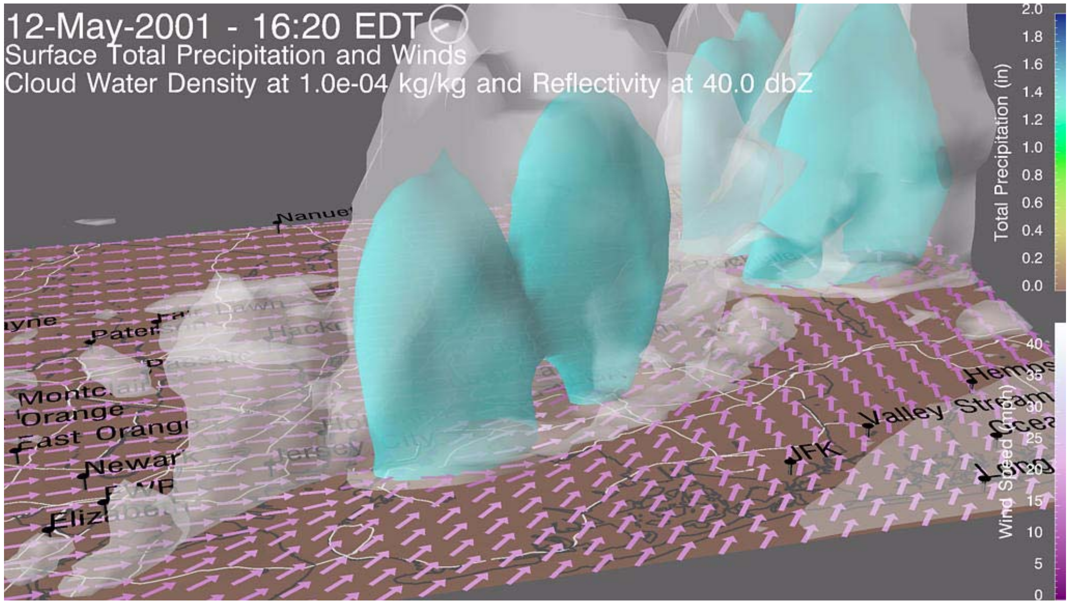
A User-Driven Meso-γ-Scale Numerical Modelling and Visualization System for Weather-Sensitive Decision Making



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A User-Driven Meso-γ-Scale Numerical Modelling and Visualization System for Weather-Sensitive Decision Making

- **Background and motivation**
- **System architecture & implementation**
- **Visualization issues**
- **Some case studies**
- **Discussion and future work**

Applications (User) Motivation

- **Problem**: weather-sensitive business operations are often reactive to short-term, local conditions due to (*real* or *perceived*) unavailability of appropriate predicted data at this scale
  - Energy, transportation, emergency management, agriculture, insurance, broadcasting, sports, entertainment, tourism, construction, communications, ...
- Meso-γ-scale (cloud-scale) NWP has long shown "promise" as a potential enabler of proactive decision making for both economic and societal value
  - Can business and meteorological value be demonstrated beyond physical realism?
  - Can a practical and usable system be implemented at reasonable cost?
- Improved feasibility although not quite sufficient today compared to a few years ago due to
  - Affordable operational computing and visualization platforms
  - Reliability and flexibility of forecasting codes
  - Availability of relevant input data

Approach

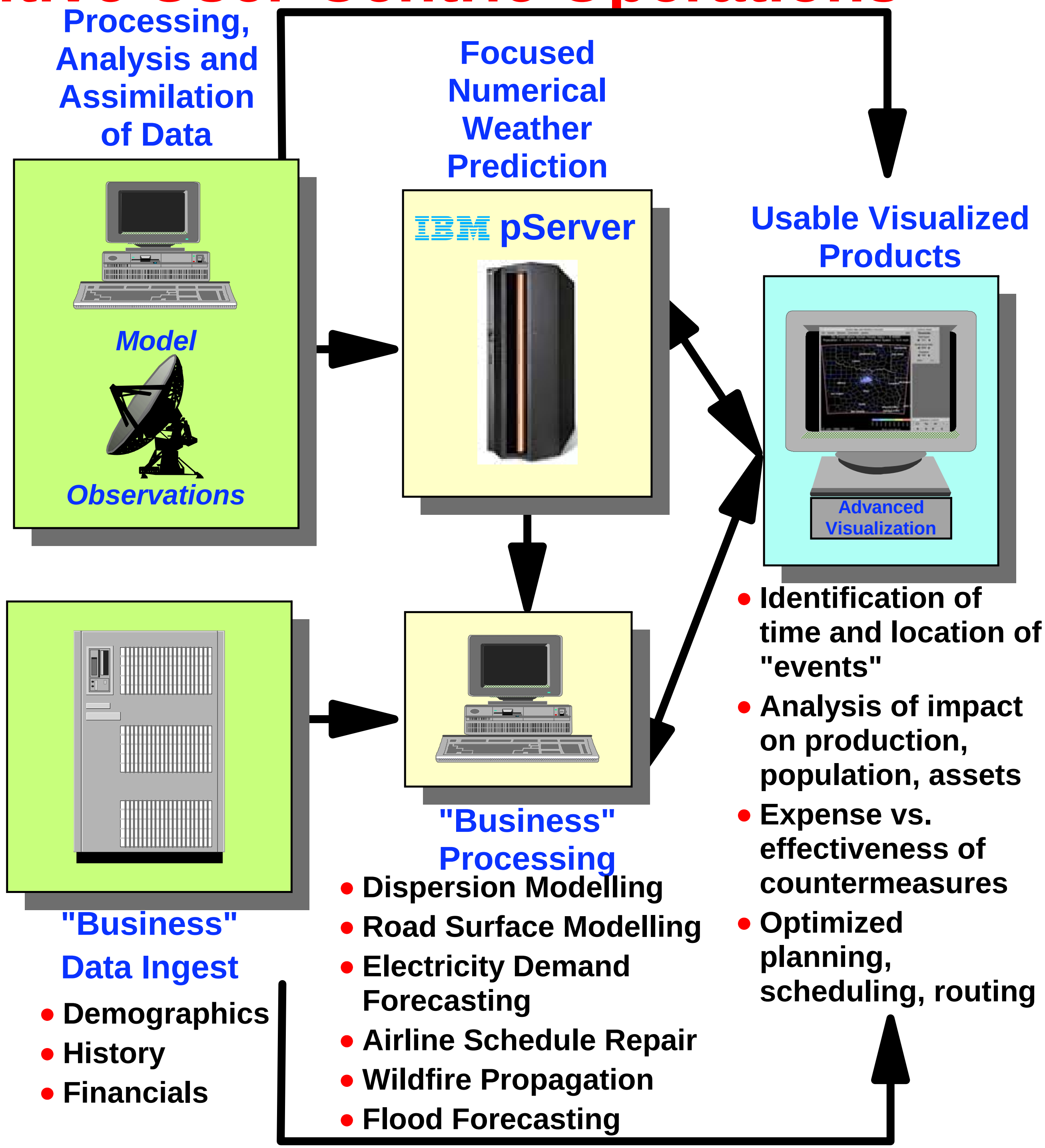
- **Solution: application of reliable, affordable, weather models for predictive & proactive decision making & operational planning**
  - NWP-based forecasts coupled to business processes
  - Products and operations customized to business problems
  - Competitive advantage, e.g., efficiency for economic & societal benefit
- **It is not about weather but integrating forecasts into decision making to optimize business processes**
- **Testbed implementation for multiple metropolitan areas -- "*Deep Thunder*"**
  - End-to-end process (user to meteorology) tailored to business needs
  - Operational infrastructure and automation with focus on HPC, visualization, and system and user integration
  - 24-hour forecasts to 1-2 km resolution with 3 to 21 hours lead time
  - New York City, Chicago, Kansas City, Baltimore/Washington, Atlanta, San Diego, Fort Lauderdale/Miami and others
  - Prototype business applications with actual end users to address usability and effectiveness issues

Customized Model-Based Forecasts for Local Weather-Sensitive User-Centric Operations

- Enable proactive decision making affected by weather
- Customize & integrate for different users
- Provide usable forecast products fast enough to enable timely decisions

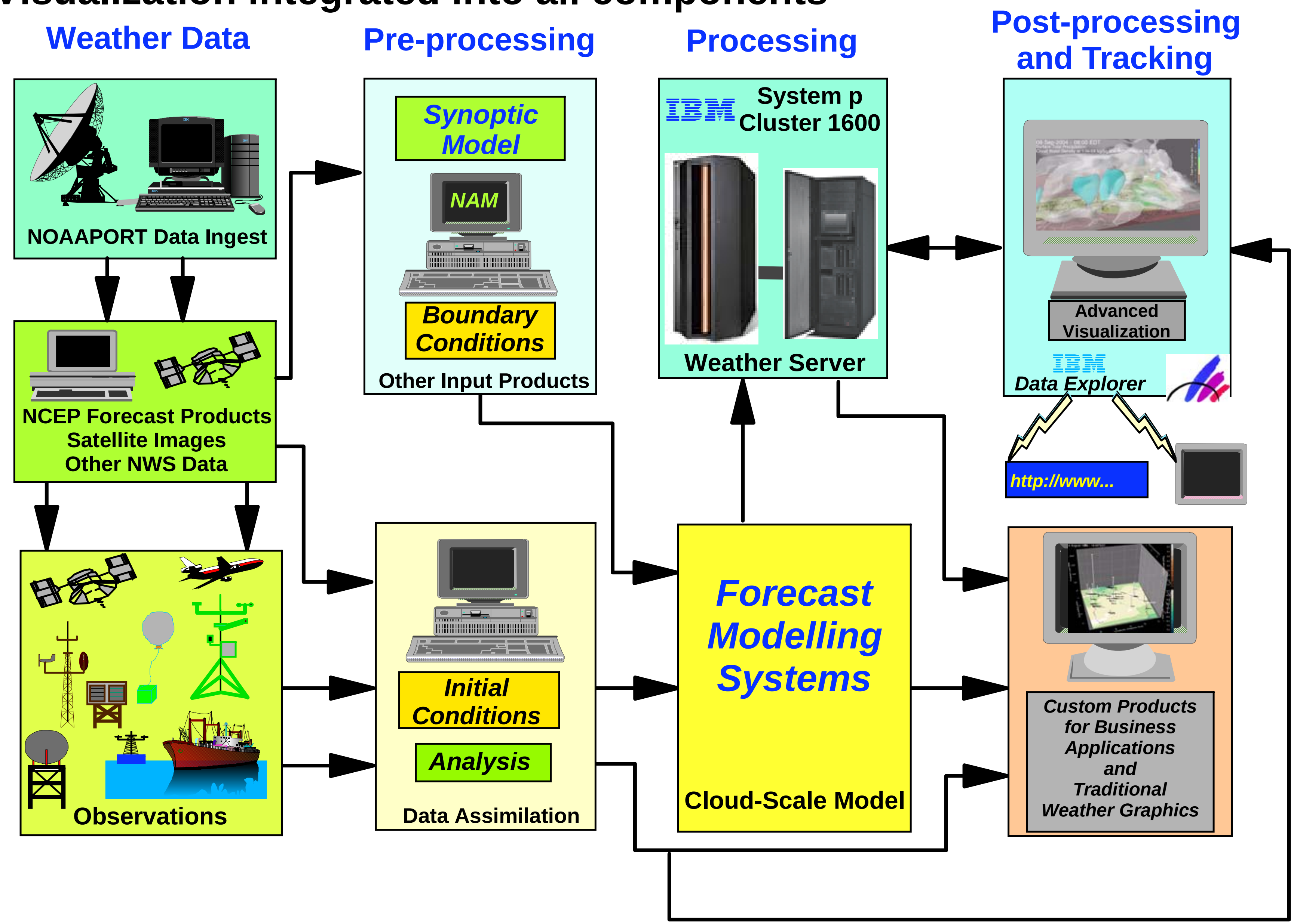
  Visualized results produced within a few hours per day of forecast

- Couple to user and business processes and models
- Past forecasts useful for scenario planning



Deep Thunder Implementation and Architecture

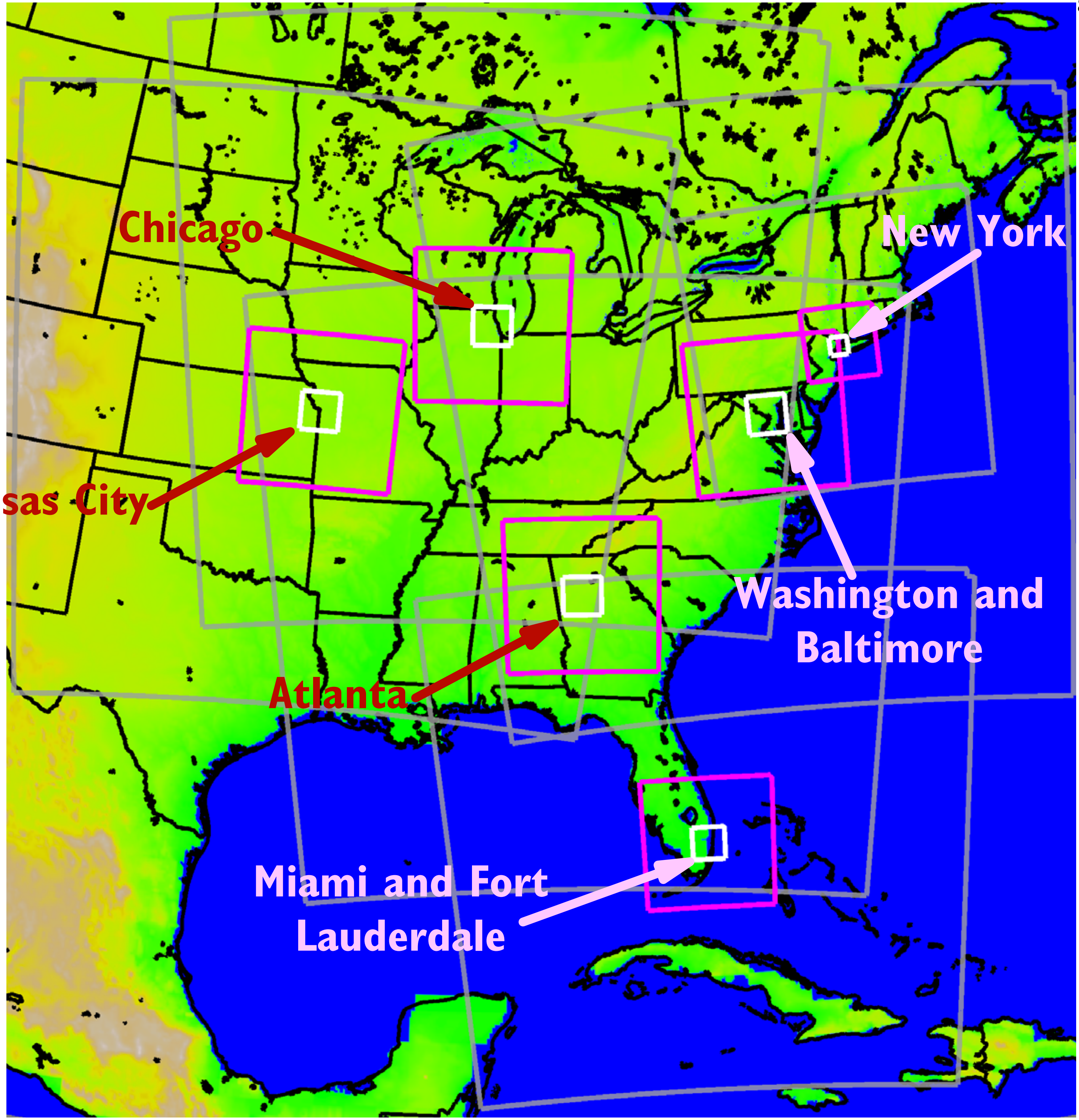
- User-driven not data-driven (start with user needs and work backwards)
- Sufficiently fast (>10x real-time), robust, reliable and affordable
  - For example, 30 minutes (20x1.7GHz Power4) for 32/8/2 km (three 66x66x31)
- Ability to provide usable products in a timely manner
- Visualization integrated into all components



Deep Thunder Operational Modelling Component

- **Originated with the Regional Atmospheric Modeling System (RAMS), but extensively modified**
  - MPI-based parallelization for IBM Power/AIX SMP clusters, including nesting
  - Instrumented for visualization
  - Upgraded bulk microphysics (five species, single moment)
  - 3-D, staggered in x-y, terrain following in z, moving grid
  - Arbitrary domain ($10\text{-}10^5$ m), nested, two-way interactive grid
- **Governing equations and numerical methods**
  - Unsteady primitive equations of motion, for all scales
  - Terms in equations are added/removed depending on scale
  - User selected physical and numerical schemes (e.g., split-explicit finite difference), both hydrostatic and non-hydrostatic
- **Operational configuration and performance**
  - 65 minutes (20x1.7GHz Power4) for 16/4/1km
  - 30 minutes (20x1.7GHz Power4) for 32/8/2 km
  - Initial and boundary conditions generated via isentropic objective analysis (θ as vertical coordinate) of relevant weather data after quality control and satellite reception reconstruction
- **Other NWP codes can be utilized**

Deep Thunder Testbeds



Visualization for *Deep Thunder*

- **Traditional meteorological visualization is driven by data for analysis -- inappropriate for other applications**
- **Timely usability of cloud-scale NWP results requires**
  - **Understanding of how weather data are used**
  - **Identification of user goals, which are mapped to visualization tasks**
  - **Mapping of data to visualization tasks**
  - **Forecast user has control over content by design or simple interaction**
  - **Non-forecaster has limited control over content (targeted design) and simple interaction**
  - **Products designed in terms relevant for user**
- **Very wide range of capabilities needed**
  - **Line plots to 2d maps to 3d animations**
  - **Assessment, decision support, analysis and communications**
  - **Automated generation of products for web sites**
  - **Highly interactive applications on workstations**

Visualization Issues

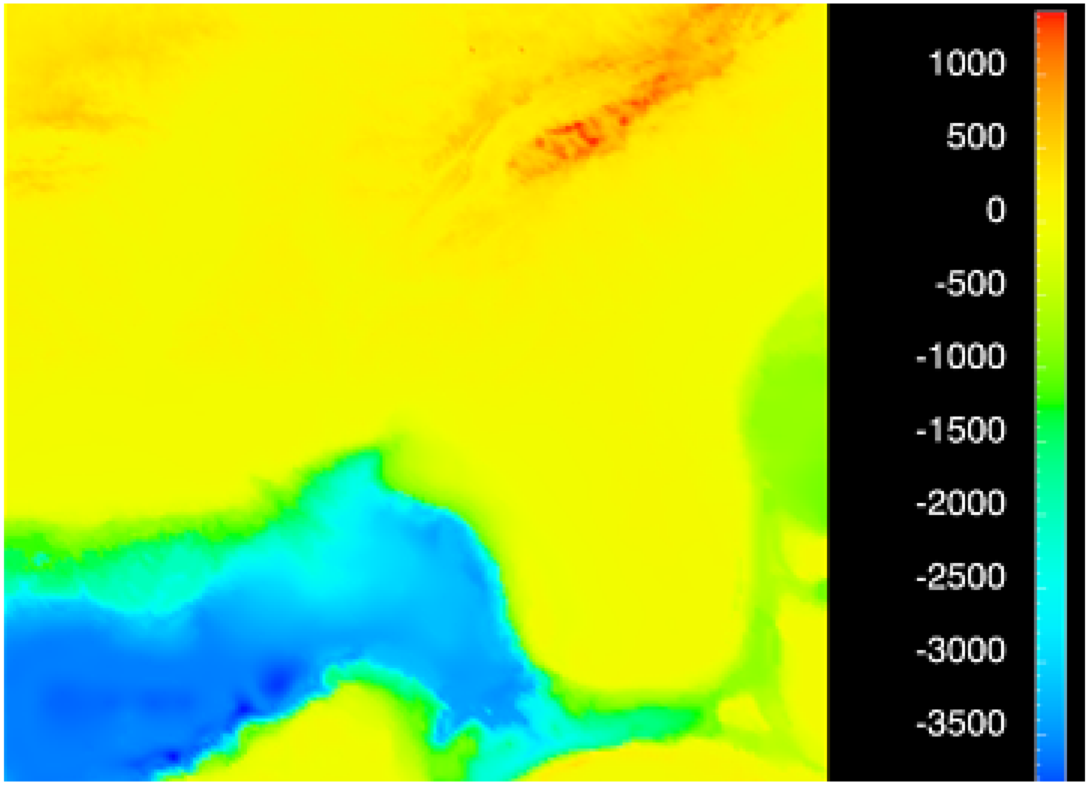
- Other types of visualization require one to
  - Understand how experienced people use their expertise in decision making
  - Enable more effective decisions with economic and societal value
  - Avoid an impedance mismatch between the compelling sophistication of the data vs. how the data should be utilized
- Timely and effective usability of data requires the visualization designer to
  - Use "good" principles of visual design
  - Understand how relevant data are used and why (e.g., human factors concerning how users work and interact)
  - Understand how users perceive and interpret visualizations
  - Design in terms relevant for user, employing familiar terminology and metaphors -- readily understood in real-time without expert interpretation and used with confidence
  - Reflect uncertainty in representation

1. Identification of user needs, goals and tasks
2. Composition of design elements and interface actions

Disciplines Needed for Effective Visual Design

(Understand Limitations in Content and Interpretation)

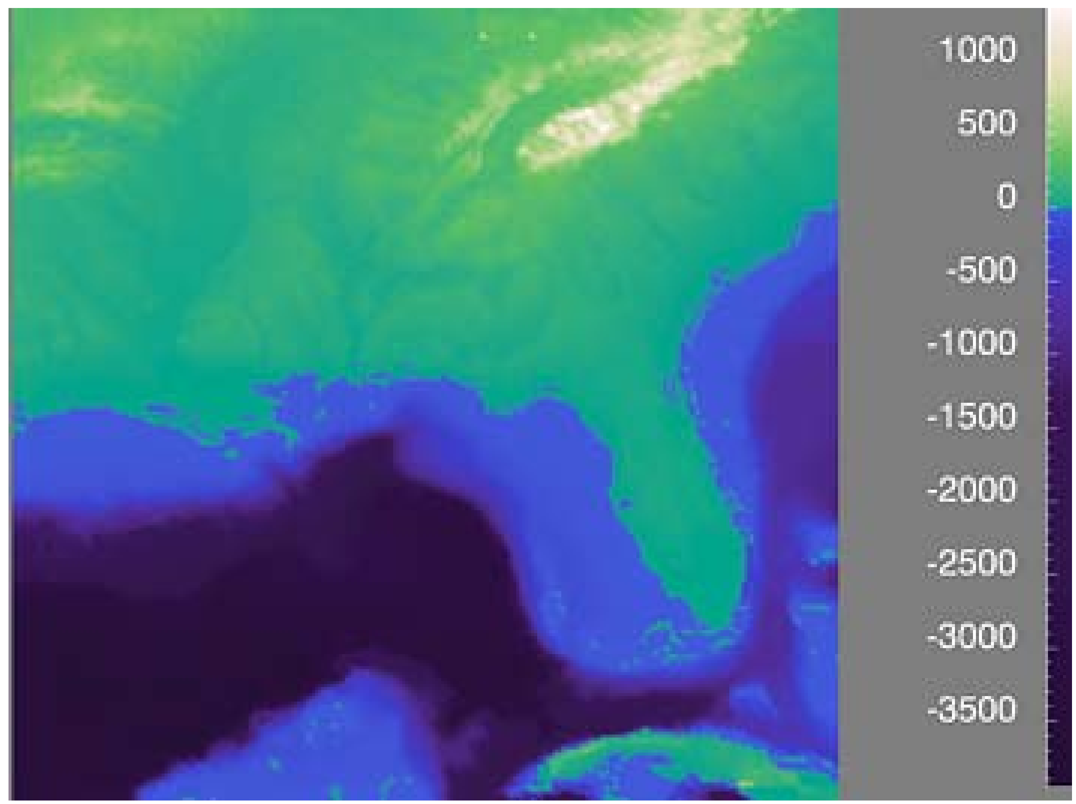
- Meteorology
  - Preserve data fidelity (and science)
- Psychophysics and human vision
  - Perceptual rules for use of color, geometry, texture, etc.
- Cartography
  - Rules for use of projections
- Computer graphics
  - Algorithms for transformation, realization, rendering, etc.
- Workflow and decision-making process



An Example of the Colormap Problem:

Which Picture is Better?

- Visualizations can be easily created today, but process is largely ad hoc
- How data are represented clearly affects interpretation
- Choosing effective strategies implies navigation through a complex design space
- Perceptual rules enable better, faster representations



Visualization Tasks in Meteorology

- ***<u>Class I</u>*: 2d (traditional weather graphics)**
  - Quantitative
  - Users are forecasters
  - Minimal interaction
- ***<u>Class II</u>*: 2d, 2-1/2d Analysis**
  - Quantitative with potentially complex appearance
  - Users are forecasters, but techniques will be new
  - Support data comparison
  - Direct manipulation important
- ***<u>Class III</u>*: 3d Browse**
  - Qualitative with simplified appearance (not necessarily content)
  - Users may or may not be specialists (e.g., forecasters & public)
  - Animation with temporal and spatial coherence important
  - Event identification for potential later analysis
- ***<u>Class IV</u>*: 3d Analysis**
  - Quantitative with potentially complex appearance
  - Users are forecasters, but techniques will be new
  - Support limited data comparison
  - Direct manipulation important

An Example Visualization Task -- Decision Support

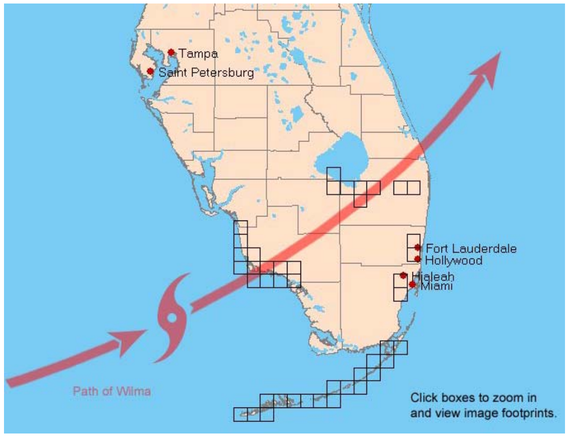
- Enable proactive decision making affected by weather
  - Rapid assessment important (visualizations may need to be almost pre-attentive) -- threshold vs. content
  - Users are not meteorologists, but should understand the impact of specific weather events
- Understand cognitive process by which skilled decision makers build a (visual) mental model in order to create effective designs
  - Understanding of how users perceive and interpret visualizations
- Customized appearance by data and geography and fusion with ancillary data
- Presentation of derived properties critical to decisions
  - Weather or secondary physical phenomena (e.g., flooding) may not be shown
  - Relevant operational problems (e.g., crew and equipment optimization [scheduling and routing] that is impacted by environmental factors)
  - Readily understood in real-time without expert interpretation and used with confidence

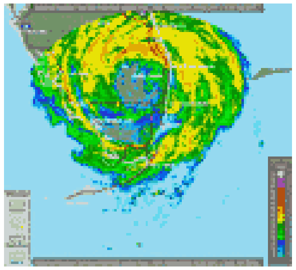
Application Case Studies

- **Meteorology: broad scale to local scale events**
  - How should the model results be evaluated?
- **Business impact: generic to specific**
  - What is the value of the forecast information?
- **Rather than monitor a storm, stage resources at the right place and time prior to the event to minimize the impact (i.e., plan not react)**
- **Example issues to consider for an electric utility:**
  - Predict specific events or combination of weather conditions that can disrupt the electrical distribution network of overhead lines with sufficient precision and lead time to enable proactive allocation and deployment of resources to minimize time to repair
  - Implement as a service tailored for the geographic, throughput and dissemination requirements of the client
  - Predict conditions that can lead to outages and their characteristics, thus allowing utility to proactively plan repairs

Hurricane Wilma -- Southern Florida: 24 October 2005

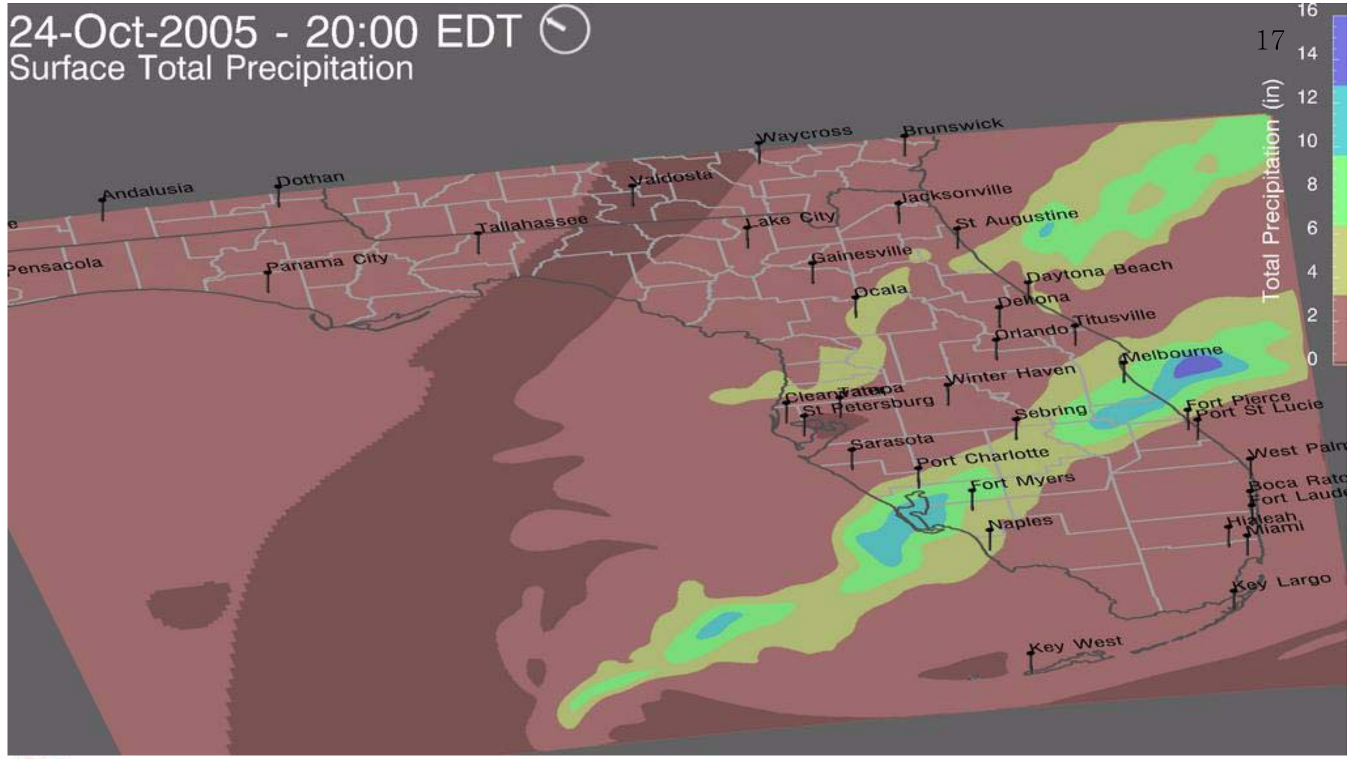
- Classic October Category 3 hurricane made landfall shortly before 0700 EDT between Everglades City and Cape Romano
- Moved rapidly northeast across the state, with an average forward speed of 25 mph, exited the east coast over northeastern Palm Beach County around 1100 EDT as Category 2 hurricane
- Exhibited a very large 55 to 65 mile-wide eye while crossing the state



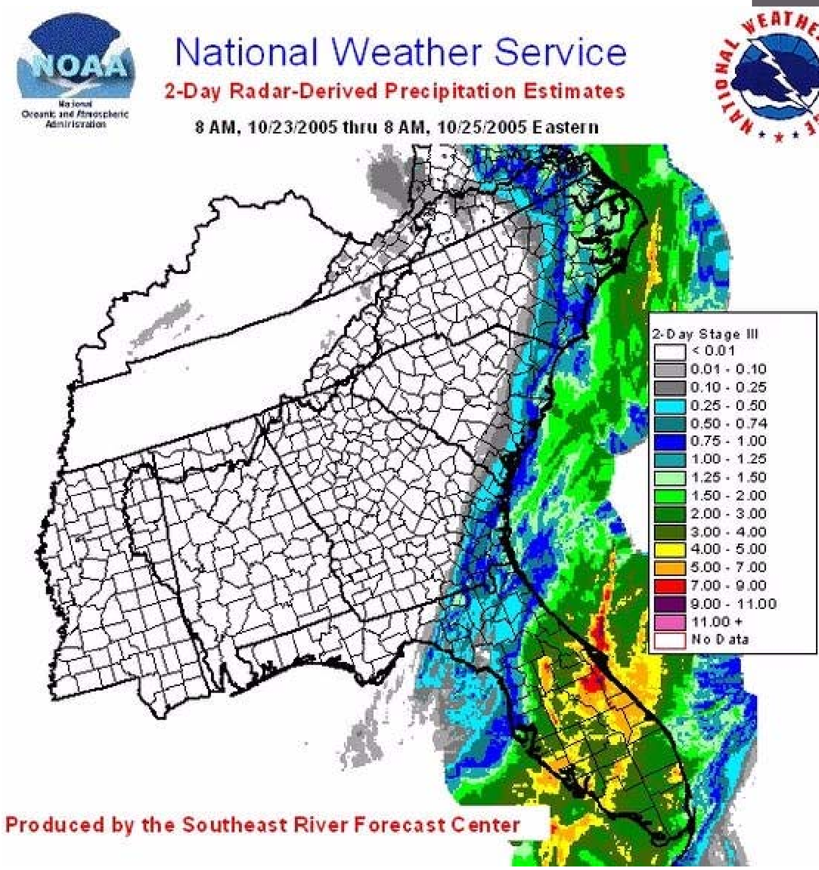


- Maximum reported sustained winds of 103 mph, although urban areas reported 66 to 85 mph with gusts from 90 to 104 mph
- Rainfall amounts ranged from 2" - 4" across southern Florida to 4" - 6" near Lake Okeechobee, with isolated amounts of up to 6" - 8"
- Damage was widespread, with large trees and power lines down virtually everywhere, causing over 3 million customers to lose power
- Structural damage was heaviest in Broward and Palm Beach counties where roof damage and downed or split power poles were common
- High-rise buildings suffered considerable damage, mainly in the form of broken windows

Deep Thunder Prediction of Hurricane Wilma: 24 October 2005



***Deep Thunder* Predicted Rainfall Totals (4 km Nest)**

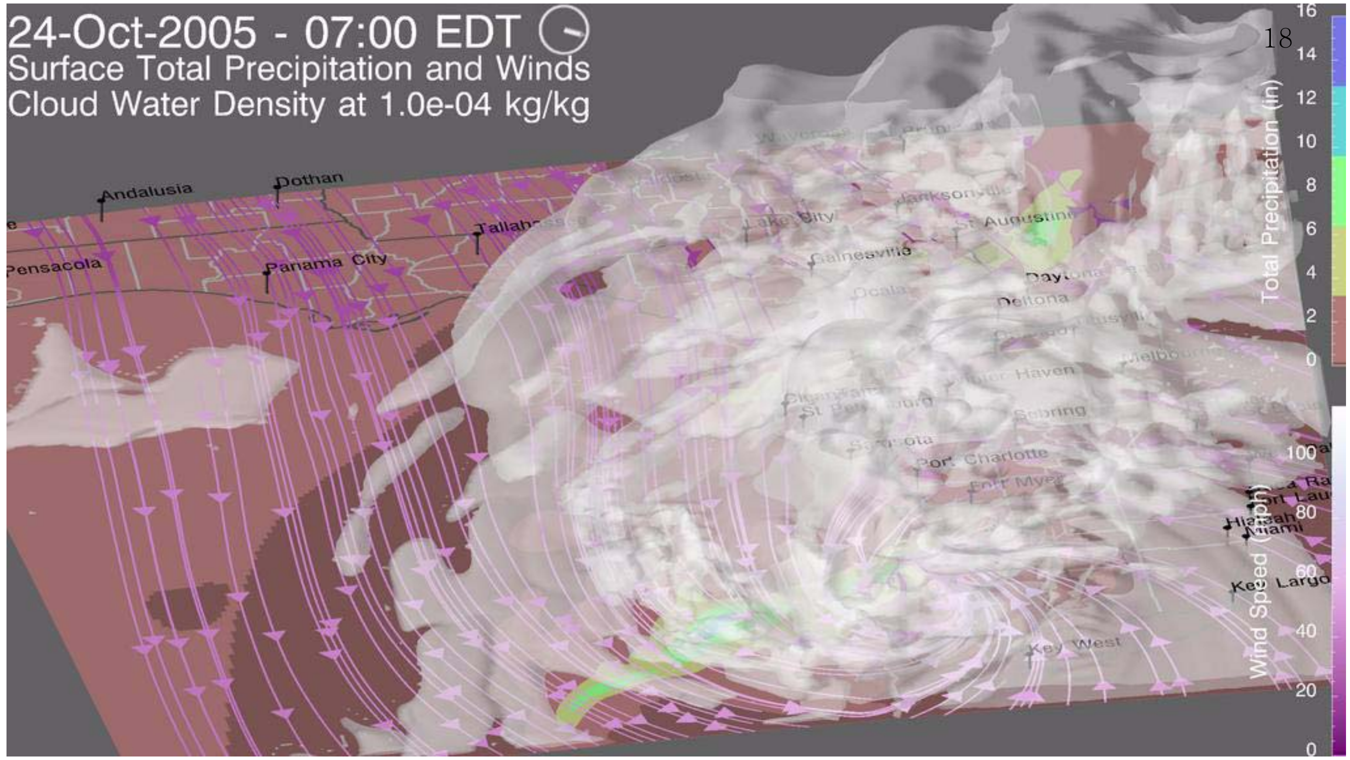


Estimated Rainfall Totals from Radar

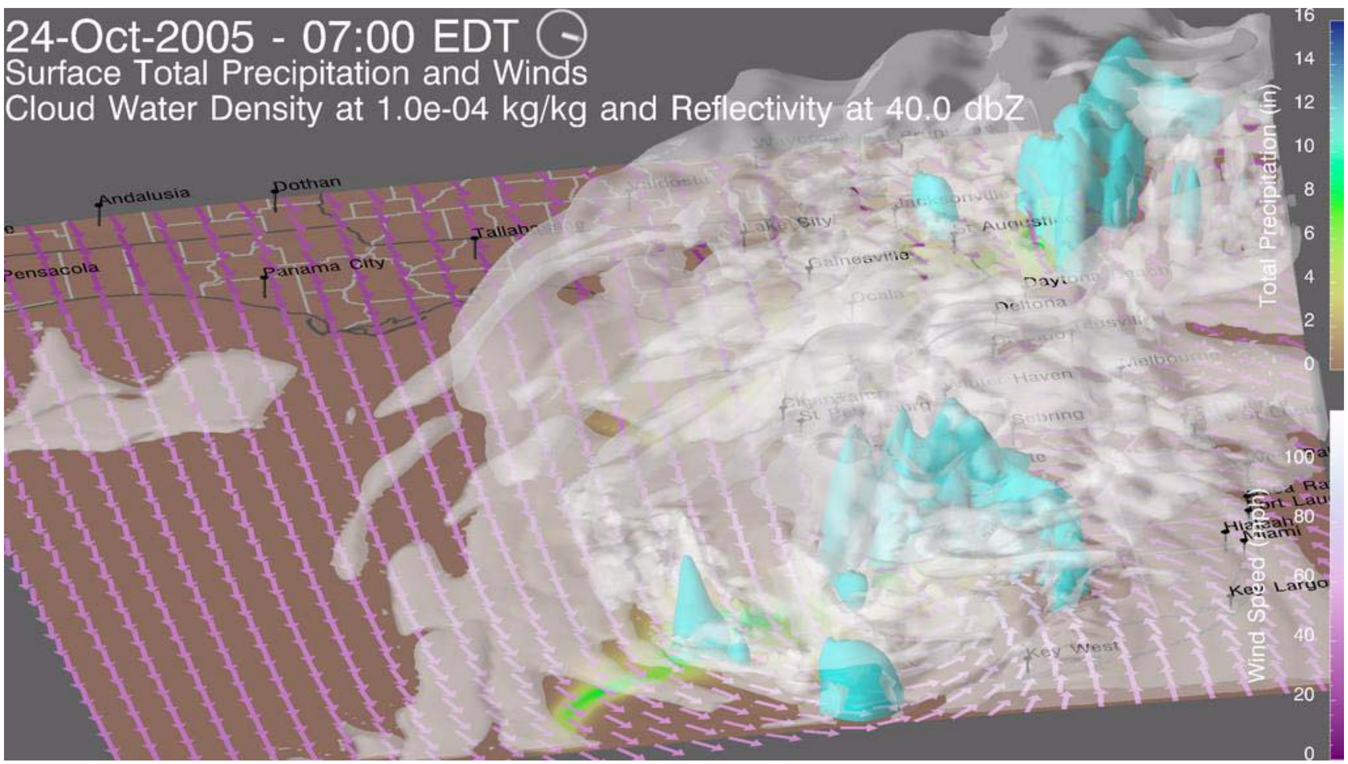
- **Initiated with data from 2000 EDT, 23 October**
- **Heavy rainfall predicted with similar distribution to reported rainfall, although a positive bias in some locations**
- **Predicted track biased to the northwest, but better than the nested southern Florida domain**

Deep Thunder Prediction of Hurricane Wilma: 24 October 2005

- Experimental hindcast with 12 and 4 km nests with 4 km coverage for all of Florida
- Forecast initiated with data from 2000 EDT, 23 October



Visualization of Hurricane Vortex and Clouds

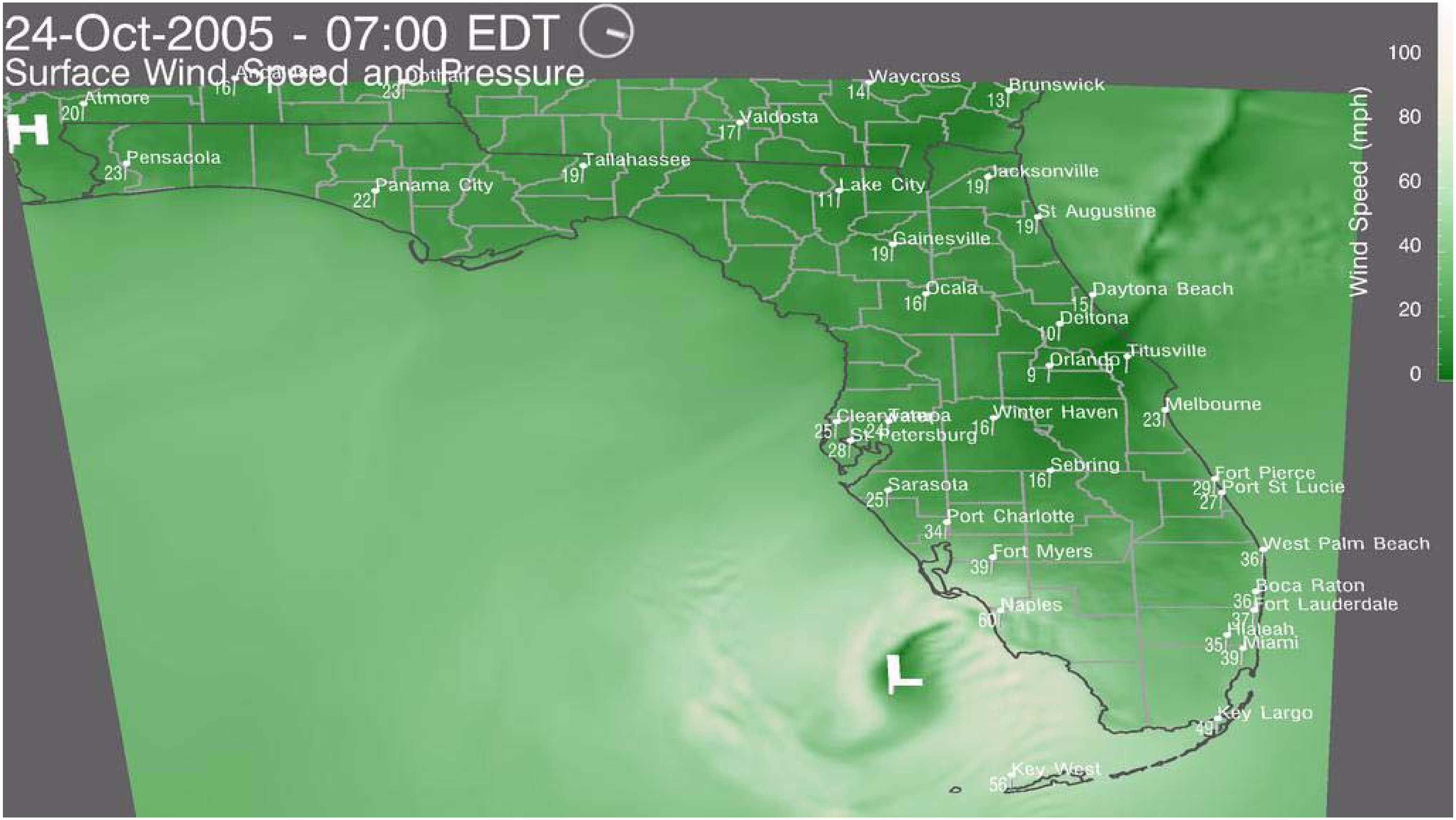


- Heavy rainfall predicted with similar distribution to reported rainfall, although a positive bias in some locations
- Predicted track biased to the northwest, but better than the southern Florida domain

Visualization of Rain Bands, Wind and Precipitation

Deep Thunder Prediction of Hurricane Wilma: 24 October 2005

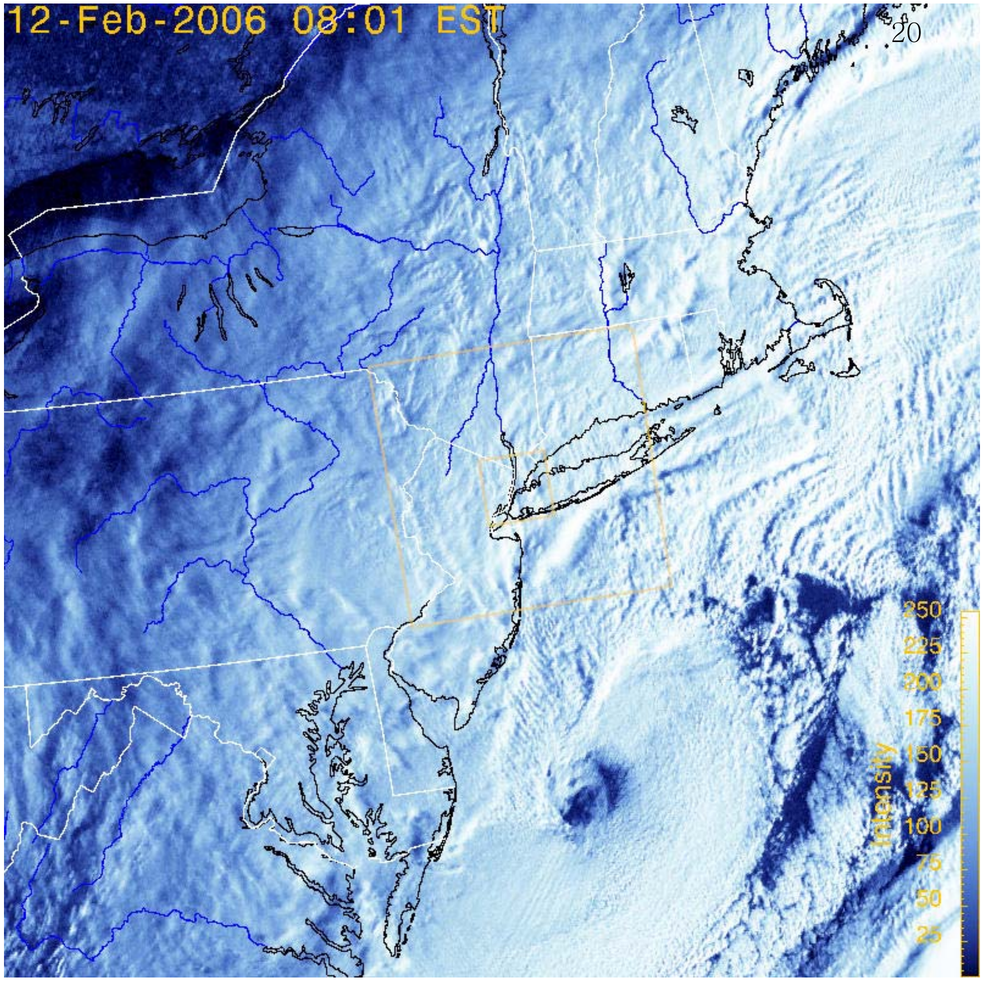
- **Experimental hindcast with 12 and 4 km nests with 4 km coverage for all of Florida**
- **Forecast initiated with data from 2000 EDT, 23 October**

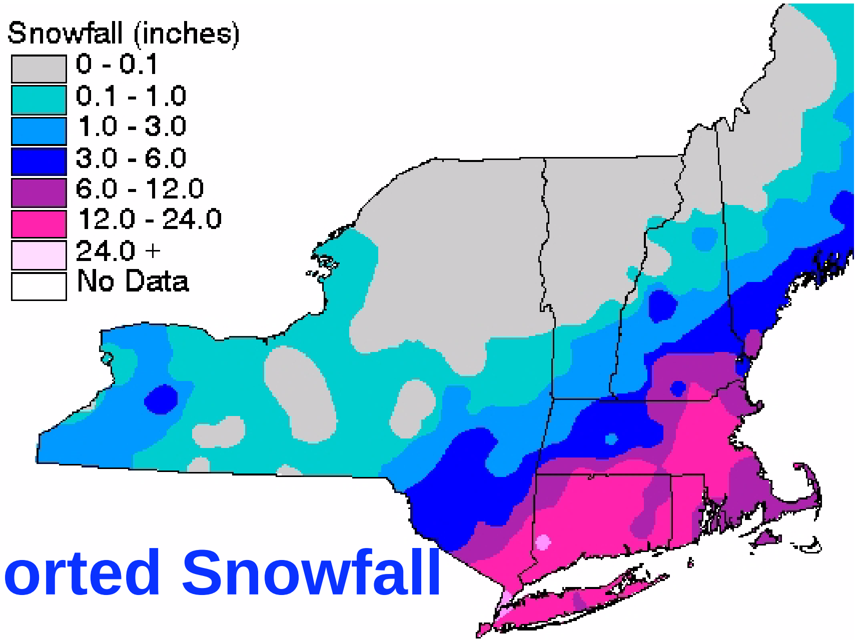


Visualization of Winds and Hurricane Eye

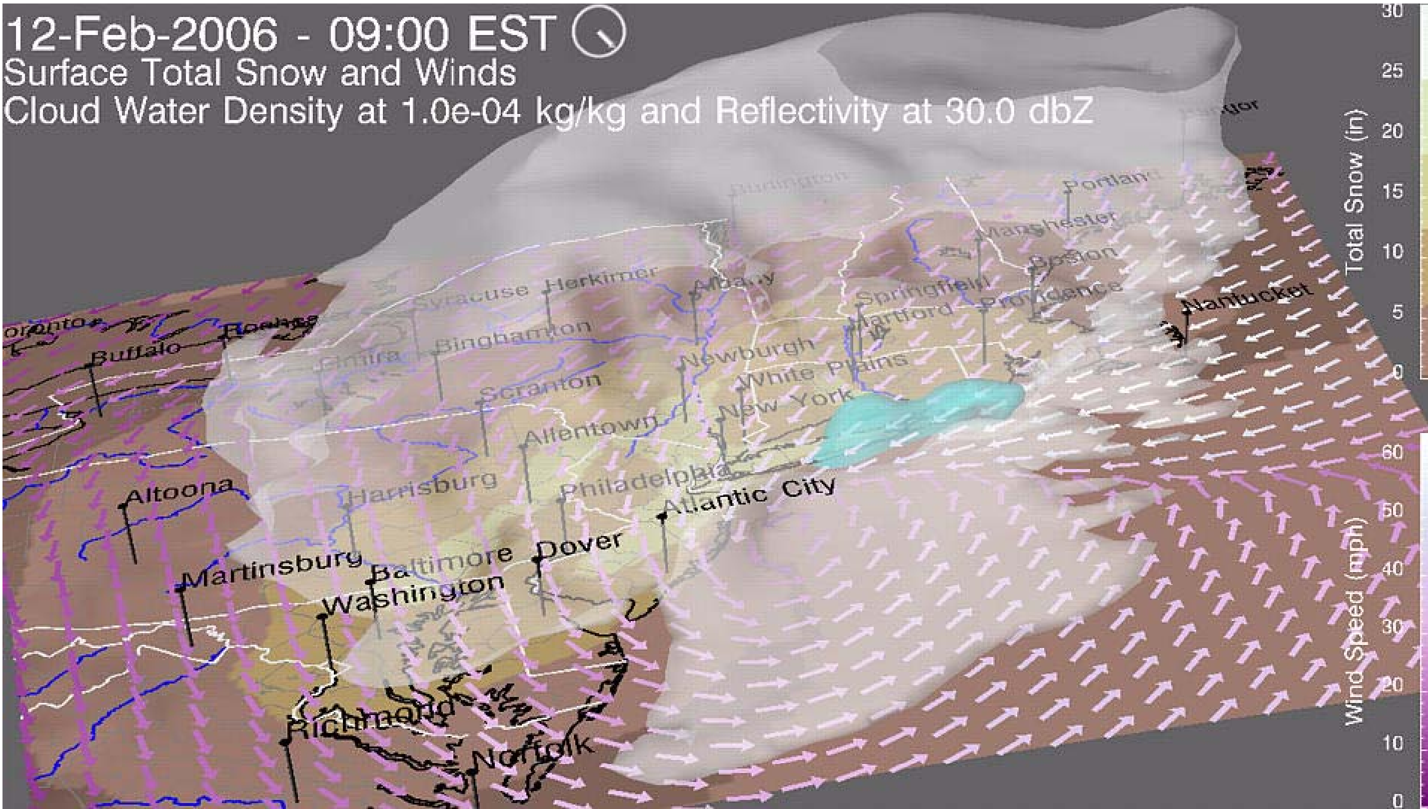
12 February 2006 "Blizzard"

- **The biggest winter storm in New York City history (26.9" in Central Park)**
- **Classic nor'easter of unusual intensity, which affected the coastal regions from North Carolina to Maine**
- **Snow was widespread and heavy, falling at rates up to 3 to 5 inches per hour**
- **15-mile-wide mesoscale band passed directly over Midtown Manhattan, the southeastern Bronx and northwestern Queens (thunder and lightning)**
- **Transportation systems were widely disrupted throughout the area**
- **Negligible impact on electric utilities in the region**





Reported Snowfall



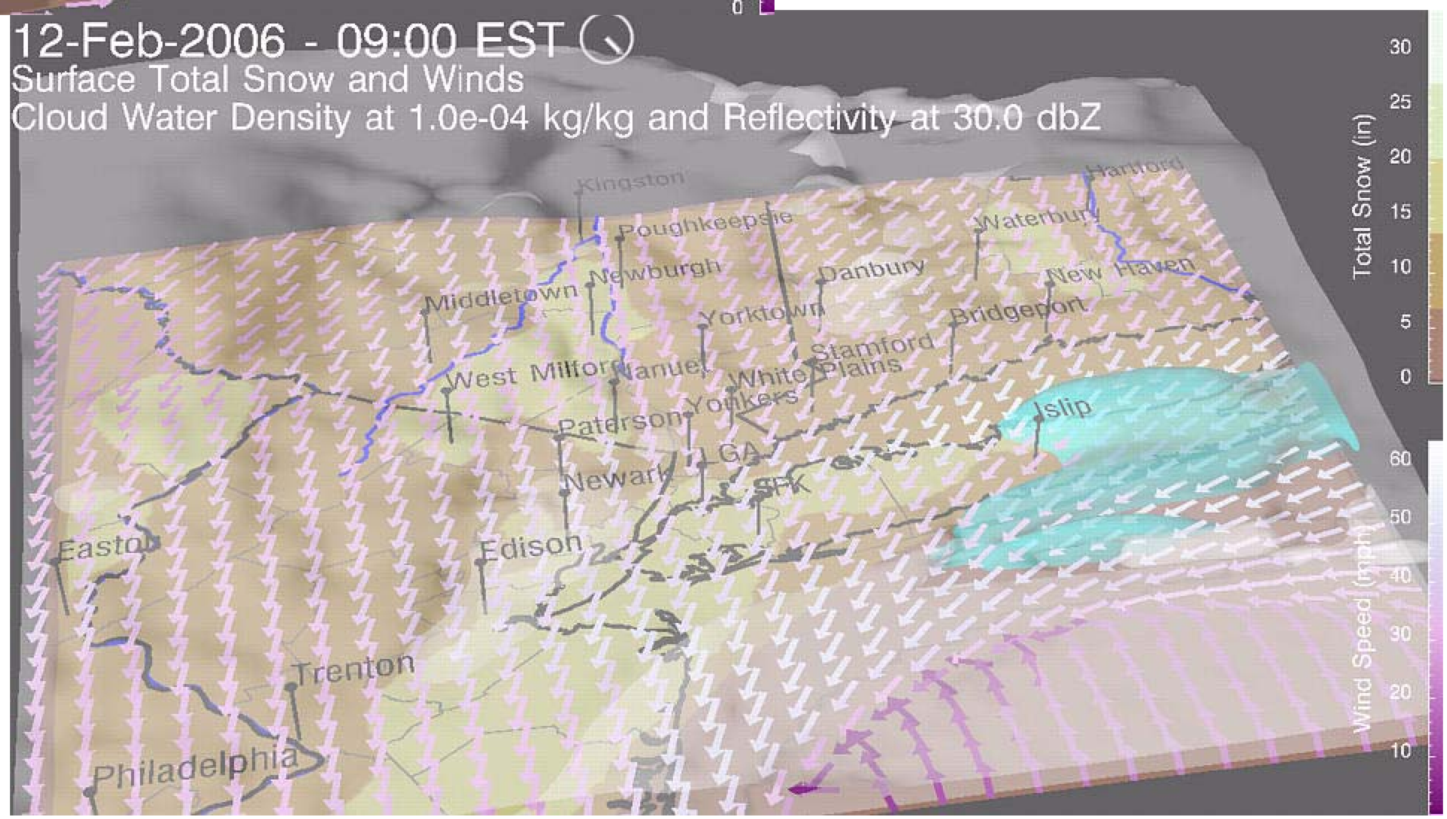
12 February 2006 "Blizzard"

Deep Thunder Forecast

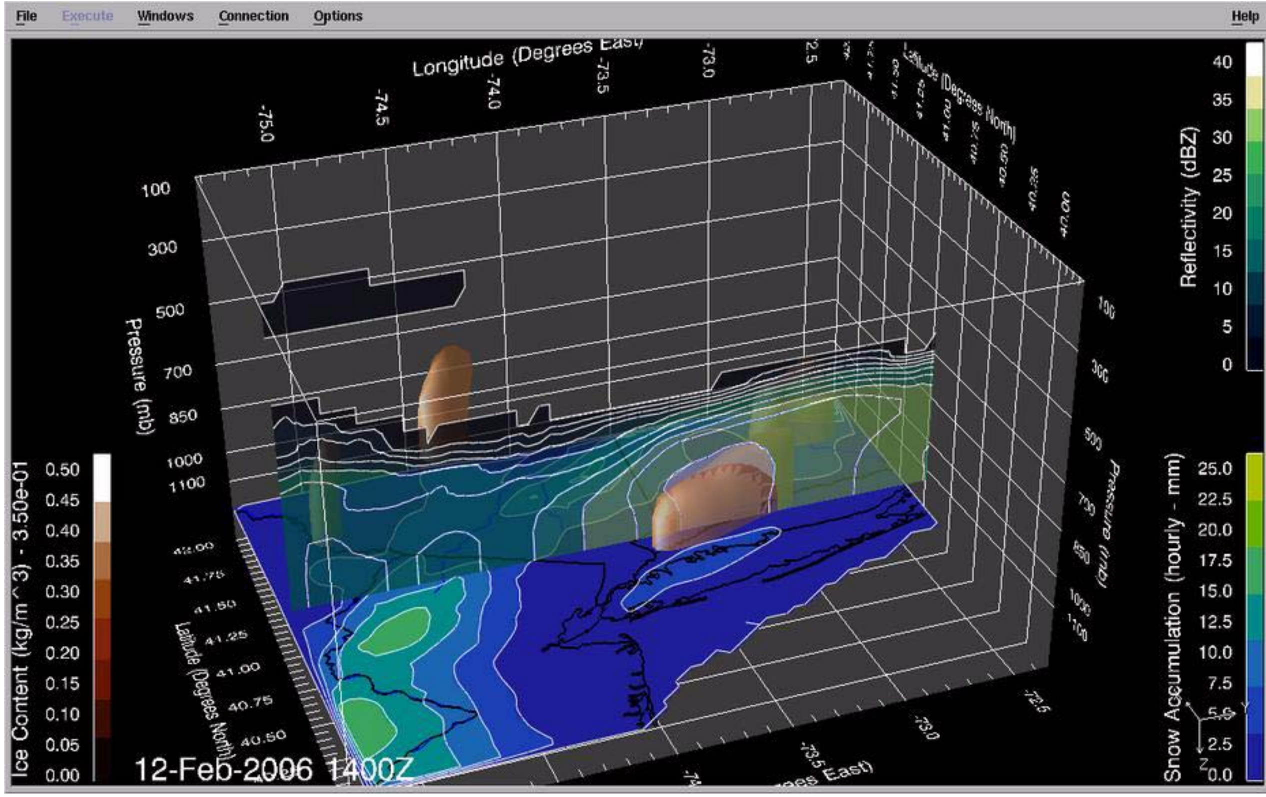
Initiated with data from 1900 EST on 2/11 with results available before midnight on 2/12.

16 km

- **Good agreement in snow totals, geographic distribution, and start and stop times**
- **Showed some aspects of the mesoscale banding**
- **Snow in some areas did start before 1900 EST, which was covered in an earlier forecast**

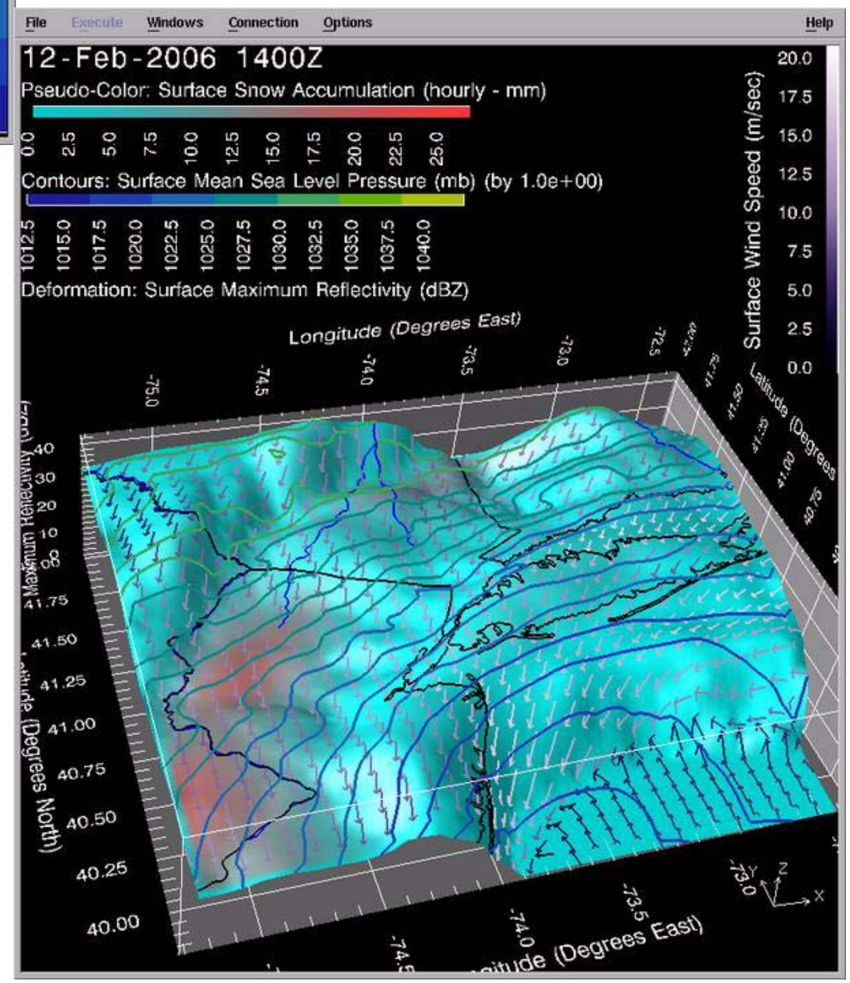


4 km



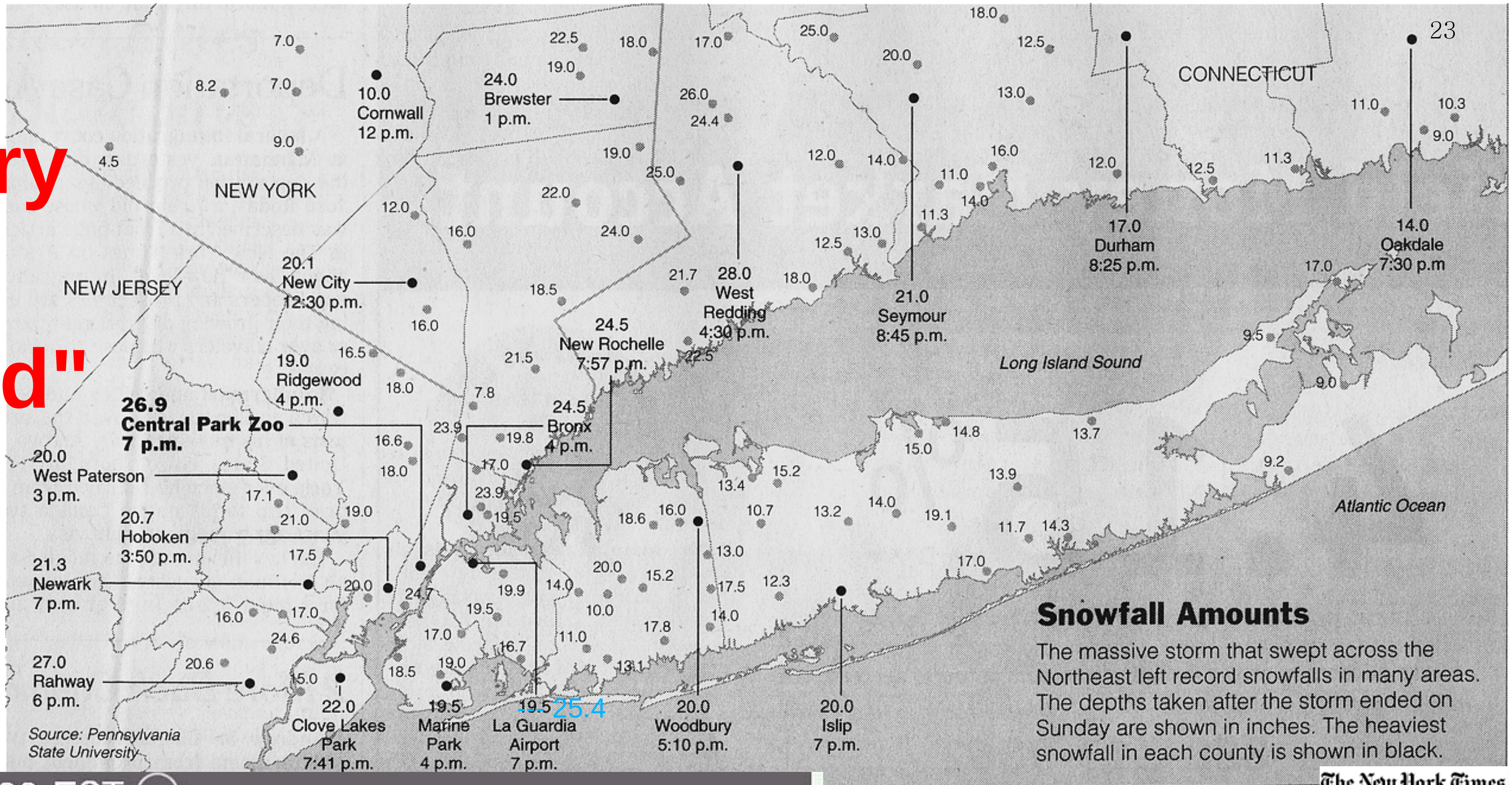
12 February 2006 "Blizzard"

Deep Thunder Forecast

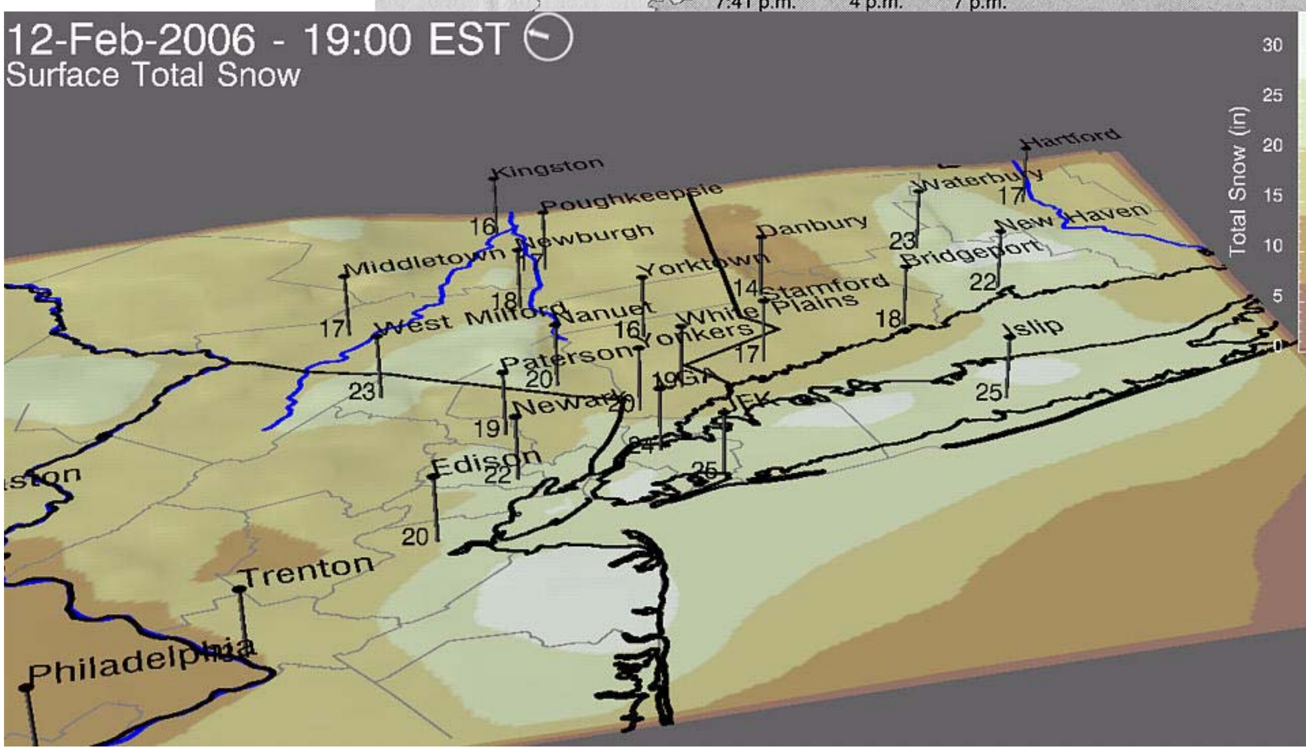


- **More detailed look at forecast of mesoscale band in 4km nest**
- **Both visualizations show hourly snow accumulation as a background field in color**
- **Top illustrates vertical reflectivity slice with 3d surface of ice content at .35 kg/m^3 (light brown)**
- **Right shows mean sea level pressure contours with surface winds and reflectivity**

12 February 2006 "Blizzard"



Reported Snowfall



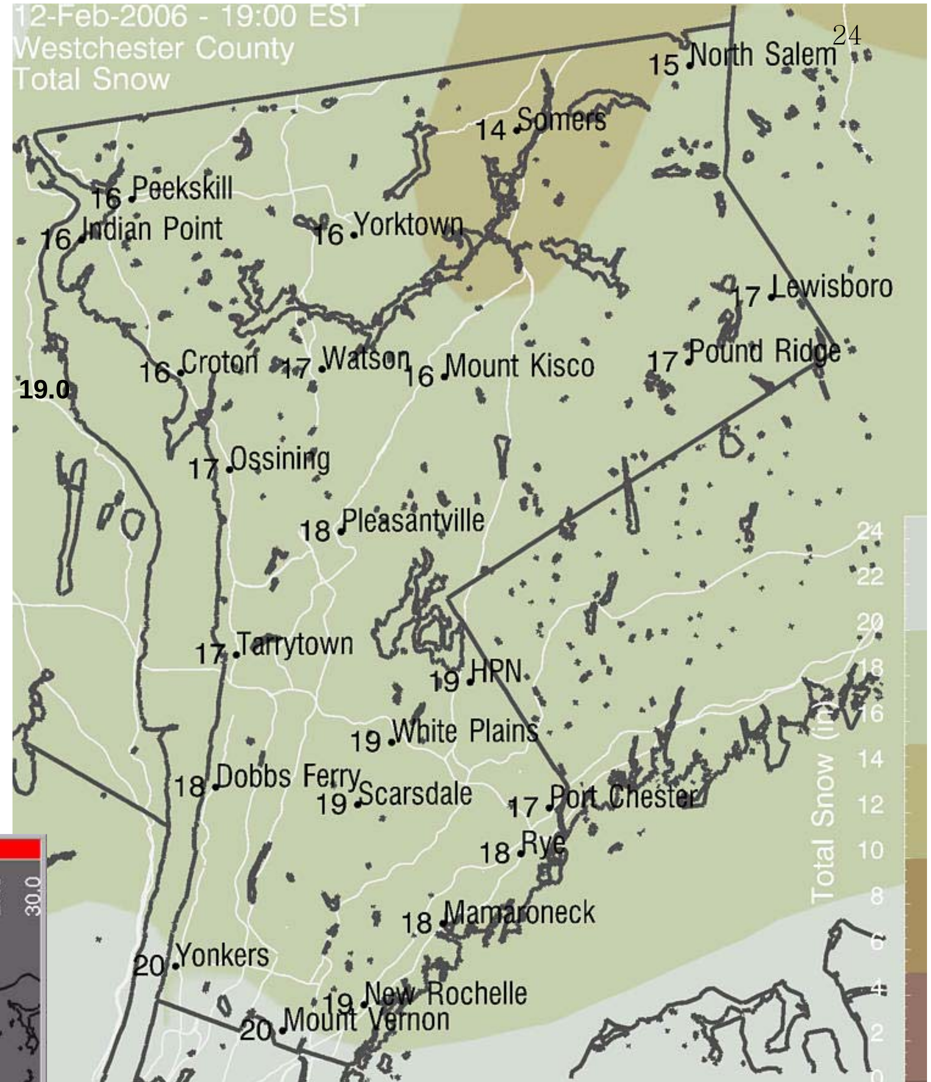
4 km

Deep Thunder Forecast

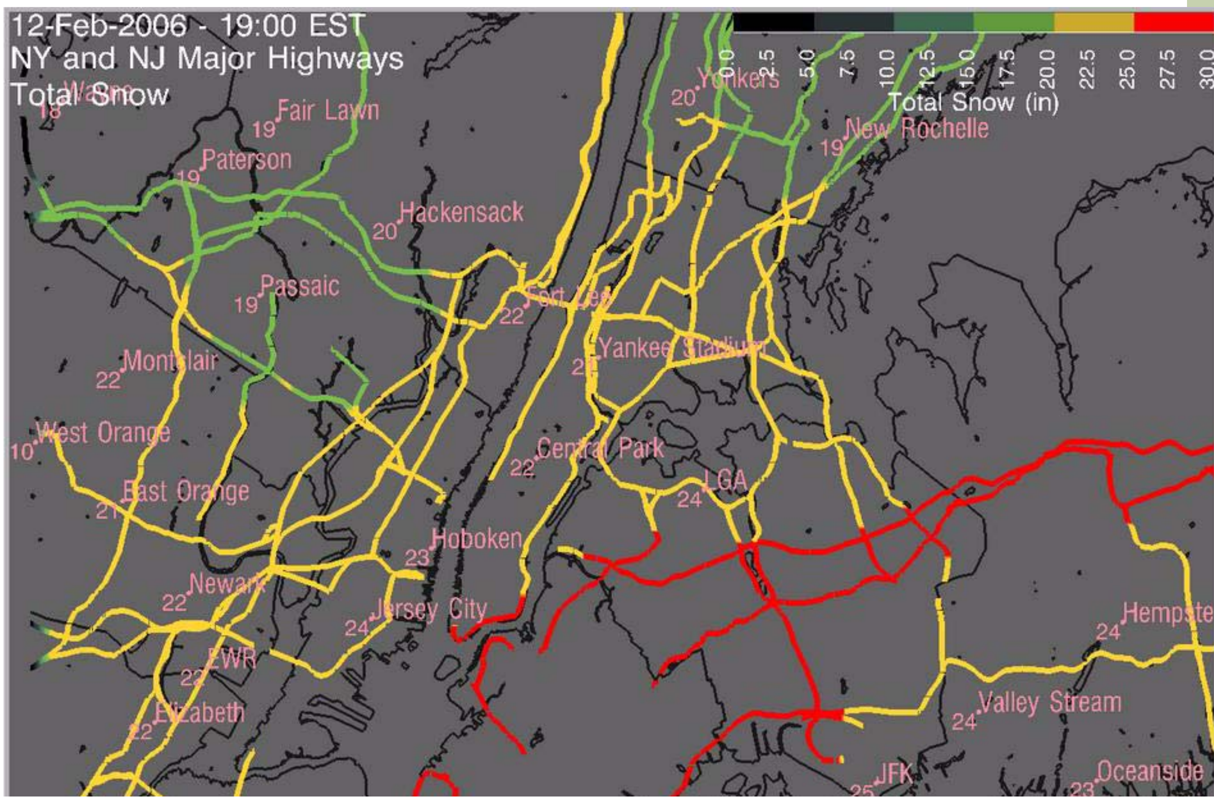
12 February 2006 "Blizzard"

Reported Snowfall (Inches)

BRONX	24.5	FLATLANDS	19.0	NORTH SALEM	19.0
PARKCHESTER	20.4	MIDWOOD	18.7	ARMONK	18.5
WOODLAWN	17.0	SUNSET PARK	18.5	CROTON	16.0
COLUMBIA U.	27.0	NEW ROCHELLE	24.5	MONTCLAIR	21.8
CENTRAL PARK	26.9	POUND RIDGE	24.0	WEST ORANGE	21.0
CHINATOWN	24.7	YONKERS	23.9	NEWARK	20.7
ASTORIA	26.0	EASTCHESTER	23.2	SOUTH ORANGE	18.0
LGA	25.4	KATONAH	22.0	WEST CALDWELL	17.6
FLUSHING	19.9	WHITE PLAINS	21.5	BELLEVILLE	17.4
RICHMOND HILL	19.5	RYE BROOK	20.0	CEDAR GROVE	17.1
FAR ROCKAWAY	17.5	BRONXVILLE	19.8	HOBOKEN	20.7
JFK	16.7	MOUNT KISCO	19.5	JERSEY CITY	20.0
				HARRISON	17.5



4 km

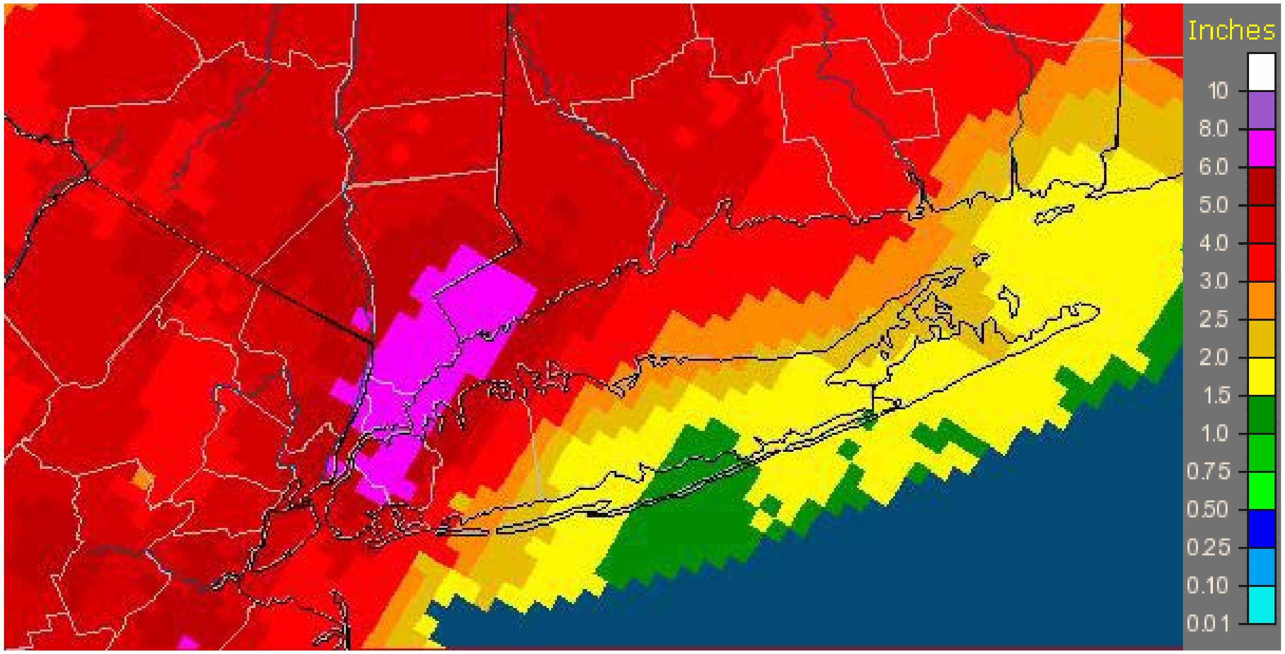


1 km

Deep Thunder Forecast

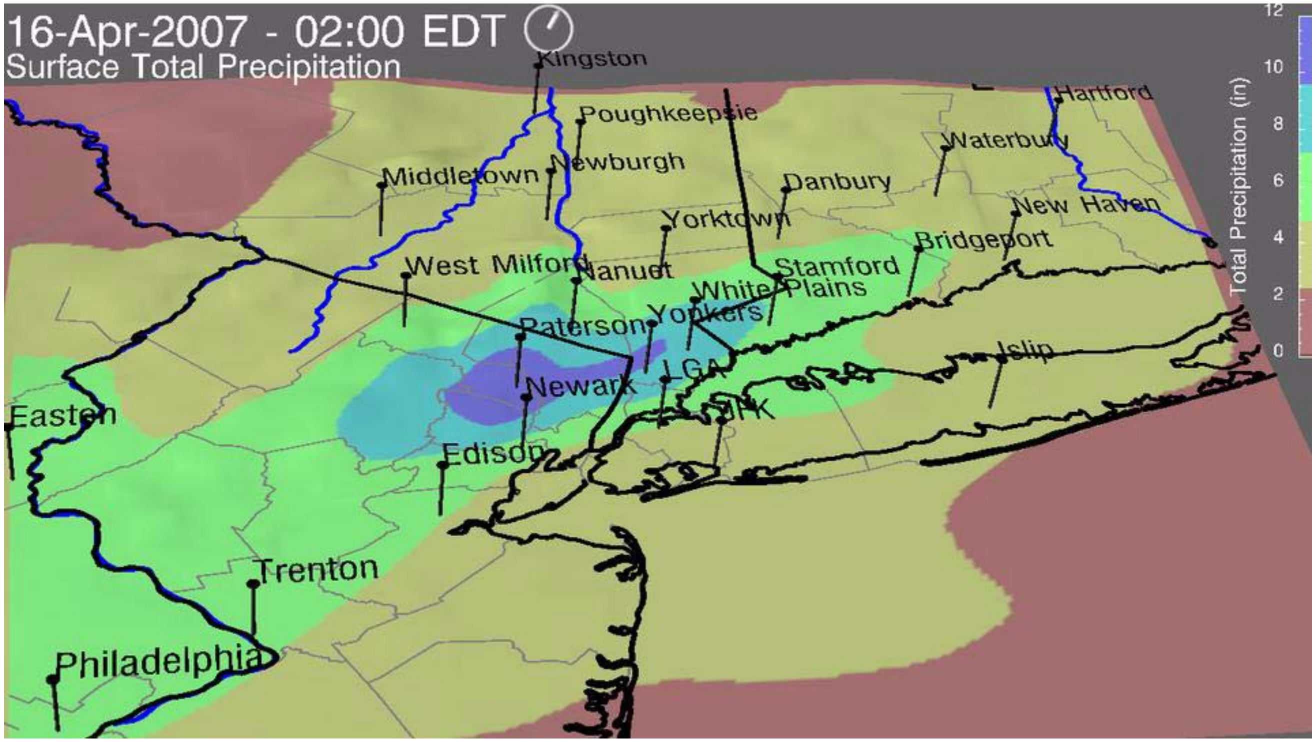
NYC Metropolitan Area Record Rainfall Nor'easter -- 15-16 April 2007

- **A rare spring northeaster masquerading as a classic winter storm roared up the coast and across the New York region and the Northeast**
- **The heaviest rainfall occurred in an area stretching from northeastern New Jersey through central Westchester County, NY with amounts in excess of 9" in some areas**
- **There was widespread disruption of transportation systems (e.g., road closures, airport delays) and power, and significant flooding in several regions**
- **Although the potential for flooding was noted by the NWS up to a couple of days before the event, flood warnings were issued at 0820 EDT, 15 April**
- **Early morning 15 April NWS forecasts indicated potential for 2-4 inches of rainfall with the likelihood of flooding of urban areas**

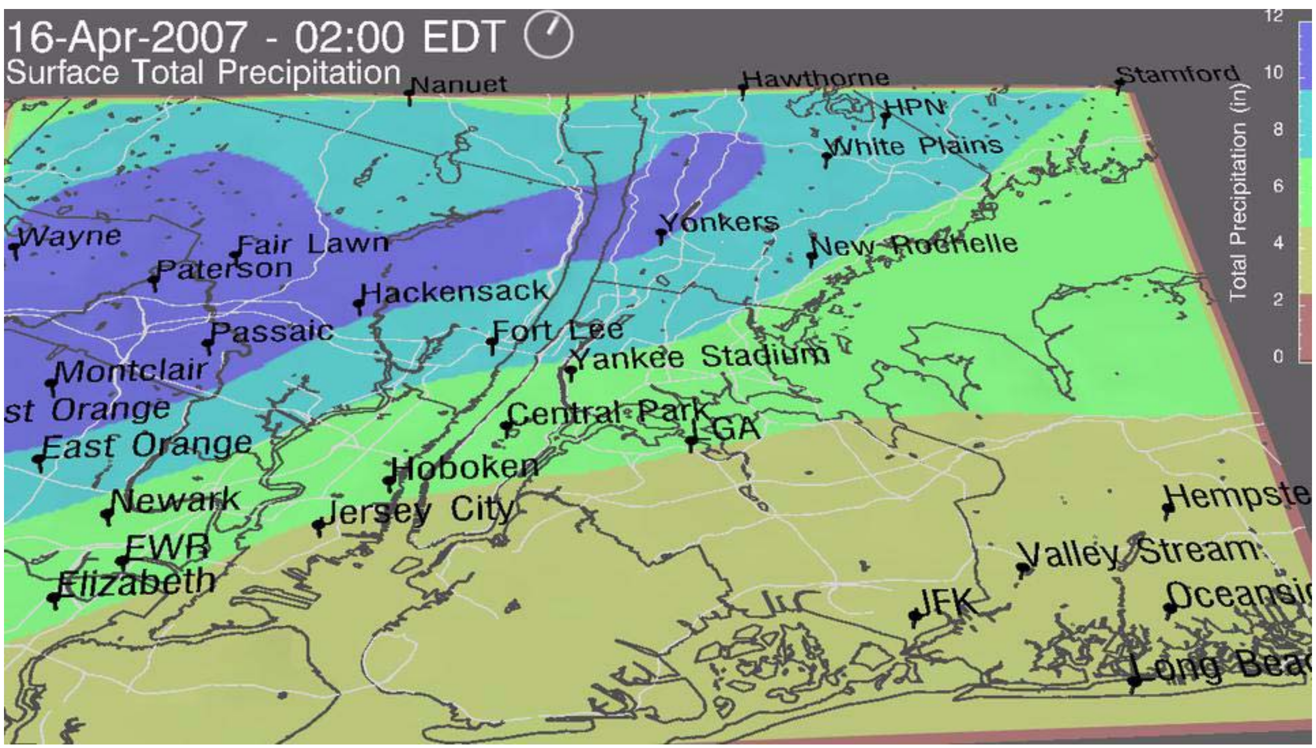


Estimated Rainfall from NOAA: 15 April 2007 0800 EDT through 16 April 2007 0800 EDT

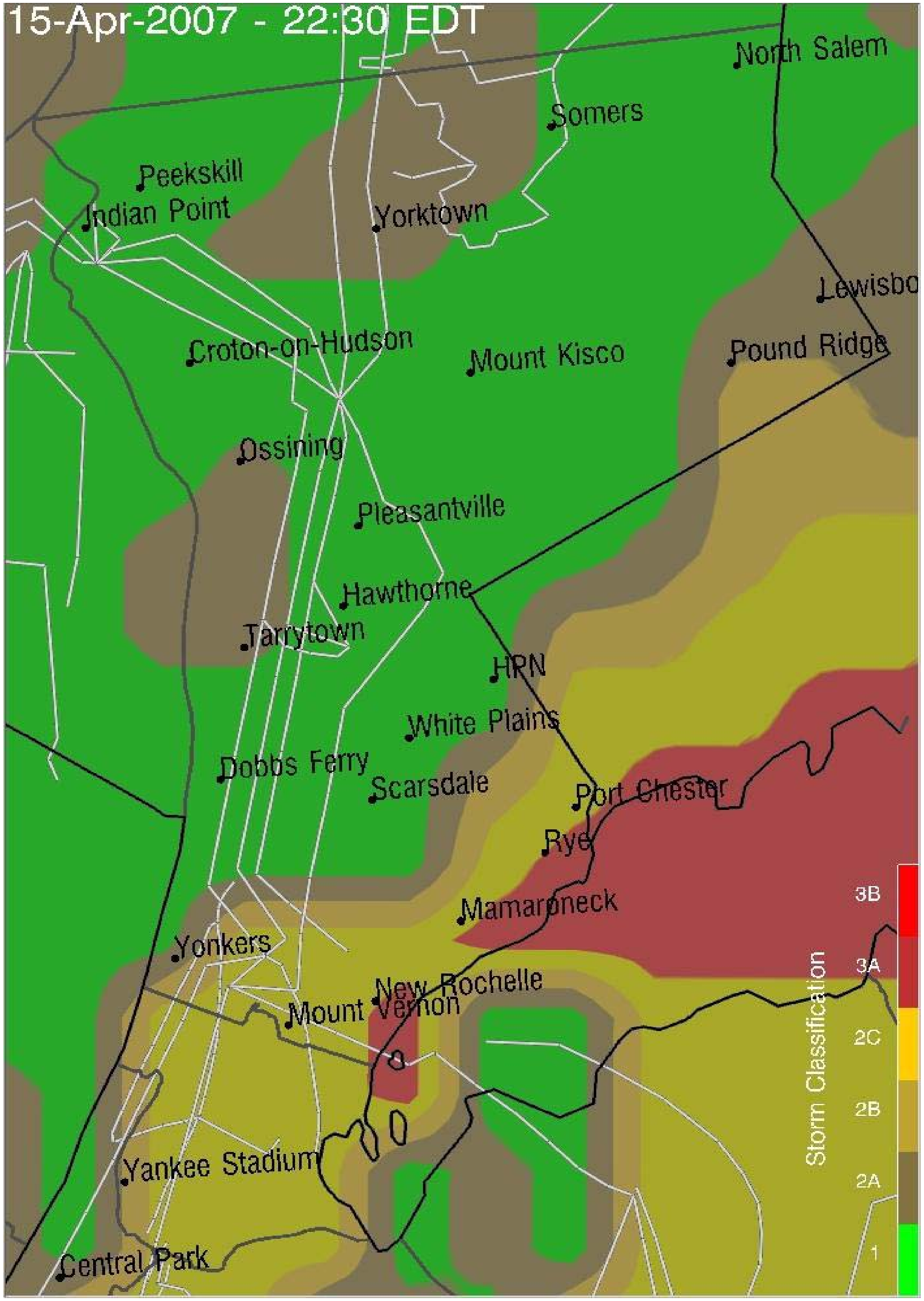
Forecast Results 15 April 2007 Early Morning



Deep Thunder **rainfall totals 4 km nest (above) and 1 km nest (below) through 24 hours**



- **Heavy rainfall predicted all day with similar distribution to reported rainfall, although some differences in totals**
- **Forecast initiated with data from 0200 EDT with results available about 0615 EDT**
- **Significant "heads-up" for event**



Forecast Results 15 April 2007 Storm Classification

- **Upgraded (e.g., thunderstorms)**
- **2A. Serious (e.g., heavy thunderstorms)**
- **2B. Serious**
- **2C. Serious**
- **3A. Full Scale (e.g., severe storm)**
- **3B. Full Scale (e.g., hurricane)**

18 January 2006 Windstorm

- **Strong cold front led to a significant wind event along with heavy rains due to a deep upper air trough with a low pressure system**
- **Gusting between 40 and 70 mph observed from 0600 to 1000 EST**
- **Innumerable downed trees and power lines**

Location	Maximum Wind Speed (mph)	Time (EST)
Central Park	41	0828
LGA	56	0729
JFK	51	0853
White Plains	57	0853
Mount Vernon	64	0749
Yonkers	57	0749
Larchmont	70	0842

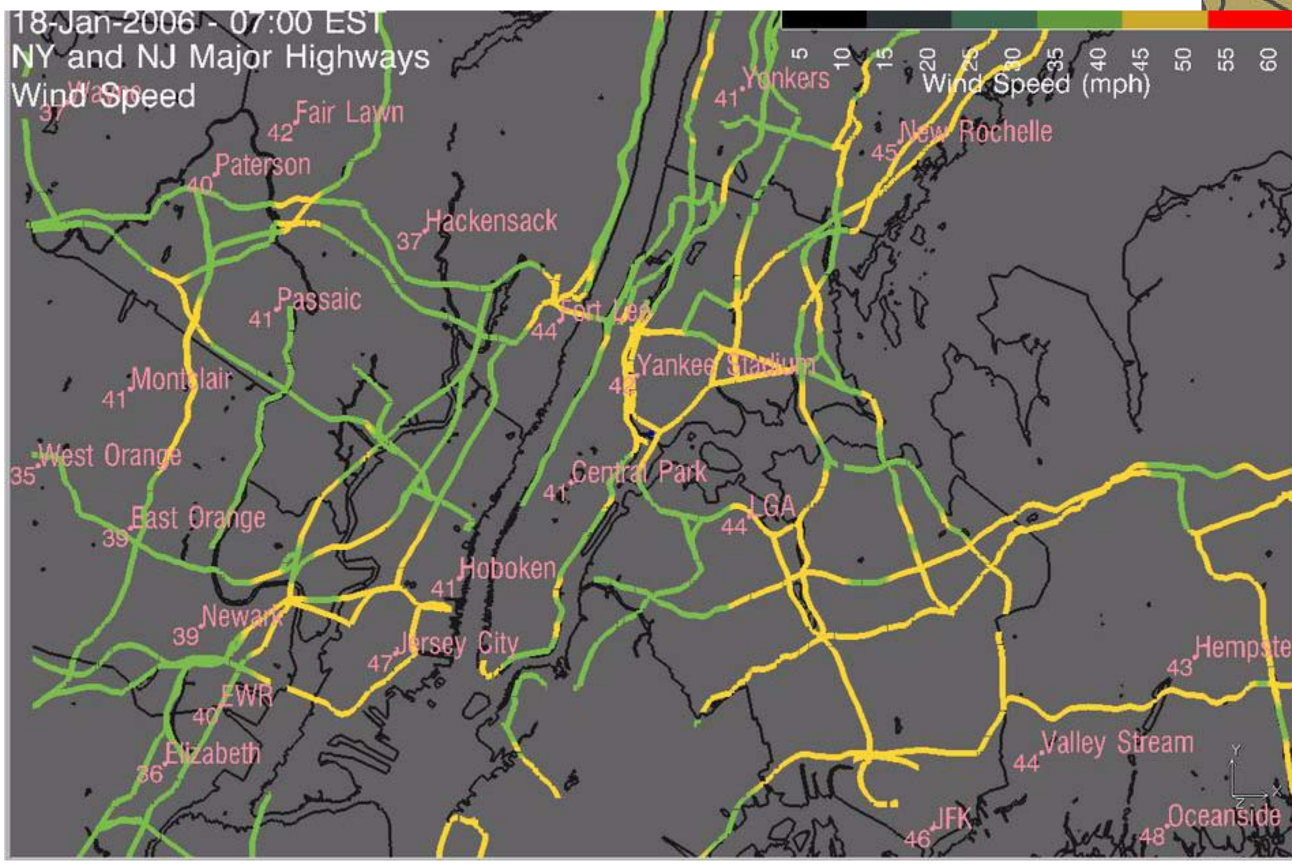
- **Electricity service was disrupted to over 250,000 residences and businesses in the New York City suburbs**
- **Widespread disruption of transportation systems (e.g., road and bridge closures, airport delays) and some local flooding**
- **Wind advisories issued (gusts to 45 mph) at 1600 EST**
- **High wind warning issued (gusts to 60 mph) at 0300 EST, 18 January**

18 January 2006 Windstorm

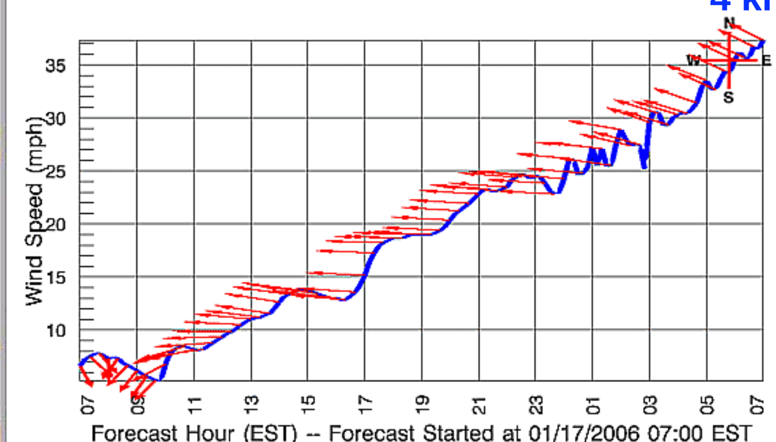
Deep Thunder Forecast

Initiated with data from 0700 EST on 1/17
with results available late morning on 1/17.

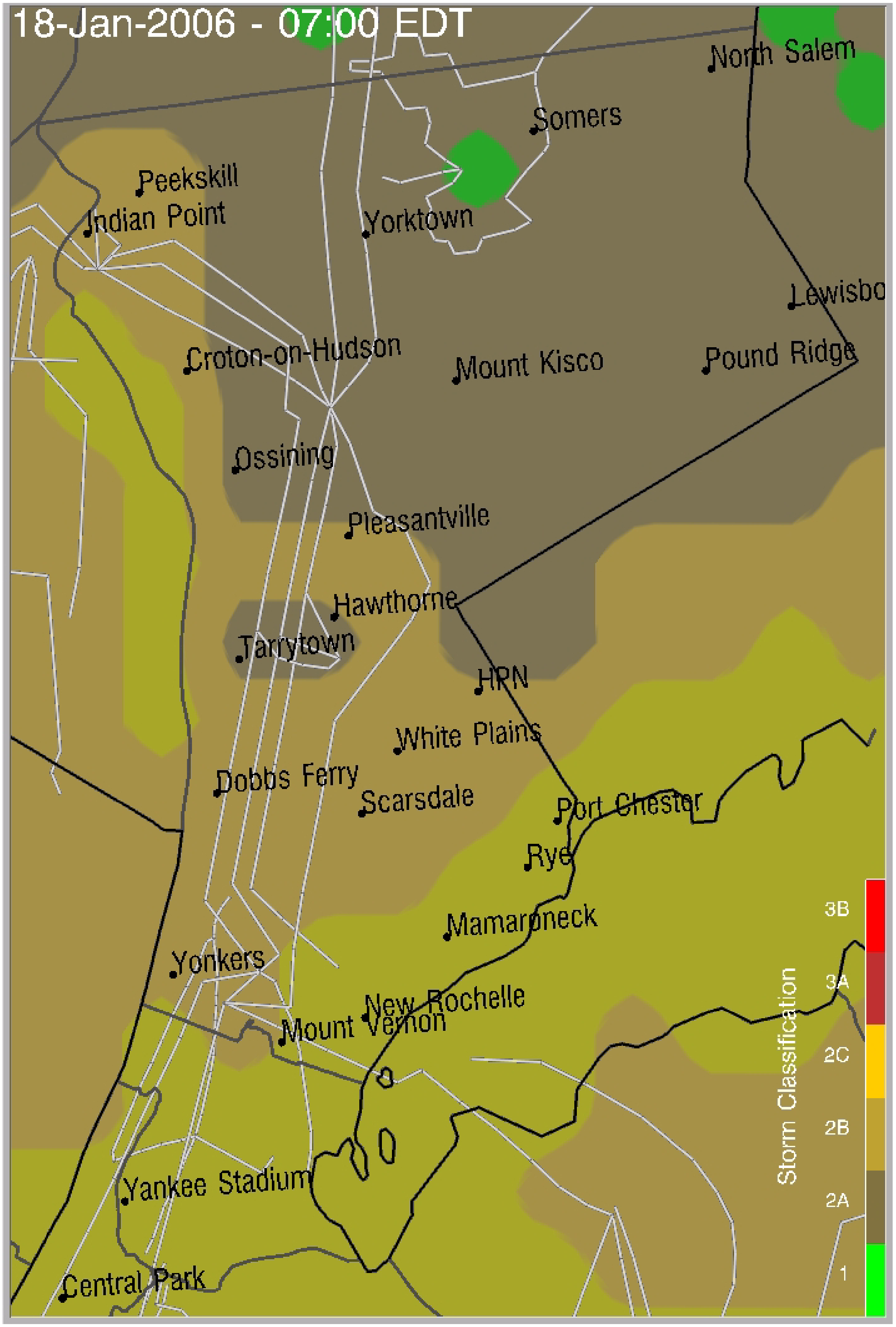
High winds shown in forecast available 18 hours ahead of event



4 km



1 km **White Plains Airport**



Forecast Results 18 January 2006 Storm Classification

- **Upgraded (e.g., thunderstorms)**
- **2A. Serious (e.g., heavy thunderstorms)**
- **2B. Serious**
- **2C. Serious**
- **3A. Full Scale (e.g., severe storm)**
- **3B. Full Scale (e.g., hurricane)**

Storm Impact and Response Prediction

- **Weather causes damage and outages**
- **Outages require restoration (resources)**
- **Restoration takes time, people, etc.**
- **Build stochastic model from weather observations, storm damage and related data**
  - **Outage location, timing and response**
  - **Wind, rain, lightning and duration**
  - **Demographics of effected area**
  - **Ancillary environmental conditions**
- **Can this model be coupled to the NWP- based predictions to enable a forecast of impact?**

Poisson Regression Model

- **Poisson regression is appropriate when the dependent variable (Y_{it}) is a count, for instance of events such as outages that happen at location, *I*, and time, *t***
- **Assume** $Y_{it} \mid X_{it1}, X_{it2}, \Lambda\ , X_{itP} \sim Poisson(\lambda_{it})$
- **Predictors** X_{it1} **is the adjusted sustained wind speed at location, *i*, and time, *t*;**

  X_{it2} **is the duration of sustained wind speed at location, *i*, and time, *t*;**

  X_{it3} **is the adjusted gust speed at location, *i*, and time, *t*;**

  X_{it4} **is the rainfall in 2 weeks at location, *i*, and time, *t*;**

  ……
- $\log(\lambda_{it}) = \beta_{i0} + \beta_{i1} X_{it1} + \beta_{i2} X_{it2} + \Lambda\ + \beta_{iP} X_{itP} + \varepsilon_{it}$
- **where** $\varepsilon_{it}, i = 1, \Lambda\ , N, t = 1, \Lambda\ , T$ **are spatially (and temporally) correlated**

Outage Prediction -- 18 January 2006

Feeder Cell	Actual Outages	Estimated Outages	95%Confidence Interval - lower bound	95%Confidence Interval - upper bound
1	124	127	109	147
2	26	26	21	32
3	12	14	10	19
4	50	45	40	52
5	61	59	47	73
6	49	45	38	55
7	58	70	58	83
8	56	60	48	75
9	89	95	79	115
10	118	125	105	148
11	75	79	64	98
12	43	37	29	47
13	114	109	94	127
14	104	96	80	116
Total	979	987		

Severe Thunderstorms Near White Marsh, MD -- 16 October 2004

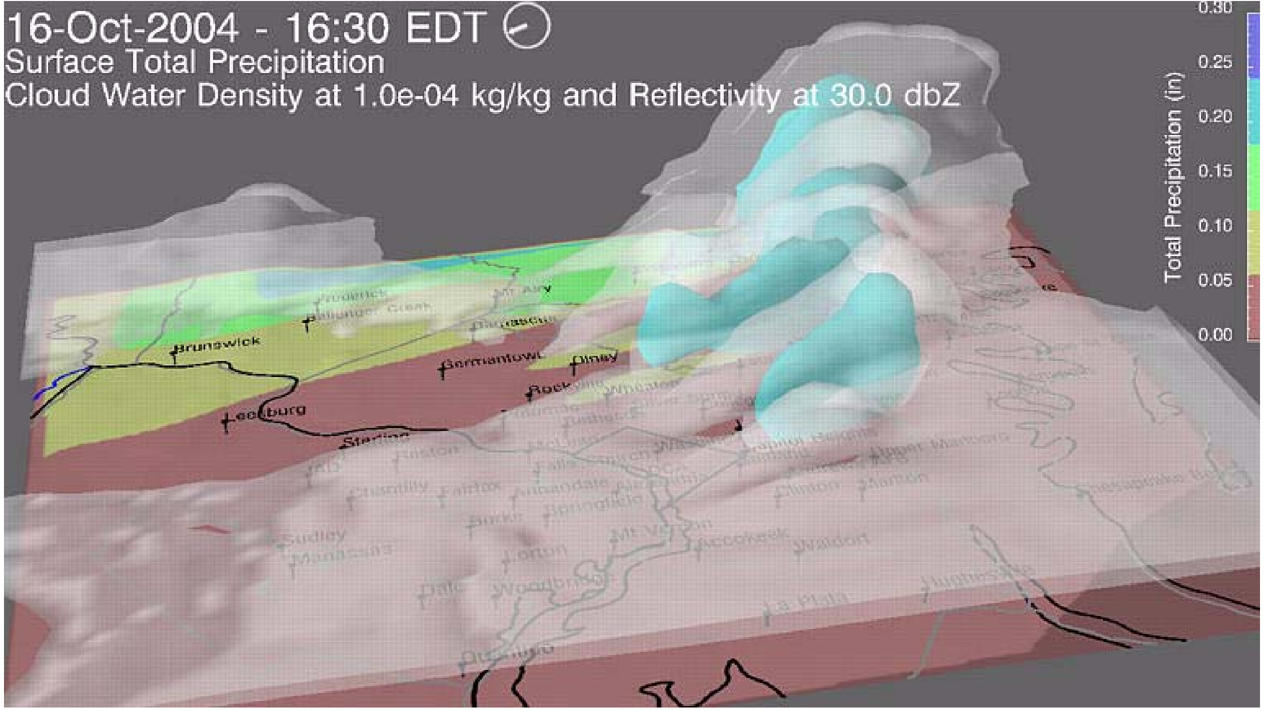
- **A fast-moving line of late-afternoon thunderstorms occurred along Interstate 95 north of Baltimore between 1600 and 1630 EDT**
- **Heavy rain, zero visibility and "pea-size hail" (graupel?) were reported**
- **There were 17 multi-car accidents, involving over 90 vehicles from White Marsh to Bel Air, starting at about 1630 EDT**
- **50 people were sent to hospitals and caused widespread traffic disruption along I-95**

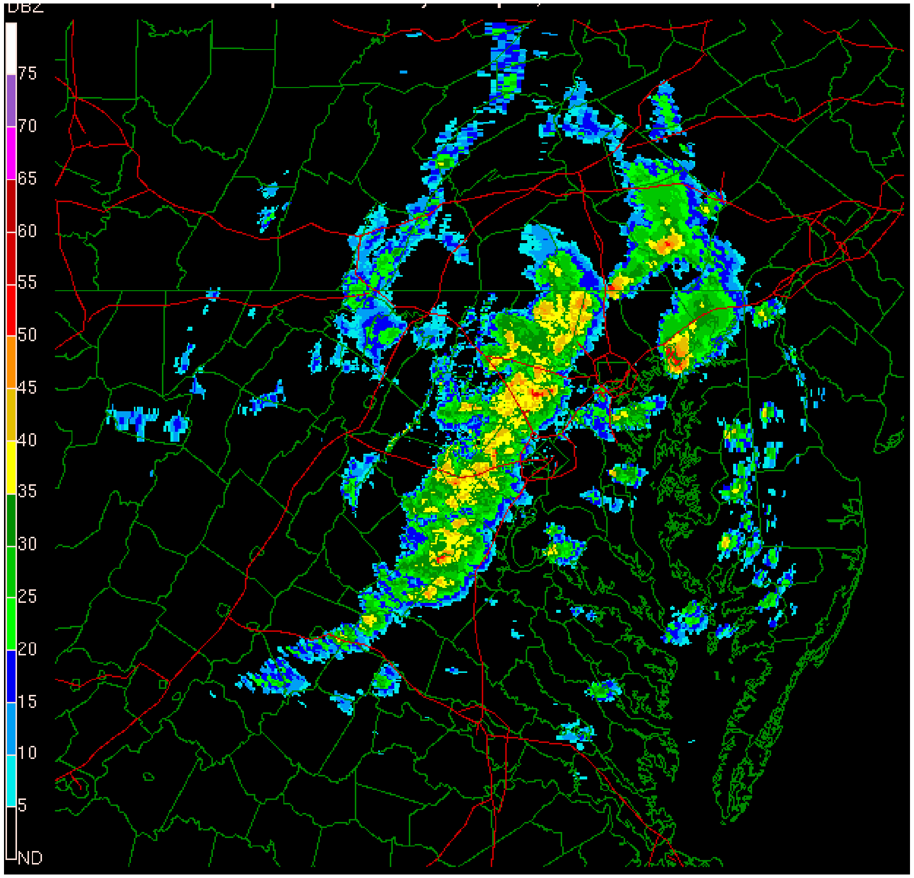
White Marsh, MD -- 16 October 2004

- **Largest mass-vehicle crash in Maryland history**
- **Most of the accidents were within a 5-mile portion of I-95**

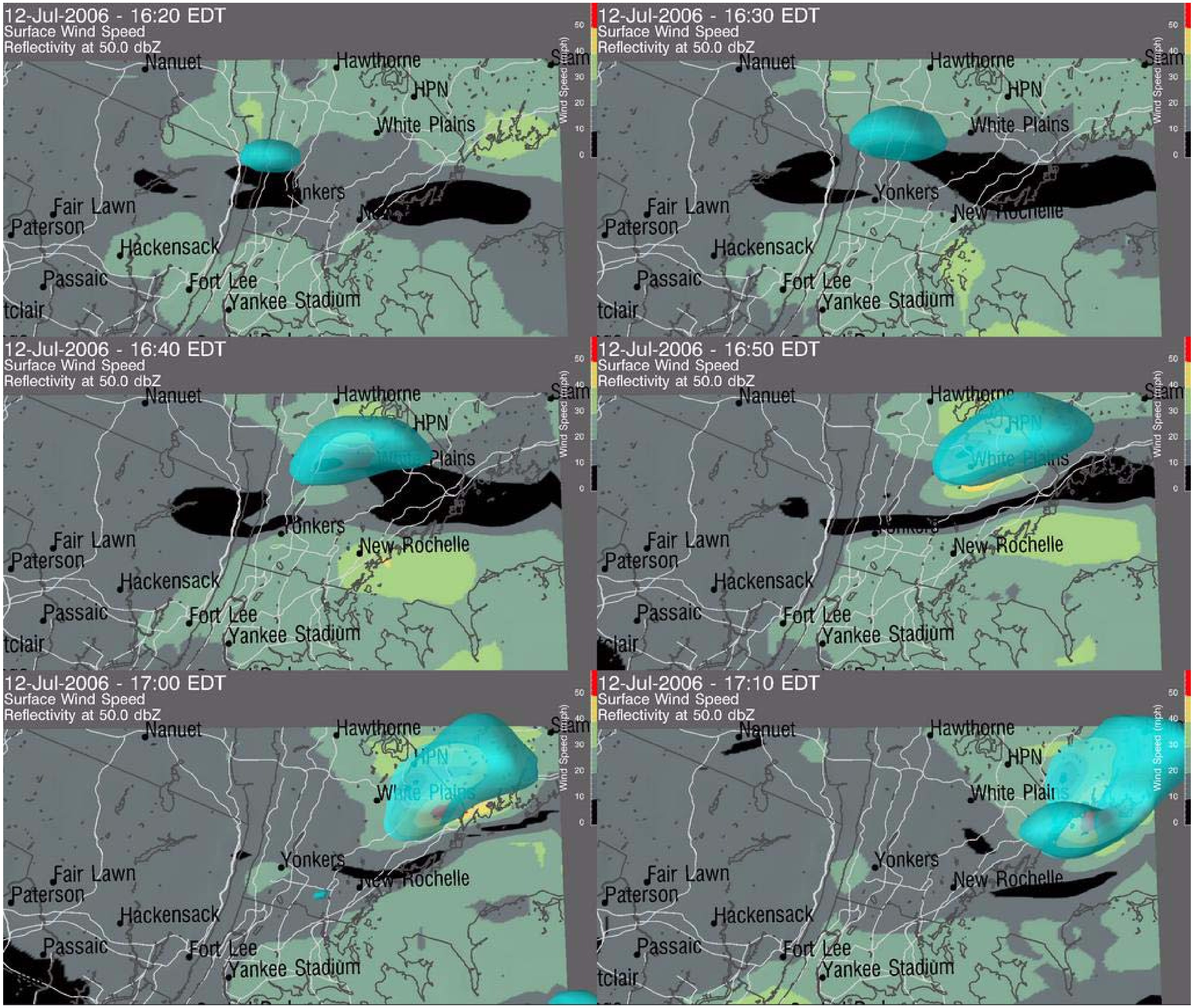
- **North- and south-bound lanes were closed for several hours**

Forecast Results 16 October 2004 Early Morning





- **Line of thunderstorms predicted for the late afternoon with similar distribution to reported rainfall, except for the southern portion of the squall line**
- **Forecast initiated with data from 0200 EDT with results available about 0600 EDT**
- **Lead time of about 10 hours before the event**



Tornado Event Afternoon 12 July 2006

- **A rare F-2 tornado touched down in Westchester County at about 1540 local time**
- **Forecast of storm cells leading to the event**
- **The timing is late and the initial path further to the south than observed**
- **Despite some error, significant "heads-up" for event**
- **What is the value of a meteorologically erroneous forecast ?**

Discussion

- **An illustration of the viability of a user-centric design**
- **Positive feedback from users, but still much work to be done**
  - **Usable forecasts are available automatically, in a timely, regular fashion**
  - **Favorable view of the ability to provide relevant and precise forecasts of severe weather**
  - **Focused visualizations have been critical to effective utilization**
  - **But improved throughput and forecast quality is still needed**
- **Fairly simple methods used to date, but will need more comprehensive methods**
  - **Increase complexity for training**
  - **Require more design iterations (user interviews)**
  - **Better representation of user view of uncertainty in current deterministic forecasts**
- **Direct interaction with and customized delivery for user critical for usability and acceptability**
  - **Comparison to currently used information needed to establish credibility**
  - **Need to leveraging user expertise into delivered products and how they are generated**
  - **Degree of integration based upon available impact data and ability to model**

Future Work

- **Enhanced forecast quality and refined application-oriented product delivery with improved throughput**
  - Operational coupling of outage prediction
  - Employ newer NWP systems (e.g., WRF-ARW)
- **Targeted verification (by area and application, e.g., damage, travel delays, resource scheduling, electricity demand)**
- **Evaluate with other related applications and data, e.g.,**
  - Near-real-time response (nowcasting via weather radar or dense mesonet)
  - NWP operating on other temporal and spatial scales
  - Flood forecasting (hydrological modelling)
- **IBM *Big Green Innovations***
  - Developing decision support services for water, energy and carbon management
  - Reference IT architecture/infrastructure
  - Partnering with leading sensor and engineering companies
- **Short-term weather impacts on local water systems**
  - Initial focus on emergency planning for flooding events
  - Extend capability to include hydrological prediction (e.g., runoff)
  - Impact on water availability and quality
  - Enable optimization of current water treatment facilities

Simple Supply Chain View of a Flooding Problem