Use of Meteorological Modeling and Computational Fluid Dynamics Modeling for Analysis of High-Impact Weather Events to Support Litigation

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Introduction

Recent high impact weather events, such as Hurricane Katrina and Hurricane Sandy, highlight the vulnerability of heavily populated coastal regions. As coastal regions continue to grow in population and infrastructure, they become increasingly vulnerable to the effects of severe weather events, such as hurricanes. Litigation and disputes regarding insurance coverage often follow extreme weather events and underscore the need for accurate and sound meteorological analyses to determine the nature and cause of storm-related damage and to identify meteorological conditions at specific locations and times. The very fine resolution of storm conditions, down to the scale of individual buildings and structures, needed for these purposes can be achieved via:

- A coupling of observational data and numerical meteorological modeling through data assimilation
- Simulations using computational fluid dynamics (CFD) modeling techniques.

Two public domain numerical meteorological models that are useful for such analyses are the Fifth Generation Mesoscale model (MM5) developed by the National Center for Atmospheric Research (NCAR) and Pennsylvania State University developed (Grell et al. 1995) and the more recent Weather Research and Forecast Model (WRF) developed by NCAR, the National Oceanic and Atmospheric Administration (NOAA), the Air Force Weather Agency, and others (Skamarock et al. 2008). These public domain models have the following important features:

- Public domain models have benefited from the research, testing, and evaluation efforts of many diverse groups of users
- Model codes are not proprietary and are fully documented in the scientific literature
- WRF model is under continued improvement and testing as new physics and numerical schemes are developed and implemented
- Models can be used for real-time forecasting and as a tool for after-the-fact meteorological analysis
- Models have sophisticated data assimilation capabilities for incorporating observations.
The meteorological output from these meteorological models can be used with other models, such as (CFD) models, to compute wind-induced pressure forces on building structures. The combination of observational data analysis, numerical meteorological modeling, and CFD modeling allows for a complete analysis of meteorological conditions contributing to structural damage during these events.

Why Not Just Rely on Observations Alone?

A key problem in meteorological analysis is a relative dearth of observations. Even relatively dense surface observation networks can miss small-scale meteorological features, such as narrow bands of high winds that may affect an area of interest. The highest impacts and maximum associated damage from some weather events, such as hurricanes, may occur on a fairly small spatial scale. The limited amounts of observational data available often hinder a complete analysis of the surface wind structure and the identification and resolution of fine-scale details, such as narrow swaths of high winds. Furthermore, the extreme surface conditions associated with these storms often interrupt meteorological measurements or destroy monitoring equipment, resulting in even less data to accurately define meteorological conditions at a particular time and location. Numerical modeling can help overcome problems related to missing or sparse observations.

Although near surface wind data may exist, there is often a lack of information about how the wind speed changes with height above ground. Numerical modeling can provide realistic estimates of changes in wind speed with height, which can then be used to assess the wind gust potential. Previous studies have shown that wind gusts associated with land-falling hurricanes can play a very large role in causing structural damage. These bursts of wind can easily be missed by the currently available meteorological monitoring stations.

Technical Approach

Our recommended approach for storm analysis is to use a blend of numerical modeling and available observational data. This approach will yield an optimized high-resolution grid of meteorological data for the meteorological event being evaluated. This information can then be used to compute other parameters via CFD modeling techniques, if needed, to further evaluate the impact of a storm on physical structures. Figure 1 shows a schematic of the analysis approach which consists of the following:

- Assessment of available meteorological observational data
- Numerical modeling with data assimilation
- CFD modeling for a microscale flow analysis.

The first step in reconstructing a meteorological event is to assess the adequacy and representativeness of the available observational meteorological data. Such data may consist of raw measurements from surface monitoring stations and upper air soundings or a gridded analysis, such as the National Hurricane Center’s HWIND [Powell et al. 1998] analysis for Atlantic basin hurricanes. If the observational data are sufficient to adequately depict meteorological conditions (i.e., wind direction and speed, temperature, etc.) during a specific event, then the application of a numerical model may not be necessary.

![FIGURE 1. Schematic of meteorological modeling and analysis procedure.](www.exponent.com)
When observations are not sufficient, then a numerical meteorological model, such as WRF or MM5, can be used to reconstruct a meteorological event. Our recommended approach is to perform numerical simulations using data assimilation techniques so that the available observational data can be used to adjust or “nudge” the model prediction towards the observations, resulting in a coupled numerical and observation-based meteorological analysis. These techniques have been successfully used for creating fine-scale, multi-year data sets for air quality studies and can also be applied to the analysis of severe storm events.

**MM5 Simulations of Hurricane Katrina**

Figure 2 shows two plots of the surface wind field of Hurricane Katrina based on high-resolution MM5 simulations conducted by Exponent scientists. This analysis was motivated by litigation for which it was critical to determine if structural damage to industrial buildings in the New Orleans area was attributable to wind or flooding. In this case, direct wind measurements in New Orleans were interrupted due to instrument damage sustained during the peak of the storm.

Figure 3 shows the vertical wind profile derived from MM5 simulations depicting how wind speed changes with height aboveground in New Orleans during the passage of the western eyewall of Katrina on the morning of August 29, 2005. Note the very rapid increase in wind speed with height with a windspeed of 134 miles per hour just a few hundred meters above the ground and even higher winds further aloft. This is typical of strong hurricanes during landfall, where the surface drag reduces the speeds near the surface creating strong wind shears. Such an environment contributes to convective wind bursts near the ground as high speed air is drawn downward. It is important to consider these effects when evaluating maximum surface wind speeds during land-falling hurricanes. Observational data are not likely to be adequate to define the vertical wind structure needed for an assessment of wind gust potential. It is important to determine if high wind gusts could have occurred when assessing whether structural damage was due to flooding or wind.

**FIGURE 2.** Surface wind field analysis (Klausmann 2009) from MM5 simulations of Hurricane Katrina during landfall at 0600 UTC (top) and 1300 UTC (bottom) on August 29, 2005. MM5 simulations used four-dimensional data assimilation using a 2-km resolution storm following grid.

**FIGURE 3.** Vertical profile from a MM5 simulation of wind speed at New Orleans at 1300 UTC on August 29, 2005 during the passage of the western eyewall of Hurricane Katrina (Klausmann 2009).
WRF Model Simulations of Tropical Storm Irene

WRF model simulations, also with data assimilation, were performed to reconstruct the wind field of Tropical Storm Irene. The simulations showed that the WRF model performed well, reproducing key aspects of the observed storm winds. Figure 4 shows the near-surface wind field (i.e., wind vectors and filled contours of constant wind speed). Time series plots of observed and model simulated wind speeds at 10 m above ground at Providence, Rhode Island and Buzzards Bay, Massachusetts showed that the model-simulated wind speeds agreed closely with the observed speeds during the storm (Figure 5). These results demonstrate the ability of the WRF model to accurately simulate the spatial structure and evolution of tropical cyclones. Such information can be used to evaluate wind conditions within an area of interest to determine the time period and location of the highest wind speeds associated with a tropical storm or hurricane.

FIGURE 4.
WRF simulated boundary-layer wind field of Tropical Storm Irene during landfall across the northeast United States. WRF simulations used four-dimensional data assimilation and were run on a 4-km resolution nested grid.

FIGURE 5.
Time series of WRF model and observed 10-m elevation wind speed at Providence, Rhode Island, and Buzzards Bay, Massachusetts.
How Do We Use Computational Fluid Dynamics Modeling?

CFD modeling can be used to determine the wind-induced pressure forces on building structures. In the case of Hurricane Katrina, simulations using the FLUENT CFD model were conducted using estimates of peak winds from MM5 model simulations. Figure 6 shows the FLUENT model computed wind induced pressure on the building walls (Klausmann 2009). The associated peak wind gusts were estimated to be 60 m/s from the northwest. The winds were from the upper left and show strong negative (outward) pressures (blue shading) on the rear of the building structure. These areas of large outward pressure on the structure walls closely matched observed building damage.

FIGURE 6. Calculated wind-induced pressure on building structures using an estimated wind gust of 60 m/s based on MM5 simulated winds during passage of Hurricane Katrina. (Klausmann 2009).

Exponent’s Expertise

The Atmospheric Sciences staff at Exponent provides consulting services in the atmospheric sciences. Our staff specializes in applied meteorology, meteorological modeling and analysis, climatological studies, and air quality modeling. Clients benefit from our multidisciplinary approach, which includes the support of staff across multiple practice areas. Our atmospheric scientists work closely with building structural and civil engineers to evaluate structural damage due to storm events. Exponent can perform both a meteorological analysis as well as storm surge analyses to help determine if damage was the result of high winds or flooding. Exponent has powerful computational capabilities, including a dedicated 120-processor Linux cluster computer, which allow us to simulate at very high spatial resolution, to run multiple scenarios, and to conduct sensitivity studies.

Exponent scientists have used a variety of available observational data to perform analyses of meteorological conditions associated tropical storms and flash flood events. These data sets include surface and upper air meteorological observations, radar data, satellite imagery, buoy data, various NOAA analyses, and high resolution terrain and land use data.

Exponent scientists have conducted numerous meteorological modeling simulations worldwide using the MM5 and WRF meteorological models coupled with available observational data to depict detailed meteorological structures associated with severe storms such as hurricanes. Exponent scientists have coupled numerical meteorological model output with CFD models to determine the pressure forces on building structures and to determine if structural damage was due to a particular storm event.

The Atmospheric Sciences staff has worked extensively with the OpenFOAM® and ANSYS FLUENT® CFD models to characterize source terms and simulate complex flows over building structures or other obstacles. Exponent staff has considerable expertise with the STAR-CCM+® CFD model from CD-Adapco.
References


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Mr. Alfred Klausmann is a Managing Scientist in Exponent’s Health Sciences Center for Exposure Assessment and Dose Reconstruction. Mr. Klausmann is a Certified Consulting Meteorologist with more than 25 years of experience in the areas of applied meteorology. He is experienced with mesoscale meteorological modeling using MM5 and Weather Research and Forecast (WRF) models and meteorological data analysis.

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