Enabling high-resolution forecasting of severe weather and flooding events in Rio de Janeiro

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Safe operation of many cities is affected by relative extremes in weather conditions. With precipitation events, local topography and weather influence water runoff and infiltration, which directly affect flooding. Hence, the availability of highly focused predictions has the potential to mitigate the impact of severe weather on a city. Often, such information is simply unavailable. The initial step to address this gap is the application of state-of-the-art weather models at an urban scale calibrated to address this mismatch. The generation of operational forecasts at such a scale for the Rio de Janeiro metropolitan area suggests a horizontal resolution of approximately 1 km and a vertical resolution in the lower boundary layer of tens of meters. Forecasting impacts from storm-driven flooding events requires the development of a coupled hydrological model that operates at a street scale with resolution of approximately 1 m, capturing local terrain effects and simulating surface flow and water accumulation, especially for overland flow and ponding depth. This coupled approach has enabled operational prediction of storm impacts on local infrastructure, as well as measurement of the model error associated with such forecasts.

Introduction

The operation of many cities is dependent to a significant degree on weather conditions, especially with regard to relative extremes in wind, precipitation, or temperature. For example, with precipitation events, local topography, surface characteristics, and weather conditions influence water runoff and infiltration, which directly affect flooding as well as drinking water quality and availability. The impact of such events creates challenges associated with public safety for both citizens and first responders for emergencies. Therefore, the availability of highly localized weather model predictions, focused on municipal public safety operations, has the potential to reduce the impact of severe weather on citizens and local infrastructure. Typically, information at such fine temporal and spatial scales is simply not available. Hence, any optimization that is applied to these processes to enable proactive efforts utilizes either historical weather data as a predictor of trends or the results of continental-scale or regional-scale weather models. Neither source of information is appropriately matched to the temporal or spatial scale of many such operations. Although near-real-time assessment of observations of current weather conditions may have the appropriate geographic locality, by its very nature it is only directly suitable for reactive response. Alternatively, such techniques known as nowcasting could be employed to enable adjustments in planned responses based on evolving weather conditions during an extreme event. However, that would still require a predictive capability at the appropriate scale to be in place.

To understand the public safety implications of these ideas, IBM Research has an on-going project, dubbed *Deep Thunder* [1]. In particular, the ability to predict specific events or combination of weather conditions with sufficient spatial and temporal precision, and lead time coupled to the operational impacts, is being addressed to enable allocation and deployment of sufficient resources (people and equipment) prior to such events to alleviate the effects of severe weather and increase time for planning [2].

Digital Object Identifier: 10.1147/JRD.2013.2263414

Motivation

The city of Rio de Janeiro, in Brazil, often faces the consequences of intense rainfall, which include landslides and flooding. In early April 2010, the city endured the worst rainstorms in 48 years, which was considered one of the most significant, global weather events of 2010 [3]. These storms led to significant flooding, including flash floods and mudslides. As a result, there was significant loss of life, and tens of thousands of people lost their homes [4, 5]. There was little advance warning of the storms and their characteristics, and no opportunity for an effective response. To assist in planning for such events in the future, the city leaders have enabled sophisticated capabilities for the coordinated management of disasters, emergencies, or planned events of importance. As part of that effort, the integration of advances in hydro-meteorological research is a key prerequisite [6]. This would lead to the ability to provide a lead time on flooding events with significant impact on the city infrastructure and citizens.

Given the geography of the city and the nature of severe weather in the region, numerical weather prediction (NWP) presents significant challenges [7]. In addition to its near-tropical setting along the coast of the Atlantic Ocean and the western portion of Guanabara Bay, there are regions where the terrain has a high aspect ratio, related to the Serra do Mar mountain range. Although sea breezes moderate the temperatures along the coast, especially during the summer, cold fronts from the Antarctic can lead to rapid changes in local weather. Of particular concern is the rainy summer season from December to March, during which precipitation events occur with more than 100 mm of rainfall per day. Given the complex terrain and surface characteristics, significant flooding becomes likely during this period [8, 9]. Further, there is evidence that low-level jets contribute to the formation of mesoscale convective systems during this season, which mature at night. This forcing for convective initiation occurs during increasingly unstable conditions driven by intense horizontal advection of heat and moisture at lower levels in the atmosphere [10].

Related work

Because of unresolved research issues for severe storm modeling at the urban scale in this region, the literature concerning operational deployment and skill is relatively sparse. This is in contrast to the considerable work focused on the morphology of these storms as outlined above. A study several years ago examined a number of weather forecasts for Rio de Janeiro, from government agencies, academia, and commercial sources. Some of the forecasts were derived from NWP results, whereas others were human-generated. In both cases, the quality of the forecasts was poor, especially with one to two days of lead time for precipitation. This included forecasts from Alerta Rio, an agency of the City Government of Rio de Janeiro [11].

Two recent efforts focused on the region have used a modern NWP code, namely the Weather Research and Forecasting-Advanced Research Weather dynamical core (or WRF-ARW) community model [12]. Ruiz et al. [13] examined model configurations, including choices of physical parameterization toward optimization of skill for 48-hour surface forecasts. Although they did not find a clearly superior set of choices, they also operated at a much more regional scale compared with the objectives herein. In addition, they did not evaluate precipitation forecasts.

In contrast, Santolim et al. [14] focused on an urban-scale problem, namely air quality in Rio de Janeiro. In this case, WRF was configured with four nests, with the innermost at 1-km horizontal resolution for the Rio de Janeiro metropolitan area. However, only 21 vertical layers were incorporated, which is far too coarse to adequately address the local orographic influences. The authors used the output of the 1-km nest as input to an air-quality model. The authors do not provide any discussion of the results of the meteorological model.

Approach

The long-term goal of this effort is to develop and deploy techniques that the City Government of Rio de Janeiro can utilize to plan for the impacts of pending flooding events, which requires a multi-step process. Initially, a coupled, predictive, hydro-meteorological model needs to be in place. That implies the use of quantitative precipitation estimates (QPEs) from a weather model or appropriate observing systems that can be calibrated for the hydrological component, which can operate independently of the source. The former would enable the approach to be used for short-term forecasting (i.e., with lead times of several hours to, potentially, a few days).

With data from an appropriate observing system (e.g., precipitation estimates from weather radar calibrated by a dense network of rain gauges), the hydrological component can be used for nowcasting (i.e., with lead times of up to a few hours). However, observing systems that can provide comprehensive and reliable precipitation estimates in real time are not yet deployed in the Rio de Janeiro metropolitan area. Therefore, this effort has focused on enabling the QPEs from the execution of a cold-start weather model, which uses only background fields and lateral boundaries derived from a coarser-scale weather model. The term "cold start" is used to indicate that the initial conditions for the model are derived only with the required fields from a coarser model and lack any small-scale features. From the hydrological component, flooding impacts can be estimated, but both its results and those of the meteorological component need to be calibrated against actual events and refined.

Current state-of-the-art NWP codes, operating at the meso-γ scale (i.e., cloud scale), have been shown to have potential in predicting specific events or combination of weather conditions with sufficient spatial and temporal precision to address the aforementioned scale mismatch. Therefore, the WRF-ARW model was utilized. Given that this work began in late 2010, version 3.2.1 of this community NWP model was adapted for use in the Rio de Janeiro area. An operational configuration was developed by retrospective analysis of recent significant precipitation events and compared against data from a network of 32 rain gauges operated by the City Government during that period. This included the aforementioned event in April 2010. The results of some of these numerical experiments are discussed below, each of which were conducted as "hindcasts" (which are equivalent to "forecasts" but are generated after the event by using only data that would have been available at the time an operational forecast model would need to have been executed).

The analysis—coupled with throughput considerations for operations, and availability of data for initial and boundary conditions as well as computational resources—led to a model configuration that uses a multi-resolution approach with telescoping meshes. In this case, four concentric meshes, each of which is 90×90 in size, horizontally, at the resolutions of 27, 9, 3, and 1 km are centered over the Rio de Janeiro metropolitan area. These meshes, or nests, are in two-way communications. Hence, the details of an inner nest have an impact on the coarser resolution nest outside of its boundaries. Although the horizontal resolution of the nests is the same as that in Santolim et al. [14], the configuration differs significantly in order to improve computational efficiency and to avoid potential numerical instability that may be caused by the high aspect ratio of the local orography.

To address the influence of the complex terrain, 65 vertical levels were established, with typically the lowest 15 or so being within the planetary boundary layer. The model orography was developed from altimetry data at 90-m resolution, available from the U.S. National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM). Static surface data from several sources are used to represent land use, soil, and vegetation. Data at 0.5-degree resolution from the U.S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) are used for initial conditions and lateral boundaries. Although these data represent potential compromises in fidelity for the modeling objectives, alternative data sources of higher quality for background fields and/or boundary conditions were not readily available to support operational forecasting at the time that this effort was performed. One-twelfth-degree resolution daily sea surface temperature data from NOAA/NCEP are also used as part of the initial conditions. There are two primary methods to access the NCEP data sets. The most timely and reliable method is through a system called NOAAport, where NOAA transmits data as soon as they are produced to a broadcast satellite in geostationary orbit above North America. These data are accessible via a NOAAport satellite receiver on the ground at IBM Research facilities in New York. Alternative access to these data sets is via an anonymous FTP (File Transfer Protocol) site, operated by NCEP for public access. As was referenced earlier, there is no real-time access to data from a comprehensive observing system. Hence, the ability to support data assimilation is lacking at the present time.

The WRF-ARW configuration, consisting of specific parameterization and selection of physics options appropriate for the range of geography in the region and the weather conditions of concern to the City Government of Rio de Janeiro, was determined via the numerical hindcast experiments. This includes the use of the following schemes: 1) Thompson, double-moment, 6-class, explicit cloud microphysics; 2) Rapid Radiative Transfer Model long wave radiation; 3) Goddard Space Flight Center short-wave radiation; 4) the Yonsei University Planetary Boundary Layer (PBL); and 5) the Kain-Fritsch cumulus parameterization. The NOAH (i.e., NCEP, Oregon State University, U.S. Air Force, NOAA National Weather Service Hydrology Laboratory) land-surface model has been used. A number of experiments with an urban canopy model were also performed to address the interaction between the effects of the aggregate buildings in a dense, urban environment on the lower portion of the PBL. However, the available surface data were of insufficient quality to enable stable and reliable model integration.

In parallel with the meteorological model deployment, a study to determine the feasibility of a predictive flash-flood model was performed to understand the flooding conditions and quality of relevant data that were available. As part of this study, the City Government of Rio de Janeiro provided access to 1-m-resolution Digital Elevation Model derived from LiDAR (light detection and ranging) data, and maps of soil type, land occupation, and city structure (streets, lakes, rivers, etc.), derived from their Geographic Information System (GIS). However, only limited digital drainage data were available, which constrains the creation of an accurate flooding model for the city. In contrast, very comprehensive historical flooding data were available. At least 232 recurrent locations of flooding have been cataloged. Although changes in the city drainage system at these locations are being made, these data include only the location and approximate peak time of flooding. At a few sites, a polygon has been mapped to outline the peak flooding area for particularly severe events. Detailed streamflow measurements as well as urban system drainage data are not available.

The study attempted to determine appropriate representations of the soil in the city, which are important for flood models. Some of the issues included estimating rainfall interception by vegetation and calculating the soil infiltration rate and the time when rainfall leads to immediate surface runoff. One approach to predict those physical processes is to simulate them with numerical models, taking into account the soil moisture balance and the transfer of runoff to the outlets of a catchment, etc. [15, 16]. However, such methods require detailed data that are not always available. As an alternative, probabilistic distributions can be used to estimate the point of soil saturation. The surface runoff can then be calculated as a function of past rainfall, potential evaporation, and function parameters [17]. The surface runoff produced by WRF-ARW has been adopted while the alternatives are evaluated.

For the simulation of overland flow, the governing equations should include conservation of mass and momentum (i.e., Navier-Stokes equations). In the cases where eddy viscosity and/or density variations are important (e.g., spatial variation of temperature), the full three-dimensional model should be employed. However, for problems such as gravity-driven flash flooding in Rio de Janeiro, subsurface vertical effects are negligible. Therefore, one can integrate the continuity and the momentum equations over the depth, applying appropriate boundary conditions at the bottom and the free surface to obtain the two-dimensional shallow water equations. Since this is one equation with one unknown, depth, it can be solved implicitly with a linear system.

This approach is similar to how Abderrezzak et al. [18] address flows in an urban area. For the work described herein, higher-resolution terrain data to describe more complex urban geography were used, in addition to coupling to an atmospheric model for initial conditions.

Therefore, using the limited historical data, a simplified high-resolution analytical model for flooding prediction has been implemented. It takes into account the geo-morphological and historical data. At the present time, it uses the results of the aforementioned WRF-ARW configuration as initial conditions. The solution for the shallow water equations with such precipitation estimates is used for analysis if a site that is historically prone to flood could receive a surface runoff flow that could cause a flooding event at these locations [19].

Implementation

After the convergence of the numerical hindcasts to successfully reproduce a number of past events, the resulting WRF-ARW configuration was put into operation in May 2011. As part of the Deep Thunder system and service, this included automated preprocessing and postprocessing of data, generation of statistical analysis of forecast quality, and dissemination of forecasts. When considering both throughput and the lead time required for emergency management planning, a capability was established to produce 48-hour forecasts, updated every 12 hours (i.e., initialized at 00 and 12 UTC [Coordinated Universal Time], daily). Beginning in July 2011, the flood prediction model was placed into operation as a postprocess for each execution of the weather model.

Given the time-critical nature of weather-sensitive decisions, if the weather prediction cannot be completed sufficiently fast, then it has no value. Such predictive simulations need to be completed at least an order of magnitude faster than real time. To scale for multiple applications and be modest in cost, including cost of operations, IBM POWER*-based SMP (symmetric multiprocessing) clusters running AIX* are used. For this class of modeling, two types of systems are employed. One is an older POWER6* processor-based cluster of four-core blades, where timely throughput is achieved with two BladeCenter* systems of 14 nodes. A newer POWER7* processor-based system with four 32-core nodes also is used to achieve operational throughput. In both cases, InfiniBand** is employed as a high-speed, multi-stage, low-latency interconnect switch. Hybrid, spatial-domain decomposition using the OpenMP** (Open Multiprocessing) programming interface within a node, and the MPI (message passing interface) between nodes, across the switch fabric, is employed as well as asynchronous input and output on the POWER7 system, whereas MPI only decomposition is used on the POWER6 cluster.

For the hydrological model, which operates as a postprocess for the weather model, the same throughput requirement exists. The simulation is also parallelized via spatial decomposition, but at a basin level as determined via analysis of the terrain data. The computation for each basin is mapped to a thread on a single, small-footprint SMP server with 12 Intel Xeon** cores running Red Hat Enterprise Linux (RHEL).

However, rapid computation is insufficient if the output cannot be easily and quickly utilized. In this case, the results of each model-based forecast are provided to the City Government of Rio de Janeiro via a web portal in its integrated command center, which has been dubbed, in Portuguese, Previsão Meteorológica de Alta Resolução (High-Resolution Weather Forecast), or PMAR. This web portal is populated with a variety of fixed visualizations. They range from techniques to enable more effective analysis to strategies focused on the applications of the forecasts. It includes high-definition-television resolution animations of various two-dimensional and three-dimensional visualizations of key weather variables, specialized plots or meteograms depicting many weather variables at 62 locations such as key landmarks and weather stations within the city, detailed tables of the forecasted weather data at those sites, and a Google Earth**-based interaction with

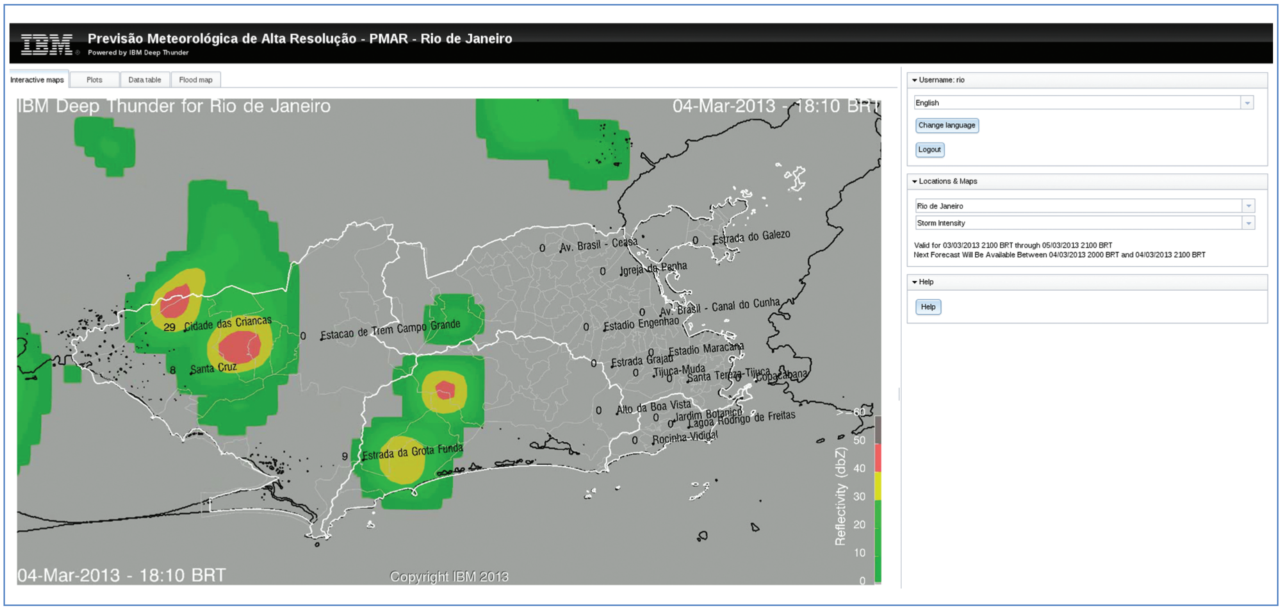

Figure 1

Example screen capture of the PMAR web portal showing a frame from a forecast animation of predicted composite reflectivity, which is indicative of storm intensity. The data are shown as color band contours following the legend at the lower right. Areas in red and dark gray are indicative of strong convective cells. The data are overlaid with maps of the hydrological basins and neighborhoods in Rio de Janeiro. Landmarks in the city are also indicated with the forecasted reflectivity at those locations shown (e.g., see Estádio Maracañа or Cidade das Crianças). Via the selector at the right, other forecast animations can be selected. Through the tabs at the upper left, other content such as site-specific forecasts and tables can be selected, as well as an interactive view of the results of the flood prediction.

the flood model output. Some of these features are illustrated in **Figure 1**. The variables include precipitation totals and rate, composite reflectivity, runoff, temperature, wind, humidity, pressure, etc. All of the web-based weather content contains information every 10 minutes of forecast time (i.e., in the animations, meteograms, and tables) for each 48-hour model run to capture the inherent dynamics at the urban scale. The visualizations are customized to the model configuration and the requirements of the end users and incorporate data from the GIS of the city.

Results

To illustrate the capabilities of the coupled model configuration, one of the critical historical events is discussed. The heavy rainfall between April 4 and 6, 2010, was driven by a strong, fast-moving cold front from northern Rio Grande do Sul and southern Santa Catarina. As a result, significant rainfall began in and around Rio de Janeiro in the late afternoon and early evening of April 5. Tipping buckets operated by the city of Rio de Janeiro recorded more than 300 mm of rain in a 24-hour period.

To simulate this event with a hindcast with lead time, consider a model run initialized at 00 UTC on April 5 (2100 BRT [Brasilia time] on April 4) using the aforementioned configuration. **Figures 2** and **3** show results of the meteorological component, while **Figure 4** depicts results of the hydrological component. Such visualizations are produced operationally as part of the Deep Thunder implementation for Rio de Janeiro.

In Figure 2, cloud properties are visualized as a three-dimensional isosurface of total cloud water density at a threshold of 10^{-3} kg of water from all microphysics species per kilogram of air. Shown is a single frame from an animation of 289 time steps (every 10 minutes during 48 hours). The isosurface is rendered in a three-dimensional coordinate system with true altitude, derived from the time-varying geopotential of the model, registered with the model orography, which can be colored by other data generated by the model. In particular, instantaneous precipitation rate is shown as colored contour bands following the legend to the upper right. Areas in green correspond to 80 to 100 mm/hr and are correlated with strong convective cells depicted as the isosurfaces early in the storm on April 5. The contours are overlaid with arrows that illustrate horizontal wind velocity at an altitude of ten meters, along with a map of Rio de Janeiro (in white). The arrows are colored by wind speed, following the legend to the lower right. The direction of the arrows corresponds to the direction to which the wind flows. The arrows form a starburst pattern, indicative of a downburst, in areas

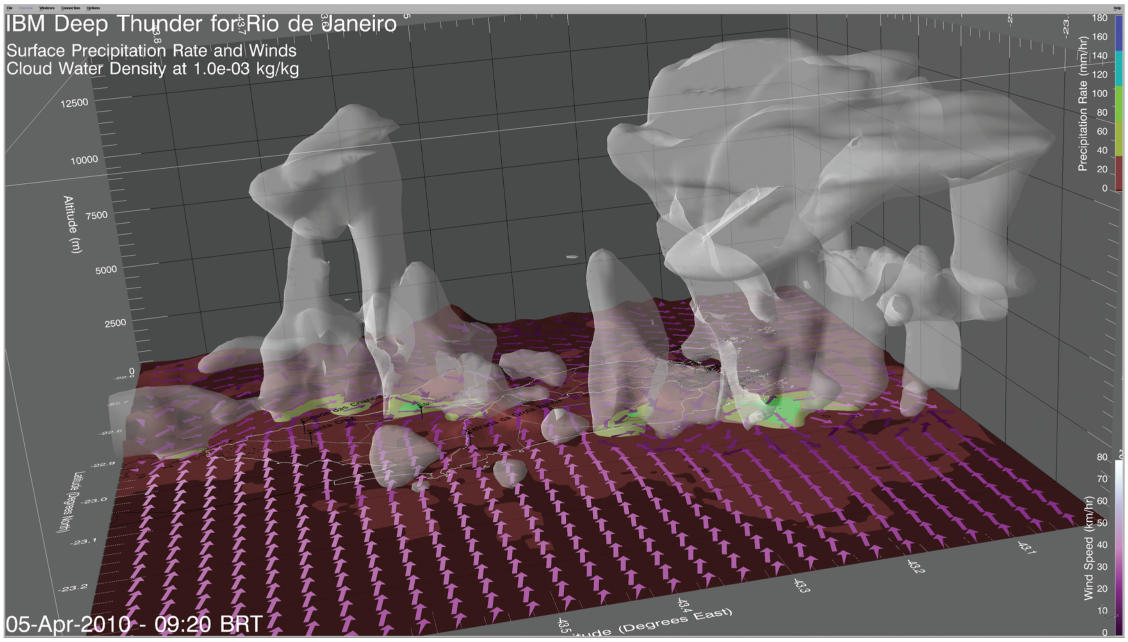

Figure 2

Meteorological hindcast of the April 2010 storm event showing cloud properties, wind, and precipitation. In this frame from an animation of a 48-hour forecast, clouds are shown as an isosurface of total cloud water density coupled with contour bands of precipitation rate at the surface, overlaid with arrows that depict horizontal wind velocity at an altitude of 10 m.

where the precipitation rate is highest (i.e., in green). In addition, the tops of the intense convective cells can be seen at an altitude of more than 10 km.

Figure 3 shows a site-specific hindcast for one of the locations of the 32 rain gauges operated by the City Government at that time, via a multi-panel meteogram. Of particular note are the bottom two panels. One (left) shows accumulated precipitation (red) and precipitation rate (blue). The other panel (right) shows simulated reflectivity (red) and surface runoff (blue). To evaluate the precipitation forecasts, the panel with that information is shown in greater detail. Given rain rates of this magnitude, the ability for this rain gauge to accurately record precipitation is unclear. However, the data did indicate an accumulated rain amount of 221.2 mm as of 1749 BRT on April 6. The hindcast had rain stopping at this location at 1800 BRT with a total of 207 mm. The rain gauge recorded a maximum hourly accumulation of 32 mm at 0204 on April 6. This corresponds well to when the hindcast shows a maximum rainfall rate, which is instantaneous and produced as output at 10-minute intervals as shown on the plot, not hourly accumulation (i.e., 43.5 mm/hr at 0200, 70.3 mm/hr at 0210, 83.5 mm/hr at 0220, and 19.6 mm/hr at 0230). Both of these features are highlighted in Figure 3.

Although details of the coupled flood model are discussed elsewhere [19], Figure 4 illustrates results from the hindcast of the April 2010 event. The top panel is the final frame of an animation that depicts hourly changes of the flooding through 48 hours. The gravity-driven terrain channeling is shown by a colored overlay of water depth on a digital elevation map, following the legend to the lower right. The bottom panel shows a relatively small portion of the city area, which is marked on the map in the upper panel. The area in that portion of the city (Mangue-Maracanã) that was affected by the floods during that event is highlighted in yellow, as an overlay in Google Earth. The hindcast results of the flood model are illustrated via a colored overlay, following the same color map for water depth as used in the upper panel. Although the model results are more detailed than the flooding reports, the spatial correlation is clear.

Forecast verification

Although the results discussed previously with the April 2010 hindcast are compelling, more comprehensive validation of model-based forecasts is required to properly assess the quality of the model in operation. In order for decision makers within the City Government to use the operational forecasts with confidence, quantitative information on meaningful accuracy, and relative uncertainty

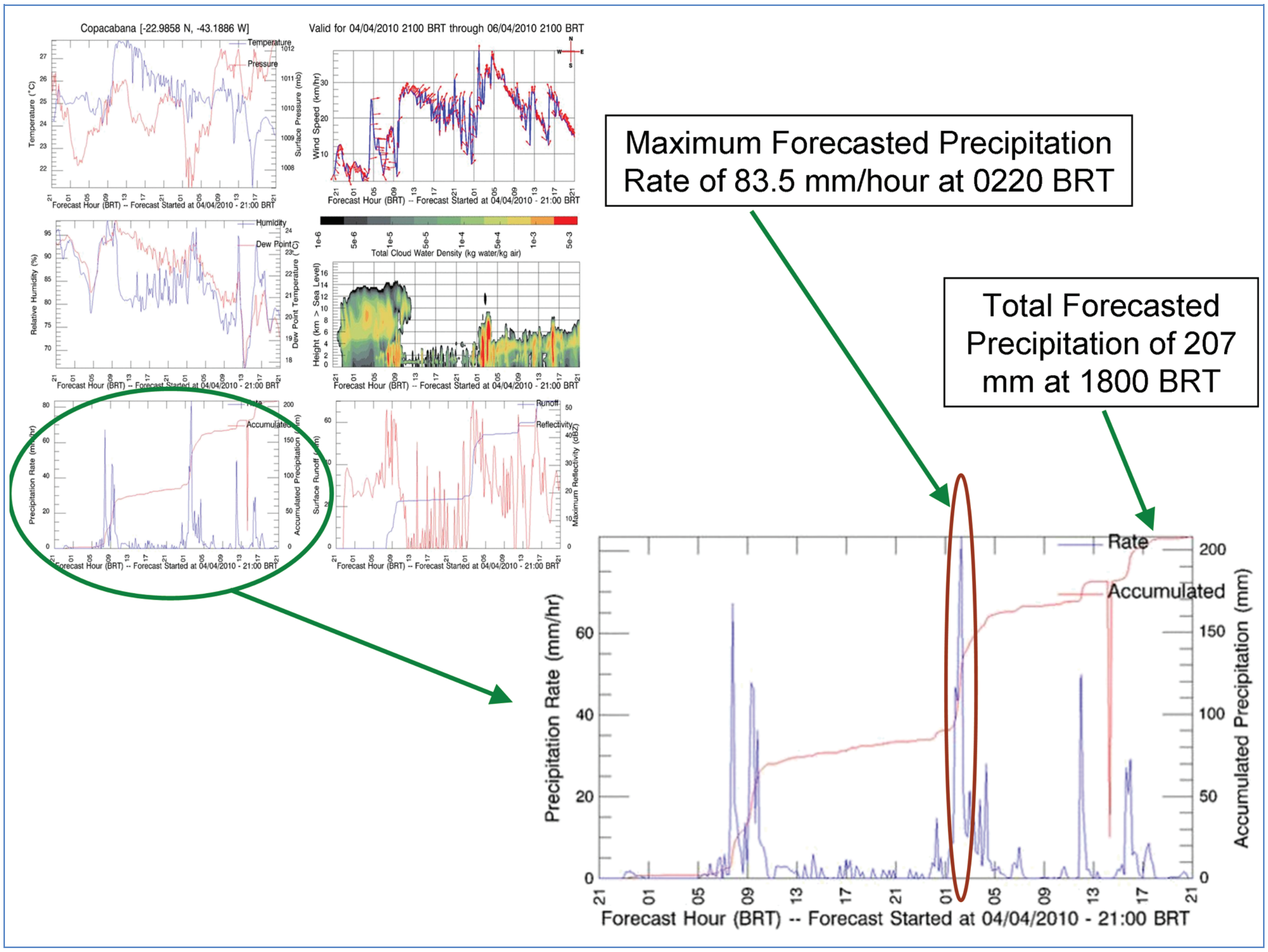

Figure 3

Site-specific hindcast for the rain gauge at Copacabana for 48 hours starting from 00 UTC on April 5. This multi-panel meteogram illustrates ten different variables from the weather model, plotted as a function of forecast time. The bottom left panel is shown in more detail, given its focus on total precipitation and instantaneous precipitation rate. The period of maximum forecasted rate is marked, along with the time that the rain is forecasted to stop.

are required. Currently, obtaining quantitative information is focused on the meteorological component of the coupled model and is complementary to traditional meteorological metrics. A further challenge involves the availability of reliable and comprehensive measurements to which a model can be compared. Alerta Rio within the City Government now operates 33 rain gauges in Rio de Janeiro. Only two of those sites have a full complement of meteorological instruments. There are also five stations within the city limits operated by Instituto Nacional de Meteorologia (INMET) for which data were obtained beginning in late December 2011. Data from ten additional stations operated by the Instituto Estadual do Ambiente (INEA) were included, starting in January 2012.

Because the primary concern at the present time is the reliability of the precipitation forecasts, statistical metrics tailored to the needs of the City Government were developed. In particular, the focus is on the amount of precipitation, connected to how flood warnings are issued. The underlying mechanics of the calculations were implemented through the Model Evaluation Tools (MET) community software [20].

Two different metrics were developed. The first metric analyzed the amount of rainfall observed hourly at the 33 Alerta Rio stations, while the second metric utilized the hourly rainfall from the 48 locations where Alerta Rio, INMET, and INEA have their instrumentation. Despite concerns about the accuracy of measurements by tipping buckets during high rainfall rates, as well as siting and maintenance constraints, the observations were considered perfect for the purpose of forecast verification. Given the categorical nature of these data, statistics were based on the use of contingency tables.

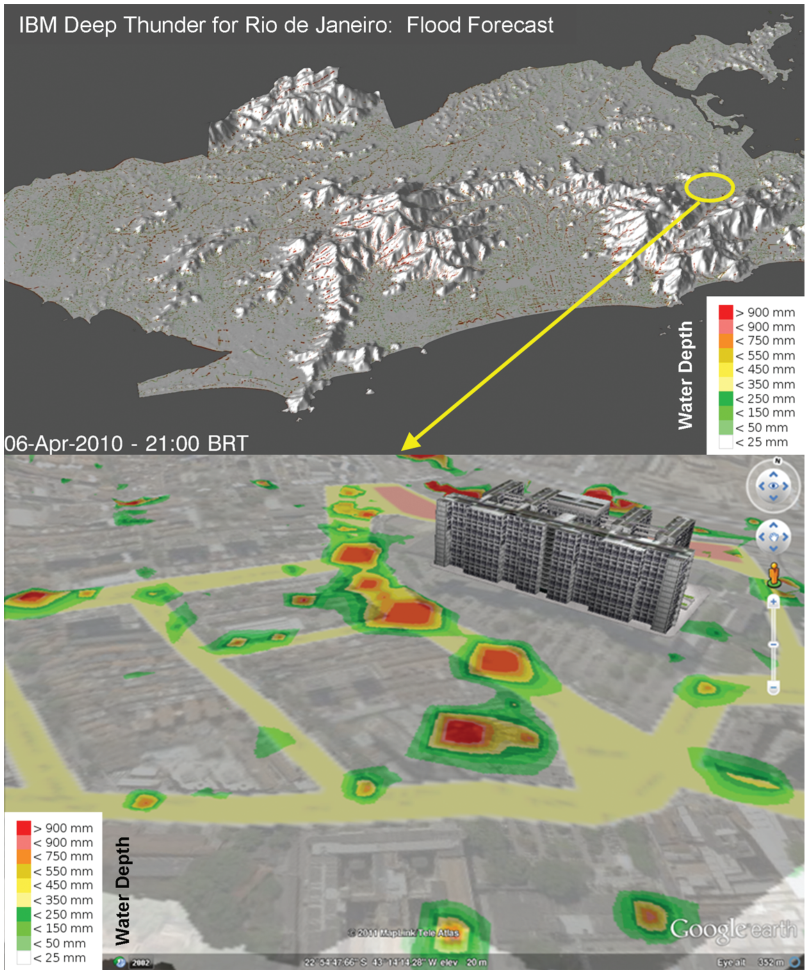

Figure 4

Coupled hydrological hindcast of the April 2010 storm event, showing areas of flooding. The top panel shows the full gravity-driven terrain channeling from the predictions of total precipitation as a colored overlay of water depth on a digital elevation map. A small area of the city (as marked) is shown in greater detail in the bottom panel. The reported flooded areas are highlighted in yellow, while the hindcast results are illustrated via a colored overlay.

The first metric considered every 12-hour period within the 48-hour forecast cycle. Although the Alerta Rio observations are made roughly every 15 minutes and the model results are produced every 10 minutes, only hourly resolution was considered. The rainfall measurements and forecasts were categorized by magnitude, corresponding to the way the City Government responds to different types of events, namely, less than 5 mm (weak); 5 to 25 mm (moderate); 25 to 50 mm (strong); and more than 50 mm (very strong). Given this categorization, a 4 $\times$ 4 contingency table was applied. Hence, a correct forecast means that the amount of rainfall predicted at the rain gauge location must be within the correct range as observed during the appropriate 12-hour period. This approach was applied to all of the forecasts covering rain events between May 26, 2011 and January 6, 2012. The accuracy for all categories was 93.6% for hours 00 to 12, 91.8% for hours 12 to 24, 93.1% for hours 24 to 36 and 92.8% for hours 36 to 48, with no tolerance at the category boundaries (i.e., the forecast must be exactly within the category of the observed rainfall). The accuracy for all hours for weak events, moderate events, strong events, and very strong events was 94.1%, 93.7%, 98%, and 97.4%, respectively.

To extend the understanding of the forecast quality from January 2012 onward, a second, more stringent metric was developed. In this case, accumulation through 6-hour periods was considered in examining both timing and location, using data from all 48 sites. The rainfall is no longer categorized. Rather, tolerances are introduced to determine whether a point forecast is correct. The tolerance applies to no-rain forecasts and evaluation of false positives. Specifically, every 6-hour accumulated precipitation forecast (AF) is compared with the corresponding (in timing and location) accumulated observed precipitation (AO):

a. A tolerance of $\pm 20\%$ of AO is considered when comparing AF to AO. If AO is lower than 25 mm, a minimum tolerance of ± 5 mm is considered in the comparison. A function, $\delta(AO)$, can be defined to describe this tolerance as follows:

$$\begin{aligned}\delta(AO) &= 0.2 \times AO, \text{ if } AO \geq 25 \text{ mm}\\ &= 5 \text{ mm}, \text{ otherwise.}\end{aligned}$$

b. It is considered a *hit* if the forecasted value AF is in the range $[AO - \delta(AO), AO + \delta(AO)]$.

c. The same tolerance range is applied to handle no-rain forecasts and false positives (i.e., a rain forecast when a no-rain event was observed).

Given this approach, a 2×2 contingency table is employed to evaluate the forecasts at each rain gauge location. An accuracy score is used, which is the ratio of the number of hits to the total number of forecast comparisons. Reports are generated weekly, showing forecast performance on a daily, weekly, and monthly basis. Typical accuracy remains over 90%, with results always over 80% for all of 2012.

Conclusions and future work

A coupled model approach to enable highly accurate and precise, operational, short-term forecasts of severe weather events has shown to be feasible for Rio de Janeiro. It has enabled the City Government to better anticipate and plan for the storm impacts on local infrastructure. As experience with the system grows, efforts to further improve and validate the forecasts will continue. The data used for verification will be enhanced to include an additional eight weather stations, operated by other agencies within the 1-km resolution forecasting domain. Out of the new total of 56 locations, 16 have a full suite of instrumentation, which will enable some validation for temperature, wind speed, and dew point. Additional metrics are likely to be developed to examine spatial and temporal phase errors, accuracy of precipitation rates, and sensor reliability.

In parallel, efforts to improve the forecast quality will focus on the deficiencies of the various input surface data sets and their implications on model physics. This will include the incorporation of 1-km resolution sea surface temperature data available from NASA, and evaluation of land use and soil data collected by the City Government in their GIS as well as from the Moderate Resolution Imaging Spectroradiometer on the Aqua and Terra spacecraft operated by NASA. Complementary to this effort will be the consideration of updates to various physics schemes and new implementations available from the WRF community.

The forecast dissemination will be enhanced to include additional visualization of diagnostic fields. This has the potential to improve the ability of the City Government to assess potential extreme events and apply the capabilities to other applications.

Since the observing system infrastructure is not available in Rio de Janeiro to enable data assimilation to consider both hot-start execution and potential nowcasting applications, this work is being applied in other regions. The term "hot-start" indicates having a high-resolution, near-real-time representation of the initial conditions, which includes local-scale features. For example, both the meteorological and the hydrological component of this coupled model system have been deployed in parallel to consider extreme precipitation events in Brunei Darussalam, where there are strong orographic influences in this tropical setting. Unlike in Rio de Janeiro, the Brunei Meteorological Service has recently deployed a dual polarization radar system. The data from this radar will provide both detailed spatial coverage for rainfall estimates as well as near-real-time data to enable local data assimilation.

Acknowledgments

We thank the City Government of Rio de Janeiro for support of the development and deployment of the PMAR system at the Center of Operations. For the work in Brunei, building upon our efforts in Rio de Janeiro, we thank A. G. Naim, H. Hassan, and S. A. Husain of the UBD|IBM Centre at the Universiti Brunei Darussalam, with whom we are working and who have provided access to hydrometeorological and surface data.

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Received November 15, 2012; accepted for publication December 11, 2012

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