Towards a Fuzzy Spatial Database for Nowcasting

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Abstract. Advances in GIScience related to spatial uncertainty are relevant to severe weather warning production and weather forecasting in general. Sources of uncertainty in radar imagery are presented, as well as cognitive aspects of warning text. In order to make warnings more specific it is necessary to first understand the inherent fuzziness of natural language. Automating some aspects of warning generation would enhance public safety, but database techniques for fuzzy spatial concepts need to be developed. . . .

1 Introduction

Weather forecasting organizations have long used sophisticated software for display and analysis of geo-referenced meteorological data. Oddly, development of geographic information systems (GIS) and meteorological production systems have taken separate paths, at least until recently. Perhaps the biggest difference is that meteorological data have a very short "useful" life (minutes or hours) compared to natural resource and infrastructure data. Historically, this high data turnover rate was not compatible with commercial off-the-shelf database systems; hence meteorological database systems were developed in-house, often by government organizations. In spite of such differences, there are many applications where databases of different kinds need to interact, and there is common ground with geographic information science (GIScience) on issues of interpolation and uncertainty representation.

Uncertainty is a fact of life in meteorology. Great effort is exerted in attempting to remove uncertainties from weather forecasting, but the economic reality is that there will never be enough observations, and the chaotic nature of the atmosphere precludes exact prediction of future states. Hence, uncertainty is inevitable, and the best one can do is minimize it and quantify it.

The Meteorological Service of Canada (MSC) has a mandate for issuing severe weather warnings. It is in the public and commercial interest that such warnings be as specific as possible. Currently, despite an array of computer generated inputs, warning production is largely a manual process, and outputs are limited to a spatial scale approximating the county level. Useful detail, obtainable from weather radar and other remote sensing instruments, is often lost in the process of compiling information within the constraint of a narrow time window. Much progress could be made by melding these observational technologies with geographically intelligent databases. Some stages could be automated or semi-automated.

Nowcasting is a term used in the meteorological community for very short term forecasting, usually less than 6 hours into the future. Nowcasting tends to rely on forecasters being able to conceptualize physical processes in accordance with recent observations, although numerical modeling contributes as well. The latter is limited by difficulties in assimilating data such as radar imagery into numerical models in near real time. The U.S. National Weather Service routinely issues short term text forecasts of significant weather to the public, but this level of service is unavailable in Canada. Enhanced nowcasting capability is the motivator of current research towards intelligent databases, but there is application to general weather forecasting as well.

2 Uncertainty in Precipitation Estimation

A major observational tool for nowcasting is weather radar. Like all remote sensing instruments, weather radar has limitations in measuring the "truth", in this case extent, type, and quantity of precipitation. Such limitations are well documented, for example by Harrison, et al. [1]. Good estimates require stable hardware components and accurate sensitivity calibration, an ongoing concern for aging equipment. Ground clutter is caused when the main beam or side lobes encounter non-atmospheric reflectors such as buildings. Anomalous propagation occurs when there is beam bending due to changes in refractive index, such as in humid areas over lakes. When barriers such as topography obscure views, there is occultation. Heavy rain can cause signal attenuation depending on frequency (Canada uses C-band radars), meaning it is more difficult to accurately measure areas beyond the heavy rain. Variations in precipitation type can result in varied drop size distributions, hence a faulty relation between the measured reflectivity (Z) and the deduced rainfall rate (R). The vertical profile of reflectivity can change depending on phase differences due to precipitation growth cycles and wind shear. Snow flakes beginning to melt and thereby forming a liquid shell will enhance reflectivity in a non-uniform layer called the bright band. Also, radar beams can overshoot low level precipitation due to scanning angle and earth curvature at longer distances.

Clearly the problem of quantitative precipitation estimation from weather radar is very complex. Improved confidence can be gained by using additional instruments, if available. Rain gauges are an obvious choice, and these are used extensively for calibration. However, rain gauges are not always spatially representative, especially in areas of localized convective weather. First guess fields from mesoscale models together with optimal interpolation schemes can enhance analyses in some cases.

Where it is economical to do so, multiple radar views of the same area can be beneficial. Figure 1 shows a storm over Southwestern Ontario at 8 p.m. local

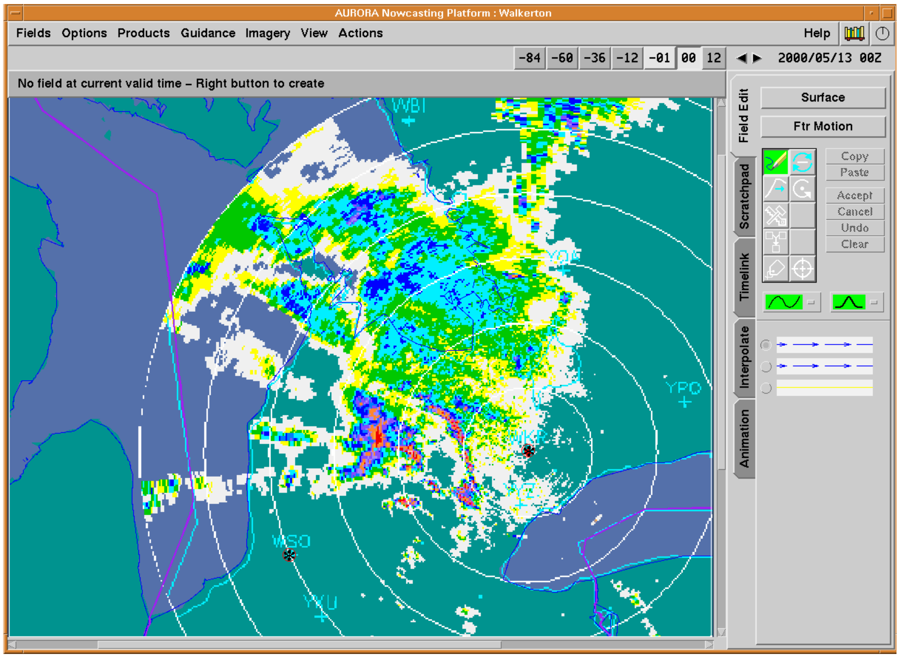

Fig. 1. Radar image centred on King City, Ontario, 8 p.m., May 12, 2000

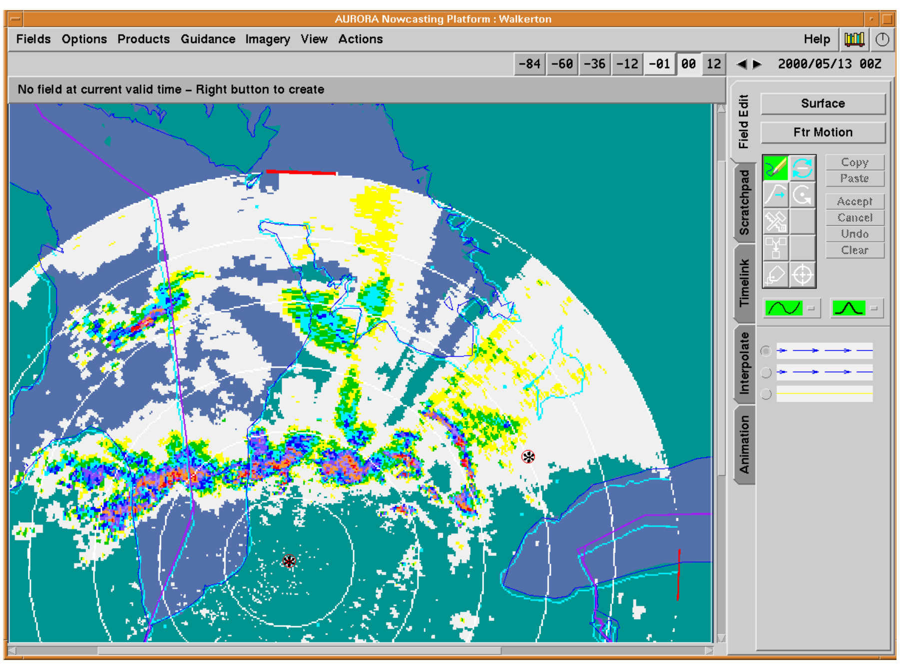

Fig. 2. Radar image centred on Exeter, Ontario, 8 p.m., May 12, 2000

time, May 12, 2000, as seen from the King City radar. Figure 2 shows the same storm as seen from the Exeter radar. Because of high rain intensity, both images exhibit attenuation, but at different angles. The King City image has a large chunk missing to the west over Lake Huron. The Exeter image captures the east-west extent of the storm much better, but is almost devoid of detail to the north. An intelligent composite maker would take attenuation into account, but for some pixels there is no unobstructed view. Areas of low confidence could be flagged, and treated accordingly in output products.

3 Cognitive Aspects of Weather Warnings

At 7:43 p.m. on May 12, 2000, moments before the images of Figures 1 and 2, MSC issued the following severe thunderstorm warning text:

> Severe thunderstorms developed over Michigan and Lake Huron and have moved on shore near Kincardine at 7.20 this evening. This thunderstorm has had large hail.. wind gusts to 140 km/h and tornadoes associated with it over Michigan and Lake Huron. Radar indicated that the storm is moving quickly eastward and is expected to reach the Kitchener area around 8pm, the Toronto area around 9pm or a little later. Some localities in the warned area can expect large hail.. damaging winds and possibly a tornado.

Humans are very adept at assimilating vague descriptions within natural language. Given that the warning text is in effect a summary that needs to convey much information within a small space, fuzziness is both unavoidable and even desirable. What does “near Kincardine” mean? In this case, it is a length of shoreline several kilometers on either side of latitude 44°11′N, longitude 81°39′W. The phrase “near Kincardine” is a compact way of expressing this indeterminate length of spatial reality. This relation between language and fuzzy boundaries is a topic of GIScience [2].

Kitchener is a city halfway between the Exeter and King City radars. Although Figures 1 and 2 do not show it, the preceding sequence of images from both radars indicate a distinct west to east storm movement. Most of the action is clearly to the north of Kitchener, but Kitchener is the largest city in that general area, hence the phrase “Kitchener area” must be understood in a very broad sense. This phrase does little to warn inhabitants of a town such as Orangeville, which lies on the leading (east-most) arc of severe cells in Figure 2.

Depositing radar images onto a cable news channel, as is commonly done today, is only a half measure. Given the training needed to interpret conventional radar images, let alone Doppler radar, the best way to convey severe weather information to lay people is through a combination of pictures and words. Also, we live in an age of inexpensive global positioning systems, and cellphone location tracking. People would like to have weather information specific to their location. With a geographically intelligent database and an automated production system, personalized service would be economical with associated improvements in public safety.

4 Fuzzy Database Concept

Nowcasting takes on multiple seasonally dependent flavors such as predicting the duration of snow streamers off a lake, predicting the extent of freezing rain, or predicting whether a thunderstorm could spawn a tornado. Many such tasks entail finding features in radar imagery that correspond to known physical processes, for example bow echoes indicating updrafts or gust fronts indicating outflow boundaries. Obviously, the limitations of radar described above still apply. The outcome of all cases is the delineation of a risk area.

Any means of quantifying uncertainty, such as running models in an ensemble mode, are welcome. However, risk is often a judgement call, delineated by a polygon on a map. Although polygon edges imply crisp boundaries, it is intuitive that risk is not a step function. What-if scenarios indicate possibilities as opposed to probabilities. Advances in GIScience related to indeterminate boundaries are of interest.

To generate warning events, fuzzy risk polygons must intersect a landmark database. The concept "near Kincardine" would be handled by a fuzzy membership function centered on Kincardine. Kincardine could also have a "coastal" attribute for switching to a different membership function if the context is "the shoreline around Kincardine". Membership functions could also be devised for land features such as the Niagara escarpment. However, to make searches efficient, it might be necessary to organize landmarks in crisp bins first.

Such a landmark database could be constructed with different levels of granularity. Higher levels might include only larger cities, for example. Questions arise, however, about how to deal with mixed granularity, for example, wanting to warn a campground near a larger city about risk of tornadoes. Mennis, et al.[3] describe a pyramid framework for aggregate relationships such as "has-parts". That reference interestingly uses a regional scale storm system called a mesoscale convective complex (MCC) as its main example.

Little mention has been made of temporal uncertainty, but this dimension is also important. There are many applications in meteorology where uncertainty in spatially and temporally defined parameters may be studied. Perhaps through increased interaction between the meteorological and GIScience communities, progress can be made.

References

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