Mapping spatial distribution of a disease forecasting model using precipitation and relative humidity measurements provided by weather radar.

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements of the degree of Master's in Sciences

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July 2001

0-612-75328-X

Abstract

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Many applications of remote sensing in agriculture have been developed since 60 years but mostly since the launch of Landsat 1 in 1972. With time, improvements in spatial, spectral and temporal resolution have been made and generated a resurgence of remote sensing popularity. Combined with agricultural systems modelling, remote sensing data such as weather radar measurements can help to obtain an accurate tool in real-time for agricultural decision-makers. Indeed, precipitation and relative humidity (RH) could become available for the agricultural decision-makers using the McGill Doppler S-band radar. At present, precipitation measurements are available with a spatial resolution of 1 km up to a range of 240 km and RH data could be available with a resolution of a few kilometres up to a range of 40 km. Both weather variables could be available with a time scale of 5 min if requested. These measurements would compensate for the actual lack of a dense weather station network prevailing in southern Quebec.

So far, the reliability of weather radar measurements has been tested by the scientific community for precipitation data but has never been tested for the RH data. In this study, a comparison between RH measured at three weather stations and RH calculated from weather radar measurements was made using consecutive time interval of 240 hours in 1997 and 336 hours in 1998. A valid t-test designed for simple linear regression analysis with two time series as dependent and explanatory variable, and based on the first-difference ratios (FDR) of the time series clearly showed that RH calculated from radar measurements is comparable to the one measured at weather stations. Thereafter, the possibility of integrating weather radar measurements (precipitation and RH) in a geographic information system (GIS) to map the variability of a crop disease was verified. Results indicated the potential of weather radar measurements in agriculture.

Résumé

M.Sc. Hélène Laurence Agrométéorologie

Depuis 60 ans, de nombreuses applications de la télédétection en agriculture ont été développées et ce, surtout depuis le lancement en 1972 du satellite Landsat 1. Avec le temps, des améliorations dans les résolutions spatiale, spectrale et temporelle ont engendré un regain de popularité de la télédétection dans la communauté scientifique. Les données de télédétection, jumelées à la modélisation de systèmes agricoles, peuvent en effet fournir un outil précieux dans la prise de décision dans la régie agricole. Tel est le cas des données fournies par le radar météorologique Doppler en bande S localisé à l'Université McGill. Grâce à ce type de radar, des données de précipitation sont disponibles avec une résolution spatiale de 1 km jusqu'à 240 km de portée et des données d'humidité relative (HR) pourraient être disponibles avec une résolution spatiale de quelques kilomètres jusqu'à 40 km de portée. Dans les deux cas, les données peuvent être disponibles aux 5 minutes si nécessaire. Ainsi, l'excellente résolution spatiale des données provenant du radar météorologique viendrait combler le manque de stations météorologiques du sud-ouest du Québec. Ces dernières sont en effet distancées les unes des autres par 40 à 50 km et aucune donnée n'existe présentement sur la quantité de précipitation ou l'HR observées entre deux stations.

Jusqu'à présent, la fiabilité des données de précipitation mesurées par le radar météorologique a été testée par la communauté scientifique mais aucune étude n'a été réalisée sur les données d'HR. Dans ce projet, une comparaison entre l'HR mesurée à trois stations météorologiques et l'HR calculée à partir de mesures radar a été effectuée. La comparaison a été réalisée sur des données horaires, soit 240 heures en 1997 et 336 heures en 1998. Un test t valide conçu pour l'analyse de régression linéaire simple avec deux séries chronologiques comme variables dépendante et indépendante, et fondé sur les ratios des différences premières des séries chronologiques a clairement indiqué que les deux méthodes d'obtention de l'HR sont comparables. Par la suite, les données de précipitation et d'HR provenant du radar ont été intégrées dans un système d'information géographique (GIS) dans le but de cartographier la répartition spatiale d'une maladie

répandue sur nos terres agricoles. Les résultats de cette dernière étape confirment le potentiel des données provenant du radar météorologique en agriculture.

Acknowledgements

Thanks go to my supervisor, Dr. Isztar Zawadzki, who's science and multiple interests, humour, modesty, philosophy and precious listening were all sources of motivation.

Thanks go also to my co-supervisors, Dr. Gaétan Bourgeois from Agriculture and Agri-Food Canada, for transmitting his passion for agricultural systems modelling, for his availability, philosophy and magnanimity; and Dr. Frédéric Fabry, who's help in the supervision of my work was indispensable and reassured me during the project.

I would also like to thank Dr. Pierre Dutilleul, who's contribution was precious and for taking the time to pass on part of his knowledge in statistics.

To the four of you, Isztar, Gaétan, Frédéric and Pierre, I say thank you for the intellectual capacity you are gifted with, I admire each of you and wish you all the best.

Thanks also to the agricultural systems modelling team at Agriculture and Agri-Food Canada for believing in me and providing me with precious advices for my seminars, special thanks to Nathalie and Dominique. Thanks also to the radar team at Sainte-Anne-de-Bellevue for letting me discover an all-new area in science.

Thanks to some of my personal friends, Guy Boivin, Caroline Roger, Walid Homsy, Marie-Josée Gauvin and Geneviève Gay, for taking the time to listen and providing judicious advices. Thanks also to Claude Godin, who's previous work was an example to follow.

Thanks a lot to Marie Kubecki, from the Department of Natural Resource Sciences, I don't believe students can go through such studies without her. Thanks also to Dr. Peter Schuepp, who let me studied in his department.

This work was supported in part by scholarship grants from Natural Sciences and Engineering Research Council of Canada (NSERC) and financial support from Agriculture and Agri-Food Canada, Saint-Jean-sur-Richelieu, Quebec. Thank you.

Finally, and most of all, I would like to thank Claudette and Jean-Pierre, who's personal vision of life was and still is a motivation through all.

...and thanks to Harry Potter, for making me laugh during that time.

Thesis format

"Candidates have the option of including, as part of the thesis, the text of paper(s) submitted or to be submitted for publication, or the clearly-duplicated text of a published paper(s). These texts must be bound as an integral part of the thesis.

If this option is chosen, connecting texts that provide logical bridges between the different papers are mandatory. The thesis must be written in such a way that it is more than a mere collection of manuscripts; in other words, results of a series of papers must be integrated.

The thesis must still conform to all other requirements of the "Guidelines for Thesis Preparation". The thesis must include the following: a table of contents; an abstract in English and French; an introduction which clearly states the rational and objectives of the research; a comprehensive review of the literature; a final conclusion and summary, and a thorough bibliography or reference list.

Additional material must be provided where appropriate (e.g. in appendices) and in sufficient detail to allow a clear and precise judgement to be made of the importance and originality of the research reported in the thesis.

In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contribution of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this statement at the doctoral oral defence. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the co-authored papers.

In no case can a co-author of any component of such a thesis serve as an external examiner for that thesis."

Contribution of co-authors

The following persons contributed to the third chapter **Mapping spatial distribution of a disease forecasting model using precipitation and relative humidity measurements provided by weather radar**. This paper will be submitted to Agricultural and Forest Meteorology shortly after the deposition of this thesis.

Dr. Frédéric Fabry: As the second author and specialist in atmospheric sciences, Dr. Fabry provided some weather radar measurements; assisted the work of the candidate to transform refractivity measurements into relative humidity data; helped the candidate to understand some atmospheric events and revised the paper.

Dr. Pierre Dutilleul: As the third author and specialist in statistics, Dr. Dutilleul advised the candidate in the proper statistical tests to use; supervised the statistical work; revised the paper and contributed to write the statistical sections of the paper.

Dr. Gaétan Bourgeois: As the fourth author and specialist in agricultural systems modelling, Dr. Bourgeois assisted the work of the candidate to modify the computer program of the carrot leaf blight disease; helped the candidate to understand some agrometeorological events and revised the paper.

Dr. Isztar Zawadzki: As the fifth author and specialist in atmospheric sciences, Dr. Zawadzki provided a briefing to the candidate on the reliability of precipitation data measured with weather radar and revised the paper.

All co-authors provided constructive comments on the paper.

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I. Introduction

A large number of remote sensing applications in agriculture have been developed in the last 60 years especially since the launch of Landsat 1 in 1972. Over time, the improvements in spatial, spectral and temporal resolution have generated a resurgence in the popularity of remote sensing, prominence and possibilities in agriculture (Johannsen et al., 2000). Farmers want to see their profit margins increase and remotely sensed data, combined with derived products, can be used to improve the capacity and accuracy of decision support systems (DSS) as well as direct crop diagnosis (e.g. aerial photography, hyperspectral imagers). Remote sensing in agriculture could be used to help reduce the quantity of agrochemicals required in field management, which would increase the profits for farmers and would decrease public concern about the amount of chemicals used in agriculture (Brown et al., 1994).

Remote sensing is often associated to aircraft or satellite imagery but other devices are remote sensing equipment as well, such as the weather radar. In southern Quebec, at the McGill Doppler S-band weather radar (Sainte-Anne-de-Bellevue), precipitation data are available with a spatial resolution of 1 km up to a range of 240 km and relative humidity (RH) data could be available with a resolution of a few kilometres up to a range of 40 km. Both weather variables could be available with a time scale of 5 min if requested. These measurements would fill the gap of resolution due to the lack of weather stations in that region. Furthermore, weather radar measurements could be integrated in a geographic information system (GIS) and, combined with agrometeorological modelling, provide real-time disease or insect forecasts to agricultural decision-makers. Weather data measured at stations are already used in models such as the Computer Centre for Agricultural Pest Forecasting (CIPRA) which provides insect and disease forecasts for various crops and predicts their development. Predictions are available in real-time for most of the Quebec weather station network. For instance, a model has been developed on carrot leaf blight disease [*Cercospora carotae* (Pass.) Solh.] by Carisse and Kushalappa (1990), based on temperature and leaf wetness duration, and implemented in CIPRA by Bourgeois and Carisse (1996). In that context, weather radar measurements could be integrated in such a model or in a GIS to provide the same type of forecasts but, with the advantage of a high spatial resolution.

The first objective of this study is to compare RH calculated from weather radar measurements to RH measured at weather stations. To the best of our knowledge, no study has been done on that topic so far. Since 1996, Fabry et al. (1997) have shown that refractivity (N) could be extracted from radar measurements and that high resolution moisture information could be calculated from it. This study propose to compare both sources of RH data. As for precipitation data, numerous comparisons between radar and rain gauges can be found in the literature. The second objective is to verify the possibility of integrating weather radar measurements (RH and precipitation), combined with agricultural systems modelling, in a GIS in order to run the carrot leaf blight disease model. That disease was chosen because it is well spread in southern Quebec, a reliable forecast model is available for that disease and weather data influencing its development are available on radar.

Since almost no study has been done on applications of weather radar measurements to agriculture, the following literature review concerns the influence of weather on plants, the applications of remote sensing (multispectral and radar, other than weather radar) in agriculture and few examples found in literature on weather radar measurements applied to agriculture. Another section describes the development of carrot leaf blight disease.

II. Literature Review

1 Role of weather in agriculture

Weather plays a major role in agriculture. Variables such as temperature, rainfall, moisture or solar radiation influence plant growth, plant yield, insect development, and disease propagation (Huber and Gillespie, 1992). The impact of weather in agriculture is so well recognised by the scientific community that it constitutes a discipline by itself: the agrometeorology.

Agrometeorologists are interested, among other things, in the relationship between plant canopy and the atmosphere at a microclimate scale (1 mm to 300 m). In epidemiology, which is the "study of the temporal and spatial changes that occur during epidemics of plant diseases that are caused by populations of pathogens in populations of plants" (Campbell and Madden, 1990), micrometeorological factors are some of the most important ones involved in the development and propagation of fungal pathogens (Huber and Gillespie, 1992). Hence, it becomes primordial to measure weather factors and to put efforts into modelling them. To ensure a good monitoring of crop microclimate, the following factors should be measured continuously: temperature, relative humidity (RH), leaf wetness (LW), rain, wind and irradiance. A review of the effects of each of these factors on plant canopy is presented in this section. This will be a general review where the physical principles underlying the interactions between plant canopy and the above-mentioned factors are not discussed. Readers are referred to Monteith (1975), Campbell and Madden (1990) and Jones (1992) for further information on that topic.

1.1 Air temperature

Air temperature and precipitation are the most important factors in the spatial distribution of plants on earth. Indeed, the agricultural potential of a region depends on these two factors (Doucet, 1994). Soltner (1989) has divided the action of temperature on plant growth into four areas.

The first area pertains to the daily temperature cycle. If a plant grows under the same conditions of temperature day and night, its development will be slower than if the nightly temperature is lower than the daily temperature. Celery (*Apium graveolens* L.) is one of the crops affected by the daily temperature cycle. Like other biennials, celery needs a prolonged exposure to low temperature for flower initiation to occur (Roelofse et al., 1990). If this need is not fulfilled, premature and rapid development of a seedstalk (bolting) might occur resulting in considerable loss of income for growers (Pressman and Sachs, 1985; Roelofse et al., 1989; Roelofse et al., 1990). Low temperatures at germination may also incite bolting in sugar beet (*Beta vulgaris* L.) while high temperatures in July might have the same effect on radish (*Raphanus sativus* L.), spinach (*Spinacia oleracea* L.) and lettuce (*Lactuca sativa* L.), especially in dry conditions (Doucet, 1994).

The second area of influence of temperature on plants is the rapidity of growth. For example, two corn plants under the same environmental conditions but submitted to different temperatures will reach the same size but the one under the higher temperatures will reach it faster.

The third impact concerns the notion of base temperature (Tbase). Under a certain threshold, varying from one crop to another, the plant growth stops. Beyond that threshold, plant growth is directly linked to the increases in temperature until it reaches an upper threshold, generally between 25 and 30°C, then it stops in reaction to excess heat. For example, corn and bean (*Phaseolus vulgaris* L.) have a standard Tbase of 10°C (Jenni et al., 2000) while peas (*Pisum sativum* L.) have a standard Tbase of 5°C (Bourgeois et al., 2000).

The fourth area is an application of the concept of base temperature. As an index of plant growth and development, the sums of daily mean temperatures can be used. Agricultural decision-makers and scientists, mostly in horticultural crops, use the growing-degree days (GDD) concept to monitor the development of the crops and predict the maturity. The simplest and standard method to calculate degree days (DD) was elaborated by Arnold (1960). The Tbase value is subtracted from the mean daily temperature. From a graphic point of view, the computation of a DD total is a measurement of an area. The equation is as follows:

$$DD = \frac{(T\max + T\min)}{2} - Tbase \qquad (1)$$

where *T*max is the maximum daily temperature (°C), *T*min is the minimum daily temperature (°C) and *Tbase* is the base temperature (°C). Other methods have also been elaborated, including Baskerville and Emin (1969) whose formula differ from the standard one by calculating the area of a sinusoidal curve and Allen (1976) whose equation uses also the area of a sinusoidal curve but for half days only.

Besides the action of temperature on plant growth, temperature has also a major effect on each epidemiological stage of a fungal disease (Friesland and Schrödter, 1988; Huber and Gillespie, 1992). Effectively, temperature controls the rate at which spore germination and infection occurs (Van der Wal, 1978). Alderman and Lacy (1983) studied the influence of dew periods and temperature on onion infection (*Allium cepa* L.) by the leaf blight disease (*Botrytis squamosa* J.C. Walker) and found that lesion production was optimal at 20°C, lower at 15°C and greatly reduced at 25°C. In the case of carrot leaf blight disease (*Cercospora carotae*, (Pass.) Solh.), Carisse and Kushalappa (1990) found that, in general, the number of lesions increased with an increase in temperature and wetness duration. Furthermore, Beckman and Payne (1983) studied the favourable conditions in greenhouse for growth and sporulation of corn leaf disease (*Cercospora zeae-maydis*) and found that lesion development was greater when the temperature of the greenhouse was kept between 22-28°C.

1.2 Rain

As mentioned in the previous section, the agricultural potential of a region depends on precipitation and temperature (Doucet, 1994). For crop growth, sources of water are rain and irrigation that turn into free water. Free water is defined as the water in the soil in excess of field capacity, that is free to move in response to the pull of gravity (Glossary of geology, 1980). In epidemiology, the source of water or moisture can also be RH, dew, fog, guttation, intercellular and intracellular water (Yarwood, 1978).

Soltner (1989) has divided the lack of water supply on crops into three outcomes. The first outcome is, in the case of persistent lack of water, a decrease in the photosynthesis capacity, which varies depending on each plant resistance level. If it is a brief drought only, agricultural decision-makers know by experience that it might be beneficial for the crop since a drought is associated with sunny conditions, consequently to active photosynthesis.

The second effect is a slowing down in flower initiation for most plants. A lack of water supply limits the number of flowers, as the plant submitted to dry conditions limits itself so that it will have fewer fruits to nourish eventually. However, in some cases, a short period of drought could help flower initiation. In the case of alfalfa (*Medicago sativa* L.), when the vegetative stage growth is slowing down, drought could help the transition towards the reproductive stage.

The third effect of lack of water on plant growth is on crop yield. Should a humid period follow a drought, some plants will be able to catch up the delay in growth (e.g. sugar beet), whereas some others will not be able to (e.g. corn). Effectively, corn crops are unable to catch up the growth delay when a drought occurs in July or in August even if it rains in September. The degree of severity depends finally on the aptitude of each crop to draw water from the soil, hence the depth of the root system.

Besides its action on plant growth, rain is the most firmly established source of water for fungal infections (Yarwood, 1978; Grove et al., 1985). Rain plays a major role in the release and dispersal of inoculum (Fitt et al., 1989; Huber and Gillespie, 1992). Furthermore, Van der Wal (1978) mentioned that intermittent showers and wind are ideal for release and dissemination of spore-laden small drops but that constant heavy rain cleans the air immediately from the spore-laden. This behaviour was observed on papaya (*Carica papaya* L.) fruits with mycelium mats of *Phytophtora palmivora*. Also, the heaviest raindrops would be the most efficient in dispersal of inoculum by rain-splash (Fitt et al., 1989).

With RH and LW, which are discussed in the next section, plant pathologists seem to agree that free water is necessary for infections (Yarwood, 1978; Friesland and Schrödter, 1988). One such example is the case of clubroot of crucifers [*Plasmodiophora brassicae* (Wor.)] who is characterised by two generations of zoospores that use free water in the soil to move around. These zoospores infect susceptible plants through tiny root hairs or through wounds (Tremblay et al., 1999).

1.3 Relative humidity and leaf wetness

"Relative humidity, expressed as a percentage, is the ratio of the amount of water vapour in the air at a given temperature to the amount of water vapour that could be contained in the air at that temperature (i.e. when saturated), multiplied by 100." (Campbell and Madden, 1990). When expressed without an indication of temperature, RH is useful only in a qualitative way (Rosenberg et al., 1983). Leaf wetness refers normally to dew or rain on aerial plant surfaces (Sutton et al., 1984). In terms of plant growth, RH and LW are part of the exchange between internal plant spaces and external atmosphere. In epidemiology, RH and the duration of LW play a major role in the development and propagation of fungal pathogens (Sutton et al., 1984; Friesland and Schrödter, 1988; Huber and Gillespie, 1992). Leaf wetness appears to play also a role in the deposition of pollutants on crops (Huber and Gillespie, 1992; Schuepp, 1989).

Relative humidity and LW influence plant growth through the stomata, depending on the water vapour gradient. Stomata are pairs of kidney-shaped cells, which regulate the exchanges of gases and water vapour between internal spaces and external atmosphere (McGraw-Hill dictionary of scientific and technical terms, 1989); they do so by opening and closing movements. They are found more frequently on leaves but can be found in other green tissues (Jones, 1992). Stomata are characterised by a protective behaviour, as water potential decreases (i.e. water stress increases), the stomata close (Salisbury and Ross, 1985).

In epidemiology, before the impact of RH on plant diseases was well known, Yarwood (1978) reported that when the late blight of potato [*Phytophthora infestans* (Mont.)] caused the Irish Famine in 1845-1846, the disease was already associated with cloudy, rainy, foggy and cool weather. The rate of moisture required for a disease to develop varies depending on the disease (Yarwood, 1978). In the case of *C. carotae*, Carisse et al. (1993) found that for all temperatures, the number of lesions per plant increased with an increase in humidity level. These authors showed that high RH or LW and warm temperatures (20-28°C) favoured sporulation. In the infection of onion by *B. squamosa*, Alderman and Lacy (1983) found that the number of lesions per plant increased sigmoidally with an increase in dew duration. Even the moist conditions under the snow make it possible for the fungus to grow considerably and show up in spring, when the snow cover melts (Van der Wal, 1978).

1.4 Wind and turbulence

Wind is defined as the air motion relative to the earth's surface, while turbulence is associated to the irregular motion produced when air flows over a comparatively uneven surface (International meteorological vocabulary, 1966). In agriculture, air motion can have either positive or negative outcomes on crops. Soltner (1989) has described four positive effects of a moderate wind and three negative effects when it reaches a certain force.

The advantages of a moderate wind in agriculture are as follows: it helps in the evaporation of water contained in soil, contributing to its aeration; it dries out the foliage, helping the crops to better resist to fungus and reducing the internal temperature in summer; it is essential to cross-pollination in numerous species and it dries the harvested material (e.g. hays, cereal grains). The wind becomes a nuisance, however, as soon as it reaches a certain velocity. Three kind of negative actions are associated with wind and turbulence: mechanical, thermal and physiological. The most sensible crops to wind damage are the gourd family (*Curcubita*) and nightshade family (*Solanaceae*) (Doucet, 1994).

Mechanical actions include soil erosion, foliage laceration (e.g. in orchard), fruits falling, troubles with pollination, tree deformation, lodging of cereal crops, perturbation of irrigation by sprinkling, spore dissemination and weed seed dissemination.

Thermal actions are related to the cooling of soils under the effect of intensive surface evaporation and, under cold winds, the possibility that crops are less precocious. Physiological actions of wind on plants are an increase in evapotranspiration caused by the desiccation of air, resulting in a premature closing of stomata and the stopping of photosynthesis, and a delay in plant growth caused by a decrease in RH and soil temperature.

In epidemiology, wind associated with the action of rain or soil directs the spread of pathogens and may injure plants. The resulting wounds from these injuries are infection sites for many pathogens (Sutton et al., 1984). It is essential to realise that without dispersal of pathogen inoculum, there would be no epidemic. Spores of many fungal pathogens are passively released from the host by wind while some others are released independently of wind. The faster and more turbulent wind will generate a higher escape of spores, whether or not the spores are passively removed from their host (Aylor, 1990). Turbulence plays a decisive role in the change of spore density per volume of air, hence it is a very important factor in the spread of pathogens (Friesland and Schrödter, 1988). Aylor (1990) published an excellent review of the role of wind in the dispersal of fungal pathogens. To protect crops and to create a more equable microclimate, windbreaks have been used for a long time (Grace, 1977).

1.5 Irradiance

Irradiance is defined as the flux of radiant energy or power divided by surface area (Compendium of chemical terminology, 1987). Approximately 35% of the irradiance is absorbed by the leaves and potentially useful for photosynthesis. The chloroplasts absorb this light, mostly in the red and blue colours of the spectrum (Soltner, 1989). Photosynthesis is divided into two types of reactions: 1) a light reaction, which is a photochemistry reaction, depending on light but insensitive to temperature and 2) a dark reaction, which is a enzymic reaction, slower, sensitive to temperature and insensitive to light (Cambridge dictionary of biology, 1990). The first reaction is necessary to the second one, i.e. light is essential for the first process of photosynthesis. Solar radiation, and not heat, is the principal source of energy in photosynthesis (Doucet, 1994).

In epidemiology, light intensity and quality (wavelength) can influence the infection cycle, especially spore germination, formation of fruiting bodies and sporulation (Van der Wal, 1978). Friesland and Schrödter (1988), mentioned that light also influences the induction of periodic events in the development cycle of the parasite (i.e. change of light and darkness, variation of day length).

2 Remote sensing in agriculture

Remote sensing is defined as the measurement of electromagnetic radiation that is reflected or emitted from the surface of the earth or the surrounding atmosphere. This measurement can be done from a ground-, aircraft- or satellite-based platform and it can either be passive or active. During passive measurement, the platform collects the portion of the irradiance reflected or emitted by the target, whilst during active measurement, a signal is emitted and the backscatter is collected.

The following is a list of some of the major past or present projects involving remote sensing: Large Area Crop Inventory Experiment (LACIE) ran from 1974 through 1978 and demonstrated the feasibility of utilising satellite-based multispectral data to estimate wheat production (MacDonald and Hall, 1980); Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) conducted by the United States Department of Agriculture (USDA), the National Aeronautics and Space Administration (NASA), and the National Oceanographic and Atmospheric Administration (NOAA) focused on more crops and regions than LACIE did and was started in 1980 (AgRISTARS, 1983); Coordination of Information on the Environment (CORINE) began in 1985, it consists of mapping the land cover of the European member states from satellite images at an original scale of 1:100 000 (Hill et al., 1995); Monitoring Agriculture with Remote Sensing and Statistics (MARS) started in 1988 and provided estimates of agricultural production at the European level with a combination of remote sensing, geographic information system (GIS) and agrometeorological modelling techniques; and Famine Early Warning System (FEWS) ran from 1985 until June 2000 and used remote sensing imagery to obtain weather data and to calculate vegetation indices. FEWS NET has taken over until June 2005.

In the following section, a general overview of remote sensing techniques and applications in agriculture is given. The literature review does not include the recent advances in technologies of variable-rate production input applications and global positioning systems (GPS). These tools also provide powerful analysis for farm management (Moran et al., 1997) but are not the subject of this thesis.

2.1 Optical remote sensing in VIS-NIR

This sub-section on optical remote sensing applied to agriculture is beyond the scope of this master study but since it has been traditonally used to provide information about crops (Lefevre et al., 2000), it is relevant to provide a general overview of it. In the electromagnetic spectrum, the visible (VIS) extends from wavelengths 400 nm to 700 nm. As for the near infrared (NIR), it ranges from 700 nm to 1300 nm. Optical remote sensing is mostly passive, i.e. the platform collects the portion of the irradiance reflected or emitted by the target (the crops).

The scientists have studied the behaviour of plants in the electromagnetic spectrum since the early 1970's. It is well known that in the visible spectrum, the red colour (630-690 nm) is absorbed by leaf pigments (chlorophyll a and b) while in NIR (760-900 nm), the radiation is strongly reflected by the leaf cellular structures (Tucker, 1979). Together, the red and NIR portions of the spectrum consistently reveal more than 90% of the information relating to vegetation (Baret et al., 1989). For a plant under certain stresses (e.g. nutrient deficiency, salinity, water deficit, disease, and insect attack), the production of chlorophyll will be reduced, causing leaves to absorb less in the red spectrum. They will consequently appear as yellowish or chlorotic (Bauer, 1985). The reflectance in the NIR tends to remain the same, unless the stressed vegetation suffers from a decrease in biomass. Indeed, the reflectance in the NIR is positively correlated with the amount of multiple scattering at the interfaces between cells and the air, and therefore to biomass (Knipling, 1970). This deviation in reflectance observed between the red and NIR is generally exploited through various so-called vegetation indices (VIs).

Vegetation indices (VI) are quantitative measurements reflecting the vigour of vegetation (Campbell, 1987), where a high VI value indicates a healthy vegetation. The VIs are useful in the interpretation of remote sensing images, evaluation of vegetative cover density, crop discrimination and crop prediction (Baret et al., 1986). The ideal VI is defined as: "highly sensitive to vegetation, insensitive to soil background changes, and only slightly influenced by atmospheric path radiance" (Jackson et al., 1983).

In order to enhance vegetation response and to minimise the other effects (e.g. soil brightness, shadow, soil colour, and moisture), over forty vegetation indices have been developed in two phases during the last two decades. The first phase was solely based on linear combinations or raw band ratios, without consideration for other factors. The second phase has been developed integrating physical phenomena, which explain interactions between electromagnetic radiations, the atmosphere, the vegetative cover and the soil background (Bannari et al., 1995).

Vegetation indices can be calculated by ratioing, differencing, ratioing differences and sums, and by forming linear combinations of spectral band data (Jackson and Huete, 1991). One of the most used and successful VI is the normalised difference vegetation index (NDVI) proposed by Rouse (1973) and Rouse et al. (1974), based on the following ratio:

$$NDVI = \frac{\rho IR - \rho R}{\rho IR + \rho R} \tag{2}$$

where ρIR is the radiation reflected in NIR and ρR the radiation reflected in red. Nowadays, the NDVI remains the most used VI given its simplicity. Among the other VIs, Clevers (1989) developed the weighted difference vegetation index (WDVI) to estimate the leaf area index (LAI) by correcting for soil moisture. Huete (1988) defined the soil-adjusted vegetation index (SAVI) which takes into account the soil brightness. Since then, numerous modifications of the SAVI have been reported, where Baret et al. (1989) transformed the SAVI to obtain the transformed soil-adjusted vegetation index (TSAVI), Baret and Guyot (1991) readjusted the last version of the TSAVI to minimise the effects of soil brightness and, finally, Rondeaux et al. (1996) proposed the optimised SAVI (OSAVI). A classical review on available VIs can be found in Bannari et al. (1995).

2.2 Radar remote sensing

Radar is an acronym for Radio Detection And Ranging. In the electromagnetic spectrum, radar is associated to microwaves, which extend from wavelengths 1 mm to 1 m. The radar is active, i.e. it provides its own source of transmitted energy. First, a signal (microwave pulse) is sent towards a target; then the radar receives a returned portion of the transmitted signal (backscatter); finally, the radar observes the strength (detection) and the time delay from the time the signal is emitted towards the target and the returned signal (ranging). Through its ranging capability, radar can accurately measure the distance from the antenna (where the signal is sent) to the target (Campbell, 1987). The backscatter is dependent on the target object (geometric shape, surface roughness, moisture content) as well as on the characteristics of the radar (transmission direction, frequency, polarization).

All the significant advances in microwave technology were made during World War II and resulted in the development of radar as an operational military tool, used for aircraft or ship detection. The civilian uses for terrain analysis and natural resources surveys started during 1960s. It is over the last 3 decades that various agricultural applications has been intensively studied and research has been conducted to augment or replace optical remote sensing with radar remote sensing because of the advantages of radar (Brisco and Brown, 1998). The main advantages are the all-weather system capability (microwaves penetrate through clouds and light rain); the day and night data acquisition (radar provides its own source of energy) and the subsurface and surface information retrieval (microwaves penetrate partially soil and vegetation canopy). However, the radar interaction with agricultural targets is still considered more complex than the optical interaction (Lefevre et al., 2000).

2.3 Applications

This sub-section is a general overview of applications of optical and radar remote sensing in agriculture. Moran et al. (1997) published an excellent review addressing the potential of remote sensing in providing spatially and temporally distributed information in agricultural crop management. Eight areas of applications were identified: 1) converting point samples to field maps; 2) mapping crop yield; 3) mapping soil variability; 4) monitoring seasonally variable soil and crop characteristics; 5) determining the cause of the variability in crop production; 6) mapping spatially distributed information on meteorological/climate conditions; 7) producing fine-resolution digital elevation data; and 8) addressing time-critical crop management applications. Readers are referred to Jackson (1984), Bauer (1985), Hatfield and Pinter (1993), and Johannsen et al. (2000) for equally good reviews on this topic. In this thesis, I have divided the applications of remote sensing in agriculture into five areas: mapping, detection of stresses, yield prediction, monitoring crop characteristics and modelling.

2.3.1 Mapping

Mapping is one of the most traditional applications of remote sensing in agriculture, which can be done from aerial or satellite imagery. With the rapid progress of techniques for crop discrimination, crop types can be classified with more than 80% accuracy using satellites that provide high resolution imagery in the range of visible and infrared bands (Akiyama et al., 1996).

During the agricultural growing season, either stable or variable parameters can be mapped. The seasonally stable parameters include soil type and land cover. Mapping soil type has the advantage of identifying homogeneous areas and of reducing the number of needed soil samples (Moran et al., 1997). Mapping land cover could lead to the interpretation of land use, like in the case of the USDA verifying compliance by landowners and farmers using aerial photography for over 25 years (Johannsen et al., 2000). Closer to us, in the province of Quebec, the Financière agricole du Québec (FAQ) is currently using remote sensing technology to define the dimensions of the fields for insurance purposes.

The seasonally variable parameters include weed or insect infestation, crop stress, crop disease, crop yield and soil moisture. For example, Hanson et al. (1995) presented an operational technique for mapping the infestation of wild oats (*Avena fatua* L.) in wheat fields (*Triticum aestivum* L.). Crop yields have been mapped using final grain yield correlated with either a single observation of the NDVI or, in a more complex fashion, with multiple NDVIs at specific times during the growing season (Yang and Anderson, 1996). Soil moisture has also been mapped based on a simple linear correlation with the backscatter of the synthetic aperture radar (an alternative design for an imaging radar) signal in microwaves (Boisvert et al., 1996). Furthermore, Njoku and Entekhabi (1996), and Wigneron et al. (1998) found that passive microwave remotely sensed data has also a great potential for providing estimates of soil moisture.

2.3.2 Detection of stresses

Crop stresses are conditions that alter growth patterns such as nutrient deficiency, water stress, soil erosion, weed, insects and disease infestations as well as weather damages (drought, standing water, wind, frost, hail) (Johannsen et al., 2000). Remote sensing imagery obtained over agricultural lands is primarily used for stress detection in vegetation (Jackson et al., 1983). It can be done from ground measurements, aerial imagery or satellite imagery.

The detection of nutrient deficiency in vegetation has focused mainly on nitrogen. Using remotely sensed imagery, Blackmer and White (1998) found that corn (*Zea mays* L.) with adequate or excessive N presented a dark green colour, while N-deficient corn displayed a lighter colour. The difference in colour was shown to be proportional to the nitrogen deficiency. Recently, Perry et al. (2000) used reflectance monitoring to determine the specific wavelengths that are most sensitive to water stress and nitrogen deficiency in potato (*Solanum tuberosum* L.) crops. Using NDVI calculated from narrow bands, early results have shown some promise indicating optimum nitrogen availability at the following bands 695, 760 and 700 nm.

The detection of weed infestation can be done using aerial imagery. The advantages have been identified (e.g. cost, timing, and accuracy) by Hanson et al., (1995). Using image analysis of digitised low-altitude aerial photographs, Brown and Steckler (1995) noted weeds in no-till corn fields. They subsequently prepared maps, imported them in a GIS and designed a decision model for pre-plant and post-emergence weed control recommendations. Their results indicated that herbicide use could be reduced from more than 40%.

Multispectral remote sensing has also been used to assess insect infestation (Moran et al., 1997). Through reflectance measurements in narrow bandwidths (visible and NIR), Peñuelas et al. (1995) observed chemical changes in apple trees due to infestation by European red mites (*Panonychus ulmi* Koch). However, to detect insect infestation, the radar remains the most frequently used remote sensing technique. At first, radar was developed to track large metal objects such as ships and aircraft. Metal is a good reflector of radar signals and, in fact, water was found to be almost as reflective as metal. Given that insects contain a high proportion of water in their bodies, radar reflectors can detect them at ranges of more than a kilometre (Riley, 1990). Research in that area has been going on for over 30 years and more than 200 papers have been published related to that topic (Riley, 1999). Further information can be found at the following web site: http://www.ph.adfa.edu.au/a-drake/trews/.

Some early work has been done by Toler et al. (1981) to detect plant diseases through false colour photography (IR) and they identified the Phymatotrichum root rot (*Phymatotrichum omnivorum*) of cotton (*Gossypium* Spp.) in the Blackland region of Texas. At that time, contrasting spectral signatures of diseased plants could delineate infested areas. Later on, Malthus and Madeira (1993) observed differences in the changes of spectral reflectance for Botrytis (*Botrytis fabae* Sard.) infection of field beans (*Vicia faba* L.) and suggested the possibility to distinguish broad classes of diseases using remote sensing.

Recently, Carter (1999) defined a crop anomaly classification system that recognised natural and human induced anomalies (i.e. chemical, mechanical and management). He studied the detection of change within a farmer's field by remote sensing, established a classification system out of it and grouped the anomalies, or the crop stresses by categories.

2.3.3 Yield prediction

At the scale of farm and field, remotely sensed imagery has been used to give relative estimates of yield variation within a field prior to harvest (Johannsen et al., 2000). As mentioned in section 2.3.1, final grain yield has been correlated with either a single observation of the NDVI or with multiple NDVIs at specific times during the growing season (Yang and Anderson, 1996), and maps have been produced. To obtain accurate yield prediction at the field level, more work remains to be done since indexes like the NDVI do not correlate perfectly with actual yields (Johannsen et al., 2000). Most studies suggest that NDVI should be combined with inputs from an agrometeorological model to increase the accuracy of yield prediction (Patel et al., 1991). But even then, close attention needs to be paid when interpreting the predictions because it is usually implicitly assumed that input parameters in modelling are error-free, which results in impressively precise predictions untainted by the uncertainties associated with the inputs

(Monteith, 2000). Besides the NDVI, the LAI is another parameter that is estimated by remote sensing techniques and is used in yield prediction to calibrate, reinitialise or reparameterise the models (Maas, 1988; Bouman, 1992; Bouman, 1995; Moran et al., 1995) as well as the NIR reflectance and ground cover (Maas et al., 1999).

2.3.4 Monitoring crop characteristics

Besides the crop characteristics mentioned in the previous sections, phenology, growth and evapotranspiration rate can also be monitored using remote sensing devices.

For example, to identify the developmental stage of some cereal crops, Railyan and Korobov (1993) have studied changes in the red edge position (boundary between the visible and NIR reflectance, 660-670 nm) and found that relative positions of the red edge varied according to the plant growth stage. With the same purpose, wheat crops vegetative, reproductive and senescing phases have been discriminated based on red edge and bidirectional reflectance measurements (Zipoli and Grifoni, 1994). Moreover, Boissard et al. (1993) showed that it was possible to estimate an agronomic variable related to phenological development from multidate data in the satellite SPOT (Satellite Pour l'Observation de la Terre) bands. Using this experimental approach, they found it was possible to monitor the developmental stage of wheat after anthesis and to detect accurately the end of grain filling.

To monitor crop growth, the empirical correlation of VIs with variables such as LAI, percent vegetation cover, vegetation phytomass and fraction of absorbed photosynthetically active radiance (f_{APAR}) have been most commonly used (Moran et al., 1997). Furthermore, Moran et al. (1998) suggested that synthetic aperture radar backscatter in short wavelengths could also be used to monitor crop cover and relative growth.

Monitoring the transpiration rate of the crop has been a major issue in remote sensing given that a decrease in the evapotranspiration rate is often related to crop stress. It is well known that the difference between the potential and actual crop evapotranspiration is proportional to the loss in biomass, hence it becomes primordial to measure it. Private firms are also interested to provide their users with a product such as evapotranspiration data, as is the case of EARS (Environmental Analysis and Remote

Sensing), a private firm located in the Netherlands, which provides evapotranspiration data from METEOSAT satellite used for crop yield forecasting in Africa and Europe (http://www.ears.nl/EARShome/).

2.3.5 Modelling

The main objective of combining remote sensing and modelling is to obtain an accurate tool in real-time for agricultural decision-makers. This combination is often linked with a GIS where spatial organisation is allowed. The latest review of linkages between agricultural models and GIS can be found in Hartkamp et al. (1999).

Remote sensing measurements have been used in crop modelling to provide accurate input information such as LAI and VI to calibrate, reinitialise or reparameterise crop models (Wiegand et al., 1986; Maas, 1988; Bouman, 1992; Bouman, 1995; Moran et al., 1995). Remote sensing measurements can also be used for model validation (Fischer, 1994) and to detect spatial patterns of yield during individual growing seasons when combined with GIS (Carbone et al., 1996; Maas and Doraiswamy, 1997). Furthermore, remote sensing measurements are used to improve crop yield prediction (refer to section 2.3.3).

2.4 Weather radar remote sensing

A summarised review of the role of weather in agriculture and the use of optical and radar remote sensing in agriculture was presented in the previous sections. The term remote sensing in agriculture is most often solely associated to either optical or radar imagery. Weather radar measurements are remote sensing data as well, since weather radar measures backscatters that are reflected from the surrounding atmosphere (i.e. active remote sensing). In the atmosphere, the radar pulse (signal sent from the radar antenna) passes unnafected through fog and cloud, but when it hits rain, snow or ice particles, some of the energy is scattered back to the radar's antenna. The amount of energy returned is proportional to the intensity of precipitation; the heavier the rain or snow, the more energy is scattered back. The delay between the emission and the return of the signal gives information on the position of the precipitation.

To obtain rainfall rates from weather radar measurements, the relationship between rainfall rate (R) and radar reflectivity (Z) is put into an equation. The most commonly used Z-R relationship is due to Marshall and Palmer (1948), it is $Z=200R^{1.6}$. The Z-R relationship is known to introduce errors in the estimation of rainfall rates by radar, but some scientists agree that these errors are frequently overemphasised (Zawadzki, 1984; Joss and Waldvogel, 1990). Other errors can influence rainfall rates estimated with weather radar measurements errors are related either to the characteristics of precipitation or to the radar itself. These errors related to the characteristics of precipitation include, in addition to the variability in the drop-size distribution, the differences in the vertical reflectivity profile and how representative the precipitation data is in space. Indeed, the great variability in time and space affecting precipitation data introduces an additional uncertainty in the radar measurements, but also raises the question of spatial representation of point measurements made by rain gauges (Joss and Waldvogel, 1990). As for the errors related to the characteristics of radar (ground clutter, attenuation, radar site, calibration, etc.), their contribution to the rainfall rates is better estimated. The main limitation for measurement of precipitation by radar remains meteorological factors (Joss and Waldvogel, 1990).

Most comparisons between radar and rain gauge measurements have shown discrepancies on the order of 25 to 30% (Bellon and Austin, 1984). In both cases, the measure of precipitation is not error-free. As mentioned above, the errors affecting rain gauges are mainly due to poor sampling. In a comparison between radar and rain gauges, Zawadzki et al. (1986) pointed out that the standard deviation of any one gauge with respect to the average of six gauges was 47% and that radar estimates of rainfall over areas of 40-90 km^2 and over a 5 min accumulation time reached a satisfactory precision, comparable to one gauge over the same area.

Relative humidity is also a variable that can be calculated from weather radar measurements. Since 1996, the refractivity field has been extracted from radar measurements and converted to RH following a procedure elaborated by Fabry et al. (1997). The refractivity is a variable that has long been recognised to depend upon weather variables such as pressure, temperature and moisture (Bean and Dutton, 1968). Since the effects of temperature and pressure fluctuations are relatively small during the summer, Fabry and Creese (1999) showed that accurate high-resolution moisture information could be extracted during that period.

Weather radar measurements have a great potential in agriculture since, using for instance the McGill Doppler S-band (wavelength of 10.4 cm) weather radar located in Sainte-Anne-de-Bellevue, precipitation data are available with a spatial resolution of 1 km up to a range of 240 km and RH data could be available with a resolution of a few kilometres up to a range of 40 km. Both weather variables could be estimated with a time scale of 5 min if requested. These measurements would fill the gap of spatial weakness observed with most weather station networks. This gap prevails in the province of Quebec (Viau et al., 1994), as well as in Europe (Vogt, 1996) and in United States (Carbone et al., 1996). Furthermore, weather radar measurements could be integrated in a GIS and, combined with agrometeorological modelling, could provide real-time disease or insect forecasts to agricultural decision-makers.

So far, few scientific works have been done on the uses of weather radar measurements in agriculture. Precipitation measurements have been a long time interest for hydrologists but rarely used by agrometeorologists. Yet, Westcott and Kunkel (1999) tried to identify areas of possible crop damage due to excessive or insufficient rainfall using weather radar data. However, the biases on the radar rainfall and soil moisture estimates at that time were still too important to succeed. On the other hand, Duke et al. (2000) used weather radar precipitation data to relate Fusarium head blight [*Fusarium graminearum* (Schwabe)] in wheat to rainfall patterns using a GIS. Rainfall data were provided by the U.S.A. National Weather Service WSR-88D weather radar and covered the region of the study, southwestern Ontario (Canada). For the crop data, mycotoxin deoxynivalenal (DON) concentrations, produced by the pathogen, were measured in grain samples and this data was integrated into the GIS. The results of the study showed the utility for crop management of integrating weather radar data combined with growth models in a GIS. However, the WSR-88D Nexrad data did not correspond exactly to that of the DON measurements. Duke and colleagues are presently working further on that topic and do expect to establish a clearer relationship between the radar-derived precipitation data and the occurrence of the Fusarium head blight in wheat.

As for RH, to the best of our knowledge, RH measurements calculated from weather radar information have never been used. This project should be the first to use RH data calculated from weather radar measurements.

3 Cercospora carotae development and weather radar measurements

The main disease affecting carrots in the province of Quebec is Cercospora blight, caused by the microscopic fungus *Cercospora carotae*. It is a major foliar disease that was first reported in Italy in 1889 (Barnett, 1960, Sherf and Macnab, 1986) and in Canada in 1978 (Crête, 1978). The disease is also present in the province of Ontario (Crête, 1978, Sutton and Gillespie, 1979) and in the United States (Thomas, 1943).

The disease does not affect the edible root of the carrot. The pathogenic fungus produces circular greyish to tan lesions on leaves and darker lesions on petioles. The lesions can be seen on any aerial parts of the plant and will enlarge rapidly under warm and humid conditions, coalesce and often cause the death of an entire leaf (Carisse, 1991). Problems develop when the lesions on the petiole of the leaves are particularly severe, the leaf detaches easily from the crown reducing the grip required for mechanical harvesters to pull the roots. Consequently, the roots are left in the ground and the yield is reduced (Brodeur et al., 1996). During severe epidemics, the leaf blight disease also causes a certain reduction in photosynthesis and hence a reduction in the size of the carrot.

In the life cycle of *Cercospora carotae*, it is believed that the pathogenic fungus overwinters in the soil in crop residues, which may explain the presence of blight year after year in virtually every cultivated field (Brodeur et al., 1996). During spring and summer, the fungus releases spores, which are carried by wind in dry weather to healthy leaves. When it rains, the spores germinate, penetrate the leaves and infection occurs. To cause an infection, the *Cercospora* fungus requires six hours of dry weather (less than 90% of RH) for the dispersion of the spores by the wind followed by a period of LW of at least 24 hours. Favourable conditions for LW are either rain or RH greater than 90% (Brodeur et al., 1996). After several days of incubation, circular lesions appear and produce other spores, which are dispersed by the wind, renewing the life cycle.

Numerous studies have shown that both temperature and LW play a critical role in the infection process of foliar diseases (Alderman and Lacy, 1983; Arauz and Sutton, 1989; Bulger et al., 1987; Jones, 1992). In the case of carrot leaf blight, Carisse and Kushalappa (1990) developed a forecasting model based on a good understanding of the influence of weather on disease development. The forecasting model was implemented in the Computer Centre for Agricultural Pest Forecasting (CIPRA) software by Bourgeois and Carisse (1996) and now helps carrot growers schedule fungicide applications only when they are needed, rather than on a regular basis. Since rain and RH are measurements available with the use of weather radar, they could be integrated in the forecasting model to calculate the LW duration. This project is the first to use rain and RH data provided by weather radar to create a forecasting model of the development of carrot leaf blight.

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Chapter submitted to: **Agricultural and Forest Meteorology.**

III. Mapping spatial distribution of a disease forecasting model using precipitation and relative humidity measurements provided by weather radar

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Abstract

Temperature, precipitation and moisture play a major role in many agricultural and biological processes, particularly in the occurrence and propagation of plant diseases. Based on air temperature and leaf wetness duration, a mathematical model was developed to predict the infection of carrot leaves by *Cercospora carotae* (Pass.) Solh. Predictions for *C. carotae* integrate precipitation and relative humidity (RH) measurements and are available in real-time for the Quebec weather station network. In southern Quebec, hourly weather data are provided by automated weather stations located 30 to 50 km apart. Since precipitation and RH vary considerably in space and time, there is a lack of reliable information on them in between weather stations. By calculating leaf wetness index from precipitation and RH provided by weather radar, forecasts of *C. carotae* could become available on an hourly basis with a spatial resolution of a few kilometres. Comparisons between weather station and weather radar measurements have been an object of study in the past for precipitation but never for RH. In this study, we compared RH measured at three weather stations to RH calculated from weather radar measurements using time interval of 240 hours in 1997 and 336 hours in 1998. A valid t-test designed for simple linear regression analysis with two time series as dependent and explanatory variables, and based on the first differences ratios (FDR) of the time series clearly showed that RH calculated from radar measurements is comparable to the one measured at weather stations. The possibility of using weather radar measurements to map the variability of *C. carotae* in a geographic information system (GIS) is discussed.

Keywords

Agrometeorological modelling; *Cercospora carotae*; plant disease modelling; relative humidity; weather radar application

Introduction

Weather plays a major role in agriculture. Variables such as temperature, rainfall, moisture or solar radiation influence plant growth, plant yield, insect development and propagation of diseases (Huber and Gillespie, 1992). The impact of weather in agriculture is so well recognised by the scientific community that it constitutes a discipline by itself: the agrometeorology. Aware of that impact, for many years scientists have been working to develop models that simulate the plant-atmosphere interaction. Such models strive towards the general objectives of agrometeorology, namely that to practise sustainable, high quality agriculture with less risks, less cost, and less environmental pollution and damage (Rijks and Baradas, 2000). For instance, models of agricultural systems have been developed such as the Decision Support System for Agrotechnology Transfer (DSSAT) in the United States (Hoogenboom et al., 1994), the Simple and Universal Crop growth Simulator (SUCROS) in the Netherlands (van Keulen et al., 1982) and STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) in France (Brisson et al., 1998). An extensive list of agricultural system models provided by the University of Kassel (Germany) can be found at the following Internet address http://eco.wiz.uni-kassel.de/ecobas.html.

In the province of Quebec (Canada), Bourgeois and Carisse (1996) have been developing since 1994 the Computer Centre for Agricultural Pest Forecasting (CIPRA) sofware that provides insect and disease forecasts for various crops and predicts their development. Predictions are available in real-time for most of Quebec weather station network (e.g. Fig. 1). Most of the agricultural system models integrate weather measurements. In CIPRA, some of the more common weather variables input are air temperature, relative humidity (RH) and precipitation. The last two variables are useful to calculate the leaf wetness index which, depending on the duration, favours the development of various crop diseases. In the southern part of the province of Quebec, the actual weather station network includes about 10 stations, corresponding mostly to agricultural areas. The distance between weather stations in that area varies between 30 to 50 km. Since RH and precipitation have a great spatial and temporal variability, this implies that a farmer located at mid-distance between two weather stations will have access to less reliable pest or disease forecasts. The network is inadequate regarding the number as well as the location of weather stations (Viau et al., 1994). This lack of a dense weather station network also prevails in Europe (Vogt, 1996) as well as in United States (Carbone et al., 1996). To fill this lack of information, weather radar measurements could be used.

In Sainte-Anne-de-Bellevue (Quebec, Canada), the McGill Doppler S-band weather radar collects data at 24 elevation angles every 5 min. Detailed specifications can be found in Marshall and Ballantyne (1975). Using the McGill radar, RH data could be available with a resolution of a few kilometres up to a range of 40 km and precipitation data are available with a spatial resolution of 1 km up to a range of 240 km. To the best of our knowledge, RH measurements calculated from weather radar information have never been used. As for precipitation measurements provided by weather radar, they have been a long time interest for hydrologists but rarely used by agrometeorologists. Yet, Westcott and Kunkel (1999) have tried to identify areas of possible crop damage due to excessive or insufficient rainfall using weather radar data. However, the biases on the radar rainfall and soil moisture estimates at that time were still too important to succeed. On the other hand, Duke et al. (2000) used weather radar precipitation data to relate Fusarium head blight in wheat to rainfall patterns using a geographic information system (GIS). In that case, results showed the utility of integrating weather radar data in a GIS.

In 1999, a project was elaborated at McGill University in collaboration with Agriculture and Agri-Food Canada. The objectives were : 1) to test whether RH calculated from radar measurements are comparable to RH measured at weather stations and, 2) to verify the possibility of using RH and precipitation measurements provided by weather radar to map the distribution of a plant disease in a GIS. The project focused on one particular problem: the carrot leaf blight disease (*Cercospora carotae* (Pass.) Solh.). That disease was chosen for three reasons: it is a common and widespread disease affecting that crop in Quebec, a reliable forecast model is available for that disease and weather variable data influencing its development are available on radar. Fig. 2 is a schematic representation of the required inputs to map the spatial distribution of the carrot leaf blight disease. The informative layers of precipitation and RH are provided by weather radar while the informative layer of air temperature is obtained by interpolation of weather station measurements.

In this paper, we present the results of our two objectives but first, we summarise the theory behind the measurement of RH using weather radar and the latest state-of-the-art on the reliability of precipitation measurements provided by weather radar.

Weather radar measurements

Relative humidity

To measure RH, humidity sensors such as hygrometer, humidity-sensitive condenser and psychrometer have been traditionally used. By following a unique procedure elaborated by Fabry et al. (1997), the refractivity field can be extracted from radar measurements since 1996 (Fig. 3) and converted to RH.

The refractivity N is a unitless variable that has long been recognised to depend upon weather variables such as pressure, temperature and water vapour pressure (Bean and Dutton, 1968):

$$N = 77.6\frac{P}{T} + 3.73\times10^5\frac{e}{T^2} \qquad (1)$$

where P is the atmospheric pressure (mb), T is the temperature (°K), and e is the water vapour pressure (mb). Equation (1) has two terms : the first is a density term and the second is an additional wet term that increases the sensitivity of N to moisture. Fig. 4 illustrates how refractivity varies with temperature and moisture. At low temperatures, the range of possible absolute humidities is small so that refractivity varies slightly with RH. As air temperature increases, so does the range of possible absolute humidities, making refractivity more sensitive to changes in moisture. Fabry and Creese (1999) have shown that accurate high-resolution moisture information can be extracted during the summer, since the effects of temperature and pressure fluctuations are then relatively small. The technique to extract the refractivity field is based on visible ground targets (buildings, towers, power poles, etc.). Therefore, the RH measurement calculated from that refractivity is representative of moisture conditions at the height of the ground targets, which is generally around 15 m. Readers are referred to Fabry et al. (1997) for further information on the technique of measurement.

From refractivity measurements, RH (%) is calculated using:

$$RH = 100\frac{e}{e_s} \tag{2}$$

where e is the water vapour pressure (mb) and e_s is the saturated water vapour pressure (mb). The numerator of equation (2) is calculated from the relationship between N and the rearrangement of the meteorological variables pressure, temperature, and moisture from equation (1):

$$e = \frac{T(NT - 77.6P)}{3.73\times10^5} \tag{3}$$

where T is the temperature (K), N is the refractivity, and P is the atmospheric pressure (mb). The denominator of equation (2) is calculated from:

$$e_s = 6.112\exp\left(\frac{17.67T}{T + 243.5}\right) \tag{4}$$

where T is the temperature (°C) (Rogers and Yau, 1989).

Under the assumption that the refractivity field is extracted from radar measurements (Fabry et al., 1997), we expect that RH calculated with McGill Doppler S-band radar measurements will be comparable to RH measured at weather stations. Relative humidity could then be calculated with radar measurements and be used as input for models of agricultural systems in replacement or in addition to RH measured with automated weather stations.

Precipitation

For a century, the rain gauge has been the standard for measuring precipitation and is often assumed to be ground truth because of its long service and widespread use (Hunter, 1996). However, weather radar, if properly calibrated, can also provide precipitation measurements based on reflectivity information.

Numerous comparisons between radar and rain gauge measurements were carried out (Woodley and Herndon, 1970; Wilson and Brandes, 1979; Zawadzki et al., 1986; Austin, 1987; Brandes and Wilson, 1988; Wilson et al., 1997). Most of the comparisons found a radar-rain gauge difference of the order of 25 to 30% (Bellon and Austin, 1984) and results show that the radar usually underestimates precipitation. For radar meteorologists, it is well known that radar rainfall measurements suffer from several types of errors that are mainly due to the fact that radar does not measure rainfall rate directly but the backscattered energy (reflectivity) from precipitation particles in an elevated volume (Wilson and Brandes, 1979; Zawadzki, 1984). Besides radar reflectivity factor error, evaporation and advection of precipitation before reaching the ground, variations in the drop-size distribution and vertical air motions are also other sources of errors (Fabry et al., 1994).

Since radar rainfall measurements suffer from several types of errors, rain gauge observations are still considered as close to the true rainfall as we can get with the present day technologies (Krajewski, 1997). However, due to poor sampling, rain gauge observations suffer from errors as well. Indeed, Zawadzki et al. (1986) pointed out in a comparison between radar and rain gauges that the standard deviation of any one gauge with respect to the average of six gauges was 47%. In their comparison, if the average of six gauges was considered as ground truth, radar estimates of rainfall over areas of 40-90 km^2 and over a 5 min accumulation time reached a satisfactory precision, comparable to one gauge over the same area. Thus, the reliability of rain gauge data is questionable also and calibration of the radar with a rain gauge, although an attractive idea in principle, may introduce as many problems as solutions (Zawadzki, 1984).

Even with radar-rain gauge discrepancies of 25 to 30%, rainfall measurements provided by radar are useful in cases of gauge malfunction, interruption of gauge data transmission and studies where knowing the exact value of water amount is not essential. It would be the case for modelling some crop diseases such as the carrot leaf blight, because its development depends on temperature and leaf wetness. In that case, the water amount is not useful to know, what matters is if it rained or not (or RH higher than 90%), the number of consecutive hours of leaf wetness and the temperature (Carisse and Kushalappa, 1990). The expression leaf wetness refers normally to dew or rain on aerial plant surfaces (Sutton et al. 1984).

Representativeness of radar humidity measurements

Approach

Collection of data

The periods from 12 to 21 July, 1997 (240 hours) and from 15 to 28 June, 1998 (336 hours) were selected to compare the RH calculated from weather radar measurements to the RH observed at weather stations. Those periods were chosen for three reasons: 1) plant disease symptoms (carrot leaf blight) were observed in southern Quebec fields during both periods, 2) weather radar and automatic station data were available, and 3) both dry (1997) and humid (1998) summer conditions were represented.

Three Environment Canada weather stations located in southern Quebec provided their RH data : Dorval (YUL : lat. 45°28′N, long. 73°45′W), McTavish (WTA : lat. 45°30′N, long. 73°35′W), and Sainte-Anne-de-Bellevue (WVQ : lat. 45°25′N, long. 73°56′W). Relative humidity data were measured using a HMP35C probe (Campbell Scientific Inc., Logan, Utah), containing a Vaisala capacitive RH sensor and a thermistor for measuring temperature. Measurement error is reported to be ±2% between 0 and 90% RH, and ±3% between 90 and 100% RH. The sensor was positioned at a height of 1.5 m and provided hourly data corresponding to a mean of 12 measurements in the last minute of the hour.

The McGill Doppler S-band radar located at Sainte-Anne-de-Bellevue provided the weather radar data. Following the approach of Fabry et al. (1997), surface refractivity N was extracted from radar measurements. The N measurements were taken at a height of about 15 m every 5 min. The mean of 12 N measurements over an hour was calculated and used as hourly data. From hourly measurements, RH (%) was calculated using the equations (2), (3) and (4).

The weather stations provided the atmospheric pressure and the temperature data used in equations (3) and (4). This was done since Fabry and Creese (1999) showed that when the weather stations were used to supply pressure and temperature, the average error on radar-derived vapour pressure estimates was not larger than the error of traditional weather station instruments. Finally, maps of RH data were produced on a hourly basis from the refractivity fields. Radar data just above the Dorval, McTavish, and Sainte-Anne-de-Bellevue weather stations were extracted to be later compared to the corresponding weather station data.

Analytical procedure

Data for each year and location were treated separately in assessing whether RH measured by weather stations are comparable to RH calculated with weather radar information. The normality of the data distribution was verified using SAS procedure UNIVARIATE (SAS Institute Inc., 1997). The 1998 data needed to be transformed with the arcsine-square root function to improve the normality of their distribution. The few missing data of the weather radar were replaced with interpolated data provided by the SAS/ETS procedure EXPAND and temporal autocorrelation was analysed using SAS/ETS procedure ARIMA (SAS Institute Inc., 1997).

Consider the linear regression equation:

$$Y_t = a + bX_t + \varepsilon_t \tag{5}$$

where Y_t is the RH measured by a given weather station at time t, a is the intercept, b is the slope, X_t is the RH calculated from radar information at time t and ε_t is the random error term at time t. First-difference ratios (FDR) were calculated for each year and location as follows:

$$FDR_t = \frac{DiffY_t}{DiffX_t} \tag{6}$$

where $DiffY_t$ is the difference between the RH measured at a given weather station at time t+1 and that measured at the same weather station at time t (i.e. Y_{t+1} - Y_t), and $DiffX_t$ is defined similarly for the RH calculated from the weather radar information (i.e. X_{t+1} - X_t). When the denominator of equation (6) was equal to 0 (rate of occurrence: 8% in 1997 and 4% in 1998), a pseudo-random number between 0 and 1 was subtracted from the RH data X_{t+1}; that pseudo-random number was generated by SAS function RANUNI (SAS Institute Inc., 1997). When both the numerator and the denominator of equation (6) were equal to 0 (rate of occurrence: 0% in 1997 and 5% in 1998), a pseudo-random number generated similarly was subtracted from the RH data Y_{t+1} and X_{t+1}. That usually happened when RH was 100%.

In equation (5), two conditions need to be satisfied to support that RH measured from radar information is comparable to RH measured at weather stations, that is in statistical terms, two hypotheses had to be tested and found acceptable: the slope b is equal to 1 and the intercept a is equal to 0. The t-test performed to assess the first hypothesis (b=1) was:

$$t(df) = \frac{\overline{FDR} - 1}{\sqrt{\frac{S^2_{FDR}}{n-1}}} \qquad (7)$$

where df is the number of degrees of freedom, n-2, where n is the number of hourly RH data for a given year and location, $\overline{FDR}$ is the sample mean of the first-difference ratios and S^2_{FDR} is their sample variance. The t-test performed to assess the second hypothesis (a=0) was:

$$t(df) = \frac{\overline{D}}{\sqrt{\frac{S^2_D}{n-1}}} \qquad (8)$$

where $\overline{D}$ is the sample mean of the differences between RH radar data and RH weather data and S^2_D is their sample variance. Whenever the error term ε_i was found to be temporally autocorrelated, the S^2_D term was replaced by a corrected variance estimate following Legendre and Dutilleul (1991). In the corrected variance estimates, the autoregressive parameters of the error time-series processes were estimated by the SAS/ETS procedure ARIMA (SAS Institute Inc., 1997).

Justification of the analytical procedure

To test the two hypotheses above, we could not use the classical regression model in which the regressor is fixed (i.e. Model I: Sokal and Rohlf, 1995). Indeed, both the dependent variable (i.e. RH measured at a weather station) and the regressor (i.e. RH calculated from the radar data) were random and subject to measurement error in our case. Thus, the regression Model II (Sokal and Rohlf, 1995) and geometric mean regression (Ricker, 1973) would have been appropriate if at least one of the two variables had not been temporally autocorrelated. Otherwise, testing the association between temporally or spatially autocorrelated variables requires modified procedures in regression Model II (Rao and Griliches, 1969) and correlation analysis (Clifford et al., 1989; Dutilleul, 1993). We used the so-called "FDR t-test" because of the strong and positive autocorrelation of both types of RH time series data (see the results below), following Alpargu (2001) who compared 31 testing procedures for their validity using simulations and found the FDR t-test to be valid in a situation like ours. The validity of statistical testing based on the first differences of spatial data was demonstrated by Wu and Dutilleul (1999) in the context of experimental design.

Comparisons with surface data

All data sets for RH measured at a weather station (Y_t), RH calculated from the radar information (X_t) and the difference between the two were found to be temporally autocorrelated in 1997 and 1998. Specifically, autocorrelation was positive and strong at the first time lag, with a sample autocorrelation coefficient at lag 1 generally equal to 0.9 or more. This means that successive time-series data were much more similar than two purely random data and the use of first differences was thus appropriate. At later lags, autocorrelation decreased exponentially before fluctuating between negative autocorrelation at odd multiples of 12 hours and positive autocorrelation at multiples of 24 hours. Indeed, RH is generally high at dawn, decreases as the sun rises and increases again in the evening. Compared to the autocorrelation at lag 1, the autocorrelation of periodic type was of intermediate importance. On a theoretical basis (Searle, 1971), one can show that the bias in the sample variance S^2_D was due to the first-order autoregressive component of the differences $Y_t - X_t$ rather than their daily periodicity, and this is why we focused on the former in our correction of the variance estimate.

In Table 1, the FDR t-test for the first hypothesis indicated that the slope (b) was not significantly different from 1 (P>0.05) for all cases. Thereafter, the FDR t-test for the second hypothesis was performed and indicated that the intercept (a) was not significantly different from 0 (P>0.05), except in 1998 for the Sainte-Anne-de-Bellevue weather station. Note that in this station, the humidity sensor was found to be defective at that time (Bernard Girard from Environment Canada, pers. comm.). Disregarding the Sainte-Anne-de-Bellevue weather station in 1998, the FDR t-test results indicated no significant difference between RH measured at weather stations and RH calculated with radar information, as expected. Our results clearly indicate that the possibility exists for using weather radar data as a substitute to weather station data in measuring RH.

Both RH curves (station and radar) showed similar pattern over time (Fig. 5). However, RH calculated from radar data slightly underestimated RH during the evening, There are at least two possible reasons for this.

A first explanation lies in the difference in the height of measurement. Humidity sensors at weather stations register their measurements at a height of 1.5 m, while weather radar measures refractivity (converted into RH) at a height of about 15 m. This difference in the height of measurement may create a time lag in the measurement of RH, especially during the evening hours. The time lag could be explained by the drop in temperature occurring at dusk, which slows down vertical movements (convection). Therefore, if evapotranspiration occurs, moisture near the ground will increase and take more time to reach the height at which radar measurements are taken because of the slowdown in convection.

Secondly, the type of measurement is also different. As mentioned previously, the weather radar measures refractivity and not RH. Relative humidity is then calculated from the well-known relationship between pressure, temperature, water vapour pressure and refractivity, as shown in equation (1). Due to the drop in temperature occurring at dusk, creating a slowdown in convection, temperature measured at a height of 1.5 m may be quite different from temperature that would be measured at a height of 15 m. Since weather stations provide temperature data that are used to calculate RH from weather radar measurements, radar-derived RH might be less representative because they are calculated from less representative temperature data.

To understand the reasons of the underestimation of RH measurement by radar, we have briefly looked at weather conditions (solar radiation, cloud cover, wind speed, precipitation and temperature profiles) prevailing during both periods of study. No evident correlation was found with any of these variables. We have also considered if it was not the weather station instruments that were overestimating RH. This idea was discarded as logic leads to the conclusion that, since the deviations were observed mostly in the evenings, the slowdown in convection was affecting mostly weather radar measurements because of the height in measurement. Further work is certainly necessary and may eventually lead to the definition of a correction factor. However, farmers and agricultural decision-makers can rely on RH data obtained with weather radar measurements if the requested data cover a period of a few days. On the other hand, replacing RH data measured by weather stations with RH calculated with weather radar information for only few hours, especially during the evening, may not be so appropriate because of the discrepancies occurring at that time.

To the best of our knowledge, this report is the first to compare RH measured at weather stations to RH calculated from weather radar measurements. The potential for the use of RH data provided by weather radar in agricultural crop management is tremendous, since RH data could be available every 5 min upon request with a resolution of a few kilometres. Using weather radar data would fill the actual gap of spatial RH information created by the distance between weather stations and would reduce the need for increased density of the station network. However, the coverage of the McGill Doppler S-band radar for RH ranges between 20 and 40 km (Fig. 6), which covers very little of the southern Quebec agricultural region. This is a limitation of the technique used to extract refractivity information from weather radar measurement that needs visible ground targets on flat terrain to be applicable. At long ranges, the earth curvature is a limiting factor. In the Canadian Prairies, the refractivity coverage could be more useful because of the radar proximity to the fields. In that case, RH data from weather radar measurements could be convenient to monitor, for example, the spatial distribution of stem rot caused by *Sclerotinia sclerotiorum* (Lib.), a disease affecting cereal crops that are present in many regions of Canada (Morrall and Dueck, 1982). The technique to extract refractivity from weather radar exists, and we have statistically shown that RH calculated from it is comparable to RH measured at weather stations. This knowledge could be exported wherever a weather radar is installed. For instance, the Canadian weather radar network includes 22 radars across the country, soon to be increased to 31.

Integration in a geographic information system

Procedure

To achieve the second objective of this study, the period of weather data selected was from 15 to 27 June, 1998 (308 hours). This period was chosen for two reasons : 1) plant disease symptoms (carrot leaf blight) were observed in southern Quebec fields during that period and 2) precipitation data already corrected by the McGill radar team were available for that period. The corrections for precipitation data are needed to eliminate the ground clutter and the bright band (melting snow with higher reflectivity than snow or rain) echoes. The territory covered for this second part of the project ranged from latitude 44°97′N to 45°51′N (≈60 km) and from longitude 73°31′W to 74°57′W (≈100 km), corresponding mostly to agricultural areas.

To run the carrot leaf blight model, two parameters were required as inputs (refer to Fig. 2): the leaf wetness (LW) duration and the temperature. To calculate LW, the McGill Doppler S-band radar provided the precipitation measurements and the information to calculate the RH (refer to the section titled "Relative humidity") on an hourly basis. Leaf wetness was defined as a binary variable, the leaf being either wet or dry. The leaf was considered wet as soon as there was precipitation or when RH was larger than or equal to 90% (Huber and Gillespie, 1992). The spatial resolution of the radar measurements was fixed at 1 km. For the territory covered, it meant a total of 6000 points of data per weather variable, per hour. To compute LW for the period of study, 308 files were created using computer programming, each file corresponding to one hour of data. To facilitate the integration in the MapInfo GIS software (MapInfo Corporation, Troy, NY), the resulting files were in text format and created following the same structure, i.e. three columns: latitude, longitude and the LW binary value.

For the temperature data, interpolation between the weather station measurements was sufficient to provide an estimation of temperature at every 1 km. This was done since temperature is a weather variable quite uniform in space. The interpolation method used was the inverse square distance method:

$$T_j = \frac{\sum \frac{1}{d^2_{ij}} T_i}{\sum \frac{1}{d^2_{ij}}} \qquad (9)$$

where T is the air temperature (°C), and d_{ij} is the distance between weather station i and weather station j. Weather station data were provided either by Environment Canada or the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Quebec (MAPAQ). In 1998, hourly temperature data from nine weather stations shown in Fig. 6 were available and used in the interpolation. As for LW, 308 files were created in ASCII format, based on the same structure, i.e. three columns: latitude, longitude and the temperature value.

To map the spatial distribution of forecasts of carrot leaf blight disease, the source code, elaborated within CIPRA by Bourgeois and Carisse (1996), was modified to integrate spatial data instead of site-specific data. Using LW, air temperature data and computer programming, 308 new text files were created structured in three columns: latitude, longitude and the corresponding carrot leaf blight index value. The latter text files were imported in MapInfo software and maps of spatial distribution of carrot leaf blight disease were created. The index of risk of infection of carrots by *C. carotae* ranges between 0 and 10. For visual convenience, three classes were mapped: 0 to 1; 1 to 2 and 2 and over.

Results

Our results show that it is possible to use weather radar measurements to map the spatial distribution of *C. carotae* forecasts in a GIS. Fig. 7 illustrates the spatial distribution of the carrot leaf blight disease in southern Quebec at four different times (3:00, 9:00, 15:00 and 21:00) on June 26, 1998. The progression of the disease forecasts over time is remarkable. The index of risk value of 2, combined with a sporulation period, correspond to the treatment threshold (refer to Fig. 1). When agricultural decision-makers use CIPRA software to get a forecast in real-time of the disease at a specific weather station, farmers located near that station are advised to apply fungicide as soon as a high index of risk value (≥ 2) comes with a sporulation period. Future work will have to focus on finding a way to illustrate the sporulation period simultaneously with the index of risk of infection by *C. carotae* in the GIS. Furthermore, future work should put emphasis on field testing to establish the validity of the model (Monteith, 2000). Even if evaluating with field observations was not the objective of this study, severe cases of carrot leaf blight disease were observed at the experimental farm of Agriculture and Agri-Food Canada in Sainte-Clotilde during that period of study. To eventually validate the model, a larger range of weather radar data will be needed because of the duration of life cycle of *C. carotae*, like the incubation period, which last just by itself about 7 to 10 days (Brodeur et al., 1998).

In this part of the project, to map the spatial distribution of carrot leaf blight disease, computer programming was used to obtain 308 text files of carrot leaf blight index values (refer to the "Procedure" section). The resulting values were integrated in MapInfo GIS software to create the maps. Another procedure well-known in GIS approach could have been done. Instead of integrating only the final informative layer to be mapped, all the weather variables (precipitation, RH and air temperature) could have been integrated in the GIS as informative layers and, since GIS usually have their own programming language, the result of an arithmetic operation between the informative layers could have been mapped. The latter procedure was not chosen for sake of simplicity, the source code of the carrot leaf blight disease model being already programmed in another computer language.

We tested the possibility of using weather radar measurements to predict the carrot leaf blight disease as an example but it could have been done using other crop or pest forecasts. As long as the development of those diseases or insects depends upon weather variables available on the weather radar and do not request quantitative measurements of precipitation. As mentioned in "Precipitation" section, weather radar precipitation data might not be reliable enough yet since comparisons between radar and rain gauge data have shown discrepancies of the order of 25 to 30%; these comparisons still remain an active issue in weather radar research. For RH measurement, data are reliable as it has been statistically shown in the "Comparisons with surface data" section.

This project is an example of combining remote sensing and modelling. Surprisingly, when we think about remote sensing technology, we rarely think about weather radar but it is a remote sensing tool as well as aircraft or satellite imagery. For agricultural purposes, the main objective of combining remote sensing and modelling is to obtain an accurate tool in real-time for agricultural decision-makers. This combination is often linked with a GIS, like in this project, where spatial organisation is allowed. The latest review of linkages between agricultural models and GIS can be found in Hartkamp et al. (1999). So far, remote sensing measurements have been used in crop modelling to provide accurate input information such as leaf area index (LAI), vegetation index, surface evaporation and land surface temperature. Leaf area index and vegetation index are useful to calibrate, reinitialise or reparameterise crop models (Wiegand et al., 1986; Maas, 1988; Bouman, 1992; Bouman, 1995; Moran et al., 1995). Remote sensing measurements can also be used as a means of model validation (Fischer, 1994) and to detect spatial patterns of yield during individual growing seasons when combined with GIS (Carbone et al., 1996; Maas and Doraiswamy, 1997). Moreover, remote sensing measurements are used to improve crop yield prediction.

Furthermore, maps of spatial distribution of crop diseases can be animated using an animator freeware or simulation could be done directly on the Web. An attempt has been made by Geogiev and Hoogenboom (1999) to create an Internet-based decision support system for delivering weather data and executing near real-time weather applications and crop simulation on the Web (http://www.griffin.peachnet.edu/bae). Besides creating maps of disease or insect forecasts, precipitation or RH provided by weather radar information, combined with GIS technology, can be useful for fieldman and farmer to plan their sowing or harvest date or irrigation schedule. Other informative layer such as topography could be included in the GIS to provide additional information. However, careful attention has to be paid on the accumulation of errors when multiple layers are integrated in a GIS.

Concluding remarks

As Hoogenboom (2000) proposed, denser weather station network might be needed to account for spatial weather variability; the use of observed weather data for model input provides more precise simulations than simple interpolation. In the meantime, before installing new weather stations, attention should be paid on existing weather radar measurements.

Our results show that RH calculated from weather radar measurements are comparable to RH measured at weather stations; and that it is possible to use weather radar measurements such as RH and precipitation to provide data for agricultural system modelling. The main advantage of weather radar measurements compared to traditional weather station measurements is the available time and spatial scale. Using McGill Doppler S-band radar, data could be available every 5 min with a resolution of a few kilometres for RH and 1 km for precipitation.

As Maracchi et al. (2000) mentioned, the operational application of agrometeorology in the last 30 years has been slowing. "The challenge research, therefore, is to develop new systems extracting this information from remotely sensed data, giving to the final users, near-real-time information."

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Table 1. Probabilities of significance of the FDR t-test for the slope and of the t-test with corrected variance for the intercept in the comparisons of RH measured by the weather stations to RH calculated from radar information.

Year	Site	$H_{0(1)}$: b=1 $\hat{b}$ /P-value	$H_{0(2)}$: a=0 $\hat{a}$ /P-value
1997 (n = 240)	Dorval	0.99	0.70
		0.32	0.48
	McTavish	-1.07	0.14
		0.29	0.89
	Sainte-Anne-de-Bellevue	1.02	0.67
		0.31	0.50
1998[a] (n = 336)	Dorval	-1.45	1.67
		0.15	0.10
	McTavish	0.83	0.95
		0.41	0.34
	Sainte-Anne-de-Bellevue[b]	0.10	3.68
		0.92	<0.01*

[a]Because of lack of normality, all 1998 RH data were transformed using the arcsine-square root function.

[b]At that time, the humidity sensor located at Sainte-Anne-de-Bellevue was found to be defective.

*Significantly different from zero (α=0.05).

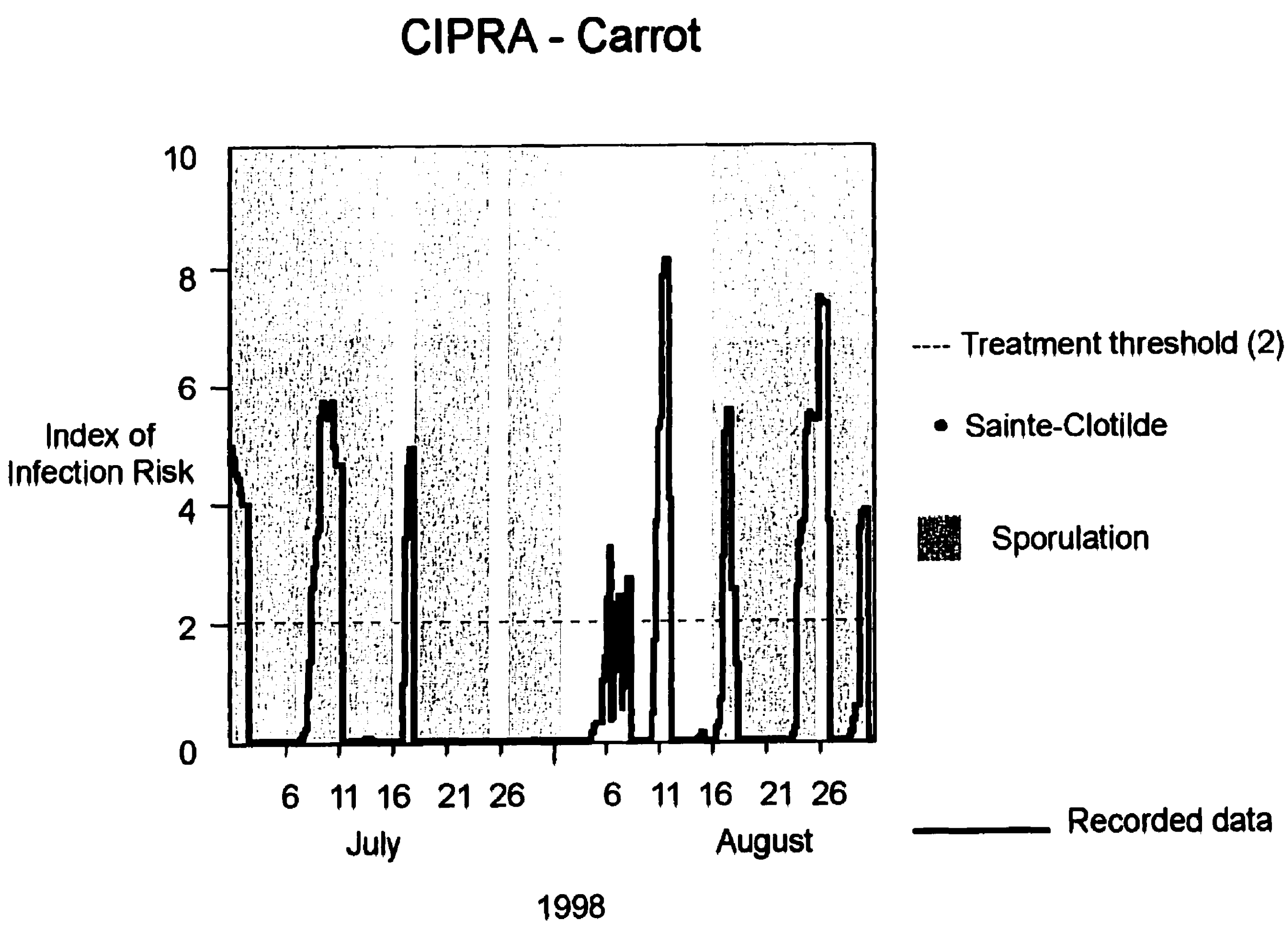

Fig. 1. Example of an output provided by CIPRA software. The index of infection risk by *C. carotae* is shown for the period of July and August, 1998, using data from Sainte-Clotilde weather station.

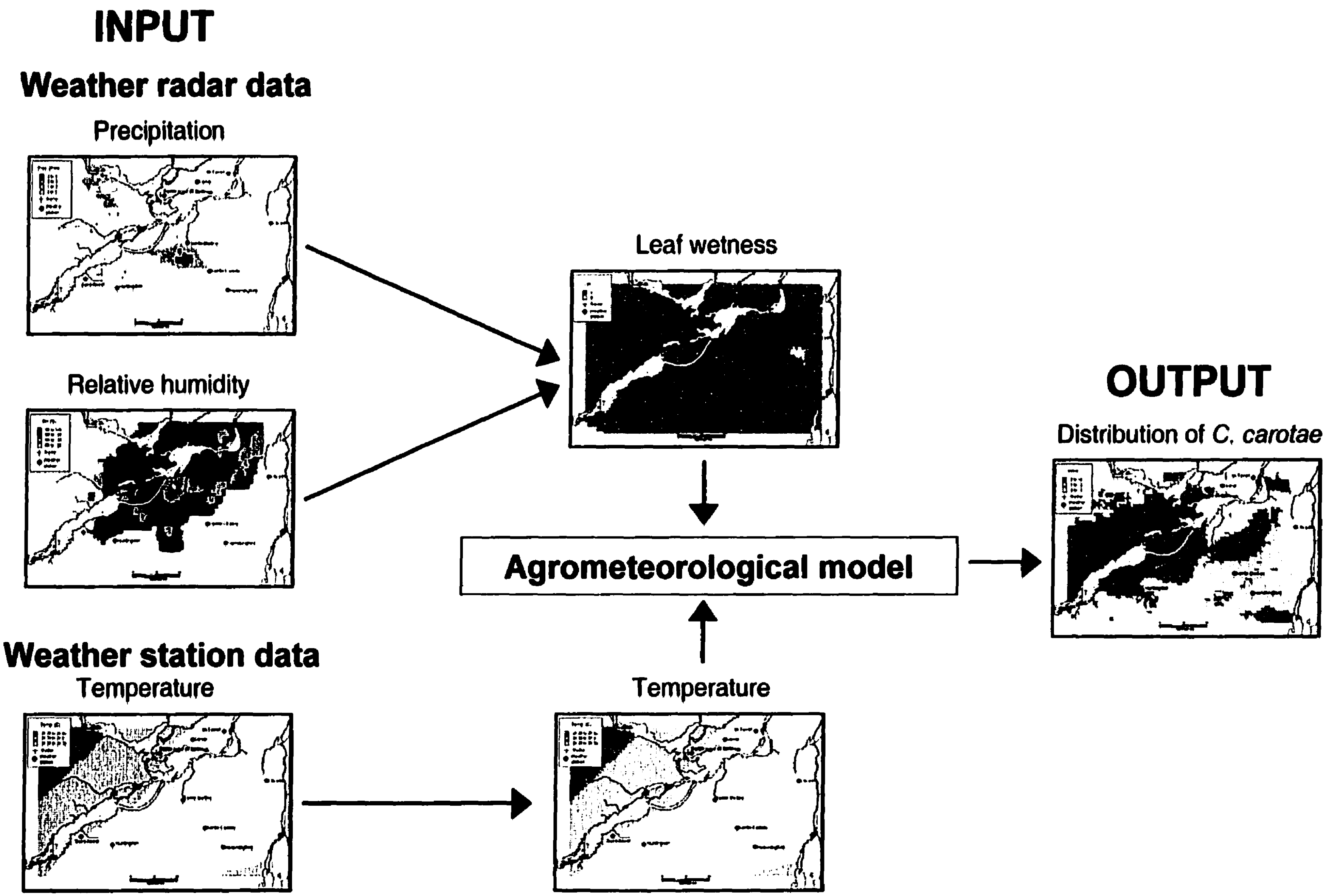

Fig. 2. Schematic representation of the steps required for mapping the spatial distribution of the carrot leaf blight disease.

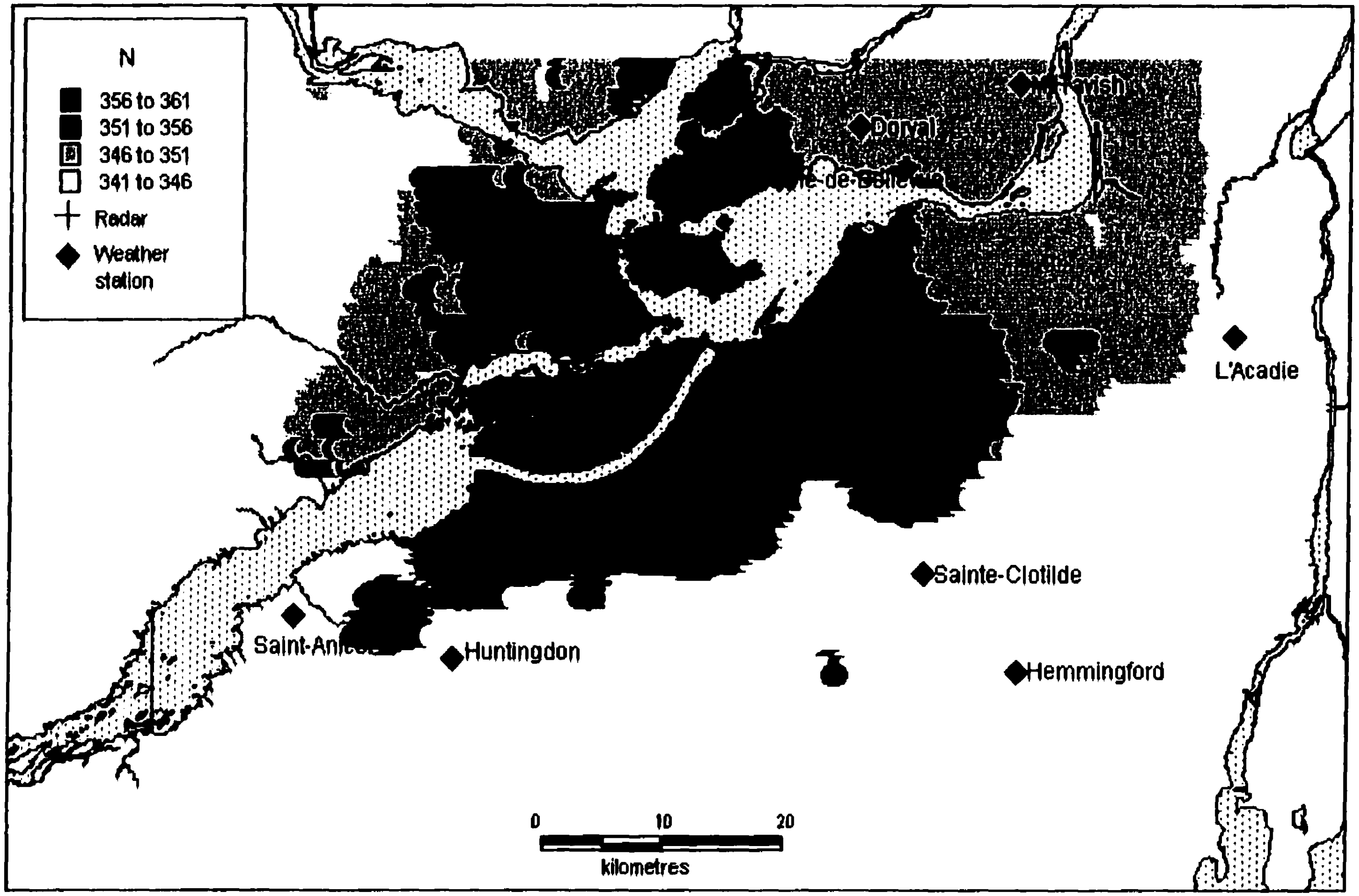

Fig. 3. Spatial distribution of refractivity N in N-units on 18 June 1998, 15:00 (Eastern Standard Time).

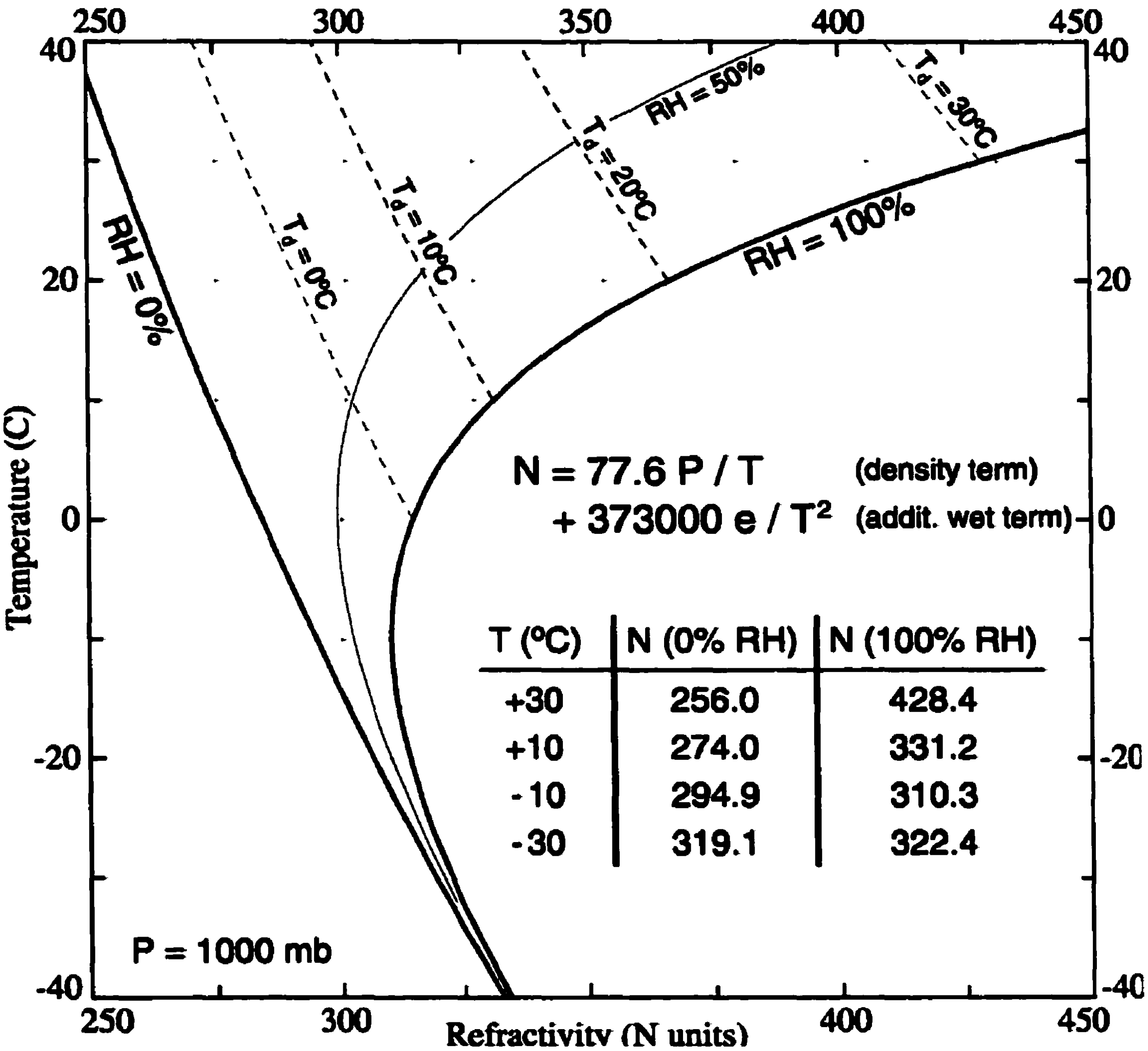

Fig. 4. Diagram illustrating the values that refractivity can take for a given temperature and moisture for a pressure of 1000 mb. In inset, the formula used to compute *N*, as well as refractivity values calculated for a dry and saturated atmosphere at a few temperatures are shown. This figure is reproduced from Fabry et al., 1997.

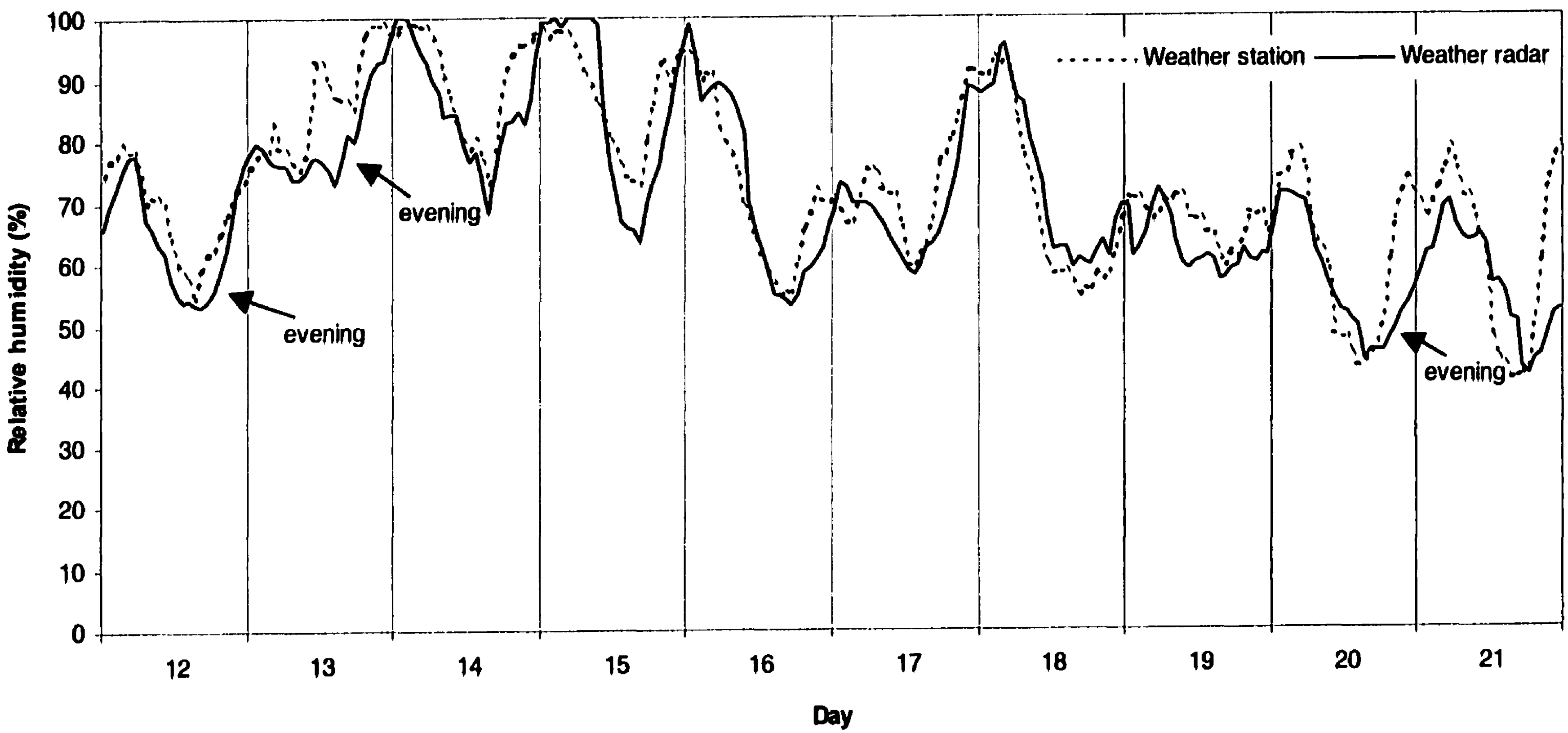

Fig. 5. Time sequence of relative humidity measured by radar and by a surface station at Dorval, from 12 to 21 July 1997.

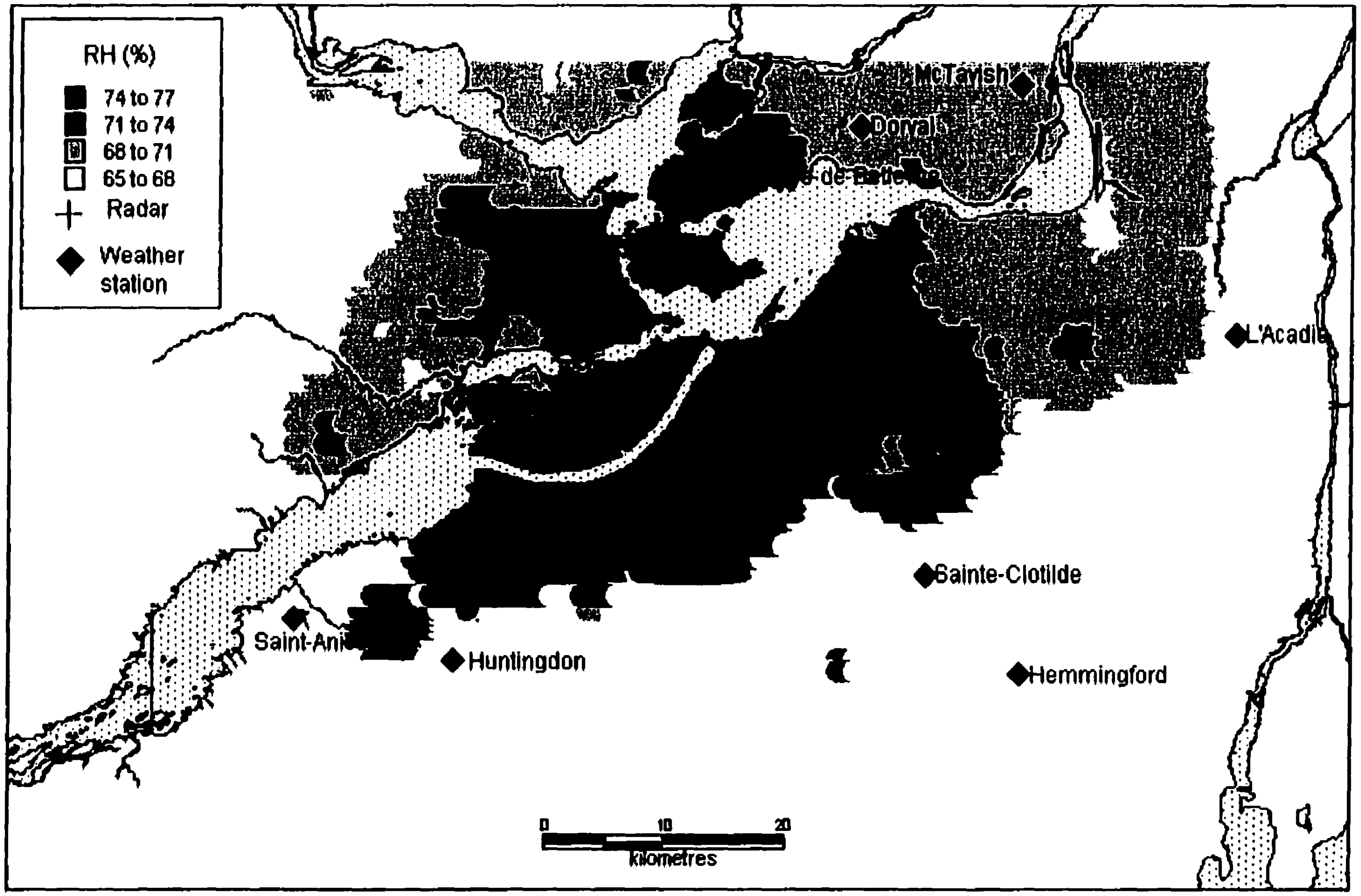

Fig. 6. Spatial distribution of relative humidity on 18 June 1998, 15:00 (Eastern Standard Time).

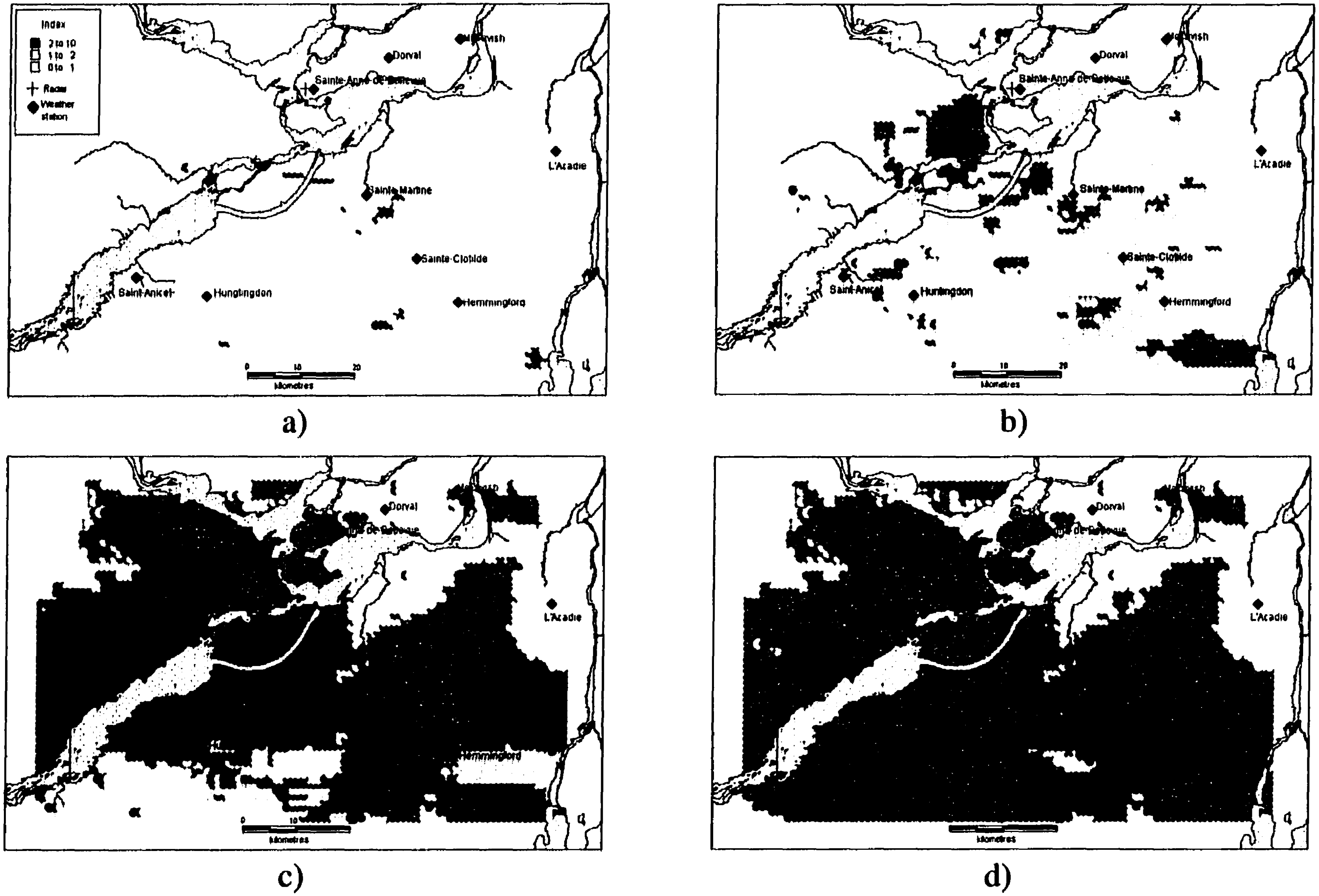

Fig. 7. Spatial distribution of *C. carotae* forecasts on 26 June 1998 at 3:00 (a); 6:00 (b); 9:00 (c) and 21:00 (d) (Eastern Standard Time).

IV. General conclusion

The objectives of this research were: 1) to compare RH calculated from weather radar measurements to RH measured at weather stations; and 2) to verify the possibility of integrating weather radar measurements (RH and precipitation), combined with crop modelling, in a GIS in order to run the carrot leaf blight disease model. The McGill Doppler S-band radar located in Saint-Anne-de-Bellevue provided the weather radar measurements. Precipitation measurements were available with a spatial resolution of 1 km up to a range of 240 km and RH data were available with a resolution of a few kilometres up to a range of 40 km. Hourly data were used in this study but both precipitation and RH measurements could be available with a time scale of 5 min upon request.

Comparisons of relative humidity data. The statistical results for the first objective have clearly indicated no significant difference between RH measured at weather stations and RH calculated with radar information. To the best of our knowledge, this study was the first to compare RH measured at weather stations to RH calculated from weather radar measurements. This research was done using the McGill radar measurements but could have been done using measurements provided by other weather radars. Indeed, it would be possible to extract refractivity measurements and estimate RH wherever a weather radar is installed. Even if the results have shown the reliability of RH calculated from weather radar measurements, they also indicated the tendency of the radar to underestimate RH, especially during the evening. So far, the reasons for this underestimation remain uncertain and should become an object of study in the near future.

I concluded that farmers and agricultural decision-makers can rely on RH data obtained with weather radar measurements if the requested data cover a period of a few days. The main advantage of weather radar measurements over traditional weather station measurements is certainly the available time and spatial scale. Thus, relative humidity data obtained from weather radar technology could be of a great interest in agricultural crop management, especially in the time decision making. For example, with an automated system distributing RH estimated by radar measurements, an agricultural decision-maker could evaluate the development of a disease almost in real-time based on these data, get a spatial picture (every few kilometres) of what is happening in his fields and take the decision to apply treatment or not. However, even with positive statistical results, the substitution of RH data measured at weather station with RH data calculated from weather radar measurements over a short period (few hours), especially during the evening, is not appropriate because of the underestimation by the radar. Furthermore, in the southern part of Quebec, the spatial coverage of McGill Doppler S-band radar ranges between 20 to 40 km and its location covers much more the city than the agricultural area of southern Quebec (refer to Fig. 6 in the previous section). Consequently, it is not useful to explore any further the RH data calculated from the weather radar at Sainte-Anne-de-Bellevue for agricultural purposes. By applying somewhere else the scientific knowledge of extracting refractivity measurements (e.g. the Canadian Prairies), the RH coverage would not be larger (limited by the earth curvature) but the radar proximity to the fields could justify the application of this method.

Integration in a geographic information system. For the second objective of the study, the results are promising for two main reasons: 1) the integration of the *C. carotae* forecasting model in the GIS was easily feasible and; 2) the spatial coverage of precipitation is 240 km, which covers a large portion of the agricultural territory of southern Quebec. In the development of *C. carotae* symptoms, as for many other diseases, the leaf wetness (LW) parameter plays a key role. The RH and precipitation data were used to estimate this parameter. The RH data obtained from the McGill Doppler S-band radar information could be omitted to calculate the LW parameter because of its small spatial coverage. For agricultural purposes, emphasis could be put on the potential of precipitation data only. The latter might be sufficient to calculate LW because of the height of measurement of precipitation by radar. Indeed, weather radar measures reflectivity to estimate precipitation at around 1.5 km height and is capable of detecting small raindrops that rain gauges might not detect (because of the potential evaporation before reaching the ground). Furthermore, the precipitation data could also be used to calculate water balance and to help farmers in planning their irrigation schedule, sowing or harvest date as well as pest or disease treatments (as shown in this project). Even if the reliability of precipitation data measured from weather radar (as for the ones measured with rain gauges) is questionable, the potential of those in agriculture is excellent. Nowadays, comparisons between rain gauges and weather radar data remain an active issue in the scientific community and improvements in the reliability of weather radar data should be visible soon. For instance, the installation of new weather stations in the next two years in southern Quebec will provide new data for the McGill radar research team to improve the calibration of the weather radar located in Sainte-Anne-de-Bellevue. If the agricultural decision-makers located in southern Quebec are interested in precipitation data measured by weather radar, an agreement will be needed between the partners (Environment Canada, McGill University and a third party) to decide how the distribution will be done, the cost of it and the computer system needed to manage this quantity of data.