Decision Making Regarding Aircraft De-Icing and In-Flight Icing Using the Canadian Airport Nowcasting System (CAN-Now)

by

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ABSTRACT

The Canadian Airport Nowcasting Project (CAN-Now) has developed an advanced prototype all-season weather forecasting and nowcasting system that can be used at major airports. This system uses numerical model data, pilot reports, ground in-situ sensor observations (precipitation, icing, ceiling, visibility, winds, etc), on-site remote sensing (such as vertically pointing radar and microwave radiometer) and off-site remote sensing (satellite and radar) information to provide detailed nowcasts out to approximately 6 hours. The nowcasts, or short term weather forecasts, should allow decision makers at airports such as pilots, dispatchers, de-icing crews, ground personnel or air traffic controllers to make plans with increased margins of safety and improved efficiency. The system is being developed and tested at Toronto Pearson International Airport (CYYZ) and Vancouver International Airport (CYVR). A Situation Chart has been developed to allow users to have a high glance value product which identifies significant weather related problems at the airport. Some new products combining observations and numerical model output into nowcasts are being tested. This talk will describe the uses of the system for decisions regarding aircraft de-icing at the ground and in-flight icing over the airport. Some statistical verifications of forecast products regarding precipitation amount, precipitation type, in-flight icing, etc, will be given.

INTRODUCTION

Operations at airports are very sensitive to weather. This not only includes the obvious take-off and landing phases of aircraft, but also activities that are essential components of an airport such as active runway selection, snow removal, de-icing, safety of ground personnel during lightning events, etc. Many decisions are made that require weather information on short time scales. Nowcasting is weather forecasting on such short time scales, typically less than 6 hours. The Canadian Airport Nowcasting (CAN-Now) project was initiated in 2006 to help address the need for improved short term weather forecasting. It is a follow-on to an earlier project which was titled the Airport Vicinity Icing and Snow Advisor (AVISA; Isaac et al., 2006). AVISA focused on icing at the airport but it was recognized that such a system would not be implemented unless it considered potential weather hazards during all seasons. The current work will focus on the winter of 09/10 and the forecasts related to icing but it will also introduce the other capabilities of CAN-Now.

The main objective of CAN-Now is to develop a four-season forecasting/nowcasting system at a major airport which will be able to produce detailed nowcasts and forecasts of weather phenomena (see Table 1). This information should allow airport-related decision makers (pilots, dispatchers, de-icing crews, ground operations, air traffic control, etc) to make decisions that have increased margins of safety and improved efficiency. For this project, Toronto Pearson International Airport (CYYZ) and Vancouver International Airport (CYVR) have been chosen to demonstrate such a system. The prototype nowcasts rely on existing routinely available weather information including Numerical Weather Prediction (NWP) model output, site climatologies, radar and lightning network observations, and measurements from on-site routine sensors (e.g. wind, precipitation, visibility, ceiling, temperature), augmented by other specialized information from high resolution local area models and from high time resolution instrumentation such as microwave radiometers, vertically pointing radars, and particle type sensors. For several years now, the prototype system has run in a nowcasting mode, detecting weather hazards and providing forecasts out to about 3-6 hours for most phenomena, and out to 36 hours for some subset of phenomena.

Table 1: Phenomena considered by CAN-Now System

Snow and rain events
Freezing precipitation and ice pellets
Frost
Blowing snow
Icing aloft
High winds/gusts
Wind shifts/shear
Turbulence
Lightning
Low ceilings
Low visibility and fog
Convective cells

BASIC DESIGN OF CAN-NOW SYSTEM

It is known that persistence and trends of observations produce better forecasts on very short time scales, and numerical models produce more accurate forecasts on longer time scales, usually greater than 4-6 hours (see Golding 1998). CAN-Now blends observation and numerical model data to produce better nowcasts. A schematic view of CAN-Now is given in Figure 1.

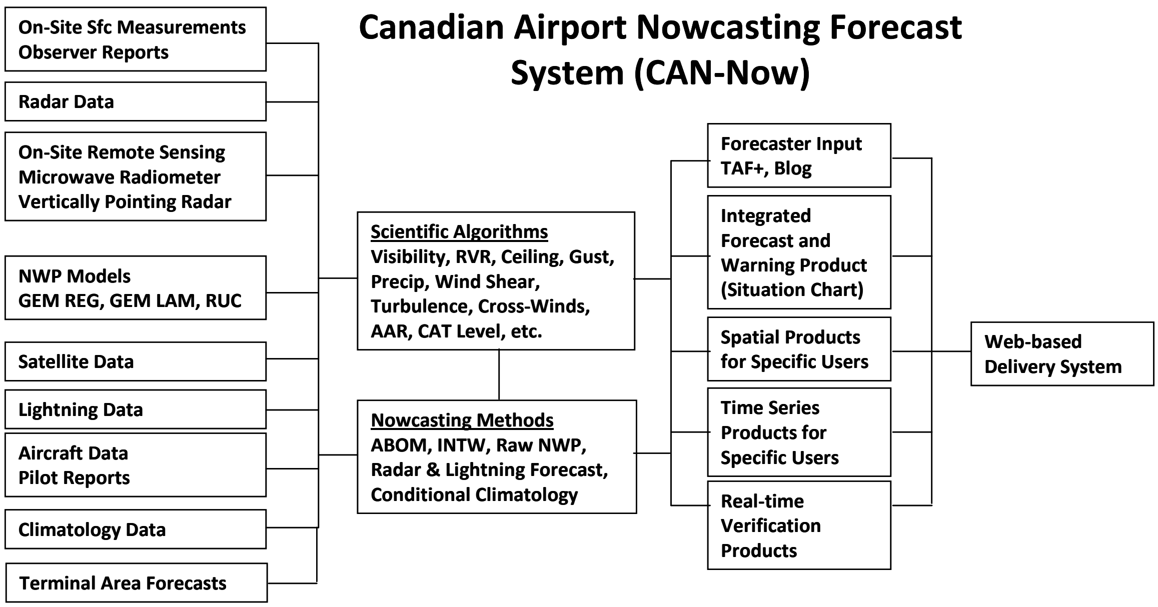

Figure 1: A schematic representation of CAN-Now. The abbreviations will be described in the text.

Basically the system ingests any information that is currently available. It integrates the data and applies a number of scientific algorithms to produce an increased set of weather parameters. Such aviation-relevant parameters include: visibility (Gultepe et al., 2006; Boudala and Isaac, 2009; Gultepe and Milbrandt, 2010), wind gust (modified Brasseur, 2001), runway visual range (Boudala et al. 2011), and precipitation type (Bourgouin, 2000 and direct model output). For ceiling, model estimates are used based on simple thresholds. In GEM REG cloud base occurs at the lowest level where the cloud fraction is greater than 0.01. In GEM LAM, similar to RUC, cloud base is chosen at the lowest level where the cloud water mixing ratio is 10^{-6} kg/kg. .Nowcasting methods then make use of the system inputs, plus the algorithm results, to generate new forecast products. The CAN-Now system also includes forecasts of ceiling and visibility obtained from an application that combines current conditions, conditional climatology and model-based conditions (Hansen 2007). A Web-based system is used for delivery of the products.

OBSERVATIONS AT THE AIRPORT

In addition to using the reports from the official human observers at both CYYZ and CYVR, instruments were installed to obtain high temporal resolution measurements of temperature, relative humidity, wind speed and direction, ceiling, visibility, precipitation rate and type, as well as cameras that could monitor current conditions. Whenever possible, some of parameters were measured by more than one instrument which increased the robustness of the system. At CYYZ, the largest HUB airport in Canada, some specialized instruments were installed, including a Vertically Pointing X-Band Radar, manufactured by McGill University, and a TP3000 profiling microwave radiometer from Radiometrics. The instruments at CYYZ were located near the existing meteorological compound just off one of the main runways. At CYVR, the instruments were located between the major runways (see Figure 2).

Figure 2: Shows the location of the on-site instruments installed at CYYZ (left panel) and CYVR (right panel) as marked on a Google Map. The major runways at CYYZ are highlighted in blue. The de-icing pad at CYYZ is marked with a letter A.

The data at both sites were recorded on-site and at the main project server. Most of the measurements were acquired at 1 min intervals. Experience has shown that there are many rapid fluctuations in variables like wind speed and direction, visibility, and ceiling which require 1 min data in order to get an accurate picture of what is happening at the airport.

NOWCAST SYSTEMS

Several short term weather forecasting or nowcasting systems have been developed for use with CAN-Now.

A radar extrapolation scheme moves radar echoes or precipitation echoes forward based on the history of their past motions. This gives approximately a two hour "nowcast" of precipitation that will occur at the airport. The system predicts the most likely precipitation rate, as well a possible maximum amount based on a 16 degree arc of potential precipitation echo trajectories. This point forecast process is currently implemented in Environment Canada's Unified Radar Processor (URP) software and is based on the scheme developed by Bellon and Austin (1986). A similar scheme has been implemented in the Weather Support to Deicing Decision Making (WSDDM; Rasmussen et al., 2001) system.

A Weighting, Evaluation, Bias Correction and Integrated System for Nowcasting (WEBIS), or Integrated Weighting System (INTW; Huang et al., 2009) for its short title, examines several different models, dynamically weighs those models based on past performance (6 hours), and applies dynamic and variational bias corrections to produce a short term forecast to 6 hours. The INTW system uses the 1) Canadian GEM Regional Model (GEM REG) with a 15 km spatial resolution with a 7.5 min time step, 2) the U.S. Rapid Update Cycle (RUC) Model with a 13 km spatial resolution 6 hour forecast updated every hour, 3) the Canadian GEM Local Area Model (GEM LAM) with a 2.5km resolution at 5 min intervals in the east and 1 min in the west. It also uses the 1 min data from the observation sites at YYZ and YVR.

A system called the Adaptive Blending of Observations and Models (ABOM; Bailey et al., 2009) considers three parameters: the actual weather, a forecast change in weather extrapolating the past history of the observations, and a forecast change based on a numerical weather prediction model. It then applies weights to those parameters to come up with a nowcast. The numerical weather prediction models used are the same as those for INTW but it looks at each model separately, either the Regional (ABOM REG) or Local Area Model (ABOM LAM).

SAMPLE PRODUCTS

The system produces the following products:

1) An overview map of either YYZ or YVR with all their significant alternates. Clicking on the airport brings you to a Situation Chart.

2) The Situation Chart (Figure 3) shows present weather and forecasts for crosswind for each airport runway, visibility, ceiling, shear/turbulence, precipitation, thunderstorms and lightning, icing aloft, weather-only arrival rate, CAT level, and runway condition. The nowcasts produce output for each 10 min in the first two hours and then hourly out to 6 hours. The buttons on the Situation Chart change color when certain thresholds are crossed as defined in a clickable table. For CYYZ and CYVR, on-site cameras provide visual images of the weather, and a current enhanced forecast is available from the Canadian Meteorological Aviation Centre. Forecasts for the “bedposts” in the form of time-height plots can be examined.

3) Charts showing the past three hour data and forecasts, along with forecasts for the next 6 hours are available (e.g. Fig 4a, b).

4) Nowcasts using the ABOM and INTW techniques are also available (Figs. 5a, b).

5) Many spatial products such as scanning radar imagery, satellite photos, pireps, and lightning charts.

6) A suite of model forecasts out to 36 hours.

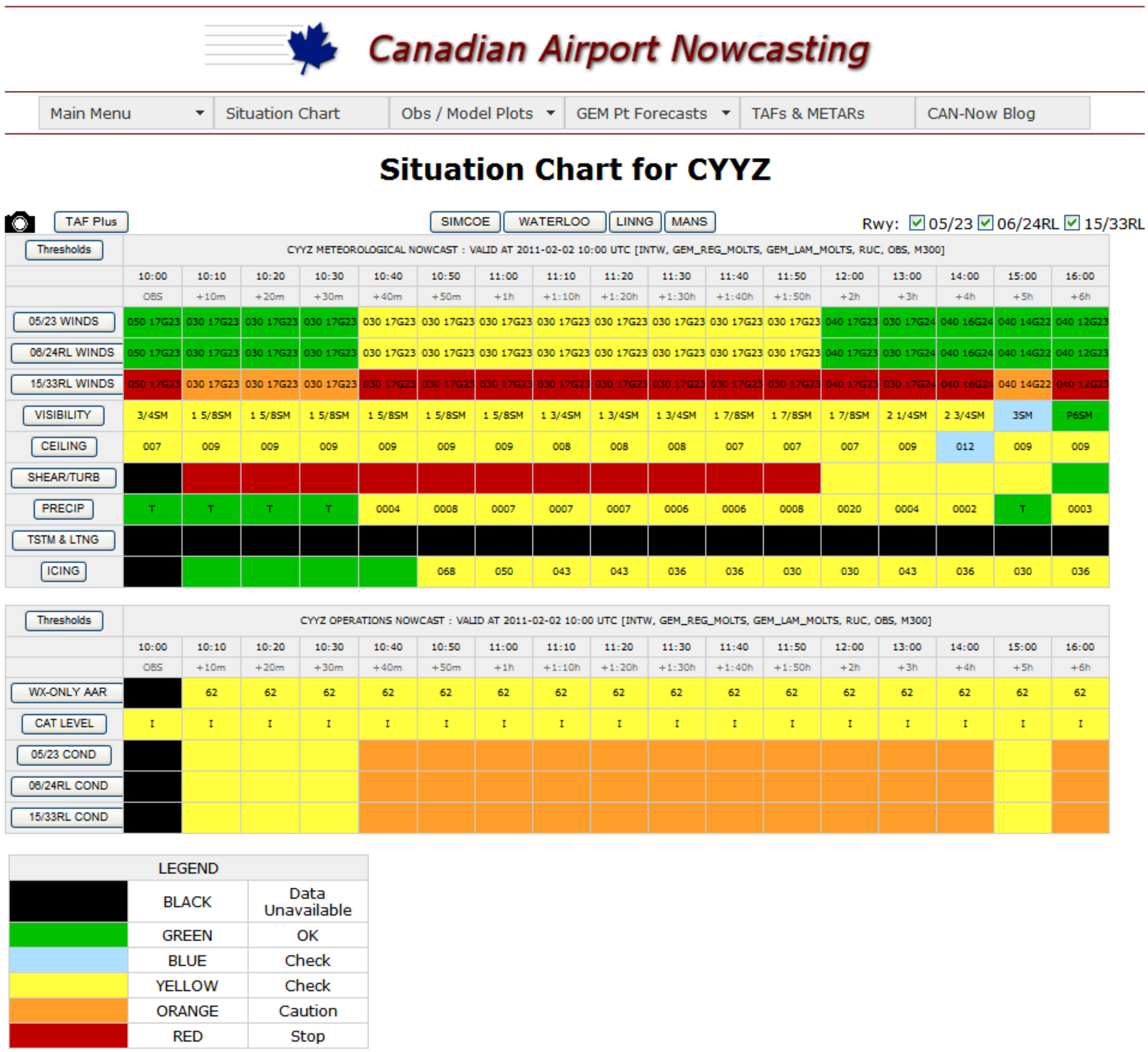

Figure 3: An example of the Situation Chart for CYYZ on 2 February 2011. Time bars are drawn at 10 min intervals for the first two hours and then hourly out to 6 hours. Parameters include crosswinds for 3 runway directions, visibility, ceiling, shear/turbulence, precipitation, thunderstorms and lightning and icing. A weather only Airport Arrival Rate (AAR), CAT level, and runway condition are also calculated.

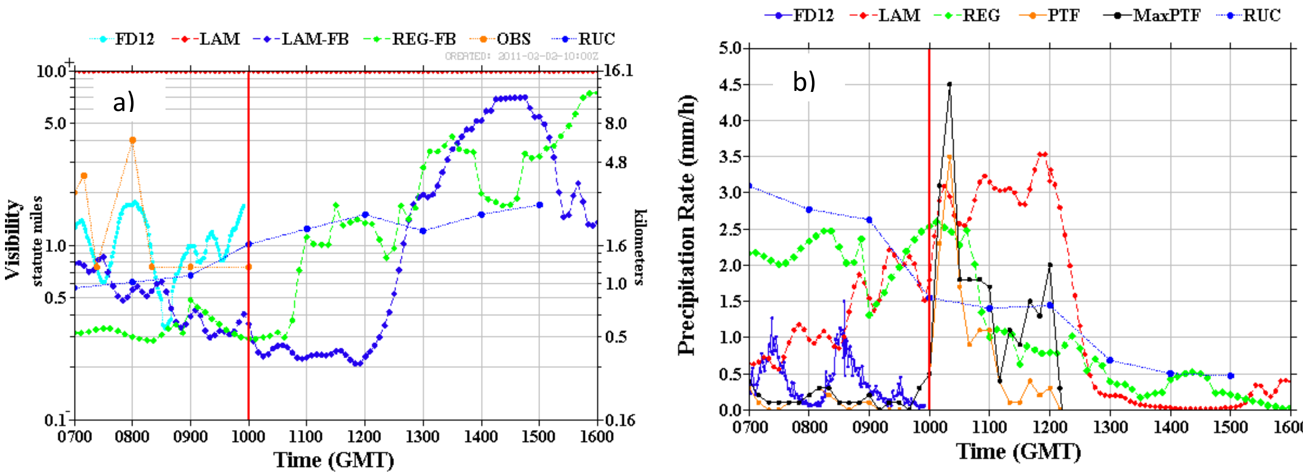

Figure 4: a) shows visibility as measured for the past three hours (FD12) and forecast for the next 6 hours for 2 February 2011. The official observer observations are marked as orange dots. The red vertical line indicates the current time. Predictions from the Canadian GEM Regional and U.S. RUC model are included. b) shows precipitation rate in the same format as 4a. Measurements from the Vaisala FD12P, the King City Radar precipitation point forecast (PTF) and maximum in an extrapolated arc (MAXPTF). The GEM REG, the GEM LAM, and RUC forecasts are plotted.

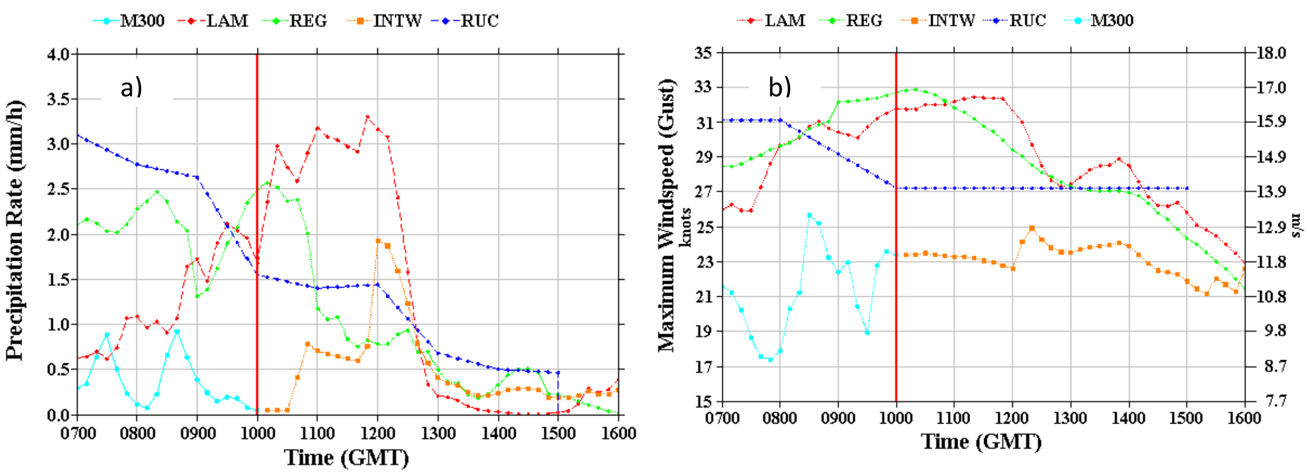

Figure 5: a) shows the precipitation nowcast plot showing the measurements (M300), the NWP model predictions and the INTW nowcast for 2 February 2011. b) shows the wind gust nowcast plot showing the NWP model forecasts along with the INTW nowcast.

WINTER VERIFICATION

A verification of the numerical weather prediction models used in the CAN-Now system was done for the winter of 2009/10. This is summarized in Table 2. Some conclusions from this table are as follows. First, there is no obvious preferred numerical model. Second, the INTW nowcast system does appear to outperform the NWP models. Third, the large errors in relative humidity, even with INTW, make forecasting fog very difficult. Fourth, the wind direction errors are quite large, especially for CYVR being close to 40 degrees. The reason for this large error is unknown but it does make forecasts for runway selection difficult, as reflected in the large runway crosswind speed errors.

The numbers in Table 2 represent averages over all times of the day. However, errors change as a function of time of day. Figure 6 gives one example of this using the mean absolute error in temperature at CYYZ. One can use the temperature at 03, 09, 15 and 21 UTC to make a forecast out to six hours and Figure 6 shows that this persistence forecast can be better than the numerical models. A persistence forecast is statistically the better forecast in the short term (hours) for most variables. In situations of rapid change however, persistence is not a good forecast method.

Figure 7 shows the mean absolute error in relative humidity (left) and wind gust (right) by nowcast lead time for the NWP models, persistence and INTW at CYYZ. Because of the averaging process, the numerical model errors are almost straight lines. Forecast errors in persistence and INTW grow with time for relative humidity and wind gust. For relative humidity, persistence of the observations (OBSP) and INTW beat the models out to 6 hours. For wind gust, persistence beats the NWP model out to 3 hours. However, the INTW system nowcast is the more accurate forecast out to 6 hours. Generally, the INTW system outperforms the persistence forecast after one or two hours and is the more accurate forecast out to 6 hours for all variables.

Table 2: Mean Absolute Error (MAE) for Significant Variables
(From 1 December 2009 to 31 March 2010 for CYYZ and CYVR)

Variables	**Units**	**CYYZ MAE**				**CYVR MAE**				
		REG	LAM	RUC	INTW	REG	LAM	RUC	LAM1km	INTW
Temperature	**^{o}C**	**1.7**	**2.3**	**1.9**	**1.1**	**1.4**	**1.1**	**1.7**	**1.4**	**0.9**
Relative Humidity	**%**	**10.5**	**9.0**	**12.3**	**5.4**	**8.0**	**7.7**	**10.5**	**7.1**	**5.0**
Wind Speed	**m/s**	**1.6**	**1.2**	**1.4**	**1.1**	**1.4**	**1.4**	**2.6**	**1.3**	**1.2**
Wind Direction	**deg**	**19.4**	**20.6**	**23.7**	**17.8**	**40.8**	**42.4**	**48.4**	**42.6**	**37.9**
Gust	**m/s**	**2.3**	**2.4**	**1.7**	**1.4**	**2.0**	**2.8**	**3.1**	**1.9**	**1.5**
XWIND1	**m/s**	**2.8**	**2.9**	**2.4**	**2.3**	**1.8**	**1.9**	**1.9**	**1.8**	**1.3**
XWIND2	**m/s**	**2.8**	**2.9**	**2.4**	**2.3**	**2.0**	**2.4**	**2.7**	**2.3**	**1.6**
XWIND3	**m/s**	**2.6**	**2.7**	**2.3**	**2.1**	**N/A**	**N/A**	**N/A**	**N/A**	N/A

GEM REG: Run 4 times per day 0, 6, 12, and 18 UTC
GEM LAM East: Run once per day at 12 UTC
RUC: Run once per hour but only 6 h forecast used.
GEM LAM Olympic 2.5km (West): Run twice per day at 9, 21 UTC up to Dec 9 and 6, 15 UTC afterwards
GEM LAM Olympic 1km (West): Run twice per day at 11, 23 UTC up to Dec 9 and 11, 20 UTC afterwards
INTW: MAE run every 10 min and averaged over the first 6 hours of the forecast.
The Canadian GEM model has been described by Côté et al. (1998a and 1998b) and Mailhot et al. (2006). The RUC 13 model is described by Benjamin et al. (2004, 2006).
For CYYZ, XWIND1, XWIND2 and XWIND3 refer to cross wind on runways 05/23, 06/24RL, and 15/33RL respectively. For CYVR, XWIND1 and XWIND2 refer to runways 08/26RL and 12/30 respectively.

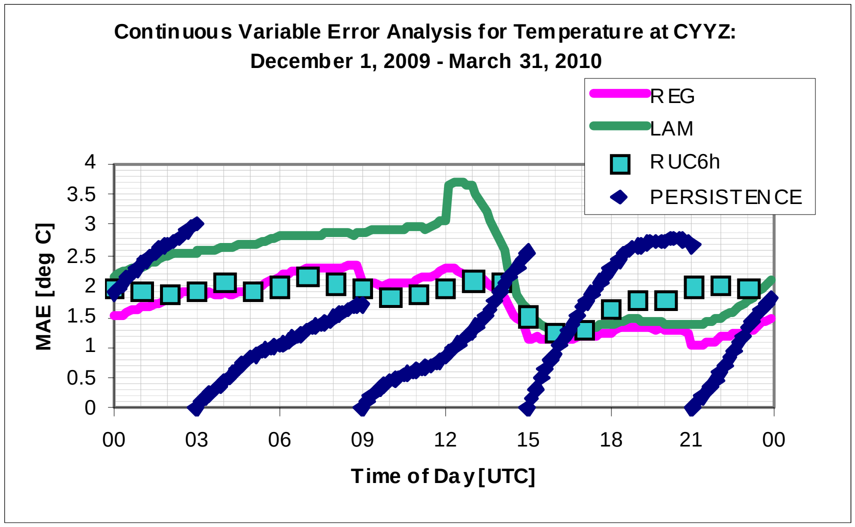

Figure 6: Shows the mean absolute error (MAE) for the winter of 09/10 as a function of time of day for the three numerical models at CYYZ. The MAE assuming persistence for six hours after 03, 09, 15 and 18 UTC is given. The jump in the GEM LAM at 12 UTC coincides in time with a new model run.

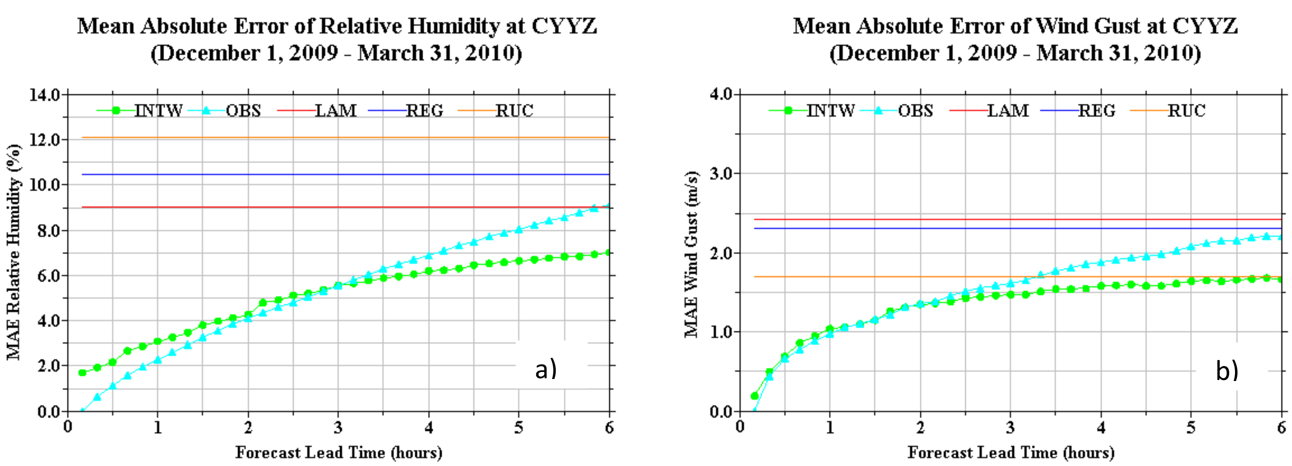

Figure 7: Shows the mean absolute error (MAE) in relative humidity (a) and wind gust (b) at CYYZ for the winter of 09/10 as a function of forecast lead time averaged over the whole season. Prediction using persistence is shown as OBSP.

NOWCASTING PRECIPITATION AMOUNT/TYPE

Nowcasting precipitation occurrence, rate and type during the winter are important for conveying useful information for those doing de-icing. The main site at CYYZ is directly across the airport from the de-icing pad (see Figure 2) so it is well suited to make the appropriate measurements. There is very little snow at CYVR in comparison to CYYZ (Figure 8), so the emphasis in this section will be on CYYZ.

To forecast precipitation type using the GEM REG model, a modified version of the Bourgouin (2000) scheme was used. For the GEM LAM runs in the west, the scheme as described by Milbrandt et al. (2008, 2010) was used. However, one problem is the actual measurement of precipitation type. It can vary quickly in time and the human observer may not pick up changes with a special report between the normal hourly observations. Figure 8 shows that different gauges can report different precipitation types, although the dominant types are clearly clear, snow, rain, and drizzle. However, the Vaisala instrument is reporting more freezing rain and drizzle and ice pellets than the other instruments at CYYZ. This difference is significant and requires further study. It should be mentioned that the instruments use the WMO definitions for precipitation type reporting. However, the models sometimes do not, with more sophisticated cloud microphysical schemes preferring to use graupel to define a range of precipitation particles like small hail, ice pellets, snow grains, etc. This also introduces problems in forecasting.

Another significant problem is the measurement and forecast of rain or snow amount. Short term forecasts of precipitation amount can be made using scanning radars (see Figure 4b), but they require a “Z-R” relationship which converts radar reflectivity to precipitation rate. This relationship is usually obtained through climatological averages and may have substantial errors for specific events. Sometimes this relationship can be tuned in real time with local gauges, but for snow, it is very difficult to get an accurate snowfall amount over a short time scale. This makes such adjustments difficult and probably not precise.

Numerical models can also be used to forecast precipitation amount and Figure 9 shows an example of the cumulative amounts for the winter for GEM-REG and GEM-LAM compared with the Vaisala FD12P at CYYZ. The example shows good agreement, especially with GEM-REG, between the model and the instrument for the whole winter of 09/10, with significant differences happening for specific snow events. The climate normal for Pearson is about 102 cm of snow, so assuming that 1 mm of water equivalent is about 1 cm of snow, it shows that 09/10 got much less snow than normal.

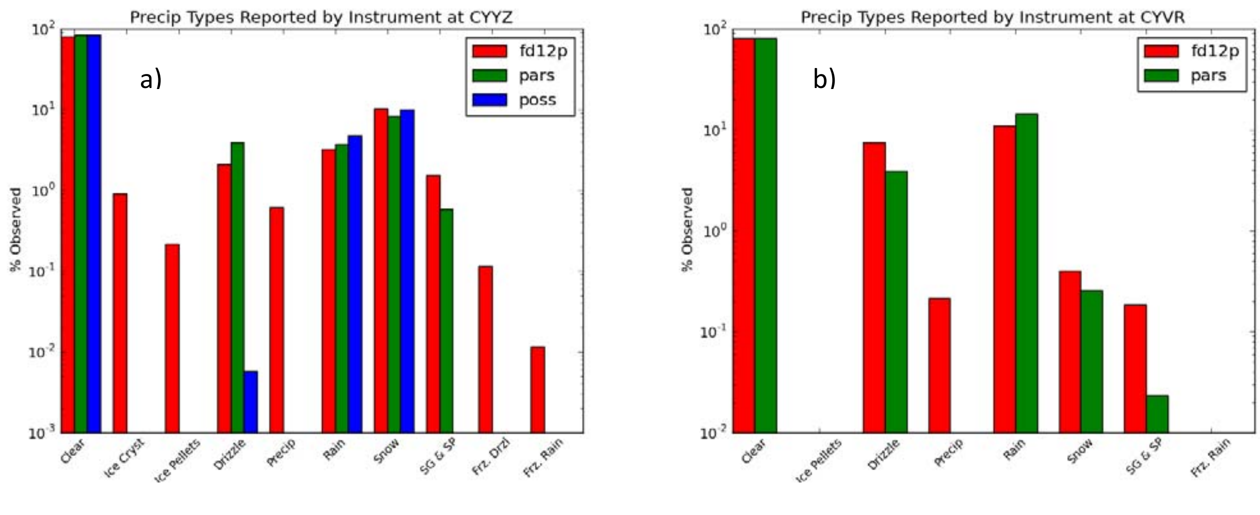

Figure 8: Percentage of time precipitation types were observed at CYYZ (a) and CYVR (b) by three different instruments: the Vaisala FD12P, the OTT Parsivel and the POSS (Sheppard and Joe, 2008) averaged over the period 1 December 2009 to 31 March 2010. Types were determined at 10 min intervals.

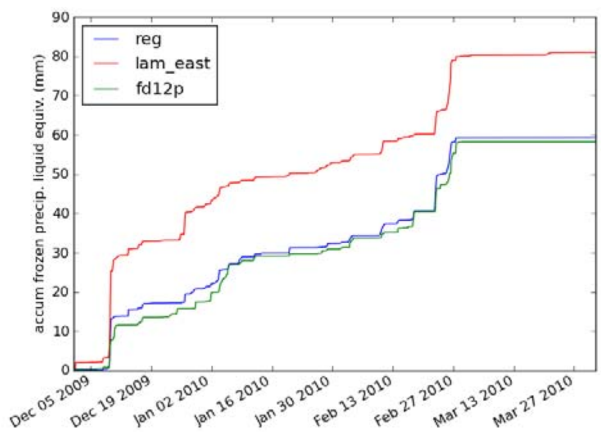

Figure 9: Shows the model GEM REG and GEM LAM cumulative snowfall amounts versus the Vaisala FD12P frozen precipitation (snow, snowgrains, and ice pellets) for the winter of 09/10 at CYYZ. The precipitation amount is in mm water equivalent. The climate data, which are obtained from independent data sets give 140 mm of rain and 52 cm of snow for same the four month period. The climate normals (1971-2000) are 119 mm rain and 102 cm of snow.

NOWCASTING FOR DE-ICING ACTIVITIES AT CYYZ

The ability of the numerical forecast models to predict specific holdover conditions was tested for the winter of 09/10. Specific holdover tables can be found at: **http://www.tc.gc.ca/eng/civilaviation/standards/commerce-holdovertime-menu-1877.htm**.

Table 3 shows how often specific conditions for the holdover tables existed during the winter using the hourly climate archive and the precipitation type reported as either fog, snow, freezing drizzle (ZL), freezing rain (ZR) and rain. Table 4 shows the hours in each holdover condition as forecast by the RUC. Fog and freezing drizzle (ZL) are not a forecast type by the RUC model. Snow corresponds to the 'SN' category, while rain corresponds to 'RA'. Slightly more freezing rain and snow, at slightly colder temperatures (see above), were forecast by the RUC. Table 5 gives the number of hours matching the de-icing criteria as forecast by the GEM-Regional model with lead times of up to 6 hours. While the occurrence of cold temperatures was similar between GEM-Regional and the observations, the GEM-Regional over-predicted the occurrence of snow and freezing rain.

Figure 10 shows the Heidke Skill Score (HSS) for the various models for predicting snow for 6 to 24 hours. The HSS score measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance. A negative score indicates no skill and a +1 is a perfect score. Figure 10 was formed assuming that the forecasts were perfect. That is snow and temperature had to be exactly predicted at the time it was forecast. So if the forecast was off by one hour, the forecast was wrong. However, Figure 10 gives a rough indication of how each model performs. Generally the RUC model did the best at 6 hours, the only forecast lead time available for this model. The GEM REG scores were basically the same out to 24 hours. The GEM LAM was only run once per day which made it more difficult to compare with the other models, however, it also showed some skill. Remember, the data sets are small so the differences between models may not be statistically significant.

TABLE 3: Observed Hours matching Holdover Criteria

	Precipitation Type				
Temperature	**Fog**	**Snow**	**ZL**	**ZR**	**Rain**
T(°C)≥-3	109	179	0	2	99
-14≤T(°C)<-3	3	263	0	0	0
-14>T(°C)	0	3	0	0	0

TABLE 4: RUC Total Hours matching Holdover Criteria

	Precipitation Type				
Temperature	**Fog**	**Snow**	**ZL**	**ZR**	**Rain**
T(°C)≥-3	--	189	--	0	118
-14≤T(°C)<-3	--	335	--	10	0
-14>T(°C)	--	32	--	0	0

TABLE 5: GEM-Regional Total Hours matching Holdover Criteria

	Precipitation Type				
Temperature	**Fog**	**Snow**	**ZL**	**ZR**	**Rain**
T(°C)≥-3	--	215	--	14	151
-14≤T(°C)<-3	--	301	--	0	0
-14>T(°C)	--	24	--	0	0

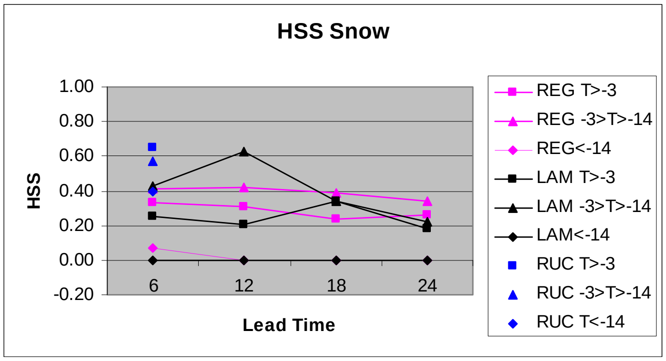

Figure 10: The Heidke Skill Score (HSS) for snow for the various temperature conditions in the Holdover Tables.

NOWCASTING ICING CONDITIONS OVER CYYZ

For CAN-Now, for each airport, icing is forecast above that airport using the GEM regional prediction of total water content as a function of height and the freezing level. If there is a total water content greater than 0.1 g m^{-3} at temperatures colder than $0^{o}C$, the height of the lowest level and the total water content at that level is indicated and the situation chart indicates a potential hazard. In terms of real time detection, a TP/WVP-3000 Microwave Radiometer (by Radiometrics) is located in the instrument compound and indicates the possible presence and amount of liquid water aloft. The vertically pointing radar also has a detection algorithm which indicates the presence of drizzle aloft and if it occurs above the freezing level, supercooled drops are possible.

Figure 11 shows the prediction of icing aloft using the GEM REG model verified against the microwave radiometer. It appears that this simple technique, although showing some skill, generally predicts the icing at warmer temperatures and at lower altitudes than the radiometer would suggest. There is room for improvement in this technique.

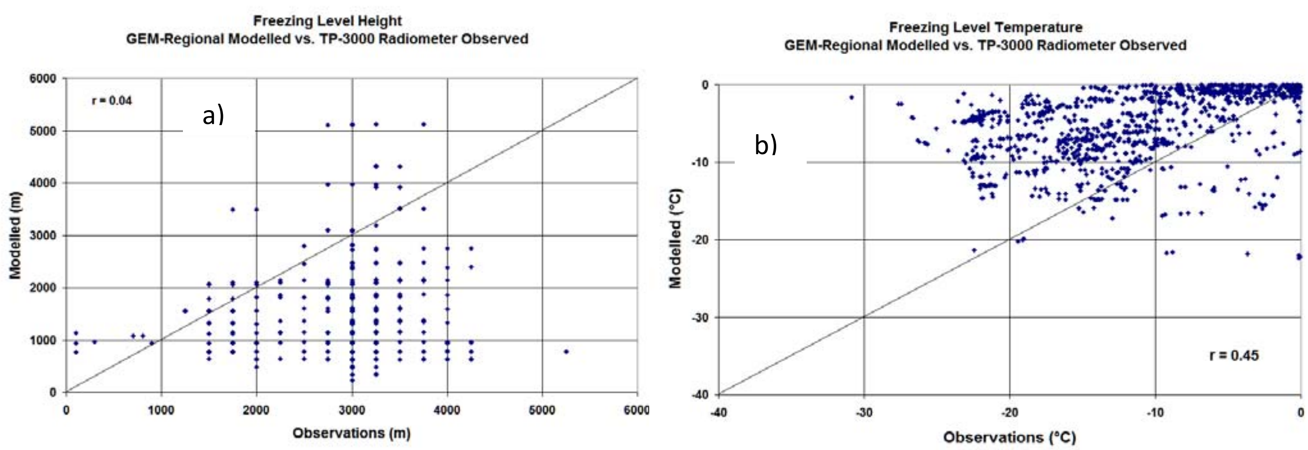

Figure 11: A comparison of the microwave profiling radiometer height (a) and temperature (b) of the lowest possible 0.1 g m^{-3} versus that predicted by the GEM-REG model.

CONCLUSIONS

The CAN-Now system has been evaluated with a full field test during the winter of 09/10. A study is also underway evaluating its performance during the summer of 2010. The project attempts to statistically verify all the products it produces and this paper shows some of that work. Some basic conclusions can now be reached.

1) The web-based Situation Chart is a useful quick glance tool for alerting users to potential problems. Once those problems have been identified, it is relatively easy to get more information. However, it is probably more complex than is necessary for some users in the airport environment, for example at the de-icing pad, so further improvements are necessary to get high-glance information to all users. Specific users generally require tailored displays focusing on their needs.

2) There is a need for measurements at high time resolution. Perhaps not adequately discussed in this paper, conditions at the airport can vary quickly on scales of several minutes. Relying on a human observer is not adequate although the human observations are also very useful given the uncertainties in the observations.

3) There is value in using more than one numerical weather forecast model in the products. Often one model captures a high impact event more accurately than another.

4) The nowcast systems developed, especially the WEBIS or INTW system, have demonstrated skill. In the future, it might be useful to use INTW forecasts for the algorithms predicting such parameters as precipitation rate, visibility, and ceiling.

5) There is a great deal of future work necessary to more accurately measure precipitation amount and precipitation type. These are very critical parameters necessary in the application of de-icing fluids. Obviously, improvements in our ability to forecast these parameters are needed as well.

6) The current icing aloft forecasts in CAN-Now can be improved through better use of the existing instrumentation (microwave radiometer and vertically pointing radar) and the newer versions of GEM which predict liquid water content directly. Satellite based techniques can also be considered and some products are currently being produced. However, predicting icing severity remains a big issue because the existing definitions are given in parameters that are specific to aircraft types (e.g. icing rates on leading edges).

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