# Climate change in New Brunswick (Canada): statistical downscaling of local temperature, precipitation, and river discharge

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2004

## Canadian Technical Report of Fisheries and Aquatic Sciences 2544

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by

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Cat. No. Fs. 97-6/2544E ISSN 0706-6457

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Correct citation for this publication:

Swansburg, E., N. El-Jabi, and D. Caissie. 2004. Climate change in New Brunswick (Canada): statistical downscaling of local temperature, precipitation, and river discharge. Can. Tech. Rep. Fish. Aquat. Sci. 2544: 42p.

## Project Team / Groupe du projet

This project was funded under the Climate Change Action Fund (Project # A367) to the following project team:

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## ABSTRACT

Swansburg, E., N. El-Jabi, and D. Caissie. 2004. Climate change in New Brunswick (Canada): statistical downscaling of local temperature, precipitation, and river discharge. Can. Tech. Rep. Fish. Aquat. Sci. 2544: 42p.

Climate change is expected to alter global temperature and precipitations patterns, exerting significant pressure on water resources. According to Global Circulation Models (GCMs), air temperature is projected to increase by 1.4 to 5.8 ºC, and precipitation by 3 to 15 % globally in the 21st century. However, specific regional projections about the impact of climate change are hampered by the limited spatial resolution of global circulation models, making it difficult to determine the degree of climate change, how fast it will happen, and where it will occur. Statistical downscaling, was used to generate local climate scenarios in New Brunswick from 2010-2099. Given a tripling of carbon dioxide concentrations in the next 100 years, maximum and minimum air temperatures in New Brunswick are expected to increase by 4 to 5 ºC, with central regions warmer more than the most northerly and southerly regions of the province. A warmer New Brunswick climate will have significant effects on the abundance, diversity, and distribution of aquatic species inhabiting New Brunswick streams and rivers and alter the characteristics of the hydrological cycle, particularly in winter and summer. Precipitation is expected to increase annually throughout the province, particularly in northern New Brunswick, increasing the frequency and magnitude of flooding. However, no change in summer precipitation in southern New Brunswick is anticipated. This, coupled with higher air temperatures, will result in a reduction in available water resources in southern New Brunswick. Climate change in New Brunswick will undoubtedly alter the quantity and quality of our water resources. However, their vulnerability is highly dependent on the adaptation of water management systems and on the capacity of rivers to sustain water demands under low flow conditions.

## RÉSUMÉ

Swansburg, E., N. El-Jabi, and D. Caissie. 2004. Climate change in New Brunswick (Canada): statistical downscaling of local temperature, precipitation, and river discharge. Can. Tech. Rep. Fish. Aquat. Sci. 2544: 42p.

On s'attend à ce que le changement climatique va influencer les températures ansi que les précipitations globales. Ceci va certainement avoir un impact sur les ressources hydriques. Selon les modèles de circulation générale (MCG), il est prévu que la température de l'air va augmenter de 1,4 à 5,8ºC et les précipitations vont augmenter de 3 à 15% globalement pendant le 21$^{e}$ siècle. Cependant, la résolution spatiale limitée des modèles de circulation générale nuit aux prévisions régionales au sujet de l'impact du changement climatique. Il est donc difficile d'identifier le degré, la localisation et la vitesse à laquelle le changement climatique va se produire. La désagrégation statistique a été utilisée afin de produire des scénarios localisés pour le Nouveau-Brunswick de 2010 à 2099. Étant donné un triplement du dioxide de carbone dans les prochains 100 ans, il est prévu que les températures maximales et minimales vont augmenter de 4 à 5ºC avec les régions centrales plus chaudes que les régions au nord et au sud. Un climat plus chaud au Nouveau-Brunswick aura des effets significatifs sur l'abondance, la diversité et la distribution des espèces aquatiques qui habitent les rivières et les ruisseaux de la province et modifiera les caractéristiques du cycle hydrologique surtout en hiver et en été. Il est prévu que les précipitations annuelles vont augmenter à travers la province surtout au nord; ce qui va augmenter la fréquence et l'intensité des innondations. Cependant, aucun changement est prévu dans les précipitations estivales dans le sud de la province. Ceci, accompagné de températures plus chaudes, va résulter en une réduction de la disponibilité en ressources hydriques dans le sud du Nouveau-Brunswick. Le changement climatique va sans doute influencer la quantité et la qualité des ressources hydriques au Nouveau-Brunswick. Cependant, la vulnérabilité des ressources hydriques face au changement climatique dépendra grandement de l'adaptation des systèmes de gestion de ressources en eaux aux conditions hydro-climatiques changeantes et sur la capacité des rivières à répondre à la demande en eau dans des conditions de débits faibles.

## 1.0 INTRODUCTION

Global climate change is currently taking place due to elevated concentrations of 'greenhouse gases' in the atmosphere (Smith 1990). Since the industrial revolution (mid-18th century), concentrations of naturally occurring (e.g. water vapour [$H_2O$], carbon dioxide [$CO_2$], methane [$CH_4$], nitrous oxide [$N_2O$], etc.) and man-made (e.g. chlorofluorocarbons or CFC's) greenhouse gases have increased due to intensified industrial, agricultural, and other human activities (Houghton et al. 2001). As a result, the heat trapping capability of the earth's atmosphere has been enhanced and consequently, global temperatures have warmed, and wind, rain, snow and storm patterns have changed.

According to the Intergovernmental Panel on Climate Change (IPCC), mean global surface temperature increased 0.6 ± 0.2 ºC in the 20th century. Snow cover decreased by 10% since the late 1960's, and the duration of ice cover in lakes and rivers decreased by two weeks in mid and high latitude regions of the Northern Hemisphere. Average sea level rose 0.1 to 0.2 metres globally, and precipitation increased by 0.5 to 1% per decade, with an increase in the frequency of heavy precipitation events (Houghton et al. 2001). In the 21st century, greenhouse gas concentrations will continue to rise, however, the rate of increase and thus the response of the global climate system remains largely unknown, limiting our ability to anticipate and adapt to these changes.

General Circulation Models (GCM's), based on mathematical representations of atmosphere, ocean, ice cap and land surface processes, are considered to be the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations. Accordingly, mean surface air temperature is projected to increase by 1.4 to 5.8 ºC globally in the next 100 years, with more rapid warming in the northern regions of North America. Precipitation is expected to increase by 3 to 15 % globally, with intense precipitation events occurring more frequently. Global sea level is projected to rise by 9 to 88 cm, with significant regional variations (Houghton et al. 2001).

According to the Canadian Global Coupled Model (CGCM1) in conjunction with the greenhouse gas + aerosol emission experiment (GA1) (Boer et al. 2000a, b; Flato et al. 2000), maximum and minimum temperature will increase by ~4.0 °C, while precipitation will increase by 3 to 5 % annually in New Brunswick. However, the extent of climate change and therefore, the subsequent local impacts across the province of New Brunswick are relatively unknown due to the limited spatial resolution of General Circulation Models (GCM). And while the complexity of the global climate system is well captured by GCM's, they are unable to represent local scale features and processes due to limited spatial resolution (Wigley et al. 1990; Carter et al. 1994; MacKay et al. 1998; Wilby 1998). Large geographic areas represent the basic unit of the GCM. The Canadian Global Coupled Model (CGCM), for example, has a surface grid resolution of roughly 3.7º latitude x 3.7º longitude (i.e. approximately 120,000 $km^2$) (Fig. 1). Limited spatial resolution of GCM output results in the simplification and homogenisation of climatic conditions of large geographic areas, contributing to the loss of characteristics which may have important influences on regional climate. At odds with GCM resolution, researchers focusing on the impacts of climate change are primarily interested in the local and regional consequences of large-scale changes (Xu 1999).

Given these limitations, methods to derive more detailed regional and site-specific scenarios for climate studies have emerged in recent years. Statistical "downscaling" is based on GCM output and involves the development of significant relationships between local and large-scale climate. Statistical downscaling, a transfer function approach, assumes that regional climate can be determined by the large-scale climatic state and regional / local physiographic features (e.g., topography, land-sea distribution and land use) (von Storch 1995, 1999). Regional or local climate information is derived by first developing a statistical model which relates large-scale climate variables, or "predictors", to regional and local variables, or "predictands" (Fig. 2). Large-scale predictor variables are then extracted from GCM output and used to drive the statistical model, generating local-scale climate projections for a future time period.

The objectives of this study are to generate a site-specific future climate scenario (2010-2099) for locations across New Brunswick, Canada by statistical downscaling of GCM projections. Each scenario will be compared to past climate trends and effects on water resources (i.e. low flow, water availability, and aquatic resources) will be discussed.

# 2.0 MATERIALS AND METHODS

## 2.1 Site description

New Brunswick lies on Canada's Atlantic coast, and is bordered by ocean on its southern (Bay of Fundy), northern and eastern (Gulf of St. Lawrence) shores. Despite its coastal location, the province has a typically continental flavour to its climate, with continental and maritime influences blending near the coasts. Generally, average temperatures in New Brunswick range from –10 ºC in January to 19 ºC in July. New Brunswick receives approximately 1100 mm of precipitation annually, with 20 to 33% falling as snow. Precipitation tends to be highest in southern parts of the province (Phillips 1990).

Major rivers and many smaller streams radiate outward from the interiour highlands of New Brunswick. Major rivers include the Saint John River, Miramichi River, and Restigouche River. Rainfall, snowmelt, and groundwater all contribute to the volume of flow, producing variations from season to season and year to year. Most high flows and floods are caused by spring snowmelt. Heavy rainfall can also cause high flows and floods, especially on small streams. Lowest flows generally occur in late summer, when precipitation is low and evaporation is high, and in late winter, when precipitation is stored until spring in the form of ice and snow (Environment Canada 2001).

## 2.2 Data Collection

Daily maximum and minimum air temperature and total precipitation data (1961-1990) from seven meteorological stations in New Brunswick were obtained from Environment Canada's National Climate Data Archive (Fig. 3, Table 1). Air temperature data was "homogenised" at six of the seven stations to remove any non-climatic inconsistencies due to station alterations including changes in site exposure, location, instrumentation, observer, observer program, or a combination of the above (see Vincent 1998). Homogenisation of precipitation data is incomplete and therefore, quality controlled, archived data was used.

Daily discharge ($m^3/s$) data (1961-1990) from seven hydrometric stations in New Brunswick were obtained from Environment Canada's National Water Data Archive (HYDAT CD-ROM) (Fig. 3, Table 2). A single station was selected from seven distinct precipitation zones (Hebert et al. 2003) in New Brunswick. At all stations, natural, rather than regulated, flow was observed at all stations and daily discharge was recorded using both manual and recording gauges under continuous operation.

### 2.3 Statistical downscaling

Outputs from the Canadian Global Coupled Model in conjunction with the greenhouse gas + aerosol emission experiment (CGCM1-GA1) were used to generate site-specific scenarios in New Brunswick (Boer et al. 2000a, b; Flato et al. 2000). This model was driven by the Intergovernmental Panel for Climate Change (IPCC) "IS92a" emissions scenario in which the change in greenhouse gases forcing corresponds to that observed from 1900 to 1990 and increases at a rate of 1 % per year thereafter, effectively tripling $CO_2$ concentration (476 to 1422 ppm) by 2100 (Alcamo et al. 1995).

Surface and upper-atmospheric predictor variables (Table 3) were obtained from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis dataset (Kalnay et al. 1996). Observed NCEP/NCAR predictor data were interpolated to the CGCM grid and made available by the Canadian Institute for Climate Studies (CICS). Predictor variables (5) were selected for statistical downscaling according to a strong and consistent correlation with the predictand as determined by stepwise multiple regression (STATISTICA, StatSoft, Tulsa, OK) (Wilby et al. 2002).

Statistical downscaling models were developed from daily series of maximum ($T_{MAX}$, equation [1]) and minimum ($T_{MIN}$, equation [2]) temperature:

$$T_{MAX_i} = \alpha_0 + \alpha_T T_i + \alpha_{T_{i-1}} T_{i-1} + \sum_{j=3} \left(\alpha_X X_i\right)_j \qquad [1]$$

$$T_{MIN_i} = \delta_0 + \delta_T T_i + \delta_{T_{i-1}} T_{i-1} + \sum_{j=3} \left(\delta_X X_i\right)_j \qquad [2]$$

where $T_i$ = mean air temperature at 2-m;
$X_i$ = other variables (3) selected on a per site basis (see Table 4);
$\alpha$, $\delta$ = regression constant and coefficients

and wet-day amounts of precipitation (P, equation [3]):

$$P_i = \sqrt{\mu_0 + \mu_{q_{500}} q_{500i} + \mu_{U_s} U_s + \sum_{j=3} \left(\mu_X X_i\right)_j} \qquad [3]$$

where $q_{500}$ = specific humidity at 500 hPa;
$U_s$ = surface zonal velocity;
X = other variables (3) selected on a per site basis (see Table 5);
$\mu$ = regression constant and coefficients

and river discharge (Q, equation [4]):

$$Q_i = 10^{\lambda_0 + \lambda_q q_i + \lambda_{q_{500}} q_{500i} + \lambda_T T_i + \sum_{j=2} \left(\lambda_X X_i\right)_j} \qquad [4]$$

where q = near surface specific humidity;
$q_{500}$ = specific humidity at 500 hPa;
$T_i$ = mean air temperature at 2-m;
X = other variables (2) selected on a per site basis (see Table 6);
$\lambda$ = regression constant and coefficients

and five NCEP/NCAR predictor variables (Table 4-6). Variability associated with the models diminished as more predictor variables were added. However, the inclusion of more than five predictors did not substantially improve the models. Using Statistical Downscaling Software (SDSM, Version 2.2), downscaling models were calibrated using observed predictor variables and the observed predictand from 1961-1975 and validated with data withheld from the calibration process (i.e. 1976-1990) (Wilby et al. 2002). Following validation, models were re-calibrated with all 30 years of data to increase robustness (Table 4-6). Some predictors were consistent among stations, while others were selected per station according to the strength of their association with station specific observed data sets. Using the calibrated and validated models, daily climate data from 2010-2099 was generated at each station using Statistical DownScaling Model Software (SDSM, Version 2.2, Wilby et al. 2002).

### 2.4 Analysis of downscaled results

Annual and seasonal trends in air temperature, precipitation, and river discharge were examined according to 30-yr time slices; 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). The IPCC recommends this approach because most GCMs exhibit substantial inter-decadal climate variability, making it difficult to distinguish a climate change signal from background noise. Tri-decadal values of average temperature, precipitation, and river discharge were compared by analysis of variance (ANOVA), followed by post-hoc comparisons (Least Square Difference). Seasons were defined as follows; winter (December-January-February, DJF), spring (March-April-May, MAM), summer (June-July-August, JJA), and autumn (September-October-November, SON).

## 3.0 RESULTS

### 3.1 Air temperature

Given a tripling in $CO_2$ concentrations, annual and seasonal maximum and minimum air temperature (Figures 4-5) are expected to increase significantly ($p<0.05$) across New Brunswick from 2010-2099 compared to current climate conditions (1961-1990). Annually, minimum air temperature may increase by approximately 4 to 5 ºC, while maximum temperature may increase by approximately 4 ºC at all meteorological stations. Larger increases in air temperature are anticipated at central New Brunswick stations (i.e. Aroostook, Chatham, Doaktown, Fredericton, and Moncton) than in northern (i.e. Charlo) or southern (i.e. Saint John) regions of the province. Seasonally, the greatest increases are expected in maximum spring air temperature (~ 5 to 6 ºC; Fig. 6) and minimum winter air temperature (~ 4 to 6 ºC; Fig. 7). Much of the increase in winter temperature is anticipated in 2010-2039, while in spring, summer, and autumn the greatest increases in temperature are anticipated in 2070-2099.

### 3.2 Precipitation

Mean daily annual precipitation may increase significantly from 2010-2099 ($p<0.001$) compared to current climate conditions (Fig. 8). Precipitation may increase from 25-50 % in northern and central stations and 9-14 % in southern stations. Seasonal precipitation may increase significantly and by similar percentages at northern and some central stations (i.e. Charlo, Aroostook, and Chatham) (Fig. 9). At remaining central and southern stations, no change in summer precipitation is expected, while changes in precipitation patterns in other seasons are less consistent. No significant changes in precipitation are anticipated at Saint John. No one time slice will demonstrate consistent increases in precipitation across all meteorological stations.

### 3.3 River Discharge

Average annual discharge may increase significantly at all hydrometric stations, by 16 to 45% compared to current discharge conditions (Fig. 10). Large increases (i.e. >40%) are anticipated in both northern (e.g. Restigouche River) and central (e.g.

Northwest Miramichi River) stations, and in both large (e.g. drainage area > 2,500 km$^2$) and small (i.e. drainage area < 1,000 km$^2$) drainage basins. Winter and spring discharge may increase significantly at all hydrometric stations, with the largest increases to be observed in 2070-2099 (Fig. 11). Summer discharge may decrease significantly at all stations, while autumn discharge may decrease significantly in all rivers except the Saint John (i.e. 01AD002) and Restigouche (i.e. 01BC001) (Fig. 11).

## 4.0 DISCUSSION

Climate change is expected to alter global temperature and precipitation patterns, exerting significant pressures on water resources. However, specific regional projections about the impact of climate change are hampered by the limited spatial resolution of global circulation models, making it difficult to determine the degree of climate change, how fast it will happen, and where it will occur. Alternatively, statistical downscaling generates local climate change projections, providing future climate scenarios on which adaptation strategies can be developed.

In the 20th century, changes in climate, particularly increases in temperature, have already affected physical and biological systems in many parts of the world (McCarthy et al. 2001). In New Brunswick, air temperature increased significantly in the last century contributing to record high water temperatures and record low flow conditions (Caissie 1999a, 1999b; Caissie 2000). Given the scenario presented (~ 3 x $CO_2$ in 2100), air temperature in New Brunswick will increase by as much as 4 to 5 ºC by 2100. This rate of warming is much greater than that observed in the 20th century but is consistent with that expected by Parks Canada (1999) (2 to 6 ºC) and Houghton et al. (2001) (3 to 5 ºC) for the Atlantic provinces. Significant warming will result from both higher maximum and minimum air temperatures, particularly in spring and winter, respectively. Minimum air temperatures are expected to increase more rapidly than maximum air temperatures, following trends already observed at these stations and at stations throughout Canada in the last 100 years (Bonsal et al. 2001; Zhang et al. 2000). Anticipated increases are fairly consistent throughout the province, with slightly greater temperature change expected in the central region of New Brunswick, rather than western New Brunswick, as anticipated by Minns et al. (1995).

A warmer climate in New Brunswick would result in significant changes in water withdrawal demand and availability. A warmer climate will contribute to warmer water temperatures in rivers, lakes, and groundwater aquifers. Warmer water temperatures may result in changes in the abundance, diversity, and distribution of aquatic species inhabiting New Brunswick streams and rivers. Stream water temperature has an obvious effect on an aquatic organism's rate of growth and development (Elliott and Hurley 1997), their behaviour, and ultimately, their survival (Lee and Rinne 1980; Bjornn and Reiser 1991). Species with specific cold-water preferences, such as Atlantic salmon, will be particularly susceptible (McCarthy et al. 2001), as warmer water is significantly associated with smaller juvenile Atlantic salmon, which ultimately could reduce the overall productivity of Atlantic salmon populations in this region (Swansburg et al. 2002).

Increased rates of evapotranspiration can also be expected in a warmer climate, contributing to lower water levels in summer and increased irrigation demand. Demand for irrigation of agricultural land currently represents only a small proportion (<5 %) of water withdrawal demand in the province (New Brunswick Department of Environment and Local Government, unpublished report). However, irrigation demand coincides with peak demand (i.e. summer) from all other water users (municipal, commercial, industrial, aquaculture, etc.) in the province, and as a result, may intensify water conflict.

Warmer winter temperature will result in a shorter duration of snow cover and a reduced snow pack due to more precipitation falling as rain, hastening the break-up of ice on rivers and lakes (Hengeveld 1990; Minns et al. 1995; McCarthy et al. 2001; Natural Resources Canada 2002). Timing of the spring freshet, at least in the Miramichi River, is already advancing at a rate of 5 days/decade since the 1960s (Swansburg et al. *in press*). Earlier snowmelt and runoff advances the start of a drier spring-summer season and has been observed to contribute to more extreme low flow conditions in summer (Manabe and Wetherald 1987).

Given the scenario presented (~ 3 x $CO_2$ in 2100), annual precipitation is expected to increase significantly in the 21st century, by 0.4 mm/day (9 %) up to 1.5

mm/day (48 %) at some stations. This increase is much greater than that predicted by the CGCM1 (3 to 5 %) and the IPCC (0 to 0.25 mm/day) (Houghton et al. 2001). Large differences in precipitation scenarios are not uncommon amongst models. Precipitation is an inherently heterogeneous variable, where large differences in local precipitation patterns are common. Therefore, it is a more difficult variable to model on a large scale, and as a result, precipitation scenarios have a greater degree of uncertainty associated with them.

Increases in annual and seasonal precipitation may increase the magnitude and frequency of flooding, particularly if the frequency of extreme precipitation events also increases as predicted by the IPCC (Houghton et al. 2001). More frequent and intense floods would increase infrastructure damage, cause soil erosion and crop damage. However, increased precipitation patterns may enhance water resources (groundwater and streamflow) in northern New Brunswick, benefiting communities on the Acadian Peninsula (e.g. Dalhousie, Tracadie-Sheila) where the quantity or quality of the water supply is of concern (New Brunswick Department of Environment and Local Government, unpublished report). In southern New Brunswick, where precipitation amounts are unchanged or increasing slightly, evapotranspiration is high due to increasing air temperature, and demand for water is generally increasing due to population growth (e.g. Moncton-Dieppe-Riverview), meeting water demand may be difficult in the future.

Average annual discharge is expected to increase significantly at all hydrometric stations, by as much as 45%, due to significant increases in winter and spring river discharge. Historically, low water conditions are not uncommon in winter in New Brunswick, due to cold temperatures and a substantial snow pack. However, with warmer air temperatures, a greater proportion of winter precipitation may fall as rain, contributing to substantially larger flows. Less snow and ice build-up may also contribute to smaller spring freshets and result in less intense flooding events. However, mid-winter thaws may become more frequent, contributing to more severe ice jam conditions, damaging infrastructure and scouring river beds (Beltaos and Burrell 2003). Summer discharge, however, is expected to decrease at all stations, presumably due to increased evaporative loss. Severe low water conditions are already being observed in some streams and rivers in New Brunswick (Caissie 1995; 2000), resulting in fish kills and more frequent closures of rivers to recreational fishers. Offstream use of water resources will also be affected due to a reduction in water quantity and quality (McCarthy et al. 2001).

Climate change will undoubtedly alter the quantity and quality of water resources, presenting significant challenges in a province highly dependent on industries such as agriculture and fisheries. However, the vulnerability of water resources to climate change impacts is highly dependent on the adaptation of water management systems to changing hydro-climatic conditions and on the capacity of rivers to sustain water demands under low flow conditions.

## 5.0 ACKNOWLEDGEMENTS

We would like to thank the Climate Change Action Fund (Project A367) and Natural Sciences and Engineering Research Council of Canada for providing the funding for this project. We would also like to thank Gary Lines and Mike Pancura (Environment Canada) for providing guidance in the statistical downscaling process.

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**Table 1**. Location and average (± 1 standard error) climatic conditions (1961-1990) at meteorological stations in New Brunswick

| Meteorological Station | ID[1] | Latitude, Longitude | Mean Annual Temperature (ºC) | Mean Annual Precipitation (mm) |
|---|---|---|---|---|
| Charlo Airport[2] | 8100880 | 47º 59’ N; 66º 20’ W | 3.4 ± 0.1 | 1053 ± 32 |
| Chatham Airport | 8101000 | 47º 01’ N; 65º 27’ W | 5.0 ± 0.1 | 1087 ± 32 |
| Aroostook | 8100300 | 46º 48’ N; 67º 43’ W | 4.0 ± 0.1 | 1103 ± 30 |
| Doaktown[3] | 8101200 | 46º 33’ N; 66º 09’ W | 4.7 ± 0.2 | 1072 ± 27 |
| Moncton Airport | 8103200 | 46º 06’ N; 64º 47’ W | 5.3 ± 0.1 | 1227 ± 34 |
| Fredericton Airport | 8101500 | 45º 52’ N; 66º 32’ W | 5.6 ± 0.1 | 1133 ± 32 |
| Saint John Airport | 8104900 | 45º 19’ N; 65º 53’ W | 5.2 ± 0.1 | 1433 ± 40 |

[1] Climate ID assigned by the Meteorological Service of Canada

[2] Precipitation time series extends from 1966-1990

[3] Data was not homogenised to remove non-climatic inconsistencies

**Table 2**. Location, drainage area (km$^2$), and average (± 1 standard error) annual discharge (1961-1990) at hydrometric stations in New Brunswick

| Hydrometric Station | ID[1] | Latitude, Longitude | Drainage Area (km$^2$) | Mean Annual Discharge (m$^3$/s) |
|---|---|---|---|---|
| Restigouche R. below Kedgwick R.[2] | 01BC001 | 47º 40' N; 67º 29' W | 3,160 | 65.7 ± 2.6 |
| Saint John R. at Fort Kent | 01AD002 | 47º 15' N; 68º 36' W | 14,700 | 279.3 ± 11.9 |
| NW Miramichi R. at Trout Bk.[3] | 01BQ001 | 47º 06' N; 65º 50' W | 948 | 20.9 ± 1.0 |
| SW Miramichi R. at Blackville[3] | 01BO001 | 46º 44' N; 65º 50' W | 5,050 | 116.4 ± 4.9 |
| Nashwaak R. at Durham Bridge[3] | 01AL002 | 46º 08' N; 66º 37' W | 1,450 | 35.0 ± 1.6 |
| Canaan R. at East Canaan[2] | 01AP002 | 46º 04' N; 65º 22' W | 668 | 13.2 ± 0.7 |
| Kennebecasis R. at Apohaqui[3] | 01AP004 | 45º 42' N; 65º 36' W | 1,100 | 25.0 ± 1.2 |

[1] Station ID assigned by the Water Survey of Canada
[2] Precipitation time series extends from 1963-1990
[3] Precipitation time series extends from 1962-1990

**Table 3**. Surface and upper-atmospheric predictor variables (500 and 850 hectopascals [hPa]) obtained from the National Center for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996) and the Canadian Global Coupled Model (CGCM) for use in statistical downscaling.

| Predictor Variable | Abbreviation |
|---|---|
| Mean temperature at 2 m (ºC) | T |
| Mean sea level pressure (hPa) | mslp |
| 500 hPa Geopotential height (m) | $H_{500}$ |
| 850 hPa Geopotential height (m) | $H_{850}$ |
| Near surface specific humidity (g/kg) | q |
| Specific humidity at 500 hPa height (g/kg) | $q_{500}$ |
| Specific humidity at 850 hPa height (g/kg) | $q_{850}$ |
| Geostrophic airflow velocity[1] (hPa) | $F_s$, $F_{500}$, $F_{850}$ |
| Vorticity[1] ($s^{-1}$) | $Z_s$, $Z_{500}$, $Z_{850}$ |
| Zonal velocity component[1] | $U_s$, $U_{500}$, $U_{850}$ |
| Meridional velocity component[1] | $V_s$, $V_{500}$, $V_{850}$ |
| Wind direction[1] | $W_s$, $W_{500}$, $W_{850}$ |
| Divergence[1] (hPa) | $D_s$, $D_{500}$, $D_{850}$ |

[1] Secondary (airflow) variables derived from pressure fields (surface, geopotential height fields of 500 and 850 hPa) (Jones et al. 1993)

**Table 4**. Predictor variables selected in the calibration and validation of daily maximum and minimum air temperature models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

| Meteorological Station | Predictors | Maximum Temperature | | Minimum Temperature | |
|---|---|---|---|---|---|
| | | $r^2$ | Standard Error | $r^2$ | Standard Error |
| Charlo | $T$, $T_{i-1}$, $Z_s$, $U_s$, $U_{850}$ | 0.759 | 2.996 | 0.753 | 2.888 |
| Chatham | $T$, $T_{i-1}$, $Z_{850}$, $U_s$, $H_{500}$ | 0.744 | 3.149 | 0.740 | 3.018 |
| Aroostook | $T$, $T_{i-1}$, $Z_s$, $Z_{850}$, $q_{850}$ | 0.809 | 2.757 | 0.815 | 3.057 |
| Doaktown | $T$, $T_{i-1}$, $Z_{850}$, $V_{850}$, $q_{850}$ | 0.783 | 2.968 | 0.761 | 3.363 |
| Moncton | $T$, $T_{i-1}$, $Z_{850}$, mslp, $H_{500}$ | 0.764 | 2.975 | 0.778 | 2.701 |
| Fredericton | $T$, $T_{i-1}$, $U_s$, $q$, $q_{850}$ | 0.821 | 2.651 | 0.804 | 2.714 |
| Saint John | $T$, $T_{i-1}$, $D_s$, $H_{500}$, $q_{850}$ | 0.759 | 2.594 | 0.707 | 3.075 |

**Table 5**. Predictor variables selected in the calibration and validation of daily precipitation models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

| Meteorological Station | Predictors | $r^2$ | Standard Error |
|---|---|---|---|
| Charlo | $q_{500}$, $U_s$, $V_s$, $U_{850}$, $Z_s$ | 0.127 | 0.430 |
| Chatham | $q_{500}$, $U_s$, $V_s$, $q_{850}$, $D_s$ | 0.134 | 0.446 |
| Aroostook | $q_{500}$, $U_s$, $V_{850}$, $q$, $D_s$ | 0.082 | 0.406 |
| Doaktown | $q_{500}$, $U_s$, $V_{850}$, $Z_{500}$, $T$ | 0.075 | 0.421 |
| Moncton | $q_{500}$, $U_s$, $V_s$, $q$, $H_{500}$ | 0.143 | 0.456 |
| Fredericton | $q_{500}$, $U_s$, $V_{850}$, $Z_{500}$, $H_{500}$ | 0.137 | 0.448 |
| Saint John | $q_{500}$, $U_s$, $V_{850}$, $Z_{500}$, $H_{500}$ | 0.114 | 0.496 |

**Table 6**. Predictor variables selected in the calibration and validation of daily discharge models (1961-1990), as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1).

| Hydrometric Station | Predictors | $r^2$ | Standard Error |
|---|---|---|---|
| Saint John R. at For Kent | q, $q_{850}$, T, $V_s$, $Z_s$ | 0.336 | 1.995 |
| Nashwaak R. at Durham Bridge | q, $q_{850}$, T, $V_{850}$, $H_{500}$ | 0.341 | 2.037 |
| Canaan R. at East Canaan | q, $q_{850}$, T, $V_s$, $V_{850}$ | 0.344 | 2.618 |
| Kennebecasis R. at Apohaqui | q, $q_{850}$, T, $V_s$, $V_{850}$ | 0.352 | 2.056 |
| Restigouche R. below Kedgwick R. | q, $q_{850}$, T, $V_{500}$, $Z_s$ | 0.324 | 1.919 |
| SW Miramichi R. at Blackville | q, $q_{850}$, T, $V_{850}$, $Z_{850}$ | 0.354 | 1.879 |
| NW Miramichi R. at Trout Bk. | q, $q_{850}$, T, $H_{500}$, $Z_s$ | 0.337 | 2.018 |

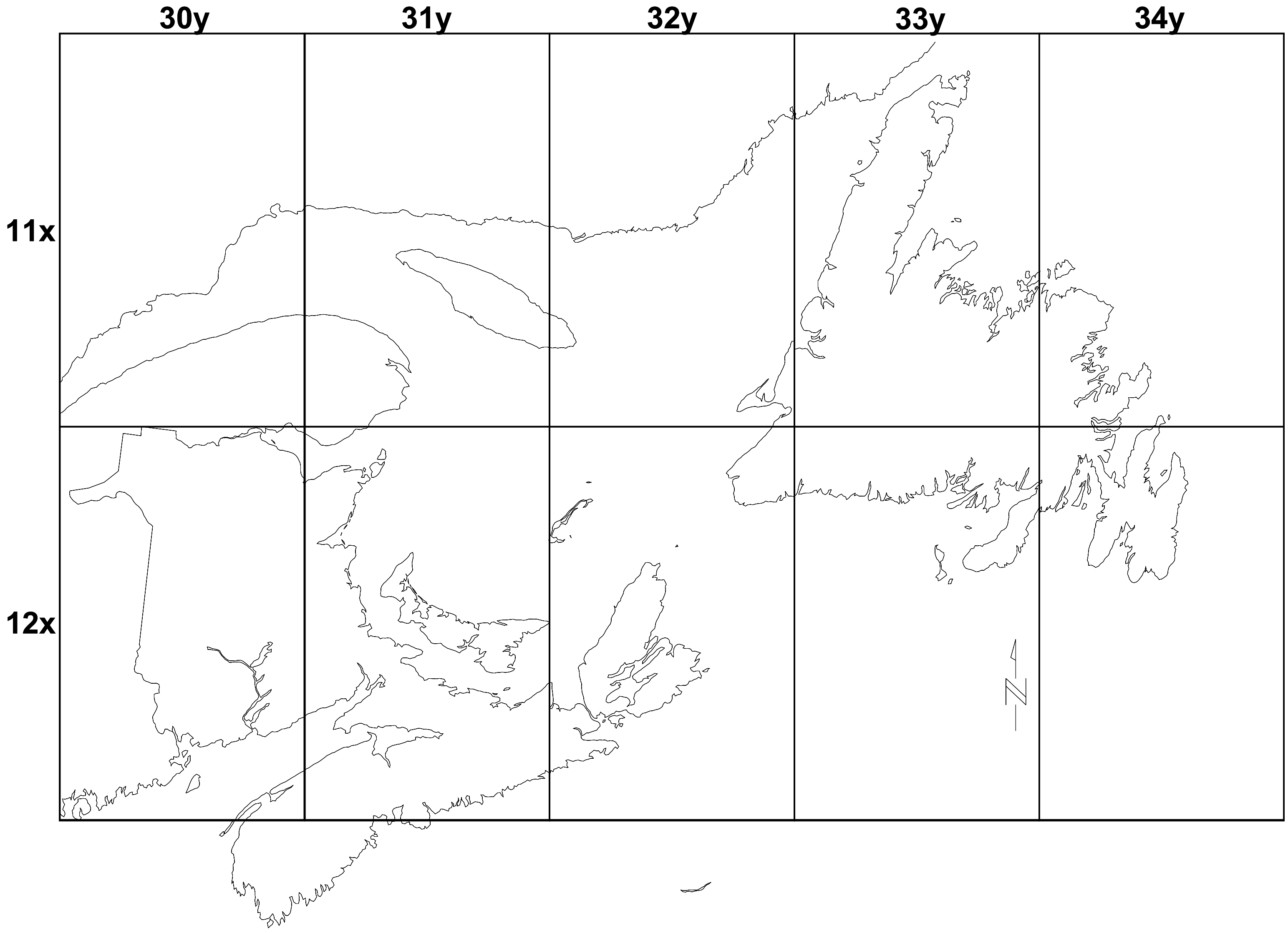

**Figure 1**. Canadian Global Coupled Model (CGCM) grid (3.7° latitude x 3.7° longitude) superimposed over Atlantic Canada

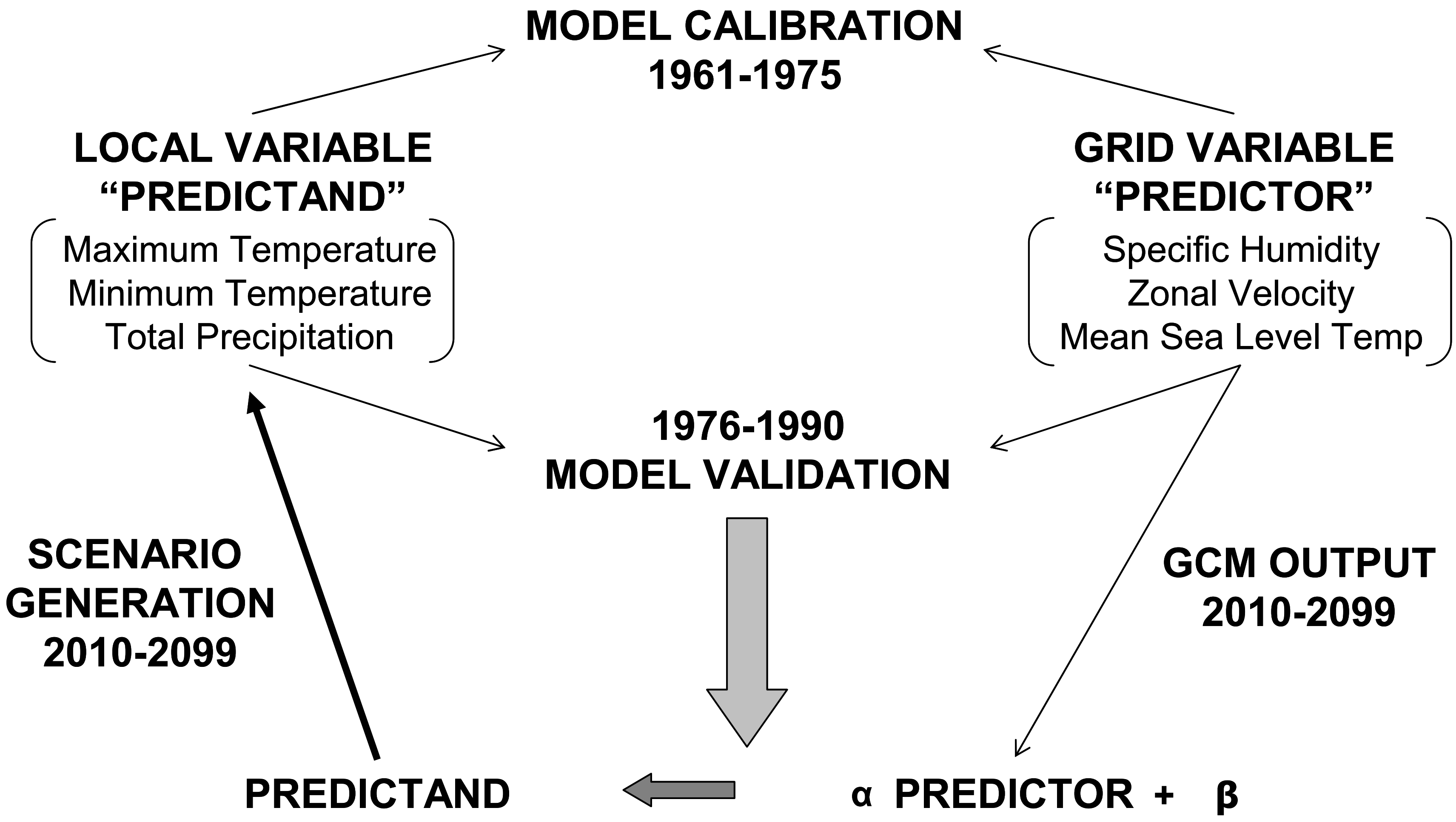

**Figure 2**. Statistical downscaling of Global Circulation Model (GCM) output to site-specific climate scenarios

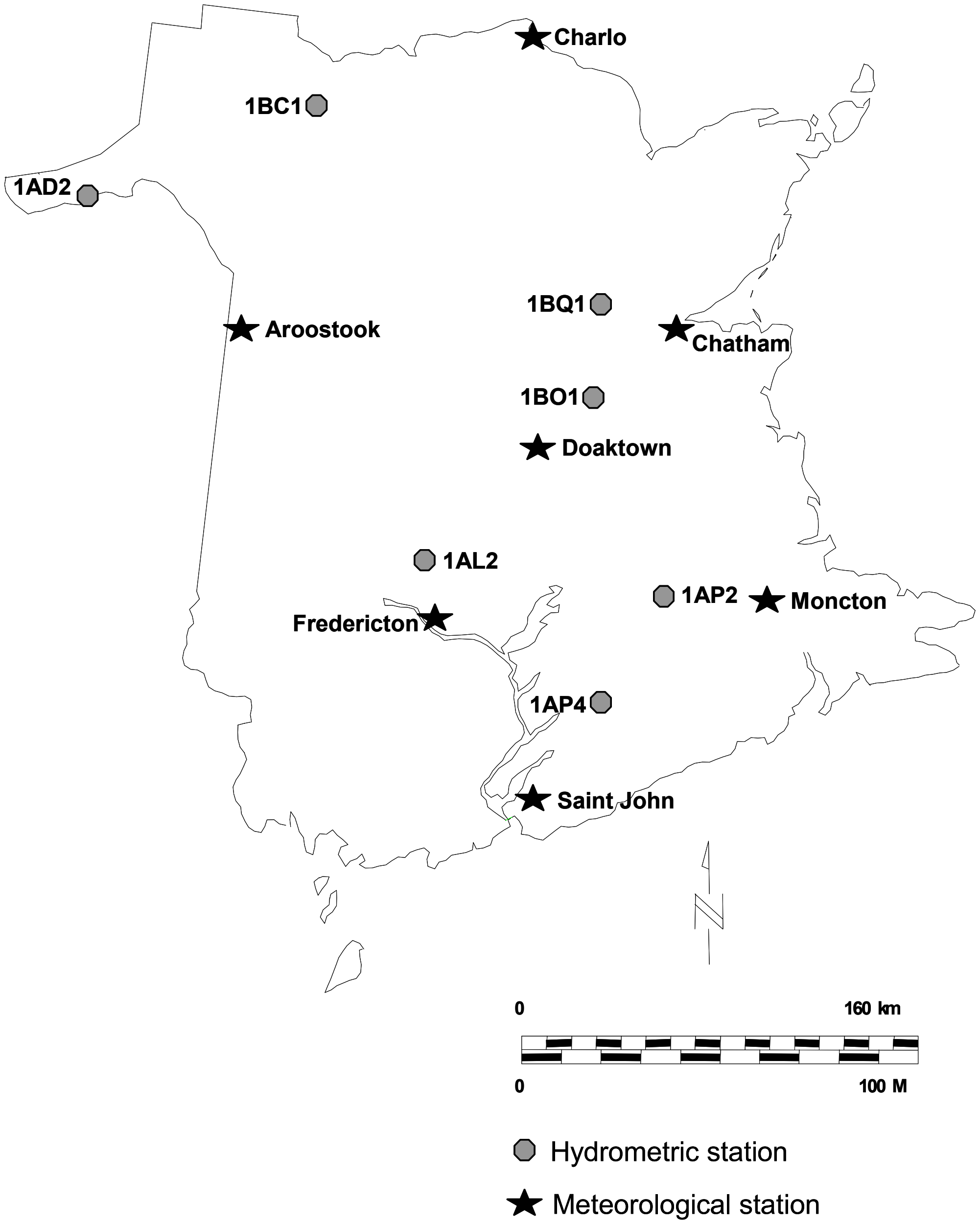

**Figure 3**. Location of hydrometric and meteorological stations in New Brunswick

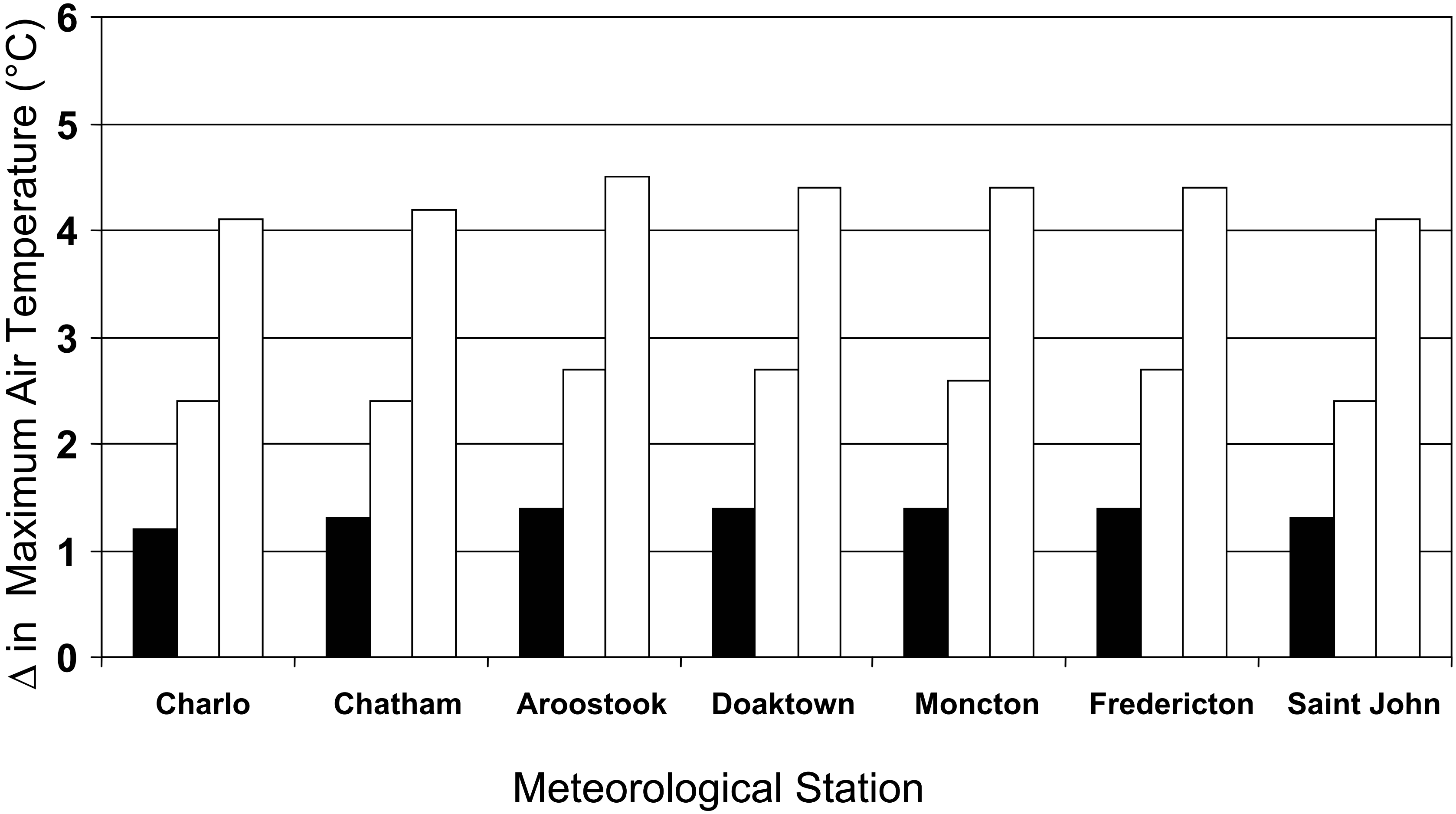

**Figure 4**. Change in mean annual maximum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

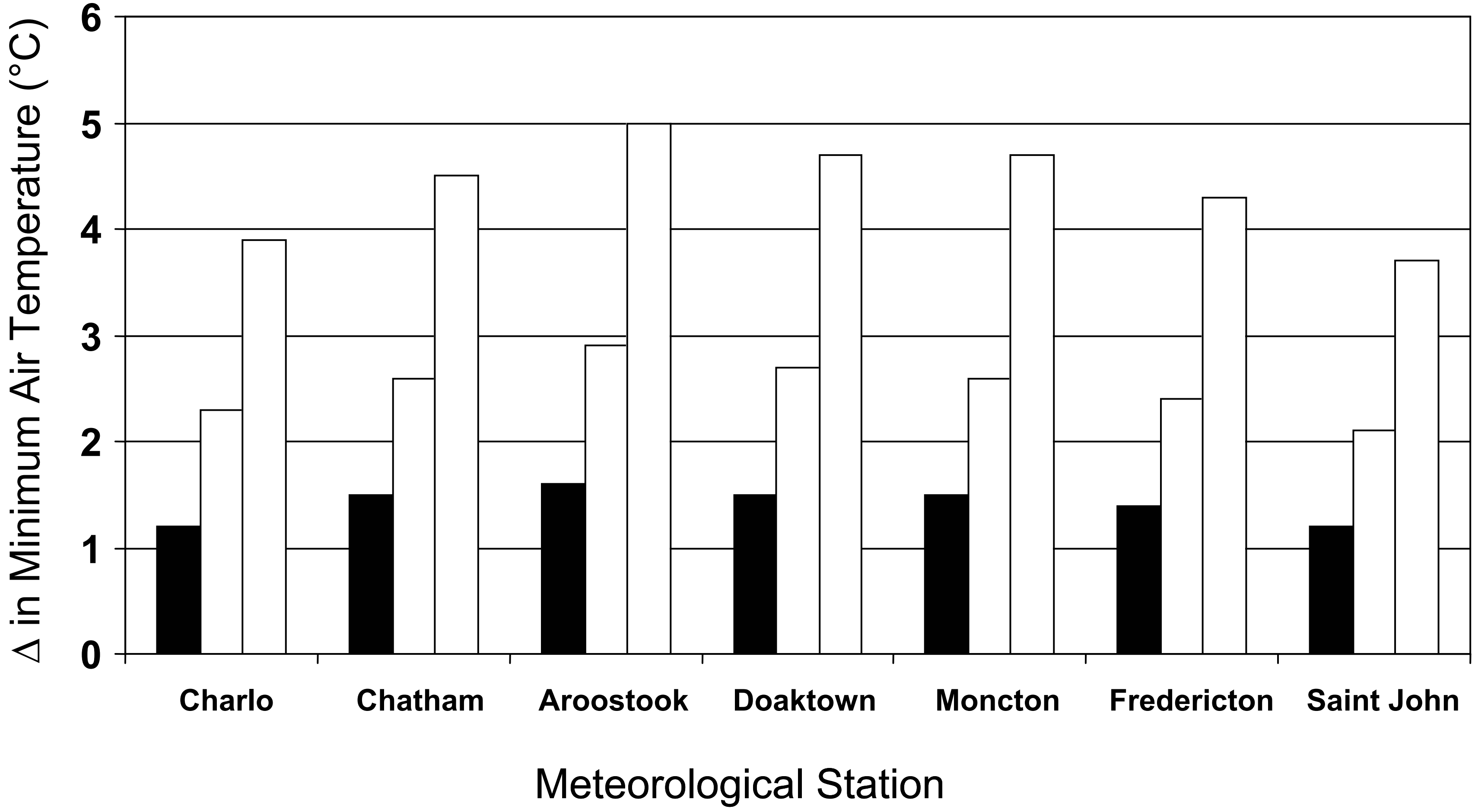

**Figure 5**. Change in mean annual minimum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

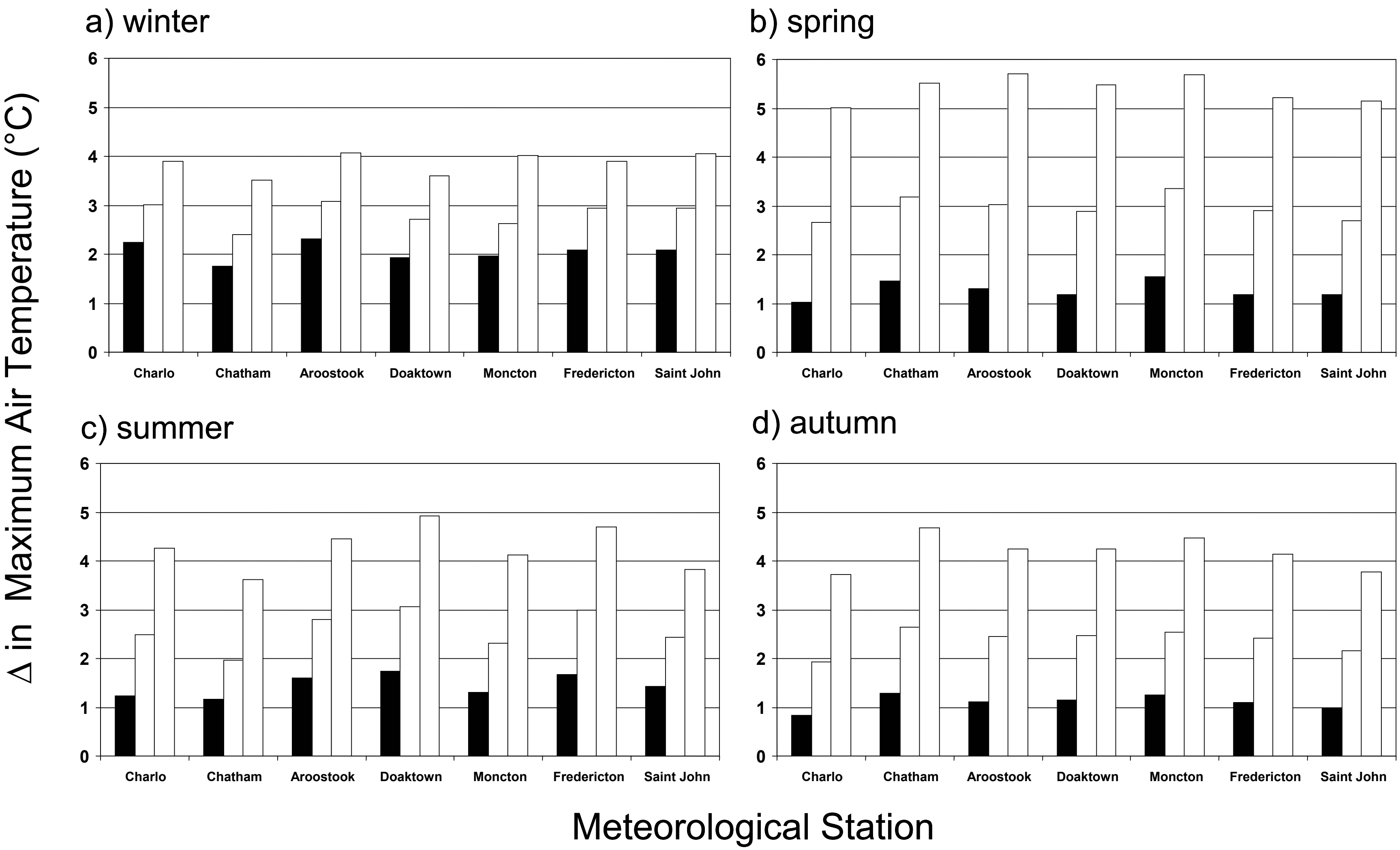

**Figure 6**. Change in mean winter (a), spring (b), summer (c), and autumn (d) maximum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

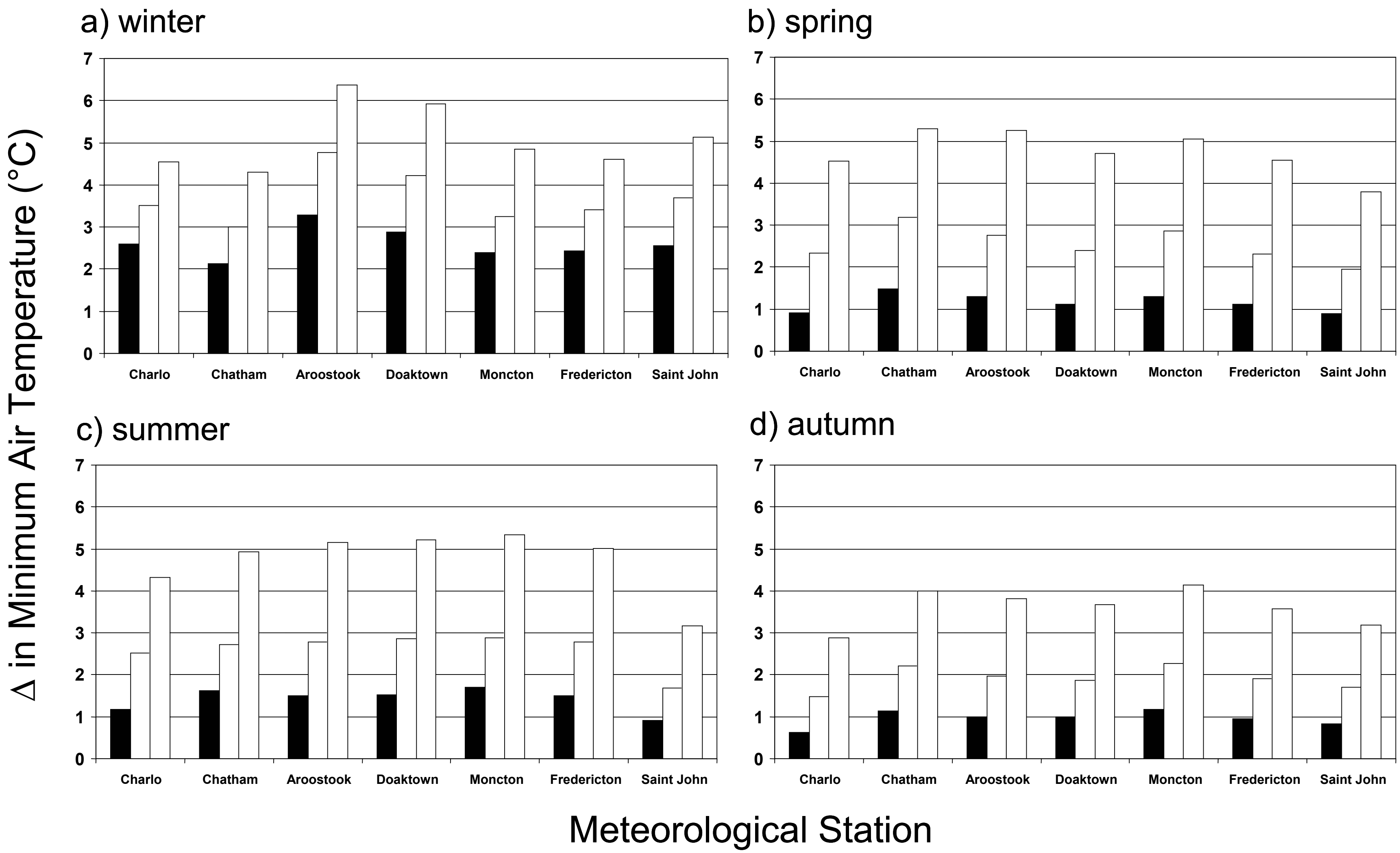

**Figure 7**. Change in mean winter (a), spring (b), summer (c), and autumn (d) minimum air temperature (ºC) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

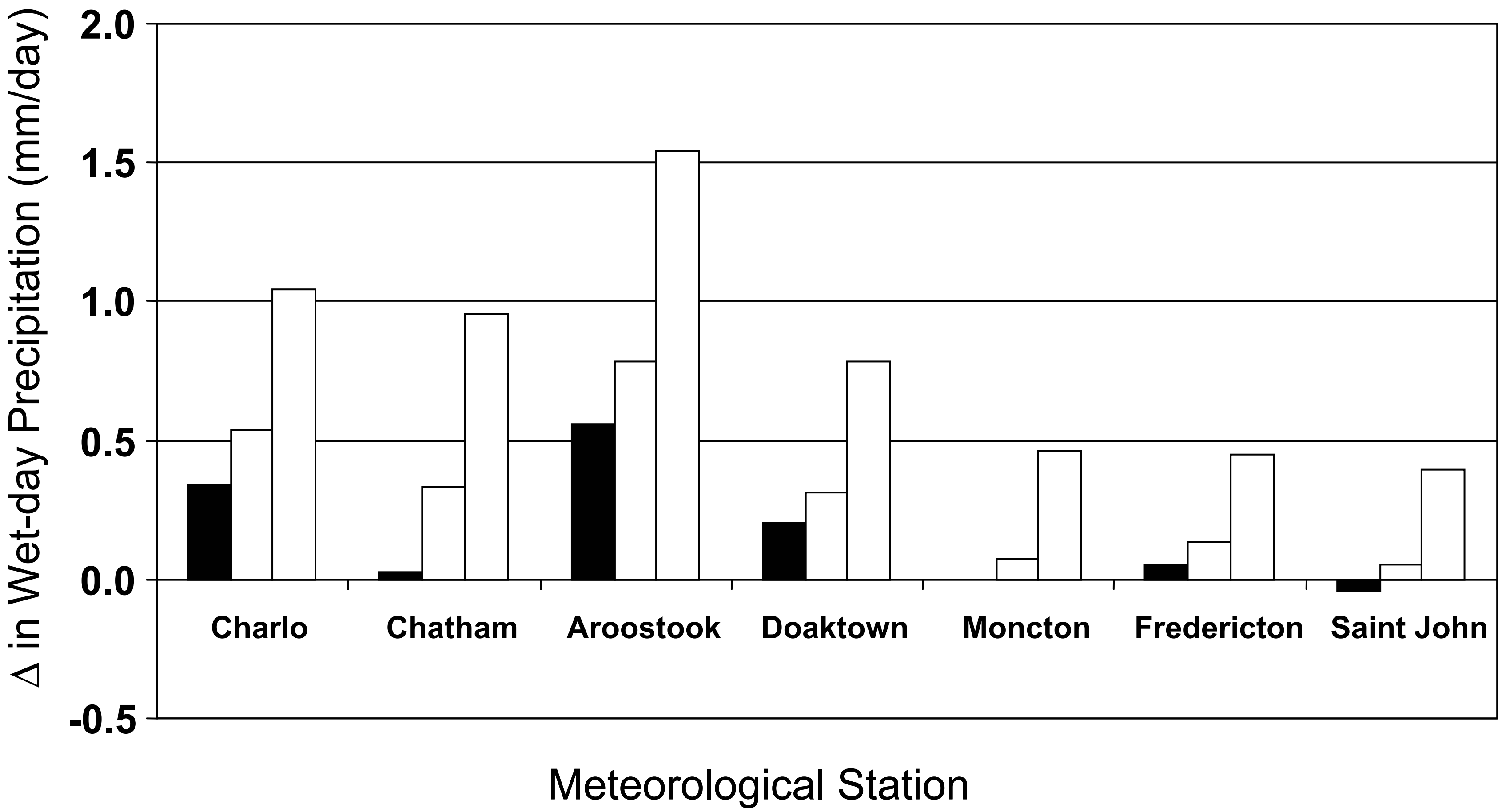

**Figure 8**. Change in wet-day precipitation (mm/day) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

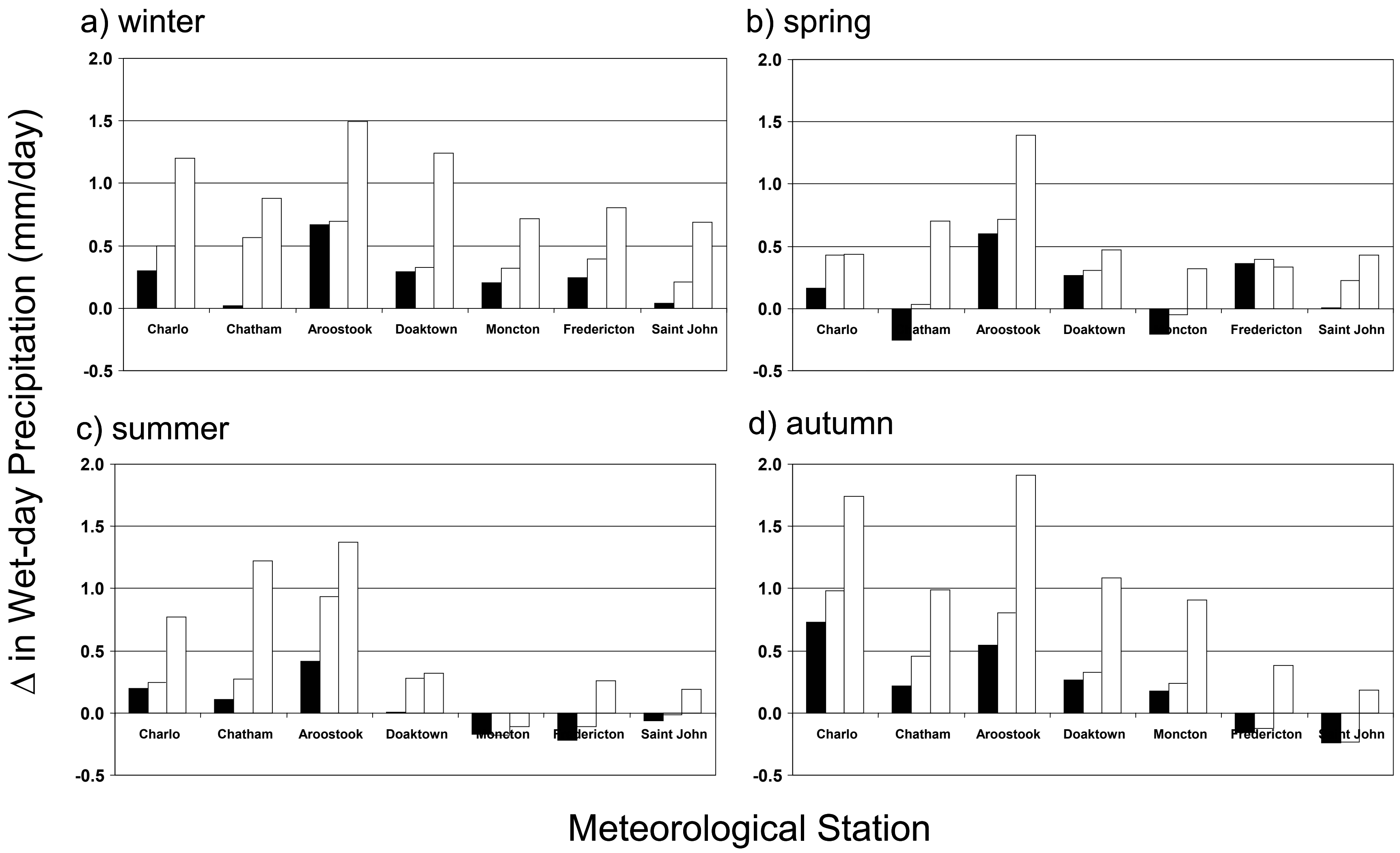

**Figure 9**. Change in mean wet-day winter (a), spring (b), summer (c), and autumn (d) precipitation (mm/day) in New Brunswick from current climate conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

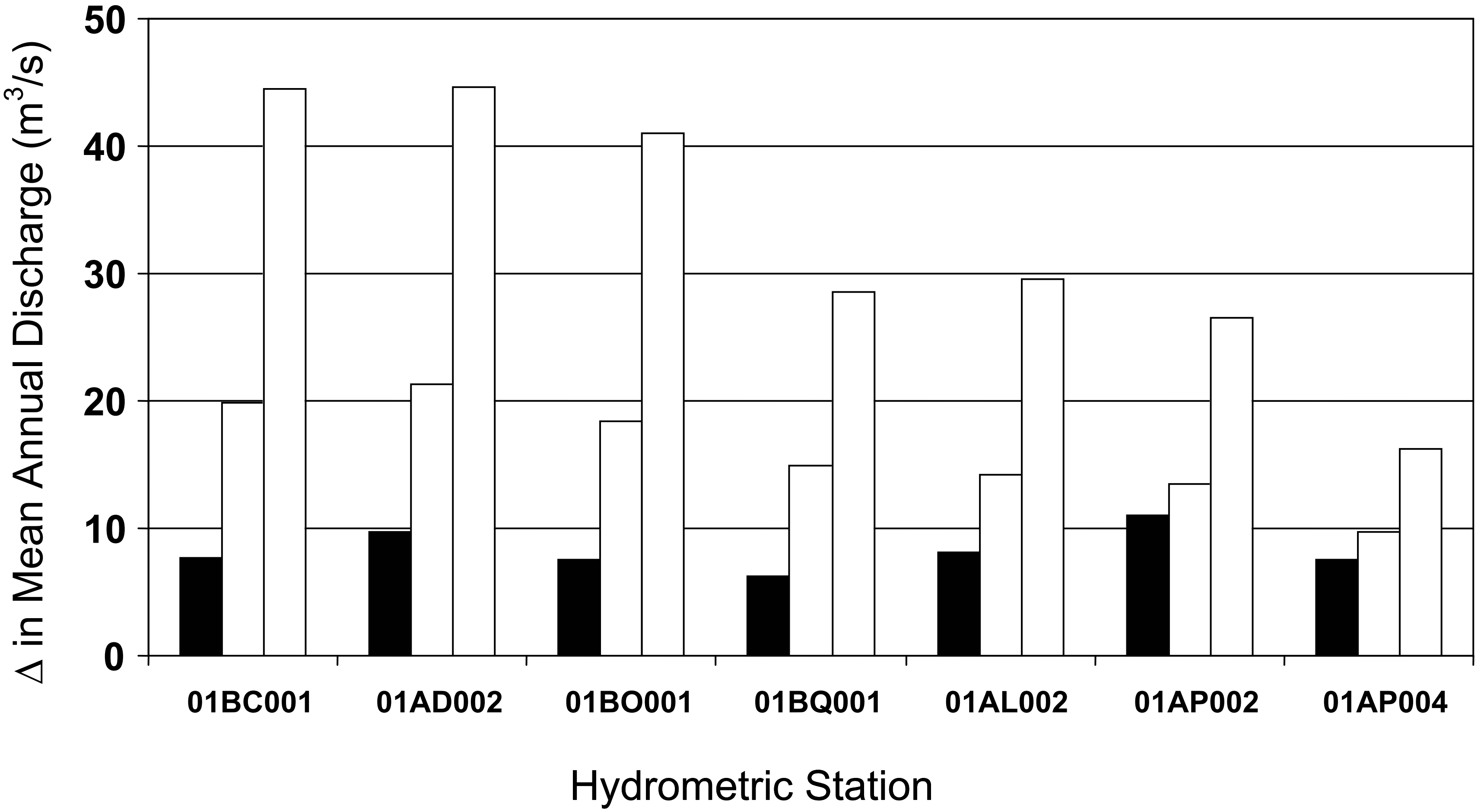

**Figure 10**. Change in mean annual discharge ($m^3/s$) in New Brunswick from current hydrometric conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)

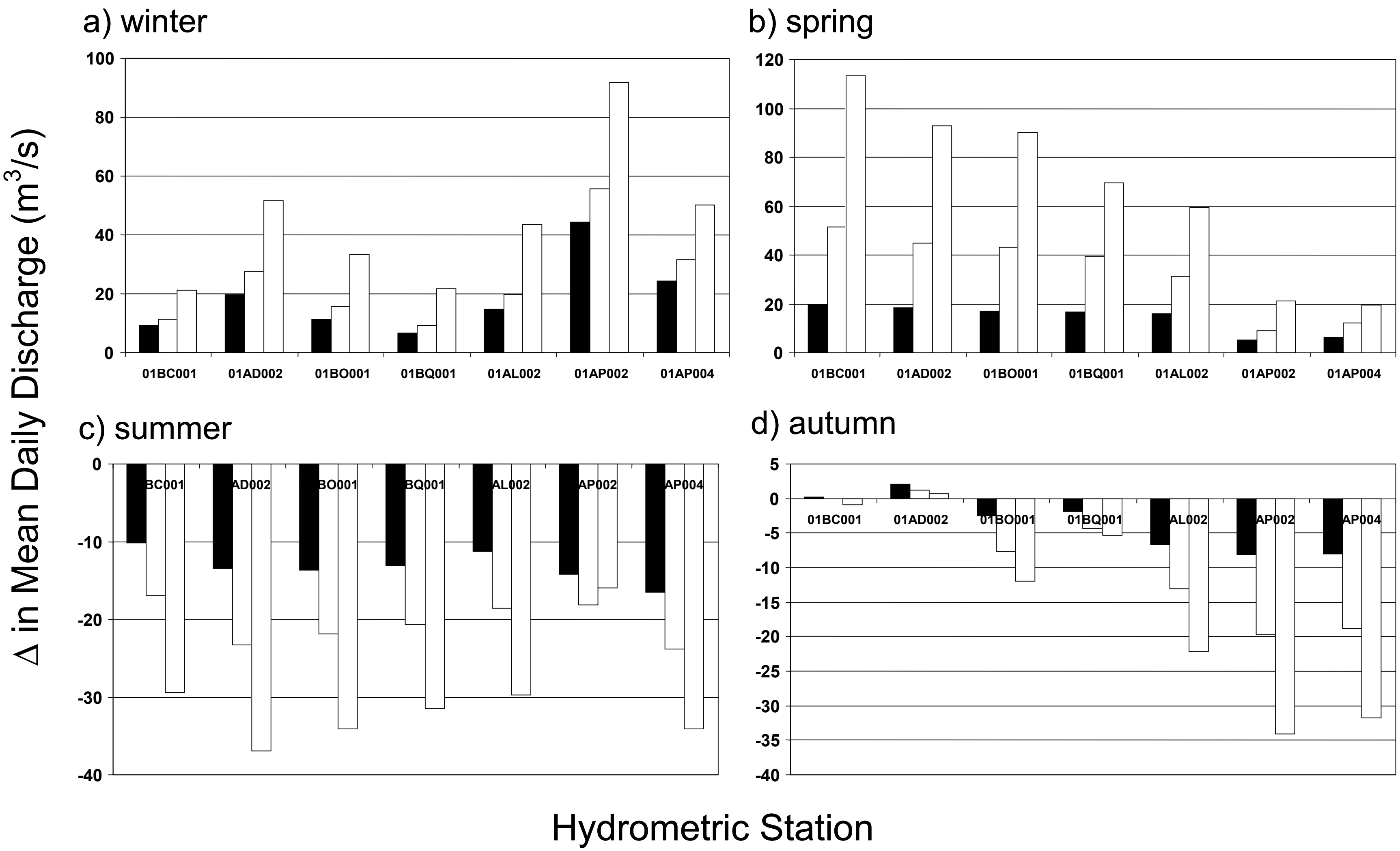

**Figure 11**. Change in mean daily winter (a), spring (b), summer (c), and autumn (d) discharge ($m^3/d$) in New Brunswick from current hydrometric conditions (1961-1990) to 2020s (black), 2050s (white), and 2080s (hatched) as derived from statistical downscaling of the Canadian Global Coupled Model (CGCM1-GA1)