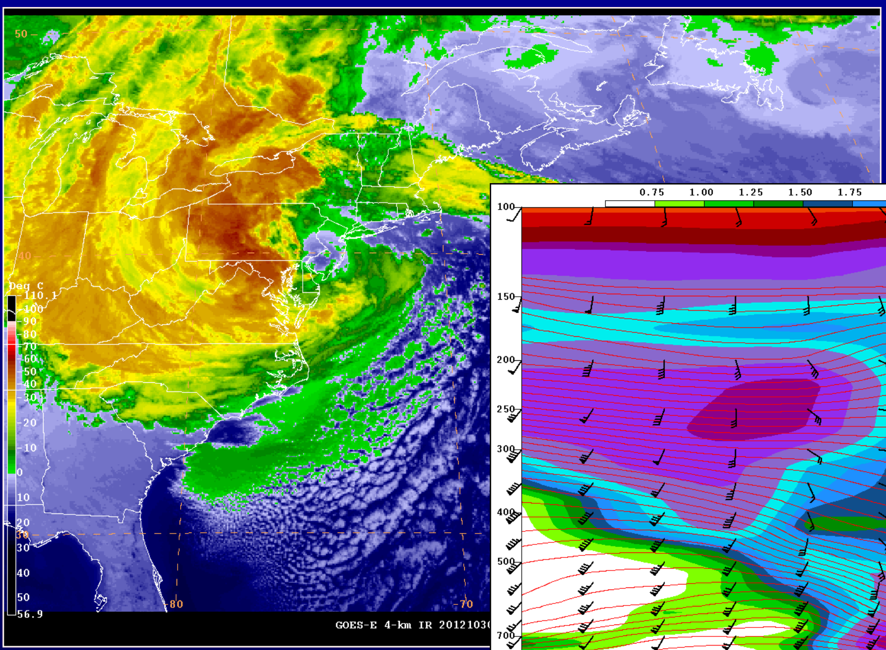
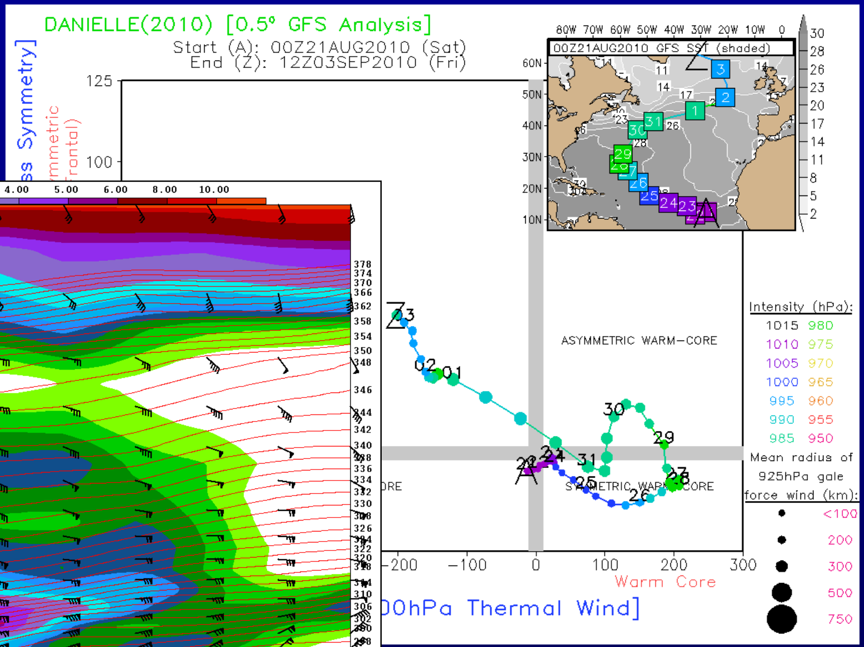
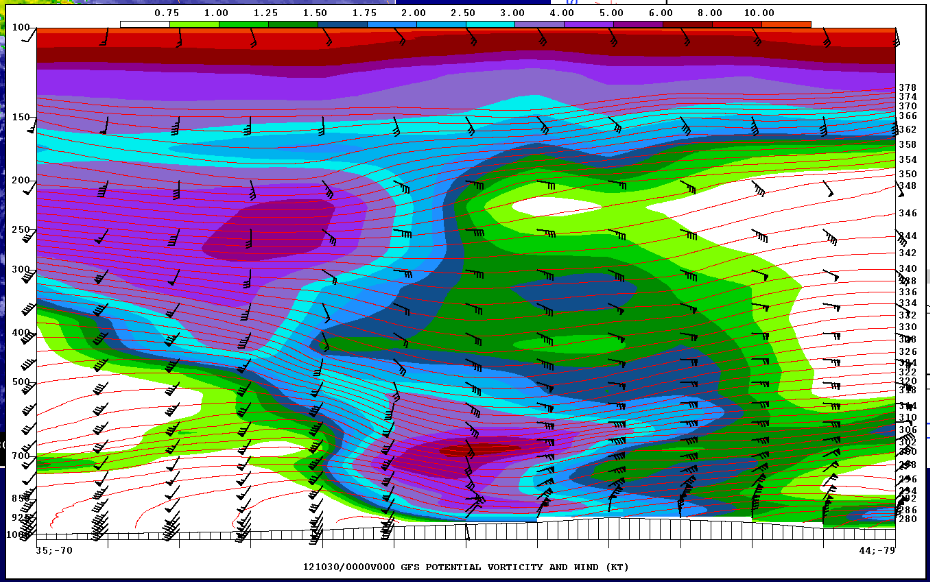
Extratropical Transition: Operational Challenges and Forecast Tools







Michael J. Brennan

National Hurricane Center

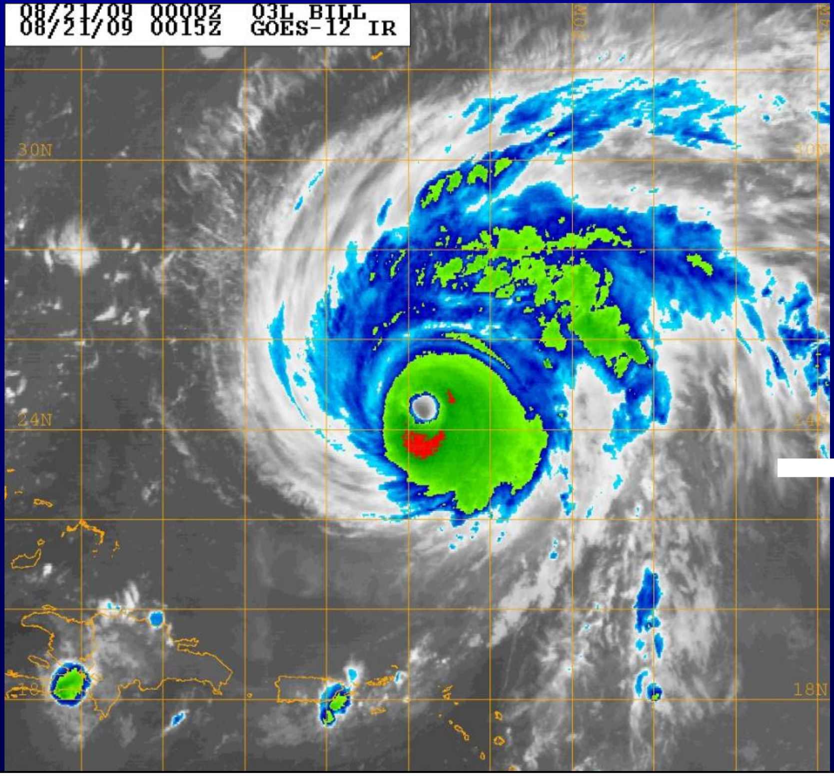
7 March 2017

Outline

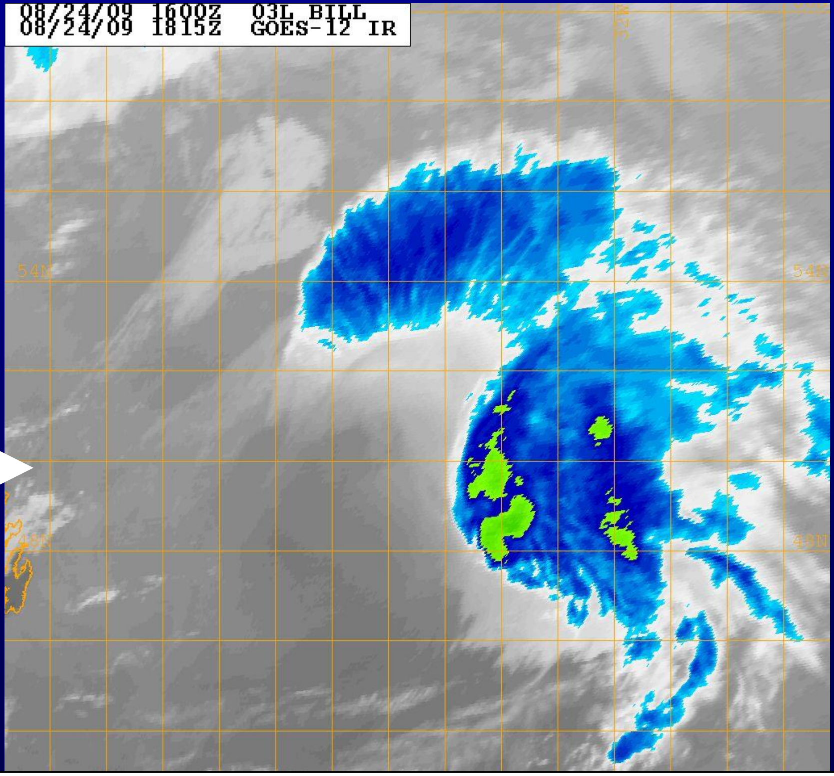
- Introduction
- Climatology
- Operational Procedures and Challenges
- Environmental/Structural Changes During ET
- Conceptual Models and Composites of ET
- Forecasting Tools
- Summary
- Exercise

Extratropical Transition (ET)

- "…a **gradual process** in which a tropical cyclone loses tropical characteristics and becomes more extratropical in nature." (Jones et al. 2003)



Hurricane Bill 00 UTC 21 Aug 2009
Maximum Wind: 110 kt
34-kt wind radii: 225NE, 200SE, 120SW, 200NW



Extratropical Bill 18 UTC 24 Aug 2009
Maximum Wind: 60 kt
34-kt wind radii: 225NE, 275SE, 240SW, 150NW

Motivation – Why Study ET?

- Numerous tropical cyclones (TCs) undergo ET
  - Nearly half in some basins
- Structural changes during ET affect distribution and magnitude of hazardous weather
- Cyclones often affect land during or after ET
  - Northeast U.S., Atlantic Canada, Britain, NW Europe
- Large impact on mid/high latitude shipping lanes
- A challenge to forecast!
  - High-impact, high-visibility events
  - Often poorly handled by NWP models
  - Impacts on downstream longwave pattern and hemispheric predictability implications

Climatology of ET

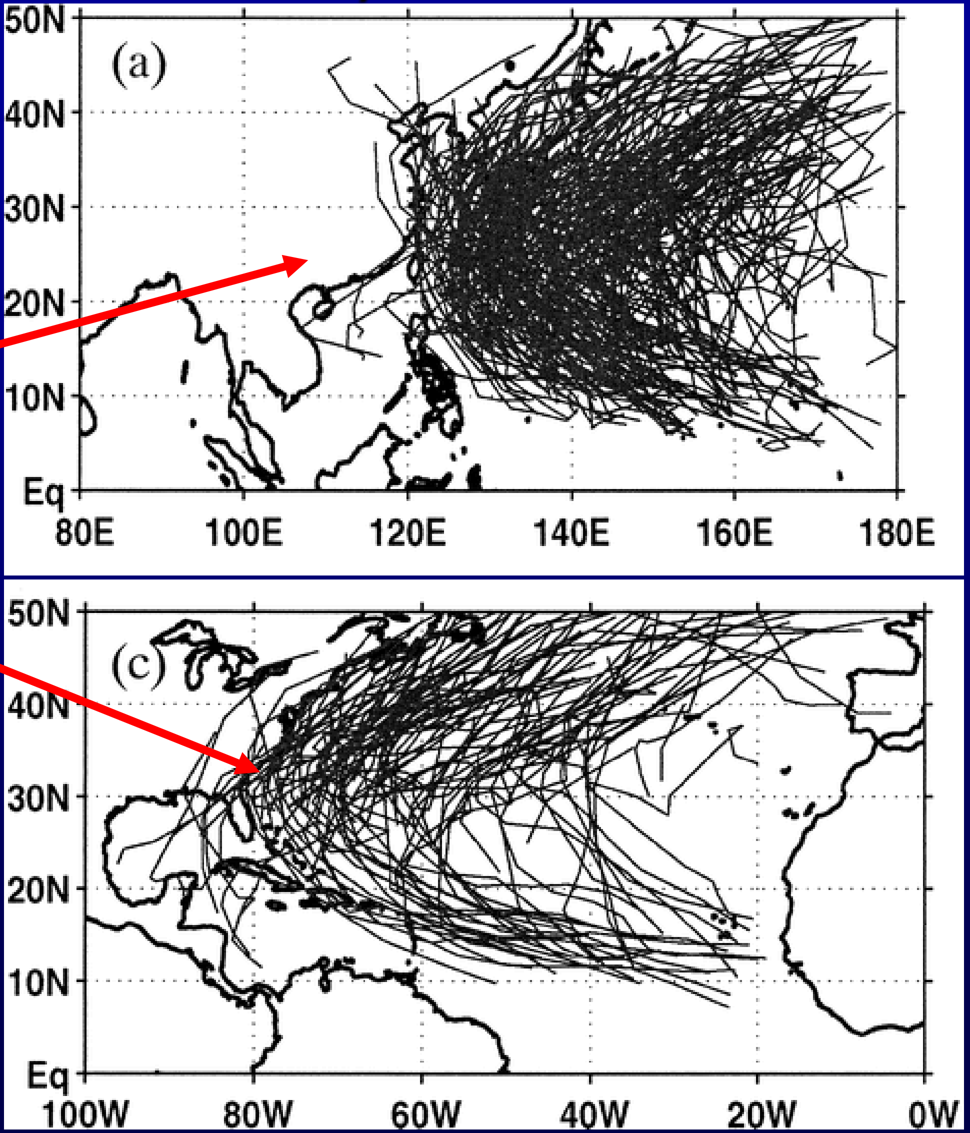
Emphasis on North Atlantic Basin

Climatology Question

- In what TC basin does ET occur least often?
  1. North Atlantic
  2. Eastern North Pacific
  3. Western North Pacific
  4. Northern Indian Ocean

Climatology of ET
(Jones et al. 2003)

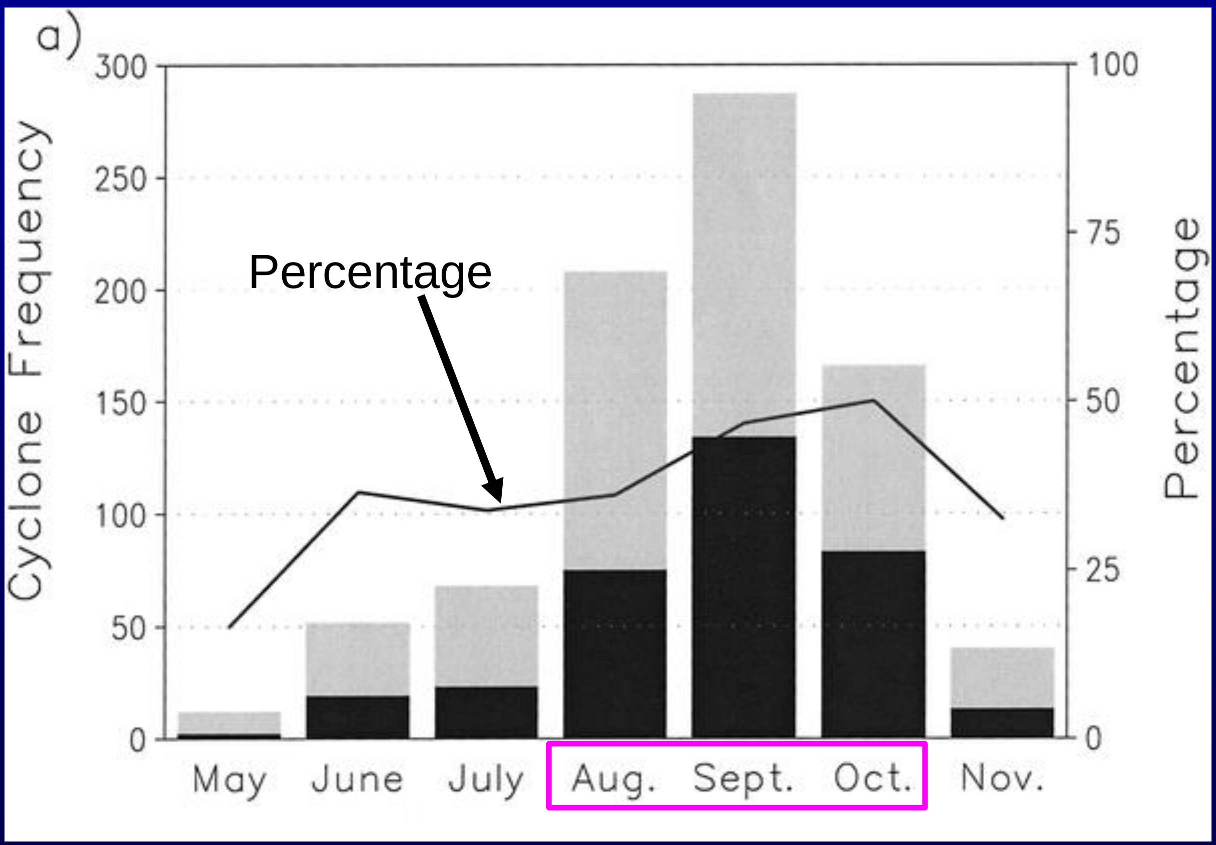
- ET occurs in almost every basin where TCs form
- Largest *number* of ET events occur in Northwest Pacific
- Largest *percentage* (~45%) of TCs undergo ET in North Atlantic
- Occurs least often in Northeast Pacific
  - Synoptic conditions and strong SST gradient not favorable for ET



Jones et al. (2003), *Wea. Forecasting*

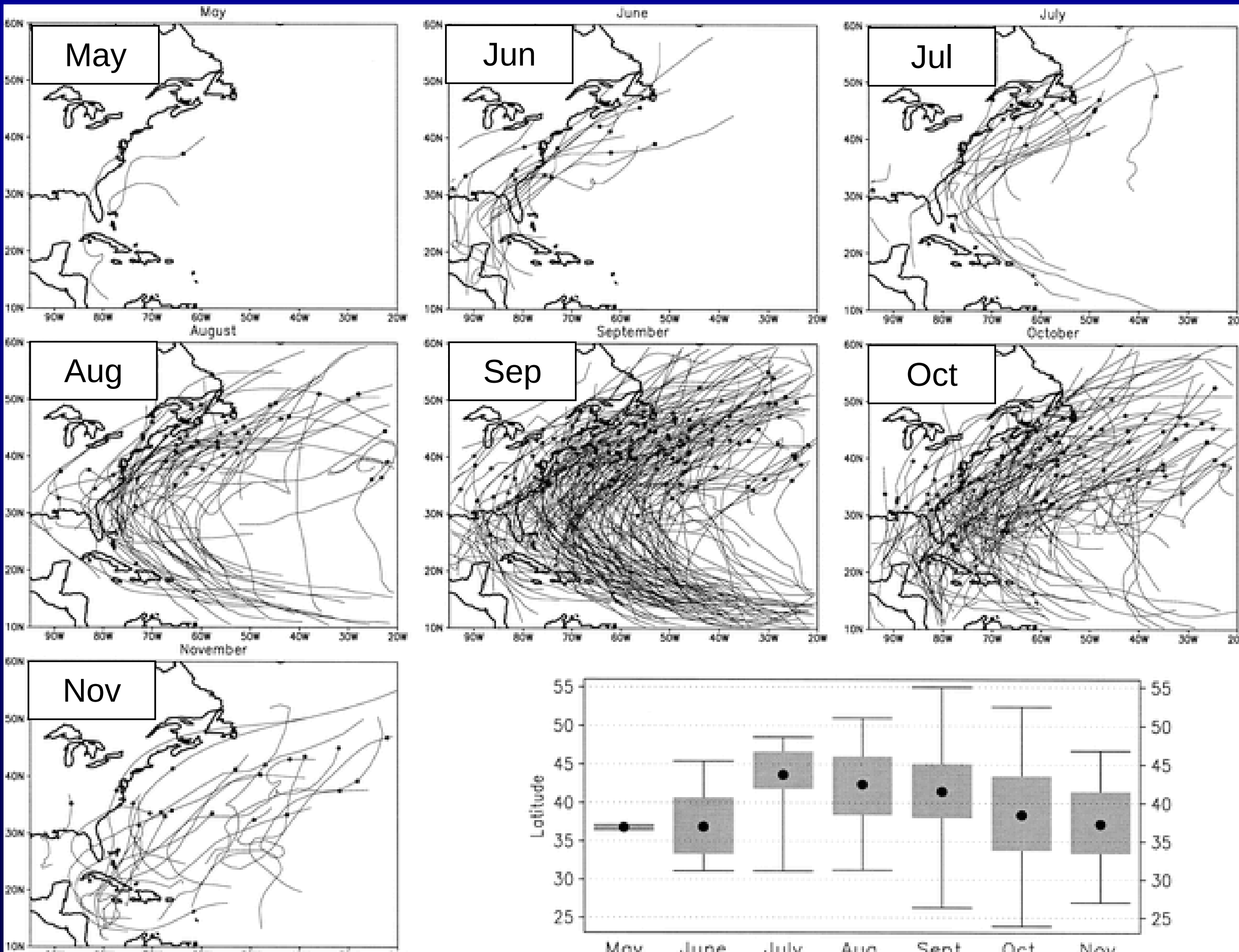
North Atlantic ET Climatology

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



Hart and Evans (2001) *Journal of Climate*

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

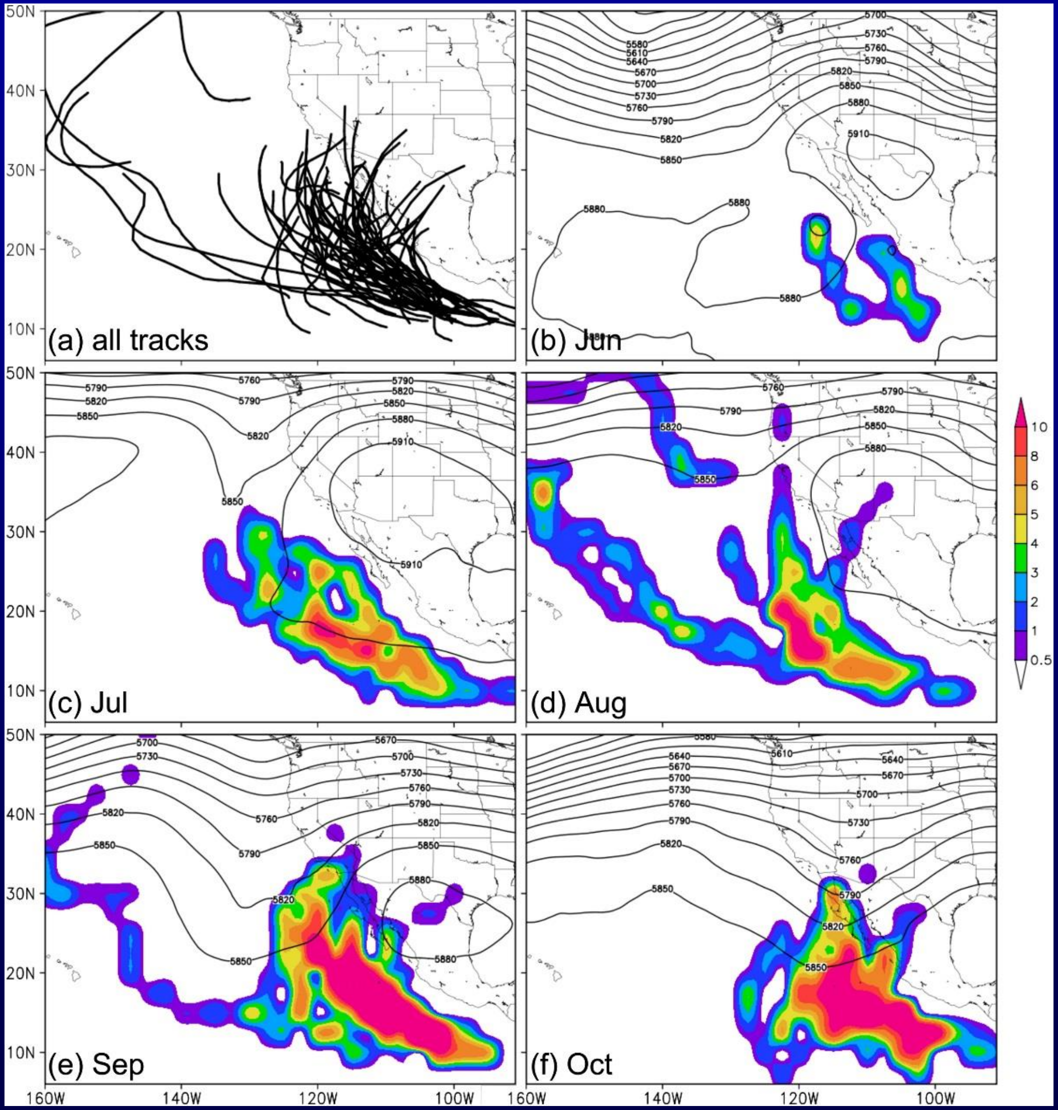
Hart and Evans (2001) *Journal of Climate*

North Atlantic ET Climatology

Hart and Evans (2001)

- 51% of storms undergoing ET from 1979–1993 intensified
  - Most initially formed in the deep Tropics (60% form south of 20°N)
- 42% of transitioning storms from 1979–1993 decayed during ET
  - Most form outside the deep Tropics (90% form north of 20°N)
- Pure tropical development initially more favorable for intensification during ET
- TCs of more baroclinic origins more likely to weaken during ET

Eastern North Pacific ET Climatology
(Wood and Ritchie 2014)



1971-2012 climatology based on phase space from JRA-55 reanalysis

About 9% of eastern North Pacific TCs underwent ET during this period (55 of 631)

Most ET event (65.5%) occur in Sep-Oct

Operational Procedures and Challenges

Operational Definitions

From NWS Directive 10-604

http://www.weather.gov/directives/sym/pd01006004curr.pdf

- **Tropical cyclone**
  - Warm-core, non-frontal, synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center
  - Includes tropical depressions (< 34 kt), tropical storms (34-63 kt), and hurricanes (64 kt or greater)
- **Subtropical cyclone**
  - Non-frontal low pressure system that has characteristics of both tropical and extratropical cyclones, with a closed surface wind circulation about a well-defined center.
  - Have organized moderate to deep convection, but lack a central dense overcast
  - Derive a significant proportion of their energy from baroclinic sources, and are generally cold-core in the upper troposphere and often associated with an upper-level low or trough
  - These systems generally have a radius of maximum winds relatively far from the center (usually greater than 60 n mi) compared to tropical cyclones, and generally have a less symmetric wind field and distribution of convection
  - Includes subtropical depressions (< 34 kt) and subtropical storms (34-63 kt)

Operational Definitions

From NWS Manual 10-604

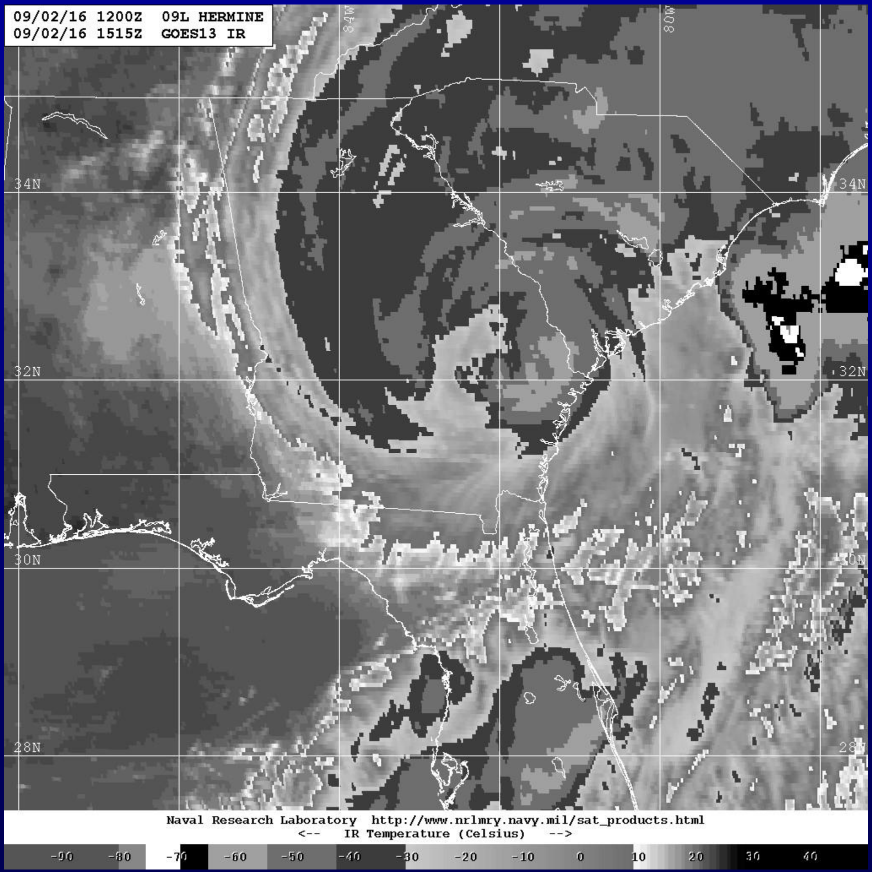
http://www.weather.gov/directives/sym/pd01006004curr.pdf

- **Post-Tropical cyclone**
  - Generic term that describes a cyclone that no longer possesses sufficient characteristics to be considered a tropical cyclone
  - Former tropical cyclones that have become fully extratropical and remnant lows are two specific classes of post-tropical cyclones
- **Remnant low**
  - Post-tropical cyclone that no longer possesses the convective organization required of a tropical cyclone and has maximum sustained winds < 34 kt
  - Most commonly applied to the nearly deep-convection-free swirls of stratocumulus in the eastern North Pacific
- **Extratropical cyclone**
  - A cyclone of any intensity for which the primary energy source is baroclinic, i.e., results from the temperature contrast between warm and cold air masses

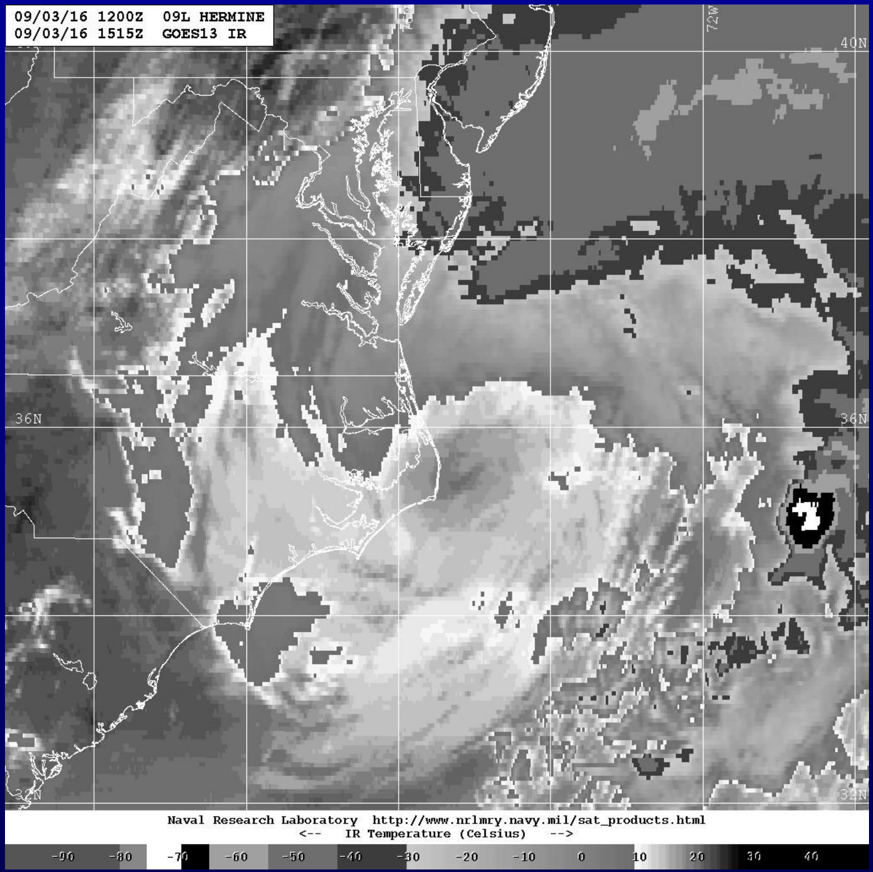
NHC Operational Procedures During ET

- Forecast periods designated **POST-TROPICAL** indicate the cyclone will no longer meet the definition of a tropical cyclone, but is not extratropical
- Forecast periods designated **POST-TROP/EXTRATROP** mean that the cyclone is expected to be extratropical
- Forecast track, intensity, and wind radii account for expected structural changes
- Forecasts collaborated with NWS partners and other nations (e.g., Canada, Bermuda)
- Advisories contain forecast information out to five days, including post-transition period, unless circulation expected to dissipate or be absorbed
- NHC will continue issuing advisories on a Post-Tropical Cyclone if it posts a significant threat to life and property and the transfer of responsibility would result in discontinuity of service
- Final NHC advisory indicates where to obtain further information on the system and highlights potential impacts

Post-Tropical Hermine (2016)

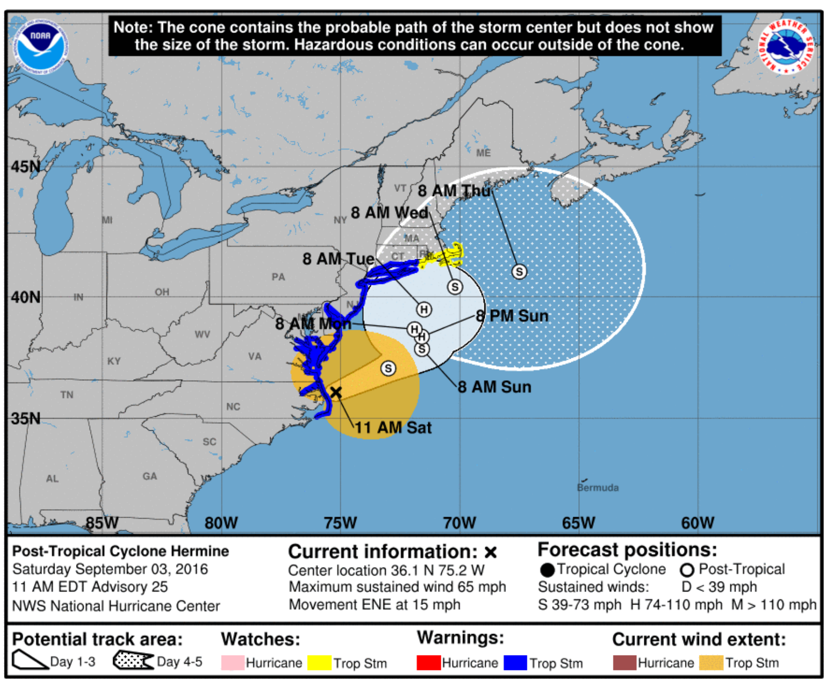


Tropical Storm Hermine
1515 UTC 2 Sep 2016



Post-Tropical Cyclone Hermine
1515 UTC 3 Sep 2016

Post-Tropical Hermine (2016)



POST-TROPICAL CYCLONE HERMINE DISCUSSION NUMBER 25
NWS NATIONAL HURRICANE CENTER MIAMI FL AL092016
1100 AM EDT SAT SEP 03 2016

Satellite imagery indicates that Hermine has become a **post-tropical cyclone**, with the coldest convective tops now located more than 200 n mi northeast of the exposed center. **Despite this change in structure, surface data from the Outer Banks indicate that some strong winds persist near the center, and the initial intensity is set to 55 kt for this advisory.** During the next 48 to 72 hours, Hermine will interact with a strong mid-latitude shortwave trough and **all of the global models show the system re-intensifying during that time and a redevelopment of a stronger inner core, albeit one situated underneath an upper-level low.** Regardless of its final structure, Hermine is expected to remain a dangerous cyclone through the 5 day period.

FORECAST POSITIONS AND MAX WINDS

```
INIT 03/1500Z 36.1N 75.2W 55 KT 65 MPH...POST-TROPICAL
 12H 04/0000Z 37.1N 73.0W 60 KT 70 MPH...POST-TROPICAL
 24H 04/1200Z 37.9N 71.6W 60 KT 70 MPH...POST-TROPICAL
 36H 05/0000Z 38.4N 71.6W 65 KT 75 MPH...POST-TROPICAL
 48H 05/1200Z 38.7N 71.9W 65 KT 75 MPH...POST-TROPICAL
 72H 06/1200Z 39.5N 71.5W 65 KT 75 MPH...POST-TROPICAL
 96H 07/1200Z 40.4N 70.2W 60 KT 70 MPH...POST-TROPICAL
120H 08/1200Z 41.0N 67.5W 50 KT 60 MPH...POST-TROPICAL
```

Operational Challenges
Is it Tropical or Extratropical?

- Cyclones don't always fit into discrete bins
  - Continuous spectrum exists between cyclones driven largely by diabatic heating (TCs) and those driven by baroclinic processes (extratropical cyclones)
  - Cyclones undergoing ET may derive energy from both diabatic and baroclinic processes
  - This often makes the decision of when to declare a TC "Post-Tropical" or "Extratropical" quite subjective
- When should NHC stop writing advisories on a tropical cyclone undergoing ET?
  - Decision has large impact on public perception of the threat associated with a system
  - Impacts watch/warning process
  - Requires large amounts of coordination for land and marine forecasts

If you get hit by 60 kt winds, 6 ft above normal tides, and/or 12 in of rain, does the exact nature of the system really matter?

Operational Challenges

- Will cyclone undergo ET?
- Will ET be continuous or be interrupted?
- Will cyclone intensify or weaken during ET?
- Will it re-intensify after transition?
- Will the TC become a discrete extratropical cyclone or be absorbed by a larger extratropical cyclone or front?

Question

- Which of the following structural changes does *not* typically occur during ET?

1. Increase in the size of 34-kt wind field
2. Redistribution of rainfall well away from the center
3. Increase in maximum winds
4. Decrease in deep convection
5. Development of frontal boundaries

Operational Challenges

Sensible Weather Impacts

- Structural and intensity changes can occur rapidly during ET
- Maximum wind often decreases, but not always
- Overall impact of high winds may increase dramatically due to expansion of wind field
  - Major implications for land (wind) and marine interests (wind, waves, swell) as area of hazardous weather can become very large
- Drastic redistribution of precipitation
  - Tropical moisture can be carried far from its origins and interaction with synoptic-scale forcing, jets, and fronts can result in large rainfall totals
- Cyclones undergoing ET often interact with continental landmasses
  - Often source of cool, dry, continental airmass
  - Interactions with terrain

Operational Challenges

Model Forecasts

- Model forecasts of ET can be highly variable due to
  - Differences in initial cyclone structure (e.g., models that use a synthetic bogus vortex and those that don't)
  - Differences in evolution of upper-tropospheric flow and other features of interest (e.g., extratropical cyclones, fronts, etc.)
  - Forecast track of TC, interaction with SST gradients, other features
  - Initial intensity of TC can be greatly underestimated by global models
- These factors determine if and when a TC begins ET, completes ET, and changes in intensity, structure and track

Hurricane Sandy (2012)

00 UTC 5 October

Intensity 85 kt

Pressure 964 mb

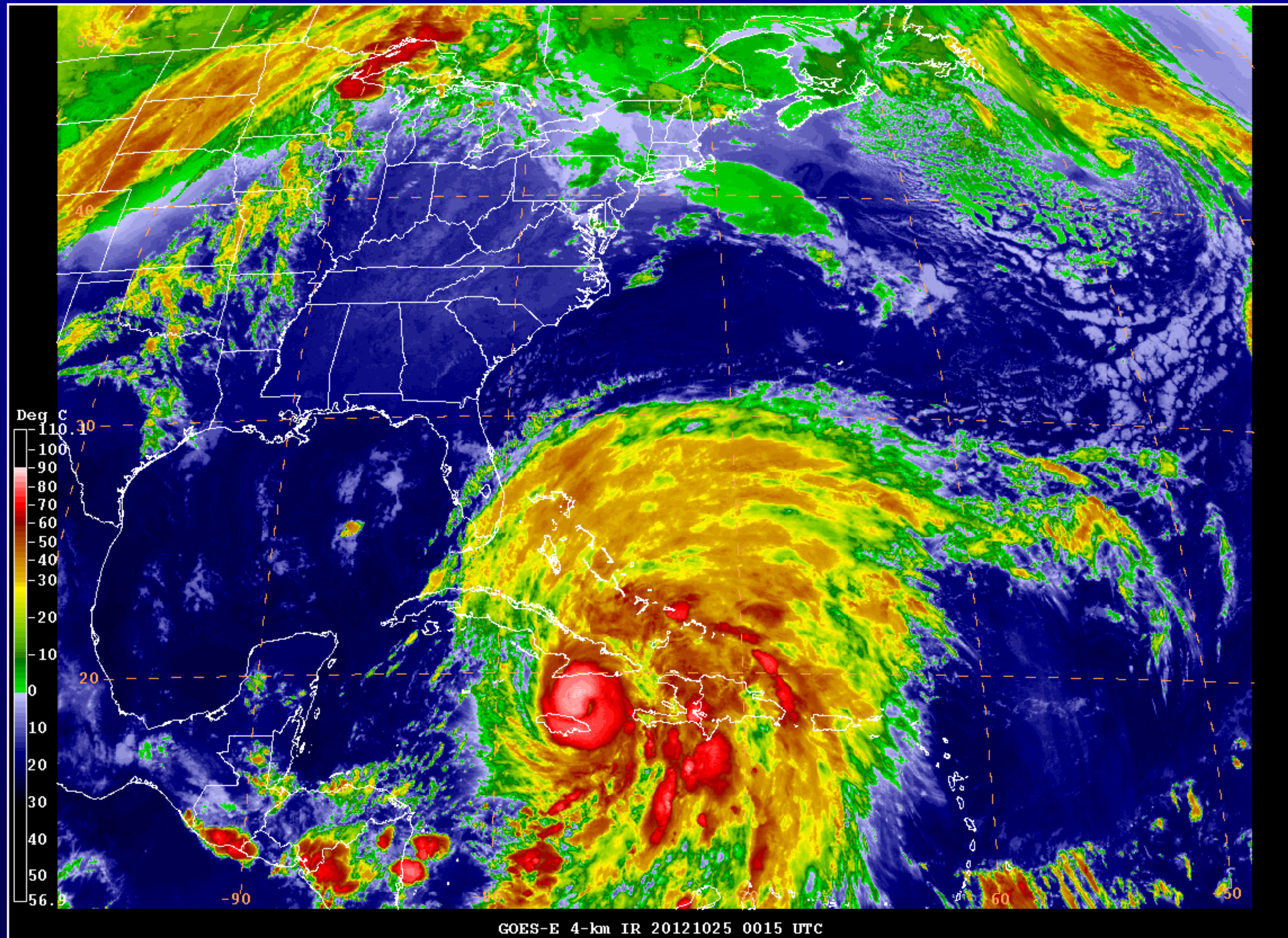
34 kt wind radii:

NE 180

SE 240

SW 70

NW 70



Hurricane Sandy (2012)

06 UTC 5 October

Intensity 100 kt

Pressure 954 mb

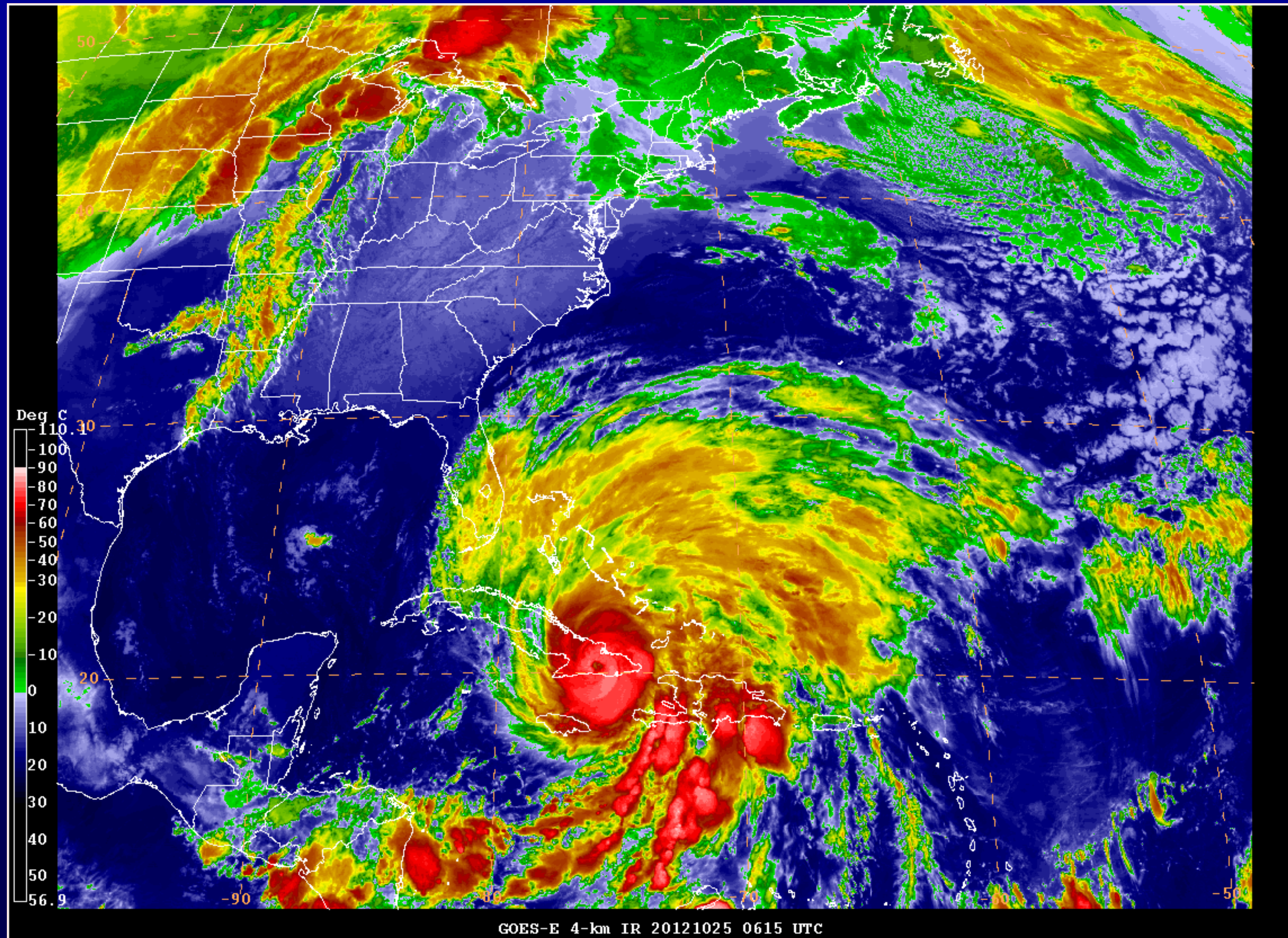
34 kt wind radii:

NE 240

SE 240

SW 70

NW 120



Hurricane Sandy (2012)

12 UTC 5 October

Intensity 95 kt

Pressure 966 mb

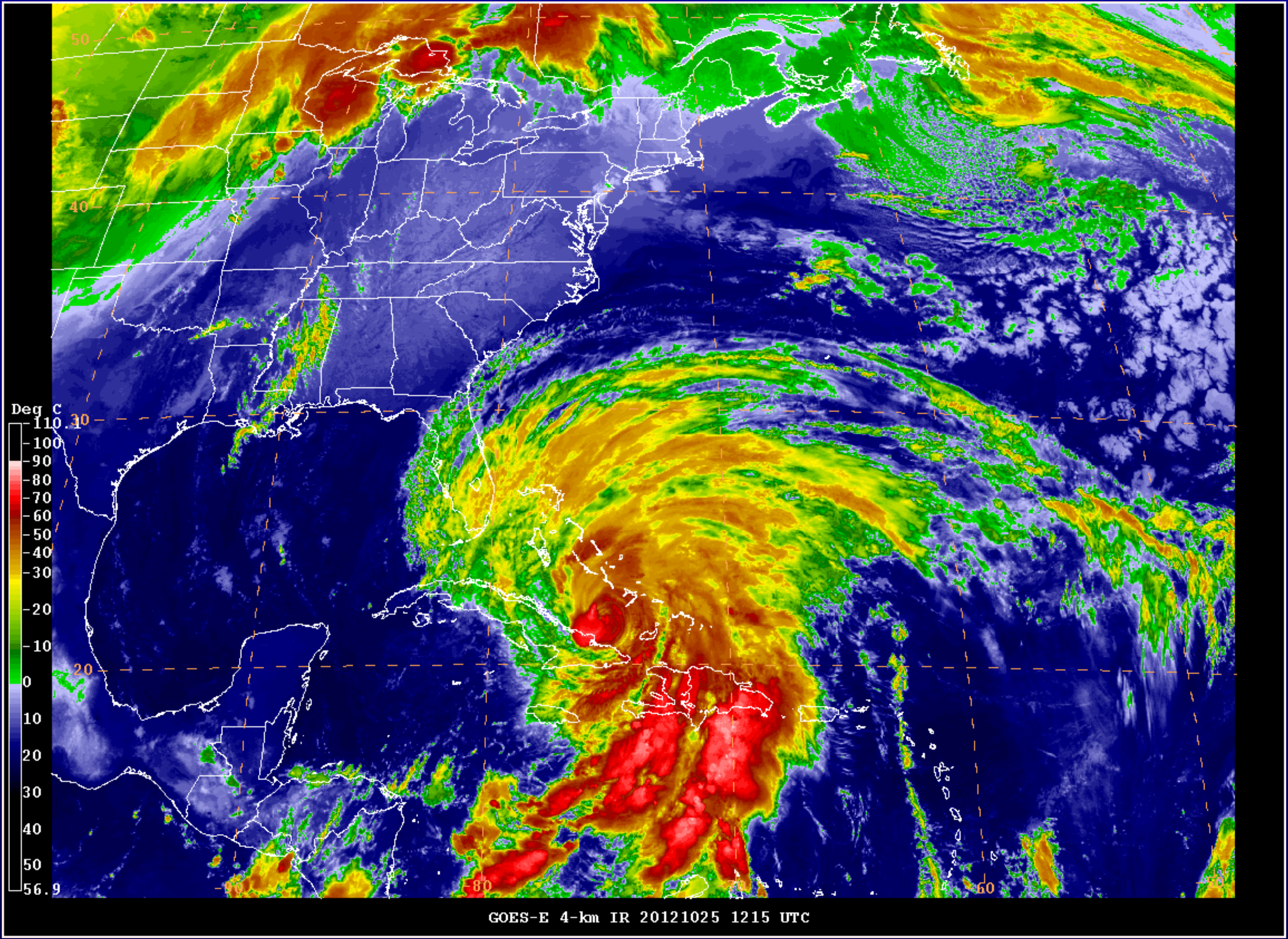
34 kt wind radii:

NE 240

SE 240

SW 70

NW 240



Hurricane Sandy (2012)

18 UTC 5 October

Intensity 90 kt

Pressure 963 mb

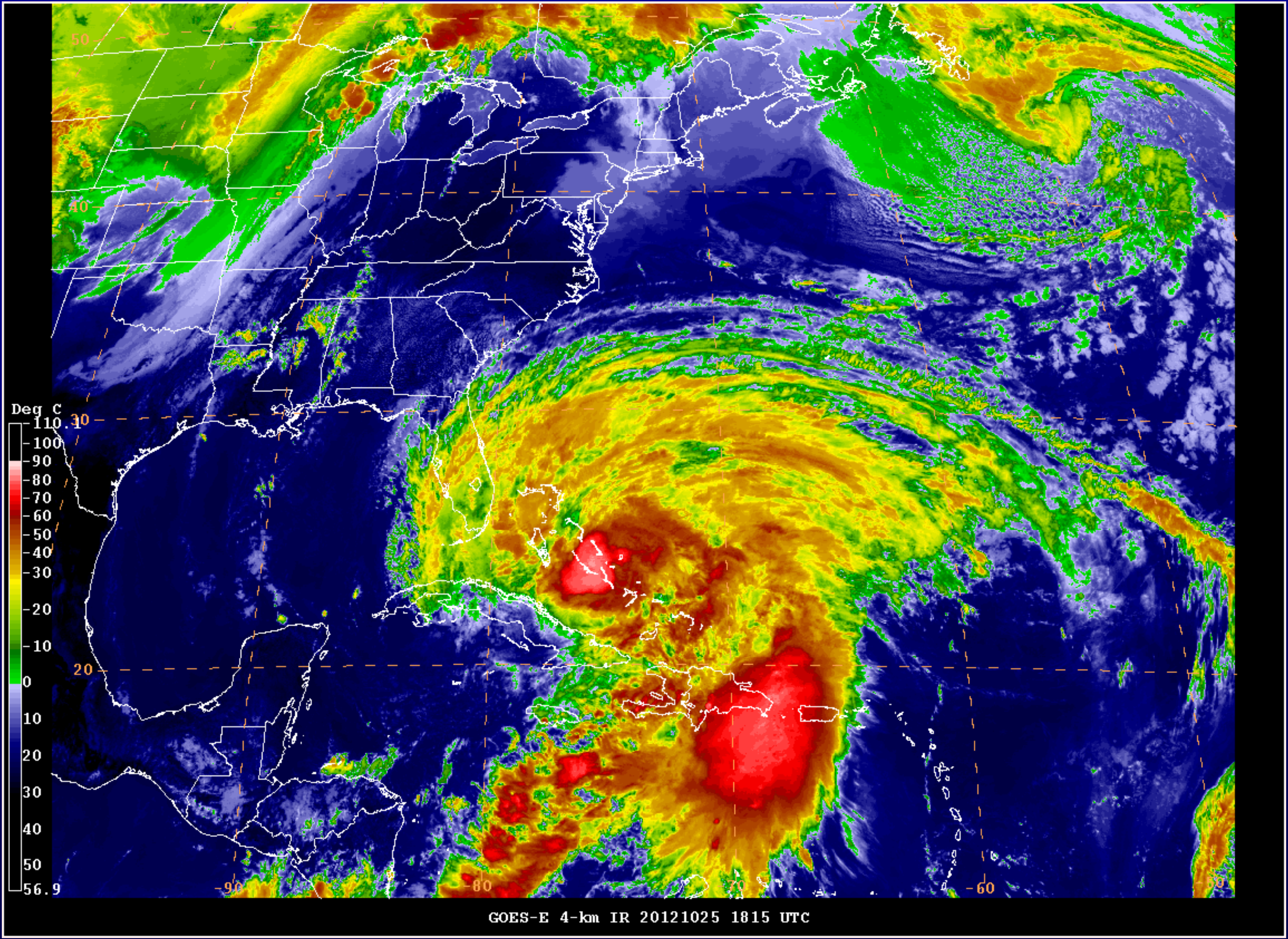
34 kt wind radii:

NE 270

SE 270

SW 120

NW 270



Hurricane Sandy (2012)

00 UTC 6 October

Intensity 75 kt

Pressure 965 mb

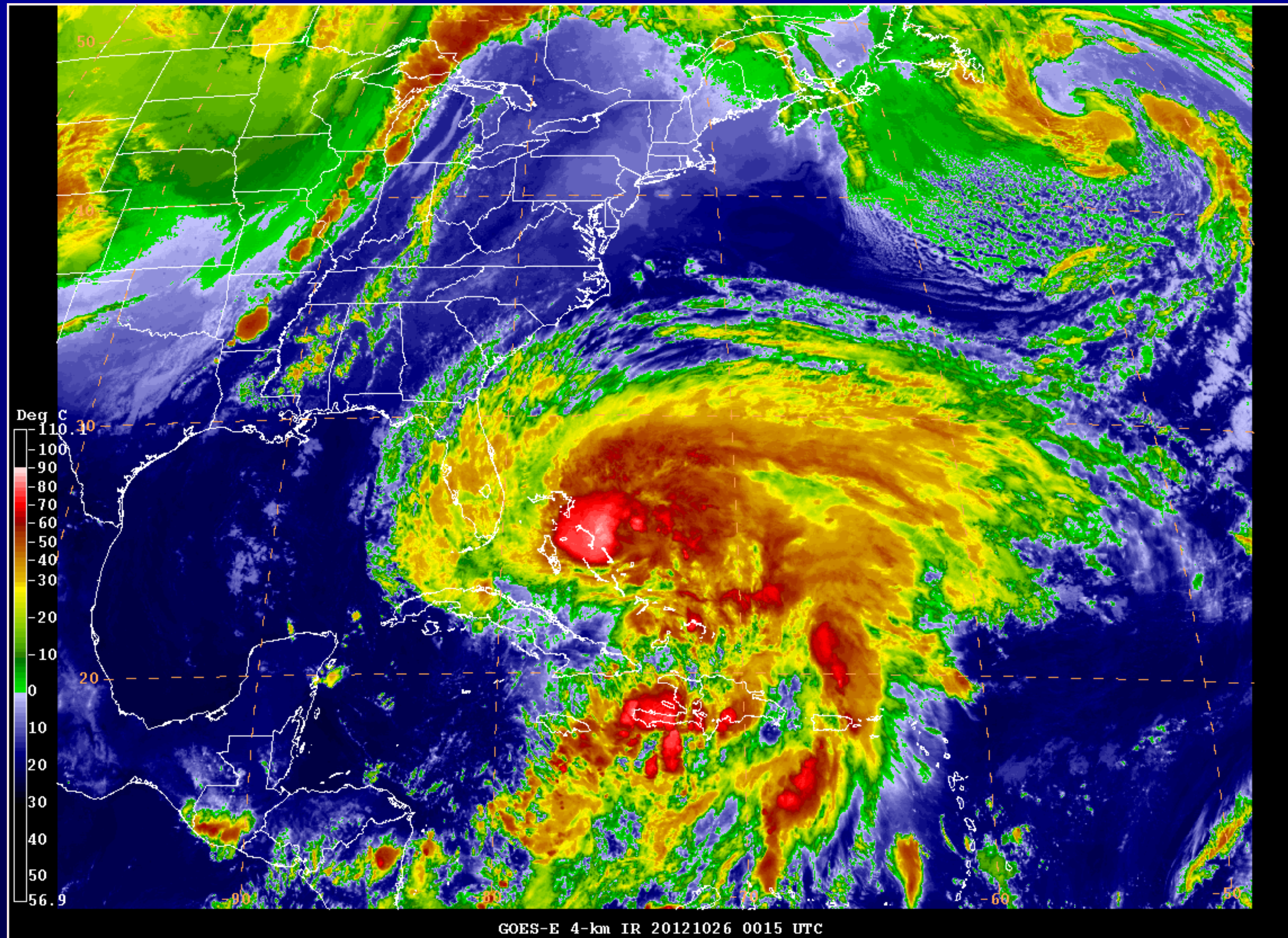
34 kt wind radii:

NE 300

SE 300

SW 160

NW 270



Hurricane Sandy (2012)

06 UTC 6 October

Intensity 70 kt

Pressure 968 mb

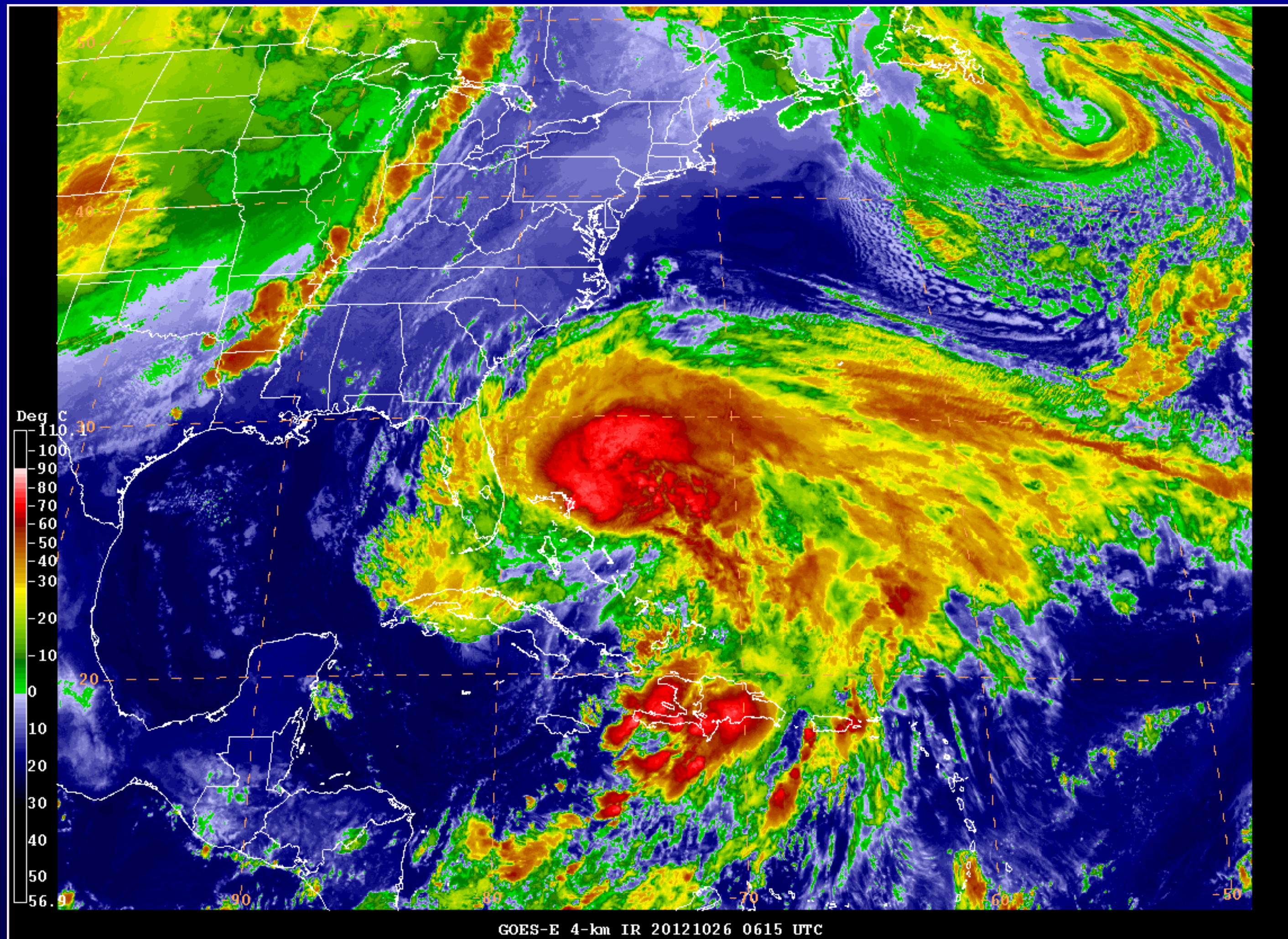
34 kt wind radii:

NE 300

SE 300

SW 160

NW 240



Hurricane Sandy (2012)

12 UTC 6 October

Intensity 65 kt

Pressure 970 mb

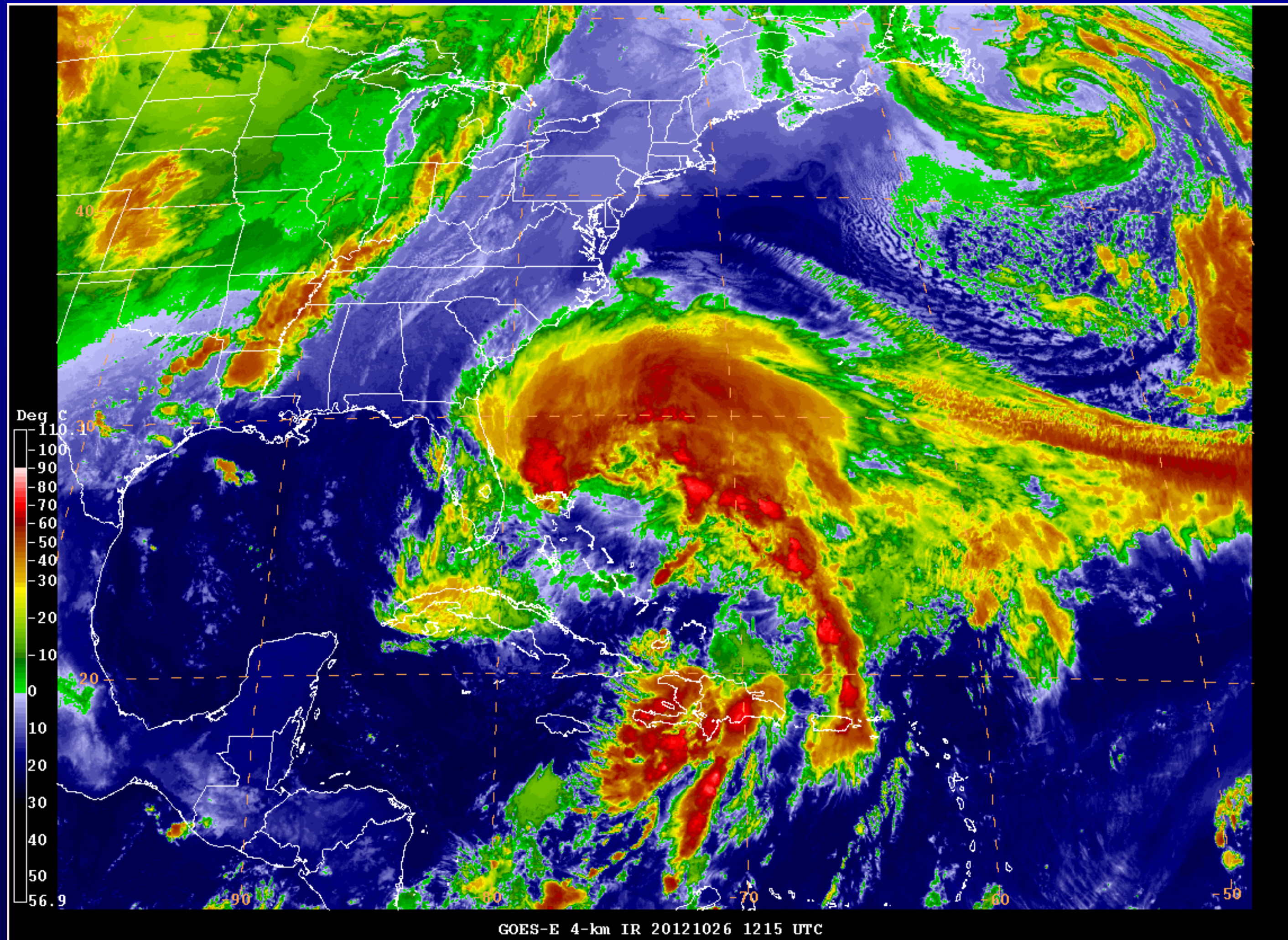
34 kt wind radii:

NE 360

SE 240

SW 170

NW 240



Hurricane Sandy (2012)

18 UTC 6 October

Intensity 65 kt

Pressure 971 mb

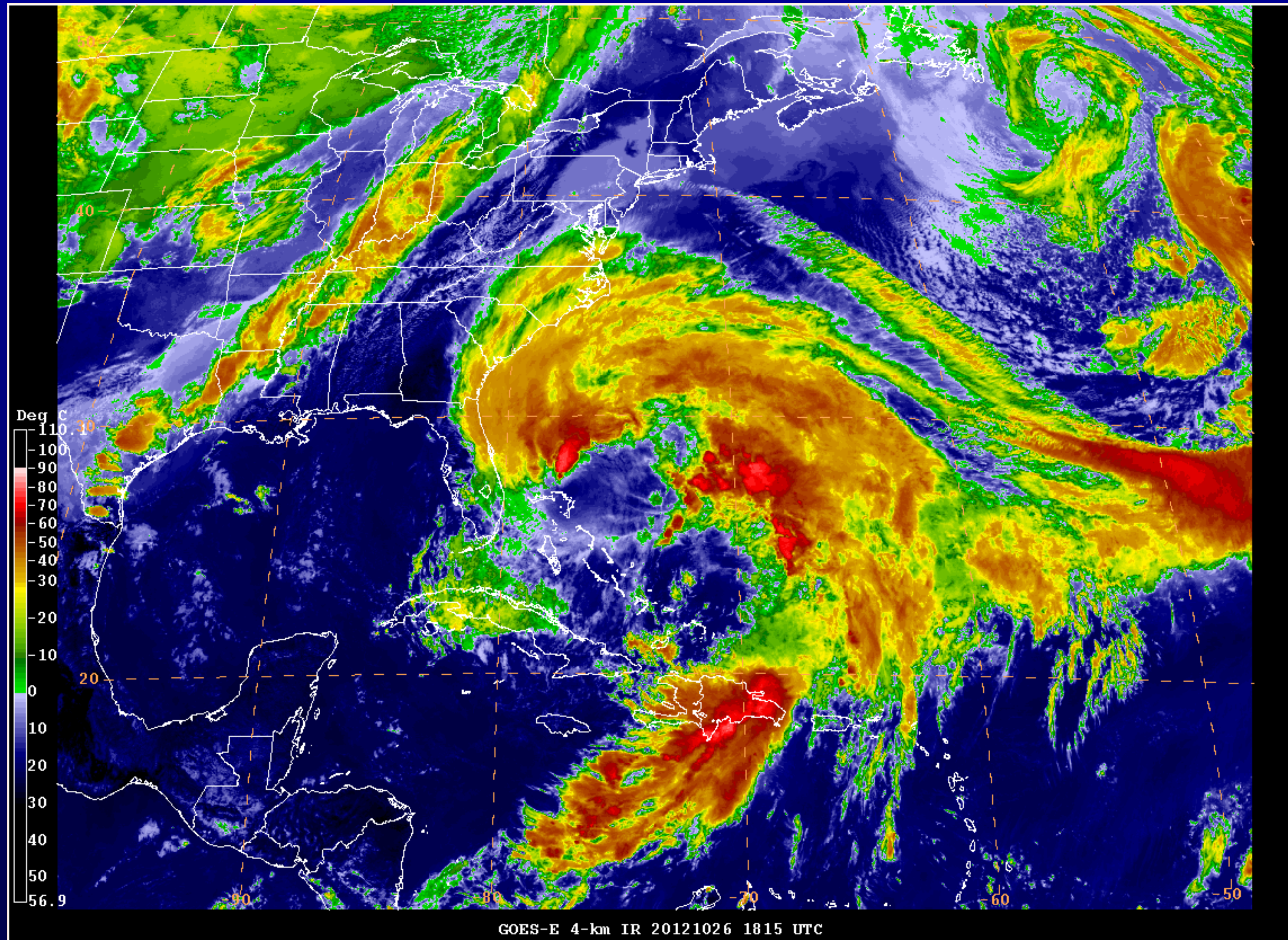
34 kt wind radii:

NE 400

SE 210

SW 170

NW 240



Hurricane Sandy (2012)

00 UTC 7 October

Intensity 60 kt

Pressure 969 mb

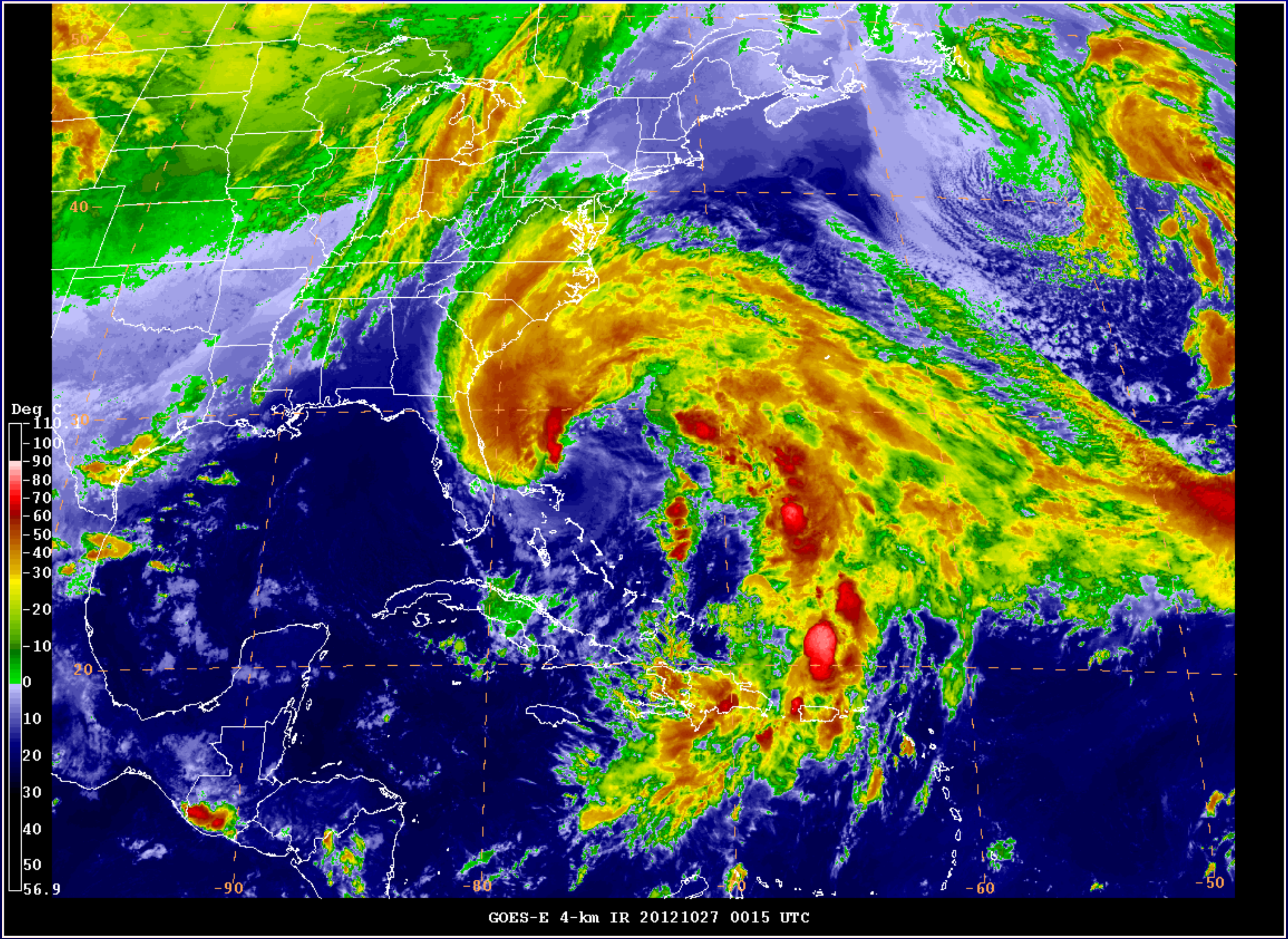
34 kt wind radii:

NE 450

SE 210

SW 180

NW 270



Hurricane Sandy (2012)

06 UTC 7 October

Intensity 60 kt

Pressure 968 mb

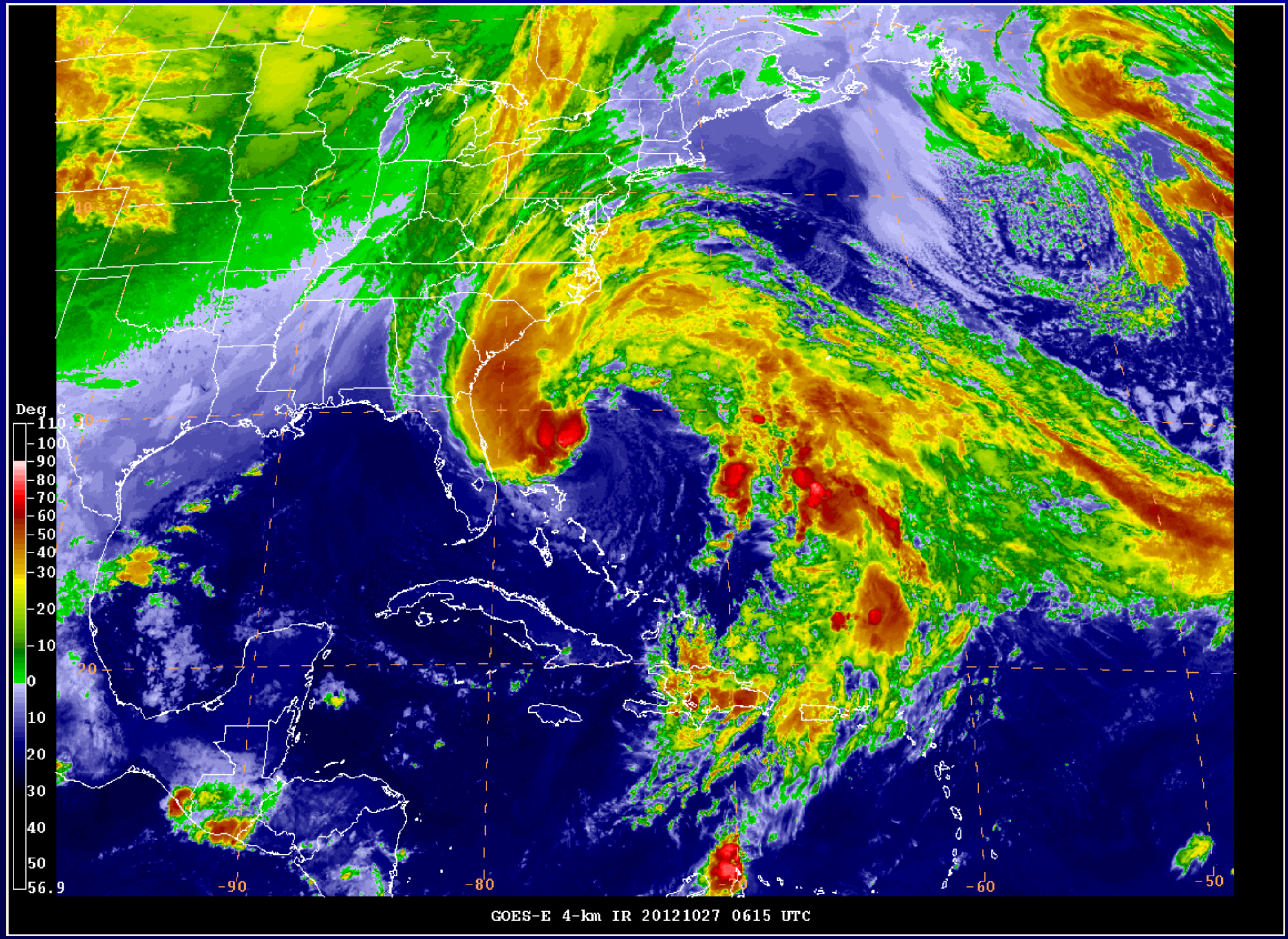
34 kt wind radii:

NE 450

SE 260

SW 180

NW 280



Hurricane Sandy (2012)

12 UTC 7 October

Intensity 70 kt

Pressure 956 mb

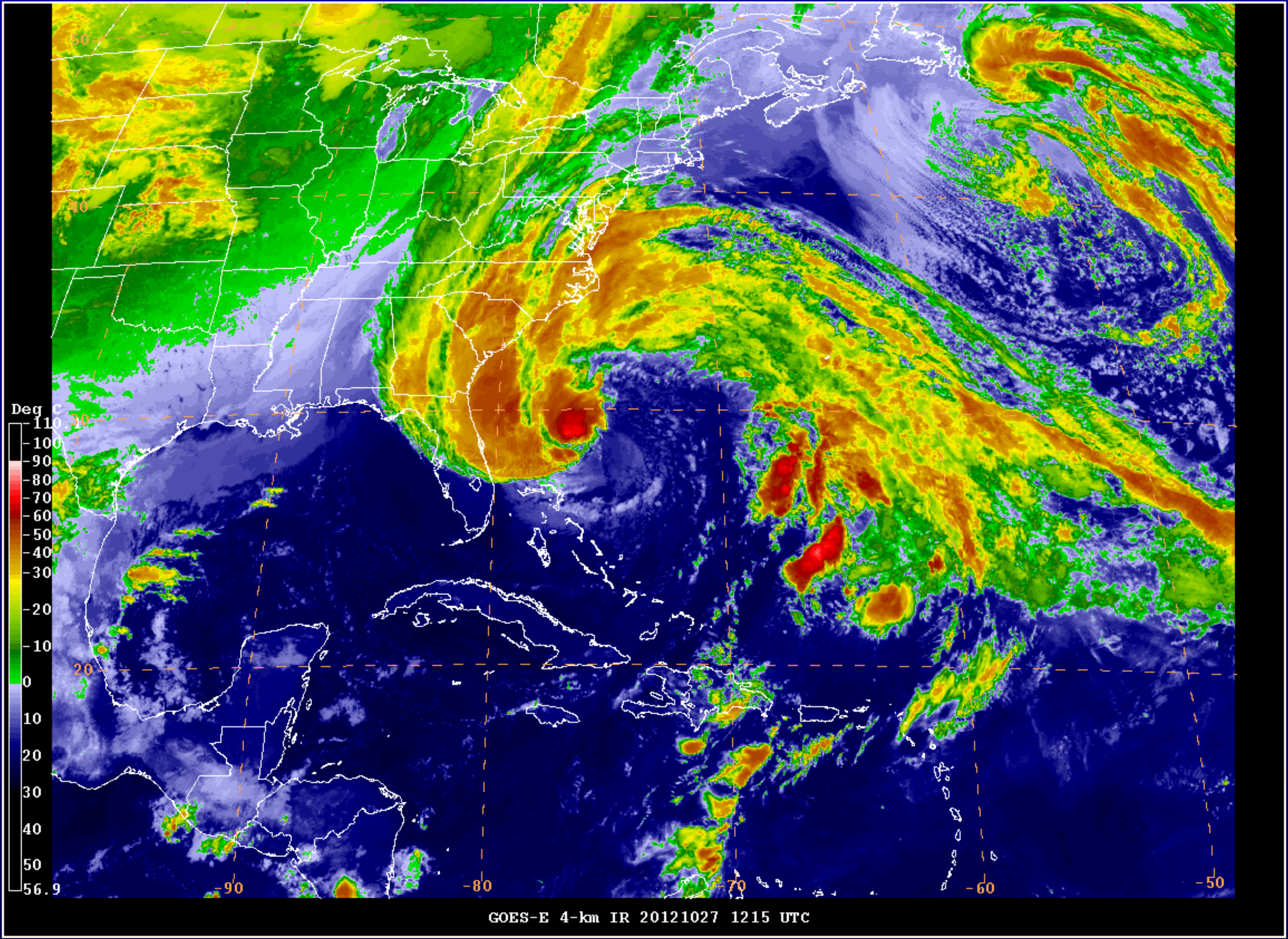
34 kt wind radii:

NE 450

SE 300

SW 210

NW 280



Hurricane Sandy (2012)

18 UTC 7 October

Intensity 70 kt

Pressure 960 mb

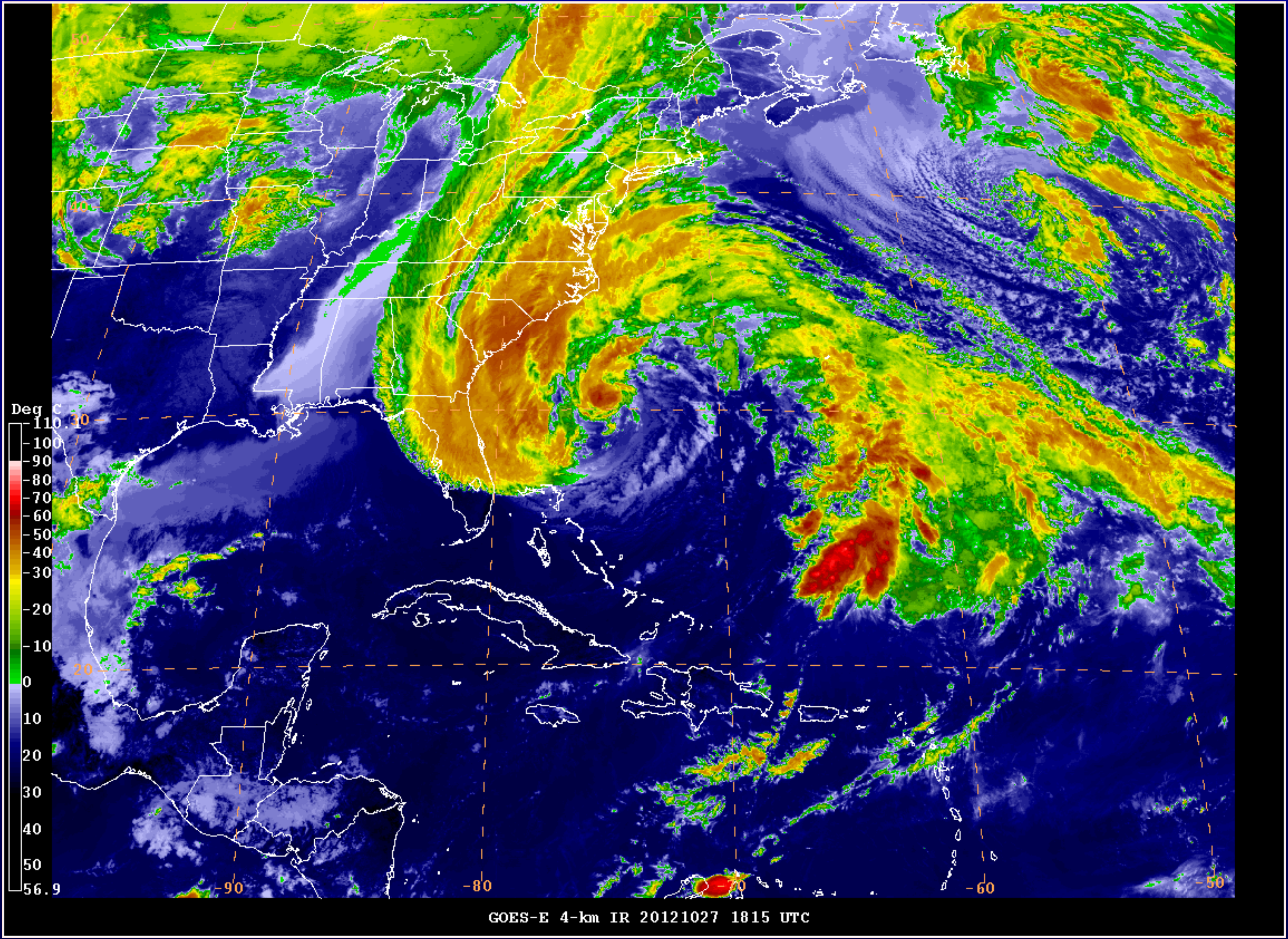
34 kt wind radii:

NE 450

SE 300

SW 240

NW 280



Hurricane Sandy (2012)

00 UTC 8 October

Intensity 65 kt

Pressure 960 mb

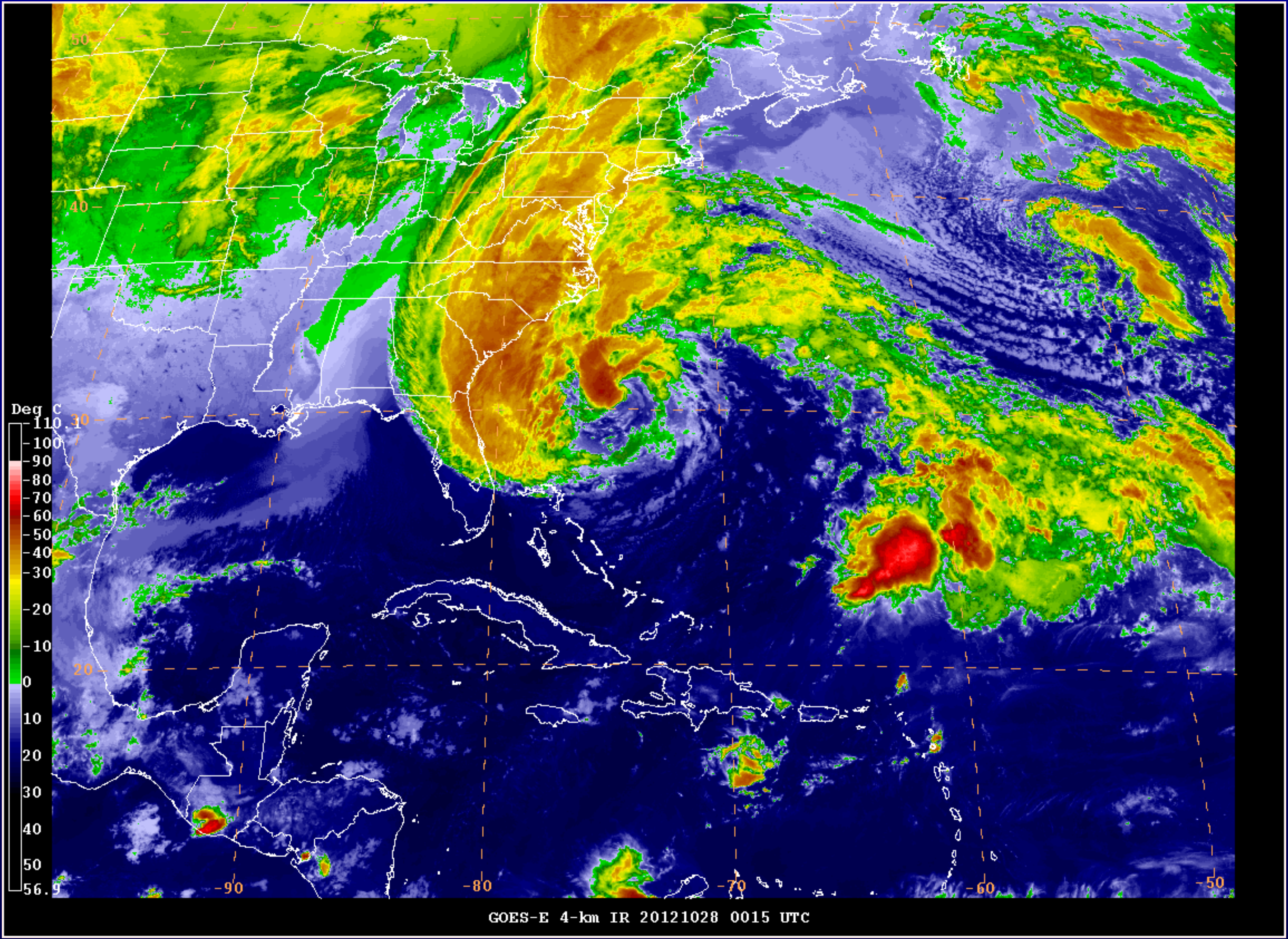
34 kt wind radii:

NE 480

SE 300

SW 300

NW 280



Hurricane Sandy (2012)

06 UTC 8 October

Intensity 65 kt

Pressure 959 mb

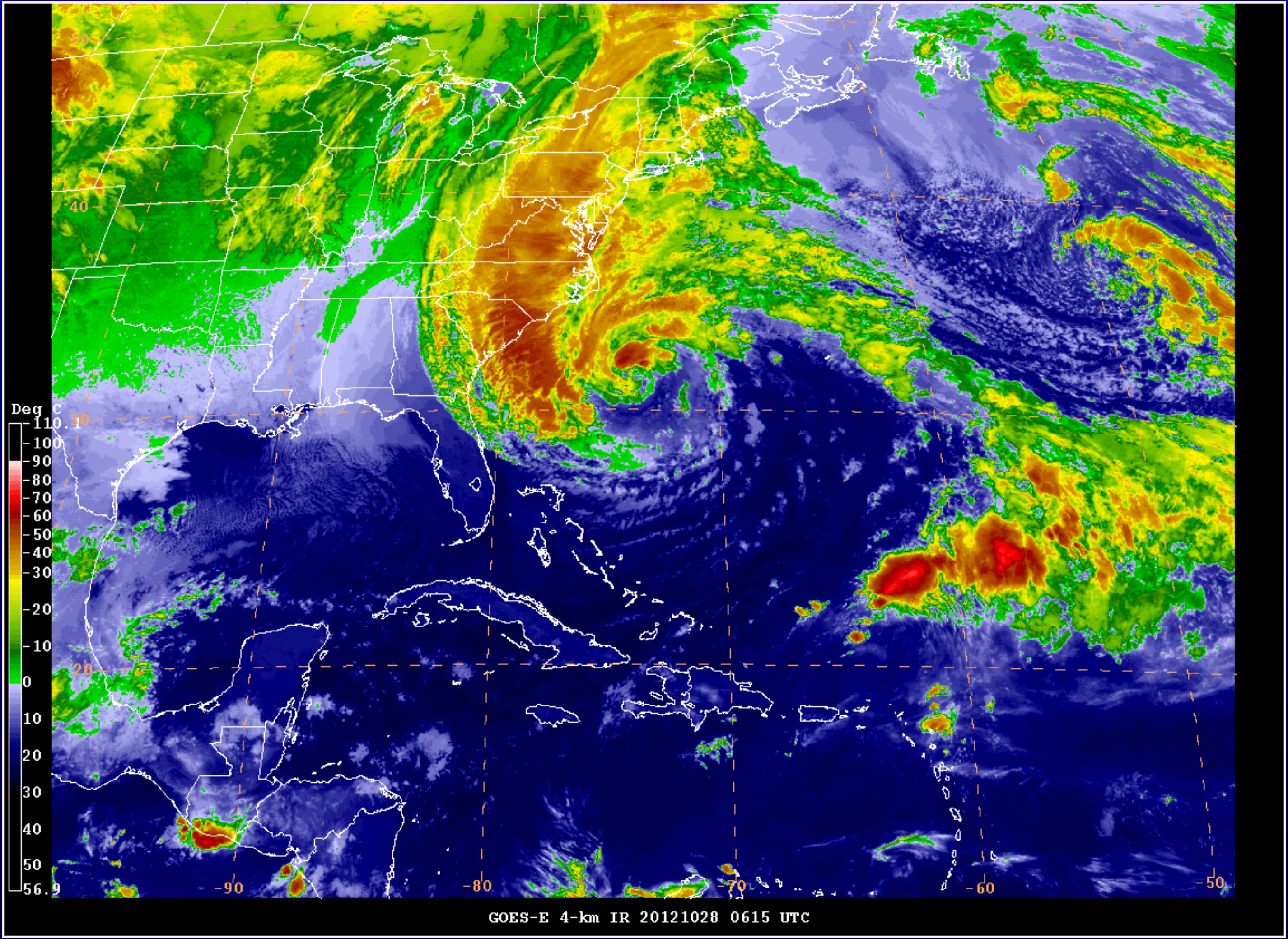
34 kt wind radii:

NE 450

SE 300

SW 300

NW 270



Hurricane Sandy (2012)

12 UTC 8 October

Intensity 65 kt

Pressure 954 mb

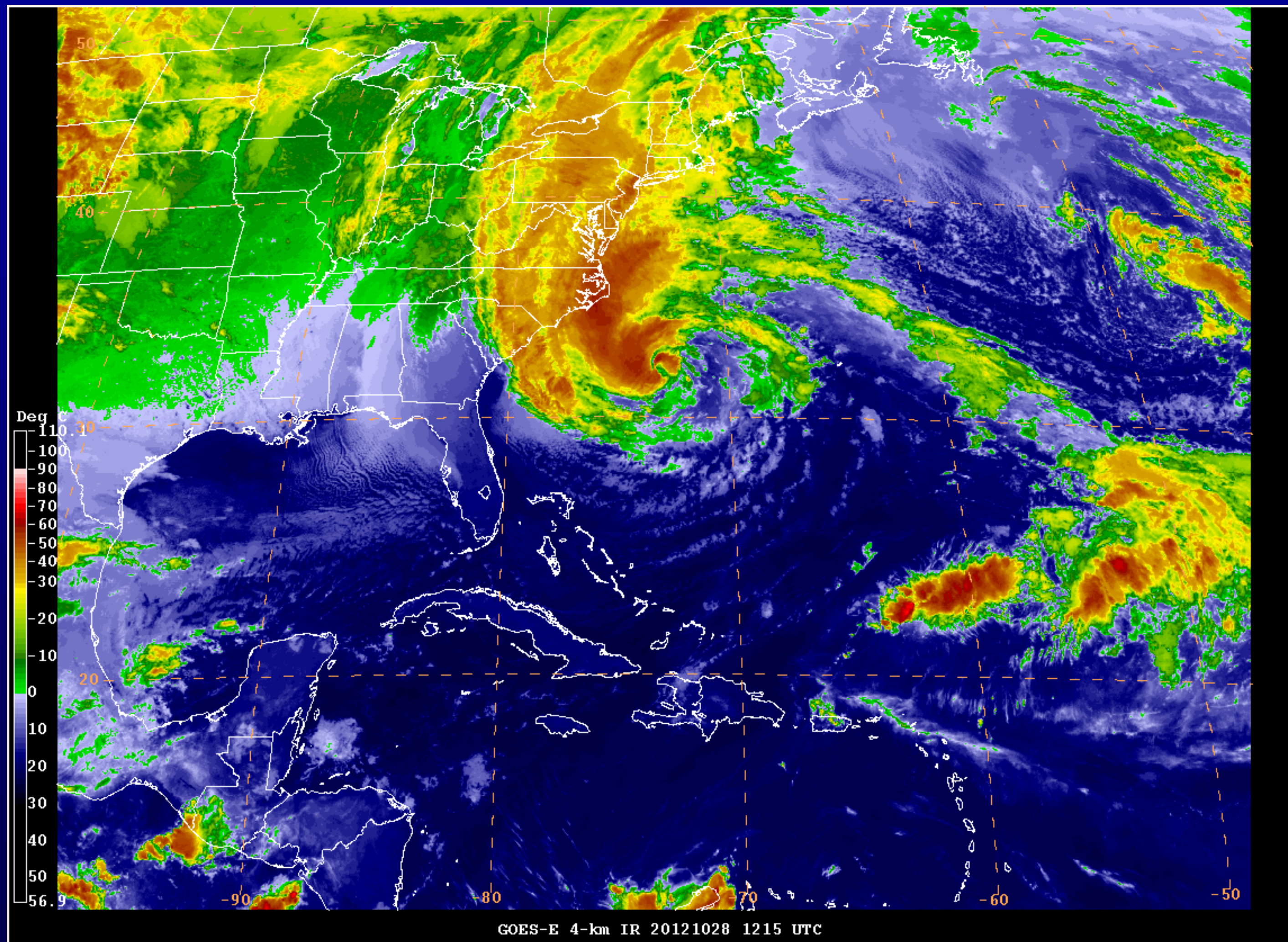
34 kt wind radii:

NE 450

SE 300

SW 300

NW 270



Hurricane Sandy (2012)

18 UTC 8 October

Intensity 65 kt

Pressure 952 mb

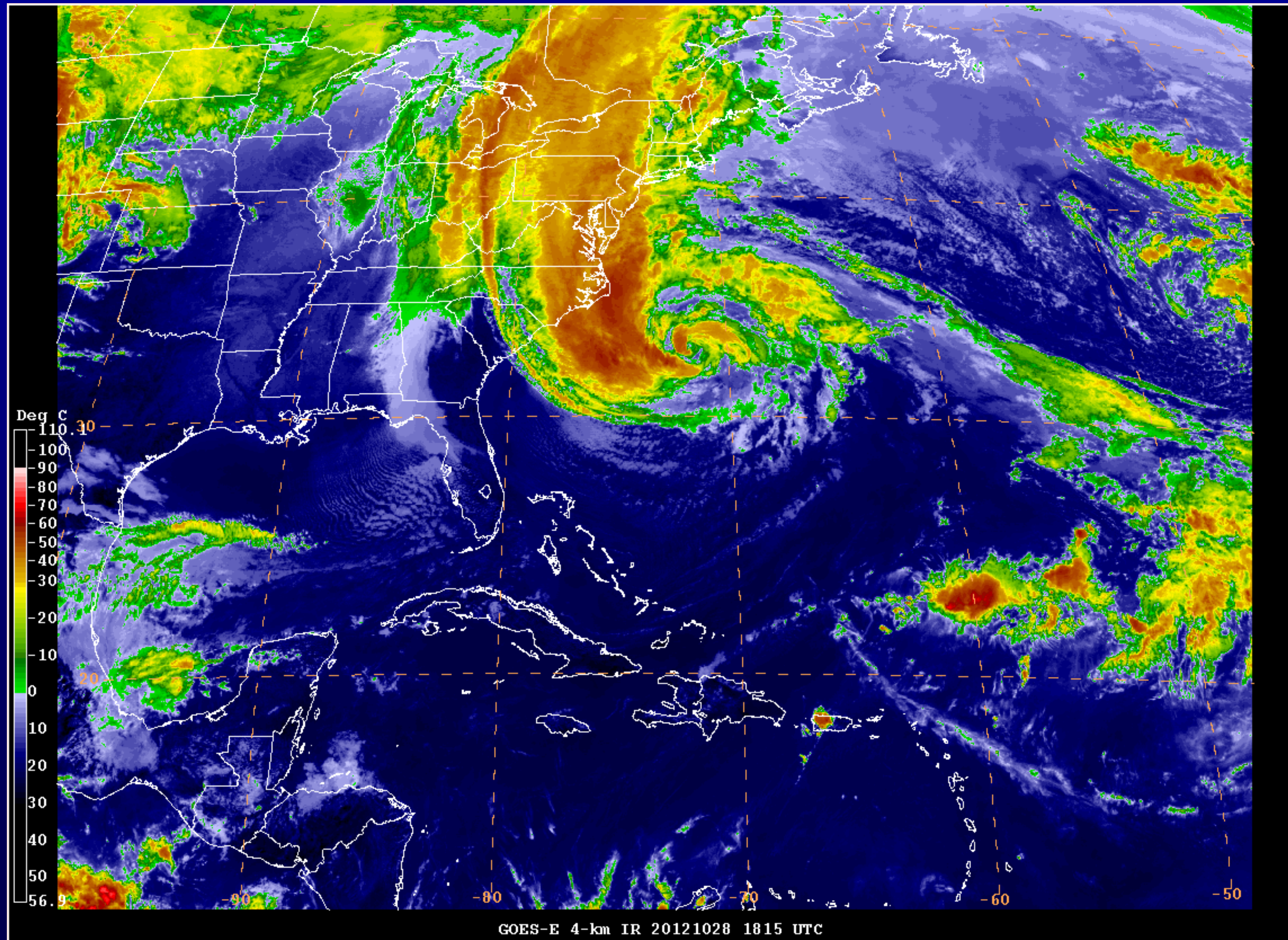
34 kt wind radii:

NE 450

SE 300

SW 350

NW 270



Hurricane Sandy (2012)

00 UTC 9 October

Intensity 70 kt

Pressure 950 mb

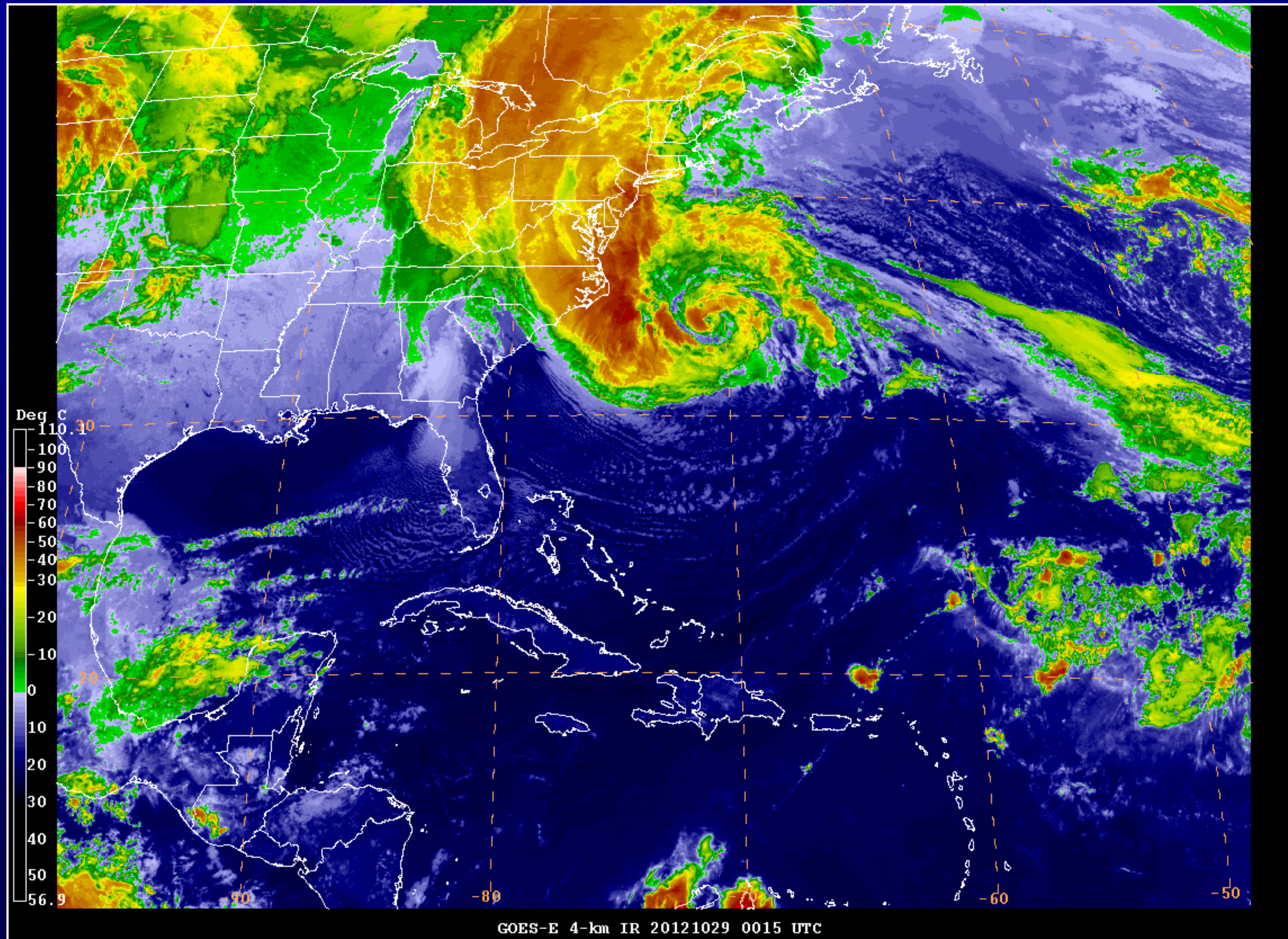
34 kt wind radii:

NE 450

SE 300

SW 400

NW 270



Hurricane Sandy (2012)

06 UTC 9 October

Intensity 80 kt

Pressure 947 mb

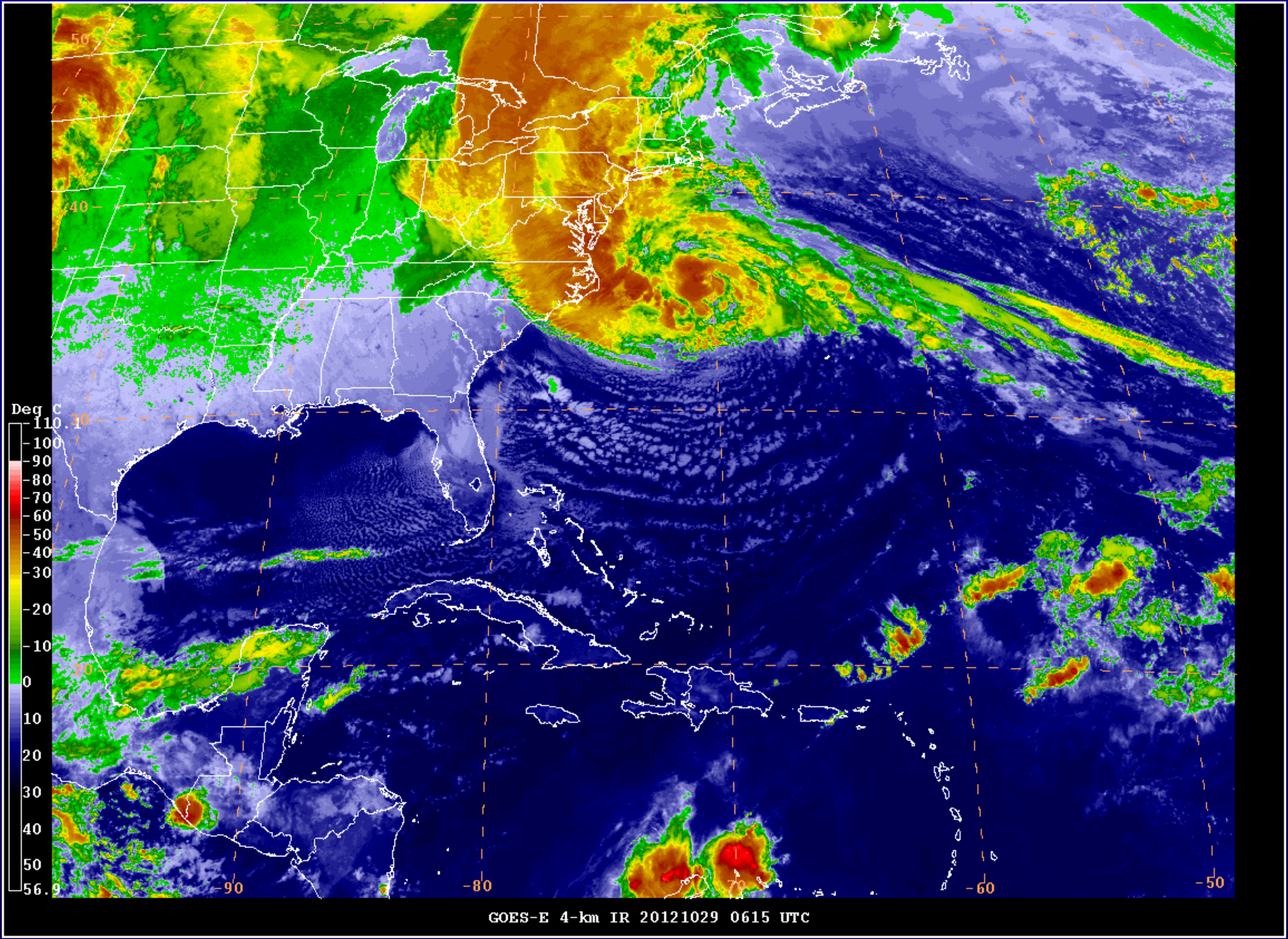
34 kt wind radii:

NE 420

SE 360

SW 450

NW 270



Hurricane Sandy (2012)

12 UTC 9 October

Intensity 85 kt

Pressure 945 mb

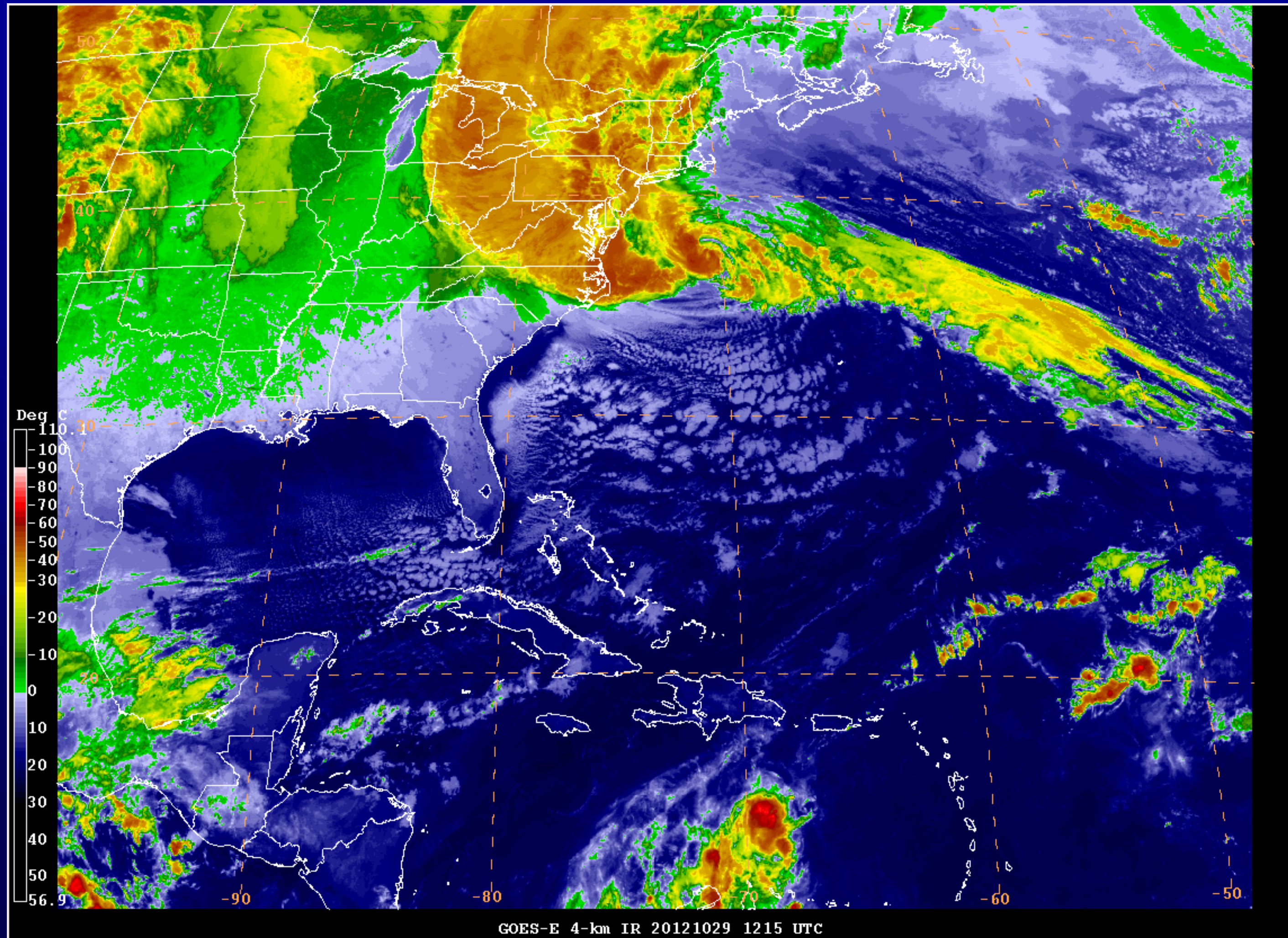
34 kt wind radii:

NE 420

SE 420

SW 400

NW 270



Hurricane Sandy (2012)

18 UTC 9 October

Intensity 80 kt

Pressure 940 mb

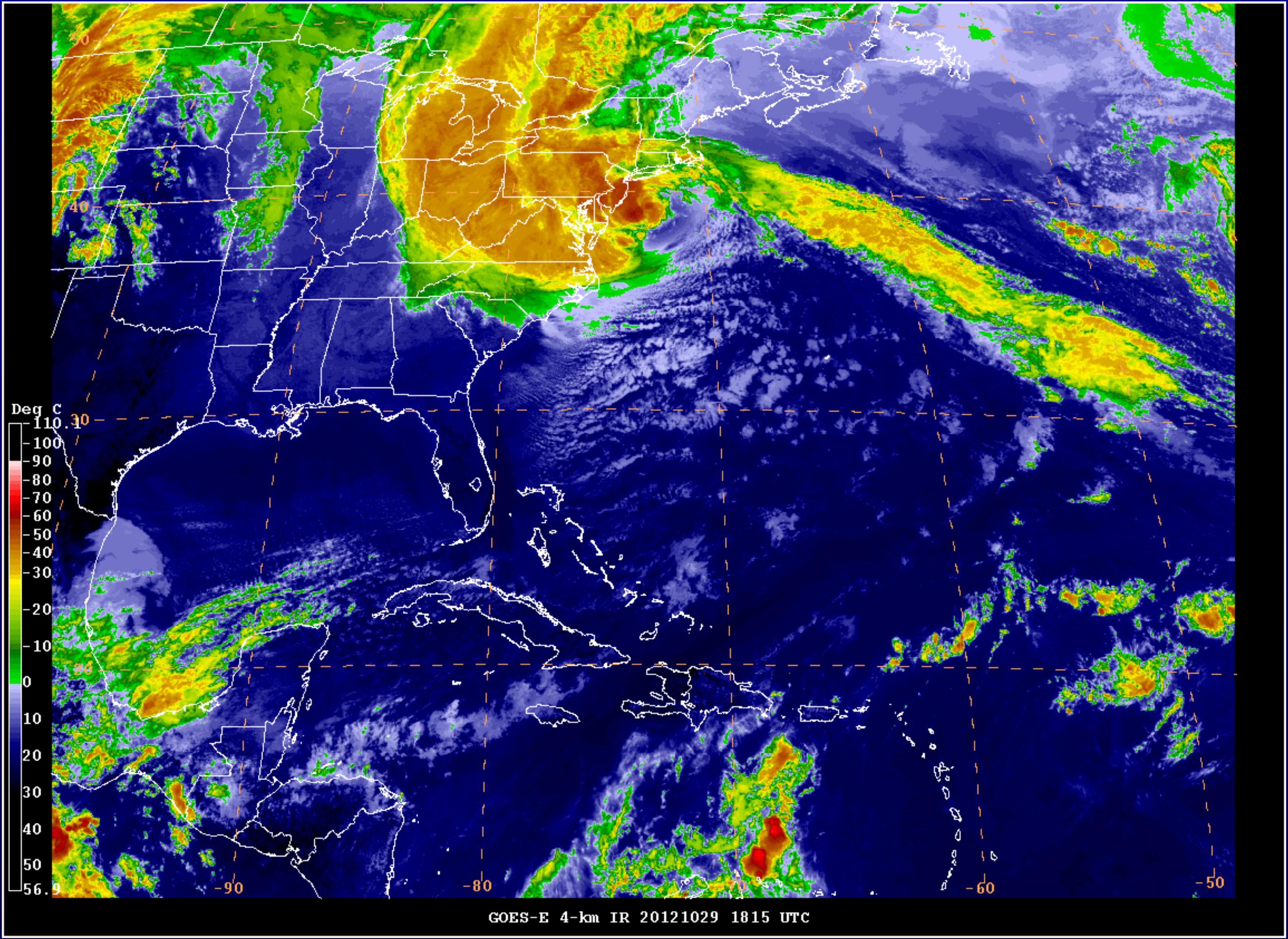
34 kt wind radii:

NE 420

SE 420

SW 400

NW 420



Hurricane Sandy (2012)

00 UTC 10 October

Intensity 70 kt

Pressure 946 mb

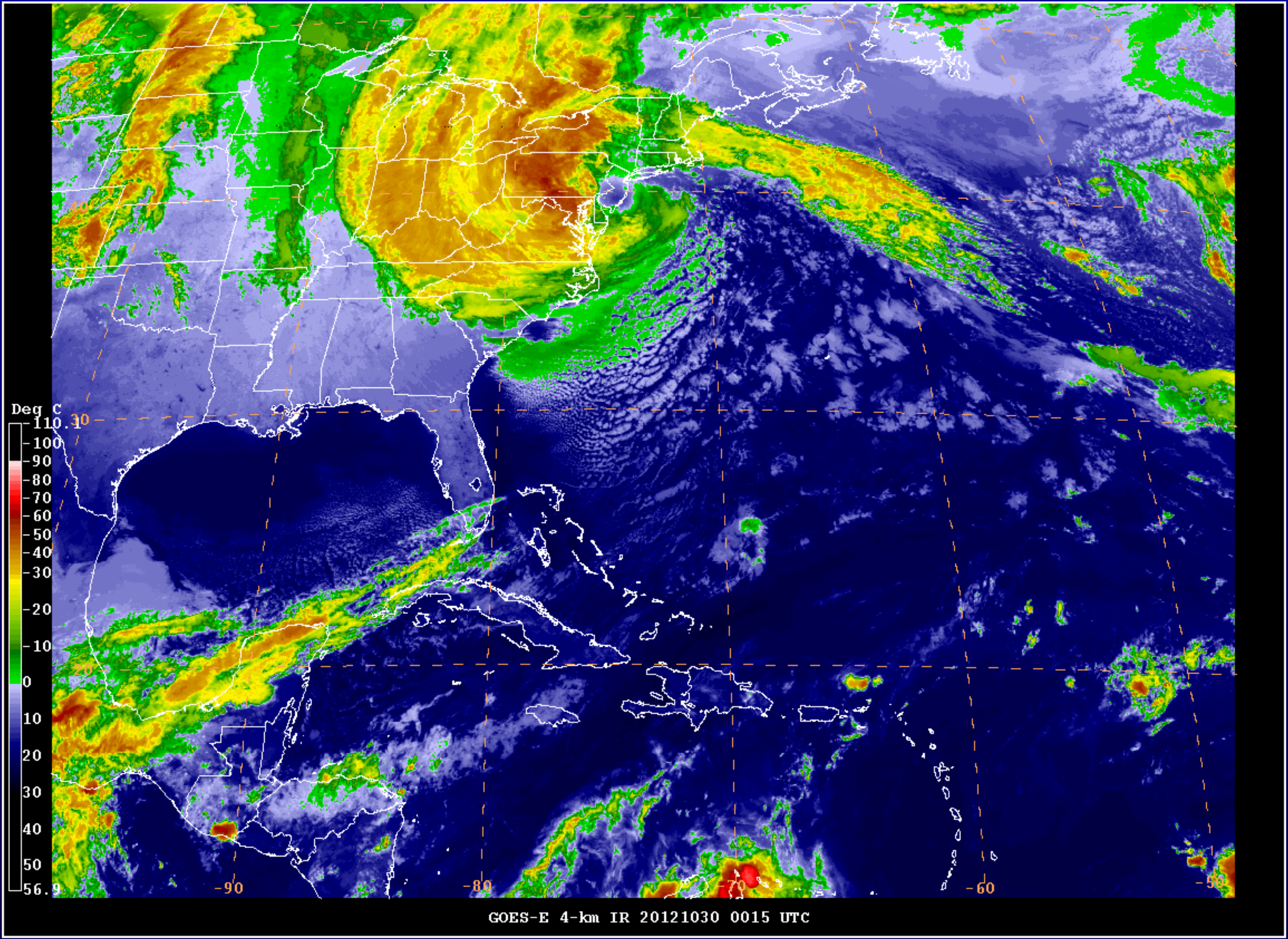
34 kt wind radii:

NE 460

SE 370

SW 400

NW 490



Extratropical

Hurricane Sandy (2012)

06 UTC 10 October

Intensity 55 kt

Pressure 960 mb

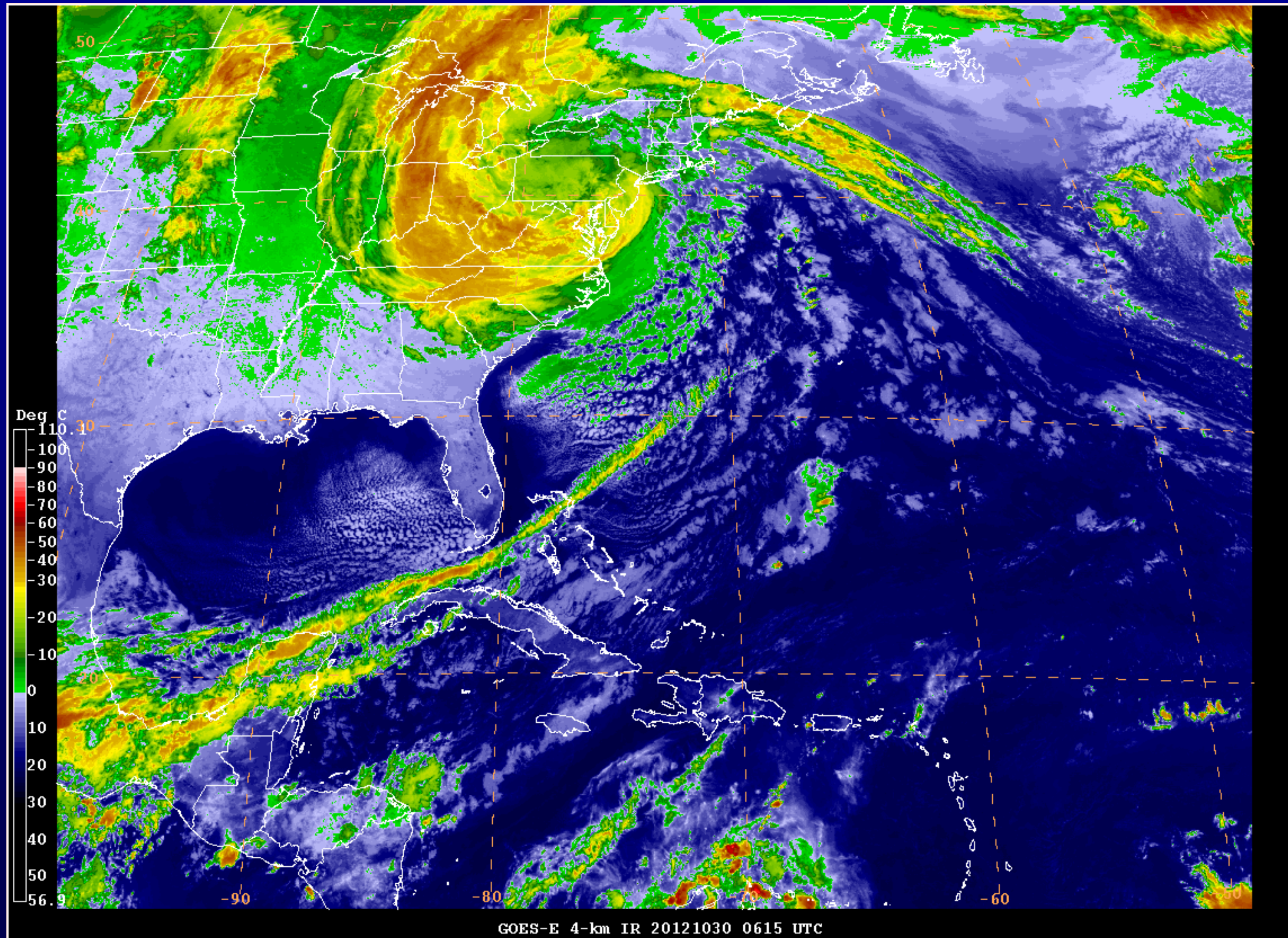
34 kt wind radii:

NE 450

SE 400

SW 160

NW 530



Extratropical

Hurricane Sandy (2012)

12 UTC 10 October

Intensity 50 kt

Pressure 978 mb

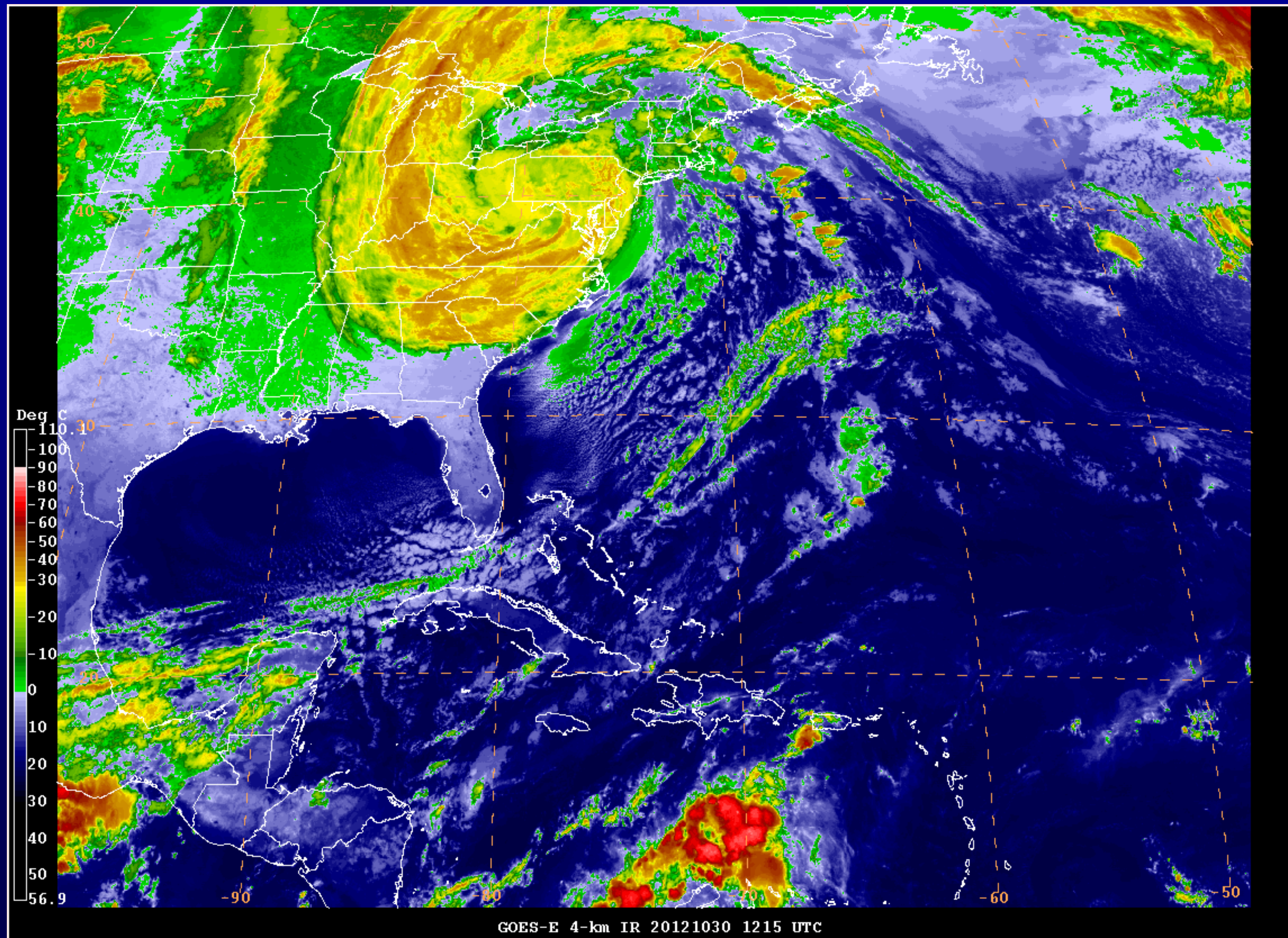
34 kt wind radii:

NE 450

SE 490

SW 0

NW 500



Extratropical

Environmental and Structural Changes that Occur during ET

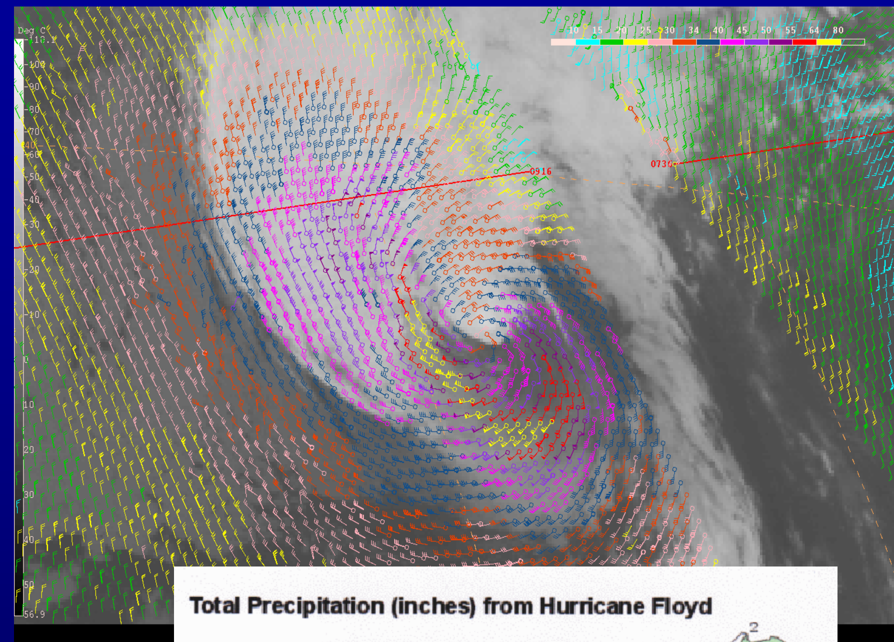
Environmental Changes Encountered During ET

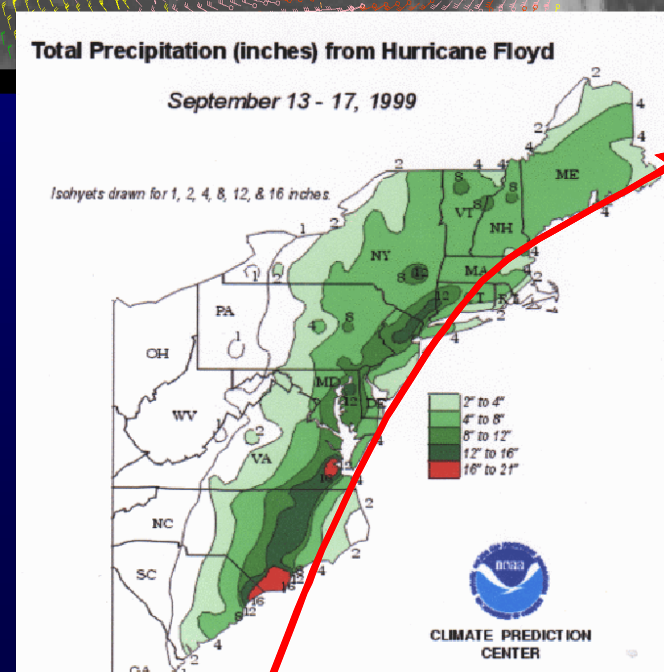
(Jones et al. 2003)

- Decreasing SST as TC moves poleward
  - Drier/more stable lower-tropospheric airmass
  - Distribution and magnitude of sensible and latent heat fluxes from ocean surface become more asymmetric and variable
- Interaction with large-scale baroclinic features
  - Upper-level troughs/jets
  - Lower-tropospheric fronts/SST gradients
  - Extratropical cyclones
- Increased wind shear
- Landfall or interaction with continental landmasses

Structural Changes Observed During ET
(Jones et al. 2003)

- Primary energy source transitions from latent heat release to baroclinic processes
  - Decrease in deep convection near center
  - Thermal advection, synoptic forcing (CVA, jet dynamics) become sources for energy
  - Can both be important during ET
- Impact of surface fluxes from the ocean surface change
  - Crucial to TC development, but more varied impact on extratropical cyclones
- Increase in baroclinity across cyclone
  - Development of fronts, asymmetric cloud and precipitation patterns due to strong thermal advections
- Reduction in maximum wind (usually but not always)
- Expansion of outer wind field





Conceptual Models and Composites of ET

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

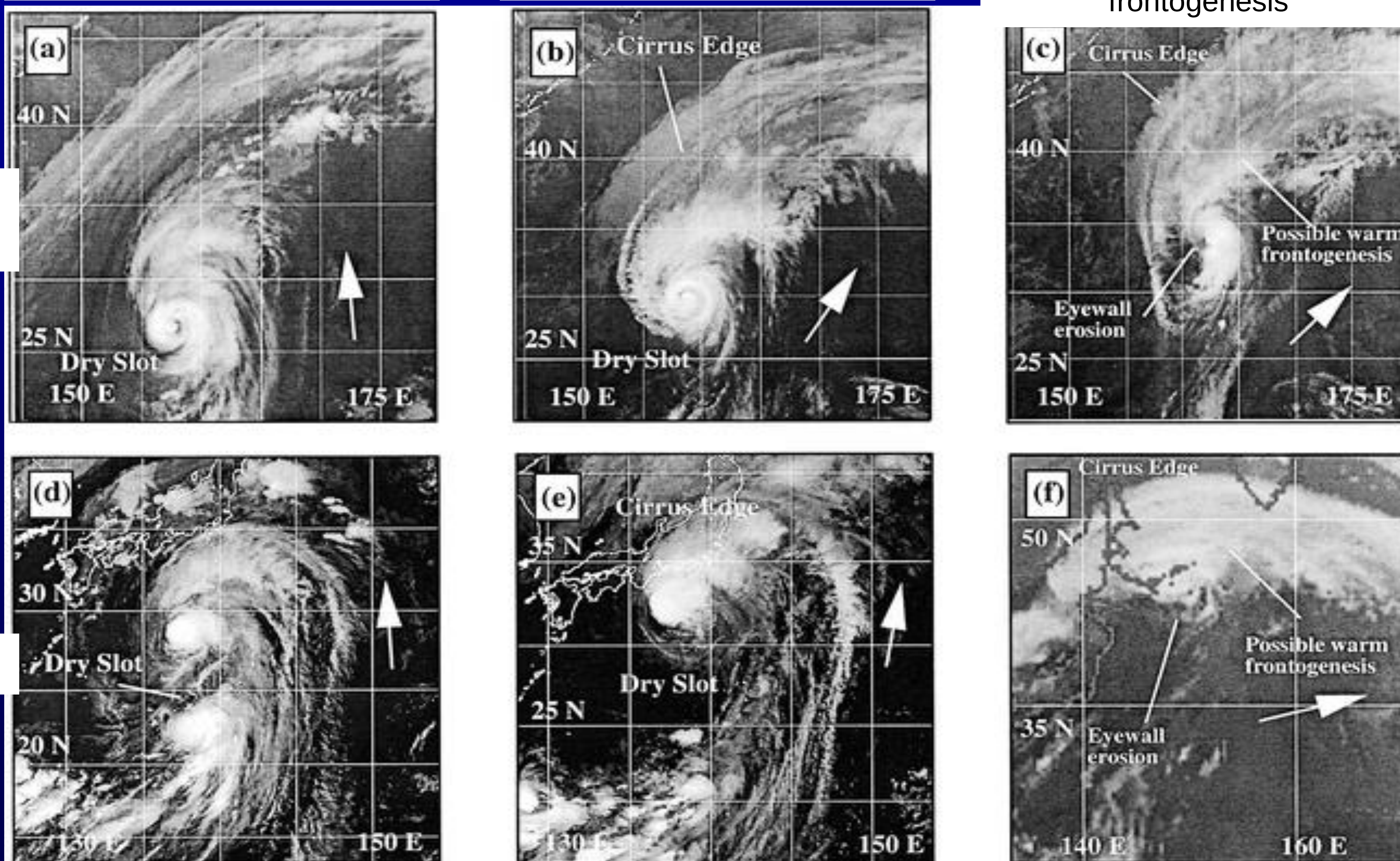
Common Satellite Features During ET

Klein et al. (2000)

Step 1	Step 2	Step 3
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

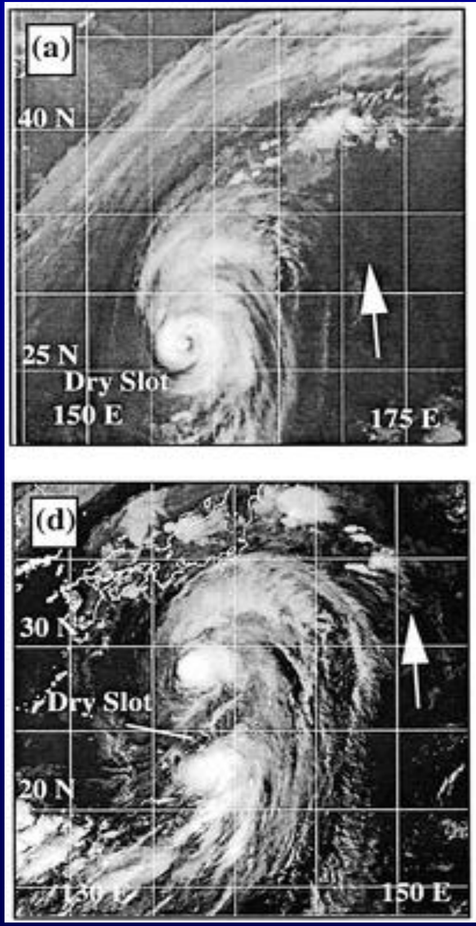
Step 3

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

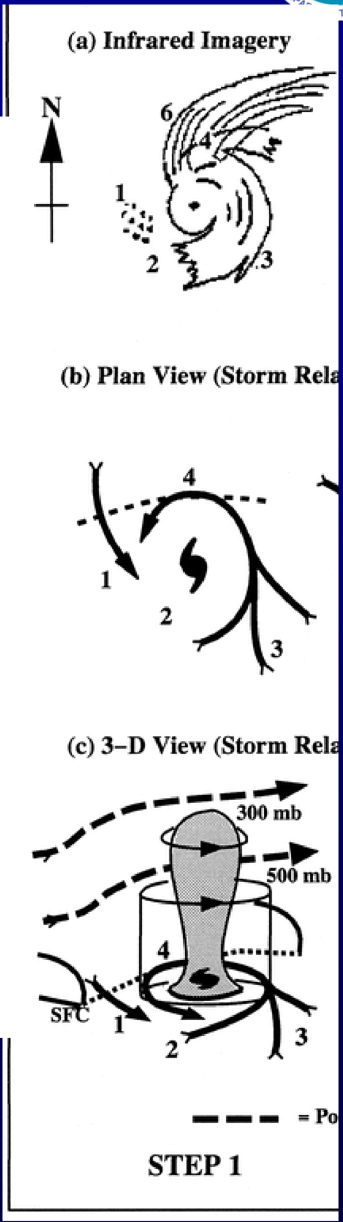
NW Pacific ET Conceptual Model

Klein et al. (2000)

- Step 1 – Transformation Begins
  - Cyclone moves over cooler SSTs
  - Interaction begins with baroclinic zone
  - Cold, dry advection begins west of center
  - Convection decreases in 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



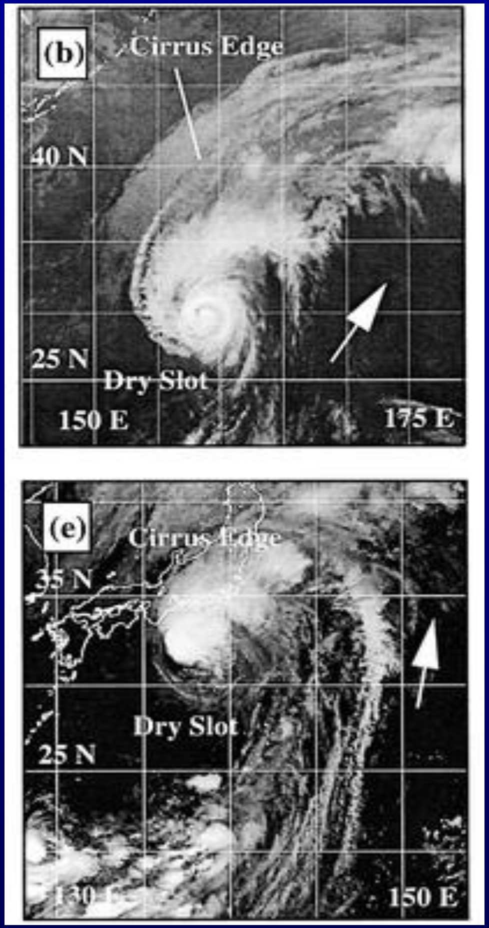
Klein et al. (2000)
Weather and Forecasting



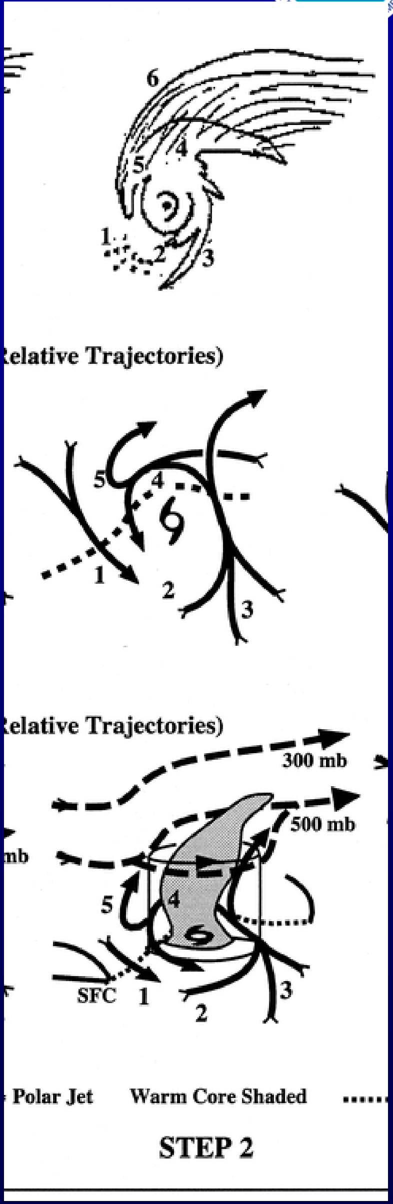
NW Pacific ET Conceptual Model

Klein et al. (2000)

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



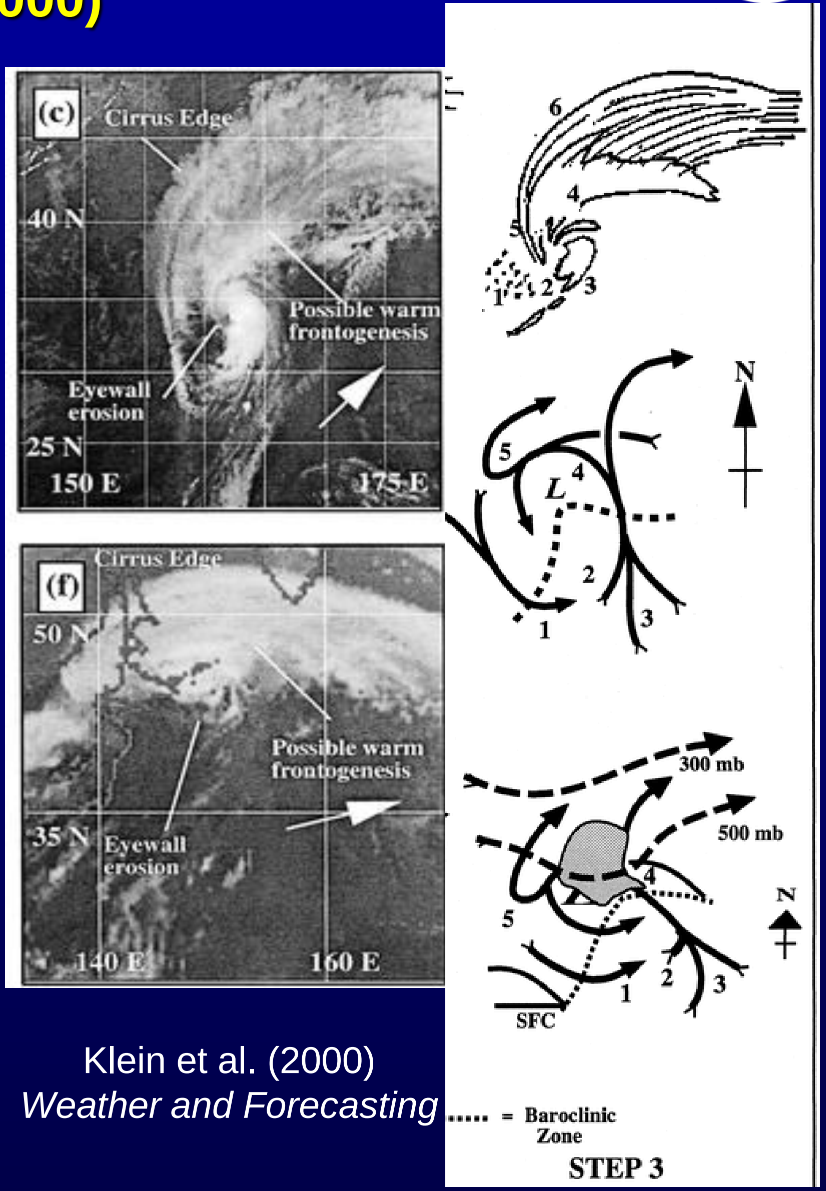
Klein et al. (2000)
Weather and Forecasting



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

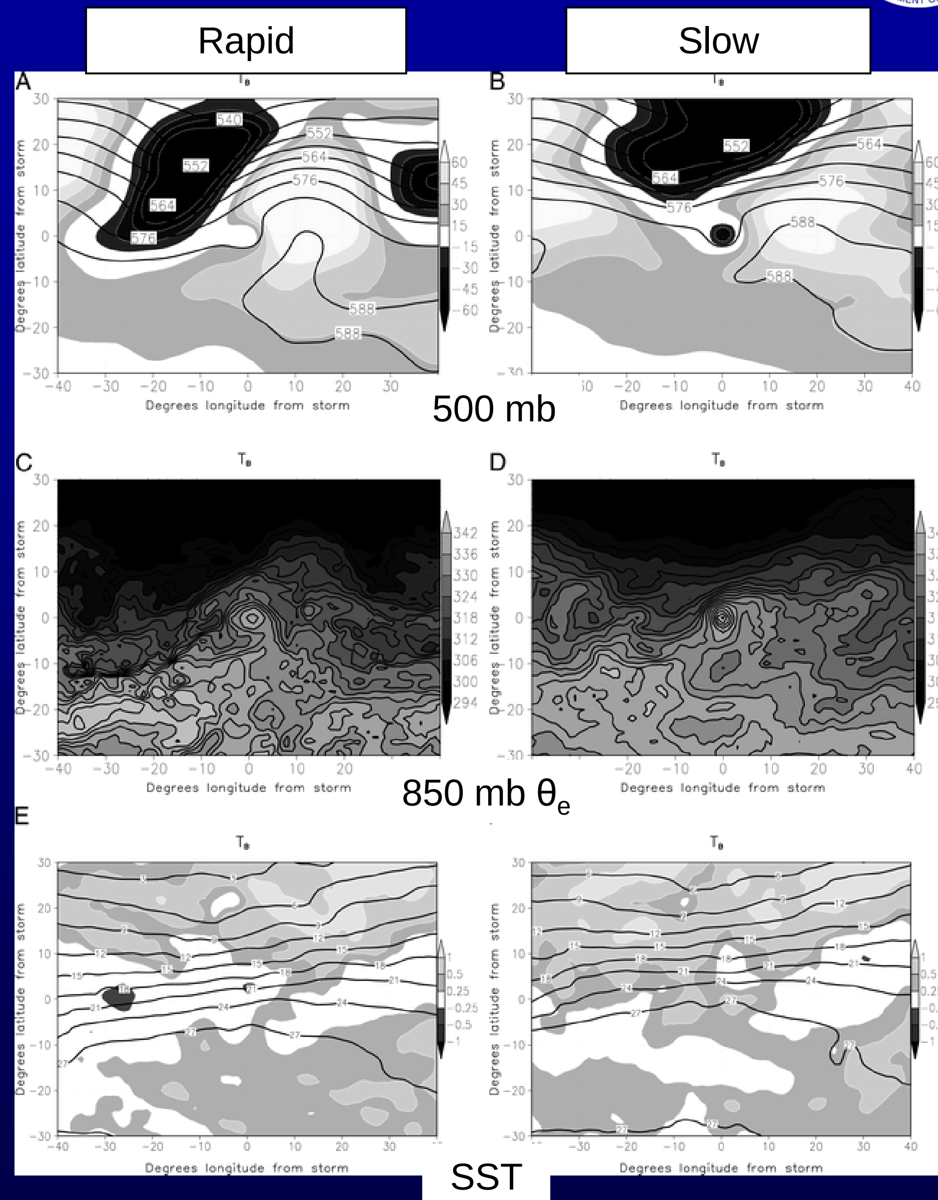
North Atlantic ET Study
Hart et al. (2006)

- Based on 34 Atlantic ET events from 1998–2003 examined using 1° NOGAPS analysis
- Examined characteristics that differed between cyclones for
  - Fast vs. slow ET
  - Post ET intensification vs. weakening
  - Post ET structure – cold core or warm seclusion

North Atlantic ET – Slow or Fast Transition?
Hart et al. (2006)

Rapid or slow transition?

- **Rapid ET (≲ 12 h)**
  - Longwave pattern meridional
  - TC initially smaller and weaker than average
  - SST << 27°C, with large SST gradient
- **Slow ET (≳ 48 h, extended hybrid phase)**
  - Longwave pattern zonal
  - SST ≈ 27°C
  - TC initially stronger and larger
  - Environmental forcing still supports tropical development



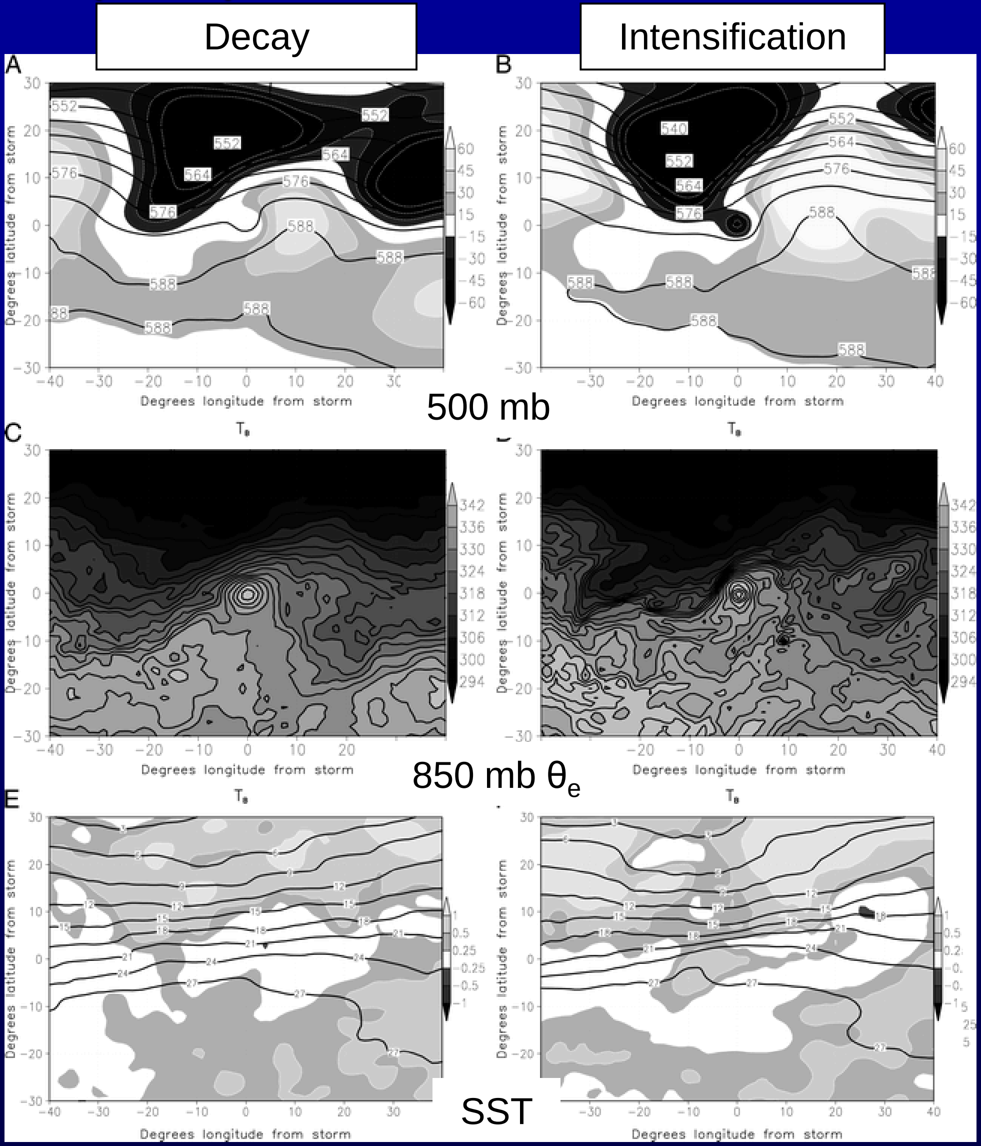
Hart et al. (2006) *Monthly Weather Review*

North Atlantic ET – Post Transition Intensification or Decay?

Hart et al. (2006)

Post-transition intensification or decay?

- **Intensification**
  - Negatively-tilted upper trough
  - Remnant TC intense and more connected to tropics
  - Stronger SST gradient
- **Decay**
  - Positively-tilted upper trough
  - Remnant TC weak and detached from tropical air
  - Warmer SST but weaker gradient



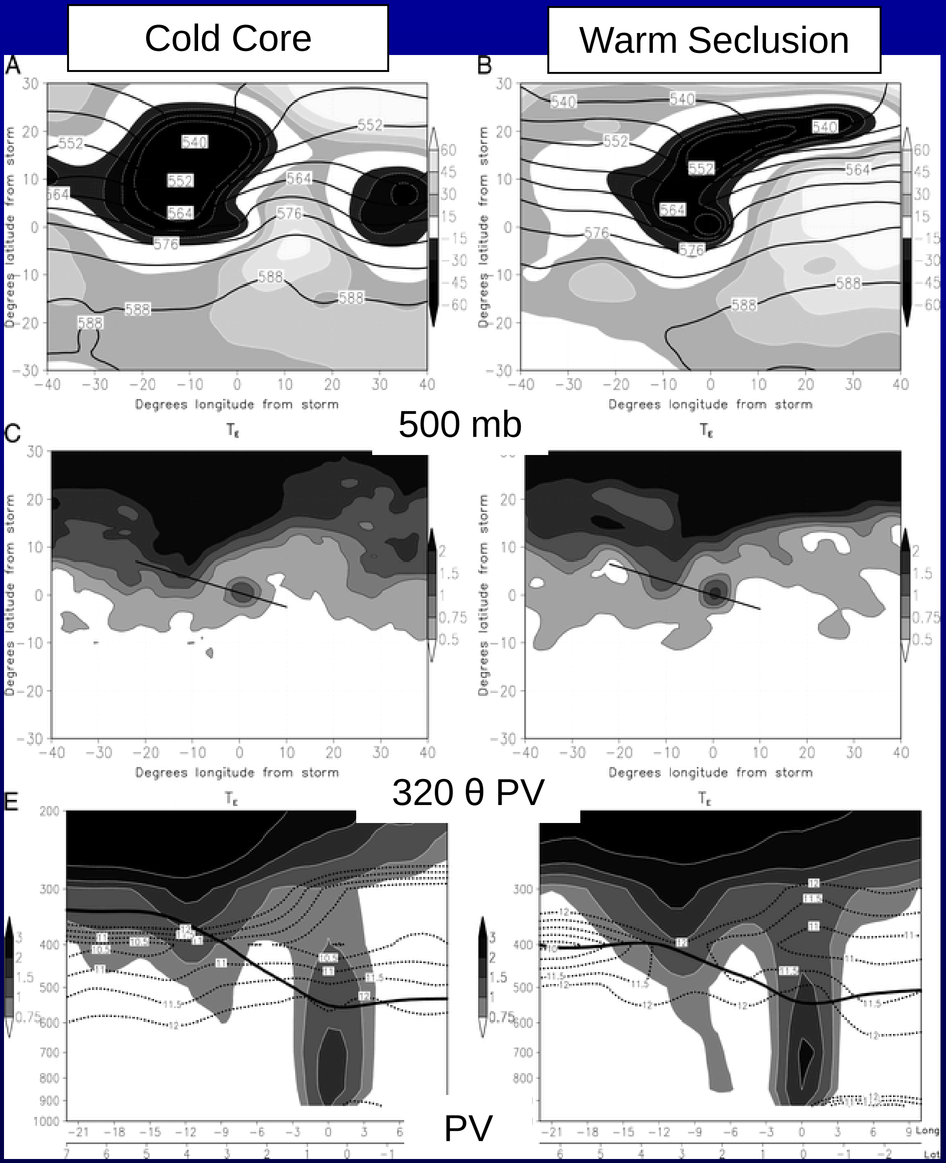
Hart et al. (2006) *Monthly Weather Review*

North Atlantic ET – Post Transition Structure
Hart et al. (2006)

Post-transition structure

- **Cold Core**
  - Large horizontal scale of upper trough does not match scale of TC
  - Trough has smaller vertical extent

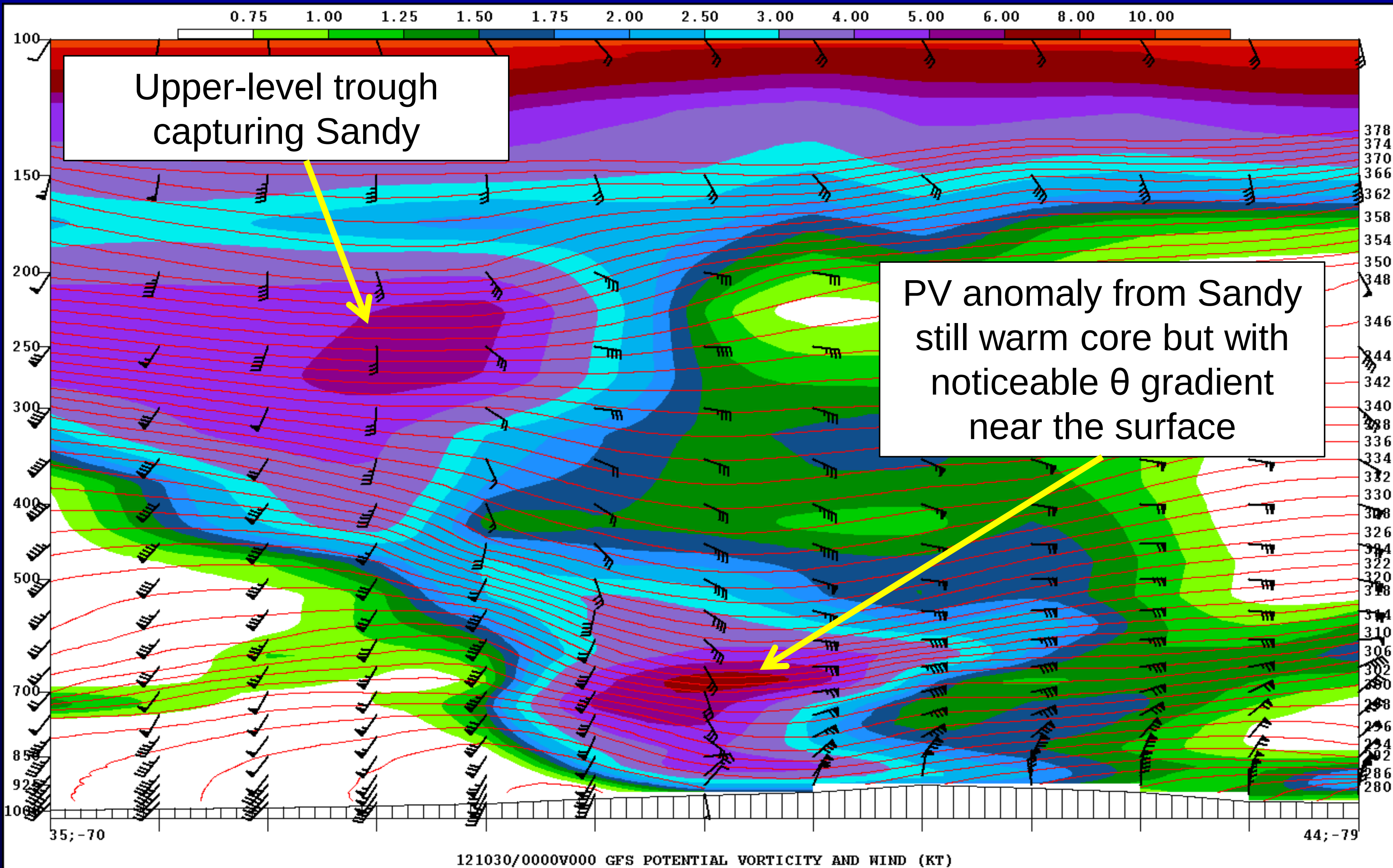
- **Warm Seclusion**
  - Scale of upper trough closely matches that of TC (usually larger TCs)
  - Narrow horizontal extent of trough, but deep vertical extent
  - Increased wind threat due to expansion of gale force wind radii *and* strong maximum wind
  - More difficult for models to forecast



Hart et al. (2006) *Monthly Weather Review*

Sandy Post-Transition

GFS Cross Section of PV, θ, Wind 00Z 30 October 2012



Forecasting Tools

Phase Space Diagrams

Hart (2003)

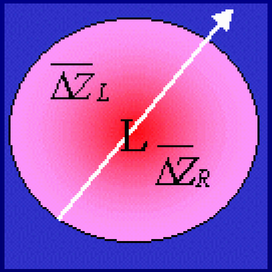
- Cyclone "phase space" diagrams provide a way to visualize the location of a cyclone in the continuum between tropical and extratropical
- Constructed from model analyses and forecasts for active cyclones – available online at: http://moe.met.fsu.edu/cyclonephase/
- Useful during ET to determine character of model analyzed cyclone and trends during the model forecast
- Three parameters used to represent the "phase" of a cyclone:

1. B – Storm-motion-relative 900–600-mb thickness gradient across cyclone
2. $-V_T^L$ – Magnitude of lower-tropospheric (900–600 mb) cyclone thermal wind
3. $-V_T^U$ – Magnitude of upper-tropospheric (600–300 mb) cyclone thermal wind

Two phase diagrams constructed plotting 1 vs. 2 and 2 vs. 3

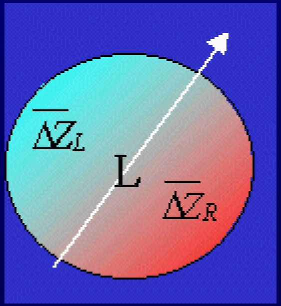
Storm-Motion-Relative Thickness Gradient (B)

- Measures the degree of thermal asymmetry across a cyclone relative to the direction of motion
- Provides a representation of how “frontal” a cyclone is



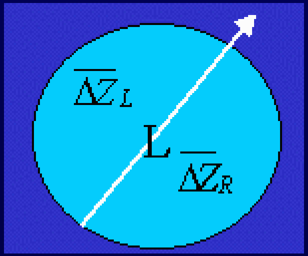
Mature tropical cyclone → B = 0 → Symmetric

Warmest temperature at center decreasing uniformly in all directions



Developing or mature extratropical cyclone → B >> 0 → Asymmetric

Pronounced thermal gradient across cyclone with well defined “warm” and “cold” sectors



Occluded extratropical cyclone → B = 0 → Symmetric

Uniform thermal structure with little change in temperature near cyclone center

Magnitude of Thermal Wind

- Lower Troposphere ($-V_T^L$)
  - Shows structure of the cyclonic circulation in the lower troposphere (900 to 600 mb)
- Middle-Upper Troposphere ($-V_T^U$)
  - Shows structure of the cyclonic circulation in the mid- to upper-troposphere (600 to 300 mb)

Circulation character

•**Warm core** ($-V_T > 0$) → circulation strength *decreases* with height

•**Cold core** ($-V_T < 0$) → circulation strength *increases* with height

•**Neutral** ($-V_T \approx 0$) → circulation strength shows little change with height

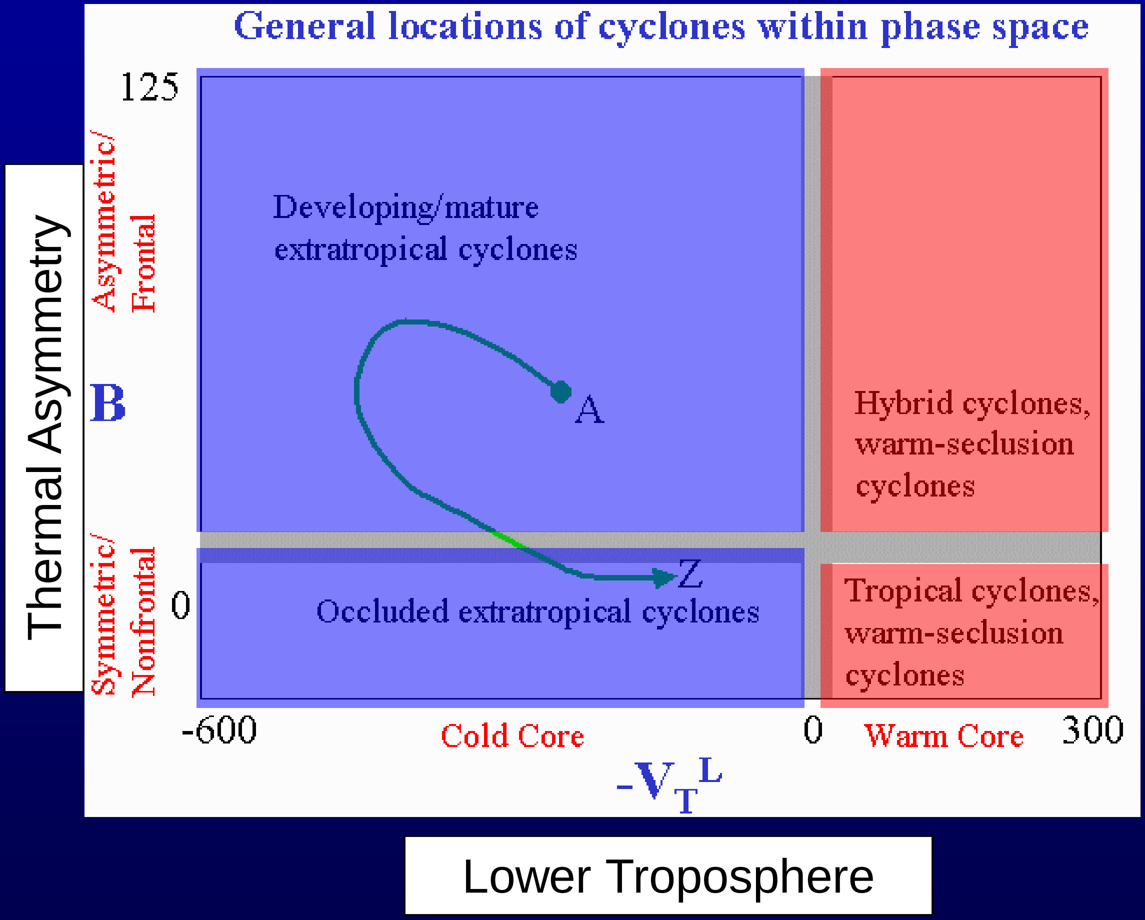
Phase Diagram 1
Thermal Asymmetry versus Lower-Tropospheric Thermal Wind

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

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

Symmetric cold core
- $B \leq 0$ and $-V_T^L < 0$
  - Occluded extratropical cyclones

Asymmetric cold core
- $B > 0$ and $-V_T^L < 0$
  - Developing or mature extratropical cyclones



Phase Diagram 2

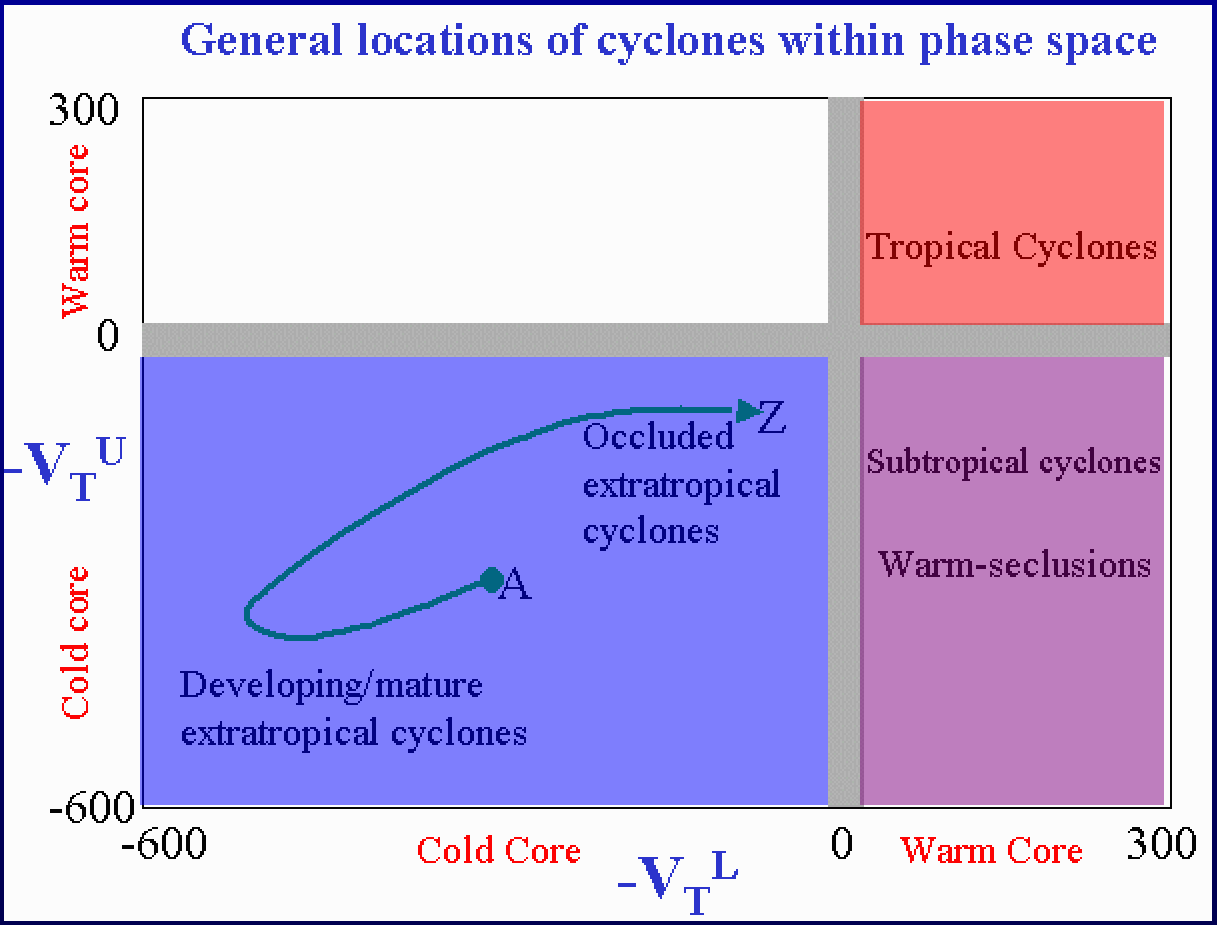
Upper vs. Lower tropospheric Thermal Wind

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

Upper Troposphere



Lower Troposphere

Classification Using Phase Space Diagrams

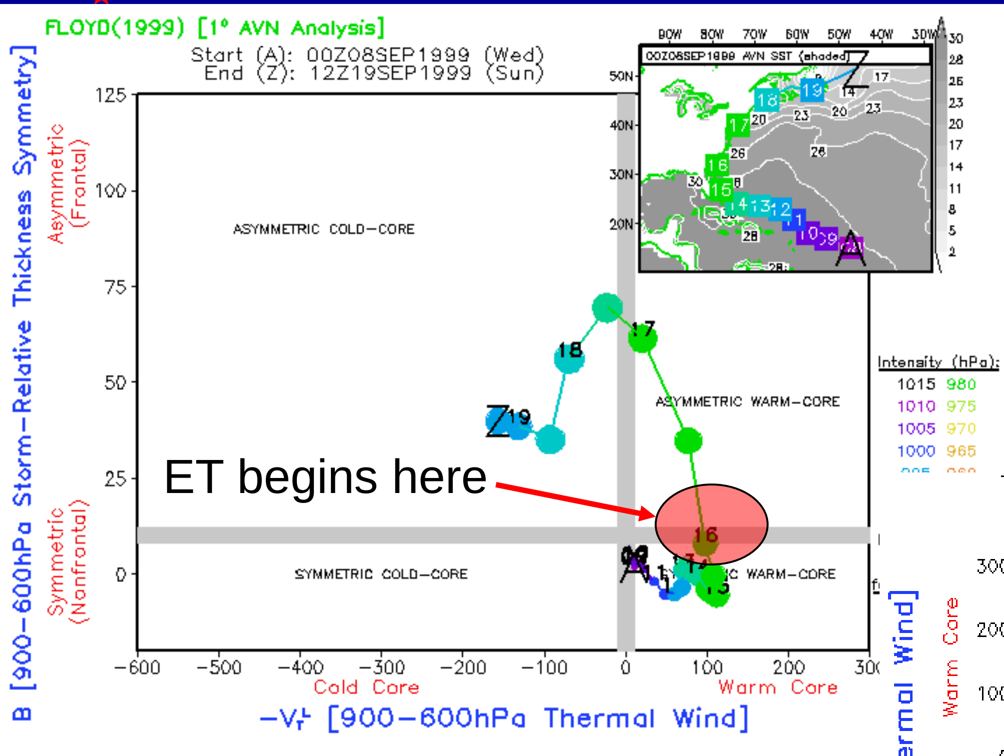
Evans and Hart (2003)

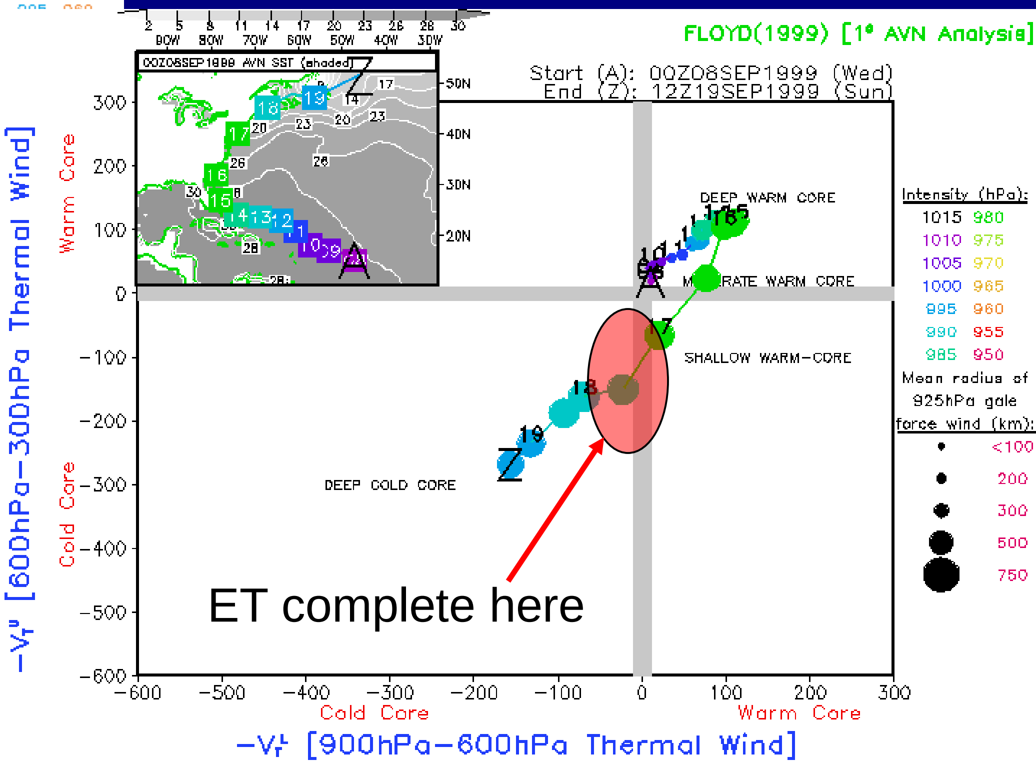
- 61 Atlantic ET events from 1979–1993 examined using ECMWF reanalysis
- Onset of ET: B > 10 m
  - Corresponds to onset of low-level frontogenesis
- ET complete: $-V^{L}_{T} < 0$
  - Vertical structure is cold-core, i.e., strongest winds aloft
- Mean transition period around 1.5 days

Phase Space Life Cycle Examples

Hurricane Floyd (1999) undergoes "typical" ET in phase space

Initially deep warm core transitions to shallow asymmetric warm core and then deep asymmetric cold core





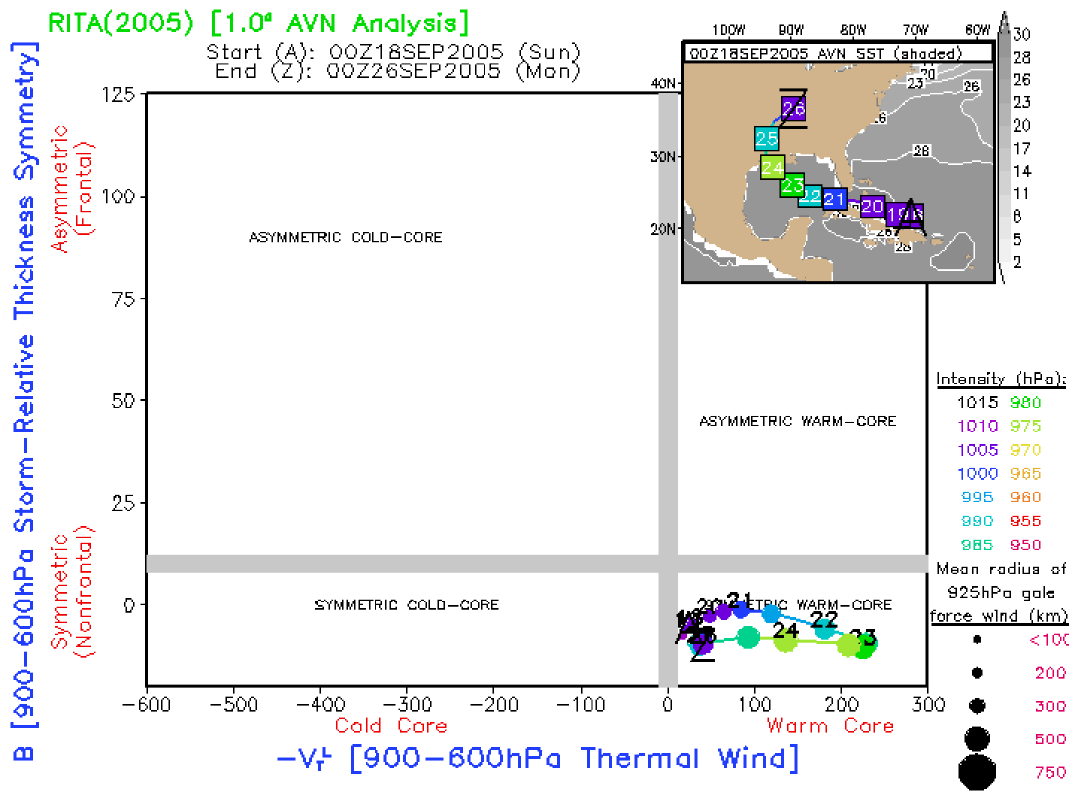
Transition of Floyd takes about 24 hours

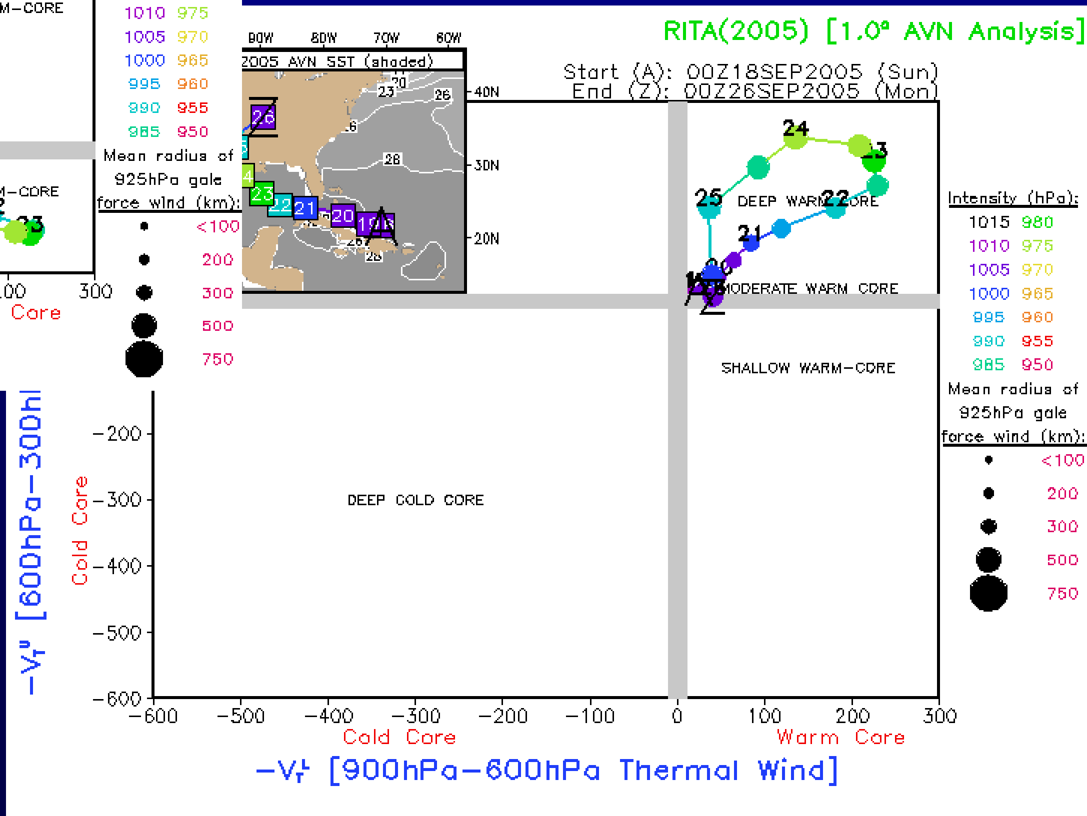
Begins early on 16 September

Ends around 12 UTC 17 September

(Evans and Hart 2003)

Phase Space Life Cycle Examples

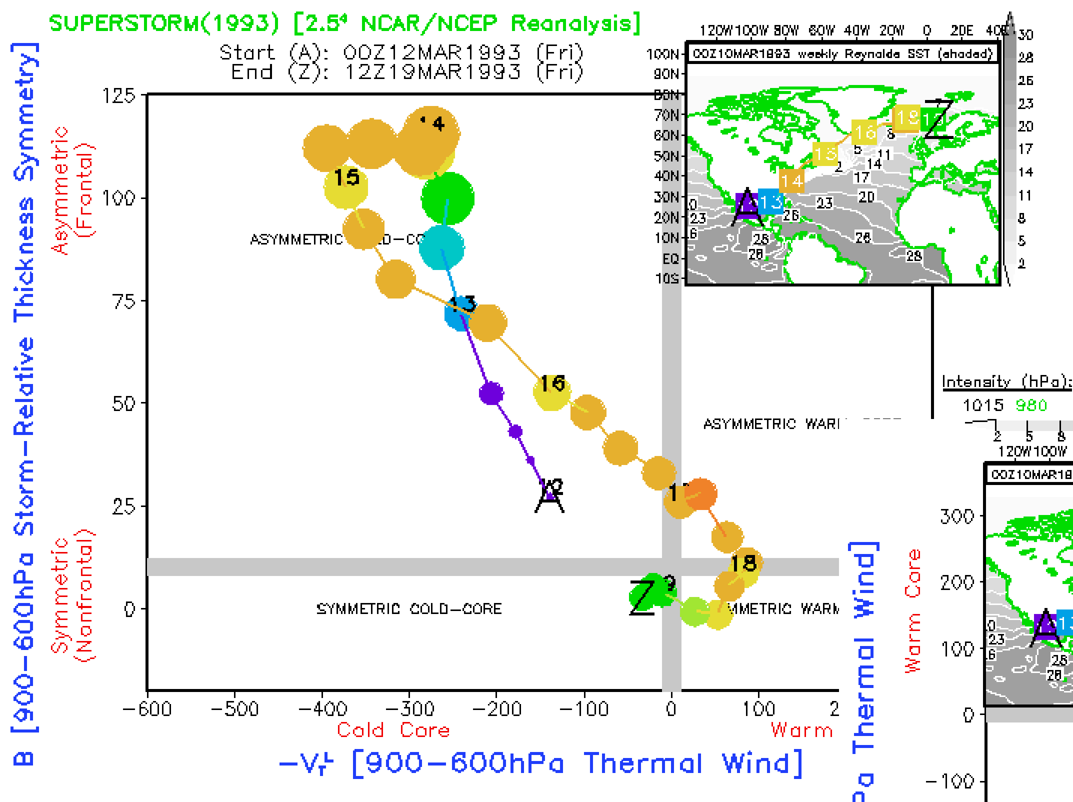


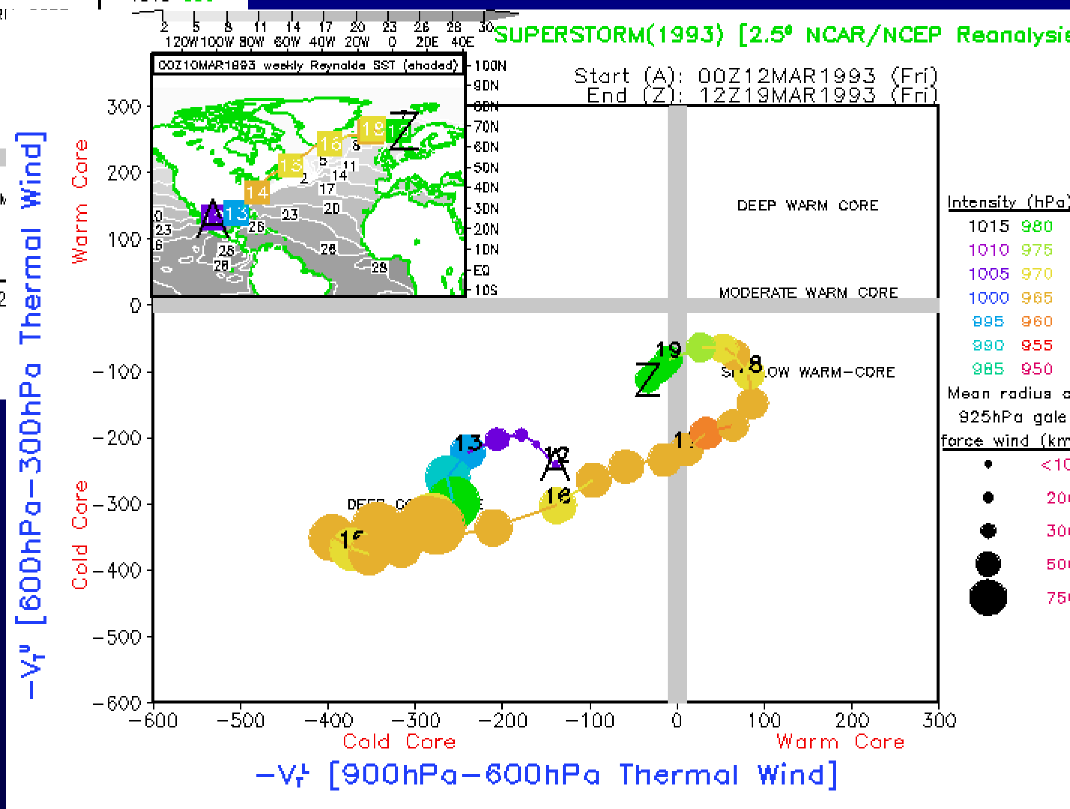


Hurricane Rita (2005)

Major hurricane, developed deep symmetric warm core, did not undergo ET

Phase Space Life Cycle Examples



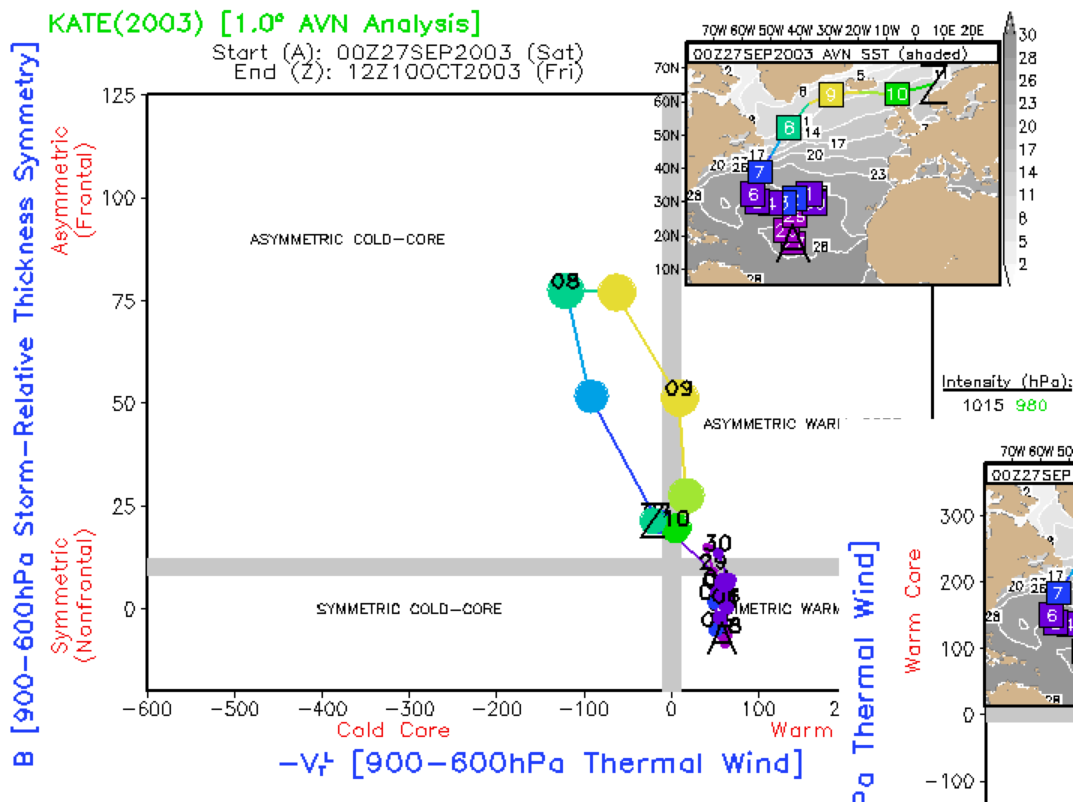


March 1993 Superstorm

Explosive extratropical cyclogenesis, deep and highly asymmetric cold core cyclone

Later acquired warm seclusion characteristics

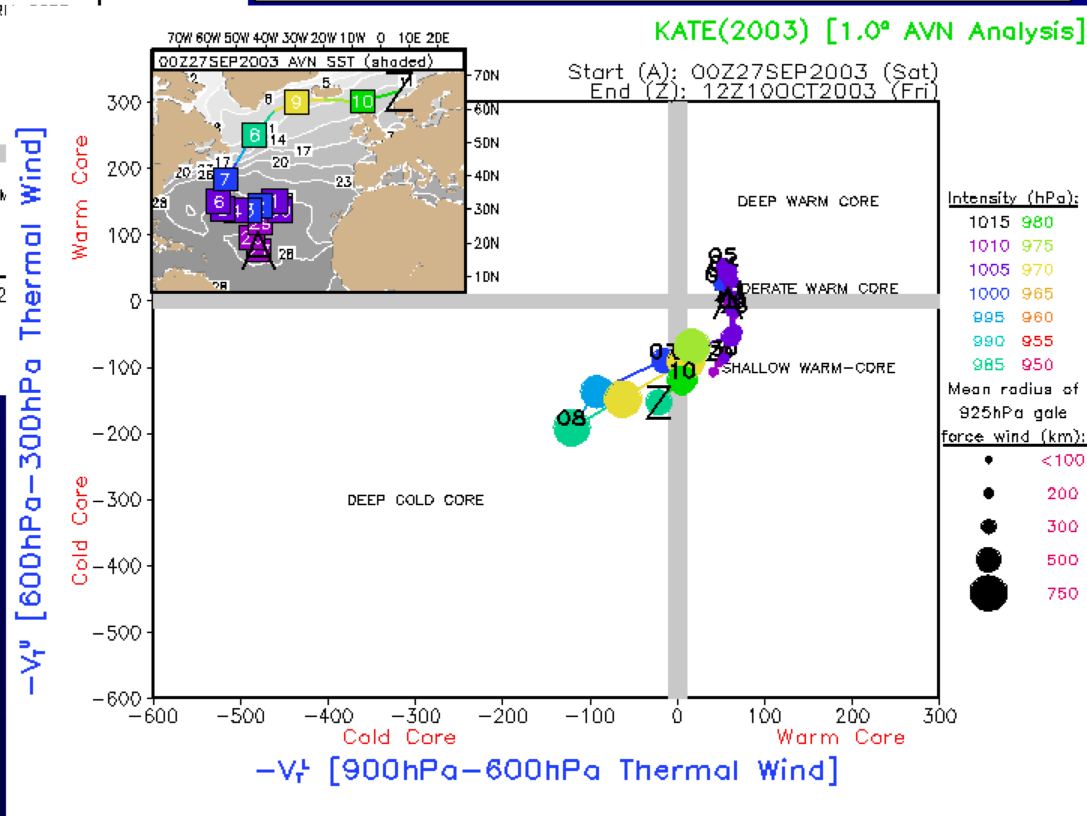
Phase Space Life Cycle Examples



Hurricane Kate (2003): ET interrupted

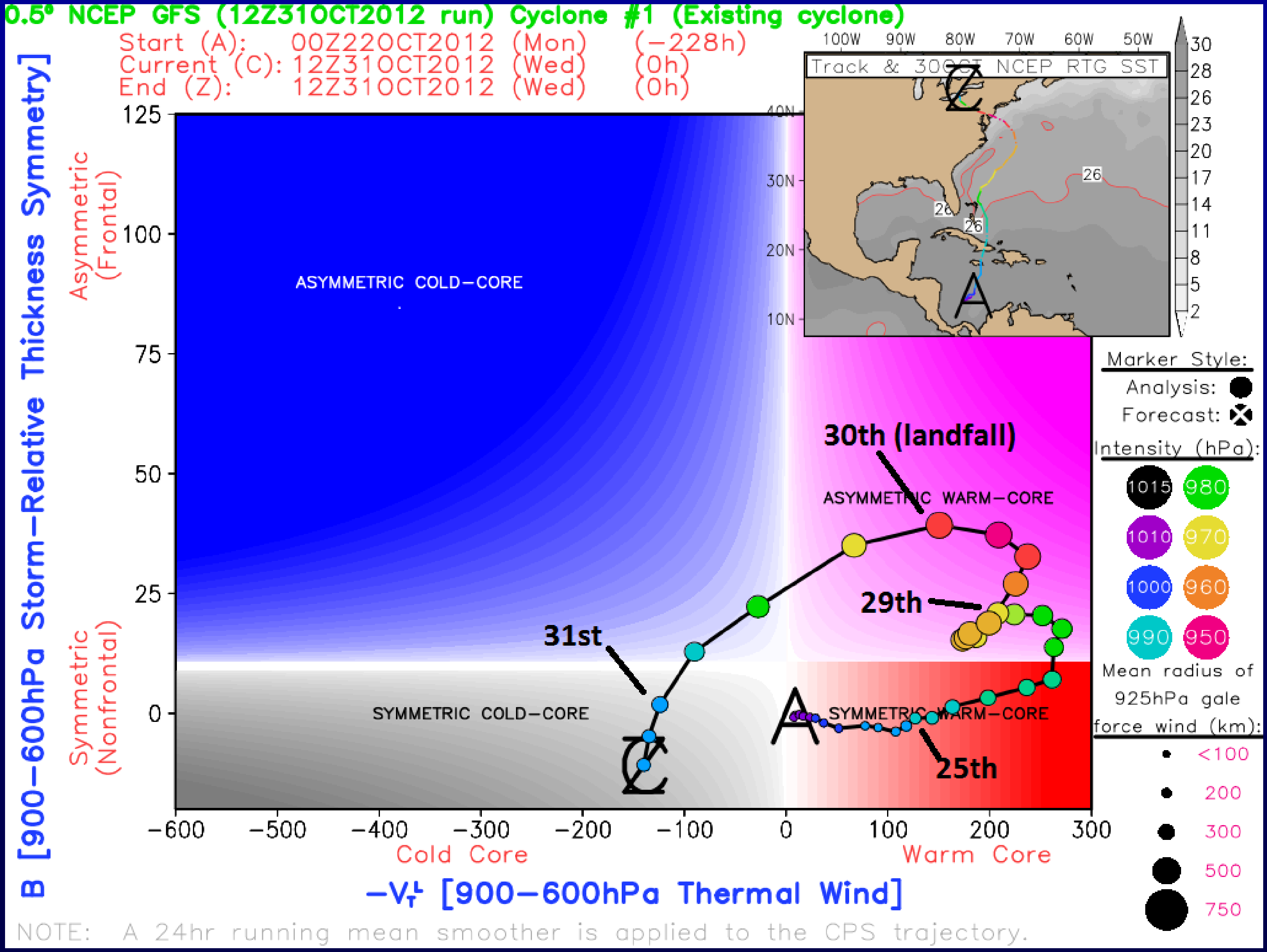
Begins ET, becoming shallow and less symmetric, only to become more symmetric and with a deeper warm core after moving over warmer water.

Finally undergoes ET later over the north Atlantic



Sandy Phase Space Diagram

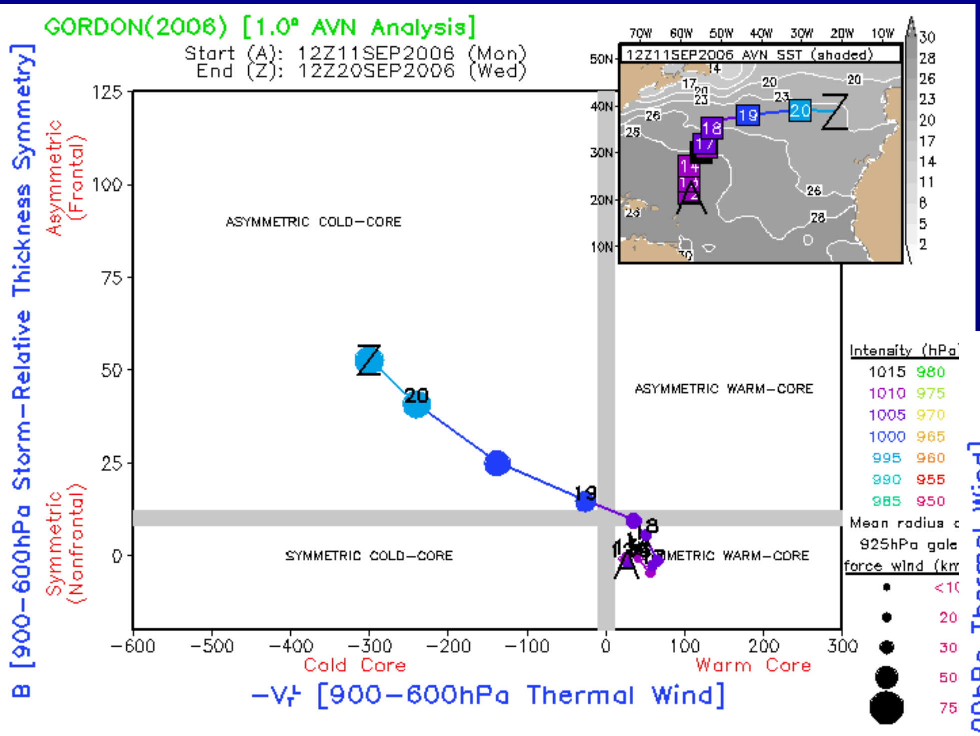
GFS Analysis



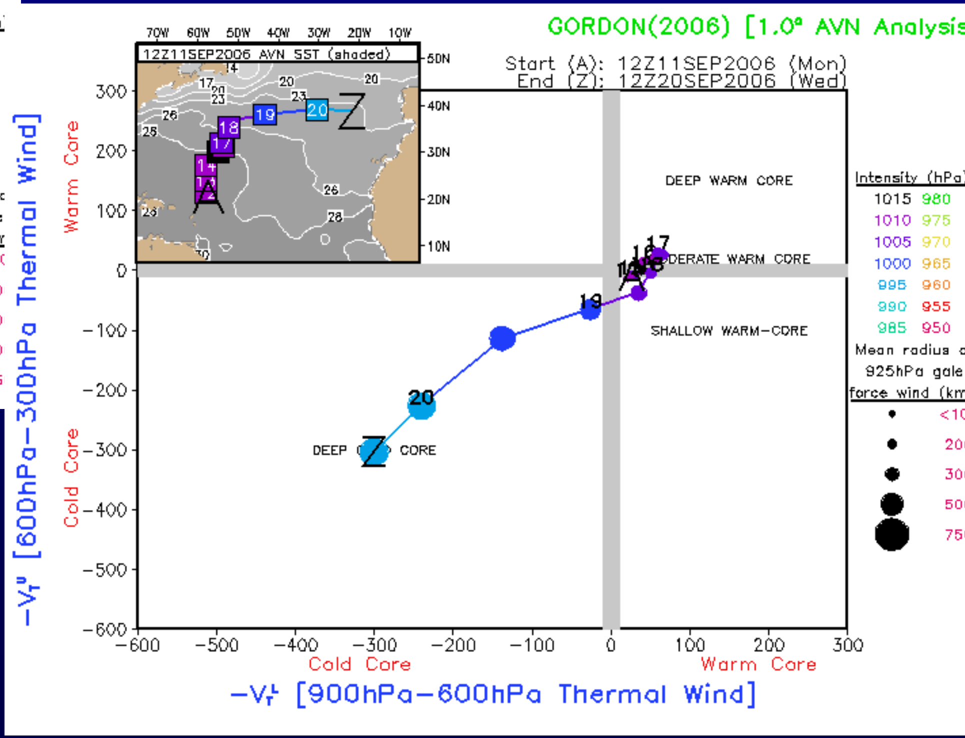
But, it isn't always that simple…

ET of Gordon (2006) Viewed Through Phase Space

From GFS analysis



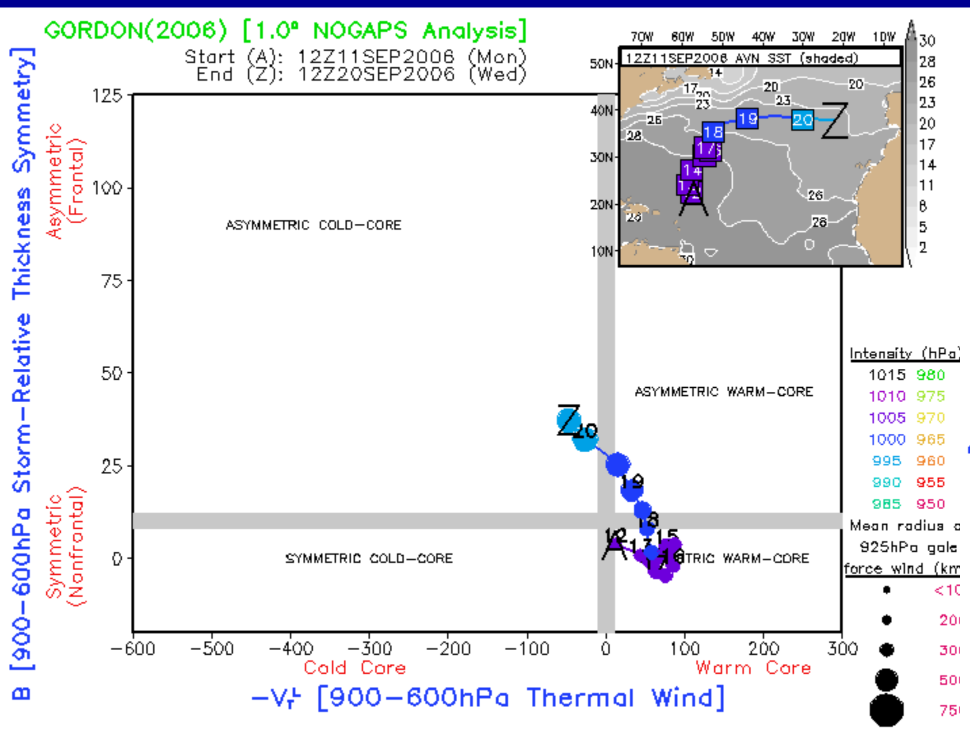
Gordon initially moderate warm core, becomes shallow and transitions to deep cold core by 19 September



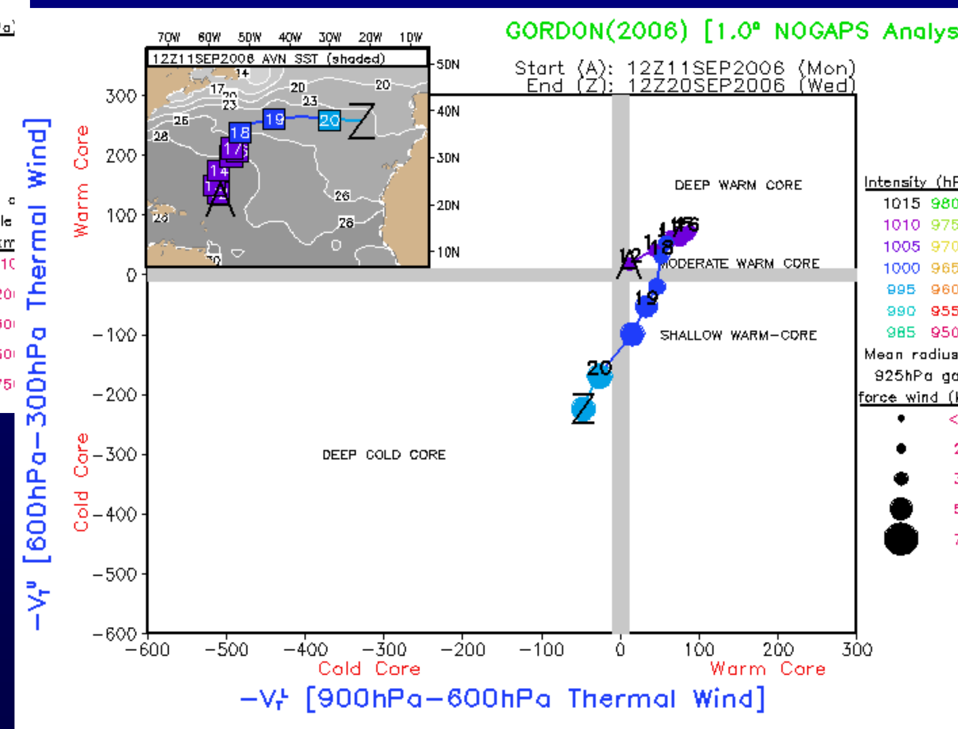
Gordon goes from symmetric warm core system to asymmetric cold core by 20 September

ET of Gordon (2006) Viewed Through Phase Space

From NOGAPS analysis



Gordon becomes moderate to deep warm core, then shallow warm core, reaching cold core status by 20 September



Gordon goes from symmetric warm core system to asymmetric warm core, and never becomes strongly cold core by 20 September

Phase Space Caveats

- Quality of phase space diagrams depends on the model analyses and forecasts used to create them
  - Errors in model analysis of cyclone intensity and structure and forecasts of track, intensity, and structure will manifest themselves in the phase space
- Model fields used to create diagrams still relatively coarse (0.5° to 1° for global models), so small scale structure not captured
- Impacts of TC bogusing
  - Stronger warm core noted for “active” TCs (i.e., advisories being written)
  - Better representation of purely tropical cyclone before ET has started
  - Warm core persists once ET has begun – may never show transition to cold-core cyclone

SHIPS Model Phase Information

- Classification scheme uses the following variables:
  1. SST
  2. Storm translational speed
  3. Cold pixel counts from IR imagery (less important during forecast period)
  4. Difference between 300- and 500-hPa tangential winds within 500 km of storm center (related to upper-level warm/cold core)
  5. 150-hPa temperature (related to tropopause height)
  6. 850–700-hPa temperature gradient within 500 km of storm center
  7. 850–200-hPa vertical shear

- Trained on NHC best track 1982-2010
  - Correct classification 91% of time at t=0
    - Most reliable for distinguishing between Tropical and Extratropical
    - Less reliable for Subtropical

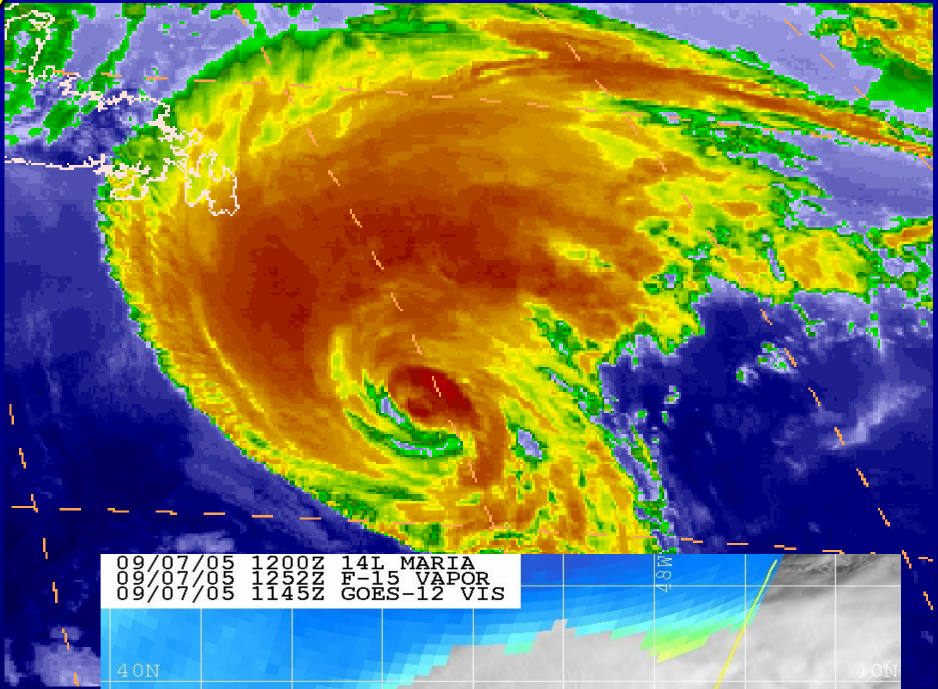
SHIPS Model Phase Information

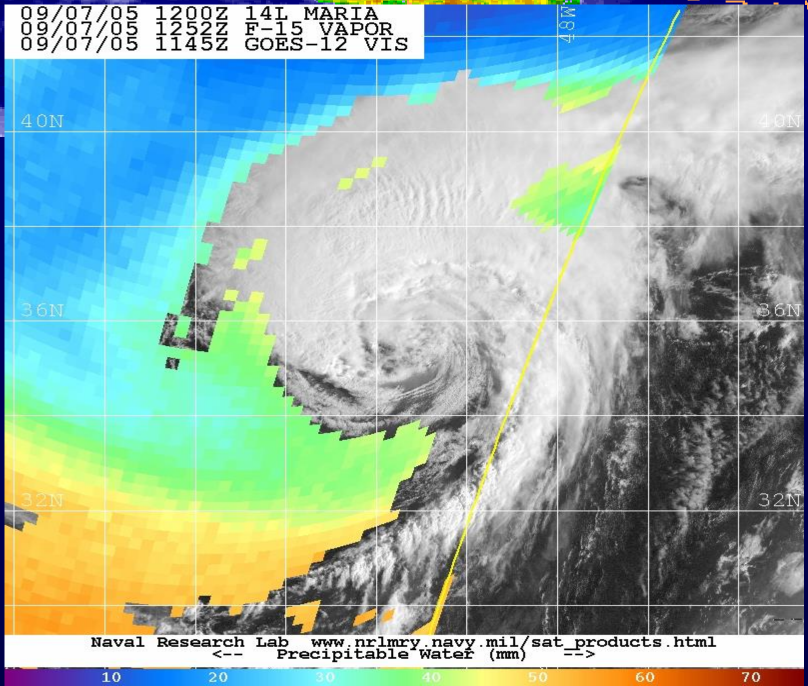
```
*   ATLANTIC SHIPS INTENSITY FORECAST      *
* GOES AVAILABLE,        OHC AVAILABLE      *
*       BERTHA  AL032014  08/04/14  12 UTC  *
```

TIME (HR)	0	6	12	18	24	36	48	60	72	84	96	108	120
V (KT) NO LAND	70	74	77	78	78	79	78	77	71	68	60	50	37
V (KT) LAND	70	74	77	78	78	79	78	77	71	68	60	50	37
V (KT) LGE mod	70	76	80	81	80	76	74	67	57	47	41	39	39
Storm Type	**TROP**	**TROP**	**TROP**	**TROP**	**TROP**	**TROP**	**TROP**	**TROP**	**EXTP**	**EXTP**	**EXTP**	**EXTP**	**EXTP**
SHEAR (KT)	21	18	20	22	22	33	45	55	54	62	60	65	71
SHEAR ADJ (KT)	1	0	0	-1	-4	0	5	-2	2	-3	0	-7	-1
SHEAR DIR	337	322	305	299	280	254	237	230	236	238	244	256	263
SST (C)	29.0	28.8	28.4	27.9	27.4	27.5	26.6	24.4	19.2	15.0	14.4	15.9	14.1
POT. INT. (KT)	153	151	145	138	132	134	124	105	81	71	70	72	70
ADJ. POT. INT.	141	138	132	124	117	119	111	93	74	68	67	68	67
200 MB T (C)	-54.1	-53.6	-53.3	-53.4	-53.6	-53.6	-53.9	-53.7	-54.2	-54.8	-54.1	-53.9	-53.1
TH_E DEV (C)	10	10	9	8	7	7	5	4	2	0	0	0	0
700-500 MB RH	55	59	62	62	63	55	55	58	62	60	60	63	71
GFS VTEX (KT)	11	11	12	11	11	14	16	19	21	27	29	29	26
850 MB ENV VOR	-77	-40	-35	-41	-29	-9	51	98	112	101	94	127	170
200 MB DIV	62	80	82	28	36	69	116	111	76	94	53	41	17
700-850 TADV	21	23	18	18	24	10	18	19	24	29	-4	-37	-27
LAND (KM)	644	672	612	503	437	593	528	409	256	256	590	961	1335
LAT (DEG N)	26.8	28.4	30.0	31.7	33.3	36.1	38.8	41.7	44.5	46.6	47.8	48.8	49.7
LONG(DEG W)	73.6	73.5	73.3	72.6	71.9	69.0	64.5	59.6	54.7	49.7	44.9	39.9	34.7
STM SPEED (KT)	15	16	17	18	17	20	23	23	22	19	17	18	17
HEAT CONTENT	35	33	17	12	7	23	13	0	0	0	0	0	0

Analysis and Short Term Forecast (0–6 h) Tools

- Where is this cyclone in the ET process?
  - Satellite/radar imagery
  - Intensity estimates
    - AMSU, Dvorak, Hebert-Poteat satellite classifications
  - Observations of surface wind field (ship/buoy, land, satellite)
  - Surface and upper-air analysis
  - Model analyses
  - SHIPS classification





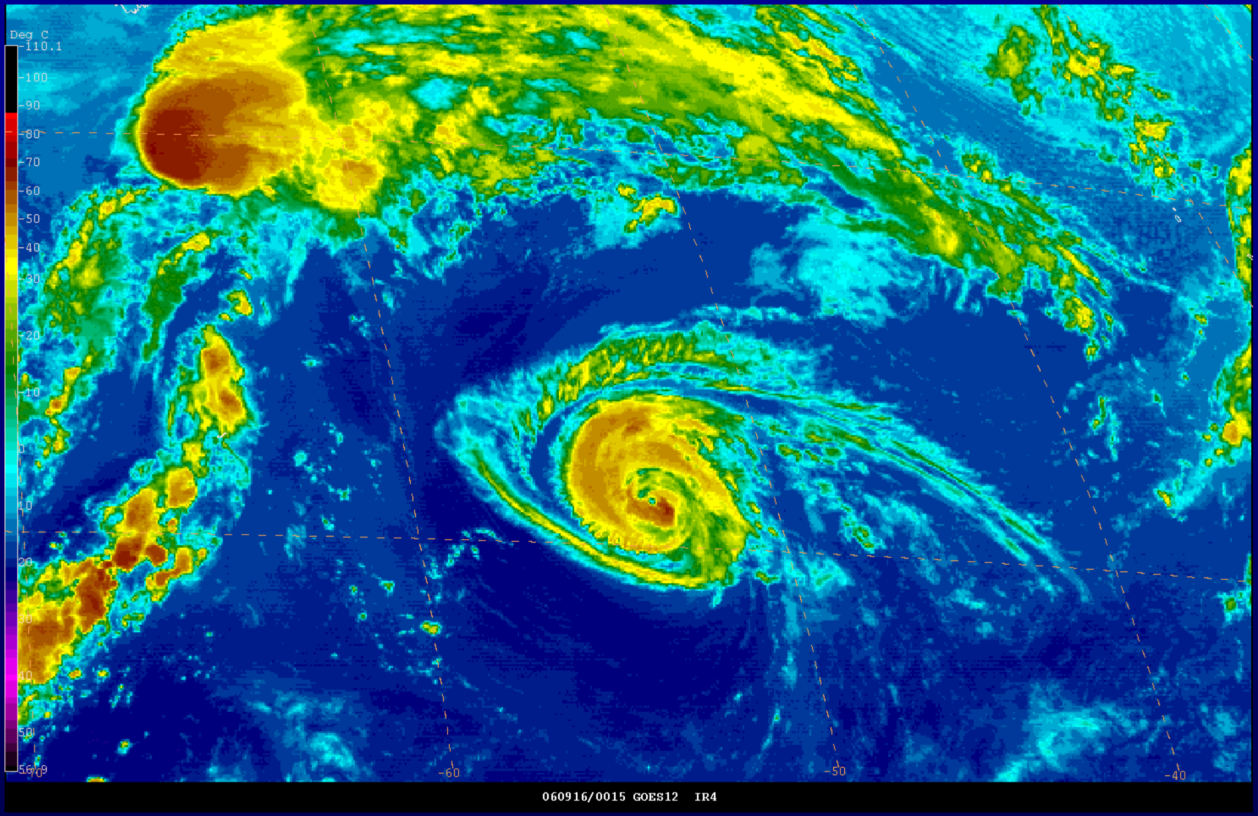
Forecast Tools (Beyond 6 h)

- NWP model guidance
  - Is analyzed structure of cyclone undergoing ET consistent with what you currently see in observations? If not, be wary!
  - Are critical features (upper-level troughs/jets, fronts, extratropical cyclones) properly represented in the model analysis?
  - What signals of ET do you see in model forecasts? Expansion of wind field, increased thermal advections, intensification through baroclinic processes?
  - How much spread is there between the various models? Do all models show ET occurring, only some? Timing different?
  - Cross sections of potential vorticity, vorticity, moisture, wind, to examine vertical structure of cyclone
  - SHIPS model classification
- Conceptual Models of ET and climatology
  - How does what you see in observations and model guidance fit into conceptual models of ET?
  - Is this event an outlier in terms of the ET climatology for the basin?

A Challenging Forecast

Gordon (2006)

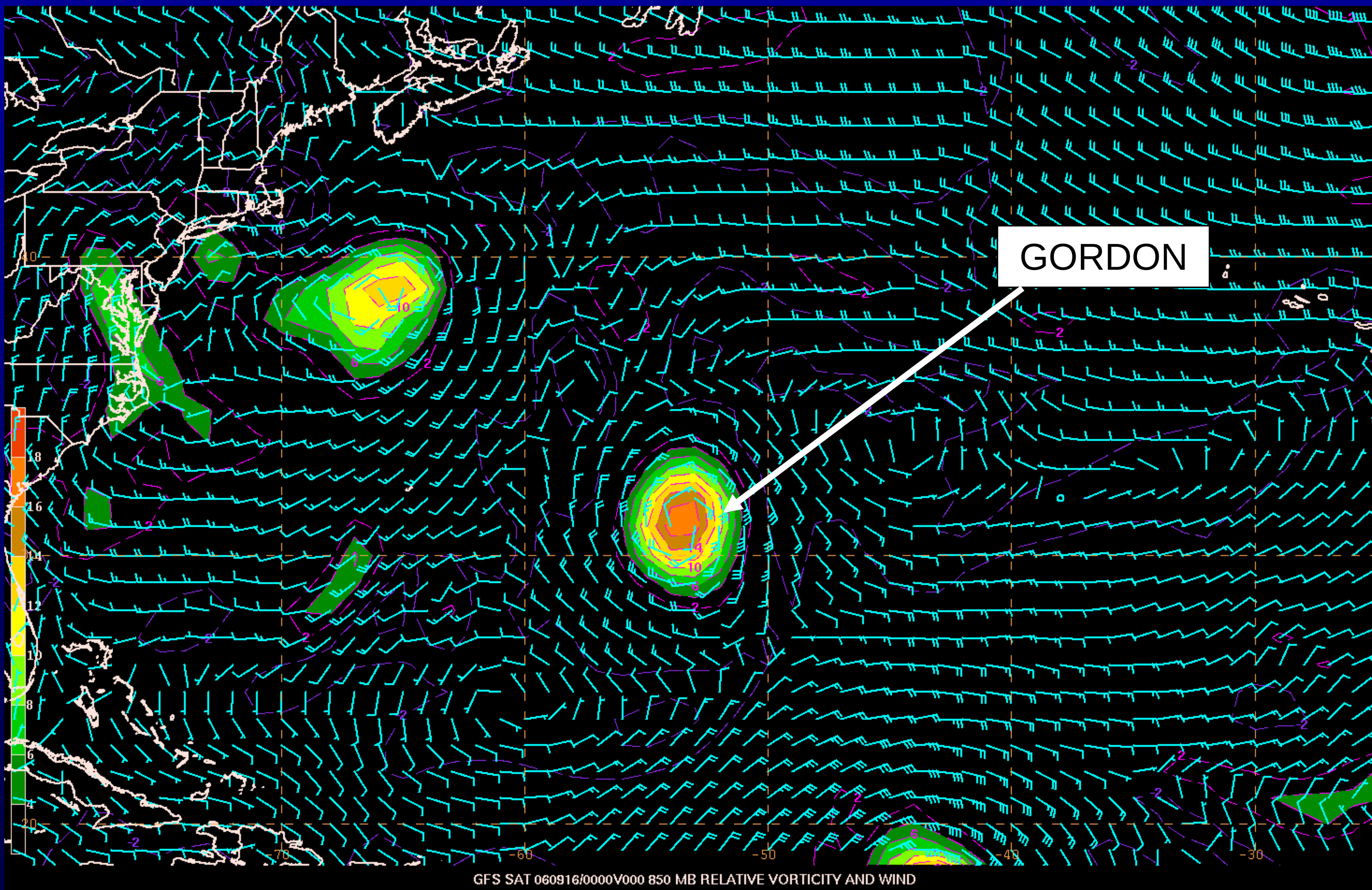
- Forecast cycle: 06 UTC 16 September 2006
- Hurricane Gordon
- Centered Near: 31.4°N 53.5°W
- Maximum Wind: 75 kt
- Central Pressure: 987 mb
- Movement: Stationary



GFS Analysis

Valid 00 UTC 16 September

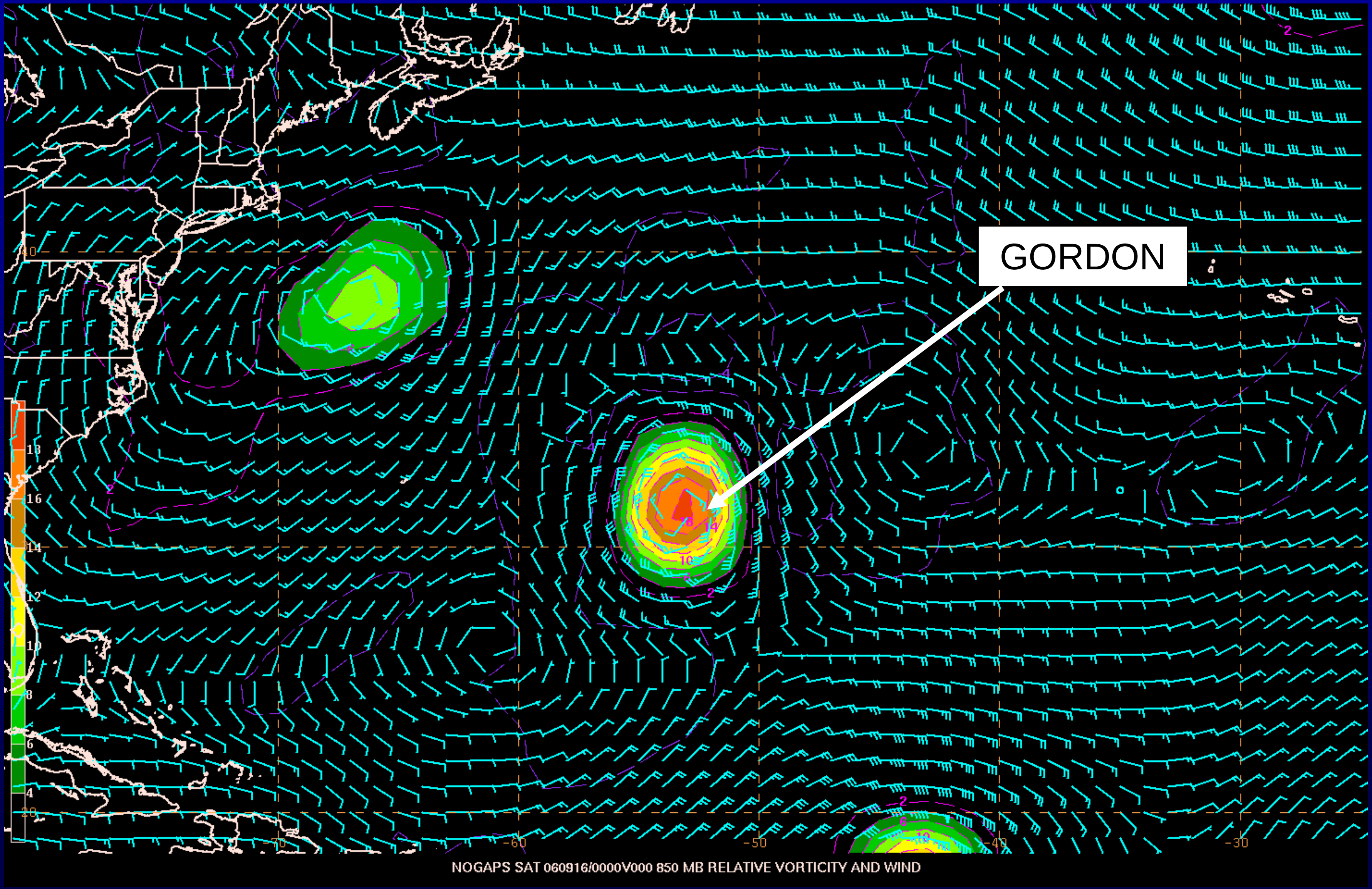
850-mb relative vort., wind



NOGAPS Analysis

Valid 00 UTC 16 September

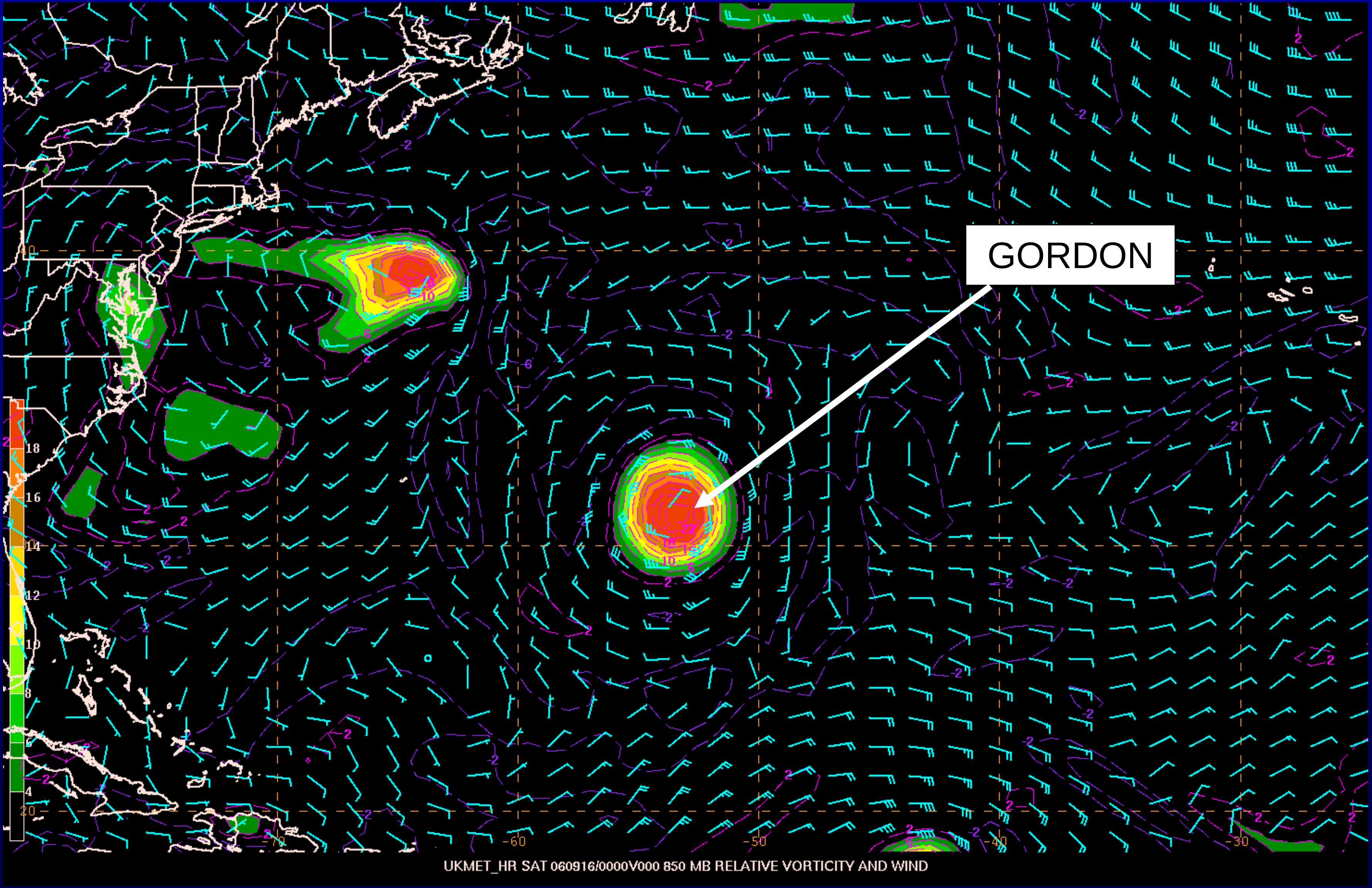
850-mb relative vort., wind



UKMET Analysis

Valid 00 UTC 16 September

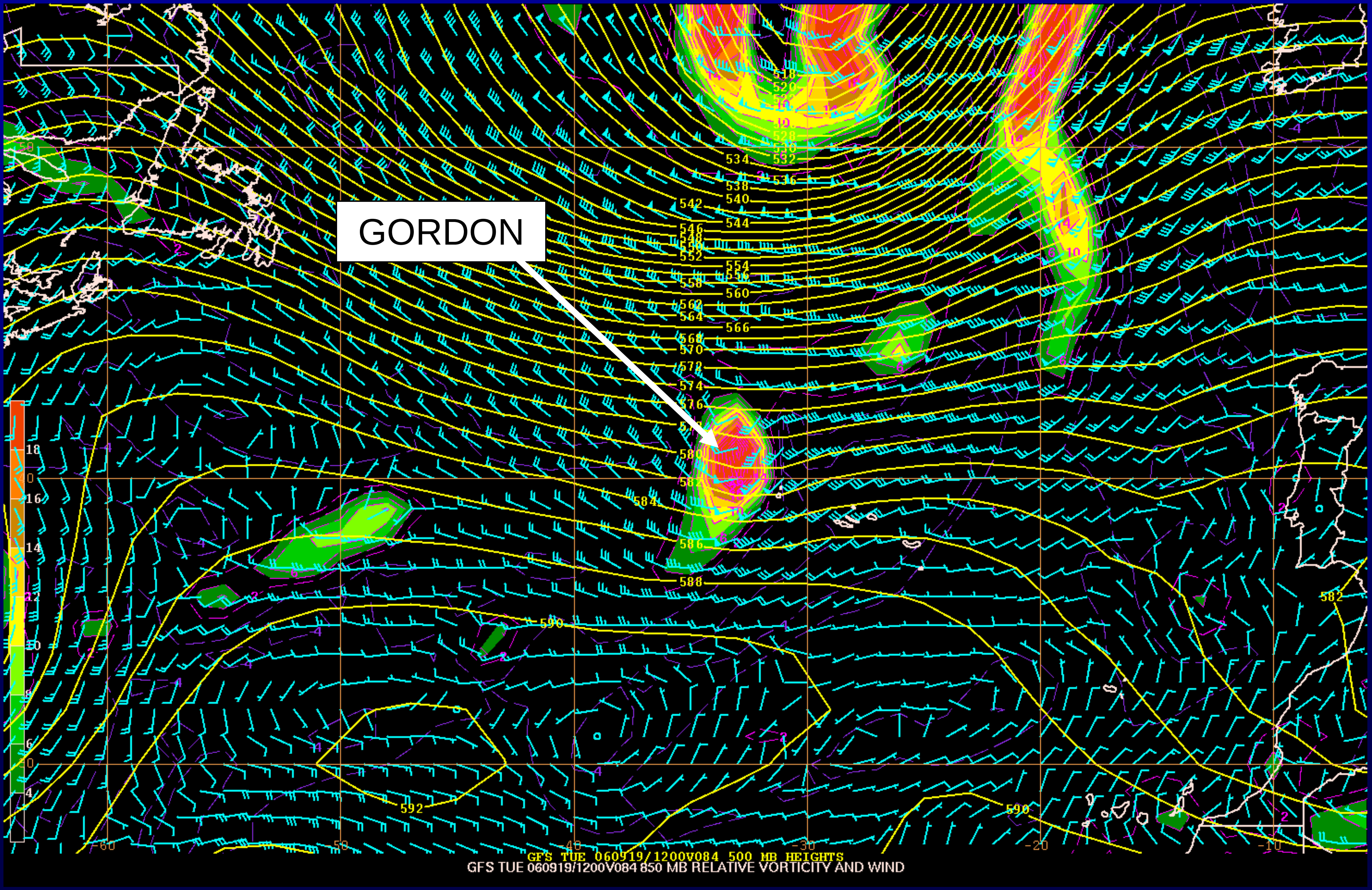
850-mb relative vort., wind



GFS 84 Hour Forecast

Valid 12 UTC 19 September

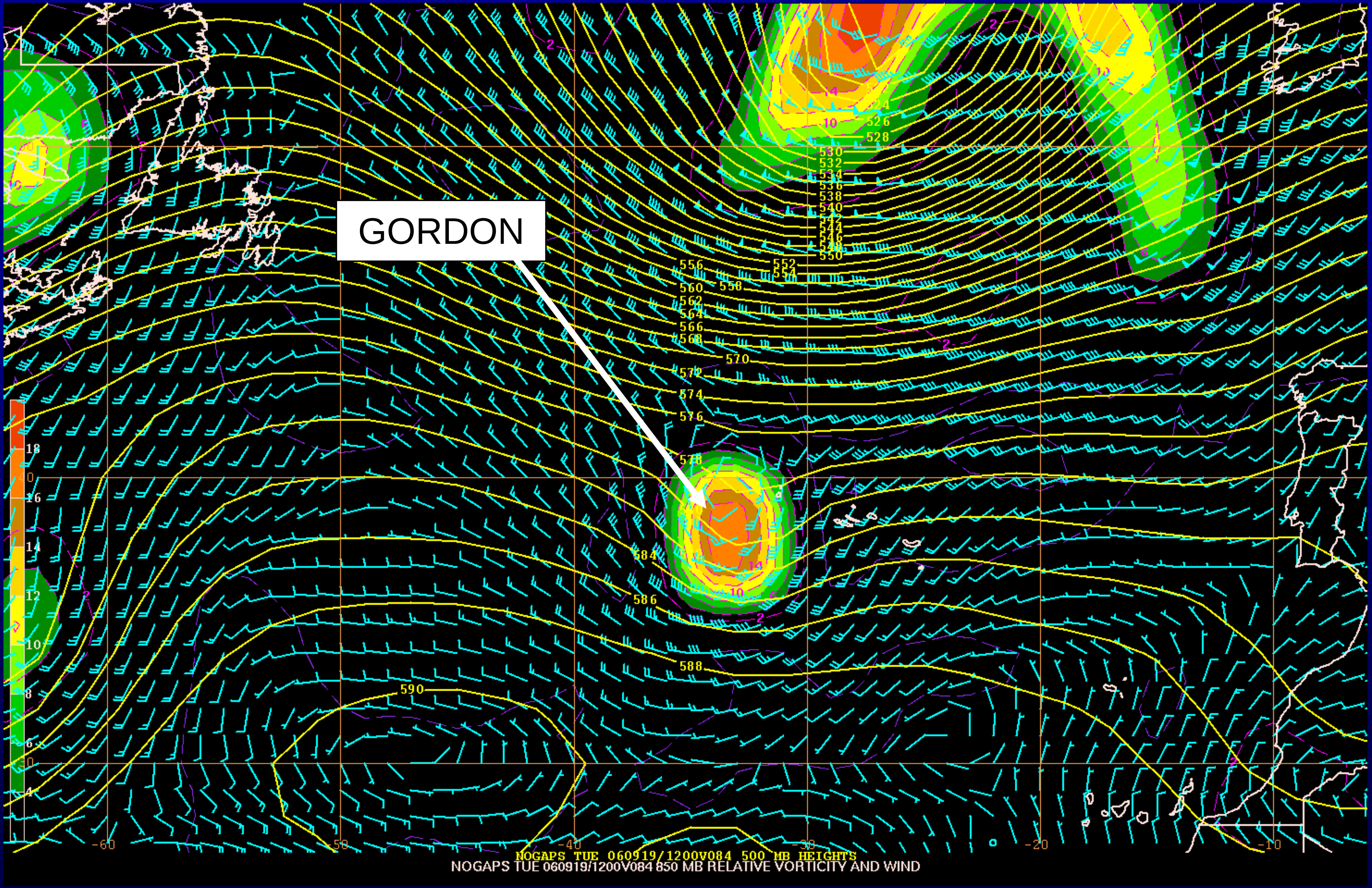
500-mb height, 850-mb relative vort., wind



NOGAPS 84 Hour Forecast

Valid 12 UTC 19 September

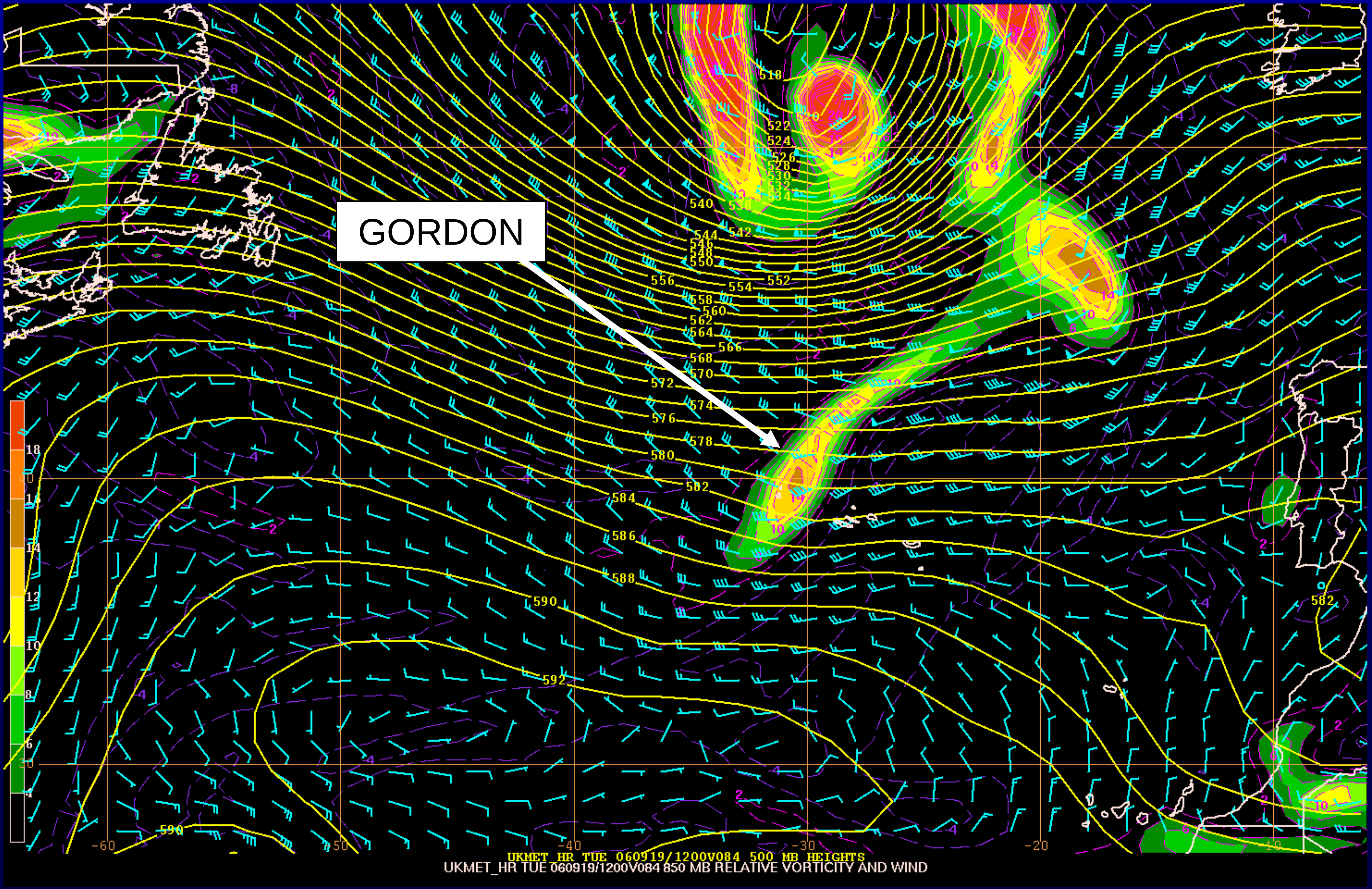
500-mb height, 850-mb relative vort., wind



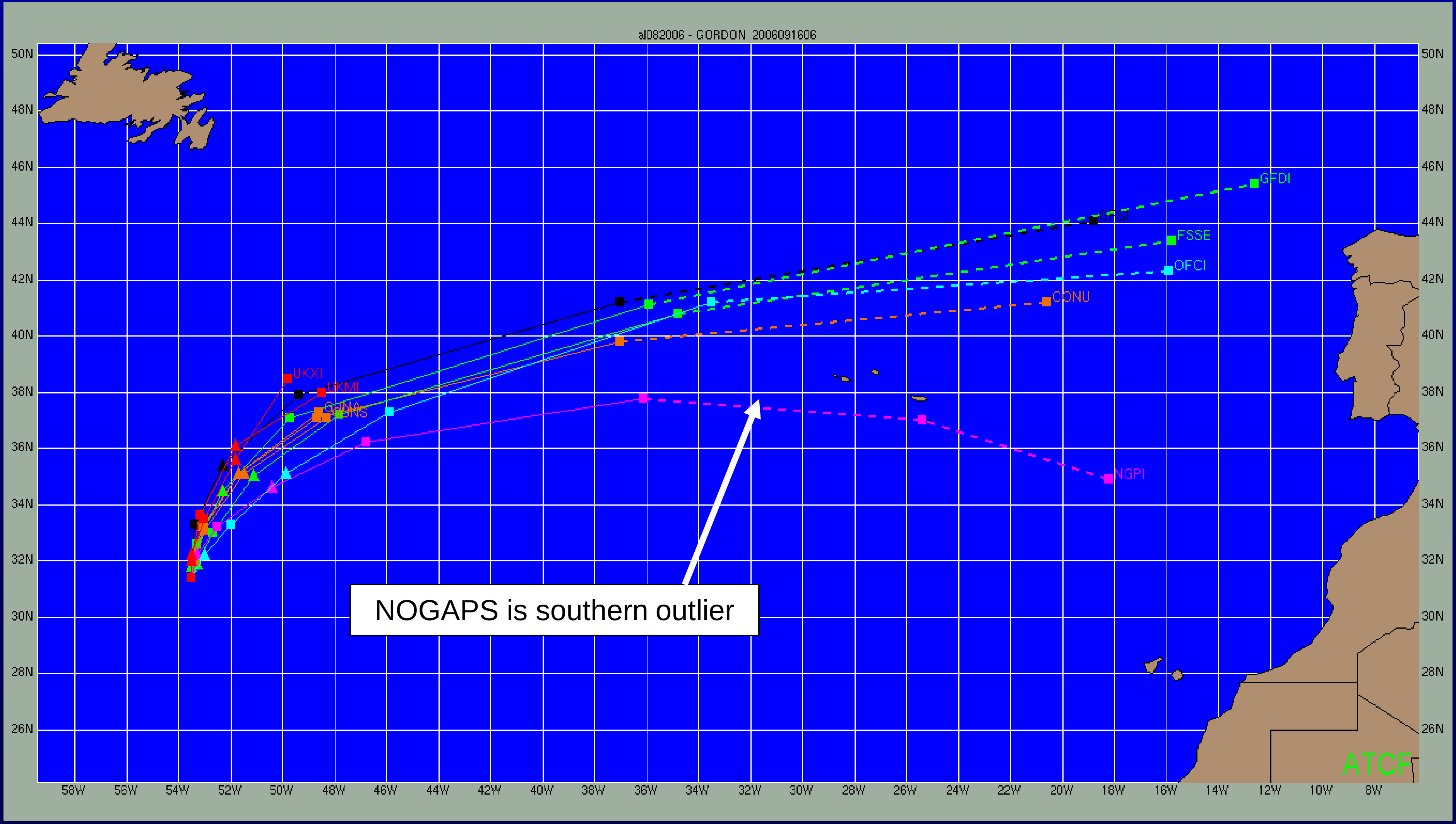
UKMET 84 Hour Forecast

Valid 12 UTC 19 September

500-mb height, 850-mb relative vort., wind



Model Track Spread



A Challenging Forecast
Gordon (2006)

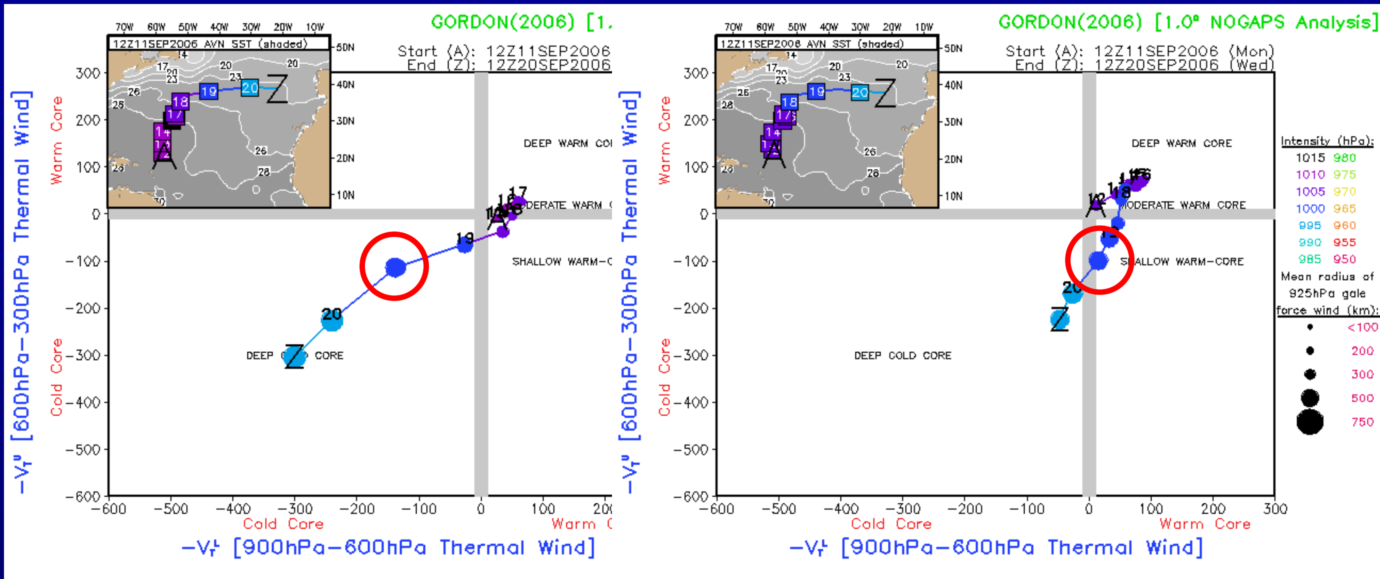
- Despite similar initial structure of Gordon, each model shows very different evolution of Gordon by 84 hours
  - Ranging from a purely tropical cyclone to absorbed by a front
- Subtle differences in TC track and interaction with upper-level trough result in large differences by day 4 of forecast of position and structure
- Official operational forecast from 06 UTC 16 September

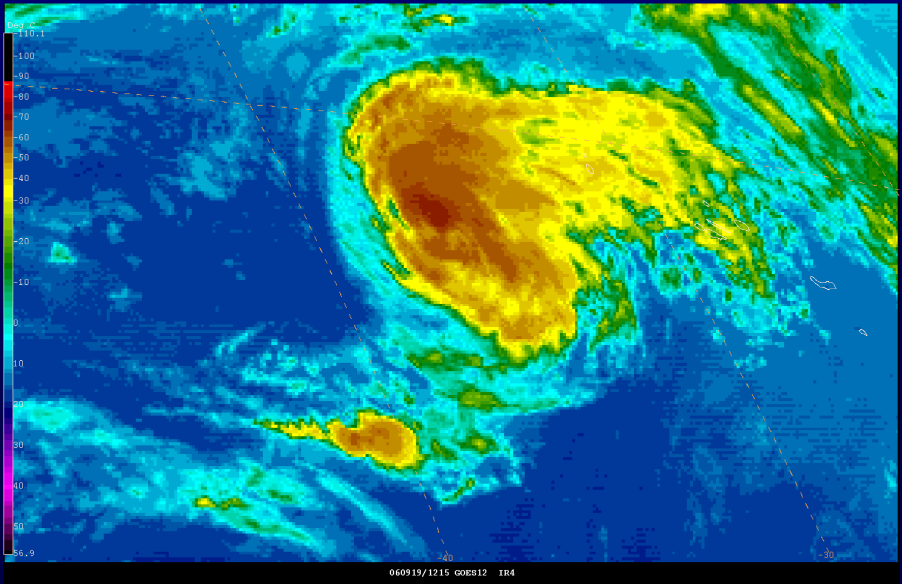
```
INITIAL 16/0900Z 31.3N 53.7W 65 KT
12HR VT 16/1800Z 32.0N 53.3W 65 KT
24HR VT 17/0600Z 33.2N 52.7W 60 KT
36HR VT 17/1800Z 35.1N 51.2W 55 KT
48HR VT 18/0600Z 37.3N 48.0W 55 KT
72HR VT 19/0600Z 40.5N 35.5W 50 KT...EXTRATROPICAL
96HR VT 20/0600Z...ABSORBED BY FRONTAL SYSTEM
```

Verification

Gordon 12 UTC 19 September 2006

- Still a Hurricane
- Max wind: 80 kt
- Pressure: 977 mb
- Phase space analysis varies on structure at this time
- Maintained hurricane intensity and impacted Azores on 19–20 September
- Became a strong extratropical cyclone after 00 UTC 21 September, bringing high winds and damage to Spain, England, Ireland
- High-impact ET event





Summary

- ET is a complex process, involving interactions between phenomena on multiple scales
- ET represents an operational challenge because cyclones exist on a continuum – they don't fit into discrete bins!
- Operational decisions during ET often take more than cyclone structure into consideration
  - Impacts, watch/warning complications, coordination
- Structural changes during ET have large impacts on sensible weather
  - Redistribution of clouds and heavy precipitation
  - Expansion of wind field has large impact for land and marine interests
  - Dramatic increase in forward speed

Summary

- Conceptual models largely based on satellite imagery and large-scale model analyses
- Cyclone phase space diagrams show evolution of structure based on model analyses and forecasts
  - Neither may be able to resolve small scale features important to individual ET cases
- Most composites and statistics based on relatively short data records and small sample sizes, so beware of outliers!
- Examine NWP model guidance carefully
  - Differences in initial structure and evolution of both the TC and larger-scale flow will can result in widely varying forecasts of cyclone structure between the models, and from run to run
  - Does initial analysis capture the correct structure of the TC and other features important during the ET process?

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Forecast Exercise

Exercise

- Break into three groups by row
- The situation
  - 00 UTC 22nd of the month
  - Satellite imagery and current status of cyclone
- Each group will have the following data from a different global model
  - Analyzed phase space diagram through 00 UTC 22nd
  - Model forecast fields every 12 h through 96 hours (00 UTC 26th)
- Using only the data available to them each group will estimate
  - Beginning time of ET
  - When the system would be declared extratropical
- Group 1: GFS
- Group 2: NOGAPS
- Group 3: UKMET

Exercise

- Next, each group will be given the analyzed cyclone phase space diagrams from the model analysis for the entire lifecycle of the cyclone and satellite imagery
- Compare your forecasts to what the model analysis and imagery shows

Exercise

- Finally, we'll look at the satellite imagery and operational NHC classification for this system and compare