User-Driven Simulation and Visualization for Decision Making in Weather-Sensitive Operations

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User-Driven Simulation and Visualization for Decision Making in Weather-Sensitive Operations

- Background and motivation
- Example forecasts (case studies) and discussion
  - Severe weather (snow, wind, thunderstorms, tropical storms, etc.)
- Architecture and implementation
- Visualization, workflow and decision support
- Conclusions and future work
User-Driven Simulation and Visualization for Decision Making in Weather-Sensitive Operations

- "User" roles include
  - Basic research
  - Data generator and algorithm development (i.e., modellers, instrumenters)
  - Application specialists (operational "end users")
- Visualization should be integral, not just post-processing

- Growing need to combine observations and simulations
- Recent convergence of science, available data and high-performance computing
  - Fidelity of simulations enabling viable decision support applications and risk assessment

Applications (User) Motivation

- Problem: weather-sensitive business operations are often reactive to short-term (3 to 36 hours), local conditions (city, county, state) due to 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
  - Numerical weather forecasts coupled to business processes
  - Products and operations customized to business problems
  - Competitive advantage -- efficiency, safety, security and economic & societal benefit

- It is **not** about weather but integrating forecasts into decision making to optimize business processes

- Prototype 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 and Fort Lauderdale/Miami
  - Prototype “business” applications with actual end users

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**Deep Thunder Testbeds**

- Kansas City
- Chicago
- Atlanta
- New York
- Miami and Fort Lauderdale
- Washington and Baltimore
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
- National Weather Service forecast on the evening of 11 February: "10 to 16 inches" in New York City metropolitan area
- Later forecasts increased to "12 to 18 inches"

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
- Only forecast so early in the event that 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"

Reported Snowfall

Deep Thunder Forecast

12 February 2006
"Blizzard"

Reported Snowfall (Inches)

<table>
<thead>
<tr>
<th>Location</th>
<th>Snowfall</th>
</tr>
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<tbody>
<tr>
<td>BRONX</td>
<td>24.5</td>
</tr>
<tr>
<td>PARKCHESTER</td>
<td>20.4</td>
</tr>
<tr>
<td>WOODLAWN</td>
<td>17.0</td>
</tr>
<tr>
<td>COLUMBIA U.</td>
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<td>CENTRAL PARK</td>
<td>26.9</td>
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<td>CHINATOWN</td>
<td>24.7</td>
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<tr>
<td>ASTORIA</td>
<td>26.0</td>
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<tr>
<td>LGA</td>
<td>25.4</td>
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<tr>
<td>FLUSHING</td>
<td>19.9</td>
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<td>RICHMOND HILL</td>
<td>19.5</td>
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<td>17.4</td>
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</tr>
</tbody>
</table>

Deep Thunder Forecast
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

- Operational forecast initiated with data from 2000 EDT, 23 October, with results available about midnight
- Heavy rainfall predicted with similar distribution to reported rainfall, although a positive bias in some locations
- Predicted track biased to the northwest
Deep Thunder Prediction of Hurricane Wilma: 24 October 2005

- Operational configuration with 24, 6 and 1.5 km nests centered on Miami-Fort Lauderdale area
- Forecast initiated with data from 2000 EDT, 23 October, with results available about midnight

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

Visualization of Rain Bands, Wind and Precipitation

Deep Thunder Prediction of Hurricane Wilma: 24 October 2005

Estimated Rainfall Totals from Radar

- Experimental hindcast 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 Predicted Rainfall Totals (4 km Nest)

Produced by the Southeast River Forecast Center
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

- 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 Hurricane Vortex and Clouds

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
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
- NWS forecast from 0330 EDT and through the day: mostly cloudy with a chance of showers and isolated thunderstorms

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
- Significantly different forecast compared to NWS forecast at any time during the day
- Lead time of about 10 hours before the event

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

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**Simplified Data Thunder Processing Data Flow**

**NOAA (NCEP, NWS)**

- Global Forecasting System: T254L64, 7 days
- Ensemble model, 2-4x/day, various products and resolutions
- Spectral, spherical solution

**IBM Deep Thunder**

- North American Model System: 12km resolution, 84 hours
- Deterministic model, 4x/day
- Primarily dynamics and physics
- Complete data assimilation

Data Used to Generate
- Boundary conditions
- Initial conditions
- Forecast verification

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*Illustrations and diagrams are not transcribed.*
Visualization Issues

- Traditional (meteorological) visualization is driven by data for analysis, and is therefore, incomplete
  - 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 (weather) simulation results 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

Visualization Tasks in Meteorology

- **Class I**: 2d (traditional weather graphics)
  - Quantitative
  - Users are forecasters
  - Minimal interaction

- **Class II**: 2d, 2-1/2d Analysis
  - Quantitative with potentially complex appearance
  - Users are forecasters, but techniques will be new
  - Support data comparison
  - Direct manipulation important

- **Class III**: 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

- **Class IV**: 3d Analysis
  - Quantitative with potentially complex appearance
  - Users are forecasters, but techniques will be new
  - Support limited data comparison
  - Direct manipulation important

- **Class V: Decision Support**
Decision Support -- Class V

- 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
- Customized appearance by data and geography and fusion with ancillary data
- Presentation of derived properties critical to decisions
  - Weather phenomena may not be shown
- Many potential applications

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
Composition Design Approach

- Identification of distinct user goals and visualization tasks coupled with knowledge of human visual perception
- Each data set processed independently to maintain fidelity and consistency with data source
- Visualization and interaction in common, cartographic coordinates
- Physical and conceptual realization
- Simplified user interface, although multiple linked displays may be used

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
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
- Customized appearance by data and geography and fusion with ancillary data
- Presentation of derived properties critical to decisions
  - Weather phenomena may not be shown
- Many potential applications, including emergency management

One Person's Emergency May Be Another's Routine

"Emergency Response Schema" *

* (based upon experience, e.g., scenario training)

Many tasks are involved in how one looks at and assesses a situation, obtains and interprets information and communicates with others.
NYC Metropolitan Area Heavy Rainfall Event -- 8 September 2004

- Remnants of Hurricane Frances moved into the New York City metropolitan area early in the morning of September 8
- The heaviest rainfall occurred in an area stretching from northeastern New Jersey through central Westchester County, NY with amounts in excess of 5" in some areas
- There was widespread disruption of transportation systems (e.g., road closures, flooded subways, airport delays) and significant flooding in several regions
- Evening NWS forecast (2130 EDT, 7 September) for the next day "showers and a slight chance of thunderstorms, rain may be heavy at times in the morning"
- Revised NWS forecast (0440 EDT, 8 September), adding "locally heavy rain possible"
- NWS issued a flash flood watch at 0748 EDT
Heavy rainfall predicted for the morning with similar distribution to reported rainfall, although some differences in totals.

Forecast initiated with data from 2000 EDT with results available about midnight.

Significantly different forecast compared to NWS forecast (available about 8 hours before flash flood warning).

Despite some error, significant "heads-up" for event.

Deep Thunder 4 km nest (above) and 1 km nest (below) at forecast hour 12 (0800 EDT).

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

Is This a Better User View?

For Which Users and Why?

- Heavy rainfall predicted for the morning with similar distribution to reported rainfall, although some differences in totals.
- Forecast initiated with data from 2000 EDT with results available about midnight.
- Significantly different forecast compared to NWS forecast (available about 8 hours before flash flood warning).
- Despite some error, significant "heads-up" for event.

Is This a Better Visualization?

- Heavy rainfall predicted for the morning with similar distribution to reported rainfall, although some differences in totals.
- Forecast initiated with data from 2000 EDT (0 UTC) with results available about midnight.
- Significantly different forecast compared to NWS forecast (available about 8 hours before flash flood warning).
- Despite some error, significant "heads-up" for event.
### Deep Thunder Road Forecast (1 km Nest) Rainfall Totals

#### Measured Rainfall (Inches)

<table>
<thead>
<tr>
<th>Location</th>
<th>Rainfall (Inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JFK</td>
<td>2.76</td>
</tr>
<tr>
<td>Mamaroneck</td>
<td>3.73</td>
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<tr>
<td>LGA</td>
<td>3.83</td>
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<tr>
<td>Central Park</td>
<td>3.75</td>
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<tr>
<td>Norwalk</td>
<td>4.25</td>
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<tr>
<td>White Plains</td>
<td>5.85</td>
</tr>
<tr>
<td>Fair Lawn</td>
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<tr>
<td>Bethpage</td>
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<tr>
<td>Orange</td>
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<tr>
<td>EWR</td>
<td>2.07</td>
</tr>
<tr>
<td>Hoboken</td>
<td>3.87</td>
</tr>
</tbody>
</table>

#### Example Precipitation Type and Total Accumulation Maps

07-Feb-2003 - 22:00 EST

- **Kingston**
- **Poughkeepsie**
- **Newburgh**
- **Danbury**
- **Bridgeport**
- **Stamford**
- **White Plains**
- **Yonkers**
- **New York**

**Legend:**
- ☀ Mixed Snow & Rain
- △ Snow, Sleet and Rain
- ▲ Snow and Rain
- △ Snow
- ▲ Sleet and Rain
- △ Sleet
- ▲ Rain
- △ Total Precipitation (In.)
- ▲ Total Snow Accumulation (In.)
- ▲ Total Sleet Accumulation (In.)
December 27 - 28, 2001 Lake Effect Snow Hindcast

Appropriate Visualization of Wind (and Temperature) Forecast?

Emergency Planning for Severe Winds (Focused Visualization)

- Geographic correlation of demographic and forecast data
- Map shows
  - Zip code locations colored by wind-induced residential building damage
  - Constrained by value, population and wind damage above thresholds
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 and 15 hours before NWS advisory.

Example Wind Forecast

Indian Point, Westchester County, NY

- Interest in surface and upper air winds dictates entirely different presentation
- “Virtual wind profilers” at two locations within 4 km nest enhanced with trajectories to show forecasted propagation
Indian Point Site-Specific Surface and Upper Air Forecast

Encourage Pattern Recognition for Rapid Interpretation

Indian Point, Buchanan, NY [41.2714 N, -73.9525 W]
Valid for 04/29/2003 0000 EDT through 04/30/2003 0000 EDT

Indian Point, Buchanan, NY [41.2714 N, -73.9525 W]
Valid for 02/16/2003 1800 EST through 02/17/2003 1800 EST

Snowstorm
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 more precise forecasts of severe weather compared to conventional sources
  - 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 other forecasts needed to establish credibility
  - Pushing “standard” forecast products inadequate
  - Listen to and integrate user expertise into delivered products and how they are generated
• Scalability from the user perspective for increased fidelity and precision suggests
  
  — Multiple feedback loops
  
  — Simulation and observation interaction is multi-layered
  
  — "Rich" metadata to capture semantics at all steps of data generation and utilization

Example – Flood Forecasting from a Hurricane

Global Weather Models
Show Likely Event, Triggering Focused Modelling

ECMWF/IFS
NCEP/GFS
UKMO/GM
EC/GEM

Request for Local Observations for Data Assimilation

UNF/WRF
FSU/MM5
IBM/DT

Meso-s Scale Models

Global Super Ensemble

Hurricane Models
FSU/GSM
GFDL/HPS

Run On-Demand in Response to Event Forecast

How are model data to be subset and provided for background fields and lateral boundaries?

Regional Super Ensemble

Flooding, Hydrological Model

Regional Super Ensemble

Tidal / Surge Model

Run On-Demand in Response to Event Forecast

How Will Precipitation and Wind Forecasts from the Mesoscale Models Be Used?

Data Provided by Each Center
Are “Raw” Data or Results of Assimilation Provided?

End-User Access
Where Are These Generated or Are Data Provided Directly to End Users?

Societal / Economic Models

Evacuation and Traffic
Disease Propagation, Morbidity, Mortality
Crop Damage
Building Damage

Visualization and GIS
Future Work

- Enhanced forecast quality and refined application-oriented product delivery with improved throughput
- Targeted verification (by area and application, e.g., travel delays, resource scheduling, electricity demand)
- Evaluate with other related applications and data, e.g.,
  - Near-real-time response (nowcasting via weather radar)
  - Hurricane mitigation (planning and schedule analytics)
- Apply work to other domains with diverse, operational users (e.g., biomedical)
- Improve methods to capture and employ workflow-level metadata
- Evaluate limitations in popular data models for usability scaling