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Feasibility Study: Adaptation of the Local Climatological Model (LCM) to Southern Ontario

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16. Abstract

This feasibility study was motivated by Aurora's desire to investigate the application of cutting-edge technology in support of winter road maintenance in North America. Aurora deems that the Local Climatological Model (LCM) is one example of such technology. This study commences with a brief description of the LCM. It then proceeds to review and contrast the geographic conditions in the area where the model is currently implemented, and the conditions in the proposed deployment area in Ontario, Canada. The report also examines some of the human factors that must be considered when contemplating the introduction of the LCM into an established operating environment. After this, the details of implementation are discussed, including adaptation of the LCM and requirements for data and supporting systems. Finally, a plan for implementation and testing of the LCM in the target deployment area is presented.

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FEASIBILITY STUDY: ADAPTATION OF THE LOCAL CLIMATOLOGICAL MODEL (LCM) TO SOUTHERN ONTARIO

Final Report
August 2001

Project Champion
Jörgen Bogren
University of Göteborg, Sweden

Co-Project Champions
Torbjörn Gustavsson
University of Göteborg, Sweden

Tim Bullock
Meteorological Service of Canada

Authors
Jörgen Bogren, Torbjörn Gustavsson, and Tim Bullock

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A report from
Aurora Program
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-7684
Fax: 515-294-0467
www.aurora-program.org

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

This feasibility study was motivated by Aurora's desire to investigate the application of cutting-edge technology in support of winter road maintenance in North America. Aurora deems that the Local Climatological Model (LCM) is one example of such technology. This study commences with a brief description of the LCM. It then proceeds to review and contrast the geographic conditions in the area where the model is currently implemented, and the conditions in the proposed deployment area in Ontario, Canada. The report also examines some of the human factors that must be considered when contemplating the introduction of the LCM into an established operating environment. After this, the details of implementation are discussed, including adaptation of the LCM and requirements for data and supporting systems. Finally, a plan for implementation and testing of the LCM in the target deployment area is presented.

The Local Climatological Model (LCM) was developed by the Department of Physical Geography at the University at Göteborg, in conjunction with the Swedish National Road Administration (SNRA). The LCM is currently in use in the Jönköping area in Sweden, where it has proven to be quite useful for maintenance operations such as anti-icing, as well as for the issuing of travel alerts to motorists.

The primary source of data used to drive the LCM is the network of RWIS field stations; the most important observed variables are the air and road surface temperatures. In addition, observations of cloud cover are required to determine the weather conditions and the prevailing weather pattern along the target roads. The number of field stations needed to drive the model is determined by the diversity of the topography, and hence the variations in local climate that can occur along the roads. It would be beneficial if the implementation of a LCM was considered at an early stage when establishing a network of RWIS field stations in a maintenance area. Using knowledge of local climatological variations together with thermal mappings when establishing an RWIS system makes it possible to optimise the number of field stations, and maximise the degree to which the observations are representative of the diversity of conditions within the maintenance area.

The LCM was developed for Swedish conditions; to apply the model in North America it will be necessary to adapt various system parameters and formulae. Comparing the climate of the two locations, the Jönköping area and Southern Ontario, it is shown that they have slightly different character, owing in large measure to differences in latitude and differences in position on their respective continents. However, the magnitude of these differences should not create a significant problem when implementing the LCM in Ontario. On smaller spatial scales, there are several important similarities between the sites, which will facilitate adjustment of the LCM to a target site in Ontario. For example, both areas feature a diversified topography, with high, elevated areas and valleys. In addition, both areas contain a mix of forested and agricultural land. Moreover, the influence of large water bodies is present at both locations.

Another fundamental question that must be addressed is whether or not the model would be considered useful by North American road maintainers. This issue is addressed by means of a questionnaire administered to the road maintainers in the target deployment area. In view of their responses, it is apparent that the problems regarding slipperiness faced by these personnel are similar to those experienced in Sweden. It can also be seen that many of the problems relating to road icing can be attributed to local climatological effects. Finally, it is noteworthy that maintainers exhibited considerable open-mindedness to further development of Road Weather Information Systems (RWIS) within their areas of responsibility.

Having demonstrated the feasibility of implementing the LCM in an Ontario target area, the study proceeds to examine the details of a trial implementation. There are seven main tasks:

1. Identification and assessment of study area
    a) Performed in the feasibility study
2. Preparation of study area
    a) The stretches of road to be covered by the LCM must be thermally mapped during different weather conditions and at different times of the day and year.
    b) A field investigation must be conducted to identify topographical and geographic features that have a discernible impact on local climate. Any available historical climate data, particularly temperatures, would be of great assistance in this phase of the analysis.
3. Preparation of LCM
    a) The target roads must be divided into segments.
    b) Any necessary alterations to the LCM algorithms (e.g. tuning to account for sun angle at different latitudes) must be identified and executed.
    c) The user interface must be adapted to meet local requirements. In part, this involves preparing the appropriate base maps on which to display LCM output.
    d) The user interface and documentation must be translated into the working language of operational personnel.
4. Preparation of operational personnel
    a) Road maintenance and meteorological service personnel must receive training on use of LCM, and interpretation of its output.
    b) Training must be done to ensure that the necessary data is collected to support model validation.
5. Operational test of LCM
    a) The necessary hardware, communications, and support systems must be in place for operational use of LCM.
    b) Procedures must be followed for collection of data necessary to perform model validation.
6. Validation of LCM test results
    a) A technical evaluation (model accuracy) must be prepared;
    b) The operational utility of the LCM (the degree to which personnel benefited from model output) must be documented.
7. Preparation of final report and recommendations.

To move from trial implementation to complete operational functionality, would require little more than the steps enumerated above. With the exception of rectification of any shortcomings noted in the report (Step 7), the only difference would be the scale of effort required to implement the LCM across the organization's area of responsibility. Thanks to the modular nature of the LCM, this could be accomplished in piecewise fashion, at a pace dictated by available resources.

1. OBJECTIVES AND DELIVERABLES

The goal of this project is to determine the necessary factors for adaptation of the LCM to a new geographical region. The various requirements are identified by:

- performing a review of the geographic conditions of the site for which the LCM was designed and those of proposed new deployment location;
- conducting a survey of operational personnel to gauge their acceptance of the LCM as an additional source of guidance;
- investigating and compiling an inventory of data and systems required for LCM implementation;
- preparing an outline of an implementation plan for the LCM at the Ontario trial site.

Specifically, the feasibility study contains the following main deliverables:

1 - Review of geographical / meteorological characteristics
   Determine locations within Ontario and Sweden to be considered within the feasibility study
   Analysis of factors important for the LCM adaptation

2 - Comparative analysis of the two sites
   Assessment of LCM transferability
   Documentation of equipment and data required for the LCM

3 - Create LCM transfer implementation plan
   Determine technical and other resources required
   Prepare outline implementation plan

These main tasks are dealt with in the report under the headings:

- Overview of geographical/meteorological characteristics
- Detailed analysis of physical factors
- Consideration of the human factors
- Segmentation of road stretches
- Finishing touches and next steps

2. DESCRIPTION OF THE LOCAL CLIMATOLOGICAL MODEL

2.1 Background: The Rationale behind the Local Climate Model

At present, the RWIS installation in a typical North American maintenance area consists of a network of field stations distributed across the maintenance area. Figure 1 depicts the RWIS network in Southern Ontario.

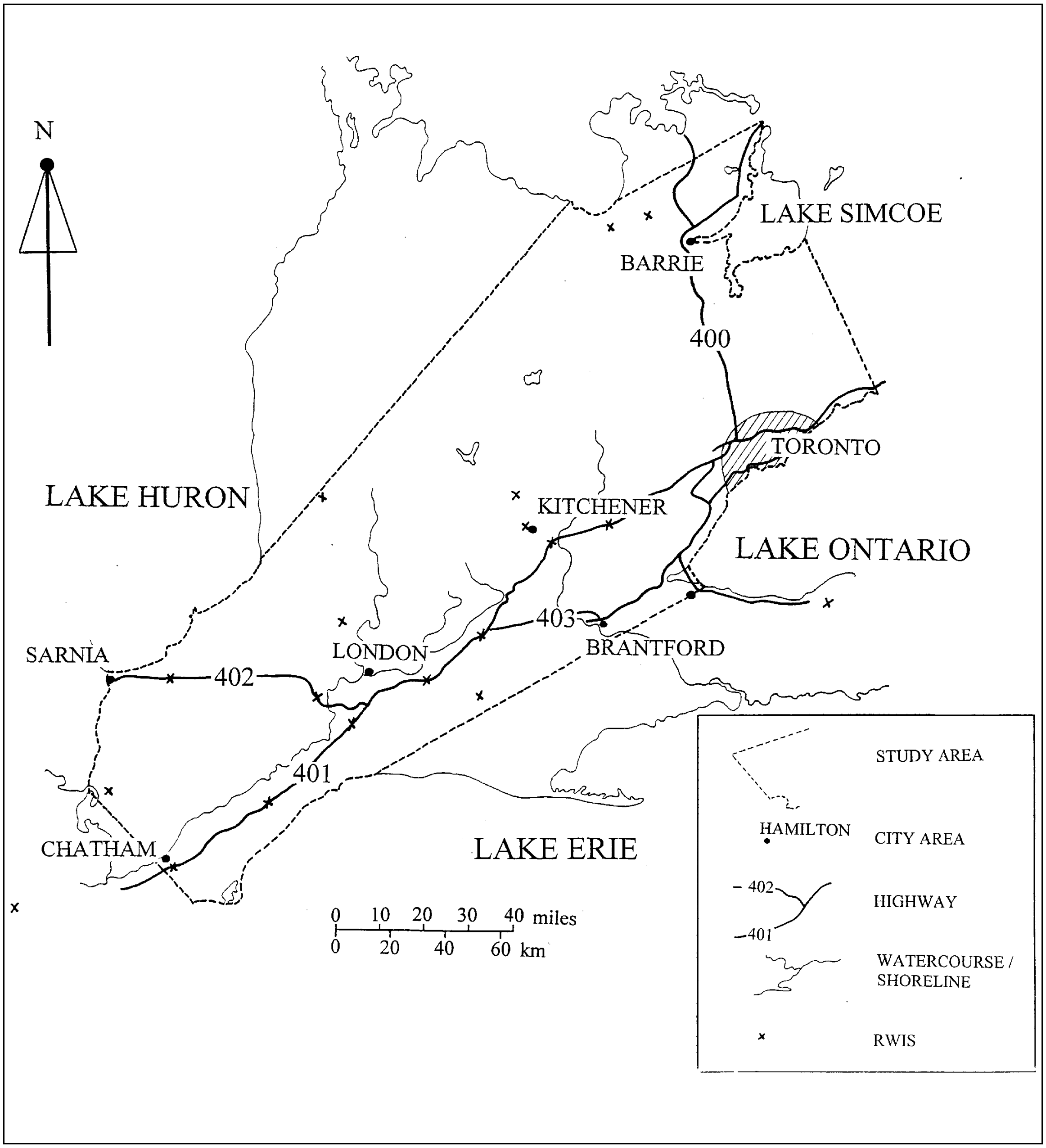


Figure 1. The Ontario area with RWIS

With a network of stations, pavement temperature information is only available for those points at which field stations are located. Ideally, one would prefer that the conditions reported by these stations are representative of the range of conditions that actually exist across the maintenance area. In practice, the degree to which the stations are representative will depend on the criteria used to determine station siting. In any case, there is a need to extrapolate temperatures from the field stations to make them valid for larger areas, before one can use them effectively to support road maintenance decisions. Such an extrapolation is not possible without taking the local topography into account.

The goal of a local climatological model is to perform the extrapolation in an objective, physically consistent manner. Using information from the network of field stations, the LCM attempts to infer the pavement temperatures along discrete stretches of road, by considering the significant climatological impacts of local topography along each stretch.

To determine the feasibility of adapting the LCM into a new area, several essential factors must be considered. These factors include: climatological conditions, structure of the maintenance organization, and availability of road weather information. In this section, the climatological considerations are examined.

2.1.1 Modeling of Local Climate - Repetition of Temperature Patterns

The fundamental idea behind modeling local climates for temperature variations is that the temperature pattern is repeated during situations with similar weather. To illustrate this phenomenon, air temperature recordings from three measuring trips along Road 132 in the County of Jönköping, Sweden are shown in Figure 2. The recordings were carried out on 4 January, 7 January, and 6 February 1994. All three runs were started at 21h LST. During the three nights, skies were clear. A light wind of approximately 1m/s was blowing on 7 January, but the other two nights were calm. The correlation between the lowest air temperatures is very high, as can be seen in the figures, and the temperature patterns along the road during the three nights are very similar. The lowest air temperature was to be found in three distinct valleys along the road, as well as in an open area of arable land at a distance of 24 km from the starting position.

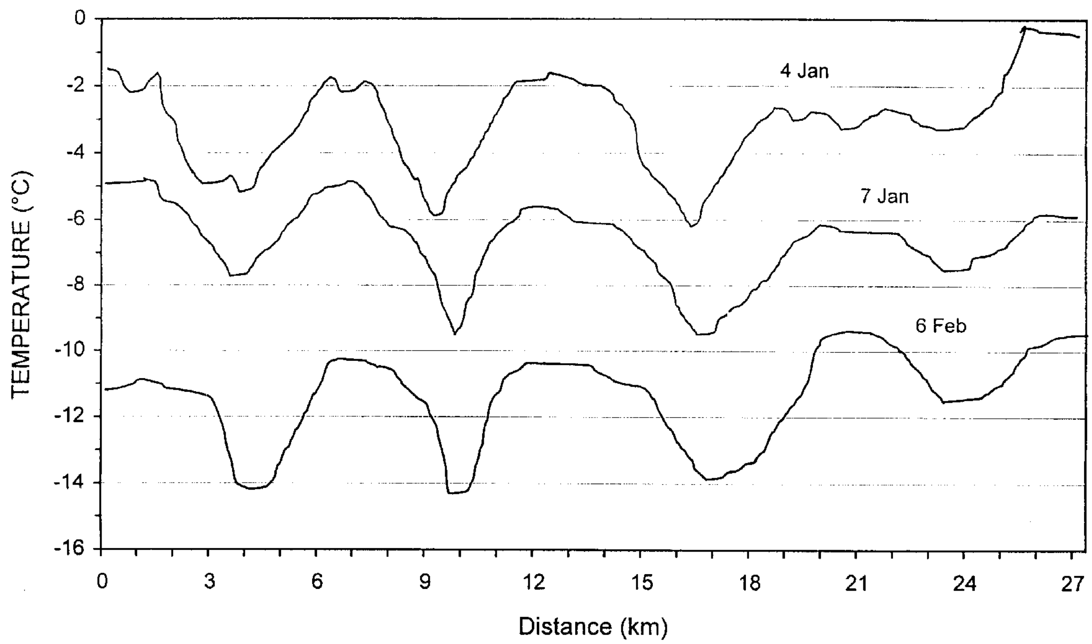


Figure 2. Repeatability of temperature pattern; recording from clear nights

The theorem of reproducibility forms the basis for modeling local climate by analogue methods. Experience indicates that it is possible to construct a highly accurate model of the temperature variation in an area, especially when simulating temperature variations along road sections that have been thermally mapped. This reasoning is also valid for weather situations that are not clear and calm, as the temperature pattern is to a high degree controlled by local topography and other factors. The relative importance of these various factors can be determined by analysis of climate data. This is discussed further in the following sections, wherein each factor is treated individually.

The LCM that is presently in use in the Jönköping area calculates the current road surface temperature, based on observed data. The development of modules to predict air temperature and humidity are subjects of on-going research at the RCC, University of Göteborg. These latter variables are necessary to determine the risk of slippery conditions. Modules are also being developed that take forecasted values into consideration to produce stretchwise predictions.

To give a better understanding of the information requirements of the LCM, a brief introduction to the fundamental climatology embodied within the model is given below.

2.2 Factors Controlling Local Temperature Variations

2.2.1 Valleys

Accumulation of cold air in valleys during clear, calm nights results in a varying air temperature pattern along road stretches. Observational studies (Gustavsson and Bogren, 1993) have demonstrated that the variation in temperature between valley bottoms and summits is a function of the valley geometry, i.e. the width and depth of the valley. Another important factor was found to be the wind exposure of the valleys. The return period of the occurrence of cold air pools, as well as the magnitude of the temperature difference, increased if the valley location was in any way sheltered from the wind by, for example, trees.

Accumulation of cold air in valleys causes a reduction of the road surface temperature (RST) compared to the RST of nearby neutral areas. It has been observed (Gustavsson 1990) that the lowering of the road surface temperature is linearly related to the lowering of the air temperature in the cold air pool. For example, an air temperature difference of 6°C results in a lowering of the RST by approximately 2,5 °C. Since one can determine the variation in air temperature in valleys in calm, clear conditions as a function of geometric factors, it is therefore possible to calculate the variation in road surface temperature, also. An example of such a calculation for the Holland Marsh, a prominent valley in Southern Ontario, is given in Section 3.

2.2.2 Variation in Altitude

Under cloudy, windy conditions, variations in temperature are highly correlated with changes in altitude, and the influence of the shape of local topography is much less significant. As a result of turbulent mixing of the air and counter-radiation from clouds, the temperature differences are generally small. In order to calculate the temperature variations during this type of weather, the station elevations are used, together with air and road surface temperatures, as inputs to a regression model. From the regression equations, the distribution of air and road surface temperature as a function of altitude is determined. Under fully mixed conditions, the temperature falls by approximately 1°C per 100m increase in altitude. This tendency is a general one and can be used for both night and day.

The effect of cloudy, windy conditions on the temperature lapse rate (i.e. change of temperature with height) is illustrated in Figure 3. The two RWIS stations used in this example cover an altitude range of 150m. Station 20 is situated at 170 meters above sea level (masl), while station 26 is sited at 320masl. The relation between the minimum road surface temperatures (RST) of the two stations is expressed by the equation:

$$RST(20)=0,7+0,96RST(26), \qquad (1)$$

with a correlation coefficient of r=0.97. The number of observations used to arrive at the above equation was 29. This implies a decrease RST of 0,64°C per 100m change in altitude. The minimum air temperature (AT) behaves in the similar way as the road surface temperature.

The regression for the air temperature is

$$AT(20)=0,98+AT(26), \qquad (2)$$

with r=0.96, i.e. a change in temperature of 0,67°C per 100m. (Bogren *et al.* 1992 and Gustavsson & Bogren 1993).

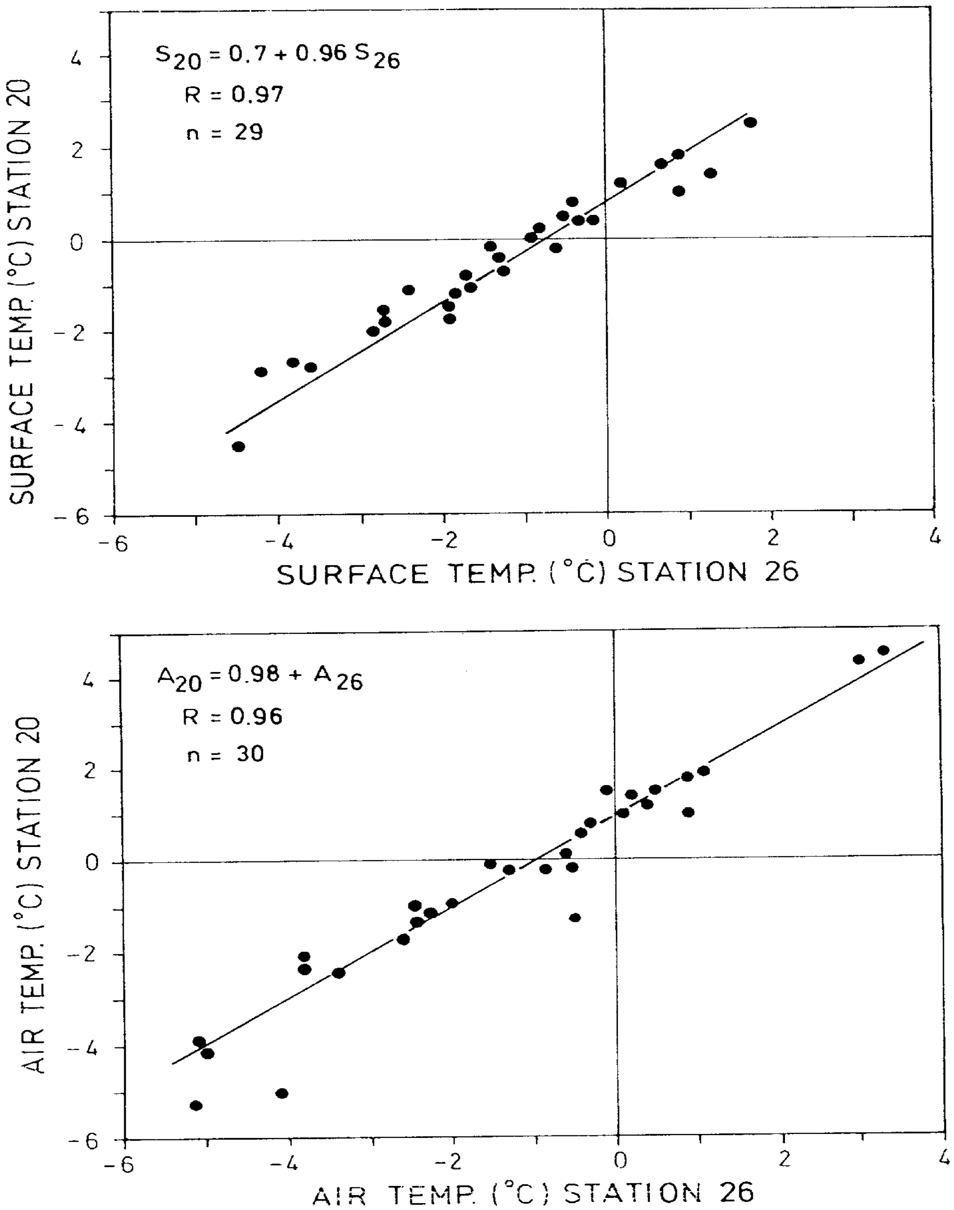


Figure 3. Temperature variation related to altitude during cloud windy conditions

2.2.3 Screening or Shading

On clear days, the screening effect must be considered when analyzing temperature variations along road sections. Especially during the spring and autumn, screened areas can be prone to localized risk of slipperiness. The factors of greatest importance when considering screening effects are the position of the sun in relation to the site (time of day and season) and the type of screening object, together with its orientation in relation to the orientation of the road. The intensity of the temperature difference that develops between screened and exposed sites is also affected by the amount of cloud. Bogren (1991) demonstrated that the orientation and geometrical configuration of the screening object are the most important factors controlling the variation in RST on sunny days.

The effect of screening objects on RST is illustrated by a thermal recording from a measuring trip taken on a sunny day, shown in Figure 4. The measuring trip was conducted in the western part of Sweden, on a road section where screened and open areas alternate. The screening objects are mainly road rock cuts. Since its orientation is primarily east-west, parts of the road are screened during the middle of the day. This configuration affords a good opportunity for study.

The measuring trip was carried out in the early afternoon on 6 March 1990. The weather preceding the measuring trip was clear and calm; these conditions also prevailed during the thermal recording. The areas that were not screened from the sun had a relatively high surface temperature, approximately 11°C. The difference in temperature between the screened and exposed parts of the road section varied among 5,7 and 2,3°C. The variation among the 13 screened areas can be explained by two of the major factors, the exact orientation of the road rock cut and its height.

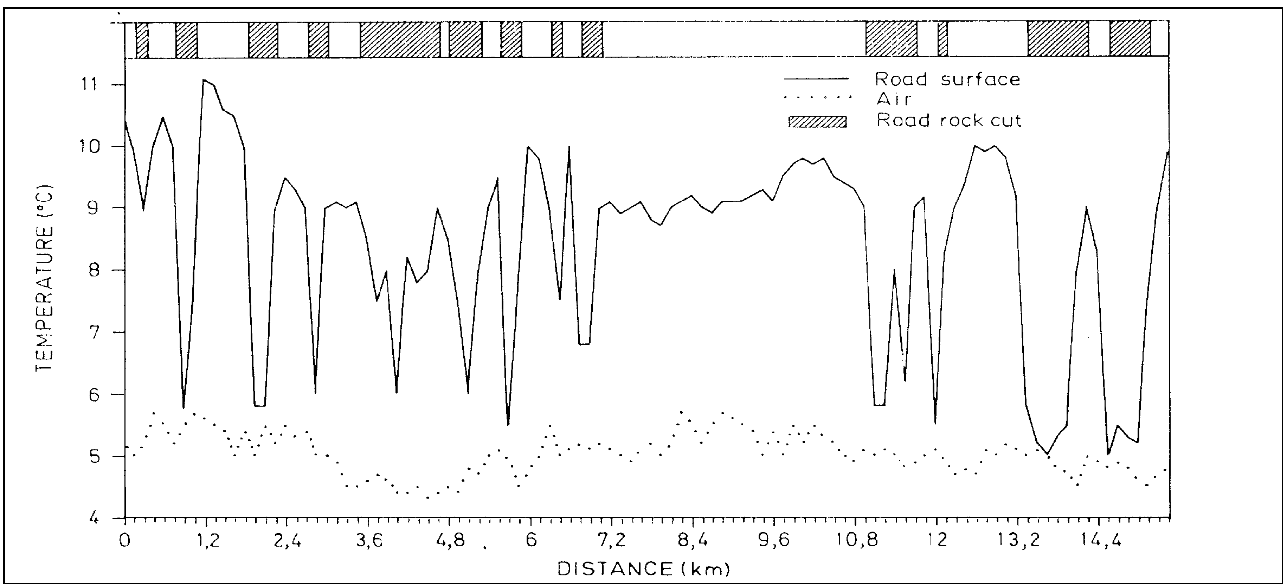


Figure 4. Variation in road surface temperatures as a result of shading on the road surface

By use of information about the position of the sun together with data on screening objects, it is possible to calculate the temperature difference between screened and sun-exposed areas. Additional input is gained from the RST values recorded at the RWIS stations along the road section in question.

2.3 Synopsis of the Functioning of the LCM

Armed with the tools for calculating RST variations under different conditions described in the foregoing section, one can develop algorithms for computing the RST along stretches of roads. The algorithms described here were first presented by Bogren and Gustavsson (1986), and form the basis of the LCM.

Since different weather conditions require different factors to be taken into account, the model is subdivided into five sections, each dealing with a specific weather condition. These are: *day /clear*, *night/clear*, *cloudy*, *windy*, and *regional pattern*. The category *regional pattern* is dynamically changeable, depending on the prevailing conditions. The LCM can use one or more of these modes or types of temperature patterns, depending on the prevailing weather situation. Selection of the appropriate mode for a given area is made based on time of day, observations from the field stations in the area, and information on cloud cover and wind speed.

The algorithm for determining which mode to employ, depicted in Figure 5, attempts to match observed conditions to those conditions that would be expected in a particular weather pattern. The first task of the algorithm is to decide whether to try to match daytime or night-time temperature patterns, based on the time of day. In the daytime the LCM tests for *day/clear* conditions by comparing the theoretical calculations for screening effect with the values that are observed by the network of field stations. If the observations do not match the calculations, the algorithm proceeds to investigate if there is a temperature decrease with increasing height, as one might expect with *cloudy* or *windy* conditions. If there is not an acceptable match, the model chooses the *regional* temperature distribution.

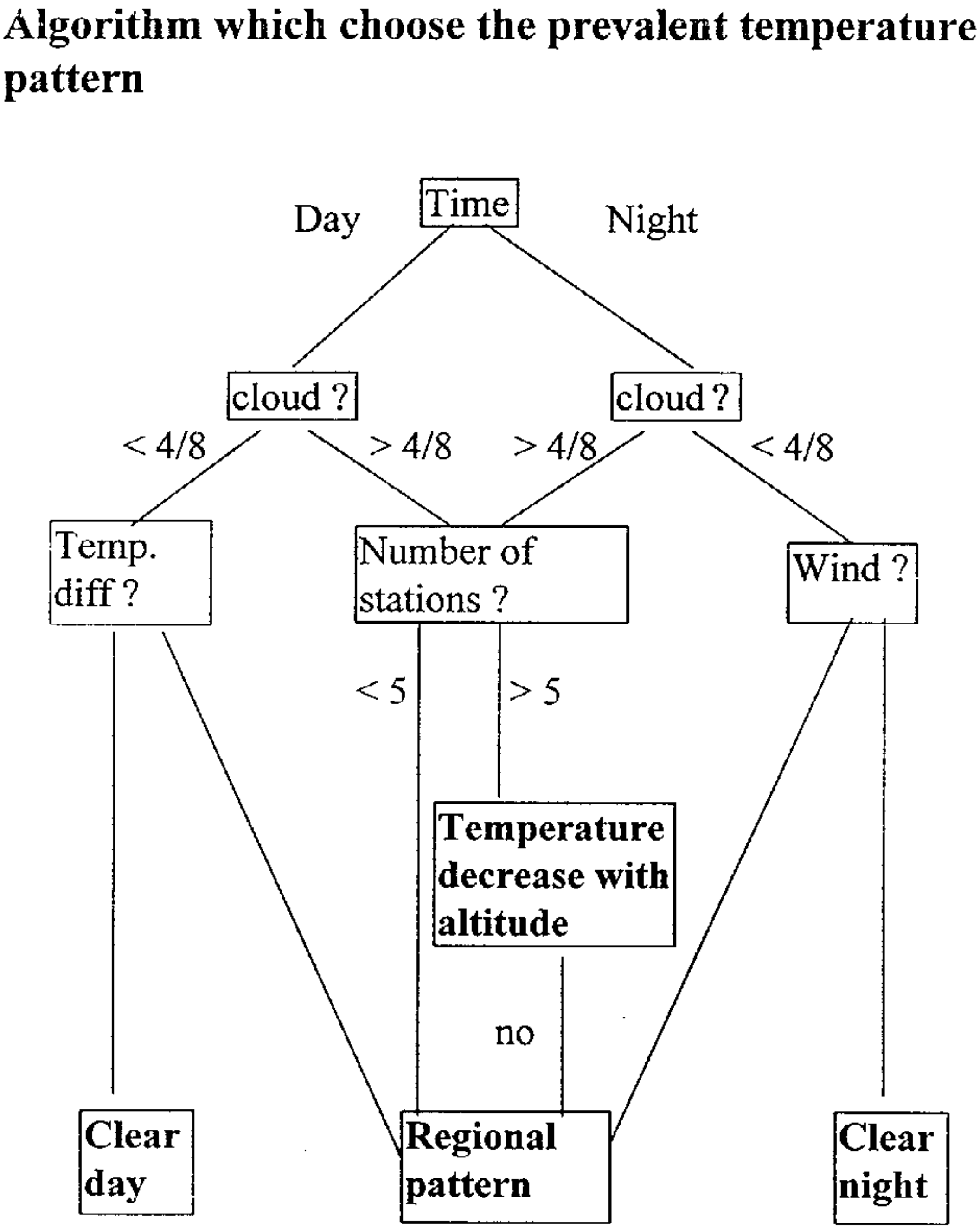


Figure 5. Flow chart showing the main decisions within the LCM

At night, the LCM tests first for *night/clear* conditions, by considering the criteria for pooling of cold air and its effect on the road surface temperature. If the required criteria regarding wind speed and temperature differences match the values observed at the field stations, the model uses the *night/clear* temperature pattern. If the wind speed is high and the temperature pattern smooth, the algorithm tests observations from the field stations to determine the correlation between station elevation and temperature fall. In situations with a high correlation between increasing height and falling temperature, the model infers that this correlation can be extended to intermediate points, as well. This accomplished with the *cloudy/windy* temperature pattern. If there is a poor correlation between station elevation and temperature, the *regional* temperature pattern is used. This temperature pattern is determined by the regional climate, as determined from historical weather data.

2.4 Benefits of LCM Output for Maintenance Decision Support

The benefits of using a local climatological model such as the one described above are several, compared with a road weather information system based only on field stations. Naturally, the most important benefit is that the area covered by the information system is much larger, resulting in a more diversified snow and ice control strategy. Computerized maps of the temperature variations along stretches of road can be used by the road authorities and by others to determine the local risk of slipperiness. The information from the model may be combined with a temperature forecast to obtain a prognosis of the temperature pattern for the coming 4-6 hours, as well as a prognosis of the risk of road slipperiness, not only at specific locations but for the whole area covered by the model. Armed with this detailed guidance, the supervisor is better able to optimize allocation of available anti-icing and snowfighting resources. One of the desired outcomes of a test implementation of the LCM in Southern Ontario would be some measurement of these benefits.

2.4.1 Adaptation of the LCM to a New Area: Overview of Geographical/Meteorological Characteristics

To investigate the conditions needed for implementation of the LCM in a new environment, it is necessary to identify the geographic and climatological characteristics of the current model domain, and contrast them with the characteristics of the proposed target area. This inventory identifies the parameters that need to be considered according to weather, topography, and other relevant factors in the target area.

2.5 The Reference Domain in Sweden and the Target Domain in Ontario

The locations that are contrasted in this study are the county of Jönköping in southwest Sweden, the reference domain, and part of Southern Ontario, in Canada, the target domain.

2.5.1 The Jönköping Area

2.5.1.1 Geographical Description

The Swedish area where the LCM is implemented, the county of Jönköping in southwest Sweden, is situated between Latitude 57°N and 58°N, and Longitude 13,5°W and 14,5°W. A general view of the area (Figure 6) shows a landscape with a diversified topography and variations in land use. Forested areas are succeeded by agricultural land; the area is also bordered by large water body, Lake Vättern. Another striking feature of the area is the large variations in altitude. The diversity and high frequency of different topographical units that are significant for establishment of temperature variations make this area suitable for modeling of local climatological variation. For example, open valleys situated within the forested areas are very susceptible to pooling and accumulation of cold air.

2.5.1.2 RWIS

The road weather information system (RWIS) is well developed within the Jönköping area; field stations are located in various local climatological environments. Figure 6 shows the spatial distribution of field stations within the area and Table 1 gives a summation of the diversity of the different local climatological environments that are represented within the RWIS network.

2.5.1.3 Climate

The climate of the area is heavily influenced by the regional topography. The distribution of annual precipitation clearly shows an orographic influence, with the highest elevated areas in the central part of the county receiving the maximum precipitation. The highest precipitation amounts, approximately 1000 mm/year, fall on the western slopes leading up to the central elevated area. From that point, annual precipitation amounts diminish progressively toward the East. The highest elevation in the county exceeds 340 masl.
The proximity to the sea in the west results in a high frequency of relatively mild westerlies, which affects the regional climate during the winter season. However, the highest elevated areas in the central part are characterized by an inland climate. In the northern part of the area, Lake Vättern exerts a local but significant influence on the climate. In the central elevated parts, the mean temperature during the coldest winter months (January and February) is approximately -3°C; during the warmest summer month (July), the mean temperature is between 15°C and 16°C.

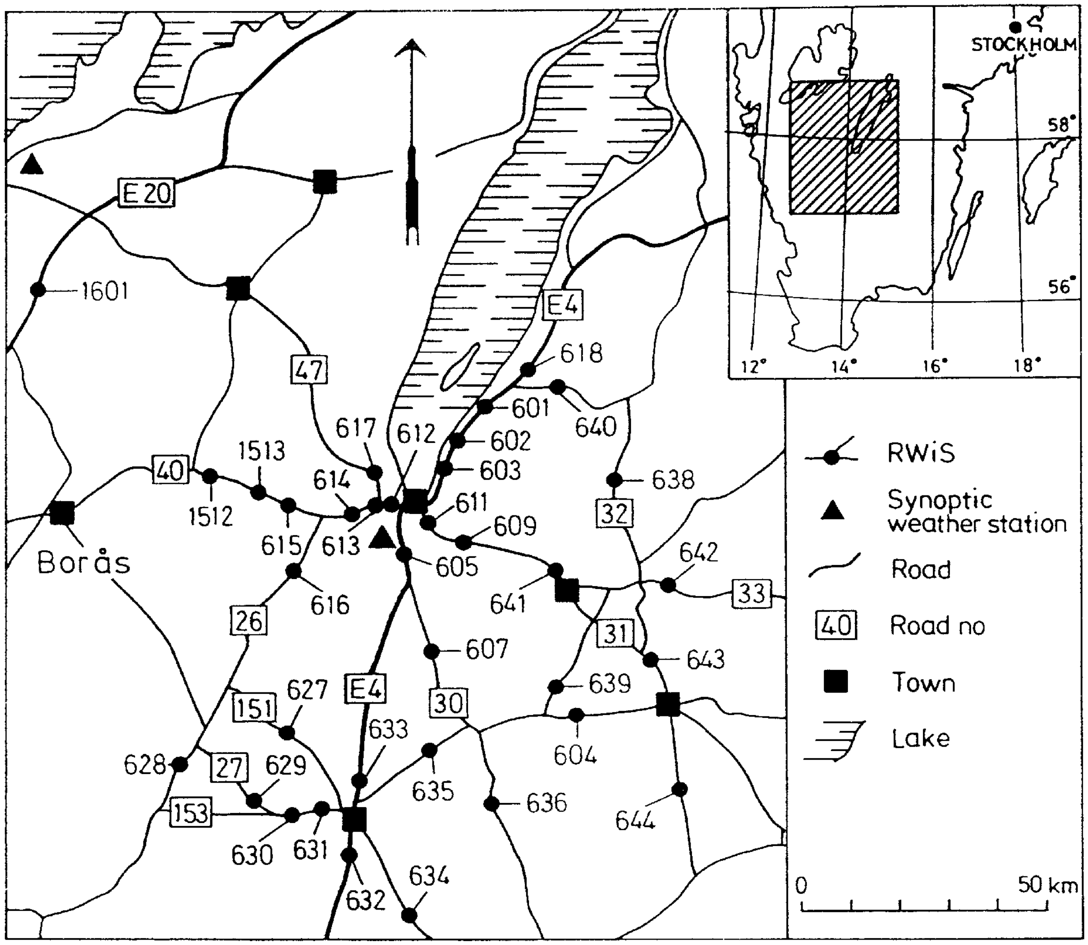


Figure 6. The Jönköping area with field stations within the RWIS

Table 1. Site description field stations in the Jönköping area

Station no.	Wind sensor	Extra surface temp. sensor	Altitude (m.a.s.l.)	Characteristics *
601	Y	Y	190	Open and wind exposed. Close to lake Vättern.
602		Y	195	Local low-point close to lake Vättern. High slope on the eastern side that screens the station during the morning.
603			130	Open and wind exposed. Close to lake Vättern. Screened by topography during the morning.
604			255	Local low-point. Close to deciduous trees.
605			220	Open and wind exposed.
607			200	Close to a small lake. Screened during afternoon by terrain and trees.
609			220	Local low point / bog surrounded by deciduous trees.
611	Y		250	Hilly site surrounded by road cuts and some trees.
612		Y	90	Relative open terrain with scattered bushes and low deciduous trees. In the lower part of a large hill close to the bridge over Taberg river.
613			230	On a hilltop surrounded by medium high coniferous trees.
614			235	Local low point surrounded by high forest.
615	Y		225	Open on the southern side and medium high coniferous forest on the northern side of the station. Situated in a small valley.
616		Y	220	Hilly site. Open on the eastern side and medium high forest on the western side of the station.
617	Y		135	Open and wind exposed. Arable fields on both sides of the station.
618			260	Height surrounded by road walls. Close to lake Vättern.
627			225	Hilly site surrounded by road cut and high coniferous forest.
628			182	Hilly site in forest.
629		Y	180	Hilly site in forest.
630			155	Local low-point in forest.
631			185	Open.
632		Y	145	Open surrounded by arable land.
633		Y	165	Flat terrain in forest/bog.
634		Y	230	Wind exposed and open at a hill crest.
635			183	Relative open with scattered bushes and trees.
636			250	Hill crest in medium high forest.
638		Y	225	Open and hilly site.

639	Y	Y	225	Open in flat terrain/bog.
640			245	Close to hill crest surrounded by topography and forest.
641			305	Close to hill crest surrounded by topography and forest.
642			255	Hill crest surrounded by deciduous trees.
643			245	Close to hill crest surrounded by forest.
644			250	Local low-point in forest.

2.5.2 The Ontario Area

2.5.2.1 Geographical Description

The target area in Canada comprises most of South-western and South-central Ontario, between Latitude 42°N and 44,5°N, and Longitude 79,5°W and 83°W, as shown in Figure 7. The dominant land use class here is agriculture and farm land. However there are also numerous forested areas, and several areas of large-scale urbanization. The most significant local factors affecting the climate in this part of the province are Lake Huron and Georgian Bay to the North, and Lakes Erie and Ontario to the South. Other features that exert a more local influence on the climate include: the Dundalk Highlands, the Niagara Escarpment, and the Oak Ridges Moraine.

For a better appreciation of the details of the local topography that are of relevance to the feasibility of implementation of the LCM, further examination of the geology of the area is necessary. The area forms part of the Great Lakes-St. Lawrence Lowland, the landscape of which is largely determined by the underlying bedrock. As in many other parts of Canada, the basement underlying the sedimentary rocks of Southern Ontario is the Canadian Shield. Although Southern Ontario is part of the great stable interior of North America, the basement has been marked by depression and uplift, which have developed basins and domes. Limestone plains occur along the northern and southern edges of the Frontenac Axis, and along parts of the Niagara Escarpment from the Bruce Peninsula to the Niagara Peninsula. At the end of the last ice age, retreating glaciers deposited masses of ground moraine, to form rolling till plains, together with long, uneven morainic ridges. These forms dominate the landscape in the Horseshoe Moraine, and the Oak Ridges Moraine. The retreating glaciers also left many small drumlins and eskers, which fan out from Georgian Bay and Lake Ontario. In other areas, such as between the middle Thames River and the middle and lower Grand River, there is deltaic sand. Thus, although the Great Lakes-St. Lawrence Lowlands may not have strong relief, the area displays a diversity of landforms. This variety of landscape helps to produce a varied local climate; under such conditions, the LCM is designed to provide much additional information for road maintainers. Figure 7 shows the variation in surface altitude within the target area. See also figure 9 for details of the studied area.

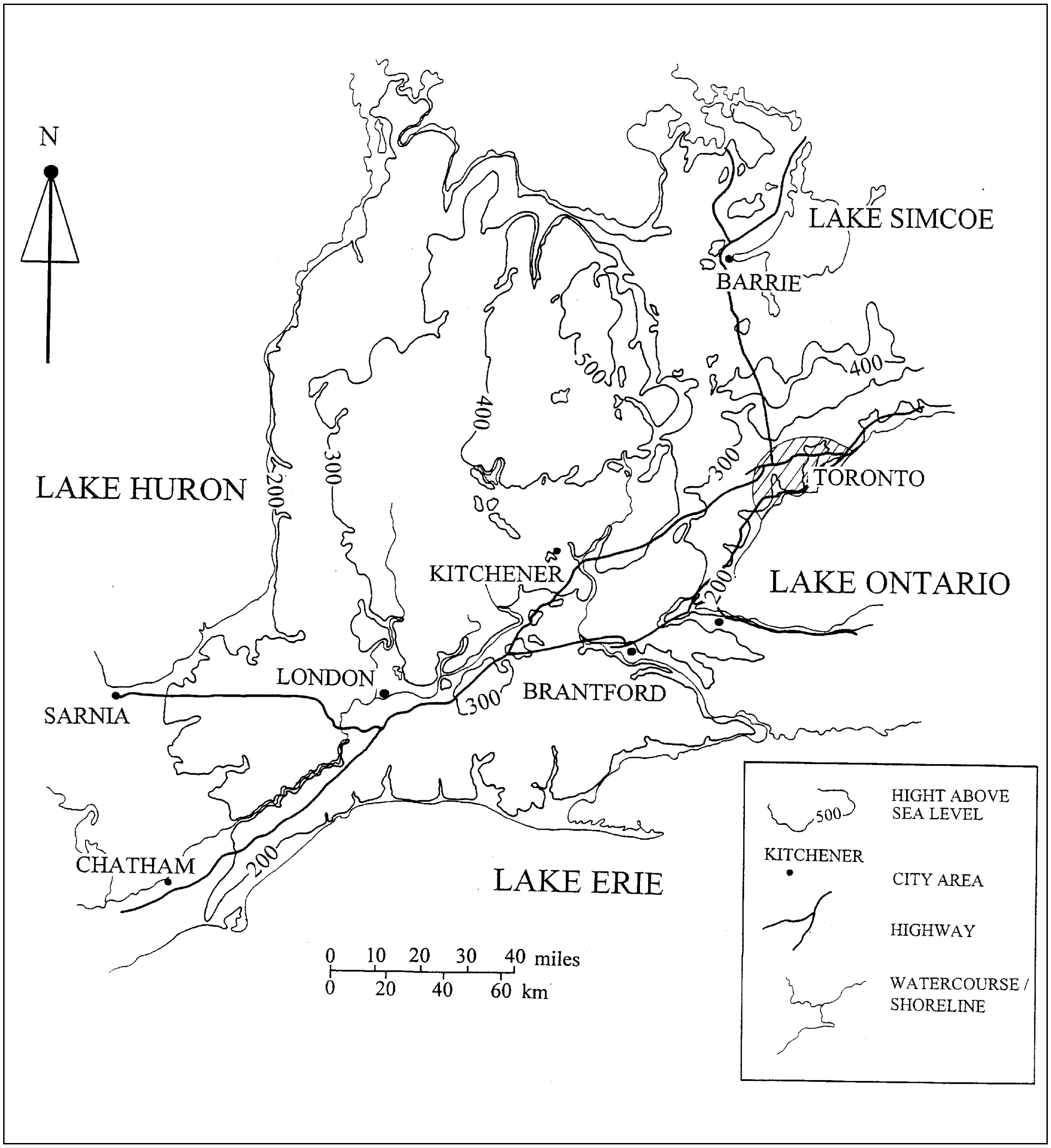


Figure 7. The Ontario area with contour lines indicating the elevation

2.5.2.2 Climate

The target area can be divided into three major climatic zones. Along the north shores of the Lower Great Lakes, the winters are cool, with mean January/February temperatures in the -3°C to -6°C range. A mix of precipitation types can be expected in all winter months. Most precipitation is produced by synoptic-scale disturbances, which pass by or through the region every three days, on average. To the South and east of Lake Huron and Georgian Bay, mean winter temperatures are in the -4°C to -8°C range. In addition to precipitation from synoptic systems, which falls mainly as rain or snow, there is a significant contribution from lake-effect snowfall (hence the moniker "snow belt"), which will be discussed in greater detail below. Finally, in central and eastern portions of the target area, away from the Great Lakes, mean winter temperatures range from -5°C to -9°C. Precipitation associated with synoptic systems falls mainly as snow, although patchy freezing rain is more common here than in areas closer to the shores of the Great Lakes. Lake-effect snow contributes to total snowfall amounts on the northern and western slopes of the uplands, with the contribution decreasing as one moves away from the shores of the Lakes.

Throughout the target area, the moderating effect of the Great Lakes is most evident. Cold outflows of arctic air are much modified by their passage over the warmer waters of the lakes; this is demonstrated by comparing the climate of Southern Ontario with that of areas at the same latitude in the Northern Plains of the United States, such as southern Minnesota, Iowa, or Wisconsin. On the other hand, the Great Lakes also impede warm, southerly flows of tropical air from overrunning Southern Ontario for much of the year. This tends to delay the arrival of spring, and prolongs the season of freeze-thaw cycles.

2.5.2.3 Lake-Effect Snows

A highly localized fall of snow immediately downwind from an open lake is known as lake-effect snow. Typically, such snows extend inland only a few tens of kilometers. Often, lake-effect snow bands cover such a small area that they are not detected by the network of synoptic weather stations. However, the impact of these events on travelers and residents in the affected area may be quite significant. Lake-effect snow is most common in autumn and early winter when lake surface temperatures are still relatively mild, and the lakes are ice-free. As outbreaks of cold air stream (or advect) over the lake, water readily evaporates and raises the vapor pressure of the lowest portion of the advecting air mass. In addition the warmer lake water heats the advecting cold air from below, reducing its stability and enhancing convection and cloud development. Often, this is enough to trigger snowfall over the lake. As the modified (milder, more humid, and less stable) air flows toward the lake's lee shore, the contrast in surface roughness between the lake and land becomes important. The rougher land surface slows onshore winds, and the consequent horizontal convergence induces ascent of air, further development of clouds and lake-effect snow. The topography of the shore also affects the amount of precipitation. Hilly terrain forces greater uplift and heavier snowfalls than does flat terrain.

Ultimately, the frequency and intensity of lake-effect snow hinge on the degree of air mass modification, which, in turn depends on: (1) the temperature contrast between the mild lake surface and overlying cold air; and (2) the over-water trajectory (fetch) of the advecting cold air. As the temperature contrast between water and air increases, so too does the potential for lake-effect snow. Hence, to the lee of the Great Lakes, the bulk of lake-effect snow falls between mid-November and mid-January, the usual period of maximum temperature difference between the lake surface and overlying air. Earlier in the autumn, lake-effect precipitation typically falls as rain. In the latter part of the winter, the Great Lakes become increasingly ice-covered. This reduces the fetch available for generation of lake-effect snow, and it displaces the edge of the open water away from the shoreline. These two factors also contribute to a decrease in the frequency of observed lake-effect snows as the winter progresses.

Cold air usually sweeps into the Great Lakes region on northwest winds. Hence, the greatest potential for substantial lake-effect snows is along the downwind southern and eastern shores of the Great Lakes, as shown in Figure 8. In these so-called snow belts, lake-effect snow accounts for a substantial fraction of the seasonal total snowfall. It is also important to note that the intensity of snowfall is usually not constant along the length of the lee shoreline. Typically, there are one or two bands, or “streamers” of very intense snowfall, and a number of lesser bands. The most intense streamers produce the heaviest precipitation, the lowest visibility, often the strongest winds, and they extend for the greatest distance inland. In extreme cases, streamers have been observed to form over the eastern half of Lake Superior, re-intensify over northern Lake Huron, cross Southern Ontario, re-intensify over Lake Ontario, and continue across the New England States, all the way to the Atlantic Ocean!

Lake effect snow poses a particular problem for road maintenance in the target area. The localized nature of the events means that conditions at the maintenance garage may not be representative of conditions across the maintenance district. The gusty winds and intense precipitation in the more energetic streamers produce white-out conditions in snow and blowing snow in a narrow swath, perhaps 5 or 10 kilometers wide, which often cuts across the road network in a maintenance district. The banded structure of the streamers means that slight shifts in wind direction can cause streamers to wander, distributing snow over a wider area. This sensitivity to wind direction reduces predictability of snowfall amounts and locations, and this in turn has an impact on maintenance practices. Many of the less-intense streamers have such a small vertical extent (less that 1 kilometer) that they cannot be detected by Environment Canada’s network of weather radars; this dearth of observational data makes it more difficult to provide accurate guidance to maintenance operations.

The challenges posed by lake-effect cloud and precipitation will also have an impact on the ability of the LCM to effectively simulate pavement temperatures in the snow belts, and further downwind, when lake-effect conditions prevail. Ultimately, the solution to this challenge lies in development of better remotely-sensed datasets, and the integration of this information into the LCM. However, such an undertaking is understood to be beyond the scope of the current project.

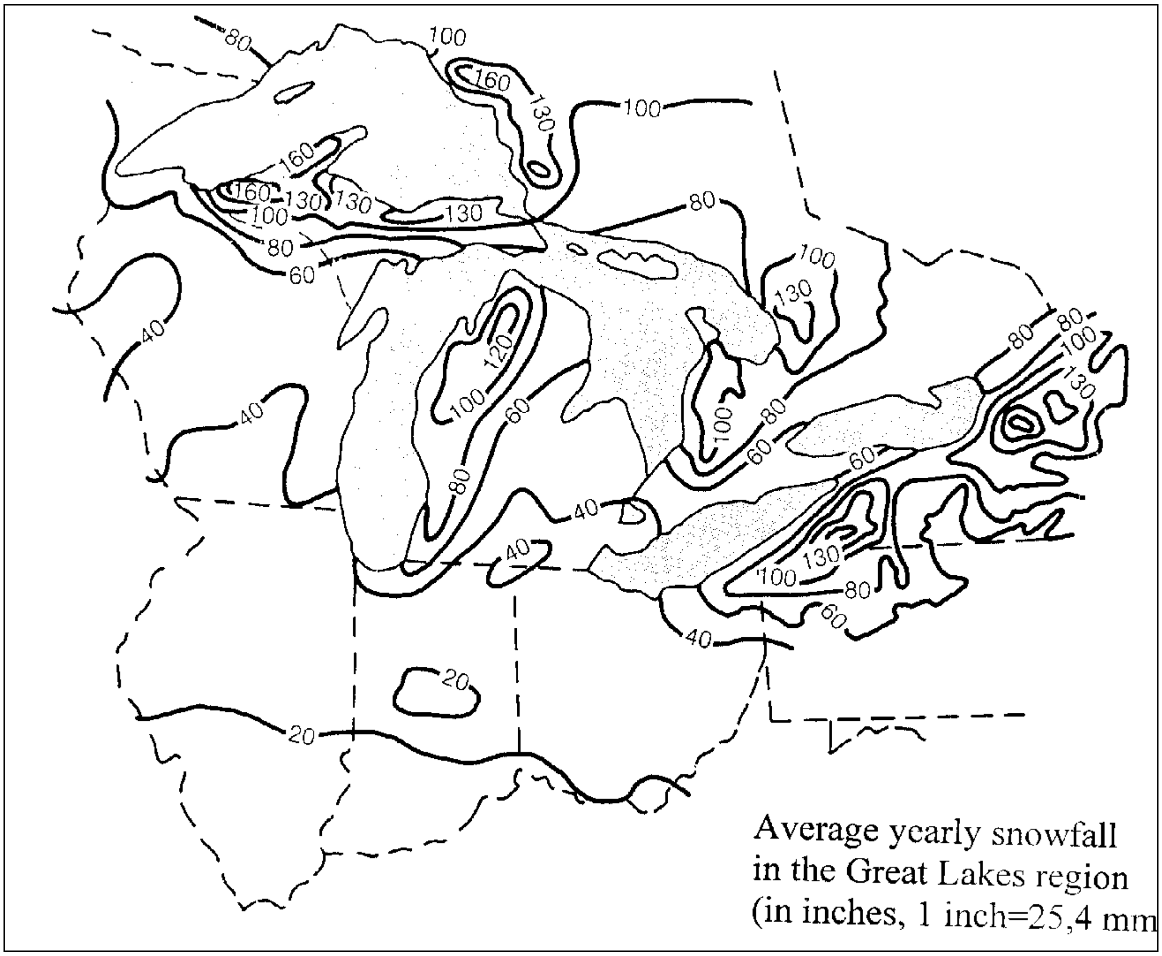


Figure 8. Lake effect snows in the Great Lakes area

2.5.2.4 RWIS

In the target area, 13 field stations (at the time for the field survey carried out in this project) have been located along the road net, as illustrated in Figure 1. Thermal mapping and local climatological factors were not considered in the determination of the siting of these field stations. Most of the sites are to be regarded as neutral with regard to local climate. Of course, the siting of the stations does exhibit some variety in altitude, local topography and land use.

2.6 Adaptation of the LCM to Southern Ontario: Detailed Analysis of Physical Factors

2.6.1 Topographical/Geographical Features

Upon closer examination of the topography and geography of Southern Ontario, it is apparent that there are many features that give rise to significant local climate variations of the kind that the LCM was designed to handle. The map in Figure 9 illustrates 13 distinct areas within Southern Ontario. In each area, the unique combination of topography and land use produces distinctive local variations in climatological conditions. A short description of each area is given below, along with the dominating features affecting the local climate, and the mechanisms for producing local climate variation that can be simulated using the LCM:

<u>1. Chatham</u> – Extremely flat landscape, intersected by channels and levees. The land use is dominated by agricultural activities. The area is significantly affected by proximity to the Great Lakes. Most of the terrain is below 180 masl. Features – exposed cooling, screening from vegetation, bridges.

<u>2. London</u> – Gently undulating landscape where several rivers are meandering and intersecting the surface. Relatively open area with increasing amount of forest vegetation in the northern part. Features – pooling of cold air, valleys, screening by forest.

<u>3. Lake Erie</u> – Steep coastal area, with several canyons intersecting the surface. Features – valleys, screening.

<u>4. Kitchener</u> – Change from a landscape dominated by swamps and coniferous forest in the northern part to areas where deciduous trees dominate. Features – screening, cold air production.

<u>5. Stratford</u> – Smooth plain surfaces with small geometrical patches of woods distributed throughout the area. Flanked by relatively high elevated areas and vast swampy areas in the northern part. A ridge in the western coastal area creates a plateau. Features – altitudinal variations, screening by vegetation.

<u>6. Lake Huron</u> – Ridge area running parallel with the coastal zone. The elevation of the ridge is 270 masl and the lake surface is at 175 masl. Features – altitudinal variations, exposed cooling.

<u>7. Swamp area</u> – Relatively small areas with a diversified composition. Large variations in frequency of continuous forest areas and size of the swampy areas. Rivers and waterways are oriented in many directions. There is also a variation between peat bogs and swampy areas. The landscape is intersected by more or less pronounced hills or ridges. Features – screening, pooling of cold air in valleys, bridges.

<u>8. Brantford</u> – Very smooth undulating landscape. In the area east of Brantford it is very flat with no relief in the landscape. The forested areas are dominated by deciduous trees. Features – radiative cooling, screening by vegetation.

<u>9. Niagara Escarpment</u> – Area characterized by steep sections with large differences in altitude. In the northern part, the crest of the Black Bank Hill is 520 masl, and Terra Nova, about 4 km

away, is at 270 masl. In the central part of the area, south of Brisbane, altitudes range from 445 to 270 masl. In the southern part, the terrain drops from 295 masl at a point south of Carlisle to Bayview at 90 masl, in a stretch of approximately 13 km. The steepest sections have a slope of 50%. Features – altitudinal variations, screening.

10. Toronto City Area – Bounded by the Oak Ridges Moraine, a high elevated area to the north and north-east; in the West, the Niagara Escarpment is a natural border. The Toronto City area, at the west end of Lake Ontario, is situated on a slope reaching approximately 170 masl, while the lake surface is at 75 masl. Features - urban effect, shading and road construction.

11. Elevated area – Dominated by forests, with mainly coniferous vegetation. The high elevated area is intersected by deep canyons. Features – valleys, screening.

12. Bogs and Mires – The western part of this area is dominated by large ridges separating clusters of bogs and mires. In the eastern part, the terrain is dominated by lower ridges. The forest is mainly coniferous. North of this area, the landscape is totally dominated by dense coniferous forests. Features – valleys, screening by forest.

13. Collingwood – This area is mainly sloping towards the shore of Georgian Bay, and is dominated by agricultural activities. Features – altitudinal variations, exposed cooling.

The above list shows that the landscape is well diversified and that there is a wide range of parameters that are of great importance for creating potential for temperature variations during different weather conditions. A comparison with the Jönköping area indicates that Southern Ontario has a similar diversity of local climatological features. However Southern Ontario has larger expanses of open, flat terrain than does Jönköping. For purposes of adapting the LCM, this means that considering the road construction at the Ontario sites is more important for optimal tuning of the model.

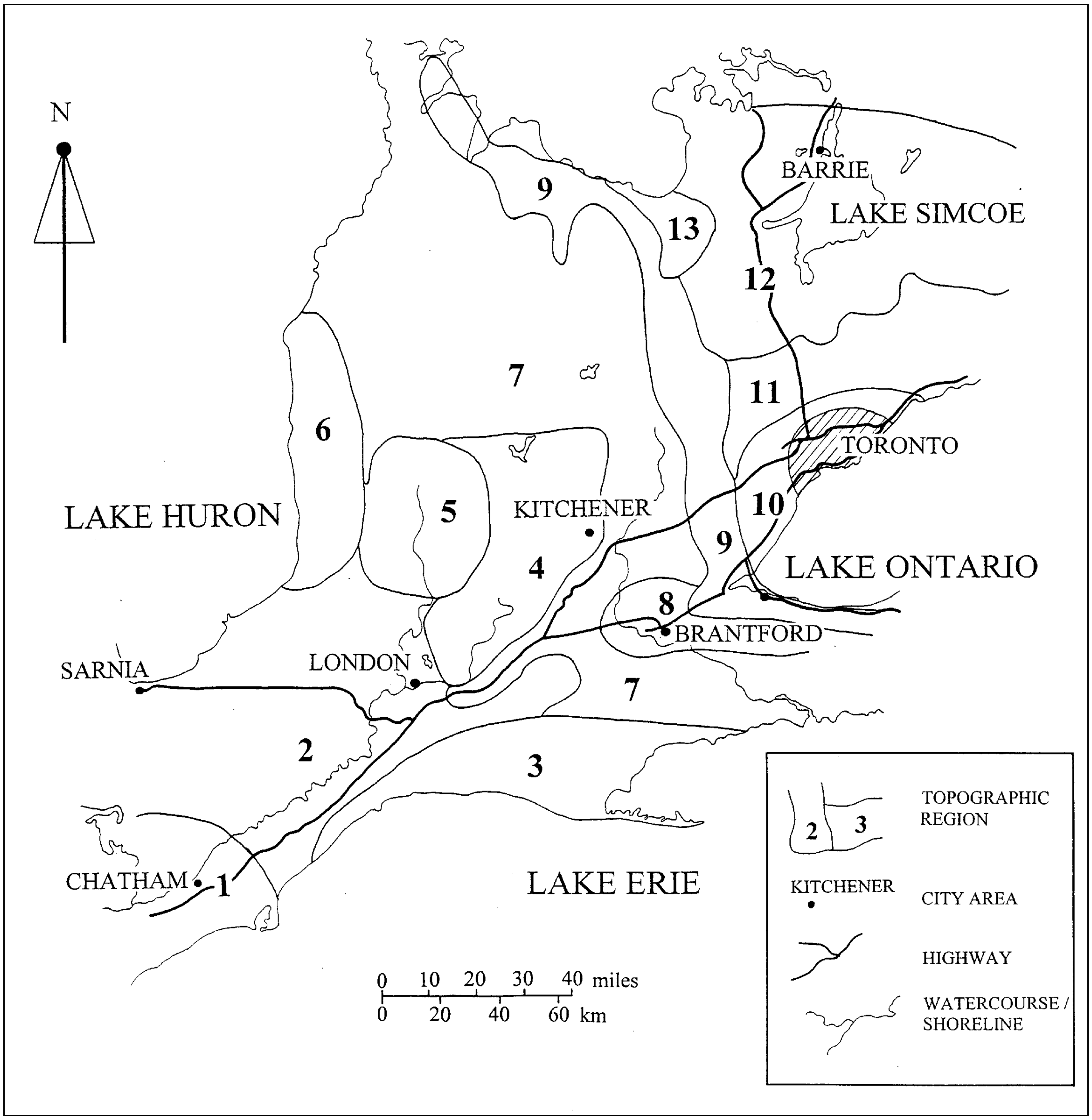


Figure 9. Southern Ontario, with its different topographical domains

2.6.2 Detailed Comparison of Climatological Parameters

Contrasting the mesoscale climate of the Jönköping area with that of Southern Ontario reveals that differences in certain climate parameters will necessitate some adjustment of the algorithms in the LCM.

The period December – March has been used for this analysis. The climate parameters that have been compared are: the temperature, cloudiness, wind speed and precipitation; these are the most significant for the successful functioning of the LCM. (See Appendix C for a more comprehensive set of figures.) Unless otherwise noted, the study contrasts climate data collected from synoptic weather stations at Jönköping and Toronto.

2.6.3 Temperature

During the winter months at the two sites, the daily mean and minimum temperatures are well below 0°C, with few exceptions. The daily maximum temperatures, on the other hand, alternate more frequently between above and below 0°C. This indicates that the general temperature regime is quite similar. However, Toronto exhibits a greater diurnal range between maximum and minimum temperatures, and this difference between the sites becomes more accentuated toward the end of the winter, as shown in Figure 10.

The temperature regime in Southern Ontario is sufficiently similar that it will not have a significant impact on adaptation of the LCM to this area. On the contrary, a tendency towards greater diurnal amplitude at the Canadian site makes a LCM even more useful.

2.6.4 Cloudiness

Cloudiness is an important parameter to consider when dealing with temperature prediction, especially when it comes to surface temperatures. Cloudiness is of utmost significance for the radiation budget, and a small variation in cloud amount can have a large impact on the road surface temperature. The effect of cloudiness on road surface temperatures is significant both during daylight hours and at night. During the day, the cloud amount will directly affect the potential for screening effects, with increasing cloud cover reducing the thermal contrast between shaded areas and sun-exposed areas. At night, clouds greatly reduce outgoing long-wave radiation, which inhibits the establishment of cold air production and thus limits the cooling of the road surface.

Comparing cloudiness at Jönköping and Toronto during the winter period, for night-time and day-time conditions, the similarities between the sites are quite striking. The cloudiness has been divided into four classes 1: 0-2 octas, 2: 2-4 octas, 3:4-7 octas and 4:7-8 octas. Examination of Figure 11 reveals that cloudy conditions predominate both during the day and at night in Jönköping and in Toronto for the period December –February. During this period, skies are cloudy almost 60% of the time. At the end of the winter, in March, there is a marked decrease in mean cloud cover. In March, cloudy conditions are observed approximately 30-40% of the time; this is the case at both locations.

During the period December – February, skies are clear 10-15% of the time. However, clear skies tend to be slightly more frequent at night than during the day; this trend is obvious at both sites. In March, clear conditions prevail about 20% of the time during the day, while at night, the frequency of clear conditions exceeds 30%. Again, this pattern is found at both sites. Although it is striking how similar the distribution of cloudiness is between Toronto and Jönköping, it must also be noted that the sky condition in Toronto is not necessarily representative of all of Southern Ontario. In particular, areas closer to Lake Huron and Georgian Bay tend to be cloudier, particularly during the first half of the winter, owing to lake effects. Sometimes, these clouds dissipate in the flow down the Niagara Escarpment or the Oak Ridges Moraine, and as a result, they are not observed in Toronto.

The increasing frequency of clear conditions towards the end of the winter means that nocturnal radiational cooling becomes more important. During daylight hours, the effect of shading becomes more pronounced as the solar elevation increases throughout the season, particularly in March, when sunny skies are more common. The effect of screening is further discussed in Section 5, where there is an example of calculated temperature differences. Road surface temperature variations caused by the screening effect are well simulated by the algorithms in the LCM.

2.6.5 Wind

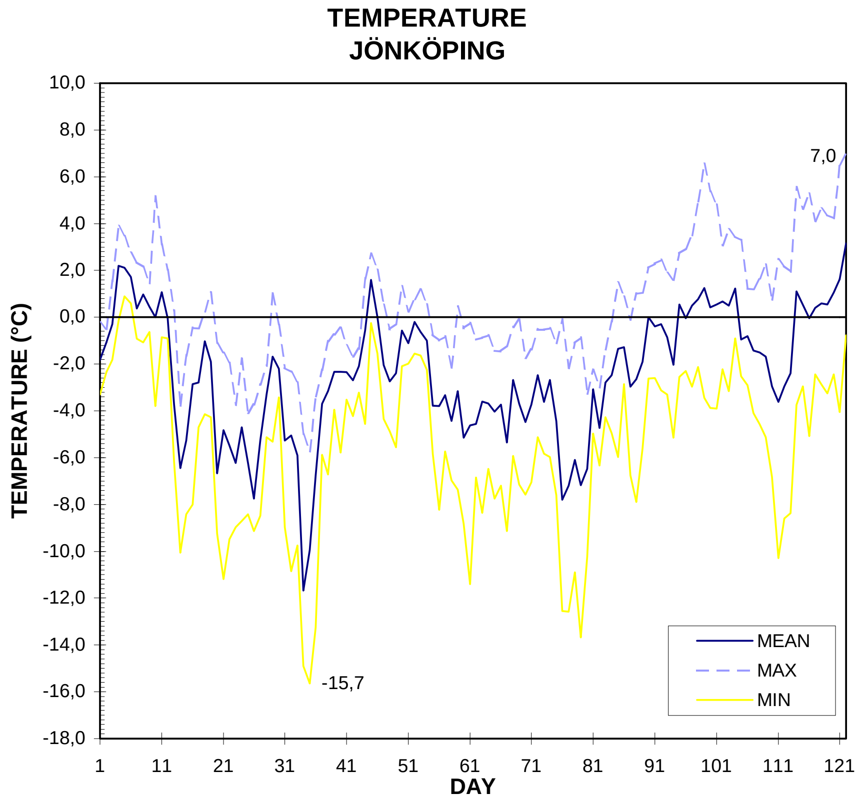
The distribution of wind speed is described by dividing the wind speed observations into three classes: 1 (low), 0-2 m/s; 2 (medium), 2-5 m/s; and 3 (high), >5 m/s. During the December – March period, the most frequently observed winds fall into the medium class, in the 2-5 m/s range. At both locations, medium speeds are observed almost 50% of the time, as shown in Figure 12. Low wind speeds and high wind speeds each account for approximately 20 –25% of observations. An exception to this pattern can be found at Jönköping during March, when high wind speeds dominate (54% of the time) and low wind speeds are only observed 6% of the time.

Low wind speeds in combination with clear skies results in a high potential for cold air accumulation and radiational surface cooling, as well. Higher wind speeds also produce a pattern of temperature decrease with increasing altitude. From the data it would appear that Southern Ontario can be treated in similar fashion to the Jönköping area with regard to wind criteria in the LCM.

2.6.6 Precipitation

This factor is the one that may pose the greatest challenge for the implementation of the LCM in Southern Ontario. At Jönköping, during the months of December through March, snowfall is recorded on 60 days in a typical year. In Toronto, in a typical year, snow is recorded on 41 days, and precipitation of some sort is recorded on 54. However, the figures for Toronto are only reflective of the area along the north shore of Lakes Ontario and Erie. In the lake-effect snowbelts (e.g. Collingwood and Lake Huron), snowfalls are much more common; for example, Wiarton Airport (on the Bruce Peninsula), receives snow on 69 days, on average. The two factors that pose a particular challenge in Southern Ontario are: the variation in precipitation type (since rain, freezing rain, and snow often fall at different locations across the area during major winter storms); and the variation in snowfall, particularly during lake-effect events.

The situations where precipitation dominates the weather are naturally associated with cloudy conditions and treated from that point of view in the LCM model.



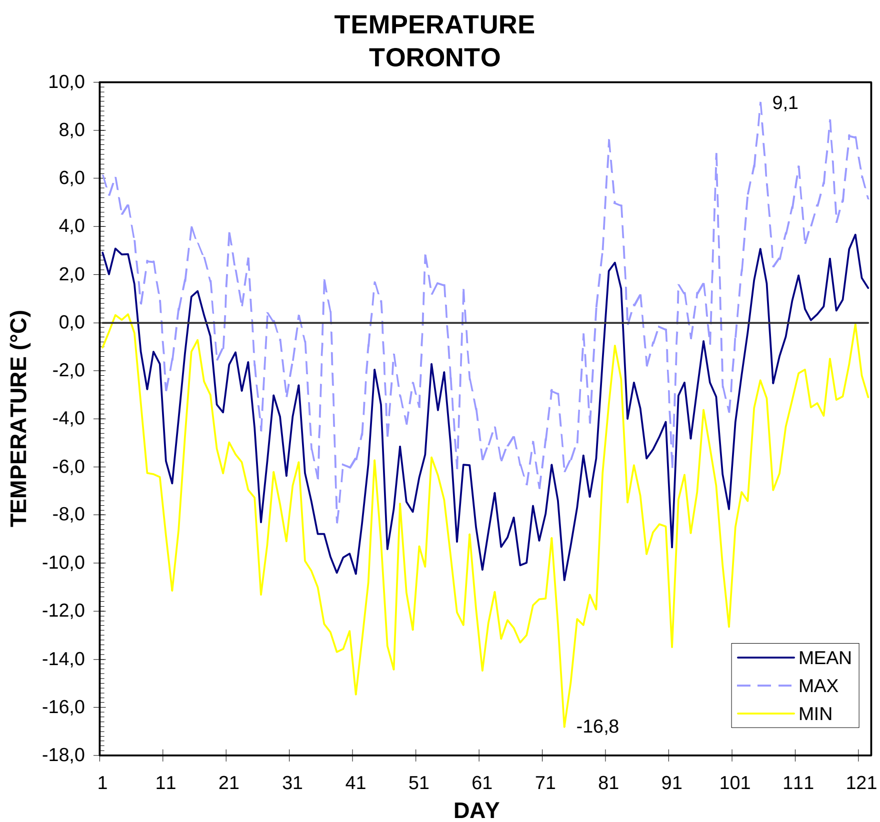
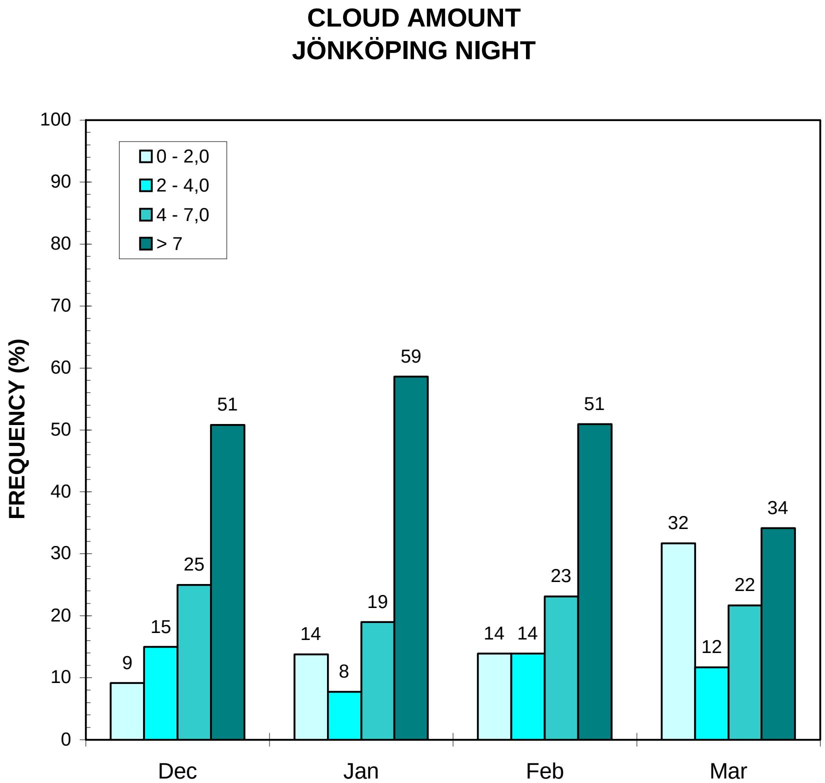


Figure 10. Winter temperatures Dec-Mar, Jönköping and Toronto



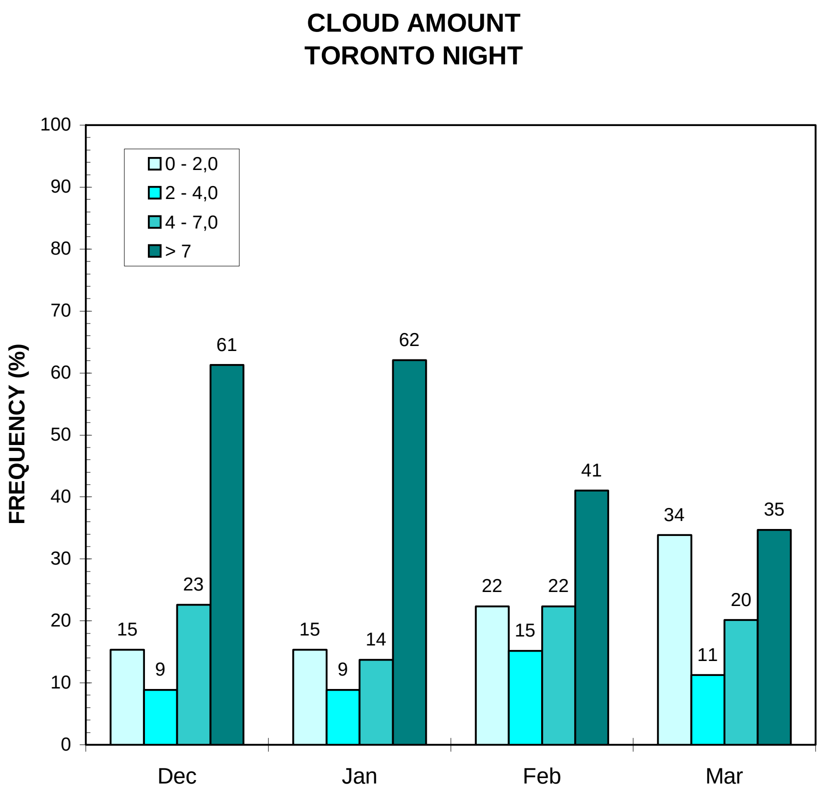


Figure 11a. Cloud cover during night time Jönköping and Toronto

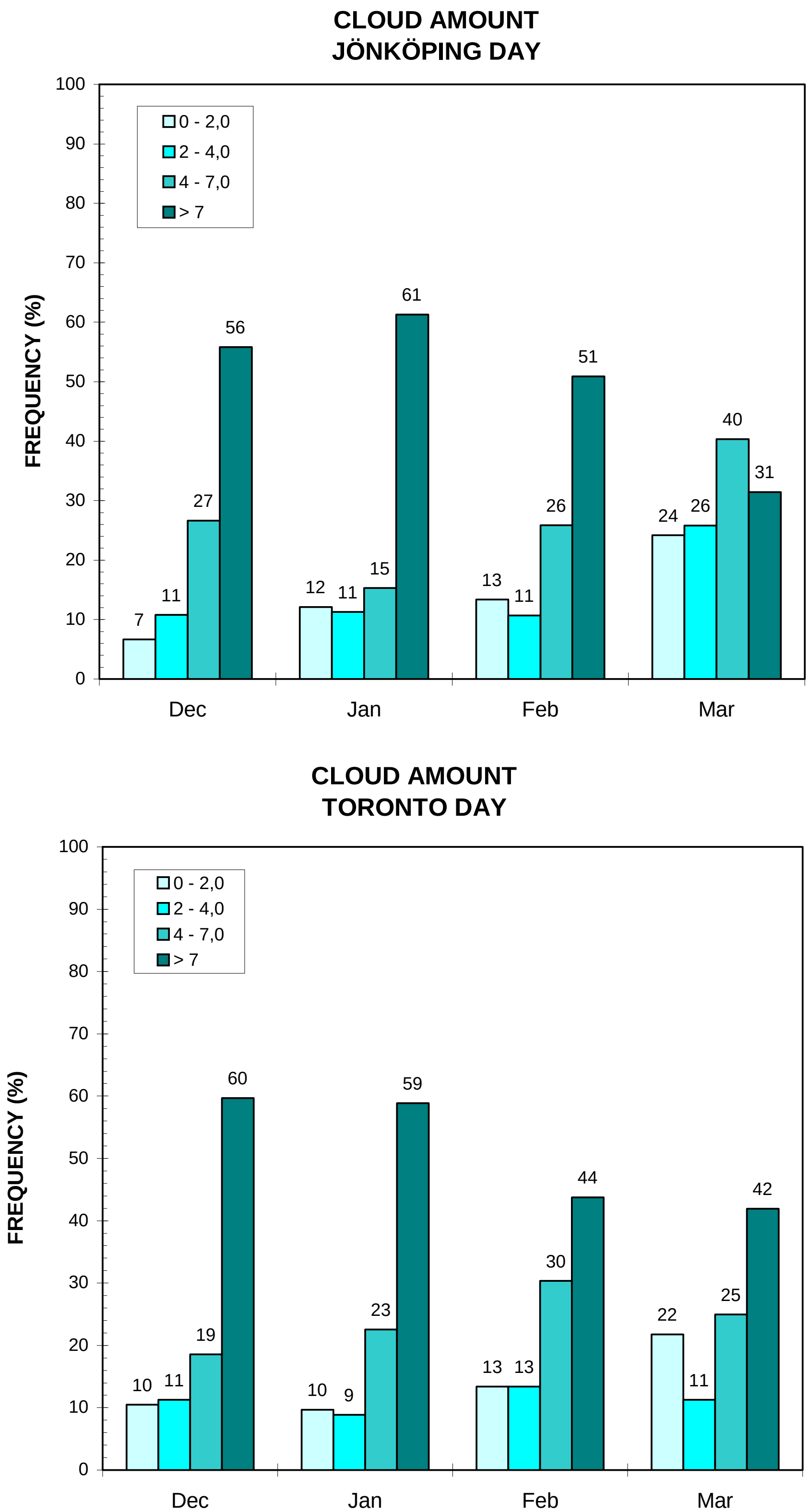
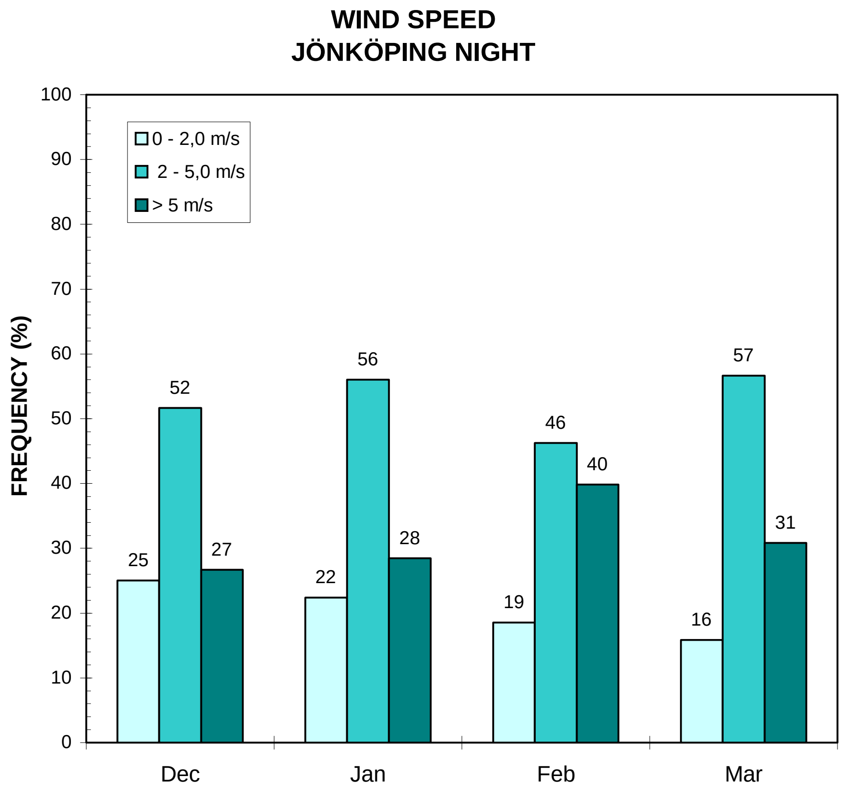


Figure 11b. Cloud cover during day time Jönköping and Toronto



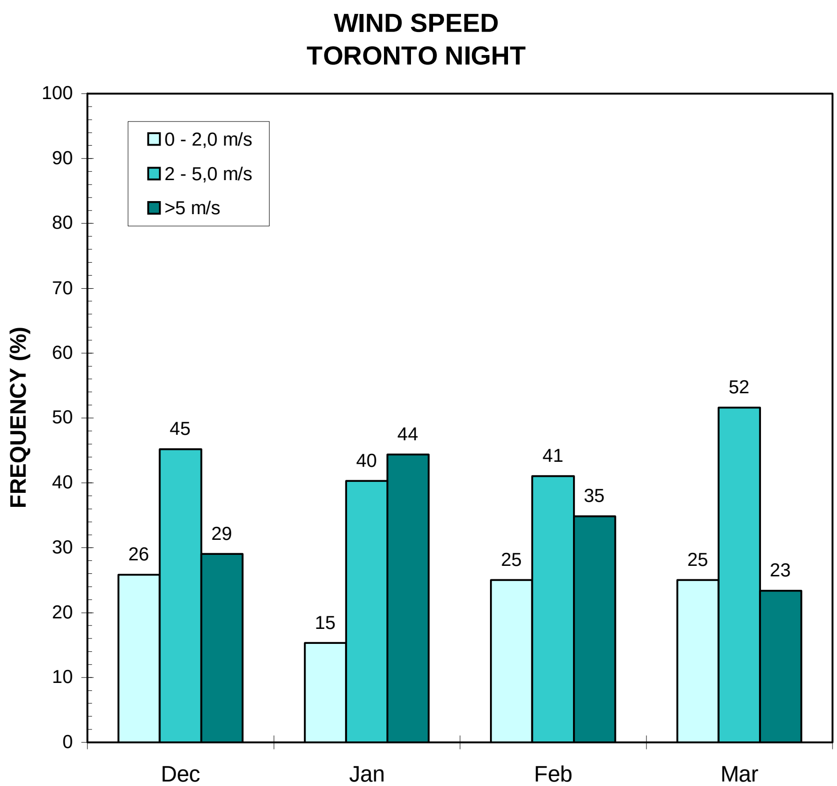


Figure 12a. Night time wind speed distribution, Jönköping and Toronto

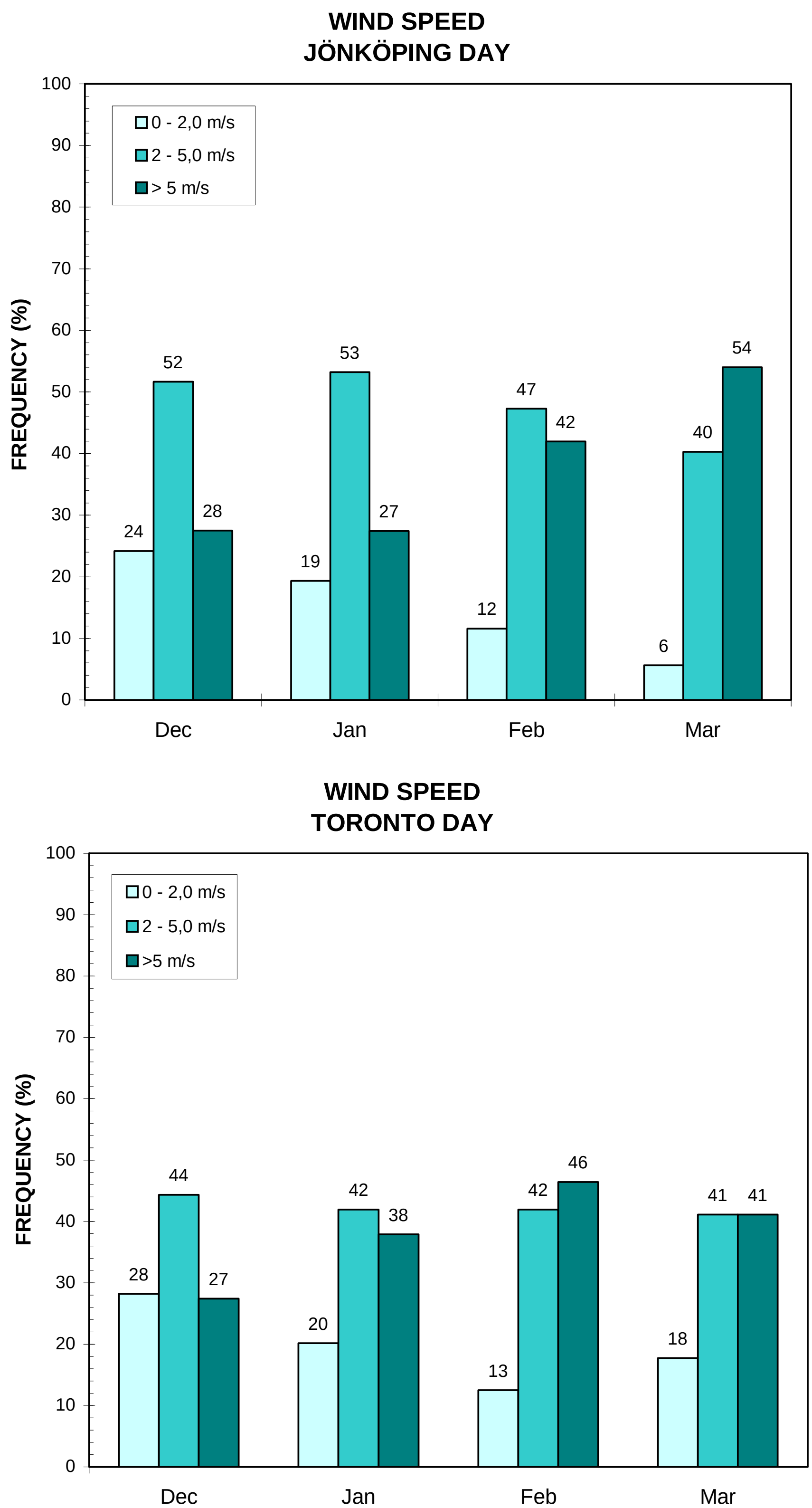


Figure 12b. Day time wind speed distribution, Jönköping and Toronto

2.7 Application of Temperature Variation Calculations to Southern Ontario

The climatological characteristics of Jönköping and Southern Ontario are sufficiently similar that the LCM can be implemented in the latter area. To give a more profound insight into how implementation and tuning of the LCM would proceed, this section provides a couple of examples of application of the calculations used to determine stretchwise temperature variations to specific features found in Southern Ontario.

2.7.1 Pooling of Cold Air

Under nocturnal conditions with clear skies and weak ambient winds, local topography is one of the major factors regulating the variation in temperature. In open areas where there is no obstruction of outgoing long wave radiation, the local topography controls the variation in temperature in two different ways: it limits mixing of the surface-cooled air layer with the warmer air above; and it allows drainage of cold air to lower–lying parts. Thus valley geometry is an important factor in determining the variation in the ability of cold air to drain, and in the reduction of turbulence near the ground. When describing valley locations, the following terms are used and defined:

i) ΔT – air temperature difference between the valley bottom and the reference temperature in surrounding areas, i.e. the intensity of cold air pools that have developed.
ii) ΔS – road surface temperature difference between the valley bottom and the reference temperature of surrounding areas, i.e. reduction in the road surface temperature owing to an accumulation of cold air.
iii) D – depth of a valley from ridge top to bottom.
iv) W – width of a valley from ridge top to ridge top.
v) Valley surface – entire ground surface of the valley
vi) Wind exposure – degree of shelter from the wind by vegetation and/or topography.

The influence of the depth of the valley on the variation in air temperature can be described by the following formula:

$$\Delta T=3{,}8+0{,}11D, \qquad (3)$$

where ΔT is measured in °C, and D is measured in meters. For further details see Gustavsson & Bogren (1989).

However, the temperature difference can not fully be described by the depth factor; the influence of valley width must be considered as well. It has been observed that magnitude of the night time air temperature differences (ΔT) can be described as a function of the horizontal distance between valley ridges (W). Studies have determined Bogren & Gustavsson (1991) that the relationship can be expressed as an exponential function of the form:

$$\Delta T=4{,}6W^{0{,}49}, \qquad (4)$$

where W is measured in kilometers (km). This relationship indicates that the change in valley width is more important for relatively small valleys than for wider ones.

Clearly, both the depth factor and width factor must be considered for a proper evaluation of the lowering of the air temperature in valleys as compared to adjacent summits, i.e. areas that are considered to have a prevailing reference temperature. Considering both these factors, a multiple regression of the form:

$$\Delta T = 0{,}57 + 2{,}2W + 0{,}06D \qquad (5)$$

can be used to calculate the lowering of air temperature in valley bottoms (Gustavsson & Bogren, 1993, and Bogren *et al.*, 1992).

Armed with equation (5), let us examine how one would calculate the air temperature difference in a valley in Southern Ontario on a clear calm night.

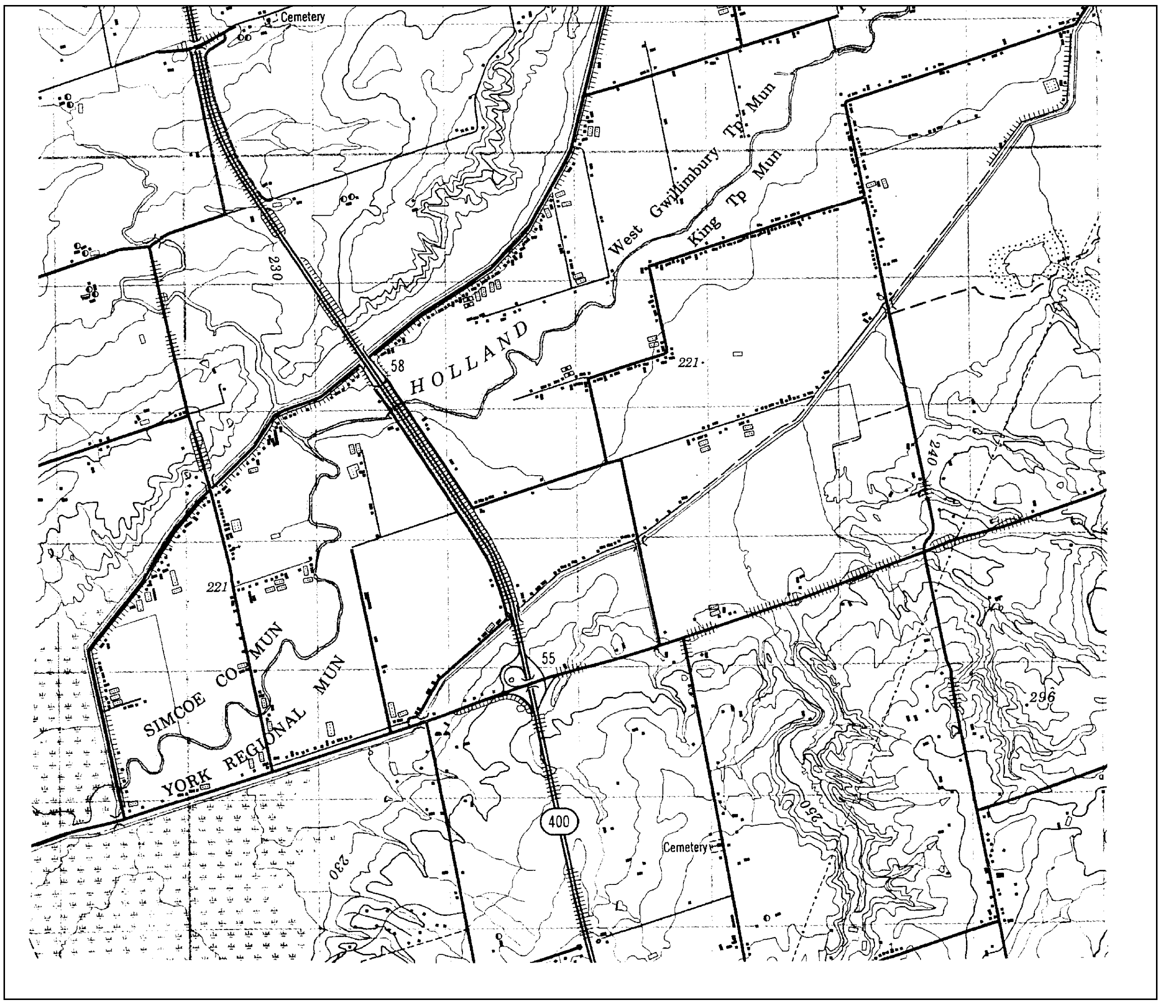


Figure 13. Potential for pooling of cold air on Highway 400, in the Holland Marsh

Highway 400 is a 6-lane expressway, running northwest from Toronto to Barrie and beyond. In addition to its growing importance for rush-hour commuter traffic, it forms the southernmost part of the main highway artery connecting Southern Ontario with Northern Ontario and Western Canada. The Holland Marsh, depicted in Figure 13, is situated approximately 40 km north of Toronto. Highway 400 crosses through the Holland Marsh at a point where several topographical features have the potential to affect the local climate along the road. The ridges on either side of the Marsh feature a mix of small woodlots and pastureland. The Holland Marsh is flat, fertile, and intensively cultivated. The Marsh itself is about 3 km wide, ringed by dikes, and often in need of drainage, a situation reminiscent of the Dutch polder. At an altitude of 221 masl, the Holland Marsh is bordered to the South by the Oak Ridges Moraine; the altitude at the crest of the slope is 290 masl. The drop of 69 meters takes place over a horizontal distance of perhaps 3 km. On the north side of the Marsh, the rise of 19 meters, to a crest at 240 masl, is more gradual. In addition to the valley configuration, which causes pooling of cold air, differences in vegetation and moisture availability can cause significant variations in road conditions along this stretch of Highway 400. A calculation of the potential for pooling of cold air in the Holland Marsh, using equation (5) results in a temperature that is more than 10°C lower in the valley bottom; such temperature ranges have been observed elsewhere.

2.7.2 Road Surface Temperature

Pooling of cold air in valleys causes great variations in air temperature, especially during clear, calm situations, as shown in Figure 2. Under such conditions, the variation in RST is linearly related to the variation in air temperature. The change in RST (ΔS) can be related to the difference in air temperature using the formula:

$$\Delta S=0{,}12+0{,}41\Delta T. \qquad (6)$$

This equation has a strong correlation where R=0,84, and suggests that an increase of 1°C in the intensity of the cold air pool produces an increase in ΔS of approximately 0,4°C. The maximum difference that has been recorded in RST is approximately 6°C.

The variations in the development of air and road surface temperature differences can be attributed to the thermal properties of the road bed. Owing to the thermal inertia of the materials used in the road construction, the drop in road surface temperature is less than the drop in near-surface air temperatures. The establishment of differences RST between valley bottoms and surrounding areas is delayed as compared with differences in air temperature. As predicted by equation (6), the air temperature differences are more rapidly developed after sunset, and are also of greater magnitude. It is therefore practical to use recordings of air temperature in order to detect road stretches where large differences in RST are likely to occur.

The air temperature differences required for the reduction of the RST by 1°C to 5°C are given in Table 2. By comparing the (ΔT) values in the table with those predicted by equation (5), it is obvious that truly large anomalies in RST can occur only in relatively wide and deep valleys. Continuing with the example of the Holland Marsh, the theoretical maximum ΔS would be approximately 5°C.

2.7.3 Clouds and Wind

The curves in Figure 14 illustrate the relationship between air temperature differences and wind speed for varying amounts of cloud cover. Using these relations, it is possible to identify the combinations of wind speed and cloud conditions that would produce a specific variation in RST. Table 2 clearly demonstrates that the variation in RST is reduced during windy and cloudy situations. Only during clear situations with weak ambient wind is it possible for great variations in road surface temperature to develop.

The variation in air temperature differences that occurs on windy nights owing to wind exposure in valleys also causes a variation in RST. For example, the average air temperature difference for a small, wind-sheltered valley, on a clear night, with a wind speed of 3 m/s could cause a lowering of the RST by approximately 1°C. The lowering of the surface temperature in a large, wind-exposed valley under the same conditions is insignificant (Bogren *et al.*, 1999).

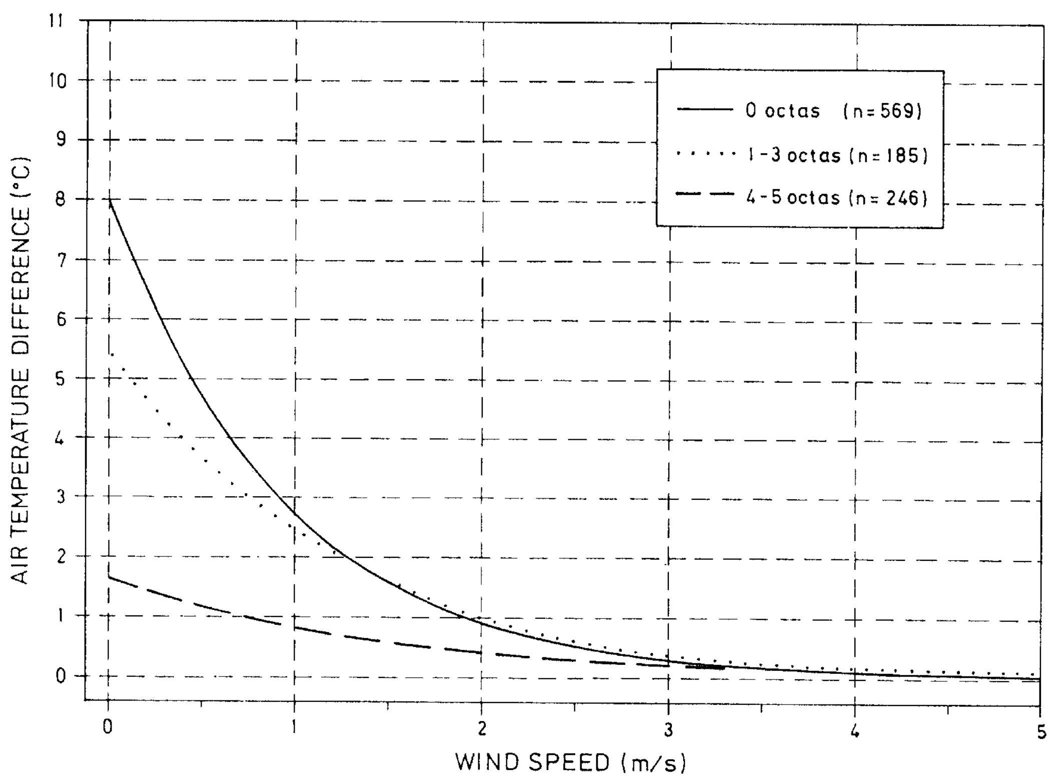


Figure 14. The effect of wind and cloudiness on the development of air temperature differences

Table 2 shows required air temperature difference (ΔT) for lowering of the road surface temperature (ΔS), by 1 to 5°C. Also shown are the limits in wind speed under clear, nearly clear, and partly cloudy conditions under which a lowering of the road surface temperature could occur (Bogren & Gustavsson, 1991).

Table 2. Required air temperature difference for lowering of the road surface temperature

ΔS (°C)	**ΔT (°C)**	**U_1 (m/s)**	**U_2 (m/s)**	**U_3 (m/s)**
1	2,1	1,2	0,5	0
2	4,6	0,5	0	-
3	7,0	0,1	0	-
4	9,5	0	-	-
5	11,9	0	-	-

U_1: clear sky, 0 octas
U_2: Nearly clear sky, 1 to 3 octas
U_3: Partly cloudy sky, 4 to 5 octas

2.7.4 Screening

A comparison of the effect of screening on a flat road surface in Southern Ontario and Jönköping shows the effect of the difference in latitude between the two locations. At the lower latitude of Southern Ontario, screening creates greater temperature differences during the mid-winter period than it does at Jönköping.

The magnitude of the solar elevation during the day determines the amount of incoming radiation and thus the temperature differences that can be developed between screened and sun-exposed areas. The maximum solar elevation (β) during the day can be calculated from:

$$\beta=(90° - \varphi)+/- \delta, \qquad (7)$$

where φ is the latitude of the site and δ is the declination. The declination can be calculated using a function of the Julian day of the year (N):

$$\delta=-23{,}4\cos(360(N+10)/365), \qquad (8)$$

(Bogren, 1991).

Using equations (7) and (8) for latitude 58°N and 42°N, the maximum solar elevations for Jönköping and Southern Ontario can be calculated for any day of the year, as shown in Table 3.

Table 3. A comparison of maximum solar elevation at the Swedish site and at the Canadian test site during some selected dates during the winter period

Date	Max. solar elevation (°) at Lat. 58°N, Jönköping	Max. solar elevation (°) at Lat. 42°N, Srn. Ontario
1 Jan	9	25
15 Jan	10,7	26,7
1 Feb	14,5	30,5
15 Feb	18,7	34,7
1 March	23,6	39,6
15 March	29,5	45,5

The Southern Ontario site has a much more pronounced potential for screening effects during the winter season, since at lower latitudes, solar elevations are greater. From the table above it can be seen that the mid-winter solar elevation in Southern Ontario is the same as that of Jönköping in spring. Knowing the maximum solar elevation, it is possible to estimate the maximum possible RST difference (maxTdiff) between a sun-exposed and a screened area on a black asphalt coating, according to:

$$\text{maxTdiff} = -2{,}7 + 0{,}47(\beta). \quad (9)$$

From the solar elevations given in Table 3, maxTdiff can be calculated using equation (9), to produce Table 4 (Bogren, 1990 and 2000).

Table 4. Calculated daily maximum temperature differences between sun exposed and screened spots on a road stretch at selected dates as a function of solar elevation; Jönköping in Sweden compared with Ontario in Canada

Date	**maxTdiff (°C) Jönköping**	**maxTdiff (°C) Srn. Ontario**
1 Jan	1,5	9
15 Jan	2,3	9,8
1 Feb	4,1	11,6
15 Feb	6,1	13,6
1 March	8,4	15,9
15 March	11,2	18,6

The calculation of possible temperature differences between screened and sun-exposed points shows that at in Southern Ontario, the screening potential must be taken into consideration, even in January, when the difference can amount to 9°C, while in Jönköping the corresponding possible difference is only 1,5°C. The mid-winter situation in Southern Ontario is similar to that of early spring in the Jönköping area.

2.8 Implementation of the LCM in Southern Ontario: Consideration of the Human Factors

The foregoing sections have demonstrated the technical feasibility and desirability of implementing the LCM in Southern Ontario. However, in order to ensure the success of such an undertaking, it is necessary to take into consideration the human factors that play a key role in the success of current maintenance practices in Southern Ontario. For the purposes of this project, three issues have been identified: 1) general maintenance practices; 2) identification and treatment of local climate variations; and 3) use of RWIS in support of maintenance decisions.

To sample the human perspective on the above three issues, a questionnaire was designed and presented to selected maintenance staff. The selection of staff was carried out in collaboration with Ray Girard, former Maintenance Operations Engineer of the Ontario Ministry of Transport's Maintenance Office. The survey resulted in 10 fully answered questionnaires. The detailed results are presented in Appendix A; here the salient details are discussed.

2.8.1 General Maintenance Practices

The extent of individual maintenance districts is large enough that spatial variability in climate within the districts could be of sufficient magnitude to cause variations in RST and slipperiness. To combat slipperiness, maintenance crews tend to use either sand or salt, with a variety of factors having an impact on the decision about what to use in a given situation. Considering the responses received, it can be concluded that the information provided by the LCM could be integrated into the current decision-making framework. Used properly, this information could help maintenance personnel to fine-tune their selection of treatment strategy.

2.8.2 Treatment of Local Climate Variations

Many responses indicate the existence of preferred locations for development of slippery or icy conditions, the existence of which can be attributed to variations in local climate. Typical areas/spots that are mentioned are: bridge decks, shaded areas and exposed areas. This shows that local climatological variations play a significant role in creating hazardous conditions. It is also evident that maintainers recognize the high degree of variability inherent in winter weather in Southern Ontario. Since different stretches of road are prone to icing during different weather conditions, the LCM can be of great assistance in determining which road stretches are most at risk. This information could be used to focus patrols, as well as treatment activities.

2.8.3 Use of RWIS in Support of Maintenance Decisions

The survey clearly showed that among maintenance personnel, a well-developed RWIS system is viewed as a helpful decision-making tool for winter maintenance operations. Many respondents indicated that they used available RWIS resources already, and most could see a need for additional pavement information. Based on the expression of need for further information, and the existence of local ‘black spots’, it may be concluded that the LCM could be a useful tool. Although the majority of respondents affirmed the need for RWIS, there were a few who admitted that they did not make use of RWIS. For these users, implementation of the LCM offers an opportunity to offer a more complete information package, which they may find more useful for refining their operational practices.

In conclusion, the survey indicates that a local climatological model (LCM), as part of a more comprehensive RWIS, could be a most useful decision-making tool. Several of the winter road maintenance problems identified in the questionnaire can be related to events that are connected to local climatological issues. Ultimately, winter maintenance activities would be more attuned to the temporal and spatial variations of slipperiness across maintenance districts; this offers the possibility of lower operating costs and reduced environmental impact.

2.9 Implementation of the LCM in Southern Ontario: Segmentation of Road Stretches

It has now been established that Southern Ontario is a suitable target area for implementation of the LCM, since the geographical conditions are favorable, and the human systems are well prepared to benefit from the additional information that the LCM will provide. To adapt the LCM to run in Southern Ontario, one of the most important tasks will be the segmentation of target road stretches

2.9.1 Data Required for Establishment of Algorithms and Segmentation of Roads

In order to establish the background information needed to model the temperature variations along stretches of road, different types of recordings are used. The data are obtained from:

a) *thermal mapping* of road sections by use of instruments attached to a specially-designed vehicle;
b) *RWIS field stations*, preferably sited in different climatological environments along road sections;
c) *field and map analysis* of topography, vegetation and geographical factors.

Each of these data sources will be considered in greater detail in the following sections.

2.9.1 Thermal Mapping Data

Thermal mapping produces continuous recordings along road sections. The thermal recordings give information about the location and extent of variations in air and road surface temperatures, as well as the relative differences in the temperature between specific areas. Air temperature is measured at 2,0 m and 0,3 m above the surface, humidity at 2,0 m. Road surface temperature is determined by use of a thermal radiometer thermometer, which has a spectral sensitivity in the interval 8-14μm and a response time of 1 second to assure a frequent logging of the parameters while driving. All variables are recorded every 10 meters. The temperature recordings are stored in a computer database, into which the driver feeds other parameters of interest to the analysis, such as information on road rock cuts, bridges, fog, and changes in road surface condition. Before and after each measuring run the prevailing weather conditions are noted, together with information about geographical location, time and date of the measurement.

From an individual thermal mapping run, one obtains a snapshot of the stretchwise temperature variations along a road section. Typically, an individual run covers from 50 to 80 km. To map a road network, a detailed planning process is required to ensure that all stretches of road are mapped efficiently, and under each of the various conditions required for the proper functioning of the LCM.

Thermal mapping runs must be performed in varying weather conditions, and at different times of the day and year to develop a comprehensive database, from which can be constructed a complete description of the thermal behavior of a stretch of road. Such a database is essential to the successful implementation of the LCM.

Irrespective of weather conditions, three main factors can be distinguished which determine the road surface temperature: a) road bed materials, b) radiation, and c) advection and stagnation of cold air. Each of these factors can exhibit spatial and temporal variability. At present, it is not practical to model all of these factors explicitly. The LCM offers the ability to estimate the combined effect of these factors, based on empirical observations, collected by thermal mapping. For further details on thermal mapping, the reader is directed to Bogren & Gustavsson (1986 & 1989), Gustavsson *et al.* (1998) and Gustavsson (1999). To give an indication of the challenges posed by these three factors, each is discussed here in greater detail.

The heat flow and storage in the road bed are determined by the thermal properties of the materials used in the road's construction. This factor influences the temperature reaction during cooling as well as during warming. The thermal properties of the road bed can be influenced by other factors, such as soil moisture or ice content, which can vary in time and space. Information about these thermal properties is not always available, and therefore it is very important to perform the thermal mapping so as to account for this factor.

Incoming solar radiation and outgoing long-wave radiation from the surface are major influences on the RST. Obviously, objects that shade the pavement from the sun influence the radiation balance during the day. However, these objects have an impact at night, too, since they also radiate heat absorbed during the day. Some of this radiated heat is absorbed by the pavement, which reduces the rate at which the pavement cools. In addition, these screening objects absorb heat radiated by the pavement at night, which slows down their own cooling, and increases the amount of radiant energy they emit during the night. The radiative and thermal properties of screening objects depend not only on the type of object (rock cuts, trees, etc.), but also on the time of year. For example, the screening effect of trees will change depending on whether or not they have foliage. In the case of evergreens, rock cuts and other seasonally-invariant objects, radiative characteristics also depend on whether or not they are snow-covered. Once again, these complex radiative exchanges are difficult to simulate deterministically, and thermal mapping is one way to measure the effects of these variations.

Finally, the impact of advection and stagnation of cold air in valleys and low points on RST has been dealt with at length elsewhere in this report. Although theoretical calculations offer an indication of the magnitude of the air and road surface temperature differences that one might expect, thermal mapping provides critical evidence to validate and fine-tune these calculations. Tables 5 and 6 below give examples of theoretical calculations and the corresponding observations for a typical stretch of road.

Thermal mapping is a very useful technique in applied climatological studies, to document the relationship between topography, weather, and temperature variations. The measurements should be planned and performed in such a way that the influence of the above-discussed factors is determined (Gustavsson, 1999). Using topographical maps (scale 1:50 000) in combination with field observations, one can distinguish several types of topographical areas and their temperature differences, relative to a reference temperature obtained from nearby neutral areas. This makes it possible to define the various segments along the actual roads. In developing the Swedish RWIS network of field stations, this analysis of thermal-mapping records was used to optimize the placement of sensor sites.

Historical note: The first documented thermal mapping carried out in Canada originates from a pre-war study on local climate, which was performed in the Toronto area. In the 1930s W.E.K Middleton designed a mobile system for measuring air temperature variations. During clear, calm nights, he performed measuring runs along Yonge Street, from the Toronto waterfront to the north side of Hogg's Hollow. This stretch covers a distance of about 12 km, and features pronounced variations in altitude and relief. The temperature differences that were recorded along this route were substantial. Temperature variations of up to 18°C were detected; moreover, they were reproducible. This was compelling evidence of the importance of local topography and land use as significant factors in producing large temperature variations.

2.9.2 Field Station Data

The field stations are ideally located at road sites that frequently suffer from slipperiness. Typical locations are valleys, bridges and road cuts. At all stations in the Swedish RWIS network, the air temperature and humidity are measured at a height of 2 m, and the RST is measured by use of a probe in the top layer of the road coating. Some of the stations have extra equipment, such as sensors for wind speed, wind direction, precipitation and for detecting dry or wet surfaces.

Historical recordings from field stations are used to confirm the temperature variations determined from the thermal mappings. These recordings are also used to study the temperature differences that occur and to correlate these differences with the prevailing weather conditions. Since the field stations are located in different topographical areas, the conditions they report allow a good overall evaluation of temperature variations between different types of location. The method used for the analyses consists of a comparison between neutral locations and sites at which one expects temperature variations caused by a topographic factor. Prevailing weather conditions are determined by augmenting field station data with weather parameters obtained from nearby synoptic weather stations.

2.9.3 Field and Map Analysis

The road sections included in the model are classified and subdivided into segments with the help of topographical maps on a scale of 1:50 000, and field measurements and checks of the topographical properties (see Figure 15). The field checks are very important, especially for determining the exact orientation of road stretches and the type and density of objects causing shadow patterns.

The basic topoclimatological parameters that must be known in order to calculate temperature variations along a road stretch are summarized separately below for each topographical unit (Bogren & Gustavsson, 1989):

i) Valleys – the important parameter is the size of the valley that can be described by width and depth. The form parameters describe the possibility for cold air to pool and the stabilization of air in open valleys. Furthermore, the wind shelter factor, caused by vegetation and/or topographical shelters around the valley, must be considered.
ii) Screened areas – objects causing a shadow pattern on the road surface can be described by height, length, orientation and distance from the road. Dense vegetation has proved to give the same effect as road rock cuts, but consideration must be taken to type and density of the vegetation causing the shade.
iii) Variation in altitude – the variation in altitude along a road stretch must be determined at an interval of 50 meters change in height to be able to predict a difference in surface temperature with good resolution
iv) Bridges – important factors regarding bridges have been found to be construction materials, length/volume and type of bridge. The local environment around the bridge can also be of importance, for example the proximity of water can influence the humidity of the air.

The regional climate and other factors, such as proximity to large lakes or to the sea, must also be taken into consideration when discussing a specific area.

2.9.3.1 Dynamic Segmentation of Road Stretches

To model the temperature patterns along a stretch of road under varying weather conditions, the stretch must be divided into significant topographical segments corresponding to areas where different temperatures can develop according to the prevailing weather situation. The segmentation of a given stretch of road is not invariant, rather the LCM identifies the current weather situation, and then selects a predefined 5segmentation that is most appropriate for that situation. This aspect of the operation of the LCM is best illustrated by considering a concrete example. Figure 15 shows an example of three different segmentation schemes, each corresponding to a different weather situation, for a stretch of road in western Sweden.

2.9.3.2 Clear/Calm Night-Time Conditions

The topographical units used to determine the temperature pattern in situations with potential for development of cold air pools are convex areas, concave areas, transition zones and local low-points. On a clear, calm night, the pooling of cold air is concentrated in the concave areas where the local low-points produce the lowest temperatures. The concave areas are often open and relatively well-exposed, which makes them favorable to accumulation of cold air but also sensitive to disturbance by the wind. Convex areas are neutral areas that are relatively elevated and thus do not permit pooling of cold air. The transition zones are located in the stretch between the convex and concave areas, and they can be affected by cold air in extreme situations. Calculated air temperature differences between the concave and convex areas based on the geometric properties of the valley, and equation (5) are shown in Table 5 for a clear, calm night. The table also includes measured temperature differences for the same situation. The variation between measured and calculated temperatures is generally small (Bogren *et al.*, 1992).

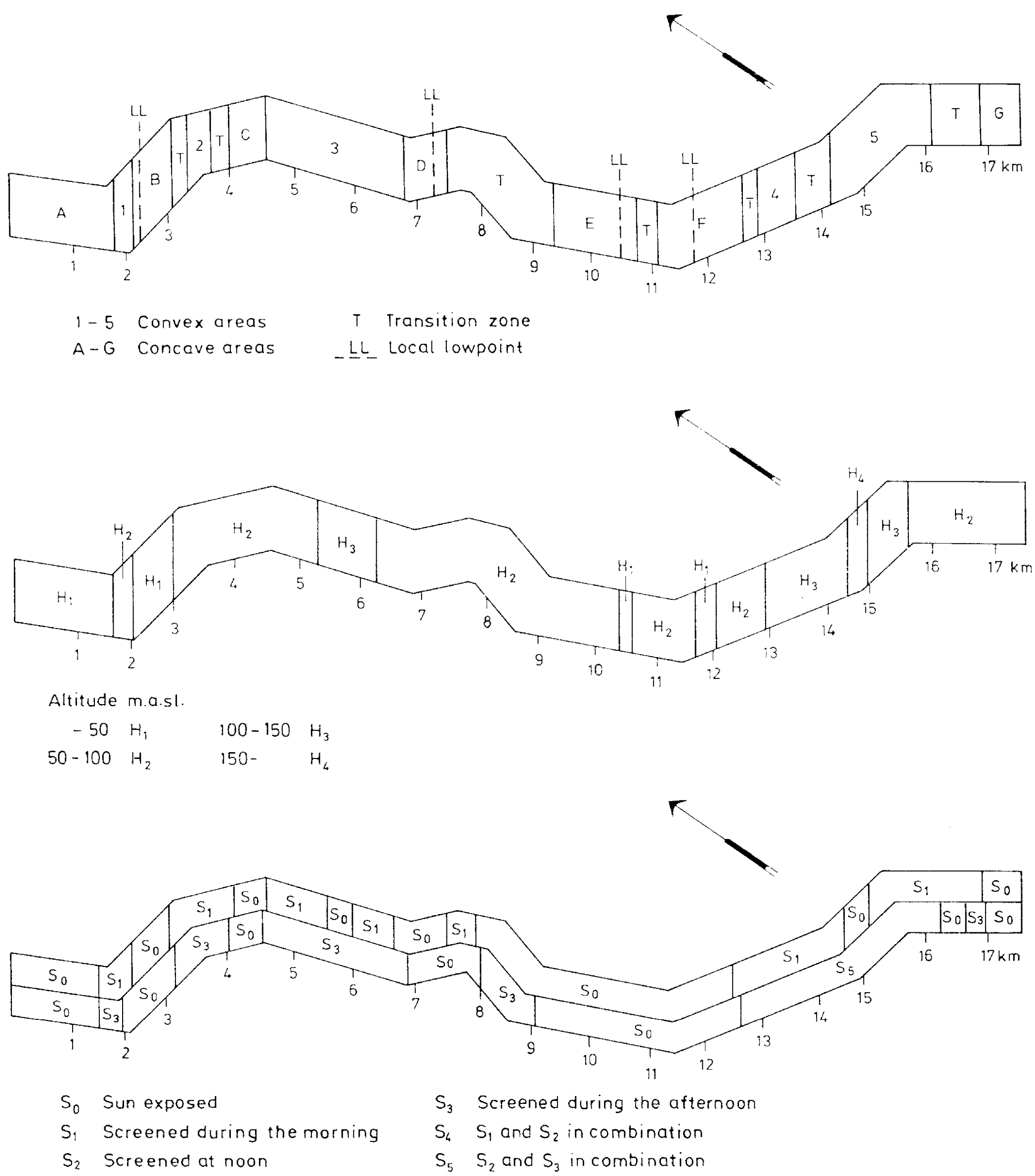


Figure 15. Example of segmentation of a road stretch according to topography

2.9.3.3 Cloudy/Windy Conditions

When the weather situation is characterized by cloudy, windy conditions the model takes advantage of the relation between the temperature lapse rate and altitude. In such situations, the temperature pattern is calculated using topographical units that are based on the absolute height above sea level of a certain road section. For the road section illustrated in Figure 15, four different levels, h1 to h4, are used. Each segment covers an interval of 50 masl, starting with h1 for the 0-50m interval. The temperature pattern may be calculated with the help of a regression calculation, where the values recorded at the RWIS stations in the area are used as input data. The result from a calculation during a cloudy, windy situation is given in Table 6. On this occasion, the temperature decreased by 0,8°C per 100m. The reference temperature is taken from a reference field station (h0) along the road. In this particular example, the reference temperature is -1,2°C; this temperature is used for the h0 segment.

2.9.4.4 Sunny Conditions

The temperature pattern under clear/day conditions is determined by the shadows cast by topographical objects. The segmentation for these conditions is done according to the time period during which there is a shadow pattern, since shadow patterns will vary according to the time of day and the time of year. The amount of screening is classified as follows:

- S0 represents a sun-exposed area;
- S1 is used for areas screened during the morning;
- S2 areas are screened around noon;
- S3 is for areas screened during the afternoon;
- S4 denotes areas screened in the morning and around noon;
- S5 indicates an area that is screened around noon and in the afternoon.

The calculated RST variations along the road under clear/day conditions are shown in Table 7. The RST differences between sun-exposed and shaded areas are calculated for 15 January, 15 February and 15 March at 10.00h and 13.00h, respectively. The calculated maximum temperature differences capture the effects of changing solar elevation at different times during the winter. (Note that the calculated temperature differences will be somewhat different for roads in Southern Ontario, since they are at a lower latitude than the stretch of road depicted in Figure 15.)

The examples given above cover three of the weather situations included in the model. The LCM is capable of identifying different weather situations in different sub-areas within the spatial domain of the model. As one would expect, the LCM then applies the appropriate calculations in each sub-area, according to the weather conditions identified therein. Weather situations other than those discussed above are dealt with using the regional temperature distribution, which is determined by the regional climate.

Table 5. Calculated and measured intensity of cold air pools

			Cold air pool intensity		
Segment	Valley width (km)	Valley Depth (m)	Calculated (°C)	Measured (°C)	Calculated – measured (°C)
A	1,8	5	4,8	5,4	-0,4
B	1,0	20	4,0	3,5	0,5
C	0,5	5	2,0	2,0	0
D	0,6	35	4,0	4,0	0
E	1,6	0	3,0	3,5	-0,5
F	1,6	0	3,0	4,0	-1,0
G	0,6	20	3,0	3,0	0

Table 6. Calculated and measured temperature related to altitude

Segment	H abs (m)	H rel (m)	RST cal (°C)	RST actual (°C)
H1	0-50	0	Tr	-1,2
H2	50-100	50	Tr-0,4	-1,6
H3	100-150	100	Tr-0,8	-2,0
H4	150-200	150	Tr-1,2	-2,4

Habs – Absolute height, interval 50m
Hrel – Height relative to H1
Tr - the road surface temperature at the reference station (Tr actual is -1,2°C)
RSTcal – calculated road surface temperature relative to Tr
RSTactual – Actual (measured) road surface temperature

Table 7. Calculated temperatures as a result of shading

Segment	15 Jan RSTdiff (°C)		15 Feb RSTdiff (°C)		15 Mar RSTdiff (°C)	
	10h	13h	10h	13h	10h	13h
S0	0	0	0	0	0	0
S1	-0,8	0	-2,5	0	-7,4	0
S2	0	-2,2	0	-3,2	0	-4,3
S3	0	0	0	0	0	0
S4	-0,8	-4,1	-2,5	-7,6	-7,4	-15,8
S5	0	-2,2	0	-3,2	0	-4,3

2.10 Implementation of the LCM in Southern Ontario: Finishing Touches and Next Steps

Hitherto, this report has concentrated on the feasibility of adapting the LCM to conditions in Southern Ontario. Clearly, this is the most important consideration, and the foregoing discussions have demonstrated that such an adaptation is not only possible, but also desirable. While the Local Climate Model is obviously the core of the system, it requires a few other supporting pieces of technology and information in order to run in an operational environment. Since the implementation of the LCM in Southern Ontario would be performed as a trial for evaluation purposes, one must also design performance measures, then collect and analyze the data from which conclusions may be drawn.

This last section of the report enumerates the supporting technologies and information, identifies some possible performance measures, and proposes an implementation plan. Finally, the section concludes with some thoughts on future directions, and additional benefits that could be realized by implementation of the LCM.

2.10.1 Supporting Technologies and other Resources Required

2.10.1.1 Input Data Requirements

The LCM requires observations from RWIS field stations, in particular, air and road surface temperatures and humidity and wind speed7direction. Ideally, these observations should be updated every 30 minutes. In addition, a cloud forecast is required, to assist in the determination of the most appropriate weather scenario.

The quality and accuracy of the calculations performed by the LCM is to a certain degree dependent on the number of field stations from which data is received. As a rough guideline, minimal acceptable coverage would be on the order of 10 to 15 field stations in an area of 200 by 200 km. However, this figure depends heavily on the topographical and climatological conditions. To determine what constitutes adequate instrumentation for a particular target area, a thorough analysis of local topography and climatology is recommended.

2.10.1.2 Data Format and Storage Requirements

It is an advantage if the data from the RWIS network is stored into a database that is updated continually and which will give access to historical information. The latter is of great value when developing new forecast tools. It is recommended that the data be stored in an ASCII format, which can be handled by the model.

2.10.1.3 Data Presentation

Obviously, effective presentation of the LCM output is a key to ensuring that the data is used and valued by the intended target audience. A number of steps are required to adapt a presentation system for the target area. In view of the fact that the first implementation would be on a trial basis, the most expedient approach would be to adapt the display system that has been developed for SNRA.

The LCM algorithms are written in the C programming language; the LCM runs under Windows on a PC. In the system developed for SNRA, the presentation of data from the LCM is integrated with the presentation of observations from the RWIS network

To adapt this display system for use in Southern Ontario, certain adjustments must be made:

1) the important geographic features, such as the stretches of road, the individual road segments, landmarks, etc. must be digitized and prepared in the proper format for integration into the display system;
2) the on-screen text and all associated documentation must be translated;
3) tuning of certain features (e.g. alarm levels) may need to be done to support operational practices in Southern Ontario;
4) existing data streams (e.g. for RWIS observations) must be adapted, or new ones created, to feed data into the LCM and the display system.

2.10.1.4 Training of Operational Personnel

All operational personnel that will be expected to use the LCM displays will need a certain amount of training. Some of this training will be functional (i.e. how to operate the system), but other training will be conceptual. For maintenance personnel, some training in climatology, and interpretation of the LCM displays may be needed. If weather forecasters are to have access to the data as well (which is recommended), then they will also need some conceptual training, so that they will know how to integrate the additional information in the most effective way to provide the best possible guidance to maintenance personnel.

2.10.2 Performance Measures

Initially, the LCM would be implemented in Southern Ontario over a limited area on a trial basis. Decisions regarding more widespread implementation would be contingent on results obtained during this trial period. To ensure that the necessary information is available to support decisions regarding future implementation of the LCM, appropriate performance measures must be designed. Moreover, collection of performance measurement data must be an integral part of the trial implementation. Broadly speaking, there are two kinds of performance measurement data, which will be discussed briefly here.

2.10.2.1 Data for Model Validation

One issue that must be resolved by this study is the performance of the LCM itself in the Southern Ontario environment. To quantify the accuracy with which the LCM is able to predict pavement temperatures, observation data must be collected. This data could consist of:

- thermal mapping runs over the model domain during the trial period;
- spot temperatures recorded by regular patrols;
- data from RWIS field stations in the domain, whose data are not made available to the LCM (e.g. data from stations owned by other agencies);
- subjective impressions from operational personnel.

The latter is not important for quantitative accuracy measurement, but it will help to explain responses to other collections of subjective data.

2.10.2.2 Data to Assess the Incremental Value of LCM Output for Operations

Another key question that must be addressed is the impact of availability of LCM output on operations. In practice, it is very difficult to define measures that clearly demonstrate incremental value. Nevertheless, there are some possible indicators:

- comparison of forecast performance for RWIS sites in areas with the LCM, versus areas without the LCM;
- comparison of operational performance measures for road maintenance, including salt use, overtime, accident rates, and so on;
- subjective impressions from operational personnel.

To construct a representative indicator, the comparisons performed in the first two tests should include spatial testing (i.e. different locations during the same winter), and temporal testing (i.e. the same locations during different winters).

2.10.3 LCM Transfer Implementation Plan

To proceed with the trial implementation of the LCM in a target area in Southern Ontario, the following sequence of activities is recommended. The main steps are enumerated here; further details are included in Appendix B.

1) Identification and assessment of study area
   This task would involve selection of a target area, compilation of an inventory of available data sources, collection of additional information (e.g. thermal mapping) as necessary, and synthesis of this information to develop a complete description of the significant climatological features in the target area.

2) Preparation of study area
   In this task, any deficiencies in data sources would be rectified (e.g. RWIS stations added). Using the information gathered in step 1, the target road stretches would be divided into segments as appropriate.

3) Preparation of LCM
   As discussed previously, each software component must be adjusted for operation in the target area. Input data must be formatted for the ingest algorithms. The LCM must be fine-tuned, or trimmed, to optimize performance. If sufficient observational data exists, the fine-tuning is done empirically. Otherwise, it is done based on a theoretical analysis, using the equations presented elsewhere in the report. Display software must be adapted, also, as described above.

4) Preparation of operational personnel
   All personnel who will use the LCM must be taught how to do so. In addition, maintenance personnel will require some training in climatology, and forecasters would benefit from additional guidance on how best to integrate LCM output into forecast products.

5) Operational test of LCM
   This phase would include not only use of the LCM in an operational environment, but also the collection of additional information from which performance measures are to be constructed.

6) Validation of LCM test results
   In this phase, the various performance measures would be analyzed. In addition, subjective impressions would be collected from operational personnel, and correlated with objective measures

7) Preparation of final report and recommendations
   The final report would include a discussion of the validation exercise, suggestions for improvements in existing systems and practices, and recommendations for expansion of the LCM to other areas in Ontario.

2.10.4 Concluding Thoughts: Looking further down the Road

Upon consideration of the various aspects treated in this report, one arrives at the unequivocal conclusion that it is possible to adapt the LCM to Southern Ontario. From the perspective of physical geography, Southern Ontario is sufficiently similar to Jönköping that the model can be implemented without major changes. Moreover, common characteristics such as diversified topography and variety of land use have been shown to create the significant temperature variations that the LCM is capable of simulating. The increased resolution of road temperature information affords maintainers the opportunity to better focus their interventions, which will help to optimize utilization of human and physical resources. Moreover, this information can also give motorists and maintainers greater advance warning of adverse road conditions.

In addition to the obvious benefits, a number of additional advantages accrue as a result of LCM implementation. First, by implementing the LCM in a maintenance area at an early stage in the development of a network of RWIS field stations, the number and siting of stations can be optimized, thereby reducing capital investment and operating and maintenance costs, and increasing the degree to which the stations are representative of the conditions across the area.

The current implementation of the LCM can also be used as a stepping stone to future systems that will further enhance the quality of information available to road maintenance decision-makers. For instance, since cloud cover and precipitation play such key roles in the radiation balance of a road surface, LCM performance would benefit from enhancements in the resolution of cloud and precipitation data. Remotely-sensed datasets, such as satellite imagery and radar reflectivities could be integrated into the input data stream of the LCM, improving its ability to discriminate between different radiative regimes.

Another active area of research and development that would benefit from LCM output is that of very high-resolution numerical modeling of weather and pavement conditions. The FORETELL initiative is one example of a research project that is addressing the challenge of integrating a high-resolution atmospheric model with a state-of-the-art pavement condition model. One obstacle to the development of such a system is the lack of high-resolution datasets to perform model validation. Thermal mapping provides a critical source of data to support advances in this area. Moreover, the output from a well-tuned LCM will offer a reference against which to compare the output of higher-resolution, coupled models, as the latter are developed during the next decade or so.

In summary, implementation of the LCM offers benefits not only today, but for many years to come.

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APPENDIX A:

Questionnaire - Winter Maintenance Practices and Road Weather Information Systems

In order to determine the present situation regarding maintenance activities and openness to new information tools, a questionnaire was sent out to the people involved in these activities. Another goal of the questionnaire was to see if maintenance personnel were aware of local climate and temperature variations within their maintenance districts.

The questionnaire consists of a total of 19 questions, divided into 3 groups: Maintenance Practices, Treatment of “Black spots”, and Road Weather Information Systems.

The questions about maintenance aim to detect the spatial extent of a typical maintenance area, in order to see how it compares with the scale of local climatological variations. It is also important to know if the maintenance activities could benefit from increased information about local climate and temperature variations.

Information about black spots, or slippery patches, is crucial, since the presence of these spots often is very well correlated to temperature anomalies that might vary a great deal within short distances. The treatment and location of these spots reveal a lot about the significance of local climate within an area. The variability in weather is a related issue that indicates if there are changing characteristics of the temperature variations determined by topography and other local climatological factors.

Questions focusing on Road Weather Information Systems attempted to elicit the perspective of the maintenance personnel regarding the need for improved decision support tools, and also the attitude towards new developments and new technologies.

Below is a list of the different questions, a summary of the responses received, and the significance of these responses with respect to the LCM.

Questions/Answers/Comments

Part I: Maintenance Practices

1) What area are you responsible for? How many kilometers of what class of highway are you maintaining?

The answers range from 243 km to 750 km, with a mean of 333 km.

Based on these answers, one may conclude that the size of the maintenance areas is sufficiently large that local climatological anomalies can occur within an area.

2) What kind of de-icing, anti-icing and abrasives does you use?

Salt and sand are used in all districts. One respondent also reported using brine.

Given the extensive use of salt, there is a possibility that preventive action could increase the efficiency of maintenance activities.

3) What criteria do you use to determine when to use de-icers as opposed to abrasives?

Different criteria are used as a basis for the decision. The criterion cited most frequently is temperature, by 9 out of 10 respondents, followed by wind speed and road condition. Time of day and traffic density were also mentioned. The frequency of consideration of the various criteria is summarized in the table below. (Note that several factors can be included in one answer.)

Temperature	Wind	Road Condition	Precipitation	Traffic density	Time of Day
90%	40%	40%	30%	20%	10%

The frequent consideration of weather- and climate-related factors in the decision-making process indicates that road weather forecast models could be useful.

4) Who makes the final decision about whether or not to treat? How is the decision made?

The final decision is to a large extent based upon what the road patrols observe. The answers received were as follows: road patroller 50%, private contractor 20%, shift supervisor 20%, weather forecast 10%.

Historically, the information required to choose a treatment strategy has been supplied by road patrols, which offer good spatial coverage of the road network, but lack in temporal coverage, since a patrol vehicle can only be in one place at one time. The addition of RWIS stations has augmented the available information by supplying information on a continuous basis, albeit only at a limited number of locations. Output from the LCM would further enhance the supply of information that can be used to support decision-making.

5) How much sand and salt do you use on average during a winter season?

For some reason, this question was not answered by all respondents; only 50% did answer the question. Of the answers received, the amount of sand ranges from 1811 tons to 6500 tons, and the usage of salt ranges from 500 tons to 4200 tones. If these figures are related to length of road maintained, salt use for a typical winter would be in the range of 2 tons salt/km to 17 tons salt/km.

6) What distribution rates do you use for sand and salt? Do you use different rates for different conditions or different temperatures?

The distribution rates for salt and sand vary as follows, salt 130-170 kg/km and for the sand 570 kg/km is used.

The answers reflect the recommendations for salt use given by the authorities.

PART II: TREATMENT OF 'BLACK SPOTS'

1) Are 'black spots' common in your area?

Respondents answered this question as follows: yes, 60%; occasionally, 10%; no, 20%; no answer, 10%.

The high frequency of affirmative answers clearly indicates that areas prone to local climatological temperature divergences are present. Usually, black spots refer to areas that are exposed to radiation cooling and pooling of cold air. The LCM is designed to provide assistance in detecting such areas.

2) How do you treat a black spot?

Salt is used either solely or in combination with sand by 80% of the respondents. Of the remainder, 10% did not answer the question and 10% indicated that there is no problem with black spots.

The usage of salt makes it possible to pursue a proactive treatment strategy, if a forecast of the temperature development is available.

3) Are there any areas of your patrol that are particularly difficult to maintain due to local climate phenomena, or that ice up easily or quickly? Please identify these areas on a 1:50,000 scale map?

This question really highlights whether or not maintenance personnel can identify any local climatological spots/areas. From the answers, it is obvious that there is a correlation between the occurrence of black spots and specific local climatological areas. Bridge decks are most frequently identified as prone to slipperiness. In addition, open areas with a high sky view often have lower temperatures causing black spots. It is also observed that shaded areas are more prone to slipperiness than open, exposed areas. Another salient feature of the responses is that black spots are common in wheel tracks, especially when drifting occurs. Culverts, where the road bed has different thermal properties, are also often struck by road icing.

4) What kind of weather situation is associated with the different types of slipperiness that you may have in your area?

The answers vary according to the list below; the most frequent answer is freezing rain.

Weather/slipperiness	Frequency (%)
freezing rain	26
drifting snow	21
wet snow	17
frost	13
dry snow	5
packed snow	5
freeze and thaw cycles	5
freezing fog	4
fog	4

The range in alternative answers shows that slipperiness occurs in a wide variety of circumstances, and is caused by a number of different mechanisms. With a knowledge of the stretchwise variation of air- and road surface temperatures, there would be a better chance for advance warning and preventive action. Clearly, information about type and amount of precipitation is of high importance since several of the “problems” are associated with some kind of precipitation.

5) Do you have stable weather conditions during the winter or does the weather change a lot?

The different answers cover a wide range of temporal scales, from diurnal to interannual. However, there is general agreement that the weather and temperature display a high degree of variability over short timeframes, as well as within limited areas.

Answering alternatives are such as:
Changes a lot; variable conditions temp -23°C to +8°C, rain fog, freezing rain, snow flurries-squalls, mod to heavy snowfalls; lots of changes; last few years weather has changed a lot; rapidly changing weather conditions, freeze and thaw cycles 1-2 times the day, weather in the southern parts of the district also varies greatly to the northern part; weather varies one end to the other due to lake-effects; changes a lot, in a 48 h period it can go through a freezing and thaw cycle 4-5 times; boarding on Lake Huron causes unstable winter conditions that change with wind direction and velocity, many freezing and thawing cycles; weather can change daily; changes a lot range from -25 to +5°C.

It is obvious from the answers that local climate variations play a significant role in causing adverse road weather conditions. Spatial and temporal temperature/weather changes are present at the local climatological scale in all the different maintenance areas. The range and variety of the answers indicate that considering the local climatological effects could be very beneficial for monitoring and forecasting.

6) Is there a difference in the weather patterns between the beginning and end of the winter?

The answers about how the weather evolves over the course of a typical winter included the following:

Not significant differences; begin cooler more flurries, during colder-snow, end warmer-wet flurries-more rain; no; yes; conditions change as the lake freezes or open water exists; January and February are normally worst months; may have less Great Lake effect later in the winter if the lakes get frozen over or close to frozen across.

Most of the answers (80%) indicated some evolution of weather patterns over the course of the winter period. In general, three phases could be distinguished: early winter, with lake effect snows and frequent alternating temperature cycles; mid-winter, with relatively stable conditions, dominated by cold and snow; and late winter, with warmer temperatures and a return to alternating conditions.

These perceptions are consistent with the synoptic climatology of the Southern Ontario: the main storm track (and associated jet stream) lie astride the Lower Great Lakes during the early winter and late winter. In mid-winter, the storm tracks are depressed further to the South, and cold, arctic air is more or less entrenched over Southern Ontario.

Part III: Road Weather Information Systems

1) What sources of information do you have today as tools for decision making regarding winter maintenance?

The variety of answers are as follows:
winter weather reports, radio room, local radio, TV forecast
weather forecast environment Canada, IR pavement temperature sensors, RWIS road sensors
weather reports, RWIS
daily weather reports
local and regional weather reports from TV and radio, Internet environment Canada
local and regional forecasts, RWIS
weather forecasts, RMOS system
maintenance special provisions, winter operations for snow and ice control
ARWIS, information from other patrols, radio room, news media
SCAN for Windows

Evidently, there are numerous sources of information, which maintainers can consult when making maintenance decisions. At least 50% of the respondents indicated that they have access to RWIS. All decision makers have access to some sort of weather forecast. However the source and updating interval varies considerably. It would appear that there could be a demand for a weather and pavement condition information service that is more closely tailored to the specific needs of the road maintenance community.

2) How many road weather field stations do you think are necessary in your area?

Answers range from 1 additional to 11.

Evidently, maintainers are expressing a need for more field stations. However it is recommended that the stations station requirements be determined by considering other factors(e.g. climatological complexity and size of the actual maintenance area).

3) What information are you looking for from these field weather stations?

All measured parameters are mentioned together with variables that must be calculated by some kind of model.

Measurable variables:
air and road surface temperature
wind speed and direction
precipitation type and amount
(road surface status)

Calculated:
time to freezing
road surface status
temperature forecast (air and road)

The range of information that is sought suggests that RWIS is already acknowledged as a source of valuable information by the maintenance personnel answering this question.

4) Where do you think these field stations should be located?

The answers are to an overwhelming degree related to geometrical/spatial considerations. The most common criteria cited for station distribution was uniform spacing within the maintenance area. Previous responses indicate that local climate is a significant factor to consider, but apparently, personnel do not completely appreciate the connection between local climate variability and optimal station siting. One exception is that long bridge decks were identified as possible field station sites.

5) Do you think that you could work more efficiently if you had access to a road weather information system?

Answer	Frequency (%)
positive	70
negative	10
no answer	20

The majority expect to be able to increase the efficiency of winter road maintenance operations, with access to RWIS.

6) If you had access to a road surface temperature forecast, for how long of a time period should it be valid?

This question proved to be ambiguous; consequently a range of responses was given. However from the answers provided, it is apparent that the winter season is deemed to run from 1 November to 15 April. Those responses that addressed the issue of forecast valid period (which was the intended objective of the question) varied from 12 hours in advance to 15 or 30 minutes in advance.

It is interesting to notice that the focus of interest is on short-term forecasts. This is reassuring, since this is the timeframe during which the RWIS can provide guidance with acceptable accuracy.

7) *Do you think it would be useful to have pavement temperature information for the section of highways between the ARWIS field stations?*

Answers:

Alternative	Frequency (%)
positive	50
negative	10
not answered	40

A majority of those who expressed an opinion could see the benefits of having road surface temperature information for entire stretches of road. Of course, this is precisely the goal of the LCM.

APPENDIX B:

Detailed LCM Implementation Plan for a Trial Area in Southern Ontario

Local Climate Model Implementation Project
Phase II - Limited Area Test in Southern Ontario

		Total: LCM Project Phase II			

Part 1: Identification and Assessment of Study Area					
Timeline	**Task**	**Description**	**Resources**	**Responsible Agency**	**Estimated Cost ($US)**
		Specification of study area	Maps, GIS	MTO	
Oct 2000 to		Inventory of available weather information	Weather station databases	EC	
Apr 2001		Detailed description of regional physiography	Maps	GVC	
		Detailed description of regional climate	Climate data, 1-3	EC, GVC	
		Detailed description of local climate (thermal mapping)	Specially equipped vehicle, trained personnel (patrol supervisor ?)	MTO, GVC	
		Comparison of thermal mapping and detailed knowledge of local maintenance crews	Personnel, surveyor	MTO, GVC	
		Specification of requirement for additional real-time data	Maps, 1-5, 1-6	MTO, EC, GVC	
		Total: Part 1			$6,500
					plus thermal mapping

Part 2: Preparation of Study Area					
Timeline	**Task**	**Description**	**Resources**	**Responsible Agency**	**Estimated Cost ($US)**
Apr 2001 to		Acquisition of additional RWIS stations (if necessary)	Results of 1-7	MTO	
Oct 2001		Installation of additional RWIS stations (if necessary)	Results of 1-7	MTO	
		Division of road stretches into climatological segments	Maps, 1-5, 1-6, 1-7	GVC	
		Total: Part 2			

Part 3: Preparation of LCM

Timeline	Task	Description	Resources	Responsible Agency	Estimated Cost ($US)
		Limited validation of formulae for various weather conditions	RWIS data, atmospheric data	GVC	
Apr 2001 to		Linkage of road segments to appropriate formulae	Maps, site surveys	GVC	
Oct 2001		Normalising ingest of RWIS and atmospheric data into LCM database	Decoded data from SSI (or other) sensors	GVC, MTO, EC	
		Normalising ingest of forecast data into LCM database	Decoded forecasts from EC	GVC, EC	
		Development of graphical user interface and data and forecast presentation tools	GIS data, RWIS data, other atmospheric data, translation of software, manuals	GVC, EC, MTO	
		Pre-season testing of functionality of software suite	Idiots (for idiot-proofing) - I volunteer	GVC, MTO	
		Final tuning of LCM and preparation for operational use by MTO, EC	CS resources	GVC, MTO, EC	
		Total: Part 3			

Part 4: Preparation of Personnel					
Timeline	**Task**	**Description**	**Resources**	**Responsible Agency**	**Estimated Cost ($US)**
		Assessment of need for training of EC and MTO operational personnel	Experience from SNRA, SMHI, survey	MTO, EC, GVC	
Oct 2000 to		Development of training materials as appropriate	Training materials from SNRA, SMHI, EC, MTO	MTO, EC, GVC	
Oct 2001		Delivery of training courses to EC, MTO personnel	Travel for operational personnel, adequate class facilities	MTO, EC, GVC	
		Hands-on training with LCM as part of pre-season test	Linked to 3-6	MTO, EC, GVC	
		Familiarisation with final form of LCM	After 3-7, as necessary	MTO, EC, GVC	
		Total: Part 4			

Part 5: Operational Test of LCM

Timeline	**Task**	**Description**	**Resources**	**Responsible Agency**	**Estimated Cost ($US)**
		Daily operational use of LCM for a winter season		MTO, EC	
Oct 2001 to		Identification of challenges with use		MTO, EC	
Apr 2002		Rectification of minor problems, where possible		MTO, EC, GVC	
		Identification of opportunities to improve service, operations		MTO, EC	
		Limited collection of thermal mapping data for validation		MTO, GVC	
		Recording of subjective impressions for report, validation		MTO, EC	
		Total: Part 5			

Part 6: Validation of LCM Results

Timeline	**Task**	**Description**	**Resources**	**Responsible Agency**	**Estimated Cost ($US)**
		Statistical comparison of LCM output with thermal mapping data	Thermal mapping data	MTO	
Apr 2002 to		Comparison of LCM output with hi-resolution model output	Model output from Mesoscale Modeling Project	EC, MTO	
June 2002		Comparison of LCM output with subjective impressions		MTO	
		Comparison of forecast performance for stations with and without LCM (different stations in same winter, and same stations in different winters)	Forecast and observed data	EC, MTO	
		Comparison of operational performance measures for road maintenance	MTO operational performance measures (salt use, O/T, accident rates, etc.), as a function of weather, to remove effects of interannual variability	MTO	
		Total: Part 6			

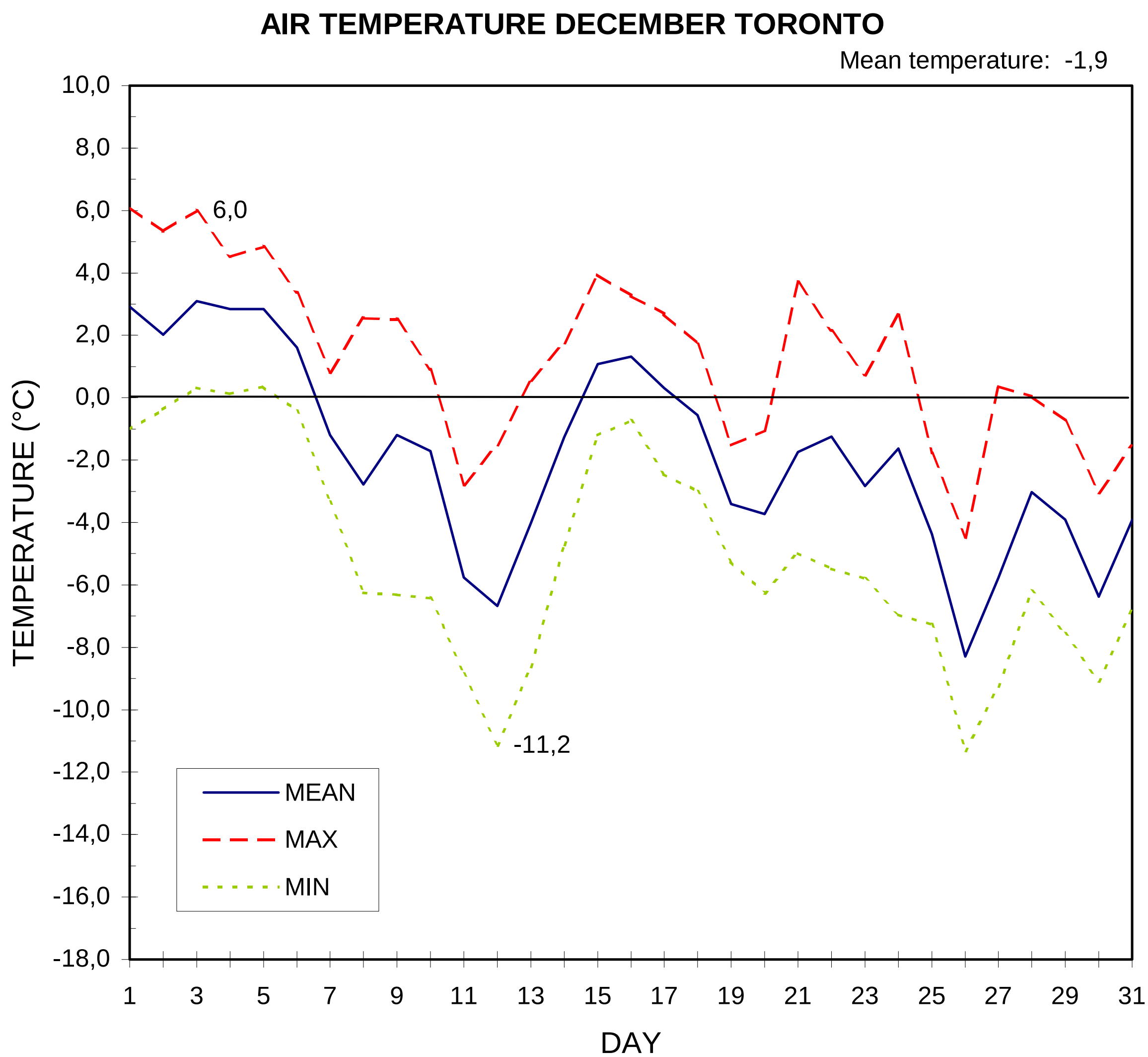
Part 7: Preparation of Report and Recommendations

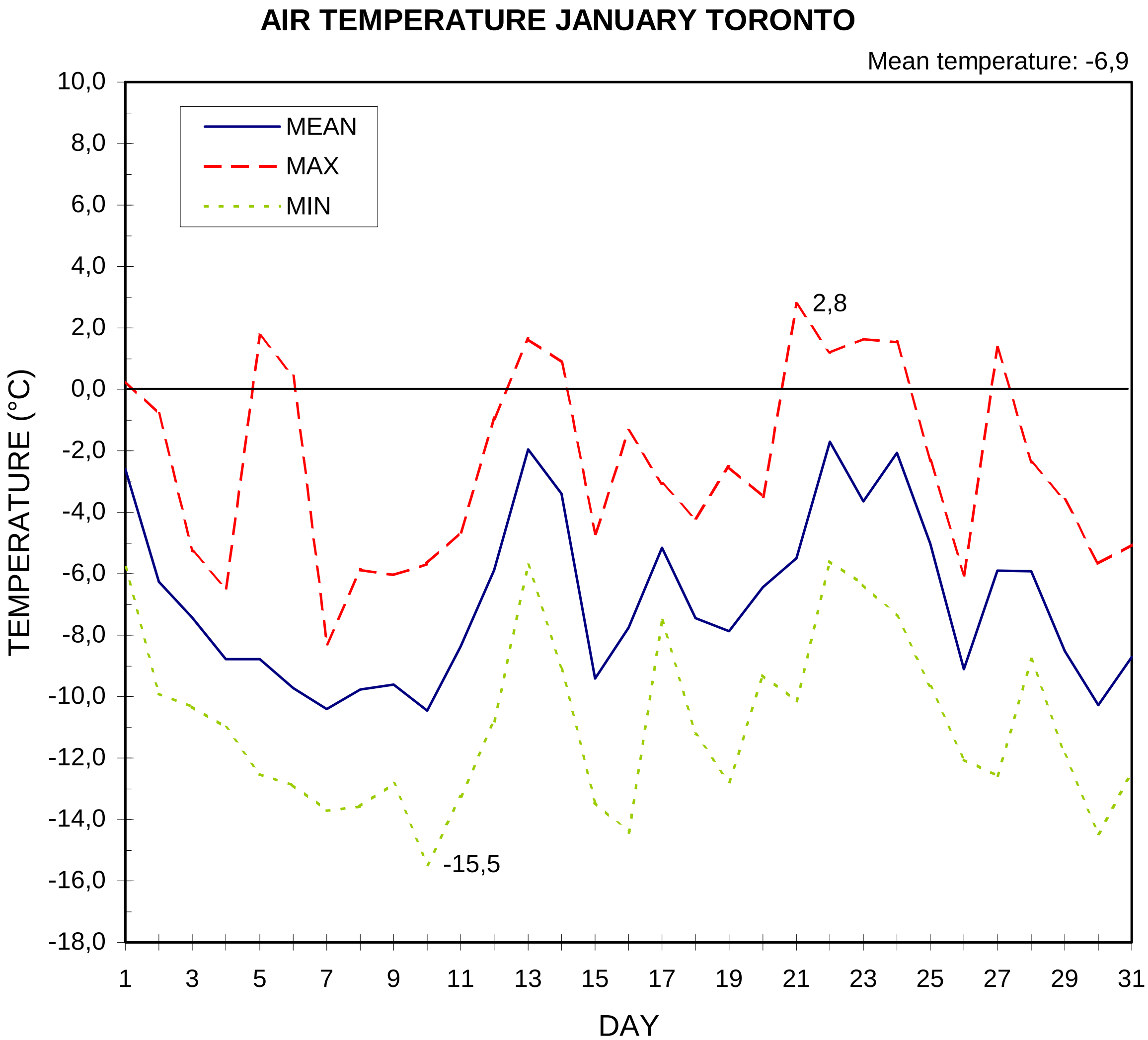
Timeline	Task	Description	Resources	Responsible Agency	Estimated Cost ($US)
		Compilation of objective and subjective validation results		MTO, EC, GVC	
		Recommendations for improving implementation of LCM		MTO, EC, GVC	
		Recommendations for improving utilization of LCM information in operations, including possible new forecast products		MTO, EC, GVC	
July 2002 to		Recommendations on application of LCM into other areas of Ontario		MTO, EC, GVC	
October 2002		Recommendations on synergistic use of LCM, high-resolution numerical model output		EC	
		Total: Part 7			

		Total: LCM Project Phase II			

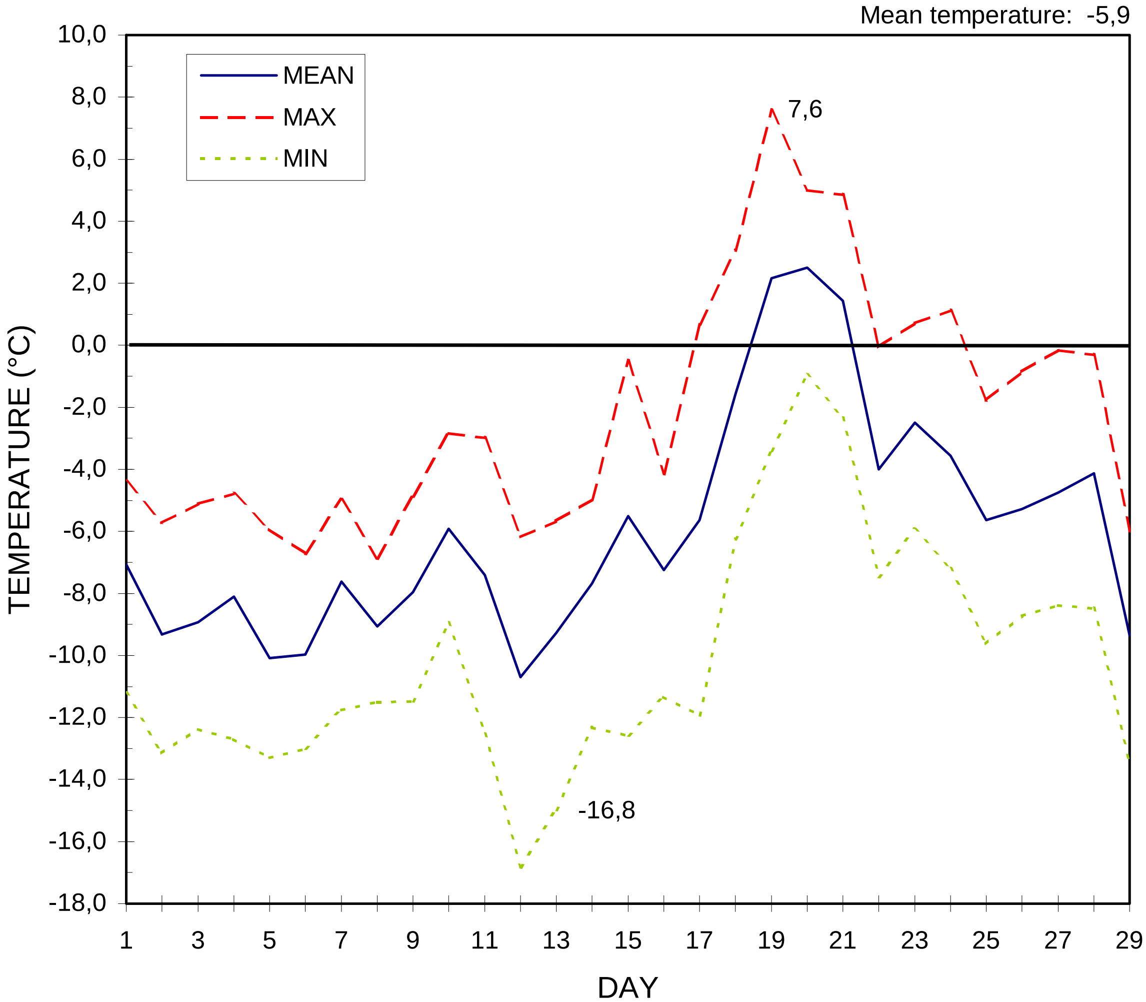
APPENDIX C:

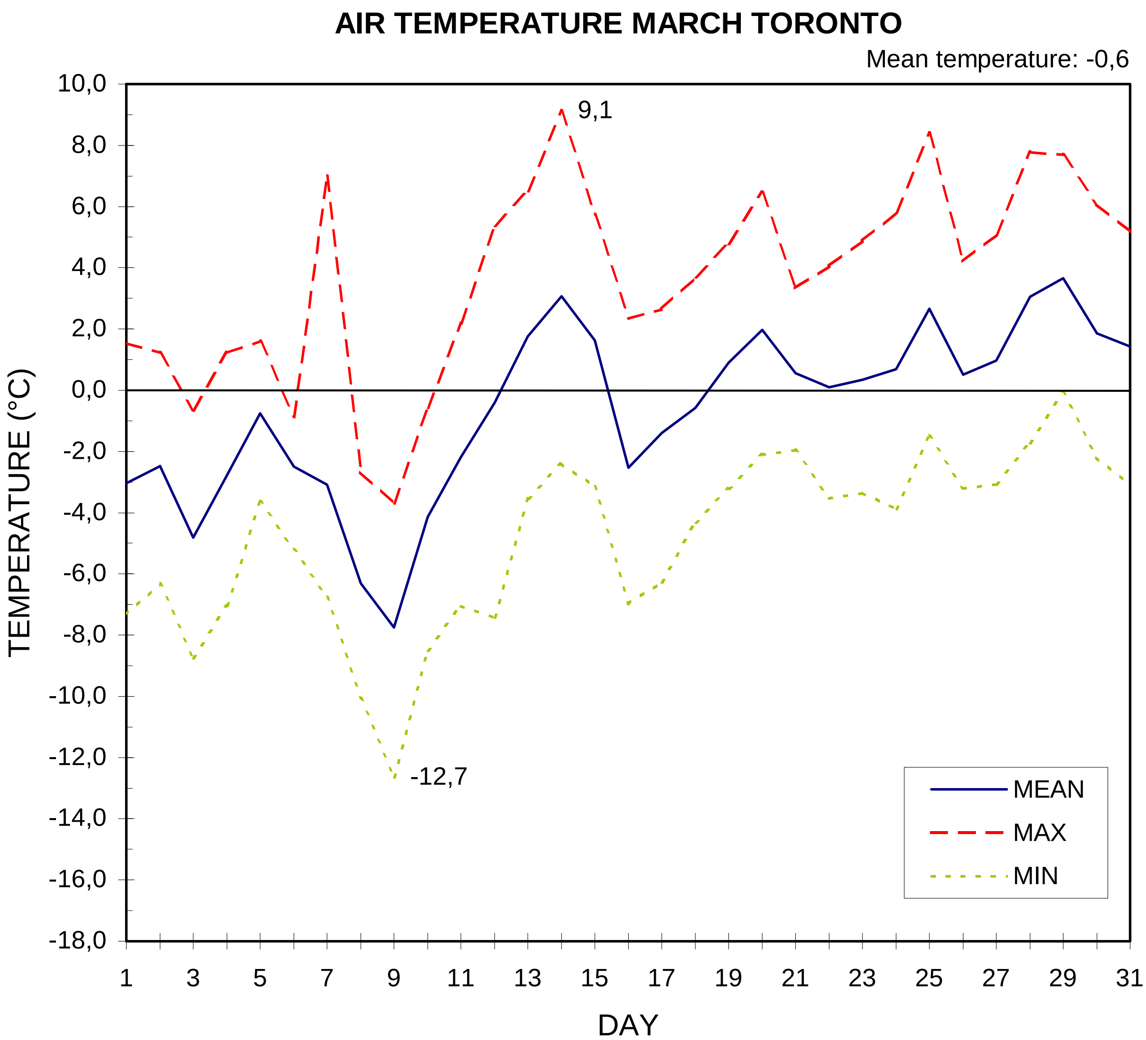
Additional Figures for Comparative Climate Analysis

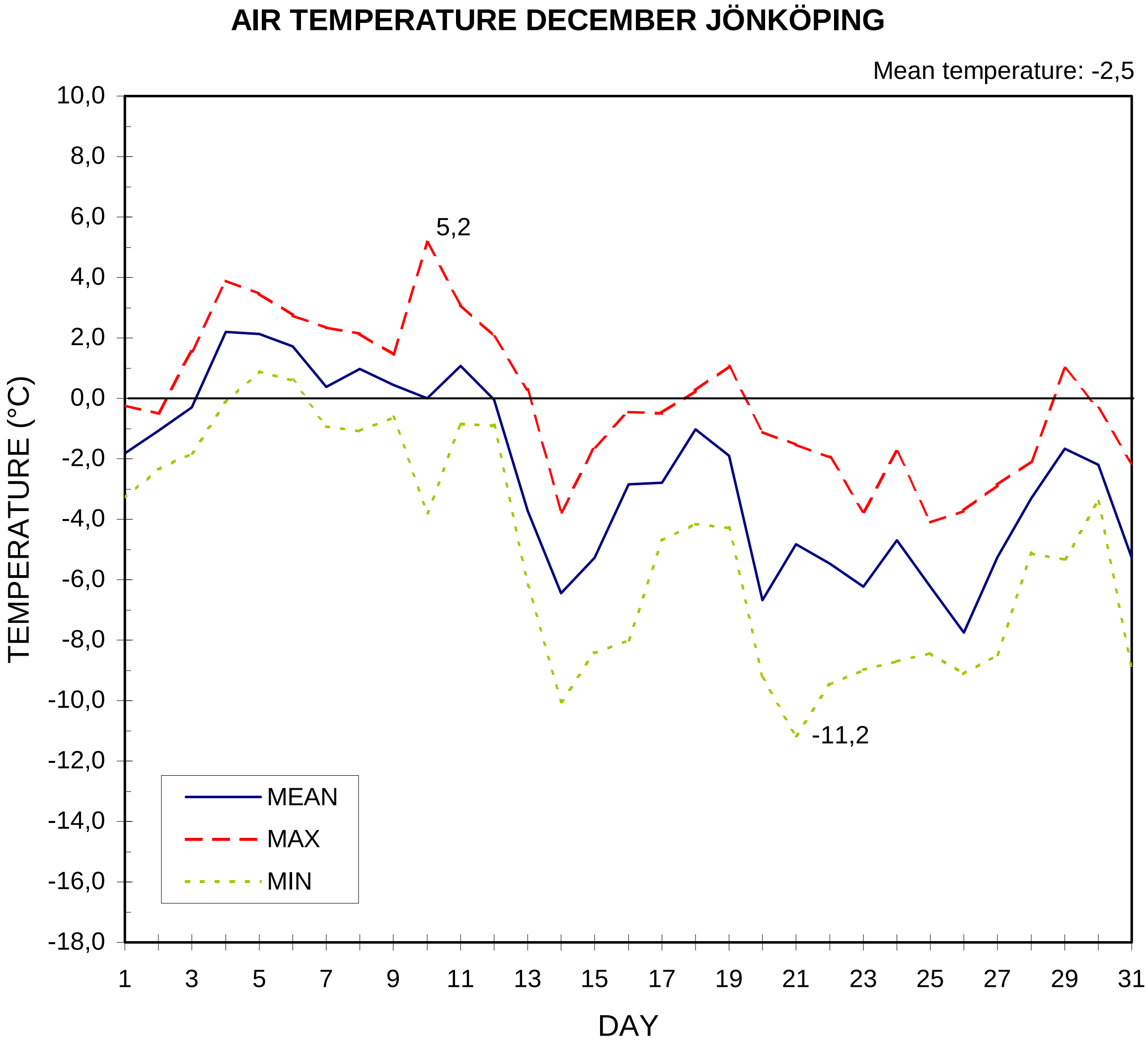



AIR TEMPERATURE JANUARY TORONTO
Mean temperature: -6,9
MEAN
MAX
MIN
2,8
-15,5
TEMPERATURE (°C)
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
DAY

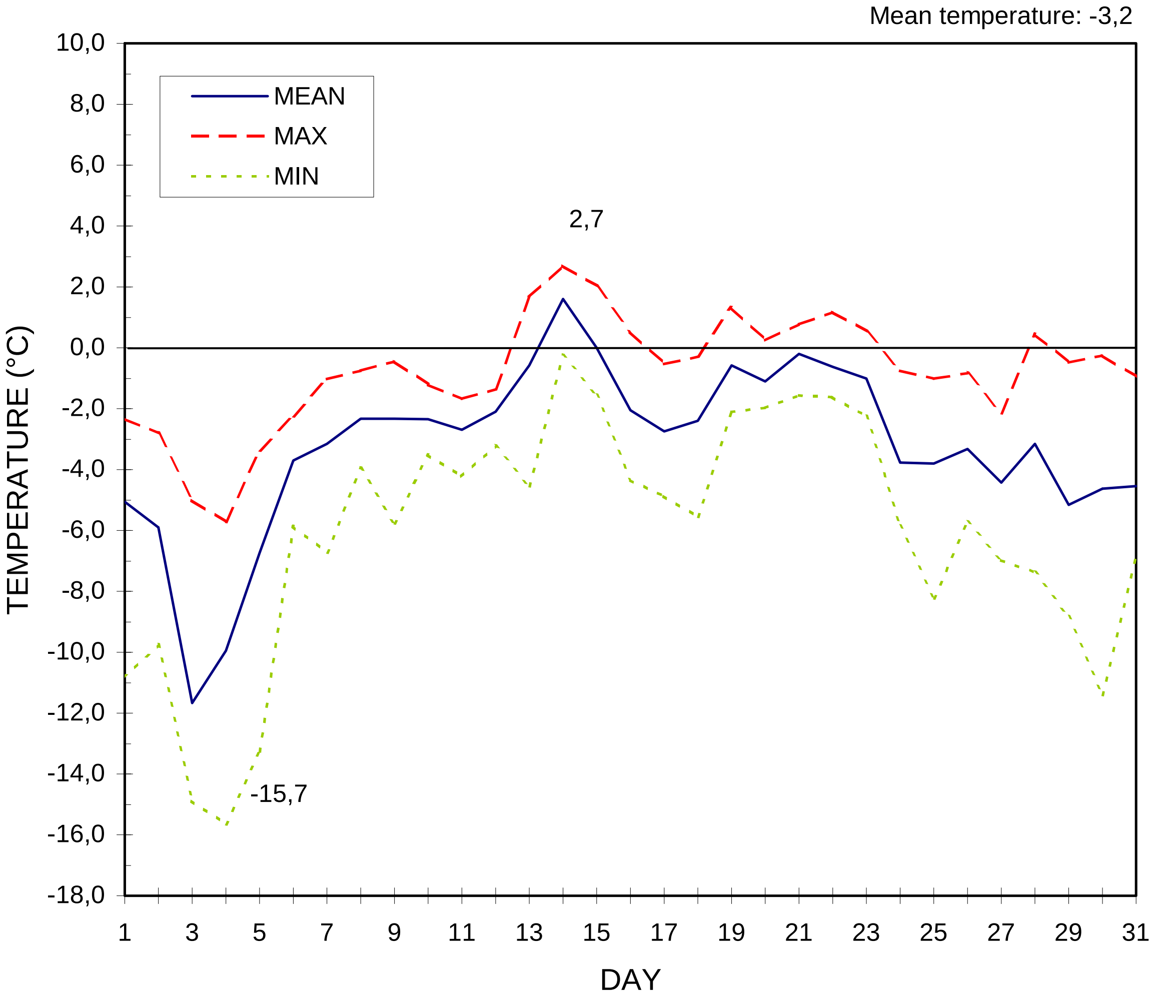
AIR TEMPERATURE FEBRUARY TORONTO

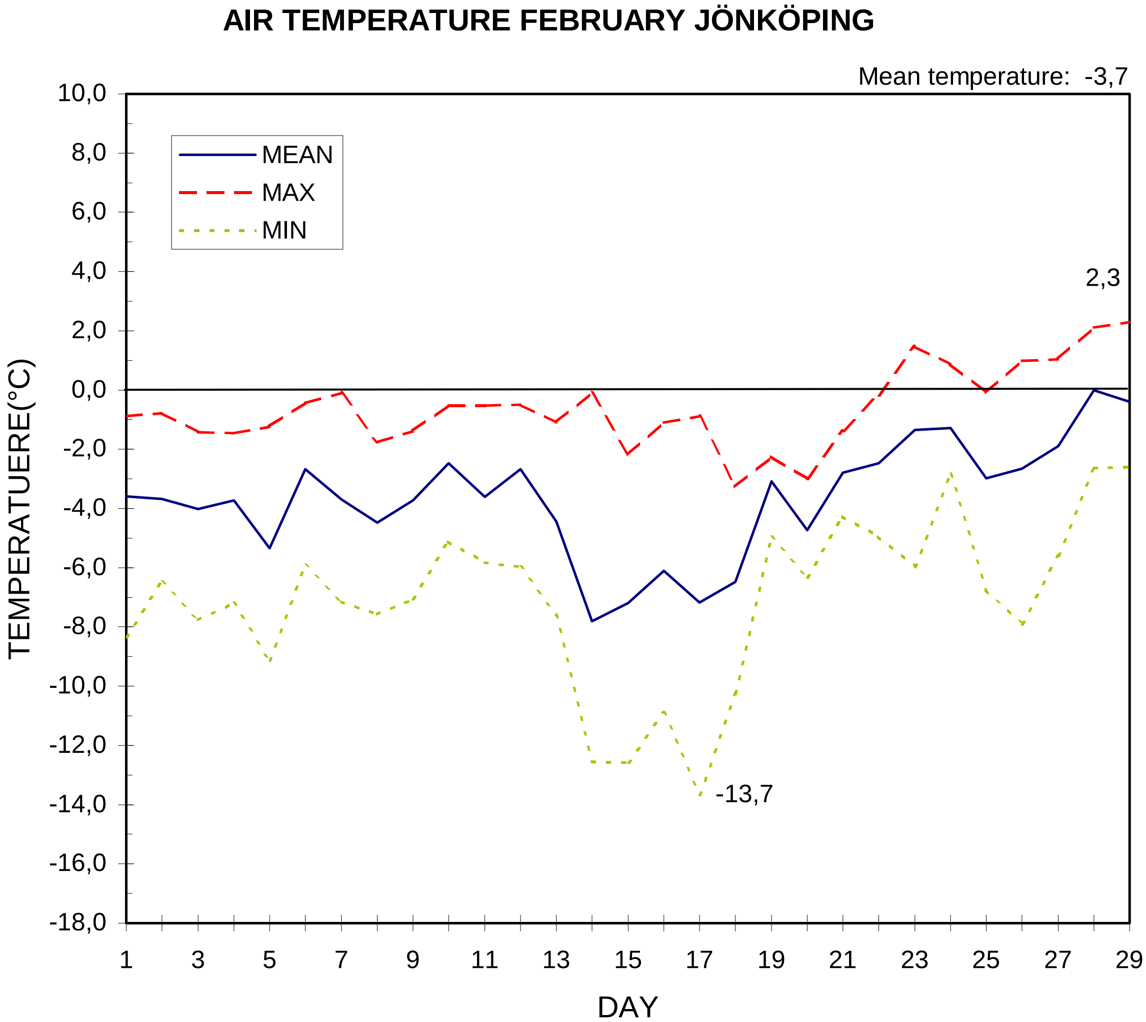



AIR TEMPERATURE MARCH TORONTO
Mean temperature: -0,6
TEMPERATURE (°C)
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0
9,1
-12,7
MEAN
MAX
MIN
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
DAY


AIR TEMPERATURE DECEMBER JÖNKÖPING
Mean temperature: -2,5
TEMPERATURE (°C)
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0
5,2
-11,2
MEAN
MAX
MIN
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
DAY

AIR TEMPERATURE JANUARY JÖNKÖPING




AIR TEMPERATURE FEBRUARY JÖNKÖPING
Mean temperature: -3,7
MEAN
MAX
MIN
2,3
-13,7
TEMPERATUERE(°C)
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
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1
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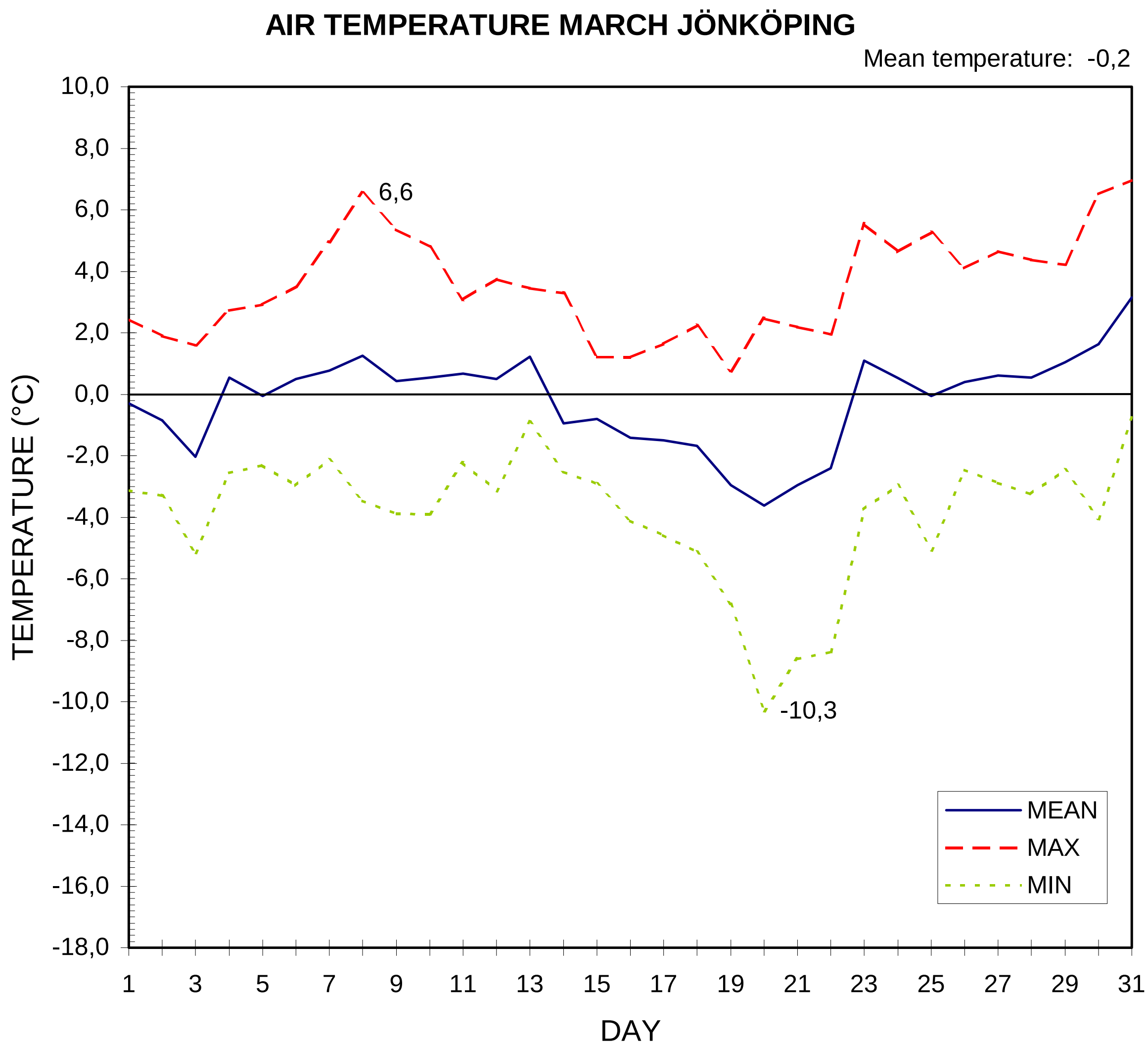
23
25
27
29
DAY



AIR TEMPERATURE MARCH JÖNKÖPING
Mean temperature: -0,2
10,0
8,0
6,0
4,0
2,0
0,0
-2,0
-4,0
-6,0
-8,0
-10,0
-12,0
-14,0
-16,0
-18,0
TEMPERATURE (°C)
6,6
-10,3
MEAN
MAX
MIN
1
3
5
7
9
11
13
15
17
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21
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25
27
29
31
DAY