CAN FROST DAMAGE IMPACT WATER DEMAND FOR CROP PRODUCTION IN THE FUTURE?

Michel Baraer[1]
Chandra A. Madramootoo[2]

ABSTRACT

One of the most efficient techniques used to protect the buds, flowers, and fruits of apple trees against potentially damaging spring frosts, is by spraying irrigation water on the fruit trees via a sprinkler irrigation system. The purpose of this study was to evaluate the impacts of global warming on frost occurrences for the fruit growing conditions in Québec, with the long-term objective being to evaluate how this will alter amounts of water used for frost protection. Frost injury risk is characterized by using a phenological model coupled with a risk index generator. The phenological model was selected amongst a group of models for its ability to maintain a satisfactory level of accuracy when tested under different climatic conditions. Based on meteorological and phenological observations on apple trees in the Monteregie region of Québec, the model calibration and validations provided evidence of the ability of the selected model to reproduce and predict frost injury risk trends. Local climatic conditions downscaled from a GCM were used to assess the effects of future climate scenarios on the risk of frost injuries. Under the tested scenario, the risk index increases significantly, suggesting that the number and / or the severity of spring frost injuries would increase in the future. This would imply that the use of a sprinkler system as a protection method against frost injuries has to be taken into consideration for the assessment of climate change impacts on overall water demands for crop water requirements.

INTRODUCTION

Spring frost injuries sometimes negatively affect annual fruit production in Canada. In Québec orchards, major frost occurs once every 10 years on average, impacting up to 40% of the annual crop yield. Milder events occur more frequently but are not systematically recorded. Between 1961 and 1986, a significant reduction in harvest due to spring frost injuries was apparent five times (Charette and Krueger, 1992). Taken individually, they might represent an important financial loss for the producers. According to the Fédération des producteurs de pommes du Québec, the total provincial revenue at the farm level for apple production in Québec was up to $33.8 million in 2003, representing around 22% of the Canadian production. Therefore, frost damage can lead to a significant economic loss at the provincial level as well. Several protection methods exist for producers to avoid or limit the effects of spring frost on their production. Among the most frequently recommended is sprinkler irrigation. It exhibits advantages other protection methods cannot provide such as the low energy costs and the dual-purpose of the

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[1] MScA Candidate; Brace Center for Water Resources Management, Faculty of Agricultural and Environmental Sciences, McGill University, 21111 Lakeshore Road, Montreal, Québec H9X 3V9; Michel.Baraer@mail.mcgill.ca
[2] Dean of the Faculty of Agricultural and Environmental Sciences and Director of the Brace Center for Water Resources Management, McGill University, 21111 Lakeshore Road, Montreal, Québec H9X 3V9; Chandra.Madramootoo@mcgill.ca

equipment (summer irrigation and spring frost protection). In addition, sprinkler protection has the potential to protect against some advective frosts while other methods such as wind machines or helicopters are applicable to radiation frosts only. Though specific disadvantages are also related to the use of sprinkler under negative temperatures, some consider sprinkler irrigation as the most attractive method for plants and trees frost protection (Koc et al., 2000; Jolivet, 2006).

From an environmental point of view, water consumption represents the most important drawback of sprinkler irrigation for protection against frost. Snyder and De Melo-Abreu (2005) recommended an application of 2.5 to 5.8 mm h^{-1} of water depending on the meteorological conditions. These rates lead to an annual water consumption of 1000 to 3000m^3 yr^{-1} ha^{-1} for 6 frost protection utilizations, each of 10 hours duration. This consumption level represents a significant threat for water availability. The National Water Research Institute of Canada observed that irrigation use for frost protection is increasing and that this practice further stresses water resources (NWRI, 2003). In a context of increasing competition between water users, this trend on water demand needs to be further analysed.

The purpose of this study was to make predictions on climate change impacts for damaging frost occurrences in Québec, with the long term objective to facilitate the evaluation of the impact it could have on water demands. Apple production represents the dominant fruit growing activity in Québec. Therefore it has been selected to be the reference crop for this research.

The conditions that lead to a spring frost injury are directly related to the phenological stage of the tree. If exposed to a temperature of -4°C for more than 30 minutes, a blooming bud will not survive, while if exposed during the first step of its development, the buds are not affected.

This means that a study on the impact of climate change on frost injuries has to cover both the prediction of future spring minimum daily temperatures as well as temperature change on the bud development process. The relation that exists between climate variations and the phenology of plants is described by Schwartz and Reiter (2000) who have observed an average advance of five to six days toward earlier springs in North America over a 35-year period from 1959-1993. Wolfe (2005) also observed an advance in spring weather conditions, with a slope for mid-bloom date versus year of -0.2 day/year, which is qualitatively consistent with a warming trend. His analysis was based on phenological observations between 1965 and 2001 on different horticultural species, including apple trees, in North-Eastern US. Since the early 1990’s, phenological models predicting the timing of budburst of trees are regularly used to predict the effects of climate change on tree phenology. On the other hand, as available phenological models are suspected of not being adapted for climate change studies, consequences of global climate change on phenology remain controversial (Chuine 2000). Hanninen (1995) tested 96 models on both natural conditions and on semi-controlled conditions simulating climate change. He found that Degree-Day models (DD) provided good results in predicting the phenological events under natural conditions, but failed by about 70 days in predicting the phenology under the climate change simulation. Linkosalo (2000) also found that temperature based models, even if they are widely applied to phenological research, provide predictions that are quite different than the ones from light-climate triggered models. His conclusion was that light-climate models should be used for climate warming studies. On the other hand, a large number of studies, even the most recent ones, consider climate based models for use under global warming conditions. Zinoni (2004) proposed a chilling-forcing model for apple trees to study climate change effects on Italian agriculture. Picard (2005) tested four phenological models for bud-burst prediction in Siberia and concluded that among the tested models, the simplest DD model was found to perform just as well as more complex models accounting for a chilling requirement. The contradicting results of these different studies highlight the need for specific attention to the selection of an appropriate phonologic model.

METHODOLOGY

Phenological models

The models selected for this study strive to be representative of the three different model types that are most often recommended for phenological development prediction: the simple degree-day models; the chilling-forcing models; and the light-temperature models.
The Degree-Day models are among the most commonly used and simplest models designed for phenology stage prediction. They are based on the concept that the air temperature at the growth period is the most significant factor triggering bud development. The Degree-Day model (DD) used for this study, starts accumulating at 32 days.
The chilling–forcing models (CF) cover two physiological stages of trees: the dormancy period and the growing period. The CF model, selected for this study, is an adaptation of the “Chill” model developed by Cesaraccio (2005). It is a chill/anti-chill day’s model that corresponds to an improved version of a temperature based sequential chilling-forcing model. This model has shown the best performance in predicting the phenological stages of 22 different crops when compared with seven other models tested under similar conditions. In addition, the “Chill” model has been described as being the best model for application onto apple trees by Zinoni (2004). The CF model differs from the Chill model by having a fixed harvest date and by being adapted to very cold winters.

In light-temperature models (LT) both daylight and temperature are used as predictors for bud development stages prediction. In total three light-temperature models are employed in this study, two are based on published models, LT3 and LT6, and one has been developed for this project, LT5.

LT3 is based on a model designed for the prediction of the flowering time for the Narrow-leafed Lupin (Reader et al., 1995). The model adaptation consists of fixing the day of calculation starting on February 1 (sowing date in the original model). In order to improve the accuracy of the predictions, mean daily temperature is considered when larger than +5°C only.

LT5 uses daily irradiance and mean temperature as its driving parameters. As a degree-day model, it accumulates units of temperature when these exceed a given threshold. In addition, units of light, represented by the daily irradiance, are systematically accumulated from February 1. The model is described by the following equations:

$$\begin{cases} \text{if } \overline{T}_j < Tc \text{ then } LT_j = bL_j \\ \text{if } \overline{T}_j \geq Tc \text{ then } LT_j = a\overline{T}_j - Tc + bL_j \end{cases} \tag{4}$$

$$\text{and}: \sum_{j=k}^{n} LT_j \geq TLD \tag{5}$$

Where T_j *bar* (°C) is the daily mean temperature, L_j (KWh/m^2) is the irradiance value, T_c is a temperature threshold and LT_j represents the daily heat and radiation accumulation. The day that corresponds to the phenological event, *n*, is defined as the moment when the units accumulation LT_j becomes larger than a given threshold, TLD. *a* and *b*, are crop and site related parameters.

Finally, LT6 is a model described as the one providing the most accurate results under climate change conditions by Hanninen (1994) in a test of 96 models. Its application to apple tree phenology does not require specific adaptation.

Area and crop

The phenological models described above are applicable to different crops and cultivars. However this study is limited to the McIntosh Apple, the most frequently observed apple cultivar in Québec. Seven phenological stages are considered: Green tip (S1); Half-inch Green (S2); Tight Cluster (S3); First Pink (S4); Full Pink (S5); Full Bloom (S6) and Calices (S7). Phenological models require temperature data sets that cover more than just the growing period. They are therefore calibrated using meteorological parameters from nearby stations.

The study focuses on the largest apple production area in Québec, the Montérégie. Simulations were conducted for three different sites: Rougemont, Farnham and Freligsbourg (Figure 1). The Farnham station (45°15'N; 72°58'O) time series are used to calibrate phenological models at Farnham and Rougemont (45°25'N; 73°6'O) while the time series from Brome (45°10'N; 72°34'O) serve as calibration data for Freligsbourg (45°3'N; 72°52'O). Details on data sets used are given in Table 1.

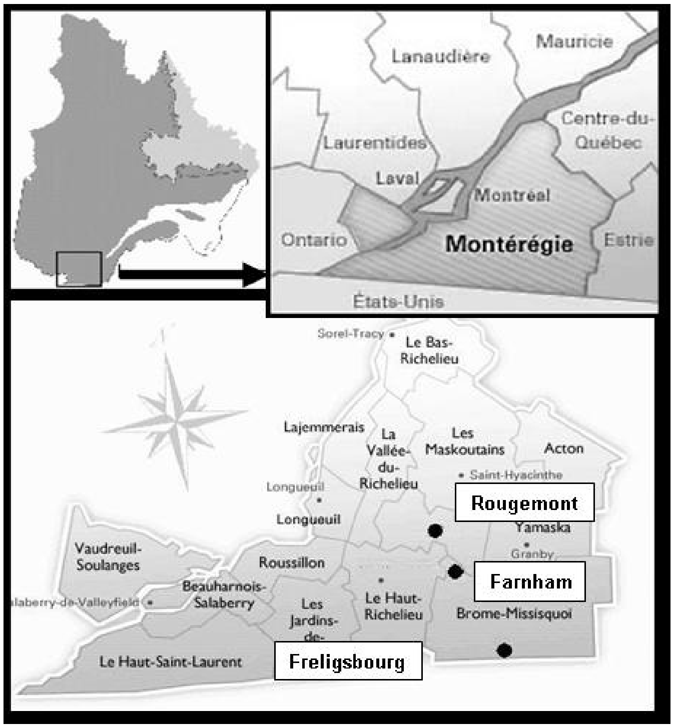

Figure 1. Map of Montérégie & location of the three experimental sites.

Table 1. Description of the used observation time series

Type	Location	Use	# of years	Period
Phenology all stages[3]	Farnham	calibration and validation V1	28	1960-1988
Phenology all stages[3]	Rougemont	calibration and validation V1	28	1977-2005
Phenology all stages[3]	Freligsbourg	calibration and validation V1	27	1977-2004
Phenology S7	Monteregy av.	Validation phase V2		1926-1950
Phenology S7[3]	6 sites, Montegerie	Statistical tests	26	1979-2005
Station T°	Farnham	calibration and downscaling	48	1926-2001
Station T°	Brome	calibration and downscaling	51	1926-2005
Orchard T°[3]	Farnham	Tcrit module	16	1972-1988
Orchard T°[3]	Rougemont	Tcrit module	22	1972-1995
Orchard T°[3]	Freligsbourg	Tcrit module	20	1972-1995
Daylight	All	LT3 & LT6 models	85	1920-2005
Solar radiations	regional	LT5 model	averaged	-

Model selection procedure

There are three basic requirements a phenological model should meet in order to be used for a climate change impact study. First, the selected model should demonstrate a good ability in reproducing phenological events observed on a period adjacent to the calibration data time series. Secondly, the model should be able to reproduce observed phenological events that are distant enough from the calibration period to be representative of climate change conditions. At this stage, the model should not show signs of systematic susceptibility to changes in climatic

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[3] IRDA: Institut de recherche et de développement en agroenvironnement/ Réseau-pommier du Québec

conditions. Finally, the model should consistently provide realistic predictions under climate forcing simulations. For example, no odd predictions such as bud burst being predicted before the pink tips, phenological stage not being predicted at all, or the model showing error messages should not be observed. Presently, phenological models are evaluated for these criteria through two validations phases called V1 and V2 and through a screening of individual predictions obtained under the climate change scenario. The first validation step, (V1) covers recent observations while V2 is based on a set of phenological observations that were recorded in the first half of the last century. The oldest time series are given for the whole production region, not for individual stations. It is assumed that the regional observations are equivalent to the mean of observations from six well spread out sites. This average of six sites being very well correlated with the mean of the three pilot stations (correlation coefficient = 0,996), this value is accepted to represent the regional observation. V2 is performed for the full bloom stage, S7, only. The root mean square error, *Re*, is the primary parameter used for the models calibration. The calculation of the coefficient of determination, R^2, completes the utilisation of the root mean square error for the models evaluation at the different validation phases. A third indicator is introduced at the validation phase V2, called S_b. It measures eventual systematic bias in model predictions, and is defined as follows:

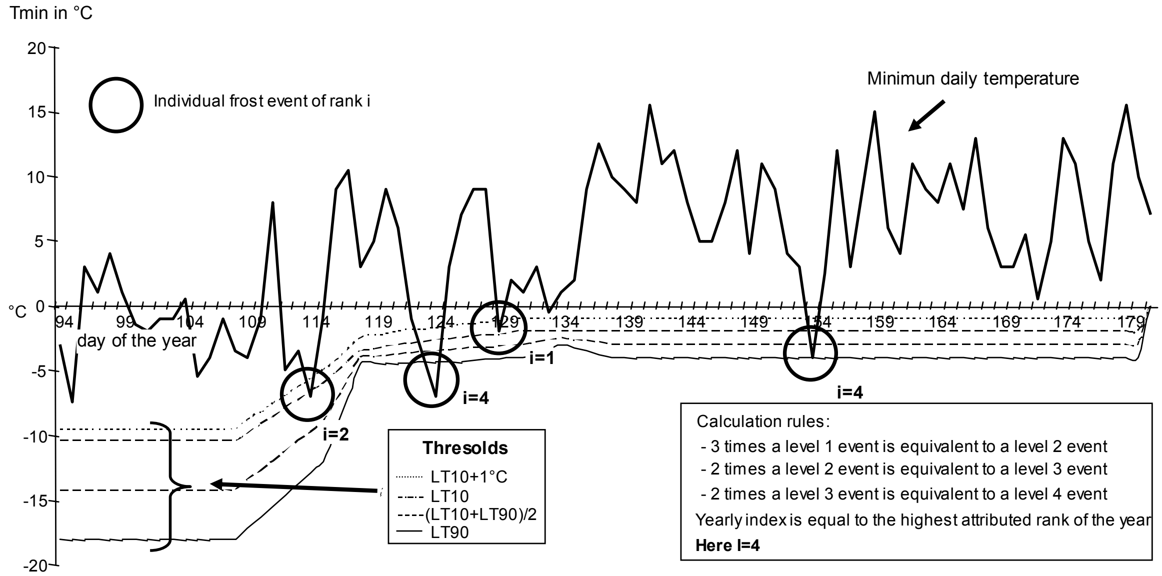
$$S_b = \frac{\left(\sum_{i=1}^{n} D_{V2pred} - \sum_{i=}^{n} D_{V2obs}\right)}{n} + \frac{\left(\sum_{j=1}^{m} D_{V1obs} - \sum_{j=1}^{m} D_{V1pred}\right)}{m} \qquad (10)$$

Where *n* and *m* are the number of predictions made on the V2 and V1 periods respectively and *D* is the yearly full bloom date predicted (pred) or observed (obs) during the period of V1 or V2.

Tcrit model

The risk of spring frost injury is characterised on a yearly basis by frost index *I*. It represents the severity of the most harmful events predicted during the year. Each predicted frost event is rated on a scale from 0 to 4; 0 representing no risk of injury, 4 a risk of severe damages.

In order to identify the risk related to an event, the index calculation module, called Tcrit, bases its index ranking calculation on four threshold levels. Wees (2001) published lethal temperatures, LT_{10} and LT_{90} (temperatures at which 10 and 90 percent of the buds are destroyed), associated with the bud growth stages for apple trees in Québec. These temperatures combined with predicted phenological phases are, in the present study, used as moving thresholds to characterise the injury risk related to projected daily minimum temperatures. Each time the minimum temperature reaches a threshold line an individual frost event is ranked from 1 to 4. Tcrit then converts the annual frost events ranked in a yearly spring frost index. The threshold calculation for each phenological stage is illustrated in Figure 2. Ranking limits for days that stand between two phenological stage times are calculated by assuming a linear trend for the lethal temperatures between two phenological events.



Calculation rules:
- 3 times a level 1 event is equivalent to a level 2 event
- 2 times a level 2 event is equivalent to a level 3 event
- 2 times a level 3 event is equivalent to a level 4 event

Yearly index is equal to the highest attributed rank of the year

Here I=4

Figure 2. Tcrit module calculation principle.

Coupled with a phenological model, Tcrit provides an easy to use yearly indicator, which is used in this study to identify eventual trends in spring frost injury risks for the present century.

Climate change scenario

Projections of future climatic conditions originate from the Canadian Global Circulation Model called CGCM1, run under the IPCC scenario IS92a. Minimum, maximum and average temperatures at the three different sites of interest are obtained through downscaling. LARS-WG, a stochastic weather generator, is the downscaling tool that was selected to generate temperature predictions at the station level. For each downscaled climatic parameter, two-thirds of the collected measures are used for model calibration.

Four different periods representing four different climatic conditions were considered during downscaling: 1970-1999; 2010-2039; 2040-2069; 2070-2099. These periods cover 30 years of homogeneous climatic conditions. This means that the differences between yearly climatic conditions within a period are random. For example, the meteorological projections for the years 2010 and 2039 are based on the same climatic assumptions while the differences between the years 2039 and 2040 are both due to randomness and to climatic forcing. This is the reason why all model outputs related to climatic projections are presented as period averages rather than as single year results.

RESULTS

Climate change effects observations

The effect of global warming between the two validation periods V1 and V2 is verified through a multivariate Mann-Kendall trend analysis on the growing period daily mean temperatures

(March, April, May) and on the regional mean full bloom date for the period 1926-2005. The standardized test statistic MK Stat shows a significant positive trend for the growing period average temperature (MK stat = 2.3 with a p-value = 0.021) and a significant negative trend for the full bloom date (MK stat = -2.21 with a p-value = 0.027). Between 1926-1950 and 1979-2005 there is a 0.97°C increase in the average growing season daily temperatures while the regional full-bloom date is advanced by 4.36 days on the time interval.

The change in the apple tree phenology between the two periods corresponds to an average rate of -0.08 day/year. This value is situated below figures reported by Schwartz and Reiter (2000), or by Wolfe (2005), respectively at -0.16 day/year and at -0.2 day/year.

Model validation V1

The calibration is performed for each phenological stage, each site and model. Every model is associated with a cluster of 21 different sets up that are challenged during the validation stages. Results from this phase are presented in Figure 3. Most of the models exhibit a strong ability to reproduce contemporary observations.

The coefficient of determination R^2 for all models excepted for LT3, are over 0.9. This performance is confirmed by the root mean square error. All models have a *Re* median lower than 4 days and a Q_{75} quartile below 5 days. LT3, the less accurate model at this stage, is the only one presenting outliners over 7 days. LT5 and LT6 are here the most accurate models. LT6 shows both the best R^2 and *Re* values. For comparison, Hanninen (1994) reached a *Re* of 4.1 days with the similar model on a shorter period of observation.

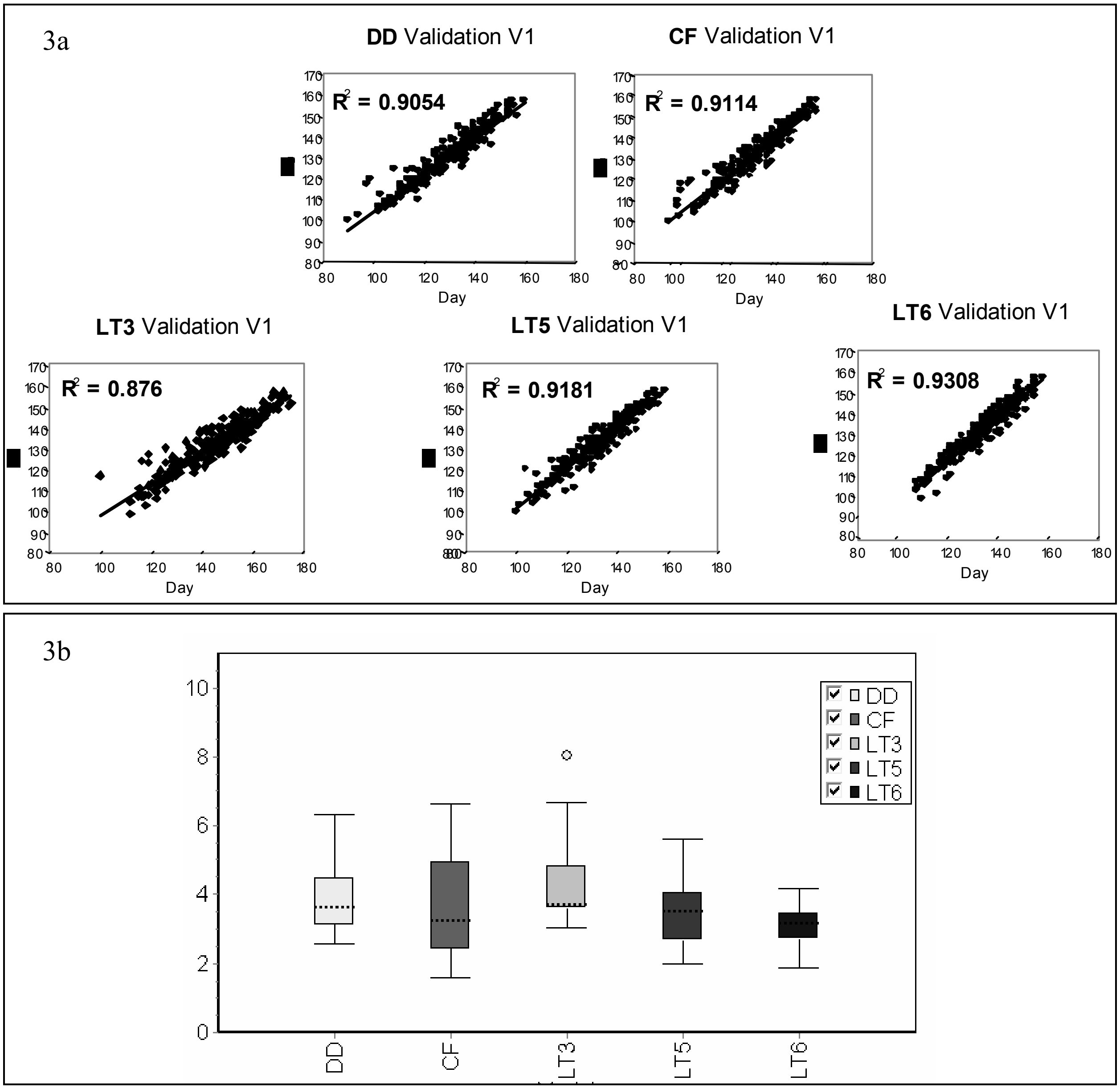


Figure 3. V1 Validation results.3a: Scatter plot of observed versus predicted values and coefficient of determination results; 3b: Box plot of roots mean square errors, the dotted line represents the median value, the box materialises the inter quartile range (IQR), the whisker is the min or max value that stands within the 1.5 *IQR* value, spots are outliners.

Models validations V2

Old phenological observations are not guaranteed to be as reliable as the recent ones and care should be used in V2 result analysis. The three performance indicators calculated for each model are presented in Figure 4. This chart suggest that both the DD and the LT3 models could be susceptible to change in climatic parameters as both of them present a systematic bias indicator close to one day. In addition both the *Re* and *R2* values for the DD model are the weakest observed. Here again the LT5 and LT6 models exhibit good results. LT5, by reaching the best value for each of the three indicators, comes out as the most adapted model for uses under climate change conditions.

Climatic predictions

As for the phenological model, the downscaling tool is calibrated for two thirds of the meteorological observations and validated for the remaining part. For each station three meteorological parameters are extracted: Tmin, Tmean and Tmax, respectively, the monthly average of daily minimum, average and maximum temperatures. The predicted monthly minimum average temperatures for the four considered time periods: 1972-200l; 2010-2039; 2040-2069 and 2070-2099 are presented in Figure 5.

The increase of the yearly temperatures predicted by the model between periods 1972-2000 and 2070-2099, +4.55°C, is unevenly distributed across the year. For the first six months of the year, the most important period for apple tree phenology, the most significant temperature increase between 1972-2000 and 2070-2099 is + 8.9°C predicted for the month of February, while the smallest temperature deference would be observed in April with a difference of +3°C.

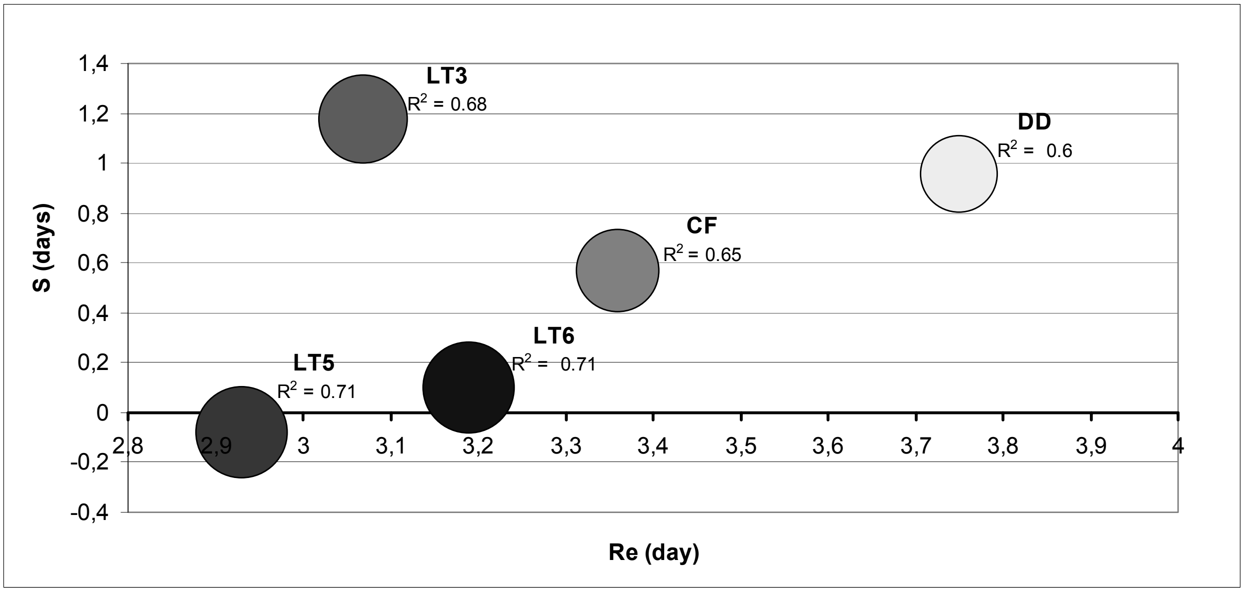


Figure 4. Bubble chart of the model performance indicator at V2 stage. The size of the bubbles represent the coefficient of determination, the x axis stands for the roots mean square error while the systematic bias parameter is read on the y axe. Models that exhibit large bubbles, low *Re* and S_b close to the 0 line perform well under V2 conditions.

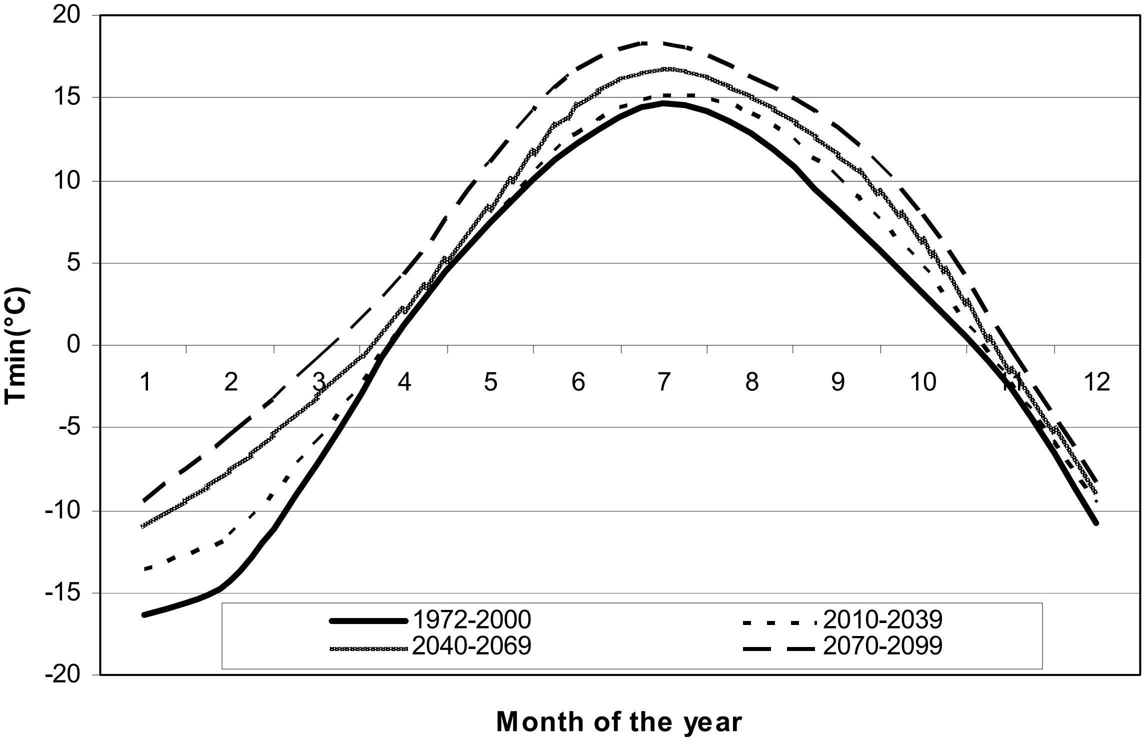


Figure 5. Evolution of the monthly average of minimum temperatures as predicted under downscaling conditions (1972-2000 based on simulated data).

Phenological models response to climatic scenarios

Two phenological models produce a significant number of wrong predictions under climatic forcing conditions. LT3 is the most unstable of the models with an average 10% of odd values generated. This percentage is low for the period 2010-2039 and increases with time. For the period 2070-2099 almost all years are affected by wrong predictions for one or more phenological stages. The CF model does not demonstrate an acceptable ability to be used under long term climate change predictions either. The proportion of generated errors is negligible during the periods 2010-2039 and 2040-2069, and it reaches almost 50% in the years for the period 2070-2099. Other models do not generate significant proportions of odd values under the predicted conditions. Average phenological projections under climate change predictions are presented in Figure 6 for these three models. As suggested during the validation phase V2, the DD model reacts more to change in climatic parameters than the two remaining LT models: excepted for the last phenological stages, the DD models predict the different stages in average two to three days earlier than the LT models. The systematic difference in prediction is particularly large for the first development stages. The three models do not predict an important change in apple tree phenological behaviour between the periods 1972-2000 and 2010-2039. The shift in phenological event dates is much stronger from the period 2040-2069 and 2070-2099, reaching almost 20 days for the latest events.

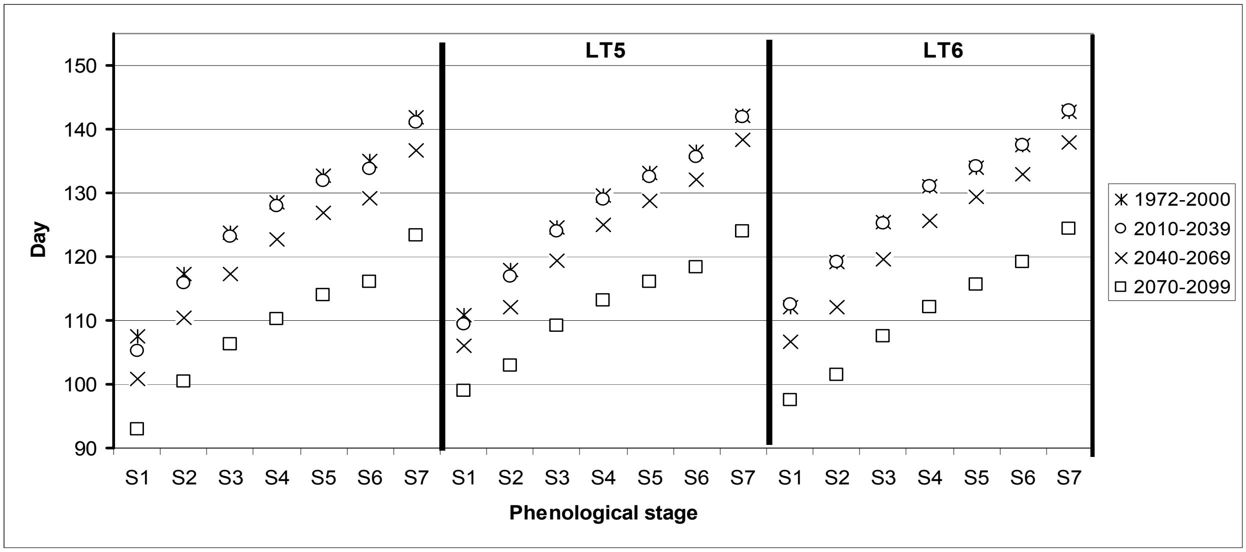


Figure 6. Average phenological events prediction for the different time-periods for DD. LT5 and LT6 models.

LT5 and LT6 are the models that demonstrate the best ability to fit with requirements that were stated for the model selection process. These two models only are utilised for the final part of the study.

Frost injury risk index projections

The phenological projection obtained through models LT5 and LT6 are introduced into the Tcrit model, which generates a frost injury risk index for each year and for each site. Yearly station related indexes are then compiled into a time period regional average index. The resulting values are shown in Figure 7.

There is a clear positive trend in the index regardless of which one of the two phenological models are used. This means that under the study conditions, the Tcrit model predicts an increase in frost injury risk for the 21st century. The difference between the LT5 and LT6 based projections is neglectable for the 2040-2069 and 2070-2099 periods. On the 2010-2039 time period, the use of LT6 suggests a negligible change in damaging frost occurrence while the LT5 based predictions show a slight risk of increase for the first time period.

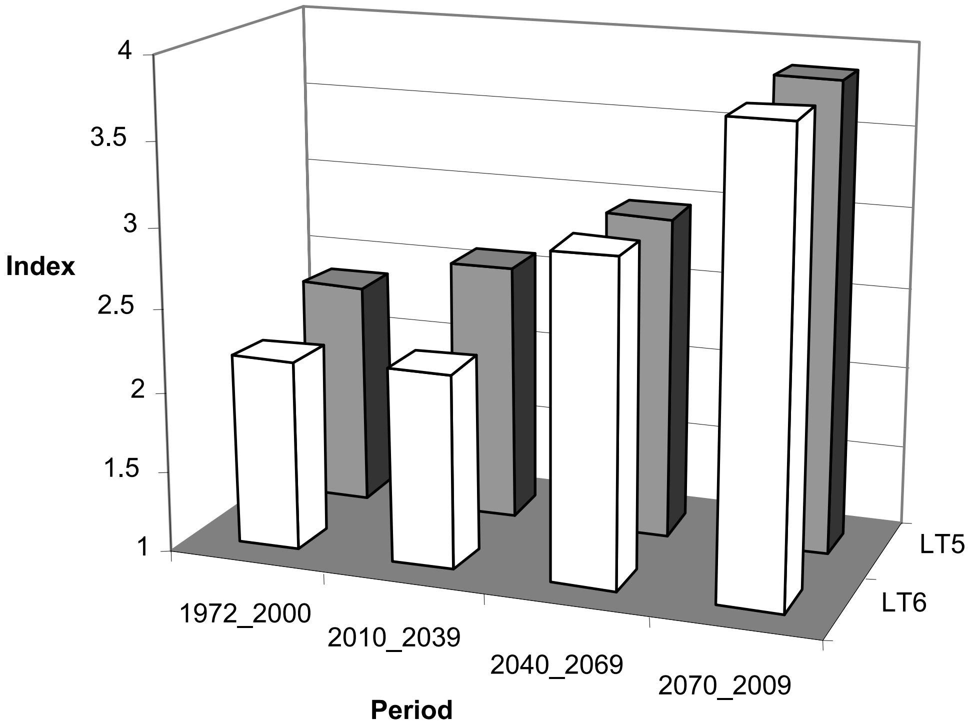


Figure 7. LT5 and LT6 based spring frost injury risk index projection for the 21st century

DISCUSSION

Climate change impact prediction studies are all dependant on the reliability of climatic projection. This is the case in this study where the uncertainty of the GCM is amplified by the use of a downscaling method. Even if a selection process is used to make use of phenological models that are well adapted with the intended use, the uncertainty brought by these models remains significant and cumulates with climatic projections ones. The use of old phenological observations at the V2 validation stage is also a factor in prediction inaccuracy in the present study. This means that particular care should be used in drawing conclusions from the results presented above. In addition, complementary tests should be conducted with a larger set of climatic scenarios as they are needed to confirm the frost injury risk trends suggested here. With this understanding of the limits related to this study, several observations can be made from its output.

The model selection process showed that some of the models tested did not comply with the requirements, based on the purpose of this study. Phenological models LT3 and CF that were adapted from published models show average to unsatisfactory performances at the different evaluation steps. This leads to the conclusion that these adaptations are not successful. Even if the DD model does not produce unrealistic values under the climate change scenario, its accuracy is not up to the level of the LT's. Furthermore, the DD model reacts strongly to change in climate scenarios than LT5 and LT6 do. This would confirm Hanninen (1994) observations on the non light triggered models susceptibility to changes in climatic scenarios. LT5 and LT6 are the best performing models under the test conditions. LT6 shows slightly better performance at the V1 stage while LT5 appears as the most reliable model at the V2 stage. Based on these observations, the two models could be recommended for climate change impact studies. LT6 being based on a published model, it presents the interest of having been tested in different research situations. LT5, a model specifically designed and developed for this study, exhibits a high potential under climate change conditions and has the advantage of being based on less parameters than LT6. The latest can be an advantage for utilisation in conditions affected by a lack of long observation time series, which is needed for model calibration purposes.

The trend in risk of buds damage for apple trees in Québec due to spring frost under tested conditions shows an apparent increase. If confirmed through the use of the tools selected above under a representative number of climatic scenarios, the result would suggest that either a larger number of damaging frost events, their intensity, or both should increase in the future. Representative climatic scenarios could be obtained by using different CGM outputs, different emission scenarios and possibly other downscaling techniques. In addition, the applicability of such conclusions to a large number of different fruit production hypotheses would need to be verified through further tests on different crops prior to being accepted.

The increase in damaging frost occurrence prediction can possibly be explained by the characteristic of the climate change projections. As shown in Figure 5, the yearly average predicted temperature increase is not evenly distributed among the months. For instance, the month of January and February are predicted to be more affected by the temperature increase than April or May. In January-February, the apple trees ontogenetic development process is ongoing. A temperature increase in these months would therefore speed up the bud development process. If the temperature in April and May, the most critical months for the spring frost injuries, does not increase as fast as in January or February, spring low temperatures would affect buds developed to more temperature sensitive stages.

CONCLUSION

In the context of rising concerns of potential negative impacts of climate change on water resources, water demand management is of strategic importance. The utilisation of sprinkler irrigation as a frost protection method, due to the quantity of water required for an efficient protection, represents a risk of increase in overall crop water use for irrigation that needs to be further evaluated. The present study, by showing that climate change may increase the need for more protection against frost, suggests that more attention should be given to sprinkler irrigation frost protection practices. It also suggests that further studies should be conducted in order to validate the present findings, by using the phenological and Tcrit models under a large number of climatic scenarios.

The methodology that is used for trend analysis integrates two new models that have demonstrated their usefulness in the present conditions. Tcrit and its related spring frost injury risk index produces simple and efficient indicators of trends. Finally, the light-temperature triggered phenological model LT5 is the most suitable of the models tested in this study for apple tree phenological event predictions under climate change scenarios.

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