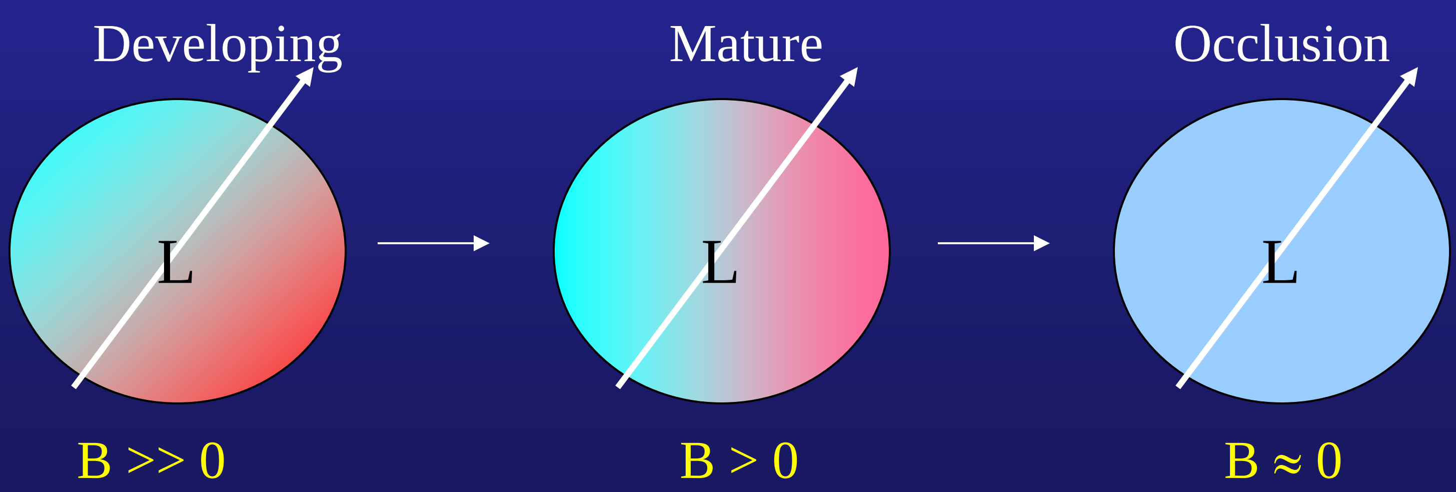
B≈0: Nonfrontal

Cyclone Parameter B: Thermal Asymmetry

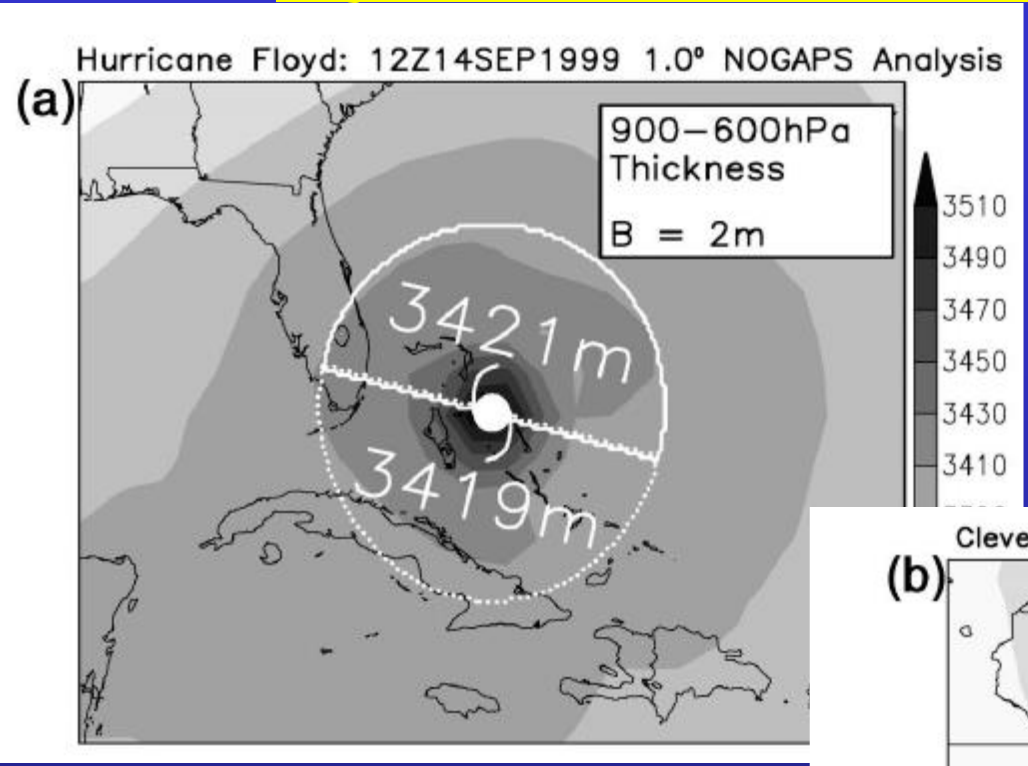
Conventional Tropical cyclone: B ≈ 0

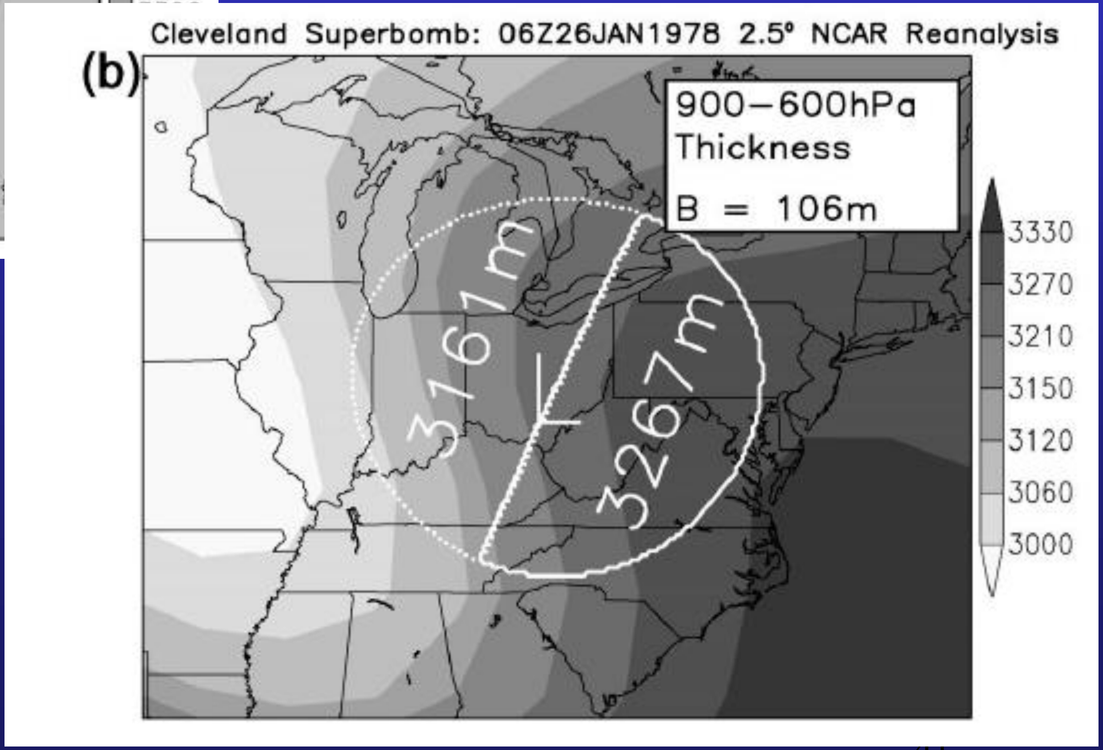


Conventional Extratropical cyclone: B varies



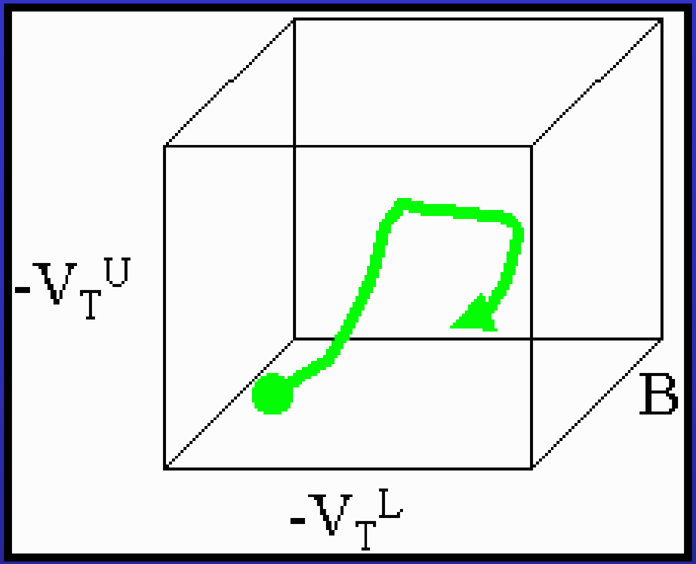
Cyclone Parameters Overview: B





Constructing Phase Space

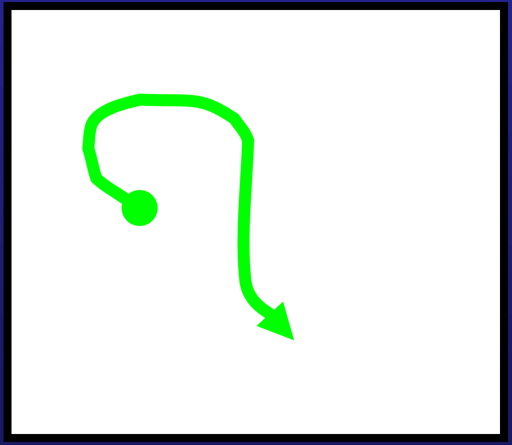
Constructing 3-D phase space from cyclone parameters: B, $-V_T^L$, $-V_T^U$



A trajectory within 3-D generally too complex to visualize in an operational setting

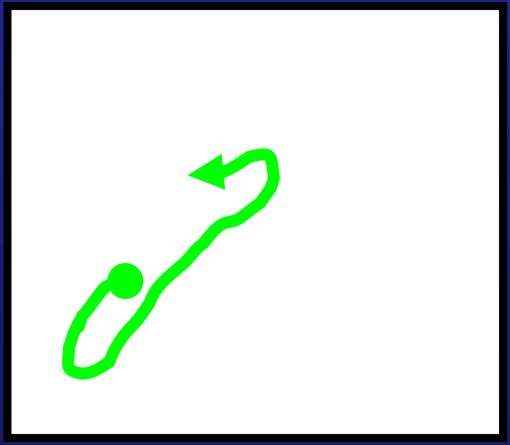
⇒ Take two cross sections (slices) :

B



$-V_T^L$

$-V_T^U$



$-V_T^L$

Phase Diagram 1

Thermal Asymmetry versus Lower-Tropospheric Thermal Wind

Symmetric warm core

- B ≤ 10 and $-V_T^L > 0$
  - Tropical cyclones, warm seclusions

Asymmetric warm core

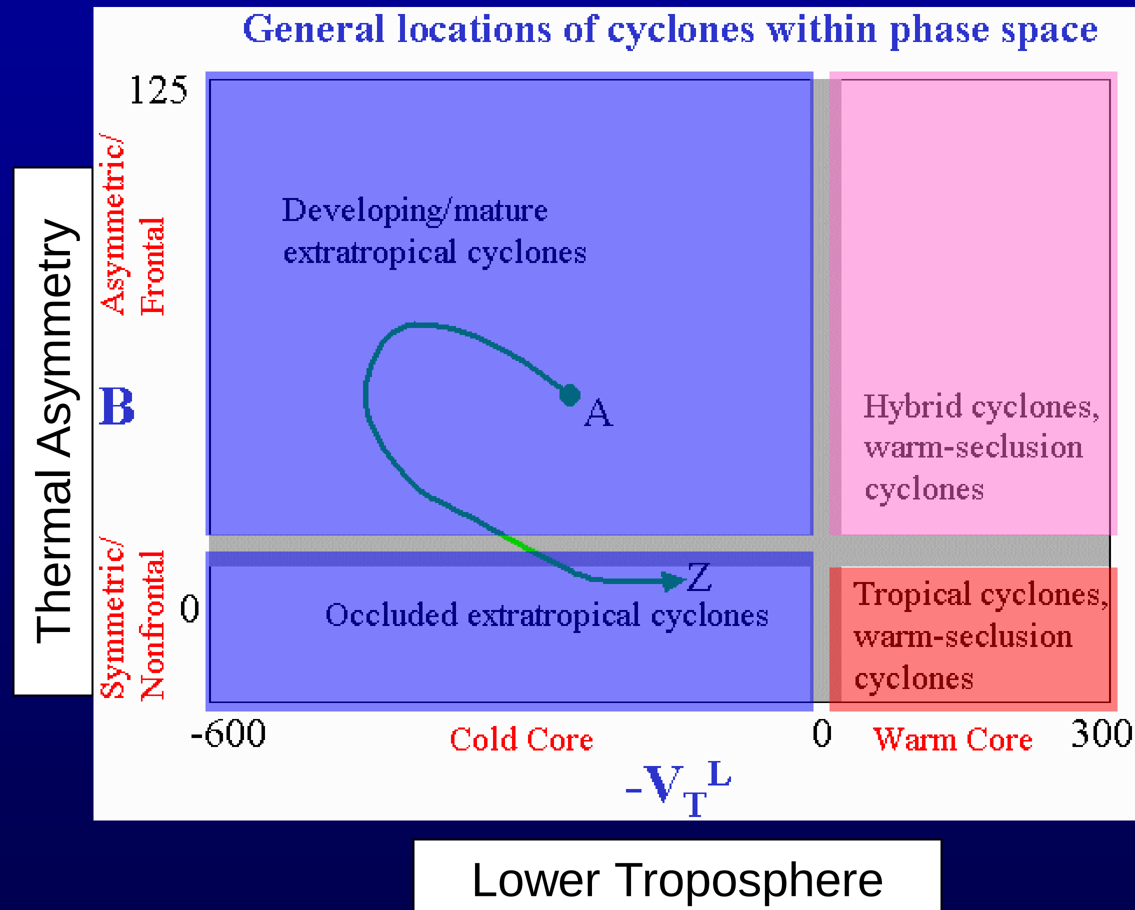
- B > 10 and $-V_T^L > 0$
  - Hybrid cyclones, warm seclusions
  - Most cyclones undergoing ET found here

Symmetric cold core

- B ≤ 10 and $-V_T^L < 0$
  - Occluded extratropical cyclones

Asymmetric cold core

- B > 10 and $-V_T^L < 0$
  - Developing or mature extratropical cyclones



Slide courtesy of Dr. Mike Brennan, NHC

Phase Diagram 2

Upper vs. Lower tropospheric Thermal Wind

Deep warm core

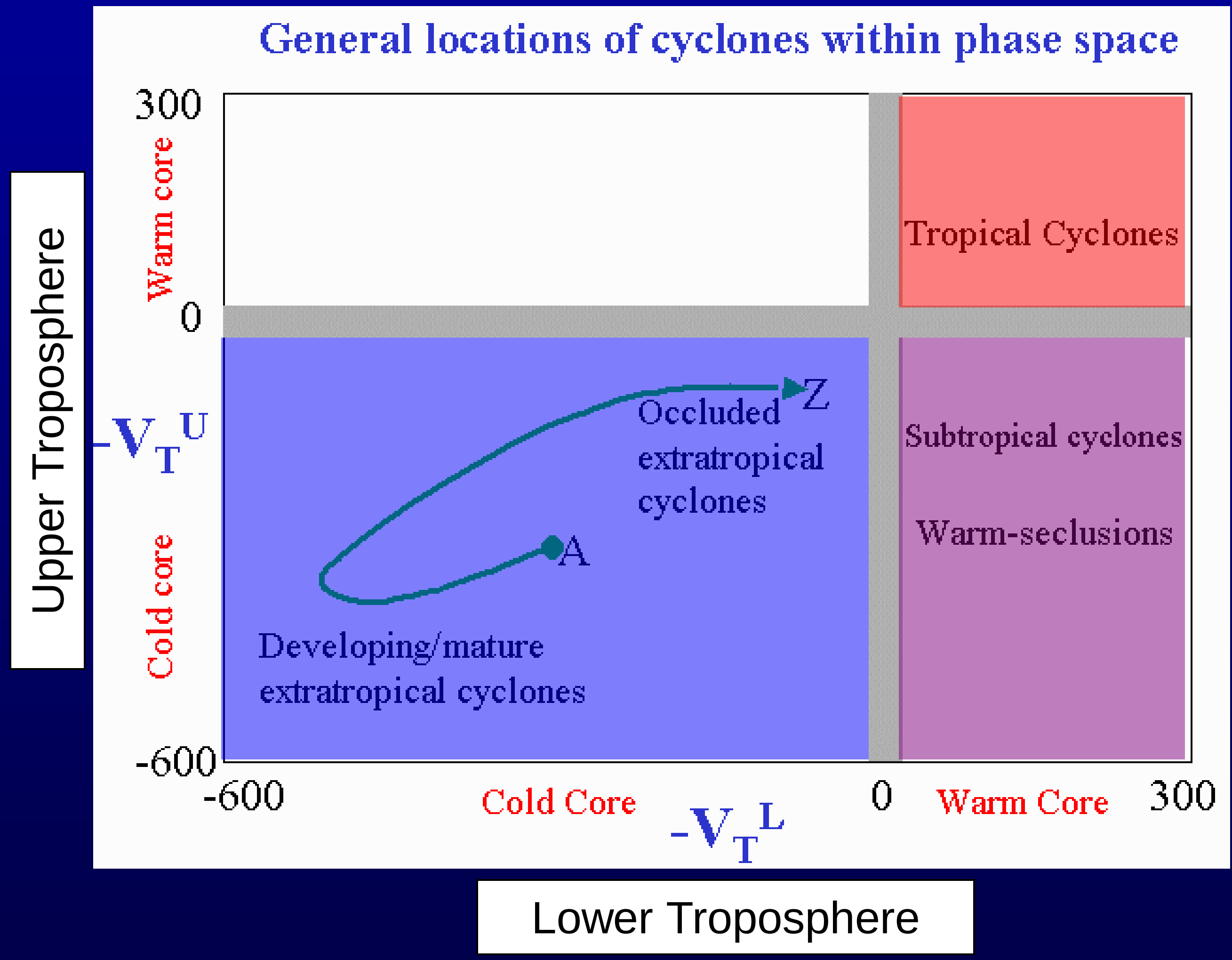
- $-V_T^L > 0, -V_T^U > 0$
- Tropical cyclones

Deep cold core

- $-V_T^L < 0, -V_T^U < 0$
- Extratropical cyclones

Shallow warm core

- $-V_T^L > 0, -V_T^U < 0$
- Subtropical cyclones, warm seclusions



Slide courtesy of Dr. Mike Brennan, NHC

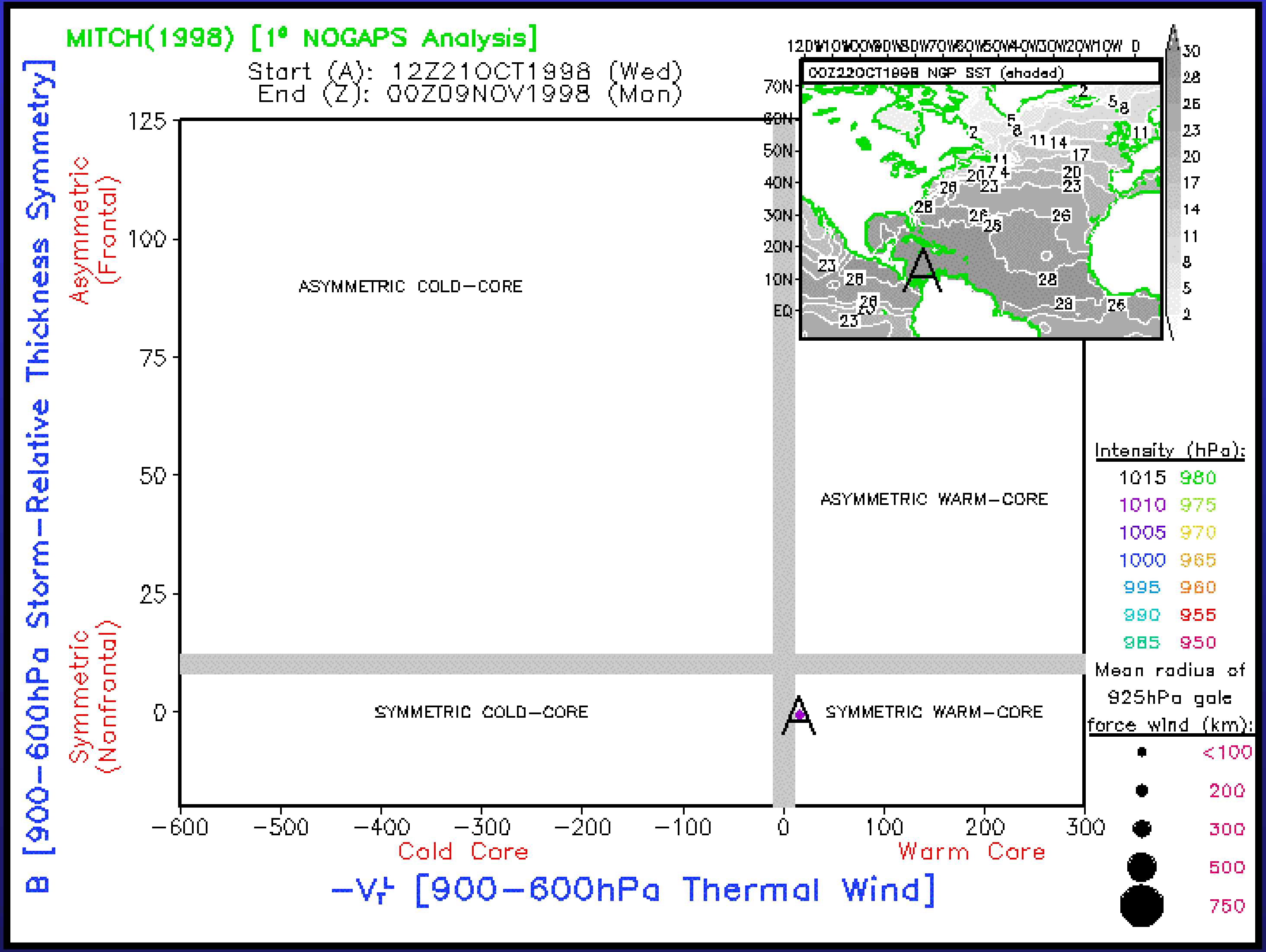
Hurricane Mitch (1998)

Case of symmetric, warm-core development and decay

Classic tropical cyclone

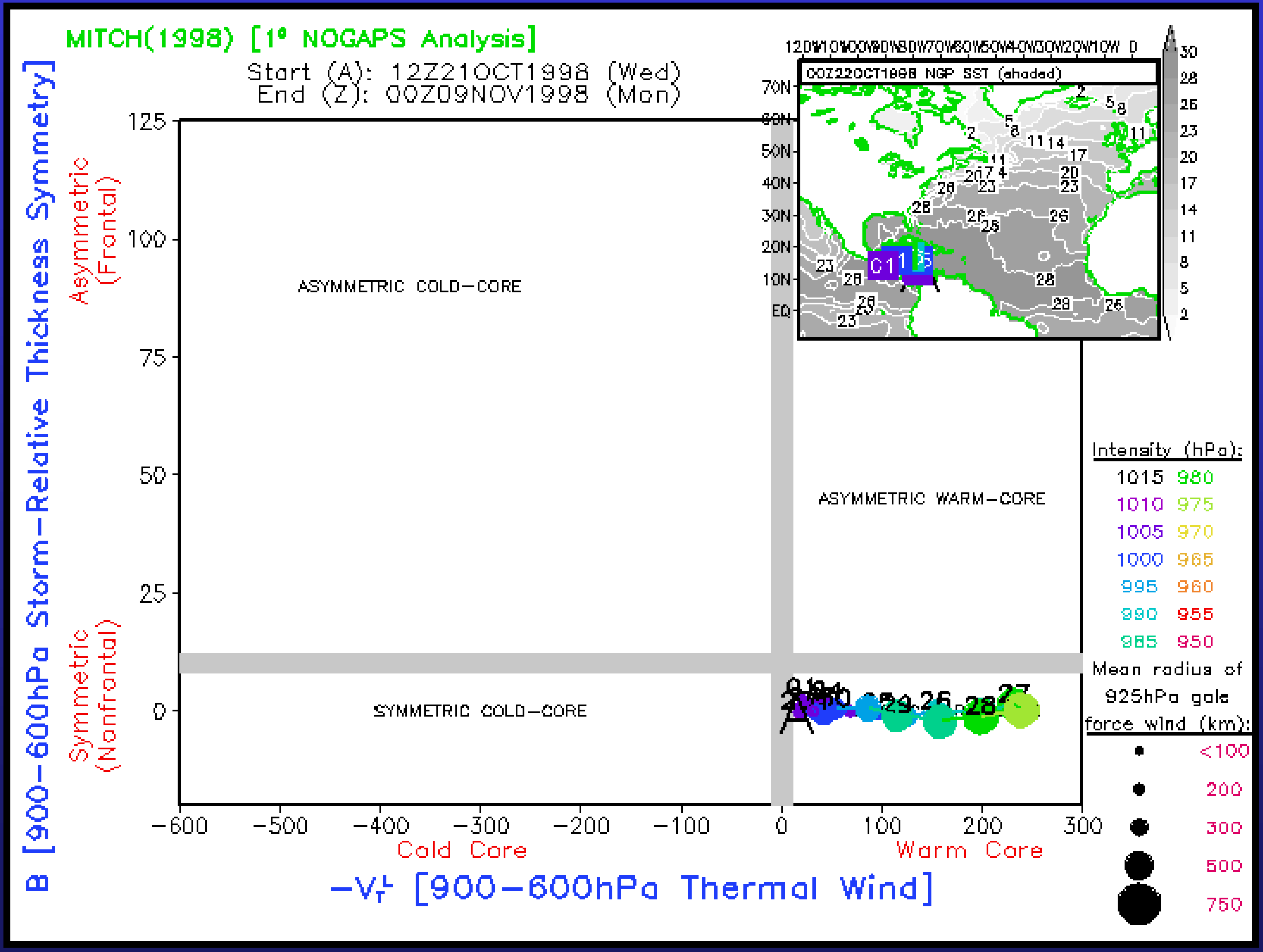
Symmetric warm-core evolution: Hurricane Mitch (1998)

Slice 1: B Vs. $-V_T^L$



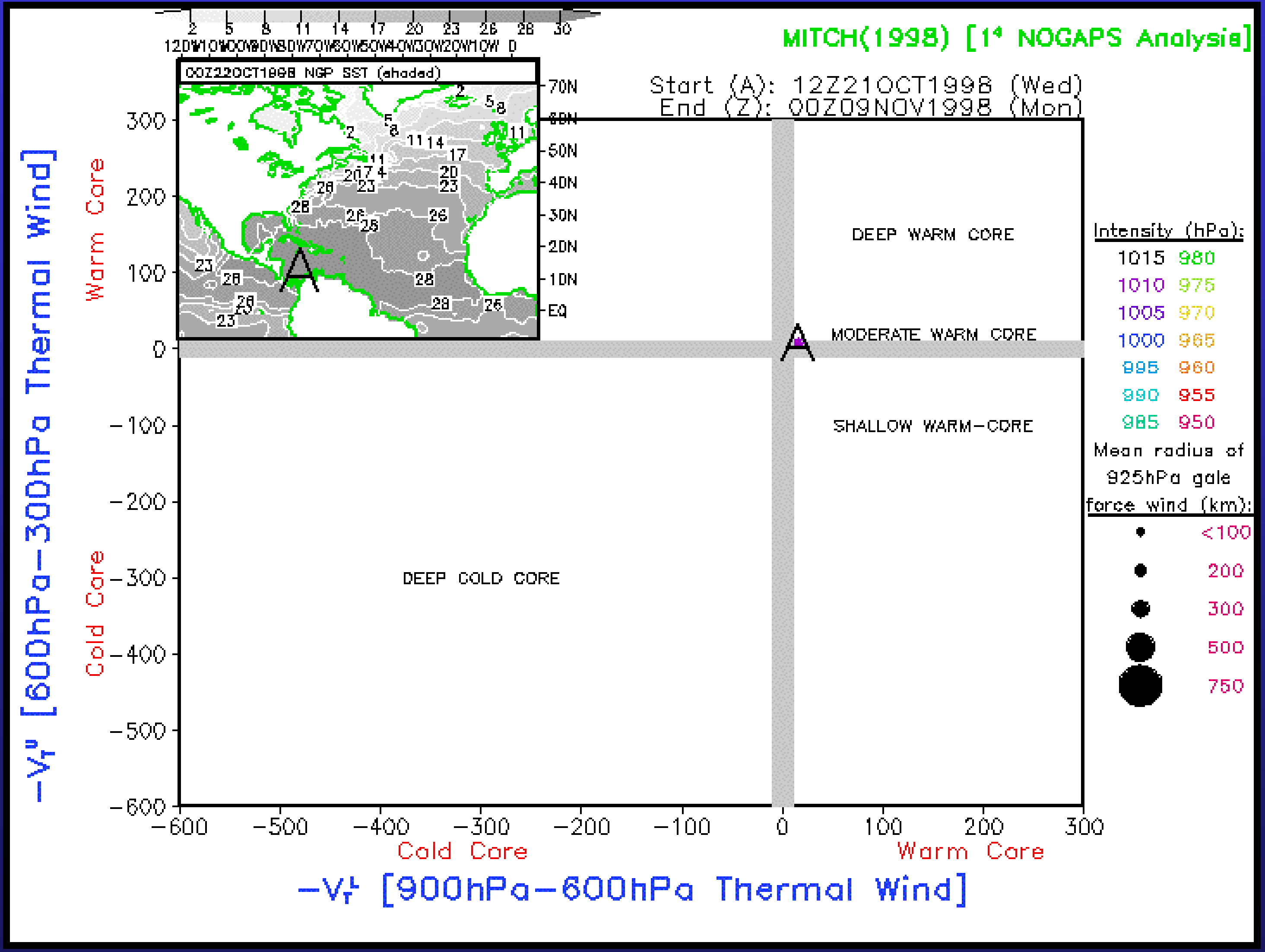
Symmetric warm-core evolution: Hurricane Mitch (1998)

Slice 1: B Vs. $-V_T^L$



Symmetric warm-core evolution: Hurricane Mitch (1998)

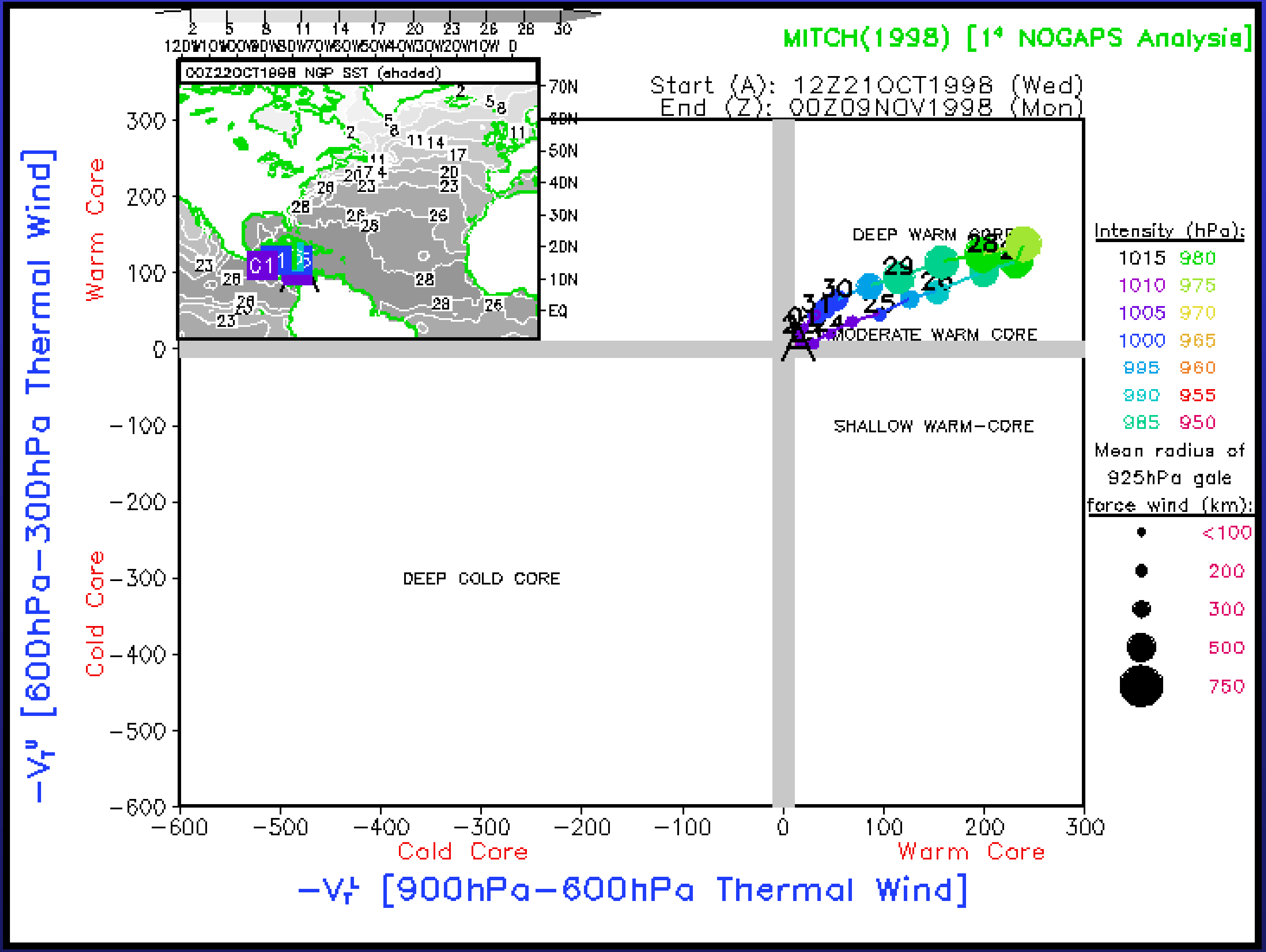
Slice 2: $-V_T^L$ Vs. $-V_T^U$



Upward warm core development maturity, and decay.

With landfall, warm-core weakens more rapidly in lower troposphere than upper.

Symmetric warm-core evolution: Hurricane Mitch (1998)
Slice 2: $-V_T^L$ Vs. $-V_T^U$



Upward warm core development maturity, and decay.

With landfall, warm-core weakens more rapidly in lower troposphere than upper.

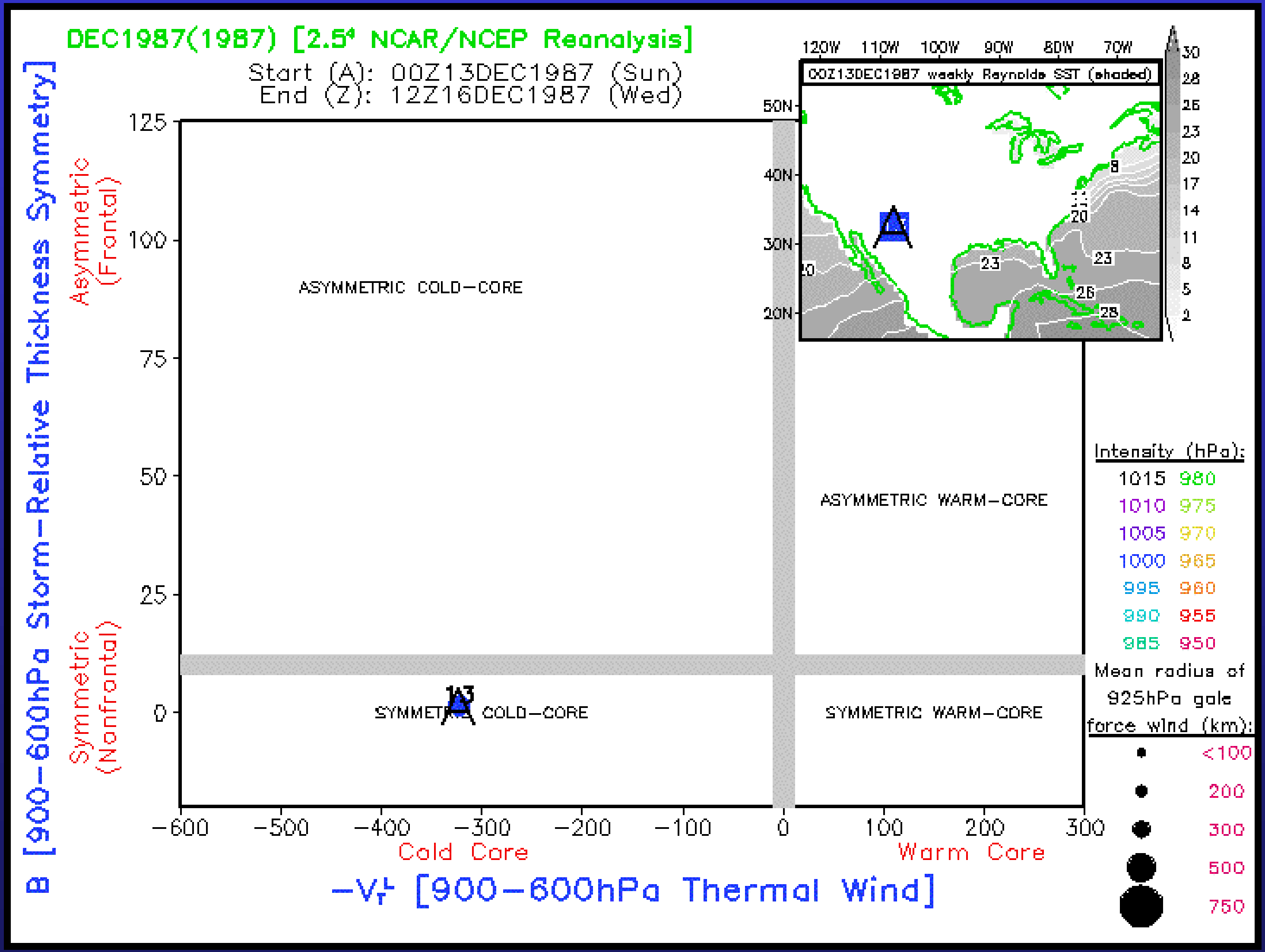
December 1987 Extratropical Cyclone

Case of asymmetric, cold-core development and decay

Classic occlusion of an extratropical cyclone

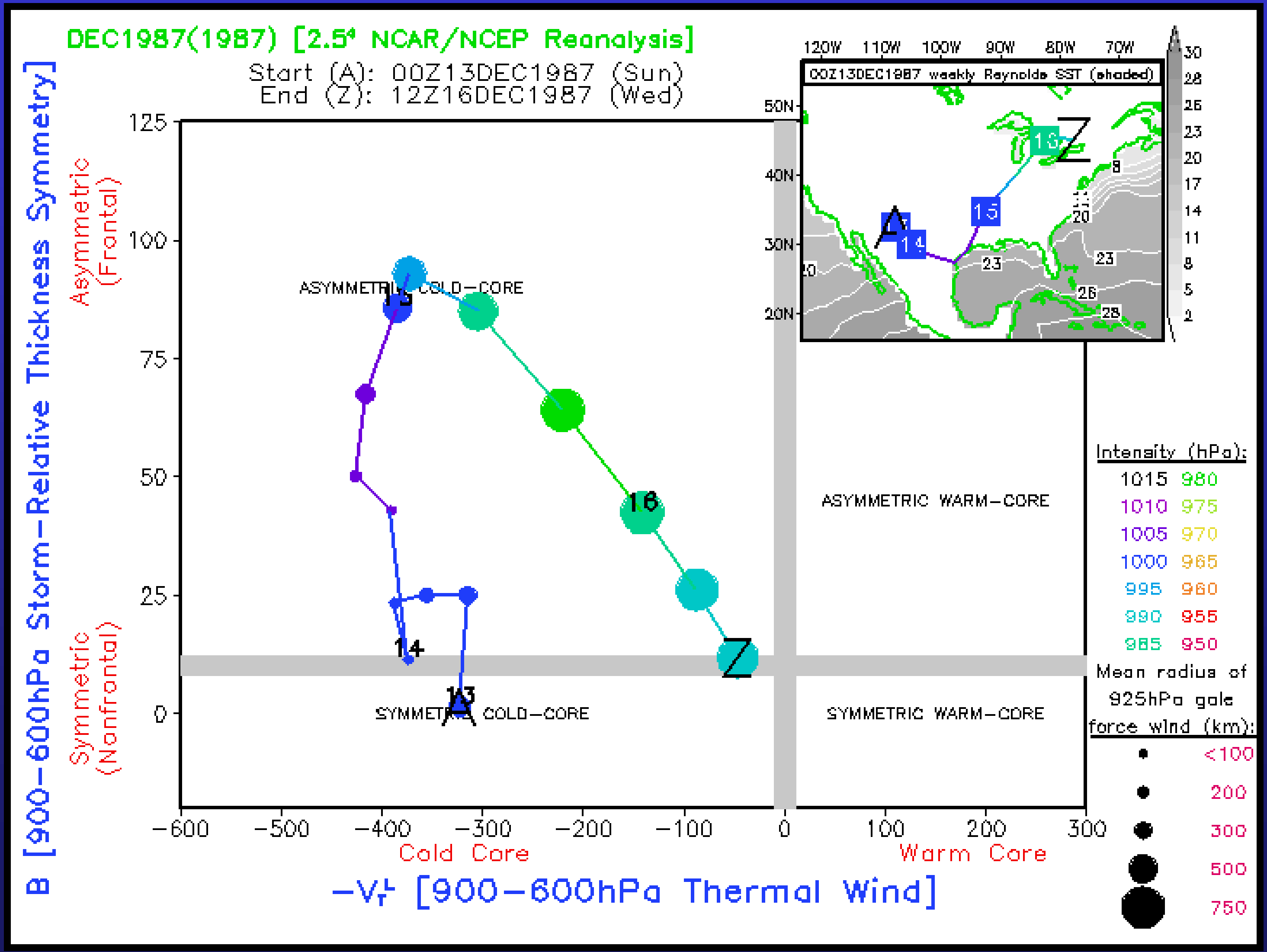
Asymmetric cold-core evolution: Extratropical Cyclone

Slice 1: B Vs. $-V_T^L$



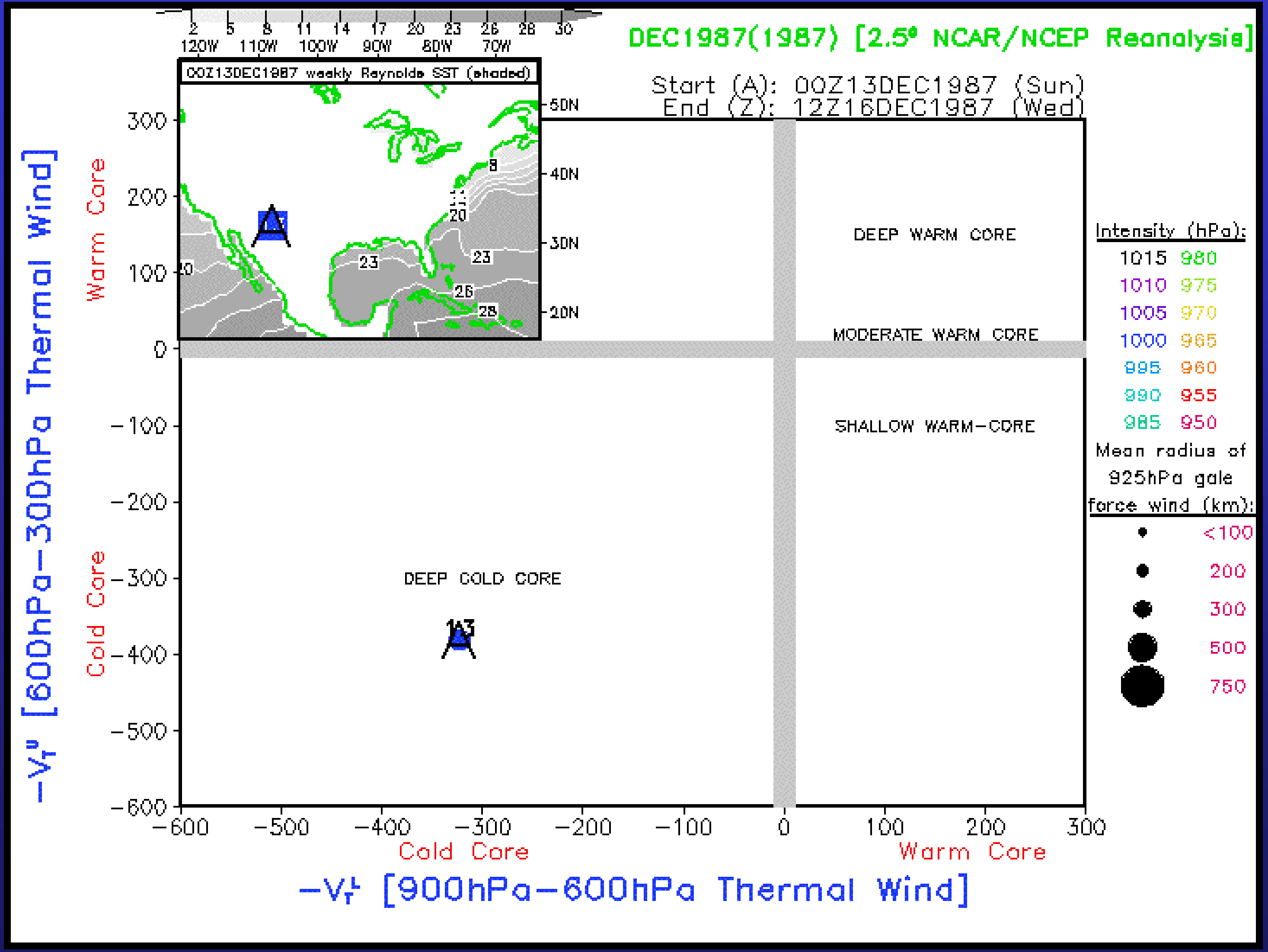
Asymmetric cold-core evolution: Extratropical Cyclone

Slice 1: B Vs. $-V_T^L$



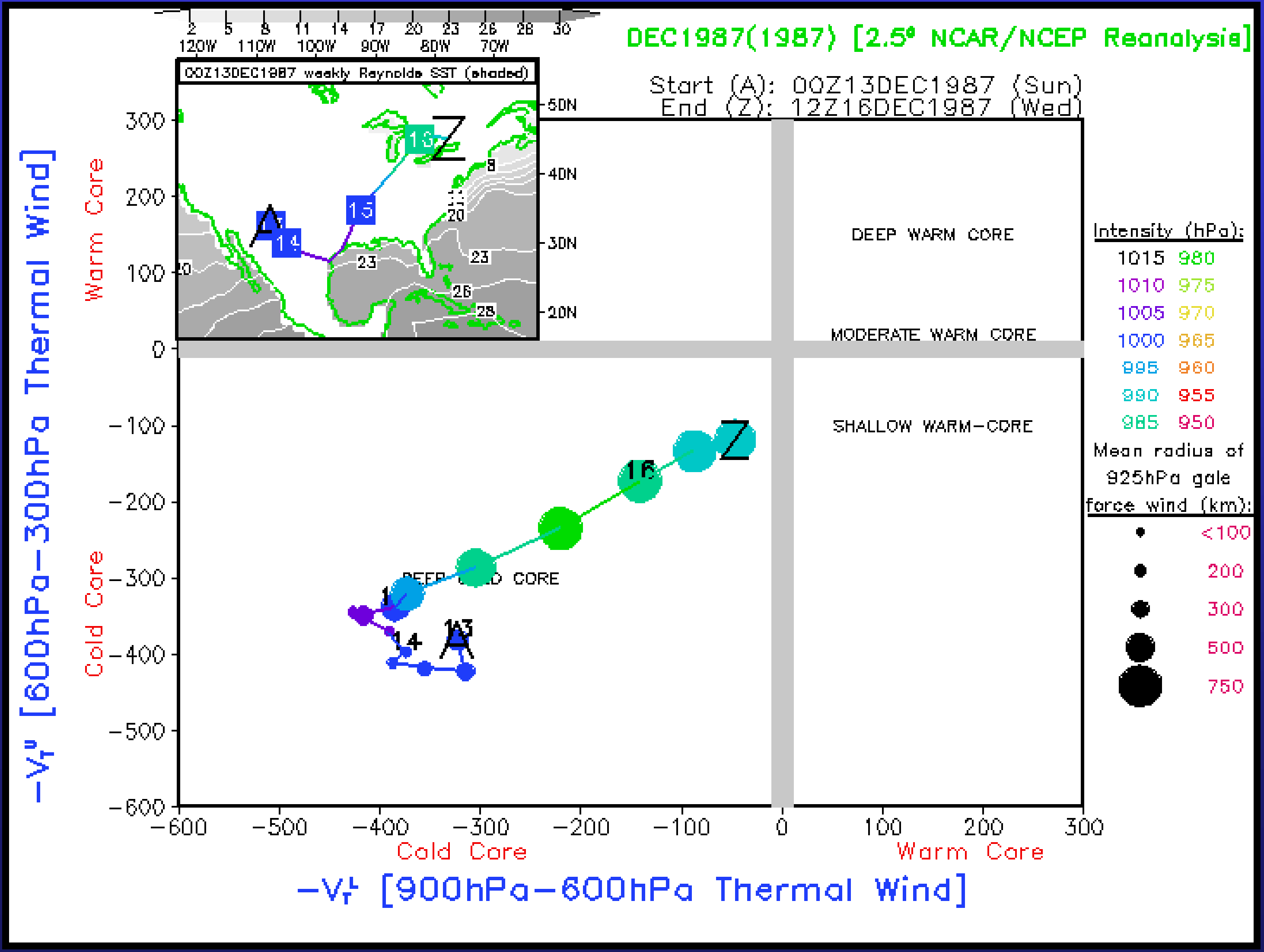
Asymmetric cold-core evolution: Extratropical Cyclone

Slice 2: $-V_T^L$ Vs. $-V_T^U$



Asymmetric cold-core evolution: Extratropical Cyclone

Slice 2: $-V_T^L$ Vs. $-V_T^U$



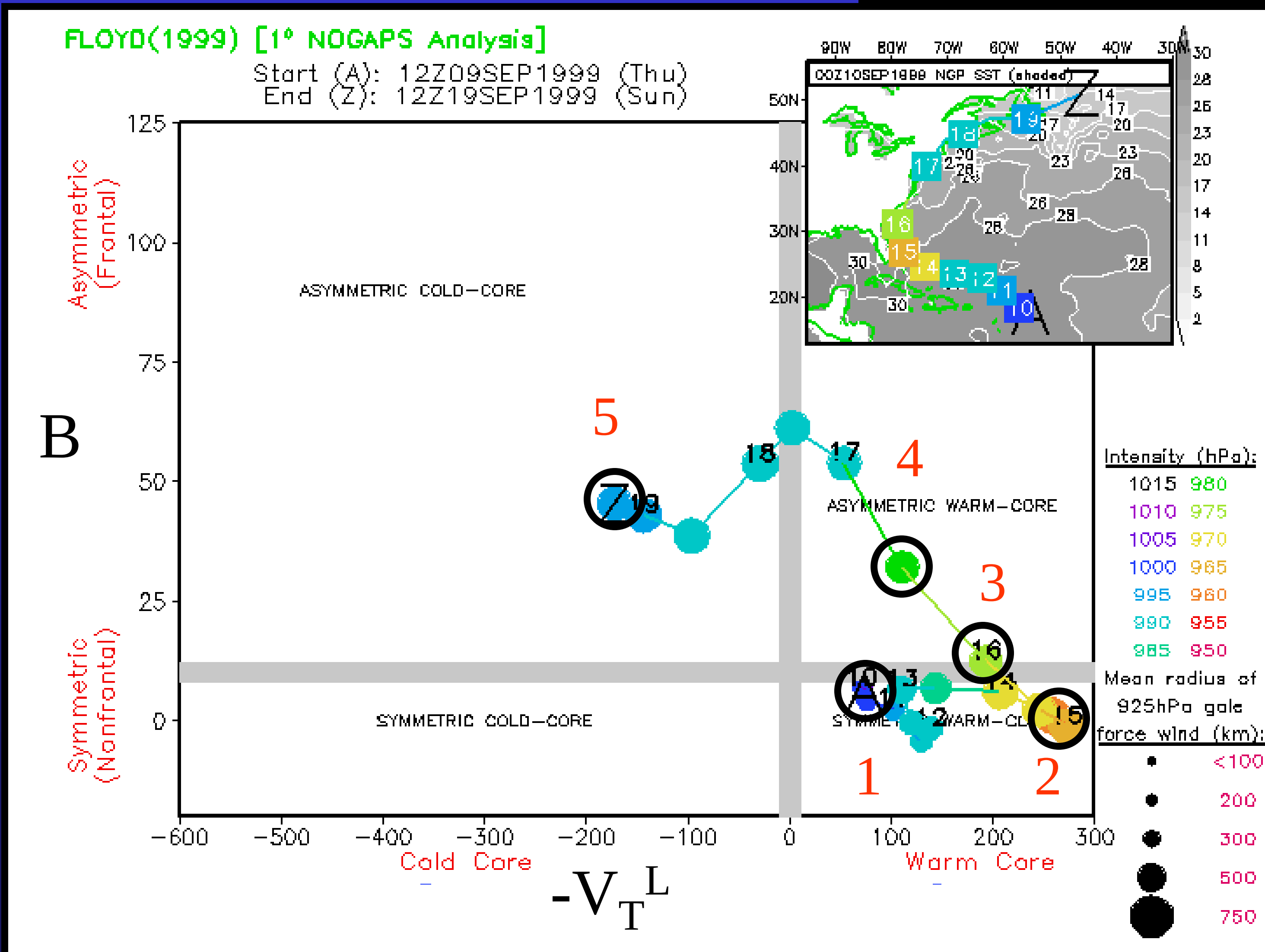
Hurricane Floyd (1999)

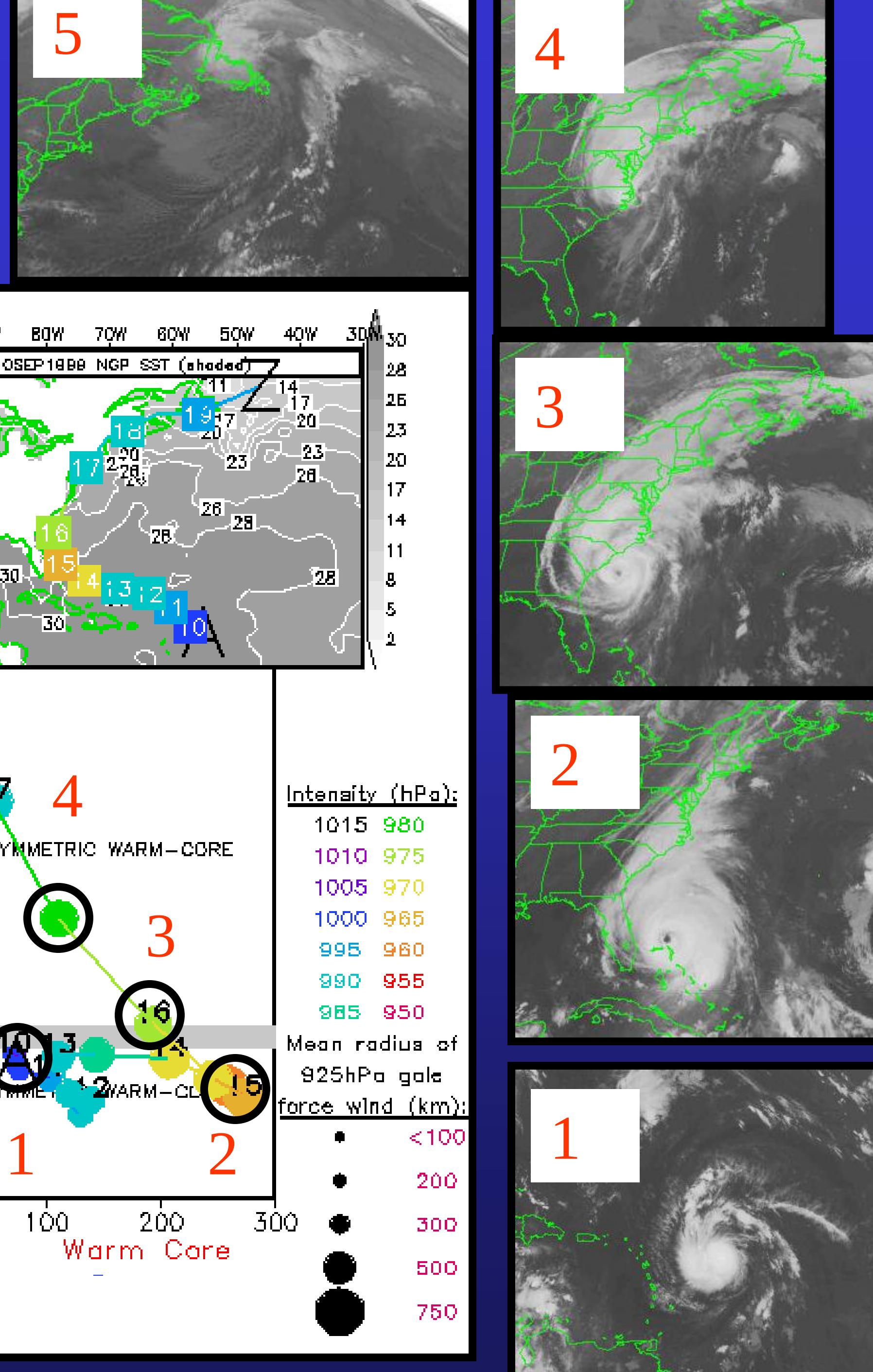
Multiple phase evolution:

Case of extratropical transition of a tropical cyclone

Warm-to-cold core transition:

Extratropical Transition of Hurricane Floyd (1999): B Vs. $-V_T^L$

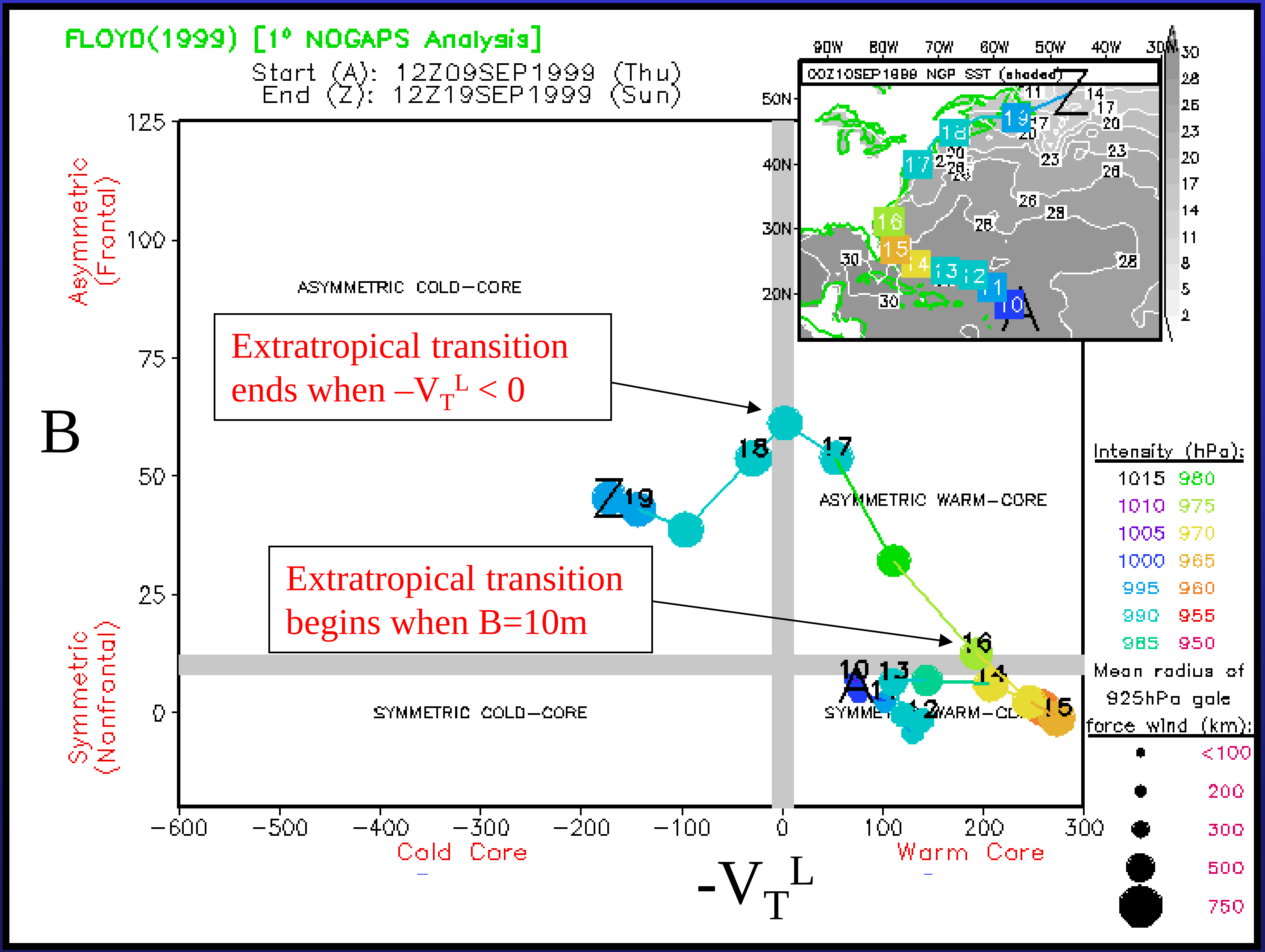




Warm-to-cold core transition:

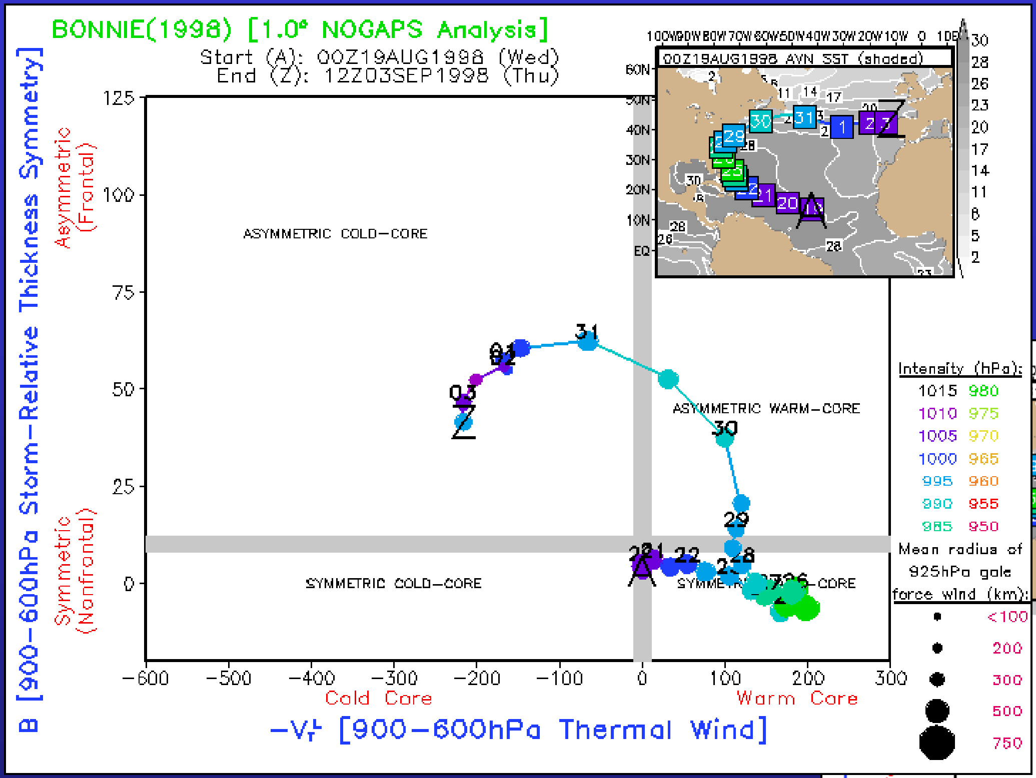
Extratropical Transition of Hurricane Floyd (1999)

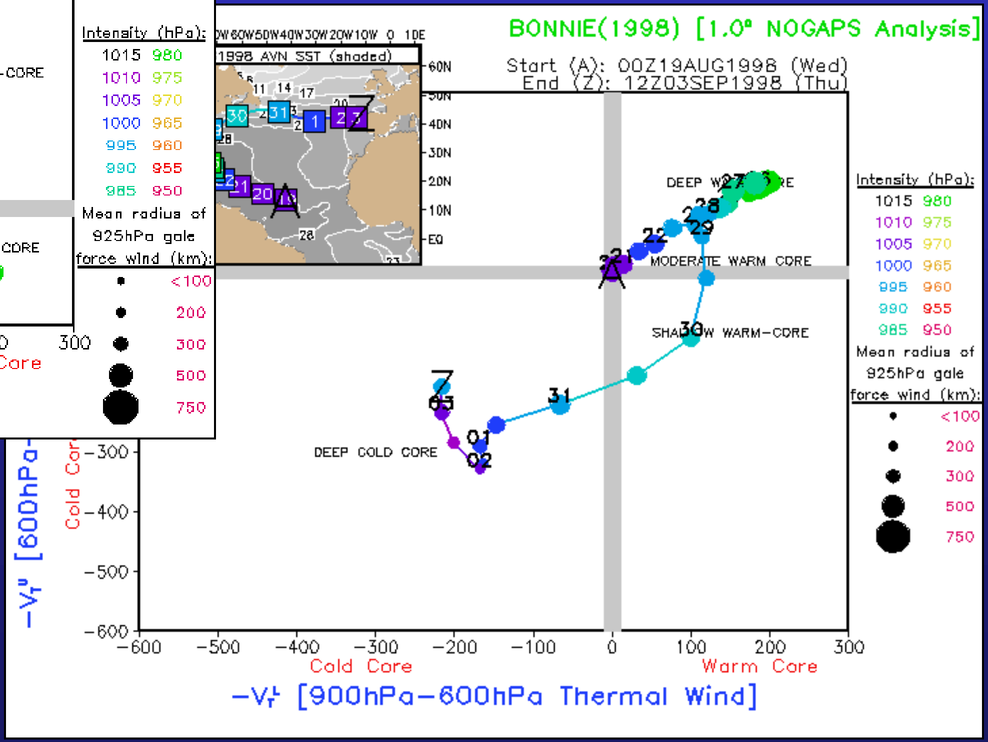
B Vs. $-V_T^L$



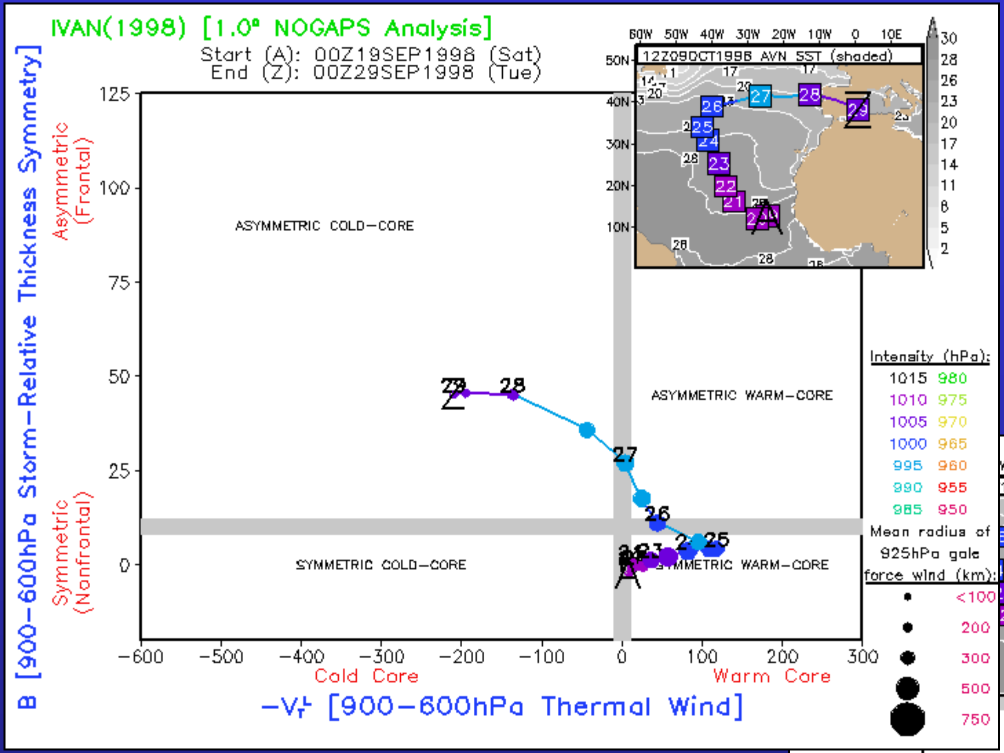
⇒Provides for objective indicators of extratropical transition lifecycle.

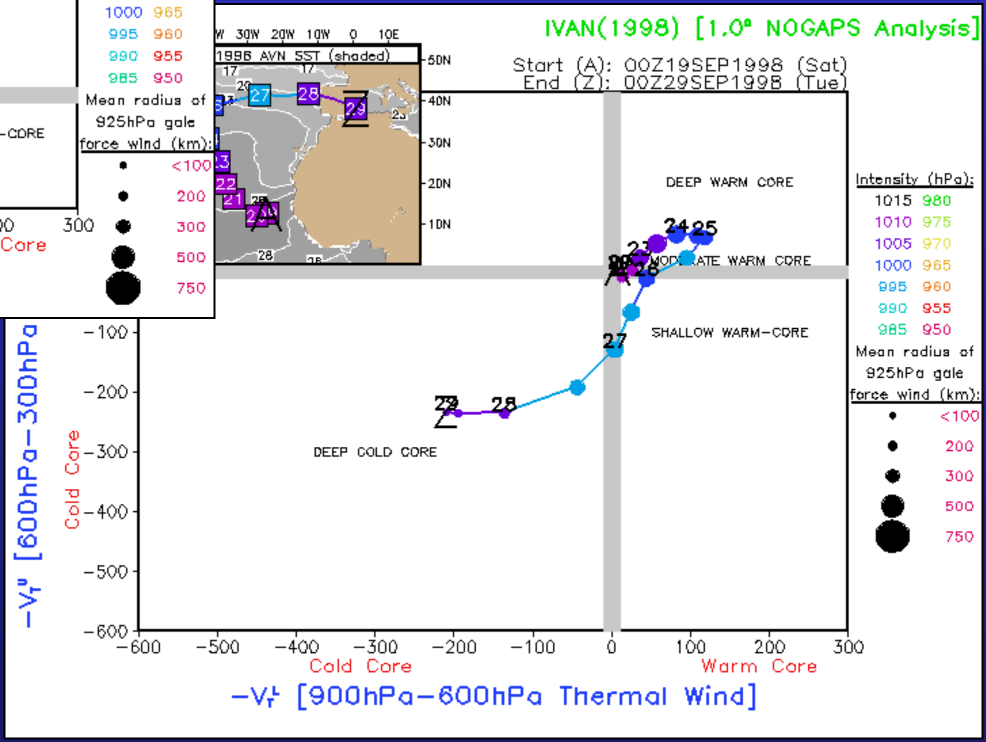
ET Phase Trajectory Example: NWATL



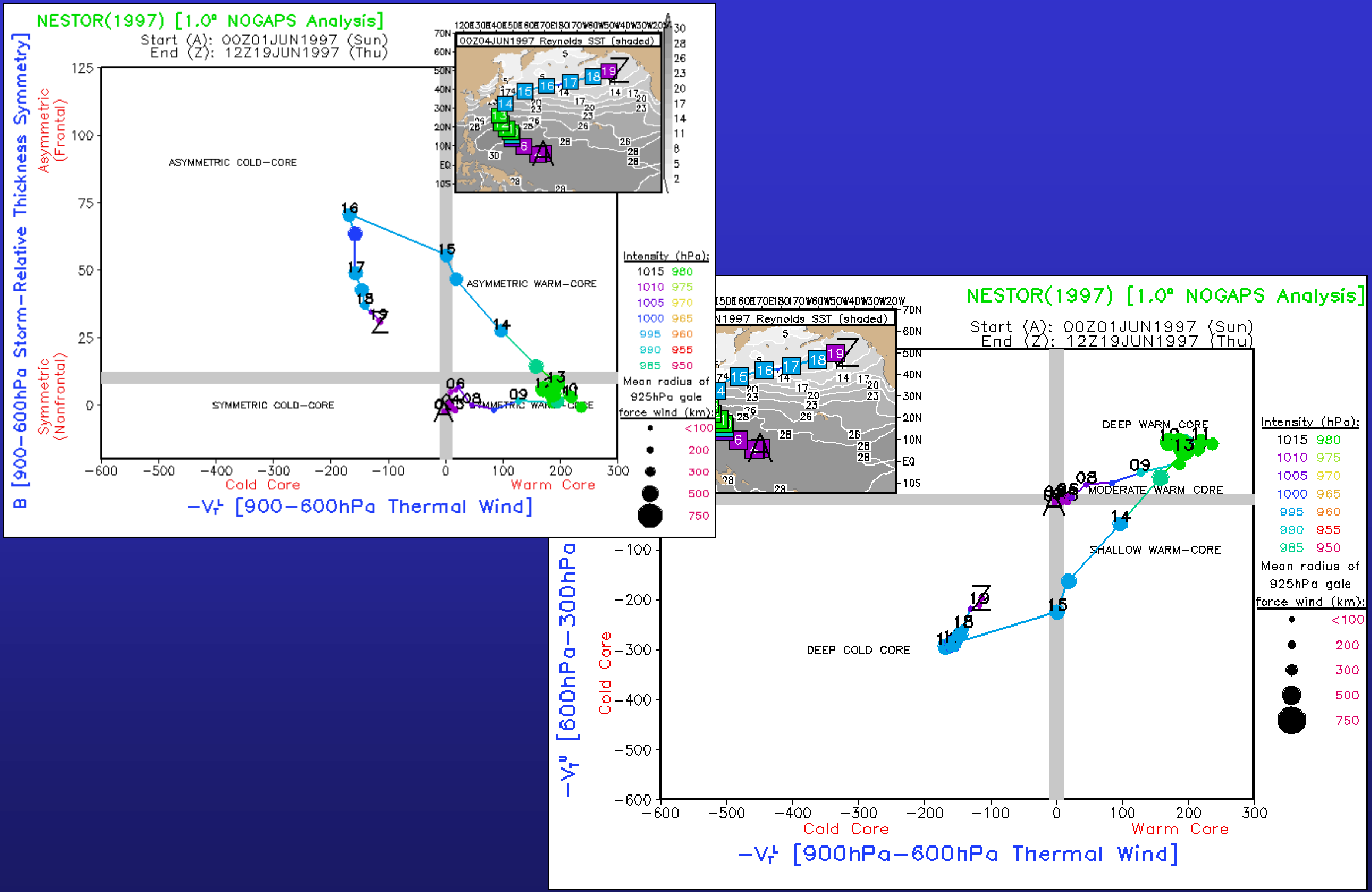


ET Phase Trajectory Example: NEATL

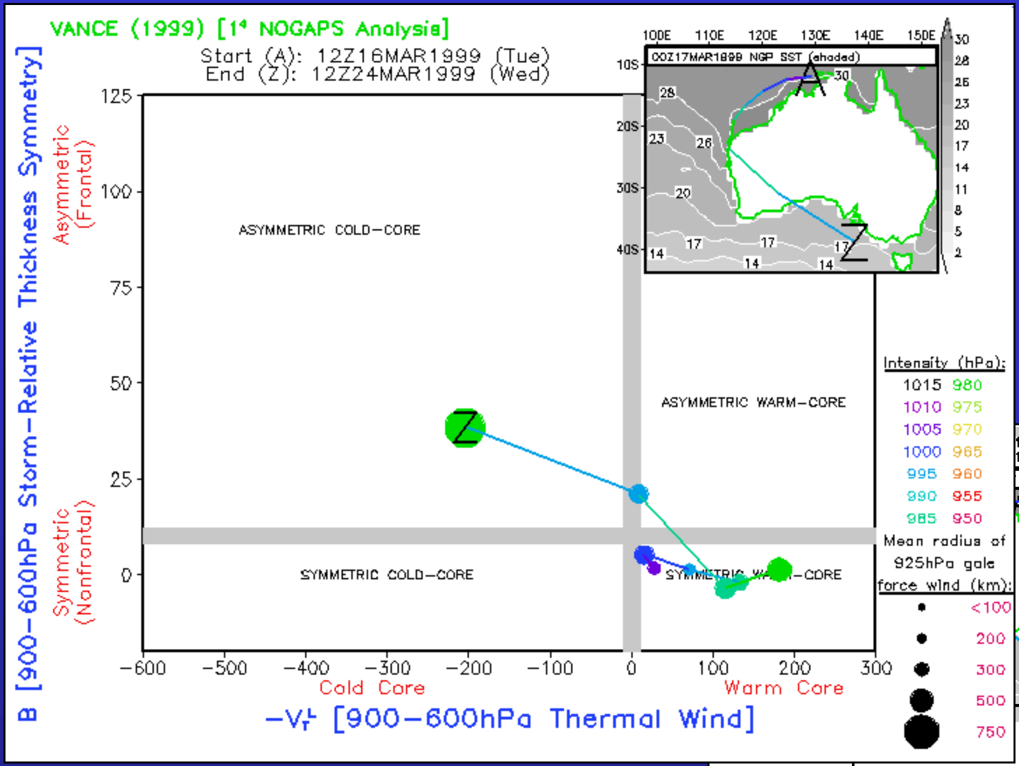


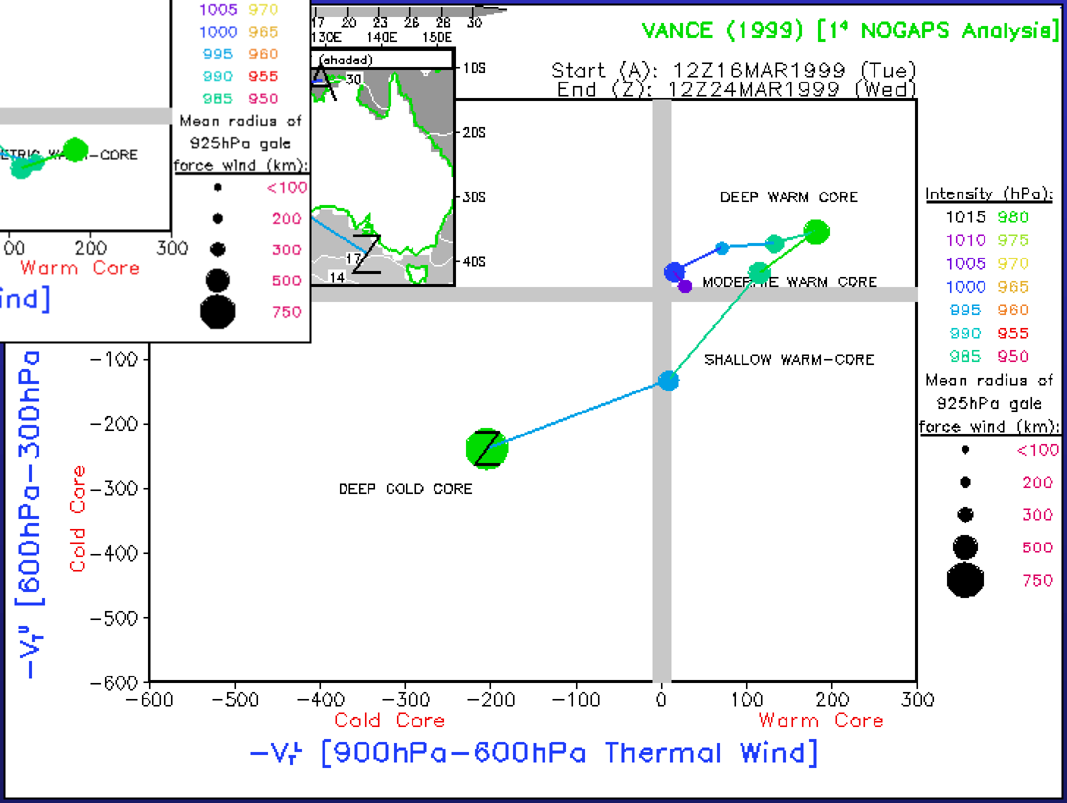


ET Phase Trajectory Example: WPAC

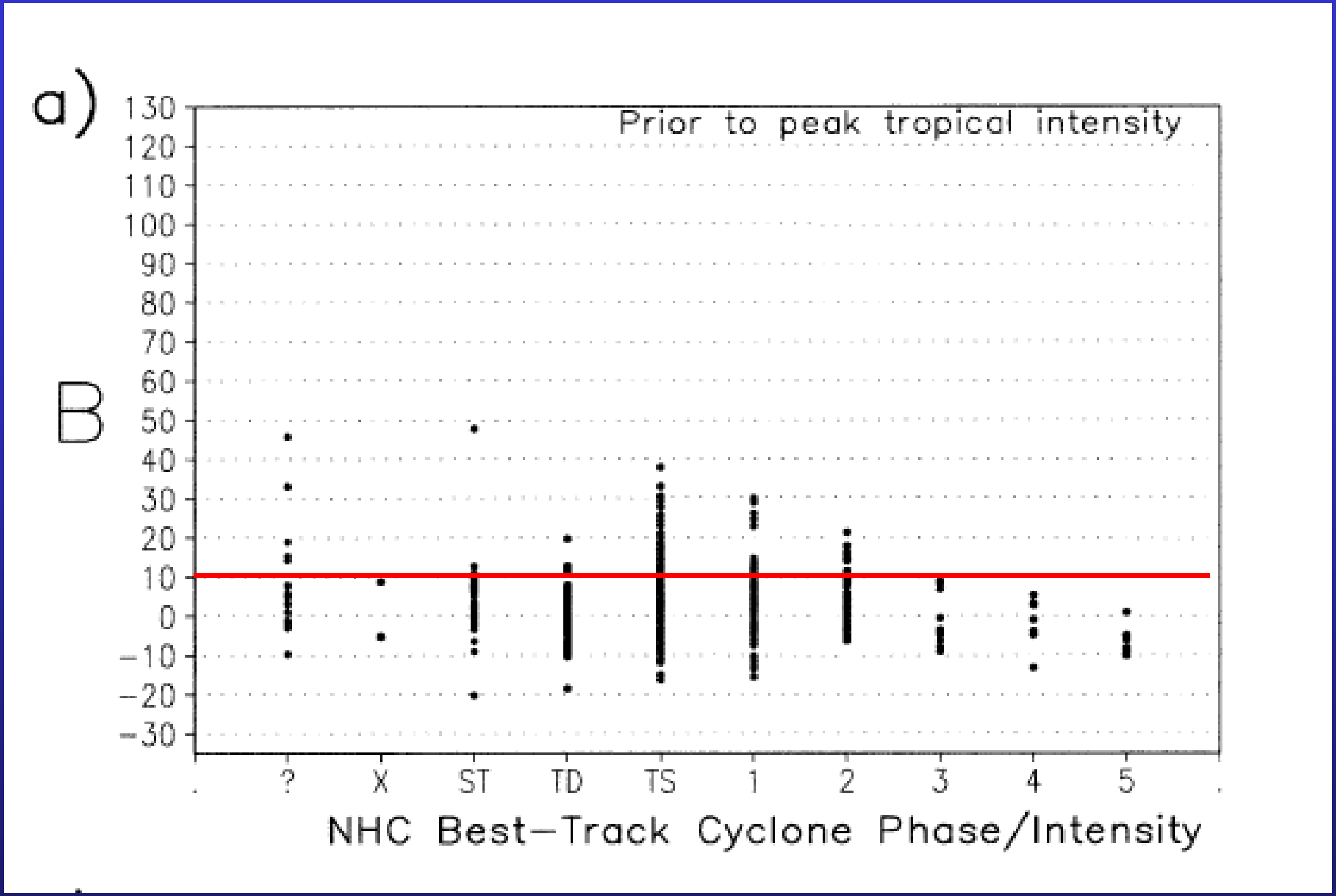


ET Phase Trajectory Example: Aust





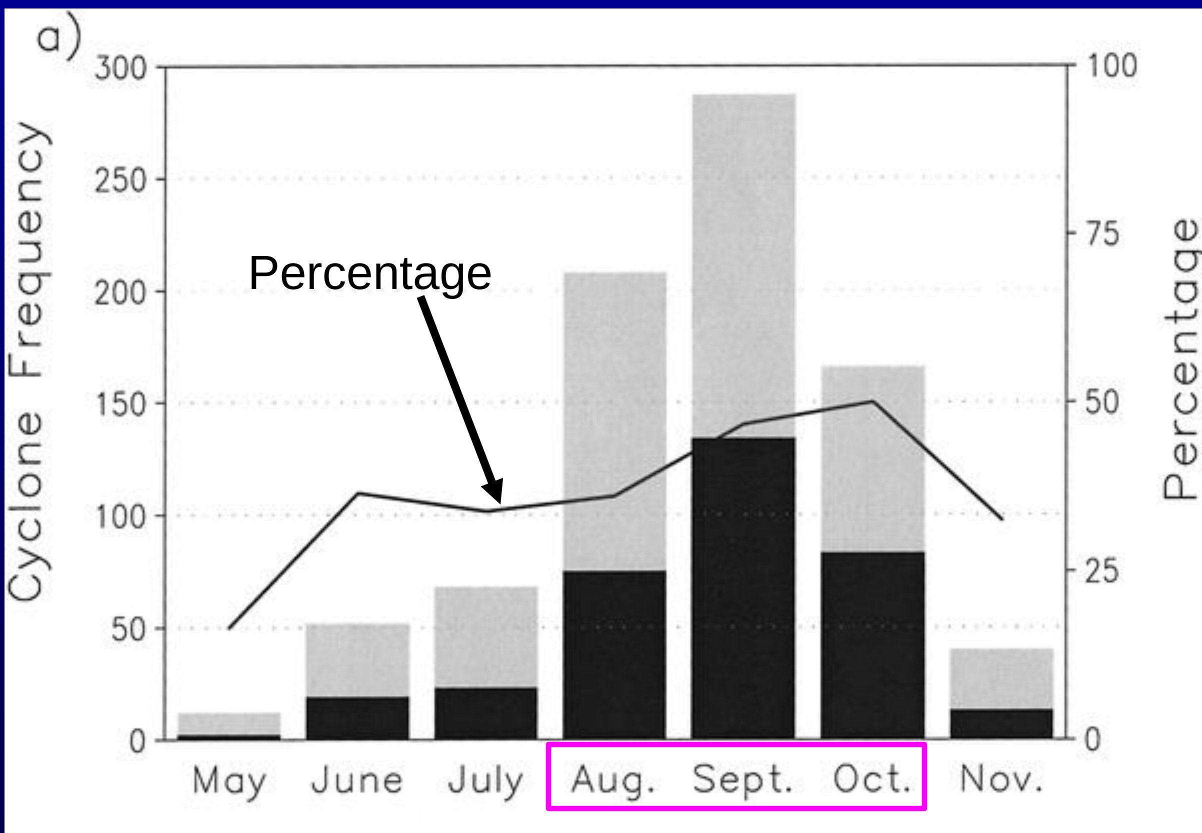
Cyclone Parameters Overview: B



Evans & Hart 2003

North Atlantic ET Climatology

Number and percentage of North Atlantic TCs undergoing ET by month 1899–1996



Number of TCs

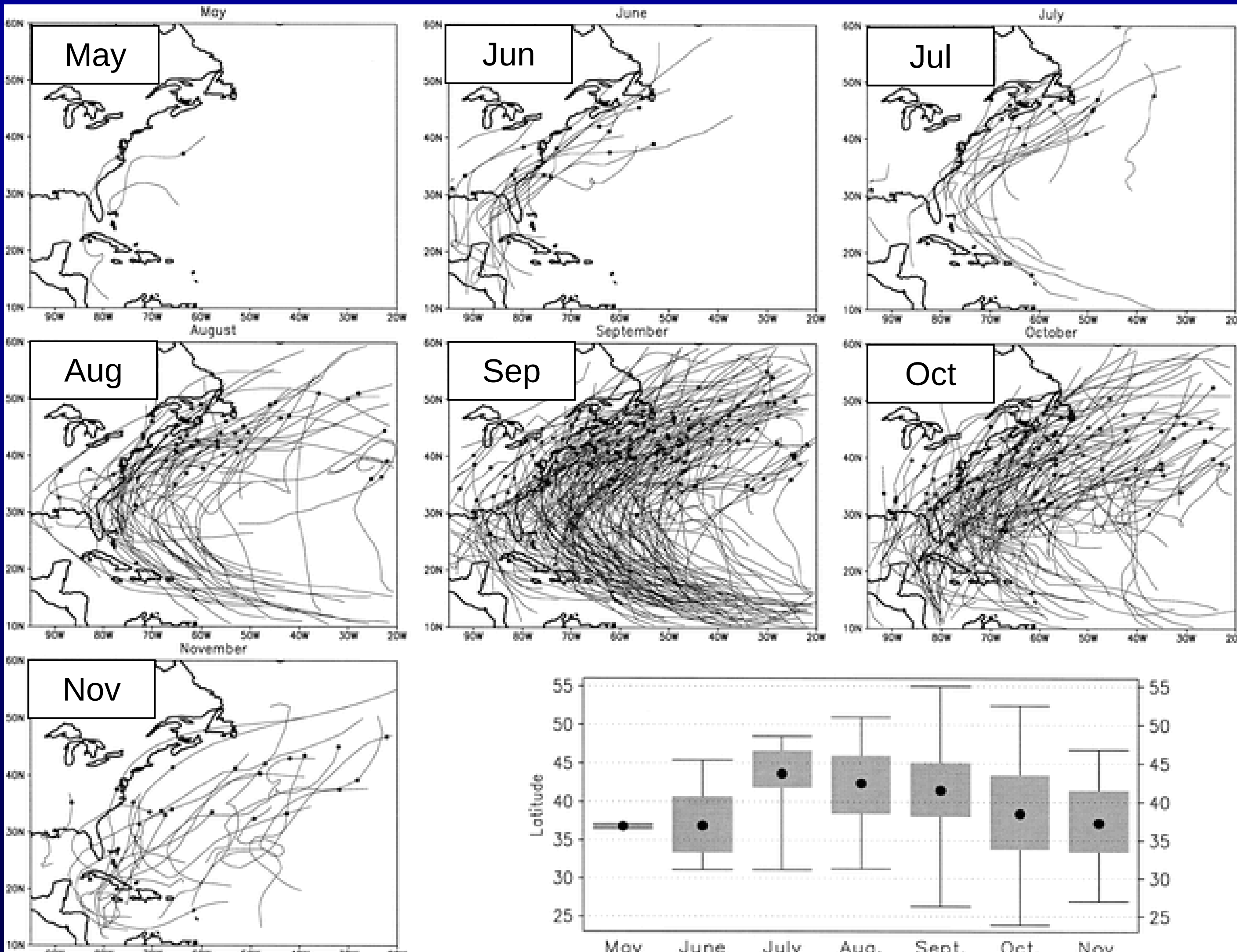
Number of TCs undergoing ET

Largest number of Atlantic TCs undergo ET from August through October

Hart and Evans (2001) *Journal of Climate*

Slide courtesy of Dr. Mike Brennan, NHC

North Atlantic ET Climatology



Latitudinal distribution of ET in North Atlantic varies widely:

July through Sept: 40–50°N

Earlier and later in the season: 35–40°N

Hart and Evans (2001) *Journal of Climate*

Slide courtesy of Dr. Mike Brennan, NHC

Hurricane Olga (2001)

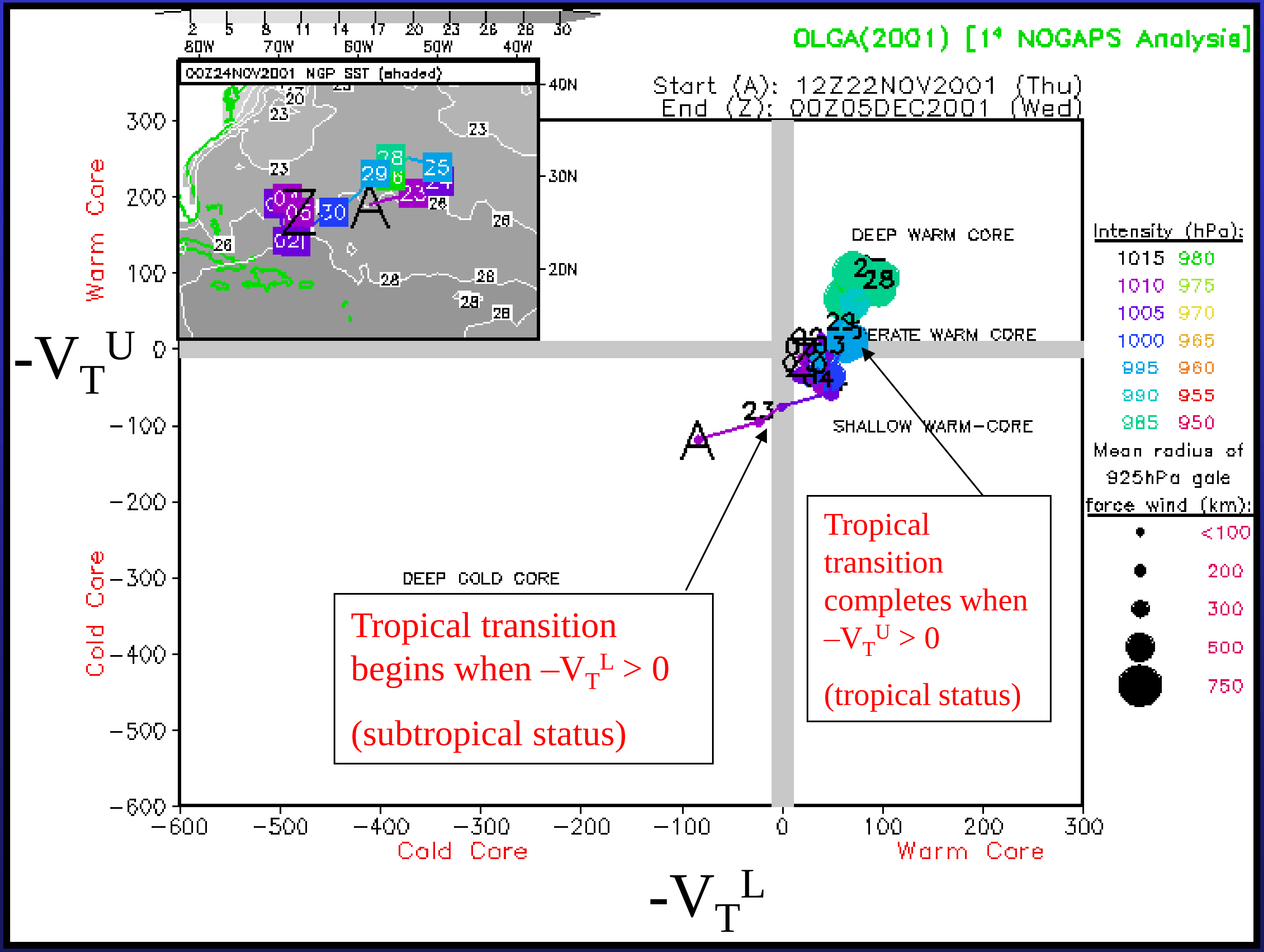
Multiple phase evolution:

Case of tropical transition of a cold-core cyclone

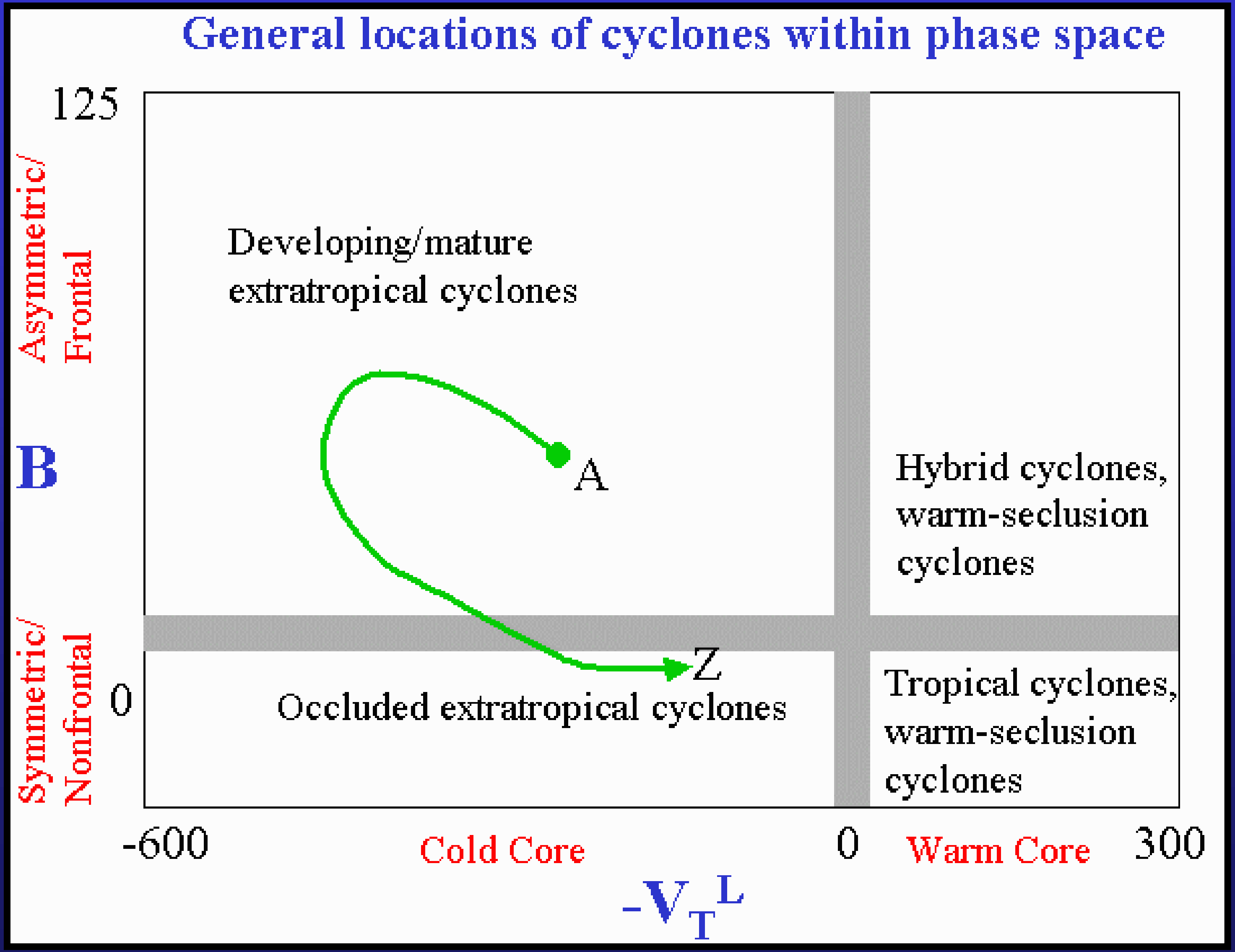
Cold-to-warm core transition:

Tropical Transition of Hurricane Olga (2001)

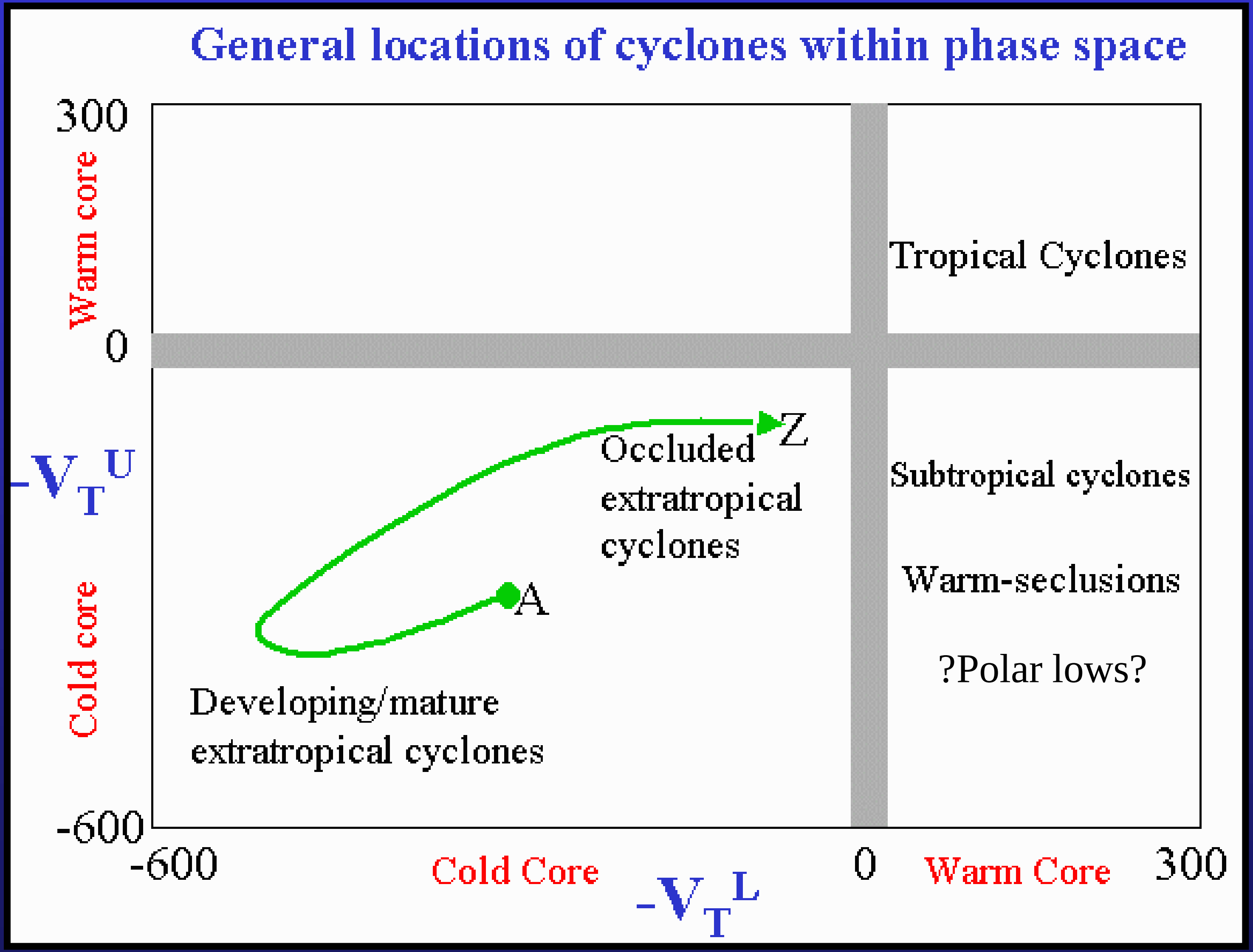
$-V_T^U$ Vs. $-V_T^L$



Summary of cyclone types within the phase space



Summary of cyclone types within the phase space



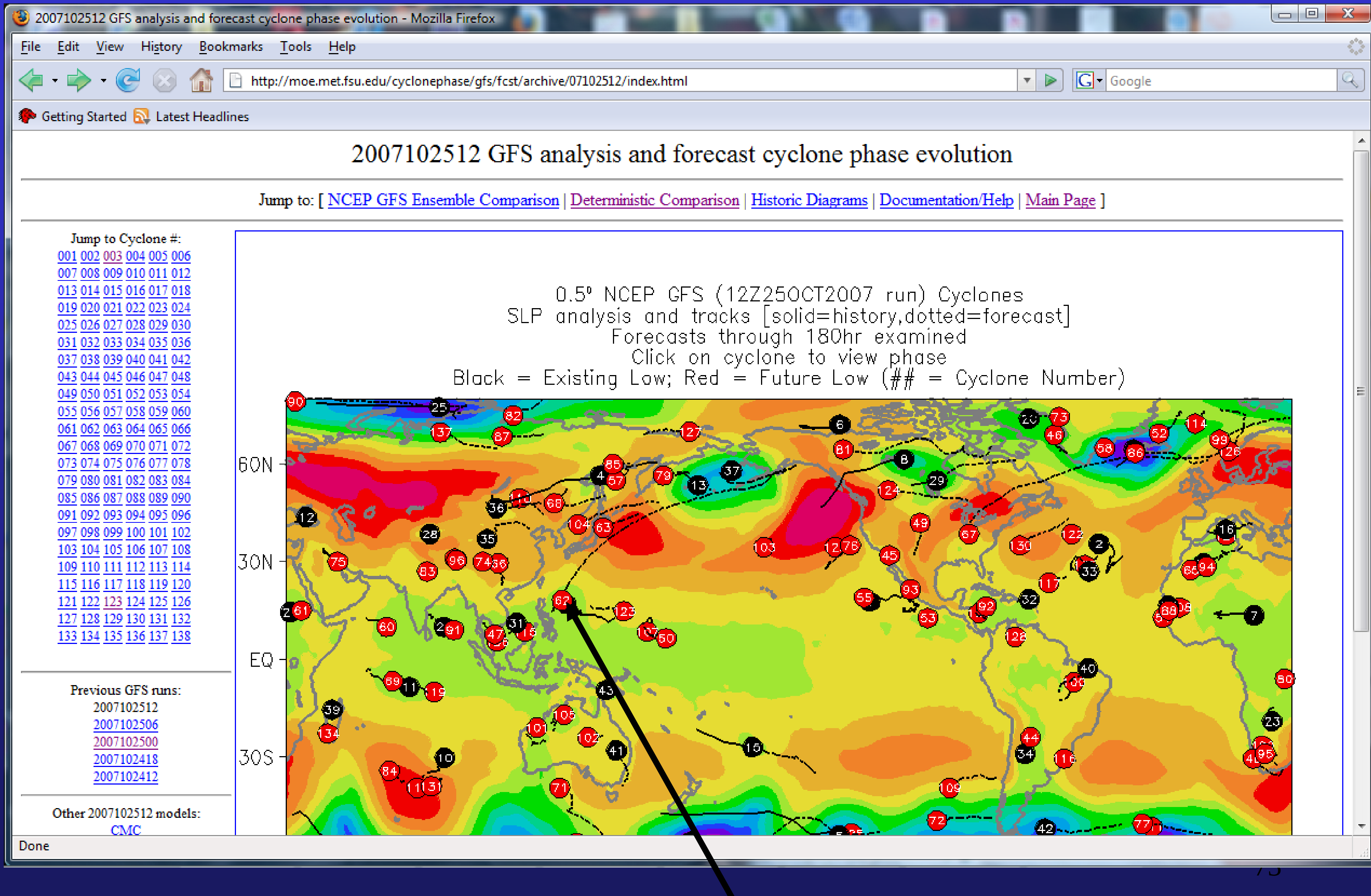
Real-time web page

http://moe.met.fsu.edu/cyclonephase

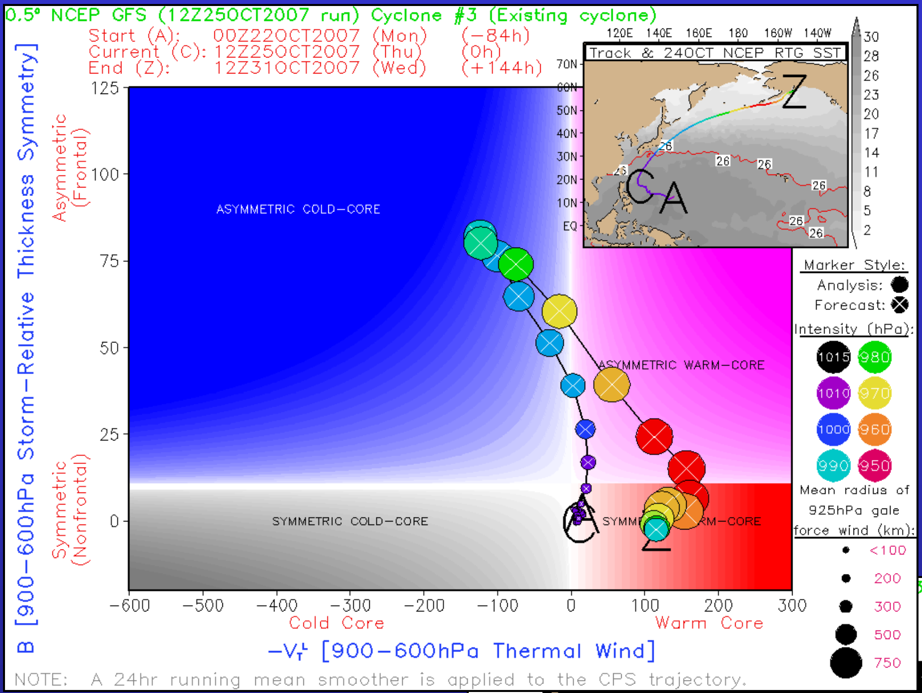
Real-time Cyclone Phase Analysis & Forecasting

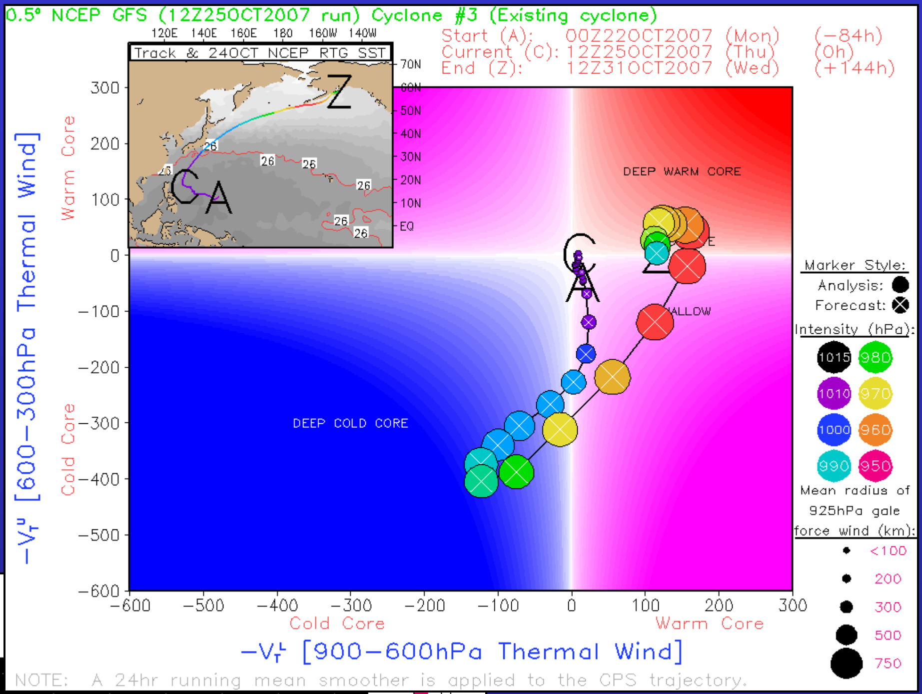
- Phase diagrams produced in real-time for various operational and research models.
- Provides insight into cyclone evolution that may not be apparent from conventional analyses
- Web site: http://moe.met.fsu.edu/cyclonephase
- Also available a historical archive of CPS diagrams for nearly 200 cyclones

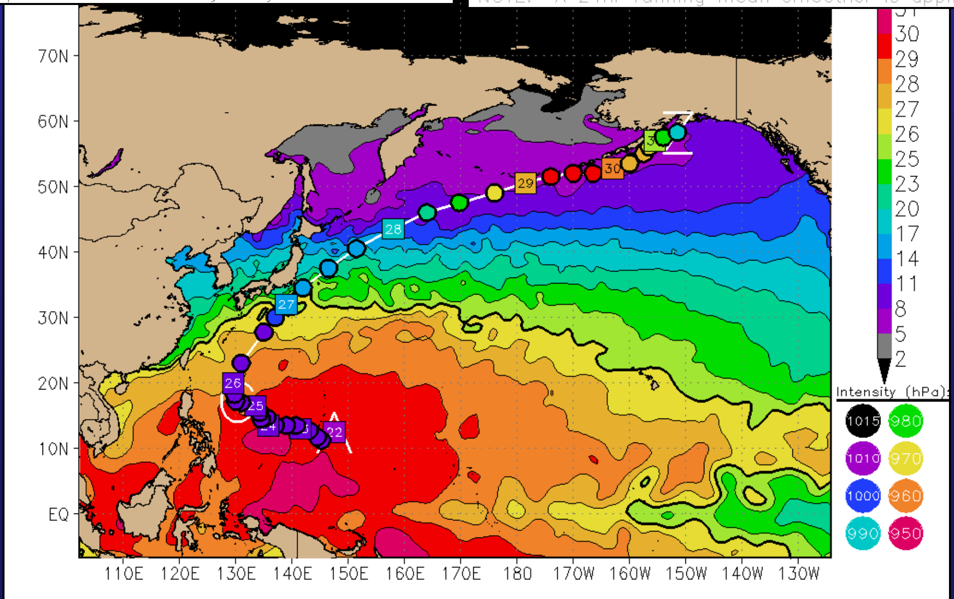
Cyclone Phase Web Page Overview



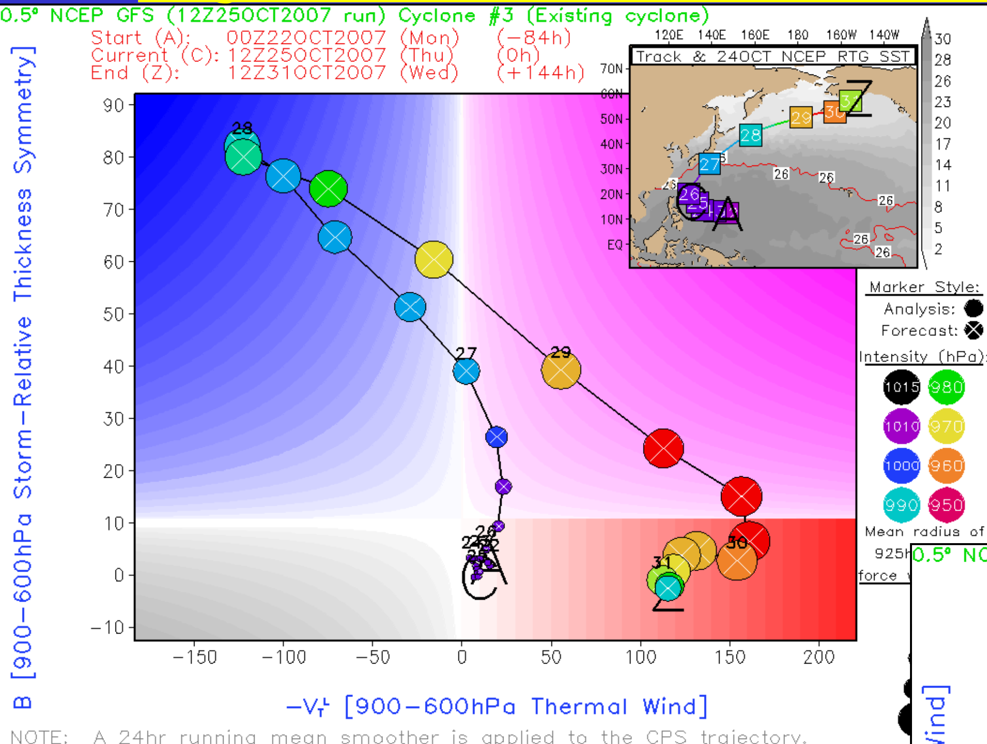
Cyclone Phase Web Page Overview

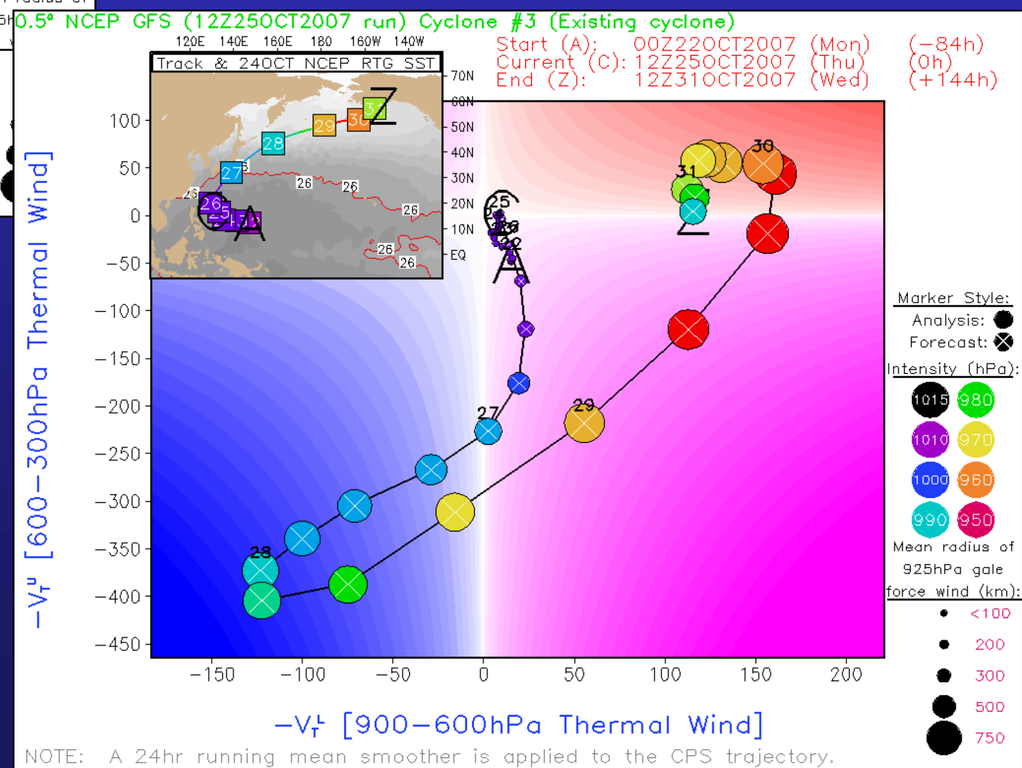






Cyclone Phase Web Page Overview





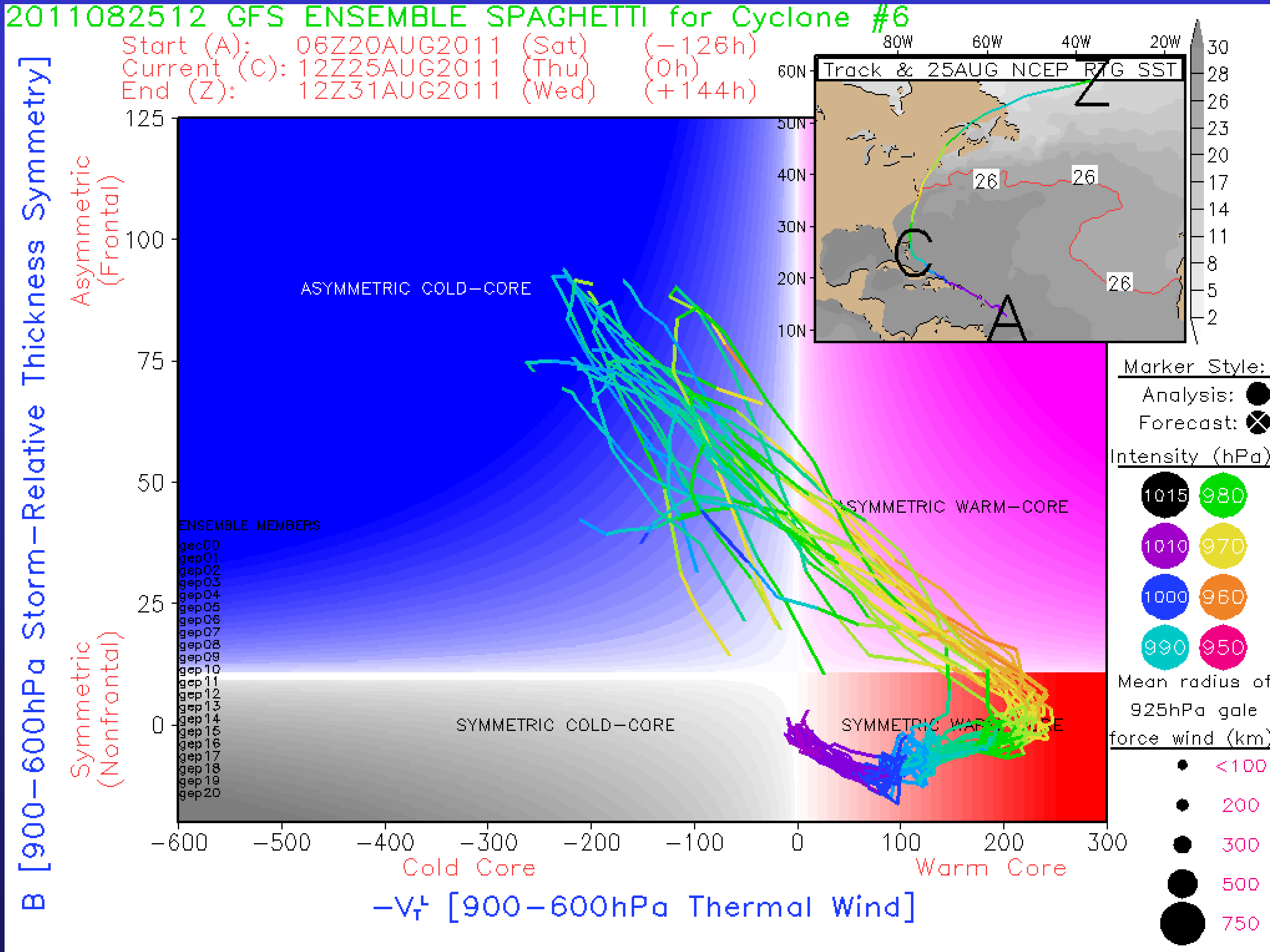
Cyclone Phase Web Page Overview

- Trajectory through phase space describes structural evolution
  - A = When cyclone was first detected
  - C = Current analysis time
  - Z = Cyclone dissipation time or end of model forecast data
  - $A \rightarrow C$ = cyclone structural history
  - $C \rightarrow Z$ = cyclone structural forecast
  - Date is labeled at 00Z along phase trajectory
- Color of trajectory gives cyclone intensity in MSLP
- Size of marker gives average radius of 925hPa gale-force wind
- Cyclone track & underlying SST provided in inset
- Phase diagram quadrants are shaded to give more rapid interpretation

Ensemble cyclone phase

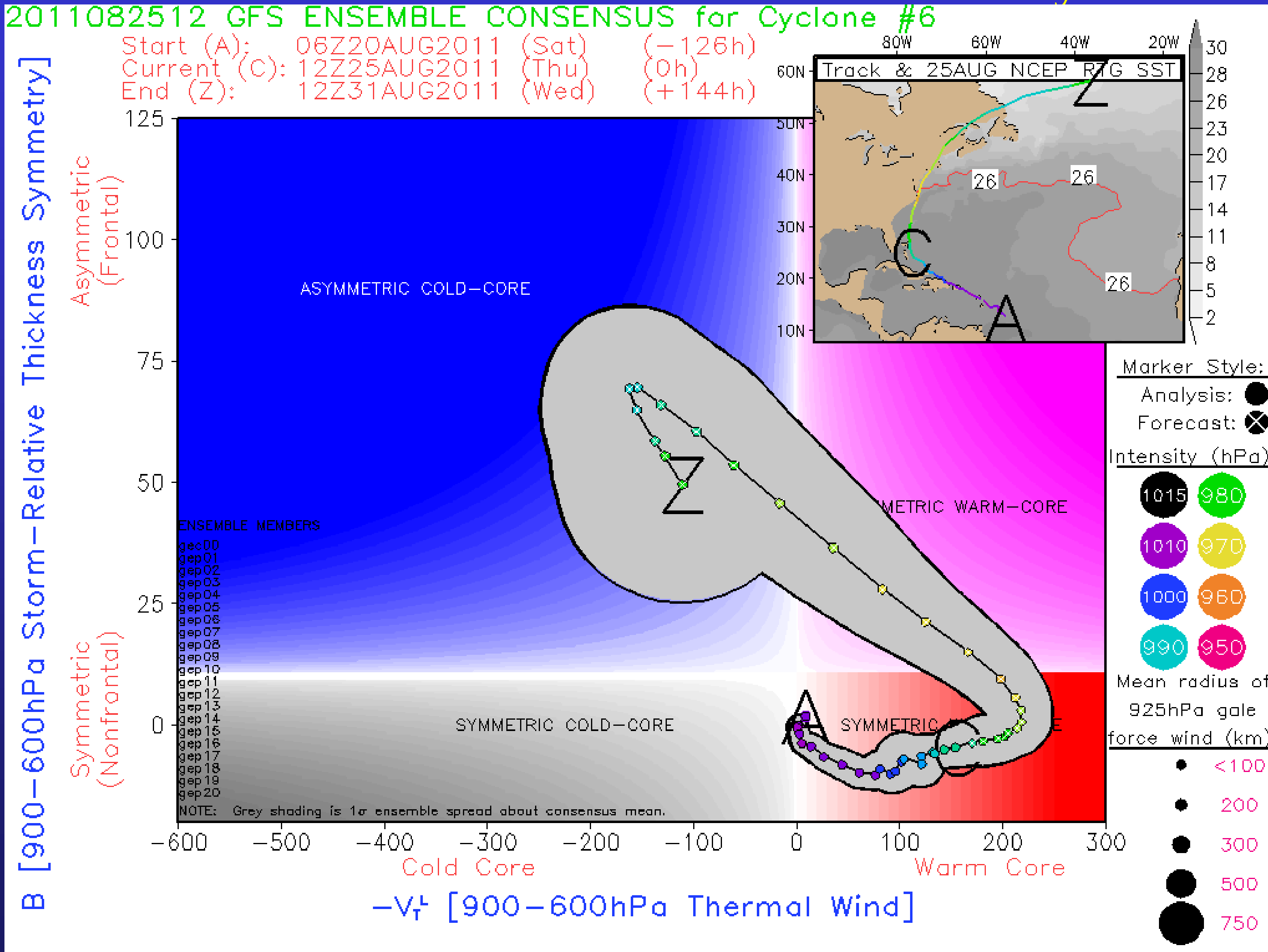
- Four sets of ensembles are produced:
  - All available deterministic models initialized within 6hr of each other
  - 20 GFS Ensembles
  - 20 CMC Ensembles
  - 20 NAVGEM Ensembles
  - 60-member combination
- All aim to provide forecast guidance for structural uncertainty

Multiple model solutions:
Measure of structural forecast uncertainty

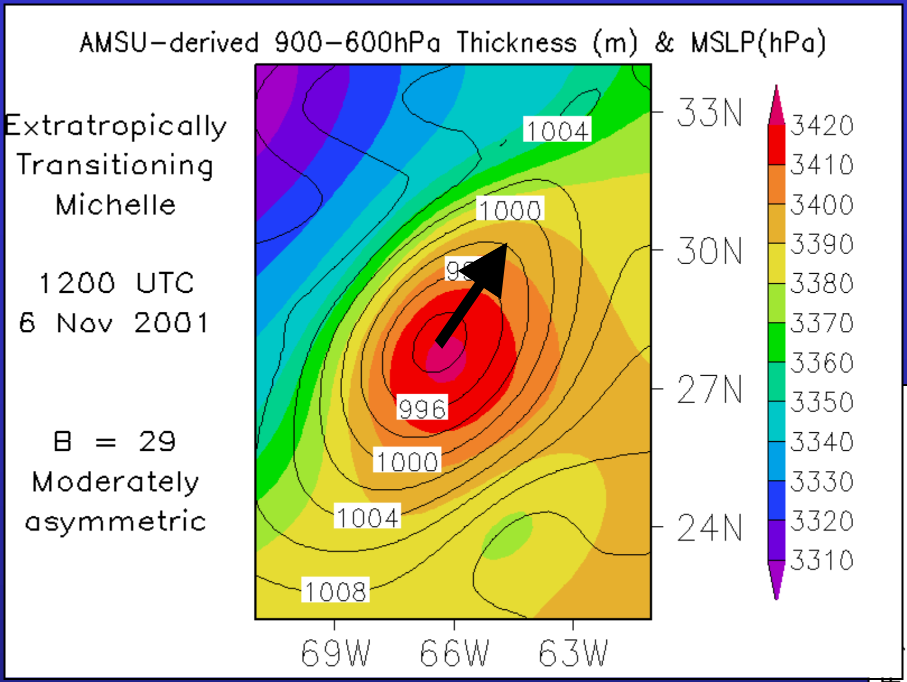


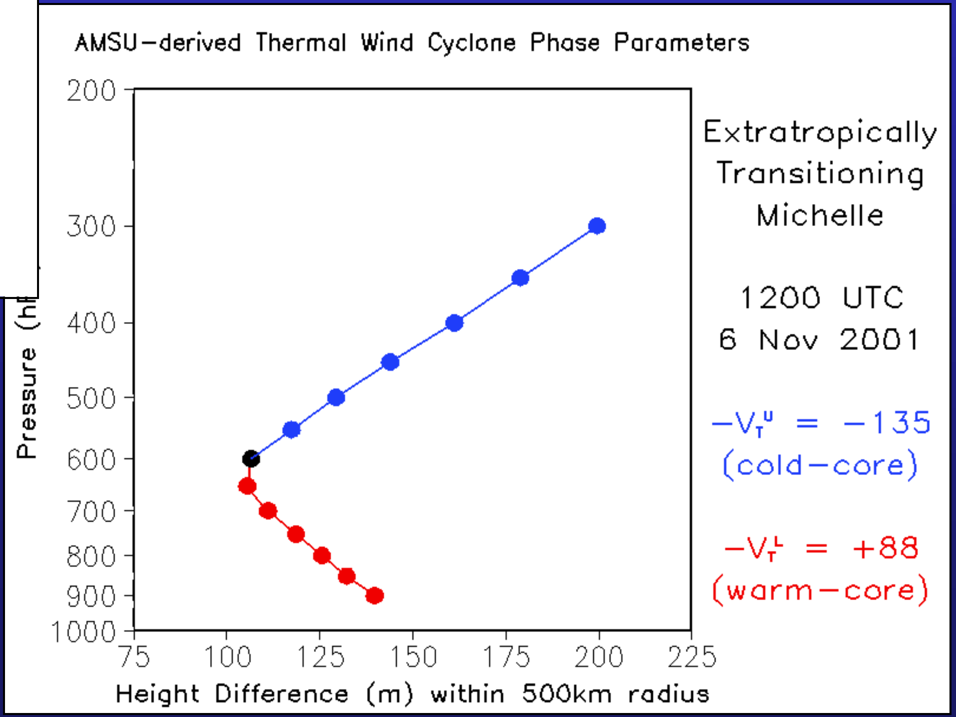
Multiple model solutions:

Measure of structural forecast uncertainty

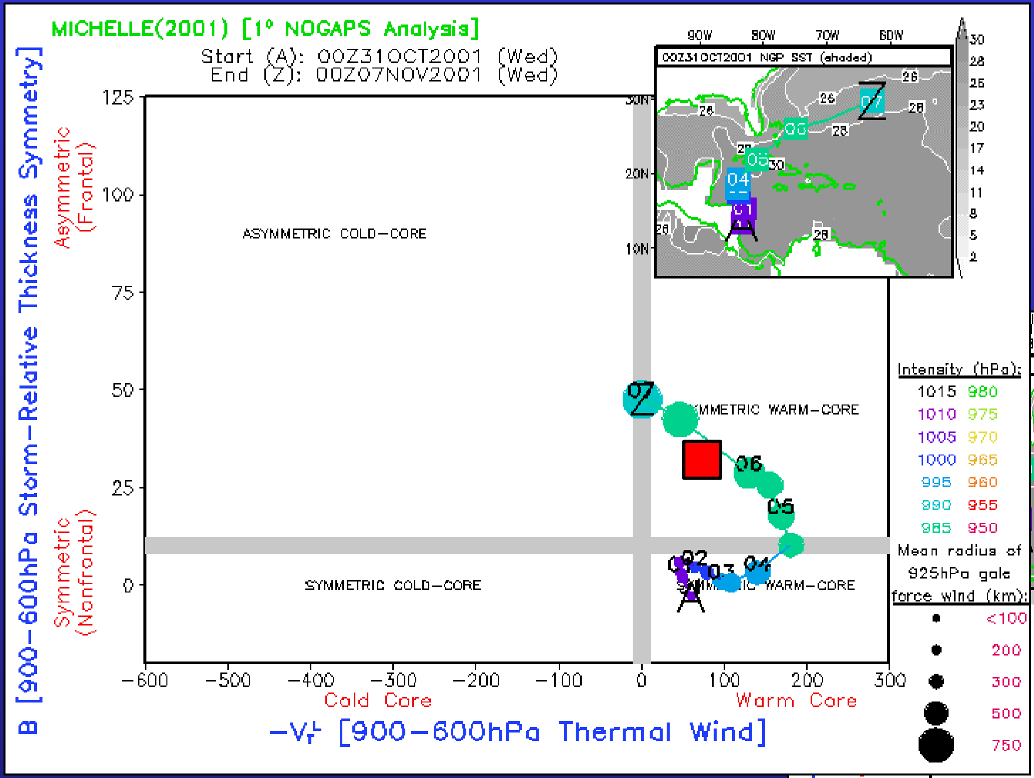


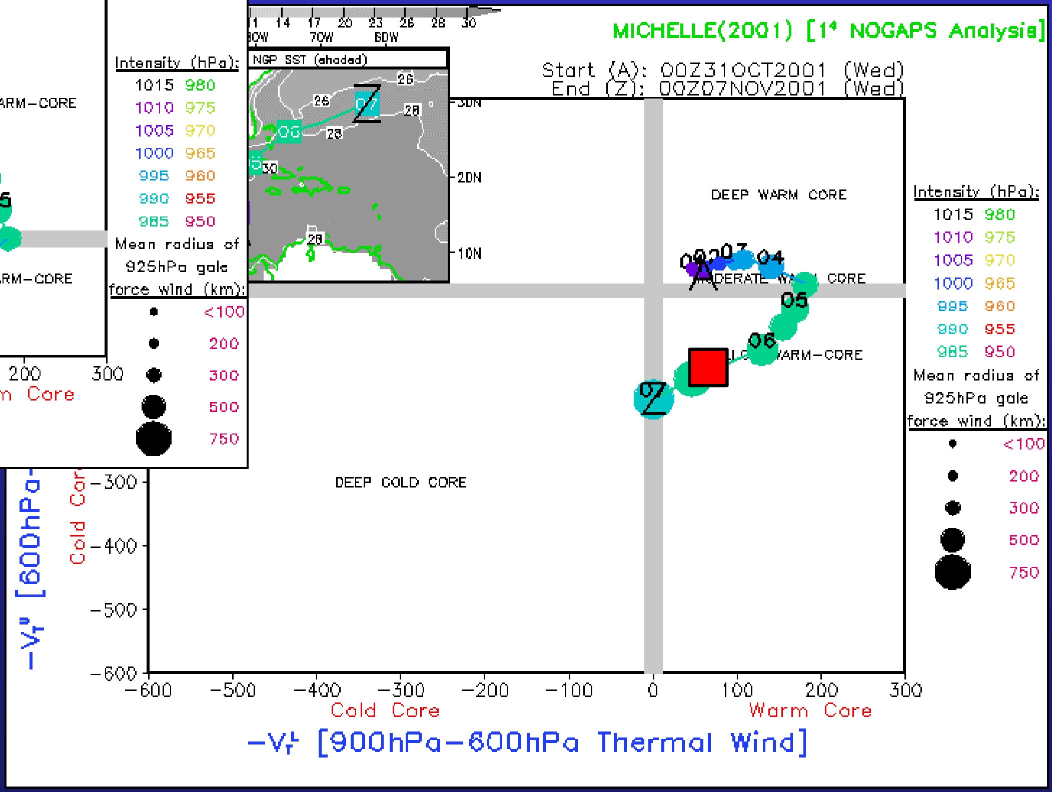
Hurricane Michelle (2001): Calibration from AMSU-based Phase Diagnostics





Hurricane Michelle (2001): Calibration from AMSU-based Phase Diagnostics





The human element

- CPS diagrams:
  - Most helpful in the context of a firm understanding of cyclone development theory
  - Most helpful with an understanding of the strengths & limitations of NWP models
  - Most helpful with an understanding of individual model biases
  - Most helpful with a synthesis with all other tools available
  - Do not describe the finer (mesoscale) detail of storm evolution
  - While the diagrams are objective, their interpretation can still be subjective and dependent on forecaster model experience and conceptual models learned

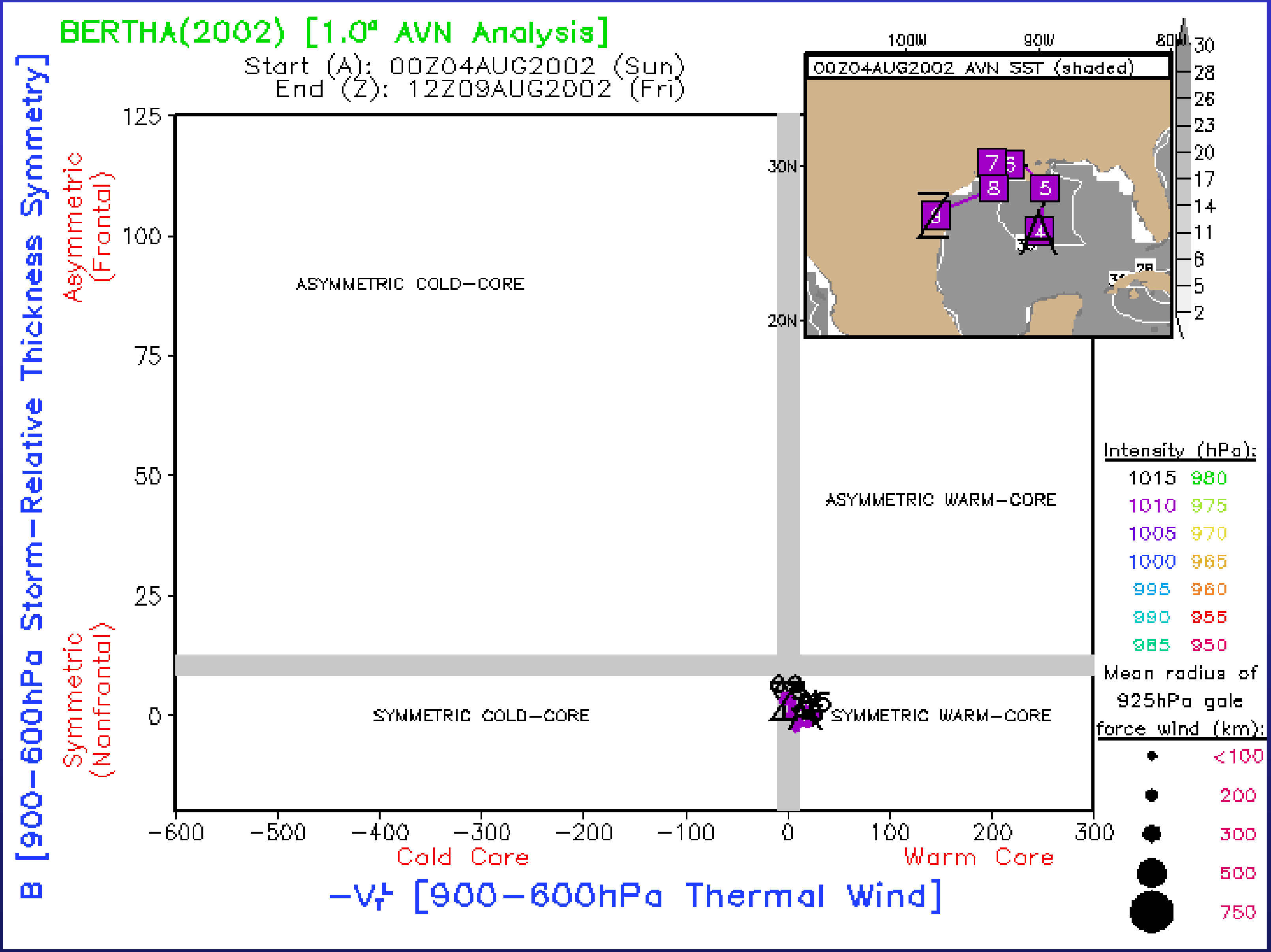
Other Past/Current CPS Uses

- Tropical cyclone genesis diagnosis/forecasting
- Subtropical cyclone genesis diagnosis/forecasting
- Timing of extratropical transition
- Timing of tropical transition
- Diagnosis of structural predictability
- Diagnosis of when to switch NEXRAD radars to tropical mode

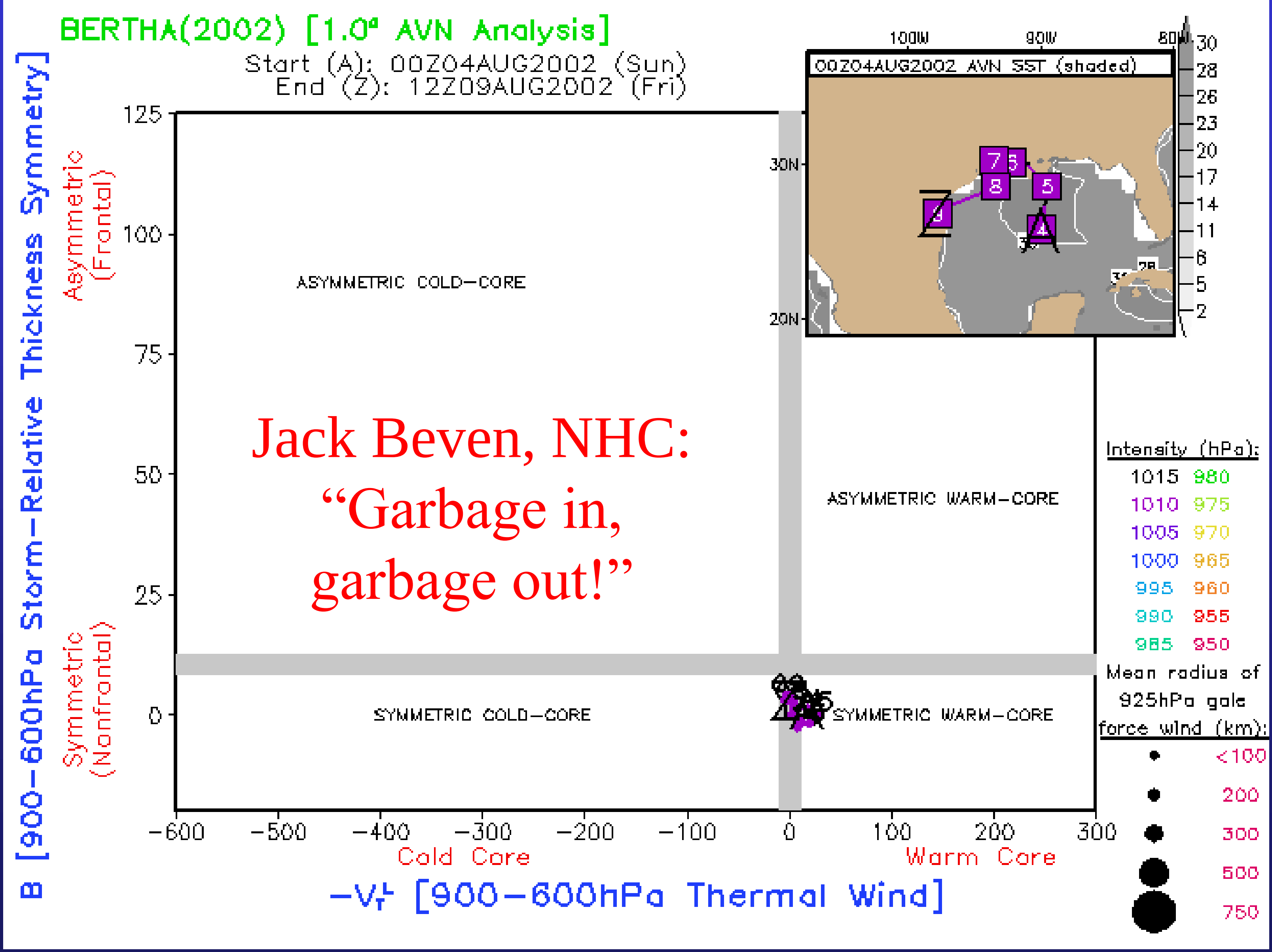
Phase space limitations

- Cyclone phase diagrams are dependent on the quality of the analyses upon which they are based.
- Three dimensions (B, $-V_T^L$, $-V_T^U$) are not expected to explain all aspects of cyclone development
- It cannot inform you directly on why a cyclone has evolving structure or transitioning. This is why the diagrams must never replace, but instead supplement, traditional analyses and cross sections
- However, the chosen three parameters represent a large percentage of the variance & explain the crucial structural changes.

Often model analysis representation is poor



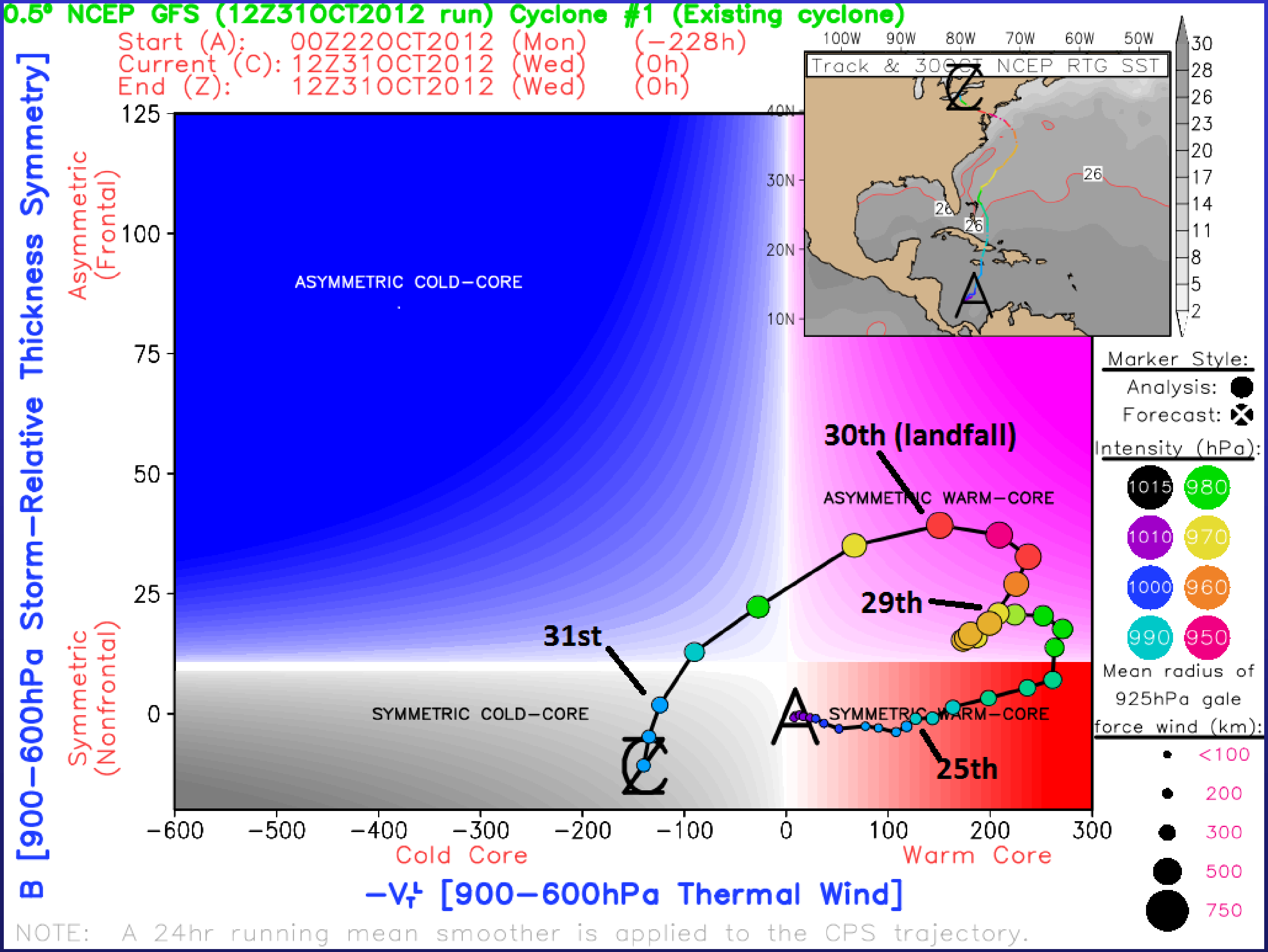
Often model analysis representation is poor



Jack Beven, NHC:
"Garbage in,
garbage out!"

"Instant" Warm-Seclusion Dilemma:

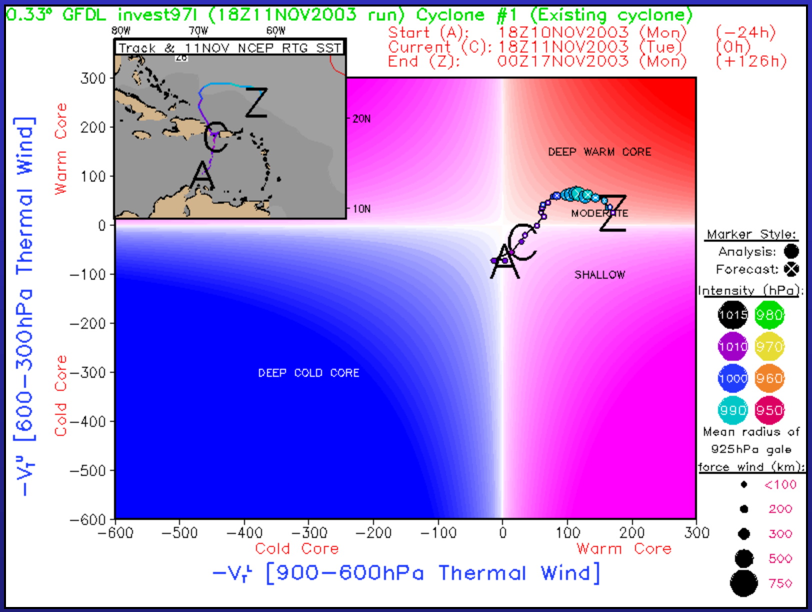
Hurricane Sandy (2012)

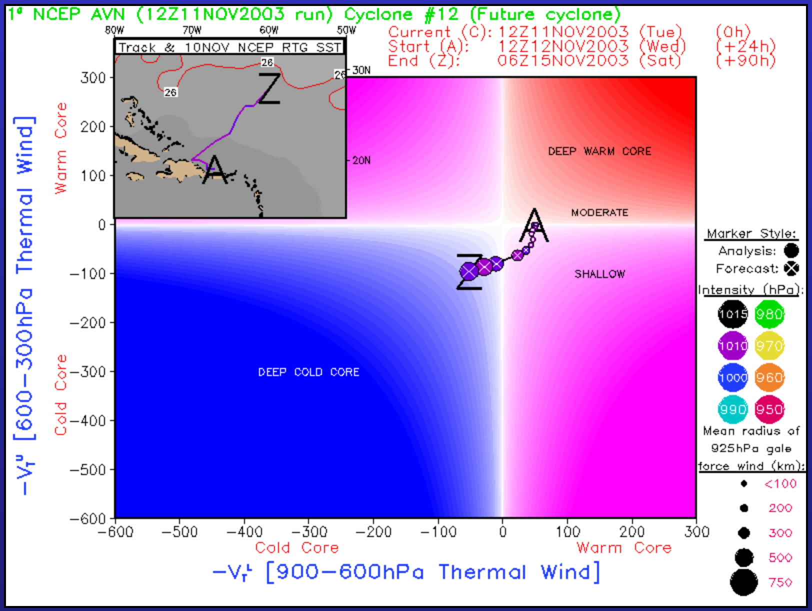


Model sensitivity

- Often there is phase dependency on the type of data assimilation or model physics

11 November 2003 GFDL vs AVN





Other approaches to ET

- The cyclone phase space approach has as another limitation that it requires three-dimensional data to calculate
- Other equally useful approaches (specifically to ET) have been designed that have lead to conceptual models based largely on satellite imagery
- Example: Klein et al. (2000)

Satellite-Imagery Based Conceptual Model

Klein et al. (2000)

- Examined satellite imagery and NWP analyses for 30 cyclones undergoing ET in the Northwest Pacific 1994–1998
- Three step transformation stage
  - Begins when cyclone starts to interact with baroclinic zone
    - Satellite imagery shows developing asymmetry in clouds and large decrease of deep convection on western side of TC
  - Ends when cyclone is fully embedded in baroclinic zone
    - Satellite imagery shows baroclinic features and cyclone center embedded in cold, descending air

Common Satellite Features During ET

Klein et al. (2000)

Decrease in cloudiness in western semicircle

Development of dry slot

Convective asymmetry

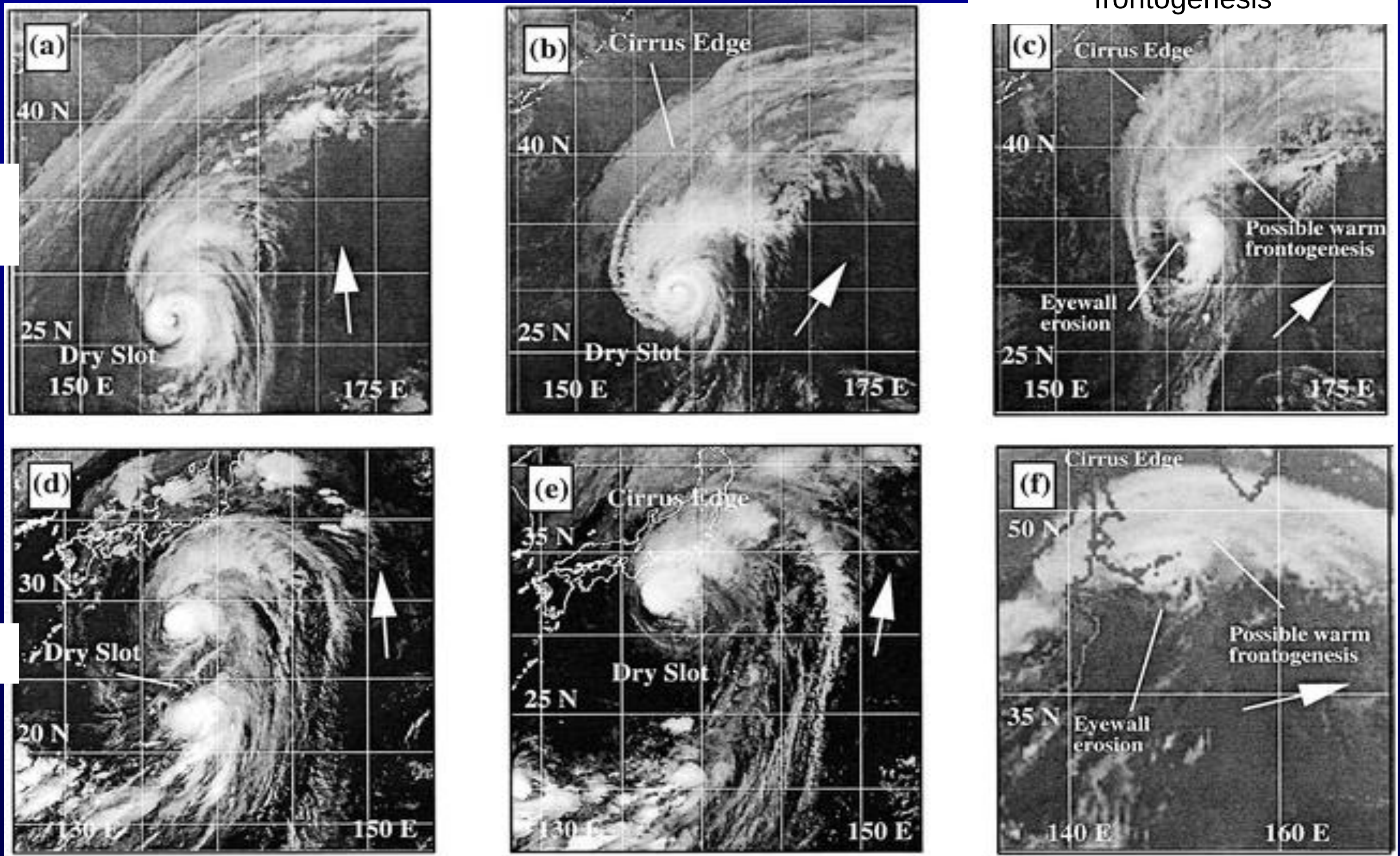
Cirrus shield marks interaction with polar jet

Inner core deep convection eroded – gap in eyewall

Signals of strong warm frontogenesis, only weak cold frontogenesis

Supertyphoon Ginger

Typhoon Opal



Step 1

Step 2

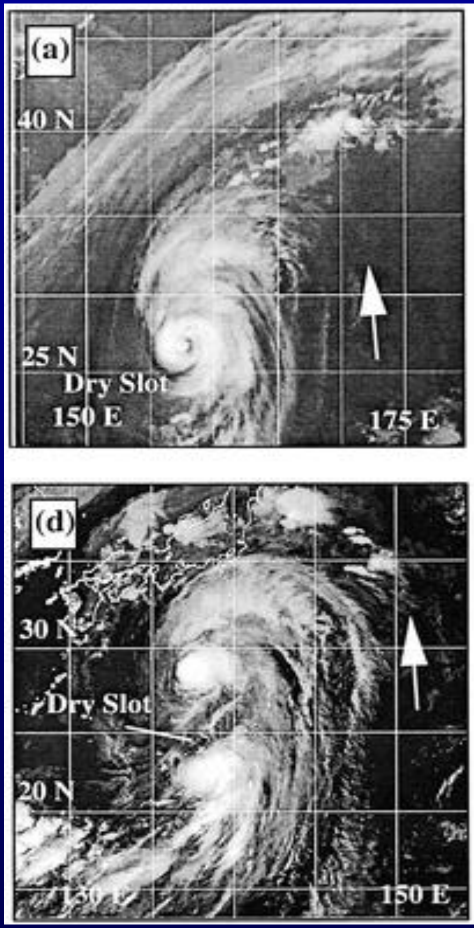
Step 3

Klein et al. (2000), *Weather and Forecasting*

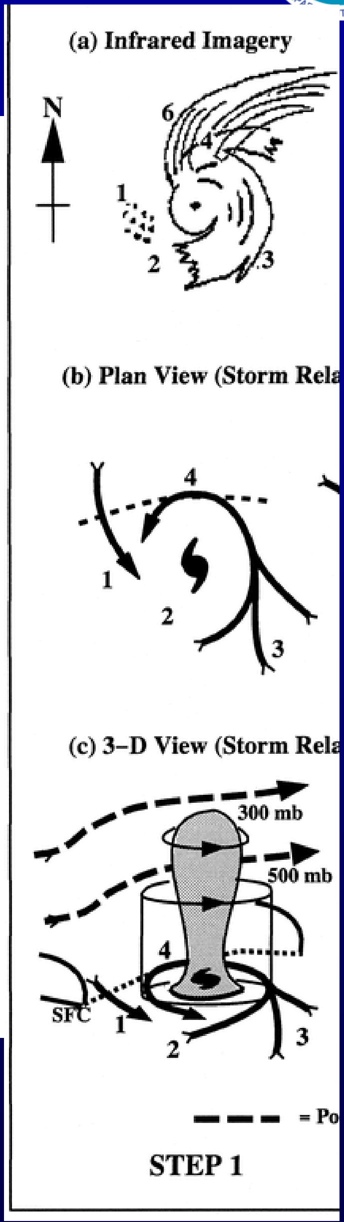
NW Pacific ET Conceptual Model

Klein et al. (2000)

- Step 1 – Transformation begins
  - Cyclone moves over cooler SSTs
  - Interaction begins with mid-latitude baroclinic zone
  - Cold, dry advection begins west of center
  - Convection decreases western semicircle of outer circulation
  - Dry slot forms in southwest quadrant
  - Warm, moist advection maintains convection in northeast quadrant
  - Cirrus shield develops in poleward outflow



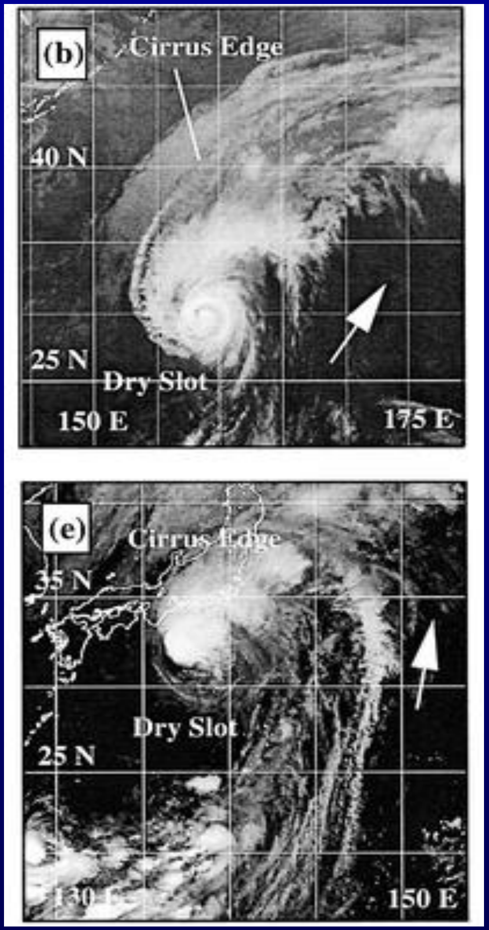
Klein et al. (2000)
Weather and Forecasting



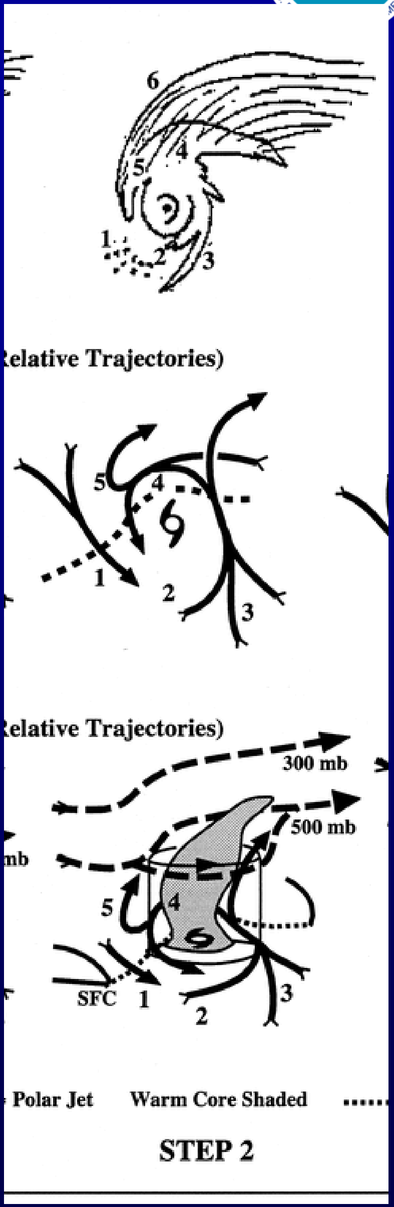
NW Pacific ET Conceptual Model

Klein et al. (2000)

- Step 2 – Transformation begins
  - Cyclone just south of baroclinic zone
  - Thermal advection increases as cyclone circulation impinges on baroclinic zone
  - Cloud pattern asymmetry increases
  - Dry slot increases in size
  - Increasing vertical wind shear begins to distort vertical alignment of TC inner core at upper levels
  - Convection persists in inner core



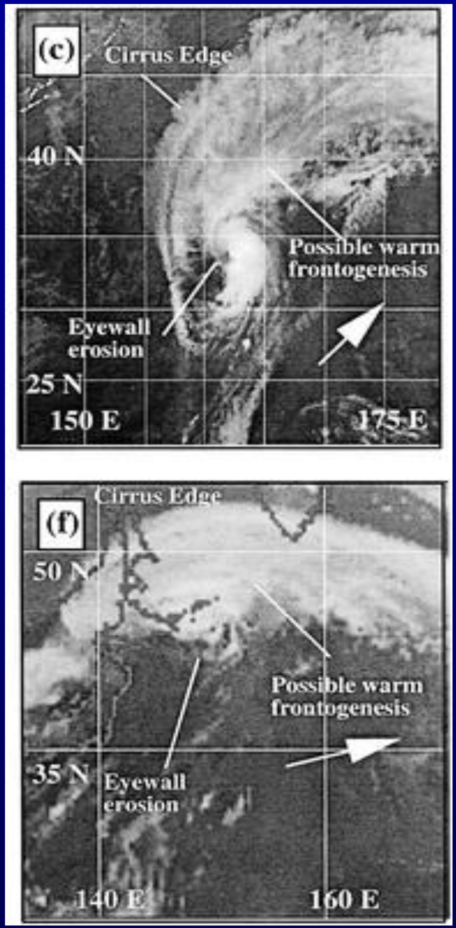
Klein et al. (2000)
Weather and Forecasting



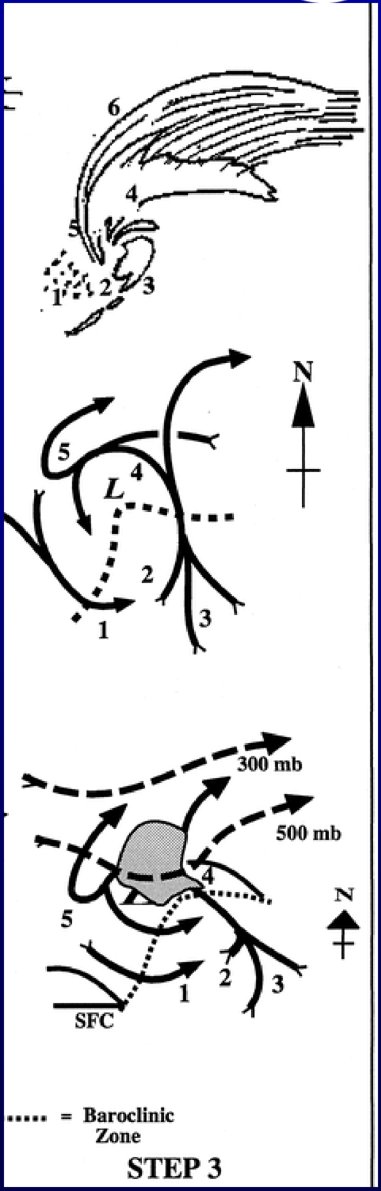
NW Pacific ET Conceptual Model

Klein et al. (2000)

- Step 3 – Transformation complete
  - Cyclone completely embedded in baroclinic zone
  - Thermal advections continue to intensify
  - Cloud asymmetry grows
  - Vertical shear advects upper-level warm core downstream
  - Weaker, lower-level warm core persists over cyclone center
  - Inner core convection disrupted and eyewall erodes on south and west sides
  - Pronounced warm frontal cloud band and weaker cold frontal cloud band visible



Klein et al. (2000) *Weather and Forecasting*

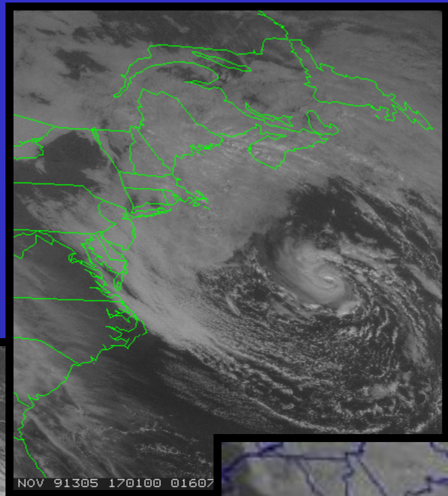


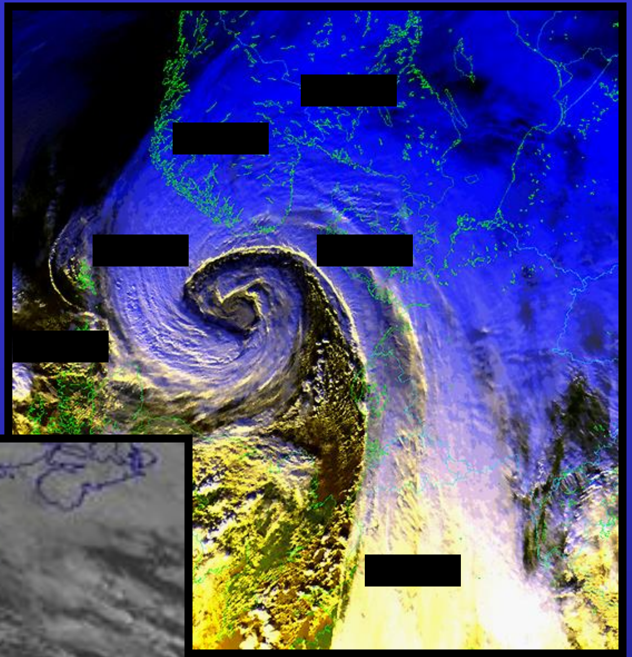
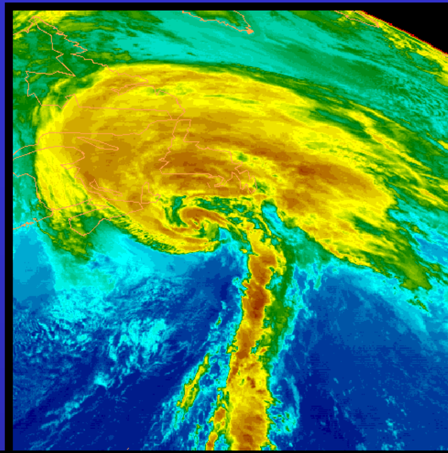
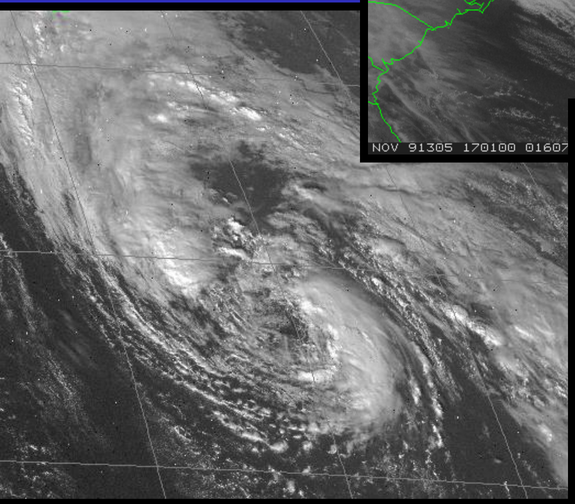
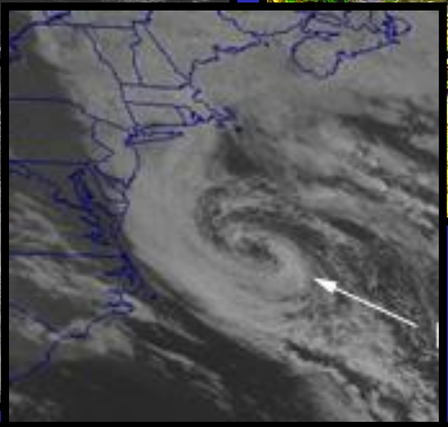
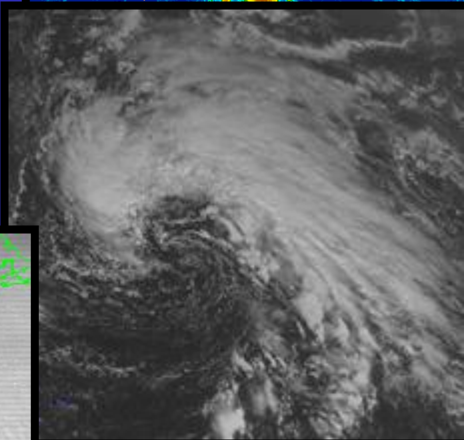
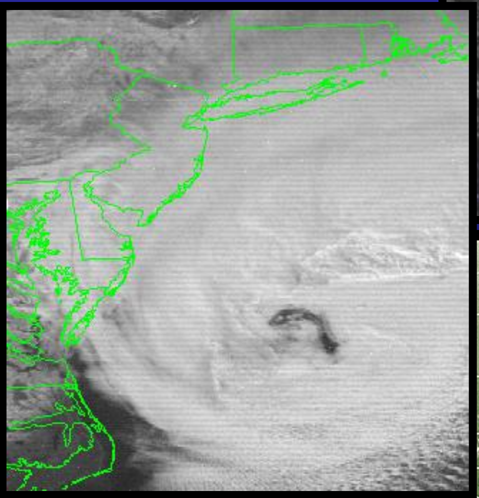
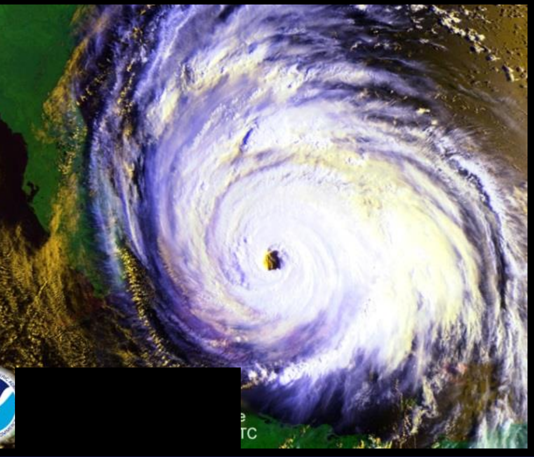
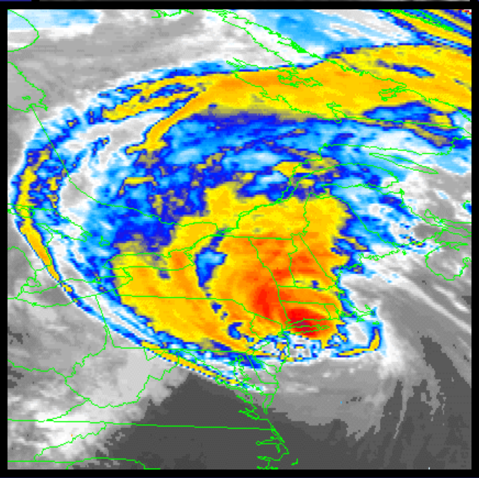
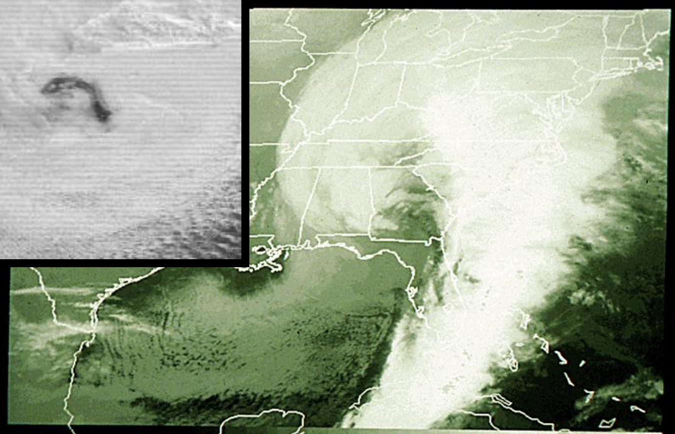
Closing

- We have separate fundamental theories of lifecycle evolution of tropical cyclones and extratropical cyclones
- We do not have a concise theory on how one cyclone evolves from one textbook type to the other: the sensitivity between utter destruction of the TC vs. harmonious evolution from shear as a detriment to shear as a requirement is very poorly understood
- However, we have multiple tools that help forecasters analyze and time structural evolution: CPS (4D gridded) and Klein Satellite-based (pseudo ET-Dvorak)
- Regardless of ET Tool, timing this structural evolution is essential from a practical impact and predictability question: wind field expansion, wind field asymmetry, intensity change processes, rainfall asymmetry
- We must always remember that while sometimes we treat intensity, track, and structure as separate forecast metrics, they are intimately related – and ET often highlights that relationship.

Quiz: Separate the 5 tropical cyclones from the 5 extratropical.

Images courtesy NCDC



Separate the 5 tropical cyclones from the 5 extratropical.

Images courtesy NCDC