# iCAST: A PROTOTYPE THUNDERSTORM NOWCASTING SYSTEM FOCUSED ON OPTIMIZATION OF THE HUMAN-MACHINE MIX

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ABSTRACT

A prototype thunderstorm nowcasting system, tentatively named iCAST (interactive Convective Analysis and Storm Tracking), is being developed at Environment Canada with an emphasis on optimizing the 'human-machine mix'. The prototype aims to build on the strengths of the human forecaster in the thunderstorm nowcasting process while making the best use of machine computing capabilities.

iCAST is being prototyped on a platform developed at Environment Canada called Aurora. Aurora is an object-oriented conceptual modeling system that allows forecaster interaction with graphical objects such as grids, areas, lines, points, and time links. Aurora also ingests NWP (currently the Canadian GEM and US RUC models), high-resolution satellite data, radar data (Canadian and US), surface station observations, and lightning network data.

iCAST employs a three-stage approach to nowcasting. First, NWP model output, past weather, current observations, and conceptual models are used to generate a mesoscale prognosis for the T+6 timeframe. The forecaster identifies and creates objects for both synoptic-scale features (such as fronts and jets) and mesoscale features (such as lake-breeze fronts and outflow boundaries). In addition, the forecaster identifies areas where convection may be expected to occur at that time.

Next, mesoscale analyses are performed hourly by the forecaster to verify the existence and locations of the mesoscale features using mainly observations, but also some NWP guidance. The forecaster must use pattern recognition and conceptual models to build a coherent depiction of the weather, despite any missing or conflicting data.

Lastly, once thunderstorms are present or imminent, storm-scale nowcasting is undertaken. We are currently experimenting with storm track modification and filtering as a way to achieve an optimal human-machine mix at storm-scale. The forecaster may use conceptual models, analyzed/nowcast mesoscale feature information, current observations, and NWP model output to modify cell tracks and convective trends for the highest priority storms.

In the prototype phase, iCAST will help to assess the value of human input to the convective nowcast problem via an automated verification process. In addition, we will test whether a semi-automated warning generation interface leads to more efficient and effective warning generation.

It is anticipated that successful components of the iCAST prototype will be proposed for transfer to Environment Canada's national forecaster workstation presently under development (NinJo).

iCAST will be used in a real-time, operational setting during the summer of 2009 via a Research Support Desk at the Ontario Storm Prediction Centre in Toronto. Preliminary results will be presented at the symposium.

## 1. INTRODUCTION

A prototype thunderstorm nowcasting system, tentatively named iCAST (interactive Convective Analysis and Storm Tracking), is being developed at Environment Canada with an emphasis on optimizing the 'human-machine mix'. The prototype aims to build on the strengths of the human forecaster in the thunderstorm nowcasting process while making the best use of machine computing capabilities.

iCAST employs a three-stage approach to convective nowcasting:

1. generation of a mesoscale convective prognosis for the T0+6 timeframe,
2. mesoscale analyses at hourly intervals when severe weather is possible or occurring, and
3. storm-scale nowcasting focused on the evolution / initiation of individual storm cells.

This article will review the motivation for the iCAST prototype, provide scientific background, describe interactive convective nowcasting systems at other institutions, discuss the iCAST prototype in detail, and then conclude with a summary.

## 2. NOWCASTING AT MSC

Nowcasting can be defined to mean weather analysis and diagnosis at T0 with prognosis out to about T0 + 6 hours. It has historically leaned heavily on extrapolation methods using observational data such as that from radar. After about T0+6 hours, mesoscale models typically begin to outperform extrapolation, as depicted in Fig. 1.[1]

As stated in the current Meteorological Service of Canada (MSC) vision, nowcasting of severe and/or high-impact weather is now the main focus for MSC forecasters[2]. MSC needs state-of-the-art nowcasting data, models, tools and products to meet its mandate. This includes:

- data at increased spatial and temporal scales, especially in the boundary layer (wind profilers, surface observations, radar, satellite),
- new NWP systems that give short-term, mesoscale ensemble forecasts, and have a rapid update cycle,
- tools that employ data fusion and are designed to facilitate an optimal human-machine mix, and
- products issued with greater frequency that use graphical and probabilistic representations and are disseminated using the latest communication technologies.

Canada is the second largest country in the world by area. Nowcasting is particularly challenging here due to the wide variety and frequency of severe weather that affects the country as well as the scarcity of observational data, especially in remote regions. At each Storm Prediction Centre (SPC, see Fig. 2), staffing is modest and the area of responsibility is immense - more than 1,000,000 squared km. MSC severe weather forecasters must monitor

[1] The values presented in Fig. 1 are two decades old but, surprisingly, lead times have generally improved only slightly since that time. There is one exception: some mesoscale NWP systems that assimilate radar data have demonstrated skill above Lagrangian persistence in the first six hours (J. Milbrandt, personal communication).
[2] See Sills (2009) for more details on recent changes at MSC.

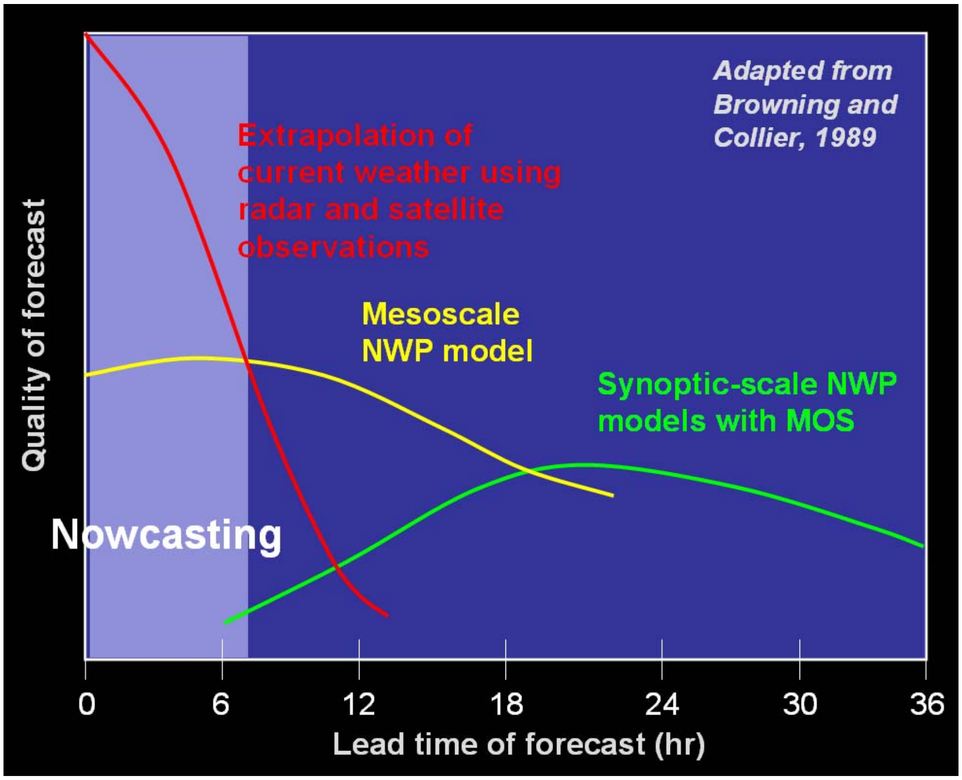



Figure 1. A graph of forecast quality versus lead time. Adapted from Browning and Collier (1989)

data from a large number of sources, including 10 or more radars, to maintain situational awareness. To further complicate the problem, storm development in many regions is greatly influenced by mesoscale processes (e.g. thunderstorm initiation at drylines / lake breeze fronts / gust fronts, lake effect snow in winter, etc.). Thus, nowcasting in Canada requires intensive use of mesoscale data (observations and NWP), and mesoscale features are of critical importance.

Currently, MSC employs a variety of sophisticated *analysis and diagnosis* tools using data from various observational platforms such as radar, satellite, surface and upper-air stations. These include the Unified Radar Processor (URP), ImageManager, MetManager, XTephi, and most recently the first operational version of the NinJo workstation (see Koppert et al. 2004). Some very limited extrapolation-based radar tools are available for nowcasting. Severe weather bulletins continue to be issued via a stand-alone bulletin generation system.

Beyond the T0+6 hour time frame, the majority of *prognosis* guidance used by the severe weather forecaster comes from operational numerical weather prediction (NWP) models, such as the Global Environmental Multiscale (GEM) model (Côté et al. 1998), and associated statistical output (e.g. UMOS, Wilson and Vallée, 2002).

Clearly, MSC lacks sophisticated prognostic tools for nowcasting in the 0-6 hour time frame, including tools for bulletin/product generation.

## 3. THE OPTIMUM HUMAN-MACHINE MIX

For reasons discussed below, it is assumed that human forecasters will continue to be very


Figure 2. Environment Canada Storm Prediction Centres and office locations. Note that both the PASPC and the ASPC have two offices.

much a part of the nowcasting process in the future. A nowcasting system combining sophisticated representation of observational data, NWP, and artificial intelligence (AI) techniques is needed to help the forecaster cope with nowcasting in the Canadian context. It is recognized, however, that such a system needs to be carefully designed so that it does not erode forecaster expertise. Thus, the human-machine mix must be optimized to make the best use of both human and machine strengths.

Computers are still a long way from doing what humans do best. During the Sydney 2000 nowcasting demonstration project, the relative success of the NCAR Auto-Nowcaster system at nowcasting deep, moist convection compared to other nowcasting systems was based on the ability of the human forecaster to correctly analyze and diagnose low-level convergence boundaries (hereafter 'boundaries') and enter boundary information into the system (Wilson et al. 2004). Also, Project Phoenix, an ongoing initiative at the Prairie and Arctic SPC, has consistently shown that forecasters generate considerably better short-range predictions when NWP is withheld and they are forced to spend more time on analyses and diagnoses, and creating their own prognoses (McCarthy et al. 2007).

There are several areas where the ability of the human forecaster remains superior and will be so for some time, including:

• pattern recognition,
• use of conceptual models,

• judgment / decision-making, and
• adaptive strategies.

Conversely, machine strengths currently include:

• dealing with large volumes of data,
• integrating numerous datasets,
• rapid handling of complex calculations and complicated parameter interactions, and
• performing tedious tasks.

The 'optimum' human-machine mix may be different for various applications. For some applications, an entirely automated forecast product may be sufficient, providing useful information 90% of the time. However, for the purposes of nowcasting severe weather, that extra 10% may represent the most significant weather events. In addition, the ability to respond to any type of situation, even those that are rapidly changing or unexpected, is essential. Thus, it is suggested that the optimum human-machine mix for a severe weather nowcasting system will be achieved when both the human and machine strengths listed above are fully exploited in a complementary manner.

## 4. THE ROLE OF THE HUMAN FORECASTER

Studies on the appropriate role of the human forecaster have appeared in the peer-reviewed literature since Snellman introduced the term "meteorological cancer" to describe over-reliance on NWP in the 1970s (Snellman 1977). See Sills (2009) for a complete list of such articles.

Based on the idea of achieving the optimal human-machine mix, Sills (2009) proposed the following:

"The primary role of the human forecaster should be to develop and maintain a shared weather-object database that uses a sequence of plan-view composite depictions evolving through time to best represent the current and future states of the atmosphere. This would be accomplished using an area-based, object-oriented analysis / forecast system with an intuitive user interface, plus a toolbox of NWP guidance and carefully designed artificial intelligence (AI) assistants. The emphasis would be on sensible weather near the surface since that region of the atmosphere has the greatest impact on the activities of the public."

This proposed role is illustrated in Fig. 3. As shown in the flowchart, most of the interaction would be between the human forecaster and the analysis / forecast system. However, the forecaster could also influence quality control, observations (e.g., targeted or special observations), and NWP.

As new data arrive throughout the day, the forecaster would test and refine hypotheses related to HIW made earlier in the day by producing detailed analyses, comparing observations with NWP / AI output, and evaluating 'what if' scenarios. If necessary, prognoses would be revised. All of this activity would take place within the analysis / forecast system.

For convective nowcasting, radar and satellite imagery, lightning data, and surface observations would be used in conjunction with conceptual models, 'rapid update cycle' / high resolution model output, and AI algorithms to forecast the future track and intensity of storms, and/or the development of new convection. Warnings would be generated when storms are forecast to become severe, with enhanced content provided by underlying GIS information (e.g., locations

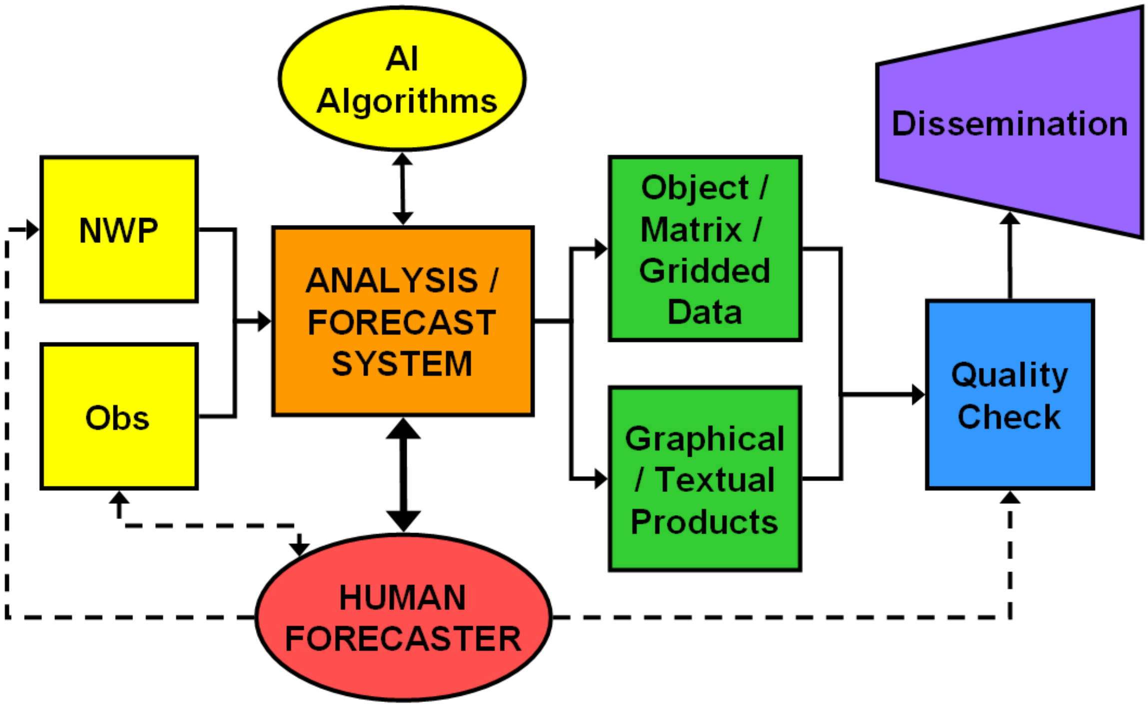



Figure 3. Flowchart (left to right) showing the proposed role of the human forecaster in the forecast production process. Yellow boxes represent various inputs while green boxes represent various outputs. Bold arrows indicate that the main interaction is between the human forecaster and the analysis / forecast system. The human forecaster also may influence NWP, observations, and quality checking (all shown as dashed arrows). Public reports of severe weather events are a special type of observation that could go directly to the human forecaster (also shown as a dashed arrow). This figure first appeared in Sills (2009).

of urban areas, highways, schools, etc.). Uncertainty (aside from probability of precipitation) would be expressed via products that include graphics (e.g., cones of uncertainty) and free-form text.

The goal is that the daily activity of the forecast team would be focused on meteorology, not the details of generating products, thereby maintaining shared situational awareness at all times. The use of ‘weather objects’ allows the forecaster to focus on simplified ‘weather feature’ representations and their interactions, rather than the details of 4-D gridded data or a multitude of time series representations at points. Manipulating weather features via objects is also much more intuitive for the forecaster, and better enables the use of conceptual and mental models.

## 5. BOUNDARIES AND CONVECTIVE NOWCASTING

Research in North America has shown that mesoscale boundaries are preferred locations for convective initiation due mainly to enhanced lift, and can act to enhance the intensity of storms, including those that produce severe weather. Purdom (1976) used satellite imagery to show that intersecting boundaries often initiate intense convective development. Wilson and Schreiber (1986) found that 79% of storms in their study were initiated in association with radar-observed boundaries. This increased to 95% for storms with radar reflectivities of 60 dBZ or greater. Several recent field experiments have continued to examine the issue of convective initiation at boundaries (e.g., ELBOW - Sills et al. 2002; IHOP - Weckwerth and Parsons 2006, UNSTABLE - Taylor et al. 2008).

Boundaries are also known to have a large impact on the structure, duration, and movement of thunderstorms. The organization and motion of severe storms was found by Weaver (1979) to be influenced more by intense convergence at boundaries than by upper-level winds. Corfidi (1998) showed that mesoscale convective systems propagate in the direction of the greatest system-relative low-level convergence. This convergence is typically associated with a low-level jet but can also be provided by boundaries. Wilson and Megenhardt (1997), among others, have shown that a storm's organization and lifetime are greatly enhanced when storm motion is roughly equal to that of the storm's gust front.

Finally, it has been found that boundaries can provide the vorticity necessary for the development of rotation at low levels of a storm, potentially leading to the development of a tornado (e.g., Wakimoto and Wilson 1989, Brady and Szoke 1989, Maddox et al. 1980). Markowski et al. (1998) found that nearly 70% of significant supercell tornadoes during the 1995 Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) occurred near preexisting boundaries. Wakimoto et al. (1998), Rasmussen et al. (2000), Sills et al. (2004) and others have also documented cases of tornadic supercell storms involving preexisting boundaries.

Based on the above, boundary detection and prediction will be a critical aspect of any convective nowcasting system. It allows nowcasting to go a step beyond extrapolation by enabling the prediction of surface-based convective initiation, something that extrapolation-based systems are, by their nature, unable to do.

## 6. INTERACTIVE CONVECTIVE NOWCASTING SYSTEMS

A large number of nowcasting systems have been developed over the last several decades. What follows below is a discussion of convective nowcasting systems at institutions other than Environment Canada that have included an interactive component that exploits human strengths. All but one of these (TIFS) are prototype systems, though some have been tested and/or used in operational settings.

### 6.1 NCAR Auto-Nowcaster (see Mueller et al. 2003)

Despite its name, the Auto-nowcaster system is one that makes use of human strengths. According to its developers, boundary detection and monitoring by the forecaster is the single most important part of the Auto-Nowcaster since it allows the prediction of convective initiation. Auto-Nowcaster combines multiple observationally derived data sets, NWP output, and forecaster identified low-level boundary information and forecasts storm initiation, growth and dissipation via extrapolation and fuzzy logic techniques. Output from the system is 0-2 hr storm location and intensity. This system was used successfully at both the Sydney 2000 and Beijing 2008 forecast demonstration projects. Verification studies show a consistent improvement over extrapolation forecasts when boundaries are detected and entered by forecasters (e.g. Wilson et al. 2004).

### 6.2 BOM TIFS (see Bally 2004)

The Thunderstorm Interactive Forecast System (TIFS) is used operationally by the Australian

Bureau of Meteorology to create both general warnings for thunderstorms, and also highly detailed thunderstorm nowcasts based on tracking and forecasting of individual thunderstorm cells. Storm tracks are generated via several different algorithms, and can be deleted, filtered, or modified by the forecaster. The forecaster interface is a combination of direct editing and drop-down menus. This system was used with some success at both the Sydney 2000 and Beijing 2008 forecast demonstration projects.

### 6.3 Météo-France SIGOONS (see Sénési et al. 2004)

SIGOONS (Significant Weather Object Oriented Nowcasting System) from Météo-France is focused on the detection and tracking of significant weather ‘objects’. The first-guess objects are generated by automated processes. Currently, product generation is also purely automated and the forecast horizon is limited to one hour. The addition of forecaster expertise at the scale of organized convective systems in order to lengthen this horizon up to three hours is undergoing development. The forecaster interface is mainly drop-down menus.

## 7. THE INTERACTIVE CONVECTIVE ANALYSIS AND STORM TRACKING SYSTEM

The “interactive Convective Analysis and Storm Tracking”, or iCAST, system is being developed using the Aurora prototyping platform (see Greaves et al. 2001) and combines a number of features from each of the interactive nowcasting systems discussed in the previous section. The goal is to achieve an optimal human-machine mix as discussed in section 3, and implement the role of the forecaster suggested by Sills (2009) and described in section 4. It is anticipated that successful components of the iCAST prototype will be proposed for transfer to the NinJo workstation presently under continuing development.

iCAST employs a three-stage approach to convective nowcasting. First, past weather, analysis of current weather, NWP model output, and conceptual models are used to generate a mesoscale prognosis for the T0+6 timeframe. While synoptic-scale features such as fronts and jets are included, the focus is on interactions on the mesoscale. The forecaster identifies and creates objects for both synoptic-scale features (such as fronts and jets) and mesoscale features (such as lake-breeze fronts and outflow boundaries). In addition, the forecaster identifies areas where convection may be expected to occur over the valid time period. An example of a mesoscale prognosis is shown in Fig. 4.

Next, mesoscale analyses are performed hourly by the forecaster to verify the existence and locations of mesoscale features using mainly observations such as surface observations, radar data, and satellite imagery, but also NWP guidance where useful. The forecaster must use pattern recognition and conceptual models to build a coherent depiction of the weather, despite missing or conflicting data. An example of a mesoscale analysis is shown in Fig. 5.

Lastly, once thunderstorms are present or imminent, storm-scale nowcasting is undertaken. How storm-scale nowcasting is achieved is an active area of research at Environment Canada, and at centres in other countries. We are currently experimenting with storm-track editing as a means of achieving an optimal human-machine mix at storm scale.

Environment Canada’s URP radar system uses a radar-based cell identification and tracking algorithm (TITAN, see Dixon and Wiener 1993) to generate cell properties, past tracks, and extrapolated nowcast tracks. Data from this URP algorithm are brought into Aurora. For each storm track, the forecaster has four options: use the URP-generated nowcast track as is, modify

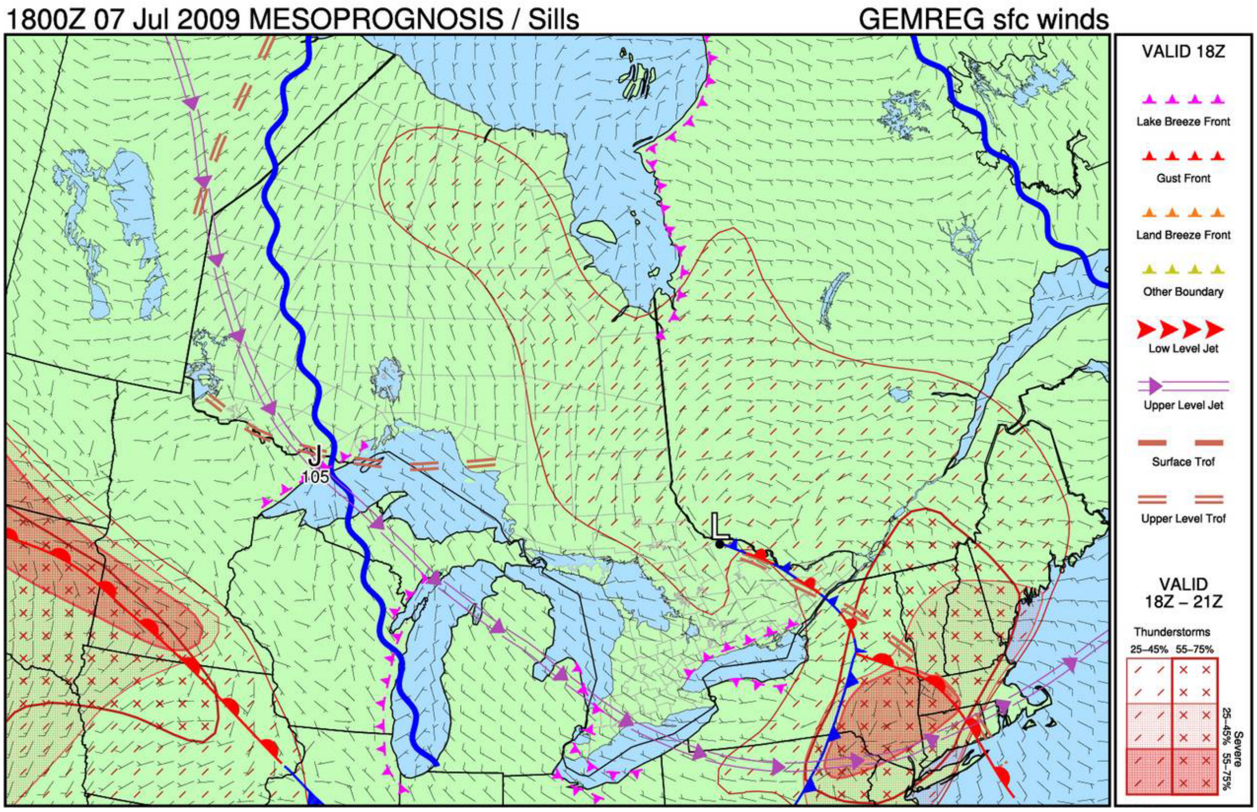



Figure 4. Mesoscale prognosis valid at 1800 UTC on 7 Jul 2009. Weather objects such as synoptic scale fronts, upper-level trough, and lake-breeze fronts are superimposed over the surface wind field from the GEM Regional model. The red hatching represents 'chance' and 'likely' thunderstorm areas while red shading represents 'chance' and 'likely' severe storm areas. Both of these are valid between 18 UTC and 21 UTC (2 pm and 5 pm local time).

the URP-generated nowcast track, modify the track from the previous depiction, or generate a completely new nowcast track.

A conceptual drawing showing a URP-generated track, and the same track modified by the forecaster, is provided in Fig. 6a. Open circles represent past cell locations at 10 minute intervals, the closed square represents the current cell location, and closed circles show the nowcast cell locations at 10 minute intervals. Ellipses give a simplified representation of the storm cell area having reflectivities greater than or equal to 40-dBZ. The colour of the ellipse indicates whether the cell intensity is nowcast to increase (red), decrease (green), or not change significantly (grey), or if cell initiation is expected (yellow).

When the forecaster modifies a nowcast track, a number of parameters can be changed including, most obviously, the location of the nowcast track. However, the forecaster can also change the cell intensity nowcast and the ellipse size. Modifications are based on conceptual models, analyzed/nowcast mesoscale feature information, current observations, and NWP model output. Fig. 6b shows the forecaster-modified nowcast track from Fig. 6a with cell intensities and ellipses changed to match the forecaster's mental model. In this case, the presence of a lake breeze front (magenta line) means that the thunderstorm will likely intensify as it approaches the front, and then dissipate once it moves into stable marine air.

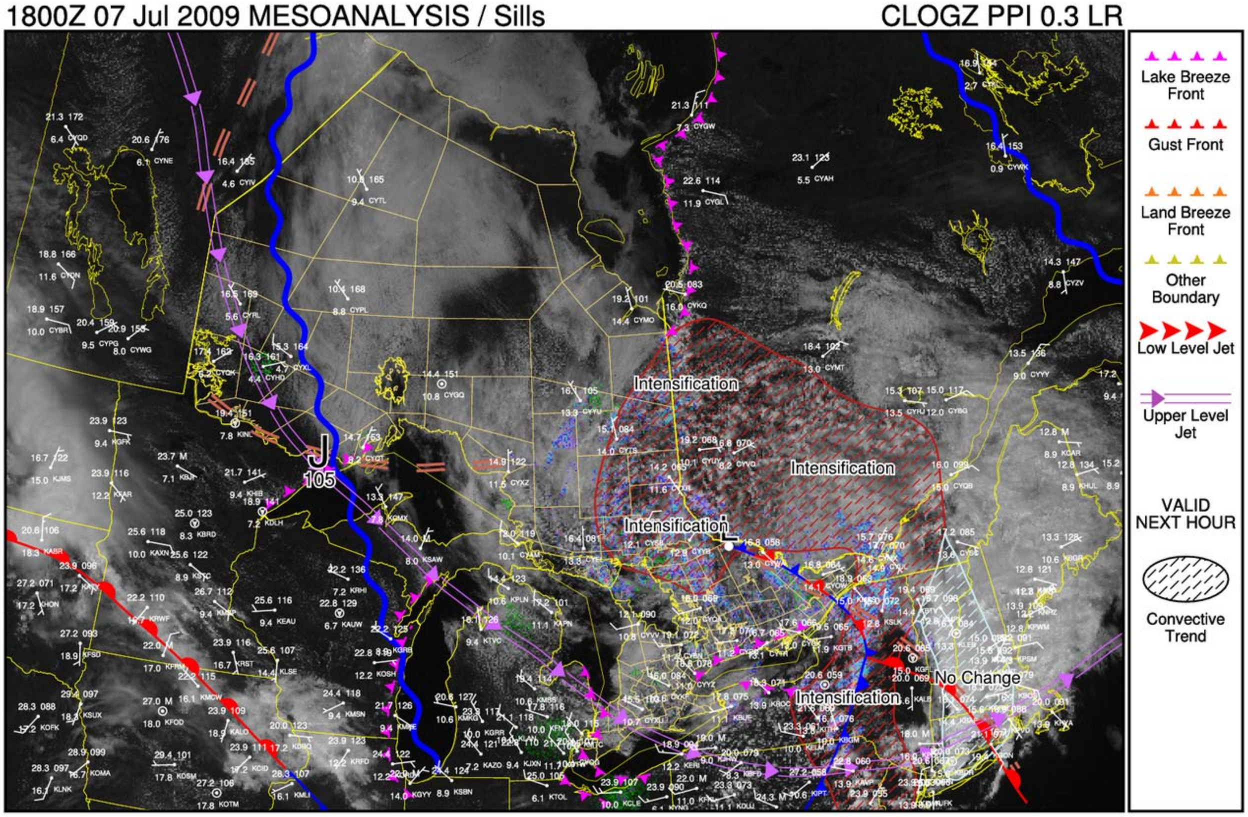



Figure 5. Mesoscale analysis valid at 1800 UTC on 7 Jul 2009. Weather objects such as synoptic scale fronts, upper-level trough, and lake breeze fronts are superimposed over surface observations, radar reflectivity and visible satellite imagery. Hatched area represent convective trend forecasts for the next hour (initiation, intensification, no change, or dissipation).

If the forecaster expects the storm to become severe, then a warning area may be drawn as shown in Fig. 6c. Here, the forecaster-drawn warning area contains several different information elements. First, the area is drawn from the current location, indicating that the storm is currently severe. Second, the area is drawn out to the point where the storm is nowcast to dissipate. Third, the area expands laterally through time, indicating that the degree of uncertainty in the nowcast track.

The nowcast track is also used to provide content for the warning message. Cell speed and direction can be computed from the forecast track. Also, affected warning regions, as well as cities, towns, critical infrastructure, etc., can be identified using an underlying GIS database.

As discussed previously, to go beyond extrapolation a nowcast system must incorporate convective initiation. iCAST allows the forecaster to introduce a new cell and nowcast track, then modify the cell intensity trend and ellipse size to match the forecaster’s mental model. An example is shown in Fig. 6d.

Another activity being explored for iCAST is track filtering. The TITAN algorithm used by URP occasionally generates spurious tracks, or a number of tracks along the length of a one linear storm. The forecaster should have the ability to delete these tracks, or to filter tracks by

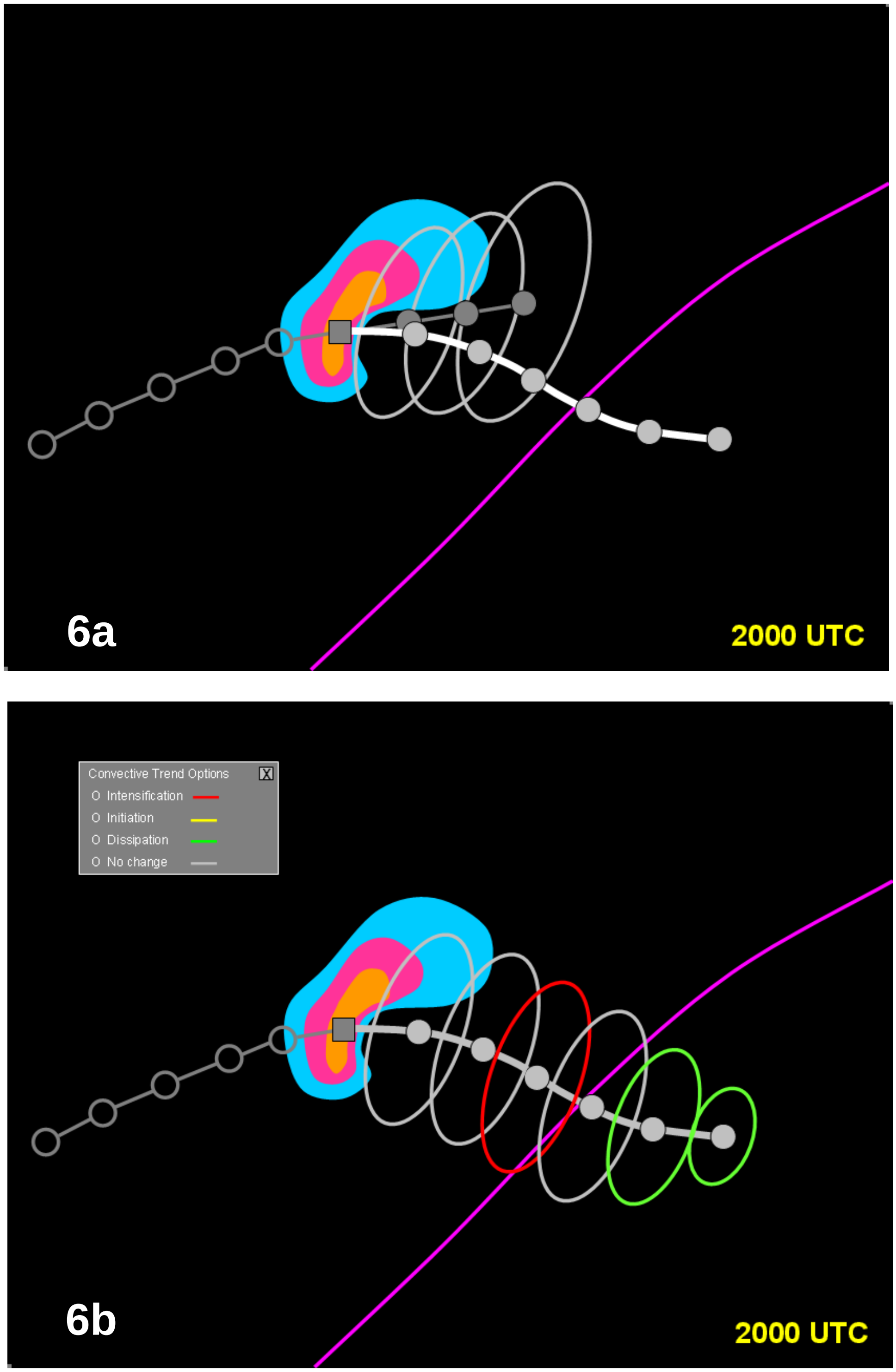
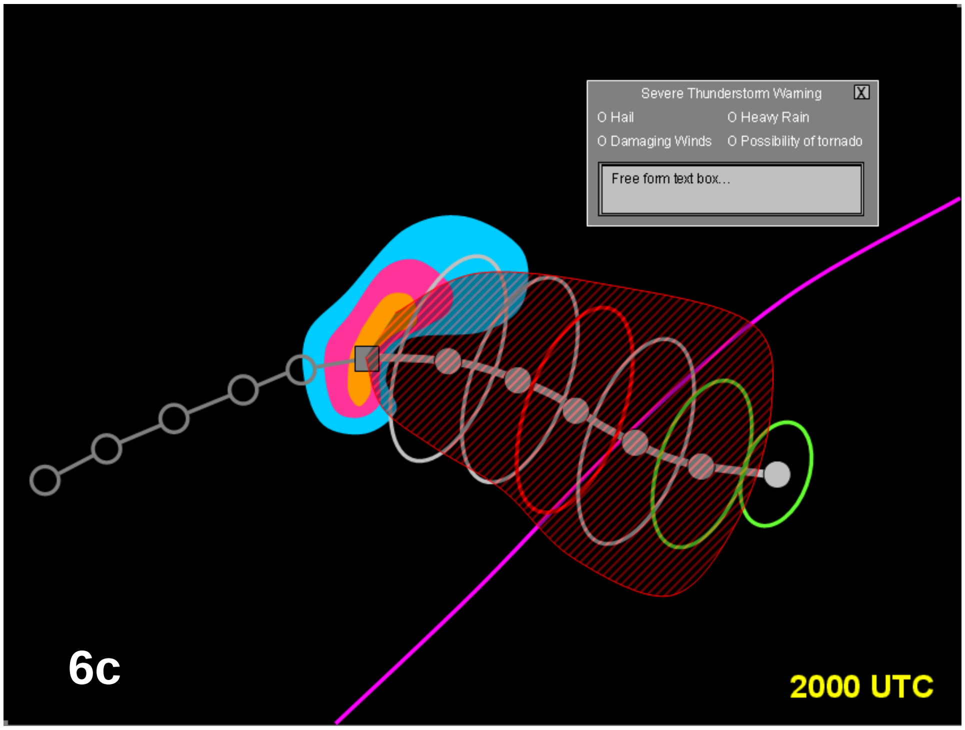



Figure 6a-d. Cell tracks and ellipses are brought into Aurora from URP and displayed. Open circles represent past cell locations, closed squares represent the current cell location, and closed circles represent future cell locations. 6a shows the URP-generated future extrapolation nowcast, as well as the same track moved and extended by the forecaster (white line). In 6b, ellipses along the forecaster-generated track indicate modifications made to cell intensity and size. The magenta line represents a lake breeze front with the lake on the right side of the line.



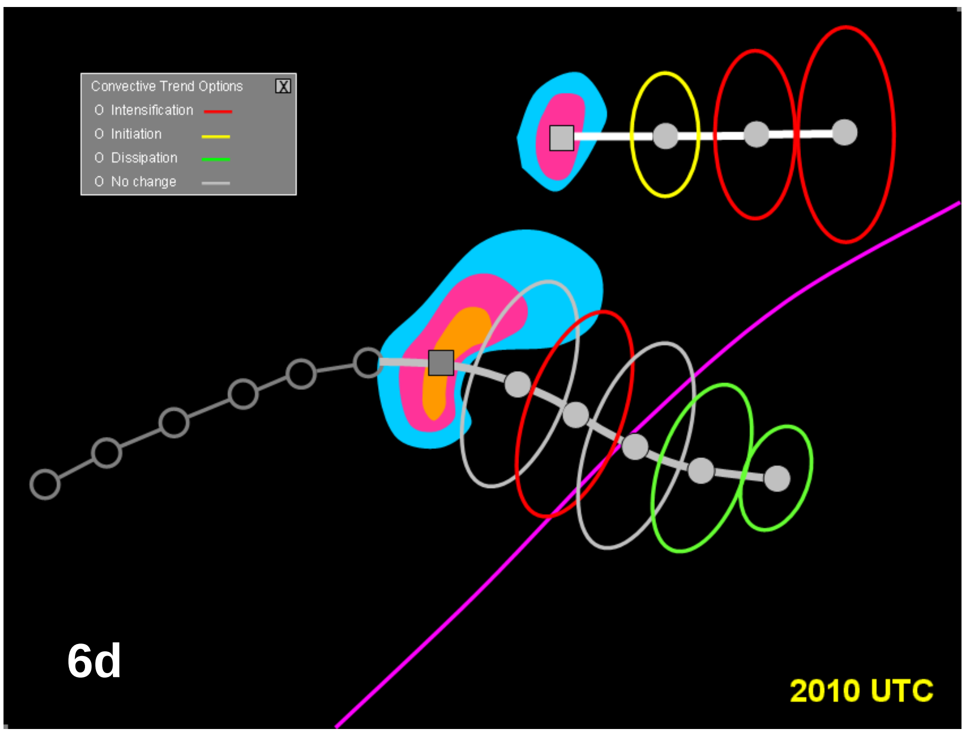




Figure 6a-d *continued*. In 6c, a warning area has been generated by the forecaster to cover locations where the thunderstorm may produce severe weather. Note that the track widens with time to indicate the degree of uncertainty in the forecast track. A pop-up window allows the forecaster to select the severe weather threat to be emphasized and enter free-from text. In 6d, the forecaster has inserted a new cell (at top) to indicate that convective initiation is expected in the area where weak reflectivity has been detected. Yellow ellipses indicate convective initiation, red ellipses indicate intensification, green ellipses indicate dissipation, and grey ellipses indicate that no significant change in intensity is expected.

changing the intensity threshold at which storm cells are identified. This would serve to decrease the number of tracks that may need forecaster modification.

URP-generated cell and tracks are updated every 10 minutes, and it will be challenging to design an iCAST prototype that makes the forecaster's workload reasonable. Clearly, on days with numerous storms, the forecaster will not have time to examine and, if necessary, modify each nowcast track in an SPC's large area of responsibility.

URP generates a table of priority-ranked storm cells that is used by forecasters to select the most important storms for further interrogation. This table, as provided by URP, will be used for iCAST to identify the cells that require the most attention, and may need track and cell modifications. Overall, the iCAST user interface will have to be fast, robust and intuitive to meteorologists in order for track modification to be feasible.

Once fully developed, iCAST would accomplish several things. First, the forecaster would focus on meteorology rather than the details of product generation. Second, it would allow a 'warn on nowcast' approach at storm scale. This means that forecasters would issue warnings based on the *nowcast* severity of the storm. Current MSC tools make this difficult, so many warnings are issued based on *diagnosed* storm severity. This should result in a significant increase in lead times for warnings.

Lastly, at the OSPC and several other SPCs across Canada, lead times and accuracy are reduced because the warning preparation software used requires several unintegrated steps, making the process tedious and time consuming. Forecasters at the OSPC have been clamouring for a new tool for warning region selection and bulletin preparation for many years. iCAST would eliminate the need for such a tool since warning preparation would be based on storm object depictions generated by the forecaster.

The first iCAST prototype is being used in a real-time, operational setting during the summer of 2009 via the Research Support Desk at the OSPC in Toronto. It is hoped that by the end of the summer, the concept will be shown to be valid and the process feasible.

## 8. FURTHER INTO THE FUTURE

In the prototype phase, iCAST will help to assess the value of human input to the convective nowcast problem via an automated verification process. Currently, thunderstorm prognosis areas are compared to lightning observations (see Fig. 7) to provide feedback to the forecaster. Verification scores can be calculated using these fields. Processes are also being developed to compare forecaster-modified tracks, intensity forecasts, ellipse sizes and convective initiation forecasts against URP-generated data derived from radar observations. In addition, we will test whether a semi-automated warning generation interface leads to more efficient and effective warning generation.

There are several other important facets of the iCAST system where significant improvements are anticipated. These include major revisions to the URP cell tracking code, the addition of a lightning-based cell tracking algorithm, new convective initiation indices based on the latest field work and modelling science, and the introduction of artificial intelligence algorithms to handle complex parameter interactions and provide first-guess fields for parameters such as convective initiation and cell intensity trend.

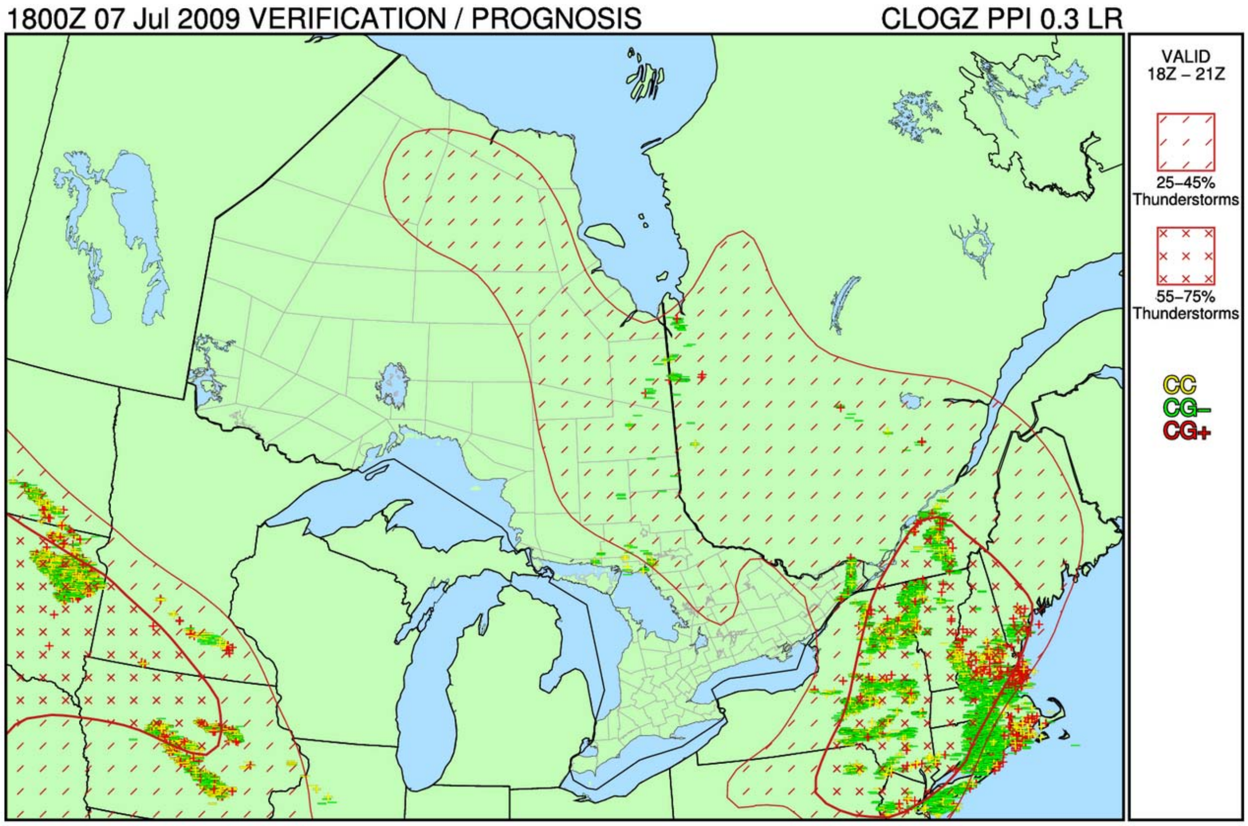



Figure 7. Thunderstorm prognosis verification product valid between 1800 UTC and 2100 UTC on 7 Jul 2009. The single-hatched area represents locations where a 25-45% probability of thunderstorms was forecast, while the double-hatched area represents locations where a 55-75% probability of thunderstorms was forecast. Yellow lightning symbols represent cloud-to-cloud flashes, red lightning symbols indicate positive cloud-to-ground flashes, and green lightning symbols represent negative cloud-to-ground flashes.

To enhance the utility of iCAST, improvements to mesoscale observations and NWP are also required. There will be a need for:

- better ‘clear air echo’ radar scanning strategies in order to facilitate the detection of boundaries,
- high-resolution visible satellite imagery with parallax removed in order to increase the accuracy of boundary detection,
- higher time resolution for surface observations to the increase the ability to detect boundaries,
- mesoscale networks of surface stations and boundary-layer profilers in known storm generation areas such as southwestern Ontario (lake breeze front interaction zone) and southwestern Alberta (dryline zone),
- the ability to detect more of the in-cloud lightning that is currently missed by lightning detection networks since in-cloud lightning is very useful for storm nowcasting, and
- high-resolution rapid update cycle and mesoscale ensemble NWP systems.

Lastly, iCAST depends heavily on human strengths such as the use of conceptual/mental models and decision making. Thus, there will continue to be a need for field studies and indepth case studies to establish new conceptual models and improve upon current ones. There will also be an increased need for forecaster training on conceptual models and decision-making strategies.

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