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Foreword / Avant-Propos

We thank Terry Allsopp who has completed his term as associate editor and welcome John Dublin from AES Atlantic Region as his replacement.

Nos remerciements à Terry Allsopp à la fin de son terme de rédacteur associé et à la fois à John Dublin du SEA (région Atlantique) qui remplace Terry.

Alec Paul
Editor/Rédacteur en chef

Moisture Risk Assessment for Spring Wheat on the Eastern Prairies: A Water-Use Simulation Model

G.H.B. Ash,[1]
C.F. Shaykewich[2]
and
R.L. Raddatz[3]
[Original manuscript received 3 February 1992; in revised form 8 June 1992]

ABSTRACT

A water use simulation model for spring wheat was formulated and applied to historical weather records (1929-1988) from the eastern Canadian Prairies. Water use was estimated from daily potential evapotranspiration calculated from daily climatological data. Crop water demand was obtained by multiplying potential evapotranspiration by a consumptive use factor. This factor varied according to the stage of phenological development which, in turn, was computed using Robertson's biometeorological time-scale. Water to meet crop demand was supplied by precipitation and from the available soil moisture in a "growing" root-zone whose depth was estimated from the stage of phenological development. The ever reducing ability of roots to extract water as soil dries was accounted for by proportionately limiting the water supply when root-zone moisture dropped below 50% of the available water holding capacity. The shortfall between water demand and supply was termed "moisture stress".

The simulation indicated that, on the eastern Prairies, most of the year-to-year variability and the east-to-west increase in the average moisture stress on spring wheat crops is due to temporal and spatial changes in the supply of water from spring soil moisture and growing-season precipitation rather than variation in crop water demand. The general decrease in average yields from east to west may be due, in large part, to moisture stress as the wheat crops progress from the heading to the soft dough stage.

RÉSUMÉ

Nous avons conçu un modèle de simulation de la consommation d'eau pour des cultures de blé du printemps et l'avons appliqué aux données climatiques de 1929 à 1988 de l'est des Prairies canadiennes. On a ensuite déterminé la consommation d'eau à partir de l'évaporation potentielle journalière, calculée à son tour, à l'aide des données climatiques journalières. Enfin, on a obtenu le besoin en eau des cultures en multipliant

[1] Department of Geography, University of Manitoba, Winnipeg, Manitoba. R3T 2N2
[2] Department of Soil Science, University of Manitoba, Winnipeg, Manitoba. R3T 2N2
[3] Winnipeg Climate Centre, Environment Canada, 266 Graham Avenue, Room 1000, Winnipeg, Manitoba. R3C 3V4

l'évapotranspiration potentielle par un coefficient de consommation. Ce coefficient varie en fonction du stade de développement phénologique qui est calculé à partir de l'échelle de temps de Robertson. L'eau nécessaire pour satisfaire au besoin de cette culture provenait des précipitations et de l'humidité contenue dans le sol au niveau des racines dont la profondeur était déterminée par le stade de développement phénologique. On a de plus pris en compte la capacité des racines d'extraire l'humidité du sol à mesure que celui-ci s'asséchait en réduisant proportionellement la quantité d'eau dès que l'humidité au niveau des racines était inférieure à 50% de la capacité de rétention de l'eau disponible. L'écart entre le besoin en eau et la quantité d'eau disponible se définit comme le stress causé par manque d'humidité.

Cette simulation a démontré que, dans l'est des Prairies, la plus grande partie de la variabilité, d'une année à l'autre, et l'accroissement du manque d'humidité moyen d'est en ouest des cultures de blé du printemps sont attribuables aux changements spatio-temporels de la quantité d'eau contenue dans le sol au printemps et aux précipitations durant la saison de croissance, plutôt qu'à la variation du besoin en eau des cultures. La baisse générale des rendements moyens d'est en ouest peut, en grande partie, s'expliquer par le manque d'humidité lorsque les cultures évoluent du stade de l'épiaison au stade de la pâte molle.

1. INTRODUCTION

There is a constant need to improve the characterization of the climatic resource of the eastern Prairies as it impacts on agriculture. An important part of any such characterization is a moisture risk assessment, particularly as it relates to the most important crop on the Prairies — spring wheat. Moisture from growing-season rainfall and soil water is the pivotal climatic factor in wheat production. Thus a water-use simulation model for spring wheat is a fundamental requirement for any assessment of Prairie climate.

The current model is based on that used by Dunlop (1981) to simulate and map agroclimatic parameters for Manitoba (Dunlop and Shaykewich 1982). This model was further developed by Raddatz (1989) for use in operational agroclimatic monitoring for the entire Prairies. The current simulation represents the most recent developments in the formulation of a water-use model for spring wheat (Ash, 1991).

Components of the model are described in Section 2 and its application to historical weather records for the eastern Prairies is outlined in Section 3. The resultant agroclimatic moisture risk assessment is given in Section 4.

2. WATER-USE SIMULATION FOR SPRING WHEAT

Continuous cropping, that is spring wheat monoculture, was assumed. The model was run on a daily time-step; inputs were the basic climatological observations — daily temperature extremes and total precipitation. Spatial representativeness was maximized (average station spacing was approximately 50 km) by using all available climatological data for the eastern Prairies from the 1929-1988 period — 146 stations with 15 to 60 years of record (Figure 1) were used in the analysis.

Site specific available water holding capacities (AWC) for the top 120 cm of soil at each climatological site were abstracted from maps generated by de Jong and Shields (1988) from soil texture data. The AWC, defined as the difference between field capacity and permanent wilting point, was assumed to be uniformly distributed over the soil profile.

2.1 *Model Components*

Simple parametric representations of a number of physical and biological processes, including phenological development and root growth, soil moisture recharge and crop water use, snowpack accumulation and snowmelt, were combined in a model to simulate water use by spring wheat. A brief description of the model follows.

2.1.1 *Phenological Development*

Phenological development was estimated from planting dates and Robertson's (1968) biometeorological time scale. This scale recognizes six phenological

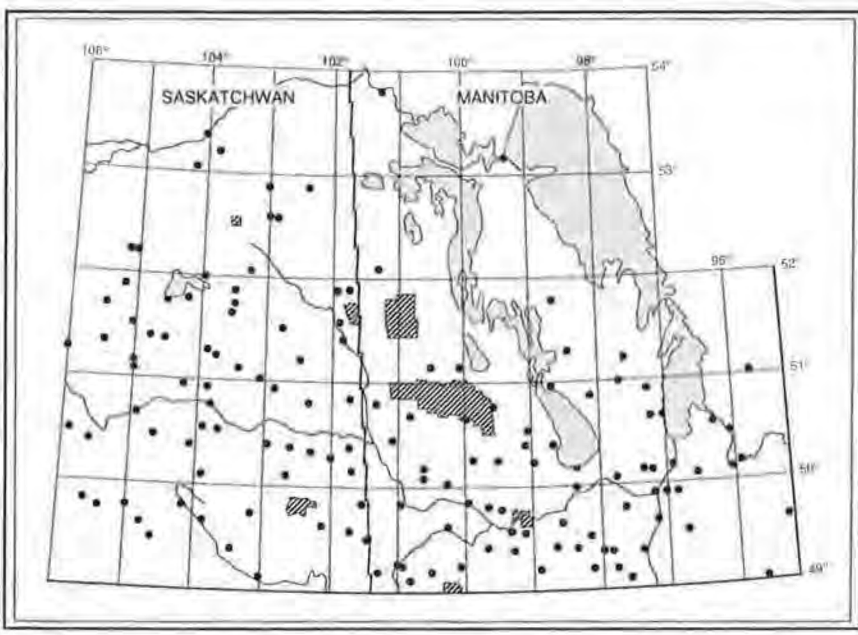

FIGURE 1. Climatological stations within southern Manitoba and southeastern Saskatchewan used in this analysis.

events: planting, emergence, jointing, heading, soft dough and maturity, with bmt values of zero to 5, respectively. For the years 1952-1988, actual planting dates for each climatological station obtained from Statistics Canada (1989) were used. Planting dates for the earlier period (1929-1951) were estimated from a regression equation relating known planting dates (1952-1988) to soil tractability based on soil moisture budgeting (Selirio 1969, Dunlop 1981, Ash 1991). Subsequent growth stages were estimated from daily maximum and minimum temperatures and photoperiod.

2.1.2 *Root Growth*

The depth of the root-zone was estimated from the stage of phenological development of the crop (Rasmussen and Hanks 1978). The initial value was 5 cm — planting depth — and it was assumed to reach a maximum of 120 cm at biometeorological-time of 3.5, i.e., halfway between heading and soft dough. The relationship used was:

$$rz = 5.0 + (120.0–5.0)/(1.0 + \exp(5.0–(8.0 \times (bmt/3.5))) \text{ for } bmt \leq 3.5,$$

and

$$rz = 120 \text{ cm for } bmt > 3.5$$

Onofrei (1986) found that a model using this equation for approximating root growth estimated field soil moisture with acceptable accuracy.

2.1.3 *Soil Moisture Recharge*

An earlier agroclimatic risk analysis for Manitoba (Dunlop and Shaykewich 1982) assumed that soil moisture was at field capacity when crops were planted. This study, expanded to include more arid eastern Saskatchewan, employed simple water budgeting techniques during the "off season" to obtain soil moisture levels at planting which were more in tune with the antecedent weather conditions. Precipitation which occurred between crop maturity and October 31 was assumed to be rain. During this period, daily evaporation from the soil was assumed to be one-third of the potential evapotranspiration amount which was estimated as described in section 2.1.4, Crop Water Use.

For the period November 1 to the earlier of April 1 or the date when the snowpack completely melted, on days when the mean temperature was below $-1°C$, the water equivalent of precipitation in the form of snow was accumulated. The snow-to-water ratio was assumed to be 10:1 for ordinary climate sites, while actual measurements were provided by principal stations. Sublimation losses from the snowpack were assumed to be one-third of the potential rate, since a snowpack can be treated as a freely evaporating surface (Baier *et al.* 1979)

The percentage of over-winter snowfall that contributes to soil moisture recharge decreases from arid to more humid regions (Steppuhn 1981).

Nevertheless, as a first approximation, a universal "blow-off" factor of 60% was applied to all locations based on the results of Staple *et al.* (1960) for the Bad Lake Research Basin of Saskatchewan.

Daily snowmelt on days with no rainfall was estimated from a relationship using Julian day and maximum temperature (McKay 1964). On days with rain, snowmelt was calculated using an equation developed by the U.S. Corps of Engineers which estimates melt from rainfall amount and mean temperature (Johnstone and Louie 1984).

Rates of infiltration into frozen soil are dependent upon soil porosity and moisture content (Street *et al.* 1986). Soil temperature was estimated from a ten day running mean of daily maximum temperature. If soil temperature was less than or equal to 0° C, infiltration was calculated by multiplying the amount of rainfall plus snowmelt by the fraction of soil pore space available for moisture recharge, i.e. field capacity minus existing moisture content. In cases in which daily rainfall plus snowmelt exceeded 25.4 mm, the additional restriction of the Baier *et al.* (1979) infiltration equation was imposed. Complex frozen soil states like those described by Granger and Gray (1986) were not considered.

After snowmelt was completed, all precipitation was assumed to be rainfall. As in the fall period, daily soil water evaporation was assumed to be one-third of potential evapotranspiration. This simulation was continued until planting date.

During the "off" and growing seasons, each day's rainfall plus snowmelt water, if any, was first made available to meet the day's evaporative or crop water demand. The excess, if any, contributed to soil moisture recharge. This attempts to represent the rapid wetting and drying of the surface soil layer.

To account for heavy rainfall and/or snowmelt events where runoff occurs even though there is unfilled field capacity, total daily water input was partitioned between soil moisture recharge and runoff. On days with total daily input $\leq$ 25.4 mm, the amount of water infiltrating the soil was limited only by its field capacity. When daily water additions exceeded 25.4 mm, soil moisture recharge was controlled by the Baier *et al.* (1979) infiltration equation.

If the water added to the soil exceeded the amount required to bring the root-zone to field capacity, the excess amount was uniformly distributed in the sub-zone. The lower boundary of this zone was 120 cm so that its thickness shrank as the root-zone grew in depth. The soil moisture content of the root and sub-zones was not allowed to rise above field capacity — excess water was assumed lost to deep drainage.

2.1.4 *Crop Water-Use*

The upper limit of crop water use — potential evapotranspiration — was estimated from a simple regression equation using daily climatological observations (Baier and Robertson, 1965; Baier, 1971):

$$ETp = 0.086\ (-57.334 + 1.6704\ Tmax + 1.6794\ Range + 0.20334\ Qo)$$

ETp is potential evapotranspiration (mm/day), Tmax is the daily maximum temperature (°C), Range is the difference between the daily maximum and minimum temperatures (°C), and Qo is solar energy received at the top of the atmosphere (MJ m^{-2} day^{-1}). The latter was calculated as described by Robertson and Russelo (1968).

It should be noted that the above equation is not a very accurate estimator of daily potential evapotranspiration. It was developed by regressing Tmax, Range and Q_0 on daily Bellani plate evaporation (Baier and Robertson 1965). The resulting equation had a correlation coefficient of only 0.68. Its use here assumes that over the growing season, the positive and negative errors in the estimation approximately cancel and that the error in the seasonal total is relatively small. Despite its shortcomings, the equation has been found to be the most reliable method of estimating potential evapotranspiration from the climatological weather station data (de Jong and Tugwood 1987).

The daily crop water demand is the maximum amount of water that would be used, if readily available, at the particular stage of phenological development. Hobbs and Krogman (1963) measured water demand by growing crops under conditions in which water was not limiting, i.e. under irrigation. They defined a consumptive-use factor, CU, as the ratio of actual water use to potential evapotranspiration. Based on their work, CU for wheat was defined as follows:

$0 < bmt < 1$	$CU = 0.3$
$1 < bmt < 2$	$CU = 0.3 + 0.5\ (bmt - 1)$
$2 < bmt < 3$	$CU = 0.8 + 0.2\ (bmt - 2)$
$3 < bmt < 4$	$CU = 1.0 - 0.2\ (bmt - 3)$
$4 < bmt < 5$	$CU = 0.8 - 0.3\ (bmt - 4)$
$5 < bmt$	$CU = 0.3$

$$\text{Daily Crop Water Demand} = CU \times ETp.$$

The daily crop water demand not met by that day's infiltrated rainfall was supplied, at least in part, by moisture from the soil. Water was assumed to have been extracted uniformly over the depth of soil penetrated by roots. The rooting-depth, from 5 to 120 cm, was calculated daily as described previously. The extent to which the daily crop water demand, not met by daily rainfall, was met by soil moisture draw-down was governed by the soil water content of the root-zone.

The nature of the relationship between relative ease of water withdrawal and soil water content has been the subject of a large number of studies. There seems to be general agreement that there is a range of water content over which water is "equally and easily available". As an example, Meyer and Green (1981) found that so long as water content was greater than 30% of the available water holding capacity, water was easily and equally available. On the other hand, de Jong and Bootsma (1988) suggest that the threshold water content is 50% of the available water holding capacity. Below the threshold water content the decrease in relative availability with decreasing water content may be linear or curvilinear (Baier *et al.* 1979), depending upon soil type and other factors. In addition, it has been shown that the nature of these relationships was very dependent upon the rate of potential evapotranspiration under which the study was conducted (Denmead and Shaw 1962).

It was beyond the scope of this study to account for all the factors which influence soil moisture withdrawal by crops. Therefore, a relatively simple approach was used: If the water content was above 50% of the available water holding capacity, water uptake was assumed to be sufficient to meet the crop water demand. At lower water contents, the ratio of actual water uptake to crop water demand decreased linearly from 1.0 to zero as available water decreased from 50 to 0%. This simulated the increasing difficulty that crops experience in extracting moisture from soil as it became drier. The daily crop water use was the actual evapotranspiration.

When the daily crop water use fell short of the crop water demand, the unsatisfied demand was termed moisture stress. That is,

$$\text{Moisture Stress} = \text{Crop Water Use–Crop Water Demand} \leq 0$$

The daily stress values were summed to give accumulated moisture shortfalls at selected phenological stages.

3. AGROCLIMATIC MOISTURE RISK ASSESSMENT

In order to define the risk associated with a particular agroclimatic parameter, an appropriate frequency distribution must be ascribed to the parameter. The Kolmogorov D Statistic (Stephens, 1974; SAS, 1985) indicated that all of the moisture parameters described above, except moisture stress, were normally distributed (Table 1). (This result does not imply that all simulated temporal soil moisture distributions will be normal. The actual distribution would be dependent upon the relative dryness of the climate of the region and the soil type. Thus, the result obtained here should be regarded more as fortuitous than expected.) For each climatological station, the average, and 10 and 25% risk-level values were calculated for the following moisture supply parameters as described by Ash (1991):

1. Available Soil Moisture at Planting,
2. Growing Season Precipitation.

As an example of the above, the mean value of soil moisture at planting at Regina was 153.9 mm and its standard deviation was 50.7 mm. To calculate the 10% risk value, the standard deviation, 50.7 was multiplied by the t

TABLE 1 Results of the Kolmogorov D Statistic test for normality

Station	Parameter*								
	1	2	3	4	5	6	7	8	9
Davidson	>.05	<.01	>.15	<.01	>.065	<.01	>.05	>.15	>.15
Midale	>.15	>.15	<.01	<.01	<.01	>.15	<.01	>.02	>.15
Indian Head	<.15	>.15	>.05	>.05	<.01	>.15	>.15	>.15	>.04
Regina	>.04	>.05	>.062	<.01	<.01	>.05	>.15	>.15	>.037
Morden	>.15	>.15	>.15	>.10	<.01	>.079	>.05	>.15	>.05
Brandon	>.15	>.15	>.15	<.01	<.01	>.15	>.05	>.10	>.05
Winnipeg	>.06	>.10	>.15	<.01	<.01	>.15	<.01	>.15	>.078

Note: Any value <.05 represents a rejection of the null hypothesis, i.e. the data are not normally distributed.

* Definition of Parameters
1 Soil moisture amount at planting
2 Soil moisture amount at heading
3 Soil moisture amount at soft dough
4 Plant moisture stress amount at heading
5 Plant moisture stress amount at soft dough
6 Soil moisture amount at maturity
7 Soil moisture amount on October 31
8 Accumulated growing season precipitation
9 Accumulated growing season actual evapotranspiration

statistic at $P = 0.10$ and 60 degrees of freedom, 1.285, and the product subtracted from the mean, 153.9, to give a value of 88.8. Similarly, values at 25% risk were also calculated, taking t at $P = 0.25$.

The average seasonal crop water demand and the mean moisture stress from planting to the heading and to the soft dough stages were also calculated. In the case of risk maps, the 10 and 25% risk values were calculated for each weather station using the mean and standard deviation for that station and the resulting values were used in producing maps. The SURFER (Surfer, 1987) analysis package was used to map these parameters (Figures 2 to 7).

4. RESULTS AND DISCUSSION

The simulated average crop water demand (Figure 2) characterizes the requirement of spring wheat for moisture when grown on the eastern Prairies. Most of the region has an average growing season water demand of approximately 300 mm, with southeastern Saskatchewan having an average crop water demand of 320 mm. There was some year-to-year variation in annual crop water demand but it was relatively small; the average standard deviation was about 25 mm. Applying the risk calculation procedure outlined above showed that in areas with a mean of 300 mm, one year in four had a crop water demand less than or equal to 285 mm, and at the other extreme, one year in four had a crop water demand more than or equal to 315 mm.

On the supply side, the most important source of water for Prairie spring wheat crops is the rain that falls during the growing season (planting to maturity). For most of the region the average amount is about 200 mm (Figure 3), with southeastern Saskatchewan receiving about 175 mm. The year-to-year

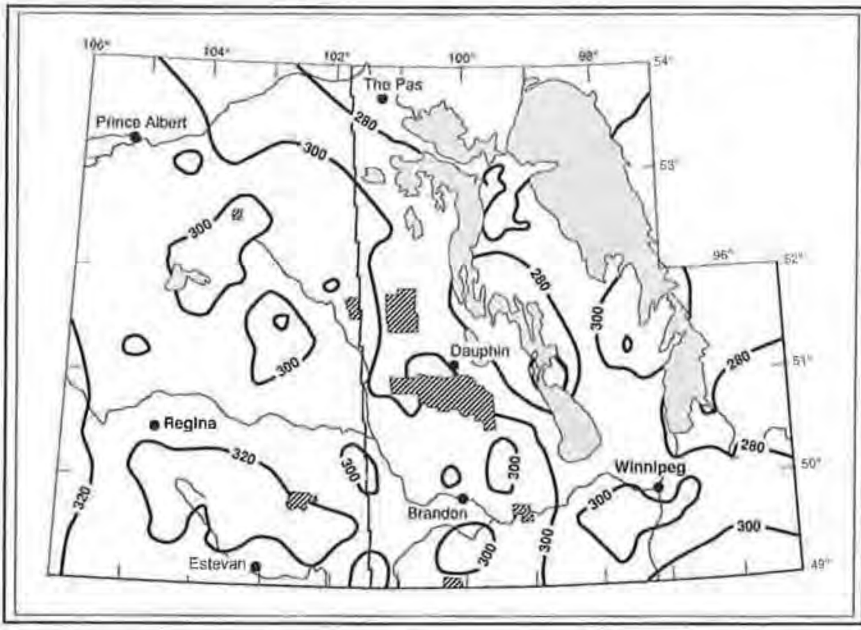

FIGURE 2. Average seasonal water demand for spring wheat (mm).

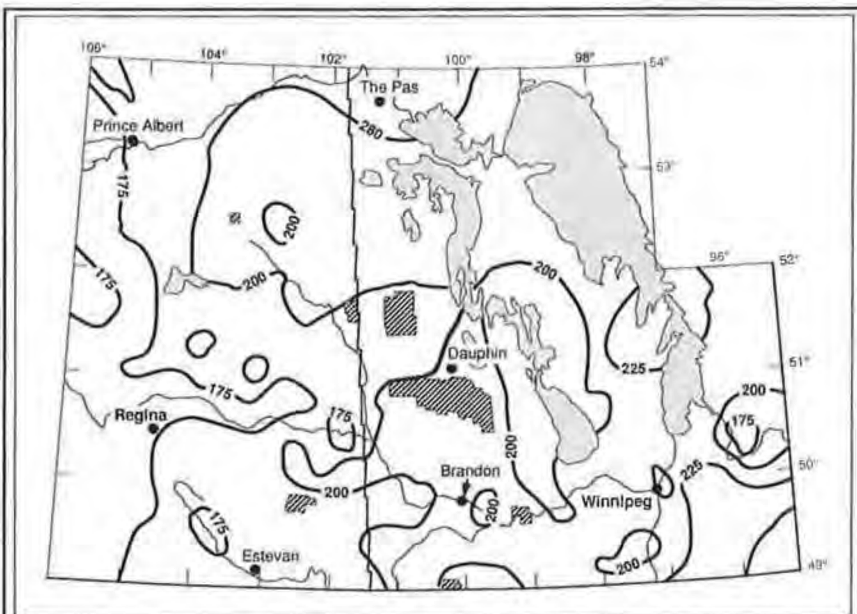

FIGURE 3. Average accumulated growing-season (planting to ripe) precipitation for spring wheat (mm).

variation in growing season precipitation was large; standard deviations varied between 50 and 100 mm, with an average standard deviation of about 75 mm. Results of the risk calculation described above showed that in one year in four, growing season precipitation was less than 150 mm over most of the region and less than 125 mm in southeastern Saskatchewan (Figure 4).

The other source of water for wheat was the available soil moisture at planting (Figure 5). This represents water stored from fall rains after crop maturity, conservation of water from snow, and spring rains prior to planting. (The reader is referred to section 2.1.3 — Soil Moisture Recharge for a description of soil moisture budgeting models used during these time periods). Average planting soil moisture exhibited very large spatial variability, decreasing from over 200 mm in central regions of Manitoba to 125 mm in southeastern and central Saskatchewan. The average standard deviation of available soil moisture at planting was about 35 mm. Risk calculations showed that one year in four had available soil moisture levels at planting of 175 mm or less in central Manitoba and of 100 mm or less in southeastern and central Saskatchewan.

The average accumulated moisture stress from planting to heading, i.e., the additional amount of water that the crops would have used had it been available, varied from near zero in central Manitoba to more than 35 mm in southeastern and central Saskatchewan (Figure 6). By the soft dough stage, the

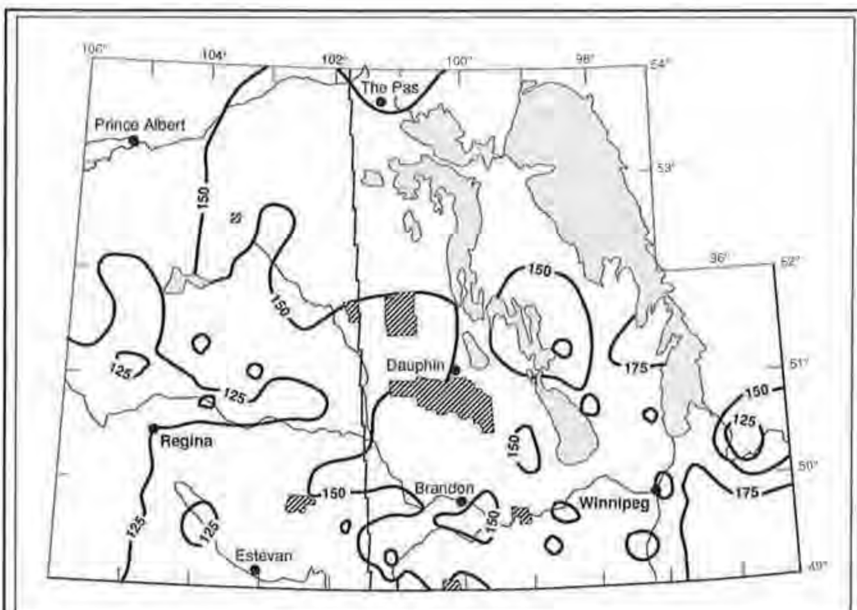

FIGURE 4. 25% risk for growing season precipitation for wheat — over the long-term, one year in four will have this much or less precipitation.

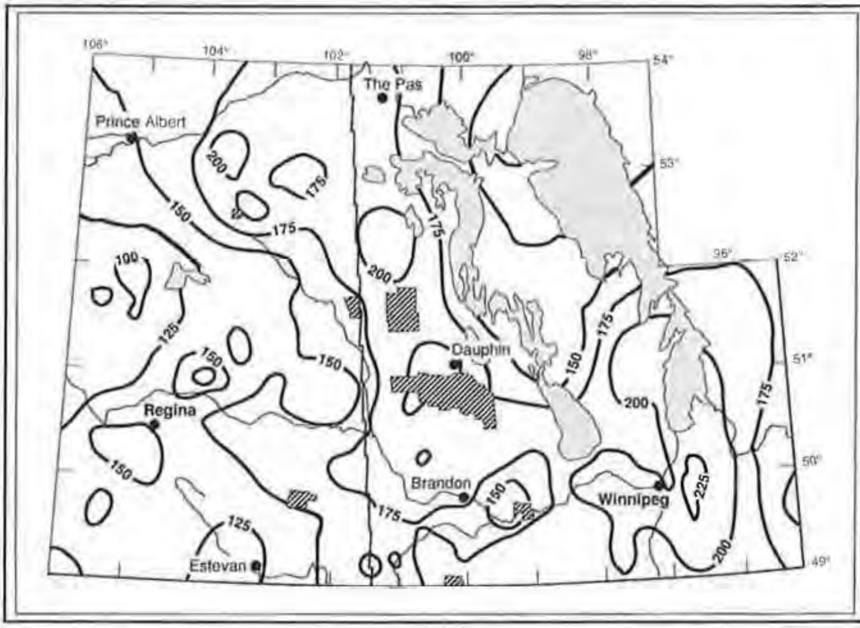

FIGURE 5. Average available soil moisture at planting for spring wheat (mm).

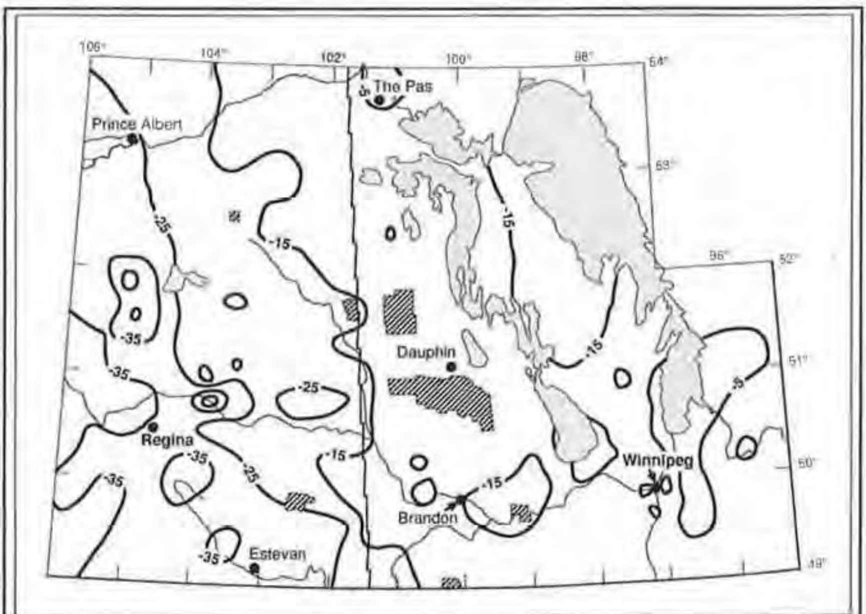

FIGURE 6. Average moisture stress (shortfall) to the heading stage of spring wheat (mm).

average accumulated moisture stress increased to 5-15 mm in central Manitoba to 50-75 mm in Saskatchewan (Figure 7).

It can be seen that most of the year-to-year variation and the east-to-west increase in the average magnitude of the moisture shortfall for spring wheat crops was due to variability on the supply side of the moisture stress equation, i.e. growing season and non-growing season precipitation. Clearly, only a small portion of the variability was due to temporal and spatial variations in crop water demand.

One of the most important factors controlling spring wheat yields on the eastern Prairies is the moisture availability at the critical stages of heading and soft dough (Lehane and Staple, 1962). A visual subtraction of the contour values in Figure 6 from those in Figure 7 gives an estimate of the average moisture shortfall as the spring wheat crop progressed from the heading to the soft dough stage. The larger heading to soft dough moisture stress values in more western areas correlate with lower average yields in this region.

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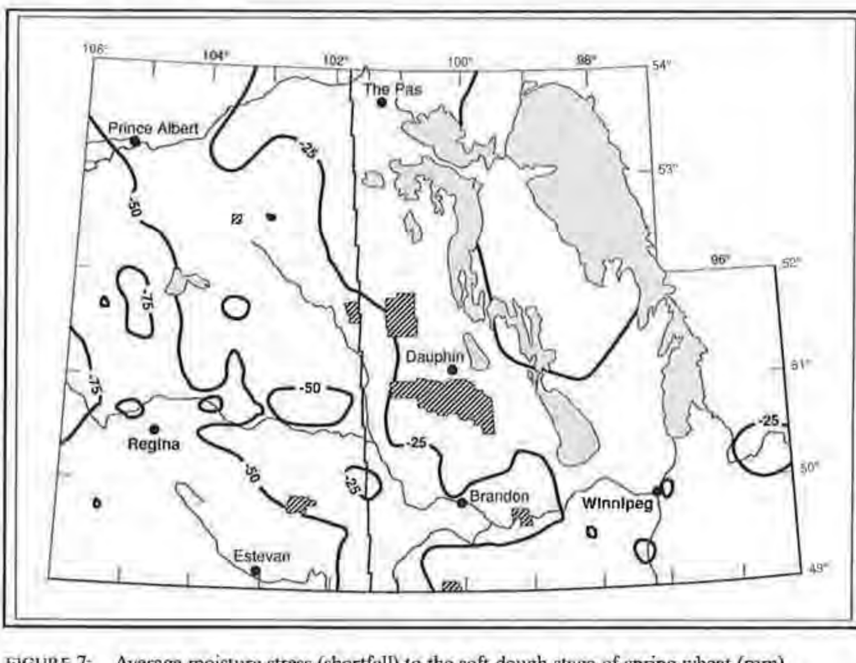

FIGURE 7: Average moisture stress (shortfall) to the soft dough stage of spring wheat (mm).

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Potential Impacts of CO_2-induced Climate Change using the GISS, GFDL and CCC Scenarios on Corn Yields in the Essex County Region of Ontario, Canada

Alain A. Viau[1]
and
Constance M. Mitic[2]
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ABSTRACT

This study examines the effect of a CO_2 -induced climate change on corn yield using a multivariate regression model in conjunction with three General Circulation Models: GISS, GFDL and CCC scenarios. A historical study over the baseline period from 1960 to 1990 inclusive shows a very strong correlation between corn yields and the climatic variables of precipitation, temperature and evapotranspiration. These relationships are then used to estimate possible changes in corn yield as a result of changes in climate. The GFDL showed a decrease in corn yields of 12.4% and the GISS an increase of 6.3%. The CCC scenario also estimates a decrease in corn yields by 14.4%. The generalized effect of the combined scenarios is a decrease in precipitation for June, August, and September, an increase in temperatures throughout the growing season and an increase in evapotranspiration throughout the growing season. The net effect of these changes translates into water stress for corn, especially during the critical stages of its development. The results of the study clearly indicate that irrigation systems are going to become even more important for future cultivation of corn in the Essex county region. Development of systems with the flexibility to accommodate changes in climate appears imperative.

RÉSUMÉ

Cette étude examine l'effet d'un changement climatique dû à un doublement du CO_2 sur les rendements aux champs du maïs à partir d'un modèle à régression multivarié en conjonction avec des scénarios issus de trois modèles de circulation générale de l'atmosphère GISS, GFDL et CCC. L'étude des données historiques pour la période allant de 1960 à 1990 inclusivement indique une forte corrélation entre les rendements au champs et les variables climatiques comme la précipitation, la température et

1 Département des Sciences géodésiques et télédétection, Université Laval, Sainte-Foy, Québec G1K 7P4
2 Department of Geography, University of Windsor, Windsor, Ontario N9B 3P4

l'évapotranspiration. C'est à partir de cette relation qu'une estimation de l'impact d'un changement climatique sur le rendement au champs du maïs a été effectuée. Les applications des scénarios GFDL et GISS démontrent respectivement une baisse de 12,4% et une augmentation de 6,3%. Pour le CCC ce dernier indique une diminution de 14,4% des rendements au champs. Dans l'ensemble l'effet combiné des scénarios est une baisse au niveau de la précipitation pour les mois de juin, août et septembre avec une augmentation des températures et de l'évapotranspiration tout au long de la saison de croissance. L'effet globale se traduit en terme d'augmentation du stress hydrique spécialement durant les stages critiques de développement du maïs. Les résultats de cette étude démontrent clairement que l'utilisation de système d'irrigation va devenir indispensable pour maintenir les rendements au champs actuels dans la région du comté d'Essex. Le développement de systèmes ayant une grande flexibilité s'avère impératif.

INTRODUCTION

There is growing scientific evidence that increasing concentrations of carbon dioxide could result in a rise in the global mean temperature in the range of 2.8°C - 5.2°C, an 8 - 15% change in precipitation and a 3.8% change in evaporation (Cohen, 1990a). The magnitude of this climate change could be sufficient to bring about long-term changes in agricultural potential. Such changes could be reflected in spatial shifts in cropping patterns and/or regional changes in agricultural output. Due to the nature of the climatic system, feedback effects could result in changes in water resources, soil fertility, soil erosion and consequently in crop yields.

The agricultural industry represents an important aspect of society, and provides for one of humanity's basic needs. It therefore becomes very important to investigate any possible effects that a change in the atmospheric composition, such as an increase in carbon dioxide concentration, may have on its potential. A review of the literature shows extensive work in the area of climate change and agriculture in Canada and the United States covering large areas and utilizing a variety of methodologies (LEG, 1985, 1986; Oram, 1985; Parry and Carter, 1985; Parry, 1985; Rosenzweig, 1985; Williams, 1985; Arthur *et al.*, 1986; Smit, 1987; Parry *et al.*, 1988; Williams *et al.*, 1988; Warrick, 1988; Smit *et al.*, 1989; Cooter, 1990; Singh and Stewart, 1991). Similar efforts have taken place in Australia (Pearman, 1988), New Zealand (Moe, 1988), and under the auspices of international organizations such as UNEP and IIASA (Parry and Carter, 1985; Parry *et al.*, 1988). This study is more localized, and uses statistical empirical reasoning with existing approaches and methods to assess the climatic sensitivity of corn yields to CO_2 induced climate change in the Essex County region, one of the most productive corn producing areas in Canada (Mitic, 1991). Essex County is located in the southernmost part of the agricultural belt of southwestern Ontario (Figure 1), and during the growing season experiences very high temperatures. However, it also experiences a large moisture deficit, resulting in extensive use of irrigation systems. Corn, although

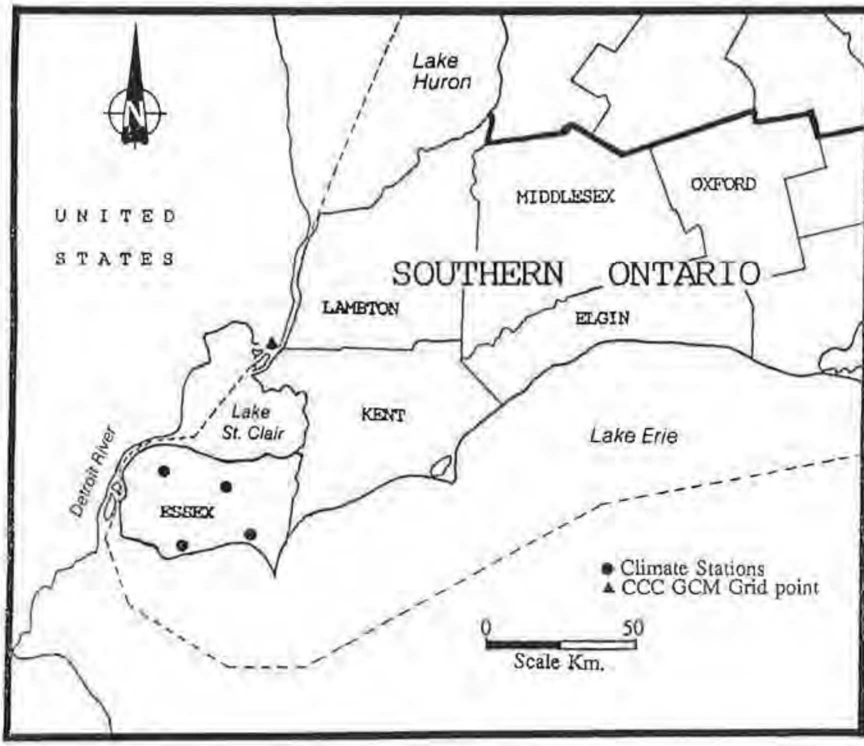

FIGURE 1: Location of Essex County study area showing climate stations and location of the CCC GCM grid point used in the study. The coordinates for the GISS and GFDL GCM grid points are given in Table 2.

able to withstand high temperatures, is particularly sensitive to water stress. This stress is often reflected in reduced yields.

There is a possible advantage to increases in CO_2 concentration. Wittwer (1978) states that, with plants grown experimentally in greenhouses, growth response often exceeding 100% occurred when atmospheric CO_2 concentration was enhanced, under high fertility and water inputs, since CO_2 is one of the components that plants use in the photosynthetic process. This advantage, however, may well be offset by other effects of increased CO_2 such as changes in temperature and moisture conditions.

Although greenhouses are a large part of Essex County's crop cultivation method, corn is still predominantly grown in open fields. It will therefore be exposed to CO_2 induced changes in the thermal and moisture regimes, given Essex County's high moisture deficit during the growing season.

A number of studies on the sensitivity of crop production to such changes in thermal and moisture regimes have recently been carried out. In southern Saskatchewan (Stewart, 1986; Williams *et al.*, 1988) and Manitoba

(Arthur *et al.*, 1986), spring wheat yields would be reduced on average by 18%, as a result of water stress induced by higher temperature that is not offset by increased precipitation. In Quebec (Singh *et al.*, 1987; Singh and Stewart, 1991) the largest increases in potential yields would occur in corn and sorghum. They also found that yields would increase for soybeans, potatoes and phaseolus beans and would decrease for cereal and oilseed crops. In Finland (Mukala, 1988), barley and oats yield increased, but not as substantially as they might have with lower precipitation. Studies done by Smit *et al.* (1989) on a variety of crops in Ontario indicate an across-the-board increase in grain corn for northern, eastern and central Ontario, and a mixed response for south-central, western and southwestern Ontario. Particularly in southwestern Ontario, only one land type out of six shows an increase in grain corn of 5.8% while others show a decrease of up to 33.3% (Smit *et al.*, 1989). All other crops in the southwestern region, particularly soybeans and barley, but with the exception of hay, show an across-the-board decrease in yields on all land types. These reductions, for the most part, are related to some stress in the water regime.

OBJECTIVES AND TERMINOLOGY

In order to examine the sensitivity of corn productivity, the study focuses on four basic objectives: (1) To establish the relationship between corn yields and the relevant climatic variables which are important to corn growth and productivity; (2) To examine the changes in the growing season for corn, with respect to the relevant climatic variables, as a result of a doubling of the carbon dioxide concentration; (3) To determine changes in corn yields as a result of climate change; (4) To determine possible changes in the supplemental irrigation of corn.

At this time some basic terms that are used throughout this study will be clarified. *Equilibrium control climate* is assumed to be present climate conditions at current carbon dioxide concentration, referred to as $1xCO_2$. *Climate change* will be taken as change in the equilibrium climate as a result of a doubling of the carbon dioxide concentration, referred to as $2xCO_2$. *Corn productivity* is described in terms of crop yields (bushels per acre) for grain corn.

ASSUMPTIONS

The behaviour of the climate system during the transition between $1xCO_2$ and $2xCO_2$ equilibrium states is not considered. During this time climate feedback as well as corn feedback processes occur. These effects have not been adequately researched, and consequently are not built into accepted methods for impact analysis. The study assumes that weeds, pests, disease and nutrient availability do not limit crop growth. This is because factors affecting the transport, migration and dispersal of pests require more extensive research before they can be effectively modelled. The availability of nutrients is a feedback effect which is not built into the models used in the study. The background economic conditions are assumed to be constant and technology will be represented by the time trend over the study period.

CORN GROWTH

Corn is chosen for study because its physiological development is well documented, and because it is one of the major crops grown in the Essex County region. Another interesting feature of corn is that there seems to be no upper temperature limit specific for corn production, although yields usually decrease with very high temperatures. There seems also to be no upper limit of rainfall beyond which corn does not grow. Corn is grown in areas where annual precipitation ranges from 25cm to 500cm. The lower limit for corn growth at extremely depressed yields is 15cm. Corn yield increases with irrigation to an optimum at 51cm above which there is no response to added water (Larson and Hanway, 1971).

A number of workers have attempted to define the limiting climatic conditions for corn production during its stages of physiological development. A minimum of 10°C is required for planting and a midsummer temperature between 21°C and 27°C for optimal growth. For the purpose of this study the six stages of development proposed by Larson and Hanway (1971) will be considered.

CLIMATE SCENARIOS

General Circulation Models (GCMs) are the most widely used to examine climate change as a result of a doubling of CO_2 concentration. They have been used in all the impact studies done for Environment Canada in the Climate Change Digest series, as well as the UNEP and IIASA studies (Bach, 1988). The GCM's vary in accuracy and resolution. The two most commonly used are from the Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Stouffer, 1980) and the Goddard Institute for Space Studies (GISS) (Hansen *et al.*, 1983). The Canadian Climate Centre model (CCC) (Boer *et al.*, 1984) has the highest resolution to date. The outputs for the various scenarios are given for grid points defined by longitude and latitude. One limitation of GCMs which may be significant in the context of Essex County's proximity to Lake Erie is that almost all continental grid points are classified as land, and in most GCMs there are no points over the Great Lakes classified as water. The GISS model attempts to modify the effect of this limitation by using the percent of land and water within grid squares containing both surfaces. The sensitivity of a CO_2 climate change model is often measured by how much the global average temperature of the surface air increases when CO_2 is doubled. The GISS model warms 4.2°C, the GFDL 4°C and the CCC 3.5°C for a doubling in CO_2 concentration.

The conventional approach for developing scenarios of climate warming is to utilize the 1951-1980 normals as the baseline (other baselines have been used), and the difference between (or ratio of) the $2xCO_2$ and $1xCO_2$

outputs as the simulated climatic change. The versions of the GISS, GFDL and CCC models used in this study have a 1951-1980 baseline period.

Cohen (1990b) identified four general approaches for scenario application: (1) The study area baseline climate is combined with the scenario anomaly of the nearest centre of a GCM grid square; (2) The scenario anomaly field is objectively interpolated (empirically), and the baseline value is combined with the interpolated scenario value for the study area; (3) The baseline field is objectively interpolated, so that data are produced for the same point as the scenario anomaly field; (4) The baseline and the anomaly fields of several scenarios (GCMs, historical, etc) are interpolated and combined into one scenario using dynamic/empirical reasoning. This study will utilize a version of the second approach, which will be discussed further in the methodology section. It is important to note that the outputs of all GCMs do not represent variations on small spatial scales. The smaller the study area, the greater the risk that its climate will not be truly reflected in the GCM outputs. It is therefore necessary to consider the differences between the GCM outputs and the local climate when interpreting the results of this study.

CROP CLIMATE MODELS

A variety of approaches have been used to examine crop response to climate variations. The procedure employed by Stewart *et al.* (1984) was used in the southern Ontario case studies. The studies done by UNEP and IIASA (Parry *et al.*, 1988) used agroclimatic indices along with simulation models and statistical empirical models.

The empirical-statistical model (ESM) takes a sample of annual crop-yield data together with a sample of weather data for the same area and time period, and relates them through statistical techniques such as a multiple regression analysis. This technique is most effective when careful and well informed selection of suitable explanatory variables, based on close understanding of basic crop physiology, is done (Parry *et al.*, 1988). The simulation models generally treat the dynamics of crop growth over the growing season through a set of mathematical expressions of the interrelationship of plant, soil and climatic processes. This procedure is restrictive for analysis of climatic variations over periods greater than a few years, and is more suited for complex large data bases, where some variables may be generated internally.

ESM's may be used with regional averages derived from a number of sites, any one of which need not necessarily provide a continuous record. Based on a comparison of the two models discussed above, the ESM is more suited for this study, and is the one used. The empirical-statistical approach was used in the UNEP/IIASA studies (Parry *et al.*, 1988) to examine variations in productivity for spring wheat in Finland, rice in Japan, livestock in Kenya, barley in Finland, and various crops in Brazil.

METHODOLOGY

The *a priori* model developed for this study (Fig. 2), treats Essex County as a single climate region over which climatic variables can be averaged without losing accuracy. Variation in annual crop yields is as a result of variation in climatic elements and time. Corn requires a particular climatic environment in which to survive. The two major factors of importance for corn to develop and produce are the availability of water and adequate temperature. These two in turn affect the evapotranspiration rate of corn as well as the length of the growing season defined by Corn Heat Units (CHU). Depending on the climatic environment, corn will yield a particular level of productivity.

Following the above line of argument, changes in the climatic environment as a result of a doubling of CO_2 concentration may result in changes in corn productivity and/or changes in the structure of the growing season. This may occur due to the combinations of the magnitude and direction of change in the climatic environment and ultimately different crop responses.

The relationship between corn yields and climate is examined in a baseline study of historical data over a thirty-one year period, from 1960 to 1990 inclusive. This time period was chosen because a minimum of 30 years is necessary to establish long term climatic normals and trends in climatic variations, and because of the availability of continuous data for the study area. The climatic normals for the time periods 1951-60 and 1980-90 show no extreme difference, indicating that the difference between the GCM normals (1951-80) and the study baseline normals (1960-90) do not represent a source of error in the results of this study. Climatic requirements for the physiological growth and development of corn vary over the growing season. It is therefore necessary to divide the growing season into subperiods which will reflect the various stages of corn growth. For convenience, and because the stages of growth can be related to months, the growing season is divided into five months, from May to September (Table 1).

The climate data used in the study were taken from the climate stations in Essex County with the longest continuous record reported in the Meteorological Observation Records of Canada. The mean monthly temperature and total monthly precipitation for May, June, July, August and September were taken for the following weather stations: Leamington, Windsor Airport, Woodslee and Harrow. The values were then averaged to produce regional values for Essex County. When available, all four station values were used and always at least two stations were used to derive the regional averages.

The evaporation data used are those reported by the Harrow Research Station, the only one in the study area to record evaporation, and which is assumed to be representative of the region. The Class A Pan evaporation data were converted to potential evapotranspiration using a Kc ratio calculated by Tan and Fulton (1979a, 1979b) at Harrow.

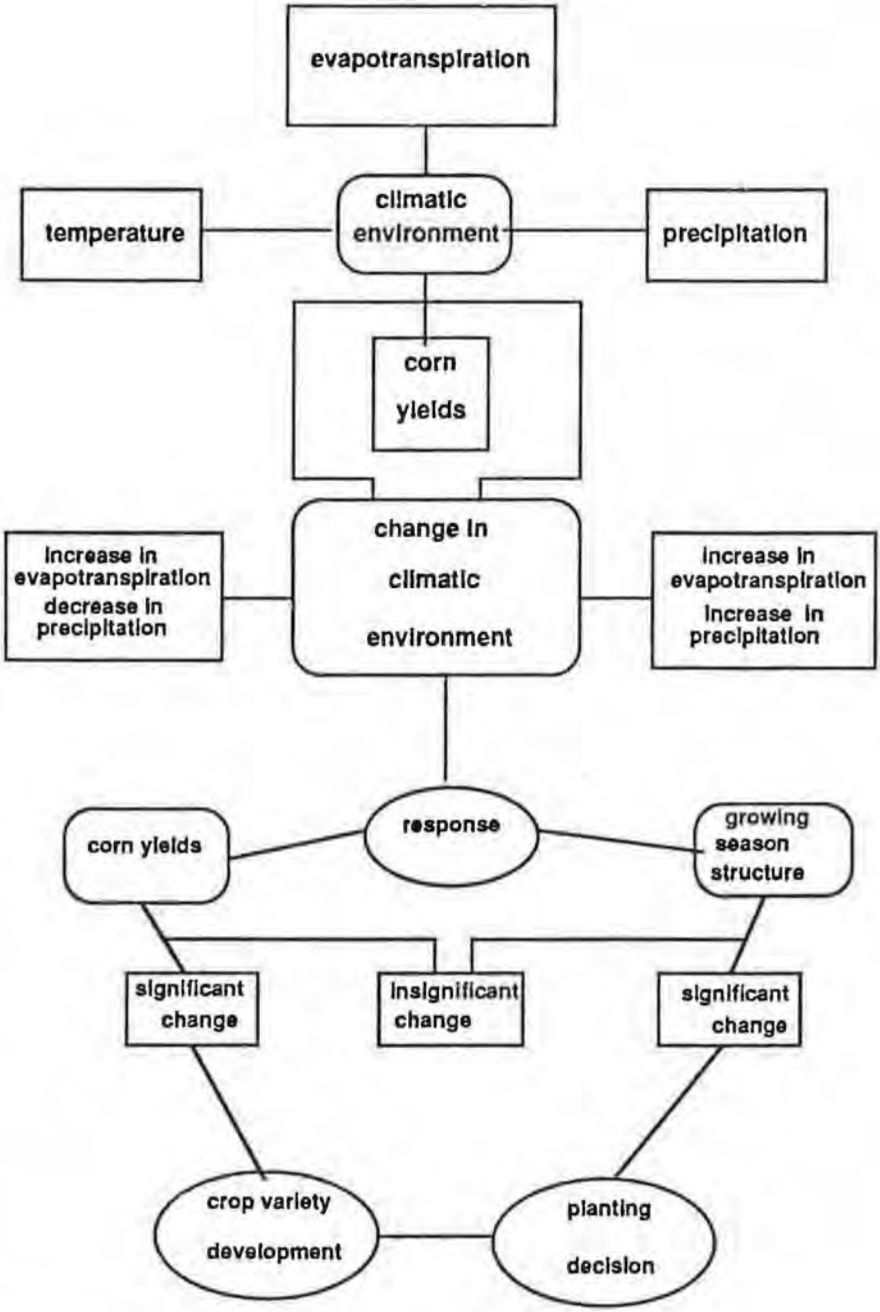

FIGURE 2: A Priori Model.

TABLE 1: Variables in the multivariate regression and the corresponding stages in the development and growth of corn.

VARIABLES	GROWTH STAGES
1. MAY MEAN TEMPERATURE (MMT) 2. MAY TOTAL PRECIPITATION (MTP) 3. MAY TOTAL POT. EVAPOTRANSPIRATION (MTE)	PLANTING AND EMERGENCE
4. JUNE MEAN TEMPERATURE (JNMT) 5. JUNE TOTAL PRECIPITATION (JNTP) 6. JUNE TOTAL POT. EVAPOTRANSPIRATION (JNTE)	VEGETATIVE GROWTH
7. JULY MEAN TEMPERATURE (JYMT) 8. JULY TOTAL PRECIPITATION (JYTP) 9. JULY TOTAL POT. EVAPOTRANSPIRATION (JYTE)	POLLINATION AND SILKING
10. AUGUST MEAN TEMPERATURE (AMT) 11. AUGUST TOTAL PRECIPITATION (ATP) 12. AUGUST TOTAL POT. EVAPOTRANSPIRATION (ATE)	MATURITY STAGE
13. SEPTEMBER MEAN TEMPERATURE (SMT) 14. SEPTEMBER TOTAL PRECIPITATION (STP) 15. SEPTEMBER TOTAL POT. EVAPOTRANSPIRATION (STE)	LATE MATURITY DRY DOWN STAGE
16. CORN HEAT UNITS (CHU)	DEFINE GROWING SEASON
17. CROP YIELDS	DEPENDENT VARIABLE
18. TIME	GROSS INDICATOR OF MODERNISATION

The mid-month Kc values were used to convert the monthly total evaporation values using the equation proposed by Doorenbos and Pruitt (1977):

$$ET = E \times Kc \quad (1)$$

where:

ET = potential evapotranspiration (mm)
E = Class A Pan evaporation (mm)
Kc = crop coefficient

Daily Corn Heat Units (CHU) are used to define the growing season length for corn. These values were either obtained from the Harrow Research Station (1971-1990) or calculated (1960-1970) using the following equation proposed by Brown (1978):

$$\text{Daily CHU} = (Ymax + Ymin)/2 \quad (2)$$

where:

$$Ymax = 3.246\,(Tmax-10.0) \quad (3)$$
$$Ymin = 1.8(Tmin-4.44) \quad (4)$$

and:

Tmax = maximum daily temperature (°C)
Tmin = minimum daily temperature (°C)

By definition, the start of the growing season is the beginning of the CHU record for each year, which is May 10, and the end of the growing season is September 30. The regional corn yields for Essex County over the thirty-one year period are those reported by the Ontario Ministry of Agriculture and Food (Agricultural Statistics for Ontario).

For the purpose of interpolation of the GCM outputs, the regional values for CHU, potential evapotranspiration, precipitation and temperature are given a geographical point location with the average longitude and latitude of the four stations used. The station locations, and those of the grid points used in this study for each GCM model, are given in Table 2.

YIELD MODELS

Before proceeding with the crop climate model (regression analysis), preliminary examination of the data set was done to identify years with extreme events. The three climatic (independent) variables were each plotted against yields and outliers in each plot identified. Outliers are data values which lie outside the general cluster of points. This procedure allows limits to be placed into the data set in order to exclude extreme events. For plots with outliers, the outlier value(s) were removed from the data set and replaced by the previous ten year average of

TABLE 2: Climate stations and GCM grid point locations

STATIONS	LONGITUDE	LATITUDE
HARROW	82.90° W	42.03°N
LEAMINGTON	82.63° W	42.05°N
WOODSLEE	82.73° W	42.22°N
WINDSOR AIRPORT	82.97° W	42.27°N
REGIONAL AVERAGE	82.81° W	42.14°N
GCM GRID POINTS		
GISS MODEL	90.0° W	50.87° N
	90.0° W	43.04° N
	90.0° W	35.22° N
	80.0° W	50.87° N
	80.0° W	43.04° N
	80.0° W	35.22° N
	70.0° W	50.87° N
	70.0° W	43.04° N
	70.0° W	35.22° N
GFDL MODEL	90.0° W	46.70° N
	90.0° W	42.20° N
	90.0° W	37.80° N
	82.5° W	46.70° N
	82.5° W	42.20° N
	82.5° W	37.80° N
	75.0° W	46.70° N
	75.0° W	42.20° N
	75.0° W	37.80° N
CCC MODEL	82.5° W	42.68° N

that variable. A comparison between the long term means of the original data set and the normalized data set (extreme values removed) shows that the differences in the mean values are less than 15% (Table 3). Although extreme events help to define the climate of a region, in this particular case their removal does not significantly affect the long-term climatic normals, and provides a normally distributed data set for analysis.

TABLE 3: Long term normals over study baseline (1960 – 1990)

VARIABLES	ORIGINAL VALUES	REVISED VALUES	% DIFFERENCE
YIELDS bus/acr.	90.0	90.0	0.0
MMT °C	14.2	14.2	0.0
JNMT °C	19.4	19.7	1.2
JYMT °C	22.2	22.2	0.1
AMT °C	21.3	21.3	0.0
SMY °C	17.4	17.3	1.0
MTP mm/m	77.0	67.1	12.9
JNTP mm/m	93.6	89.4	4.5
JYTP mm/m	88.5	77.1	12.5
ATP mm/m	86.2	74.6	13.4
STP mm/m	83.5	71.4	14.6
MTE mm/m	30.4	29.3	3.6
JNTE mm/m	94.0	94.4	0.4
JYTE mm/m	172.8	166.4	3.7
ATE mm/m	162.3	167.1	2.9
STE mm/m	76.3	73.4	3.8

The new data set of climatic variables was then used to develop a crop-climate model. In order for a more accurate and valid comparison of the three models, potential evapotranspiration values are calculated for the GISS and GFDL models, which do not have potential evapotranspiration as a direct output variable. The Priestley-Taylor method for calculating lake evaporation is used to derive the potential evaporation values:

$$\mathrm{ELAKE} = \{ a\,(S/(S+\gamma))(Q^* - QG)\}/L \tag{5}$$

where:

- S = Air temperature-dependent slope of the saturation vapour pressure curve (Pa/°C).
- Q^* = Net radiation (MJ/m^2/month).
- QG = Soil heat flux (MJ/m^2/month).
- L = Latent heat of evaporation (MJ/kg).
- γ = Psychrometric constant (Pa/°C).
- a = Non-dimensional surface evaporability factor (1.26).

The term $S/(S+\gamma)$ is derived from a polynomial regression to 2 degrees. The resulting equation is:

$$S/(S+\gamma) = 0.388636 + 0.0168712\ T + 0.0001378879\ T^2 \quad (6)$$
(100% of residuals about mean explained)

where:

T = Temperature (°C).

QG accounts for less than 5% of the net radiation, and is therefore assumed to be negligible. $Q^* - QG$ is taken to mean Q^*, which is calculated by using the equation developed by Davies *et al.* (1975):

$$Q^* = 0.72\ K{\downarrow} - 0.36 \quad (7)$$

where:

Q^* = Net radiation ($MJ/m^2/day$).
$K{\downarrow}$ = Incident solar radiation ($MJ/m^2/day$)(direct output from GISS and GFDL models)

A regression analysis has a number of assumptions which must be satisfied. Before the regression analysis was performed, tests for a normal distribution were done on the standardized variables using the Kolmogorov-Smirnov Lilliefors one sample test. All the variables were found to be normally distributed. The Lilliefors probabilities are listed in Table 4. The Durbin-Watson D statistics were used to test for temporal autocorrelations. The baseline was split into two symmetrical time periods, with 1975 being the pivot year. This was done to stabilize the time period in order to perform the test for autocorrelation. There were no temporal autocorrelations in the data set. The results are given in Table 5. From viewing the plots of yield and the climatic variables, adequate linearity exists. The plots of residuals and estimates suggest relative homoscedacity. Collinearity was not seen as significant due to the nature of the data.

The model uses corn yields (Y) as the dependent variable, and the climatic variables listed in Table 1 as the independent variables. It takes the form of:

$$\begin{aligned} Y_{CCC,GFDL,GISS} = {} & Constant + a(MMT) + b(JNMT) + c(JYMT) \\ & + d(AMT) + e(SMT) + f(MTP) + g(JNTP) \\ & + h(JYTP) + i(ATP) + j(STP) + k(MTE) \\ & + l(JNTE) + m(JYTE) + n(ATE) + o(STE) \\ & + p(CHU) + q(TIME) + E \quad (8) \end{aligned}$$

where:

E = error term

At a significance level of 0.15 (default value), a stepwise regression analysis was performed and the resulting significant variables were put into an equation to be used to predict crop yields for the $1xCO_2$ and $2xCO_2$ scenarios.

TABLE 4: Kolmogorov-Smirnov one sample test using standard normal distribution (significance level=0.05, hypothesis: distribution is not significantly different from normal)

VARIABLES	N-OF-CASES	MAXDIF	LILLIEFORS PROBABILITY (2-TAIL)
YIELDS	31	0.134	0.165
MMT	31	0.139	0.132
JNMT	31	0.092	0.748
JYMT	31	0.108	0.463
AMT	31	0.067	1.000
SMT	31	0.132	0.182
MTP	31	0.137	0.142
JNTP	31	0.095	0.683
JYTP	31	0.122	0.270
ATP	31	0.082	0.948
STP	31	0.117	0.332
MTE	28	0.135	0.211
JNTE	28	0.095	0.790
JYTE	28	0.101	0.678
ATE	29	0.121	0.328
STE	29	0.140	0.151
CHU	31	0.065	1.000
TIME	31	0.070	1.000
Z	31	0.080	0.977

TABLE 5: Test for autocorrelation (Significant at 0.05, upper critical value=1.49 and lower critical value=1.35 for D)

VARIABLES	DURBIN-WATSON D STATISTIC	1st ORDER AUTOCORR.
MMT	2.406	–0.211
JNMT	2.018	–0.011
JYMT	2.156	–0.105
AMT	1.521	0.209
SMT	1.972	0.013
MTP	1.580	0.151
JNTP	2.447	–0.226
JYTP	1.645	0.156
ATP	2.034	–0.047
STP	2.028	–0.137
MTE	1.817	0.075
JNTE	2.227	–0.113
JYTE	2.165	–0.076
ATE	1.983	0.019
STE	2.493	–0.248
CHU	2.070	–0.077
YIELDS	2.547	–0.280

The ultimate test of any model is to assess how closely its predictions correspond to actual measured observations. The outputs from the two regression models were verified against average ten-year independent crop yield data. The average values of the significant independent variables, for five ten-year periods, were put into the equation to derive the predicted corn yields.

These predicted yields were then compared to the actual yields. The mean differences between the actual yields and the predicted yields were then used as correction factors (cf) in the regression equation, to stabilize the equation and put the predicted yields within a closer range of the actual (Table 6).

As mentioned before, the method used in this study to apply the $1xCO_2$ and $2xCO_2$ scenarios is one in which the scenario anomaly field is objectively interpolated and the baseline value is combined with the scenario anomaly. For the GFDL and GISS models, outputs from nine grid points were used to create isopleth maps, and the closest grid point to the region was used for the CCC model (82.5° W 42.68° N). The output values were then interpolated for the regional point location of Essex County (82.81° W 42.14° N). The baseline normals were adjusted to $2xCO_2$ according to the predicted change in the models output. Using the slightly modified regression (correction factor added), corn yields were calculated for $1xCO_2$ and $2xCO_2$ equilibrium climates.

Using the baseline long term normals and the CCC, GFDL and GISS models' predicted changes in the climatic variables, a gross water balance was calculated for each scenario. This is used to assess any changes in the amount of irrigation supplement needed by corn to maintain its evapotranspiration needs. It is also used to identify the periods during the growing season when the greatest amounts of moisture stress occur. The equation used takes the form:

$$IS = ET - P \tag{9}$$

where

IS = irrigation supplement (mm)
ET = potential evapotranspiration (mm)
P = precipitation (mm)

Finally the structure of the growing season (defined by CHU) is assessed with regards to monthly changes in the climatic variables. These changes are related

TABLE 6: Validation of regression equations on 5 ten year series from within the baseline period

SERIES	ACTUAL YIELDS	ESTIMATED YIELDS
		YCCC,GFDL,GISS
1960-1969	75.29	16.90
1965-1974	79.35	11.53
1970-1979	96.81	27.02
1975-1984	96.10	37.91
1981-1990	107.00	47.09
Mean difference in Yields (cf)		62.88

to the physiological development of corn in an attempt to explain the predicted changes in corn yields.

ANALYSIS OF RESULTS

The stepwise regression analysis for the crop-climate model resulted in identification of six variables which are significant at a 0.15 confidence level. These are listed in Table 7 with the corresponding correlation coefficients. The variables were then used in a new model to estimate the corn-climate relationship. The regression analysis indicates that ATP, STP, JNTP, JYTE, MMT, MTE and JNTE account for 77% of the variability in corn yields. All except JYTE and MTE have a positive relation with corn yields. The resulting equation to be used to predict corn yields is:

$$Y_{CCC,GFDL,GISS} = 0.113 + 0.385(ATP) + 0.276(STP) + 0.223(JNTP) - 0.407(JYTE) + 0.599\,(MMT) - 0.352(MTE) + 0.255(JNTE) + 0.539 \quad (10)$$

To test the stability of the correlation coefficients, the significant variables were used in the model with three twenty-year series from within the baseline period 1960-1990 (Table 8). The correlation coefficients remained fairly stable, with less than 0.1 difference in almost all cases, and accounting for more than 80%

TABLE 7: Crop-Climate Model, stepwise regression with alpha to enter and remove of 0.15. (Subset model includes the following predictors: ATP, STP, JNTP, JYTE, MMT, MTE, JNTE.)

STEP= 1	ENTER	ATP	R=0.548	RSQUARE=0.341
STEP= 2	ENTER	STP	R=0.699	RSQUARE=0.489
STEP= 3	ENTER	JNTP	R=0.739	RSQUARE=0.546
STEP= 4	ENTER	JYTE	R=0.768	RSQUARE=0.590
STEP= 5	ENTER	MMT	R=0.818	RSQUARE=0.669
STEP= 6	ENTER	MTE	R=0.856	RSQUARE=0.732
STEP= 7	ENTER	JNTE	R=0.882	RSQUARE=0.777

TABLE 8: Multiple regression coefficients for three twenty year periods from within the study baseline, to test the stability of the coefficients used to predict corn yields in the regression model.

SIGNIFICANT VARIABLES	1960-80 COEFF.	1966-85 COEFF.	1971-90 COEFF.
MMT	0.594	0.608	0.447
JNTP	0.054	0.227	0.345
ATP	0.248	0.378	0.522
STP	0.269	0.280	0.051
MTE	0.266	-0.351	-0.133
JNTE	0.236	0.262	0.320
JYTE	-0.343	-0.414	-0.388
MULTIPLE R	0.810	0.870	0.707

of the variability in yields. The exceptions were three cases of precipitation, where the differences range from 0.1 to 0.2, higher in two cases and lower in one.

The correction factor derived from the validation process discussed previously is placed into the yield model. Based on equation 10 the final regression equation is defined as:

$$\begin{aligned} Y_{CCC,\,GFDL,GISS} = {} & 0.113 + 0.385(ATP) + 0.276(STP) \\ & + 0.223(JNTP) - 0.407(JYTE) + 0.599(MMT) \\ & - 0.352(MTE) + 0.255(JNTE) + 62.88 \\ & + 0.539 \end{aligned} \qquad (11)$$

where the correction factor was 62.88.

The output values for the $1xCO_2$ and $2xCO_2$ scenarios corresponding to the significant variables are inserted into the final regression equation. The output values for the GISS, GFDL and CCC models and the predicted yield results are listed in Table 9.

To correctly interpret the results of the analysis, the accuracy with which each model describes the local climate must be examined. Figures 3, 4, and 5 show the climatic variables for the $1xCO_2$ and $2xCO_2$ scenarios as well as

TABLE 9: CCC, GFDL, GISS climate change scenario values (significant variables) for $1XCO_2$ and $2XCO_2$ scenarios (Study baseline 1960 – 1990;Regional Point Location — 82.21° W 42.14° N)

	MTE mm	MMT °C	JNTE mm	JNTP mm	JYTE mm	STP mm	ATP mm	CORN YIELD b/a
CCC								
$1XCO_2$	20.9	12.0	71.4	168.5	126.1	103.7	121.8	143.3
$2XCO_2$	24.1	17.1	76.3	140.0	136.9	67.4	114.0	122.7
CHANGE	+3.2	+5.1	+4.9	-28.5	+10.8	-36.3	-7.8	-20.6
GFDL								
$1XCO_2$	21.2	16.9	75.7	78.3	136.9	71.1	53.0	87.3
$2XCO_2$	28.0	20.4	87.2	69.0	159.3	34.0	74.0	76.5
CHANGE	+6.8	+3.5	+11.6	-9.3	+22.4	-37.1	+21.0	-10.7
GISS								
$1XCO_2$	23.7	11.3	66.4	99.4	156.1	53.5	64.1	75.2
$2XCO_2$	30.1	14.8	70.9	106.0	152.9	35.1	75.0	79.9
CHANGE	+6.4	+3.6	+4.5	+6.6	-3.3	-18.4	+10.9	+4.7
STUDY								
$1XCO_2$	29.3	14.2	94.4	89.4	166.4	71.4	74.7	86.5
CCC								
$2XCO_2$	32.2	19.3	99.3	60.9	177.2	35.1	66.9	66.0
CHANGE								-20.5
GFDL								
$2XCO_2$	36.1	17.7	105.7	80.1	187.8	34.3	95.7	76.2
CHANGE								-10.3
GISS								
$2XCO_2$	30.7	17.8	98.9	96.0	163.1	53.0	85.6	91.2
CHANGE								+4.7

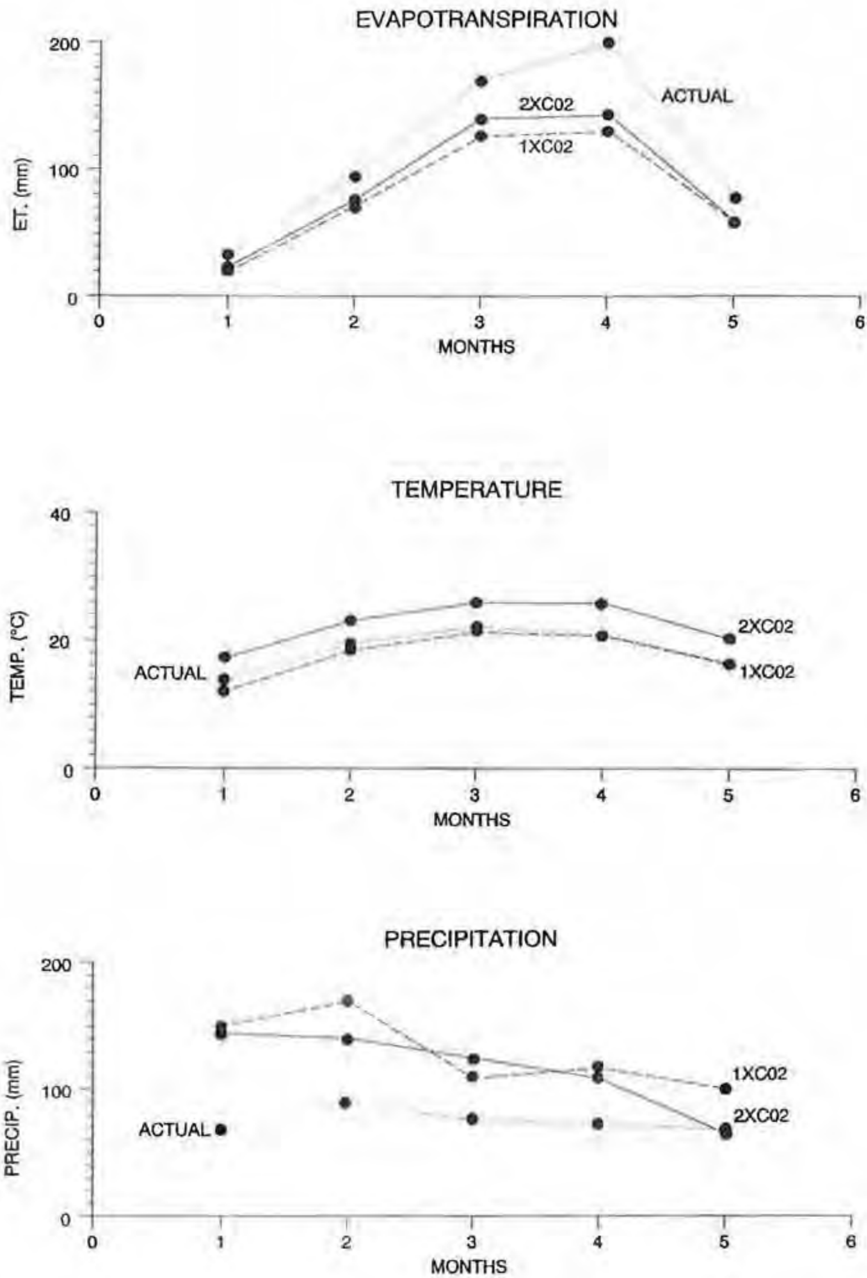

FIGURE 3: GISS Model for $1XCO_2$ and $2XCO_2$ scenarios for potential evapotranspiration, precipitation and temperature from the months of May (1) to September (5)

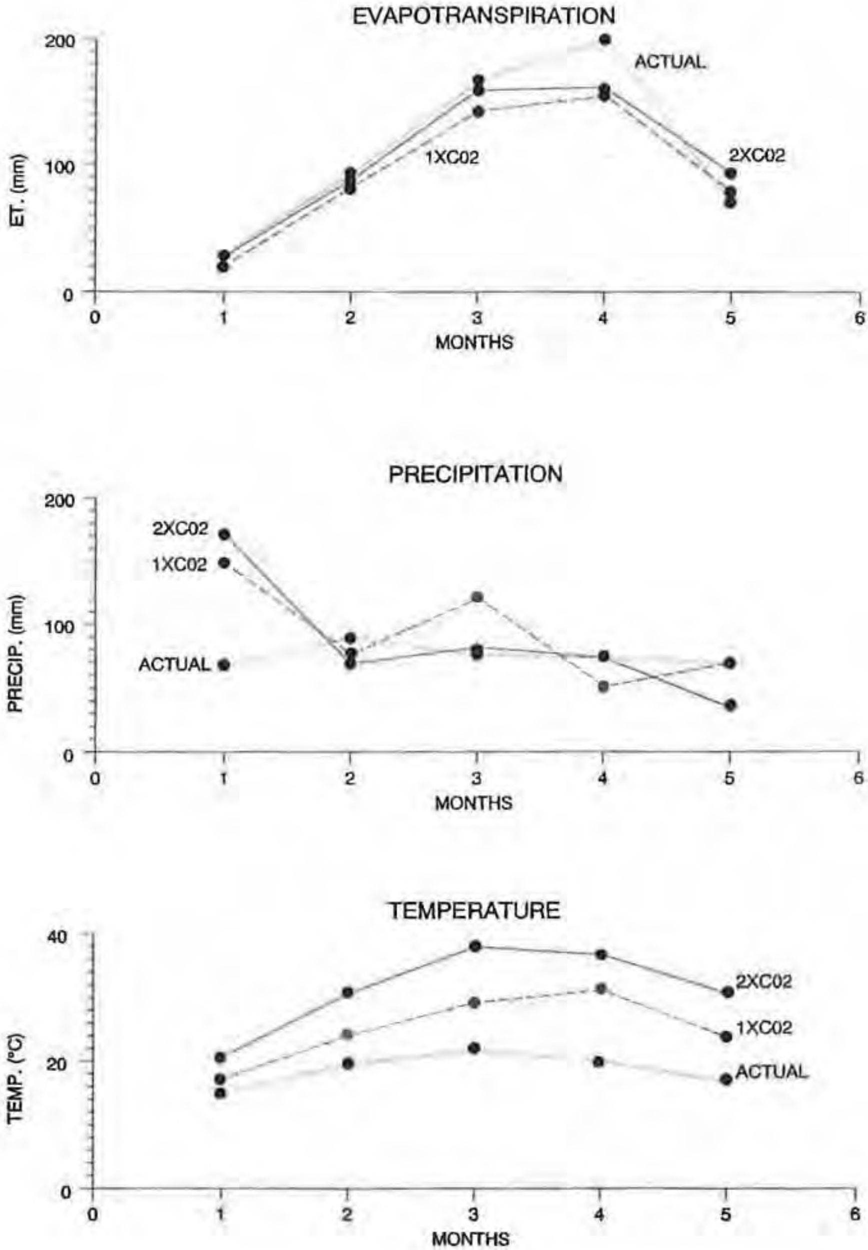

FIGURE 4: GFDL Model for $1XCO_2$ and $2XCO_2$ scenarios for potential evapotranspiration, precipitation and temperature from the months of May (1) to September (5).

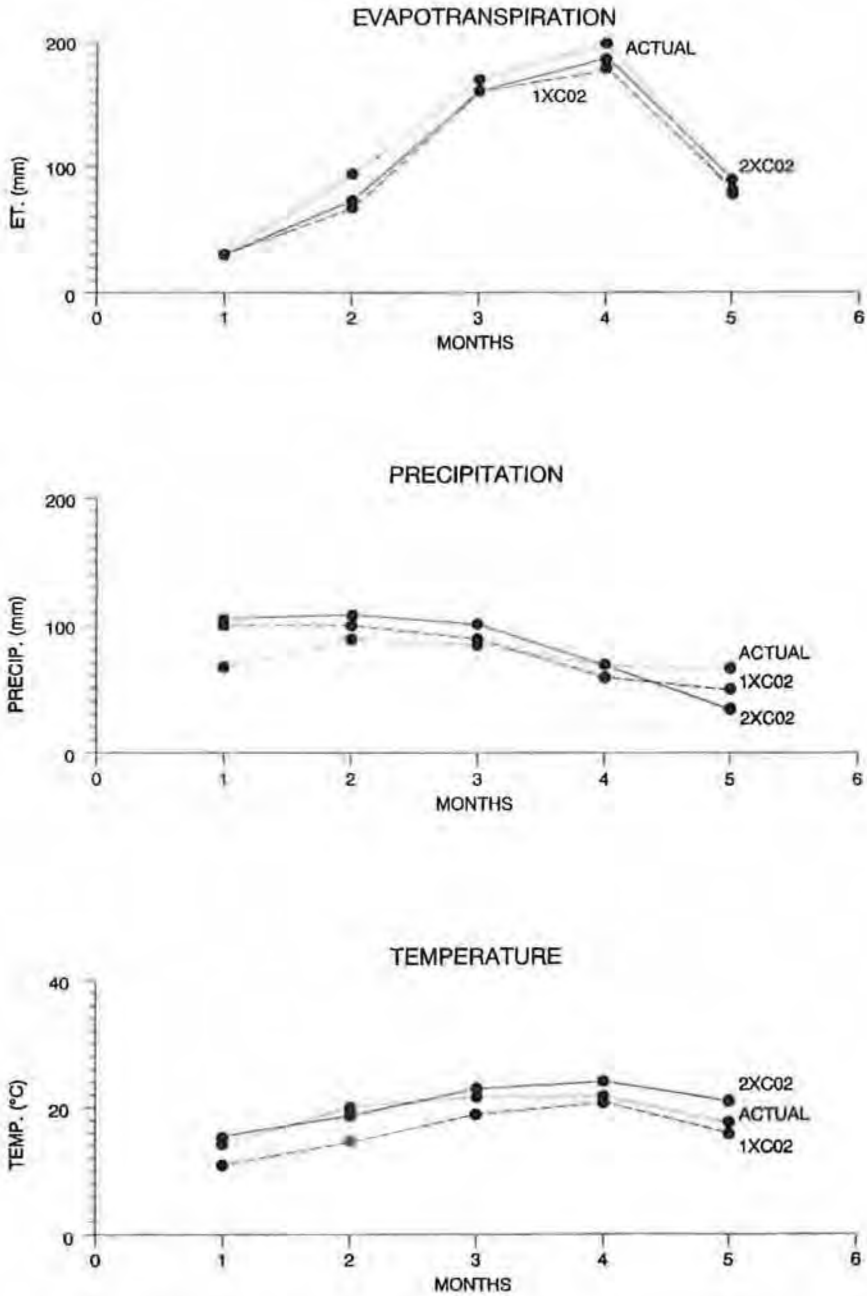

FIGURE 5: CCC Model for $1XCO_2$ and $2XCO_2$ scenarios for potential evapotranspiration, precipitation and temperature from the months of May (1) to September (5)

the long term normals for the study area. In general, the CCC model underestimates potential evapotranspiration and overestimates precipitation, but gives an almost perfect approximation of temperature. The GFDL model underestimates potential evapotranspiration, underestimates precipitation for June and August while overestimating it for May and July, and overestimates temperature. The GISS model underestimates potential evapotranspiration and temperature, and overestimates precipitation for August and September while underestimating it for May, June and July. With regards to the significant variables used to predict corn yields, the GFDL model comes closest to estimating the local climate, followed by the GISS model. The CCC model shows the poorest performance. It is therefore fair to infer that the GFDL predicted changes will be more likely to occur.

The changes in the significant variables are used to derive the modified climate for the study area. The study area baseline normals are adjusted by the changes in the CCC, GFDL and GISS models to produce $2XCO_2$ scenarios corresponding to the individual models. These baseline mirrored scenarios should give a more accurate suggestion of absolute magnitude of change. Both the CCC and the GFDL models indicate a decrease in yields, of 20.6 and 10.7 bushels/acre respectively, while the GISS model shows an increase of 4.7 bushels/acre.

Preliminary examination of changes in the climatic variables indicates that the reduction in yields predicted by the CCC and GFDL models may be a result of the decrease in precipitation and the increase in potential evapotranspiration, while increase in yields predicted by the GISS model may be the result of increased May temperature, increased June precipitation and decreased July potential evapotranspiration.

The GISS, GFDL, and CCC models all indicate an increase in temperature (Figures 3,4,5). The increase in May temperature is of particular importance, because it shows a significant relationship with corn yields. This is the planting and emergence stage for corn. With increased temperatures, there will be less likelihood of crop failure due to late frost, or temperature below the lower threshold for germination. The GISS model in Figure 3, and the GFDL model in Figure 4, indicate an increase in May precipitation while the CCC model in Figure 5 shows a decrease. This does not significantly affect yields, however, as May's precipitation does not appear to affect corn productivity. The CCC, GFDL and GISS models also indicate an increase in potential evapotranspiration for May (Figures 3,4,5). Although May potential evapotranspiration has a significant relationship with corn yields, there is not much vegetative cover at this time so yield reduction as a result would be negligible.

The CCC and the GFDL models indicate a decrease in precipitation for June (Figures 4 and 5). This is a period when water availability is important to the vegetative growth of corn, and the decrease in June precipitation may be partially responsible for the predicted reduction of yields by

TABLE 10: Change in corn yields for $2XCO_2$ scenario

SCENARIO	CHANGE IN CORN YIELD	
	Bushels/Acre	Percentage
CCC	-20.6	-14.4
CCC BASELINE	-20.6	-14.4
GFDL	-10.7	-12.4
GFDL BASELINE	-10.3	-11.9
GISS	+4.7	+6.3
GISS BASELINE	+4.7	+5.4

the CCC and GFDL models. The CCC, GFDL and GISS models (Figures 3,4,5) also indicate an increase in potential evapotranspiration for June. In conjunction with the increase in temperature and decrease in precipitation, the higher potential evapotranspiration rate reinforces the water stress placed on corn at this time. Research indicates that up to 4% yield decrement per day of water stress is possible during this period.

The only significant variable for the month of July is the rate of potential evapotranspiration for which the CCC and GFDL models indicate an increase and the GISS a small decrease. This is a critical stage for corn at which time pollination and silking occur. High potential evapotranspiration rates may contribute to water stress, which could result in up to 8% yield reduction per stress day during this time. The large decrease in precipitation for September predicted by all three models (Figures 3,4,5, and Table 9), may also be a significant contributing factor in the predicted yield reduction.

The reduction in yields indicated by the CCC and GFDL models may be counteracted in two ways. Farmers may plant more drought-resistant species, or they may increase supplemental irrigation. With the current deficit in the water balance during the growing season, increasing irrigation may be a problem in itself. This is one aspect where further research is needed, as indicated by the study. It has already been established by the CCC and GFDL models that there will be a need for increased supplemental irrigation. This is further investigated in the next section.

CHANGES IN THE IRRIGATION REQUIREMENT FOR CORN

A gross index for irrigation requirements can be calculated for corn, using the baseline long-term normals, and the changes indicated by the CCC, GFDL and GISS $2XCO_2$ scenarios. The result of this procedure will verify the predicted corn yield results, as well as indicate areas within the growing season which may experience the most water stress. Runoff is not considered, and changes in irrigation requirement are a direct result of changes in precipitation and potential evapotranspiration. It must again be stressed that, because of the gross nature of the water balance used, the direction of change holds more significance than the magnitude of the change.

The irrigation supplement may be calculated for corn using Equation 9. When precipitation is greater than potential evapotranspiration, no supplemental water is needed and IS will be negative, indicating a surplus of water available. Tables 11 and 12 give the data inputs used in calculating the water balance, as well as the changes in the water balance as a result of changes in the climate.

Under the current climatic conditions of Essex County there is a need for irrigation supplement of 151 mm over the growing season. There is a surplus of water in May, but June, July, August and September show a need for supplemental water, with July and August having the greatest need. As a result of climate change, the CCC, GFDL and GISS models indicate that the need for irrigation supplement would increase by 94mm, 104mm and 14mm respectively for the growing season. The CCC model shows substantial increase in irrigation need for June, August and September, whereas July indicates a small reduction, although substantial irrigation supplement is still required for that month. The GFDL model shows large increases in irrigation need for June, July and September, and a reduction for August. The GISS model indicates an increase in irrigation supplement for August and September and a decrease for June and July.

Overall, irrigation supplement is expected to increase and Table 12 corroborates the predicted yield results of the GFDL and CCC models, where the reduction in yields may be attributed to possible water stress.

TABLE 11: Data input for irrigation need calculation.

	1XCO2 (mm)				2XCO2 (mm)		
PERIOD	IS	P	ET	MODEL	IS	ET	P
MAY	-37.80	67.10	29.30	CCC	-26.8	32.5	59.3
				GFDL	-54.0	36.1	90.1
				GISS	-40.4	30.7	71.1
JUNE	5.00	89.84	94.40	CCC	38.4	99.3	60.9
				GFDL	25.9	106.0	80.1
				GISS	2.9	98.9	96.0
JULY	89.30	77.10	166.40	CCC	81.7	177.0	95.3
				GFDL	151.5	187.8	36.6
				GISS	73.0	163.1	90.1
AUGUST	92.50	74.60	167.10	CCC	110.4	177.3	66.9
				GFDL	77.5	173.1	95.6
				GISS	97.4	182.9	85.5
SEPT.	2.00	71.40	73.40	CCC	41.5	76.6	35.1
				GFDL	54.4	85.7	31.3
				GISS	32.1	85.1	53.0
GROWING SEASON	151.00	379.60	530.60	CCC	245.3	562.7	317.4
				GFDL	255.3	588.7	333.7
				GISS	165.0	560.7	395.7

TABLE 12: Irrigation supplement (mm) (N/A-water surplus for May)

PERIOD	$1XCO_2$	MODEL	$2XCO_2$	CHANGE
MAY	-37.8	CCC	-26.8	N/A
		GFDL	54.1	N/A
		GISS	40.4	N/A
JUNE	5.0	CCC	38.4	+33.4
		GFDL	25.9	+20.9
		GISS	2.9	-2.1
JULY	89.3	CCC	81.7	-7.6
		GFDL	151.5	+62.2
		GISS	73.0	-16.3
AUGUST	92.5	CCC	110.4	+17.9
		GFDL	77.5	-15.0
		GISS	97.4	+4.9
SEPT.	2.0	CCC	41.5	+39.5
		GFDL	54.4	+52.4
		GISS	32.1	+30.1
SEASONAL	151.0	CCC	245.3	+94.3
		GFDL	255.3	+104.3
		GISS	165.0	+14.0

CONCLUSION

Climatic variables such as temperature, precipitation and evapotranspiration have a strong correlation with corn yields. Summarizing, throughout the growing season, from May to September: May temperature has a positive relationship with yields; June's precipitation and potential evapotranspiration, and August and September's precipitation are positively correlated with yields; while May and July's potential evapotranspiration are negatively correlated with yields. The relationship indicated by the regression analysis is very strong. The significant climatic variables account for 78% of the variability in corn yields. From these results one can infer that variability in climate has a strong impact on corn yields. This impact is reflected in the direction and magnitude of change in corn yields, caused by changes in the various climatic elements at critical times in the growing season. Climate change as a result of a doubling of atmospheric CO_2 concentration may have two consequences on corn yields in the Essex County region. Corn yield may increase by 6.3% as predicted by the GISS. This outcome may be a result of the increases in precipitation and a small decrease in potential evapotranspiration. Corn yields may also decrease as a result of climate change, as indicated by the CCC and GFDL models. All three models indicate that there will by a need for increased irrigation, lending some validation to the results of the CCC and GFDL models, and possibly reducing the already small increase indicated by the GISS model. With the GFDL model having the best estimation of the local climate, a reduction in corn yields for Essex County is the most valid conclusion.

The results of this study should be treated with some caution due to the scale of analysis of GCMs (Grotch and MacCracken, 1991), but they may have important implications for corn production in the Essex County region. A 14.4% reduction in corn yield is predicted by the CCC and a 12.4% reduction by the GFDL model. This is a significant change which may require serious adaptive strategies to ensure adequate productivity. The reduction in yields may be attributed to high water stress during the critical stages of corn growth and development (June, July and August). Water stress is a problem already faced by farmers in the Essex County region. The possibility of an increase in water stress as a result of climate change holds serious implications for this area. Farmers may adapt to these changes by planting corn varieties which are more water efficient and/or increasing irrigation. The importance of supplemental water supply for corn in the future has been clearly indicated by this study. Further research is needed in this area to specifically determine more accurately the future water need for agriculture, and the capability of the region for handling such increases in water requirement. Other possible areas of research are the improvement of GCM application techniques for smaller spatial scales, and the improvement of the precipitation inputs into GCMs. These two factors are interlinked, as precipitation is a local phenomenon which is difficult to resolve at large spatial scales.

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Étude comparative d'approches utilisées pour l'estimation de l'évapotranspiration en régions tropicales

Alain Viau,[1]
Jean Boivin[2]
et
Bhawan Singh[3]
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RÉSUMÉ

Dans les régions tropicales les stations agrométéorologiques utilisent les bacs à évaporation (classe "A") pour estimer l'évaporation et l'évapotranspiration. Les stations automatiques sont rares et on a donc recours à des observateurs. Les normes de la FAO et de l'OMM, dans leurs sens le plus stricte, ne sont pas toujours respectées, réduisant ainsi la représentativité des résultats. En plus de la technique des bacs qui est généralisée à travers le monde, d'autres approches "classiques" dont la marge d'erreur est connue ont été expérimentées pour estimer l'eau utilisée par les plantes (ET). L'étude décrite dans cet article s'est déroulée à Trinité et Tobago. Les approches retenues sont celles proposées par Bowen (1926), Penman-Monteith (Monteith, 1965), Priestley-Taylor (1972) et Blaney-Criddle (1950). L'étude nous a permis de démontrer que sans aucun contrôle de qualité l'utilisation des bacs engendre une marge d'erreur non négligeable. Les valeurs obtenues peuvent véhiculer une erreur de plus de 22% sur une base journalière et d'autour de 5% sur une période d'un mois. L'approche de Blaney-Criddle s'avère nettement supérieure puisque l'erreur qui y est véhiculée est alors réduite à 10% sur une base journalière et à 2% sur un cumul d'un mois. Avec la technologie moderne et l'informatisation des banques de données agrométéorologiques, il y a lieu de reconsidérer les normes relatives à l'utilisation des bacs à évaporation voire même à implanter d'autres techniques d'estimation de l'évaporation et de l'évapotranspiration.

ABSTRACT

In most tropical countries, agrometeorological stations normally use class A evaporation pans for estimating evaporation and evapotranspiration. Automatic recording stations are rare, standard procedures are not always rigidly adhered to, and this may limit data

1 Département de sciences géodésiques et télédétection, Université Laval
2 Chargé de projet, CARTEL, Université de Sherbrooke
3 Département de géographie, Université de Montréal

quality. Apart from pan measurements, which are widely used throughout the world, we experimented with other well-known micrometeorological techniques for estimating plant water use (ET) in Trinidad and Tobago. The methods chosen were the Bowen ratio-energy balance approach (Bowen, 1926) which served as the control measurement and the Penman-Monteith (Monteith, 1965), Priestley-Taylor (1972) and Blaney-Criddle (1950) formulations. The study results show that pan measurements may give significant errors if the standards are not strictly followed. These errors can be as high as 22% on a daily basis and about 5% for a period of one month. The Blaney-Criddle approach seems to provide better results based on the fact that daily errors are of the order of 10% while the error over one month is about 2%. With the advent of modern technology in data acquisition and analysis, it is recommended that standards for pan measurements be re-examined and even that other more sophisticated and reliable techniques for estimating crop ET be adopted.

INTRODUCTION

Le développement d'approches empiriques, semi-empiriques et directes d'estimation de l'évapotranspiration en milieu agricole à fait l'objet de nombreux travaux ces dernières années. D'excellentes revues des principales approches ainsi que de leurs limites respectives peuvent être consultées dans Doorenbos et Pruitt (1977) ainsi que Brutsaert (1982). D'autres études plus spécifiques aux approches ont aussi fait l'objet de publication (ASAE, 1985).

Les approches pour déterminer l'évaporation peuvent être divisées en deux catégories: a) celles qui requièrent très peu ou pas d'information sur la surface ou la culture (directes) et b) celles qui nécessitent une banque d'information plus ou moins exhaustive du type de surface et des conditions environnementales et météorologiques au-dessus de celle-ci (indirectes).

Ainsi, selon l'application pour laquelle le taux d'évaporation ou d'évapotranspiration sera estimé ainsi que de l'échelle spatio-temporelle qui y sera associée, un nombre important d'approches hydrologiques, climatologiques et micrométéorologiques ont été proposées dans la littérature (Brutsaert, 1982). Certaines de ces approches sont très précises telles celles exploitant les lysimètres (Klocke *et al.*, 1985), le bilan d'énergie (Tanner et Pelton, 1960; Garratt, 1984) ou encore celles se référant au flux turbulent (eddy correlation) (Swinbank et Dyer, 1951). Ces méthodes sont coûteuses et demandent des visites régulières sur le terrain. D'autres approches moins coûteuses exploitant les bacs à évaporation (Doorenbos et Pruitt, 1977) ou les données des stations climatologiques et météorologiques locales (Blaney et Criddle, 1950) sont plus accessibles mais leurs précisions peuvent être un facteur limitatif au niveau de leur applicabilité.

Nous avons voulu vérifier la réponse de ces deux dernières approches, soit celle du bac à évaporation et celle de Blaney-Criddle. Elles seront confrontées à trois approches se référant au bilan d'énergie, soit celles proposées par Bowen (1926), Priestley-Taylor (1972) et Penman-Monteith (Monteith, 1965). Ces dernières approches basées sur le transfert d'énergie prennent en considération les mécanismes de transfert de la vapeur d'eau au dessus d'un couvert de végétation par l'entremise des gradients thermiques, énergétiques et d'humidité en relation avec le régime radiatif. Il faut par contre prendre en considération que toutes les approches demeurent approximatives et qu'elles ne véhiculent pas la même marge d'erreur.

Ce texte ne se veut pas une revue critique des différentes approches (bac à évaporation et Blaney-Criddle) mais plutôt une évaluation de leur réponse par rapport à l'approche proposée par Bowen (1926) et connue dans la littérature comme étant la plus adéquate (Spittlehouse et Black, 1980; Fuchs et Tanner, 1970).

Approche du rapport de Bowen/bilan d'énergie

La méthode du bilan d'énergie telle que proposée par Bowen (1926) fait appel au principe de la conservation de l'énergie. Ainsi, le calcul de la quantité d'eau transférée vers l'atmosphère s'obtient en supposant que le flux de chaleur latente est fonction de l'énergie utilisée pour le changement d'état de l'eau liquide à vapeur.

TABLEAU I: Paramètres micro-climatologiques nécessaires pour l'application des différentes méthodes d'estimation de l'évapotranspiration.

VARIABLES	SYMBOLES	Rapport de Bowen	Priestley-Taylor	Penman-Monteith	Bac à évaporation	Blaney-Criddle (FAO)
Radiation solaire nette	Q^*	✓	✓	✓		
Flux de chaleur dans le sol	QG	✓	✓	✓		
Température de l'air	T	✓	✓	✓		✓
Résistance de l'air et aérodynamique	r_a r_s			@ @		
Evaporation	E				✓	
Vitesse du vent	U			✓	@	✓
Humidité relative	RH				@	✓
Radiation solaire globale	$K\downarrow$					✓
Coefficient de culture	Kc				✓	✓
Type d'ET		R	R	R	P	P
Précision		15%	15%	≤10%	15%	<25%
Référence		Sinclair et al (1975)	Viau (1987)	Stewart (1987)	Doorenbos et Pruitt (1977)	Doorenbos et Pruitt (1977)

✓ = Donnée mesurée. R = Evapotranspiration réelle.
@ = Donnée approximée si non-disponible. P = Evapotranspiration potentielle.

Bowen (1926) suggère l'approche suivante pour obtenir l'évapotranspiration, qui sera représentée par ETβ. Il propose alors:

$$ET\beta = \frac{Q^* - QG}{1 + \beta} \qquad 1$$

où β est estimé à partir de l'équation suivante:

$$\beta = \gamma \frac{K_h}{K_w} \quad \frac{\Delta T}{\Delta e} \qquad 2$$

où

γ = constante psychrométrique (0,066 Pa/°C)
K_w, K_h = diffusivité turbulente de la vapeur d'eau et de la chaleur (cm^2/s)
$\Delta e, \Delta T$ = gradients verticaux de la pression de vapeur (Pa/m), et de la température (°C/m).

Selon de nombreuses études (Spittlehouse et Black, 1980; Fritschen et Simpson, 1989; Viau, 1987; Viau et Singh, 1991) l'approche de Bowen/bilan d'énergie (BREB) s'avère être l'approche de référence avec la plus faible marge d'erreur soit environ ±15%. Cette dernière, quoiqu'approximative, demeure une bonne référence pour l'estimation de l'évapotranspiration car les instruments de mesure utilisés sont très précis (psychromètre précis à ±0,005°C). De plus, elle constitue l'unique méthode qui tient compte des flux turbulents grâce à ΔT et Δe.

Approche de Penman-Monteith

Monteith (1965) bâtit un modèle à partir de l'approche proposée par Penman (1948) pour estimer le taux d'évaporation d'un couvert végétal. Ainsi:

$$ETpm = \frac{S(Q^* - QG) + \sigma C_p\,(e_s(T) - e(T))/r_a}{S + (1 + r_c/r_a)} \qquad 3$$

où

C_p = capacité volumétrique de chaleur de l'air (J/m^3 °C)
σ = densité de l'air (Kg/m^3)
e = pression de vapeur de l'air actuelle pour un niveau z donné (Pa).
e_s = pression de vapeur saturante de l'air pour un niveau z donné (Pa).
r_a = résistance aérodynamique de l'air (s/m)
r_c = résistance du couvert végétal (s/m)
S = pente de la courbe de pression saturante (Pa/°C)
T = température de l'air (°C)

La résistance du couvert (r_c) peut être dérivée à partir des résistances stomatiques mesurées directement sur le terrain à partir desquelles on calcule r_c (Singh et Szeic, 1981) en tenant compte des facteurs physiques qui influencent leur comportement (Viau, 1987). Dans le cas de la résistance aérodynamique de l'air (r_a) l'équation suivante proposée par Monteith (1965) est alors utilisée:

$$r_a = 1/k^2u \ \ln [(z - d)/z_0]^2 \qquad 4$$

où

d = la hauteur de déplacement du plan zéro (m)
z_0 = la longueur de rugosité (m)
u = la vitesse du vent à la hauteur z (m/s)
k = la constante de von Karman (0,41)

Approche de Priestley et Taylor

Priestley et Taylor (1972) présentent une autre approche d'estimation du taux maximum d'évapotranspiration où:

$$ETpt = \alpha' \frac{S(Q^* - QG)}{S + \gamma} \qquad 5$$

Pour une surface humide $\alpha' = 1$ alors que pour une surface sèche, $\alpha' < 1$. Dans la présente étude α' fut estimé par l'approche suivante (Singh *et al.* 1984):

$$\alpha' = \frac{S + \gamma}{S(1+\beta)} \qquad 6$$

Approche de Blaney-Criddle (FAO)

L'approche de Blaney-Criddle (FAO) est largement utilisée à travers le monde parce qu'elle est basée sur la température, paramètre mesuré dans toutes les stations météorologiques. Allen et Pruitt (1986) ont démontré que l'approche de Blaney-Criddle (FAO) offre de meilleures prédictions que l'approche de Penman telle que modifiée par Doorenbos et Pruitt (1977) et celle utilisant l'évolution du degré d'humidité du sol (Wright, 1985). D'autres prônent l'utilisation de cette méthode sur une base journalière (Cuenca et Amegee, 1987). La version la plus répandue se définit par l'équation suivante (Doorenbos et Pruitt, 1977);

$$ETbc = \{ a + b [pe(0{,}46T + 8{,}13)]\}[1{,}0 + 0{,}1(E/1000)] \qquad 7$$

alors, en simplifiant;

$$ETbc = a + b f \qquad 8$$

où

$$f = pe\,(0{,}46\ T + 8{,}13) \qquad 9$$

où ETbc est l'évapotranspiration en mm/jour, pe représente le pourcentage d'heures d'ensoleillement, T est la température moyenne de l'air (°C), a et b sont des coefficients de calibration qui tiennent compte des conditions climatiques tels que définis par Doorenbos et Pruitt (1977) et E représente l'altitude en mètres au-dessus de la mer de la station. Le coefficient "a" peut être calculé à partir de la relation suivante:

$$a = 0{,}0043(RHmin) - n/N - 1{,}41 \qquad 10$$

où RHmin (%) représente l'humidité relative moyenne journalière et n/N est l'insolation effective. Le coefficient "b" est calculé à partir de valeurs dérivées d'une table élaborée par Frevert *et al.* (1983). Ainsi:

$$b = 0{,}81917 - 0{,}0040922(RHmin) + 1{,}0705(n/N) + 0{,}065649(U) - 0{,}0059684(RHmin)(n/N) - 0{,}0005967(RHmin)(U) \qquad 11$$

où U est la moyenne journalière de vitesse du vent (m/sec) à une élévation de 2 mètres. Il faut cependant prendre note que la journée est définie arbitrairement par la FAO entre 07H00 et 19H00. Allen et Wright (1983) ont démontré que cette approche est satisfaisante sur une base journalière mais nécessite des corrections, ce que nous allons tenter d'apporter dans la présente étude.

Approche du Bac à évaporation (OMM/FAO)

L'évaporation ou l'évapotranspiration mesurée à partir du bac à évaporation est obtenue à l'aide de l'équation suivante (Doorenbos et Pruitt, 1977):

$$ETbac = Kp\ Ebac \qquad 12$$

où ETbac est l'évapotranspiration réelle, Ebac est l'évaporation du bac en mm/jour et représente la valeur moyenne journalière pour la période considérée et Kp est un coefficient de correction du bac déterminé à partir d'une table de référence basée sur l'humidité relative et la nature de la couverture végétale (Doorenbos et Pruitt, 1977).

Si on reconsidère les équations 8 et 12 et que l'on désire estimer l'évapotranspiration au-dessus d'un couvert de végétation nous pouvons alors exploiter les relations suivantes:

$$ETbac = Kc\ Kp\ Ebac \qquad 13$$

$$ETbc = Kc\,(a + b\,f) \qquad 14$$

où Kc est un coefficient de culture relatif au type de couvert de végétation. Le coefficient de culture est avant tout un facteur de correction qui ajustera l'évapotranspiration potentielle (ETP) afin de nous donner l'évapotranspiration réelle de la culture (ETR), comme l'indique l'équation [15]:

$$ETR = Kc \; ETP \qquad 15$$

Kc comprend donc les effets des caractéristiques de la culture face à ses besoins en eau. Ces caractéristiques sont entre autres la résistance stomatique, la hauteur, la rugosité, l'albédo et la couverture du sol de la culture. Kc dépendra de la date de plantation de la culture, de son taux de développement, de la longueur de sa période de croissance et des conditions climatiques (Doorenbos et Pruitt, 1977).

Le choix de l'une ou de l'autre de ces méthodes pour estimer l'évapotranspiration d'une surface donnée dépend principalement de l'accessibilité des données et du degré de précision désiré (Boivin, 1989). Le tableau I montre les variables nécessaires et un indice de la précision obtenue avec les différentes approches.

MÉTHODOLOGIE

Cette étude a été conduite sur les terrains de Caroni (1975) Ltd situés dans le comté de St-Joseph, Trinité-et-Tobago (10°05'N et 61°36'W).

Deux sites furent choisis, soit un champ de gombo (Orange Grove) *Hibiscus esculentus* (également connu sous le nom d'okra), de la famille des Malvacées, et un champ de riz (Caroni) de type Oryzica. Comme les sols soutenant les cultures étudiées appartiennent à la formation de Tacarigua, ils peuvent être décrits comme un loam limono-sableux (sol no. 423 dans la classification de Trinité-et-Tobago, Brown et Bally, 1970).

La prise des données a eu lieu du 17 janvier 1989 au 3 mars 1989. Pour chacun des sites à l'étude, une tour agrométéorologique (figure 1) supportait les différents appareils de mesure. Le rayonnement net (Q^*) a été mesuré à l'aide d'un bilanmètre (Micromet Systems) installé à 1,5 m au-dessus de la surface du sol. Le flux de chaleur dans le sol a été mesuré à l'aide de trois plaques thermopiles (HFT-1, Micromet Systems) enfouies à 5 cm de la surface du sol. La température du sol, nécessaire pour corriger QG au niveau de la divergence de chaleur entre la surface et 5 cm, est obtenue à l'aide de trois sondes RTD enfouies dans le sol à 5 cm de profondeur et à un angle de 45°, afin d'obtenir la moyenne de la température des cinq premiers centimètres de sol. La température verticale de l'air ainsi que le gradient de pression de vapeur d'eau ont été mesurés à l'aide d'une paire de psychromètres ventilés se déplaçant le long d'un rail suivant un intervalle de temps prédéterminé à l'aide d'un mécanisme d'échange automatique (M.E.A.) dans le but d'éliminer les erreurs systématiques et de calculer le rapport de Bowen. Le psychromètre du bas se trouve à 20 cm au-dessus de la végétation et le psychromètre du haut se trouve à 1 m au-dessus de celui de bas. Chaque psychromètre est ventilé par un ventilateur de 12 Vdc (Micromet Systems V581L) qui demande 50 ma de

FIGURE 1 : Vue d'ensemble des instruments utilisés lors de la collecte de données.

courant et donne un courant d'air de 4 m/s. La température des psychromètres (sec et mouillé) est donnée par des senseurs de platine encaissés dans un tube d'acier inoxydable et offrant une résistance de 500 ohms, Les quatre éléments (deux mesurant la température du thermomètre sec et deux mesurant la température du thermomètre mouillé) sont branchés en série à une source de courant constant tel que décrit par Fritschen et Simpson (1989). Avec cette technique, le même courant d'air passe à travers les éléments, ce qui permet une précision de 0,005° C et un écart de température de 40° C. Des mèches de céramique mesurant 1 cm avec un apport constant en eau distillée sont utilisées pour les thermomètres mouillés.

La vitesse du vent est obtenue à l'aide d'un anémomètre (WS-1, Remote Measurement Systems) dont la vitesse minimale d'entraînement est de 2,7 m/s. L'anémomètre est fixé à 2 m au-dessus de la surface. La direction du vent est mesurée à l'aide d'une girouette (WD-1, Remote Measurement Systems) d'une précision de ±5 degrés et fixée à 2 m au-dessus de la surface.

L'humidité du sol pour sa part est mesurée à l'aide d'un bloc de gypse (SMR-1B, Beckman Instruments Inc) enfoui à 20 cm de la surface, soit à la profondeur des racines. Parallèlement à la mesure du bloc de gypse, des mesures gravimétriques d l'humidité sont effectuées dans le sol autour du site pour les premier 25 cm de sol. Finalement un pluviomètre électronique (RG-100, Rainwise Inc.) dont le seuil est de 0,1 mm est placé près de la surface, dans un endroit ouvert à 15 m de distance de la tour.

Tous ces appareils sont reliés à un convertisseur analogue/digital qui est lui-même relié à un ordinateur portatif (PC NEC-8300). L'ordinateur est programmé pour que la séquence d'opération suivante soit exécutée indéfiniment; 1) envoi du signal au M.E.A. pour faire changer les psychromètres de niveau, 2) attente de 3 minutes pour permettre l'équilibre des psychromètres, 3) six fois la lecture de tous les instruments avec 300 secondes d'intervalle entre chaque lecture, 4) moyenne de ces trois dernières minutes et 5) sauvegarde sur disque de cette moyenne. À la fin de la journée, on obtient 240 séries d'observations.

Un bac à évaporation de classe "A" est aussi placé sur chacun des sites selon les normes de la FAO (Doorenbos et Pruitt, 1977) pour l'évaluation de l'évapotranspiration potentielle à partir d'une surface d'eau.

En plus des données récoltées par ces divers appareils, un ensemble de données météorologiques en temps réel couvrant la période d'échantillonnage fut également recueilli. Les données météorologiques provenaient du réseau national supervisé par le Water Resources Agency de Trinité-et-Tobago.

Un test de validité des valeurs prédites par rapport au valeurs observées (mesure d'erreur) est appliqué selon l'approche suivante:

- RMSE, racine de l'erreur moyenne au carré.

$$RMSE = [N^{-1} \Sigma(Pi - Oi)^2]^{0.5} \qquad 16$$

où

N = nombre de cas
Pi = valeur prédite au point i
Oi = valeur observée au point i.

- L'indice de coïncidence (d):

$$d = 1 - \frac{N\,RMSE^2}{PE} \qquad 17$$

avec PE, la variance de l'erreur potentielle :

$$PE = \Sigma\,[(|Pi - (\Sigma Oi)/N| + |Oi - (\Sigma Oi)/N|)^{0.5}] \qquad 18$$

où $(\Sigma Oi)/N$ = valeur observée moyenne.

- L'erreur cumulative ERRc (%) (Nakagawa, 1984):

$$ERRc = 100 \times (\Sigma P_i - \Sigma O_i)/\Sigma O_i \qquad 19$$

– L'erreur moyenne journalière ERRj (%) :

$$[\Sigma|100 \times (Pi - Oi)/Oi|]/N \qquad 20$$

À noter que les symboles "O" et "P" signifient respectivement valeur observée et valeur prédite.

RÉSULTATS

La façon de déterminer Kc est fort simple: il s'agit de prendre l'équation [15], comme c'est notre cas. Nous prenons la valeur d'évapotranspiration telle que fournie par le rapport de Bowen/bilan d'énergie comme valeur de ETR et la valeur de ETbc ou ETbac comme valeur de ETP. Les figures 2 et 3 nous montrent quatre graphiques illustrant les variations de Kc durant la campagne d'échantillonage. Les points indiquent les valeurs observées, la ligne pleine indique une courbe lissée reliant les points et la ligne en tireté représente la droite de régression linéaire entre Kc et les jours de croissance.

On remarque un Kc beaucoup plus stable pour le champ d'okra que pour le champ de riz, les courbes étant presque à l'horizontale. Ceci nous indique que la culture d'okra a atteint un stade de plus grande maturité en comparaison du riz. On remarque également que pour une même culture, Kc (ETbac) sera plus faible que Kc (ETbc), même s'ils suivent des tendances similaires. Les faibles valeurs "r" des figures 2 et 3 (sauf pour la figure 2 du bas) sont normales puisqu'on ne s'attend pas, à ce stade de croissance, à ce que Kc augmente avec le nombre de jours. Par contre, la grande dispersion des points de la figure 3 traduit un ETbac $<<$ ETR entre les jours de croissance 70 et 75, dû à des valeurs d'évaporation du bac (ETbac) particulièrement faibles probablement influencées par des erreurs de mesure. Ainsi Kc (ETbc) semble être beaucoup plus adéquat.

Les tableaux II et III résument les relations statistiques existant entre les différentes méthodes d'estimation de l'évapotranspiration par rapport aux valeurs observées provenant du rapport de Bowen/bilan d'énergie.

La méthode ETpt (Priestley-Taylor) se comporte différemment dépendant du milieu observé (riz ou okra), étant donné la différence de résultats d'une tableau à l'autre. Pour le champ d'okra (tableau II), on retrouve de faibles erreurs cumulatives (–2%) et journalières (5%) tandis que pour le champ de riz (tableau III), on retrouve des erreurs plus importantes ($\pm$12%). Il faut revenir au phénomène d'advection plus marqué dans la rizière pour trouver l'explication de cette différence: en présence d'advection, la valeur de $a' = 1{,}26$ mène à une sous-estimation significative de ETpt (Singh et Taillefer, 1986). En effet dans le cas de la rizière, la présence d'un chemin d'accès et de sol à nu tout autour favorise une advection d'air plus sec. Pour le champ d'okra la présence de vastes terres cultivées en périphérie du champs réduit les effets d'advection. Cette situation se

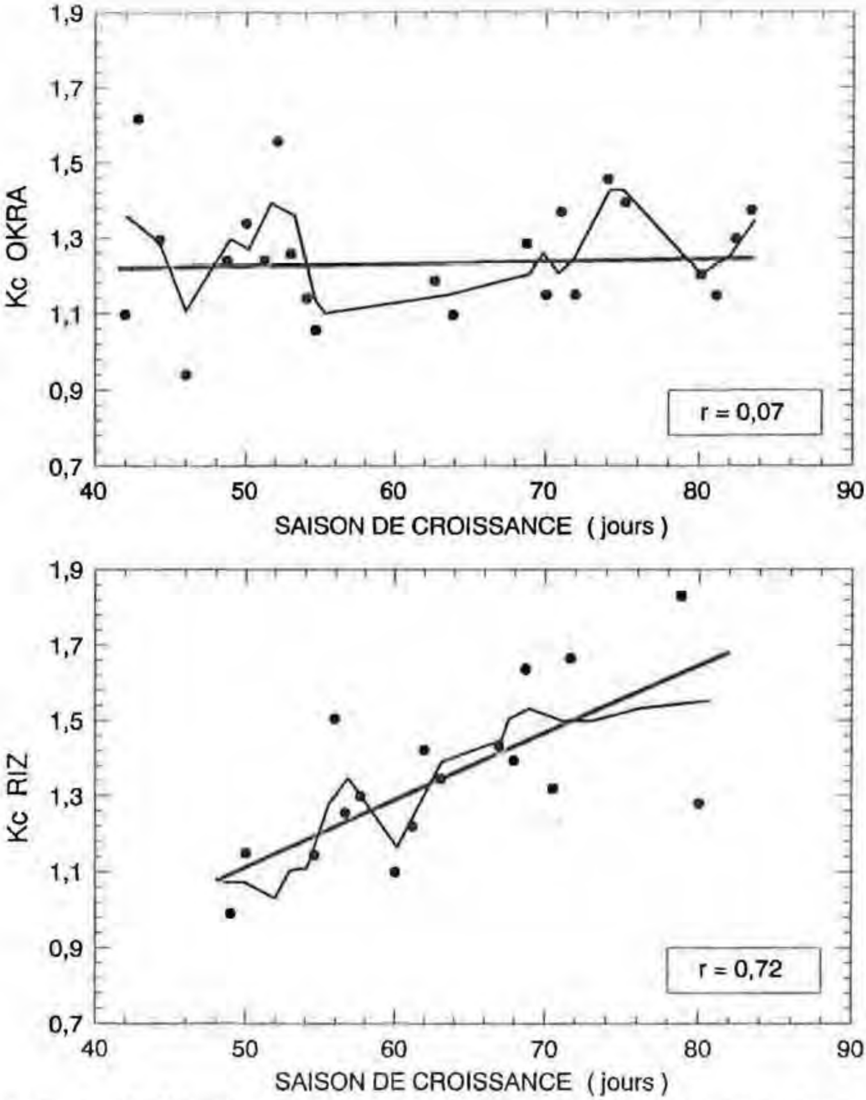

FIGURE 2 : Coefficients de culture établis à l'aide de la méthode de Blaney-Criddle pour le champ d'okra et le champ de riz.

traduit donc par des "d" et "r" excellents pour le champs d'okra (respectivement 0,98 et 0,97) et plus faible mais acceptable pour le champ de riz (0,79 et 0,78). Il faut mentionner une erreur RMSE particulièrement faible (0,05) dans le champ d'okra. L'approche de Priestley-Taylor constitue en général une excellente méthode ce qui est en accord avec Viau (1987) qui a observé un r de 0,90 entre ETpt et ETβ dans un milieu forestier.

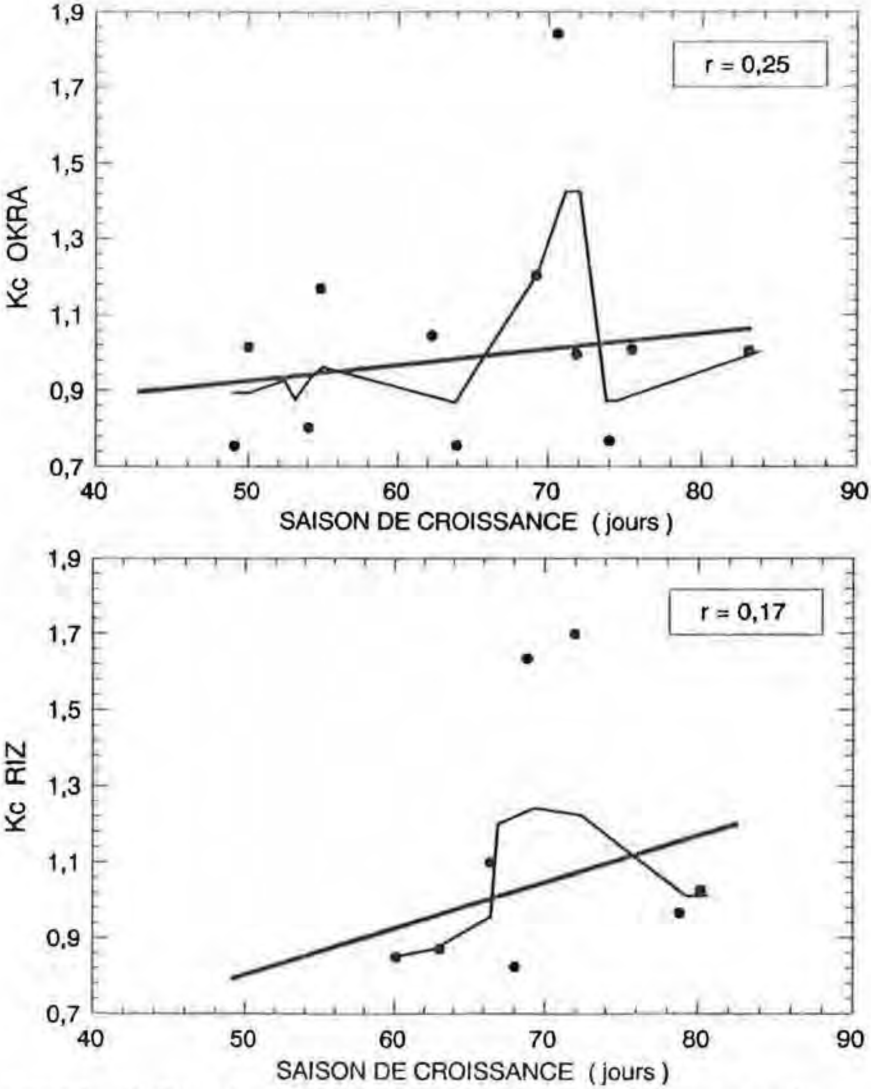

FIGURE 2 : Coefficients de culture établis à l'aide de la méthode du bac à évaporation pour le champ d'okra et le champ de riz.

Tout comme ETpt, l'approche de Penman-Monteith, ETpm, varie selon le milieu étudié, étant donné les différences entre les deux tableaux. On note une très faible erreur (ERRc de -4% pour l'okra et +1% pour le riz) sur une base cumulative par rapport à la valeur observée; de plus, la moyenne (MOYp) et l'écart type (Sp) sont pratiquement identiques à ceux de la valeur observée (ETb). Les coefficients "r" et l'indice "d" démontrent un bon accord

TABLEAU II: Mesures statistiques de la performance des différents modèles d'estimation de l'évapotranspiration en comparaison au rapport de Bowen/bilan d'énergie pour le champ d'okra. (SUM=sommation, MOY=moyenne, S=écart-type, r=coefficient de corrélation de Pearson, d=indice de coïncidence, RMSE=racine de l'erreur moyenne au carré, ERR=erreur cumulative (c) et journalière (j), l'indice o pour les valeurs observées et p pour prédites, a et b sont les coefficients de la droite de régression.)

	APPROCHES			
	Priestley-Taylor ETpt	Penman-Monteith ETpm	Blaney-Criddle ETbc	Bac à évaporation ETbac
N	23	23	23	14
SUMo (mm)	98	98	98	64
SUMp (mm)	96	94	96	66
ERRc (%)	-2	-4	-2	13
ERRj (%)	5	5	10	16
MOYo (mm)	4,3	4,3	4,3	4,6
MOYp (mm)	4,2	4,1	4,2	4,4
So (mm)	0,79	0,79	0,79	0,73
Sp (mm)	0,81	0,81	0,67	1,67
a	0,96	0,95	0,95	0,40
b	0,28	0,36	0,28	2,70
RMSE (mm)	0,05	0,07	0,23	0,85
d	0,98	0,97	0,89	0,75
r	0,97	0,96	0,81	0,67
Relation α = 0,01	oui	oui	oui	oui

entre la méthode de Penman-Monteith et l'approche de Bowen (d = 0,97 et r = 0,96 pour l'okra et d = 0,81 et r = 0,65 pour le riz) quoique la corrélation soit faible pour le riz et peut-être due à une mauvaise estimation empirique des résistances r_a et r_s. En effet les faits que la plante soit au tiers dans l'eau et qu'il n'en résulte aucun stress hydrique favorisent une transpiration plus régulière entraînant une valeur de r_s qui diffère de celle estimée empiriquement. D'autre part, la faible longueur de rugosité de la surface (z_0) et le faible plan de déplacement (d) affecte l'estimation de r_a. À noter que Viau (1987) a observé une forte corrélation (r = 0,88) entre ETpm et ETb en milieu forestier.

Les méthodes de Penman-Monteith et de Priestley-Taylor reproduisent assez bien ce qu'on retrouve dans la littérature (Viau, 1987; Viau et Singh, 1991) quoique l'on peut y observer une erreur de 3% à 5% induite par r_c pour ETpm et par a' pour ETpt (Viau, 1987).

L'approche ETbc possède une faible erreur cumulative (-2%) et une erreur journalière moyenne de 9-10%. La moyenne est semblable à celle de la valeur observée. La relation existe pour les deux cultures (r = 0,81 okra et 0,73 riz) et l'indice "d" est relativement fort dans les deux cas (0,89 okra et 0,84 riz). Le milieu ou du moins les conditions de surface et atmosphériques ne semblent pas avoir une influence sur la méthode Blaney-Criddle. On peut conclure que la

TABLEAU III: Mesures statistiques de la performance des différents modèles d'estimation de l'évapotranspiration en comparaison au rapport de Bowen/bilan d'énergie pour le champ de riz. (SUM=sommation, MOY=moyenne, S=écart-type, r=coefficient de corrélation de Pearson, d=indice de coïncidence, RMSE=racine de l'erreur moyenne au carré, ERR=erreur cumulative (c) et journalière (j), l'indice o pour les valeurs observées et p pour prédites, a et b sont les coefficients de la droite de régression.)

	APPROCHES			
	Priestley-Taylor ETpt	**Penman-Monteith ETpm**	**Blaney-Criddle ETbc**	**Bac à évaporation ETbac**
N	20	20	20	10
SUMo (mm)	99	99	99	51
SUMp (mm)	87	100	97	47
ERRc (%)	-12	+1	-2	-7
ERRj (%)	12	11	9	27
MOYo (mm)	4,9	4,9	4,9	5,1
MOYp (mm)	4,3	5,0	4,8	4,7
So (mm)	0,86	0,86	0,86	1,00
Sp (mm)	0,80	0,95	0,73	1,64
a	0,83	0,59	0,86	0,10
b	1,33	2,00	0,79	4,61
RMSE (mm)	0,65	0,57	0,36	3,27
d	0,79	0,81	0,84	0,47
r	0,78	0,65	0,73	0,17
Relation $\alpha = 0{,}01$	oui	oui	oui	oui

méthode est en correlation avec la valeur observée et ne subit pas l'influence des conditions atmosphériques propres à chacun des sites.

La méthode ETbac véhicule une erreur cumulative comparable à celles des autres approches (+3% okra et -7% riz) mais démontre une surestimation journalière fortement marquée (16% pour l'okra et 27% pour le riz). On notera que cette approche comporte moins d'observations que les autres. La moyenne est relativement près de la valeur observée mais l'écart type est beaucoup plus fort (méthode hautement variable), ce qui entraîne un "r" faible dans les deux champs (0,67 pour l'okra et 0,17 pour le riz), tandis que les indices "d" sont acceptable mais demeurent les plus faibles des méthodes (0,75 okra et 0,47 riz). Il faut cependant prendre en considération que seulement 10 cas ont été retenus pour le champ de riz ce qui explique un "r" plus faible.

Pour mieux caractériser l'erreur imputable à chacune des méthodes d'estimation de l'évapotranspiration, il est nécessaire de passer de la résolution globale à une résolution journalière, car c'est sur cette base que les modèles de prévision des besoins en irrigation fonctionnent. Le tableau III met en lumière les différentes erreurs (ERR) observées.

L'approche de Penman-Monteith possède de faibles erreurs maximales variant entre -12% et +7% pour l'okra et des erreurs plus appréciables pour le champ de riz, entre -39% et +22%. Ces cas extrêmes sont rares; en effet l'erreur journalière moyenne de ETpm est de l'ordre de 5% pour l'okra et de 11% pour le riz. L'approche de Priestley-Taylor démontre des erreurs maximales variant entre -12% et +16% dans le champ d'okra, et entre -40% et -5% pour le champ de riz. Les erreurs de celle-ci sont imputables à a' réagissant à l'advection et aux conditions de surface (fetch). Malgré cela, l'approche ETpt véhicule une erreur journalière comparable à l'erreur de ETpm, soit entre 5% et 12% respectivement pour l'okra et le riz. Les approches de Penman-Monteith et de Priestley-Taylor possèdent une erreur constante, avec des écart-type "s" faibles dans tous les cas.

En ce qui concerne ETbc et ETbac, les erreurs journalières connaissent de plus grandes fluctuations tant positives que négatives. Cependant, l'erreur minimale et l'erreur moyenne de ETbc sont inférieures (ou comparables dans un cas) à celles de ETbac dans les deux champs. De plus, l'écart type plus prononcé de ETbac (le double et même le triple de celui de ETbc), porte à conclure une plus forte variation dans la réponse de ETbac par rapport à la valeur observée. En général, ETbc engendre une erreur journalière maximale de ±25% et ETbac de l'ordre de 37% à -70%.

Pour compléter l'analyse, la figure 4 illustre la corrélation entre les méthodes ETbc et ETbac versus ETβ. Les droites représentent ±20% d'erreur par rapport à la valeur observée. À remarquer le regroupement plus serré dans le champ d'okra pour les deux méthodes. Il en ressort pour le champ d'okra que seulement deux journées possèdent un taux d'erreur >20% pour ETbc, tandis que le bac en possède quatre. Pour le riz nous observons le même scénario, mais ETbc compte une seule journée comparativement au bac qui en possède cinq. L'erreur journalière moyenne (tableau IV) de l'approche de Blaney-Criddle est de 10%. Rappelons que Doorenbos et Pruitt (1977) et Saxton et McGuinness (1982) déterminaient l'erreur cumulative de ETbc à 25%. Pour ETbac, l'erreur journalière moyenne se rapproche plus de 22%. Cette relation entre ETbc, ETbac et ETβ contredit ce qui a été observé par Al-Sha'lan et Salih (1987) qui

TABLEAU IV: Erreurs journalières des méthodes d'estimation du taux d'évapotranspiration en comparaison au rapport de Bowen/bilan d'énergie (ETβ).

Méthode	Err Max > 0 (%)	Err Max < 0 (%)	Err Min (%)	ERRj (%)	s (%)	N
			OKRA			
ETpm	7	-12	-2	5	5	23
ETpt	16	-12	-1	5	5	23
ETbc	27	-25	-2	10	12	23
ETbac	37	-46	1	16	21	14
			RIZ			
ETpm	22	-39	-3	11	14	20
ETpt		-40	-5	12	9	20
ETbc	26	-23	0	9	11	20
ETbac	45	-70	8	27	33	10

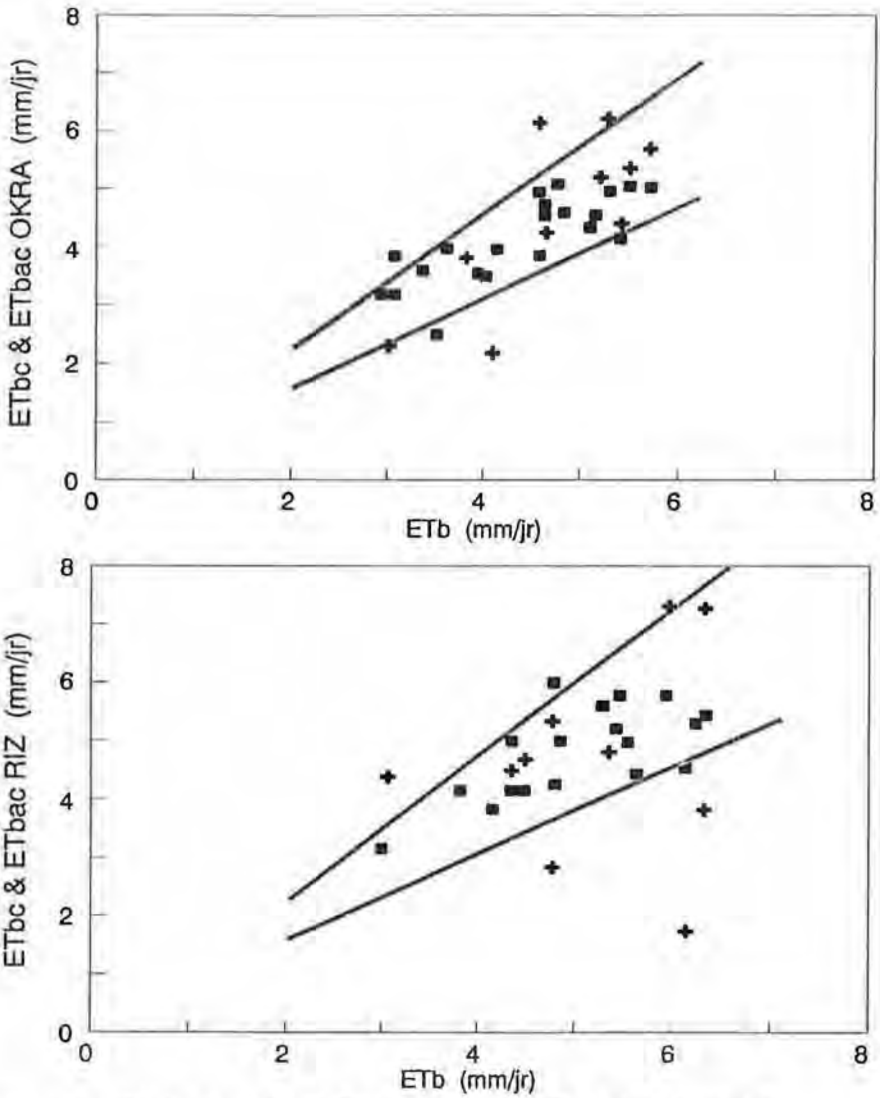

FIGURE 4 : Résultats des modèles de Blaney-Criddle (ETbc= □) et du bac à évaporation (ETbac= +) en fonction de ceux du rapport de Bowen/bilan d'énergie (ETb). Les droites représentent ±20% erreur.

classaient le bac au deuxième rang et ETbc au 17iéme rang sur 23 méthodes étudiées! Mentionnons toutefois que leur étude portait dans des conditions arides extrêmes, dans le centre de l'Arabie Saoudite. De plus il faut considérer la présence d'eau pleinement disponible pour le champ de riz et l'irrigation du champ d'okra.

CONCLUSION

Les méthodes de Penman-Monteith (ETpm) et de Priestley–Taylor (ETpt) fluctuent en harmonie avec l'approche de Bowen (ETβ). Cependant, elles démontrent une erreur plus marquée lorsque l'advection est présente. La réponse de ces méthodes est en accord avec ce qu'a observé Viau (1987). L'approche de Blaney-Criddle est plus performante que l'approche du bac à évaporation, donnant une erreur cumulative de -2% et une erreur journalière moyenne de 10%. ETbc n'enregistre pas de différence de comportement significative dépendant du milieu. Finalement, l'approche du bac à évaporation se classe en dernière position avec une covariance particulièrement faible, une erreur cumulée de 5% et une erreur journalière de 22%.

Selon nos résultats, il semblerait que l'emploi de Blaney-Criddle au détriment des bacs à évaporation soit favorable. Par contre, ces méthodes restent largement inadéquates pour une résolution journalière, telle que requise dans un modèle de prévision des besoins en irrigation, à moins de se contenter de 20% d'erreur.

La gestion et l'optimisation de l'eau en milieu agricole est un problème mondial. Le développement de nouvelles techniques d'estimation de l'évapotranspiration demeure primordial surtout pour les régions sèches ou arides. Nous croyons qu'à la lumière de ces résultats il est important de reconsidérer certaines approches d'estimation de l'évapotranspiration, plus particulièrement les méthodes simples comme celle faisant référence à un minimum de mesures directes de paramètres agrométéorologiques ou encore à un trop grand nombre de paramètres issus de tableaux et d'abaques météorologiques. Les travaux effectués jusqu'à maintenant sur cette question (Brutsaert, 1982; Sharma, 1985) démontrent clairement la fiabilité des approches basées sur les transferts d'énergie mais ne s'accordent pas tous sur l'applicabilité des approches plus empiriques (Al-Sha'lan et Salih, 1987; Garratt, 1984; Sharma, 1985). La poursuite des travaux sur cette question est primordiale.

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News and Comments / Nouvelles et commentaires

DEVELOPMENT OF AN HISTORICAL CANADIAN CLIMATE DATABASE FOR TEMPERATURE AND OTHER CLIMATE ELEMENTS

Donald Gullett, Walter Skinner and *Lucie Vincent*

Canadian Climate Centre
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H 5T4

ABSTRACT

An historical temperature database is outlined from its initiation as part of a World Meteorological Organization (WMO) project to establish a global reference climate station network to its creation and current status as a database for use in climate change studies. The database contains data from 131 Canadian locations from 1895 where possible, to present. It was assembled after missing data gaps were filled, homogeneity testing was completed and data adjustments were performed to remove local effects that might result from such inconsistencies as instrument and site changes or station relocations. Examples of the types of temporal and spatial analyses that are possible using this database are given as well as some planned future additions.

RÉSUMÉ

Une base de données historique de température a été créée initialement dans le but d'établir un réseau de stations climatologiques de référence pour l'Organisation météorologique mondiale (OMM). Cette base de données s'est développée et est devenue une source principale d'information pour les études du changement du climat. On y retrouve les séries temporelles de 131 emplacements canadiens dont la plupart ont des observations à partir de 1895 jusqu'à nos jours. Les données manquantes ont été estimées, un test d'homogénéité a été appliqué, et les séries ont été ajustées pour éliminer certains effets locaux tels que les changements d'instruments ou les changements d'emplacement. Des exemples d'analyses temporelles et spatiales sont présentées ainsi que quelques projets futurs.

1. INTRODUCTION

A number of researchers at the Canadian Climate Centre (CCC) of the Atmospheric Environment Service and elsewhere have been involved over the past several years in identifying long-term Canadian climate stations that are suitable for designation as Reference Climate Stations (RCS). This work was carried out as the Canadian contribution to a global endeavour sponsored by the World Climate Data Program (WCDP) of the World Meteorological Organization. Over 700 temperature reporting stations were examined for length of record, missing data, spatial distribution, areal representation and homogeneity with nearby stations following established guidelines (WMO, 1986). Of these a subset of 254 were selected and recommended for designation as official Atmospheric Environment Service (AES) reference or baseline climate stations.

With the extensive re-organization of the CCC in the spring of 1991 came a renewed and refocussed emphasis on climate change studies and related issues. The newly formed Climate Change Detection Division has been tasked with augmenting the earlier work and creating an Historical Canadian Climate Database (HCCD) specifically for use in climate change studies. Climate change investigations and analyses, state-of-the-climate reporting and contribution to national and international climate change activities were other new key initiatives. It was clear that an HCCD would provide a rudimentary but essential foundation upon which to base a host of climate change investigative procedures and studies.

2. METHOD

The first step in the database project was to subdivide the country into broad "homogeneous" climate regions (Figure 1) on the basis of earlier work by Hare and Thomas (1979) and by integration with the well defined ecological regions or ecozones as defined by the Canada Committee on Ecological Land Classification (Environment Canada, 1989). Stations were selected for examination such that each climate region would be spatially and temporally well represented (Figure 1). Monthly maximum and minimum temperature series by station were closely scrutinized for length of record (beginning 1895 where possible), data completeness (no gaps exceeding 4 years), regional homogeneity (no outliers, steps, or non-climate trends) and spatial distribution. Records were at times extended by "joining" portions of records from nearby stations and homogeneity assessments were carried out using a technique developed by Vincent (Vincent, 1990; Gullett *et al.*, 1991). Monthly mean maximum and minimum temperatures were assessed separately, missing data gaps filled and data adjustments made where necessary to ensure compatibility with nearby stations. These were then combined into monthly mean temperature series and seasonal and annual means computed. Additional numerical analyses (ie., cross correlations, principal components, factor analysis and discriminant analysis) of the annual mean temperature series were also used to "fine-tune" the climate regional groupings and ensure that stations were suitably assigned for subsequent regional analysis. Ultimately, a selection of stations or combinations of stations, representing 131 geographic locations as shown in Table 1, was made from the 254 RCS designates and an historical temperature database constructed from these.

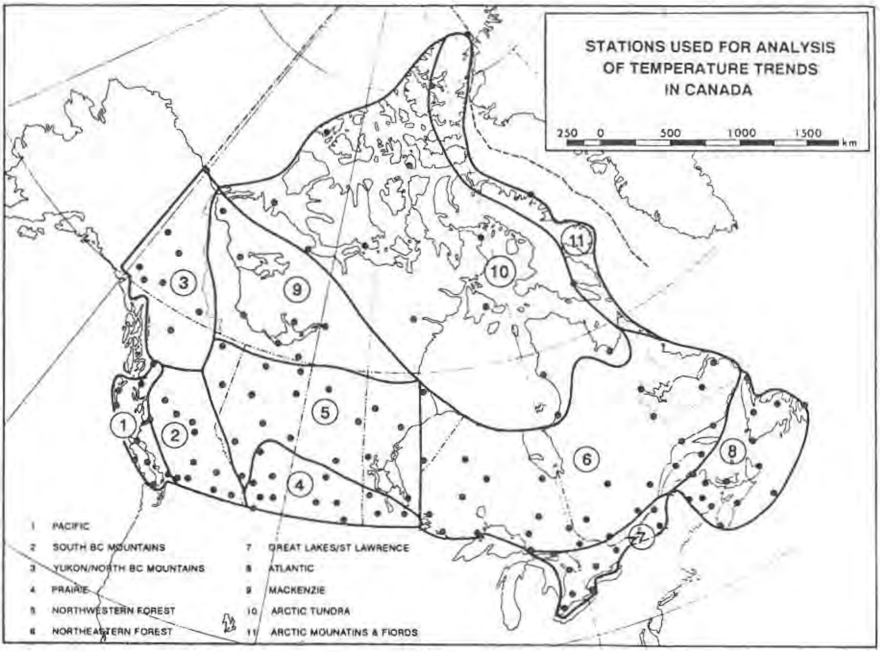

FIGURE 1: Major climate regions and spatial distribution of locations in HCCD.

3. DATABASE

The format of HCCD includes monthly, seasonal and annual means of maximum, minimum and mean temperature beginning where possible in 1895. The database contains the unadjusted original archive data, with and without missing data replacement; the adjusted values; the 1951-1980 climate normals calculated from the adjusted values, and standard deviations; and the departures from the 1951-1980 reference period averages. The data are organized by location; and by climate element, and are retained in a FORTRAN-compatible file on the Downsview Computing Centre (DCC) mainframe computer. They have also been downloaded to a micro-computer based ASCII file for off-line manipulation and analysis. Location information (e.g., location name and identification number, latitude, longitude and elevation) are contained in a second file and historical information (e.g. dates and details of observing program and site changes) are being input to a third file for easy access and reference.

4. ANALYSIS

Two examples are presented to illustrate the kinds of temporal and spatial analyses that are possible using the temperature departure data in the HCCD.

TABLE 1: List of temperature stations in HCCD by climate region.

Pacific
Amphitrite Point
Bella Coola
Cape St James
Comox
Port Hardy
Prince Rupert
Sandspit
Stewart
Vancouver
Victoria

Yukon/North BC Mountains
Burwash
Dawson
Dease Lake
Haines Junction
Mayo
Watson Lake
Whitehorse

Northeastern Forest
Bagotville
Big Trout Lake
Cartwright
Chibougamau-Chapais
Churchill
Earlton
Fort Frances
Gaspé
Goose
Island Lake
Kapuskasing
Kenora
Lansdowne House
La Tuque
Mont Joli
Moosonee
Natashquan
North Bay
Pickle Lake
Sault St Marie
Schefferville
Sept-Iles
Thunder Bay
Val D'Or
Wabush Lake
Wawa

South BC Mountains
Agassiz
Banff
Barkerville
Castlegar
Cranbrook
Fort St James
Kamloops
Prince George
Princeton
Revelstoke
Smithers

Prairies
Brandon
Calgary
Carway
Coronation
Dauphin
Edmonton
Estevan
Lethbridge
Medicine Hat
Regina
Saskatoon
Swift Current
Winnipeg

Northwestern Forest
Cree Lake
Cold Lake
Edson
Fort Chipewyan
Fort McMurray
Fort Nelson
Fort St John
Great Falls
High Level
Island Falls
Lynn Lake
Peace River
Prince Albert
Slave Lake
The Pas
Thompson

Atlantic
Aroostook
Charlo
Charlottetown
Chatham
Deer Lake
Fredericton
Gander
Halifax
Port Aux Basques
Sable Island
Saint John
St Anthony
St John's
Sydney
Yarmouth

Mackenzie District
Fort Reliance
Fort Simpson
Fort Smith
Hay River
Inuvik
Norman Wells
Yellowknife

Arctic Mountains and Fiords
Alert
Clyde
Eureka
Iqaluit

Great Lakes/St Lawrence
Gore Bay
Harrow
London
Maniwaki
Ottawa
Peterborough
Quebec
St Catharines
Sherbrooke
Wiarton

Arctic Tundra
Baker Lake
Cambridge Bay
Cape Parry
Coppermine
Coral Harbour
Hall Beach
Inukjuak
Komakuk Beach
Kuujjuag
Kuujjuarapik
Mould Bay
Resolute

Figure 2 shows a time series (1895-1991) of mean annual temperature departures from the 1951-80 reference period averages for the west-central portion of Canada. This regional analysis is produced from an integration of locations in the combined regions of the Prairies, the Northwestern Forest and the Mackenzie Basin (see Figure 1). This region shows the strongest warming in Canada over

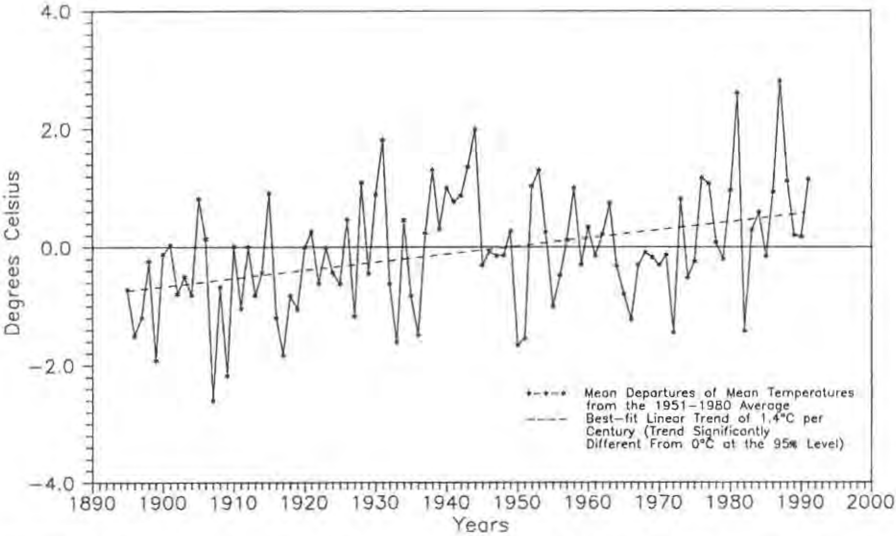

FIGURE 2: Time series of mean annual temperature departures from 1951-80 reference period averages for west-central Canada 1895-1991.

the past century and in particular, over the decade of the 1980s. A linear trend is fitted to the series with a net warming of 1.4° C over the century. The trend is significant at the α=.05 significance level. The linear model was not further examined at the time of writing; however, it is possible that a non-linear model may better describe the series. In light of this, additional analyses and investigations are currently under way. Figure 3 shows an example of the spatial analysis of mean annual temperature departures from the reference values averaged over the decade of the 1980s (1980-1989). An area of distinct warming with values near 1.0° C above the reference period averages (normal) for the decade is evident from Yukon Territory in the northwest to southern Manitoba in the southeast. On the opposite side of the ledger, near normal to slightly below normal temperatures are evident in most of extreme eastern Canada, including in the northeast over southern Baffin Island, and throughout Newfoundland and Labrador and the Maritime Provinces.

5. CONCLUSION

The Historical Canadian Climate Database and subsequent analyses described in this paper represent the first phase in a much larger project to establish, maintain and expand a national climate database of "cleaned" data suitable for use in various climate change investigations, studies and analyses. The intent is to make available to the research community a high quality Canadian climate database that is spatially representative and that spans the instrumental period. It is hoped to have completed by late 1992 a preliminary version of the database and

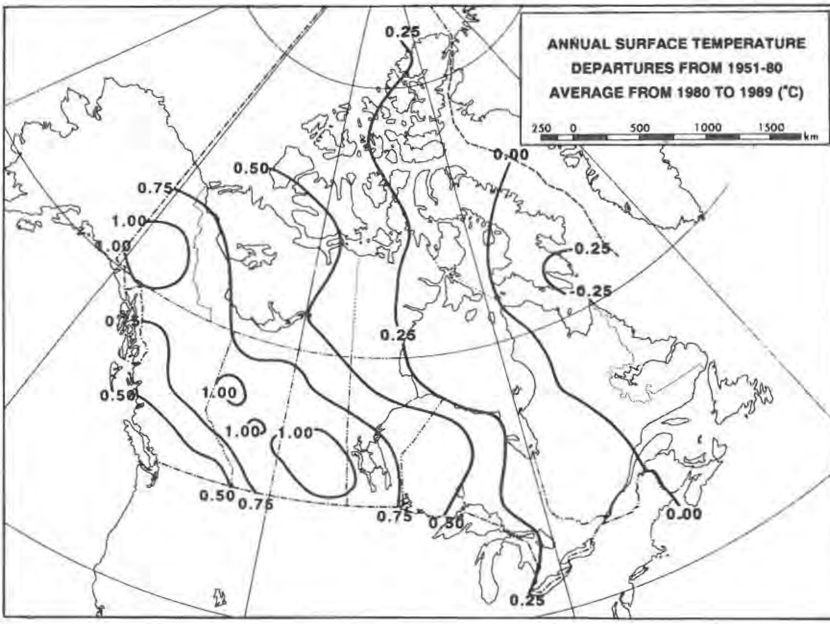

FIGURE 3: Mean annual temperature departures from 1951-80 reference period averages for the decade 1980 to 1989.

upon completion the HCCD will be made available to climate change researchers on magnetic tape and/or on PC diskettes. Other climate elements are currently under investigation and eventually will be added to the database. These include extremes of temperature, totals of precipitation, cloud cover, sunshine, snow cover, lake ice data and others as yet to be determined. In the longer term, it is also hoped to include temperature and precipitation, data derived from various historical proxy data sources.

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