The Analysis and Prediction of Hybrid Cyclones and Structural Transition From One Perspective

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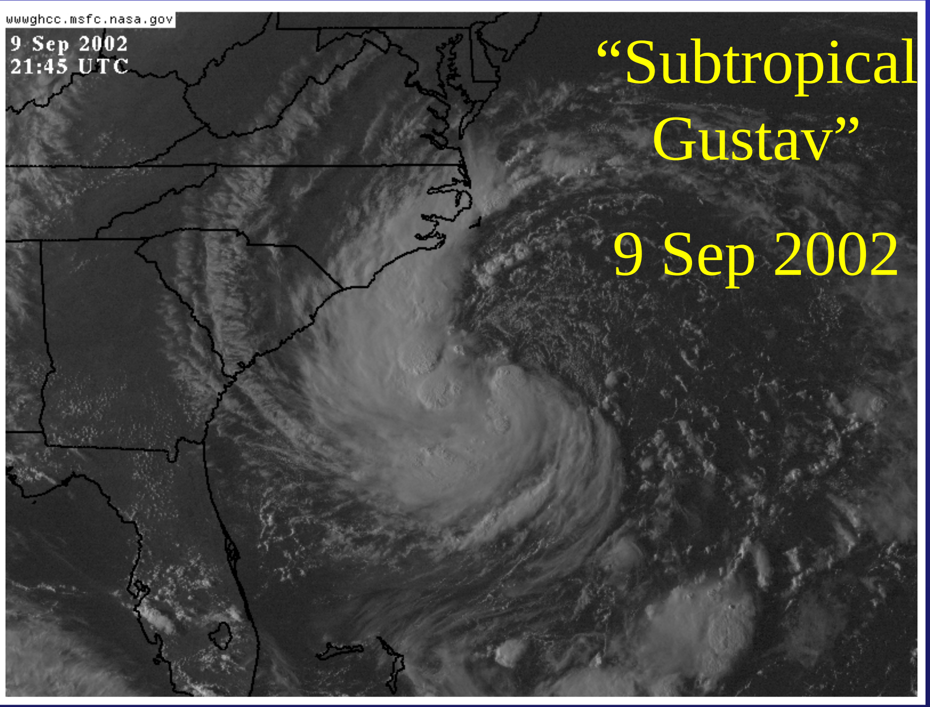


NHC 28 February 2022

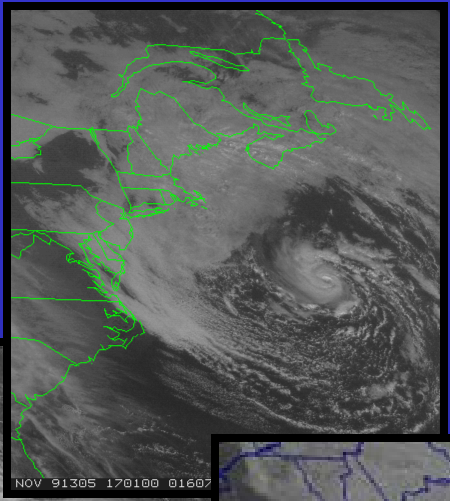
We are taught in class about two mutually exclusive cyclone “worlds”

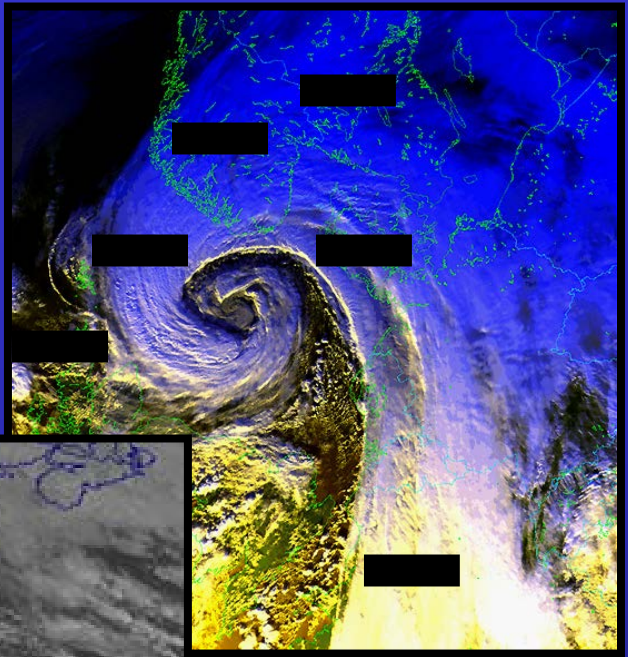
- Extratropical cyclones
  - Exist in the midlatitudes to polar latitudes
  - Form through the interaction of upper level disturbances with surface fronts
  - Intensity through baroclinic instability
  - Convert APE to EKE
  - Minimal role of diabatics

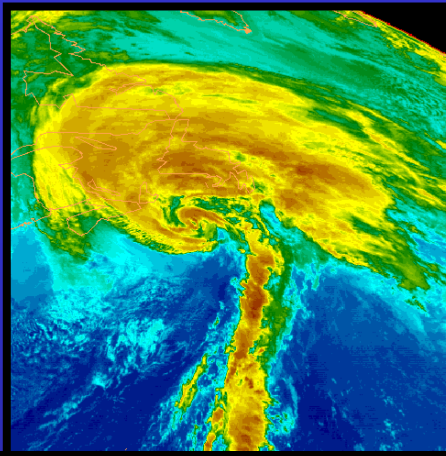
- Tropical Cyclones
  - Exist in the tropics to subtropics
  - Form through potential various methods of organizing convection
  - Intensify through flux induced latent and sensible heat
  - Convert diabatic heating to PE and KE

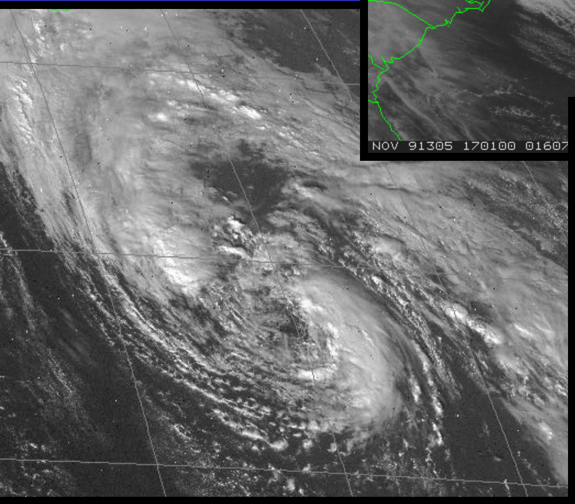
Quiz: Separate the 5 tropical cyclones from the 5 extratropical.

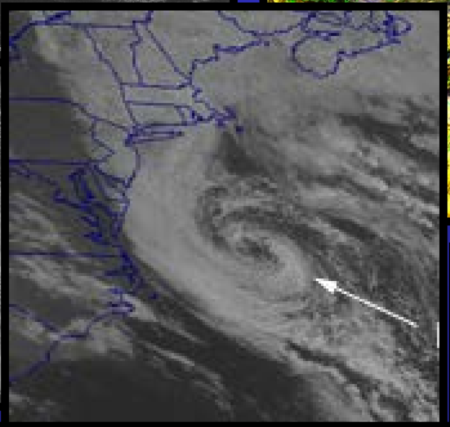
Images courtesy NCDC

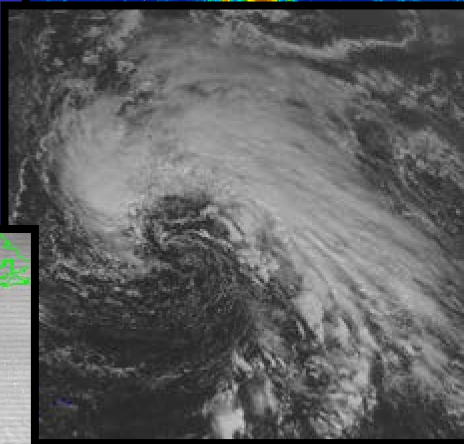


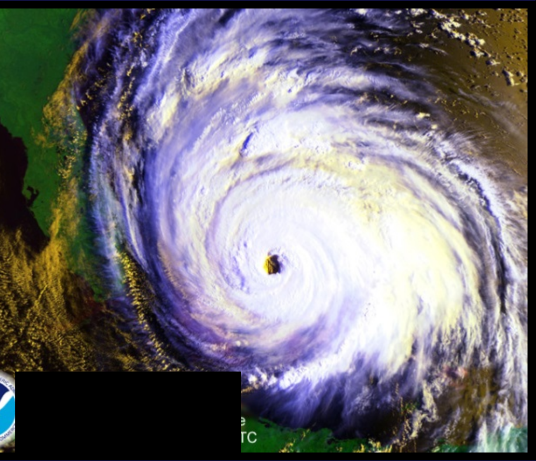


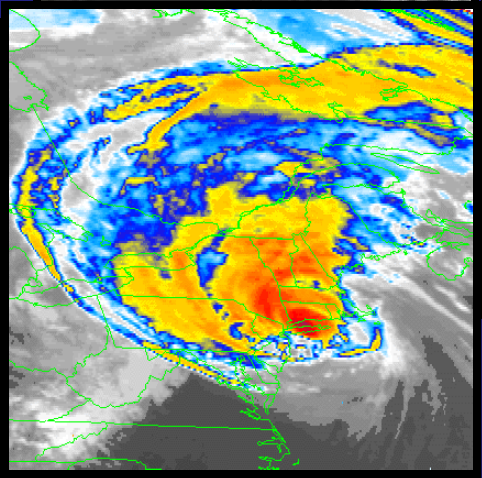


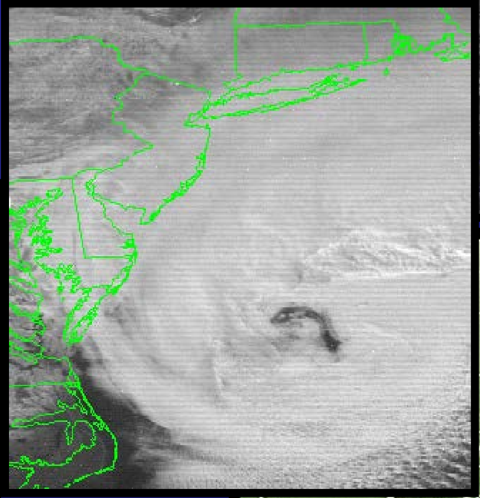


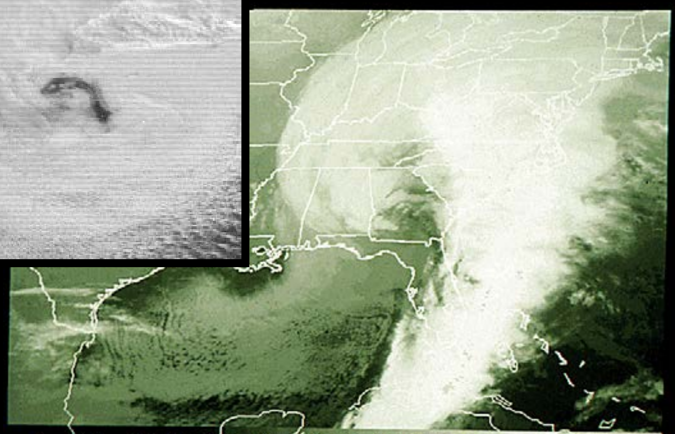




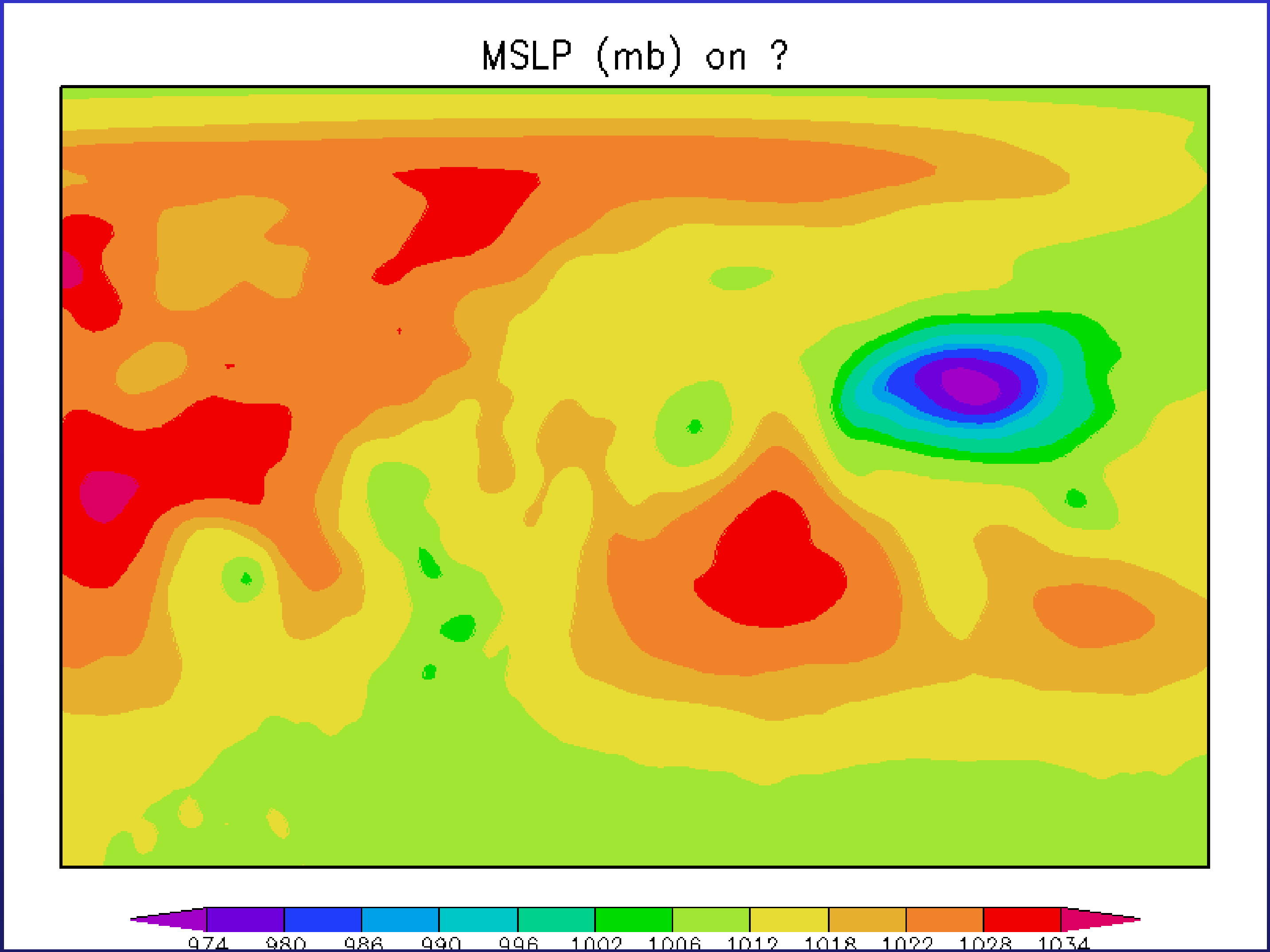




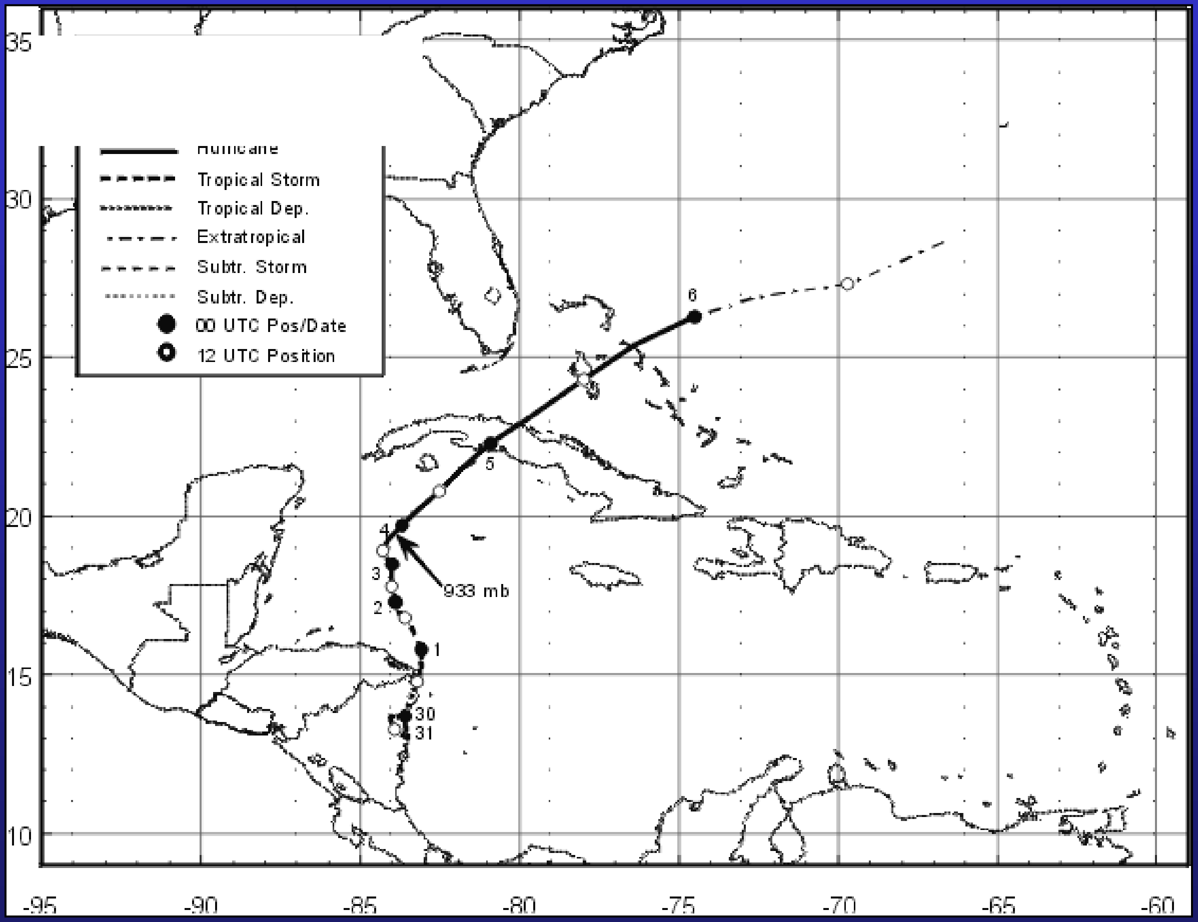




Quiz 2: The sometimes helpful, sometimes perilous reliance on time of year, geography, and SST for assuming structure

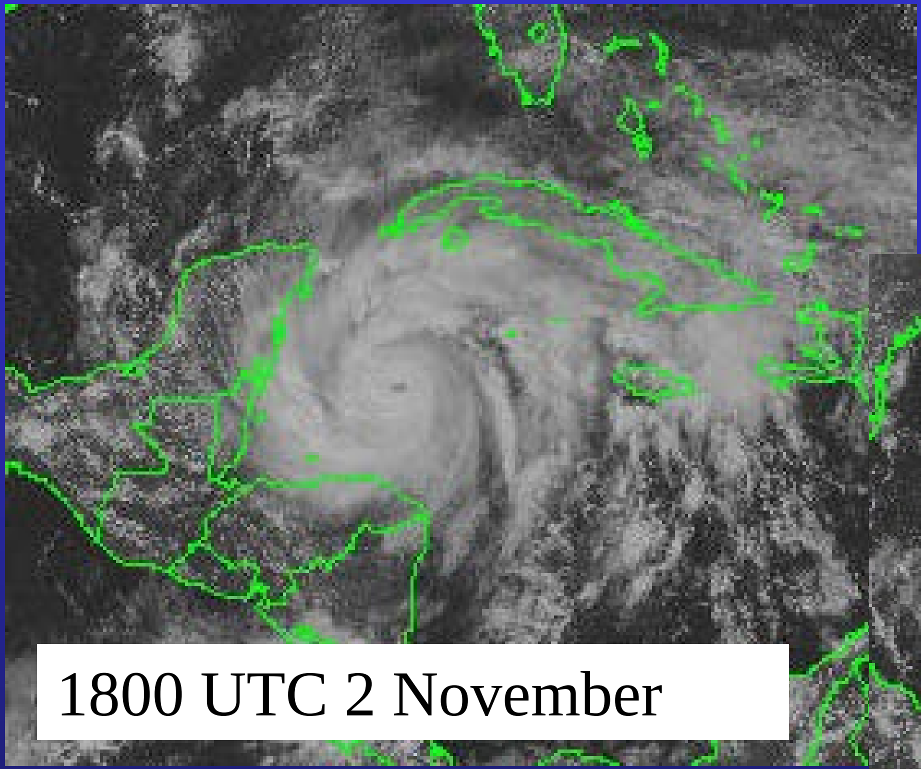


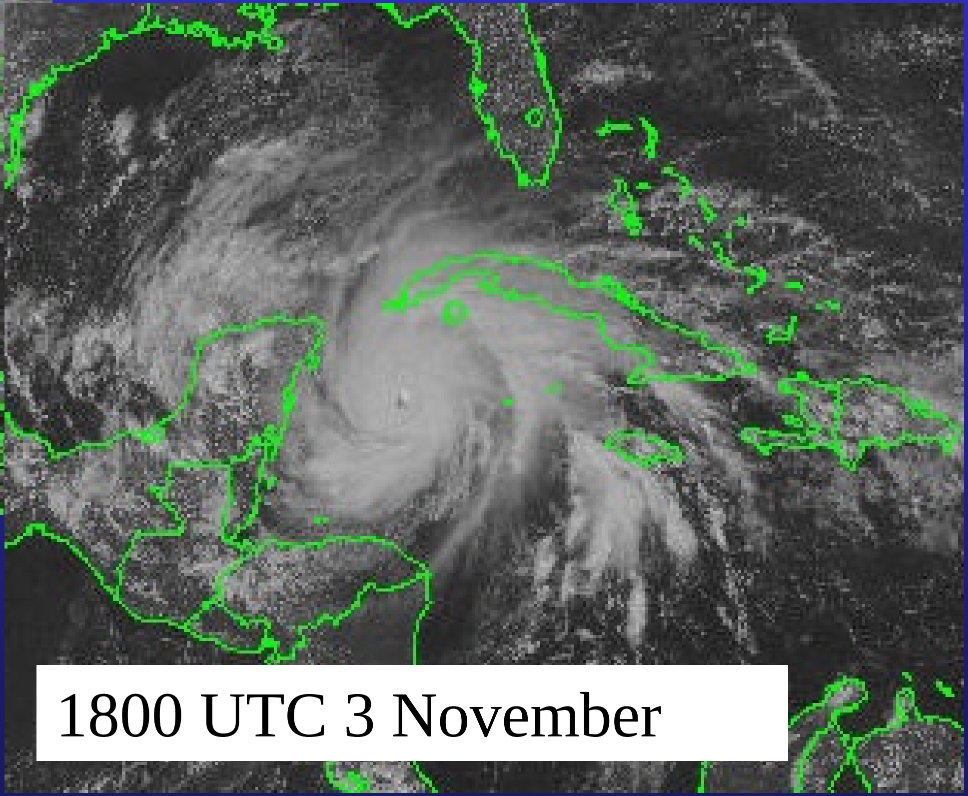
Example of misleading geography:



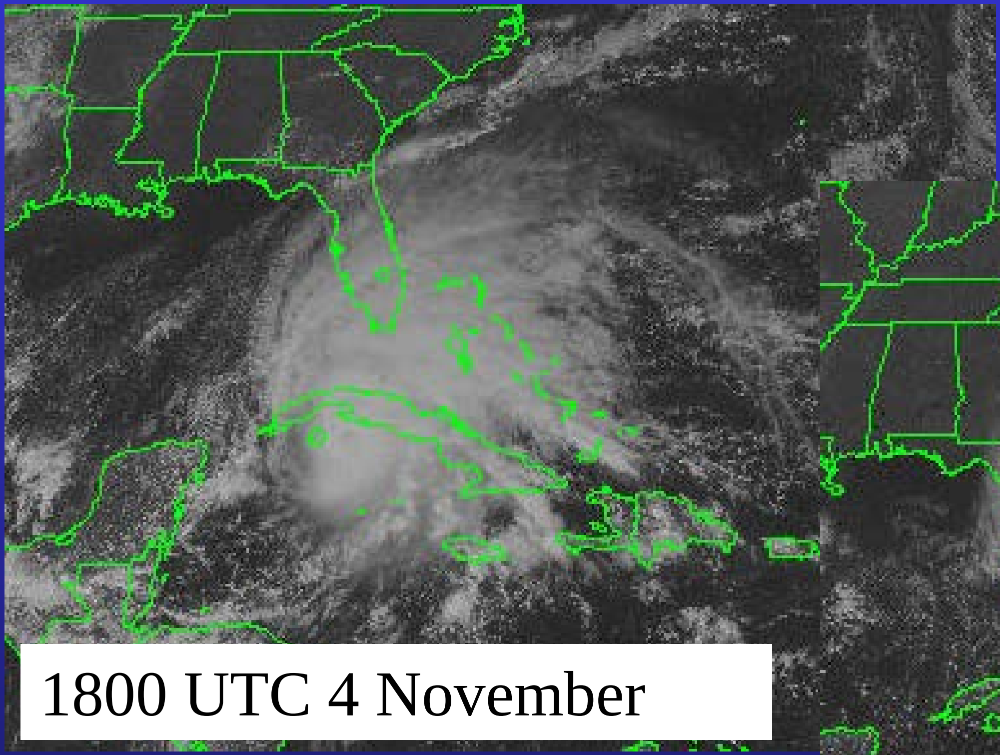
NHC Best Track from Beven (2001)

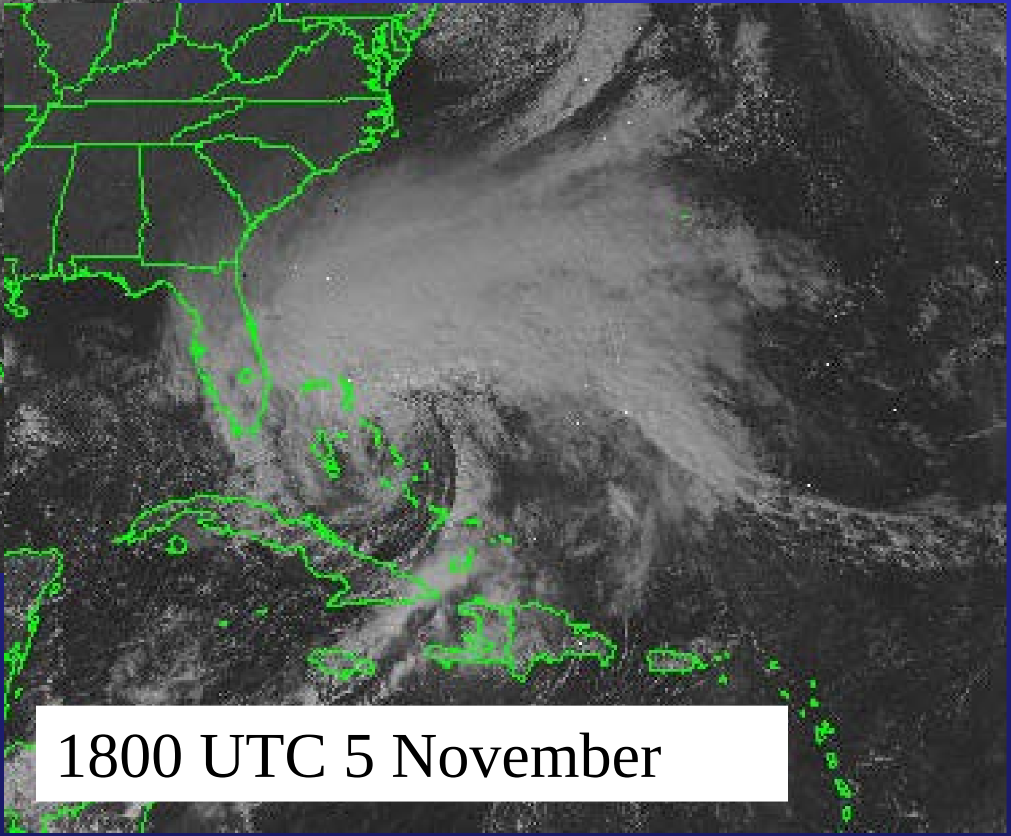
Hurricane Michelle (2001): GOES-8 Visible Imagery



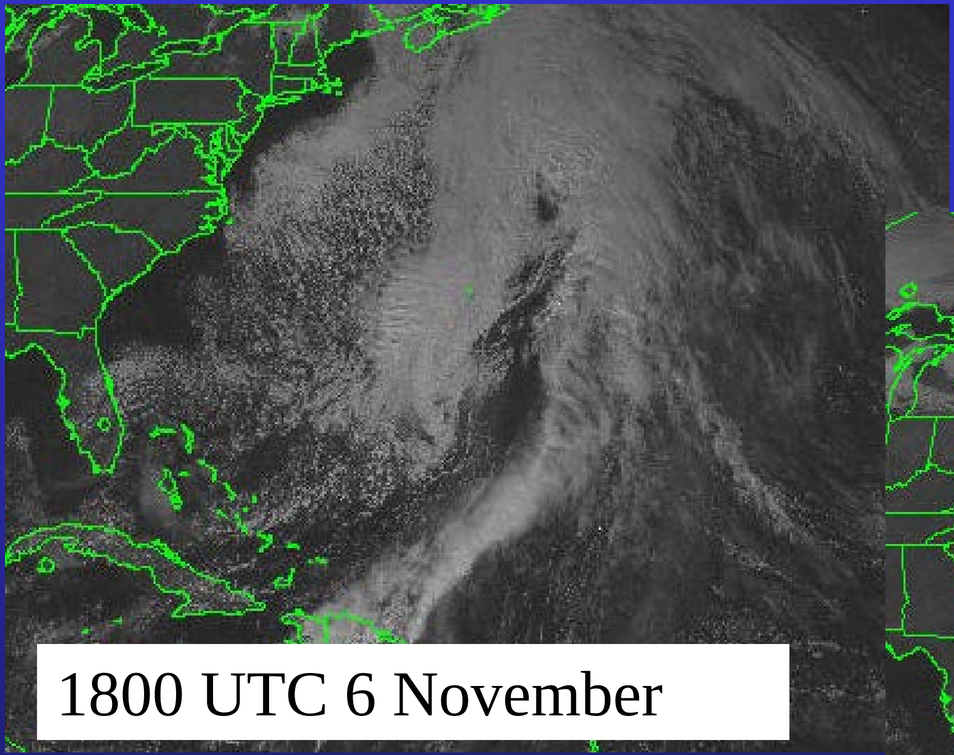


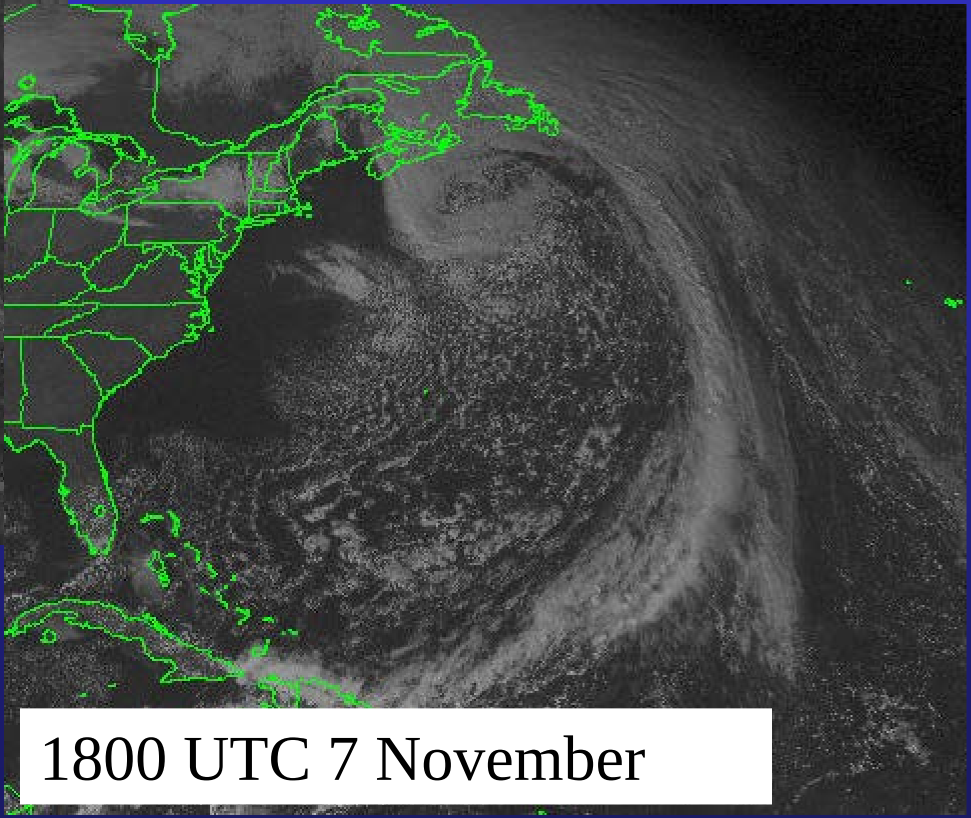
Hurricane Michelle (2001): GOES-8 Visible Imagery





Hurricane Michelle (2001): GOES-8 Visible Imagery



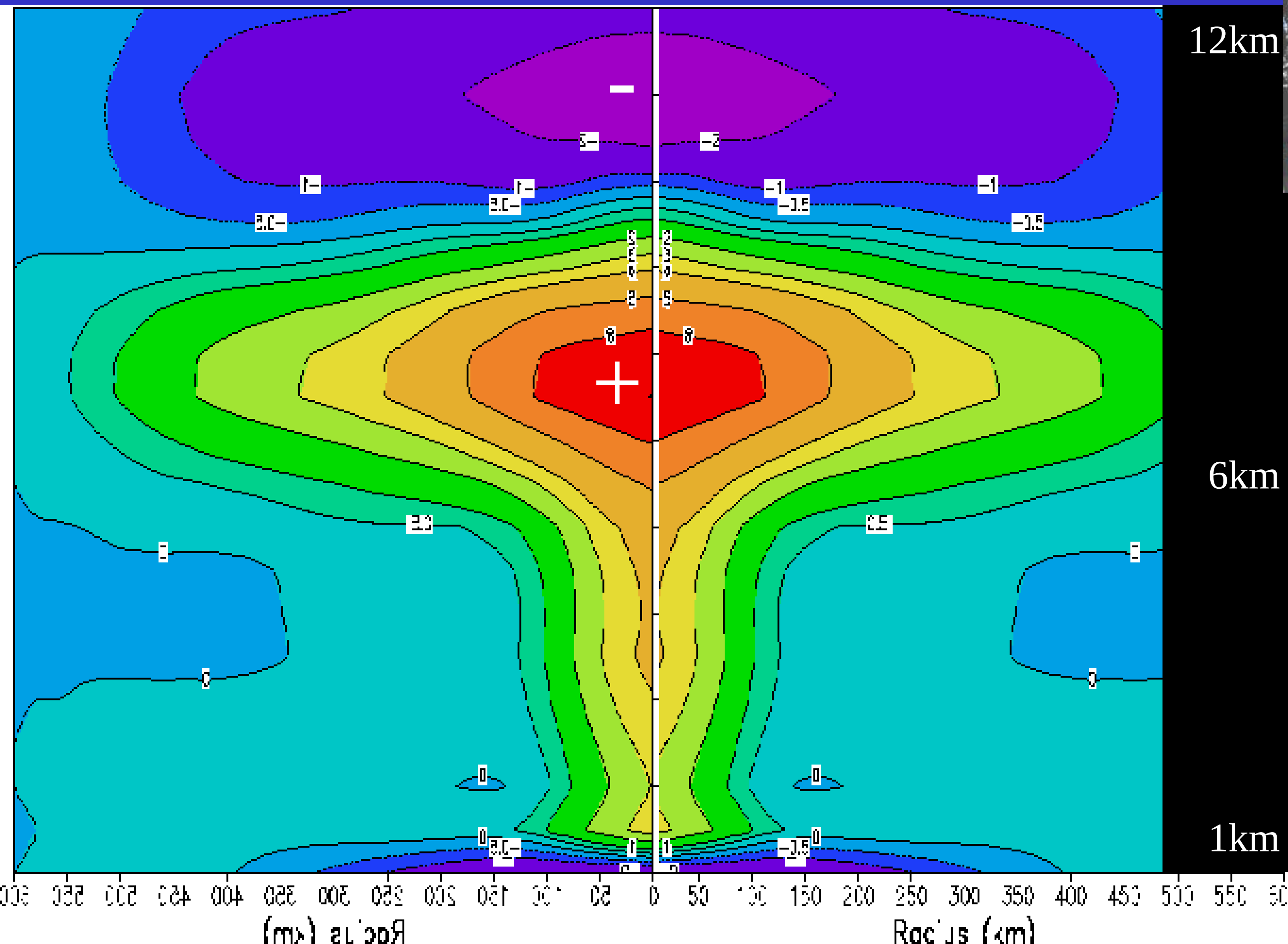


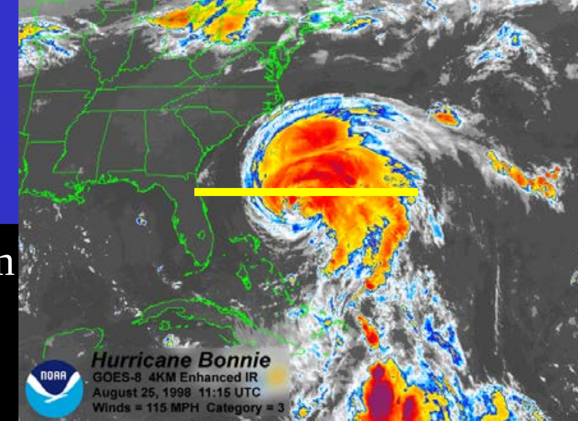
Some relevant questions…

- 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





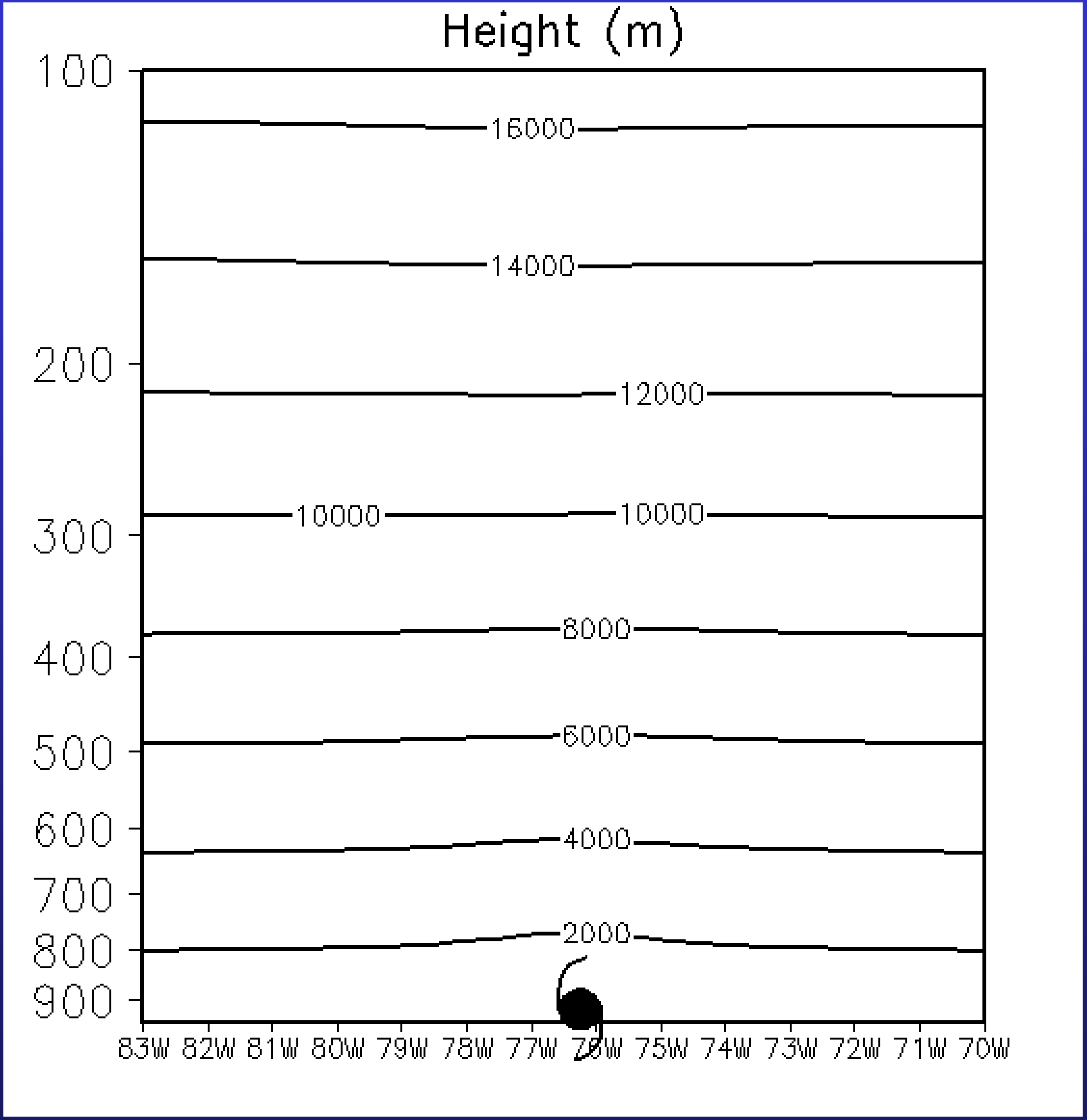
Low pressure results from column of air on average warmer than environment, with the anomalous warmth in the troposphere

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

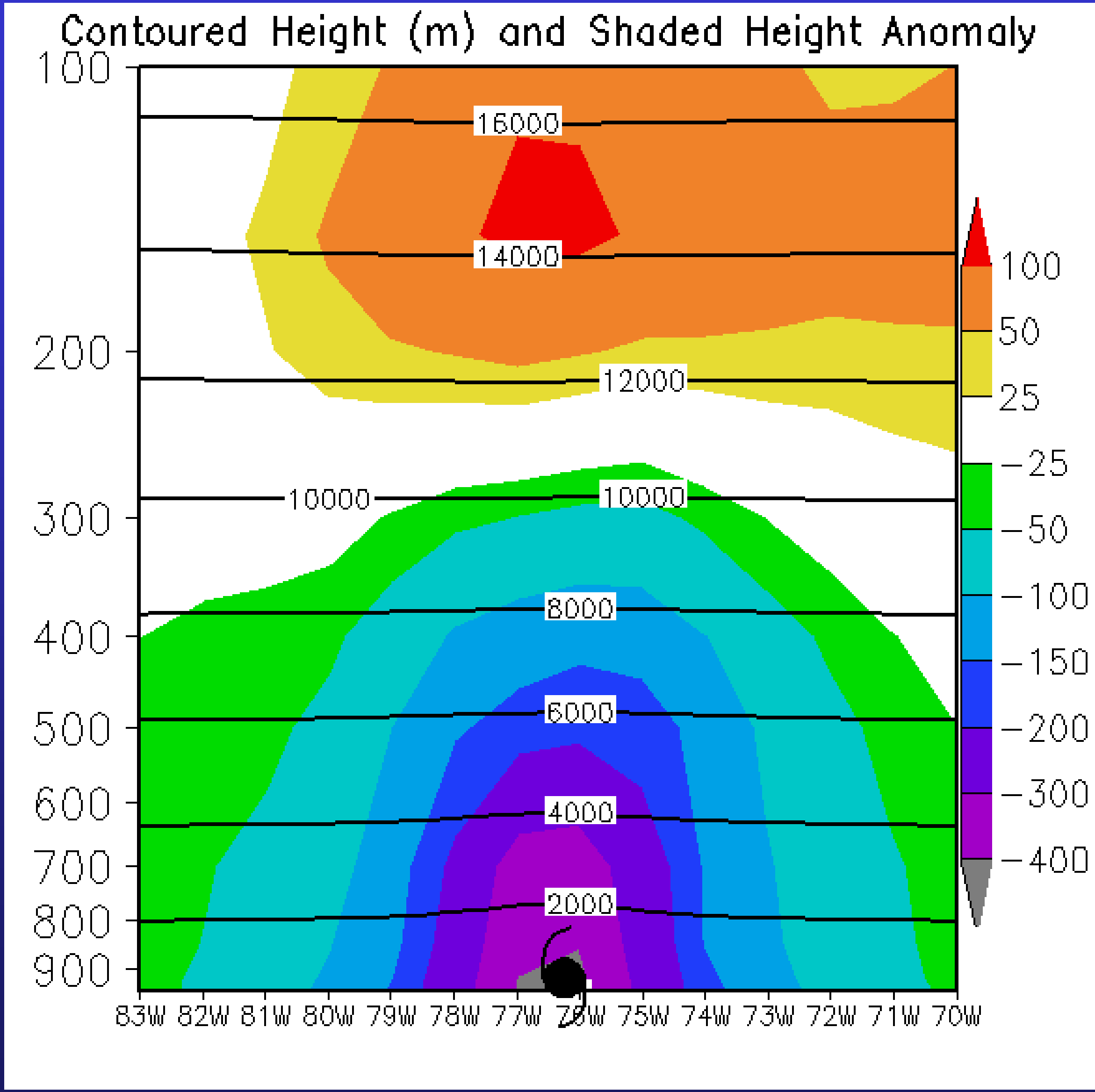


TC Height Field (m) from hydrostatic balance

Warm: expansion of surfaces

Cold: contraction of height surface

Classic warm-core cyclone: TC



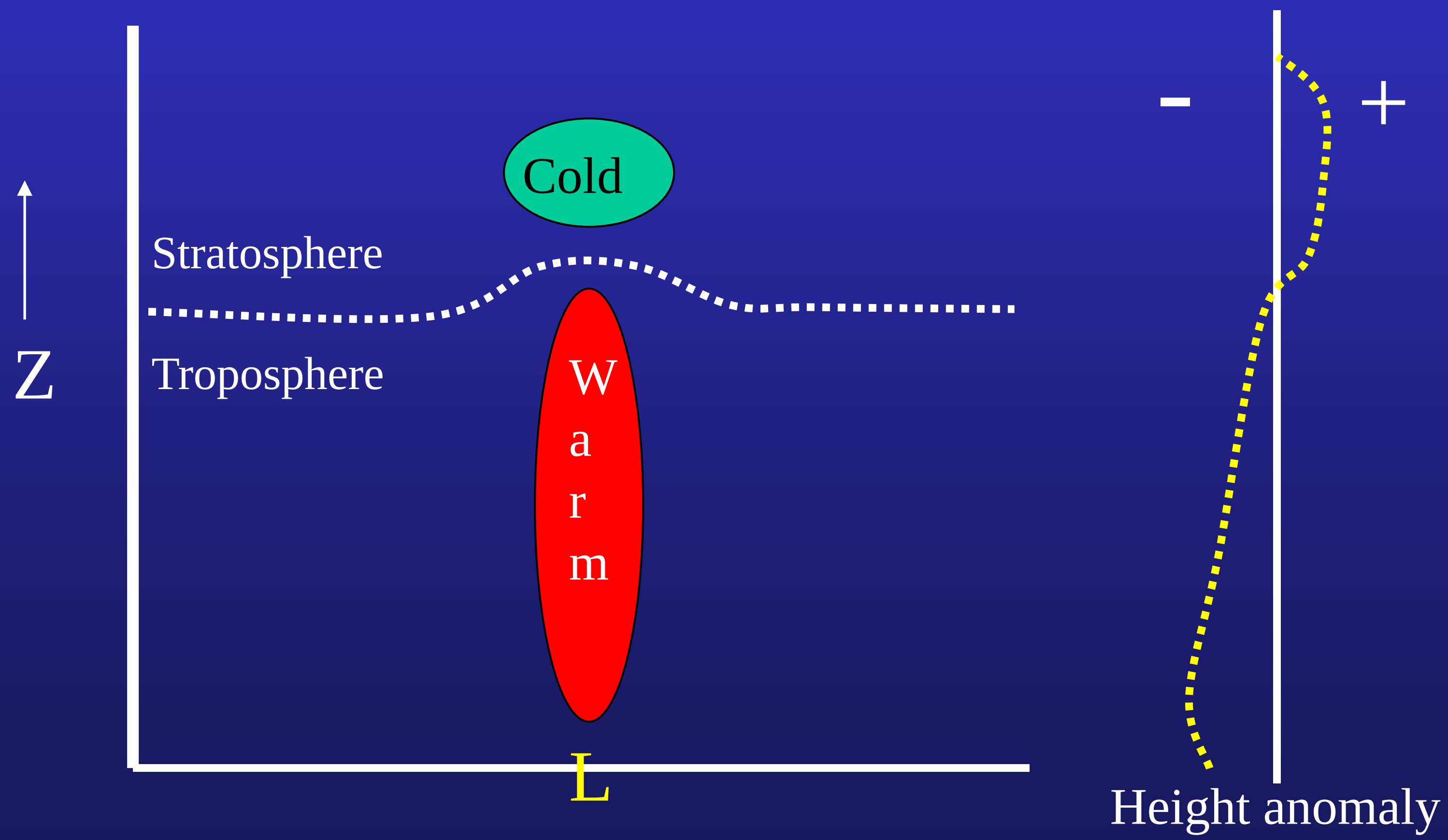
Height anomaly from zonal mean shaded

Height anomaly increases with altitude in troposphere

Classic warm-core cyclone: TC

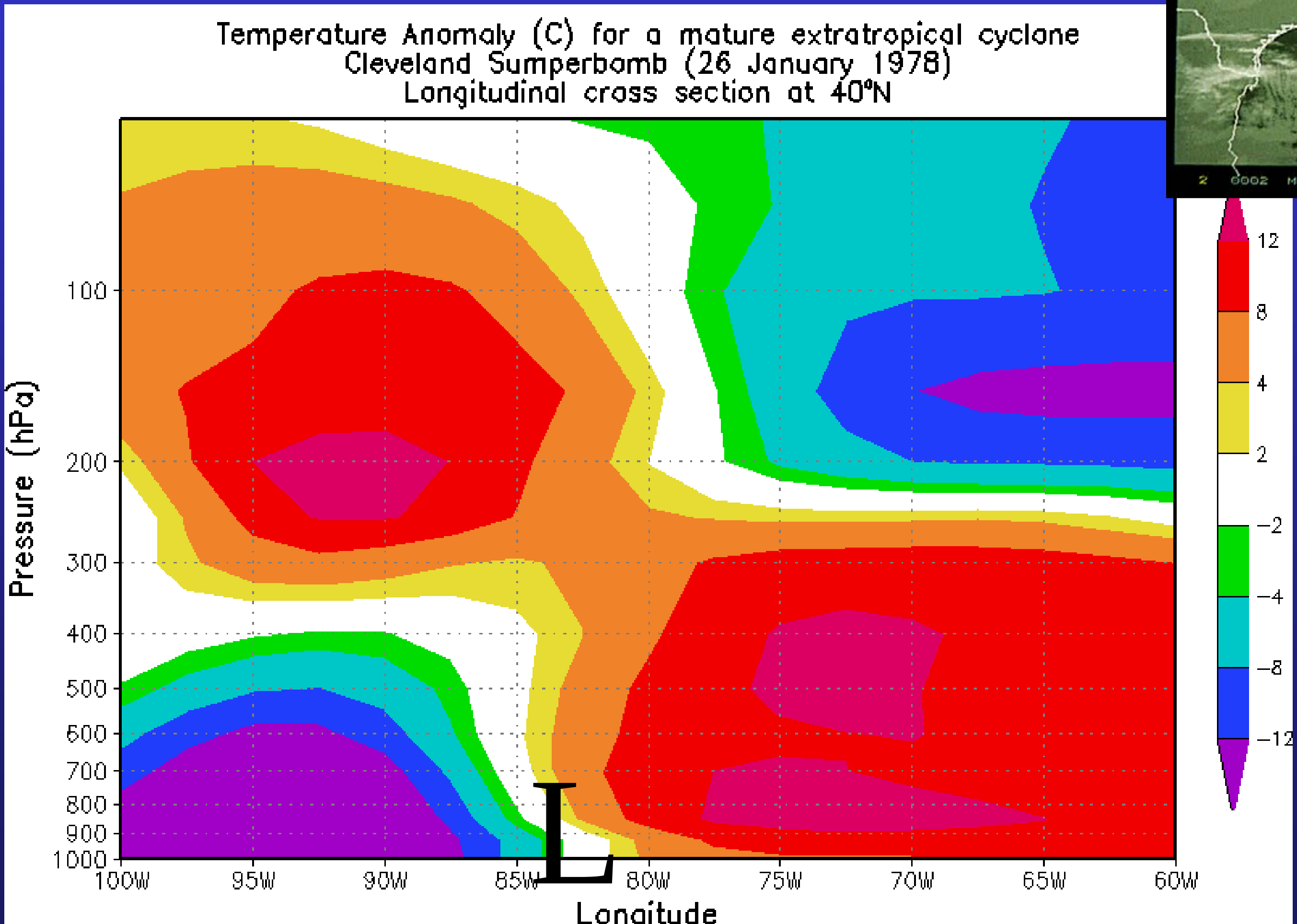
- Intensifies through: sustained convection, surface fluxes.
- Cyclone strength greatest near the top of the PBL

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

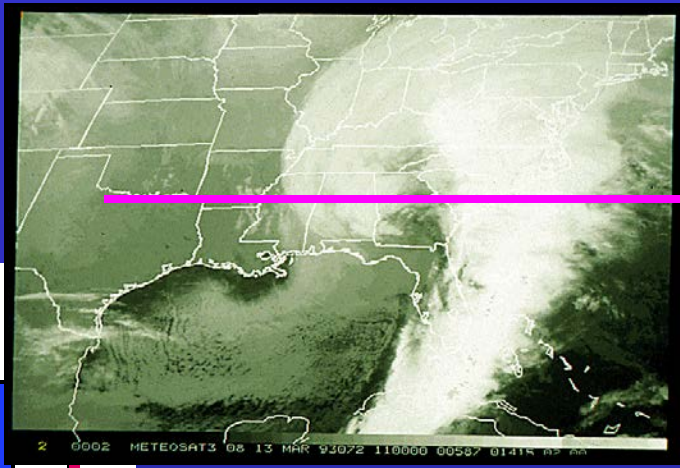


Classic cold-core cyclone: Extratropical

Cleveland Superbomb Temperature Anomaly

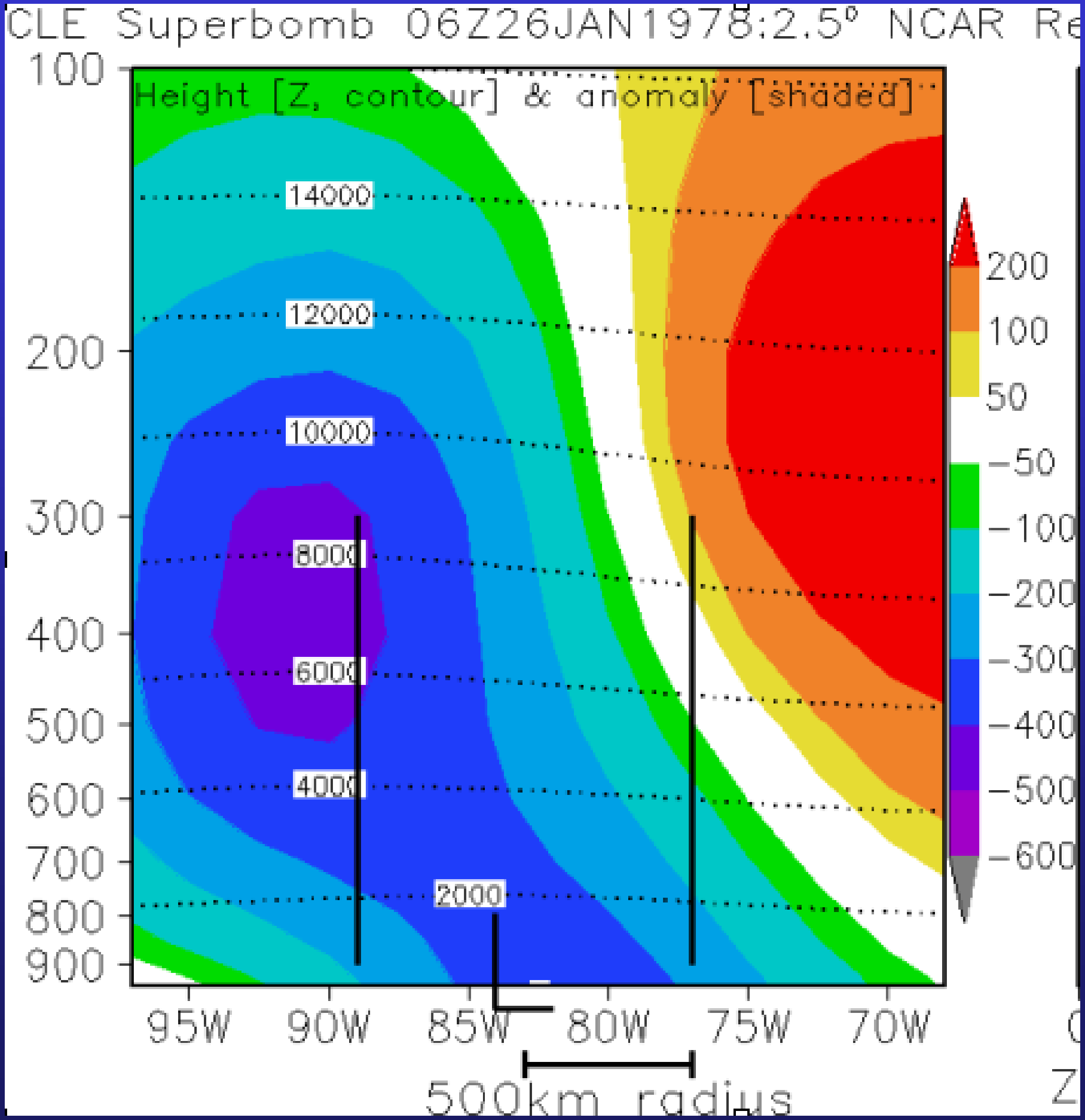


2.5 NCAR/NCEP reanalysis



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

Classic cold-core cyclone: Extratropical



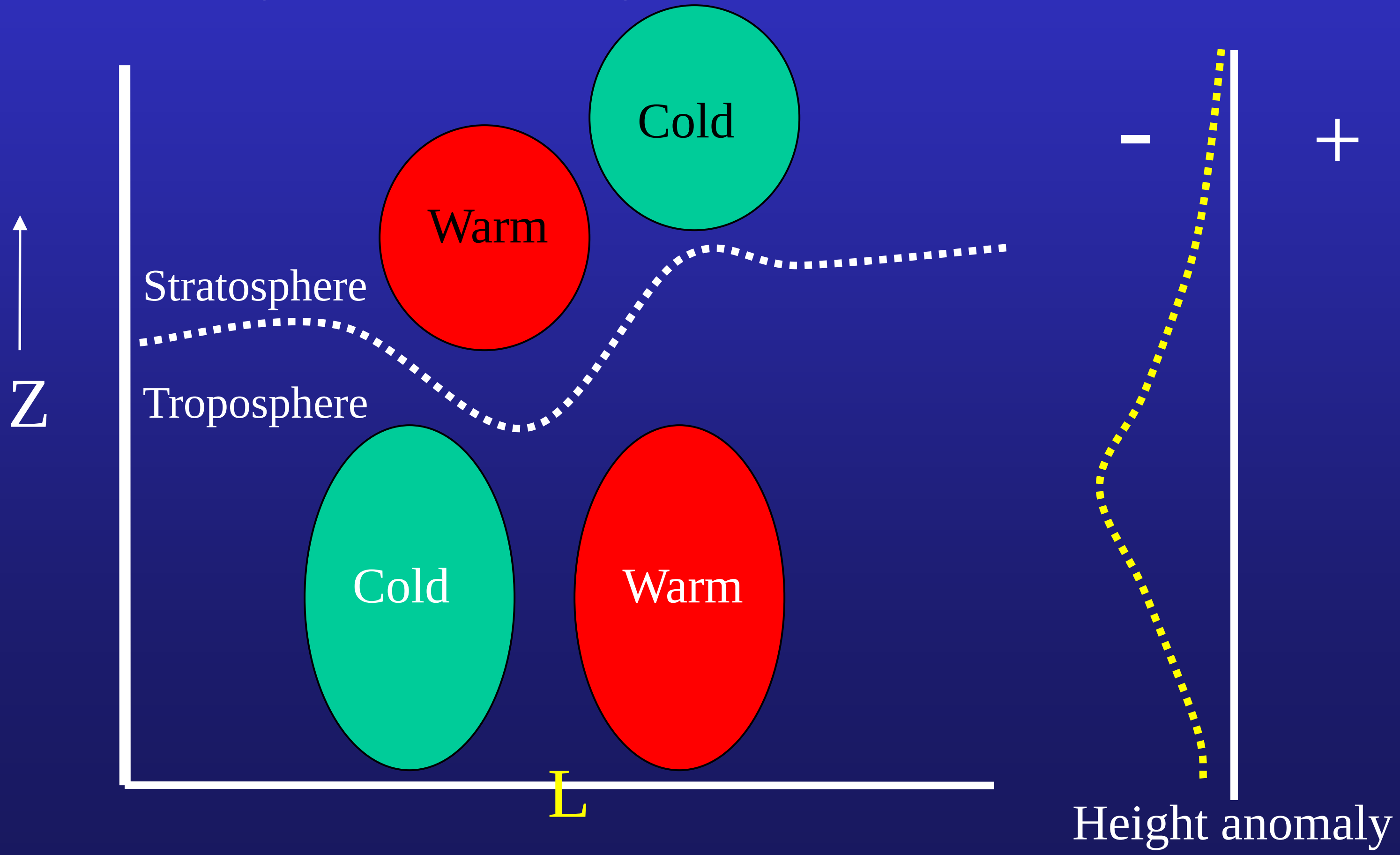
Height anomaly from zonal mean shaded

Height anomaly decreases with altitude in troposphere

Classic cold-core cyclone: Extratropical

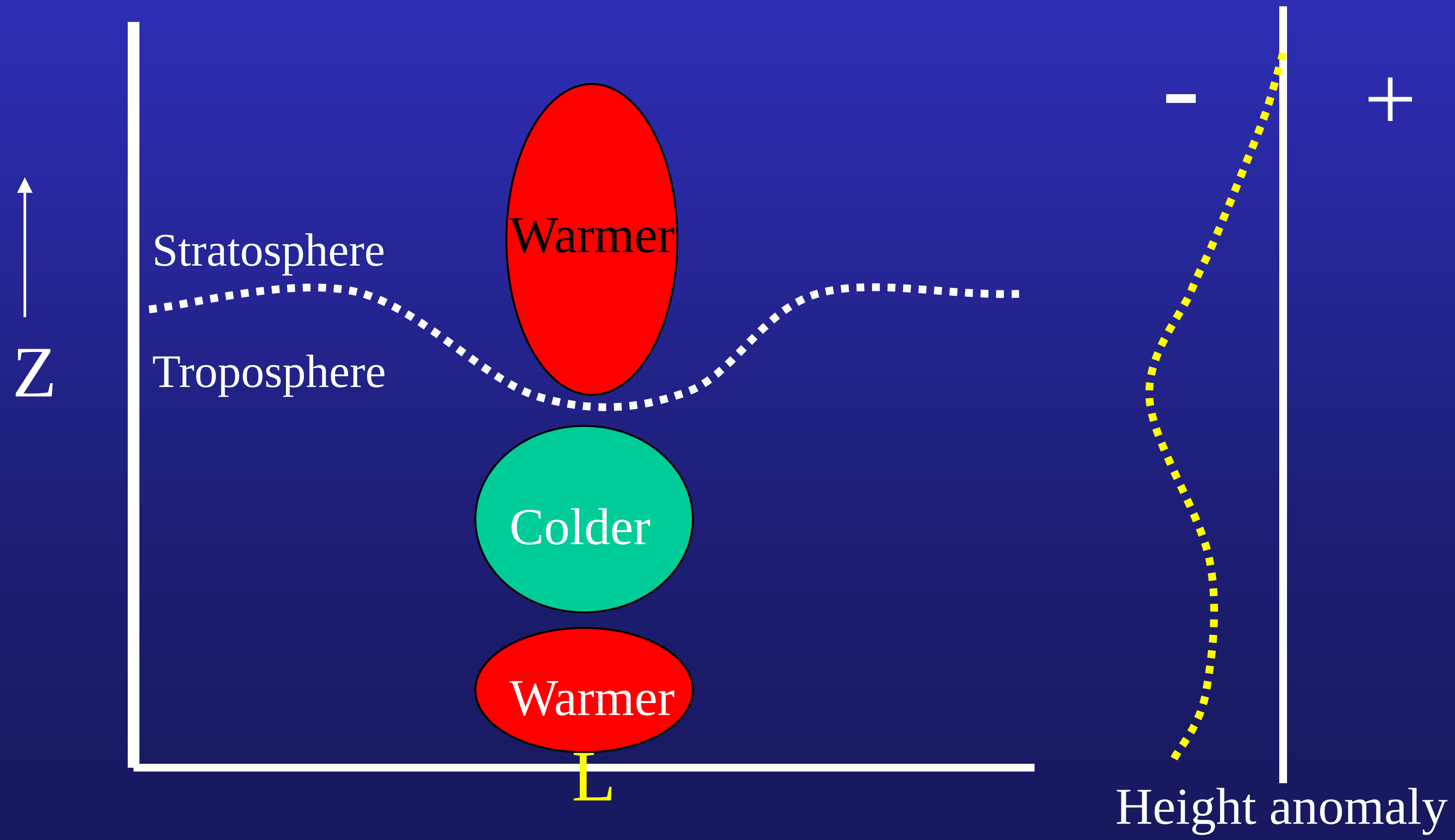
- Intensifies through: baroclinic development, tropopause lowering.
- Cyclone strength greatest near tropopause

⇒ *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.

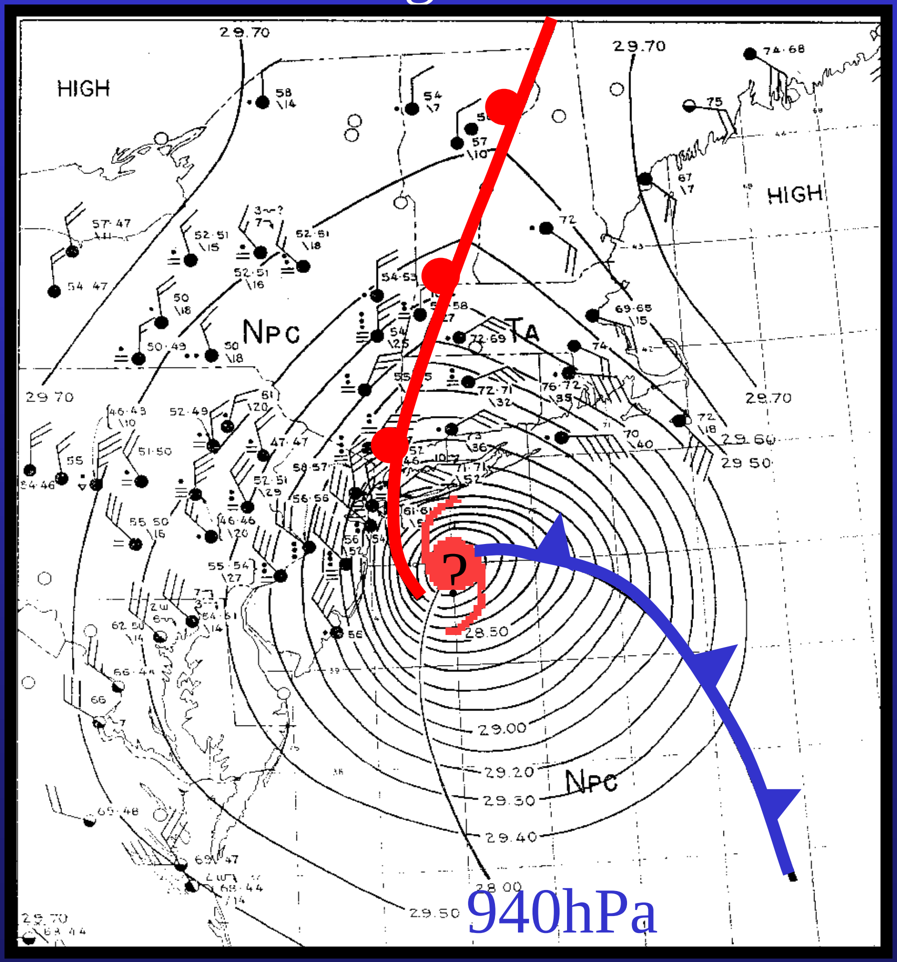


Examples of nonconventional cyclones: Past research

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

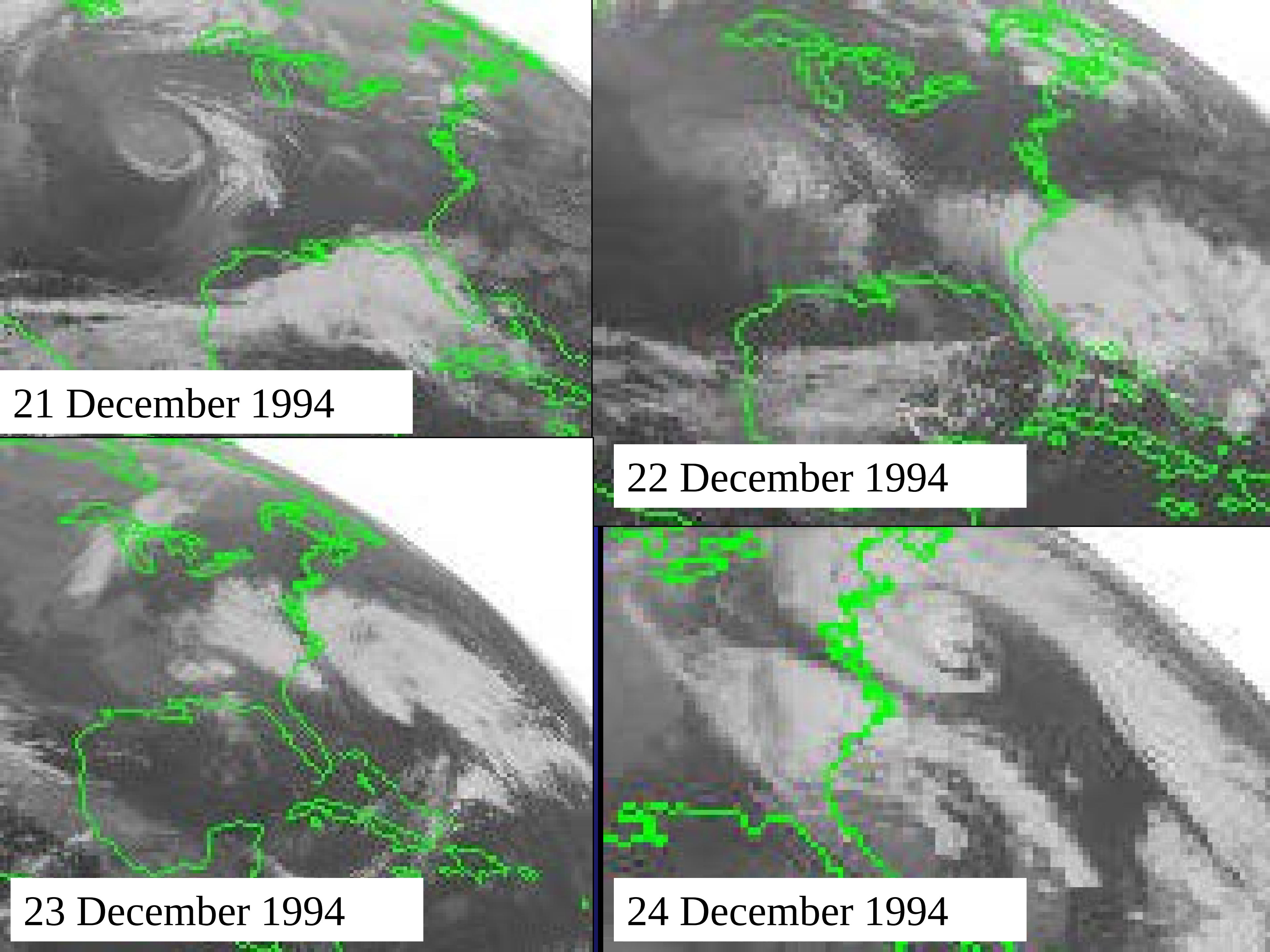
Non-conventional cyclones: Examples

1938 New England Hurricane



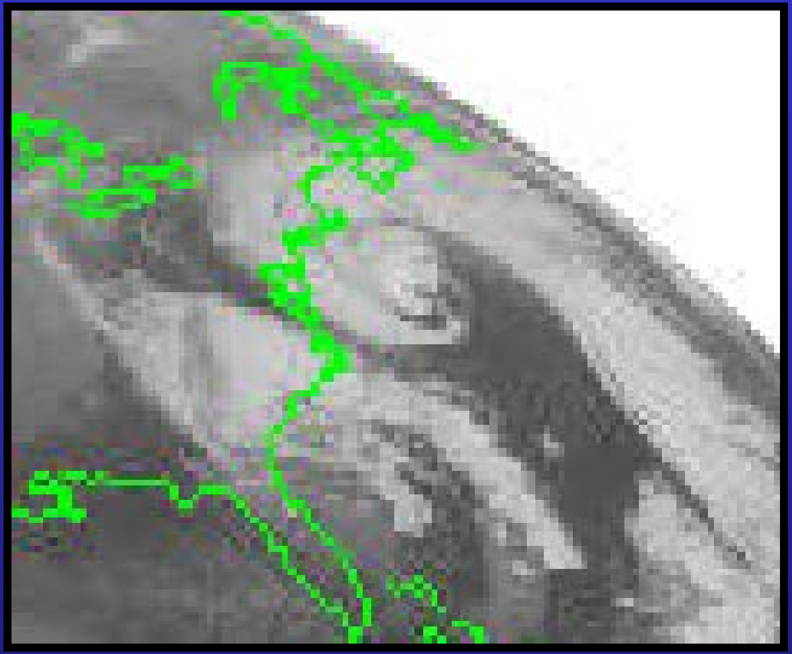
Pierce 1939

- 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

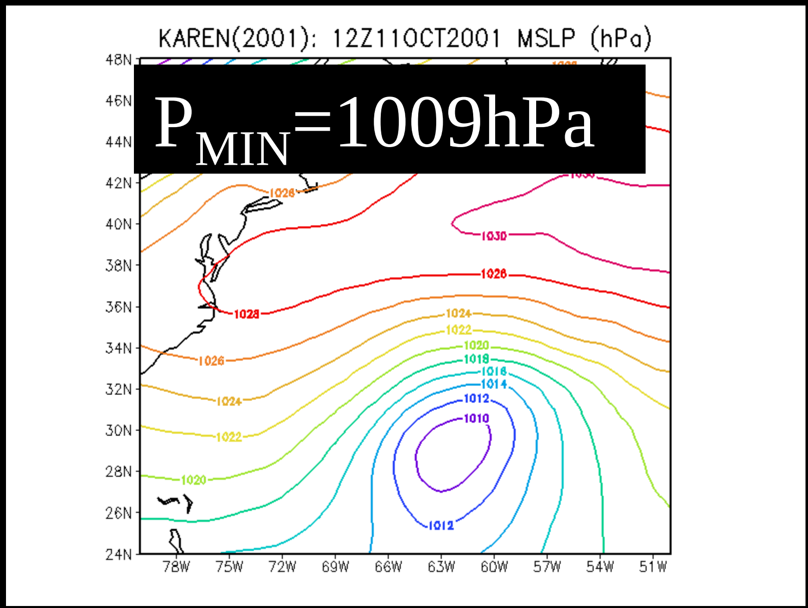
  A partial eye was observed when the cyclone was just east of Long Island

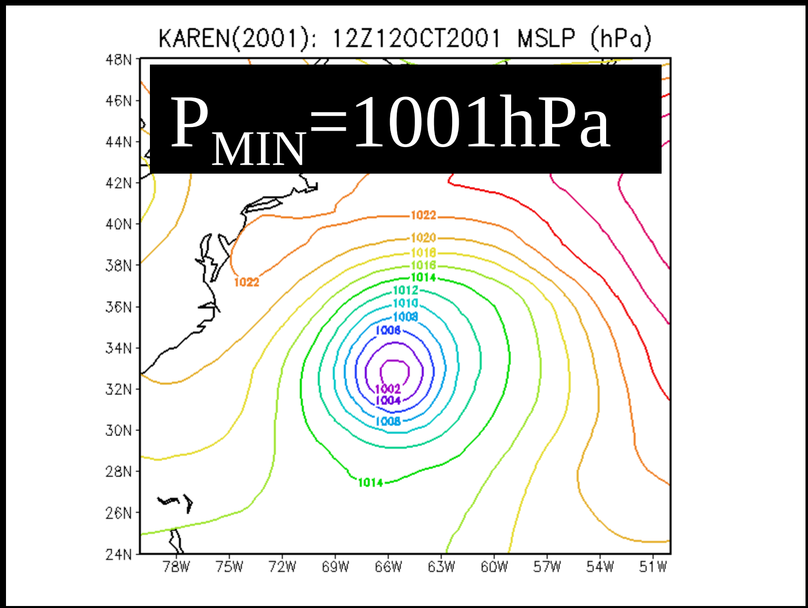
  Wind gusts of 50-100mph observed across southern New England

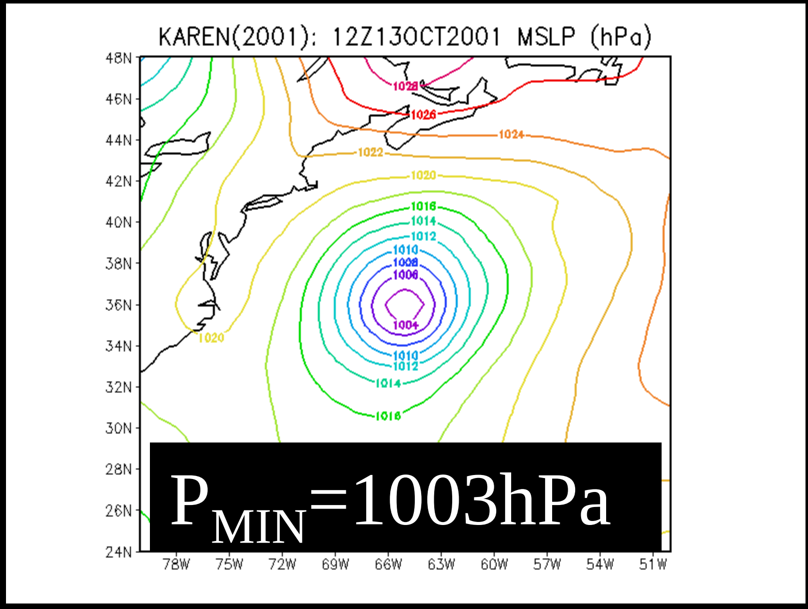
- Largest U.S. power outage (350,000) since Andrew in 1992

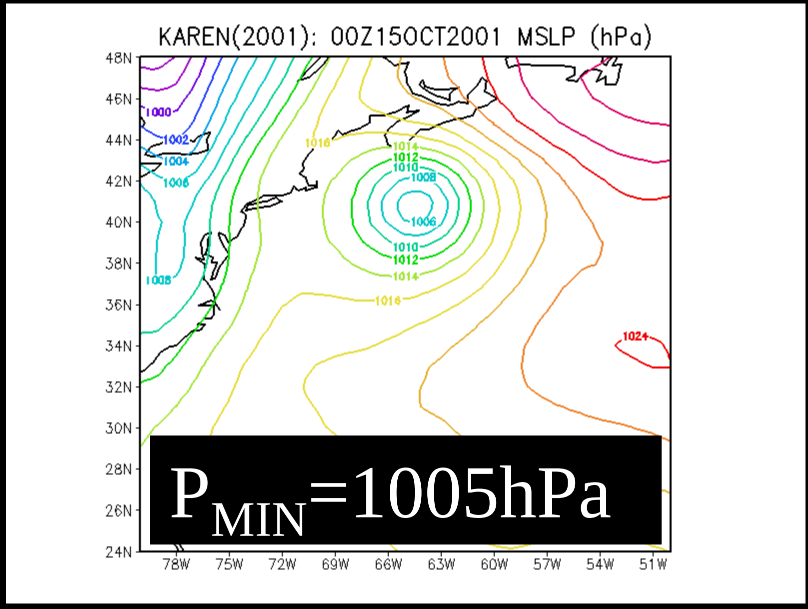
- Forecast 6hr earlier: chance of light rain, winds of 5-15mph.

Model interpretation: What type of development?



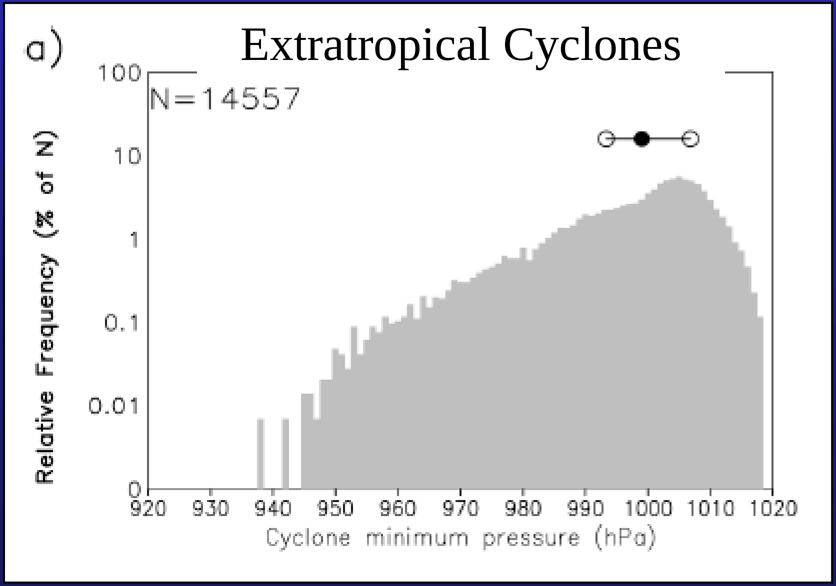


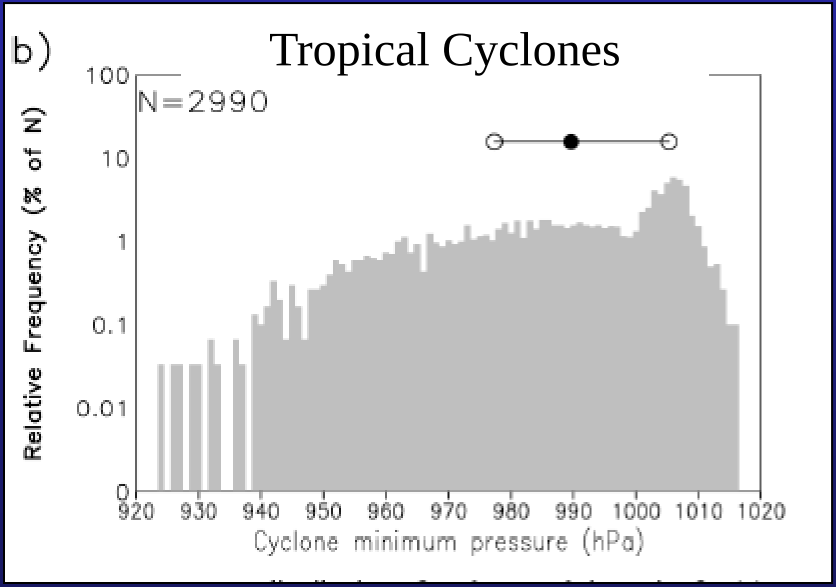




Why is the structure of a cyclone important?

- 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

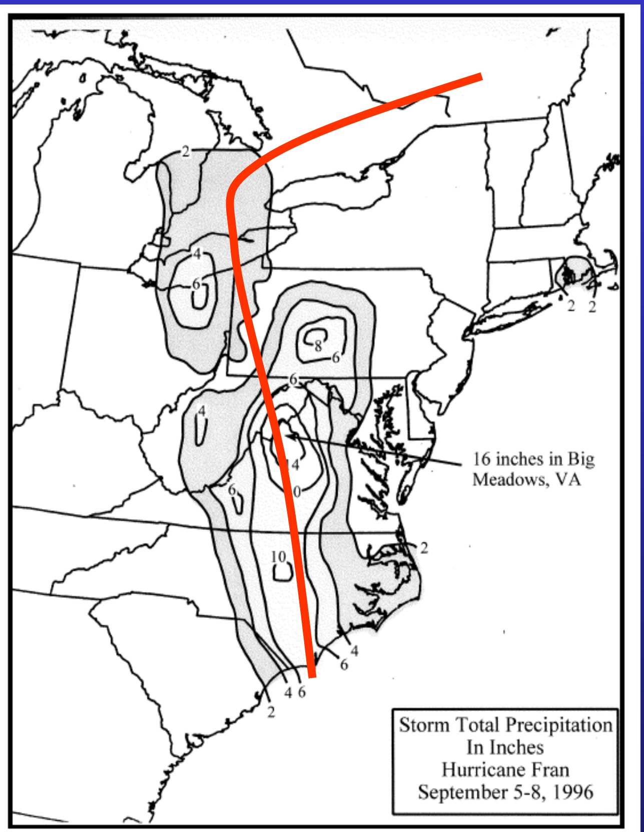
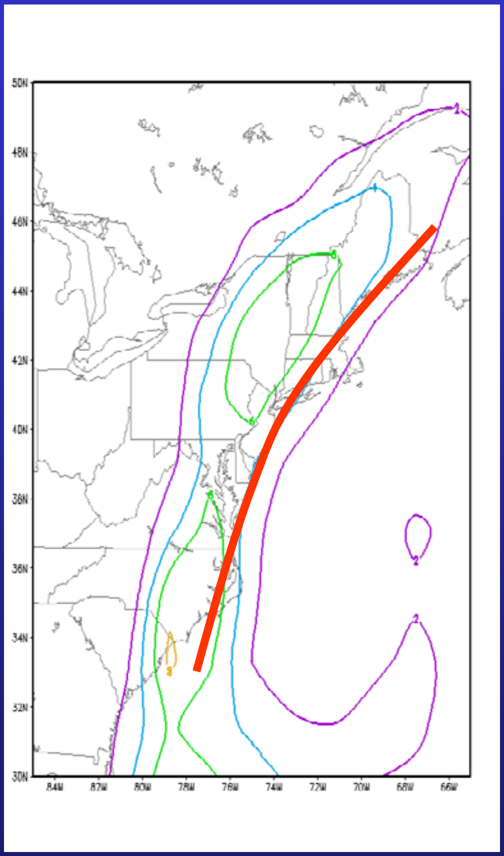


Figure 6: Storm Total Precipitation in Inches. Hurricane Fran, September 5–8, 1996.

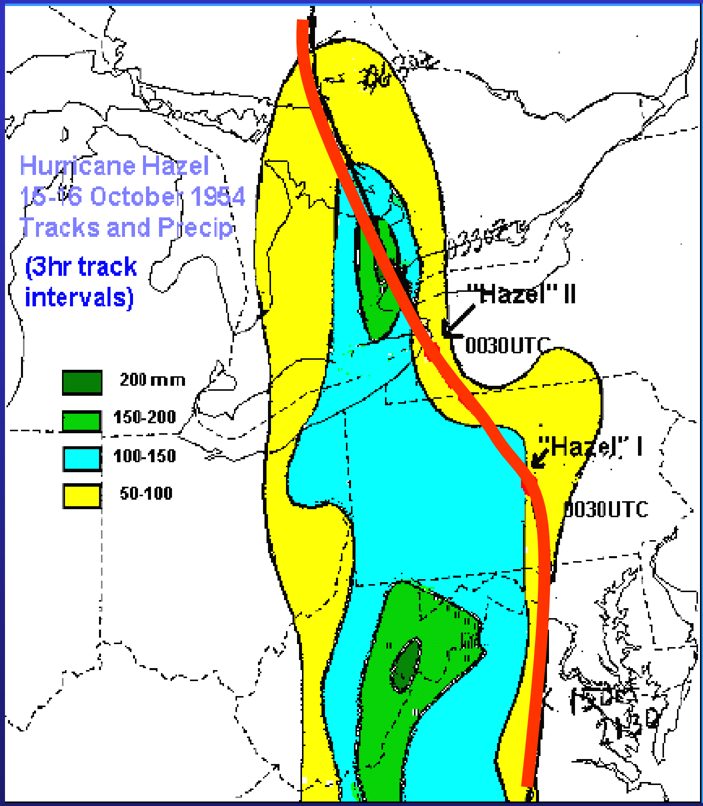
Analysis courtesy NOAA/NWS/NHC

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:

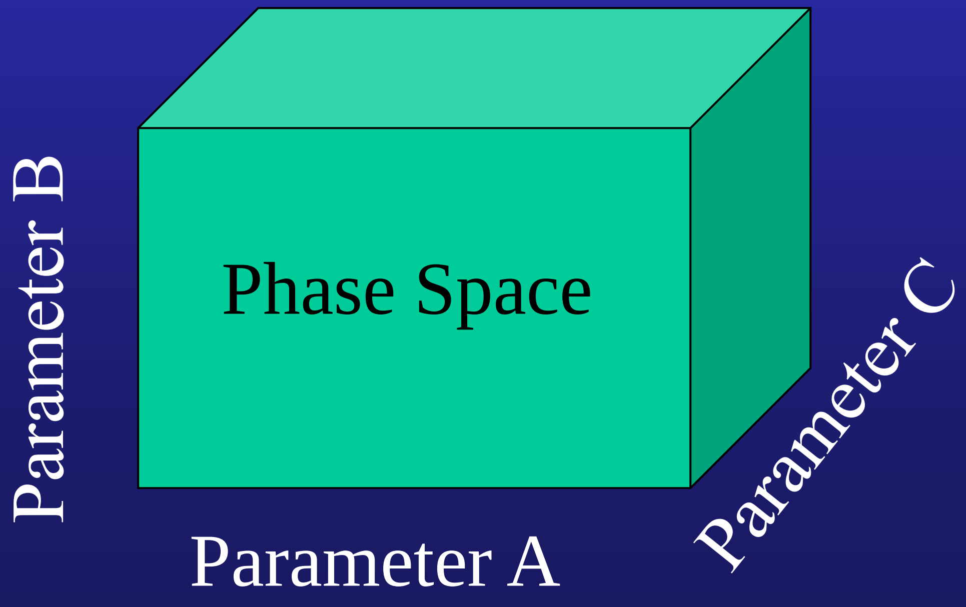
- Classification
- Better understanding of the current state
- Applying conceptual models or designing new ones
- The type/extent of expected impact/damage
- Quantifying potential for intensity change and its uncertainty
  - Scales of motion dependence
  - Maximum intensity
- How can intensity change 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:

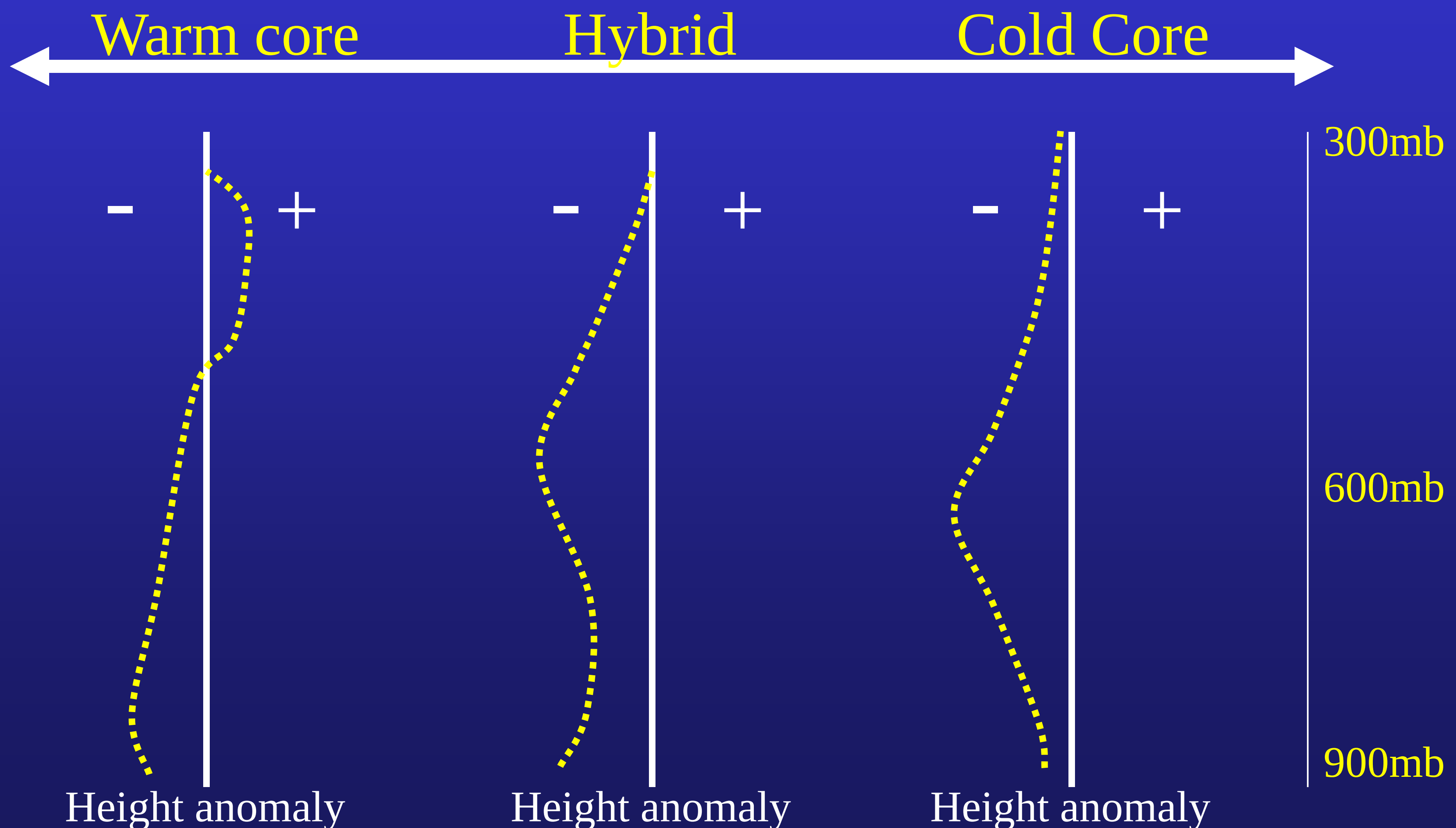
A more flexible approach to cyclone characterization

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



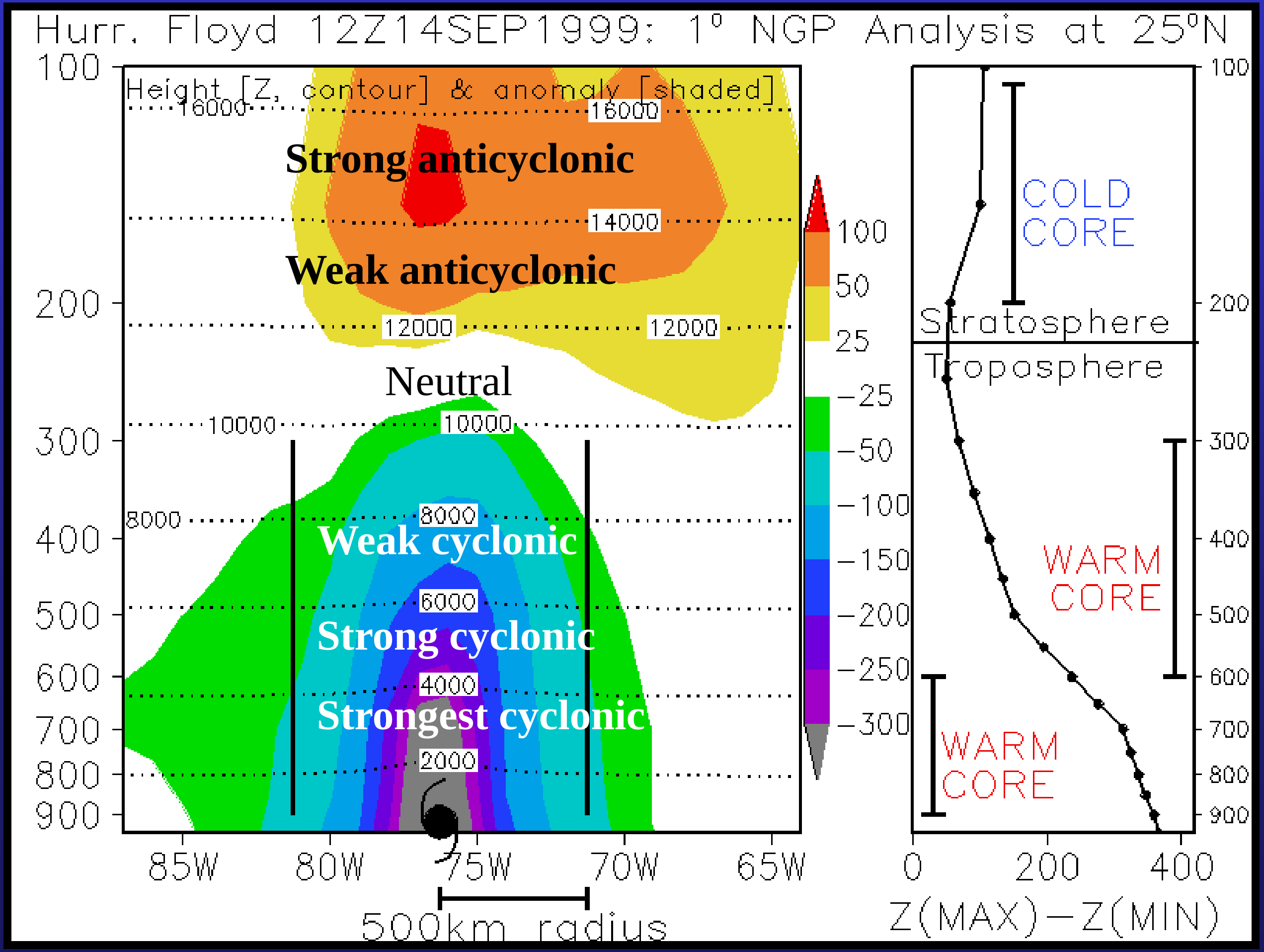
Cyclone Parameter 1: Vertical structure

$-V_T$: 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).

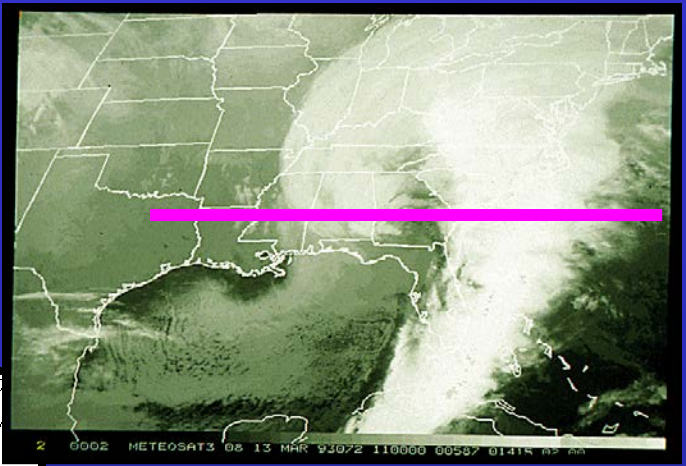
$$\frac{\partial(Z_{MAX}-Z_{MIN})}{\partial \ln p} = -|V_T|$$

Two layers of interest

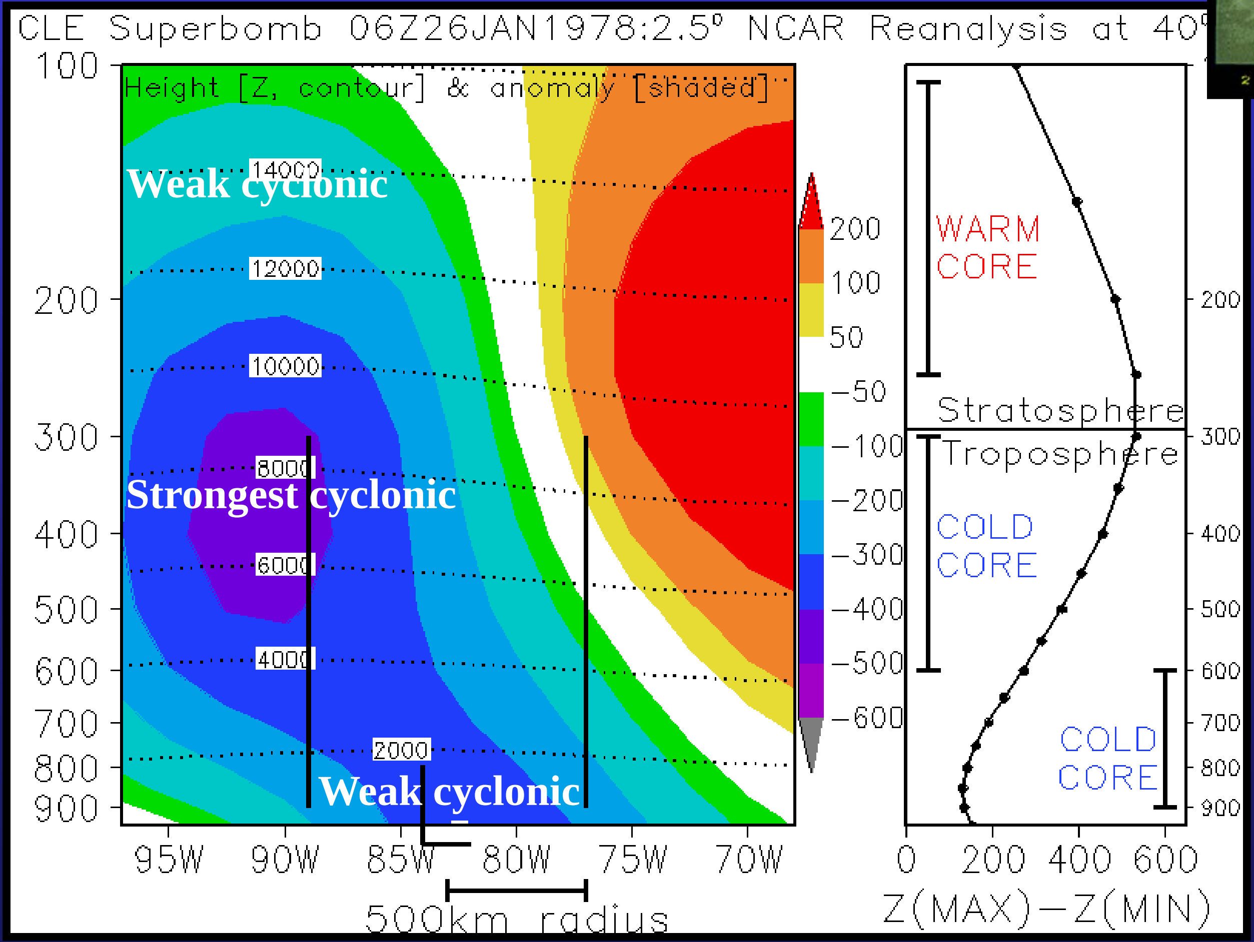
$$\left.\frac{\partial(Z_{MAX}-Z_{MIN})}{\partial \ln p}\right|_{600hPa}^{300hPa} = -|V_T^U|$$

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

Cyclone Parameter -V_T: Thermal Wind



Cold-core example:
Cleveland Superbomb 26 Jan 1978



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

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

QG Height Tendency Equation:

$$\nabla^2 \frac{\partial \Phi}{\partial t} + \frac{\partial}{\partial p}\left[\frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left(\frac{\partial \Phi}{\partial t}\right)\right] = -f_0 \mathbf{V}_g \cdot \nabla\left(\zeta_g + f\right) - \frac{\partial}{\partial p}\left[-\frac{f_0^2}{\sigma}\mathbf{V}_g \cdot \nabla\left(-\frac{\partial \Phi}{\partial p}\right)\right]$$

$$- f_0 K(p)\zeta_g - \frac{\partial}{\partial p}\left[\frac{f_0^2 R\dot{Q}}{\sigma p c_p}\right]$$

- LHS: Estimate of synoptic-scale height fall or height rise magnitude.
- LHS: How this varies in the vertical essentially drives whether a cyclone is becoming more or less cold or warm core, or evolving
- RHS: Vorticity Advection, Differential Thermal Advection, Friction, and Differential Diabatics

QG Height Tendency Equation:

$$\nabla^2 \frac{\partial \Phi}{\partial t} + \frac{\partial}{\partial p}\left[\frac{f_0^2}{\sigma}\frac{\partial}{\partial p}\left(\frac{\partial \Phi}{\partial t}\right)\right] = -f_0 \mathbf{V}_g \cdot \nabla\left(\zeta_g + f\right) - \frac{\partial}{\partial p}\left[-\frac{f_0^2}{\sigma}\mathbf{V}_g \cdot \nabla\left(-\frac{\partial \Phi}{\partial p}\right)\right]$$

$$- f_0 K(p)\zeta_g - \frac{\partial}{\partial p}\left[\frac{f_0^2 R\dot{Q}}{\sigma p c_p}\right]$$

- RHS: Vorticity Advection

  CVA $\Rightarrow$ Height Falls, AVA $\Rightarrow$ Height Rises

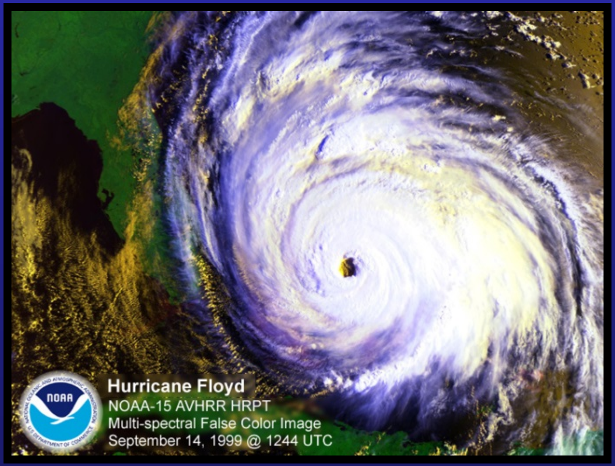
- RHS: Differential Thermal Advection, Diabatics

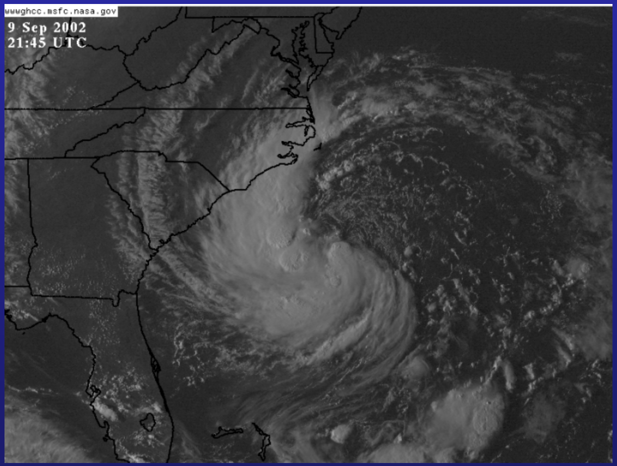
  WAA/Latent Heating increasing with height $\Rightarrow$ Height Falls at low levels, height rises aloft

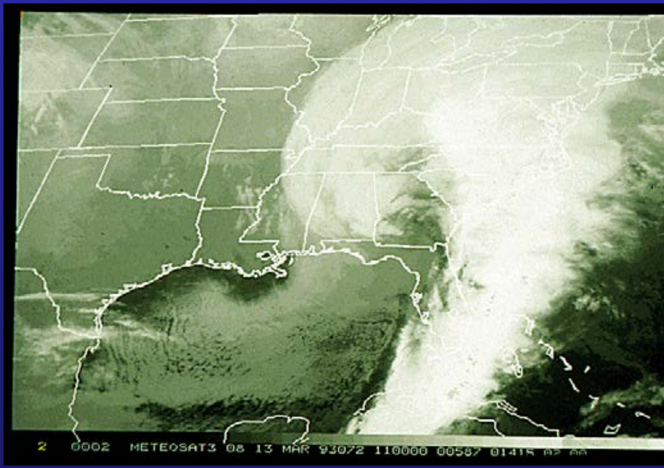
These largely determine how $-V_T^L$ and $-V_T^U$ change with time.

Cyclone Parameter 2: Horizontal structure
B: Thermal Asymmetry

Symmetric — Hybrid — Asymmetric



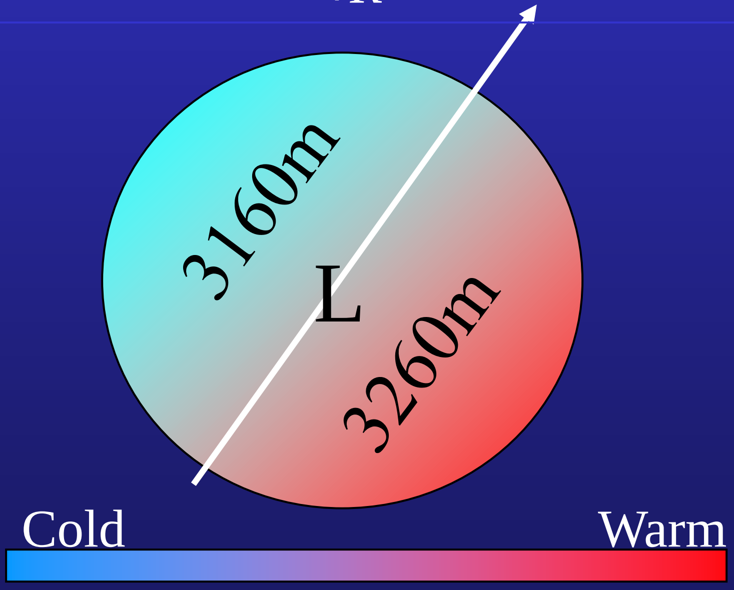




Cyclone Parameter B: Thermal Asymmetry

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

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

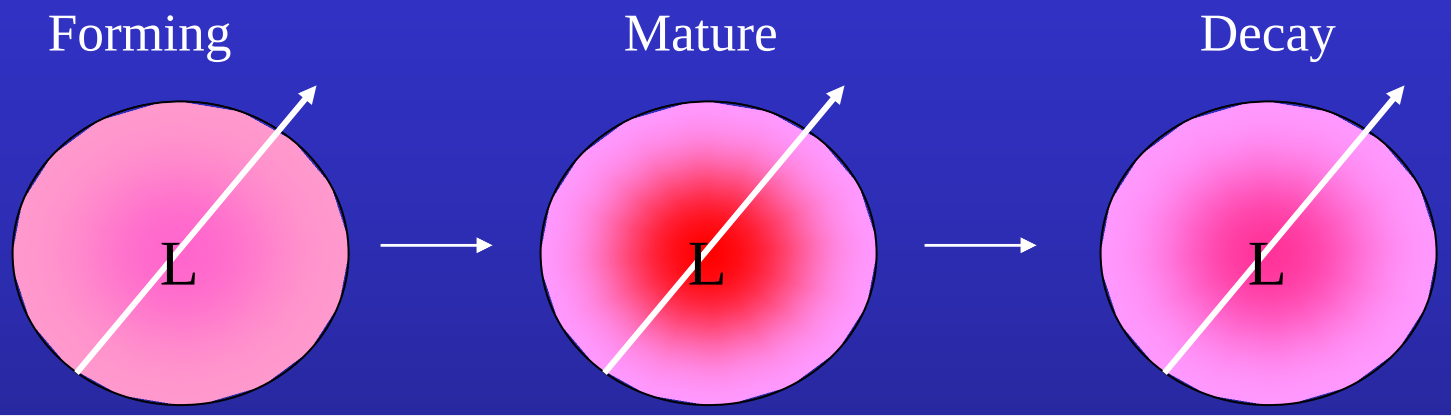


B >> 0: Frontal

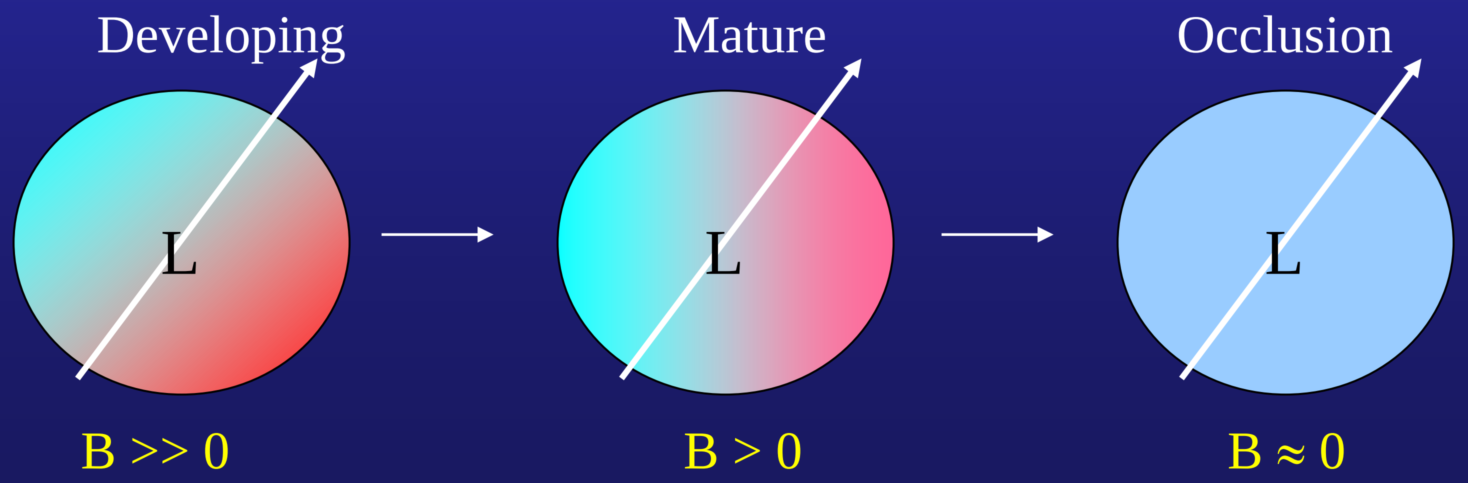
B≈0: Nonfrontal

Cyclone Parameter B: Thermal Asymmetry

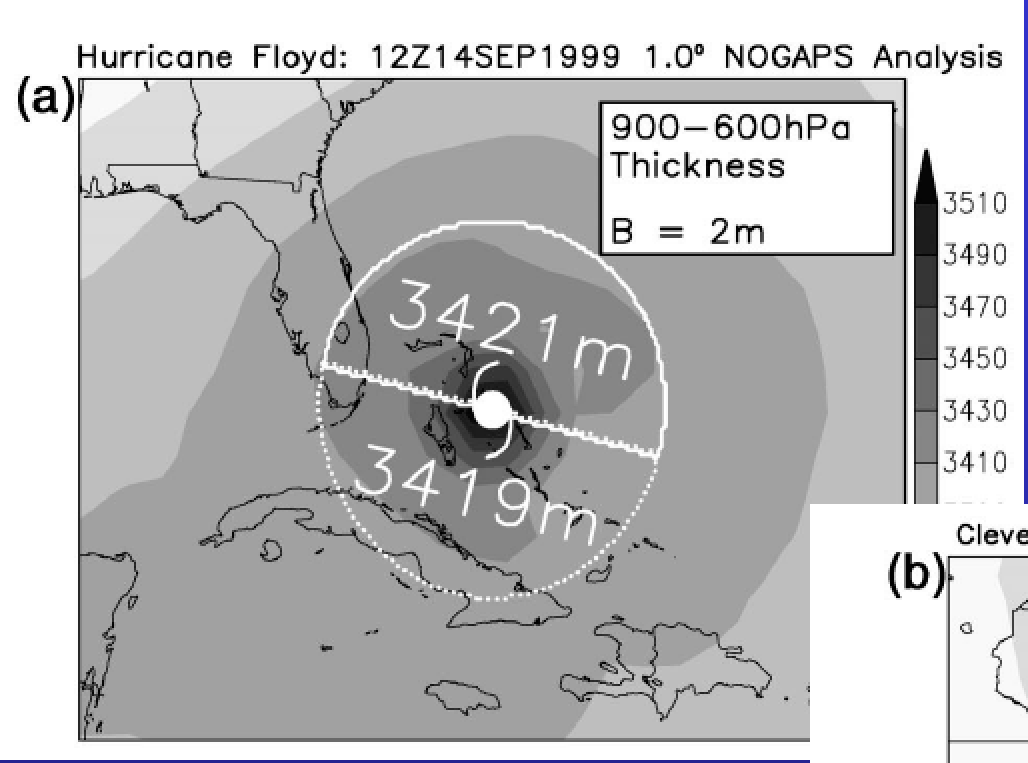
Conventional Tropical cyclone: B ≈ 0

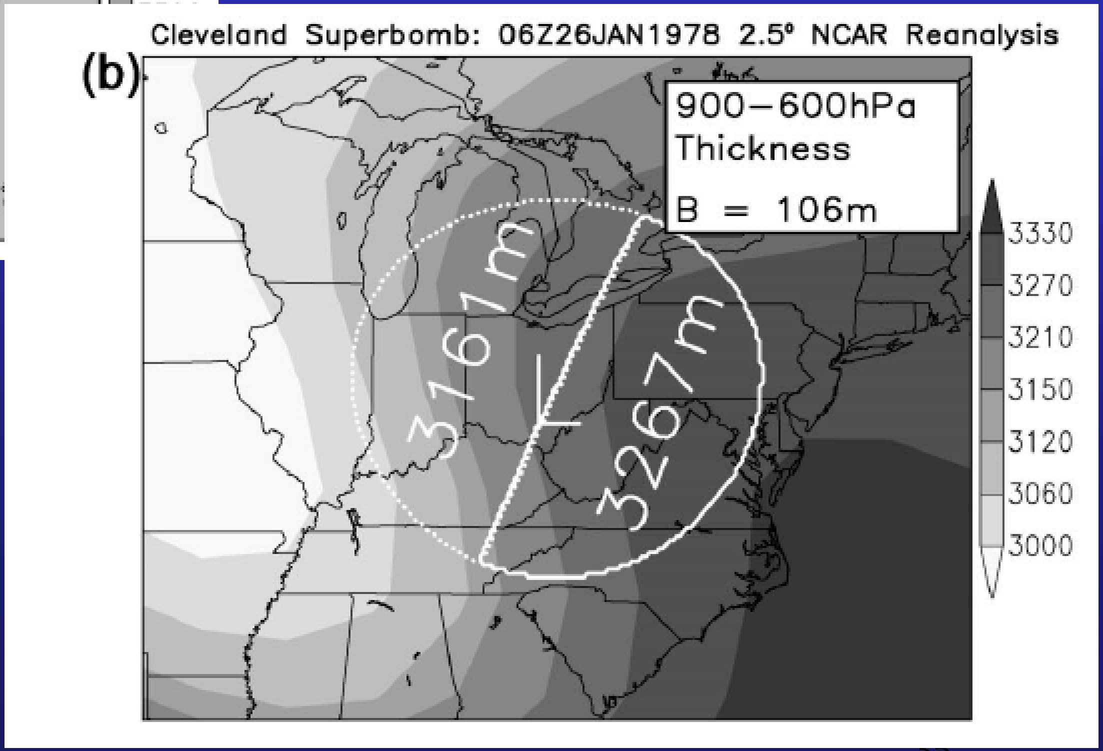


Conventional Extratropical cyclone: B varies



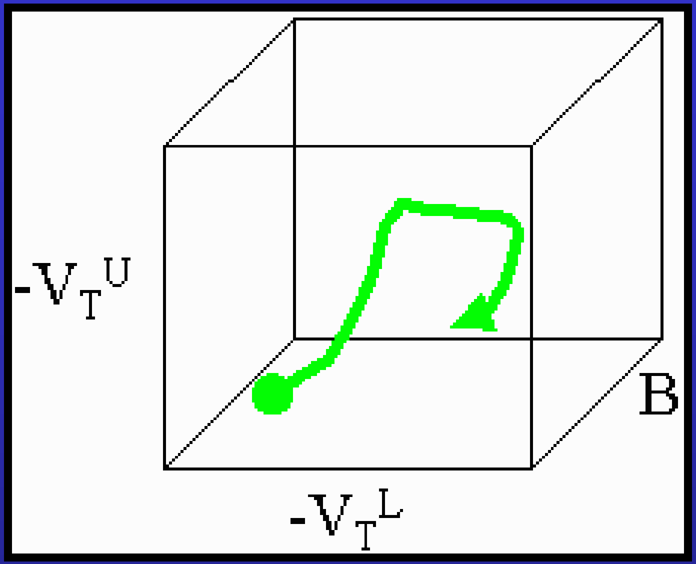
Cyclone Parameters Overview: B





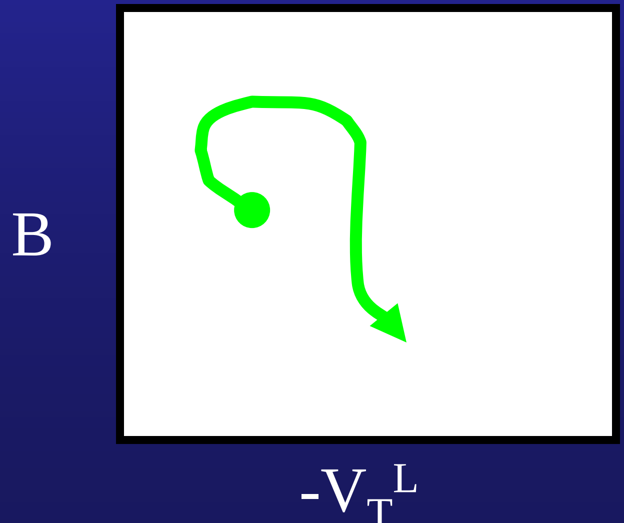
Constructing Phase Space

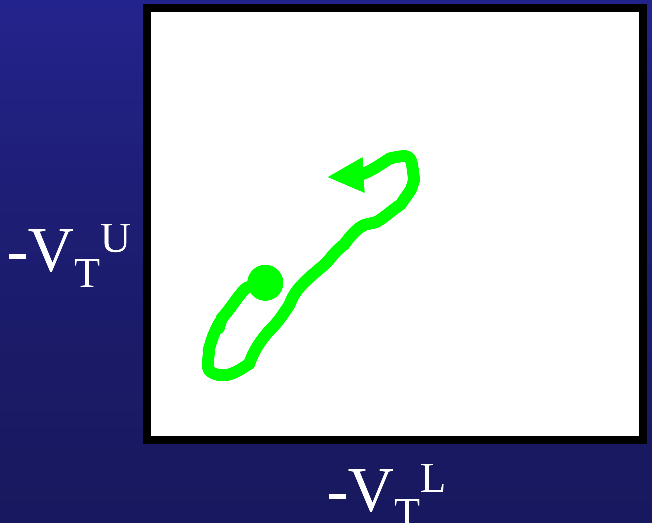
Constructing 3-D phase space from cyclone parameters: B, $-V_T^L$, $-V_T^U$



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

⇒ Take two cross sections (slices) :





Phase Diagram 1

Thermal Asymmetry versus Lower-Tropospheric Thermal Wind

Symmetric warm core

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

Asymmetric warm core

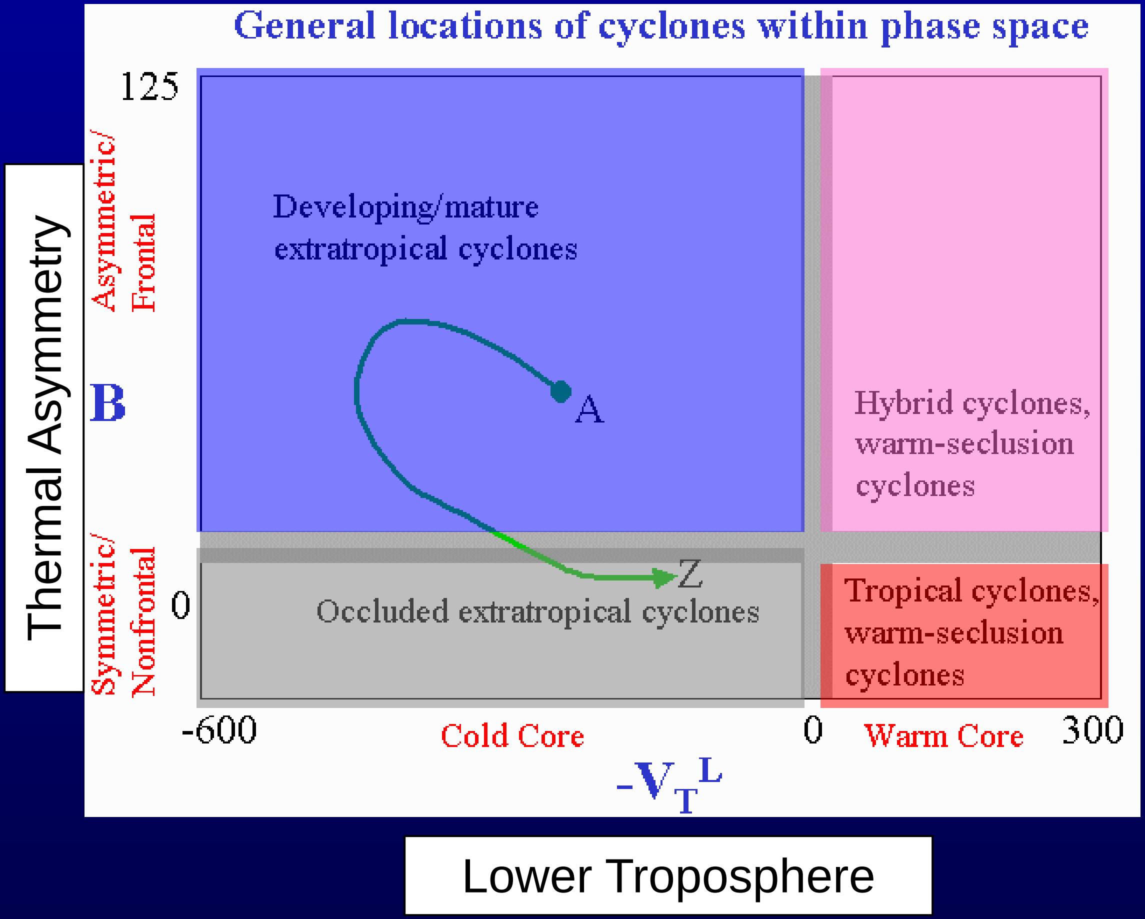
- $B > 10$ and $-V_T^L > 0$
  - Hybrid cyclones, warm seclusions
  - Most cyclones undergoing ET found here

Symmetric cold core

- $B \leq 10$ 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

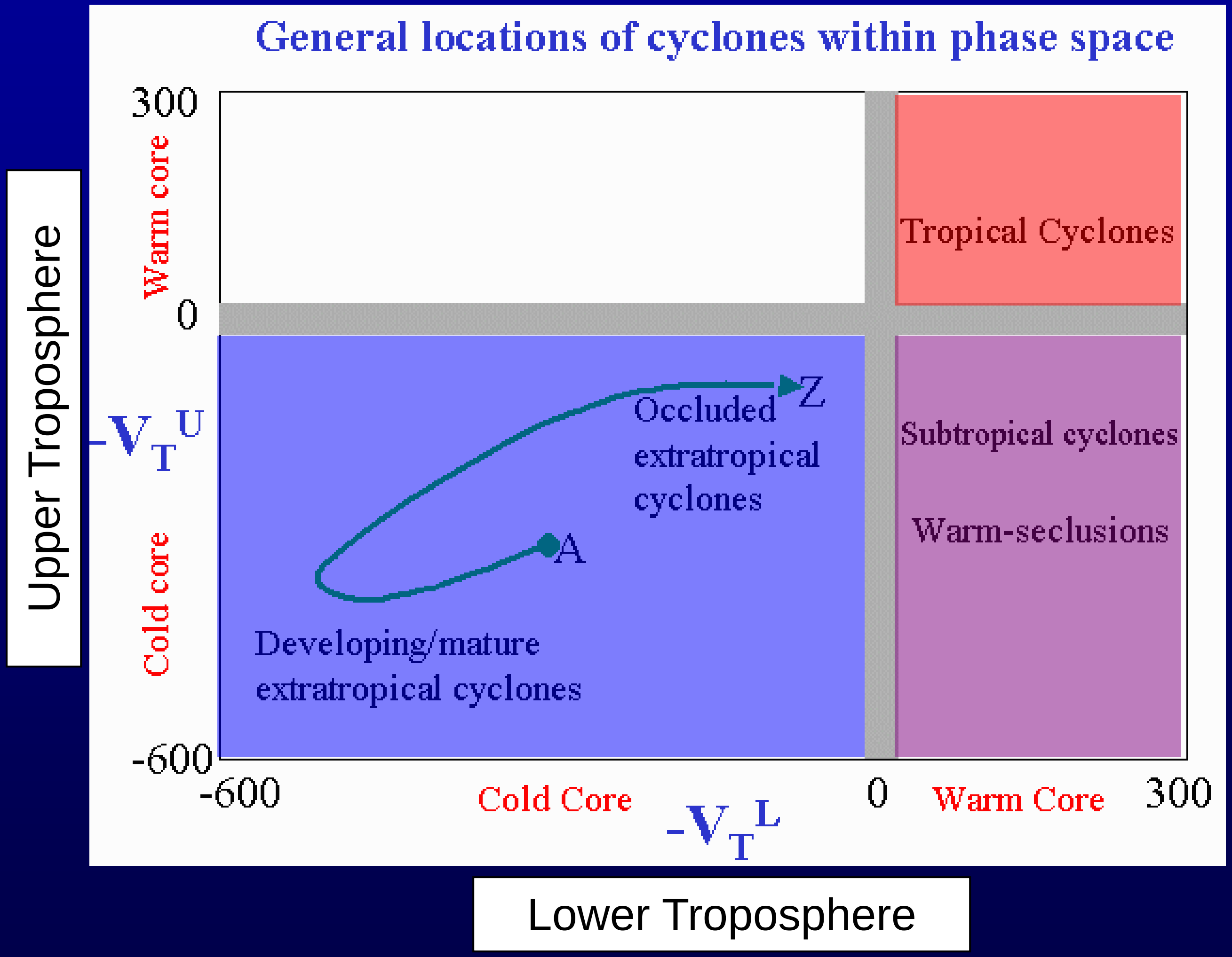
- $-V_T^L > 0, -V_T^U > 0$
- Tropical cyclones

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

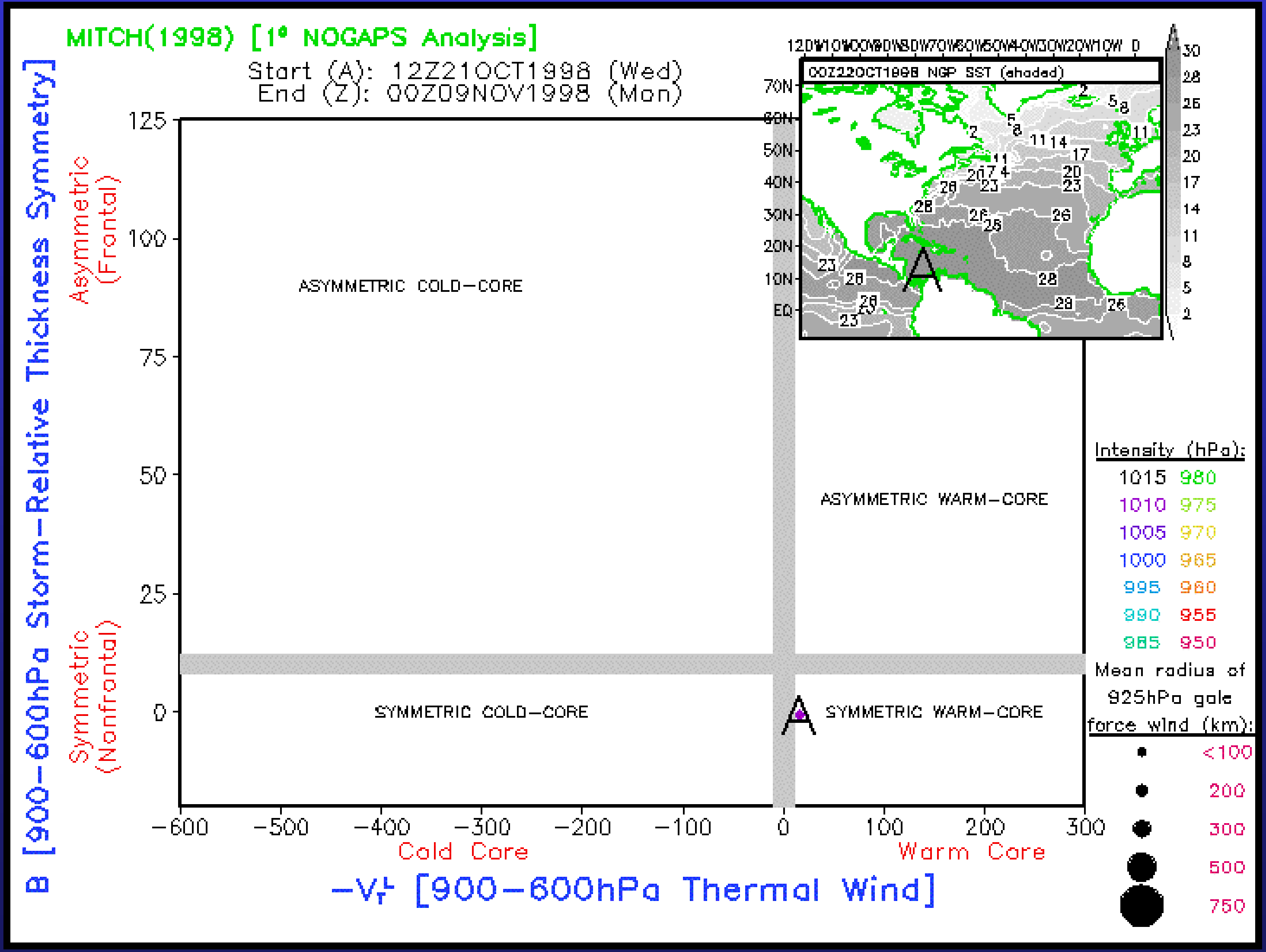
Hurricane Mitch (1998)

Case of symmetric, warm-core development and decay

Classic tropical cyclone

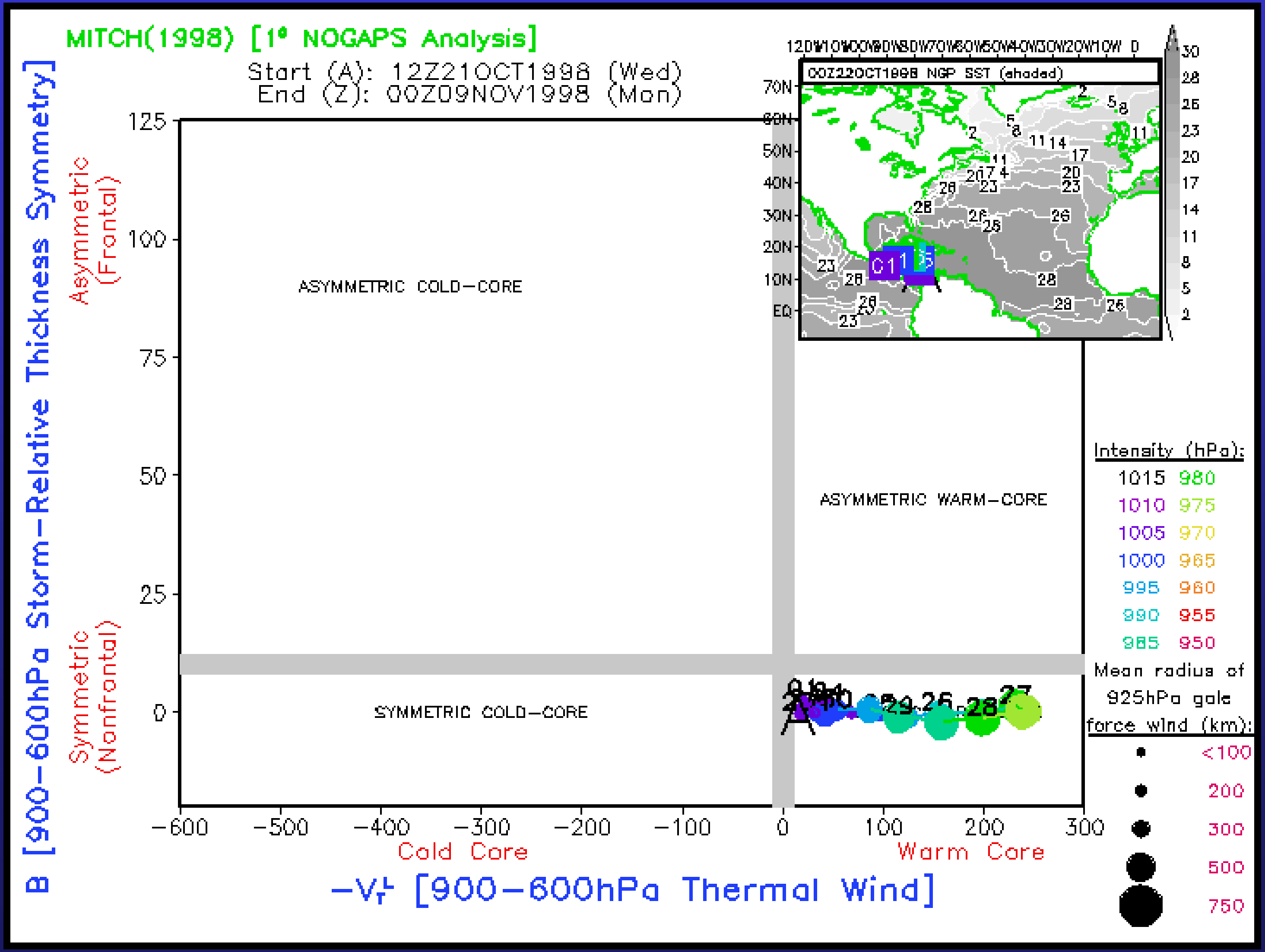
Symmetric warm-core evolution: Hurricane Mitch (1998)

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



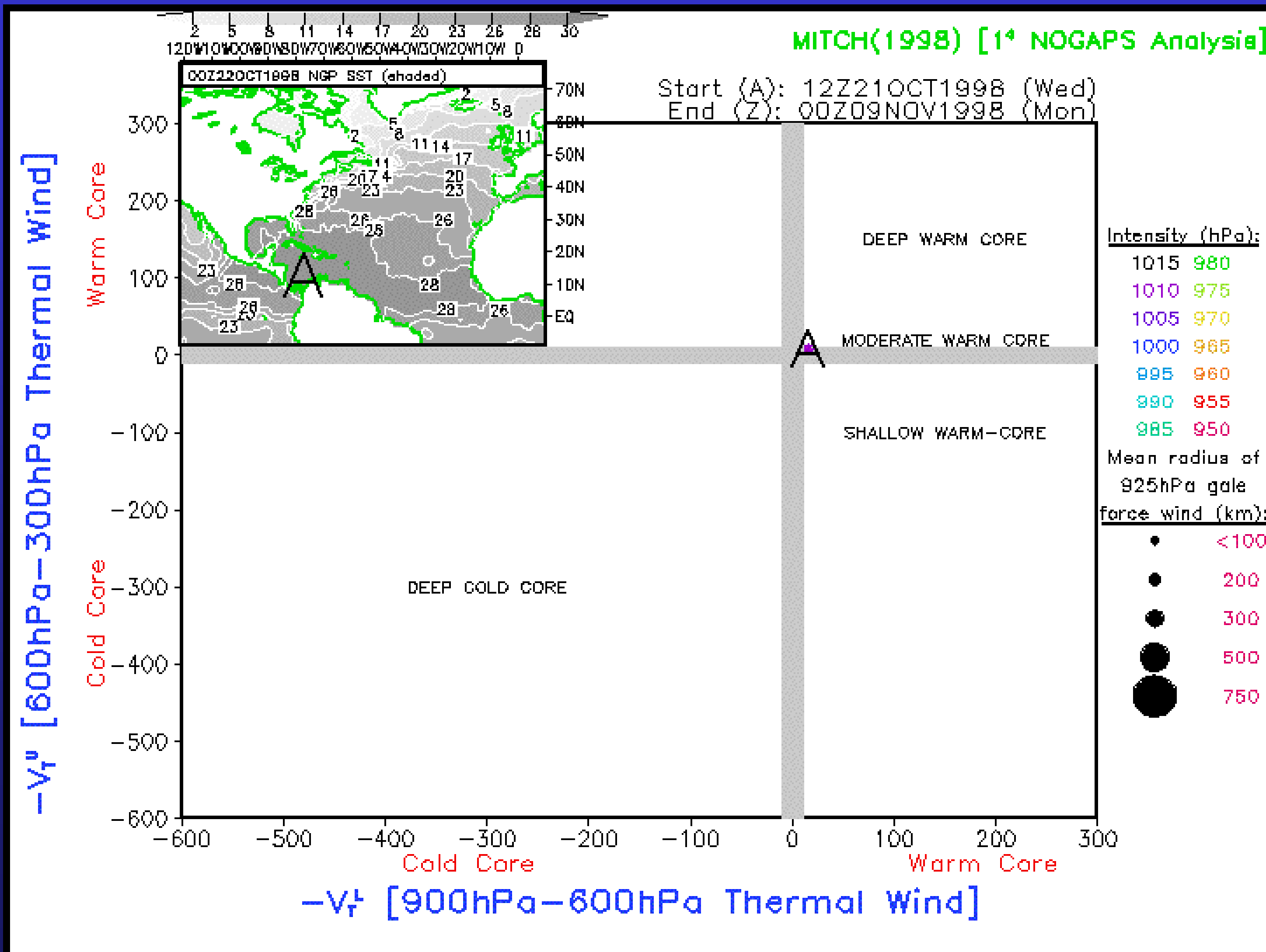
Symmetric warm-core evolution: Hurricane Mitch (1998)

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



Symmetric warm-core evolution: Hurricane Mitch (1998)

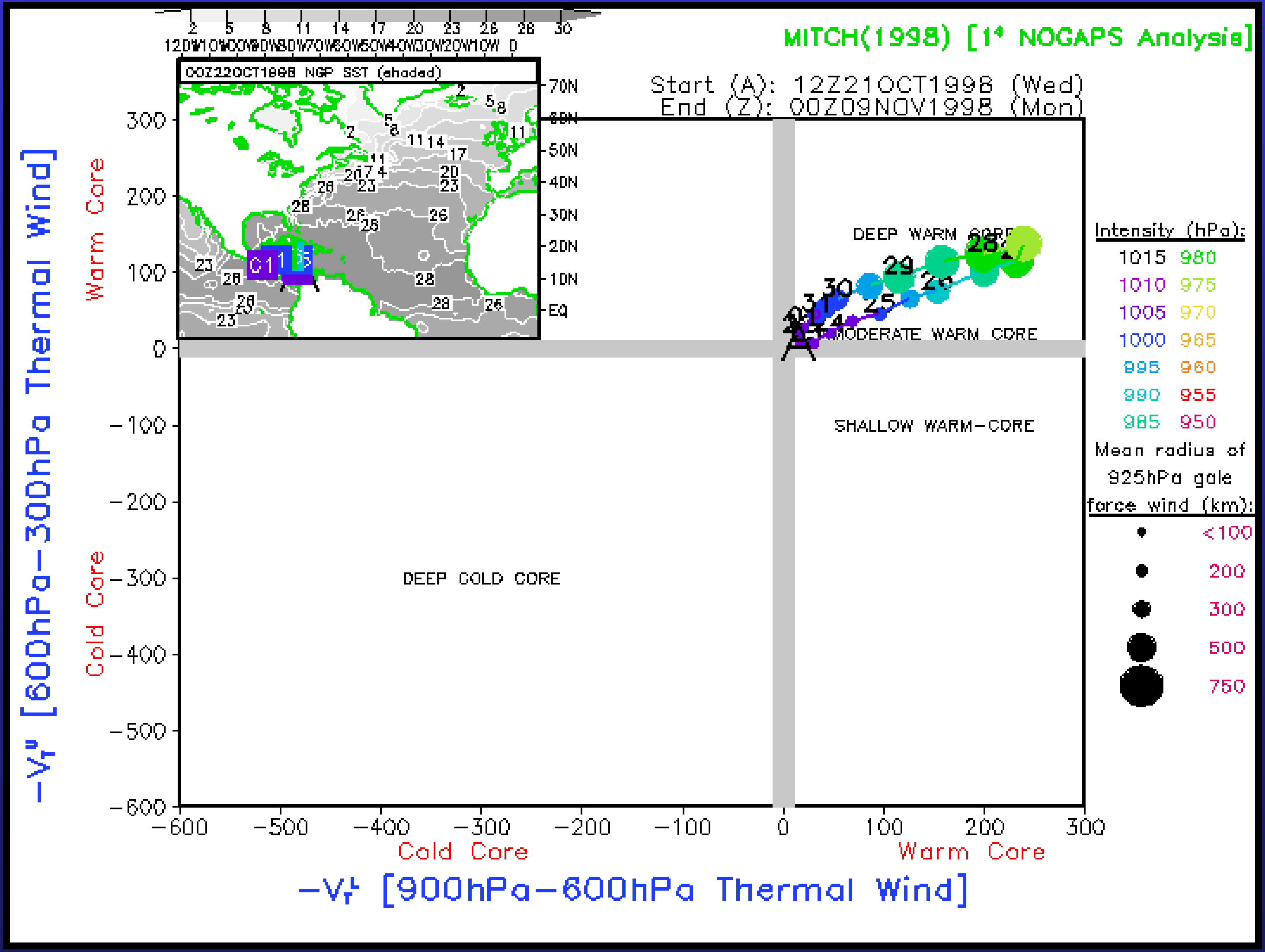
Slice 2: $-V_T^L$ Vs. $-V_T^U$



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.

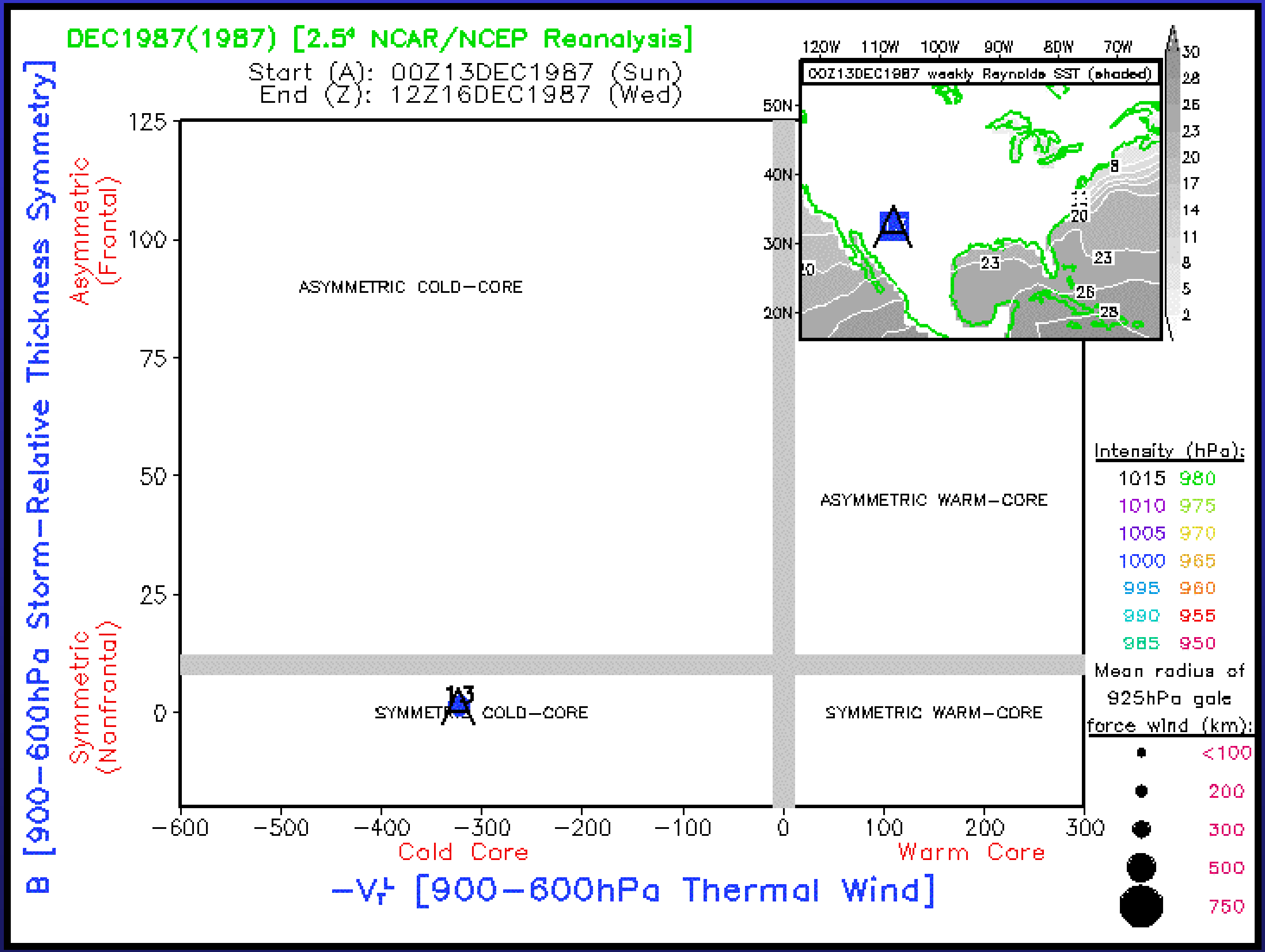
December 1987 Extratropical Cyclone

Case of asymmetric, cold-core development and decay

Classic occlusion of an extratropical cyclone

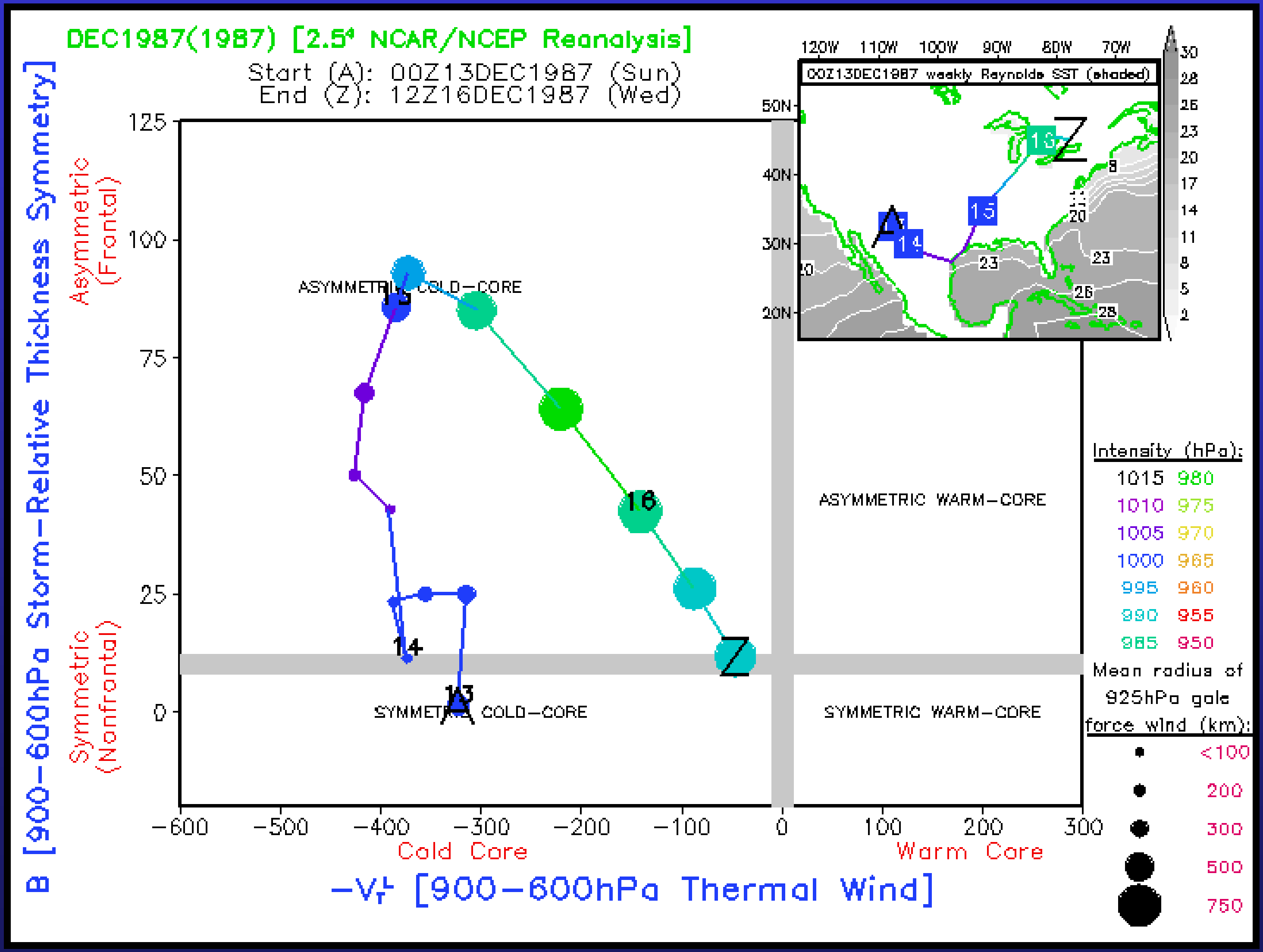
Asymmetric cold-core evolution: Extratropical Cyclone

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



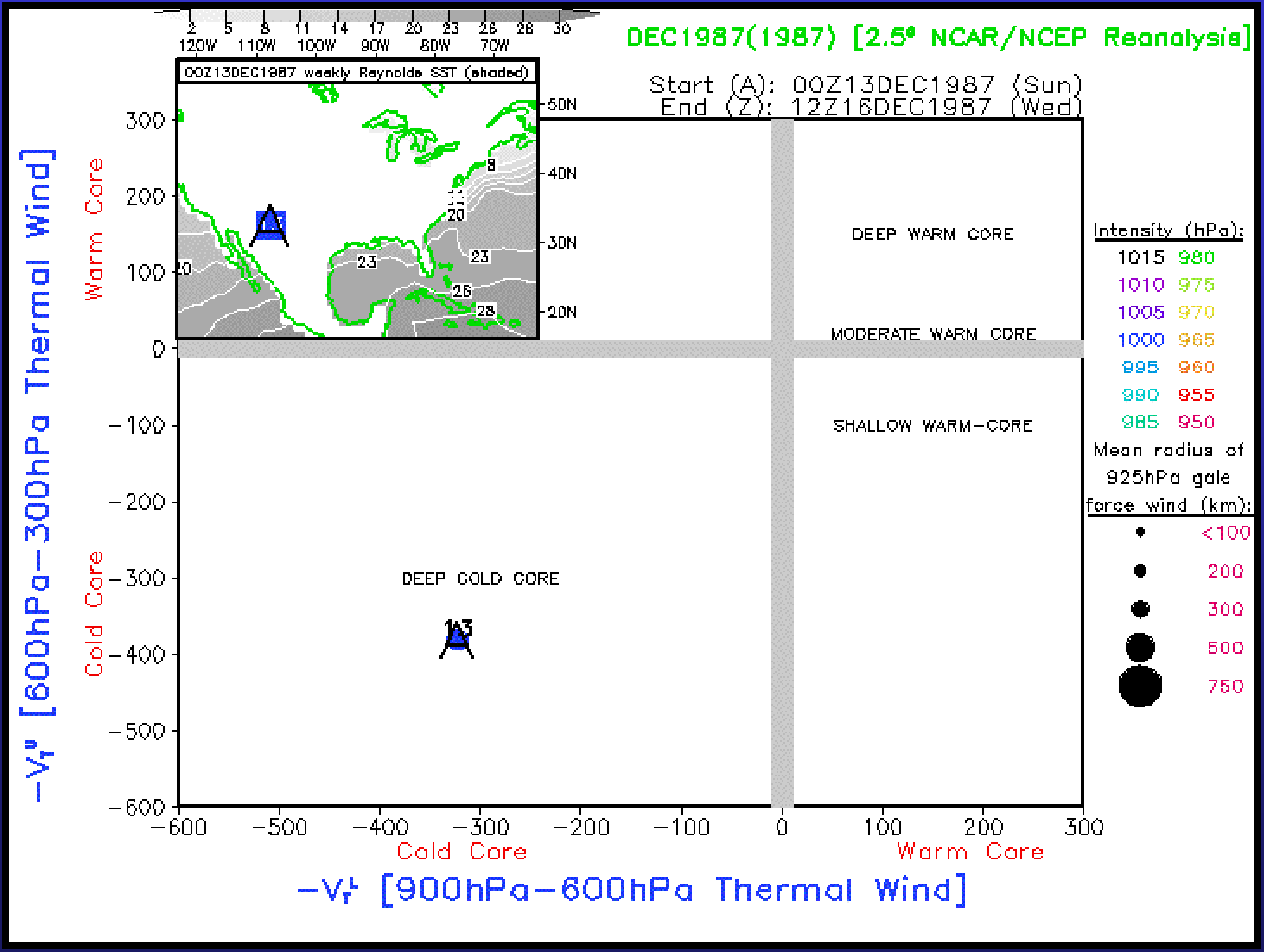
Asymmetric cold-core evolution: Extratropical Cyclone

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



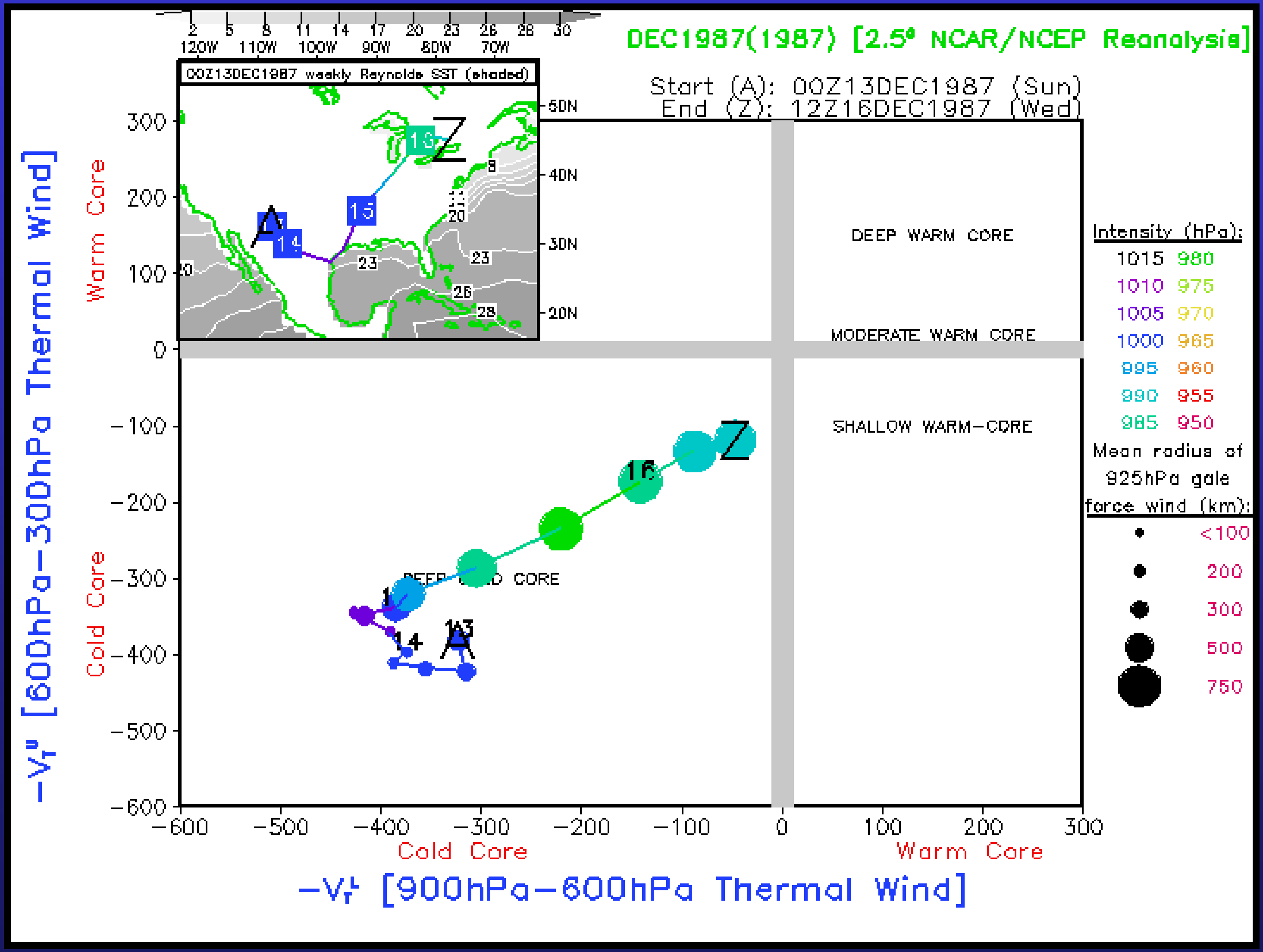
Asymmetric cold-core evolution: Extratropical Cyclone

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



Asymmetric cold-core evolution: Extratropical Cyclone

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

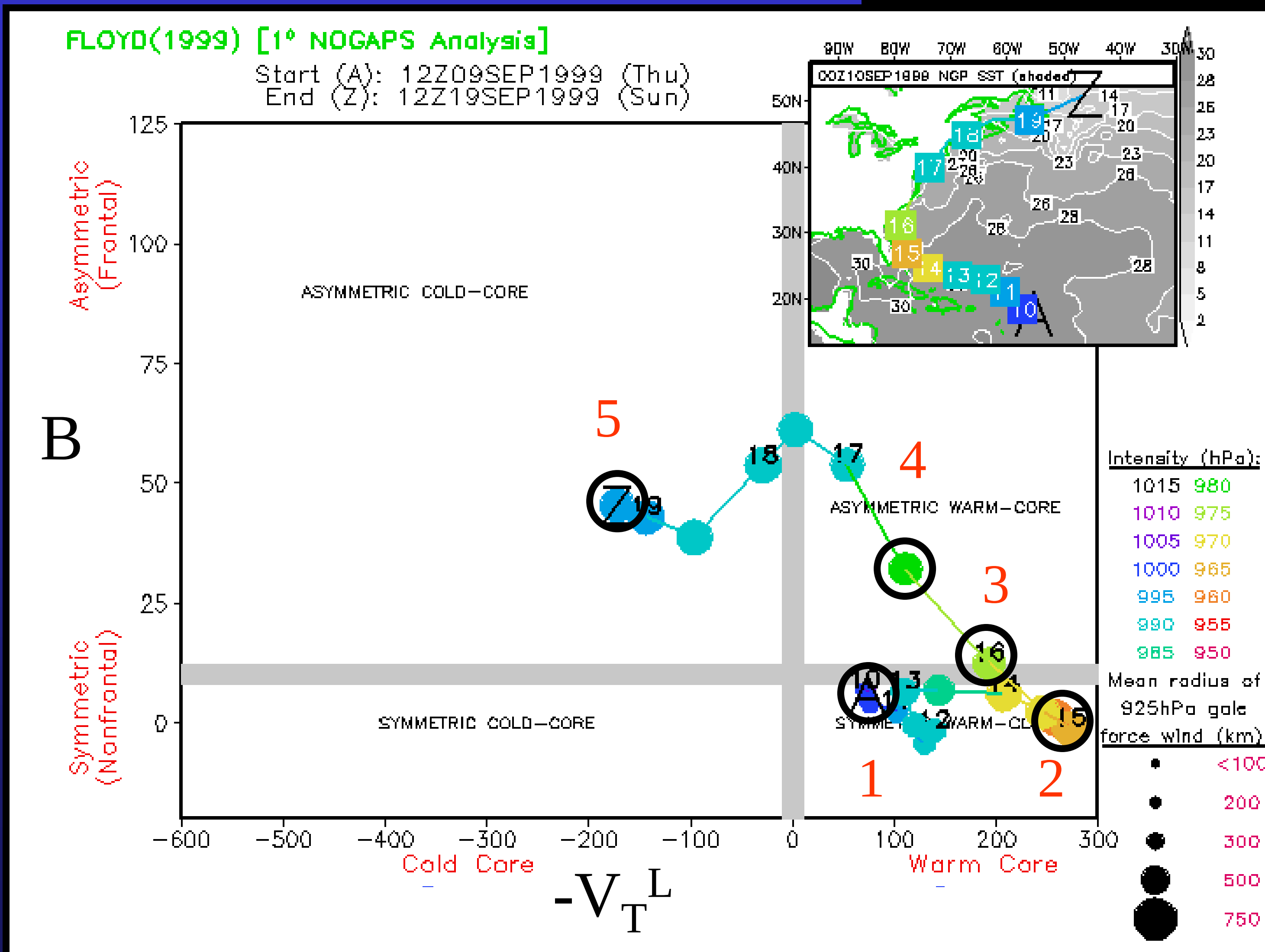


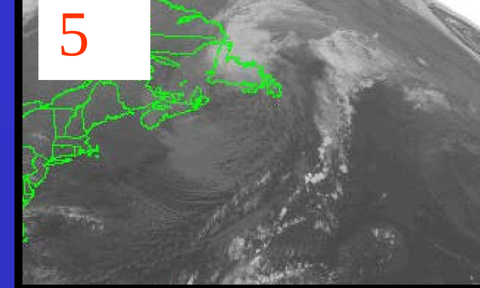
Hurricane Floyd (1999)

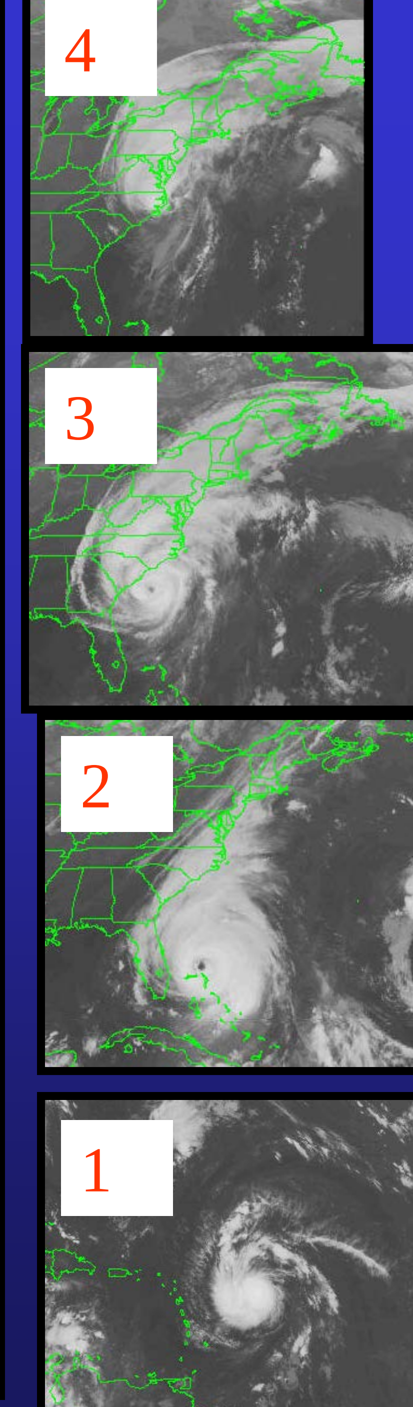
Multiple phase evolution:

Case of extratropical transition of a tropical cyclone

Warm-to-cold core transition: Extratropical Transition of Hurricane Floyd (1999): B Vs. $-V_T^L$



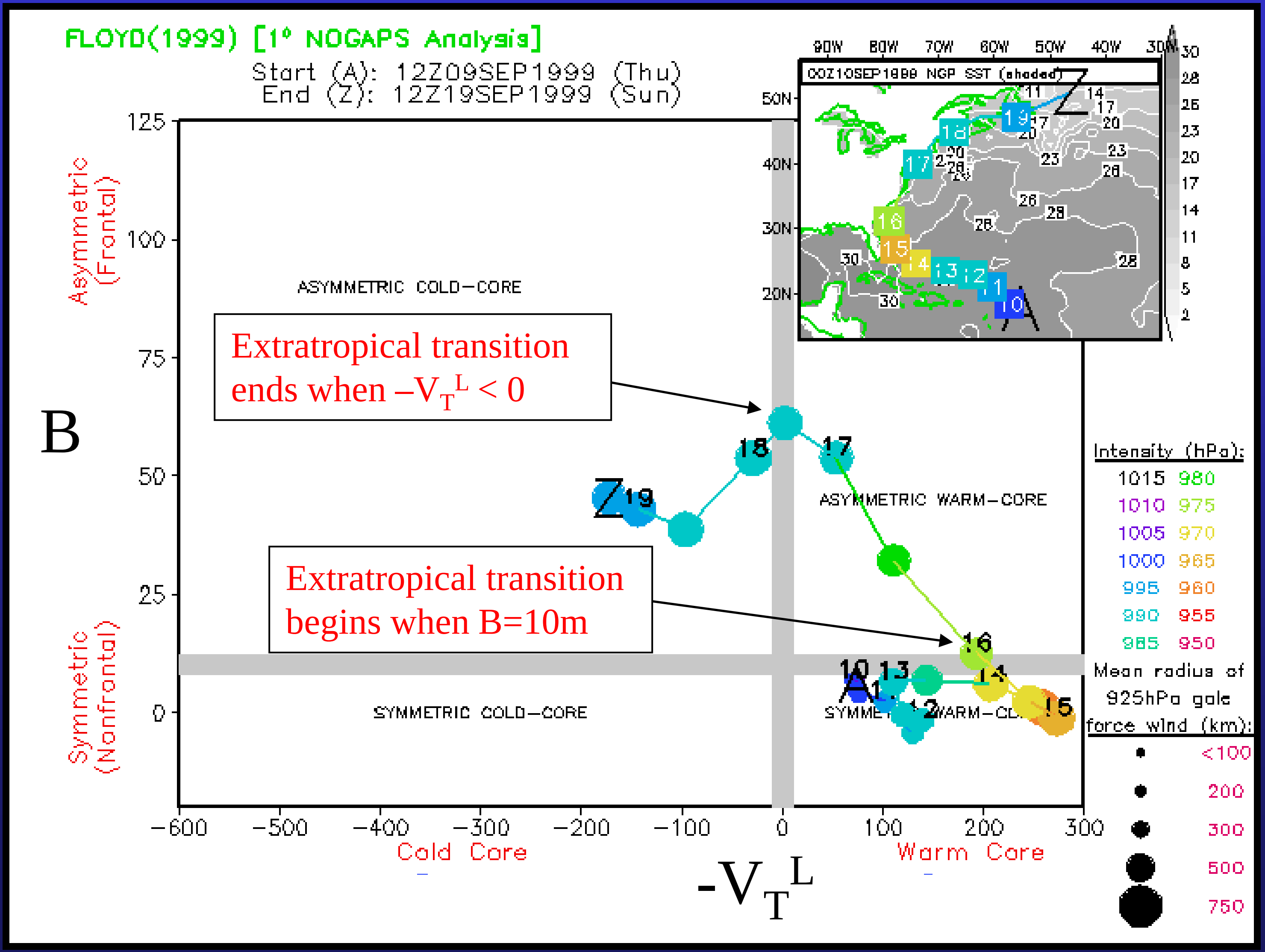




Warm-to-cold core transition:

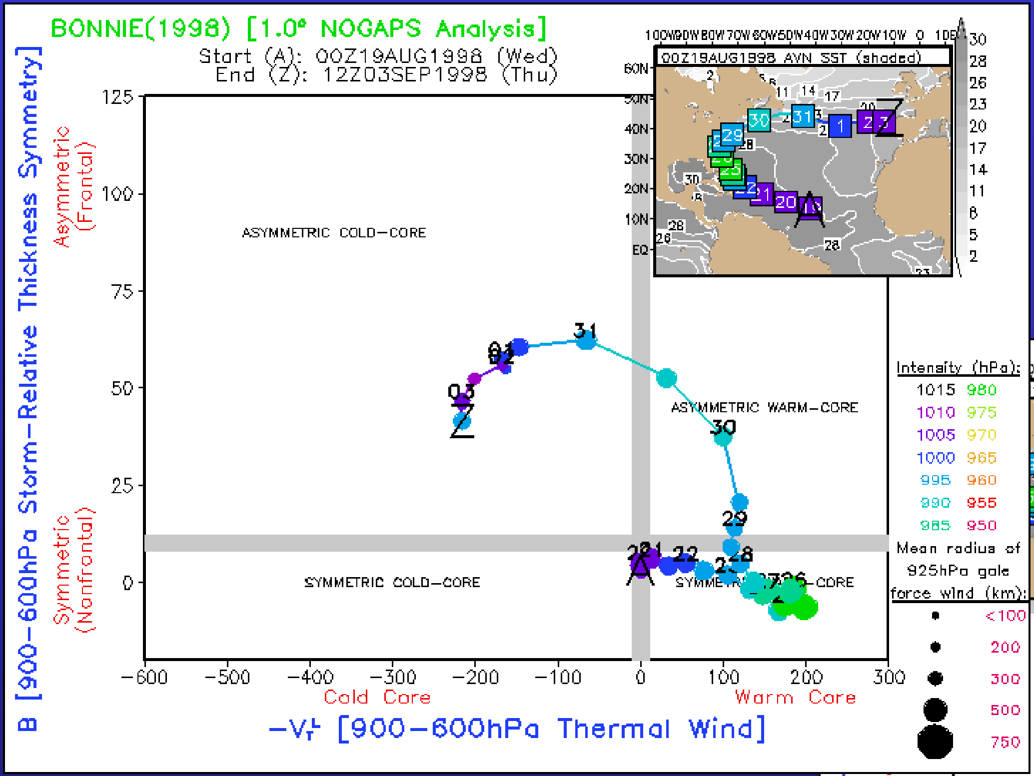
Extratropical Transition of Hurricane Floyd (1999)

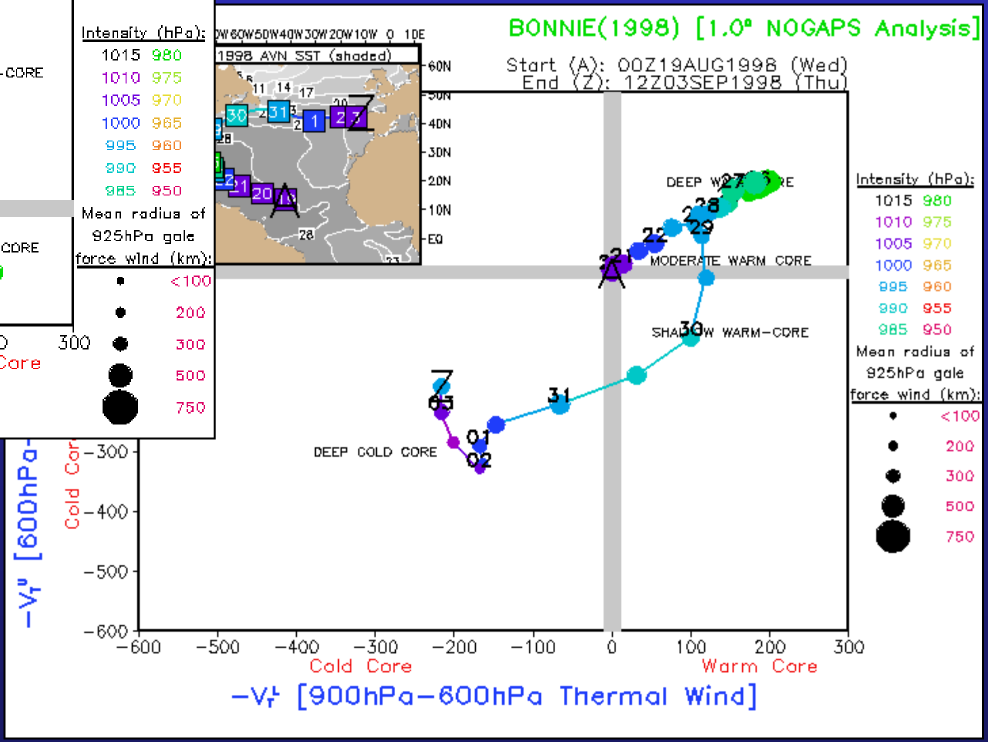
B Vs. $-V_T^L$



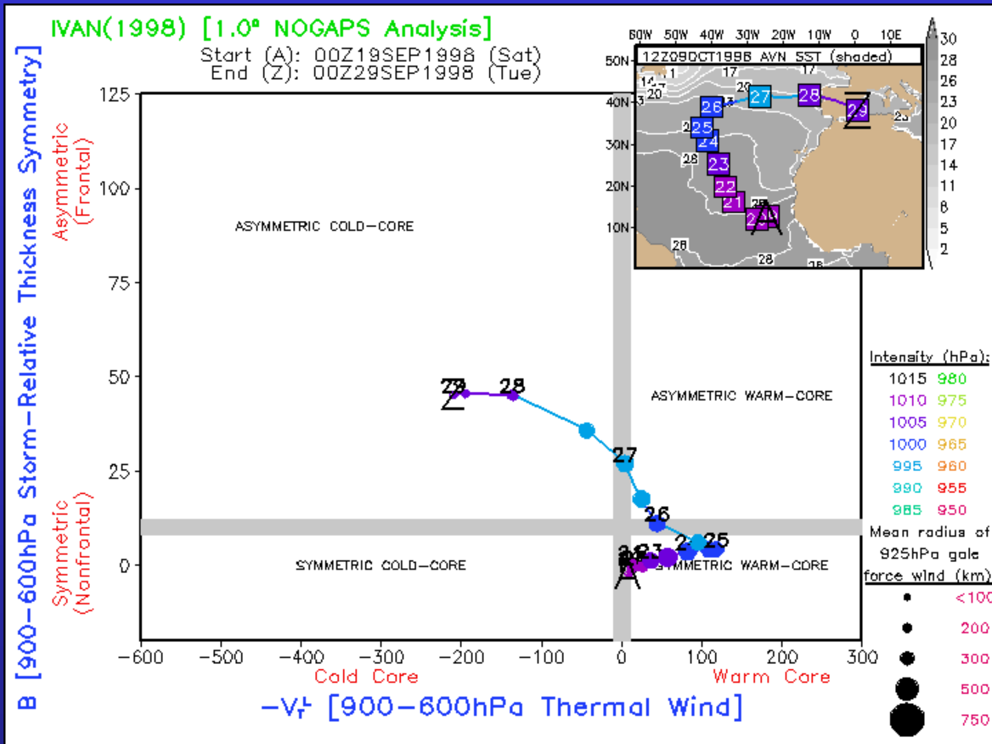
⇒Provides for objective indicators of extratropical transition lifecycle.

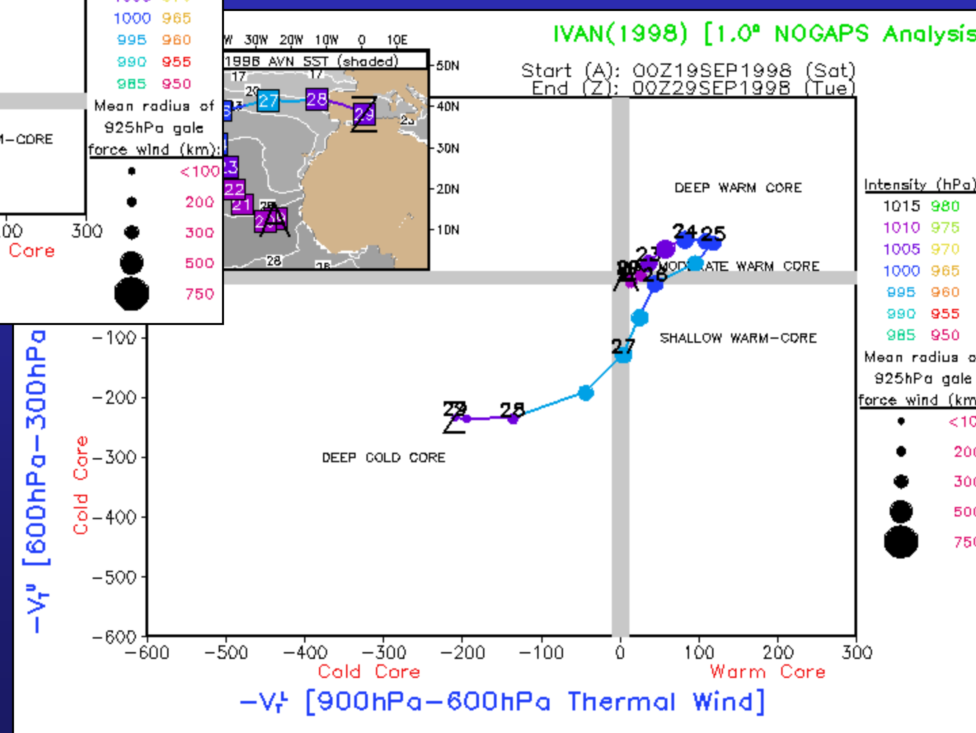
ET Phase Trajectory Example: NWATL



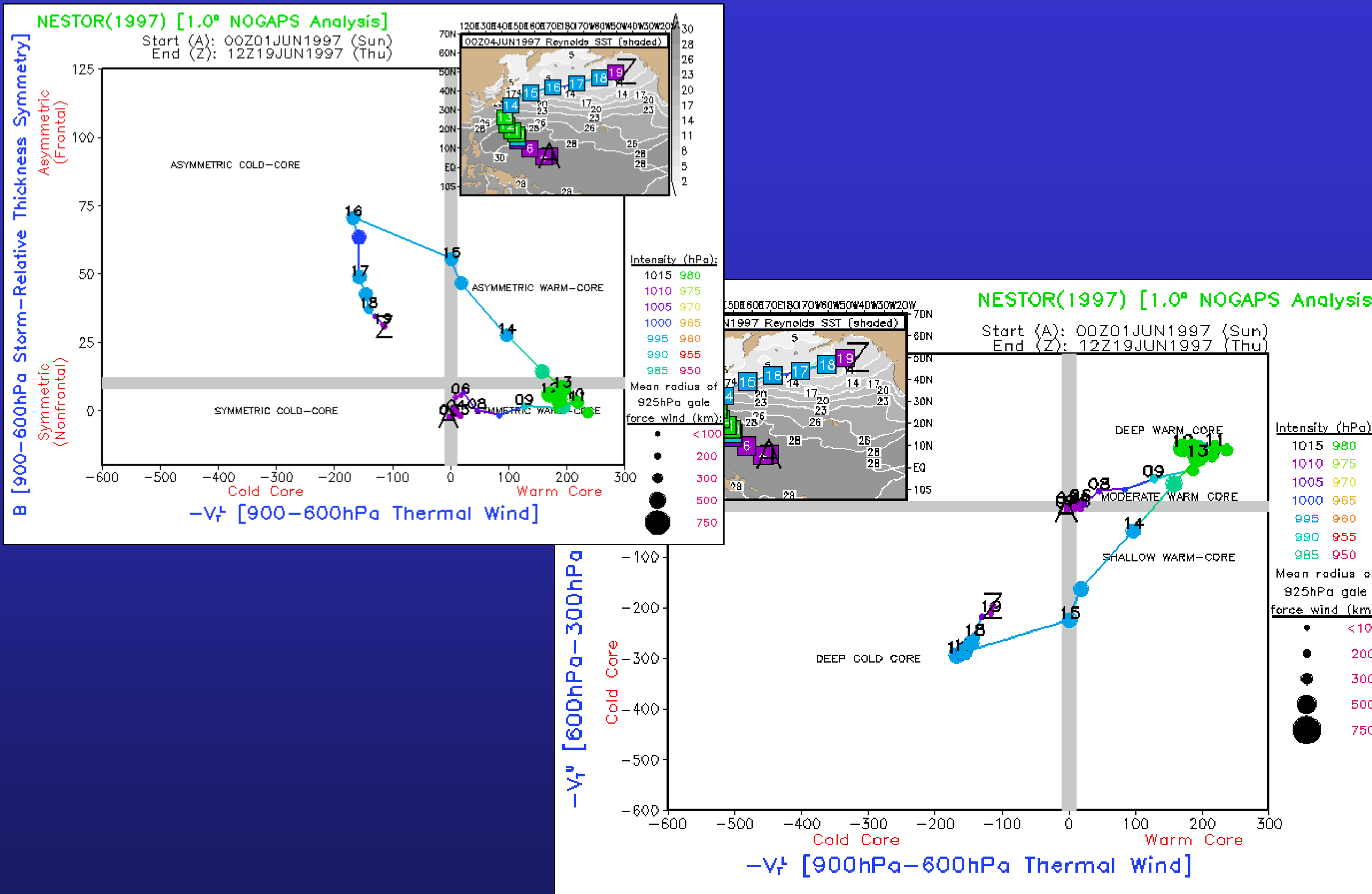


ET Phase Trajectory Example: NEATL

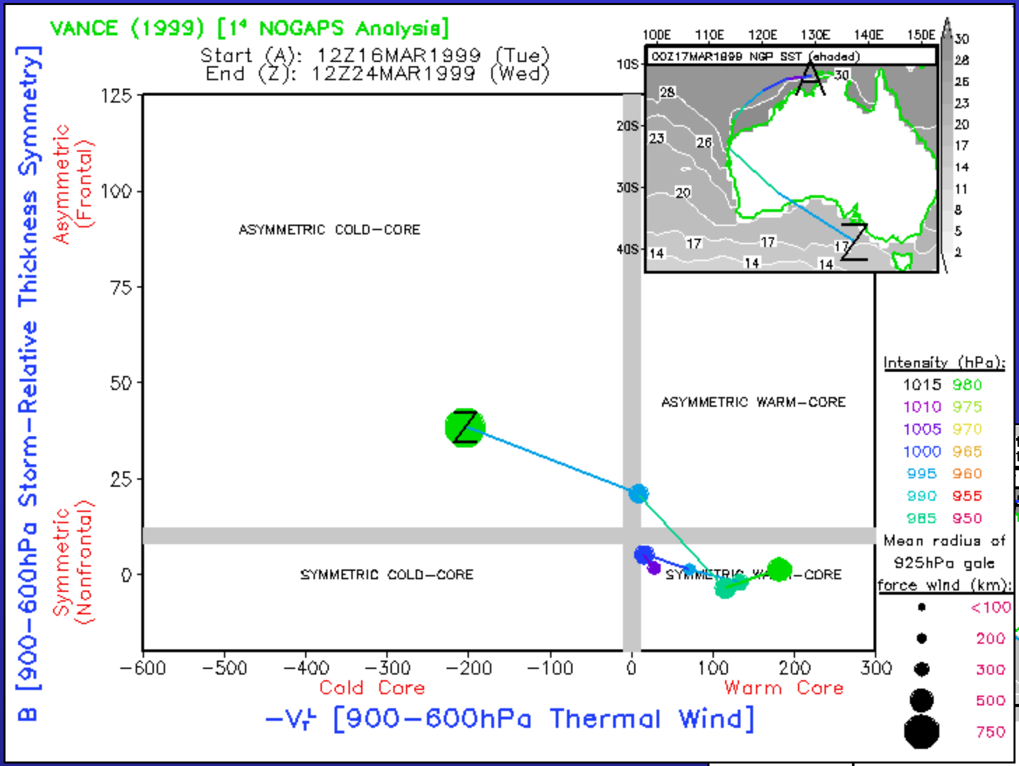


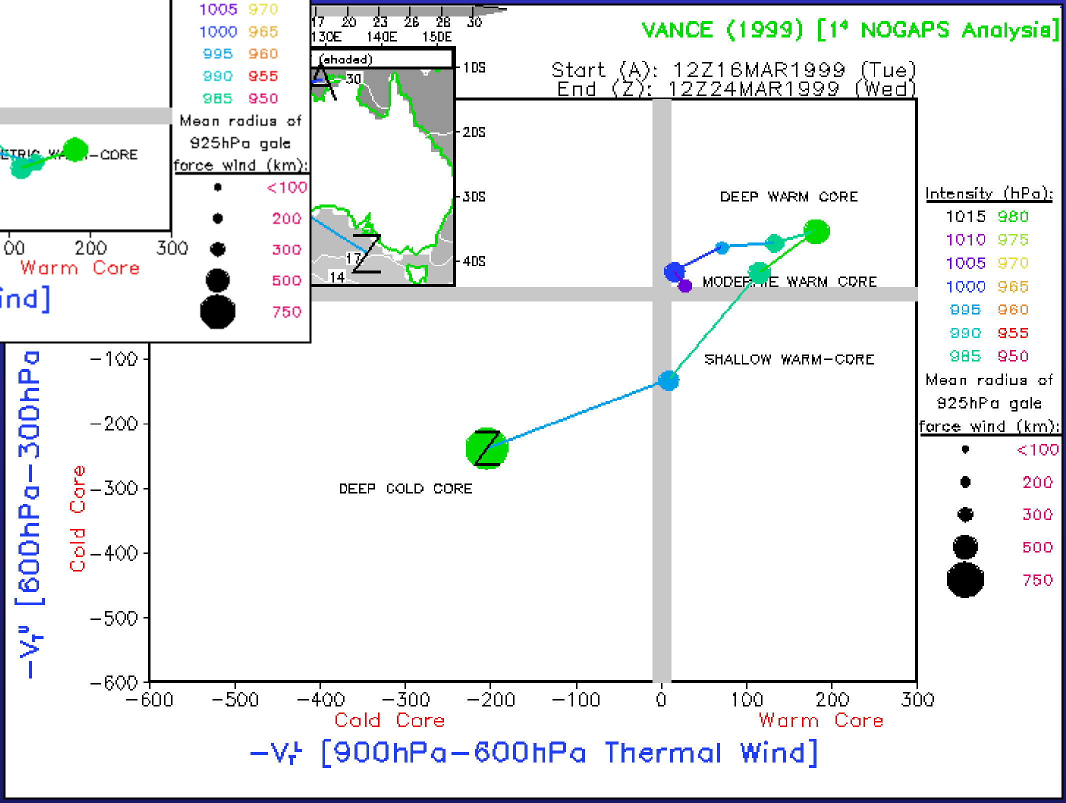


ET Phase Trajectory Example: WPAC

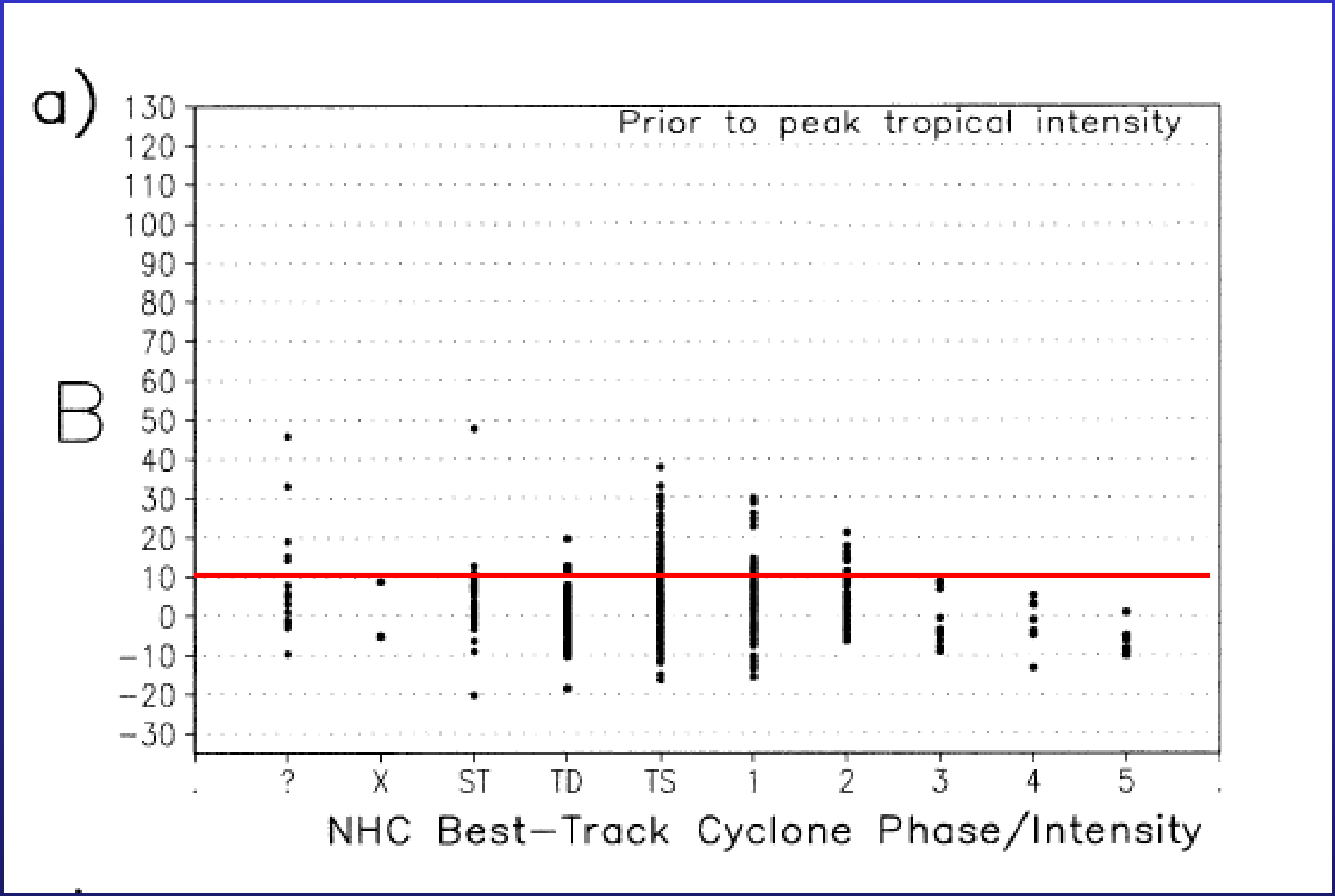


ET Phase Trajectory Example: Aust





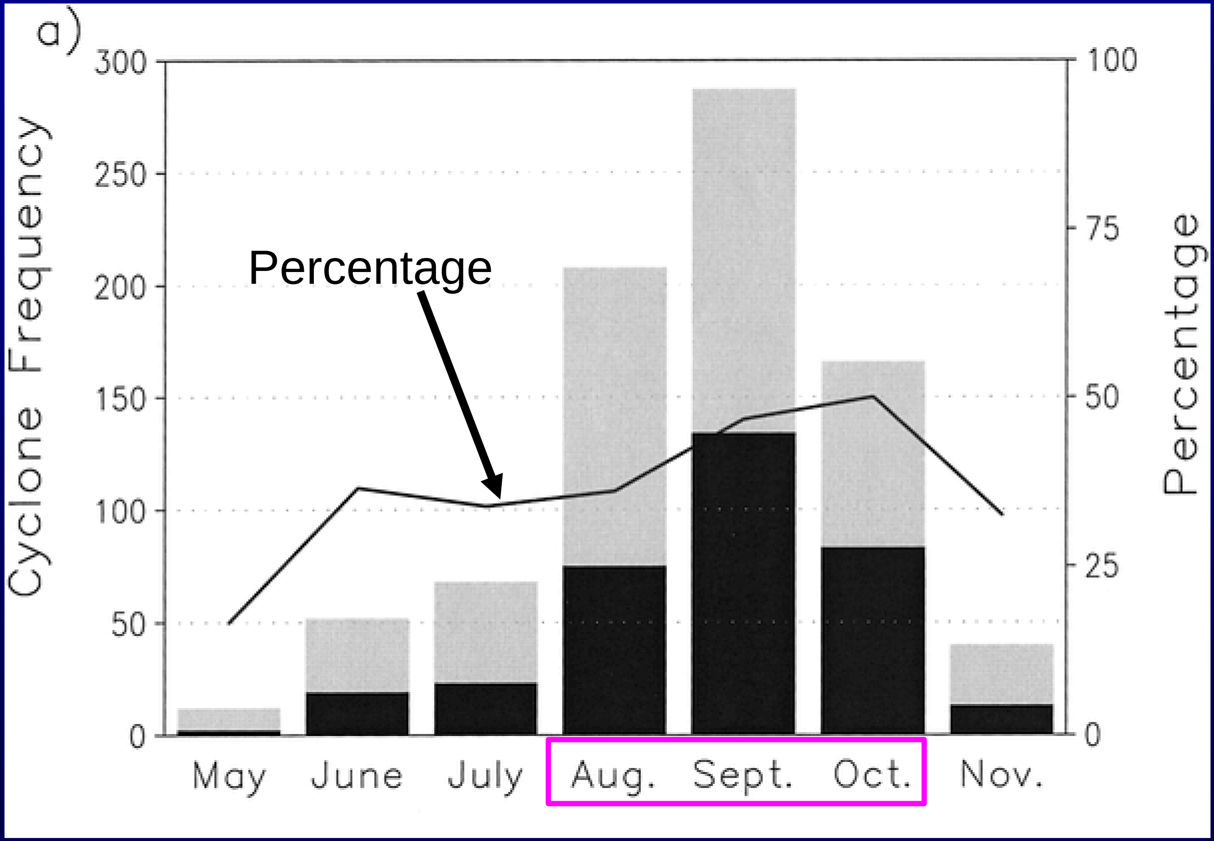
Cyclone Parameters Overview: B



Evans & Hart 2003

North Atlantic ET Climatology

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



Number of TCs

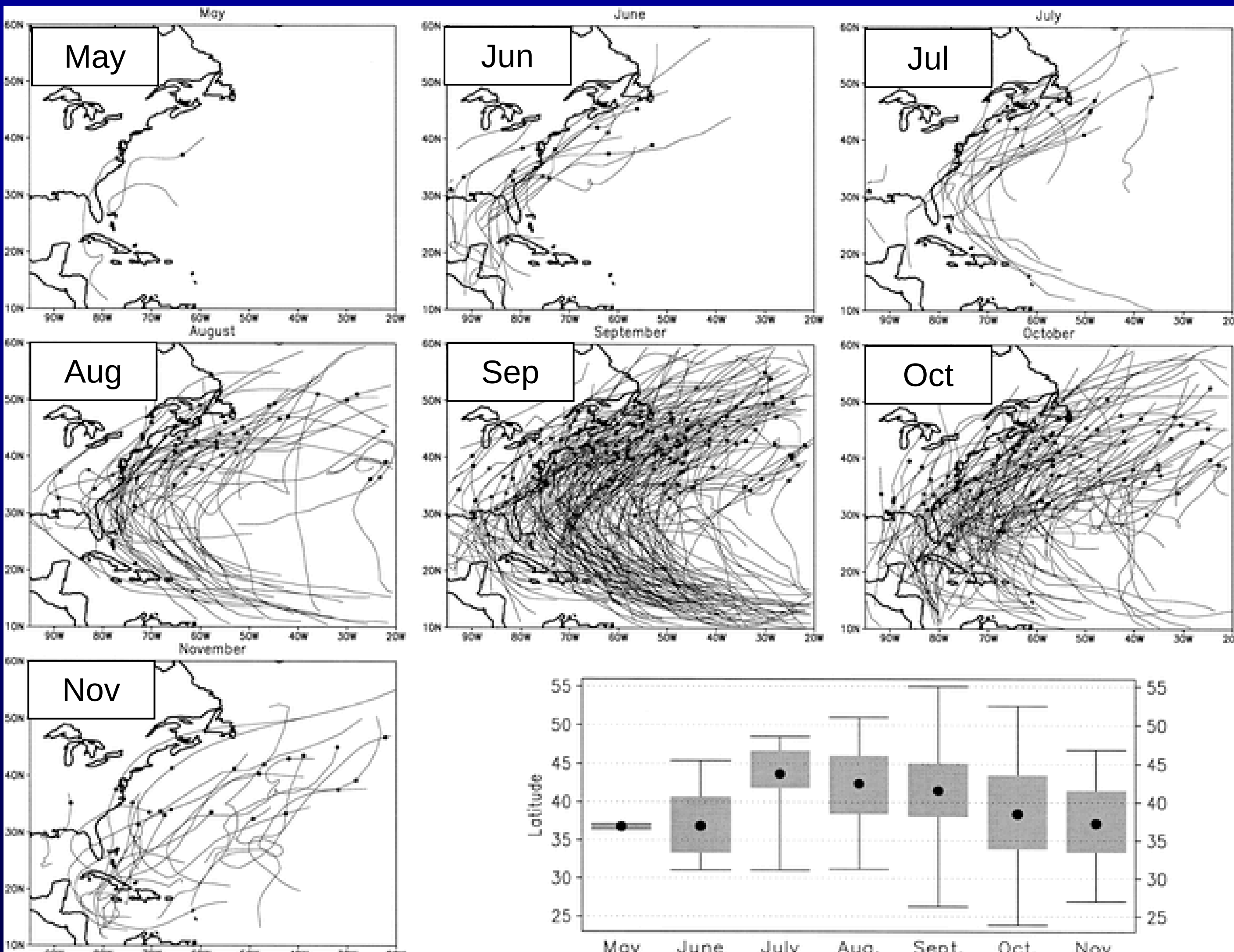
Number of TCs undergoing ET

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)

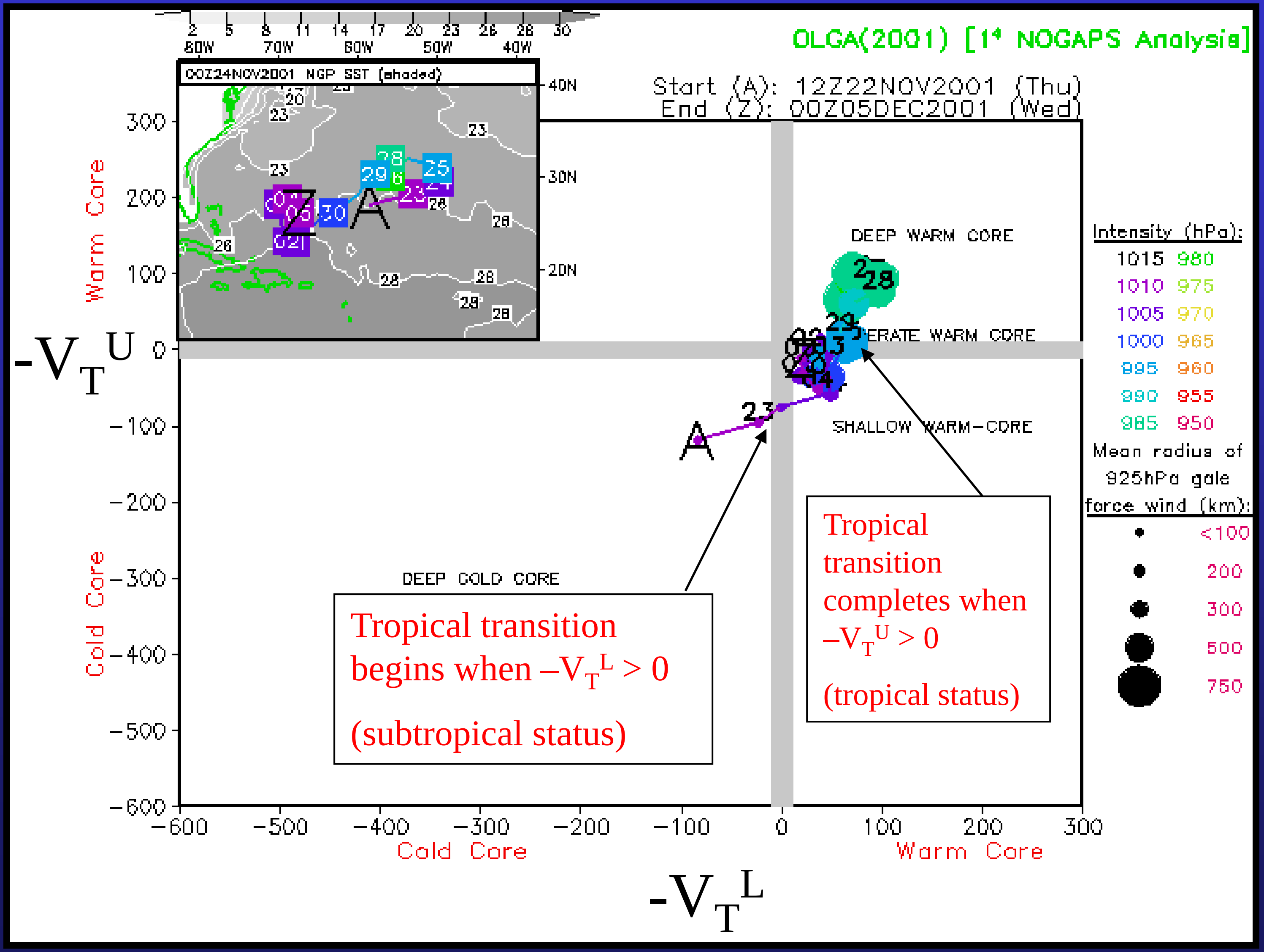
Multiple phase evolution:

Case of tropical transition of a cold-core cyclone

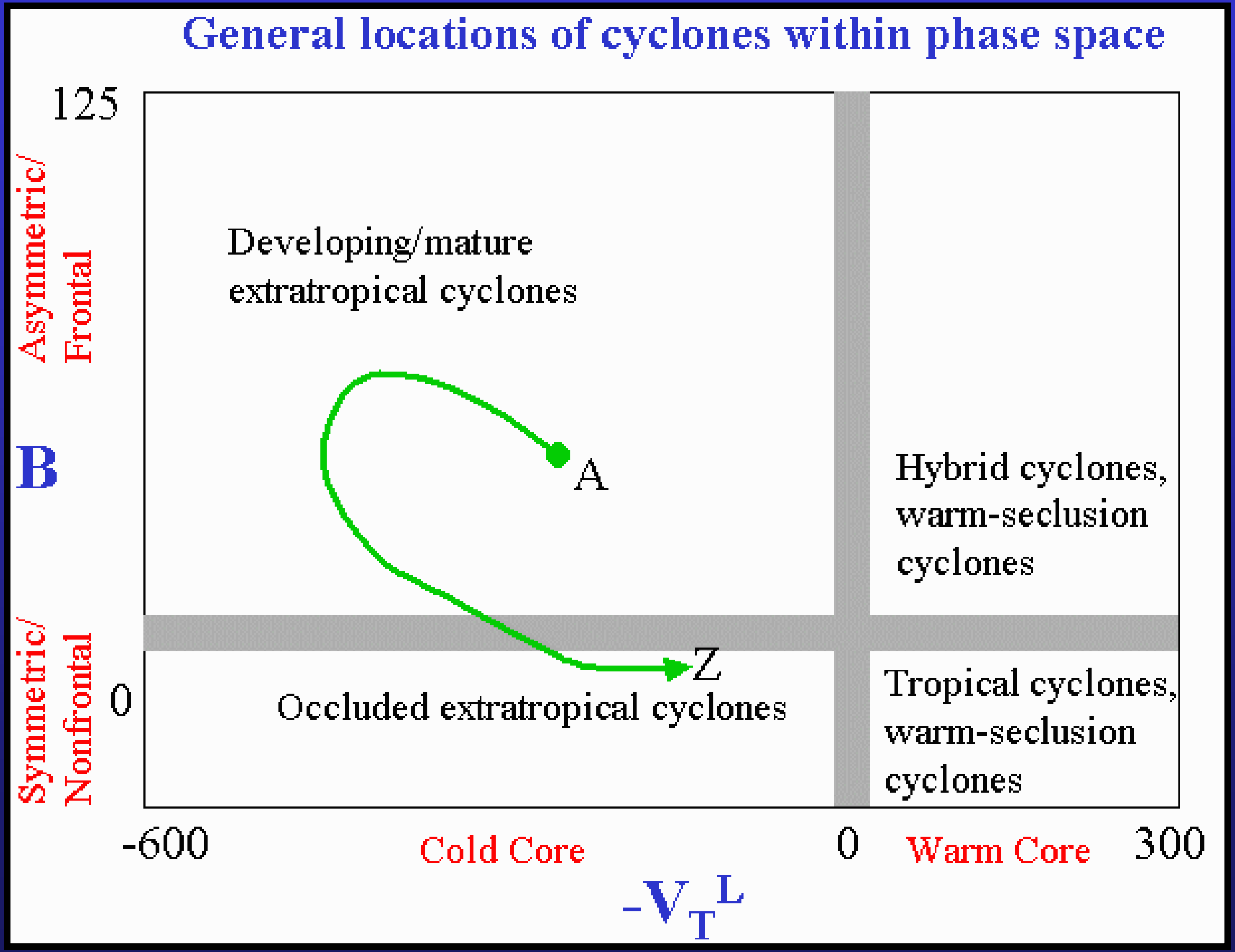
Cold-to-warm core transition:

Tropical Transition of Hurricane Olga (2001)

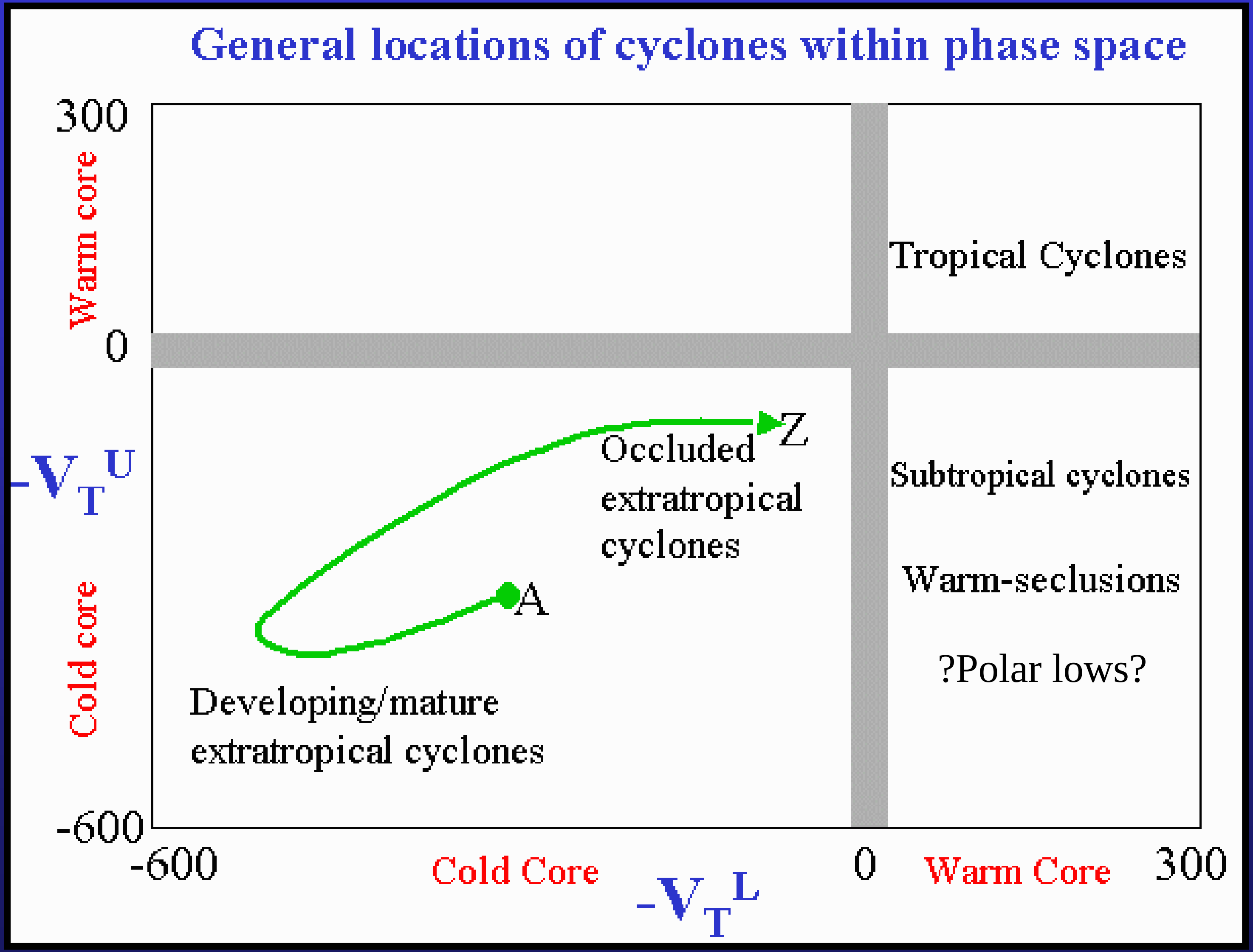
$-V_T^U$ Vs. $-V_T^L$



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, and growing every year

File Edit View History Bookmarks Tools Help

Cyclone phase evolution: Anal...

moe.met.fsu.edu/cyclonephase/

Cyclone phase evolution: Analyses & Forecasts

This page presents historical, analyzed (current), and model-forecast cyclone phase diagrams for northwestern hemisphere cyclones with the goals of improved structural forecasting, structural transition (subtropical/tropical/extratropical), cyclogenesis, and providing measures of structural predictability.

Please note that these products are experimental and not official forecasts. For official forecasts in the U.S., please refer to the National Weather Service and National Hurricane Center.

To the right are the most recently picked interesting diagrams. In this case, the UKMET analysis of extratropical transition of Ignacio and "landfall" near the Alaskan border as a weakening extratropical storm.

Latest deterministic model output:
CMC: 2015111712 GFS: 2015111712
NAVGEM: 2015111612 UKM: 2015111712

Current/recent GFDL model output:
invest90e: 2015111712 invest99e: 2015111612

Current/recent NCEP HWRF model output:
invest90e: 2015111712 invest93p: 2015111712
invest95w: 2015111618 invest97b: 2015111712
invest99e: 2015111612 twenty-se27w: 2015111712

Current/recent CIRA/NESDIS AMSU based diagrams:
ep902015: 2015111712 io972015: 2015111712
sh932016: 2015111712 wp272015: 2015111712
wp952015: 2015111700

Ensemble output:
Latest deterministic intercomparison: [2015111706 | 2015111700]

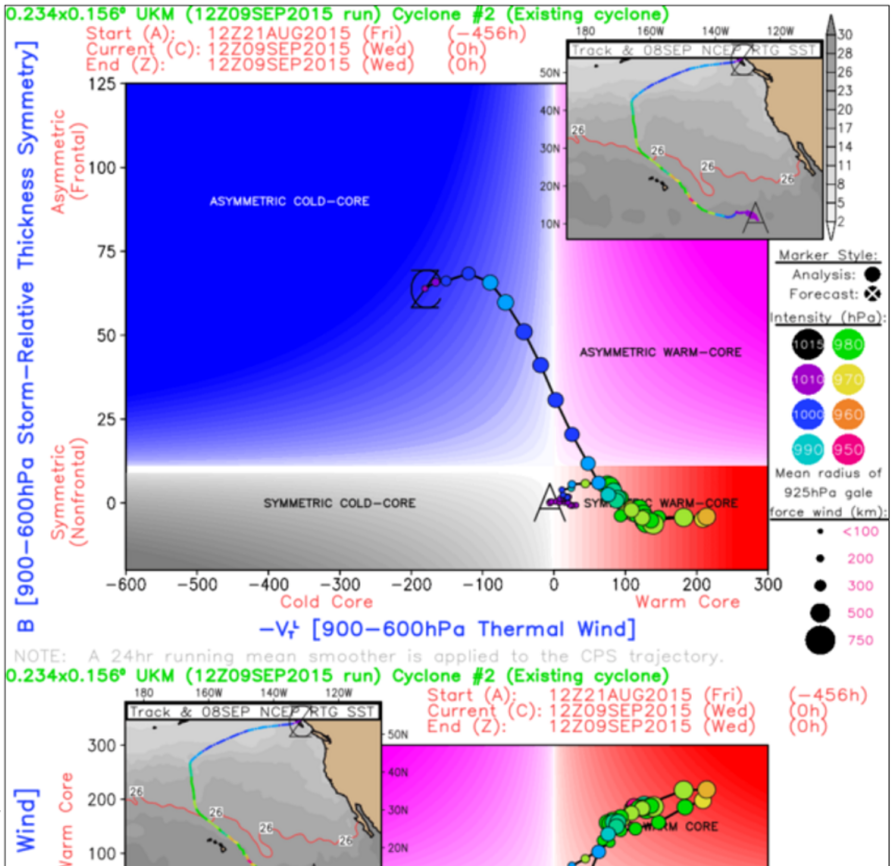
Latest CMC Ensemble: [2015111700 | 2015111612]

Latest GFS Ensemble: [2015111600 | 2015111512]

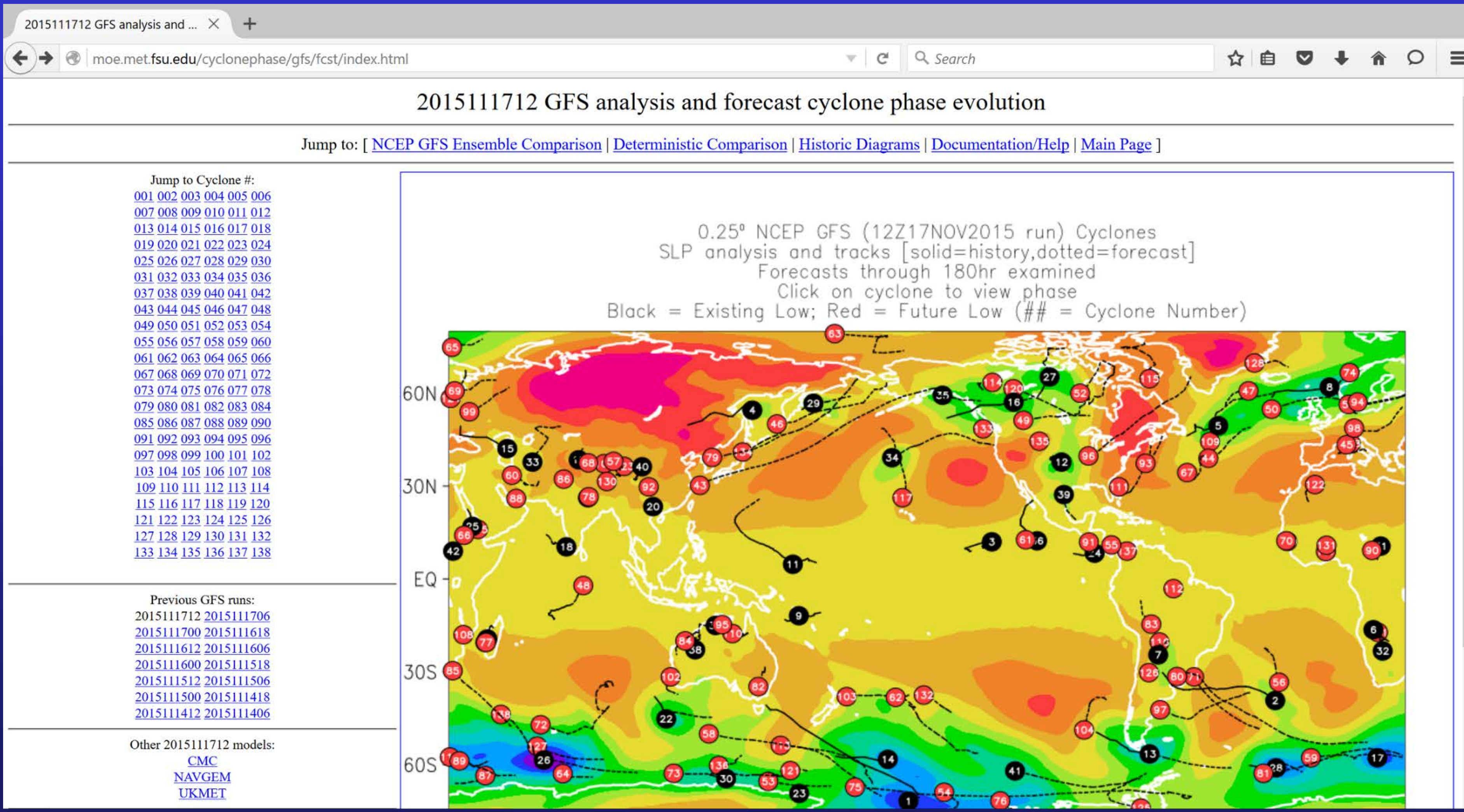
Latest NGP Ensemble: [2015111700 | 2015111612]

Latest CMC+GFS+NGP Ensemble: [2015111600 | 2015111512]

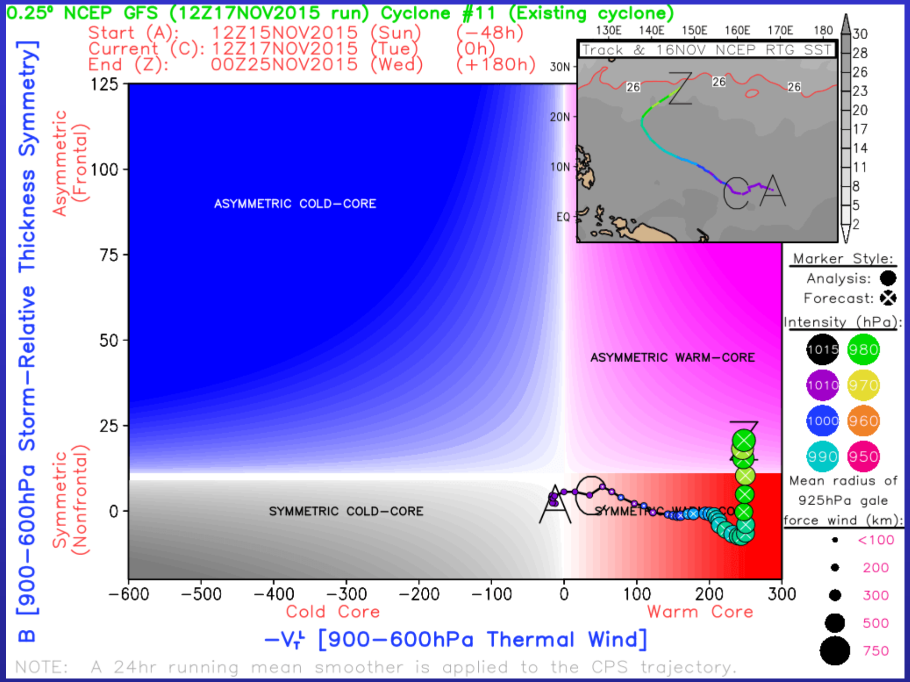
Example phase diagrams from past events: [View]



Example real-time cyclone availability for GFS

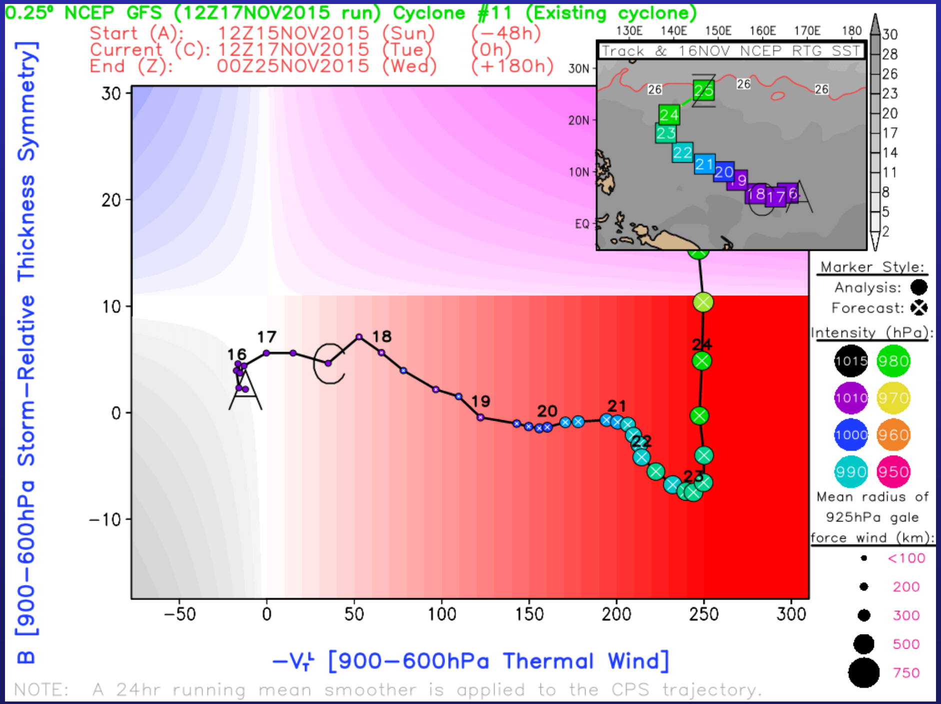


Example GFS forecast TC



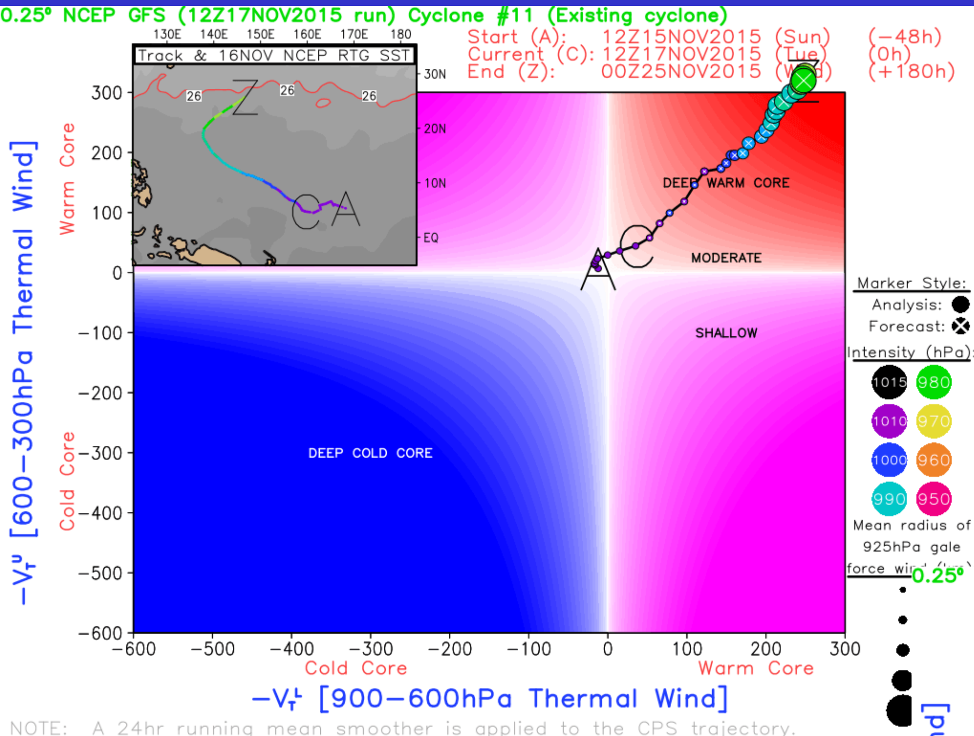
Forecast phase analysis

Zoomed

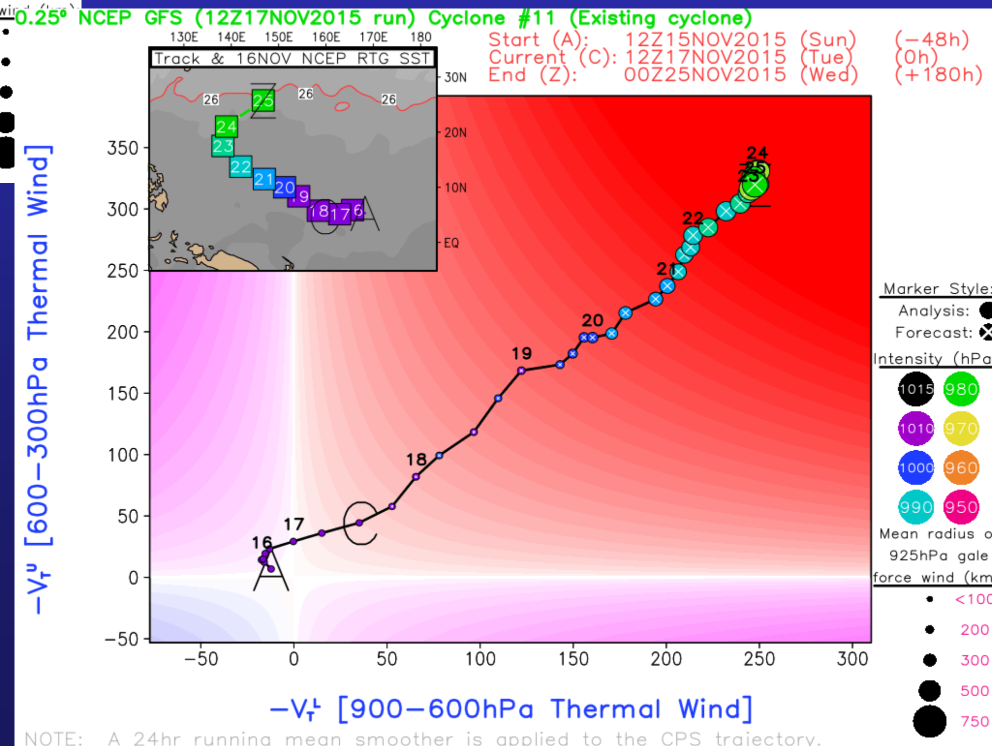


Example GFS forecast TC

Forecast phase analysis



Zoomed



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

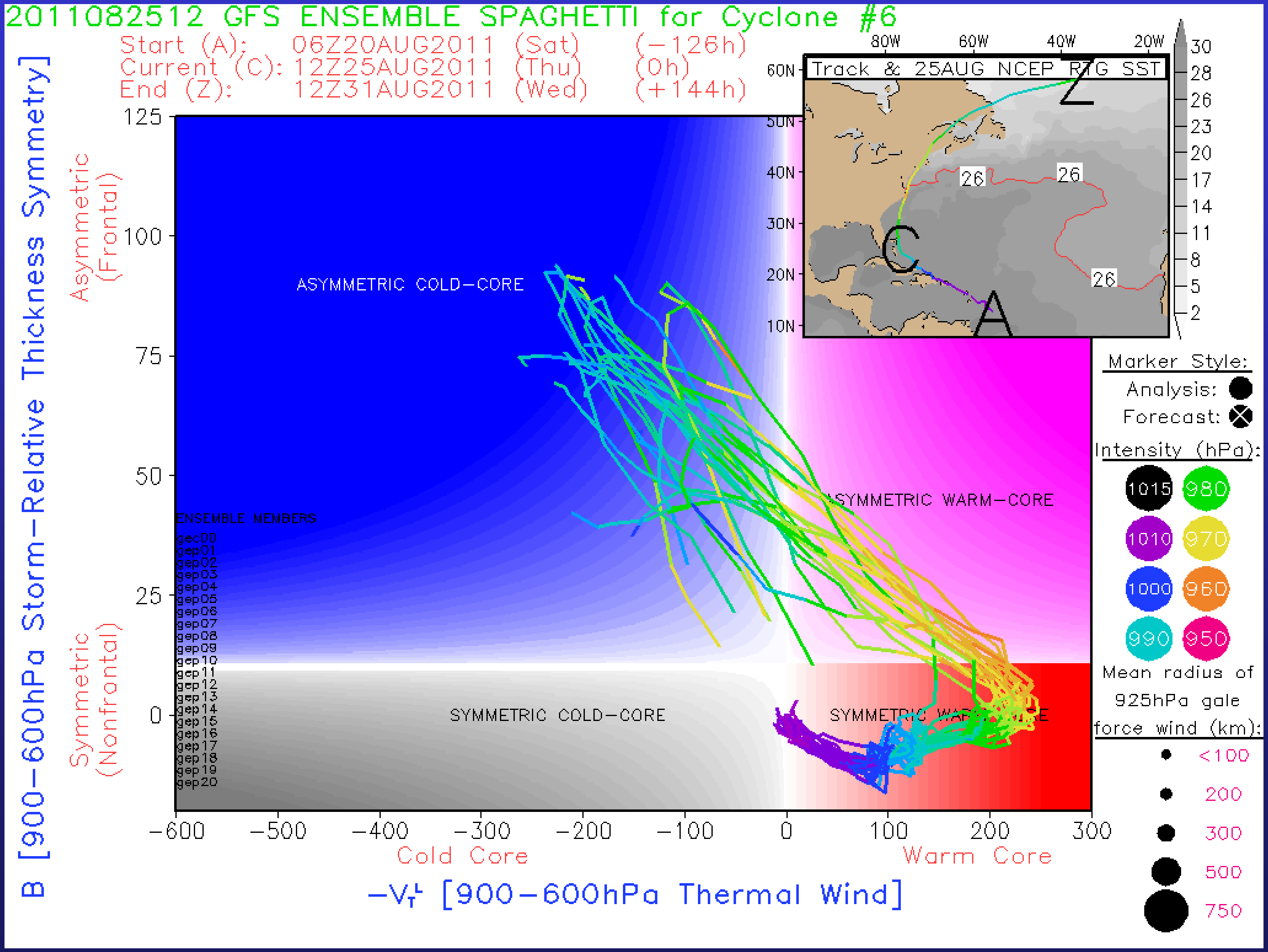
- Phase diagram quadrants are shaded to give more rapid interpretation

Ensemble cyclone phase

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

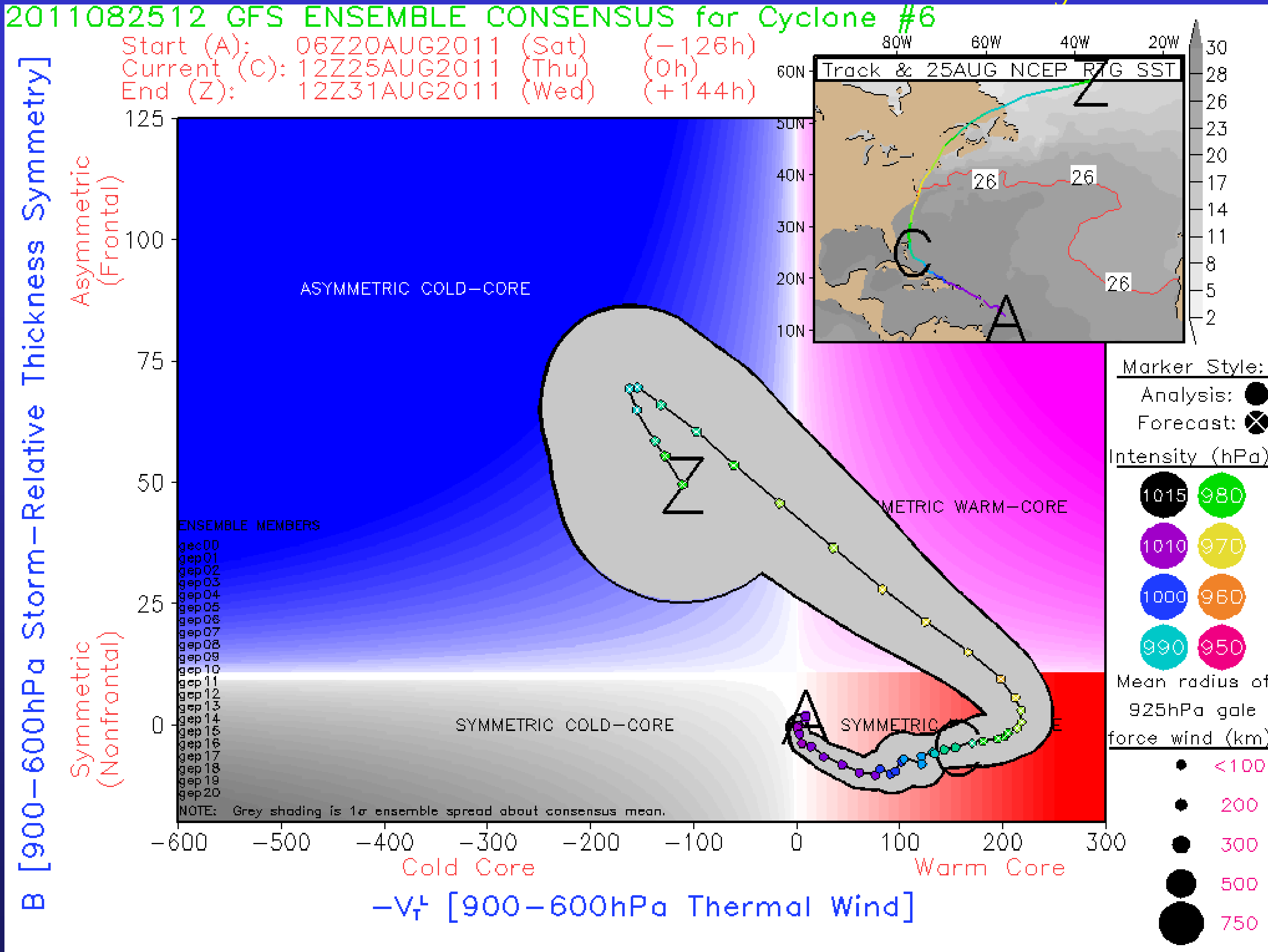
Multiple model solutions:

Measure of structural forecast uncertainty

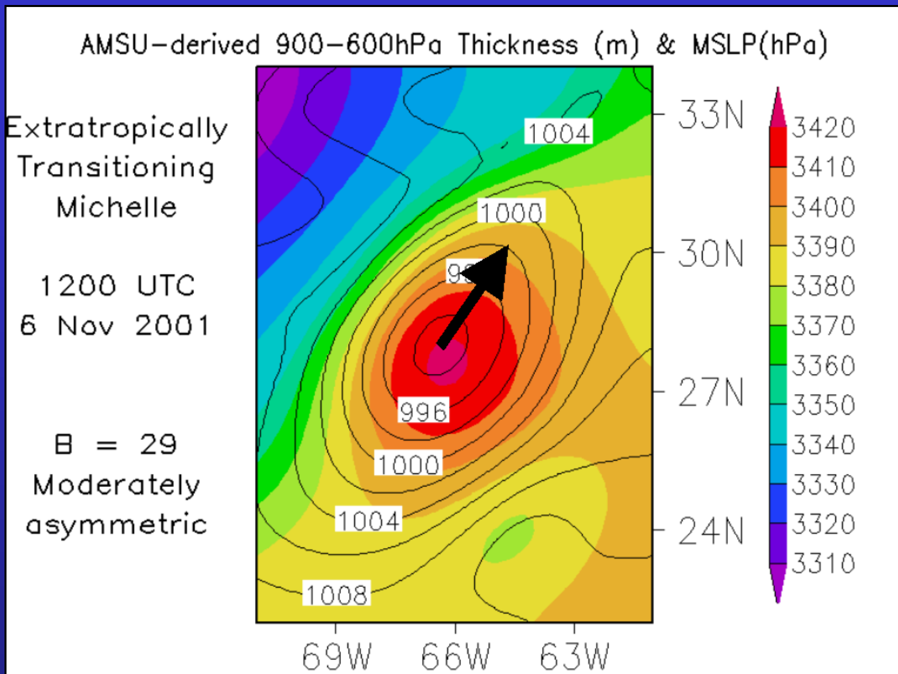


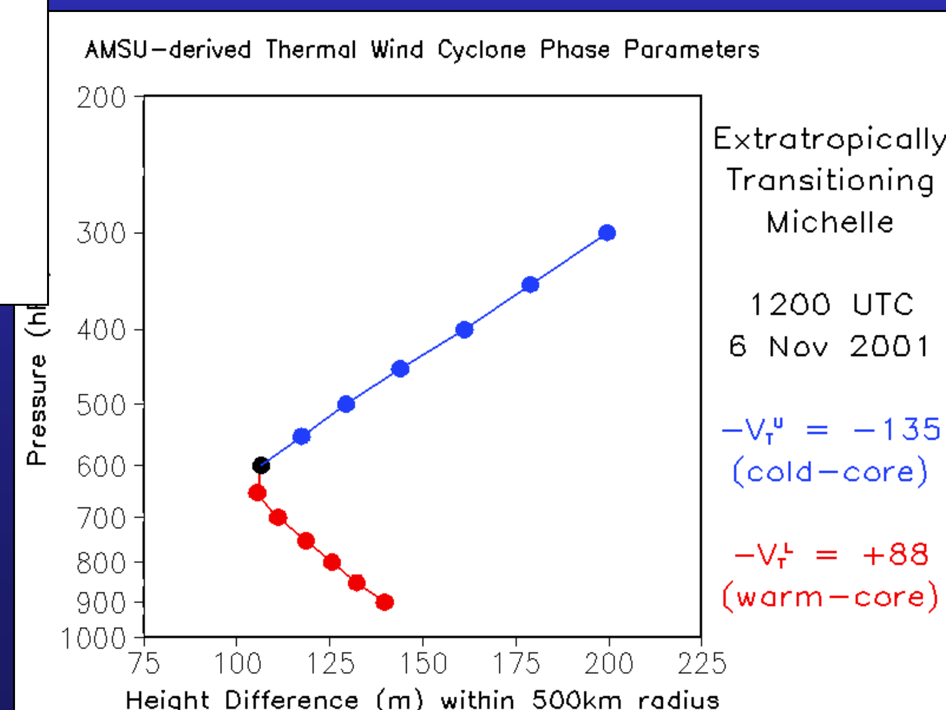
Multiple model solutions:

Measure of structural forecast uncertainty



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





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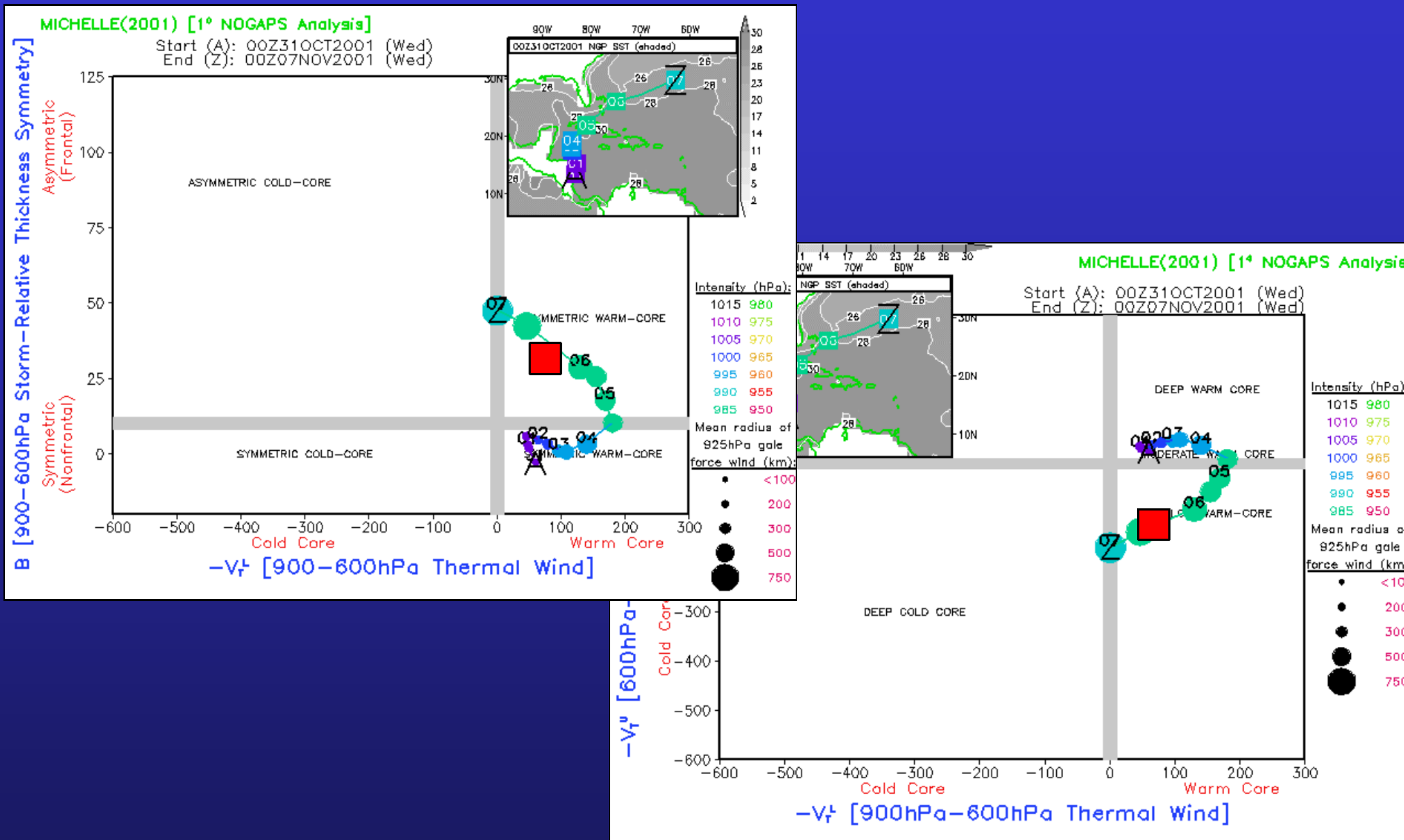


The human element

- 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

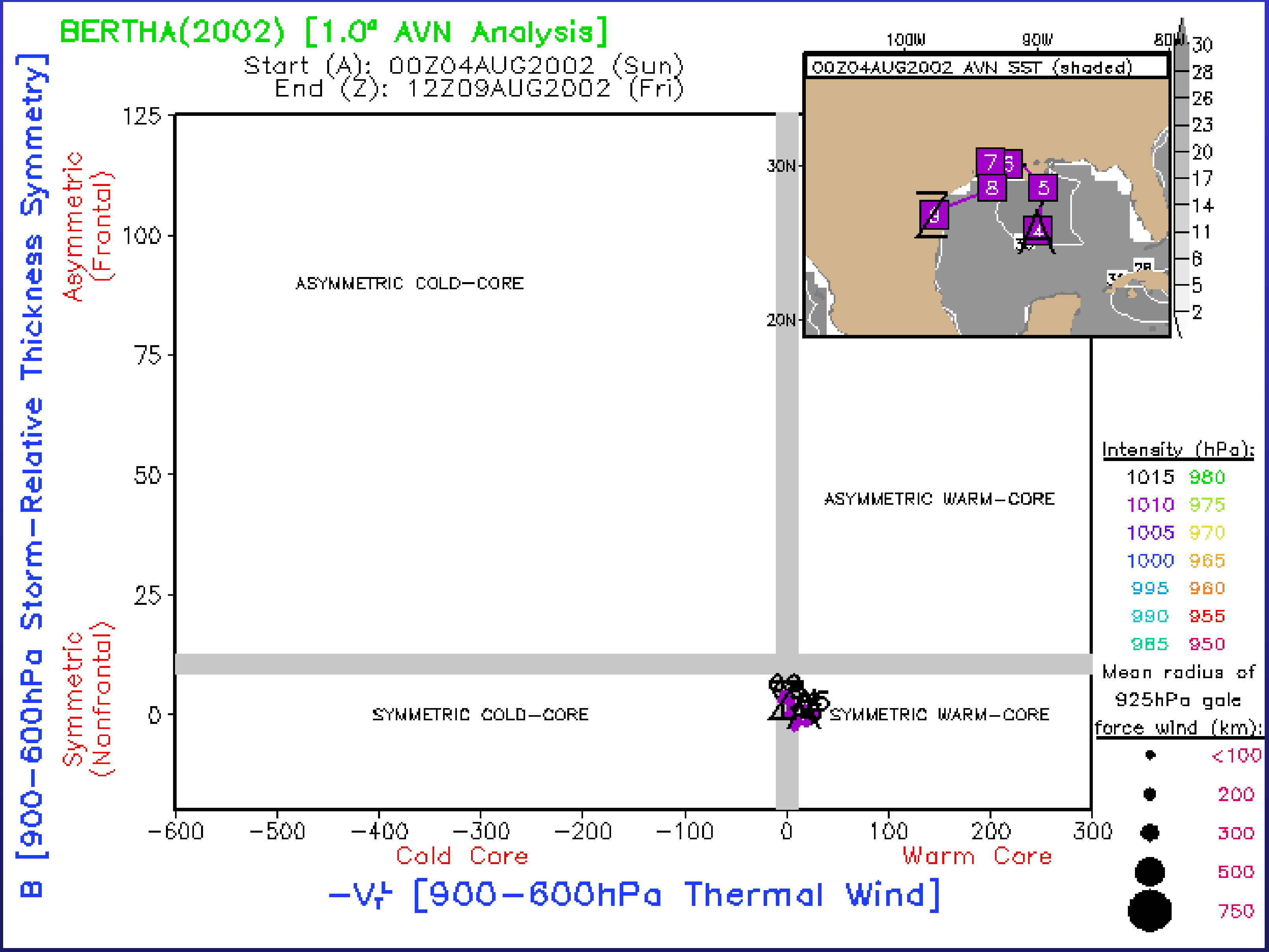
Other Past/Current CPS Uses

- 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

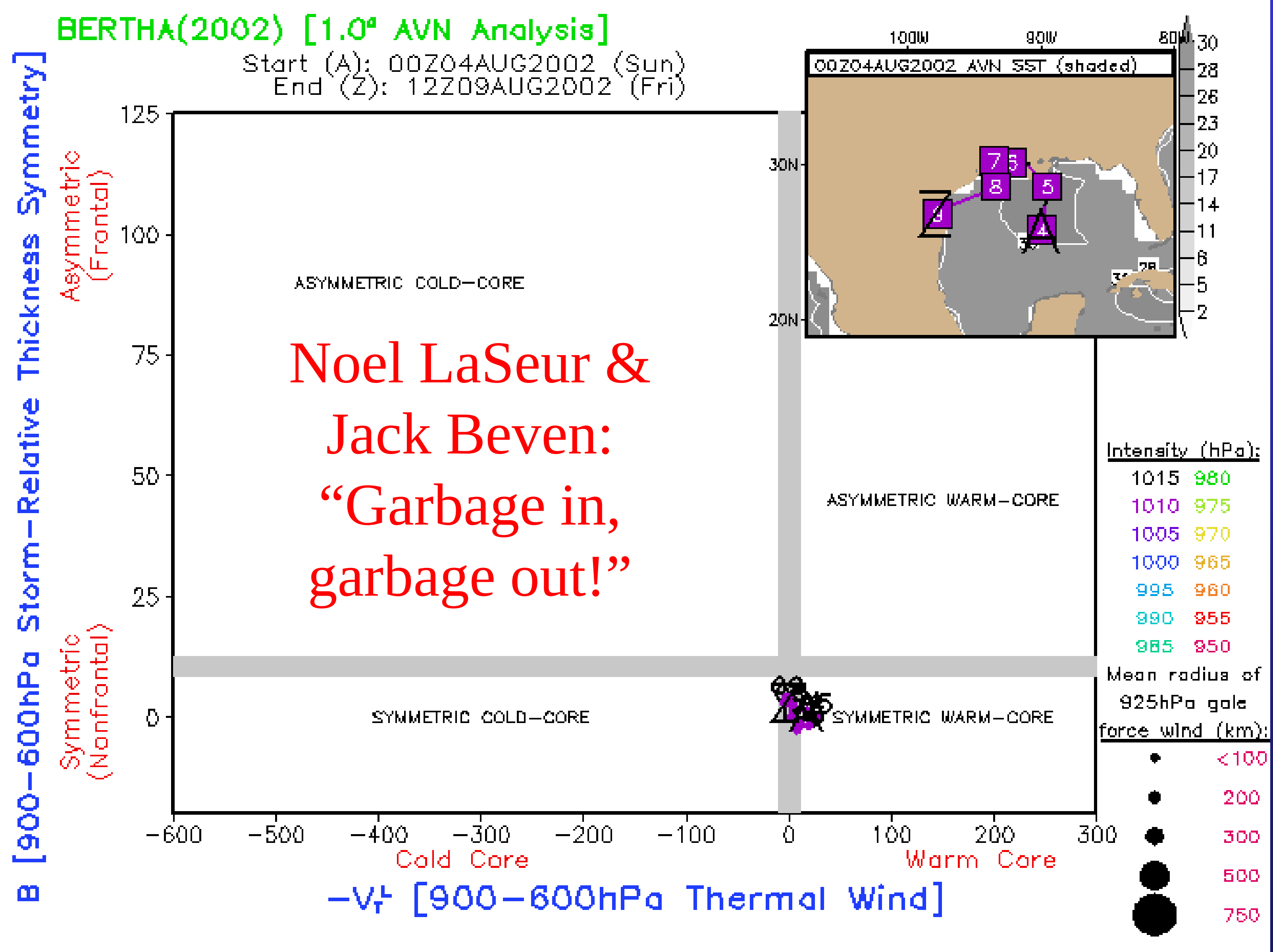
Phase space limitations

- 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
- Other potential dimensions: static stability, long-wave pattern, jet streak configuration, binary cyclone interaction, tropopause height/folds, surface moisture availability, surface roughness...
- However, the chosen three parameters represent a large percentage of the variance & explain the crucial structural changes.

Often model analysis representation is poor



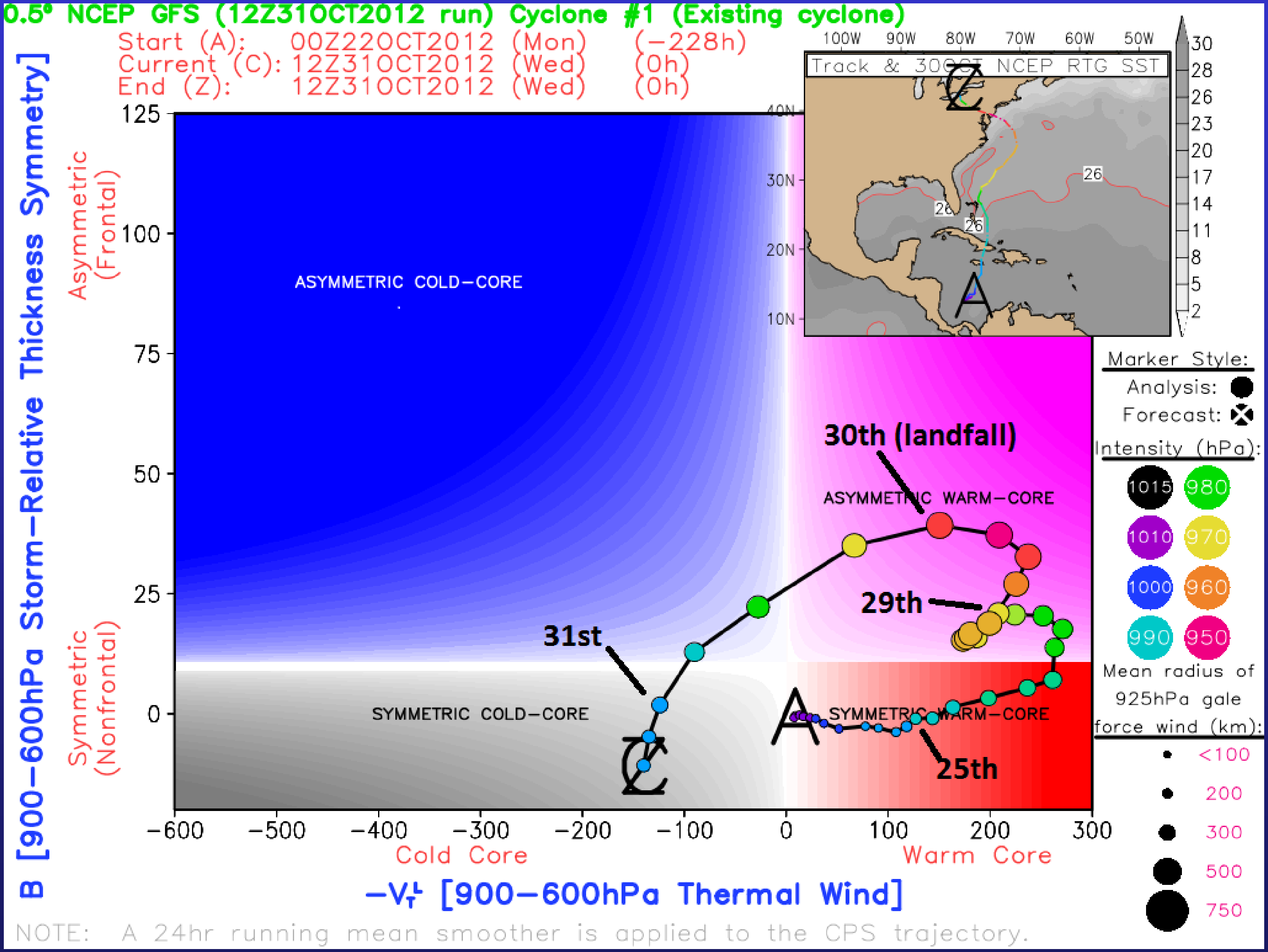
Often model analysis representation is poor



Noel LaSeur & Jack Beven: “Garbage in, garbage out!”

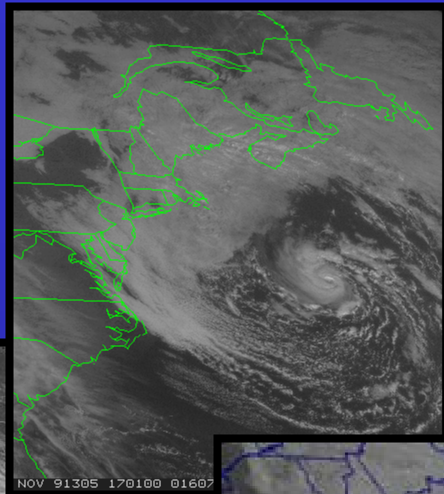
"Instant" Warm-Seclusion Dilemma:

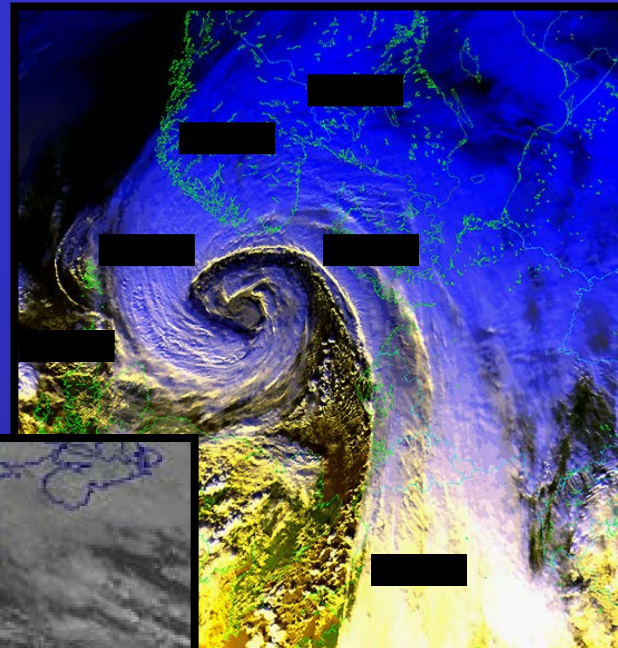
Hurricane Sandy (2012)

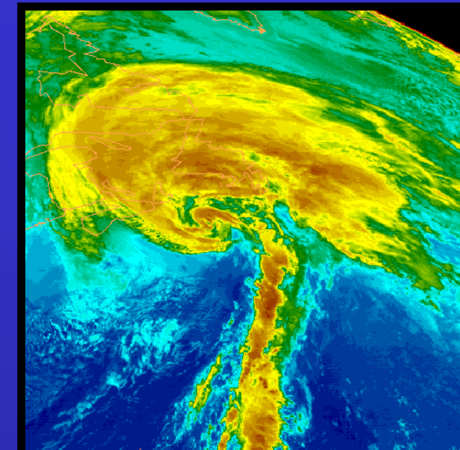


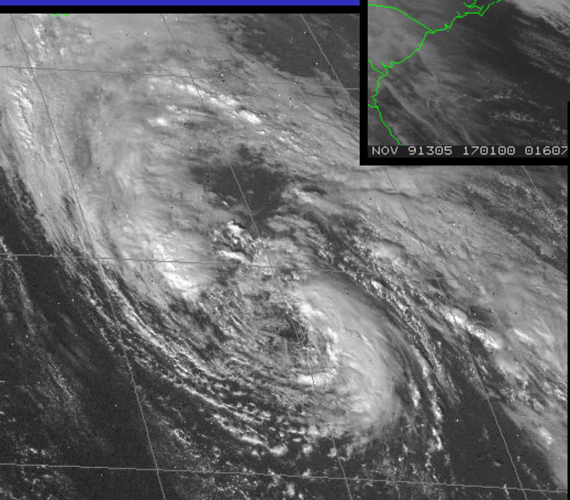
Quiz: Separate the 5 tropical cyclones from the 5 extratropical.

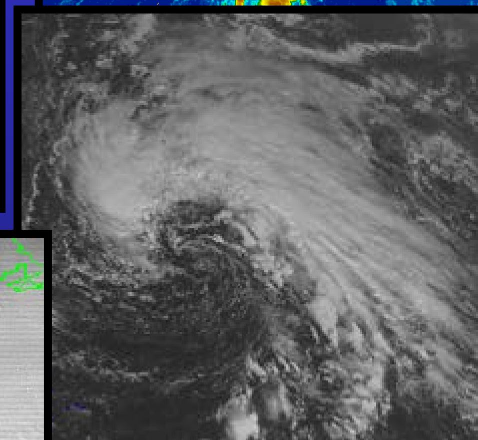
Images courtesy NCDC

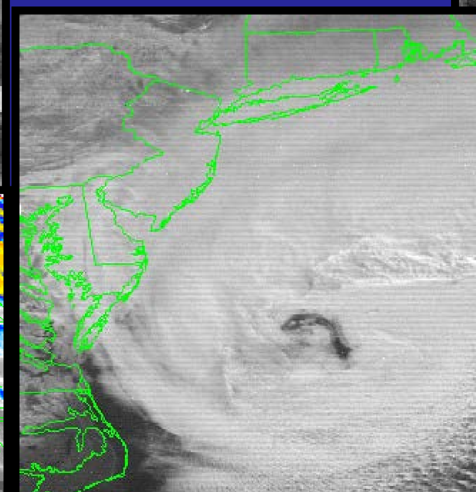


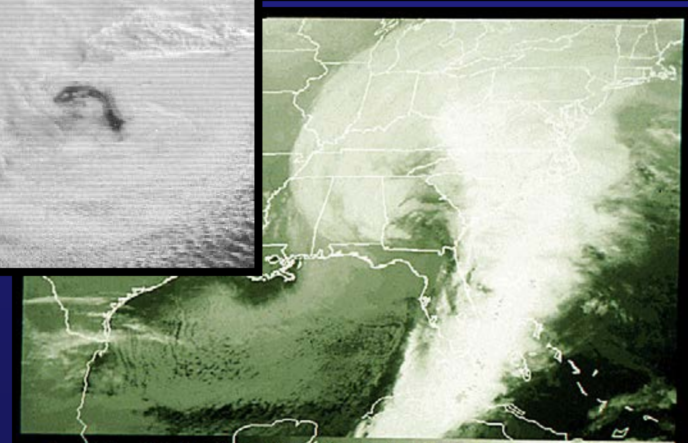


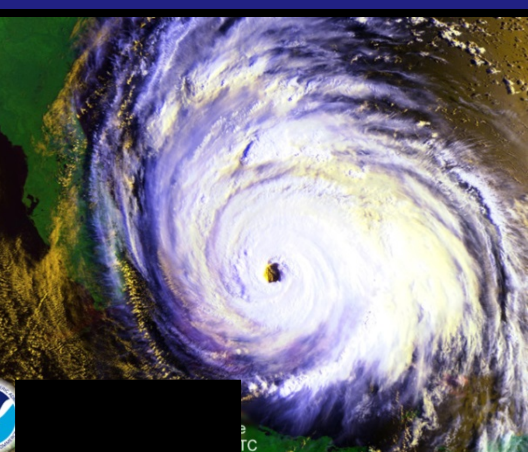


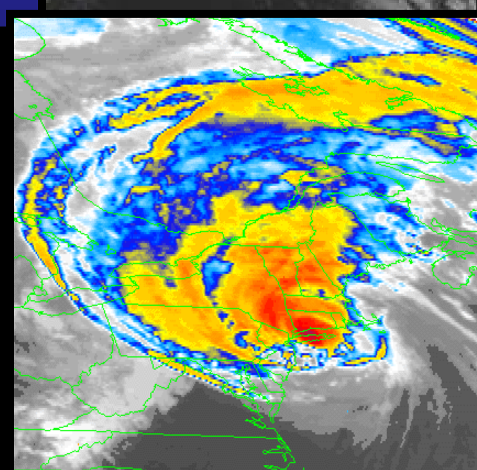












Separate the 5 tropical cyclones from the 5 extratropical.

Images courtesy NCDC