I. Introduction

There is a general recognition that linking infrastructure impact models more closely to extreme weather models, and using the growing body of historical statistics for weather-related infrastructure damage (as correlated to meteorological fields), will result in infrastructure damage forecasts with significantly higher accuracy out further in the future, and that such improvement is of interest to funding agencies and decision makers. During recent decades, there have been numerous studies quantifying the social and economic impacts of severe weather, particularly in reference to tornadoes that strike urban centers and severe hurricanes impacting coastlines. Hurricane Katrina illustrated the extent of socioeconomic disruption that one should prepare for, and it further illustrated the need to closely couple research in severe weather prediction with research in impacts and response. Over the past year, a number of agencies are positioning themselves to make major investments in the science needed to minimize impacts caused by severe weather, e.g., by developing cross-agency working groups and funding mechanisms. NOAA, DOE, USACE, ONR, DHS, DOD, and FEMA are actively discussing ways to collaborate more effectively. Among the areas of research to be supported are basic research in severe storm modeling that more accurately represents processes that have been attributed to uncertainties in prediction. For example, hurricane intensification, severe storm convection, and asymmetries in severe storm evolution, have been challenging problems to address, both in terms of representing fine scale processes and in terms of assimilating the appropriate data to make predictions in line with user requirements. In addition to the challenge of predicting severe storms, modeling and prediction of impacts has been limited by simplifications and/or assumptions in specific models as well as assimilation of the appropriate infrastructure data that extend beyond the local horizon. We believe that a long term strategy will require the community to first document the assumptions and/or limitations of existing models and prediction systems, and then follow with a strategy to develop the necessary science base to improve severe storm predictability, impacts, and mitigation strategies.

This white paper summarizes the recommendations of the February 2007 workshop where scientists and engineers working on infrastructure impact modeling came together with atmospheric scientists working on weather extremes to focus on the consequences of extreme wind, extreme precipitation, fire weather, and biochemical dispersion. The goals of the workshop were (i) to identify the science challenges affecting their work, (ii) to outline how to improve infrastructure impact models, and (iii) to document gaps between existing and desired analytic capabilities. The workshop also helped the science and impacts communities better develop joint requirements and to form multidisciplinary collaborations.

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1 See the Appendix, “Workshop Participants”, for a list of contributors. This document was edited by B. Bush, S. Fernandez, G. Geernaert, G. Holland, and R. Wagoner. The web site http://www.rap.ucar.edu/~bwb/weather-impacts/ has links to additional artifacts (presentations, notes, gap analyses, etc.) from the workshop.
2 Sponsored by Los Alamos National Laboratory and the National Center for Atmospheric Research.
In the following sections we have sorted the workshop recommendations by domain (general, extreme wind and precipitation, fire weather, and biochemical dispersion) and category (decision science, integrated modeling, validation & verification, information management, and model improvement). We have purposefully avoided duplicating domain-specific recommendations that solely focus on weather or infrastructure modeling, since other better qualified working groups, committees, and organizations have targeted recommendations for these already (see “References & Related Recommendations” below). Consequently, we emphasize cross-cutting, multi-disciplinary recommendations that typically fall outside the scope of single discipline gap analyses.

II. General Recommendations

A. Decision Science

1) Decision-Centricity. Integrated weather-infrastructure decisions support systems must be built out, starting from requirements imposed by the decision problems. This requires careful study of those decision problems and close collaboration with stakeholders and decision makers: a clearly documented taxonomy of categories of decisions, time frames, approaches to uncertainty, communication and learning styles, level of detail, costs, and types of actionable information must be elaborated and used to guide system development. Use cases for decision problems must be formally specified, and these must be linked into concrete “concept of operations” process documents. One needs to precisely identify areas where providing better impact forecasts adds value to planning, response, and mitigation decisions. The legitimacy of scientific predictions is not a given in every stakeholder community, so that needs to be addressed sensitively.

2) Communication & Visualization Techniques. Far more emphasis needs to be placed on communicating the results of infrastructure-impact forecasts to end users in ways that truly resonate with them. Realistic “virtual reality” visualizations will make results concrete and accessible to the broadest set of stakeholders. Clear definitions of likelihood, probability, and uncertainty must be consistently adopted, and detailed guidance on interpreting these ranges provided; “false alarms” and forecast system credibility require explicit discussion. There is also great value in making available the same information (albeit in multiple formats tailored to particular learning and communications styles) to all stakeholders at the same time, so as to eliminate inappropriate filtering, poor routing, and misunderstanding. The use of “boundary objects” as a learning and communications tool will let decision makers envision worst case scenarios that they can learn from and gain experience with. Advance education is critical, and this can take the form of publicizing virtual reality visualization and hazard maps. Fostering a joint culture between the scientists, engineers, and stakeholders (where scientists/engineers are part of operations) will go a long way towards improving communication and the flow of requirements.

3) Effects of Disseminating Information. The methods of human factors engineering and cognitive and social science should be brought to bear on understanding how decision makers and the general population responds and reacts to information about extreme weather and its impact on infrastructure. Different communication methods affect social systems in varied
matters, and poorly communicated information may have unintended negative consequences in an event. Better understanding is required of how data forces decisions and how decision are based on spotty or sparse information.

4) **Broadened Regional and Cultural Domains.** Weather-impacts decision support must move beyond its parochial emphasis on initiating events and primary interdependencies to include broader socio-economic and cultural consequences, which can be the dominant long term effects from high impact weather. Weather-impact studies should unequivocally support efforts to develop weather-resilient communities with robust critical infrastructure. Methodologies, data sets, and analyses should be expanded to support regional (multi-nation) and global events, as extreme weather regularly crosses such boundaries.

5) **Weather-Impacts Virtual Test Bed.** A multi-institution, multidisciplinary test bed forms the key avenue for testing weather-impacts concepts—advancing research, developing interoperable models, managing data, and verifying results. Initially, this should focus on one to three closely focused regional impact scenarios.

**B. Integrated Modeling**

6) **Standards-Based Service-Oriented Architecture [SOA] for Integrating Interoperable Multidisciplinary Simulations.** The lack of interoperability (at multiple levels) between weather and infrastructure simulations has hampered robust, streamlined analyses of impending and hypothetical extreme events. The adoption of a service-oriented architecture based on standards (e.g., the WS-* or OSGI families of standards) would greatly simplify the coupling of simulations in valid and defensible configurations. The use of well crafted standard interfaces for classes of models (numerical weather, storm surge, energy-grid impact, etc.), and that respect the multi-scale and hierarchical nature of the classes of models, would allow modular “plug & play” assembly of software components for the rapid deployment of user-specific decision support products. Such modularity would also facilitate verification and inter-model comparison.

7) **Dynamic Modeling Systems.** Event-driven “dynamic modeling” systems could take real-time inputs from meteorological forecasts and observations in order to automatically configure and launch more detailed meteorological, hydrographic, or infrastructure simulations. Automated analyses of simulation results may trigger further simulation or recommend additional data collection. The overall modeling system would systematically allocate computational resources, optimally choosing models of appropriate resolution given constraints such as the time frame for decision making. Such system would be continuously operating so there is a symbiosis between data collection, the modeling forecast, infrastructure-impacts estimation, and decision-maker needs. Data assimilation should occur throughout the metrological, hydrographic, and infrastructure models.

8) **End-to-End Ensembles.** Probabilistic and ensemble information can be propagated directly through the whole modeling process, from the numerical weather prediction models all the way to the infrastructure impacts models. It is statistically unsound to collapse ensemble information at an early stage in a coupled simulation.
9) **Pre-Computation.** Many state-of-the-art techniques are ill-suited for crisis situations due to their computational needs. In such circumstances, faster, but less accurate, techniques are used. Alternatively, one can pre-compute as many scenarios as possible using the state-of-the-art techniques and then “pull them off the shelf” during crises and gain the benefits of more powerful/accurate techniques. The drawback is that the scenarios may not exactly match the crisis, so some accuracy may be sacrificed there. One possibility is using the pre-computed scenarios to serve as a starting point for developing fast techniques that are more accurate than the current fast techniques.

C. **Validation & Verification**

10) **Coupled User-Centric Verification of High Impact Weather and Its Consequences.** There is a strong consensus that verification must focus on the end-to-end coupled weather-plus-infrastructure systems instead of simple verification of individual models, and that verification metrics must be directly relevant to infrastructure sectors and to the decision makers dealing with extreme events. This requires a new style of verification that cuts across the standard practices (which tend to focus on physical processes and do not appropriately weight events with extreme consequences) of the individual disciplines involved. Independently funded third-party verification is essential. Such verification efforts span the whole “information chain”, from raw data, through meteorological and hydrographic models, through infrastructure impact and restoration simulations, up to socio-economic consequence estimates and include a variety of possible cascading events of interest to stakeholders. Online, real-time verification would be a valuable component of an integrated modeling system, and there should be a strong emphasis on the use of remote sensing in such verification.

11) **Tuned Meteorological Analyses.** Meteorological analyses should be tuned for use in the verification of high impact weather. Standard analyses are not necessarily applicable to extreme events.

12) **Limits of Predictability.** Critical processes may be fundamentally stochastic: we need to know what we can really predict and at what lead time. A concerted multi-pronged research effort is required to quantify the limits of predictability (both fundamental and practical) of weather-related infrastructure impacts. As these are better understood, statistical techniques can be developed to work around these, so that limits of predictability can be incorporated in decision processes and communicated to stakeholders. Closely related to this topic is further studies of the uncertainties and sensitivities of coupled weather-infrastructure models.

D. **Information Management**

13) **Interoperable, Standardized Metadata.** Key to accelerated progress on weather-infrastructure interactions, rich metadata should capture information about data quality, provenance, use, subjective assertions (including assertions about those assertions), compatibility, definition of terms, and semantic mappings between terms and simulations in varied domains. Heavy reliance on established informatics standards will support complex querying, validation, search, reasoning, and knowledge extraction for the data sets. Metadata that precisely identifies data format will support interchangeability and transformation of data sets for specific applications and case studies. A “metadata workbench” would allow centralized
and unified browsable access to the diversity of information relevant for planning, response, and verification studies.

14) **Unified Data Models for Interdisciplinary Simulations.** Unified data models are the best way to support interdisciplinary simulations. If organizations have access to data that conform to such rigorous specifications, then they can rapidly ingest them into simulation models without having to reach back to raw data sources or perform conversions or translations that may affect data quality. The unified data models will include mappings to traditional standardized and *ad hoc* data formats to allow rapid, automated access to model-appropriate information, and permit input data sets or models to be easily swapped. Sensor and observation data is in particular need of standardized metadata and formats.

15) **Comprehensive, Compatible Data Libraries & Knowledge Bases.** Where warranted by the frequency of high impact weather, comprehensive data sets of observations, meteorological analyses, and model inputs should be developed and regularly refreshed. Additionally, archives of information on past historic events or notional planning scenarios should be archived, reviewed, annotated, cross-referenced, and indexed so they can be rapidly accessed and reused in crisis situations. Knowledge bases of extreme events should be consistently maintained.

16) **Impact Field Surveys.** Post-event surveys of infrastructure impacts, coordinated across multiple infrastructure domains, and correlated to observed and reconstructed meteorological fields will lay a solid basis for calibration and verification of existing models and the development on next generation ones. In addition to including key infrastructures (energy, transportation, public health, etc.), the surveys should encompass physical damage, economic effects, demographic impacts, evacuation, and cultural consequences, all in standardized formats.

17) **Robust, Timely Data Collection.** A number of sensor and observation systems (particularly wind-data-collection) lack the resilient physical infrastructure and communication network connectivity that would allow them to report real time data during extreme weather. The data feeds most susceptible to destruction are precisely those which are most vital for providing situational awareness and post-event verification. Additional use of remote sensing data can supplement physically unreliable ground-observation platforms.

E. **Model Improvement**

18) **Designed Ensembles.** The ensembles for weather-infrastructure applications should be designed specifically for such work, rather than inherited as ensembles constructed for other purposes: i.e., the modes or axes of the perturbations should be constructed to span the space of decision-relevant infrastructure consequences as well as possible, given computational resources. Such ensembles should be tuned to generate outlier events (properly weighted using importance sampling methods), as these can dominate the estimates and bracketing of possible impacts. Modern experimental design techniques can be applied in this area, too.

19) **Importance of the Boundary Layer.** Because critical infrastructure generally lies in the atmospheric boundary layer, better modeling the nuances (specifically detailed spatial and temporal profiles for meteorological fields) of boundary layer phenomena forms a critical atmospheric science research area relevant to infrastructure-impacts forecasting.

20) **Enhanced Kalman Filters.** The incorporation of enhanced Kalman filters into the initialization of atmospheric models promises to better assimilate the variety of data sources.
supporting high impact weather forecasting. The use of these in infrastructure simulations should also be explored.

21) **Supervisory Control and Data Acquisition [SCADA] Modeling.** Control systems for physical infrastructures are often not fully incorporated into current infrastructure models. This is a significant drawback that needs to be remedied as infrastructure models become more tightly coupled with weather simulations.

22) **Population Displacement.** The short and long term effects of displacement of large urban populations have not been routinely integrated into analyses. Infrastructure can be severely stressed by the need for temporary and permanent housing, changes in the size and composition of the labor force, accumulation of refugees in cities, and social/economic/psychological stresses.

23) **Cultural Costs.** The qualitative and semi-quantitative studies of the cultural costs stemming from the impact of extreme weather on infrastructure have yet to be quantitatively modeled, despite their societal importance.

III. Extreme Wind & Precipitation Recommendations

A. **Decision Science**

24) **Real-Time, Coupled Weather-Infrastructure Forecast System.** It is agreed to be completely feasible to develop a fully coupled, real time, event-driven, dynamic system that integrates infrastructure and atmospheric models with sensor systems. The baseline version would also include a real time verification system. Events from either the infrastructure or weather side could trigger (i) additional observations and (ii) adaptive computations resulting in updated forecasts and vulnerability assessments. The triggering could be geographically or domain-focused. In the three-year time frame, a demonstration area focused on a small geographic region and on a limited problem domain (perhaps ice storms impacting a subset of infrastructures), but still with a socio-economic orientation, would prove the feasibility of the long term goal.

25) **Risk Maps & Impact Scales.** Wind, precipitation, storm-surge, and flood risk can be represented geospatially and seasonally in terms of multi-dimensional risk maps (at the ZIP code level), quantifying consequence estimates tailored to needs of specific stakeholder categories, and that are based on historical or, in the context of climate change, prospective climatology. Impact intensity scales similar to the Saffir-Simpson Scale can be developed for infrastructure, economic, or societal metrics.

26) **Weather-Aware Evacuation Decision Support.** Weather, storm-surge, and flood modeling should be integrated into automated systems providing evacuation decision support. Such decision-support systems should include models (particularly agent-based models) that account for demographic variability, social networks, and compliance behavior.

B. **Integrated Modeling**

27) **Larger and Higher Resolution Ensembles for Hurricane Track & Intensity Forecasts Providing Longer Lead Times.** For major prospective hurricane landfall events, the three-to-five day forecast of landfall is barely sufficient for emergency planning. A larger ensemble of high resolution hurricane forecasts (based on numerical weather, sea surface, and ocean models) will
alleviate this situation somewhat. (The current ad hoc ensembles clearly are not sufficient.) The
ensemble-generation should explicitly support studies of the likelihood of rapid intensification.
Also, the switch to a probabilistic understanding of the infrastructure impacts based on the
probabilistic nature of the forecasts. Additionally, global models provide track uncertainty
information that is not used operationally.

C. Validation & Verification

28) Wind, Water, and Impacts Data. The current lack of (i) survivable wind sensors, (ii)
vertical wind profiles for high wind situations, and (iii) consistent measurements of high water
make reconstructing wind, precipitation, and wave fields nearly impossible. In addition to
obtaining better and more complete observations, research on statistical methods for handling
this noisy and incomplete extreme data is needed. Historical reconstructions of wind,
precipitation, and waves from hurricanes need to be correlated with surveys of physical
infrastructure damage and formatted as integrated multi-domain analyses of these hurricanes’
landfalls.

29) Uncertainty Trade-Offs. In order to invest wisely in model improvements, one needs a
clear understanding of the point at which uncertainties in impact models overwhelm the effects
of improved forecasts of hurricane landfall location and intensity.

30) Multi-Way Comparisons. Multi-way comparisons of meteorological analysis, NWP model
outputs, observed damage, and forecast damage would provide valuable guidance for model
calibration, algorithm development, and uncertainty quantification. Furthermore, various data
assimilation methods (e.g., 4D-VAR, 3D-VAR and EnKF) need to be evaluated for these
applications: in particular, the balance between computational expense versus performance
requires research.

D. Information Management

31) Data Portal. A stakeholder-accessible data portal providing real time high impact weather
and infrastructure impact forecasts should be deployed. In additional to the GIS formats that
have wide currency among emergency management and planning organizations, customizable
data feeds to mobile devices should be supported. The portal should provide continuous
situational awareness.

E. Model Improvement

32) NWP Hurricane Model Initialization. Better wind data is critical for successful numerical
hurricane model initialization. Airborne radar data is not fully utilized in initialization. Satellite
data may have utility for inner core initialization.

33) Hurricane-Land Interaction. Numerical hurricane models tend to suffer from increased
ersors near land. Overlaying the hurricane wind field model with detailed land roughness and
elevation models may significantly enhance forecast realism.

34) High Resolution Winds. Existing numerical weather models provide no information on
wind spectra, gustiness, tunneling effects in urban canyons, or the probability of super cells,
microbursts, tornadoes, or eye wall collapse. These effect may account for extreme
infrastructure damage observed in some hurricanes. Furthermore, storm surge models should be
driven directly from realistically forecasts winds, instead of smooth idealizations. New ideas are needed here: For instance, can the modeling effort learn from LES, or would it benefit from a separate module or model for the surface layer? Will mesoscale model winds suffice for driving turbulence models? Can wind spectra and gustiness be imputed from the overly smooth wind fields found in NWP model output using statistical regression?

35) **Improved Damage Heuristics.** Most infrastructure-damage heuristic models were created to work with the coarse wind and precipitation forecasts currently published by the National Hurricane Center [NHC]. Furthermore, the quality of infrastructure outage and restoration predictions are highly dependent of the fidelity of the of the wind and precipitation field’s extent and structure. As forecast models are improved and NWP output is directly used in infrastructure models, the calibration and form of the infrastructure heuristics must be revisited; a detailed sensitivity study and more research and field data are in order here.

36) **Debris & Multiphase Flow.** The transportation of debris (by wind and by water) is a difficult multiphase modeling problem, but it may account for a significant fraction of physical damage to infrastructure. Currently, debris effects are implicitly embedded in the calibration of statistical infrastructure damage, but it is undesirable to mix the typically more extreme damage caused by debris with the “background” damage cause by wind and water: separating these effects could enhance the realism of infrastructure damage models.

37) **Secondary Effects of Precipitation.** Models for the delayed effects of extreme precipitation and flooding have not been integrated with weather or infrastructure forecasts. Levee failure, dam breaks, landslides, mud accumulation, spread of urban and industrial contaminants, water/sewer system damage, and containment failures can precipitate further physical damage to infrastructure.

**IV. Fire Weather Recommendations**

A. **Decision Science**

38) **Adaptive Prioritization of Computational Resources.** When there are multiple fire starts, careful prioritization of computational resources for the more sophisticated and compute-intensive fire models is necessary. The prioritization methodology must include human and environmental health, threat to structures, potential infrastructure damage and economic effects, difficulty to fight the fires, and likelihood for rapid or unpredictable expansion. Heat waves and other long-time-horizon factors can be addressed within such a framework. The methodology should also account for logistical issues such as the deployment or pre-placement of resources to fight fires.

39) **Regional Pilot Study.** There was consensus that a pilot study linking atmospheric, fire, and infrastructure models for a small geographic region. This comprehensive coupling of models will address urban threat, infrastructure impacts, watershed effects, evacuation vs. shelter-in-place decisions, and economic consequences. Using a small geographic area will allow the construction of a state-of-the-art fuels database, the application of sophisticated models such as FireTech and WRF-Fire, and detailed validation. This will demonstrate the benefits of fire-infrastructure modeling and act as a test bed for evaluating new observation, simulation, decision, mitigation, and communication technologies.
B. **Integrated Modeling**

40) *Adaptive Real Time Observations.* There are many opportunities for adapting fire-weather and fire observations and assimilating these into fire simulations so as to improve the model forecasts. Specific technologies include: mobile stations, dropped sensors, distributed sensor networks, unmanned aerial vehicles [UAVs], and remote sensing.

41) **Urban-Wildland Interface.** Fire simulations typically do not handle the interface where wildland fires meet built-up urban area, but these are precisely the areas where economic damage and loss of life can be the greatest. Research is need to develop models for urban fire and couple these to wildland fire simulations, and infrastructure impact estimators.

42) **Focus on Watersheds.** Models of the short and long term impacts of fire on watersheds need to be coupled to fire simulation so that the potentially severe consequences of watershed disruption is quantified as an event unfolds, in order that appropriate defensive and mitigation actions can be taken in a timely manner.

C. **Validation & Verification**

43) *Spatial Sensitivity Analysis.* The sensitivity of fire models to the spatial resolution of fuel, moisture, terrain, and wind fields is poorly understood. Research on these sensitivities is critical for effective model initialization and for the efficient use of computational and observational resources. Uncertainties associated with these sensitivities must be quantified.

D. **Information Management**

44) *Improved Input Data Sets.* The key input parameters for operational wildland-fire models are fuel structure, fuel moisture, wind field, and topography. Data sets for these parameters suffer from quality issues and lack completeness. Furthermore, urban building data sets and not widely available in uniform, standard formats.

E. **Model Improvement**

45) *Multi-Phase Flow.* Spotting from burning objects needs to be better incorporated into fire models. This is particularly import for fires at the urban-wildland interface.

46) **Moving from Research to Operations.** The gap between the remarkable sophistication in current fire research models and the less sophisticated operational models should be closed through careful upgrades of the operational models using techniques and lessons learned in the research models.

47) **Neglected Consequences.** A number of significant consequences are neglected in typical quantitative analyses of fire risk: (i) watersheds; (ii) power lines, substations, pipelines, telecommunications sites, etc.; (iii) smoke on roadways; (iv) ecological impacts; (v) economic consequences; and (vi) social/psychological trauma. Estimators for these need to be developed so that they can be operationally linked to fire simulations.
V. Biochemical Dispersion Recommendations

A. Decision Science

48) Decision Frameworks. Flexible software frameworks that unify data flows for (i) real time response, (ii) source-term forensics, (iii) mitigation studies, (iv) insertion of abatement technologies, and (v) consequence assessments will facilitate a much broader style of decision support than currently possible.

B. Model Improvement

49) Neglected Consequence Models: Several areas of consequence modeling have been neglected: (i) CBRN cleanup models, including both restoration times/resources and economic costs; (ii) mid- and post-event societal response, including compliance, panic, hoarding, evacuation, and psychological effects modeling; and (iii) broad economic effects that include long-term structural impacts on local economies. Infrastructure, economic, and societal consequences models should be directly linkable to dispersion and transport models so that comprehensive analyses are possible.

VI. References & Related Recommendations


VII. Appendix: Workshop Participants

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Recommendations for Research on Extreme Weather Impacts on Infrastructure