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An Automatic Wind Warning System for Construction Projects

M.P.M. Gibbons[1], R.J. Chapman[2], D.M. Cherneski[2], C. De Jong[3], M. Gauthier[2]
[1]Rowan Williams Davies & Irwin Inc. (RWDI)
[2]RWDI AIR Inc.
[3]City of Calgary

Abstract: Environment Canada, the National Centers for Environmental Prediction (NCEP), and private weather companies provide numerical weather forecast products that cover Canada and the United States. While the spatial and temporal resolution of these numerical weather forecast products are sufficient for public consumption there are limitations to the application of these products for predicting winds at multiple working heights for construction projects. This paper summarizes an advanced wind warning system that was developed for the City of Calgary. This system combines weather forecast technology with wind engineering best practices to predict winds at multiple working heights and provide alerts to reduce incidents of falling debris and the impacts of catastrophic wind related events. Technical, scientific and operational characteristics of the system as well as the results of preliminary model verification studies will be presented.

1 Introduction

On August 1, 2009, three-year-old Michelle Krsek was struck and instantly killed when a piece of metal construction material was blown off a tower in Downtown Calgary. Her brother and father, who were with her at the time, were injured. At the time of the incident, rain and thunderstorms were reported at the Calgary International Airport (YYC), approximately 10 km northeast of the accident. METAR records from the airport indicated winds were blowing out of the west, gusting between 60 and 80 km/h. The anemometer at YYC measures wind speeds at a height of 10 m. The storm was brief, lasting only 15-20 minutes. A review of similar incidents between 2009 and 2010 revealed four additional events where substantial pieces of construction material were blown off of a construction site in Downtown Calgary with no reported injuries.

In the wake of the August 2009 tragedy and incidents like it, RWDI AIR Inc. was contracted by the City of Calgary to develop an early wind warning system for mid- to high-rise construction sites in the City of Calgary. The goal of the system is to minimize the occurrences of construction materials becoming airborne due to high winds as well as the consequences of such occurrences by providing advance warning to the stakeholders – the City, contractors, subcontractors and building owners – of near-term high wind events so that preventative measures can be undertaken. These preventative measures are simple to implement, and include securing loose material or delaying the lifting of materials to working heights. Depending on the magnitude of the wind event predicted, the measures may also include actions such as halting construction, the readying of emergency personnel, localized evacuations or the closing of city streets/blocks.

It was identified that wind gusts resulting from mechanical turbulence and convective conditions were of greatest concern to the construction of mid- to high-rise buildings. Numerical Weather Prediction (NWP) models can provide reliable near-term weather forecasts to address the mechanical turbulence and convective conditions on the order of 1-3 days in advance of a high wind event.

1.1 Mechanical Turbulence

Mechanical turbulence is a measure of the fluctuations in wind speed about a mean wind speed and originates from the generation and decay of eddies as atmospheric wind encounters various surface roughness and surface obstructions. The statistical behavior of turbulence in response to surface roughness has been well studied in the civil engineering field through numerous empirical studies and is described in the following sections.

Contemporary NWP models do not have the resolution to predict the wind conditions within a complex urban environment, where mid- to high-rise buildings are located. Additionally, the wind speeds predicted by the NWP models do not fully account for the 'gustiness' of the wind, which is induced by the surface roughness (i.e. buildings, trees, topographic features) of the upwind terrain. A built-up urban environment can cause local turbulent phenomena, such as downwash, building corner accelerations or street venturi accelerations, as illustrated in Figure 1. In order to account for these effects, wind engineering principles and techniques must be applied to the NWP models to predict gust wind speeds at multiple working heights with reasonable accuracy. These effects can be predicted and quantified with a reasonable amount of certainty using established wind engineering techniques, wind tunnel testing or computational fluid dynamics (CFD) modeling.

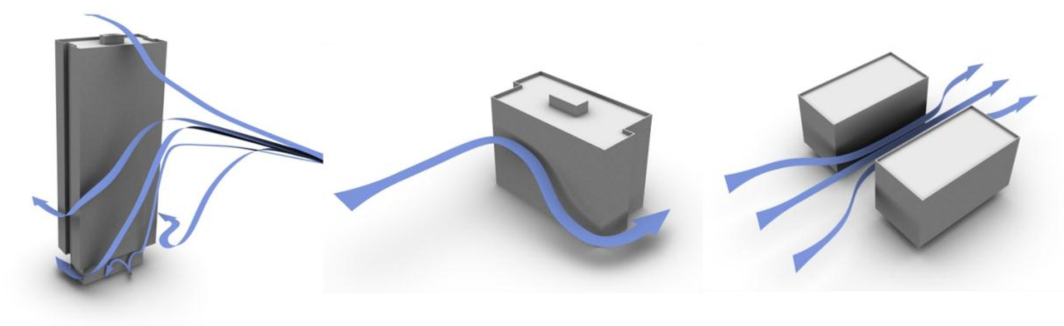

Figure 1: Illustrations of building induced downwash (left), corner accelerations (mid) and street venturi accelerations (right)

The results of a CFD simulation conducted on a section of Downtown Calgary, as shown in Figure 2, demonstrated the concepts illustrated in Figure 1. Upper level wind speed contours and surface level wind vectors are shown, with relatively faster wind speeds displayed in red (fastest) to yellow and relatively slower wind speeds displayed in green to blue (slowest). Areas of local building accelerations are prominent.

1.2 Convective Turbulence

Convective conditions typically occur in the summer months as thunderstorms can develop rapidly and generate gust events. In many cases, the scale of a convective thunderstorm is too small to be properly modeled with a NWP mesoscale model such as the Weather Research & Forecasting (WRF) model. Therefore, a "Convective Wind Gust" algorithm was developed to trigger an alarm of gust events when the meteorological conditions are favorable for the formation of Thunderstorms. The Convective Available Potential Energy (CAPE), Lifted Index (LI) and the Storm Relative Helicity (SRH) computed by an ensemble of meteorological models for the 0-180 mb layer above ground are the selected parameters used in the algorithm.

1.3 Wind Warning System Setup

The configuration of the wind warning system is illustrated in Figure 3. The NWP models, as described in Section 2 was combined with the wind gust information derived from the wind engineering and building heuristics described in Sections 3 and 4 to obtain hourly predictions of gust wind speed at multiple heights for a forecast window of 48 hours. When the gust wind speeds within the forecast window exceed a user defined threshold value, alerts are sent out to the users through text messages or email. Users are able to view forecasts over the internet using a web browser or smart phone, or they can elect to receive an email with a daily forecast. As is described in following sections, the forecasts are site specific and are available for multiple working heights, accounting for surrounding land use, structures and terrain.

Results of the system, including an investigation of an extreme wind event, are presented in Section 5, and an outline of future work is presented in Section 6.

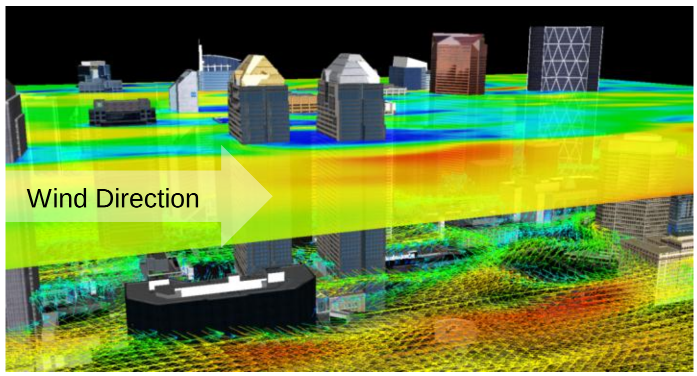

Figure 2: Results of a CFD simulation conducted on a portion of Downtown Calgary

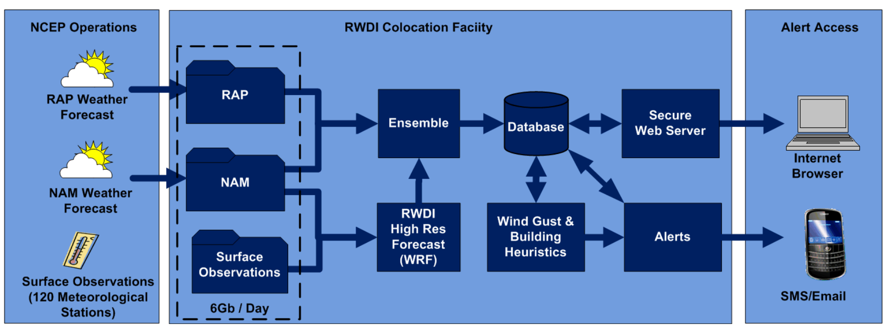

Figure 3: Schematic of the wind warning system

2 NWP Model Details

High quality NWP models are critical for predicting high wind speed events. Environment Canada and NCEP run NWP models on large computer clusters to support global and national weather forecast applications. Portions of the data output from these models are packaged into files and made available to the public over the Internet. Wind fields and other meteorological parameters can be extracted from these NWP model output files and used as input to wind gust models to provide forecasts of high wind events.

All NWP model forecasted outputs have some level of inherent uncertainty. As such, for the advanced wind warning system for the City of Calgary, an ensemble of multiple NWP models is used to address the uncertainty and reduce the risk of missing high wind events. In this project, output files from two NCEP NWP models are downloaded multiple times per day as input into the wind warning system. Two custom high-resolution NWP forecasts are added to improve the spatial resolution of the NCEP forecasts and these are then also input into the wind warning system.

2.1 North American Mesoscale Forecast System

The North American Mesoscale Forecast System (NAM) is a long-range NWP forecast model run operationally by the Environmental Modeling Center (EMC) at NCEP every 6 hours. NAM is run on a lambert conformal grid with a non-uniform 12 km lateral grid cell resolution centered over the continental USA. For further technical details, refer to McClung (2011) and Environmental Modeling Center (2013).

2.2 Rapid Refresh

The Rapid Refresh (RAP) is a NWP model run operationally every hour by the EMC at NCEP. RAP is developed by the Earth System Research Laboratory (ESRL) and is a high frequency short-range forecast that constantly assimilates the most recent measured observation data and is intended to support aviation and severe weather applications. RAP is run on a lambert conformal grid with a non-uniform 13 km lateral grid cell resolution centered over the continental USA. For further technical details, refer to Benjamin et. al. (2007) and Earth System Research Laboratory (2012).

2.3 Custom High-Resolution NWP Model Runs

The National Center for Atmospheric Research (NCAR) supports the development of a community based weather forecasting model called the Advanced Research WRF (WRF-ARW). The technical details of this model are described in Skamarock, et al. (2008). The RAP model described in the previous section is operated using a customized version of the WRF-ARW source code. Multiple high-resolution weather forecasts using the WRF-ARW are included in the system. For the advanced wind warning system for the City of Calgary, two operational NWP models using WRF-ARW v3.4.1 are included as input to the wind gust calculation algorithms. The first is a custom built operational NWP denoted WESTCAN4, with 4 km lateral grid cell resolution. The second is a project-specific NWP with 2 km lateral grid cell resolution denoted CALGARY2.

The WESTCAN4 NWP model domain is centered over the Rocky Mountains along the Alberta/British Columbia border (Figure 4, white box). The modelling domain is approximately 1300 km square (1,690,000 km^2) covering the majority of Alberta, British Columbia and extending into a portion of northwestern United States. The CALGARY2 WRF domain is centered over Calgary (Figure 4, red box) and is approximately 260 km square (66,500 km^2) covering City of Calgary and outlying regions.

WESTCAN4 is initialized and uses boundary condition data from the NAM 12 km model. CALGARY2 is nested within WESTCAN4. The vertical resolution of both operational NWP WRF-ARW models consists of 50 vertical levels with a top pressure level of 50 hPa. This vertical resolution allows the operational models to simulate approximately the lower 20 km of the atmosphere, which includes the lower stratosphere and the troposphere, where the majority of our daily weather occurs. The models are configured to use observation nudging based four dimensional data assimilation (FDDA). Table 1 lists a summary of the physics configuration used for both of the operational WRF-ARW models.

Table 1: WRF Model Physics Configuration Summary

Parameter	**Physics Configuration**
Land Surface	Unified Noah Land-Surface Scheme
Surface Layer	Monin-Obhukov (MM5) Scheme
Planetary Boundary Layer	YSU Scheme
Microphysics	WSM 6-class Graupel Scheme
Long-Wave Radiation	RRTM Scheme
Short-Wave Radiation	Dudhia Scheme
Cumulus Parameterization Scheme	Off, Explicit Convection Allowed
Urban Physics	Off
Sea Surface Temperature Update	On

Figure 4: WRF 4 km (white bounding box) and 2 km (red bounding box) domains

3 Wind Gust Determination

The atmospheric boundary layer is a key concept in wind engineering and has been described by many in the literature (see Holmes (2001), Simiu and Scanlan (1996)). As described by Holmes (2001), mean wind speed increases with height and can be described by the power law profile, as presented in Eq. 1,

[1] $$\frac{U_1}{U_2} = \left(\frac{h_1}{h_2}\right)^{\alpha}$$

[2] $$\alpha = \left(\frac{1}{\ln(50/z_o)}\right)$$

where U_1 and U_2 are mean wind speeds at heights h_1 and h_2, respectively, and α relates to the surface roughness of the upwind terrain. The parameter α can be related to the roughness length, z_o, of the upwind terrain as shown in Eq. 2. Typical values for z_o and α are summarized in Table 2 based on land use/terrain (Holmes 2001).

Table 2: Land use/terrain types and corresponding z_o and α values (from Holmes 2001)

Land Use/Terrain	z_o	α
Very Flat Terrain (water, mud flat, salt flat)	0.001 - 0.005	0.09 - 0.11
Open Terrain (open country, grasslands, fields)	0.01 - 0.05	0.12 - 0.14
Suburban Terrain (short building 3-5 m in height)	0.1 - 0.5	0.16 - 0.22
Dense Urban Terrain (tall buildings 10-30 m in height)	1 - 5	0.26 - 0.44

The power law profile is a reasonable representation of the variation of mean wind speed with height, up to the gradient height. The gradient height is the height at which the drag induced by the terrain no longer impacts/slows the wind speed. Gradient height tends to increase with the magnitude of surface level winds, with typical values for high wind events in the 500-1000 m range.

Although the power law profile does a reasonable job of relating mean wind speeds at different heights, the relationship differs when gust wind speeds are considered. As described by Wills et al. (2002) and Kordi and Kopp (2011), the liftoff of a debris source (e.g. construction material) depends on the magnitude of the gust wind speed. Durst (1960) describes a relationship between various averaging times for wind speeds, which makes it possible to relate a mean wind speed to a gust wind speed. This allows a practitioner to estimate a 3-second gust wind speed (i.e. wind speed averaged over 3 seconds) to a mean hourly wind speed by the ratio of approximately 1.52. Conversely, a 10-minute mean wind speed is related to a mean hourly wind speed by the ratio of approximately 1.065.

This relationship (known as the Durst curve) is only considered representative for surface level winds - winds at a height of approximately 10 m, in relatively open terrain. Land use/terrain has a direct impact on the turbulence profile, which in turn dictates the relationship between mean and gust wind speeds. As turbulence levels tend to decrease with height, so too does the ratio between gust and mean wind speeds. As the wind warning system is to predict wind speeds at multiple working heights, including the top of the study building, it is necessary to consider alternative methods to determine wind gust factors by height for the wind warning system.

3.1 Wind Engineering Algorithm

Based upon building characteristics, neighboring buildings, previous boundary layer wind tunnel and CFD studies of buildings in Downtown Calgary and wind engineering techniques, an algorithm to calculate wind gust factors has been prepared. This algorithm leverages decades of research and reflects the state of the art in wind engineering. Specific details of this algorithm are proprietary, although resulting wind gust factors for a sample location in Downtown Calgary have been presented in Section 5.

3.1.1 Wind Gust Measurements from NWP

The NWP models used in the ensemble also provide surface level wind gust estimates. These wind gust calculations are based on momentum transfer from winds at the height of the planetary boundary layer. A typical NWP wind gust calculation is given in Eq. 3,

[3] $$U_{gust,h} = U_h + (U_{grad} - U_h) \times \left(1 - \min\left(0.5, \frac{h_{grad}}{2000}\right)\right)$$

where $U_{gust,h}$ is the gust wind speed at height h, U_h is the mean wind speed at h and U_{grad} is the wind speed at the gradient height, h_{grad}.

It was mentioned previously that wind gust calculations from NWP models do not account for complex urban environments, where mid- to high-rise buildings are located. The wind gust system attempts to refine this prediction by comparing the wind engineering method to the gust wind speeds that are output by the NWP and reporting the highest speed to the user.

3.2 Wind Tunnel Testing

Gust factors have also been determined using wind speed sensors for buildings that have been tested in a boundary layer wind tunnel. Such studies (described by many in the literature, including as Irwin (1981), Williams et al. (1990), Soligo et al. (1998)) model a building and its surroundings at a scale typically between 1:300 and 1:500 and provide local measurements of wind gust factors at a typical height of 1.5 m. When these wind speed sensors (also known as Irwin Sensors) are mounted at ground level, they provide a measurement of pedestrian comfort. However, these sensors can also be installed at various elevations/levels of the building, which allows for wind gust factors to be directly measured and input into the wind warning system.

3.3 Liftoff Speeds of Construction Materials

As mentioned in Section 1, the choice of threshold wind speed for the wind warning system is left to the user. This reflects the different needs of the many users of this system, such as differing construction materials and sites that are in different phases of construction. In order to better inform the users of the system of the potential risks associated with certain wind speeds, the information in Table 3 was compiled which relates a gust wind speed range to items that are at risk of take-off. This was done using methodology described by Wills et al. (2002), and provides an estimation of the gust wind speed required to lift many common construction materials and items found at construction sites.

Table 3: Gust Wind Speeds and Corresponding Construction Materials at Risk of Lift-off

Gust Wind Speed Range (m/s)	Items at Risk of Lift-off
2 – 8	Ball of Crumpled Paper; Piece of Paper; Tarp; Disposable Coffee Cup, Empty; 2" Polystyrene Rigid Insulation
9 – 14	R-12 Insulation, single sheet; 3/8" Plywood Sheet; Steel Stud, 162SSP-25; Circular Ducting, 6" diameter; Sheet Metal, Aluminum, 20 gauge; 1/2" Plywood Sheet; Steel Stud, 600SSP-20; Plastic Pipe/Conduit, 1/2" diameter
15 – 17	1/4" Nut, Finished Hex; Swing stage, 5 m long, with netting; Hard hat, not on head; 4' x 4' x 4' Wooden Garbage Container; 3/4" Plywood Sheet; Rectangular Ducting, .1 by .2 m; Rectangular Ducting, .4 m by .8 m
18 – 21	Disposable Coffee Cup, 1/2 Full; R-12 Insulation, single package; 1/4" Bolt, Hex, 1" Length; Sheet Metal, Steel, 20 gauge; Drywall Sheet, 3/8"; Q Decking
22 – 25	1/2" Nut, Finished Hex; Scaffolding, with netting, 36 ft high; Drywall Sheet, 5/8", Fire Rated; Plastic Pipe/Conduit, 4" diameter
26 – 29	Disposable Coffee Cup, Full; R-12 Insulation, pallet; Rebar, 10M
30 – 33	1" Nut, Finished Hex
34+	2" Nut, Finished Hex; 1" Bolt, Hex, 3" Length

4 Convection

The wind gust algorithm detailed in Section 3 addresses gusts caused by eddies generated by interactions of the atmosphere with the surface that have a well-studied statistical behaviour. However, these are not the only source of gusts that can affect a building or construction site. Convection within the troposphere can generate strong gusts through a number of phenomena including: updrafts downdrafts, wet/dry microbursts, spreading cold pools and their frontal vortices. These events can occur as part of a single convective cell, as part of a thunderstorm, or as part of a large mesoscale convective system.

The advanced wind warning system for the City of Calgary includes algorithms to examine meteorological data in the ensemble of NWP forecasts and notifies users of times when there is potential for gusts from convection. The NWP models used in the system have lateral grid cell sizes that are too large to explicitly model the vertical movements of convection. Instead, the algorithm finds times of atmospheric instability using Convective Available Potential Energy (CAPE), Lifted Index (LI), and Storm Relative Helicity (SRH) and filters out times that are missing forcing mechanisms and times with strong caps that would prevent convection from starting based largely on Keller (2004).

5 Results

5.1 Gust Factors by Height

Wind gust factors for a generic building located in downtown Calgary have been presented in Figure 5. The influence of differing upwind terrain and surrounding buildings is evident. The wind gust factors represent the ratio between the gust wind speed at a given height and the mean speed at 500 m obtained from the NWP models. When combined with the NWP model forecasted wind speed and direction, gust wind speeds are predicted at the respective heights.

5.2 November 2011 Wind Storm

On November 27, 2011, a strong low front moved across Southern Alberta and caused strong wind speeds in the City of Calgary. The maximum mean and gust wind speeds measured at the anemometer at YYC were 67 and 91 km/h, respectively, at a time of 13:00 MST. Damage to buildings in Calgary was significant, with the total insurable losses pegged at $200 Million (McMurray 2011). Most of the damage impacted existing buildings with no incidents of windborne debris from mid- or high-rise construction sites.

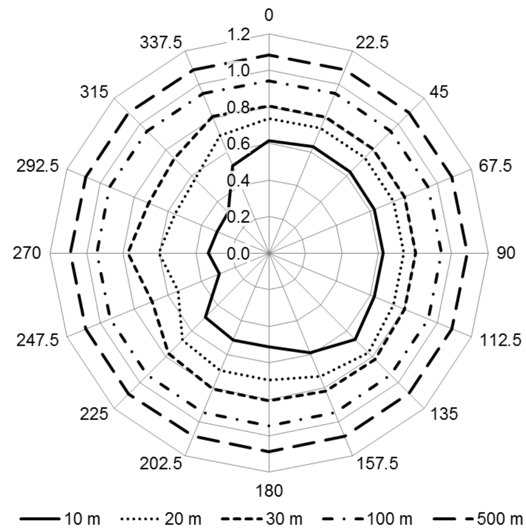

Figure 5: Wind gust factors (radial direction) by height and wind direction (azimuthal direction). Wind direction is measured clockwise from north.

The wind warning system was operational at the time of this event and a comparison of gust wind speeds at a height of 10 m to those measured at YYC is presented in Figure 6. The wind warning system was able to predict that a strong wind event would occur during the late morning/early afternoon of November 27 as early as 48 hours in advance, and predicted the timing of the peak of the event as early as 34 hours in advance. Alerts were sent to all respective stakeholders. The City of Calgary was able to shutdown sections of the downtown core and proactively deploy emergency personnel. Only minor injuries were reported, which were sustained by emergency personnel caused by falling glass from blown out windows. (Global Calgary, 2011).

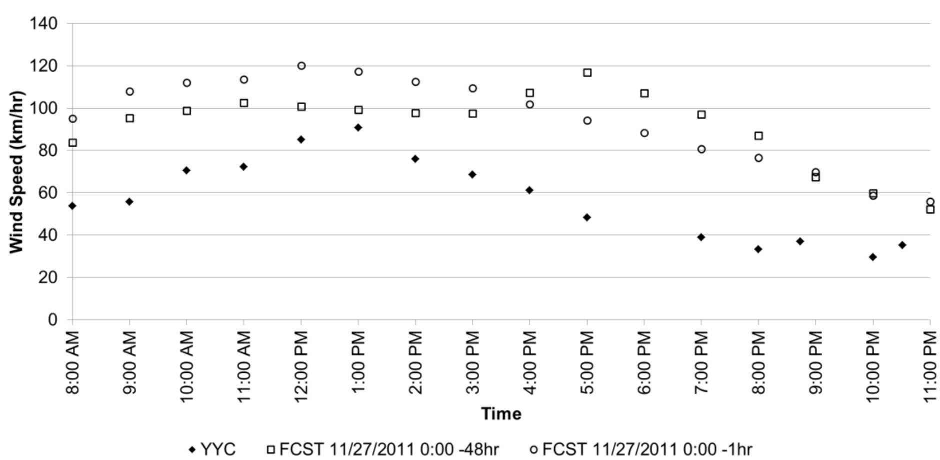

Figure 6: Comparison of gust wind speeds measured at YYC and forecasted by the wind warning system, 48 hours and 1 hours in advance of November 27, 2011 at a height of 10 m.

6 Planned Future Developments

Referring back to the schematic of the system presented in Figure 3, the wind warning system can be divided into three main components: the input NWP models, the gust calculation algorithm and the gust alert delivery system. Each of these components has areas where future development is either planned or ongoing, with the intent of improving the accuracy of the wind gust predictions and the overall user experience.

Many additional operational forecast models are available which could be integrated into the system, including the Environment Canada's 2.5 km and 15 km grid Regional Deterministic Prediction System (RDPS) models and NCEP's 4 km grid NAM model. It is expected that the inclusion of these models, particularly the 2.5 km RDPS and the 4 km NAM, will lead to better prediction of local weather systems due to increased grid resolution.

As the November 2011 event indicated, advance notice of an extreme wind event is valuable, potentially lifesaving, information for many stakeholders. The scope of this system in Calgary is expanding to include the delivery of wind warning notifications to: homebuilders; emergency personnel; and existing building owners. This expansion in scope requires a refinement of the gust calculation algorithm to ensure that the methodology is appropriate for each of the additional stakeholders.

Although the system has been implemented in the City of Calgary it is intended that this system be applied to other jurisdictions, both nationally and internationally. The application of the system to other jurisdictions would require an update to the NWP models; however the structure of the system would remain the same.

To provide the user greater flexibility in how they obtain wind gust forecasts, a smart phone application is planned.

7 Conclusions

A wind warning system for the City of Calgary has been presented. The system combines an ensemble of NWP models with a wind engineering algorithm to predict gust wind speeds at multiple working heights for mid- to high-rise buildings in the City of Calgary. The system has been operational since summer 2011 and has been applied to dozens of sites in Downtown Calgary. The system has proved to be reliable and has provided advanced warning to stakeholders up to 48 hours in advance of extreme wind events. The architecture of the system allows for developments and improvements to be implemented on an ongoing basis. Although currently only applied in Calgary, the intent is to apply the systems in other jurisdictions nationally and internationally.

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