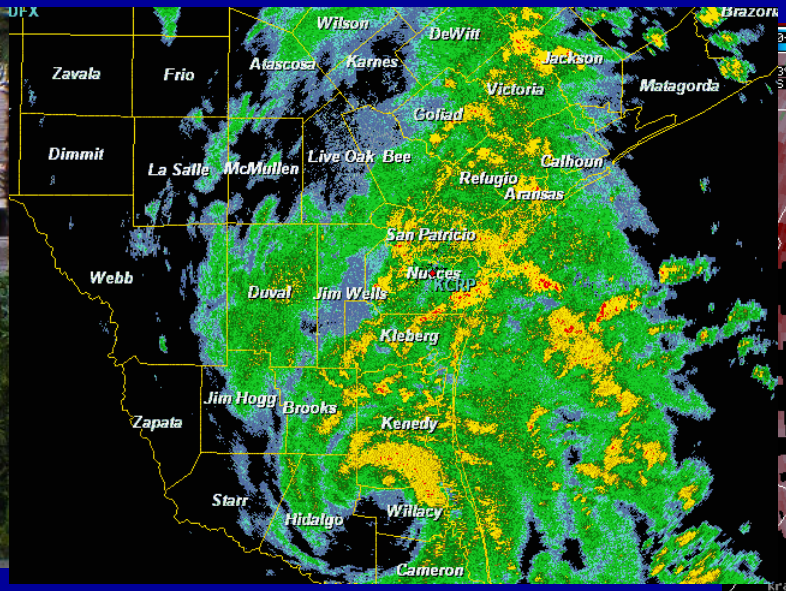
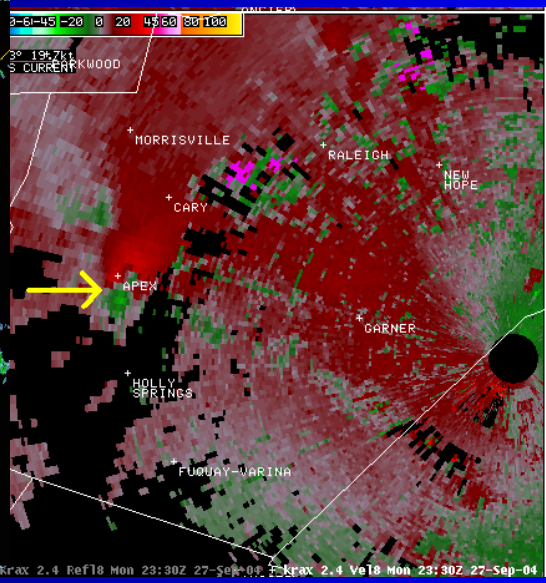
Inland Winds and Tornadoes in Tropical Cyclones





Michael J. Brennan

National Hurricane Center

National Hurricane Conference

21 April 2011

Outline

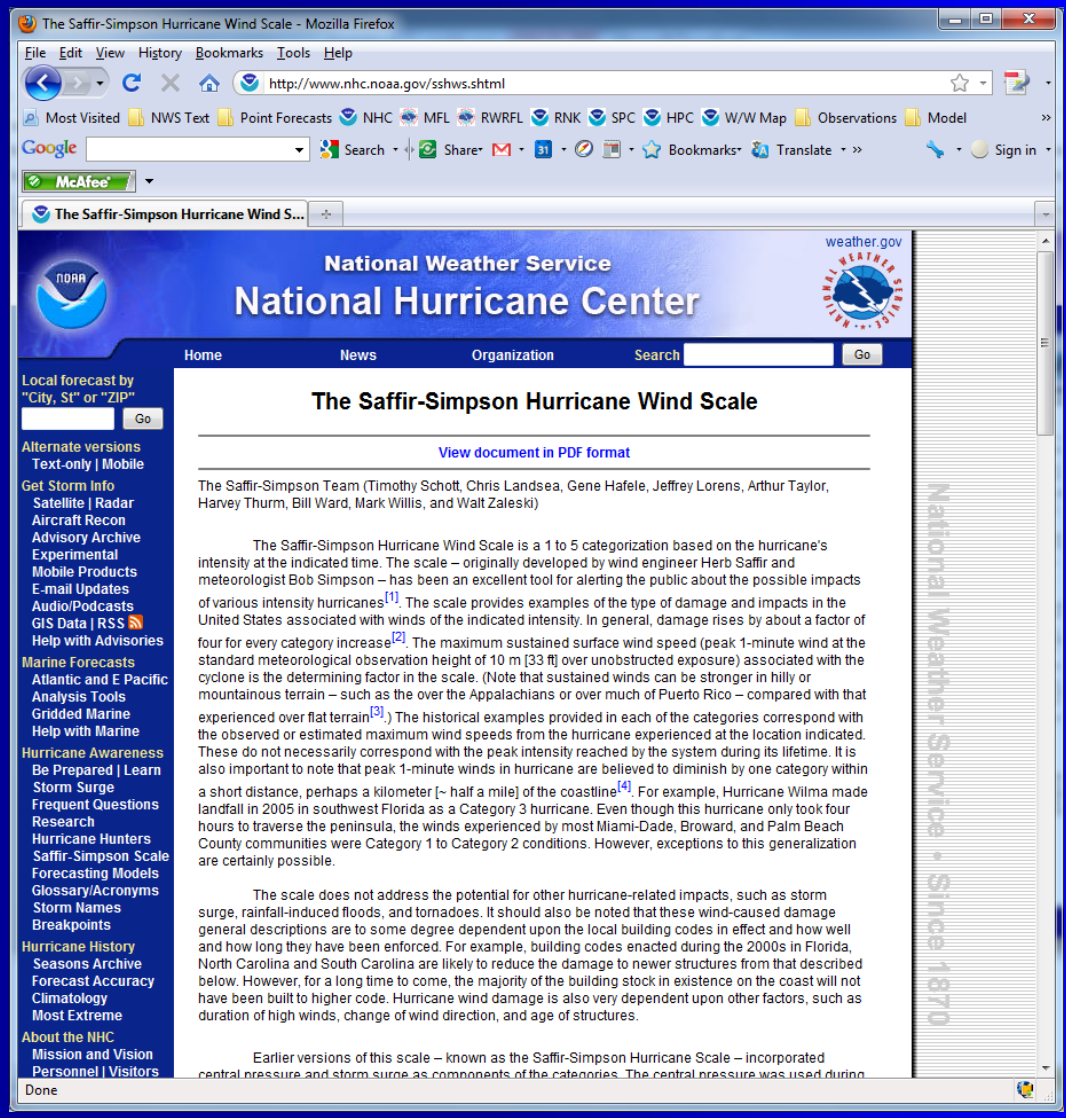
- Inland Winds
  - Overview
  - Factors Impacting Inland Wind
  - Inland Wind Forecasts, Watches, and Warnings and NHC Wind Speed Probability Products
- Tropical Cyclone Tornadoes
  - Overview
  - Impacts
  - Products

Inland Wind Threat

- The inland wind threat of a landfalling TC depends on several factors:
  - Cyclone intensity at landfall and rate of weakening
  - Forward speed of motion
  - Size of the wind field
  - Low-level stability
  - Interaction with other meteorological features
  - Topography and elevation (including gusts)

Impact of Inland Winds

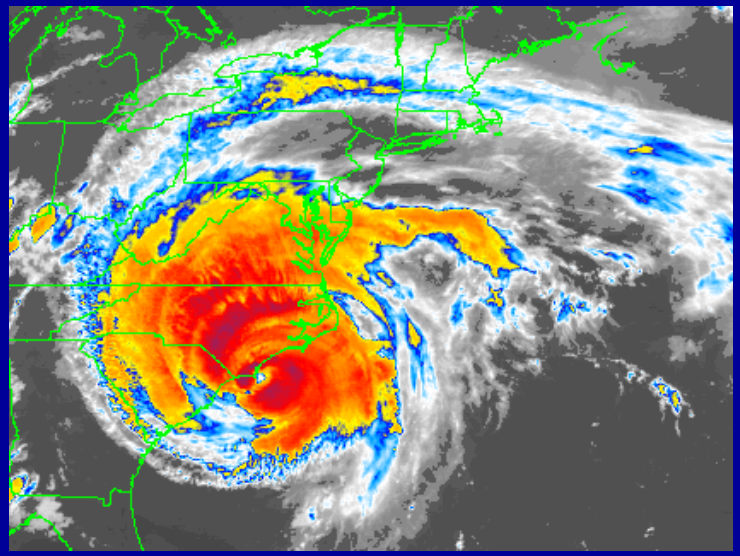
- Wind responsible for around over 10% of U.S. TC-related deaths (pre Katrina)
- Wind causes significant damage, sometimes well inland
  - Hazel (1954)
  - Hugo (1989)
  - Fran (1996)
  - Charley (2004)
  - Wilma (2005)

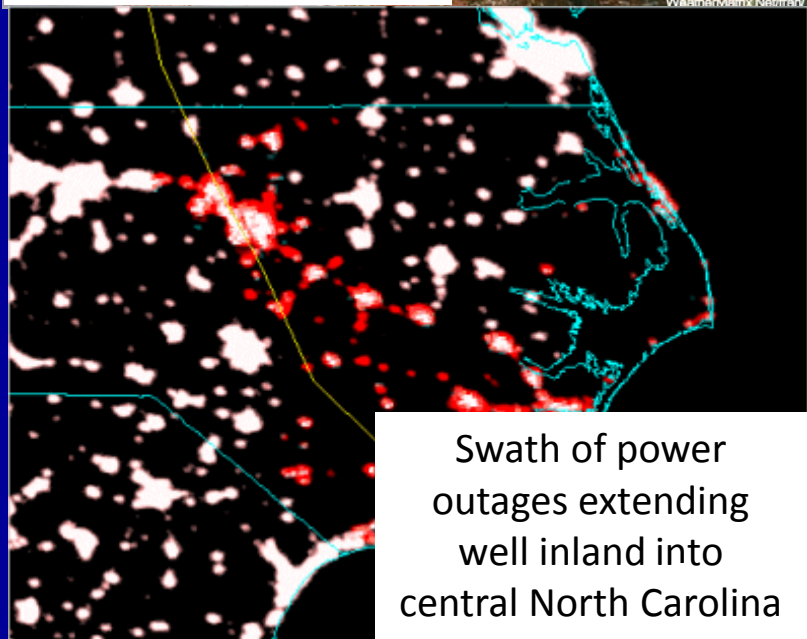


Hurricane Fran (1996)

- Made landfall as a Category 3 hurricane near Cape Fear, NC, moving at 15 kt
- Caused extensive wind damage well inland across much of central North Carolina
- Sustained winds on low end of tropical storm force, but gusts to hurricane force as far inland as Raleigh-Durham area
- Aided by deep convection as the eyewall collapsed and wet soils due to previous rainfall

Tree damage in Raleigh
Courtesy
WeatherMatrix.net

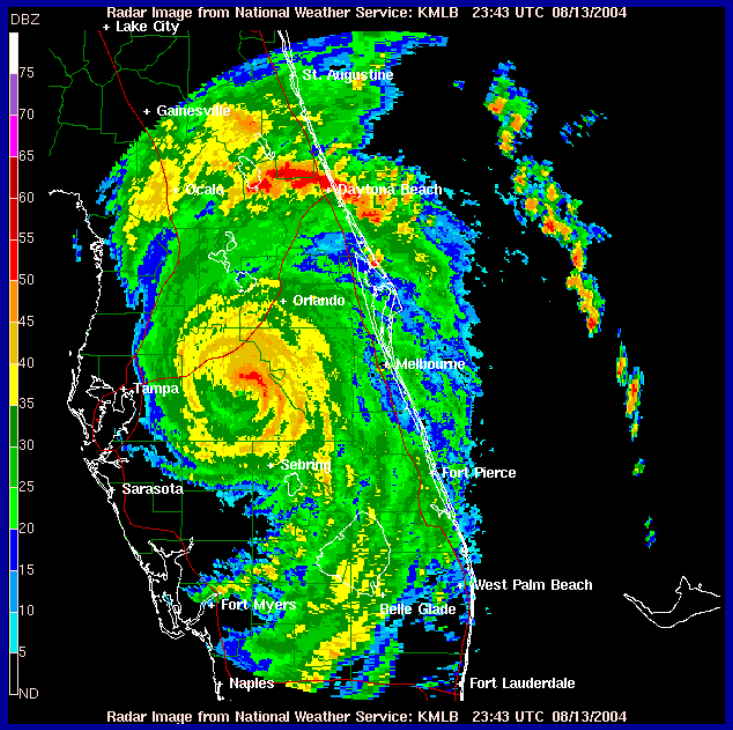




Swath of power outages extending well inland into central North Carolina

Hurricane Charley (2004)

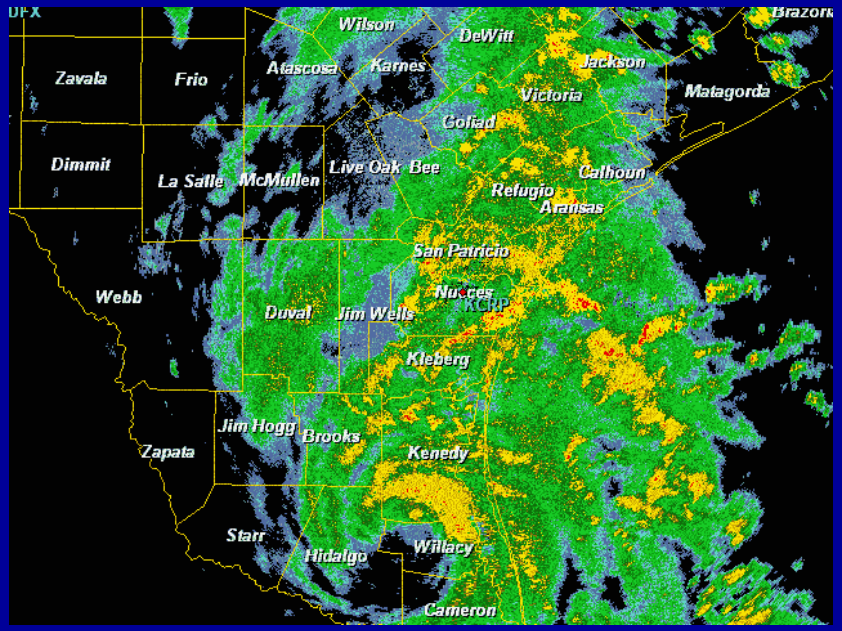
- Made landfall as a Category 4 hurricane near Cayo Costa, FL, moving at 18 kt
- Maintained hurricane intensity across the entire Florida peninsula
- Hurricane force winds caused significant damage in Orlando metro area
  - Sustained 69 kt, gust to 91 kt



Tree damage in Orlando

Tropical Storm Hermine (2010)

- Made landfall in northeastern Mexico about 30 miles south of Brownsville, TX
- Remained a tropical storm for 16 h after landfall as it moved into south-central Texas



Loop courtesy WFO Corpus Christi

Damage in Kingsville, TX – courtesy WFO Corpus Christi

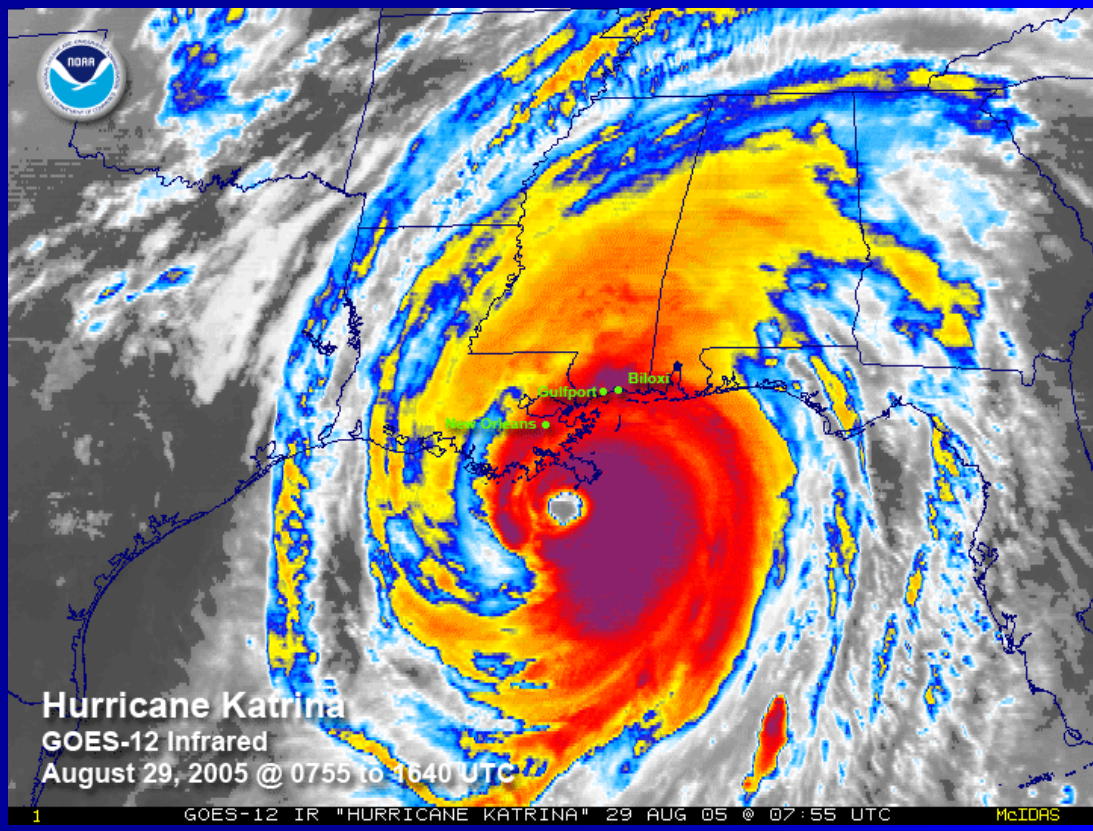
- Sustained wind of 48 mph with peak gust of 64 MPH measured in San Antonio, TX,
- Over 100,000 customers left without power in the San Antonio area

Factors Impacting Inland Wind

Intensity and Weakening Rate

Kaplan and DeMaria (1995)

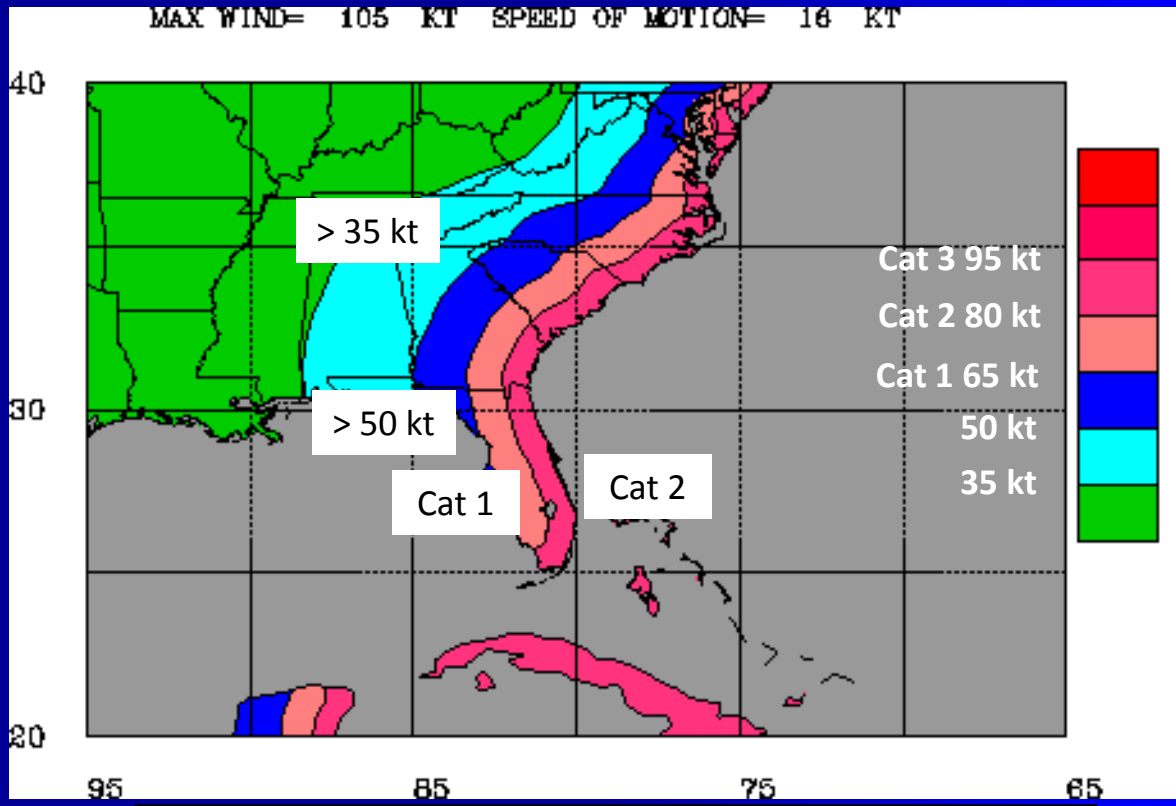
- Stronger TC at landfall can bring strong winds farther inland
- However, stronger TCs also weaken more rapidly after landfall
- Average major hurricane weakens below hurricane intensity within ~ 7 h of landfall
- All TCs decay to 25-30 kt within 24-30 h of landfall regardless of initial intensity



Bottom Line: Winds decrease relatively quickly after landfall → Speed of forward motion critical to extent of inland wind impacts

Inland Decay Model
Kaplan and DeMaria (1995)

- Empirical model based on landfall intensity and forward speed
- Estimates maximum inland extent of various wind thresholds for different regions of the U.S.

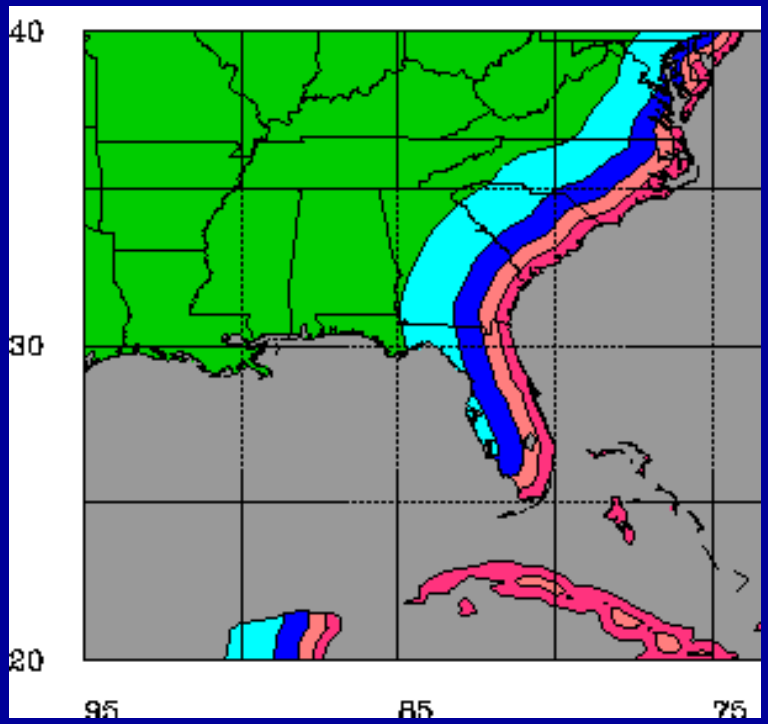


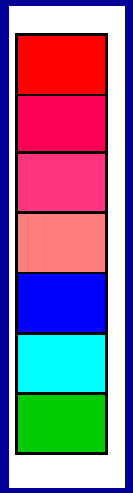
Category 3 hurricane at landfall
Moving at 16 knots (18 mph)

- Available on NHC website at:
  http://www.nhc.noaa.gov/aboutmeow.shtml

Impact of Forward Speed

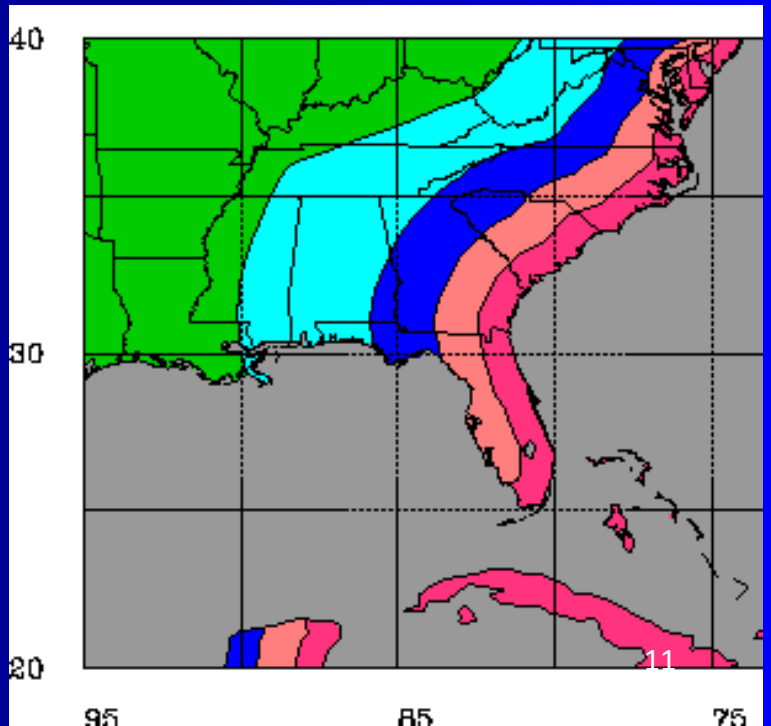
Kaplan and DeMaria (1995)





Category 3 at landfall
Moving at 8 kt (9 mph)

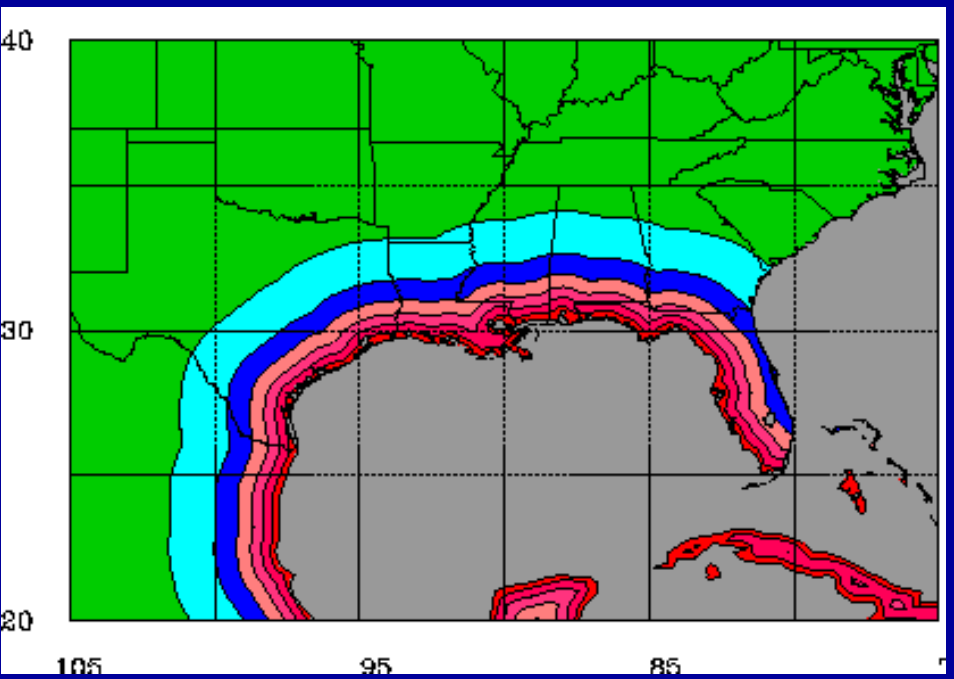
Category 3 at landfall
Moving at 20 kt (23mph)



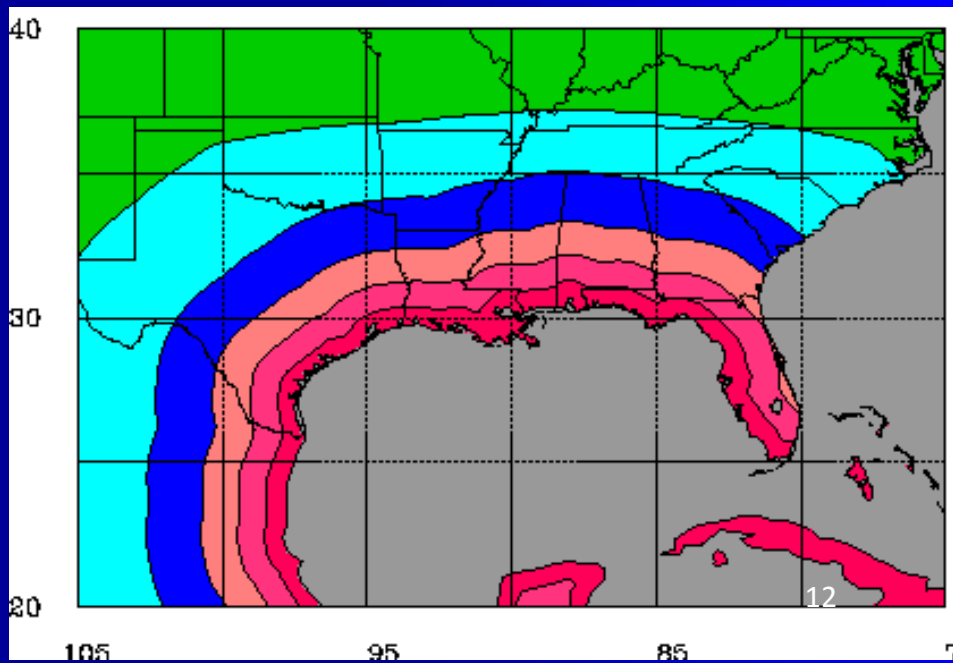
Area at risk for hurricane-force winds increases dramatically with forward speed

Impact of Forward Speed

Kaplan and DeMaria (1995)



Category 4 at landfall
Moving at 20 kt (23mph)



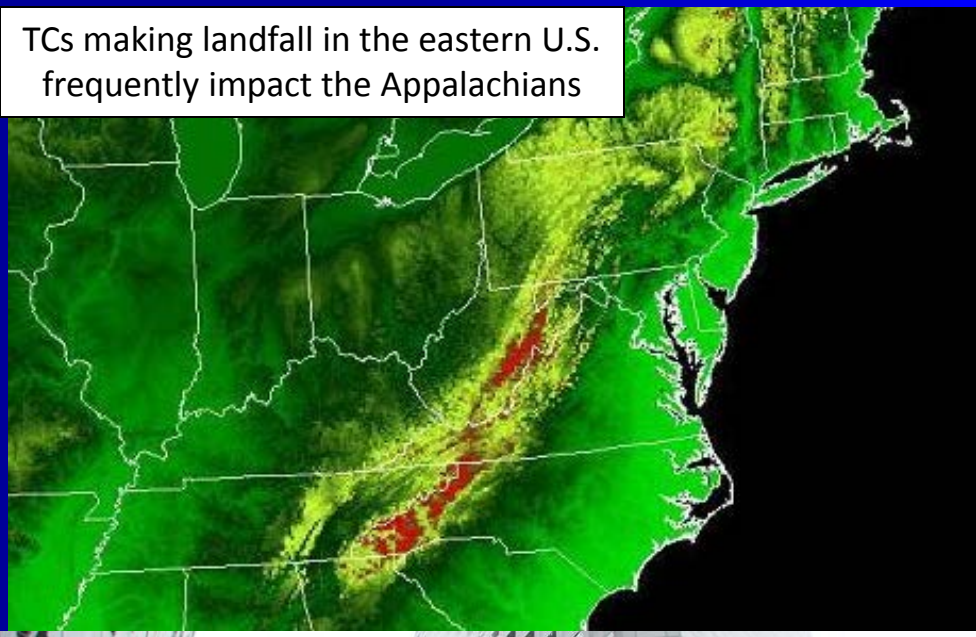
Category 5 at landfall
Moving at 8 kt (9 mph)

Even for a weaker storm at landfall!

Elevation and Gusts

- Areas of elevated terrain can experience both higher sustained winds and higher gusts
  - Also true for high-rise buildings
- Over land, gust factor of 1.3 is typically applied
  - Sustained winds 80 kt → Gusts to 105 kt
- Over complex topography and in hurricane eyewall, gust factor of 1.65 is more appropriate
  - Sustained winds 80 kt → Gusts to 130 kt
- Gusts over land can easily be one Saffir-Simpson Scale category higher than sustained winds

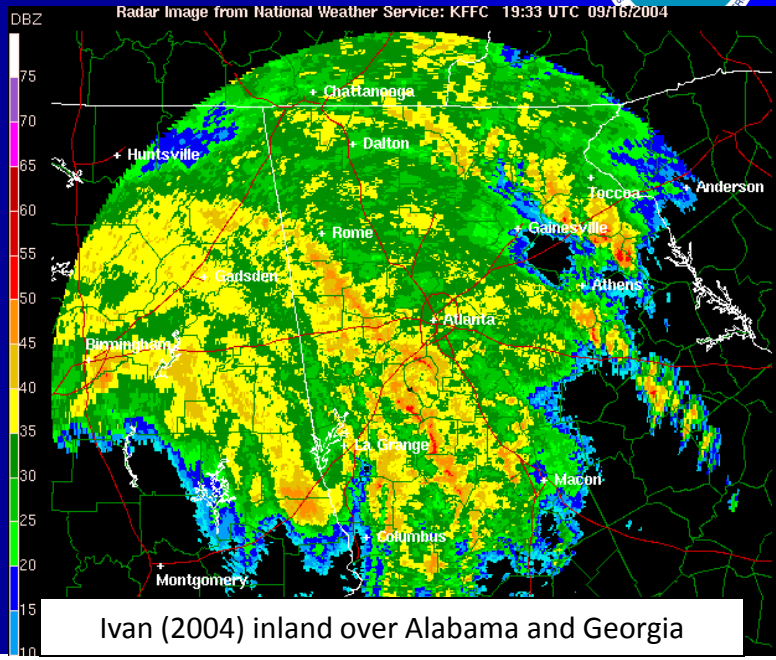
TCs making landfall in the eastern U.S. frequently impact the Appalachians



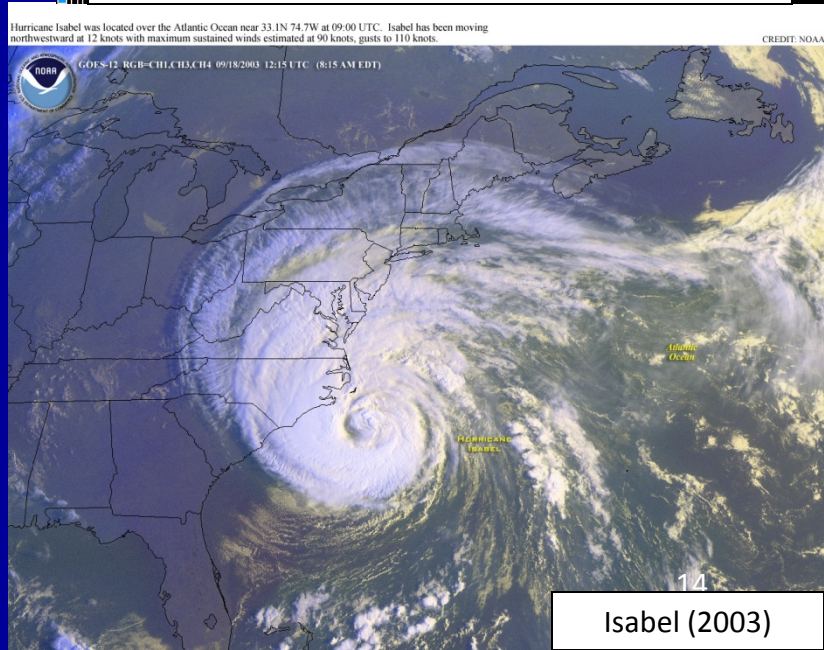
Downtown Houston after Hurricane Ike
Mark Wilson/Getty Images

Other Considerations

- Regions of stronger convective activity (eyewall, rainbands)
  - Convective downdrafts mix higher winds to surface more effectively
  - Wind in rainbands, especially during the daytime, can be very gusty
- Low-level stability
  - Enhanced low-level stability on cool side of boundary reduces vertical mixing (Floyd 1999, Isabel 2003)
  - Often occurs when TC interacting with warm front or cold-air damming setup



Ivan (2004) inland over Alabama and Georgia

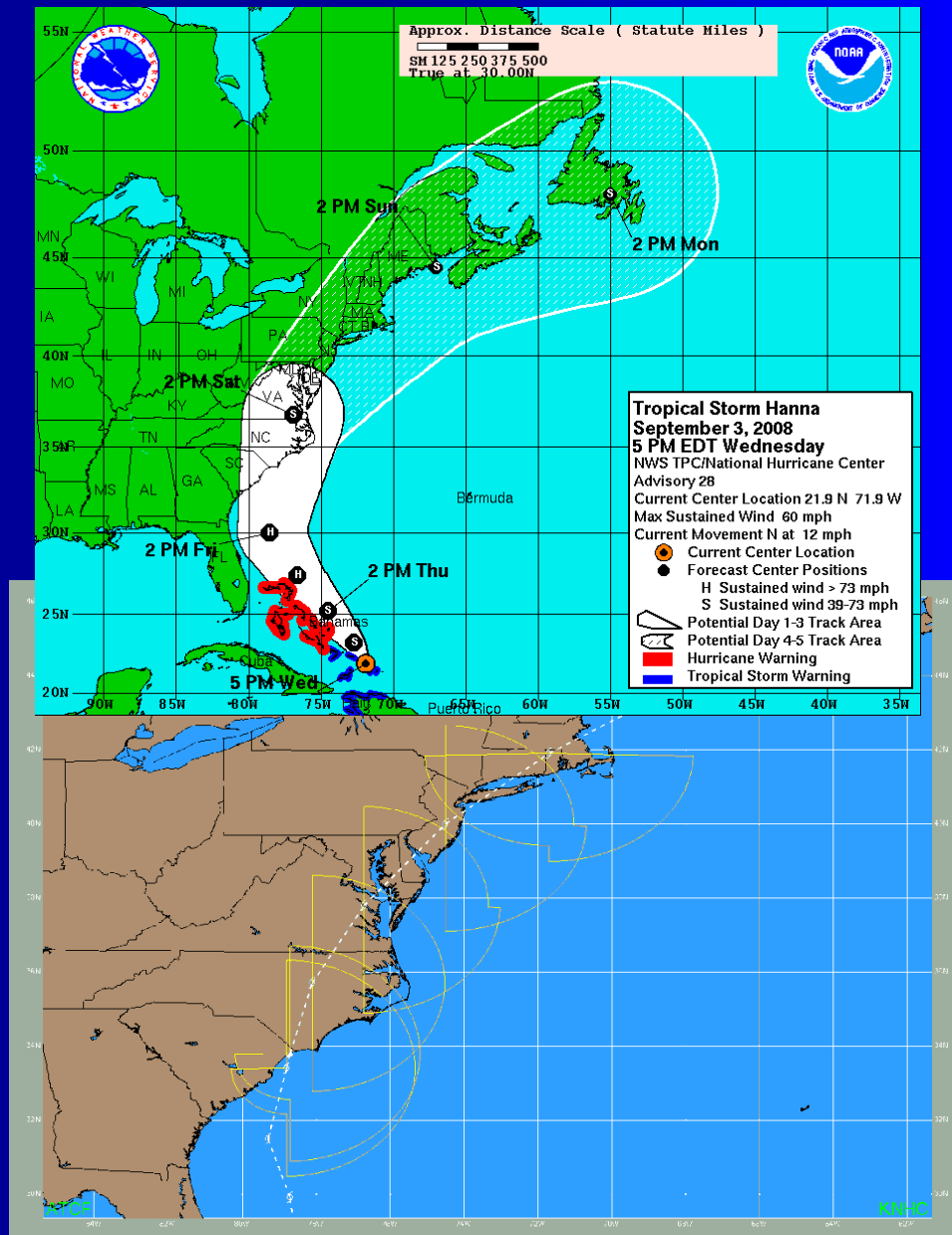


Isabel (2003)

Inland Wind Forecasts, Watches and Warnings

Current NHC Wind Forecast Products

- Intensity forecast (maximum sustained wind)
  - 12, 24, 36, 48, 72, 96, and 120 h
- Wind radii forecasts:
  - 64 kt: through 36 h
  - 50 and 34 kt: through 72 h
- Radii forecasts are for **maximum extent** of wind threshold in each quadrant of the storm
- Forecasts (and even analyses) of radii have very large uncertainty



Warnings for Inland Wind

- NHC's Tropical Storm/Hurricane watches and warnings valid only for coastal counties
- Tropical Storm/Hurricane watches and warnings for inland counties are issued by WFOs
  - Issued within Hurricane Local Statement (HLS)
  - Some WFOs still issue high wind watch/warnings products for TCs (mostly inland in Mid-Atlantic and Northeast)

Hurricane Watch/Warning

- **Hurricane Watch**: Hurricane conditions *possible* within the watch area. Watch is issued 48 hours in advance of the anticipated onset of tropical-storm-force winds.

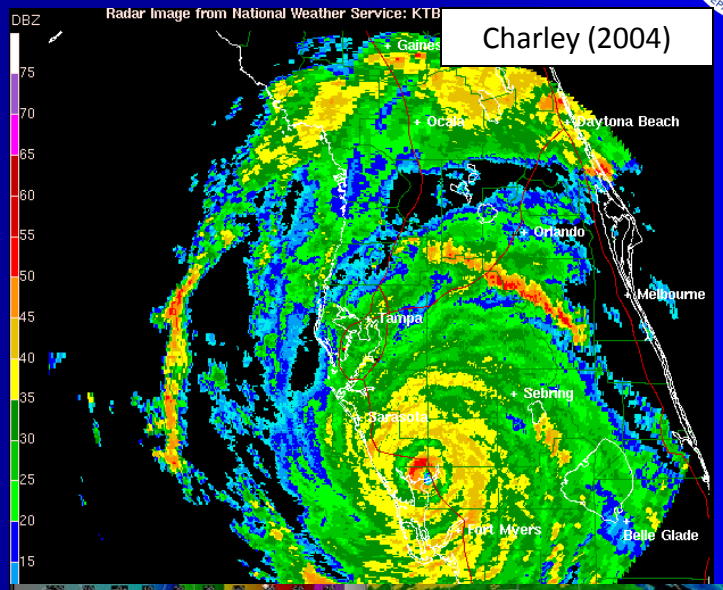
- **Hurricane Warning**: Hurricane conditions are *expected* somewhere within the warning area. Issued 36 hours in advance of the anticipated onset of tropical-storm-force winds.

Tropical Storm Watch/Warning

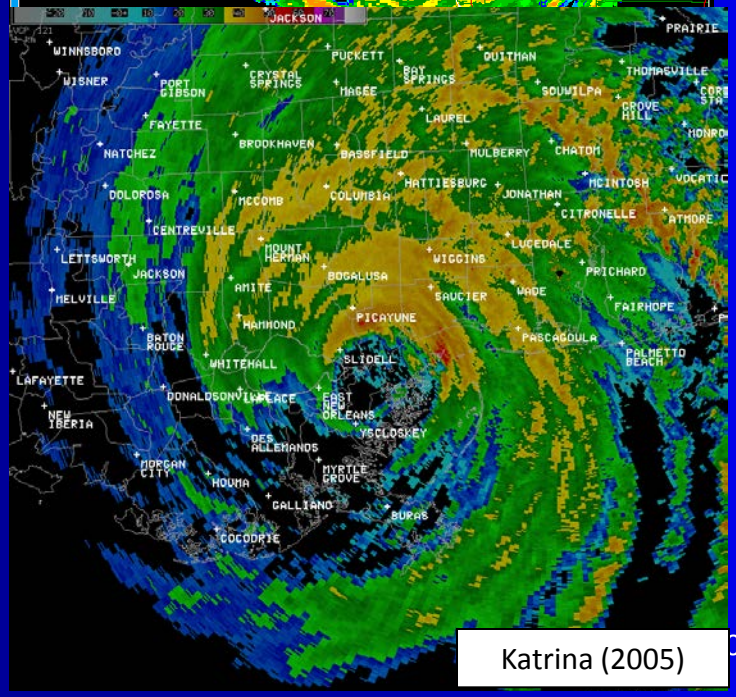
- **Tropical Storm Watch**: Tropical Storm conditions *possible* within the watch area within 48 hours.
- **Tropical Storm Warning**: Tropical Storm conditions are *expected* somewhere within the warning area within 36 hours.

Extreme Wind Warning (EWW)

- Short-fused (2-3 hours) warning issued by WFOs
- For *sustained* major hurricane force winds (100 kt or greater)
  - Usually in hurricane eyewall
- Conveys need to take immediate shelter in an interior portion of a well-built structure
  - Call to action similar to Tornado Warning



Charley (2004)



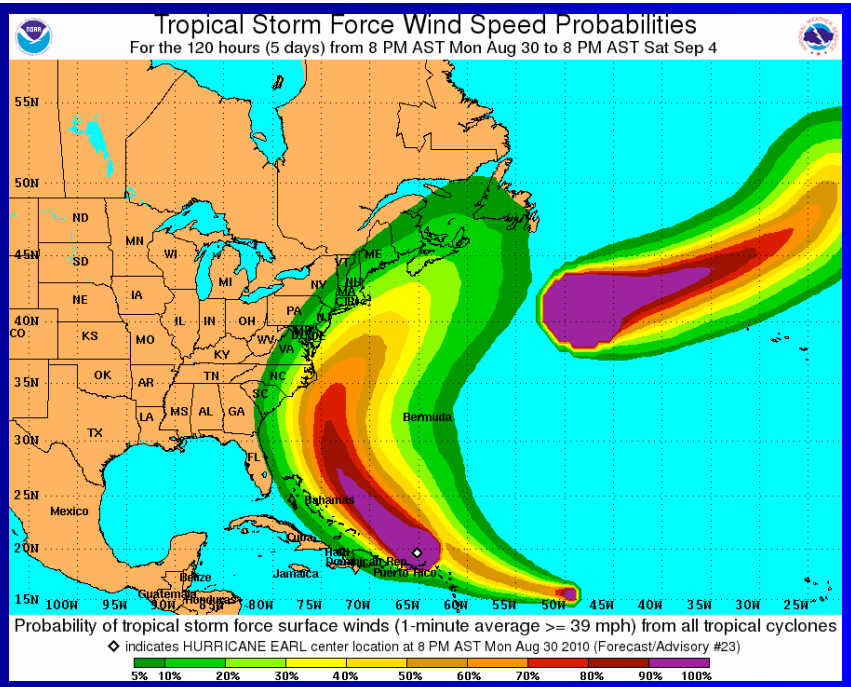
Katrina (2005)

NHC Wind Speed Probability Products

NHC Wind Speed Probabilities

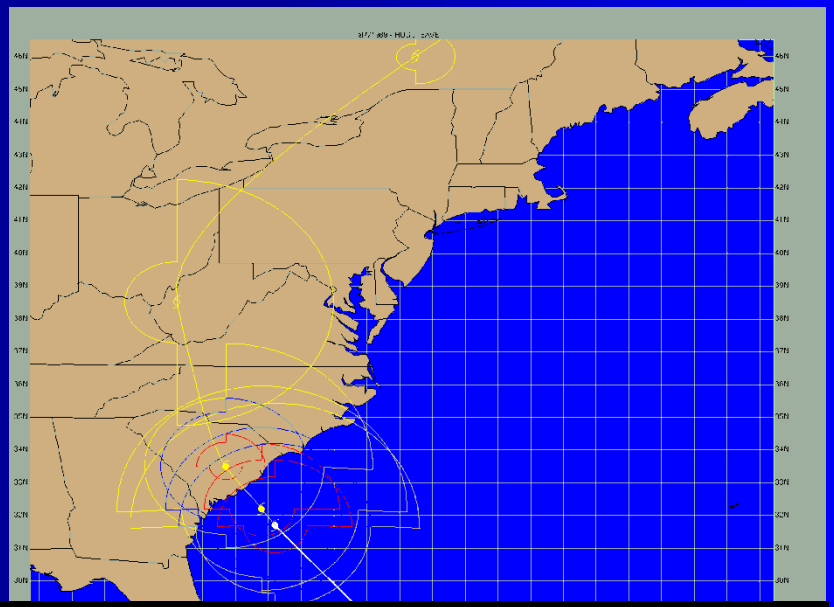
- Designed as decision-making tool for EMs, government officials, and the general public
- Account for uncertainty in forecasts of track, intensity, and wind structure
- Depict probabilities for tropical storm force, 50-kt, and hurricane force winds at specific locations
  - Text and graphical products
  - Period-specific and cumulative probabilities out to 120 hours
  - Issued with each full NHC advisory package
  - Available on NHC webpage

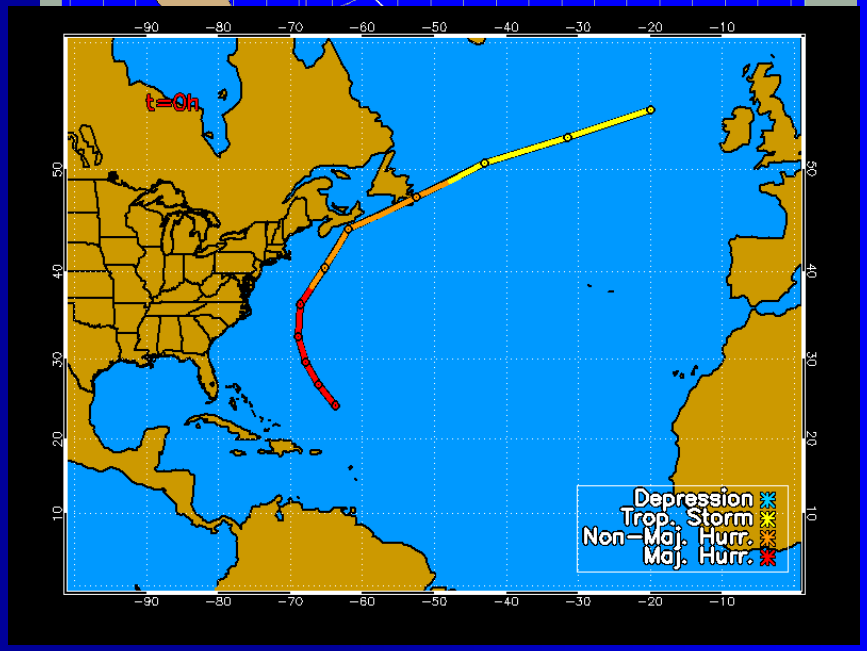
TIME PERIODS		FROM 06Z THU TO 18Z THU	FROM 18Z THU TO 06Z FRI	FROM 06Z FRI TO 18Z FRI	FROM 18Z FRI TO 06Z SAT	FROM 06Z SAT TO 06Z SUN	FROM 06Z SUN TO 06Z MON	FROM 06Z MON TO 06Z TUE
FORECAST HOUR		(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT							
MIAMI FL	34	X	X(X)	X(X)	2(2)	16(18)	23(41)	5(46)
MIAMI FL	50	X	X(X)	X(X)	X(X)	6(6)	11(17)	3(20)
MIAMI FL	64	X	X(X)	X(X)	X(X)	2(2)	5(7)	1(8)
KEY WEST FL	34	X	X(X)	2(2)	7(9)	26(35)	18(53)	3(56)
KEY WEST FL	50	X	X(X)	X(X)	1(1)	14(15)	11(26)	1(27)
KEY WEST FL	64	X	X(X)	X(X)	X(X)	8(8)	5(13)	1(14)
MARCO ISLAND	34	X	X(X)	X(X)	5(5)	20(25)	23(48)	4(52)
MARCO ISLAND	50	X	X(X)	X(X)	1(1)	10(11)	12(23)	2(25)
MARCO ISLAND	64	X	X(X)	X(X)	X(X)	5(5)	6(11)	X(11)



NHC Wind Speed Probabilities

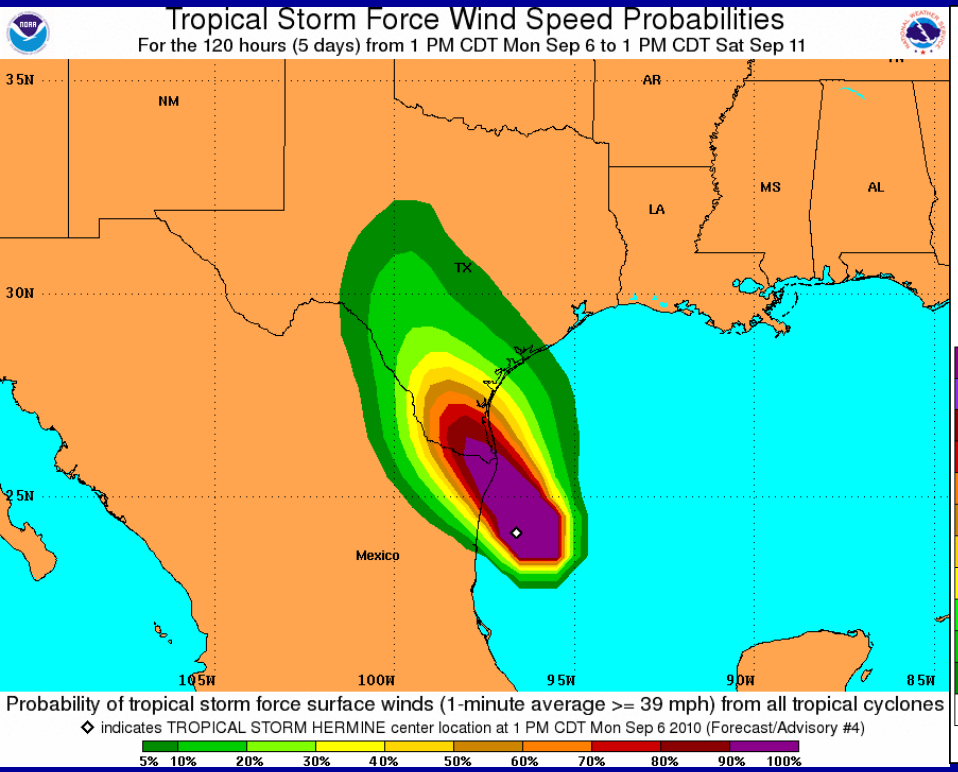
- Probabilities are constructed using
  - Official NHC track and intensity forecasts
  - Historical NHC track and intensity forecast errors
  - Climatological and persistence wind radii model (Radii-CLIPER)
- 1,000 realizations created
- Probability of exceeding 34, 50, and 64 kt wind thresholds computed at points and on 0.5°× 0.5° grid
- Accounts for inland wind decay using Kaplan and DeMaria (1995) model



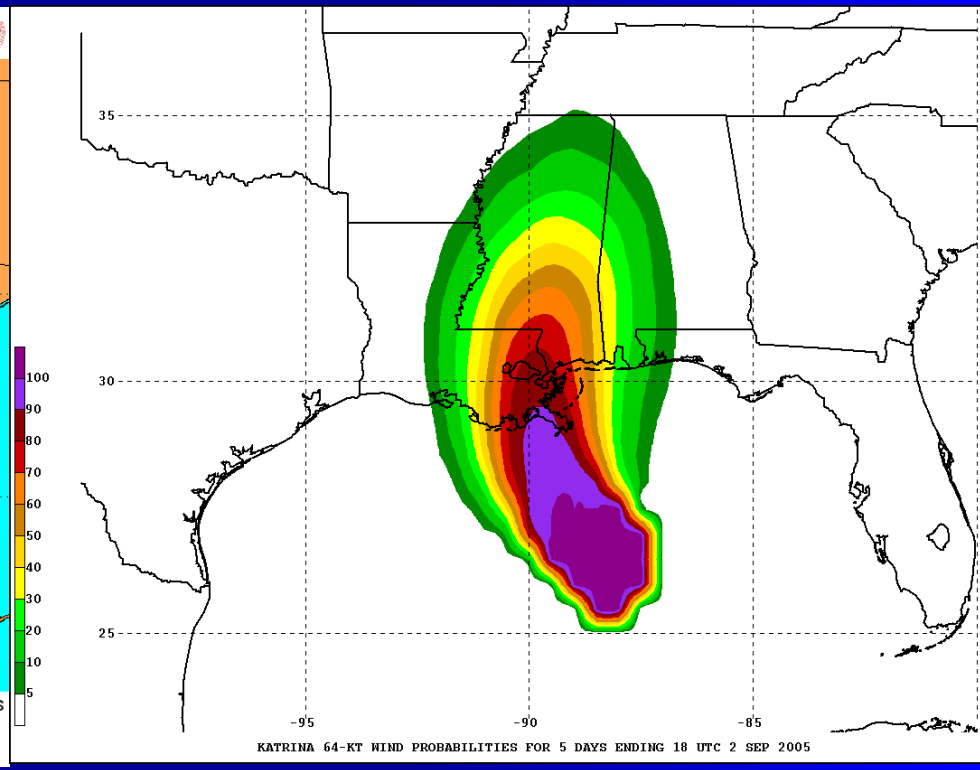


Wind Speed Probability Graphics

Show cumulative probability of winds reaching 34, 50, and 64-kt thresholds on a 0.5°× 0.5° grid



Probability of 34-kt wind through 120-h from Tropical Storm Hermine



Probability of 64-kt wind through 120-h from Hurricane Katrina

- - - - WIND SPEED PROBABILITIES FOR SELECTED LOCATIONS - - - -

Cumulative Probabilities

Onset Probabilities

TIME PERIODS		FROM 00Z FRI TO 12Z FRI	FROM 12Z FRI TO 00Z SAT	FROM 00Z SAT TO 12Z SAT	FROM 12Z SAT TO 00Z SUN	FROM 00Z SUN TO 00Z MON	FROM 00Z MON TO 00Z TUE	FROM 00Z TUE TO 00Z WED
FORECAST HOUR		(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT							
GREENSBORO NC	34	X	2(2)	15(17)	3(20)	X(20)	X(20)	X(20)
GREENSBORO NC	50	X	X(X)	3(3)	1(4)	X(4)	X(4)	X(4)
RALEIGH NC	34	X	5(5)	32(37)	5(42)	X(42)	X(42)	X(42)
RALEIGH NC	50	X	X(X)	8(8)	3(11)	X(11)	X(11)	X(11)
RALEIGH NC	64	X	X(X)	1(1)	1(2)	X(2)	X(2)	X(2)
CAPE HATTERAS	34	X	7(7)	30(37)	12(49)	X(49)	X(49)	X(49)
CAPE HATTERAS	50	X	X(X)	7(7)	4(11)	X(11)	X(11)	X(11)
CAPE HATTERAS	64	X	X(X)	2(2)	1(3)	X(3)	X(3)	X(3)
CHARLOTTE NC	34	X	4(4)	9(13)	1(14)	X(14)	X(14)	X(14)
MOREHEAD CITY	34	X	17(17)	42(59)	6(65)	X(65)	X(65)	X(65)
MOREHEAD CITY	50	X	X(X)	17(17)	3(20)	X(20)	X(20)	X(20)

Example Interpretation of Output

What is the chance that winds of tropical storm force (34 kt or greater) will occur at Charlotte NC during the next five days?

TIME PERIODS	FROM 18Z FRI TO 06Z SAT	FROM 06Z SAT TO 18Z SAT	FROM 18Z SAT TO 06Z SUN	FROM 06Z SUN TO 18Z SUN	FROM 18Z SUN TO 18Z MON	FROM 18Z MON TO 18Z TUE	FROM 18Z TUE TO 18Z WED
FORECAST HOUR	(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT						
RALEIGH NC	34 X	X(X)	X(X)	2(2)	10(12)	8(20)	10(30)
RALEIGH NC	50 X	X(X)	X(X)	X(X)	2(2)	3(5)	5(10)
RALEIGH NC	64 X	X(X)	X(X)	X(X)	X(X)	2(2)	2(4)
CAPE HATTERAS	34 X	X(X)	X(X)	1(1)	4(5)	3(8)	7(15)
CAPE HATTERAS	50 X	X(X)	X(X)	X(X)	X(X)	1(1)	2(3)
CHARLOTTE NC	34 X	X(X)	X(X)	3(3)	18(21)	12(33)	9(42)
CHARLOTTE NC	50 X	X(X)	X(X)	X(X)	4(4)	6(10)	4(14)
CHARLOTTE NC	64 X	X(X)	X(X)	X(X)	2(2)	2(4)	2(6)

34 kt probabilities at Charlotte NC

Example Interpretation of Output

What is the chance that winds of tropical storm force (34 kt or greater) will occur at Charlotte NC during the next five days?

42%

34 kt probabilities at Charlotte NC

TIME PERIODS	FROM 18Z FRI TO 06Z SAT	FROM 06Z SAT TO 18Z SAT	FROM 18Z SAT TO 06Z SUN	FROM 06Z SUN TO 18Z SUN	FROM 18Z SUN TO 18Z MON	FROM 18Z MON TO 18Z TUE	FROM 18Z TUE TO 18Z WED
FORECAST HOUR	(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT						
RALEIGH NC	34 X	X(X)	X(X)	2(2)	10(12)	8(20)	10(30)
RALEIGH NC	50 X	X(X)	X(X)	X(X)	2(2)	3(5)	5(10)
RALEIGH NC	64 X	X(X)	X(X)	X(X)	X(X)	2(2)	2(4)
CAPE HATTERAS	34 X	X(X)	X(X)	1(1)	4(5)	3(8)	7(15)
CAPE HATTERAS	50 X	X(X)	X(X)	X(X)	X(X)	1(1)	2(3)
CHARLOTTE NC	34 X	X(X)	X(X)	3(3)	18(21)	12(33)	9(42)
CHARLOTTE NC	50 X	X(X)	X(X)	X(X)	4(4)	6(10)	4(14)
CHARLOTTE NC	64 X	X(X)	X(X)	X(X)	2(2)	2(4)	2(6)

Example Interpretation of Output

What is the chance that winds of tropical storm force (34 kt or greater) will occur at Charlotte NC during the next five days?

42%

When are these winds most likely to start?

34 kt probabilities at Charlotte NC

TIME PERIODS		FROM 18Z FRI TO 06Z SAT	FROM 06Z SAT TO 18Z SAT	FROM 18Z SAT TO 06Z SUN	FROM 06Z SUN TO 18Z SUN	FROM 18Z SUN TO 18Z MON	FROM 18Z MON TO 18Z TUE	FROM 18Z TUE TO 18Z WED
FORECAST HOUR		(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT							
RALEIGH NC	34	X	X(X)	X(X)	2(2)	10(12)	8(20)	10(30)
RALEIGH NC	50	X	X(X)	X(X)	X(X)	2(2)	3(5)	5(10)
RALEIGH NC	64	X	X(X)	X(X)	X(X)	X(X)	2(2)	2(4)
CAPE HATTERAS	34	X	X(X)	X(X)	1(1)	4(5)	3(8)	7(15)
CAPE HATTERAS	50	X	X(X)	X(X)	X(X)	X(X)	1(1)	2(3)
CHARLOTTE NC	34	X	X(X)	X(X)	3(3)	18(21)	12(33)	9(42)
CHARLOTTE NC	50	X	X(X)	X(X)	X(X)	4(4)	6(10)	4(14)
CHARLOTTE NC	64	X	X(X)	X(X)	X(X)	2(2)	2(4)	2(6)

Example Interpretation of Output

What is the chance that winds of tropical storm force (34 kt or greater) will occur at Charlotte NC during the next five days?

42%

When are these winds most likely to start?

From 18Z Sun to 18Z Mon (18% chance)

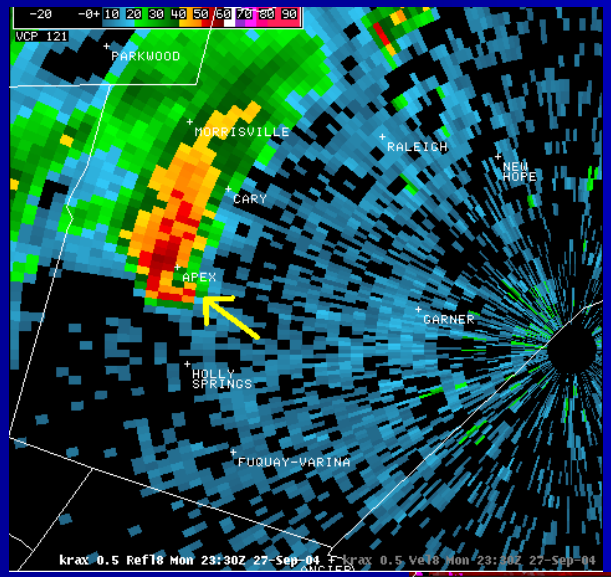
34 kt probabilities at Charlotte NC

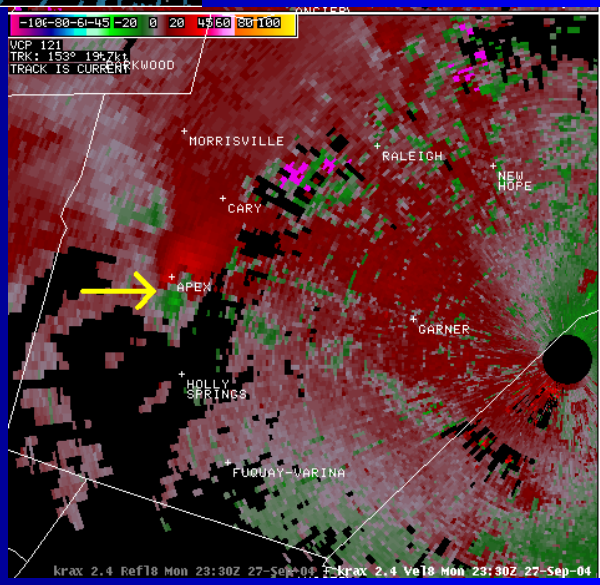
TIME PERIODS	FROM 18Z FRI TO 06Z SAT	FROM 06Z SAT TO 18Z SAT	FROM 18Z SAT TO 06Z SUN	FROM 06Z SUN TO 18Z SUN	FROM 18Z SUN TO 18Z MON	FROM 18Z MON TO 18Z TUE	FROM 18Z TUE TO 18Z WED
FORECAST HOUR	(12)	(24)	(36)	(48)	(72)	(96)	(120)
LOCATION	KT						
RALEIGH NC	34 X	X(X)	X(X)	2(2)	10(12)	8(20)	10(30)
RALEIGH NC	50 X	X(X)	X(X)	X(X)	2(2)	3(5)	5(10)
RALEIGH NC	64 X	X(X)	X(X)	X(X)	X(X)	2(2)	2(4)
CAPE HATTERAS	34 X	X(X)	X(X)	1(1)	4(5)	3(8)	7(15)
CAPE HATTERAS	50 X	X(X)	X(X)	X(X)	X(X)	1(1)	2(3)
CHARLOTTE NC	34 X	X(X)	X(X)	3(3)	18(21)	12(33)	9(42)
CHARLOTTE NC	50 X	X(X)	X(X)	X(X)	4(4)	6(10)	4(14)
CHARLOTTE NC	64 X	X(X)	X(X)	X(X)	2(2)	2(4)	2(6)

Tropical Cyclone Tornadoes

Tropical Cyclone Tornadoes

- Nearly 70% of landfalling hurricanes (1948-2000) spawned at least 1 tornado
- 40% of landfalling hurricanes spawn more than 3 tornadoes
- Some hurricanes are particularly prolific tornado producers and result in tornado "outbreaks"
  - Hurricane Beulah (1967): 141
  - Hurricane Ivan (2004): 117
  - Hurricane Frances (2004): 101
  - Hurricane Rita (2005): 90
  - Hurricane Camille (1969): 80
  - Hurricane Katrina (2005): 43



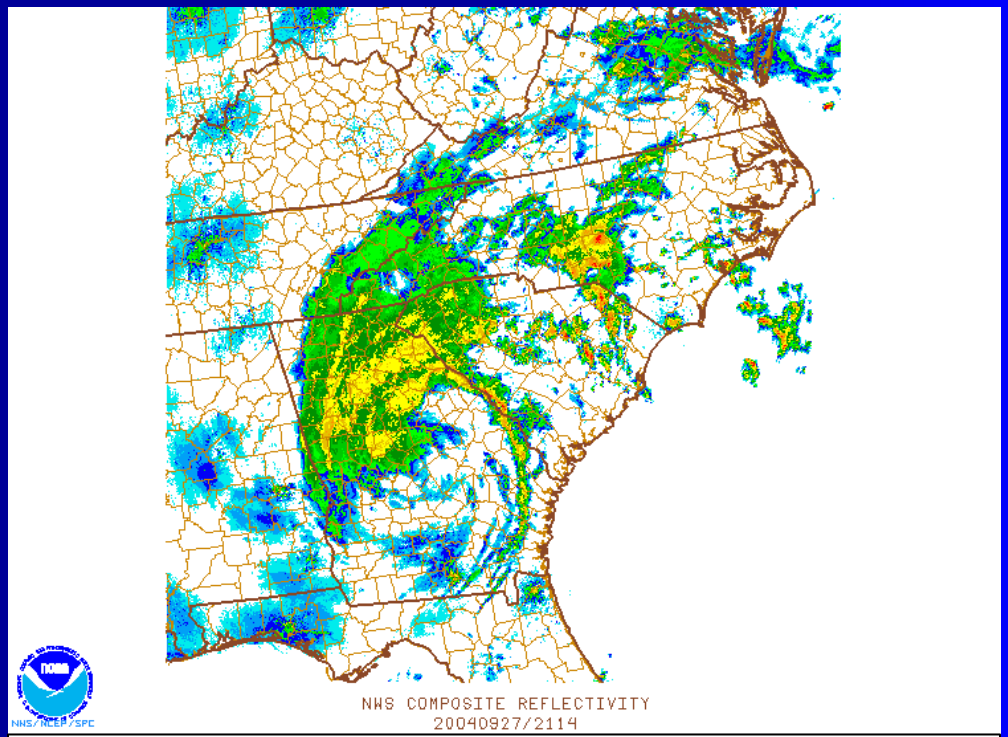


Doppler radar imagery of tornado associated with Tropical Depression Jeanne on 27 Sep 2004

Images courtesy NWS Raleigh

Tropical Cyclone Tornadoes

- Development is favored in outer spiral rainbands during the peak heating time of the day (afternoon and early evening)
- Many TC tornadoes form and dissipate very quickly, providing little time for advance warning
- Most TC tornadoes are relatively "weak", but stronger and more damaging TC tornadoes can occur
  - Edwards (2010) found 93% of TC tornadoes were F0-F1, 7% were F2-F3 and only 0.5% were F4-F5
- TCs that make landfall along the Gulf coast typically produce more tornadoes because the favored right-front quadrant is over land more than TCs that make landfall along the Atlantic coast

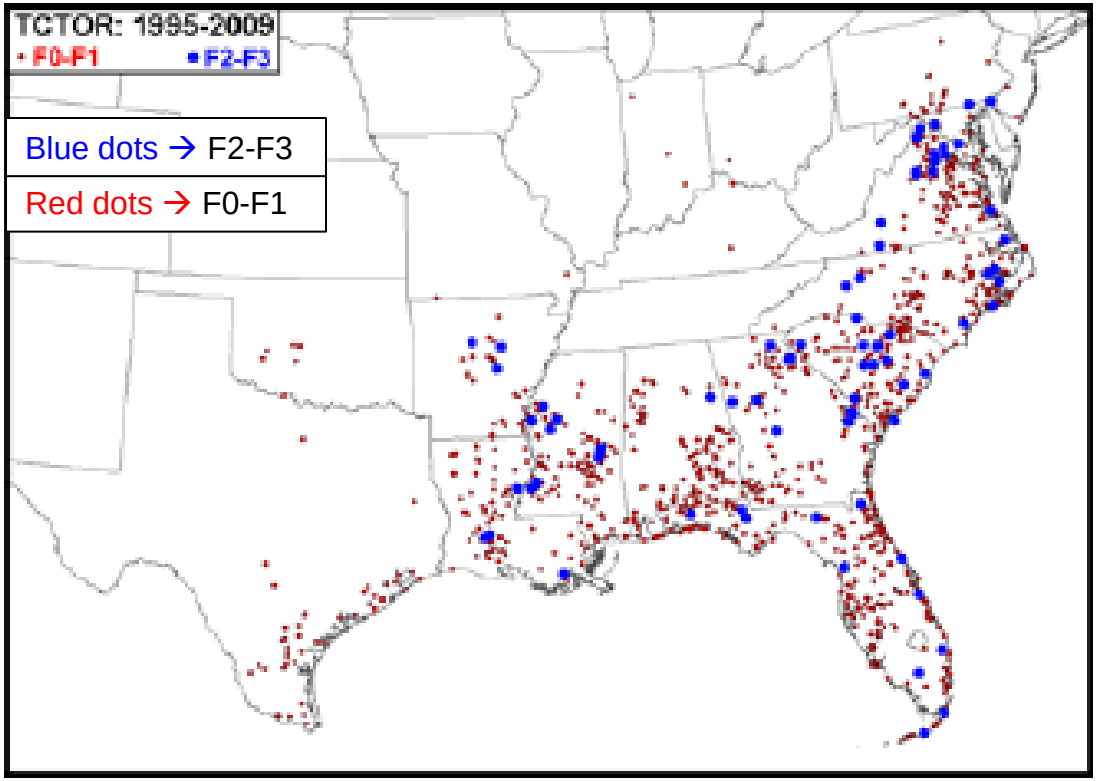


Composite radar reflectivity at 2114 UTC 27 September 2004 showing the center of Tropical Storm Jeanne inland over Georgia

Image courtesy SPC and NWS Raleigh

TC Tornado Geographical Distribution

1995-2009 – Edwards (2010)

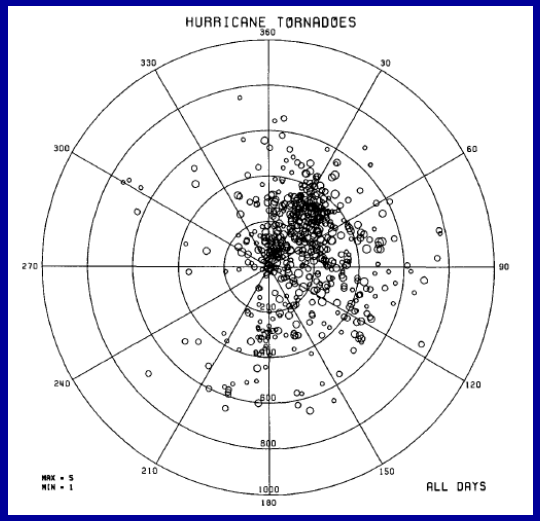


- 1160 tornadoes identified in the dataset, which included TCs and remnants in the Doppler radar era
- 73% of tornadoes occurred with non-hurricanes and 35% occurred with tropical depressions
- No strong geographical preference seen for stronger TC tornadoes in 1995-2009 dataset

http://ams.confex.com/ams/pdfpapers/175269.pdf

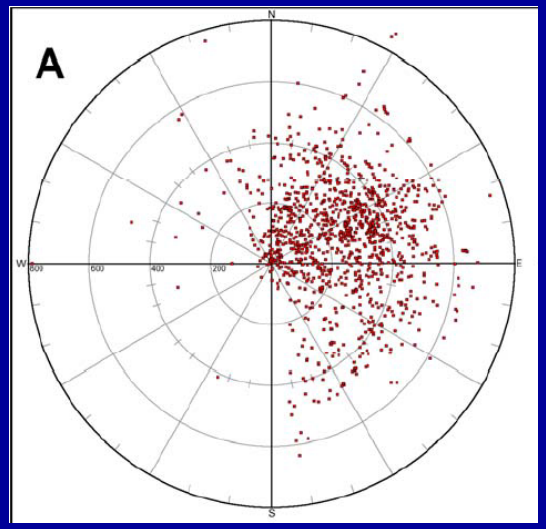
TC Tornado Characteristics

McCaul (1991)

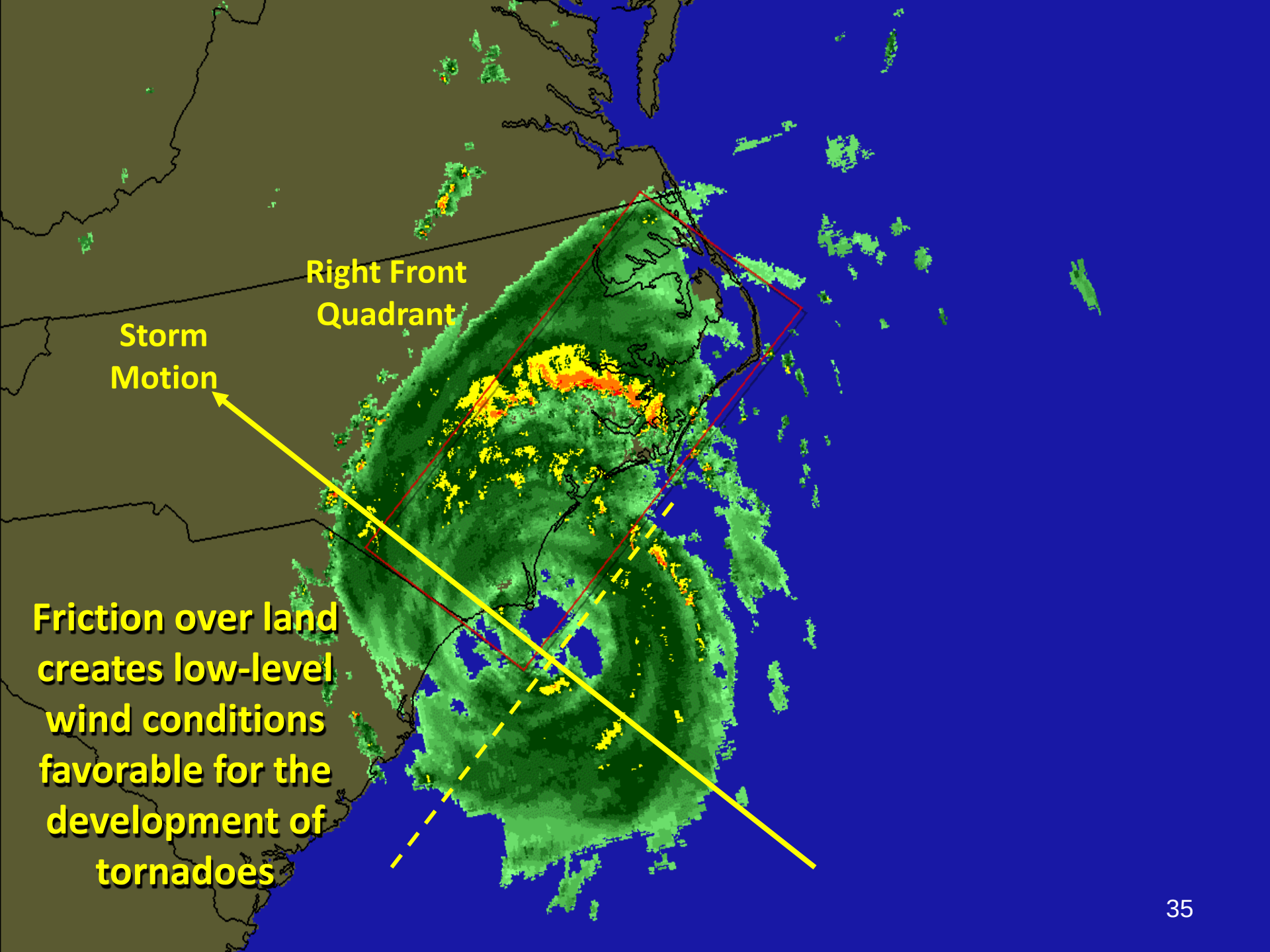


- Location of all reported hurricane tornadoes from 1948-1986 plotted with respect to the storm motion at the time of the tornado
- Tornadoes clearly favored in the right-front quadrant (relative to storm motion) where wind shear is maximized

Edwards (2010)

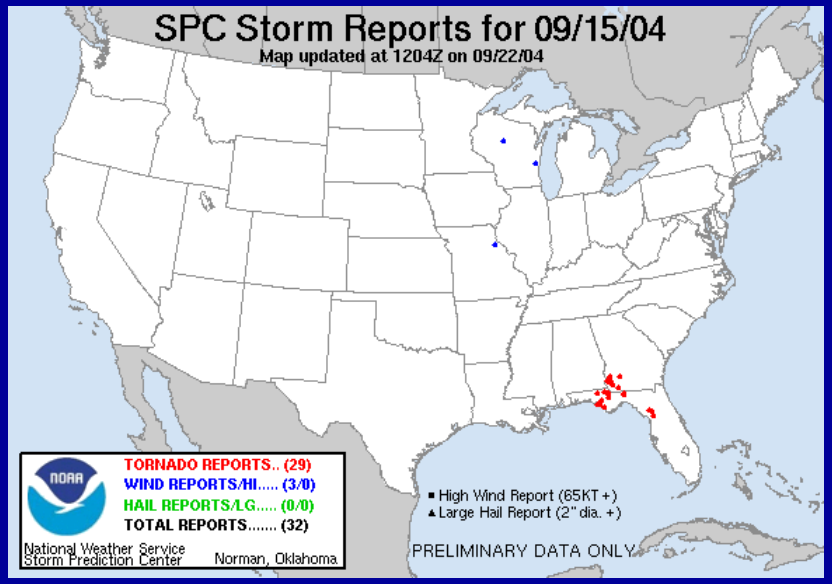


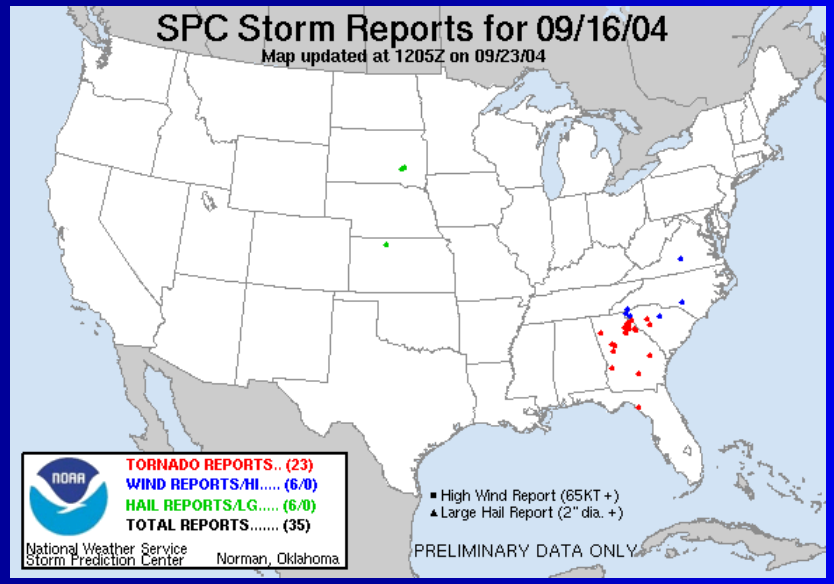
- 68% of tornado reports found in NE quadrant (relative to true north), and 26% in SE quadrant
- Only 0.7% of tornadoes found in SW quadrant

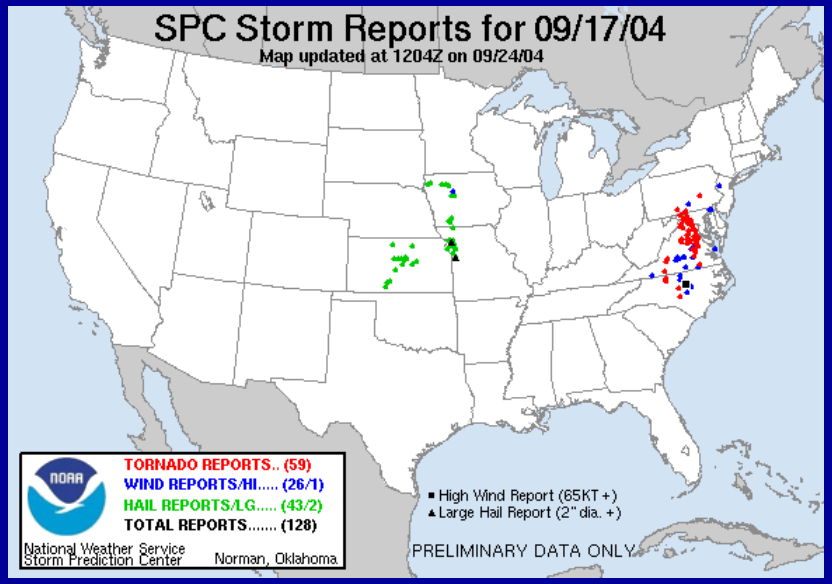

Right Front
Quadrant
Storm
Motion
Friction over land
creates low-level
wind conditions
favorable for the
development of
tornadoes

Tropical Cyclone Tornado Outbreaks

Hurricane Ivan (2004)





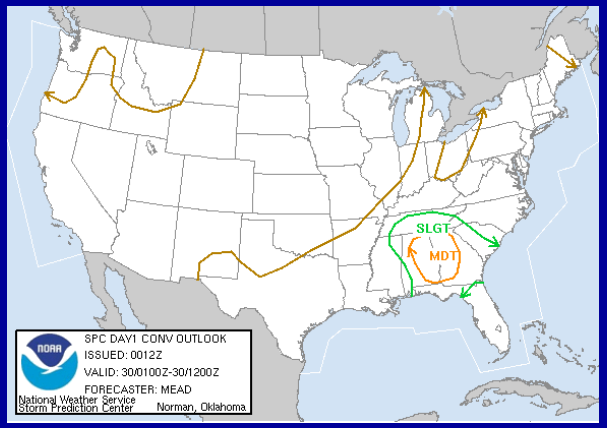


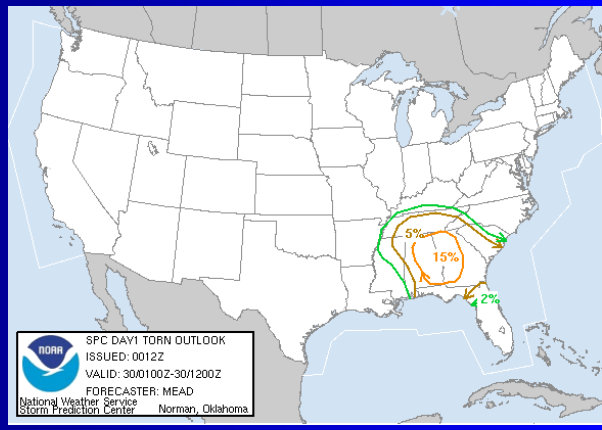
- Over a 3-day period Ivan produced 117 tornadoes from Florida to Pennsylvania
- Largest number of tornadoes (59) occurred 2 days after landfall in the Mid-Atlantic states when Ivan was a tropical depression
- At least 8 killed and 17 injured by tornadoes

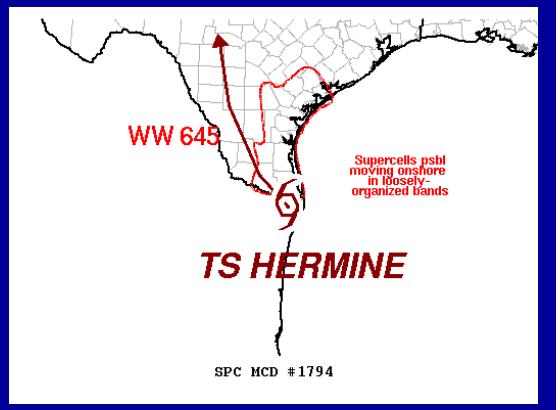
TC Tornado Guidance

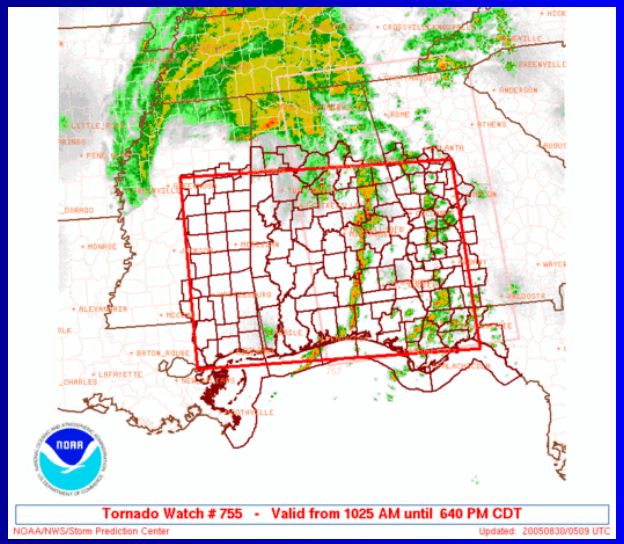
Outlooks, Discussions, Watches

- Large-scale guidance on TC tornadoes comes from the Storm Prediction Center
- Day 1, 2, and 3 convective outlooks outline broad categorical and probabilistic risk areas
- Tornado hazard statement in NHC public advisory coordinated with SPC and WFOs
- Mesoscale convective discussions highlight short-term trends and focus in on potential watch areas
- Tornado Watches mean conditions are favorable for multiple tornadoes in the watch area in the next 3 to 8 hours







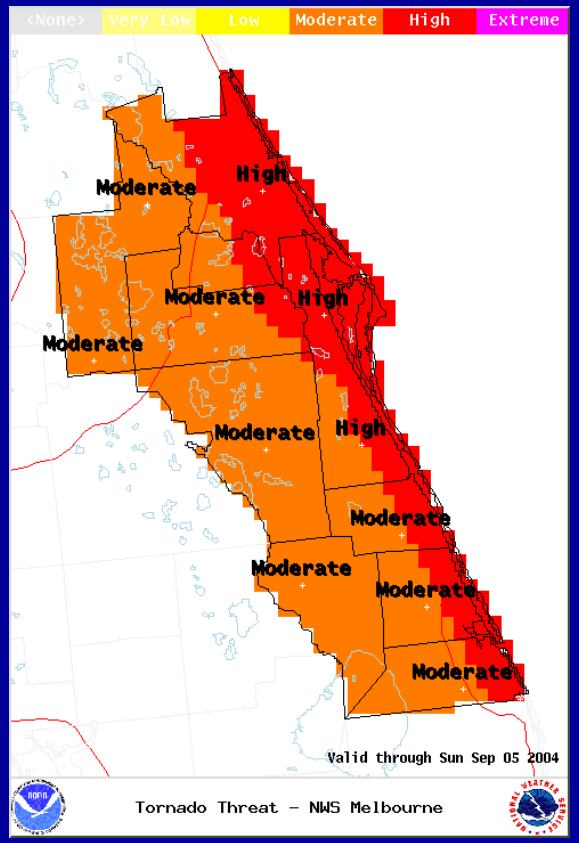


http://www.spc.noaa.gov

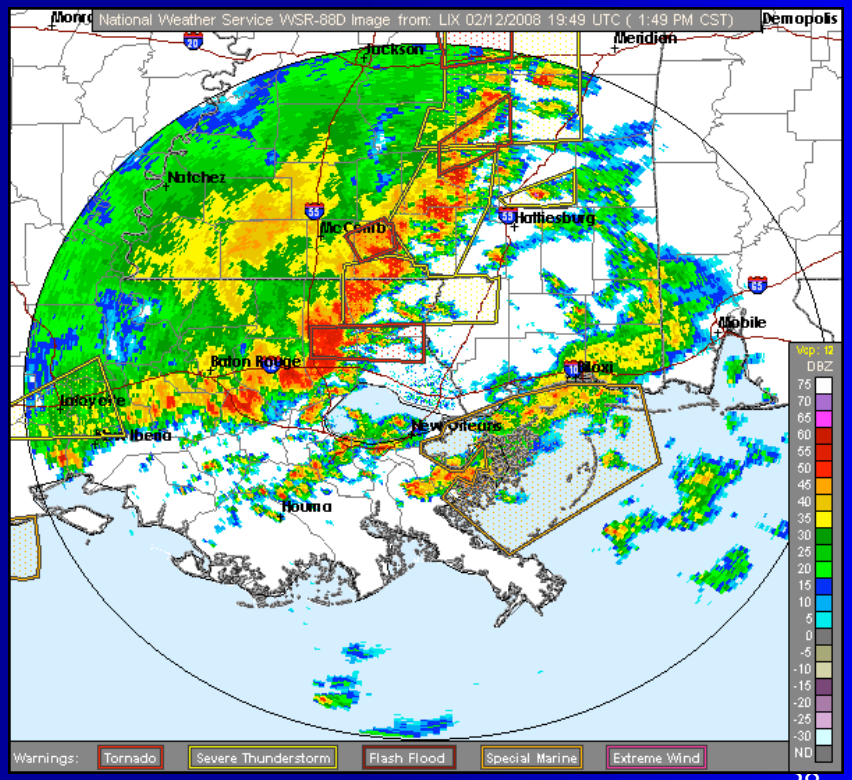
TC Tornado Guidance

Warnings and Statements

- Local tornado risk indicated in TC hazard graphics and the HLS issued by your local WFO



- Tornado Warnings, follow-up Severe Weather Statements and Local Storm Reports are issued by your local WFO



Questions?

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