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# PROJECT REPORTS 2003/2004

## **Sensitivity of tree growth to the atmospheric vertical profile in the Boreal Plains of Manitoba**

**Martin-Philippe Girardin and Jacques Tardif**

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Related SFM Network Project:

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*Fire history reconstruction and response of the dominant tree species to climate in the Duck Mountain ecoregion, western Manitoba*



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## **Project Report 2003/2004**

**Project Name:** Fire history reconstruction and response of the dominant tree species to climate in the Duck Mountain ecoregion, western Manitoba.

**Title of paper:** Sensitivity of tree growth to the atmospheric vertical profile in the Boreal Plains of Manitoba

**Authors:** Martin-Philippe Girardin<sup>1</sup> and Jacques Tardif<sup>2</sup>

1. m.girardin@uwinnipeg.ca

2. j.tardif@uwinnipeg.ca

**Affiliation:** Centre for Forest Interdisciplinary Research (C-FIR), University of Winnipeg, 515 Portage Avenue, Winnipeg, Manitoba, R3B 2E9.

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**Keywords:** tree growth, dendroclimatology, response function, climate, geopotential height, atmospheric circulation

## **EXECUTIVE SUMMARY**

The influence of surface climate and atmospheric circulation on radial growth of eight boreal tree species growing in the Duck Mountain Provincial Forest, Manitoba, was investigated. Tree-ring residual chronologies were built, transformed into principal components and analysed through correlation and response function to reveal their associations to climate (temperature, precipitation and drought data for the period 1912-1999 as well as local geopotential height data for the period 1948-1999). Geopotential height correlation maps for the Northern Hemisphere were also constructed. Correlation and response function coefficients indicated that radial growth of most species was negatively affected by temperature induced hydric stresses from the summers previous and current to ring formation. The onset of spring also showed to be a determinant factor for conifer growth. Analyses performed on geopotential height highlighted the importance of both local and global scale atmospheric circulation in the species' response to climate. The relationships were highly significant at  $p < 0.001$  with the middle and high troposphere above the region during spring and late summer (determinant factor for growing season length) and with the Northern Hemisphere stratosphere during summer. Anthropogenic changes in the state of these atmospheric layers may be of consequence for tree growth in the Duck Mountain Provincial Forest.

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## **INTRODUCTION**

Terrestrial vegetation responds to weather and climate through a variety of physiological, demographic, and ecosystem processes (Bonan 2002). Together, these processes determine where plant species grow, how well they grow, and how their arrangement within the communities' changes over time (Bonan 2002). In this context, any changes in the state of weather and climate will affect terrestrial vegetation. The impact may be direct via interference with the plants' physiology (e.g., growth) (Bonan 2002) or indirect via changes in the stand dynamics (e.g., regime of disturbances) (Weber and Flannigan 1997).

Northern Manitoba is predicted to be one of the most affected regions by anthropogenic climate change within Canada. Simulations for years 2080-2100 indicates a summer warming of 4°C to 5°C and a winter warming of 5°C to 8°C (Boer *et al.* 2000; Laprise *et al.* 2003). In terms of fire severity ratings, Flannigan *et al.* (2001) predicted large increases in area burned by wildfire with the upcoming 2xCO<sub>2</sub> scenario. Forest simulations further indicated a major shift in species composition for the southern Manitoba boreal forest (Hogg 1994). Notwithstanding the uncertainties associated with the circulation models (Laprise *et al.* 2003), development of forest adaptation management strategies (Spittlehouse and Stewart 2003) are of necessity.

A field of forest ecology that requires exploration is that of the relationship between tree growth and the atmosphere. It is noteworthy that through changes in the chemical properties of the atmosphere, climate change alters the thermal and physical properties of the troposphere and stratosphere (the innermost layers of the atmosphere) (Santer et al. 2003). Hoskins (2003) warned that continuing changes in these atmospheric layers due to human activity may have wide range implications in the climate system (namely through cloud formation, radiation, wind, temperature, precipitation, and humidity). The impact of future warming on tree growth could be significant and any insights gained from looking at the historically relationships between climate and tree growth could assist in the development of adaptation plans to copped with climate change.

This report summarises a case study (Girardin and Tardif *submitted*) in which radial growth was contrasted against variations in the atmospheric vertical pressure profile at local and Northern Hemispheric scales. Radial growth response to temperature, precipitation, and drought were also examined to provide a mechanistic interpretation of the relationship between atmospheric circulation and tree growth. This study does not intend to determine whether species will be positively or negatively affected by climate change. Rather it provides a solid basis for an assessment of the sensitivity of tree growth in the region to global atmospheric circulation.

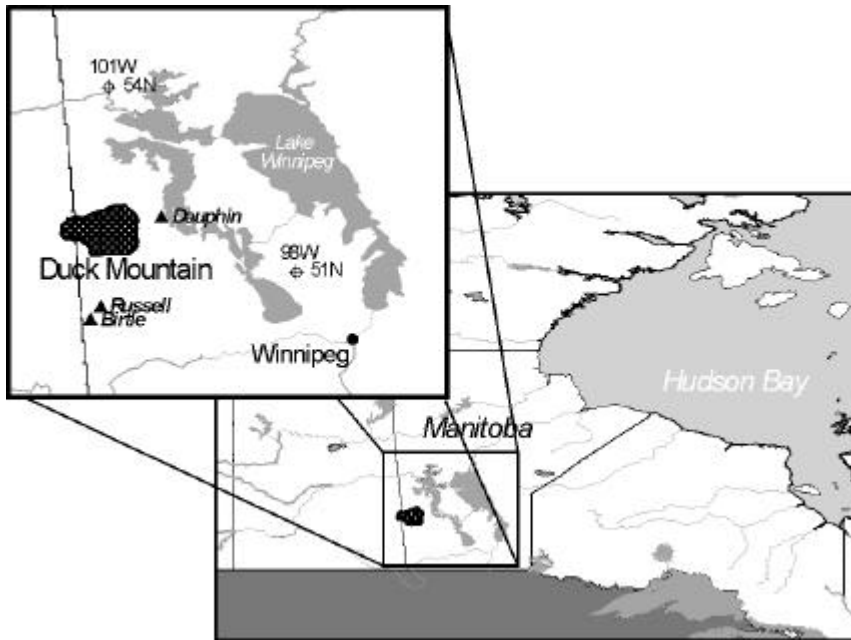
## STUDY AREA

The study was conducted in the Duck Mountain Provincial Forest (51° 39' 58"N and 100° 54' 52" W) of Manitoba, a transition zone between the boreal forest to the north and the aspen parkland and prairie to the south (Fig. 1). The Duck Mountain Provincial Forest has a mid-boreal climate with predominantly short, cool summers and cold winters. For the period 1971-2000, at Swan River (52°30'N, 101°13', elevation 346.6 m), mean monthly temperatures ranged from – 18.2°C in January to 18.1°C in July. Total annual precipitation was 530.3 mm with most precipitation falling as rainfall between months May to September (Ecological Stratification Working Group 1996; Environment Canada 2002). Compared to the surrounding lowlands, however, the Duck Mountain Provincial Forest plateau has cooler summers and winters and could receive about 50% more precipitation (Manitoba Provincial Parks Branch 1973).

## MATERIALS AND METHODS

Eight tree species were under analysis: *Populus tremuloides* Michx., *Populus balsamifera* L., *Picea mariana* (Mill.) BSP, *Picea glauca* (Moench) Voss, *Abies balsamea* (L.) Mill., *Pinus banksiana* Lamb., *Larix laricina* (Du Roi) K. Koch, *Picea mariana*. Using standard procedures (Cook and Kariukstis 1990), cores and/or cross sections were collected from mature trees (dead or alive), sanded, cross-dated, and measured. The measurement series were filtered to remove the non-climatic signals (mostly biological persistence) and averaged. In whole, nine well-replicated tree ring chronologies were developed (one for each species but including two for *P. mariana*: one for wet sites and one for dry sites) (Fig. 2).

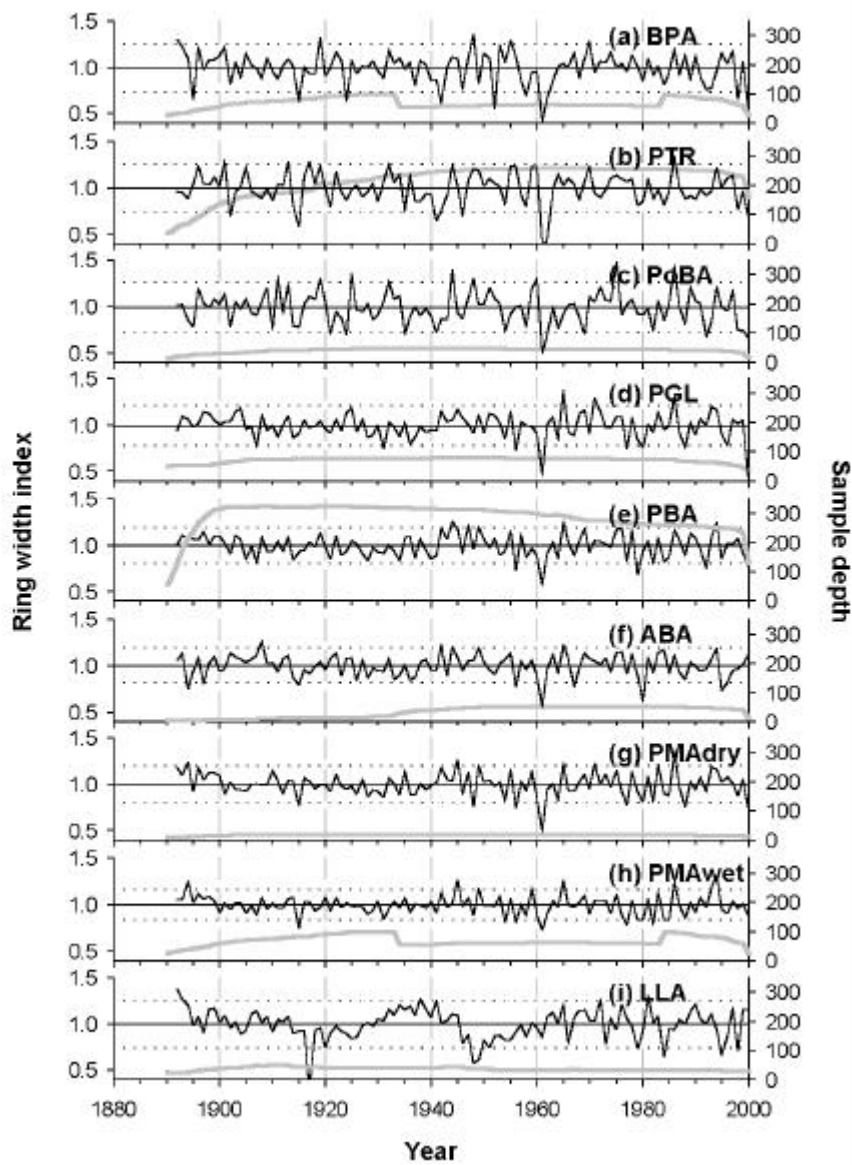
Using principal component analyses, common climatic signals in the tree ring chronologies were extracted and these signals were contrasted (period 1948-1999) against geopotential height, temperature, precipitation, and drought using correlation analyses (Briffa and Cook 1990; Fritts 1976) and bootstrap response function analyses (Fritts et al. 1991). Geopotential height approximates the actual height (in meters) of a pressure surface (hPa) above



**Figure 1.** Map showing the geographical location of Duck Mountain Provincial Forest in Manitoba. Meteorological stations are shown with filled triangles.

mean sea level. Positive height anomalies are generally associated with increased upper atmospheric pressure, temperature, and decreased storminess (Bonan 2002). Negative height anomalies are associated with decreased upper atmospheric pressure, temperature, and increased convection and precipitation (Bonan 2002; Ahrens 2003). Geopotential height data were obtained for the 50°N-100°W geographical location from the NCEP/NCAR Reanalysis project (Kalnay et al. 1996).

Geopotential heights correlation maps were also created with the aid of the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado (Kalnay et al. 1996; [www.cdc.noaa.gov](http://www.cdc.noaa.gov)). Their grid has a global spatial coverage of 2.5° latitude by 2.5° longitude with 144x73 points and a temporal coverage of 1948 to present, with output every 6 hours. Daily heights were averaged by months for each grid point.



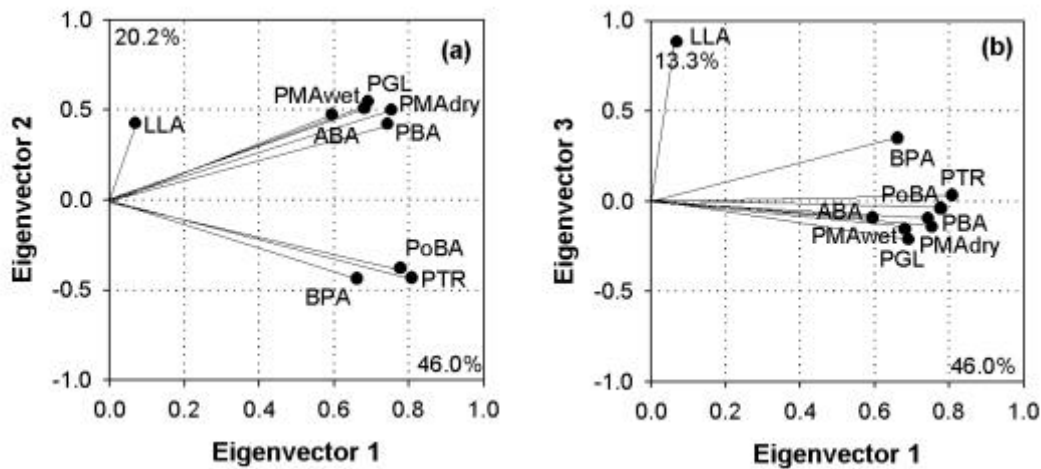
**Figure 2.** Residual chronologies of a) *Betula papyrifera* (BPA), b) *Populus tremuloides* (PTR), c) *Populus balsamifera* (PoBA), d) *Picea glauca* (PGL), e) *Pinus banksiana* (PBA), f) *Abies balsamea* (ABA), g) *Picea mariana* from dry sites (PMAdry), h) *Picea mariana* from wet sites (PMAwet), and i) *Larix laricina* (LLA). For each year, the thick-grey line shows the sample depth. Doted lines are set at 1.5 standard deviation.

## KEY FINDINGS

### *Species responses to climate*

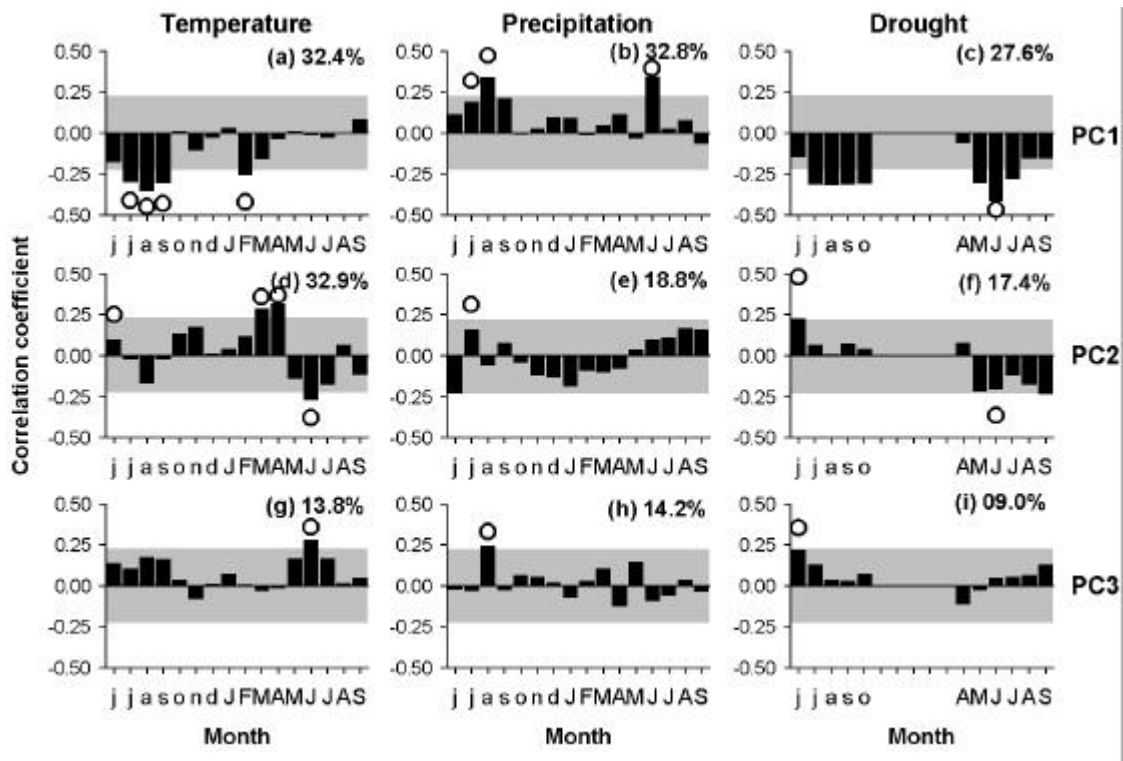
The partitioning of the variance in the principal component analysis indicated that growth of all species (with the exception of *L. laricina*) responded to common environmental signals (Fig. 3). This interpretation was stressed by the high correlation between the species' residual chronologies and the first principal component<sup>1</sup> (PC1) (correlation coefficients other than for *L. laricina* all greater than 0.59;  $p < 0.001$  with  $N=88$ ). It was across the second PC that the distinction between hardwood and coniferous species was observed.

Response function and correlation analyses indicated that the strongest signal affecting species' growth (with the exception of *L. laricina*) was the summer temperature-moisture budget (Fig. 4). This response was highlighted by the negative correlation between PC1 and temperature and drought and positive correlation with precipitation. A proper moisture budget allows optimal tree growth and assimilation of carbohydrates for next year's growth if soil moisture is sufficient to maintain foliage water potential and minimise vapour pressure deficits (Dang et al. 1998; Bonan 2002). Our results further indicated that the impact of a moisture deficiency was crucial in the year previous to ring formation.



**Figure 3.** First, second, and third eigenvector loadings of the Principal Component Analysis (PCA) conducted on the nine tree-ring residual chronologies for the period 1912-2000. The plots demonstrate the correlation coefficients between the residual tree ring chronologies (the descriptors) and the principal components (PCs). Also, the plots yield approximates the correlation coefficient among the descriptors themselves. Descriptors with arrows at sharp angles are positively correlated. By contrast, an obtuse angle between descriptors indicates a negative correlation.

<sup>1</sup> The first principal component (PCI) accounts for the maximum possible proportion of the variance in the tree ring chronologies. Succeeding PCs, in turn, account for as much of the residual variance as possible.



**Figure 4.** Correlation (vertical bars) and significant bootstrap response function coefficients (empty circles) computed between the PCs and each monthly climatic variables (mean temperature, total precipitation, and monthly mean Canadian Drought Code). Correlation coefficients exceeding the shading area are significant at  $p < 0.05$ . For the response function analyses, only those variables significant at  $p < 0.05$  are shown. Months previous to the year of ring formation (July-December) are labelled with small caps and those of current year of ring formation (January-October) are labelled with capital letters. The  $r^2$  of the response models is shown. All analyses were performed on the 1912-1999 period. Note that for Figure 4b and accordingly with Figure 3, a positive correlation with PC2 implies a positive relationship with growth of conifers and a negative one with that of hardwoods.

Additionally, differences among species were observed. First, it was found that growth of hardwoods was more sensitive to warmer June temperature than conifers (Fig. 4). In contrast, growth of hardwoods was less affected by warmer March temperature. Second, conifers were favoured by earlier spring while hardwoods were either not or negatively affected. Conifers can presumably take advantage of warm April temperature with their evergreen foliage. Earlier spring thus favours conifer radial growth but warmth temperature persisting till June could counteract the earlier effect. As for *L. laricina*, endemic periods of defoliation by the larch sawfly (*Pristiphora erichsonii*) could hide much of the climate signals.

#### **Relationship between tree growth and atmospheric circulation**

Sensitivity of tree growth to variations in height of atmospheric pressure surfaces was determined from correlation and response function coefficients computed between the principal components and the monthly geopotential height data. The results indicated that variations in



geopotential height during the period 1948-1999 accounted for more variance in tree growth than surface climate variables. For instance, the height of the 300hPa level explained 42.2% and 55.3% of the variance within PC1 and PC2, respectively (Fig. 5a and 5b, left side of chart). On the other hand, temperature, precipitation and drought accounted for 37.0% and 48.7%, 41.0% and 37.1%, and 31.7% and 25.2%, respectively. The relationship between tree growth and the atmosphere was greatest with the middle and high troposphere i.e., at 700hPa to 300hPa (or 3km to 9km above sea level) during summer the year previous to ring formation (Fig. 5a). However, results also indicated that Northern Hemisphere stratospheric circulation (e.g., between 200hPa to 10hPa or 12km to 31km above sea level) had a highly significant influence on tree growth for eight of the sixteen months under study (Fig. 5).

The sensitivity of tree growth in the Duck Mountain to large-scale atmospheric circulation features was highlighted with the creation of geopotential height correlation maps. It notably indicated that the negative correlation observed between PC1 and the stratospheric level (50hPa) during July to September the year previous to ring formation was associated with a Northern Hemisphere broad scale circulation, with a highly significant centre located above western Canada ( $r=0.43$ ,  $p<0.001$ ; Fig. 7a). In February of the year of ring formation, a similar correlation was associated with a Northern Hemisphere mid-latitude band extending from the interior North Pacific to Africa and Eurasia (Fig. 7b). At the tropospheric level (500hPa), the negative correlation was spatially reduced to a pattern located above the northwestern U.S.A. (Fig. 7c-d;  $r=0.40$ ,  $p<0.001$ ).

The correlation-maps, supported by the response function analyses, are indicating that a cooling<sup>2</sup> of the Northern Hemisphere upper atmosphere has a positive effect on tree growth in the area under study. The maps created using PC2 (results supported by Fig. 6b) however suggested that a cooling of the mid-troposphere (500 hPa) above the northwestern U.S.A. is more detrimental to conifers than hardwoods if it occurred in April (Fig. 6e), and more detrimental to hardwoods if it occurred in June (Fig. 6f).

**Figure 5 next pages.** Correlation and bootstrap response function coefficients computed between PC1 (a) and PC2 (b) and the estimated height (in meters) of various pressure surfaces (hPa), from near the Earth surface (1000hPa) to the upper atmosphere (10hPa) (read from bottom to top). On the left side of the panels is a horizontal bar chart showing the response model  $r^2$  for all levels. The thick line shows the average annual logarithmic relationship between air pressure (log-y scale; in hPa) and height above sea level (x-scale; in km). On the right sides are shown the correlation schemes. Months of the year previous to ring formation are labelled with small caps and those of the year of ring formation with capital letters. Dark-blue areas indicate regions of negative correlation (a white contour line denotes areas significant at  $p<0.05$ ). Red areas indicate regions of positive correlation (a black contour line denotes areas significant at  $p<0.05$ ). Areas of significant correlation ( $|r|>0.27$ ) are contoured and labelled at every 0.05 coefficient level. Areas for which significant response functions were obtained are crosshatched in black for positive coefficients and in white for negative coefficients. The analyses were performed on the period 1948-1999. Note that for Figure 5b and accordingly with Figure 3, a positive correlation with PC2 implies a positive relationship with growth of conifers and a negative one with that of hardwoods.

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<sup>2</sup> By definition, for a given pressure surface of the upper atmosphere, a negative height is an indication of lower temperature as colder air is more dense.

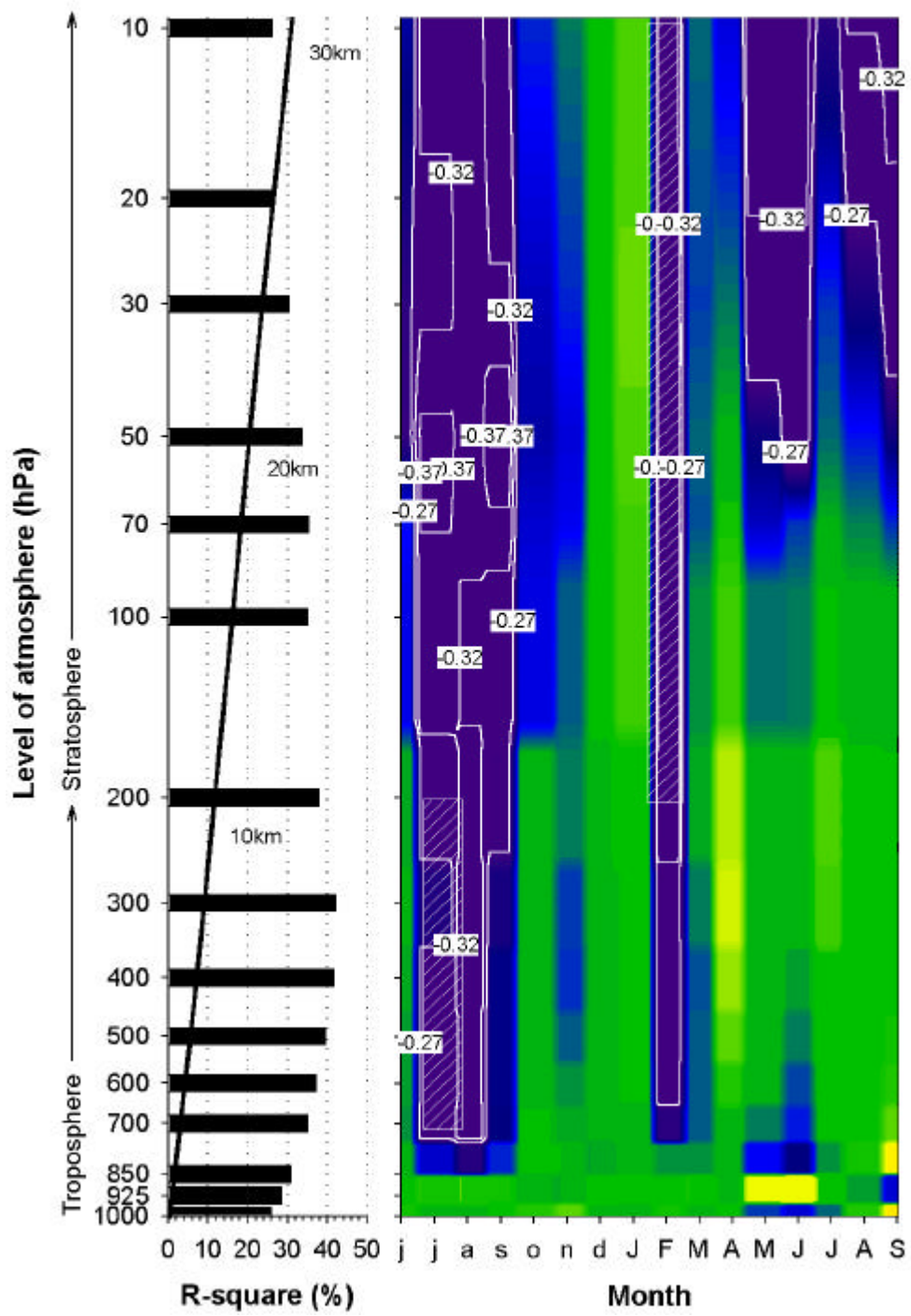


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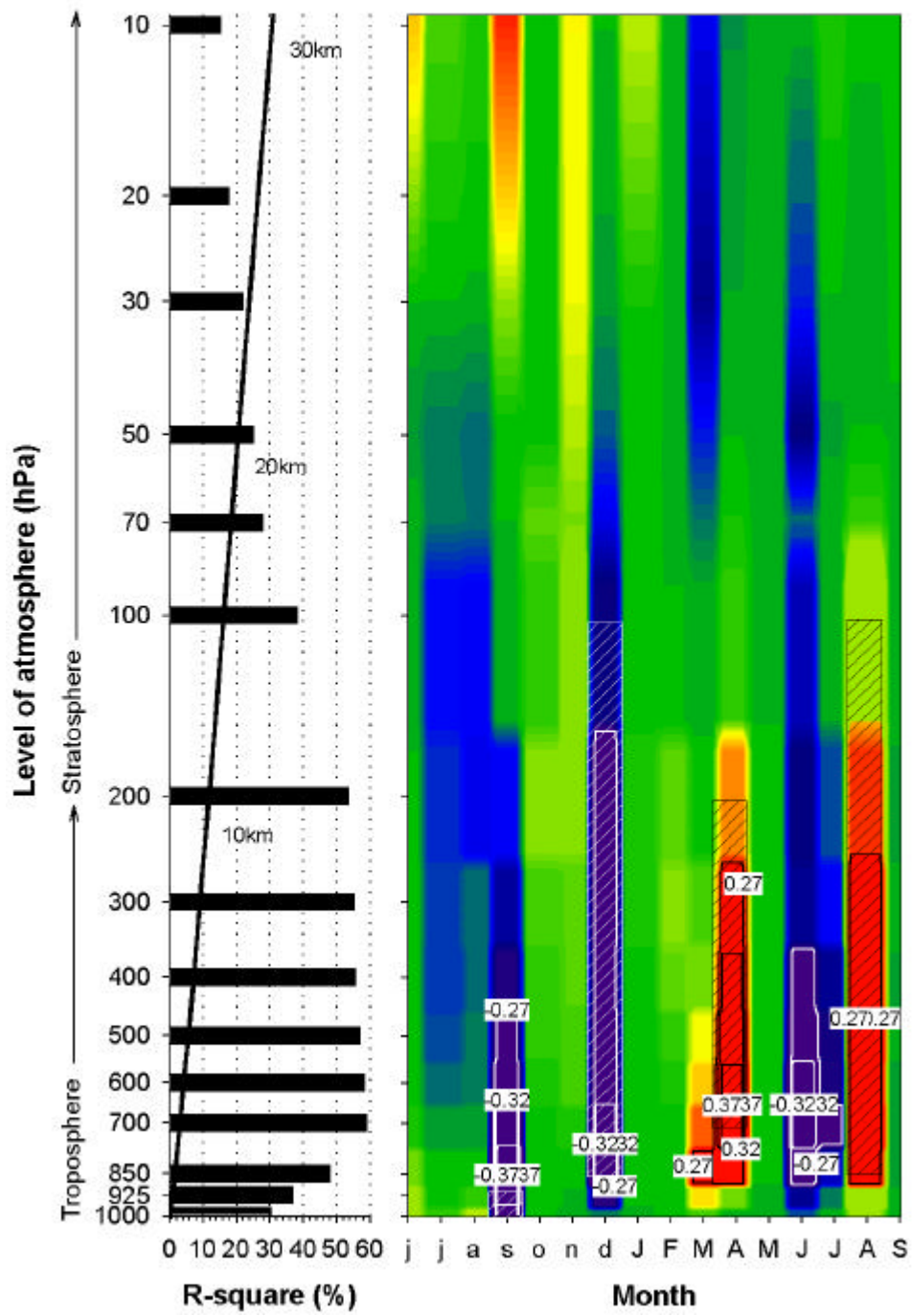


Figure 5 concludes.

The radial growth responses to the 700hPa to 300hPa levels summer height variations were in agreement with expectations i.e., optimal growing conditions occur under low height conditions. These conditions favour the development and the support of storms, which supply tree growth with moisture. The relationship with the stratosphere however remains unclear. Recent studies have reported the long-lived influence (beyond 30-days) of the stratosphere on the dynamical properties of the troposphere (Shindell et al. 1999; Baldwin and Dunkerton 1999; 2001; Thompson et al. 2002; Baldwin et al. 2003). The relationship most likely reflects the impact of anomalies in the lower Northern Hemisphere stratospheric polar vortex (Thompson et al. 2002). These anomalies affect the momentum of the troposphere's polar longitudinal winds and induce latitudinal circulation that extends to the earth's surface. Consequently they could affect the height of convection currents within the troposphere and the positions of the jet stream.

### **Management/Policy Implications**

Incorporating climate change into forest management is becoming a major concern. Earlier vegetation simulation studies, using temperature response functions models, suggested impacts in many forest types, including geographic range shrinkage and catastrophic decline or dieback. However, in a review of the simulation models, Loehle and Leblanc (1996) warned that the implemented climate-response functions used to draw these scenarios had no basis in plant physiology. Therefore, many of these scenarios may have exaggerated the direct impact of future warming on tree growth and mortality.

The results of Girardin and Tardif (*submitted*) suggested that broad-scale atmospheric circulations are important factors for growth of all tree species. Interestingly, these same patterns observed by Girardin and Tardif (*submitted*) were also identified as determinant factor for summer drought severity (Girardin et al. 2004) and forest fire (Skinner et al. 1999). It is likely that these same atmospheric patterns will influence vegetation dynamics. We thus propose that atmospheric circulation features be included in the development of a dynamic vegetation, climate and disturbance model. As indicated by Flannigan et al. (2003), a dynamic vegetation – climate – disturbance model could help describe the potential impacts of climate change and allow adaptation strategies to be explored.

**Figure 6 next pages.** Composite maps for the 300hPa geopotential height and potential evapotranspiration. In a) and b) are shown analyses made from PC1 and the 50hPa level using the seasonal average July to September of the year previous to ring formation and February of the year of ring formation, respectively. In c) and d) are shown the same analyses at the 500hPa level. In e) and f) are shown the analyses made from PC2 and the 500hPa level using April and June of the year of ring formation, respectively. Contour lines are drawn at every 0.05 coefficient level and labelled at every 0.10 level. Correlation coefficients are significant at  $p < 0.05$  when  $r > |0.27|$ . The levels and months of analyses were determined from the significance of the correlation coefficients and of the response model  $r^2$  of Figure 5.

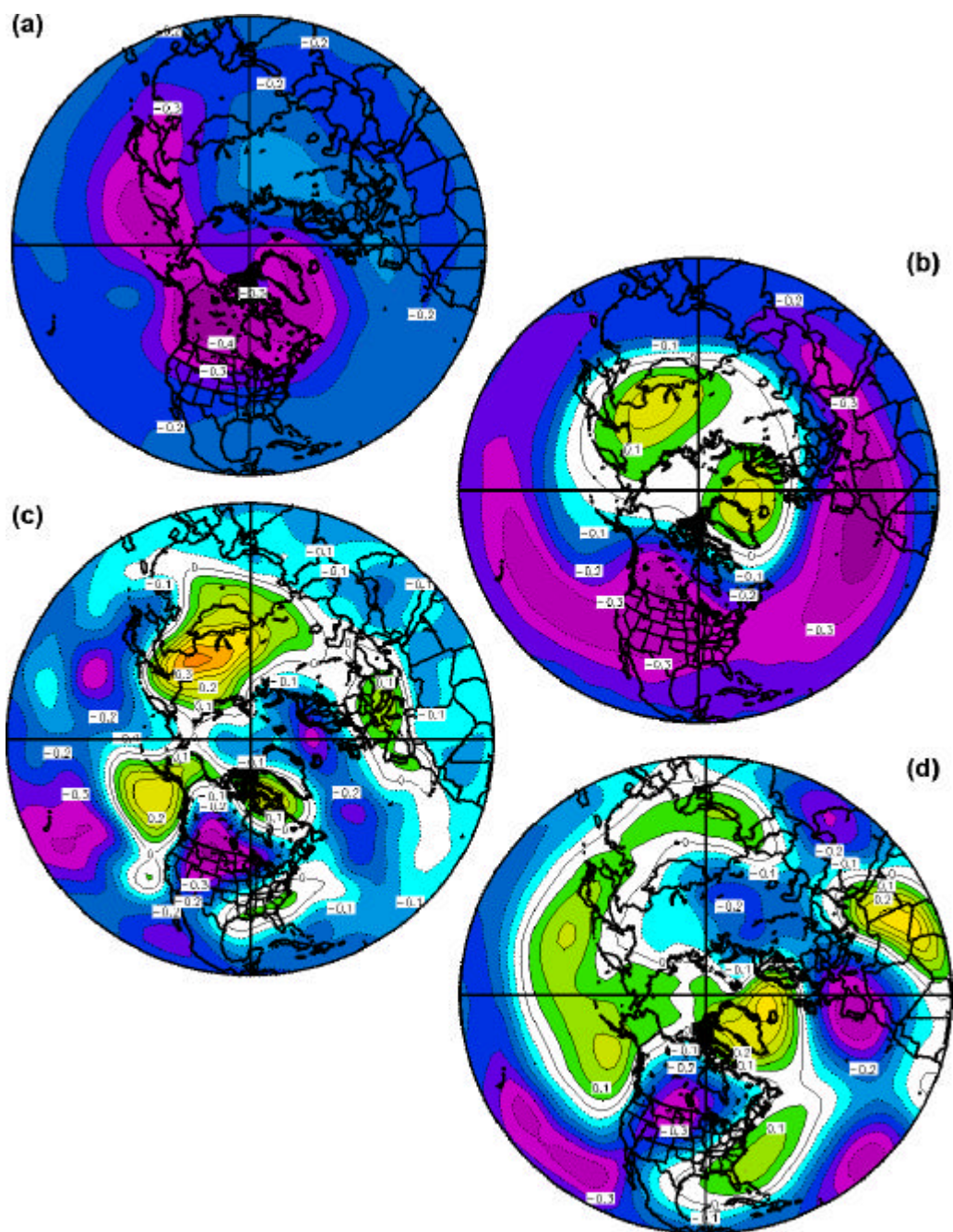
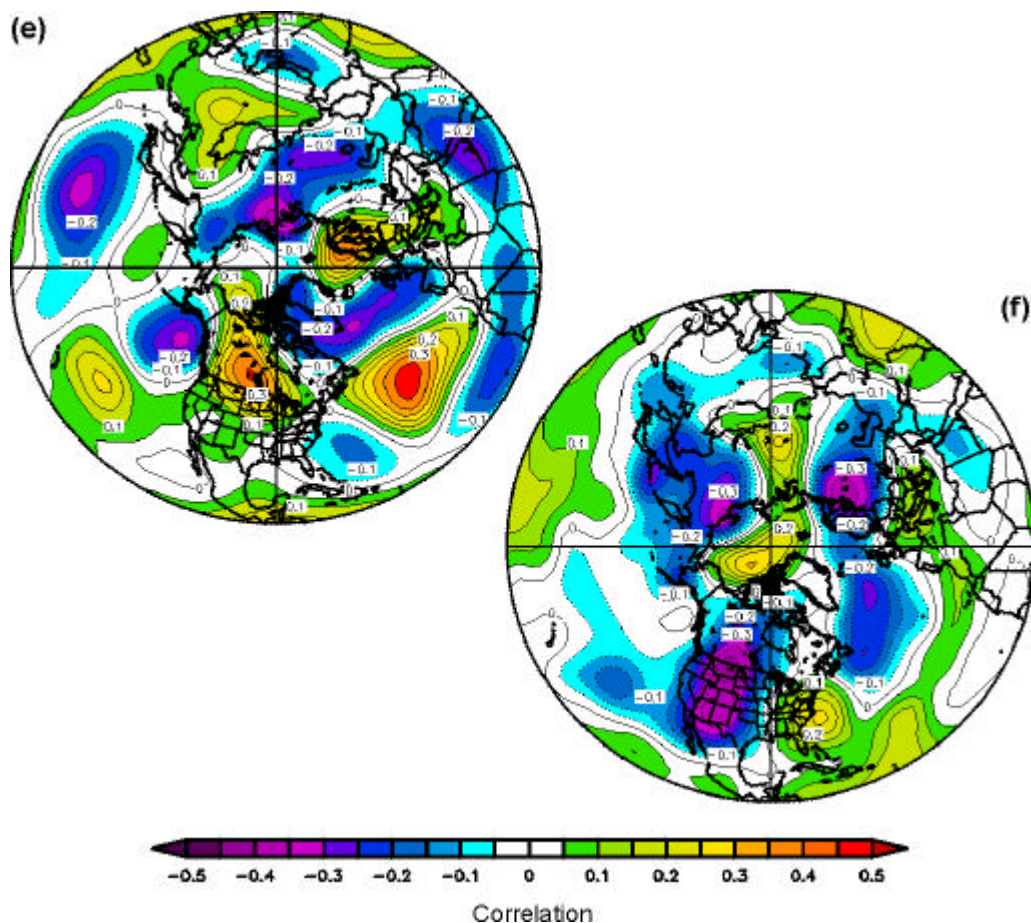


Figure 6 *continues*.



**Figure 6 concludes.**

The implementation of atmospheric circulation features in scenarios of impact of future warming would have other benefits. At the moment, scenarios are greatly limited by the uncertainty that characterises the precipitation output simulated from the general and the regional circulation models (refer to Laprise et al. 2003). This is non-trivial when it comes to determining the moisture budget on which tree growth depends. In contrast, geopotential height outputs are comparable to the temperature output in terms of confidence (Dr. Daniel Caya, Climate Simulations Group - Ouranos Consortium; personal communication). By implementing geopotential height within the vegetation scenarios as tree growth response functions, one could greatly reduce the uncertainty factor. This would also help to sharpen the management strategies to be explored.

## CONCLUSION

Surface climate response analysis indicated that all tree species (except for *L. laricina*) growing in the Duck Mountain Provincial Forest responded negatively to summer temperature induced hydric stresses. A secondary response signal was found and attributed to the evergreen nature of conifers in taking advantage of earlier growing seasons. Analyses performed on geopotential height highlighted the importance of both local (at the troposphere level) and global

(at the stratosphere level) scale atmospheric circulations in the species' response to climate. Because tree growth in the Duck Mountain forest demonstrated great relationships with Northern Hemispheric upper atmospheric circulation features, we propose the inclusion of atmosphere – tree growth responses in forest simulation models of climate change impacts. First, an extension of this study over several areas across the boreal forest may allow us to verify that the observed relationships between tree growth and the atmosphere are not simply regional features.

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