Usability Scaling for Simulation and Visualization in Applications of Numerical Weather Prediction

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Usability Scaling for Simulation and Visualization in Applications of Numerical Weather Prediction

- Background and motivation
- Computational issues and approach
- Architecture and implementation
- Example forecasts (case studies)
- Visualization issues
- Discussion
- Conclusions and future work
Usability Scaling for Simulation and Visualization in Applications of Numerical Weather Prediction

- 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

"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
A Few Dimensions of Computational Scalability

Scalability = f(Facility, Capability, Usability)
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, agriculture, insurance, broadcasting, sports, entertainment, tourism, construction, communications, emergency planning and security warnings

- **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
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

Weather Data
- NCEP Forecast Products
- Satellite Images
- Other NWS Data
- NOAAPORT Data Ingest

Pre-processing
- Synoptic Model
- NAM
- Boundary Conditions
- Other Input Products

Processing
- Weather Server
- Cloud-Scale Model
- Data Assimilation

Post-processing and Tracking
- Advanced Visualization
- Data Explorer
- Custom Products for Business Applications and Traditional Weather Graphics

Forecast Modelling Systems
- Initial Conditions
- Analysis
- Forecasting Modelling Systems
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

- Identification of time and location of "events"
- Analysis of impact on production, population, assets
- Expense vs. effectiveness of countermeasures
- Optimized planning, scheduling, routing
Weather and Climate Simulations

L = Limited Area, G = Global Area

Simulation Length

Grid Size - dx

Time Step - dt

Computationally Expensive Region

L = Limited Area, G = Global Area

Isolating the Problem May Enable Practical Solutions
Approach to Numerical Weather Prediction

- **Modelling ingredients**
  - **Physics**
    - affects state of the atmosphere, e.g., radiation, energy balance
  - **Dynamics**
    - handles state of the atmosphere, e.g., transport, advection
    - \( u,v,w,rP, ... \)
  - **Microphysics/dynamics**
    - turbulence, clouds, precipitation, ...

- **Modelling recipes**
  - Microscale - (<10^3 m)
  - Mesoscale - O(10^3 - 10^6 m)
  - Synoptic scale - O(10^6 m)
  - Planetary scale - O(10^7 m)

- **Modelling utensils**
  - (Parallel) computers
  - Numerical techniques
    - Solution of ODEs
    - Sub-grid parameterization
    - Full sub-grid computations
Classes of Weather Models for Different Geographic Scales, Time Ranges & Applications

- US National Weather Service uses a synoptic-scale model on a 12 km grid covering North America and more, but only subsets are available on three-hour intervals
- 40% physics, 50% dynamics, 10% microphysics
- Thunderstorms, wind shear, land-sea breezes, circulation induced from topography cannot be seen at this resolution
- Like trying to catch small fish with a net that has a large mesh
- Regional models employ meso- and cloud-scale grids (e.g., 1-10 km spacing), including nesting
- 50% physics, 20% dynamics, 30% explicit cloud microphysics
- Can resolve storms, winds, etc.
- Cast a finer net over coarse net
Deep Thunder Testbeds

Kansas City

Chicago

New York

Washington and Baltimore

Atlanta

Miami and Fort Lauderdale
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"
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
12 February 2006
"Blizzard" Reported Snowfall

Deep Thunder Forecast

12-Feb-2006 - 19:00 EST
Surface Total Snow
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>
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<tr>
<td>WOODLAWN</td>
<td>17.0</td>
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<tr>
<td>COLUMBIA U.</td>
<td>27.0</td>
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<tr>
<td>CENTRAL PARK</td>
<td>26.9</td>
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<tr>
<td>CHINATOWN</td>
<td>24.7</td>
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<tr>
<td>ASTORIA</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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<tr>
<td>RICHMOND HILL</td>
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<tr>
<td>FAR ROCKAWAY</td>
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<td>JFK</td>
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<td>FLATLANDS</td>
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<td>RYE BROOK</td>
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<td>BRONXVILLE</td>
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<td>MOUNT KISCO</td>
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<td>ARMONK</td>
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<td>CROTON</td>
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<td>MONTCLAIR</td>
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<td>WEST ORANGE</td>
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<td>SOUTH ORANGE</td>
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<td>WEST CALDWELL</td>
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<td>HOBOKEN</td>
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<td>JERSEY CITY</td>
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<tr>
<td>HARRISON</td>
<td>17.5</td>
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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
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.
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

- Experimental 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
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
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" *

Many tasks are involved in how one looks at and assesses a situation, obtains and interprets information and communicates with others.
Example Precipitation Type and Total Accumulation Maps
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
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

22-May-2002 - 08:00 EDT
Indian Point, Buchanan, NY [41.2714 N, -73.9525 W]

Valid for 04/29/2003 2000 EDT through 04/30/2003 2000 EDT

Encourage Pattern Recognition for Rapid Interpretation
Indian Point
Site-Specific Surface and Upper Air Forecast

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
User-Driven Interaction

- 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

Global Super Ensemble
- FSU/GSM
- GFDL/HPS

Hurricane Models
- UNF/WRF
- FSU/MM5
- IBM/DI

Meso-γ Scale Models
- Run On-Demand in Response to Event Forecast
- Request for Local Observations for Data Assimilation
- Data Provided by Each Center
  Are “Raw” Data or Results of Assimilation Provided?

Regional Super Ensemble
- Tidal / Surge Model
  - Run On-Demand in Response to Event Forecast

Flooding, Hydrological Model
- How Will Precipitation and Wind Forecasts from the Mesoscale Models Be Used?

Societal / Economic Models
- Evacuation and Traffic
- Disease Propagation, Morbidity, Mortality
- Crop Damage
- Building Damage
- End-User Access
  Where Are TheseGenerated or Are Data Provided Directly to End Users?

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