P3.32 DEVELOPING DAILY CLIMATE SCENARIOS FOR AGRICULTURAL IMPACT STUDIES

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1. INTRODUCTION

Agriculture remains a significant export activity for Canada's economy; furthermore, it is a mainstay of several regional economies, e.g. the Prairies, southern Quebec and Southwest Ontario (Bryant et al. 2000). Canadian agriculture involves a high degree of management but is still subject to failure under disastrous climate extremes, such as droughts on the Canadian Prairies.

Research on adaptation of Canadian agriculture to climatic change and variability has been focused recently more on the role of human agency – how farmers, their associates, the crop insurance industry and the whole host of government and political actors, as well as the scientific community mediate between external stimuli such as climatic change and actual results in terms of agricultural change. This represents a shift from an earlier focus on the potential impacts of climatic change on crop yields (Bryant et al. 2000). Nevertheless, future climate scenarios may still be the essential basis for the assessment of climatic change impacts and adaptation strategies. Crop models such as the Erosion-Productivity Impact Calculator (EPIC; Williams 1995) and the Decision Support System for Agrotechnology Transfer (DSSAT; Jones et al. 2003) are evaluation tools that incorporate adaptation strategies in the simulation of crop yields under climate change. Such tools rely on climate scenarios as input (e.g. Easterling et al. 2001). Therefore, developing appropriate daily climate scenarios for agricultural impact studies is still a fundamental work in the study of adapting Canadian agriculture to climate change, especially when updated GCM (General Circulation Model or Global Climate model) simulations provide improved projections of future climate change.

This paper presents a methodology using stochastic weather generators to develop future daily climate scenarios on a fine grid of 0.5˚×0.5˚ covering most agricultural regions of Canada on the basis of climate change scenarios from GCMs. Stochastic weather generator methods can provide long time series of weather variables that make it possible to evaluate variability and extremes. In addition, the methodology is used in this study to assess possible changes in agroclimatic resources using agroclimatic indices based on daily climate scenarios derived from GCM simulations.

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2. DATA AND METHODOLOGY

2.1 *Historical Climate Data*

Daily climate data for 1961-1990 were extracted from a climate data set archived at the Eastern Cereal and Oilseed Research Centre (ECORC) of Agriculture and Agri-Food Canada (AAFC). The climate data were originally provided by Environment Canada and quality controlled. Missing data were estimated using nearby stations wherever possible. Daily climate data used in this study include daily precipitation (P), daily maximum temperature (Tx), daily minimum temperature (Tn) and solar radiation (R). There were 673 climate/weather stations across Canada with observations for P, Tx and Tn in the data set. However, as stations started or closed throughout the 30-yr period, only 424 stations were retained in this study to keep a maximum number of missing data of 5 years during 1961-1990 in order to have more reliable estimation of the statistics. Daily solar radiation data were not available as widely as temperatures and precipitation, since only a very few stations have observations of R. Some stations have daily records of sunshine hours, which can be converted to solar radiation based on empirical regression equations. This conversion work was performed at ECORC and there are 304 stations in total across the country combining observed R data and those converted from sunshine hours. Keeping the same criterion for missing data as for P, Tx and Tn, only 177 stations in total were used. In the analysis for evaluating stochastic weather generators in simulating a changed climate, daily climate data for 1911-1940 and 1971-2000 were employed from the same data set for a few representative stations.

2.2 *GCM Data*

Climate change scenarios, i.e. possible changes in statistics of climate variables simulated by GCMs, are the basis for developing future climate scenarios. Climate change scenarios from different GCMs, or even the same GCM forced by different emission scenarios, can be very different. It is recommended that a few different climate change scenarios be used in order to incorporate the uncertainties. In this study, two climate change scenarios were employed: CGCM1 GHG+A1 and HadCM3 A2a. CGCM1 is the first generation coupled general circulation model developed at the Canadian Centre for Climate Modelling and Analysis (CCCma). CGCM1 GHG+A1 is one member of an ensemble of four transient climate change simulations conducted at CCCma with greenhouse gases (GHG) plus aerosol (A) forcing (Boer et al. 2000). HadCM3 (Gordon et al. 2000) is the first of a new generation of coupled atmospheric GCMs that do not require flux corrections to be made. HadCM3 A2a is one member of an ensemble of integrations performed with HadCM3 forced by the SRES A2 emissions scenario (Nakicenovic et al. 2000). The two climate change scenarios employed in this study mainly reflect the uncertainties from GCMs rather than from emissions scenarios.

Daily GCM outputs for P, Tx, Tn and R are on a grid of 3.75˚longitude×2.5˚latitude in HadCM3 A2a and roughly 3.7˚longitude×3.7˚latitude in CGCM1 GHG+A1 simulations. They were obtained from the Hadley Centre through Climate Impact LINK project and CCCma respectively. Data for 1961-1990 in the models were used to represent the present-day climate (baseline climate) and 2040-2069 data were employed to represent a future climate under approximately doubled atmospheric CO_2 concentration.

2.3 *Stochastic Weather Generator Method*

Stochastic weather generators are widely used to generate synthetic weather data, which can be arbitrarily long for input into impact models, such as crop models and hydrological models that are used for making long-term risk assessments. They are also employed as a tool to develop future climate scenarios based on GCM simulated or subjectively introduced climate changes for climate change impact models (e.g. Wilks 1992; Mearns et al. 1997; Semenov and Barrow 1997). A modified method of Mearns et al. (1992), which adds projected future changes in means to the observed historical weather series incorporating changes in variability, is still widely used in Canada for agricultural impact studies (McGinn et al. 1999; De Jong and Li 2001; Bootsma et al. 2001; McGinn and Shepherd 2003; Shepherd and McGinn 2003). As Semenov and Porter (1995) stated, a methodologically more consistent approach is to use a stochastic weather generator, instead of historical data, in conjunction with a crop simulation model. A stochastic weather generator allows temporal extrapolation of observed weather data for agricultural risk assessment as well as providing an expanded spatial source of weather data by interpolation between the point-based parameters used to define the weather generators (Hutchinson 1991). Therefore, we employ the method of stochastic weather generators in this study.

A stochastic weather generator (AAFC-WG) developed at Agriculture and Agri-Food Canada (Hayhoe 2000), was improved from Richardson's weather generator (Richardson 1981; Richardson and Wright 1984). A study indicated that AAFC-WG has the capacity to simulate statistical properties of observed weather data for agricultural applications, including a set of agroclimatic indices (Qian et al. 2004a). It was discovered that AAFC-WG is better able to simulate temperature and temperature-related statistics than LARS-WG for diverse Canadian climates, because of the use of empirical distributions for Tx and Tn in AAFC-WG. Hayhoe and Lapen (2002) presented an example of using AAFC-WG to generate future climate scenarios and to calculate agroclimatic indices on the basis of historical climate data and GCM outputs. Their study confirmed the applicability of weather generators as a tool to estimate agroclimatic indices for selected climate change scenarios. We investigated the capacity of AAFC-WG in simulating statistical properties of daily weather series under a changing/changed climate through modifications to the weather generator parameters with optimal use of available information on climate change. For example, we found that AAFC-WG can simulate the frequency distributions of the wet and dry spells fairly well by modifying the four transition probabilities of the second-order Markov chain. Figure 1 shows some examples of such simulations for 1971-2000 in comparison with those from LARS-WG when the weather generator parameters calibrated for 1911-1940 were modified for 1971-2000.

2.4 *Inverse Distance-Squared Weighting Method*

Inverse distance-squared weighting was employed to interpolate statistics of historical daily weather series at nearby stations to the 0.5˚×0.5˚grids, as well as from coarse grids in GCM outputs to the same half-degree grids as historical data. Statistics (such as long-term means) have a smoother spatial distribution than individual daily values that can be more associated with synoptic systems; thus we decided to interpolate statistics of daily station weather series rather than daily values to the grid points. To use inverse distance-squared weighted average as the value for a grid, a search radius of 100 km for statistics of P, Tx and Tn and of 350 km for R was used. In addition, a maximum of 5 nearest stations were used. Such a search radius was applied to guarantee that most grids in the study would have data and a maximum number of 5 nearest stations were used to keep accurate estimations in regions with dense stations. It appeared that changing search radius had little effect on interpolated values in regions with dense observations. Inverse distance-squared weighting was also applied to interpolate statistics of daily climate variables in GCM outputs from GCM grids to the finer half-degree grids so that climate change scenario statistics could be formed on the finer grids. In this case, only the four GCM grids around the finer grid were employed in the interpolation.

Statistics of daily climate variables involved in interpolation were means and standard deviations of daily Tx, Tn, R and logarithmic transformed precipitation amounts on wet days; transition probabilities of a wet day respectively following two consecutive wet days, two consecutive dry days, a wet day and a dry day or a dry day and a wet day. The statistics were computed for each month, and in addition, the means and standard deviations of daily Tx, Tn and R were calculated separately for wet days and dry days for the historical observations.

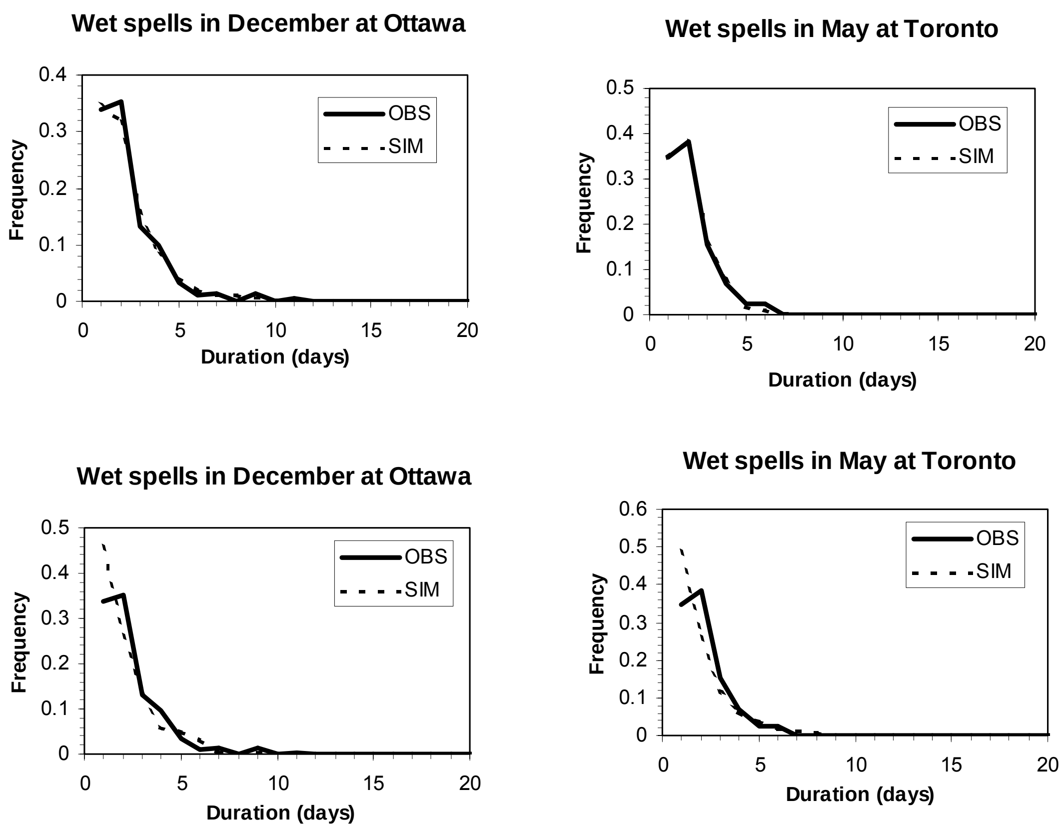

Figure 1. Observed and simulated frequency distributions of December wet spells at Ottawa and May wet spells at Toronto for 1971-2000. Upper panels are for AAFC-WG and lower panels for LARS-WG.

2.5 ***Generation of Baseline Climate Scenarios***

A total of 31 stations, geographically representing the diverse climates in the Canadian agricultural areas, were selected for calibrating the stochastic weather generator AAFC-WG. As empirical distributions employed in AAFC-WG were estimated from standardized daily Tx, Tn, R and logarithmic transformed P on wet days, it is reasonable to assume that the empirical distributions calculated from a representative station are applicable to the nearby grids with similar climate. This assumption was also applied to the correlation matrices that are used in the first-order multivariate regression for generating standardized Tx, Tn and R series. Using the weather generator parameters (empirical distributions and the correlation matrices) at the nearest representative station together with the transition probabilities and means and standard deviations on the grid, daily climate scenarios for the baseline climate (1961-1990) were generated. The synthetic data were generated for a 300-yr period to facilitate risk analysis.

2.6 ***Generation of Future Climate Scenarios***

Climate change scenarios were constructed for each half-degree grid, by computing the differences or ratios of the statistics of daily climate variables in the GCM outputs between the modeled future climate (2040-2069) and the baseline climate (1961-1990). These differences and ratios were then applied to the corresponding statistics of the observed climate of 1961-1990, which were used to generate climate scenarios for the baseline climate, to form a new set of weather generator parameters relevant to the changing/changed climate of 2040-2069. Technical details can be referred to Qian et al. (2004b). Climate change scenarios used to perturb the weather generator parameters were actually determined by GCM climate change experiments, except for the spatial interpolation from coarse GCM grids to the finer grids. Therefore strictly speaking, no downscaling was involved. It may be appropriate to call such a procedure of developing future climate scenarios as a localization of daily climate scenarios from GCM simulations. The underlying assumption is that daily climate scenarios on a coarse grid from direct GCM outputs do not have the proper statistical properties at a location because of sub-GCM grid scale processes while their effects can be reflected in local observations. Sometimes GCM outputs have been interpolated from large grids to very fine grids or locations; however, such interpolation cannot bring any effects of sub-grid processes into the interpolated data no matter how complex the interpolation method is for considering topography. Another assumption in this localization procedure is that climate change due to enhanced greenhouse effect is consistent on a considerable spatial scale.

2.7 *Computing Agroclimatic Indices*

Agroclimatic indices have been widely used to evaluate climate suitability for crop growing and potential productivity in Canada in the past. Therefore they are also suitable for assessing climate change impacts in the agricultural sector, although crop modelling has the advantage that it provides simulations of crop yields and risks. Changes in the indices can be used to rate future climatic suitability of land for crop production.

Agroclimatic indices are usually related to the growing season length, moisture stress and the amount of heat accumulation. Nine agroclimatic indices employed in this study are as follows: last date of frost in spring (FS), first date of frost in fall (FF), last date of killing frost in spring (KFS), first date of killing frost in fall (KFF), frost-free days (FFD), growing degree-days (GDD), effective growing degree-days (EGDD), crop heat units (CHU), and precipitation deficit/surplus (PDS). Frost is defined as daily Tn≤0˚C while killing frost as daily Tn≤-2˚C. The dates are presented as Julian days.

The growing season may imply different periods for a variety of crops, as the growing season for a specific crop is the period from seeding to maturing for the crop. In general, it is within the period from May 1 to September 30 in most agricultural regions in Canada. Bootsma (1994) used the date that the 5-day weighted mean temperature is and stays above 5.5˚C or is below 5.5˚C to determine the start or end of the growing season. We found that this definition and the one we used in this study for accumulating growing degree-days are closely related to each other. As most crops are sensitive to freezing temperature, we assume that it is reasonable to use the last frost date in spring, the first frost date in fall and the frost-free days to reflect the changes in growing season. In addition, dates for killing frost were employed for cold resistant crops.

GDD, EGDD and CHU are computed based on the findings of the Agronomics Interpretations Working Group (1995) and Bootsma et al. (1999). Growing degree-days, effective growing degree-days and crop heat units are all related to the amount of heat available for crops to mature. GDD represents general heat conditions for spring-seeded small grains, while EGDD is adopted to include consideration of a day-length factor for rating cereal crops, which are sensitive to photoperiod. The CHU in this study is specifically for grain corn, but it can also be an important reference for other relevant crops, such as soybeans.

GDD, EGDD, CHU and PDS are all accumulated daily during the growing season, thus different definitions of starting and ending dates may be found in practice. The starting date of the growing season for accumulating EGDD and PDS in this study is the day 10 days after the day when long-term-averaged daily mean temperature reaches 5˚C. The ending date is the long-term-averaged first frost day in fall. The starting date and ending date for accumulating GDD are the days respectively when the long-term-averaged daily mean temperature goes above 5˚C in spring and goes below 5˚C in the fall. The crop heat units (CHU) used in this study are relevant to grain corn, thus CHU start to accumulate when the day meets two conditions (i) the long-term-averaged daily mean temperature exceeds 10˚C and (ii) three consecutive days with daily mean temperature >12.8˚C occur after condition (i) is met. The third day is counted as the starting date. The accumulation terminates on the first occurrence of Tn ≤ -2˚C or when the long-term-averaged daily mean temperature is 12˚C, whichever date occurs first. PDS is calculated on a daily basis by subtracting precipitation (P) from the potential evapotranspiration (PE) and accumulating values over the growing season. PE is determined using the Baier & Robertson (1965) method to compute latent evaporation (LE) from Tx, Tn and solar radiation at the top of the atmosphere and subsequently LE is converted to PE (Baier 1971). A positive value of PDS (mm) indicates precipitation deficit while a negative indicates a surplus.

The agroclimatic indices were computed at each grid point from 300-yr long synthetic daily climate scenarios, respectively for the baseline climate of 1961-1990 and for the future climate of 2040-2069. Since the future climate of 2040-2069 can be fairly different from the baseline climate of 1961-1990, the long-term-averaged daily mean temperatures and first date of fall frost were computed separately for the two periods, reflecting the different growing season lengths.

3. RESULTS AND DISCUSSION

Three sets of daily climate scenarios were generated on the half-degree grids, one for the baseline climate (1961-1990) and the other two for the future period 2040-2069 separately based on CGCM1 GHG+A1 and HadCM3 A2a simulations. These data sets can be used in various impact studies, such as for input into a crop model. In this paper, we present only the values of the 80% probability for selected agroclimatic indices respectively for the baseline climate (1961-1990) and the future climate (2040-2069), together with the differences between the two periods. The 80% probability values for spring frost dates (FS, KFS) and fall frost dates (FF, KFF) were respectively the dates of the last frost in spring with a probability of no later frost of 80% and first date of frost in the fall with a probability of no earlier frost of 80%. The 80% probability values were also defined for precipitation deficit/surplus (PDS) as the deficit values with the 80% probability of less severity, but for all other indices, the 80% probability was the probability of exceeding the index value. The 80% probability levels were used to indicate climate condition with a lower risk of crop failures caused by low heat supply and moisture stress. In the following, the agroclimatic resources are analysed and discussed for three aspects: growing season, heat amount and moisture stress.

3.1 *Potential Changes to the Growing Season*

At present, the last frost in spring occurs in early May in southern Ontario and Quebec and in late June in northern Ontario and Newfoundland. In most regions, it occurs in late May and early June (see Figure 2 top panel). Based on CGCM1 GHG+A1, which will be referred to as the CGCM1 experiment, the last frost in spring will occur approximately 5-20 days earlier in most regions for 2040-2069, but on a much earlier (25-45 days) date in the western part of the Prairies (Figure 2 middle panel). Changes from HadCM3 A2a, which will be referred to as the HadCM3 simulation, are much smoother (Figure 2 lower panel), with the last frost in spring occurring 5-15 days earlier than in the present climate for most regions; and there is no large change in the western part of the Prairies, as was the case in the CGCM1 results.

The first frost in fall generally occurs in September across the country, for 1961-1990 period (Figure 3 top panel). It occurs later, but before the end of October, in southern Ontario, Quebec and Atlantic provinces. Spatial variability of the first frost date in fall appears larger than the last frost date in spring. Changes between 2040-2069 and 1961-1990 are usually about 10-20 days based on CGCM1, i.e. later first frost in fall in a warmer climate (Figure 3 middle panel). The largest changes, which were more than 20 days, were predicted for northern Ontario. Results from HadCM3 are similar, but larger changes for both the north and the south of Ontario were predicted (Figure 3 lower panel).

Frost-free days for 1961-1990 are longest in southern Ontario, Quebec and Nova Scotia with values from 140-160 days, while less than 100 frost-free days occurred on the Prairies and northern Ontario and Quebec (Figure 4 top panel). Corresponding to earlier dates of the last frost in spring and later dates of the first frost in fall, frost-free days would be expected to increase by 15-30 days in most regions and 30-45 days in northern Ontario based on both GCM simulations (Figure 4 middle and lower panels). Based on CGCM1 projections, an increase of more than 50 frost-free days was predicted for the western part of the Prairies, mainly as a result of a much earlier ending of spring frosts.

Killing frosts are often found 5-10 days earlier than frosts in spring at most places at the 80% probability level. Changes projected by CGCM1 are generally in the range of 5-15 days earlier, while larger changes of more than 25 days earlier are projected for the western part of the Prairies and southern Ontario. The first killing frost normally occurs 10 days later than the first frost in fall. Predicted changes are mostly in the range of 6-15 days later than in the present climate. The difference between the two GCMs is that CGCM1 projected a change of 3-12 days while HadCM3 predicted 12-21 days for southern Ontario.

The predicted changes for the frost dates indicate a longer growing season in the future, with an earlier ending of frosts in spring and a later starting of frosts and killing frosts in fall. The changes projected by the two GCMs are not very different, except for some stronger regional changes for spring frosts from the CGCM1 experiment. A longer growing season in the future could make it possible to introduce crops currently grown in warmer region or to increase crop productivity by planting new varieties that could benefit from a longer growing season.

3.2 *Possible Changes in the Amount of Heat*

In the present climate, GDD are distributed from 1800-2200 in southern Ontario and Quebec to about 1000-1200 in northern Ontario, Newfoundland and the northwest part of the Prairies (Figure 5 top panel). Most regions have GDD in the range of 1200-1600. Both GCMs predicted an increase of 200-800 in GDD for 2040-2069. CGCM1 projected 100-200 less change in GDD in Ontario and Quebec but more in the southern part of the Prairies (Figure 5 middle panel), as compared to HadCM3 (Figure 5 lower panel). EGDD are distributed similarly to GDD but they are about 200 less than GDD across the country. This is mainly due to the shorter accumulating period for EGDD.

CHU has its highest values in southern Ontario of over 3000, and is as low as or less than 1500 in northern Ontario, northwestern Prairies and Newfoundland (Figure 6 top panel). Projected changes are as high as over 1000 by both GCMs but notable differences are observed between the two GCMs. The projected largest increase on the Prairies by CGCM1 is 900-1000 in most areas (Figure 6 middle panel) while the projected increase by HadCM3 is 700-800 (Figure 6 lower panel). On the other hand, in southern Ontario and Quebec HadCM3 predicted the largest increase, which was in the range of 900-1000 CHU but CGCM1 predicted a smaller increase. The CGCM1 prediction was often 200 CHU less in Ontario, Quebec and New Brunswick, as compared to HadCM3 projections. According to Bootsma et al. (2001), grain corn yields could potentially increase by 0.64 t ha^{-1} with each increase of 100 CHU; thus a 200 CHU difference could imply a difference of 1.28 t ha^{-1} in yields between the two scenarios. This also implies a large potential increase of 5.12-6.4 t ha^{-1} for grain corn yields in these regions, as HadCM3 projected an increase of 800-1000 units. The estimates by Bootsma et al. (2001) were based on a linear regression between average grain corn yields from hybrid trials and average CHU across Ontario and the Maritime Provinces.

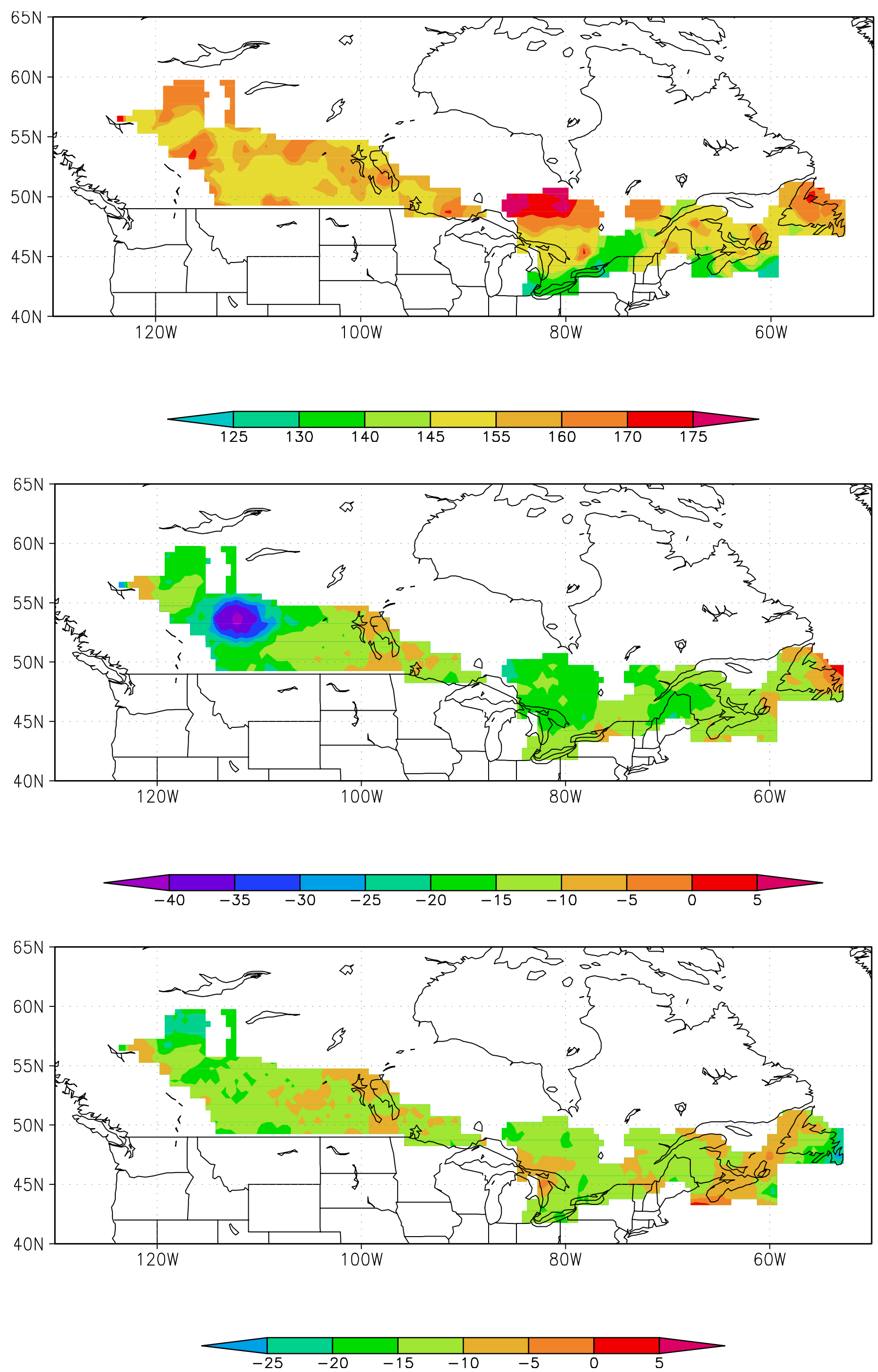

Figure 2. The 80% probability values of the date (as Julian day) of the last frost in spring (FS) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

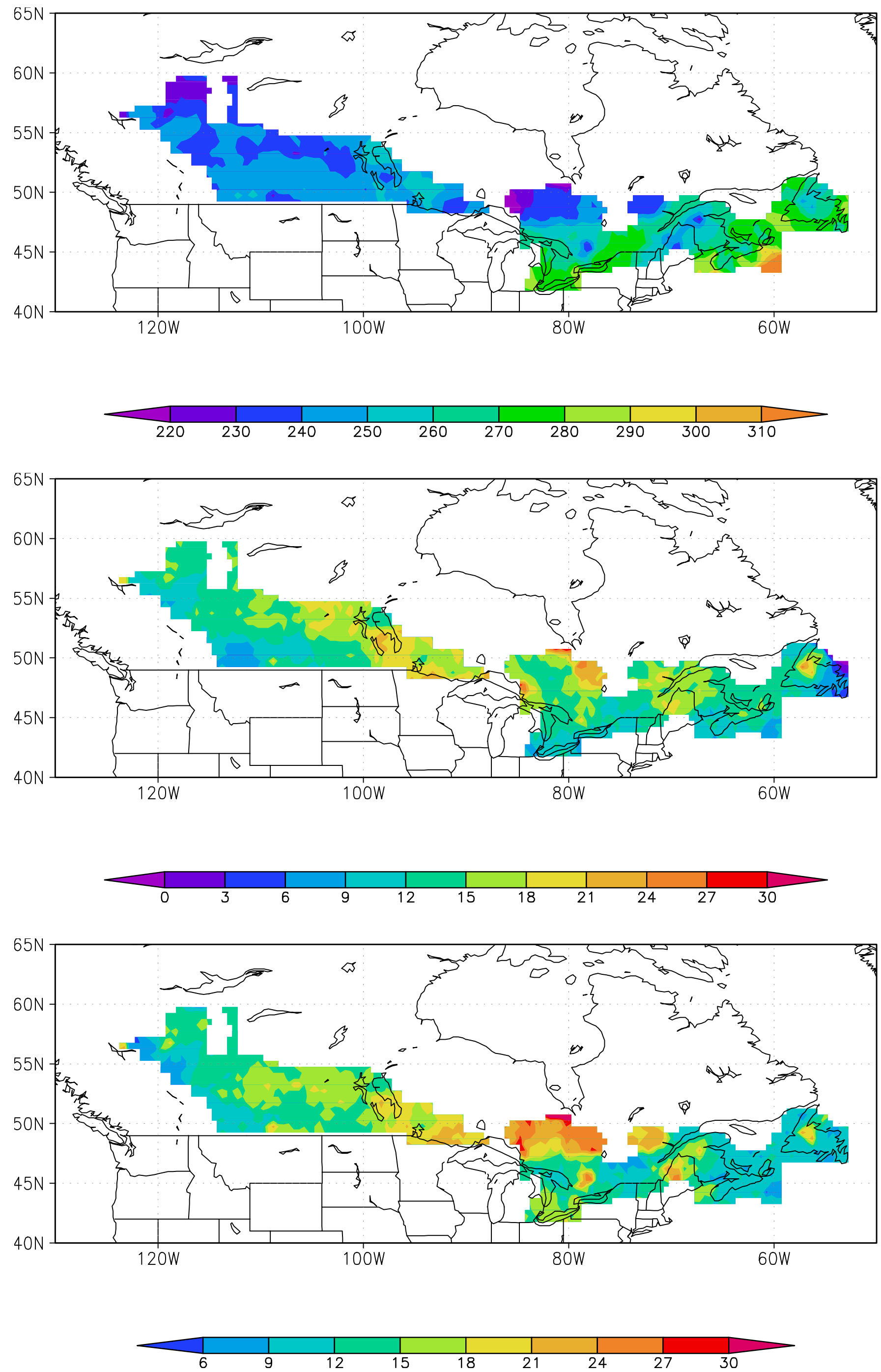

Figure 3. The 80% probability values of the date (as Julian day) of the first frost in fall (FF) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

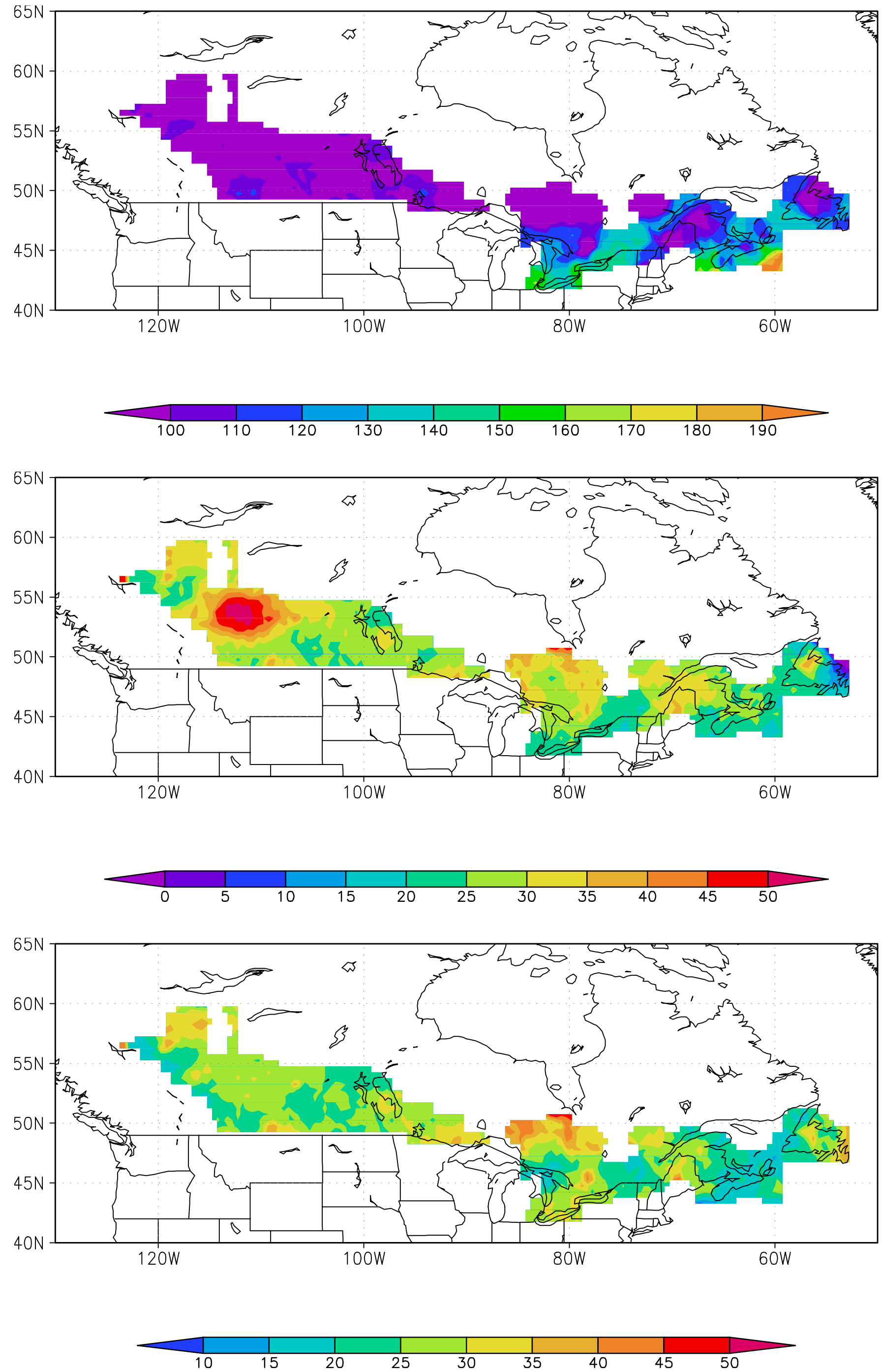

Figure 4. The 80% probability values of the frost-free days (FFD) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

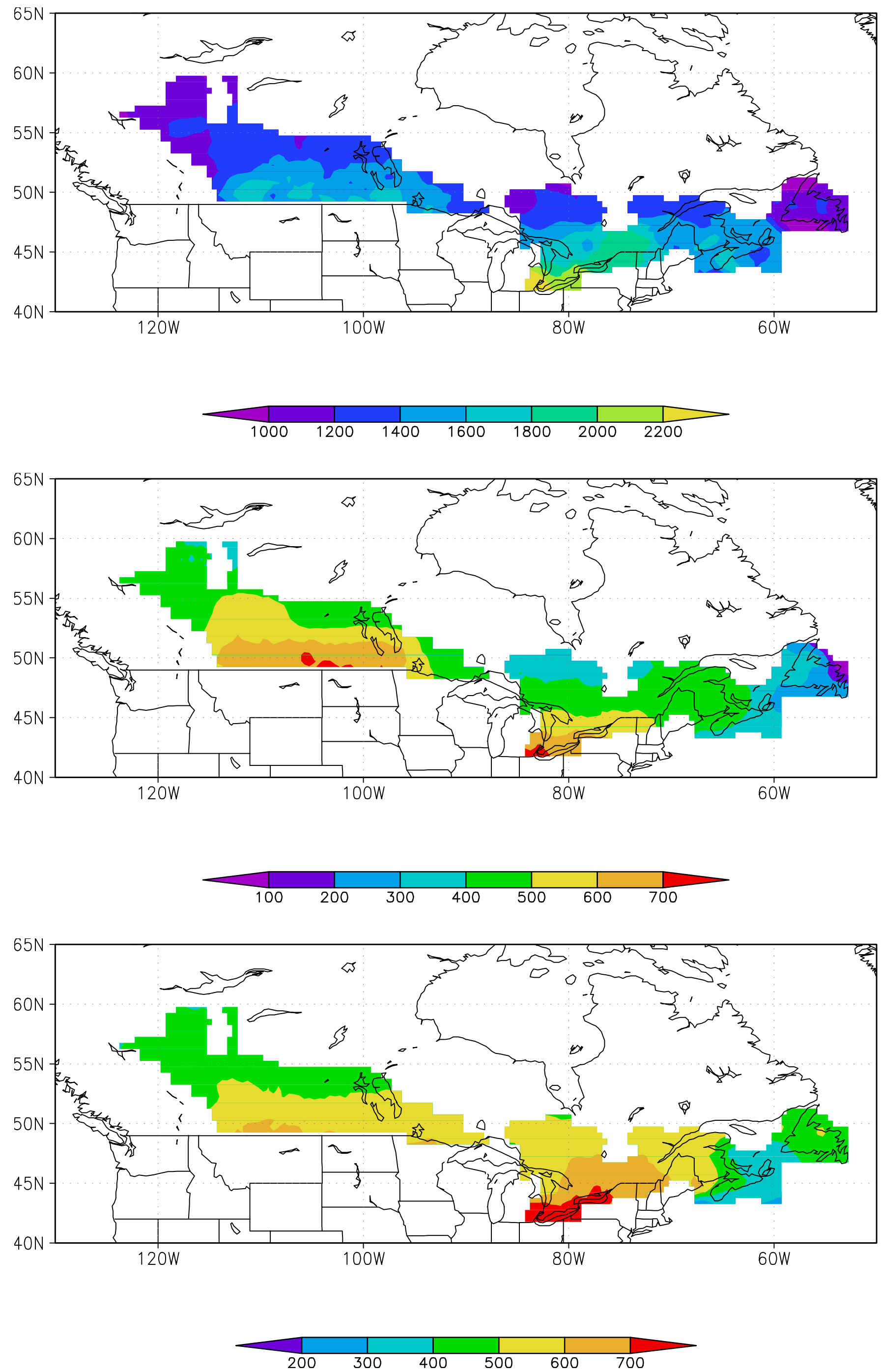

Figure 5. The 80% probability values of growing degree-days (GDD) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

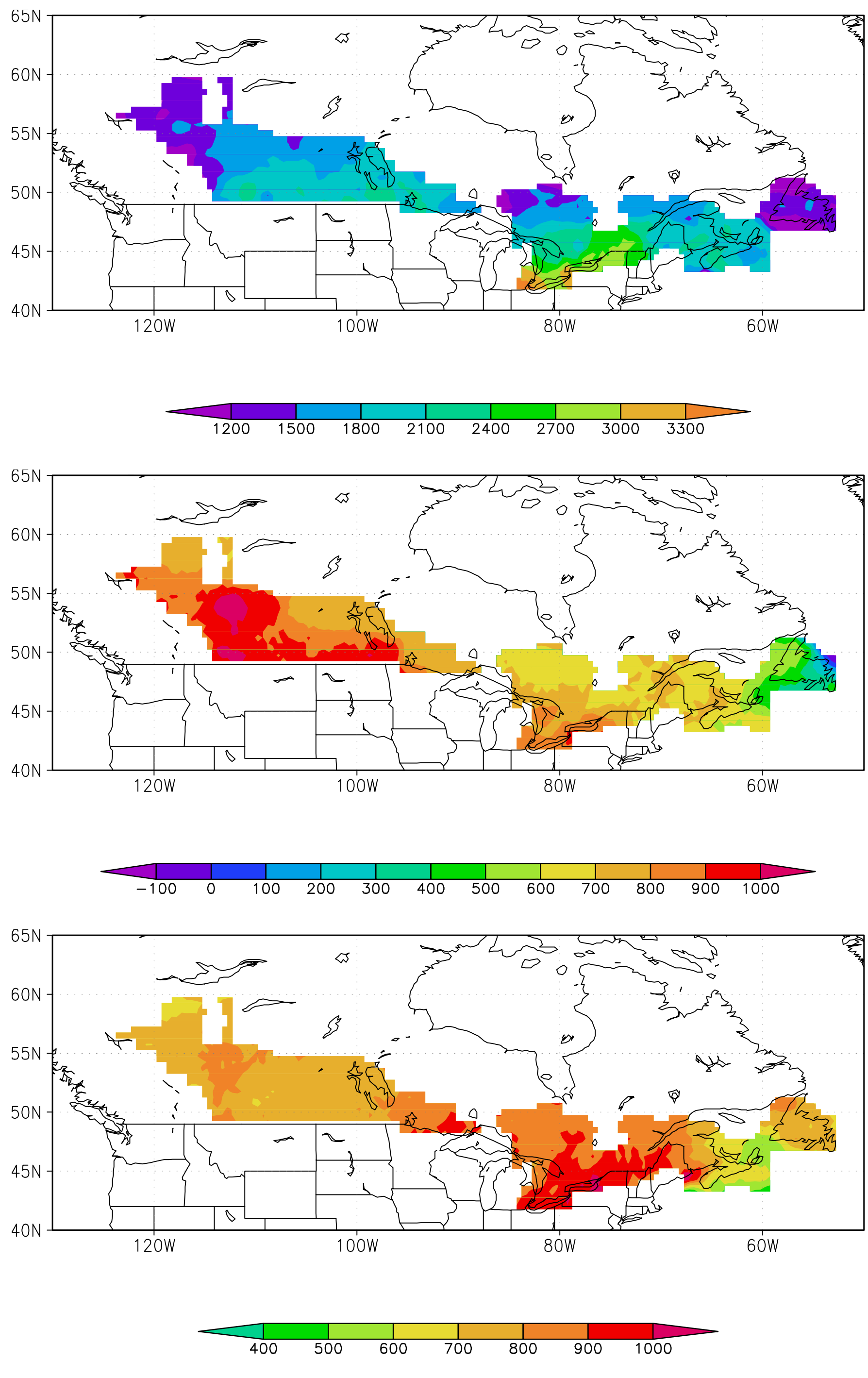

Figure 6. The 80% probability values of crop heat units (CHU) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

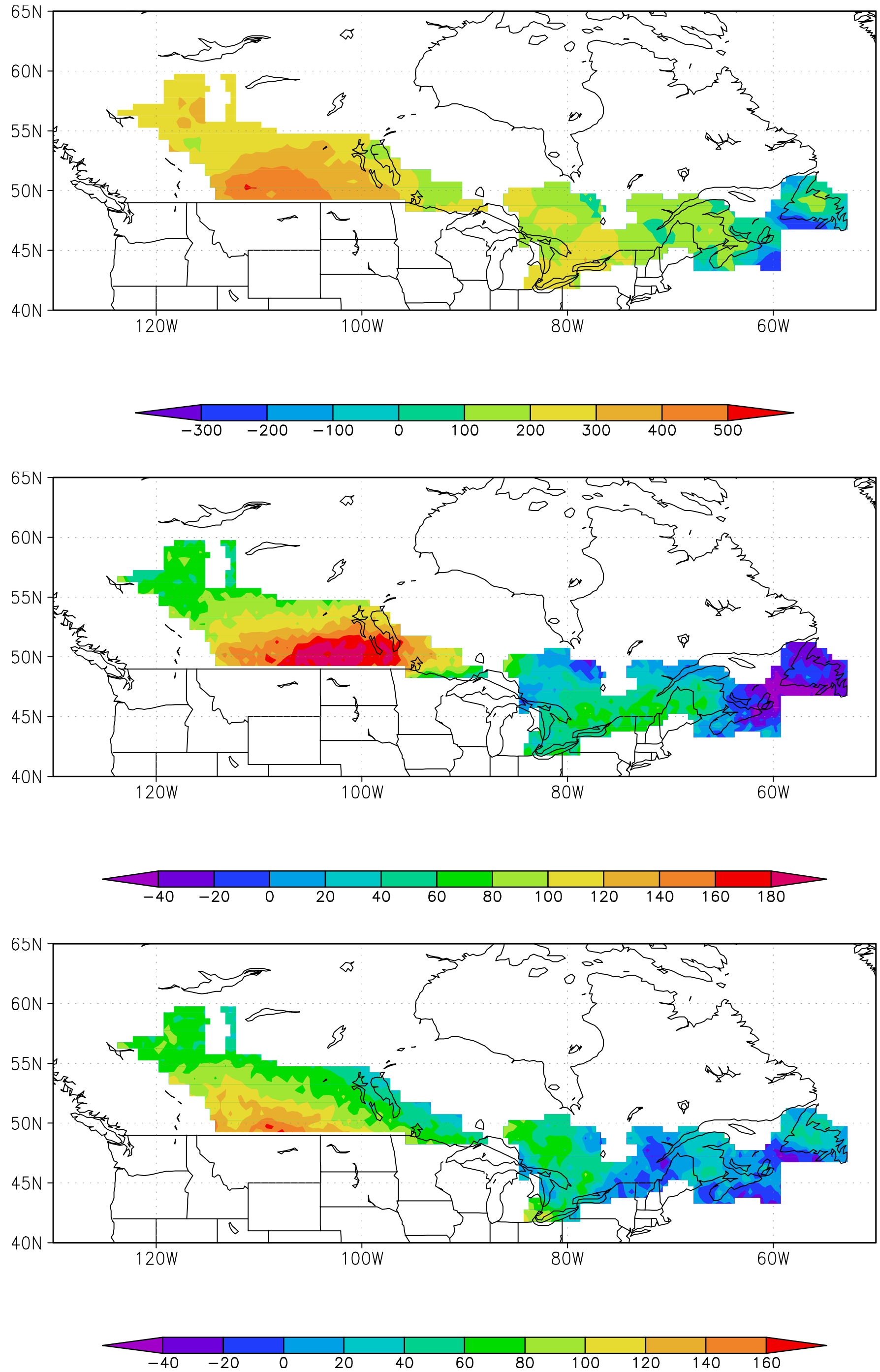

Figure 7. The 80% probability values of precipitation deficit/surplus (PDS) for 1961-1990 (top panel) and the differences between 2040-2069 and 1961-1990 translated from CGCM1 (middle panel) and HadCM3 (lower panel)

3.3 *Scenarios for Moisture Stress*

In the present climate, moisture stress is a limitation for crop growth on the Canadian Prairies. The precipitation deficit is 300-500 mm in most parts of the Prairies (Figure 7 top panel). It is 100-300 mm in Ontario and western Quebec. There is no severe moisture stress in the Maritime Provinces; a precipitation surplus is observed in some regions. The 80% probability level values are used so that the indicated precipitation deficits would not be expected to be exceeded in 80% of the years.

Projected changes in precipitation deficits by CGCM1 show the largest increase of 60-200 mm on the Prairies, and an increase of less than 80 mm in Ontario, Quebec and New Brunswick (Figure 7 middle panel). Changes in the Maritime Provinces are small. Changes predicted by HadCM3 (Figure 7 lower panel) are not as large as those from CGCM1 for the Prairies especially for the eastern part, where most increases are in the range of 60-160 mm. Instead of the greater moisture stress (40-80 mm more deficits) in Quebec predicted by CGCM1, HadCM3 projected a slight decrease (up to 40 mm less deficits).

4. CONCLUSIONS

In this study, we evaluated the performance of stochastic weather generators in simulating statistical properties of daily climate data in diverse Canadian climates and assessed parameter modification schemes for applying stochastic weather generators to climatic change impact studies. We found that stochastic weather generators are suitable for developing daily climate scenarios for agricultural applications. To demonstrate the procedure of developing daily climate scenarios with stochastic weather generators, we applied the stochastic weather generator AAFC-WG to generate future daily climate scenarios on half-degree grids in Canadian agricultural areas, based on daily outputs of common climate variables from two climate change simulations, which have been widely used in the development of future climate scenarios.

Daily climate scenarios developed in this study can be used in many areas of climate change impact studies. To demonstrate their application, daily climate scenarios were used to study potential changes in agroclimatic resources for Canadian agriculture. Various agroclimatic indices, which have been used to assess crop production potentials and to rate the climatic suitability of land for crops in Canada, were computed from synthetic daily climate data both for the baseline climate of 1961-1990 and the future climate of 2040-2069 under approximately doubled atmospheric CO_2 concentration. Changes in the agroclimatic indices at the 80% probability level were analyzed.

Agroclimatic resources, translated from agroclimatic indices, imply that global climate models projected remarkable changes. Although some details are different in two GCM simulations, changes are usually indicated in the same direction. A longer growing season with an earlier ending of spring frost, a later start of fall frost and longer frost-free period, as well as an increase in available heat, is indicated by both GCMs. In general, the last frost in spring is projected to occur about 10 days earlier than in the baseline climate and the first frost in fall is projected to start 10-20 days later, resulting in a 20-30 days longer frost-free period. Growing degree-days and effective growing degree-days are predicted to increase by 200-800 units, and the crop heat units by 700-1000 across Canadian agricultural regions. However, moisture stress may be greater in the future as increases of around 150 mm for the precipitation deficit are projected. Increases are even larger on the Canadian Prairies where moisture stress is a limiting factor in the present-day climate.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Agronomics Interpretations Working Group, 1995: Land suitability rating system for agricultural crops: 1. Spring-seeded grains. In: Pettatiece WW (ed) Technical Bulletin 1995-6E. Centre for Land and biological Resources Research, Agriculture and Agri-Food Canada, Ottawa.

Bootsma, A., Tremblay, G., Filion, P., 1999: Risk analyses of heat units available for corn and soybean production in Quebec. Technical Bulletin, ECORC Contribution No. 991396. Research Branch, Agriculture and Agri-Food Canada, Ottawa.

Baier, W., 1971: Evaluation of latent evaporation estimates and their conversion to potential evaporation. *Can. J. Plant Sci.,* **51**, 255-266.

Baier, W., Robertson, G.W., 1965: Estimation of latent evaporation from simple weather observations. *Can. J. Plant Sci.,* **45,** 276-284.

Boer, G.J., Flato, G.M., Reader, M.C., and Ramsden, D., 2000: A transient climate change simulation with historical and projected greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. *Climate Dynamics*, **16**: 405-425.

Bootsma, A., Gameda, S., McKenney, D.W., 2001: Adaptation of agricultural production to climate change in Atlantic Canada. Final Report for Climate Change Action Fund Project A214. Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa.

Bryant, C.R., Smit, B., Brklacich, M., Johnston, T.R., Smithers, J., Chiotti, Q., Singh, B., 2000: Adaptation in Canadian agriculture to climatic variability and change. *Climatic Change*, **45,** 181-201.

De Jong, R., Li, K., 2001: Potential climate change and its effects on barley yields in Canada. In Preprints to Symposium on Climate Variability, the Oceans, and the Societal Impacts, 217-221, American Meteorological Society 81st Annual Meeting, 14-18 January 2001, Albuquerque, NM, USA.

Easterling, W.E., Mearns, L.O., Hays, C.J., Marx, D., 2001: Comparison of agricultural impacts of climate change calculated from high and low resolution climate change scenarios: Part II. Accounting for adaptation and CO_2 direct effects. *Climatic Change*, **51,** 173-197.

Gordon, C., Cooper, C., Senior, C., Banks, H., Gregory, J., Johns, T., Mitchell, J., Wood, R., 2000: The simulation of SST, sea-ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, **16**, 147-168

Hayhoe, H.N., 2000: Improvements of stochastic weather data generators for diverse climates. *Climate Research*, **14,** 75-87.

Hayhoe, H.N., Lapen, D.R., 2002: Using weather generators and agroclimate indices for climate change impact assessments. In: Preprints for the 13th Symposium on Global Change and Climate Variations, 82nd AMS Annual Meeting, 13-17 January 2002, Orlando, Florida, American Meteorological Society, Boston, MA. 3 pp.

Hutchinson, M.F., 1991: Climatic analyses in data sparse regions. In Muchow RC and Bellamy JA (eds) Climatic Risk in Crop Production: Models and Management for the Semiarid Tropics and Subtropics. CAB International, Wallingford, pp 55-73.

Jones, J.W., et al., 2003: The DSSAT cropping system models. *European Journal of Agronomy*, **18,** 235-265.

McGinn, S.M., Shepherd, A., 2003: Impact of climate change scenarios on the agroclimate of the Canadian prairies. *Canadian Journal of Soil Science*, **83,** 623-630.

McGinn, S.M., Toure, A., Akinremi, O.O., Major, D.J., Barr, A.G., 1999: Agroclimate and crop response to climate change in Alberta, Canada. *Outlook on Agriculture*, **28**, 19-28.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1992: Effect of changes in inter-annual climate variability on CERES-wheat yields: sensitivity and $2xCO_2$ general circulation model studies. *Agricultural and Forest Meteorology*, **62**, 159-189.

Mearns, L.O., Rosenzweig, C., Goldberg, R., 1997: Mean and variance change in climate scenarios: methods, agricultural applications, and measures of uncertainty. *Climatic Change*, **35**, 367-396.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Gruebler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Ronger, H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000: IPCC Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599pp.

Qian, B., Gameda, S., Hayhoe, H., De Jong, R., Bootsma, A., 2004a: Comparison of LARS-WG and AAFC-WG stochastic weather generators for diverse Canadian climates. *Climate Research*, **26,** 175-191.

Qian, B., Hayhoe, H., Gameda, S., 2004b: On applying weather generators for climate change impact studies. *Climate Research*, (submitted)

Richardson, C.W., 1981: Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Research*, **17**, 182-190.

Richardson, C.W., Wright, D.A., 1984: WGEN: a model for generating daily weather variables. US Department of Agriculture, Agricultural Research Service, ARS-8. USDA, Washington, DC

Semenov, M.A., Barrow, E.M., 1997: Use of a stochastic weather generator in the development of climate change scenarios. *Climatic Change*, **35**, 397-414.

Semenov, M.A., Porter, J.R., 1995: Climatic variability and the modelling of crop yields. *Agricultural and Forest Meteorology,* **73**, 265-283.

Shepherd, A., McGinn, S.M., 2003: Assessment of climate change on the Canadian prairies from downscaled GCM data. *Atmosphere-Ocean,* **41**, 301-316.

Wilks, D.S., 1992: Adapting stochastic weather generation algorithms for climate changes studies. *Climatic Change*, **22**, 67-84.

Williams, J.R., 1995: The EPIC model. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Littleton, CO.