

Science and Research Information Report IR-14

Climate warming projections for Algonquin Provincial Park



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Cover photo: Looking west from Opeongo Lookout. Costello Creek is flowing from left to right towards Lake Opeongo. Photo by Luke Ridgway; taken January 1, 2018.

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Summary

We summarize climate warming projections for Algonquin Provincial Park based on scenarios presented in the 2014 United Nations International Panel on Climate Change (IPCC).

Changes in climate are already affecting Algonquin Provincial Park. Earlier ice-out dates on lakes and general warming of the landscape around the park over the past century provide local evidence for climate change. Temperature trends from centres near the park — Haliburton, Madawaska, and North Bay, Ontario, Canada — reflect the global pattern of a 1 °C increase in average temperature by 2016. Continuing increases in global levels of greenhouse gases, such as is shown for carbon dioxide in the Keeling Curve, point to this warming continuing for years to come.

To evaluate future climate change in the park, an ensemble of climate models was used to examine potential outcomes of two scenarios. One scenario is based on reduced concentrations of greenhouse gases by mid-21st century (RCP4.5) and another is based on increases similar to those observed today continuing (RCP8.5).

Warming occurs under both projections. If greenhouse gases are reduced by mid-century, for both scenarios average air temperature in the park will range from 6.5 to 8 °C for the balance of the 21st century. In contrast, continued increases in greenhouse gases as observed today will push average air temperature in the park to between 9 and 10 °C by 2071–2100. Current average air temperature in the park is 4 to 5 °C. No realistic climate warming scenario indicated that the park will retain the average air temperature observed today.

To put the projected temperature changes in context, the scenario of reduced greenhouse gases by mid-century will result in average air temperature in the park equivalent to today's Peterborough, Ontario. Continued increases in greenhouse gases will result in average air temperature in the park equivalent to today's Leamington – Windsor, Ontario. The general effects of climate warming on fish and freshwater ecosystems are summarized with emphasis on Algonquin Provincial Park.

Résumé

Projections du réchauffement climatique pour le parc provincial Algonquin

Nous résumons ici les projections du réchauffement climatique pour le parc provincial Algonquin sur la base de scénarios présentés en 2014 au Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) des Nations Unies.

Le changement climatique affecte déjà le parc provincial Algonquin. Les dates du déglacement des lacs et le réchauffement général du paysage entourant le parc au cours du dernier siècle témoignent du changement climatique. L'évolution de la température dans des centres proches du parc – Haliburton, Madawaska et North Bay, en Ontario – reflète la hausse de 1°C à l'échelle mondiale en 2016. La poursuite de l'augmentation des niveaux mondiaux de gaz à effet de serre, comme le montre la courbe de Keeling pour le dioxyde de carbone, donne à penser que ce réchauffement se poursuivra au cours des années à venir.

Pour évaluer le changement climatique futur dans le parc, un ensemble de modèles climatiques a été utilisé pour examiner les résultats potentiels de deux scénarios. Un scénario se fonde sur la réduction des concentrations de gaz à effet de serre au milieu du XXI^e siècle (RCP4.5), et un autre se fonde sur la poursuite de hausses semblables à celles que l'on observe aujourd'hui (RCP8.5).

Il y a deux hypothèses de réchauffement. Si les gaz à effet de serre sont réduits au milieu du siècle, pour les deux scénarios la température de l'air moyenne dans le parc sera de 6,5 à 8°C pour le reste du XXI^e siècle. Mais si la hausse se poursuit comme aujourd'hui, la température de l'air moyenne dans le parc sera de 9 à 10°C de 2071 à 2100. La température de l'air moyenne actuelle dans le parc est de 4 à 5°C. Aucun scénario de réchauffement climatique réaliste ne prévoit que le parc conservera la température de l'air moyenne observée aujourd'hui.

Pour contextualiser les changements de température projetés, le scénario de réduction des gaz à effet de serre au milieu du siècle donnerait une température de l'air moyenne dans le parc semblable à celle d'aujourd'hui à Peterborough (Ontario). La poursuite de l'augmentation des gaz à effet de serre donnerait une température de l'air moyenne dans le parc équivalente à celle d'aujourd'hui à Leamington, près de Windsor (Ontario). Les effets généraux du réchauffement climatique sur les poissons et les écosystèmes d'eau douce sont résumés ici, tout particulièrement concernant le parc provincial Algonquin.

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Introduction

The scientific consensus on climate change, as expressed in the United Nations' International Panel on Climate Change (IPCC), is that Earth's climate has been warming for several decades, slowly at first but now with increasing pace, due to human produced carbon emissions. The latest IPCC summary (2014a; pg. 40) states:

“Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen.”

“Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems.”

Based on NASA's global land-ocean temperature index (NASA 2018), 16 of the 17 warmest years on record have occurred since 2001. The year 2016 was 0.99 °C warmer relative to the average land-ocean temperature index covering the period 1951–1980. Unless emissions of greenhouse gases such as carbon dioxide (CO₂) are reduced, warming will continue, with projected increases in global temperature of approximately 1.5 to 5.5 °C for the balance of the 21st century (IPCC 2014a). Reducing and mitigating carbon emissions will slow the pace of warming and potentially avert serious human and ecological consequences.

Past climate analyses for Ontario's parks pointed to increased warming and precipitation for Algonquin Provincial Park (Lemieux et al. 2007). Temperatures in the park were projected to increase by 0.7 to 3.4 °C in the 2020s, 2.0 to 7.1 °C in the 2050s, and 3.3 to 10.6 °C in the 2080s. Precipitation in the park was projected to increase 2 to 20% over this century. This set of projections covered the park as a whole and was based on an earlier IPCC (2000) report on emissions scenarios.

A more recent summary of climate change projections for Ontario points to a 4.7 to 7.9°C increase in average annual air temperature in the Lake Huron and Ottawa River basins when compared to the 1971–2000 30 year period (McDermid et al. 2015).

Model scenarios have since been updated (IPCC 2014b), certainty with respect to weight of evidence has increased (Cook et al. 2016), and the capacity to down-scale global circulation models has improved regional-scale climate projections. The ability to project climate effects at a grid scale of 10 x 10 km allows change to be evaluated within park boundaries. Since the park landscape has different forest types, growing

conditions, and topographic patterns, a detailed examination of change within its boundaries is an important step in understanding patterns of climate change affecting all ecosystems in the park.

In the 21st century, the effects of global warming will be observed throughout Earth's ecosystems and not just in Algonquin Park. In soils, microbial decomposition will change along with microbial/plant interactions that are important for plants to thrive (Classen et al. 2015). In forests near Lake Ontario, the species composition of hardwood forests is shifting from beech-maple-birch to beech (more widespread and abundant saplings now) based on warmer temperatures and increased precipitation (Bose et al. 2017). In Canada's boreal forest, climate warming is projected to result in longer growing seasons (1–30% increase by 2100) and increased fire frequency and insect outbreaks. Because permafrost underlies 40% of the boreal forest, warming will fundamentally change the freeze/thaw patterns of soils and affect/change forest composition spanning many decades (Price et al. 2013). In oceans, increasing CO₂ is acidifying surface water and, along with warmer surface temperature, is bleaching coral reefs (Doney et al. 2009, Spalding and Brown 2015). Climate warming occurring now and projected over the 21st century is expected to reduce polar ice by amounts that in the past have significantly increased sea levels (Dutton et al. 2015). Globally, oceans are expected to rise due to melting of polar ice caps over the 21st century and beyond. In lakes, climate warming is already leading to shorter periods of ice cover in winter, warmer water in summer, and earlier spring spawning for many aquatic species (Ficke et al. 2007, Ghanbari et al. 2009, Hewitt et al. 2018).

As warming continues, many changes in how ecosystems function are projected to occur (Settele et al. 2014). For plants and animals, change will include shifts in species distribution and abundance and altered interactions in species assemblages, such as mechanisms of predation and competition. Species response will differ based on their physiology and capacity to move or adapt to new environments.

By the end of the 21st century, ecosystems may look and function quite differently than today. Given the importance of Algonquin Park in conservation and public interest, updated climate warming projections at a scale below the park boundary are needed. Such projections are now recognized as a key step in overcoming the past mismatch between climate projections at coarse scales and potential effects at fine scales in aquatic and terrestrial habitats (Maclean et al. 2017, Nadeau et al. 2017).

The purpose of this report is to summarize recent climate warming projections for Algonquin Park. Summarizing projections is important for improving understanding of potential effects on the park's organisms and ecosystems and to inform adaptation and mitigation efforts. Here we focus specifically on the effects of temperature changes on lakes.

The Keeling Curve

Beginning in the late 1950s, Charles Keeling began recording CO₂ concentration in the atmosphere from a sampling location at the Mauna Loa Observatory in Hawaii, United States. Carbon dioxide is widely recognized as a greenhouse gas contributing to global warming; therefore increasing concentrations of this atmospheric gas promotes climate warming. Keeling's time series record has continued and represents the clearest evidence of changing patterns of global CO₂. This time series is plotted in Figure 1 from the beginning of Keeling's data record to the end of December 2017. It shows that CO₂ has increased steadily over decades with greater pace in recent years. The zig-zag pattern evident in the time series is based on peak CO₂ concentration in spring (May) and low CO₂ in fall (October) each year in the Northern Hemisphere. From May onwards, CO₂ is taken in by photosynthesis in plants during the growing season and, beginning in October, it is released through decomposition until leaf-out the following spring. This pattern is repeated each year.

For the first time in human history, CO₂ concentration has exceeded 400 ppm in the last two years (Figure 1).

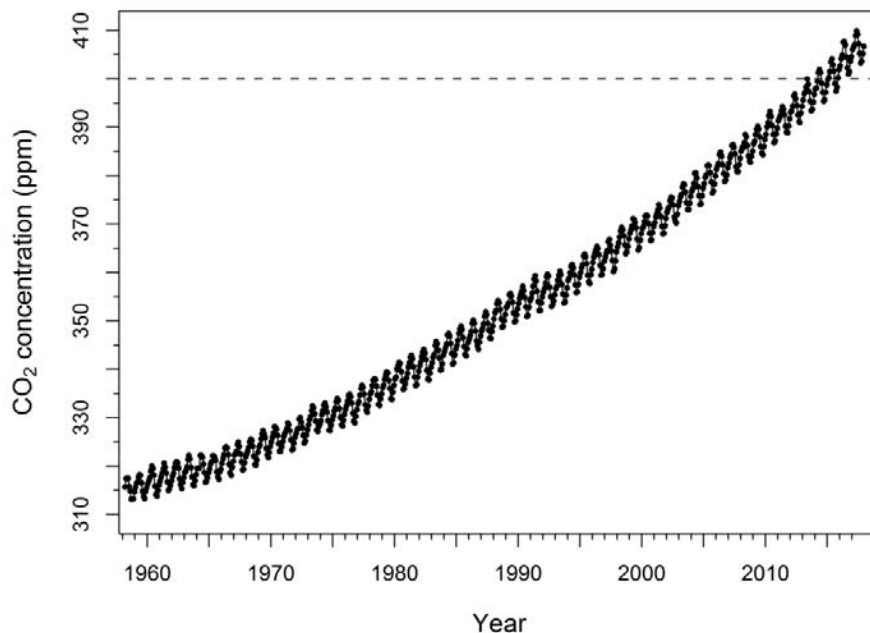


Figure 1. The Keeling Curve of carbon dioxide concentration (CO₂; parts per million), 1958–2017. The dotted line represents 400 ppm of CO₂, a threshold not previously experienced in human history.

Evidence for climate change in Algonquin Park

Evidence for climate change occurring in Algonquin Provincial Park is based on two long-term data sets. First, ice-out date at Sproule Bay, Lake Opeongo, is recorded each spring by staff at the Harkness Laboratory of Fisheries Research. Second, for nearly a century, temperature recorded at Haliburton, Madawaska, and North Bay, Ontario, provide a time series on changes in average annual air temperature northwest, southwest, and southeast of the park, respectively.

The ice-out date varies from year-to-year. Since the 1950s, the trend is earlier open water dates on Sproule Bay (Figure 2). The trend line indicates that ice-out has been advancing by 1.7 days per decade resulting in 9-day earlier ice-out since the start of the observation record. The jagged pattern in the time series is typical for ice-out data, which can be highly variable from year to year requiring decades of observation to monitor trends.

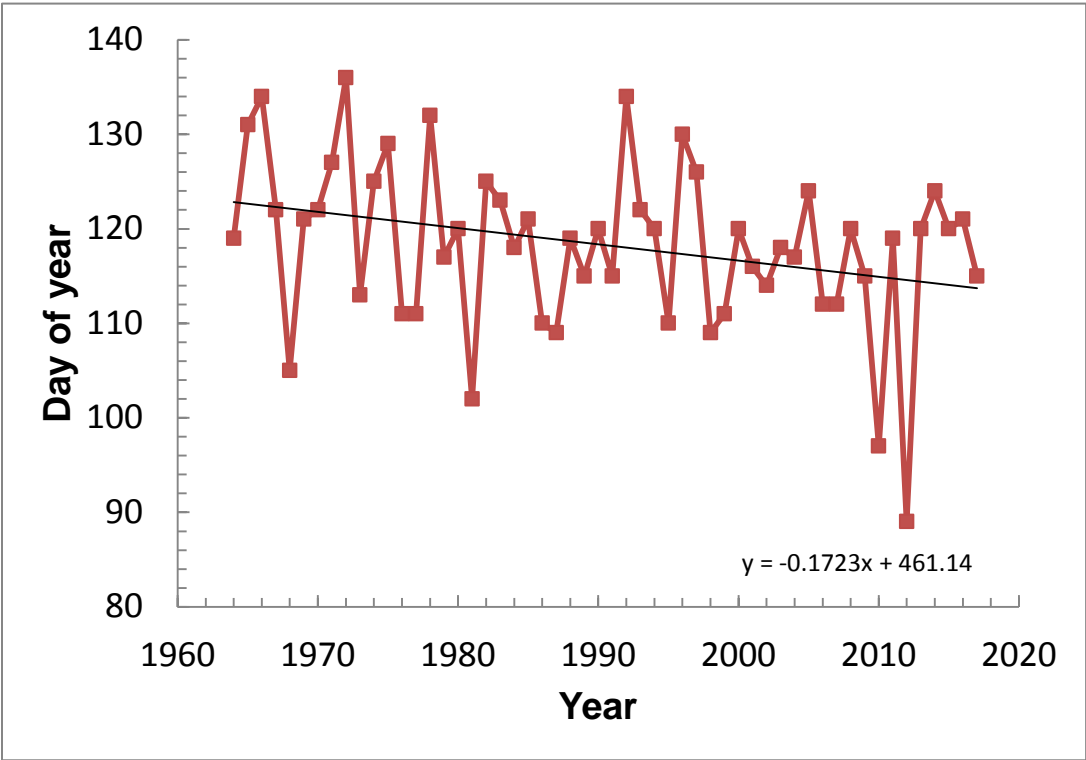


Figure 2. Ice-out day of year for Sproule Bay, Lake Opeongo, in Algonquin Provincial Park, Ontario, beginning in 1964. The trend line indicates that ice-out day is advancing at a rate of 1.7 days per decade. The latest ice-free day in Sproule Bay was in 1972 (day 136) and the earliest was in 2012 (day 89).

The average annual air temperature recorded at weather stations in Haliburton (1888–2016), Madawaska (1915–2016), and North Bay (1925–2014) provide the longest time series of air temperature near the park. As observed in the ice-out data, average annual air temperature varies from year to year (Figure 3). Over the decades of observation, the trend line demonstrates an increase in average annual air temperature of approximately 1 °C at the three sites, which is consistent with global patterns (NASA 2018).

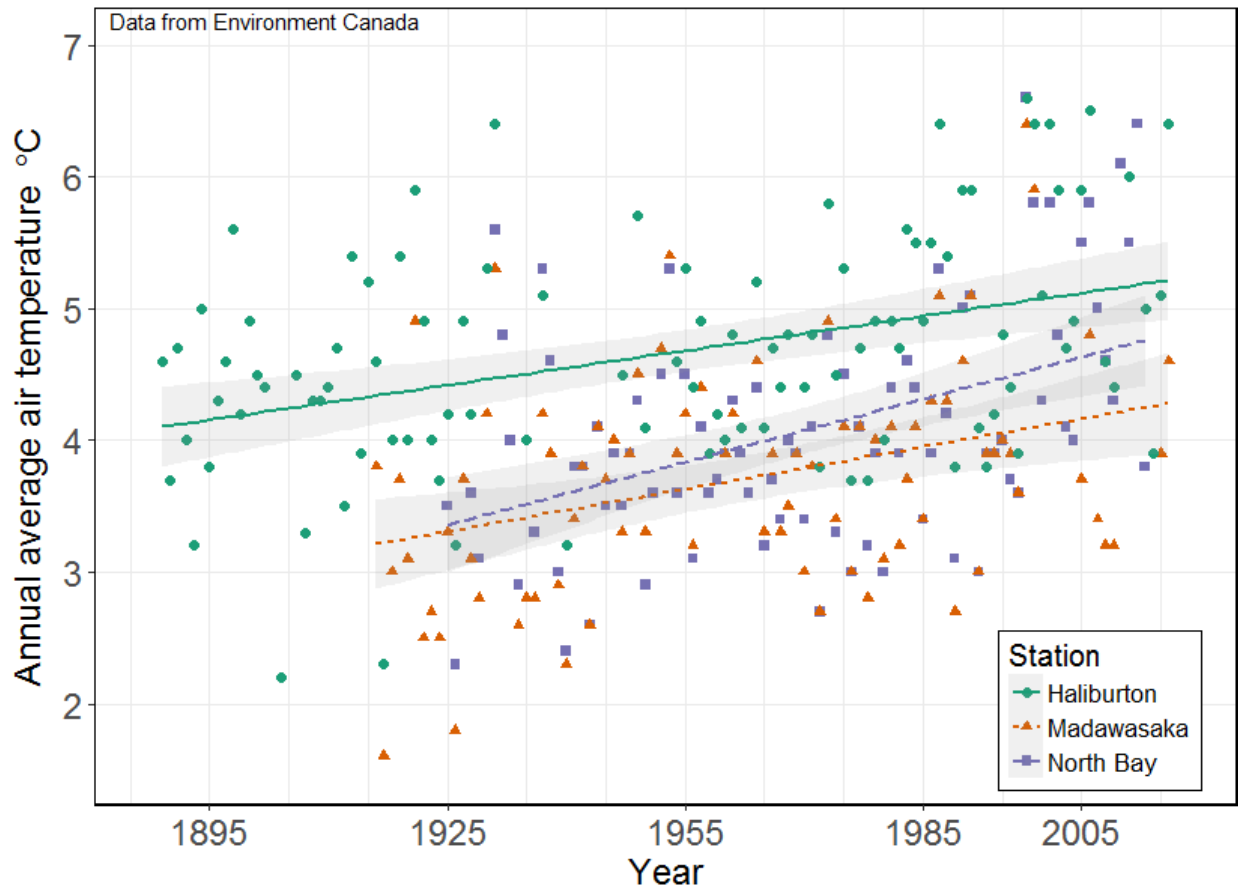


Figure 3. The long-term temperature record of average annual air temperature from the Haliburton, Madawaska, and North Bay weather stations. All show high variability from year to year but an overall increasing trend with grey areas indicating potential range of trend lines.

Temperature baseline for Algonquin Park

Using data from North Bay, Madawaska, and other locations in south central Ontario, a general map of average annual air temperature can be developed for the park (Cross et al. 2012, Ridgway et al. 2017). Figure 4 illustrates the variation in average annual air temperature across the park landscape for the period 1981 to 2010, inclusive. Figure 4 represents average temperature over this 30 year period and serves as the baseline for comparing *observed* temperatures and detecting climate warming. In this study, computer model results for this 30 year period are compared against climate projections for three future periods: 2011–2040, 2041–2070, and 2071–2100.

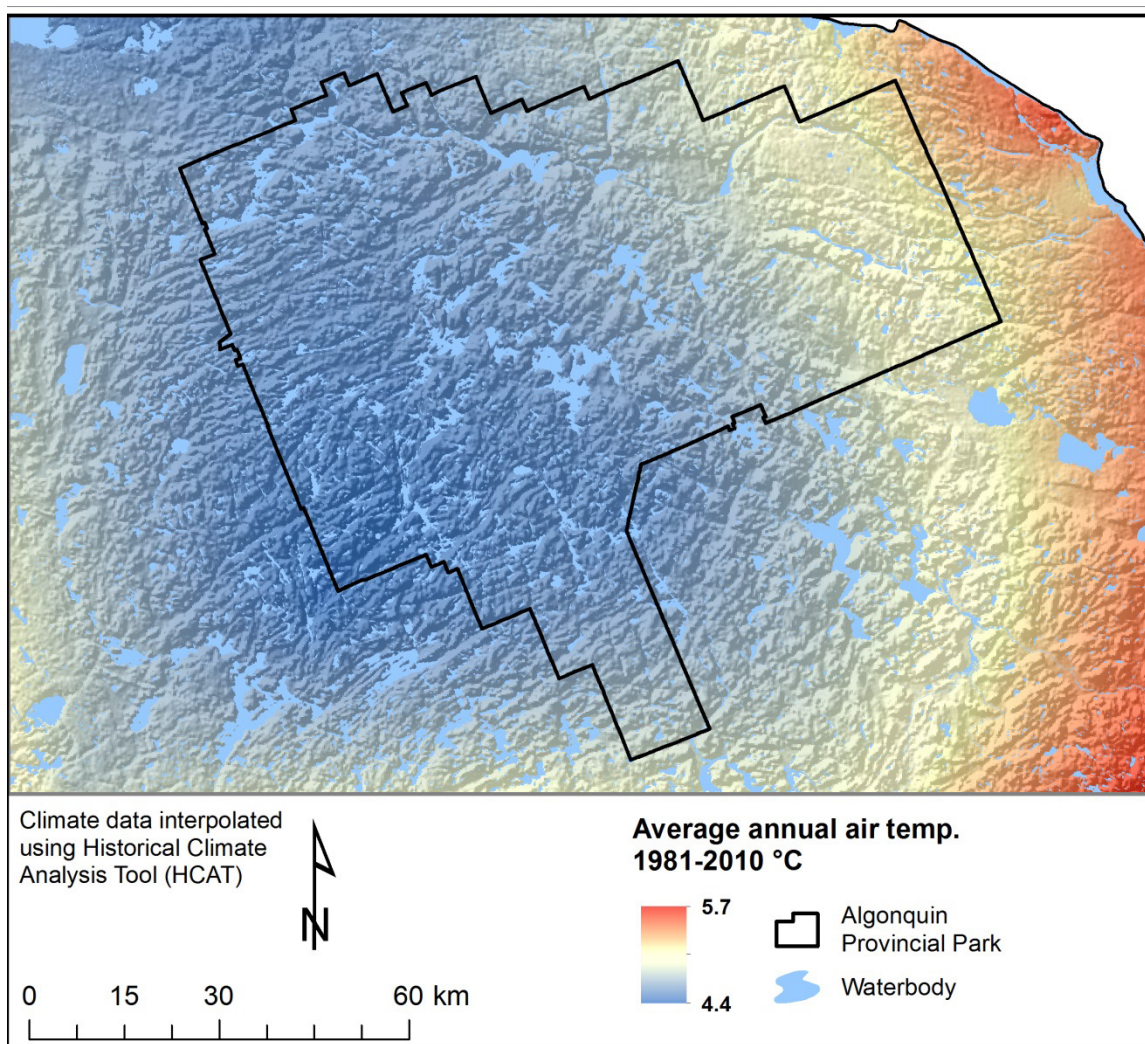


Figure 4. The observed 30 year average annual air temperature for Algonquin Provincial Park, Ontario, for the period 1981–2010. Data and model interpolation using methods presented by Cross et al. (2012).

The ensemble model approach

Different research groups and governments worldwide have developed global circulation models for the purpose of understanding climate change in their region of the world. When making climate change projections combining models into an ensemble of models provides a way to understand the ‘average’ projected change that will occur due to increasing greenhouse gases.

The ensemble model approach was used in this study. Eight of 12 models for eastern North America provided by the University of Victoria’s Pacific Climate Impacts Consortium were selected as those most relevant to Canada and Ontario (see Appendix 1). These model projections describe change in climate based on best available information as of 2017. Full details about the technical considerations and assumptions of these models are available in IPCC reports (IPCC 2014a, b). Results from these 8 models combined are reported here as the average projection for the balance of this century.

Two features of climate projection need to be understood when considering the study results. First is the importance of distinguishing weather from climate. On any given day or week, the weather may indicate that climate warming scenarios are out of step with actual temperatures. As observed in the ice-out data (Figure 2), year-to-year variation is relatively high but the trend is towards an earlier ice-out date. The difference is that weather is what we experience in the short term (days, weeks, seasons) while climate is the long term (years, decades, centuries, millennia) trend. In this study, computer models were used to project climate through the 21st century.

Second, because oceans and atmosphere are fluids, each with a different density, how they flow globally in response to one another is computationally intricate and best captured at broad scales. The ability to downscale global circulation models to regional scale makes it possible to address climate change at scales that are more relevant to people, plants, and animals for the purposes of planning and to better understand climate warming effects in ecosystems.

Downscaling circulation models to a 10 x 10 km grid results in 155 grid cells in Algonquin Park and an additional 118 grid cells around the perimeter of the park (Figure 5). This gridding allows for more detailed climate projections across the park’s landscape. Climate change projections for a given lake or location are based on associating results for the closest grid node to that lake or location.

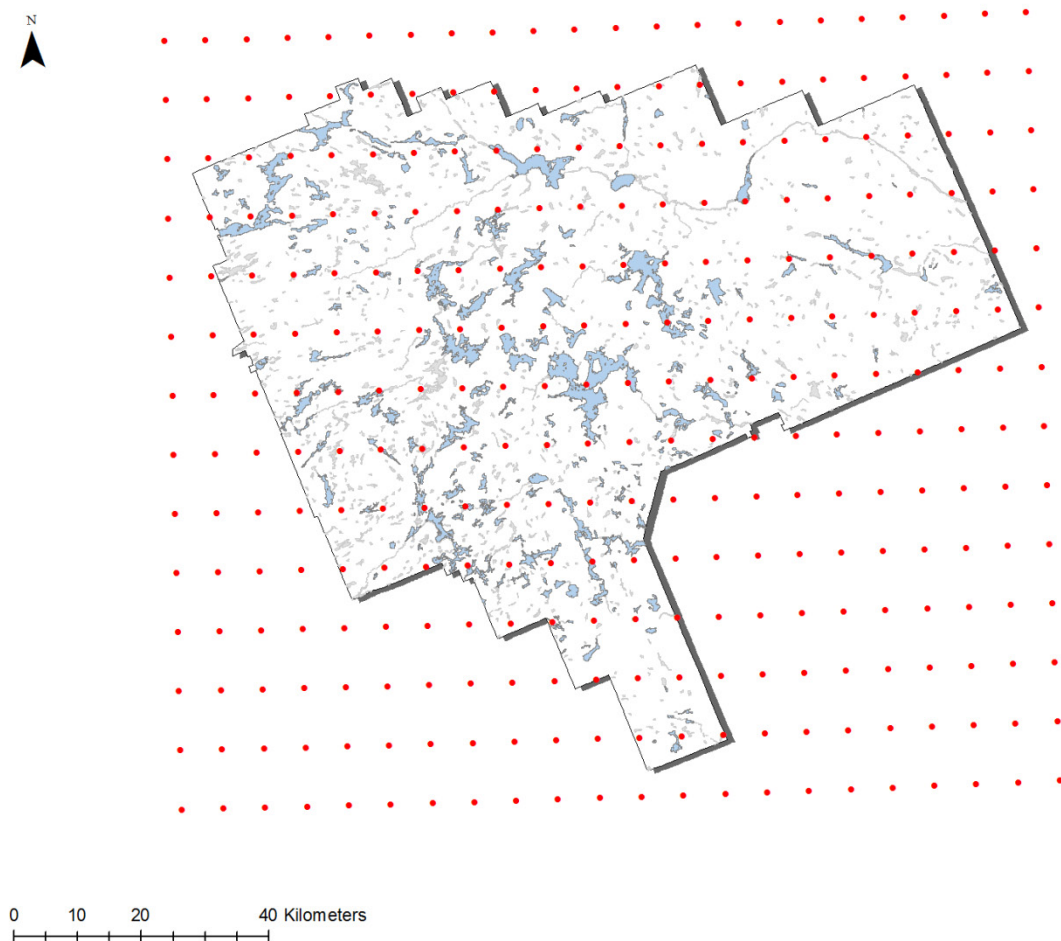


Figure 5. The grid system used in the ensemble climate model projections for Algonquin Provincial Park, Ontario, and surrounding landscape. Each node (red) represents a 10 x 10 km grid system for which climate change is evaluated. Maps of climate change patterns are based on integrating model outcomes at each node.

Climate warming projection scenarios

For consistency, a common set of scenarios are used to evaluate climate change projections around the world. These scenarios are referred to as representative concentration pathways (RCP; IPCC 2014b).

Each RCP category reflects a difference between the Sun's energy absorbed by Earth and that radiated back to space relative to the state of absorption and loss in the pre-industrial era. If energy radiated back to space is the same as that absorbed by Earth then the net change is zero. If energy reaching Earth exceeds that radiated back to space then more energy is retained in the atmosphere resulting in a net increase and thus warming. If more energy is radiated back to space than is retained by Earth the net negative change results in cooling.

Carbon dioxide has been present in the Earth's atmosphere for a very long time, resulting in conditions that have allowed life to flourish. However, increasing levels of CO₂ and other greenhouse gases are trapping more of the sun's energy, amplifying the warming effects beyond historical conditions. The potential outcomes of this warming were evaluated for Algonquin Park based on the RCP categories described in Table 1. These categories differ based on whether reductions in carbon emissions are implemented early, mid-century, late, or not at all. Implementing reductions in carbon emissions alters the trajectory of energy capture by the Earth's atmosphere and prevents further warming. Essentially, this means the rate of change in CO₂ documented in the Keeling Curve slows and eventually levels out.

The RCP categories used in this analysis were RCP+8.5 (status quo continues) and RCP+4.5 (CO₂ peaks in 2040 then declines). The RCP+6.5 (CO₂ peaks in 2060 then declines) scenario was not analyzed but represents an intermediary between RCP+8.5 and RCP+4.5, which bound the projected average air temperature in Algonquin Park. The RCP+2.6 category was not evaluated because it is based on CO₂ peaking by 2020 followed by reduced emissions, which is no longer achievable, making that scenario unrealistic. Since all RCP scenarios in this report are positive (+), the format used for the balance of the report will be as RCP4.5, RCP8.5, etc. (Table 1).

Table 1. Description of the RCP (representative concentration pathways) used in the climate warming projections in this study of Algonquin Park, Ontario. The number associated with each category is the net change in the Sun’s energy retained in Earth’s atmosphere in Watts per square metre (W per m²). A Watt is the rate of energy change (positive in this case) per unit time.

RCP category	Description
RCP2.6	Carbon dioxide concentration peaks in 2010–2020 then declines. This category was not examined in this study because it is no longer a likely option.
RCP4.5	Carbon dioxide concentration peaks in 2040 and then declines.
RCP6.5	Carbon dioxide concentration peaks in 2060 and then declines. This category is bounded by the RCP8.5 (upper bound) and RCP4.5 (lower bound) projections so was not evaluated in this study.
RCP8.5	Status quo: carbon dioxide concentration continues upward trajectory at current rate.

Patterns of climate warming projected for Algonquin Park

Climate was projected for each of the selected RCP scenarios at each node of the 10 x 10 km grid system overlain on Algonquin Park (Figure 5). To illustrate the projected trends, 2 nodes on 2 lakes were selected as examples of change in average air temperature during the 21st century. Because the ensemble models match historical observed air temperatures, trends in average annual air temperature are also presented starting in 1950. Trends for the selected lakes, which were Grand and Canoe, are shown in Figure 6.

For each lake, climate ensemble models projected continued warming into mid-21st century for both RCP scenarios (Figure 6). The projections indicated that average annual air temperature today is warmer than that during the last decades of the 20th century—an observation consistent with earlier ice-out dates (Figure 2) and observed trends in average air temperature from nearby locations (Figure 3).

Climate projections diverge in mid-century. Under the RCP4.5 scenario, greenhouse gas emissions are reduced and CO₂ concentrations stabilize, effectively flattening the Keeling Curve. After this point, climate projections show average air temperature stabilizing at 6 to 7 °C (black trend lines; Figure 6). Under the RCP8.5 scenario, greenhouse gas emissions continue as today and CO₂ concentrations continue to increase. By 2100, average annual air temperatures at both lakes is projected to be 10 °C or higher (red trend lines; Figure 6), with the Grand Lake area slightly warmer because of its lower elevation.

The range in average annual air temperature of 6 to 7 °C (RCP4.5) and 10 °C (RCP8.5) represent the most likely range of possible outcomes in climate warming projections for the park. Any possibility of achieving a stable, lower average air temperature than in the RCP4.5 is now passing since that scenario requires action on greenhouse gases by 2020.

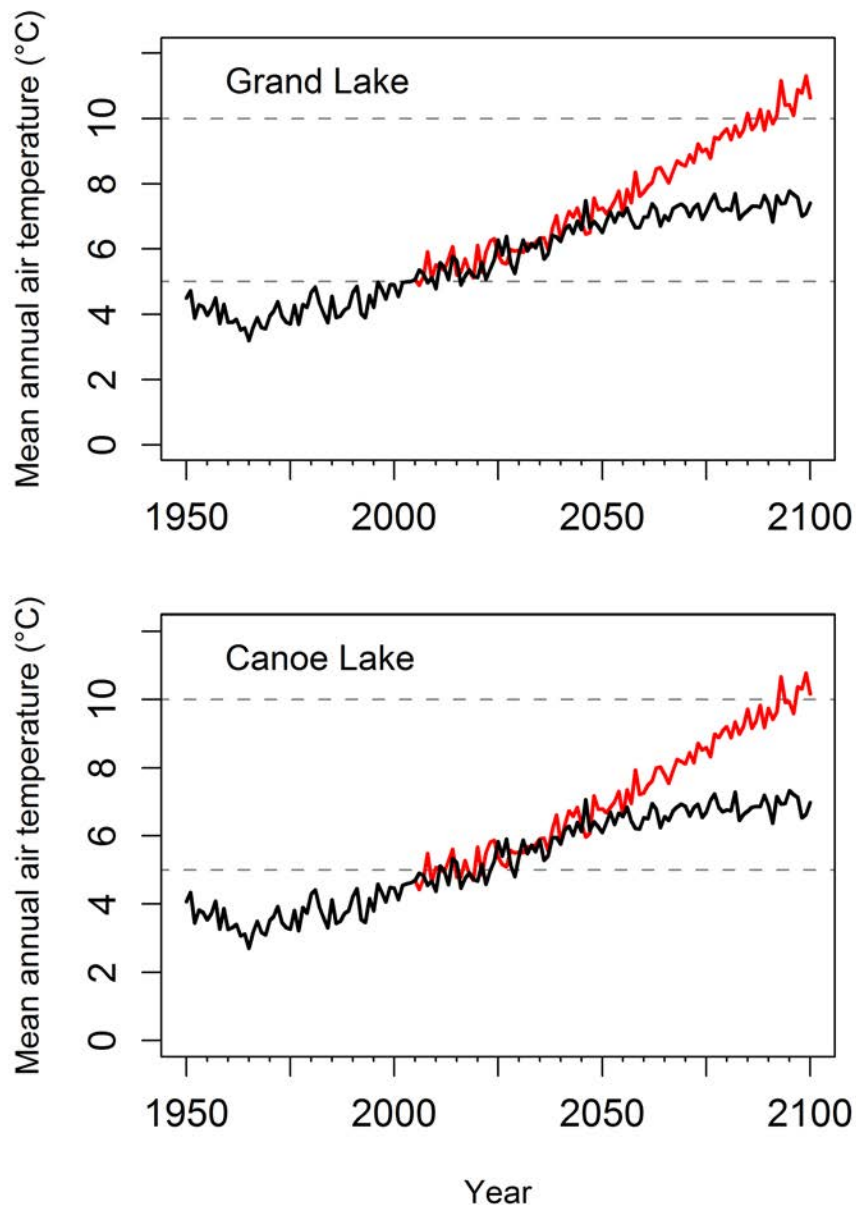


Figure 6. Two examples of average air temperature trends near lakes in Algonquin Provincial Park, Ontario, from the mid-20th to the end of the 21st century based on the ensemble model projections. In each panel, the red line is projected temperature based on a continuation of current carbon dioxide (CO₂) concentration levels (RCP8.5) and the black line is the projected trend given a global approach to reducing CO₂ concentrations by mid-21st century (RCP4.5). Dashed lines at 5 and 10 °C are shown for ease of interpretation.

The climate projections for all grid nodes (Figure 5) for each RCP scenario were averaged over several 30 year periods: 1981–2020, 2011–2040, 2041–2070, and 2071–2100. The average annual air temperature for each period was mapped with the 1981–2020 period serving as a reference condition against which to compare projections for the subsequent 30 year periods. The map for the 1981–2020 period matched observed conditions over the same period (Figure 4).

Projections for the period 2011–2040 are compared against the reference condition in Figure 7 (upper panel). For both RCP scenarios, the maps are similar indicating a 30 year average air temperature of 5 to 6°C. The projections are similar at this point because the assumption of reduction in CO₂ concentration in the RCP4.5 scenario has not come into full effect.

Projections for the period 2041–2070 are compared against the reference condition in Figure 8 (upper panel). For both RCP scenarios, average air temperature is projected to increase to 6.5 to 8°C. However, for the RCP8.5 scenario the increase is largely confined to the central areas of the park with higher elevation (lower right panel). To the east and south, the average air temperature is warmer ranging from 8 to 9°C.

Warming will occur in the park by 2011-2040 and 2041-2070 under both RCP scenarios. The central area of Algonquin Park, which represents higher elevation, will remain relatively cooler than the surrounding landscape of Ontario in each 30 year period but above current average air temperatures as shown for the temperature trends for Canoe and Grand Lakes (Figure 6).

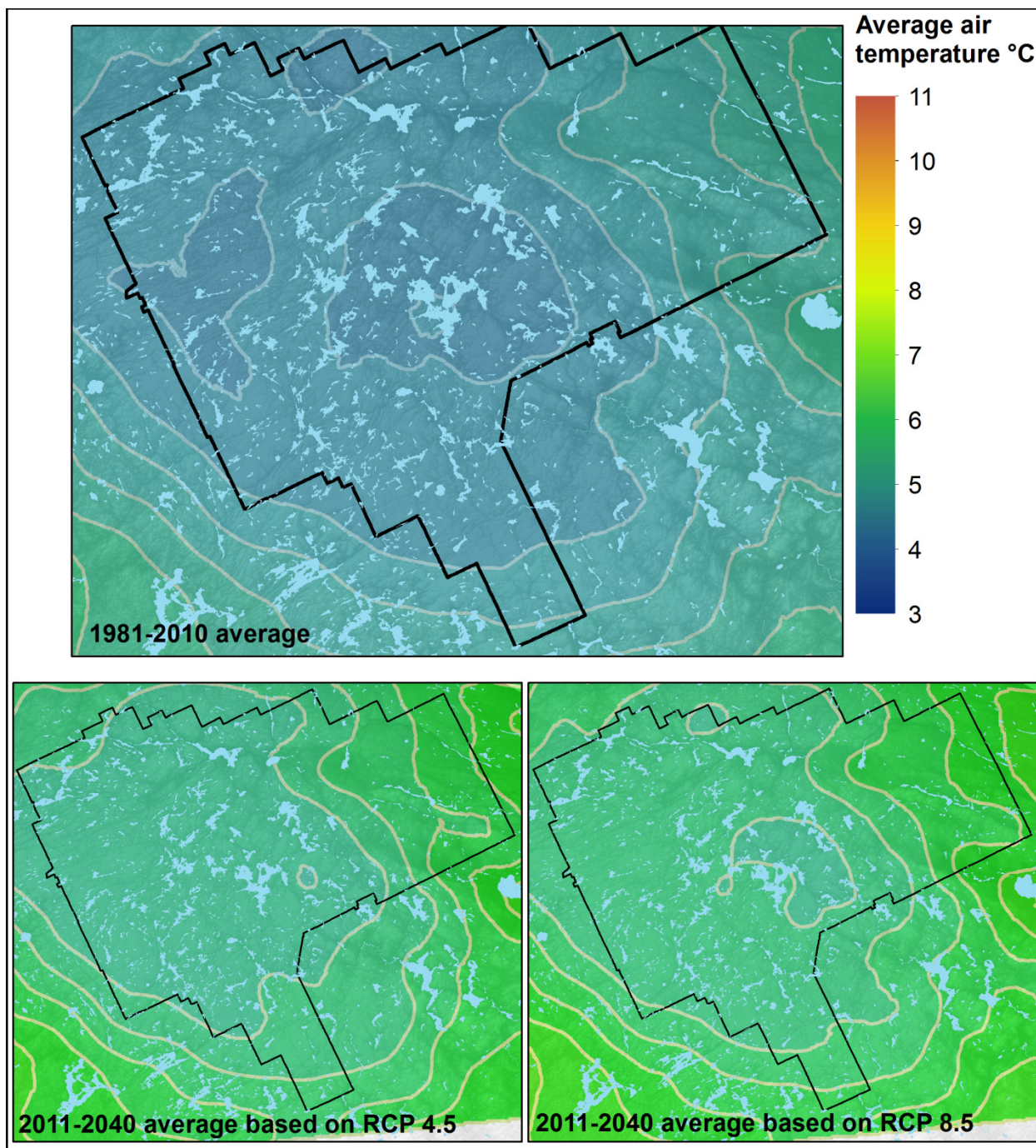


Figure 7. The average air temperature of Algonquin Provincial Park, Ontario, based on the ensemble climate projection model for the period 1981–2010 (top) and 2011–2040 based on the RCP4.5 climate projection (lower left) or the RCP8.5 climate projection (lower right). The average air temperature for the period 1981–2010 ranges from 3.5 to 5 °C, for the 2011–2040 period for the RCP4.5 scenario ranges from 5.5 to 7 °C, and for the 2011–2040 period for the RCP8.5 scenario ranges from 5.5 to 7 °C.

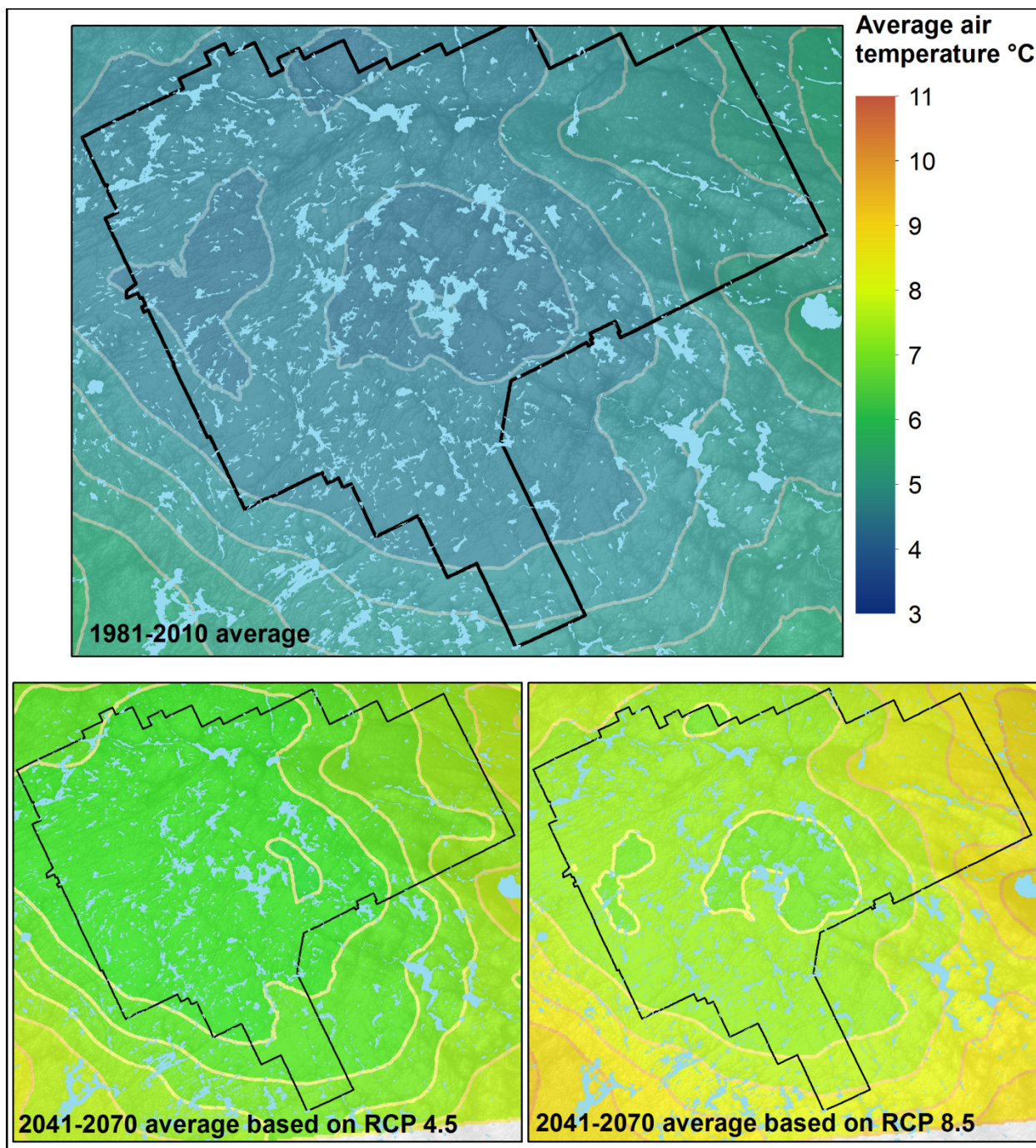


Figure 8. The average air temperature of Algonquin Provincial Park, Ontario, based on the ensemble climate projection model for the period 1981–2010 (top) and 2041–2070 based on the RCP4.5 climate projection (lower left) or the RCP8.5 climate projection (lower right). The average air temperature for the 1981–2010 period ranges from 3.5 to 5 °C, for the 2041–2070 period for the RCP4.5 scenario ranges from 6.5 to 8 °C, and for the 2011–2040 period for the RCP8.5 scenario ranges from 7 to 8.5 °C.

Projections for the period 2071–2100 are compared against the reference condition in Figure 9. By the end of the 21st century, differences in average air temperature between the RCP4.5 and RCP8.5 scenarios become more obvious. Under RCP4.5 (Figure 9, lower left panel), the pattern of average air temperature in the park remains in the range of 6.5 to 8 °C, similar to the 2041–2070 period (Figure 8). This stability results from the reductions in greenhouse gases envisioned in RCP4.5.

The lower right panel in Figure 9 shows the higher average air temperatures projected to occur with continued growth in greenhouse gases – a continuation of the trend now present in the Keeling Curve (Figure 1). The average air temperatures for this projection range from approximately 9.5°C on the Algonquin Park dome to 10-11°C in the lower elevation areas including the lower Petawawa River within eastern Algonquin Park.

To put the projected climate for Algonquin Park into context, projections were compared to the 1981–2010 climate normals for Ontario (Environment and Natural Resources Canada 2018). This allows projected average air temperature of the park to be presented relative to current climate at a location in the province.

Under the RCP4.5 scenario, the climate of the park in 2071–2100 will approximate the current average air temperature for Peterborough (6.9°C; Environment and Natural Resources Canada 2018). As this scenario results in a stable but warmer temperature by mid-century, it is possible that the park will reach these temperatures by mid-century.

Under RCP8.5 scenario, the climate of the park in 2071–2100 will approximate the average air temperature of the Leamington-Windsor region (9.6–9.9°C; Environment and Natural Resources Canada 2018). Based on the ensemble model projections, in the late 21st century Algonquin Park's climate will rest between a current average air temperature defined by the locations of Peterborough and Leamington-Windsor.

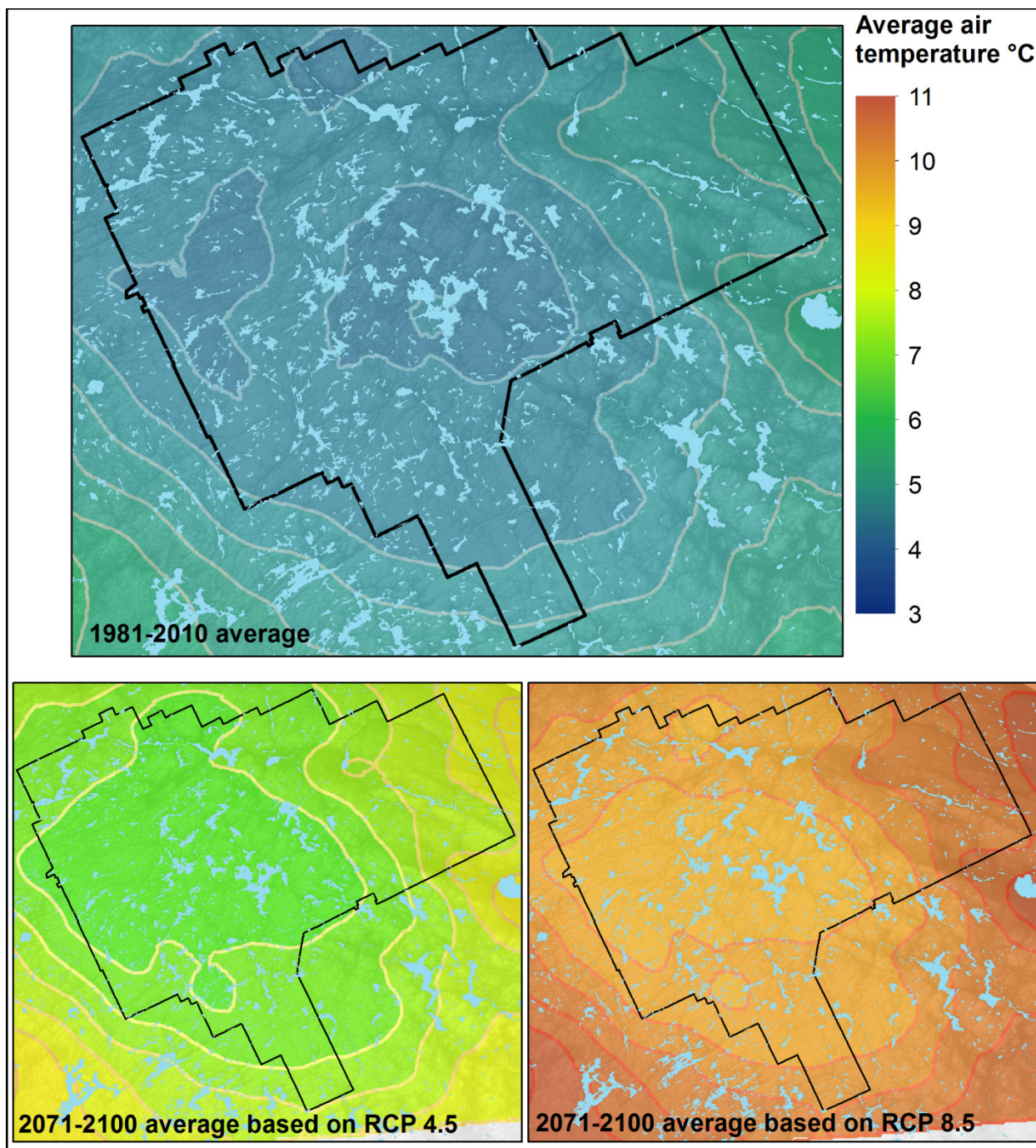


Figure 9. The average air temperature of Algonquin Provincial Park based on the ensemble climate projection model for the period 1981–2010 (top) and 2071–2100 based on the RCP4.5 climate projection (lower left) or the RCP8.5 climate projection (lower right). Average air temperature for the 1981–2010 period ranges from 4 to 5 °C, for the 2071–2100 period for the RCP4.5 scenario ranges from 7 to 8 °C, and for the 2071–2100 period for the RCP8.5 scenario ranges from 9 to 10 °C.

Climate warming and freshwater ecosystems

Many effects of climate warming have been observed or are projected to occur for fish and freshwater ecosystems. Because hundreds of lakes in Algonquin Park are home to cold water fish such as lake trout (*Salvelinus namaycush*), brook trout (*Salvelinus fontinalis*), cisco (*Coregonus artedii*) and lake whitefish (*Coregonus clupeaformis*) climate warming described in this report will affect these native species in several ways. These effects are not restricted to Algonquin Park but are expected to occur globally and are listed in Table 2. Observations over the past decades or climate model projections are the source of the information reported in Table 2.

Table 2. Summary of effects of climate change on freshwater ecosystems such as lakes and rivers (from Marcogliese 2001, Shuter et al. 2002, Lemieux et al. 2007, Sharma et al. 2007, Dove-Thompson et al. 2011, Minns et al. 2012, Lynch et al. 2016, Comte and Olden 2017, Myers et al. 2017).

Effect	Description
Increased water temperature	Lakes and rivers warm during the 21 st century from general atmospheric warming ranging from 3 to 7°C (depending on modelling scenario). The boundary between upper warm layer in lakes and deeper cold water layer will harden and reduce mixing for longer duration each year. Reduced winds will result in a shallower depth for the warm/cold water boundary.
Change in period of ice cover	Later ice formation on lakes in late fall/early winter and earlier ice-out dates now and continuing during this century. Overall declines in the duration of ice cover for lakes; open water will last 1 to 2 weeks longer by end of century.
Change in watershed environment	Increased evaporation during longer warm season and increased precipitation, depending on location, in central Canada. Main elements of environmental change are increasing temperature, increased precipitation in many areas, and increased flow in watersheds, perhaps on a seasonal basis.
Change in spawning time	Earlier spawning dates for spring spawning species. Migrations or movements to spawning areas are earlier for many species using rivers.

Effect	Description
Change in habitat	Increased nutrient flux to lakes; increased duration and volume of anoxia in lakes depending on productivity patterns; upper thermal limits of various species results in reduced occupancy due to warming waters. Loss of cold water habitat in lakes. Any increase in loss of water levels will lead to drying in wetlands.
Population increase or decrease	Declines in abundance for cisco, brook trout, and lake trout in inland lakes due to warming; less so for cool-water fish; warmwater species such as smallmouth bass (<i>Micropterus dolomieu</i>) may be more abundant — subject to density-dependent effects such as food limitation. For walleye (<i>Sander vitreum</i>), warmer summers lead to more rapid growth and earlier maturity — subject to available prey fish. Increased walleye recruitment occurs with increases in spring warming rate.
Change in species range	Northward expansion in range for species such as bass and sunfish as warm water species. A shift to dominance by warm water species in many areas. Increase in number of species due to warming because of range expansion for some species within and among watersheds. Southward shifts observed for small species, such as minnow species, due to loss of range from expanding predators.
Change in species biology	Potential for increase or decrease parasitism in prevalence based on species response to temperature increase; physiological limits exceeded by increasing water temperatures or declines in late season dissolved oxygen.
Shallow groundwater	Temperature of shallow groundwater approximates average annual air temperature. Warmer air temperature can lead to warming of shallow groundwater. Brook trout rely on shallow groundwater for spawning and rearing so temperature increases will affect the timing and potentially the suitability of this habitat for brook trout populations.

Conclusion

The climate of Algonquin Park is projected to be warmer through the remainder of the 21st century. Average annual air temperature will rise beyond what is observed today (2018) to levels that match areas in southern Ontario. If rising greenhouse gas emissions continue as indicated by the Keeling Curve (RCP8.5 scenario), by the end of the 21st century the average annual air temperature of Algonquin Park will match the current average temperature of the Leamington–Windsor area of Ontario. Under a scenario of reduced greenhouse gases by mid-century (RCP4.5), the park's temperature will match the current average annual air temperature of Peterborough. No reasonable climate scenario indicates that average annual air temperature of the park will remain as it is today. In resource planning, the range of climate projections among scenarios RCP4.5 to RCP8.5 (inclusive) should be considered as the probable outcomes for the future climate for Algonquin Park.

The projection for 2011–2040 points to warming that is underway now. The most optimistic scenario of reducing greenhouse gas emissions by 2020 (RCP 2.6) or soon afterwards appears unlikely at this time, leaving the RCP4.5 scenario as the most optimistic projection. The final average annual air temperature for Algonquin Park stemming from climate warming in the 21st century will result from decisions about emissions and carbon dioxide management at global scale.

The climate projections presented here indicate that changes in the park's ecosystems are imminent. Warming of aquatic ecosystems such as lakes and streams will occur during the 21st century. Since surface groundwater temperatures approximate average annual air temperature, groundwater temperatures will also be higher by the end of the century.

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Appendix 1. The climate models

Climate models used in this report were obtained from the Pacific Climate Impacts Consortium at the University of Victoria (http://tools.pacificclimate.org/dataportal/downscaled_gcms/map); accessed Jan 15, 2017).

The available climate models for eastern North America are listed below. Those underlined indicate models chosen for this ensemble analysis.

- MPI-ESM-LR – The Max-Planck-Institute Earth System Model – at base resolution
- CCSM4.0 – Community Climate System Model
- INMCM4.0 – Institute of Numerical Mathematics Climate Model
- CSIRO-Mk3.6.0 – Commonwealth Scientific and Industrial Research Organisation Climate System Model
- HadGEM2-CC – Hadley Global Environment Model 2 - Carbon Cycle
- GFDL-ESM2G – Geophysical Fluid Dynamics Laboratory – Earth System Model
- HadGEM2-ES – Hadley Global Environment Model 2 – Earth System
- MRI-CGCM3 – Meteorological Research Institute Coupled Global Climate Model
- ACCESS1-0 – Australian Community Climate and Earth System Simulator coupled model
- CNRM-CM5 – Centre National de Recherches Météorologiques Climat Model
- CanESM2 – Canadian Centre for Climate Modelling and Analysis Earth System Model
- MIROC5 – Center for Climate System Research Model for Interdisciplinary Research on Climate

Model selection was based on the following publications:

McKenney, D.W., M.F. Hutchinson, P. Papadopol, K. Lawrence, J. Pedlar, K. Campbell, E. Milewska, R. Hopkinson, D. Price and T. Owen. 2011. Customized spatial climate models for North America. *Bulletin of the American Meteorological Society* 92(12): 1611–1622.

Werner, A.T. 2011. BCSD downscaled transient climate projections for eight select GCMs over British Columbia, Canada. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC. 63 p.

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