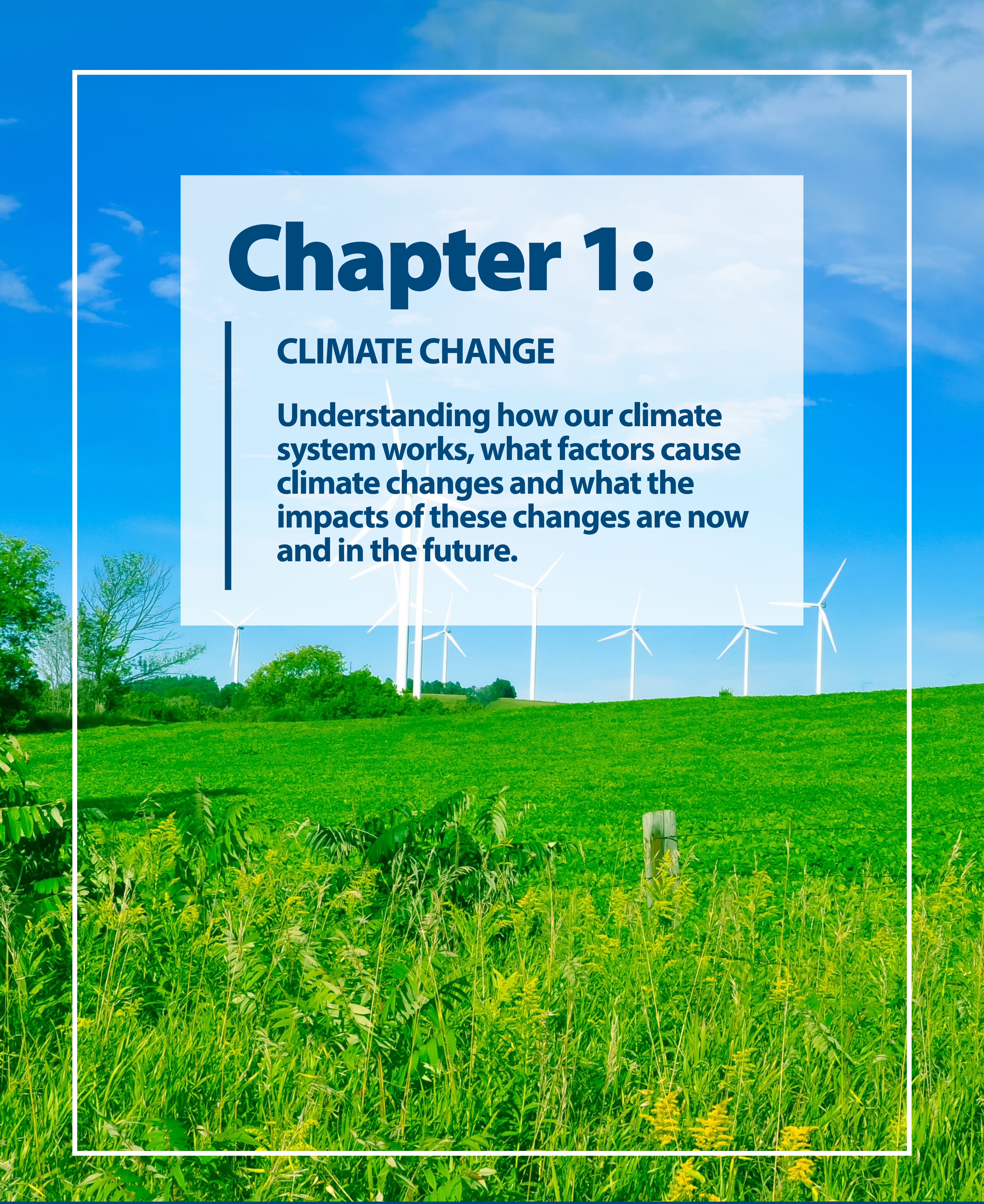


Chapter 1:

CLIMATE CHANGE

Understanding how our climate system works, what factors cause climate changes and what the impacts of these changes are now and in the future.

Key Messages

- **Current global warming cannot be explained by natural changes and are the result of increasing levels of atmospheric carbon dioxide and other green house gases (GHGs) from human activities.**
- **Human activities have caused the release of enough GHGs to increase the average global temperature by 1˚C. Most of this warming has occurred since 1950 through intensified demand for electricity, heat, manufacturing, building, transportation, food, trees, and land.**
- **Canada's current and projected average temperature is about twice the average rate of global warming.**
- **Lowering human GHG emissions is key to reducing future climate change.**
- **Scientists consider 1.5 degrees of global warming as a tipping point, after which the chances of extreme flooding, drought, wildfires, food shortages and other risks could increase dramatically. Although this degree of warming seems small, it influences whether or not the ecosystems we depend on for things like food, water, medicine, and livelihood, will remain viable.**

Acronyms

˚C	Degree(s) Celsius
CFCs	Chlorofluorocarbons
CCHVA	Climate change and health vulnerability assessment
CI	Confidence interval
CO2	Carbon dioxide
DRHD	Durham Region Health Department
GCM	Global climate model
GHGs	Greenhouse gases
GMST	Global mean surface temperature
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
NA-CORDEX	North American Coordinated Regional Climate Downscaling Experiment
PM	Particulate matter
RCMs	Regional climate models
RCPs	Representative Concentration Pathways
SCF	Snow cover fraction
SWEmax	Maximum seasonal snow water equivalent

Terms & Definitions

Aerosol

A suspension of airborne solid or liquid particles with a typical size between a few nanometres and 10 µm that reside in the atmosphere for at least several hours. This term includes both the particles and the suspending gas. They may be of either natural or anthropogenic origin although the bulk of aerosols are of natural origin.

Aerosols may influence climate in several ways: [1]

- Interactions that scatter and/or absorb radiation
- Interactions with cloud microphysics and other cloud properties
- Upon deposition on snow- or ice-covered surfaces thereby altering their albedo and contributing to climate feedback processes.

Atmospheric aerosols, whether natural or anthropogenic, are generated through two different pathways: [1]

1. Emissions of primary particulate matter (PM)
2. Formation of secondary PM from gaseous precursors

Albedo

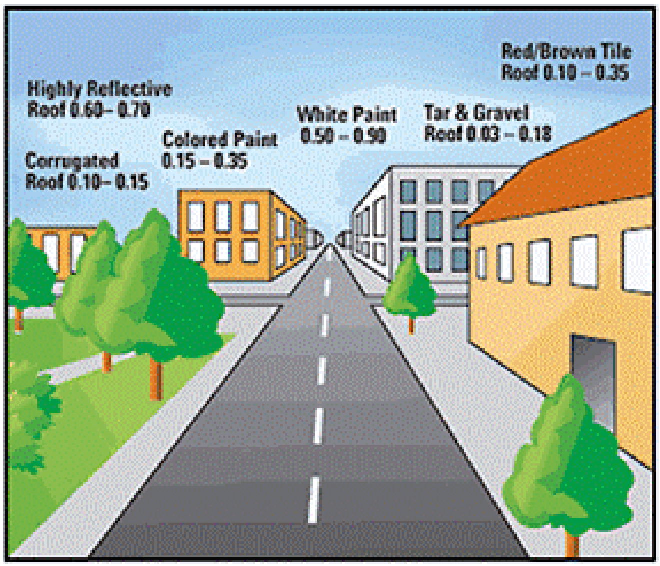


Image source: Wikimedia Commons. (September 26, 2015). Roof Albedo [Online]. Available at: https://upload.wikimedia.org/wikipedia/commons/6/6a/Roof-albedo.gif

This is the amount of sunlight, or solar radiation reflected by a surface and is usually expressed as a percentage or a decimal value, with one being a perfect reflector and zero absorbing all incoming light. White objects, like a snow-covered hill, have a high albedo. [1] Dark objects, like pavement, have a low albedo. The earth's planetary albedo changes mainly through varying cloudiness, snow, ice, leaf area, and land cover changes.

Anthropogenic

Human caused or originating from human activity.

Atmosphere

The gaseous envelope surrounding Earth. The atmosphere is divided into five layers. The troposphere is the first layer which contacts Earth's surface and contains half of Earth's atmosphere. This layer is then followed by the stratosphere, mesosphere, and thermosphere. The exosphere is the outer limit of the atmosphere.

The dry atmosphere is made mostly of nitrogen (78.1%) and oxygen (20.9%) together with several trace gasses, including the GHGs. In addition, the atmosphere also contains water vapour (about 1%), clouds and aerosols.

Baseline

A level change can be measured against, also called a reference value.

Biosphere

Refers to all the parts of Earth where life exists.

Carbon Cycle

The flow of carbon in its various forms through the atmosphere, hydrosphere, terrestrial and marine biosphere, and lithosphere.

Carbon Sinks

These are areas or environments that naturally extract carbon dioxide from the atmosphere and absorb more carbon than they release. They cover about 30 per cent of Earth's land surface and as much as 45 per cent of the carbon stored on land is tied up in these sinks.

Oceans are the main natural carbon sinks, absorbing approximately 50 per cent of the carbon emitted into the atmosphere. Forests are also significant carbon sinks, absorbing approximately twice as much carbon as they release each year.

Climate

Climate refers to the average or expected weather and related atmospheric, land and ocean conditions for a particular location over a long period of time. [2, 3] The simplest way to describe climate is to look at average conditions like temperature and precipitation over time. Other useful factors to describe climate include the type and timing of precipitation, amount of sunshine, average windspeeds and directions, number of days above freezing and/or weather extremes. [4]

Climate Change

Refers to a change in the state of the climate that can be identified by changes in statistical measures like the average (mean) and/or variability in weather and atmospheric conditions that persists for an extended period, typically decades or longer. [2, 4, 3]

Climate Change Scenario

This is a description of a possible future climate based on how Earth's climate operates, future world population levels, economic activity, and greenhouse gas emissions. [4] There are currently four main climate scenarios called Representative Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5.

Climate Drivers

These are natural or artificial factors that have a strong enough impact on Earth's climate to force it toward warmer or cooler temperatures, causing climate to change. Examples of climate drivers include GHGs, volcanic eruptions and changes in solar output from the Sun.

Climate drivers are sometimes referred to as climate forcing agents.

Climate Feedback

An interaction in which a disturbance in one climate quantity causes a change in a second and the change in the second ultimately leads to an additional change in the first. [1] The initial disturbance can be either externally forced or arise as part of internal variability.

Feedback can be either negative or positive:

- Positive feedback: is one in which the initial disturbance in enhanced or magnified.
- Negative feedback: Is one in which the initial disturbance is weakened by the changes it causes.

Climate Model

A mathematical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. [1]

Climate Projection

The term projection is often used in two ways in climate change literature.

1. A projection is a description of a possible future and the pathway which led to it.
2. Model-generated estimates of future climates. [2]

Cryosphere

This refers to all the frozen water on Earth in places where it is cold enough for water to freeze. This includes snow, sea and freshwater ice, land ice, permafrost, and seasonally frozen ground.

Deforestation

Human-induced or anthropogenic conversion of forested land to non-forested land. This can be permanent or temporary.

Downscaling

The process of generating climate projections for a finer spatial resolution or smaller geographic area from a Global Climate Model (GCM) with coarse spatial resolution. [4] There are two types of downscaling methods, statistical and dynamical.

Dynamical Downscaling

A downscaling approach which adds value to the downscaling estimates by incorporating additional physics of Earth's atmosphere (e.g., wind). [4] This approach involves running a very high-resolution statistical model once over the area or region of interest driven by global climate model boundary conditions.

Generally, you can either have 'many model runs at coarse resolution' or 'few model runs at high resolution'. [4, 5] The high-resolution models are called Regional Climate Models (RCM).

Ecozone

A very large area of land and water characterized by a distinctive bedrock zone that differs in origin and chemical makeup from the bedrock zone that is beside it. The characteristics of this bedrock zone in addition to long-term continental climatic patterns, has a major influence on the ecosystem processes occurring there. This area is generally resilient to short-term and medium-term change and responds to global or continental cycles and processes operating over thousands to millions of years. [6]

Ecoregion

A unique area of land and water nested within an ecozone that is defined by a characteristic range and pattern in climatic variables, including, temperature, precipitation, and humidity. The climate within an ecoregion has a profound influence on the vegetation types, ecosystem processes, and associated organisms (e.g., plants, animals) that live there. [6]

Extreme Weather Event

An event that is rare at a particular place and time of year.

Forestry

The management of forested land together with associated waters and wasteland primarily for harvesting timber.

Fossil Fuels

Naturally occurring substances like oil, coal, and natural gas that contain carbon and hydrogen which can be burned for energy. Fossil fuels are formed over millions of years from the remains of ancient plants and animals.

Global Climate Model (GCM)

GCMs provide projected changes in climate over Earth's surface. [5] These models divide the surface into 3D grid cells and use mathematical equations to show how energy and matter interact among the ocean, land, and atmosphere. [4] GCMs typically have a large/course spatial resolution of typically 200 km by 200 km. The smaller the grid cell, the more detailed the information will be. For example, a 200 km grid would produce less detailed information than a 100 km grid.

Global Mean Surface Temperature (GMST)

GMST is estimated as the average global temperature from measurements of sea surface temperatures and near-surface air temperatures above the land. It is currently the best-known indicator for tracking climate change. [7]

Greenhouse Gases (GHGs)

These are heat trapping gases which are an important part of the atmosphere's makeup and help warm the planet through the greenhouse effect. Although these gases are generated from natural processes, they can be influenced by human activities as well.

There are five main types of GHGs:

- Carbon dioxide
- Methane
- Nitrous oxide
- Water vapour
- Halocarbons

Halocarbons are the only GHG that are not generated from natural processes and instead are exclusively made and released by human activities and products.

Halocarbons

A term for the group of partially halogenated organic species, which includes the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride and methyl bromide. Many halocarbons have large Global Warming Potentials. [1] The chlorine and bromine-containing halocarbons are also involved in the depletion of the ozone layer.

Hot Days

The total number of days each year where the daily maximum temperature exceeds 30˚C.

Hydrosphere

The total amount of water on a planet and includes water on the surface, underground and in the air.

The Intergovernmental Panel On Climate Change (IPCC)

The IPCC was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program. The objective of the IPCC is to provide governments at all levels with scientific information they can use to develop climate policies. Reports generated by the IPCC are also used as key inputs into international climate change negotiations.

The IPCC is made of an organization of governments that are members of the United Nations or WMO and thousands of people from all over the world contribute to their work. The IPCC is divided into three Working Groups and a Task Force which work on the following:

- Working Group I: The Physical Science Basis of Climate Change
- Working Group II: Climate Change Impacts, Adaptation and Vulnerability
- Working Group III: Mitigation of Climate Change
- Task force: National Greenhouse Gas Inventories

A major product of these groups is their assessment reports. These reports depend on experts in the field who volunteer their time as IPCC authors to assess the thousands of scientific papers published each year and provide a comprehensive summary of what is known about the drivers of climate change, its impacts, and future risks, how adaptation and migration can reduce those risks. Through these assessments, the IPCC identifies the strength of scientific agreement in different areas and indicates where further research is needed. It is important to note that the IPCC does not conduct its own research.

Industrial Era

This period began around the mid-18th century and continues today. Its defining feature is the rapid increase in industrial activity powered by the combustion of fossil fuels.

Infrared Radiation

A type of radiant energy, with longer wavelengths than the visible light humans can see but shorter than radio waves. Infrared radiation, although invisible, can be felt as a sensation of warmth on the skin. Infrared energy is felt as heat because it interacts with molecules causing them to become excited and move faster which increases the internal temperature of the object absorbing the energy.

Humans emit most of their body heat through radiant heat into the environment in the infrared range. Additionally, approximately half of the sun's energy received by Earth is in the form of infrared radiation.

Infrared radiation can be used in any ways, examples include heating, cooking, night vision technologies and imaging.

Lapse-Rate Feedback

The lapse rate is how much the temperature in Earth's atmosphere decreases as altitude increases. [7]

Lower Atmosphere

The lower atmosphere begins at Earth's surface and extends six to 20 km high, depending on the distance from the equator. This is the part of the atmosphere where almost all weather occurs.

Maximum Ice Cover

This refers to the extent of ice coverage on a body of water, typically measured during the coldest period of the year. It represents the maximum area covered by ice such as frozen lakes, rivers, or polar seas. [7]

Maximum Seasonal Snow Water Equivalent (SWEMAX)

SWEmax reflects the amount of water stored by snow accumulated during the fall and winter seasons and is available for spring melt. [7]

Negative Radiative Forcing

This refers to an effect of a climate driver on our climate. Negative radiative forcing occurs when more energy leaves the climate system than what enters it, leading to a cooler climate.

Perennial Sea Ice

This refers to multi-year ice which survives the summer melt and is important for protecting the Arctic Ocean from the sun and keeping the region cool. [7]

Permafrost

The thick layer of soil below the surface that remains frozen throughout the year. It underlies about 40 per cent of Canada's landmass and its characteristics are influenced by soil properties, snow cover and ground temperatures. [7]

Planck Feedback

The higher the temperature of any object, like Earth, the more energy it radiates or releases, creating a cooling effect. [7] This is a negative climate feedback process that limits warming on a global scale.

Positive Radiative Forcing

Refers to an effect of a climate driver on our climate. Positive radiative forcing occurs when more energy is being kept within the climate system than what is leaving it, leading to a warmer climate.

Precursors

Atmospheric compounds that are not GHGs or aerosols but influence GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Radiative Forcing

Radiative forcing is used to measure how much effect climate drivers have on Earth's energy balance. [8, 4] It is defined as the net change in the energy balance of Earth's system due to an external disruption, measured in watts per square meter (Wm2).

Regional Climate Model (RCM)

A dynamically downscaled climate model which originated from a GCM and has been reanalyzed to produce climate projections on a much finer scale or smaller geographic area. [5] Compared to GCMs, RCMs have a much smaller spatial resolution, a common scale is a 25 km x 25 km grid.

Representative Concentration Pathways (RCPs)

RCPs provide time-dependent estimates of GHG concentrations from a starting period until 2100 based on assumptions about economic activity, energy sources, population growth, and other socio-economic factors. [9] Each RCP plots a different emissions trajectory or pathway and cumulative emission concentration in 2100 based on relevant available data.

Since RCPs are standardized, they allow different groups of scientists to estimate future climate projections in a consistent way. This allows for comparisons to be made. They provide a basis for assessing the risk of crossing preidentified emissions thresholds in terms of both physical change in the environment and impacts on biological, ecological, and human systems. There are currently four main RCPs used for climate change assessment: RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5.

RCP 8.5

The highest emission scenario, where rising radiative forcing pathway leading to 8.5 W/m2 in 2100 and GHG emissions are up to seven times higher than preindustrial levels. [9]

Snow Cover Fraction (SCF)

SCF reflects the proportion of days within each month that snow is present on the ground. It is affected by the timing of snow onset and snowmelt. [7]

Snow/Ice Albedo Feedback

Snow and ice reflects substantial solar energy back to space. Warming melts snow and ice, causing the now darker surface to absorb more solar radiation and heat further. This feedback only applies to regions where ice and snow are found.

Solar Radiation

Energy radiated from the sun in the form of electromagnetic waves, including visible and ultraviolet light and infrared radiation. Usually referred to as sunlight.

Urbanization

The increase in the proportion of a population living in urban areas; the process by which many people become permanently concentrated in relatively small areas, forming cities.

Chapter 1

CLIMATE CHANGE

Understanding how our climate system works, what causes climate changes and the impacts of these changes now and in the future.

1.1 | Background

Although Earth has experienced many ice ages and warm periods, current warming trends are the result of GHG emissions from human activities.

Our global climate system is made of a combination of many interconnected parts, including the lower atmosphere, hydrosphere, cryosphere, biosphere, and the land surface. Changes in one of these parts can have far reaching impacts on other climate components through many complex pathways and relationships.

Average global temperatures result from a balance between energy arriving from the sun and leaving Earth through infrared (heat) radiation. In a stable climate, global average temperatures remain relatively constant because of the balance between incoming and outgoing energy. However, climate drivers can disturb this balance and force global temperatures to rise or fall.

1.1.1 Climate Drivers

Table 1.1 | Pathways through which climate drivers influence climate and the impact of increases in these pathways on overall radiative forcing.

Pathways	Impact on radiative forcing
Increasing the amount of incoming solar radiation.	Positive (warmer climate).
Increasing the amount of incoming solar radiation that is reflected from the Earth's surface and atmosphere.	Negative (cooler climate)
Increasing the amount of infrared radiation (energy) leaving the Earth.	Negative (cooler climate)

Climate drivers are naturally occurring or human influenced factors or events that have a strong enough impact on Earth's climate to force it toward warmer or cooler temperatures.

Climate drivers are natural or artificial factors that can impact Earth's climate to force it toward warmer or cooler temperatures, causing climate to change. Examples include GHGs, volcanic eruptions and changes in solar output from the sun. These drivers influence climate through creating changes in the amount of energy either entering or leaving Earth's climate system. The effect a climate driver has on Earth's energy balance is measured by radiative forcing. Positive radiative forcing occurs when more energy is being kept within the climate system than what is leaving it, leading to a warmer climate. Negative radiative forcing occurs when more energy leaves the climate system than what enters it, leading to a cooler climate.

Generally, climate drivers affect Earth's energy balance through three main pathways. **Table 1.1**. lists climate driver pathways and their impact (positive or negative) on radiative forces.

Natural events and changes have led to many ice ages and warm periods throughout Earth's history. These include changes in Earth's orbit around the sun, variation in the amount of energy released by the sun, volcanic eruptions which produce dust and gas which shade the planet from the sun's rays, and differences in the amount of water vapour in the atmosphere. The historical warm periods between ice ages can be explained by these natural changes.

However, current warming trends cannot be explained by these natural changes and are instead explained through anthropogenic or human activities which have impacted climate by causing changes in the make-up of the atmosphere and land surfaces.

1.1.2 Greenhouse Effect

Only two-thirds of the energy from the sun that reaches Earth is used to warm the planet, the remaining warming occurs through the greenhouse effect. [10]

The greenhouse effect refers to the phenomenon of heat being trapped close to Earth's surface by greenhouse gases (GHGs). This can be thought of like wrapping a blanket around the earth, keeping the temperatures warmer than what they would be without it. Without the greenhouse effect, earth's surface would be approximately 33˚C cooler (around -16˚C) instead of the much more comfortable +15˚C.

1.1.2.1 Greenhouse Gases

GHGs are heat-trapping gases which play an important role in warming Earth's through the greenhouse effect.

There are four-main naturally occurring GHGs: carbon dioxide, methane, nitrous oxide, and water vapour. Although these GHGs are generated by natural processes, they can also be created and influenced by human activities. In addition to the four naturally occurring GHGs, there is a fifth group of GHGs called halocarbons that play a role in the greenhouse effect. These compounds are human made and do not exist naturally in the environment or atmosphere.

CARBON DIOXIDE

Of all the GHGs, carbon dioxide plays the greatest role in stabilizing and warming Earth's atmosphere. Without it, the greenhouse effect could not happen.

Carbon dioxide is an important part of Earth's carbon cycle which involves the movement of carbon through the atmosphere, ocean, land and living things. Carbon dioxide enters the atmosphere from many natural sources through plant and animal respiration (breathing). It is removed from the atmosphere by plants through photosynthesis, as well as uptake by the ocean.

METHANE

Like carbon dioxide, methane is part of Earth's carbon cycle.

Methane mostly comes from the breakdown of organic matter by microorganisms, like bacteria. The largest natural source of methane comes from wetlands.

NITROUS OXIDE

Nitrous oxide is part of Earth's nitrogen cycle which is essential for life on earth.

The nitrogen cycle passes nitrogen from the atmosphere to the soil, to living organisms, and then back to the atmosphere. Although nitrogen exists in high amounts in the atmosphere, plants, animals, and other organisms can't access it in that form. Instead, nitrogen fixing organisms first need to take the nitrogen gas from the atmosphere and turn it into forms of nitrogen that other organisms can use for essential biological processes. For example, nitrogen is a key component of genetic molecules like DNA and RNA, as well as amino acids which are used to build proteins. Nitrogen fixers are especially important for agriculture since it couldn't occur without them.

WATER VAPOUR

Water vapour is the most important GHG and the only one not impacted directly by human activities.

The amount of water vapour in the atmosphere is dependent on atmospheric temperature since there is a physical limit on how much water vapour the air can hold at any one temperature. Warm air can hold more moisture than cool air.

Increased temperatures due to natural or anthropogenic climate warming increases the amount of water evaporation from Earth's surface which increases the concentration of water in the atmosphere. This increase amplifies the warming caused by other GHGs, forming a positive feedback loop. [11]

HALOCARBONS

Halocarbons are human made chemicals that are mainly responsible for the depletion of the ozone layer and are powerful GHGs which can stay in the atmosphere for decades. [12]

Halocarbons are a group of human-made chemicals that are made up of carbon in addition to one or more halogens like fluorine, chlorine, or bromine gas. Over the past 100 years, these chemicals have been used in a wide range of applications and products. Examples include strong and non-reactive plastics, solvents, fire-fighting agents, and refrigerants.

Halocarbons are mostly responsible for the depletion of the ozone layer. [12] They are also powerful GHGs and several of them can stay in the atmosphere for decades. There are also a few of these gases that, volume-for-volume, are thousands of times more efficient at warming Earth than carbon dioxide.

1.1.2.2 Feedback Processes

Different feedback processes within the climate system determine how the climate responds to radiative forcing from GHGs. [8]

There are five well-known climate feedback processes which play important roles in climate responses to radiative forcing. These are:

1. Lapse-rate feedback
2. Snow/ice albedo feedback
3. Planck feedback
4. Cloud feedback
5. Water vapour feedback

Although these feedbacks operate globally, their strength and direction vary from one region to another and most are stronger in regions over high-northern latitudes, like in the Canadian Arctic (**Figure 1.1**). [8]

Feedback Mechanisms

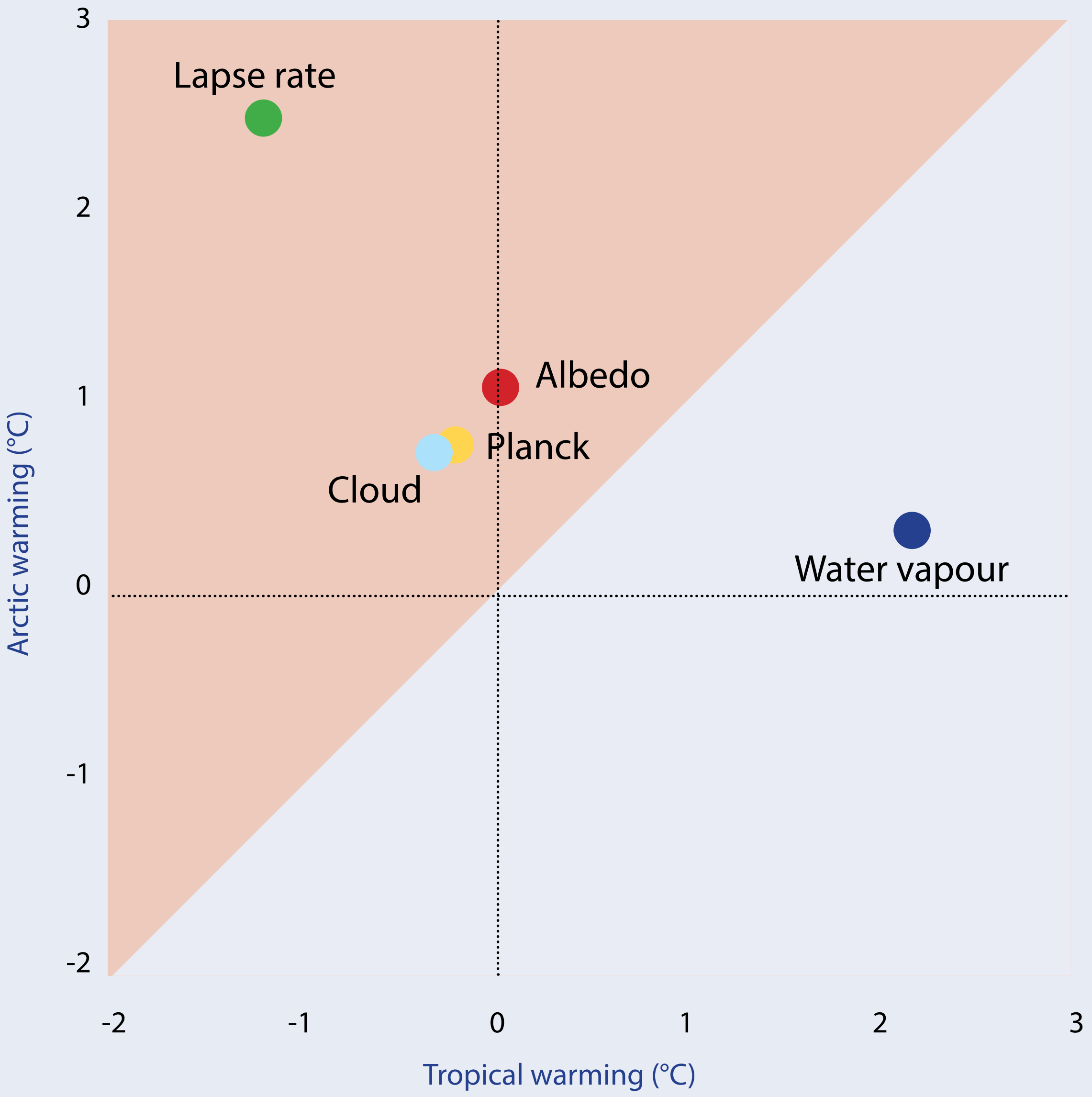


Figure 1.1 | Contributions to warming of various feedback mechanisms for the Arctic and the Tropics.

Feedbacks in the red-shaded area of the figure contribute to enhanced warming in the Arctic relative to the Tropics, whereas feedback in the blue-shaded area contribute to enhance warming in the Tropics relative to the Arctic.

Figure source: Adapted from Stuecker et al. (2018). [64]

Lapse-Rate Feedback

The lapse-rate is how much the temperature in Earth's atmosphere decreases as altitude increases.

Differences in the lapse-rate in different parts of the world affect the response to increasing GHG amounts. For example, in the Arctic, warming due to GHG forcing is largest near the surface and in the Tropics, the opposite is true where warming due to GHG forcing is greatest higher up in the atmosphere which allows radiant heat from Earth to escape to space more easily and hence cool the climate.

Snow/Ice Albedo Feedback

Snow and ice reflect substantial solar energy back to space.

Warming melts snow and ice, causing the now darker surface to absorb more solar radiation and heat further. This feedback only applies to regions where ice and snow are found. Consequently, its contribution to warming is substantial in the Arctic and negligible in the Tropics.

Planck Feedback

The higher the temperature of any object, like the Earth, the more energy it radiates or releases, creating a cooling effect.

This is negative feedback that limits warming on a global scale. However, this cooling effect is weaker in the Arctic than in the Tropics and, therefore, allows for a relatively larger warming response at high latitudes.

Cloud Feedback

In climate models GHG forcing generally results in more cloudiness in high latitudes and less in low latitudes.

In the Arctic, the increase in clouds enhances warming by trapping heat near the surface.

Water Vapour Feedback

Like carbon dioxide, water vapour is a GHG and as the atmosphere warms it can hold more water vapour, increasing warming.

The Arctic atmosphere is very dry and for this reason, the contribution of the water vapour feedback to warming is small compared to the Tropics where the atmosphere is moist.

1.2 | Understanding the Causes of Climate Change

There is overwhelming evidence that human activities have caused Earth to warm since the beginning of the Industrial Era.

Climate change is defined as "any significant change in the measure of climate lasting for an extended period of time". [1] It can result from natural variation over time, such as changes in the amount of energy received by the sun, or due to direct or indirect human activity. [1]

1.2.1 Human Influence

There is scientific consensus that atmospheric GHGs from human activities are the main cause of climate change.

Based on extensive evidence from many sources and scientific studies, the Intergovernmental Panel on Climate Change (IPCC) concluded in their Sixth Assessment Report that:

Scientists know that human activities are the primary reason for our warming climate because:

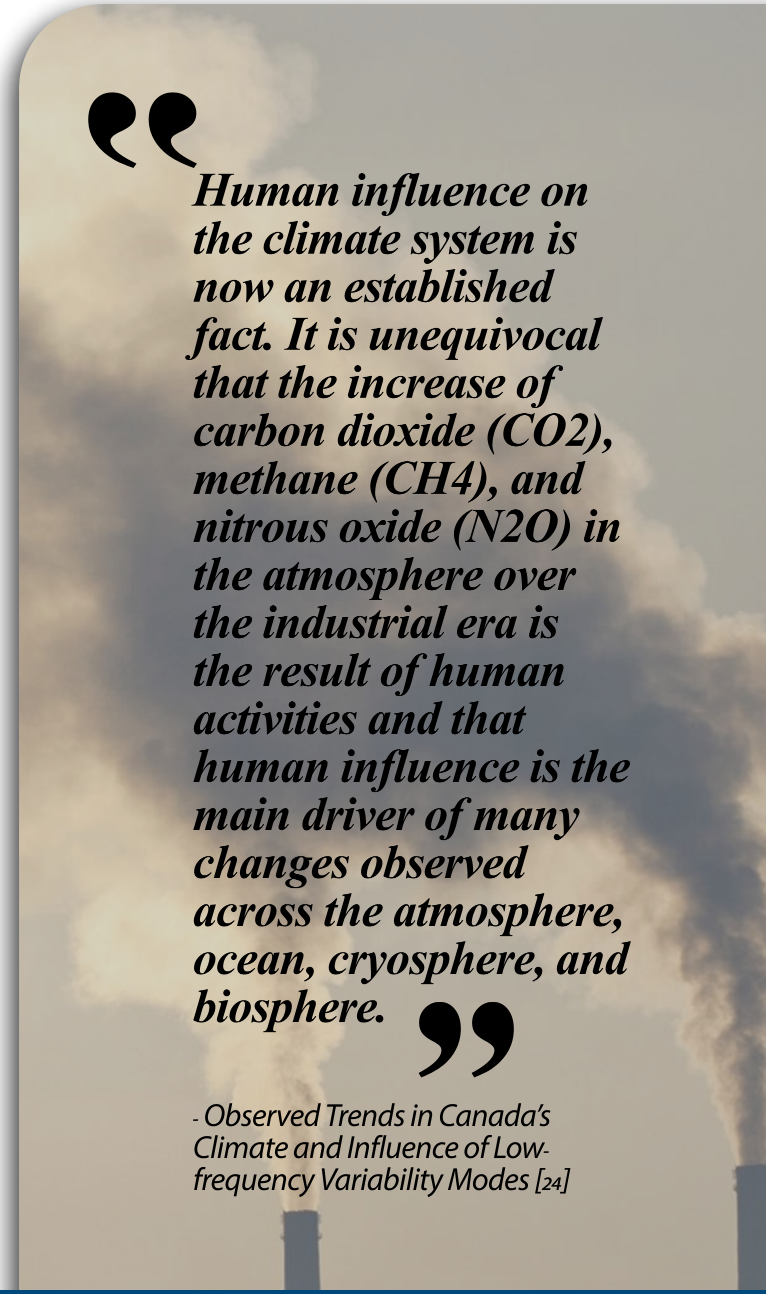
- They understand the role heat-trapping GHGs, like carbon dioxide, play in the atmosphere.
- They know why those gases are increasing in our atmosphere.
- They have ruled out other possible explanations, including natural events, variation, and changes.

Although there is scientific consensus that human activities are mainly responsible for our changing climate, understanding the extent of this impact requires multiple sources of data and evidence.

1.2.1.1 Changes in GHGs Over the Industrial Era

Rapid warming experienced across the globe can only be explained by human induced increasing levels of carbon dioxide and other GHGs in the atmosphere.

The level of carbon dioxide in the atmosphere today is higher than at any other time in the past one-million years and has been rapidly increasing since the start of the Industrial Revolution in 1750.



> *"Human influence on the climate system is now an established fact. It is unequivocal that the increase of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) in the atmosphere over the industrial era is the result of human activities and that human influence is the main driver of many changes observed across the atmosphere, ocean, cryosphere, and biosphere."*
>
> *- Observed Trends in Canada's Climate and Influence of Low-frequency Variability Modes [24]*

The Industrial Era is widely recognized as the period where human activity substantially began altering the chemical composition of the atmosphere by increasing the concentration of GHGs. [13] Over this period, humans have been adding emissions to the atmosphere at a rate faster than natural processes can remove them. This is significant, as any annual imbalance, no matter how small, where emissions exceed removals, can lead to a buildup of GHGs in the atmosphere over time. The level of imbalance between emissions and removals varies across the different GHGs. For example, almost all the annual methane emissions are removed from the atmosphere, leaving a small annual excess. [14] In contrast, only half of the carbon dioxide emissions are removed each year. [14]

Figure 1.2 below illustrates the change in global atmospheric GHG concentrations since the start of the Industrial Era in the 1750s. [8] During this time, carbon dioxide has increased by 40 per cent, methane by 150 per cent, and nitrous oxide by 20 per cent. [10] Although all three GHGs have increased substantially over this period, carbon dioxide is responsible for the greatest contribution of global warming. [15]

ATMOSPHERIC GHG CONCENTRATIONS

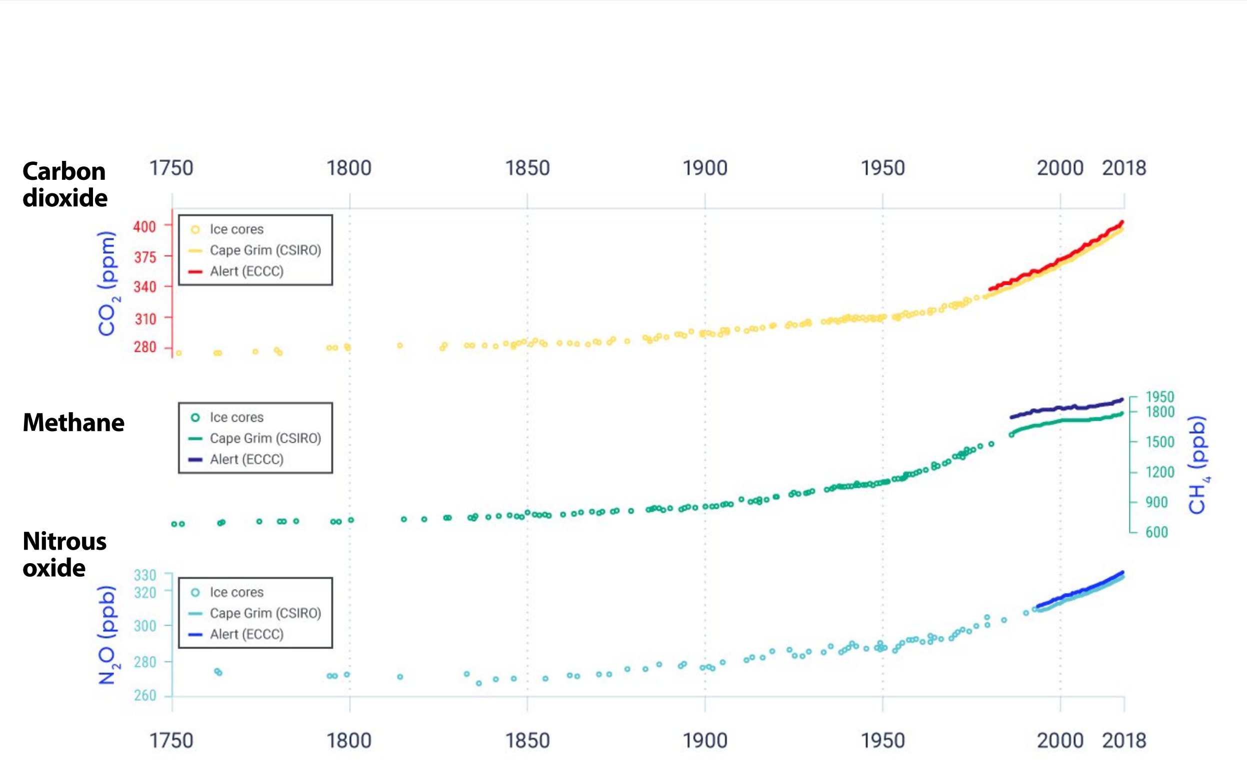


Figure 1.2 | Global mean atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from 1750 to present.

These graphs are based on data from ice cores and direct atmospheric measurements from the Cape Grim Observatory (Australia) and the Canadian greenhouse gas monitoring site at Alert, Nunavut.

Figure Source: Adapted from Canada's Changing Climate Report and Hartmann et al. 2013. [8, 10]

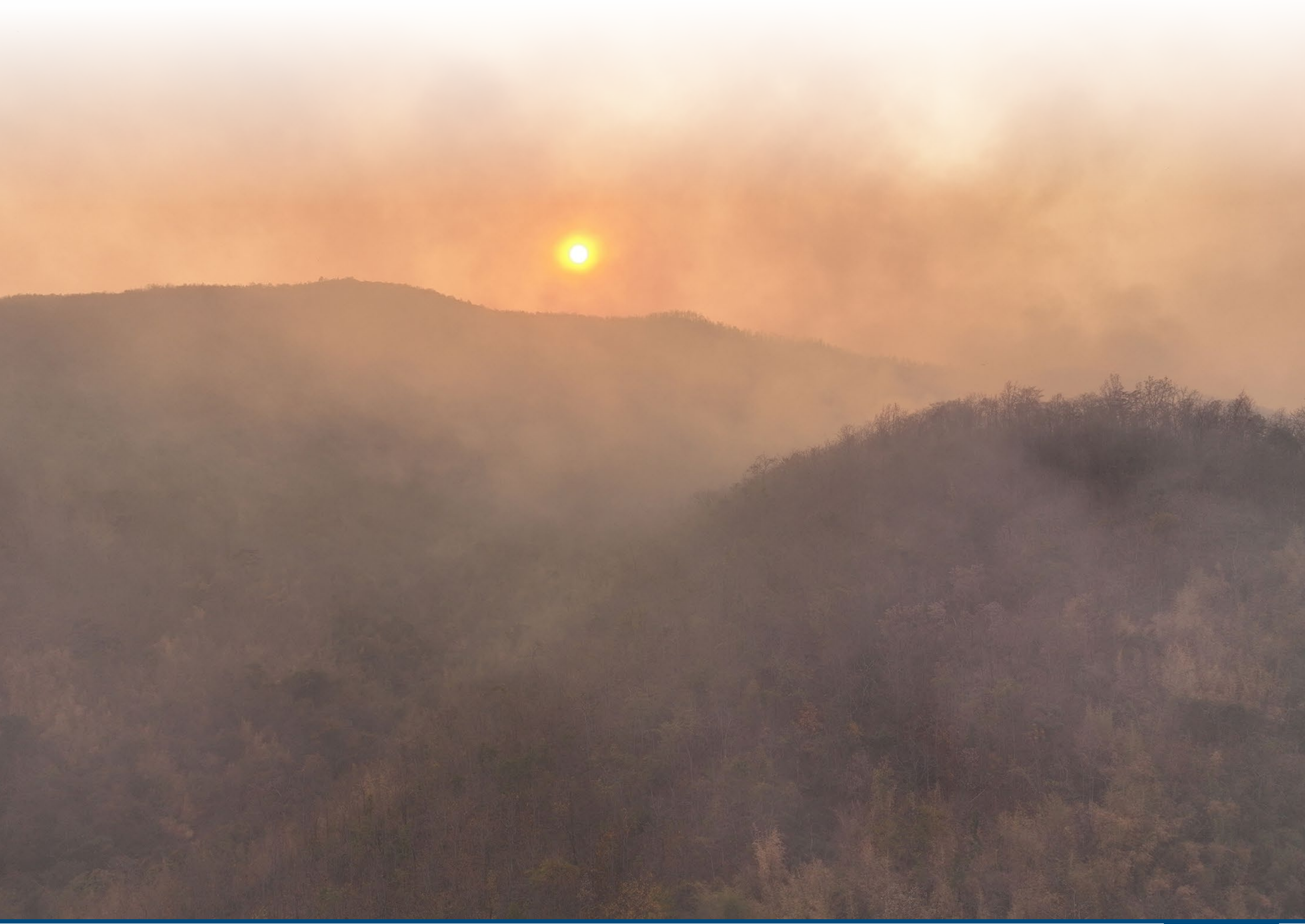
1.2.1.2 Recent Changes in GHG Levels

Over the past 270 years, human activities have caused the release of enough GHGs to increase the average global temperature by 1˚C, but most of this warming has occurred since the 1950s. [9]

To understand what has caused the accelerated warming over the past 70 years, the IPCC recently carried out an assessment to identify how much of this observed warming can be attributed to different climate drivers. [16] The five drivers that were assessed were:

1. Well-mixed GHGs
2. Other forcing caused by human activities (mostly the release of aerosols)
3. Combined forcing form all human activities
4. Natural forcings
5. Variability within the climate system

They found that emissions of GHGs from human activities are the primary cause of the observed global warming trend since the 1950s. [16] Increased emissions of atmospheric aerosols from human activities have somewhat offset the warming caused by GHG emissions, as atmospheric aerosols have climate-cooling effects. [16] Natural forcing through changes in the amount of energy received by the sun and volcanic aerosols released into the atmosphere during eruptions have only made a small contribution to climate changes over this period. [16]



1.2.1.3 Human Activities and Climate Change

Economic and population growth has increased GHG emissions due to intensified demand for electricity, heat, manufacturing, building, transportation, food production, trees, and land.

Earth's natural systems, including the atmosphere, land, marine, and freshwater ecosystems are complex and interconnected. Together, they can sustain life and enhance our livelihoods and well-being. Prior to the Industrial Era when human population sizes were small, our collective impact on the environment was minimal and localized. However, as the global population has exponentially grown, human activities have put increased pressure on these complex natural systems both locally and globally.

Economic and Population Growth

Climate change is driven by economic and population growth as a nation's economy and population grow, so does their GHG emissions. [9, 17]

The largest increases in GHG emissions are seen when economies begin to industrialize. This is because industrialization helps drive economic growth which in turn leads to societal advances, which eventually result in improved living standards and increased consumption patterns.

Our lifestyles, including our homes, how much and what kind of energy we use, how we move around, what we eat, and how much we throw away, have a substantial impact on the environment. Carbon emissions per person are the highest in countries like Canada where energy consumption is high and relatively inexpensive, as shown in **Figure 1.3**. [17] On average, a Canadian emits close to 16 tones of carbon dioxide each year. This is twice the amount as an average person living in China and over eight times as much as an average person living in India. [17]

Co$_2$ Emissions Per Capita

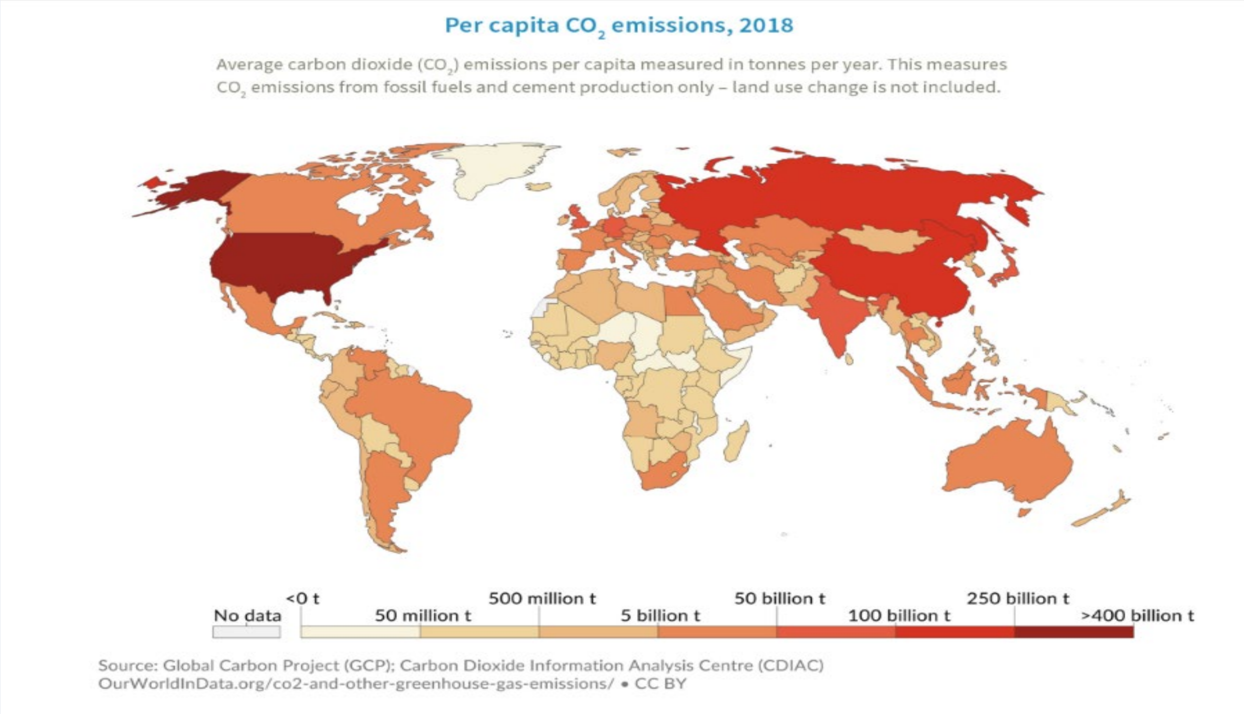


Figure 1.3 | Average carbon dioxide (CO_2) emissions per capita measured in tonnes per year.

Emissions due to land use change is excluded.

Figure source: Adapted from Global Carbon Project (GCP). [17]

Increasing GHG Emissions

The burning of fossil fuels like oil, coal, and natural gas, are responsible for approximately three quarters of annual GHG emissions globally. [18]

Fossil fuels are not a renewable resource as they take millions of years to form through the conversion of the remains of ancient plants and animals. We are currently using fossil fuels at a quicker rate than they can be made since global energy, transportation, and manufacturing industries are still heavily reliant on fossil fuels.

Approximately three-quarters of annual global GHG emissions come from the burning of fossil fuels like oil, coal, and natural gas. [18] Coal produces the most GHG emissions of all the fossil fuels, followed by oil, then natural gas. Between 1970 and 2019, global oil use doubled, and natural gas use quadrupled. [19]

The majority of global GHG emission come from:

- Electricity and heat production – 30 per cent of GHG emissions [18]
- Manufacturing, industry and building processes – 23 percent of GHG emissions [18]
- Transportation – 16 per cent of GHG emissions [18]

Electricity and heat production

Over half of the world's electricity is consumed by powering residential and commercial buildings. [18] Most of the world's electricity supply is caused by burning coal, oil, or gas, which produces carbon dioxide and nitrous oxide.

In recent years, a noticeable increase in energy-related carbon dioxide emissions from buildings has been observed. [18] This trend is due to growing demand for heating and cooling, including rising air conditioner ownership. Additionally, only one quarter of the world's electricity is generated through renewable energy sources, which give off little to no GHGs or pollutants into the air.

Manufacturing, industry and building processes

The manufacturing industry is one of the leading contributors to global GHG emissions. [18] Manufacturing and industries often burn fossil fuels to produce energy to make building materials like cement, iron, and steel, and consumer products such as electronics, plastics, and clothes. Machines used in these processes are often powered by fossil fuels. Fossil fuels can also be directly used in manufacturing processes as chemicals which come from fossil fuels are key ingredients for some products like plastics and steel.

Transportation

Transportation, including buses, cars, trucks, ships, and planes, are mostly fueled by fossil fuels. [18] Transportation is responsible for almost one-quarter of global annual energy-related carbon dioxide emissions. Due to the use of petroleum-based products, like gasoline, road vehicles account for the largest portion of transportation-related emissions. Since mobility often reflects socio-economic status, the higher per capita carbon emissions associated with transportation tend to be associated with the world's wealthiest countries. For example, in the United States, 28 per cent of the country's GHG emissions come from transportation. [18]

Unsustainable Land Use

Global agriculture, land use and deforestation are responsible for approximately one quarter of annual GHG emissions, globally. [18, 20]

Human population growth continues to dramatically shape and change Earth's ecosystems by altering forests, grassland, and other natural areas, to create farms, pasture, timberland, mines, residential, and commercial areas for human use. Based on recent estimates, we are directly using approximately 75 per cent of Earth's ice-free land. [18]

Global agriculture, land use, and forestry contribute to approximately one-quarter of global GHG emissions caused by human activities each year. [18] The greatest proportion of GHG emissions from agricultural activities mostly come from food production practices and land clearing. [21, 22]

In addition to releasing GHG emissions, industrial and intensive agricultural activities can lead to soil degradation, loss of biodiversity, increased waste production and unsustainable water use. [21]

Food production

Emissions of GHGs are created along the food production pathway including, deforestation, clearing land, digestion by cows and sheep, and production and use of fertilizers and manure for growing crops. [21, 22] Approximately half of the GHG emissions generated through food production activities come from raising ruminant livestock like cattle, sheep, and goats. [21] Production of beef has the largest ecological footprint, requiring approximately 20 times more land resources. and producing 20 times more GHG emissions per calorie of edible protein compared to plant proteins. [21]

Although carbon dioxide has the largest impact currently on climate change compared to all the GHGs, this is only due to the large amount of it in the atmosphere. Volume-for-volume, methane and nitrous oxide are much more powerful GHGs. Methane can warm 30 times more than carbon dioxide and nitrous oxide can warm 300 times more. Digestion of food by ruminant animals like cows and sheep are major sources of methane pollution. [9] Approximately two-thirds of annual nitrous oxide emissions come from manure management and nitrogen fertilizer used in industrial agriculture activities. [23]

Many current farming practices are unsustainable and destroy soil approximately 100 times faster than new soil is formed. [24] Specifically, over-plowing and over-grazing removes nutrients in fertile land and turns it into wasteland which can lead to increased food insecurity and climate vulnerability. Soils also lose their capacity to store carbon as they erode. [24]

Land clearing and forest loss

Trees and other plants are key players in Earth's carbon cycle since they take in carbon dioxide and release oxygen during photosynthesis. This means that forests are very important for climate regulation because they are natural carbon sinks, in other words, they absorb carbon dioxide. When trees are cut down, they release the carbon they have been storing. As a result, deforestation in combination with agriculture and other land use changes is responsible for approximately one-quarter of GHG emissions across the world each year. [20] In addition to releasing GHG emissions, deforestation also limits nature's ability to remove emissions out of the atmosphere. [20]

Forests cover 31 per cent of the global land area and approximately half of this area is relatively intact. [20] However, deforestation and forest degradation are occurring at alarming rates. Based on recent estimates from the Food and Agriculture Organization of the United Nations, approximately 10 million hectares (approximately the size of South Korea) of global forest was lost each year between 2015 and 2020. [20]

Globally, agricultural expansion is the main driver of deforestation and forest degradation. [20] The impacts on each region's environment varies widely because of differences in agricultural practices. The main driver of agricultural deforestation is to clear land for cattle grazing, or production of commercial crops like palm oil or soybeans. [20] For example, across North America, the majority of tree cover loss from 2001 to 2018 was a result of forestry (53%) followed by wildfires (43%) (**Figure 1.4**). [18]

Tree Cover Loss

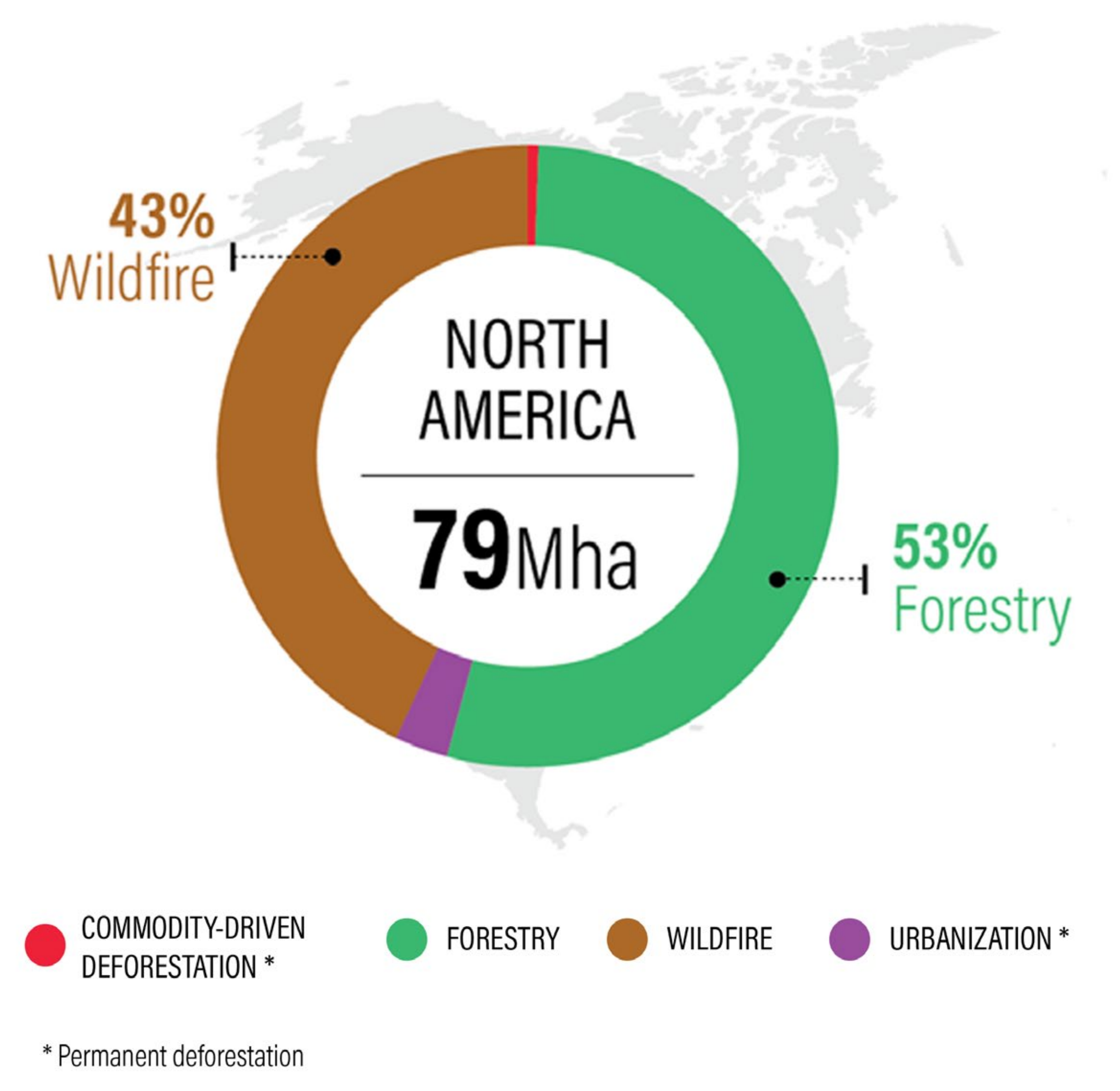


Figure 1.4 | North American tree cover loss by driver from 2001 to 2018.

Figure source: Adapted from Population Connection's Human Impacts on the Environment Report. [18]

1.3 | Observed Changes

Since the late 19th century there have been noticeable changes in temperature, precipitation, the oceans, and ice/snow cover across Canada. [8]

This section focuses on observed changes in Canada's climate. Across Canada, there have been significant observed changes in the lower atmosphere, cryosphere, and ocean over the past 60 years, with notable variation in changes across regions. [8]

1.3.1 Changes In Temperature

Annual temperatures across Canada have increased by more than 1.7˚C since the 1950s with the greatest increase observed in the winter and spring months. [7, 22]

Temperatures referred to in this chapter are surface air temperatures. These are generally measured two metres above the ground, have an immediate effect on human comfort and health, play an important role in determining the types of crops that can be grown in a region, and impact the functioning of local ecosystems. [7]

Of all the climate factors, temperature is one of the best monitored and heavily studied. Temperature data are regularly measured throughout Canada, which allows us to identify changes in current and historical data. However, the availability of temperature data are unevenly distributed across the country with a higher density of observation sites in the populated southern portion of the country. [7] Additionally, very few observation sites existed prior to 1948. As a result, the analysis of historical temperature trends for Canada is limited to the period since 1948. [25]

Annual And Seasonal Mean Temperatures

Canada's rate of surface warming is double the global rate, and the Canadian Arctic is about three times the global rate due to effects known as Arctic amplification.

Annual mean temperatures

Climate varies widely across Canada from region-to-region and involves both long and short-term natural fluctuations in temperatures over a region.

The annual mean temperature provides a simple measure of the overall warmth of a region. Annual temperatures across Canada have increased by more than 1.7˚C since 1948 (**Figure 1.5**). [8, 25] Warming has not been steady over this time, as temperatures decreased from the 1940s to the 1970s and then rapidly increased through 2016. [25] This long-term trend is consistent with what has been observed globally. [15]

Canada's rate of surface warming is much higher than what has been observed in most other countries and is approximately double the global rate. [8, 25] This difference is even more dramatic for the Canadian Arctic, where the rate of warming is about three times the global rate. [26] The increased rate of warming for Canada as a whole and the Canadian Arctic is due to effects known as Arctic amplification. [8]

Arctic amplification is due to contributions from the five climate feedback methods discussed in **Section 1.1.2.2**, which are, in decreasing order of importance, lapse-rate feedback, snow/ice albedo feedback, Planck feedback, cloud feedback, and water vapour feedback. In the Arctic, each of these mechanisms are a positive (amplifying feedback) which enhance the warming from GHG forcing. [8]

Annual Temperature Changes

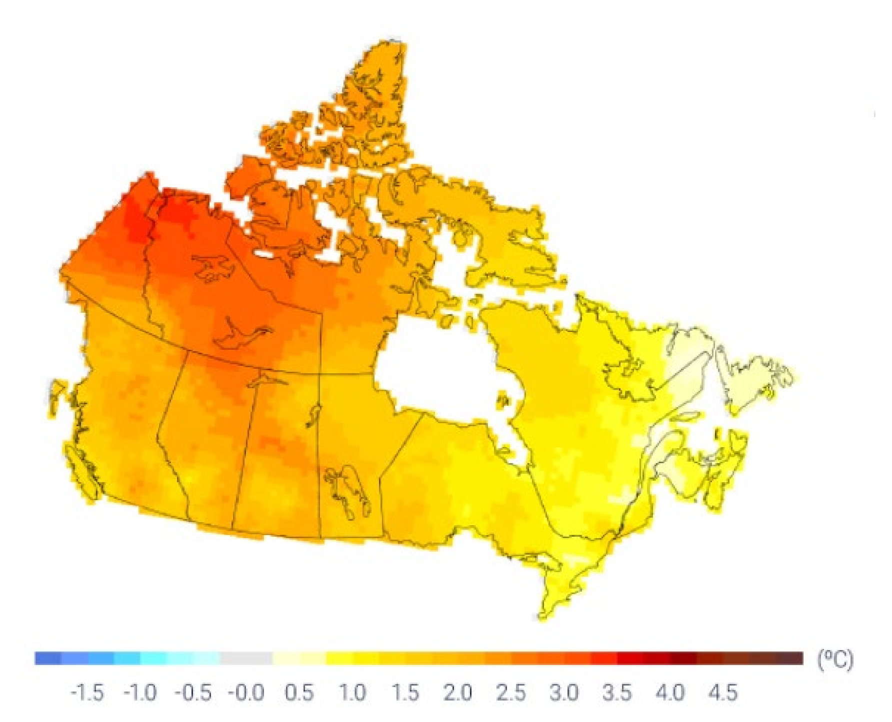


Figure 1.5 | Observed changes (˚C) in annual temperature between 1948 and 2016.

Changes were calculated based on linear trends over the period.

Figure Source: Figure Source: Adapted from Figure 2 of Vincent et al., 2015. [25]

Seasonal mean temperatures

Warming trends for mean temperatures have not been uniform across seasons, with considerably more warming in winter than in summer (**Figure 1.6**). [25] The mean temperature increased by 3.3˚C in winter, 1.7˚C in spring, 1.5˚C in summer, and 1.7˚C in autumn between 1948 and 2016.

Winter and spring warming was predominant in northern regions of the country from 1948 to 2016. Summer warming was much weaker than in winter and spring, but the magnitude of the warming was generally more uniform across the country compared to what was observed for other seasons. Autumn warming was mostly observed in the northeast regions of Canada.

Seasonal Temperature Changes

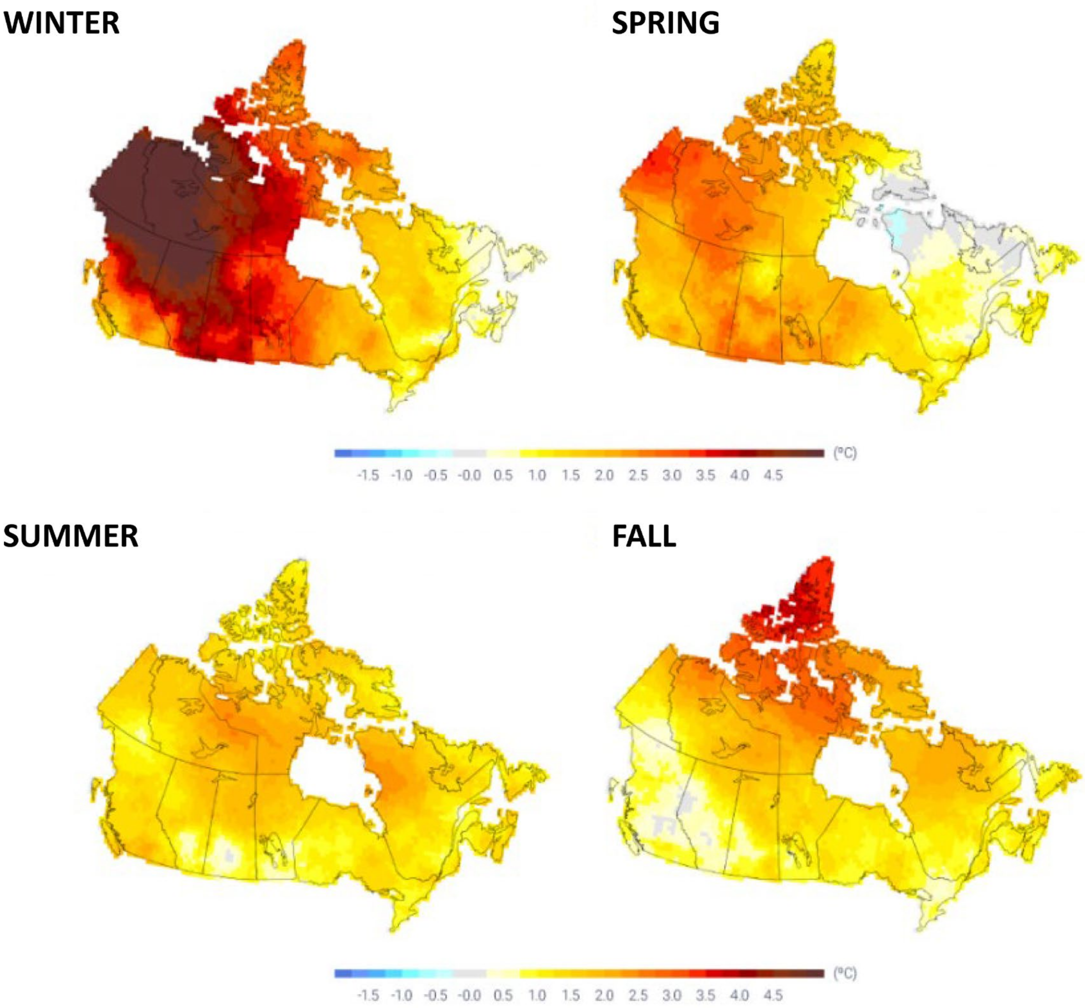


Figure 1.6 | Observed changes (˚C) in mean seasonal temperatures between 1948 and 2016 for the four seasons.

Changes were calculated based on linear trends in the gridded station data.

Figure Source: Adapted from Figure 3 of Vincent et al., 2015. [25]

Extreme temperatures

In addition to warming average temperatures, extreme temperature changes have also been observed across Canada with extreme warm temperatures increasing and extreme cold temperatures decreasing. [26]

1.3.2 Changes in the Water System

Earth's water cycle is impacted by increasing global temperatures. These impacts have been observed as changes in precipitation, the ocean, and cryosphere.

Changes in Precipitation

Although precipitation levels vary widely across Canada, especially from north to south, average precipitation levels have increased by approximately 20 per cent over the past 60 years. [25]

Compared to temperature, monitoring precipitation over a region is much more challenging. Precipitation in the form of snowfall is especially difficult to detect as a gauge can only catch a small fraction of total snowfall and drifting snow makes it even more difficult to measure snowfall amount. As a result, limited long-term precipitation data exists for identifying changes in precipitation at regional levels within Canada. This makes detection of changes in precipitation trends more difficult. [26]

In general, there is insufficient station density in Canada to calculate accurate national average precipitation values, since the distance between observation stations with long-term records are generally greater than 120-kilometres apart and there is large variation in precipitation levels across Canada. This variation is because warm air can hold more moisture than cool air, the amount of precipitation experienced across the country increases as you move from north to south.

For long-term trends at the century scale, changes in precipitation can be assessed with a reasonable amount of accuracy at the regional level for southern parts of Canada based on data from observation stations with long-term records. [7, 27] Unfortunately, this is not the case for northern Canada due to a lack of spatial coverage in observation stations which can be spaced over 1,200-kilometres apart in the north. [7] Due to a lack of data for the north, most assessments of national or regional changes in precipitation for Canada are based on locally normalized precipitation, expressed as a percentage. While this does make it possible to calculate some national and regional averages, these averages should not be interpreted as normalized averages of precipitation over space.

It is also important to mention that the introduction of new precipitation gauges over time has unintentionally introduced variability into precipitation records. The effect of weather conditions and the use of different gauges on observational data need to be carefully adjusted to accurately reflect the actual amount of precipitation observed at a particular site. These adjustments also need to be carried out prior to using historical data for generating locally normalized precipitation trends.

Average precipitation: rainfall

Although monitoring precipitation over a region is challenging and there is limited data available, there is still enough evidence to suggest that annual mean precipitation levels increased by about 20 per cent from 1948 to 2012 over Canada as a whole (**Figure 1.7**). [25, 8] The percentage increase was larger in northern Canada than in southern Canada. In terms of absolute amount of precipitation increase, significant increases were experienced in southern parts of the country since the mean precipitation amount is typically higher in southern Canada. [7]

Precipitation Trends

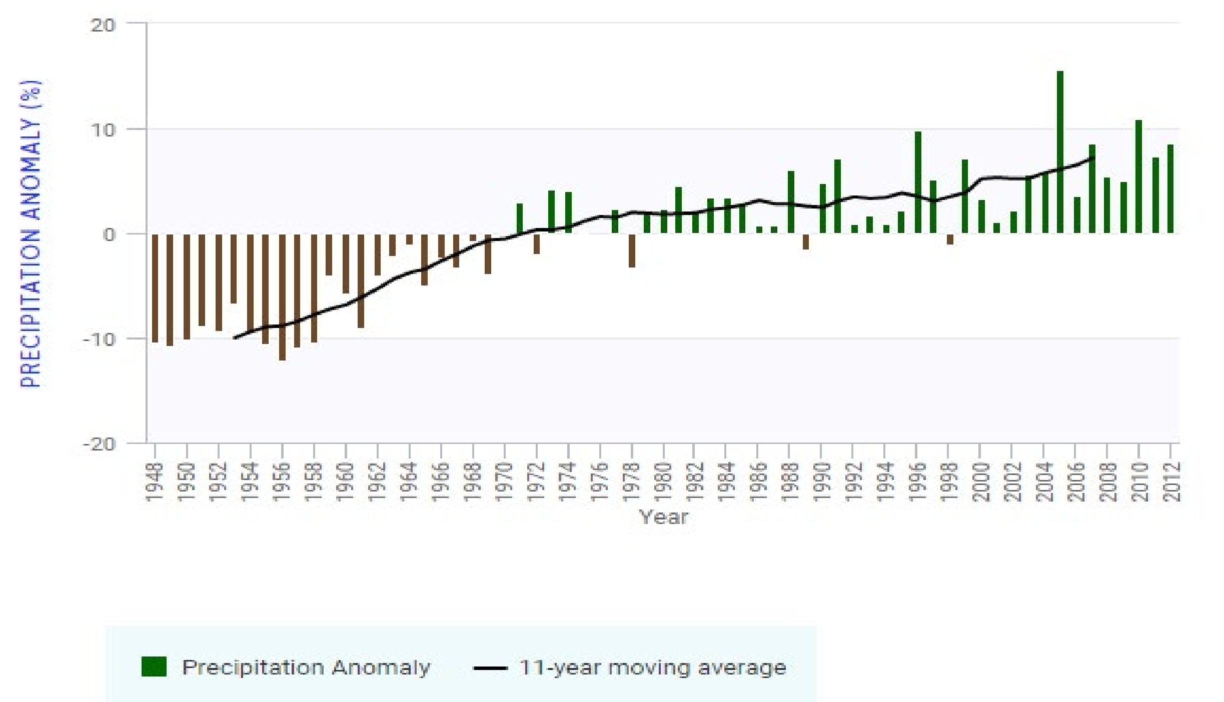


Figure 1.7 | Observed changes in locally normalized annual precipitation (%) between 1948 and 2012.

Changes are calculated based on linear trends over the period and the black lines represent the 11-year running mean (average).

Figure Source: Adapted from Canada's Changing Climate 2019 Report [8] and Figure 4 of Vincent et al., 2015. [25]

Precipitation has increased in every season in northern Canada (**Figure 1.8**). In southern Canada, increases across all seasons have also been observed but the increases are generally not statistically significant.

Seasonal Precipitation Changes

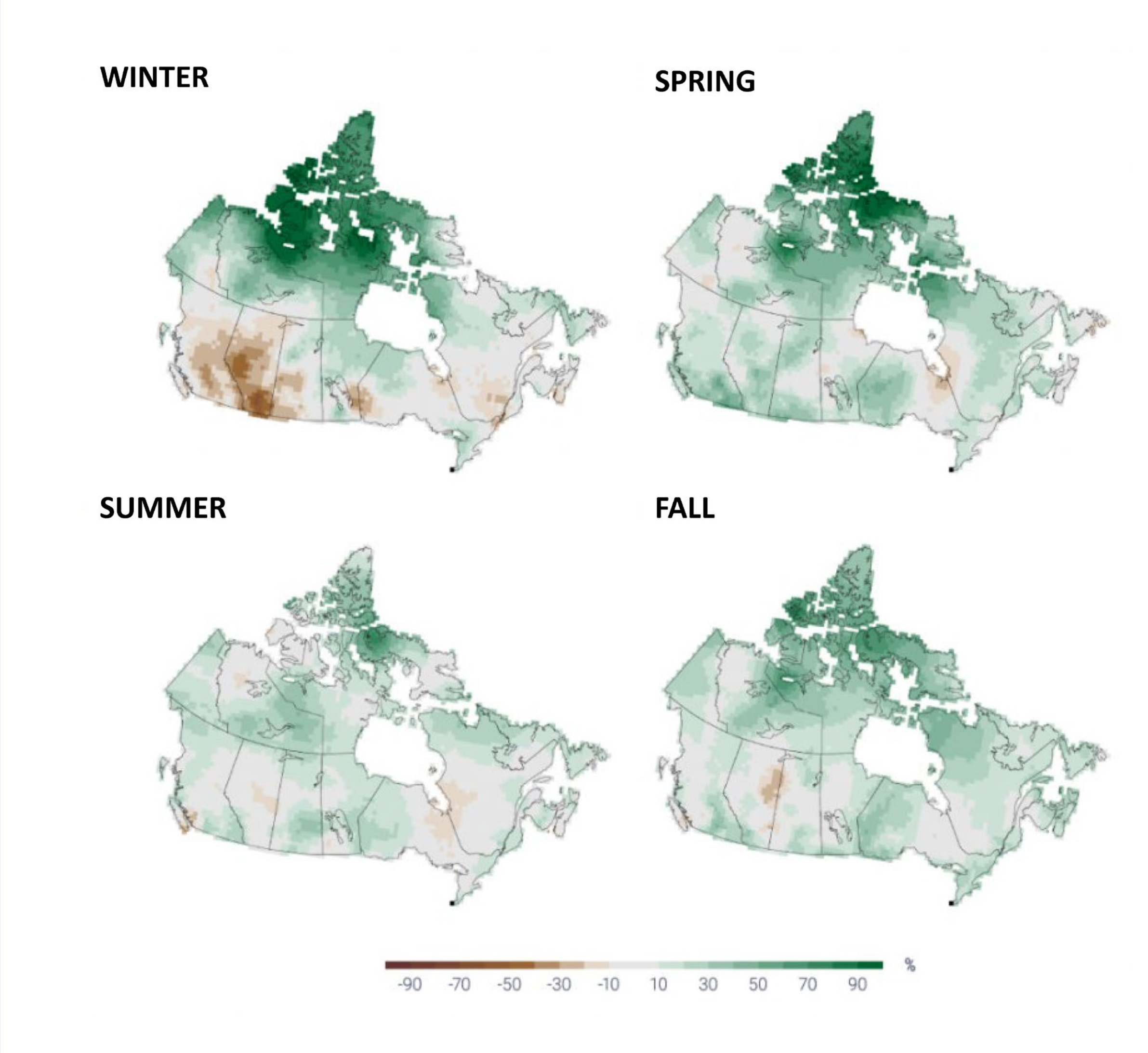


Figure 1.8 | Observed changes in normalized seasonal precipitation (%) between 1948 and 2012 for the four seasons.

Changes are computed based on linear trends over the respective periods. Estimates are derived from the gridded station data. There is a lack of data in northern Canada for this analysis.

Figure Source: Adapted from Figure 5 of Vincent et al., 2015. [25]

It is important to note that the percentage increase in normalized precipitation is larger than what may be expected from the warming-induced increase in water-holding capacity of the atmosphere. This leads to some doubt over the magnitude of the observed increases in historical trends. [7]

Average precipitation: snowfall

The ratio of snowfall to total precipitation has steadily and significantly decreased over the southern parts of Canada since the mid-20th Century because of warming temperatures. [25] These decreases have been especially noticeable during the spring and autumn. [25] There has also been a pronounced decline in summer snowfall over the Arctic Ocean and Canadian Arctic Archipelago, and this decline is predominantly caused by snowfall in the region being replaced by rain. [28] The change from snow to rain has profound impacts in other components of the physical environment. [25]

Changes in Snow Cover, Ice, and Permafrost

Observed changes to the Canadian cryosphere shows that the proportion of Canada's land and water bodies covered by snow and ice have been decreasing over time; glaciers and icecaps have been shrinking, and permafrost is warming and thawing. [8]

There have been many noticeable changes to the cryosphere (snow, ice, permafrost) across Canada over the past three decades. [8] These changes are worrisome as all parts of the cryosphere are interconnected, so changes to one individual component can have substantial impacts on the other components. For example, snow is a very good insulator, so changes in when snow cover happens in the fall and the amount of snow accumulated during the winter strongly influences underlying ground temperatures and the thickness of marine ice. [8]

Snow cover

Since almost all Canadian watersheds are dominated by snow in the winter, snow is an important component of the Canadian climate system. [8, 29] Snow is responsible for several processes that affect freshwater availability, ecosystem functions and health, and carbon dioxide exchange. [29, 8] Snow cover fraction (SCF) and maximum seasonal snow water equivalent (SWEmax) in particular, have a significant impact on the exchange of energy between land surface and the atmosphere, as well as freshwater availability. [29]

Consistent with trends observed in other northern regions in Alaska, Europe and Russia, the amount of Canadian land and marine areas covered by snow and ice has decreased over the past three decades due to later snow onset in the fall and earlier melt in the spring. [8]

Perennial sea ice

Perennial sea ice is multi-year ice which survives the summer melt and is important for protecting the Arctic Ocean from the sun and keeping the region cool. Satellite data have shown dramatic changes in Arctic Sea ice over the past four decades. [30, 31] Perennial sea ice is steadily being replaced by thinner sea ice which drifts and melts more easily. [32, 33] This has led to a decline in summer sea ice area across the Canadian Arctic. The greatest losses in multi-year ice have been observed in the Beaufort Sea and Canadian Arctic Archipelago, averaging almost 10 per cent per decade. [30, 31]

Lake and river ice

Canada is fortunate to be a lake-rich country, with one of the largest fresh water supplies globally.

Lake ice freeze-up and break-up and ice thickness play important roles in regional energy and water cycles [34], freshwater ecosystem functions, biogeochemical processes [35] and energy balance. The duration of seasonal ice cover and thickness depends on when the water freezes in the fall (ice freeze-up) and when it melts in the spring (break-up), and the timing of these events is sensitive to changes in air temperature. Whereas ice thickness is influenced by both air temperature and snow cover.

Duration of seasonal lake ice cover is declining across Canada due to later ice formation in the fall and earlier spring break-up, with implications for freshwater ecosystem functions. For example, earlier ice melt across the Great Lakes is linked to turbidity and phytoplankton activity. [36]

Specifically, ice breakup is occurring earlier and freeze onset occurring later across small lakes in southern Quebec, Ontario, Manitoba, and Saskatchewan. [37] A significant decline in the annual maximum ice cover has been observed for all the Laurentian Great Lakes from 1972 to 2010. [38] Maximum ice cover refers to the extent of ice coverage on a body of water, typically measured during the coldest period of the year. It represents the maximum area covered by ice such as frozen lakes, rivers, or polar seas. Lake Ontario has experienced the largest decrease in annual ice cover (88%) over this period. [38]

Permafrost

Permafrost, a thick layer of soil below the surface that remains frozen throughout the year, underlies about 40 per cent of Canada's landmass, extending under the ocean in parts of the Canadian Arctic. Permafrost characteristics are influenced by soil properties, snow cover and ground temperatures.

Changes in permafrost are measured by tracking changes in permafrost temperature and thickness of the active layer. Changes in permafrost temperature reflect long-term changes in climate on the scale of decades to centuries. [39] A large portion of the northern Canadian landscape has undergone changes due to permafrost thaw. Permafrost temperatures have increased across sub-Arctic and Arctic Canada in recent years, with greater changes observed in colder regions. [40] This thawing of permafrost is concerning for several reasons, as it can release GHGs [41] and contaminants [42] into the surrounding environment.

1.4 | Canada's Future Climate

Reducing GHG emissions is key to reducing future climate change.

Future changes in climate will be largely driven by human emissions of GHGs, primarily carbon dioxide. Although emissions of aerosols have cooling effects on the climate and can offset some climate warming, this effect is anticipated to decrease in coming years as aerosol emissions continue to decrease.

1.4.1 The 1.5 Degree Limit

Human activities have caused the release of enough GHGs to increase the average global temperature by 1˚C. Most of this warming has occurred since 1950 through intensified demand for electricity, heat, manufacturing, building, transportation, food, trees, and land. Limiting global warming to 1.5 ˚ C (or 2.7 ˚ F) above pre-industrial levels, is considered a critical threshold by the scientific community and policymakers. This level of warming affects the health of ecosystems, influencing shifts in the types, distribution and viability of plants, viruses, animals, and even areas of human settlement. Warming above 1.5 degrees also increases the frequency and intensity of extreme weather events such as heat waves, floods, and droughts. It also increases the rate of sea level rise, meaning that many people living in coastal communities risk losing their homes, livelihoods and communities. Explored further in **Chapter 2**, warming above this threshold also increases the risk of direct health impacts including heat-related illness, vector borne disease, and food and water insecurity.

Figure 1.9, created by the IPCC, depicts past (1900-2020) and projected (2021-2100) changes in global surface temperature, illustrating how the climate has already changed and will continue to change. Changes in projected human-caused annual global surface temperatures are presented as 'climate stripes'. Colours on the human icons indicate the projected global surface temperature, depending on greenhouse gas emission scenarios.

"Critical Windows of Viability"

Scientists consider 1.5 degrees of global warming as a tipping point, after which the chances of extreme flooding, drought, wildfires, food shortages and other risks could increase dramatically.

Although this degree of warming seems small, it influences whether or not the ecosystems that we depend for things like food, water, medicine, and livelihood, will remain viable.

Generational Experience Of Global Warming

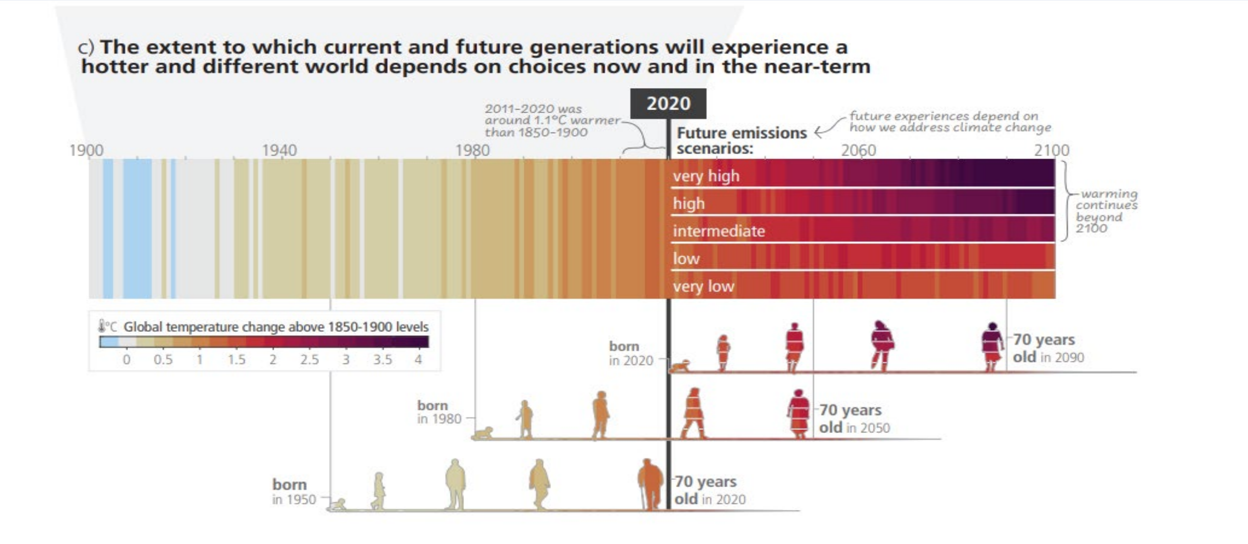


Figure 1.9 | Projected generational experience of global warming.

The extent to which current and future generations will experience a hotter and different world depends on choices now and in the near term.

Observed (1900 to 2020) and projected (2021 to 2100) changes in global surface temperature relative to the 1850 to 1900 baseline, linked to changes in climate conditions and impacts illustrate how the climate has already changed and will change along the lifespan of three generations. Those born in 1950, 1980 and 2020. Changes in annual global surface temperatures are presented as "climate stripes", with future projections showing the human-caused long-term trends and continuing modulation by natural variability.

Figure Source: Adapted from the IPCC Climate Change 2023 Synthesis Report: Summary for Policy Makers. [66]

1.4.3 Canada's Future Climate

Temperature and precipitation are fundamental climate quantities that directly affect human and natural systems. By the end of the century, communities across the country are projected to experience warmer temperatures and wetter weather. [7]

To understand how climate drivers may impact our climate in the future, scientists use climate models to make projections of future climate based on different plausible future scenarios of emissions. **Appendix 1.1** provides an overview of these methods and how they are used for making local climate projections.

Future global warming trends will have far reaching impacts across the world in terms of both annual and seasonal changes in mean temperatures and precipitation amounts. Based on current RCP scenarios, future global mean temperature change relative to the 1986 to 2005 reference period, is projected to rise about 1˚C under the low emission scenario (RCP2.6) and 3.7˚C for the high emission scenario (RCP8.5) by the end of the 21st century. (**Figure 1.10**). Canadian mean temperature is projected to increase at roughly double the global mean rate, regardless of the forcing (emissions) scenario.

The IPCC's Fifth Assessment stated that, "Global mean temperatures will continue to rise over the 21st century if GHG emissions continue unabated". [59] The connection between global mean and Canadian mean temperature indicates that temperatures will continue to increase in Canada as long as GHG emissions continue. [7] When looking at the projections using the low emissions (RCP2.6) scenario in the following sections it is important to note that for this scenario to occur, emissions of carbon dioxide need to peak almost immediately and reduce to near zero before the end of the century. [8]

Global Temperature Change By 2100

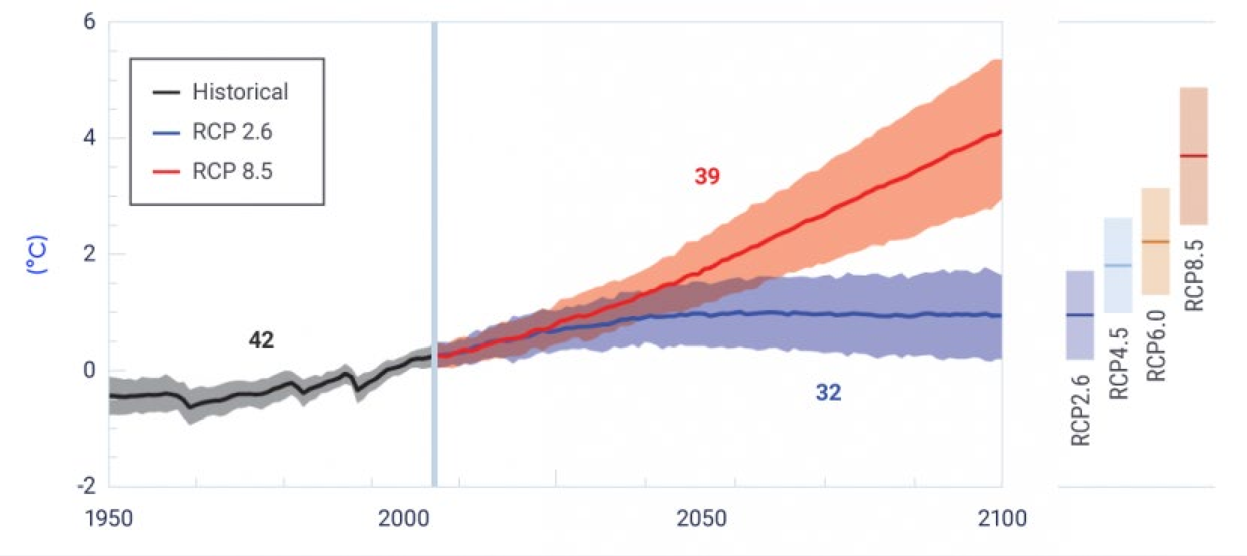


Figure 1.10 | Global average surface temperature changes relative to the reference period 1986 to 2005.

The graph shows the multi-model annual global mean surface temperature change relative to a historical reference period (1986-2005) for a range of emission scenarios. The shaded bands indicate the 5% to 95% spread across the multi-model ensemble.

Figure source: Adapted from Collins et al. 2013. [59]

1.4.3.1 Temperature

Canada's current and projected average temperature is relatively twice the average rate of global warming, under all GHG global emission scenarios.

Temperature directly affects human health and the health of the environments in which we live and depend on. Temperature influences food security such as the ability of crop and animal species to grow and thrive in a region. Temperature also influences the built environment such as building requirements for heating and cooling.

The Canadian climate has warmed and will continue to warm further in the future, due to GHG emissions. [7] Canada's rate of warming has historically been twice the rate of average global warming [8, 25] and this trend will apply to future change regardless of the emissions pathway that Earth follows. The overall magnitude of future warming, however, will be determined by the extent and success of future GHG mitigation. Increases in future temperature and extremes will affect Canada's natural, social, and economic systems. [7]

Annual and Seasonal Mean Temperatures

In the coming years, annual and seasonal mean temperatures are projected to increase across Canada as a direct result of climate changes. [7]

Annual mean temperatures

Based on current RCP scenarios, future mean temperature change for Canada as a whole compared to the 1986 to 2005 reference period, is projected to rise about 1.8˚C (IQR: 1.1—2.5) under the low emission scenario (RCP2.6) and 6.3˚C (IQR: 5.6—7.7) for the high emission scenario (RCP8.5) by the end of the century. [7]

The projected median temperature change across Canada for the end of the century based on the low emission and high emission scenarios are shown in map form in **Figure 1.11**. Under a low emission scenario (RCP2.6), annual mean warming across Canada stabilizes at about 1.8 ˚C above the reference period after about 2050 but under a high emission scenario (RCP8.5), annual warming continues throughout the century reaching about 6.3˚C warmer than the reference period by 2100. [7] Under the high emission scenario, projected temperature increases are approximately 4˚C higher when averaged for Canada as a whole, compared to the projections based on the low emission scenario. In both the low (RCP2.6) and high (RCP8.5) emission scenarios, the northern parts of the country are expected to experience the greatest increases in temperature by the end of the century (**Figure 1.11**). [7] The apparent difference in temperature change between the two emission scenarios demonstrates the long-term climate benefit associated with aggressive mitigation efforts.

Annual Temperature Changes

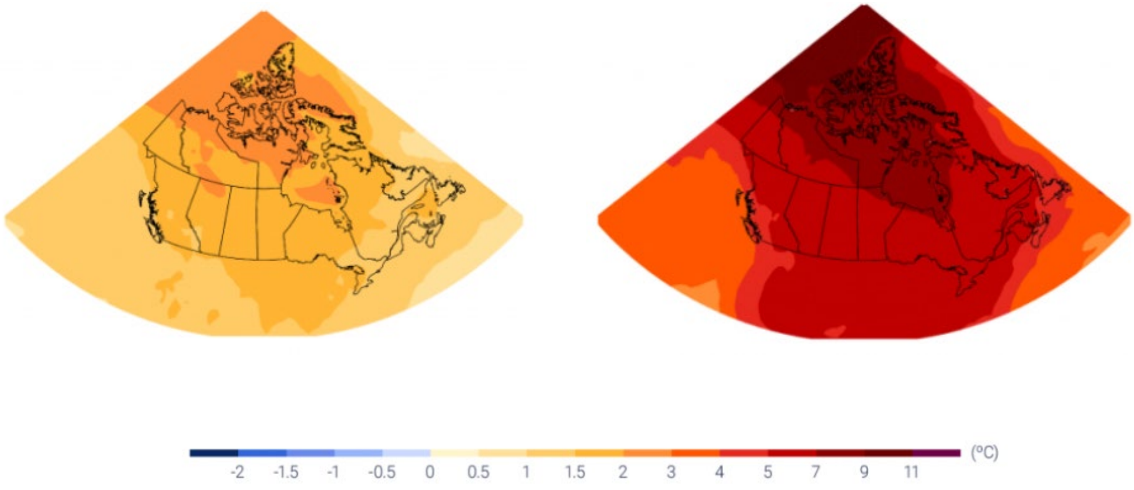


Figure 1.11 | Projected annual temperature changes for Canada by 2100 compared to the reference period 1986 to 2005 for low emissions (RCP2.6) and high emissions (RCP8.5) scenarios.

Figure source: Adapted from Climate Research Division, Environment and Climate Change Canada. [7]

Seasonal mean temperatures

Projected temperature changes for winter (December to February average) and summer (June to August average) by the end of the century are shown in **Figure 1.12.** The differences between the low emission scenario (RCP2.6) and the high emission scenario (RCP8.5) for both the summer and winter by the late century (2081-2100) are extreme.

Increased warming in northern Canada and the Arctic compared to the rest of the country is evident in the winter months regardless of the forcing scenario (**Figure 1.12**). This finding is consistent with other climate projections for Canada, as well as Earth, due to a combination of several factors. These include reductions in snow and ice and, therefore, a reduction in albedo and increased heat transport from southern latitudes. [7] This high-latitude amplification over the Canadian Arctic is negligible in the summer projection maps because summer temperatures over the Arctic Ocean remain near 0˚C (the melting temperature of snow and sea ice). [7] In southern Canada, projected winter temperature change is larger as you move eastwards, with British Columbia projected to warm slightly less than the rest of the country. [7]

Under both forcing scenarios, the projected summer change is more uniform across the country (**Figure 1.12**). [7]

Seasonal Temperature Changes

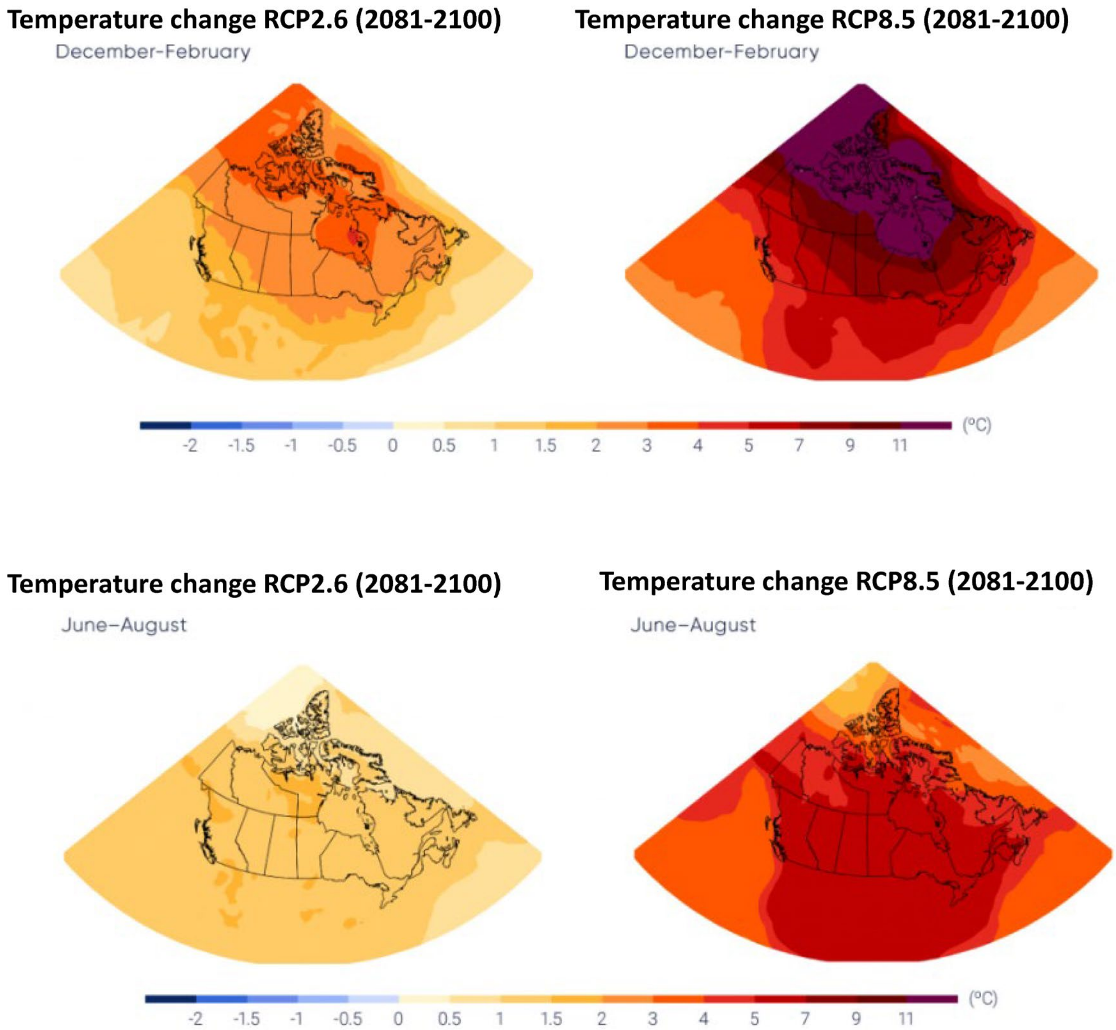


Figure 1.12 | Projected winter (top) and summer (bottom) temperature changes for Canada by 2100 compared to the reference period 1986 to 2005 for low emissions (RCP2.6) and high emissions (RCP8.5) scenarios.

Figure source: Adapted from Climate Research Division, Environment and Climate Change Canada. [7]

Extreme Temperatures

Most places in the world, including Canada, will experience more hot and fewer cold [60] temperature extremes as global average temperatures increase. [59]

Daily temperatures are projected to be substantially warmer across Canada through the rest of this century (**Figure 1.13**).

Daily Temperature Maximums

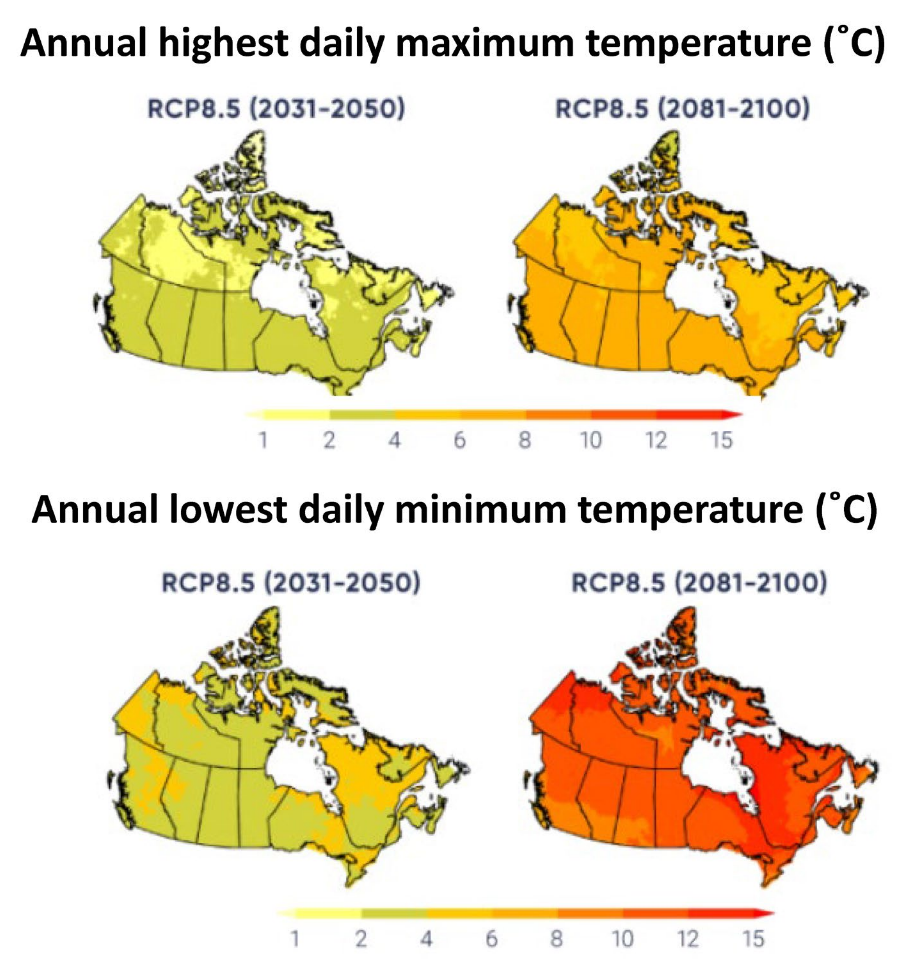


Figure 1.13 | Projected changes in the annual highest daily maximum and lowest daily maximum temperatures for Canada by 2100 compared to the reference period 1986 to 2005 for low emissions (RCP2.6) and high emissions (RCP8.5) scenarios.

Estimates were derived from multi-model median projections and all maps are based on statistically downscaled and bias-corrected temperature data from simulations by 24 Earth system models.

Figure source: Adapted from Li et al. [60]

For Canada as a whole, annual highest daily maximum temperature is expected to follow a similar trend as the projected changes in summer average temperature (**Figure 1.13**). Annual lowest daily minimum temperature, however, is projected to warm at a quicker rate than winter temperature across most of Canada, increasing the minimum temperature in southern parts of the country by about 3˚C by the end of the century under a high emission scenario (RCP8.5) (**Figure 1.13**). **Table 1.2** summarises projected changes in Canada for selected temperature indicators based on statistically downscaled temperatures from simulations by 24 Earth system models.

Table 1.2. Multi-model changes in indicators of temperature for Canada as a whole by the end of the century under low (RCP2.6) and high (RCP8.5) emissions scenarios compared to the 1986 to 2005 reference period.

Changes in temperature indicators	Emissions scenario; median (IQR)	
	RCP2.6	RCP8.5
Annual highest daily maximum temperature (˚C)	1.5 (0.8 –2.2)	6.1 (4.2—7.5)
Annual highest daily minimum temperature (˚C)	2.5 (1.7—3.5)	11.2 (9.5 –13.8)
Annual number of hot days when daily maximum temperature is above 30˚C (days)	1.5 (0.9—2.3)	13.2 (8.8—16.2)
Length of the growing season (days)	12.4 (7.0—17.7)	42.8 (31.9—53.8)

Data source: based on statistically downscaled temperatures from simulations by 24 Earth system models, adapted from Li et al., 2018. [60]

Changes in temperature indicators and extremes are closely related to changes in mean temperature. [7] Based on current projections, extreme hot temperatures are anticipated to become more frequent as we approach the end of the century. Relatively larger increases in the frequency of more rare extreme heat events are also projected for Canada as a whole. [61] The increase in the number of hot days currently projected is substantial, with an increase of more than 50 days by the late century under a high emission scenario (RCP8.5) in regions that currently experience hot days (**Figure 1.14**). The distribution of areas expected to experience hot days are projected to progressively expand northward, depending on the level of global warming experienced (**Figure 1.14**).

The occurrence of extreme cold temperatures is expected to follow an opposite trend compared to extreme hot temperatures. As we move through the rest of the century, extreme cold temperatures are expected to become less frequent. [61] Additionally, winter severity is expected to decrease across Canada, with the most dramatic decreases projected for the North. [60] Based on a high emission scenario (RCP8.5), Canada is expected to experience 40 fewer frost and ice days by the end of the century. [60]

Projections by different models for the near-term (2031 to 2050) and late century (2081 to 2100) under a high emission scenario (RCP8.5) agree on the direction (increasing or decreasing) of changes for almost all regions. This indicates the strength of projected changes in temperature indicines and extremes for the future. [7]

Hot Days

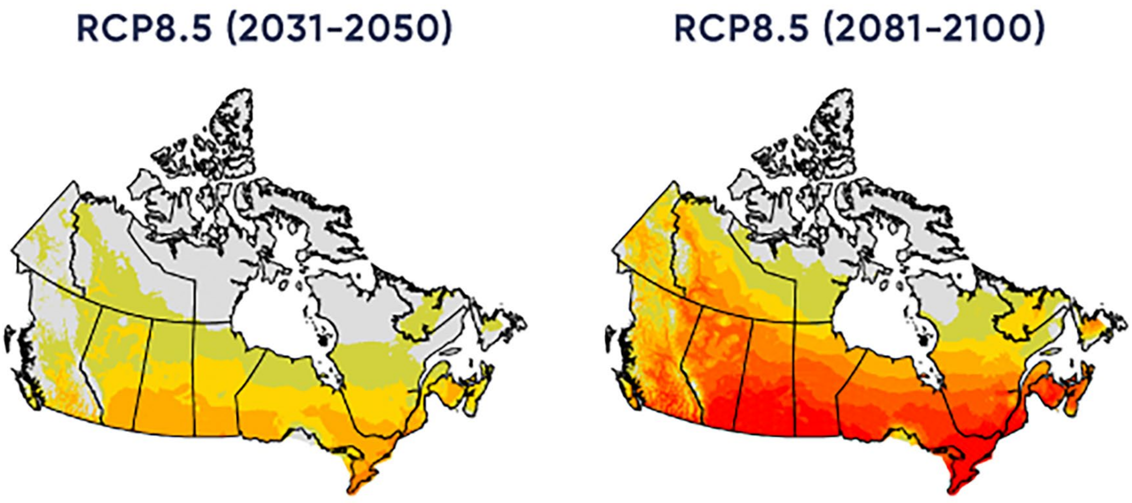


Figure 1.14 | Projected changes in the annual number of hot days (days) when daily maximum temperature exceeds 30˚C (2081 to 2100).

Estimates were derived from multi-model median projections and all maps are based on statistically downscaled and bias-corrected temperature data from simulations by 24 Earth system models.

Areas with less than one hot day per year on average are marked with grey.

Figure source: Adapted from Li et al, 2018. [60]

1.4.3.2 Precipitation

Precipitation is expected to increase across Canada over the next 80 years, particularly in northern Canada.

Precipitation affects the foundation of human health. Although human society and natural systems have evolved and adapted to changing precipitation in the past, future shifts in precipitation beyond historical ranges could have profound impacts including changes in food production and safe housing locations.

The amount of precipitation differs substantially across Canada. Since warm air can hold more moisture than cool air, the amount of precipitation decreases as you move north. Unlike temperature, monitoring precipitation over a region like Canada is challenging because a gauge measurement is a point observation and may not be typical of precipitation conditions over a large area. As precipitation is irregular in time and space, point observations of precipitation amounts in a day can represent only a small area surrounding the observation site.

Annual and winter precipitation is anticipated to increase across Canada over the next 80 years with larger percentage changes experience in northern Canada, especially in the Arctic. [7] For Canada as a whole, there is a lack of observational evidence of changes in daily and short-duration extreme precipitation. Lack of observational evidence and relevant data makes projection of extreme precipitation difficult. However, multiple sources of evidence support high confidence in projecting an increase in extreme precipitation globally, Canada included. [7] The size of this increase, however, is much more uncertain at the present time.

Annual and Seasonal Precipitation

Climate change is expected to bring more rain and less snow, particularly in northern Canada.

In general, changes in precipitation exhibit more temporal and regional variation than changes in temperatures. [7] As a result, precipitation projections have lower confidence associated with them than projections for changes in temperature.

Annual precipitation

Consistent with the IPCC's Fifth Assessment, high latitudes within Canada (i.e., the North) are projected to experience a large increase in annual mean precipitation by the end of the century under the high emission (RCP8.5) scenario, as shown in **Figure 1.15**. This projected increase is a common feature of many current climate models, which can be explained by the expected warming-induced large increase in atmospheric water vapour. [59] There is also high confidence in the projected increase in annual mean precipitation across the country by the end of the century. Relative to the baseline period of 1986 to 2005, percentage change in annual mean precipitation of 6.8 per cent (IQR: 0.4—14.4) under the low emissions scenario (RCP2.6) and 24.2 per cent (IQR: 13.7—36.2) under the high emissions scenario (RCP8.5). [7]

As our climate continues to warm, an increased likelihood of precipitation falling as rain rather than snow is expected, especially for northern Canada. [7] Regional climate projections have suggested a general increase in rain-on-snow events over the coming century. [62]

Seasonal precipitation

The confidence in projected changes in seasonal mean precipitation is lower. In general, models project less summertime precipitation for southern Canada and an increase in precipitation for the north under a high emission (RCP8.6) scenario (**Figure 1.16**). [7] The projected decrease in summer precipitation, also projected in other parts across the globe, is a consequence of overall surface drying and changes in atmospheric circulation. [59]

This small change in national average of locally normalized precipitation hides the fact that summertime precipitation changes are projected to be large and impactful in many areas in Canada. [7] Since the mean precipitation amount is much greater in southern Canada than in the north, the absolute amount of precipitation decrease in southern Canada is larger than the absolute value of precipitation increase in northern Canada. [7]

Annual Precipitation Changes

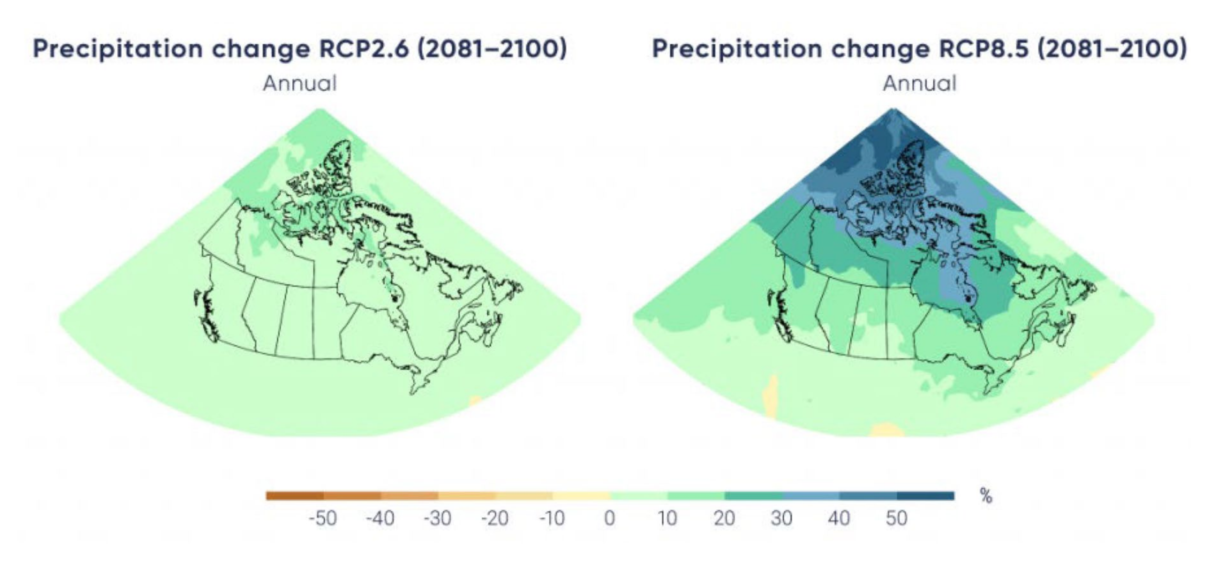
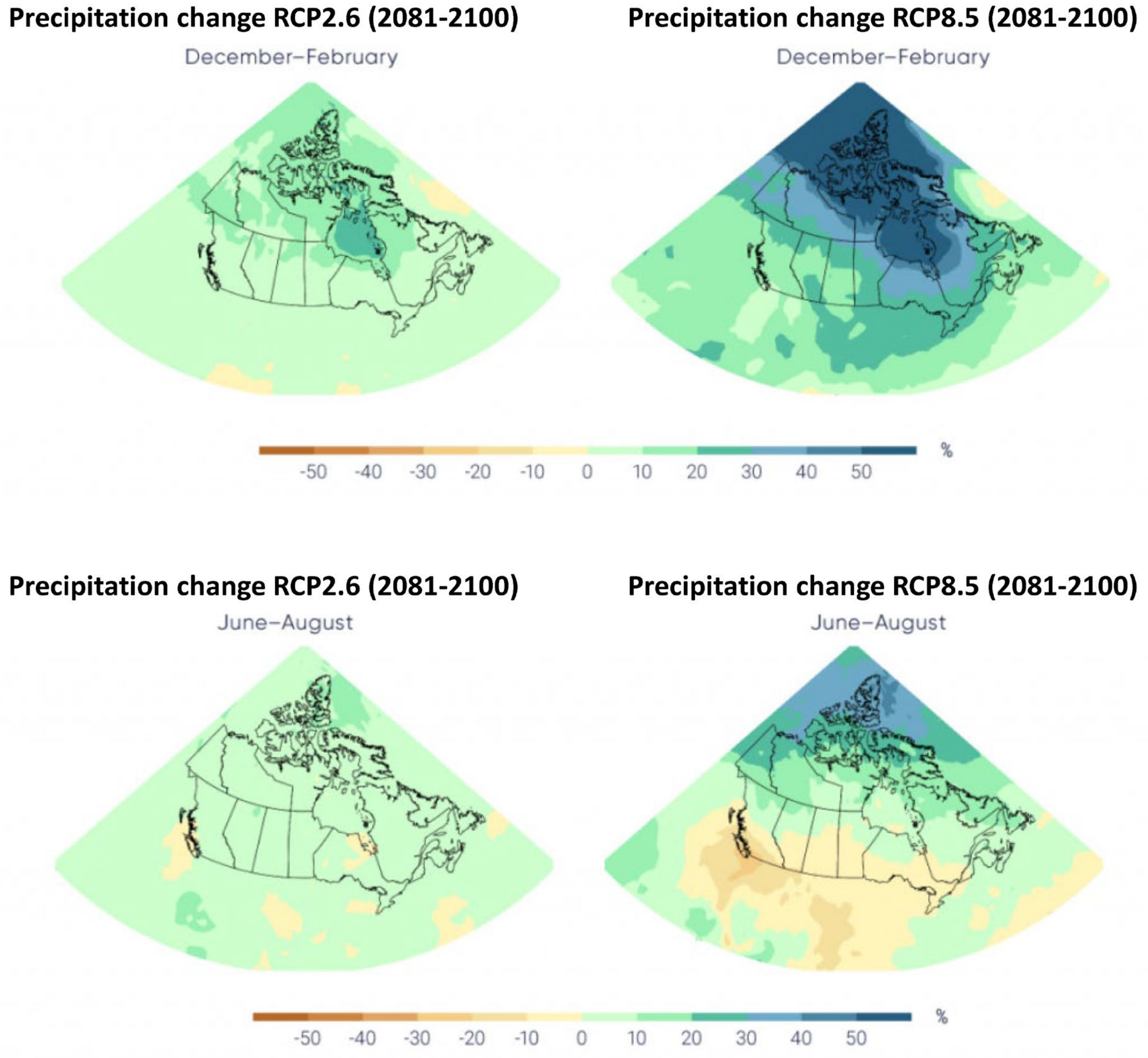


Figure 1.15 | Projected annual mean precipitation change (%) across Canada for the 2081 to 2100 period based on low emissions (RCP2.6) and high emissions (RCP8.5) scenarios.

Precipitation change (%) is represented by the median of the fifth phase of the Coupled Model Intercomparison Project multi-model ensemble. Changes are based on a comparison to the 1986 to 2005 reference period.

Figure source: Adapted from Climate Research Division, Environment and Climate Change Canada. [7]

Seasonal Precipitation Changes



Precipitation change RCP2.6 (2081-2100)

December–February

Precipitation change RCP8.5 (2081-2100)

December–February

Precipitation change RCP2.6 (2081-2100)

June–August

Precipitation change RCP8.5 (2081-2100)

June–August

Figure 1.16 | Projected winter (top) and summer (bottom) precipitation change (%) across Canada for the 2081 to 2100 period based on low emissions (RCP2.6) and high emissions (RCP8.5) scenarios.

Precipitation change (%) is represented by the median of the fifth phase of the Coupled Model Intercomparison Project multi-model ensemble. Changes are based on a comparison to the 1986 to 2005 reference period.

Figure source: Adapted from Climate Research Division, Environment and Climate Change Canada. [7]

Helpful Resources

Want to learn more?

This section provides a summary of key resources to help understand how and why Canada's climate has changed and what changes are projected for the future. While this list provides an overview of existing literature, it is not a complete list. Instead, it is intended as a starting point for learning and perhaps inspiring discussion and collaboration.

GUIDE TO CONDUCTING A CLIMATE CHANGE ANALYSIS AT THE LOCAL SCALE: LESSONS LEARNED FROM DURHAM REGION

Ontario Climate Consortium (OCC)

2020

This guide provides climate projections for the Region, and information to municipalities on how to undertake their own climate modeling studies.

CANADA'S CHANGING CLIMATE REPORT

Bush, E., Lemmen, D.S., (ed.)

Government of Canada

2019

This report is about how and why Canada's climate has changed and what changes are projected for the future. Led by Environment and Climate Change Canada, it is the first report to be released as part of Canada in a Changing Climate: Advancing our Knowledge for Action.

MOBILIZING PUBLIC HEALTH ACTION ON CLIMATE CHANGE IN CANADA: The Chief Public Health Officer of Canada's Report on the State of Public Health in Canada 2022

Public Health Agency of Canada

2022

The 2022 Chief Public Health Officer of Canada (CPHO) annual report on the state of public health in Canada focuses on the impacts of climate change in and the role that public health systems can play in taking climate action.

THE REPRESENTATIVE CONCENTRATION PATHWAYS: AN OVERVIEW

van Vuuren et al. 2011 [57]

This paper provides a summary of the development process and main characteristics of the Representative Concentration Pathways (RCPs).

AR6 Synthesis Report: Summary for Policy Makers

Intergovernmental Panel on Climate Change

2023

This report integrates the main findings of the Sixth Assessment Report (AR6) based on contributions from the three Working Groups and summarizes the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation.

References

[1] IPCC, “Annex I: Glossary,” in Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, R. van Diemen, Ed., Geneva, IPCC, 2019.

[2] IPCC, Managing the risks of extreme events and disasters to advance climate change adapation, C. Field, V. Barros, T. Stocker, D. Qin, D. Dokken, K. Ebi, M. Mastrandrea and K. e. a. Mach, Eds., Cambridge: IPCC, 2012.

[3] IPCC, Climate Change 2007: Synthesis Report, A. Allali, R. Bojariu, S. Diaz and e. al., Eds., IPCC, 2007, p. 73.

[4] F. Delaney, P. Ng, K. Dokoska, G. Milner, K. Potter and M. Notaro, “Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region,” Ontario Climate Consortium, Toronto, 2020.

[5] I. Charron, “A Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions,” Ouranos, 2016.

[6] W. Crins, P. Gray, P. Uhlig and M. Wester, The ecosystems of Ontario, Part 1: Ecozones and ecoregions, Peterborough, ON: Ontario Ministry of Natural Resources, Inventory, Monitoring and Assessment, 2009.

[7] X. Zhang, G. Flato, M. Kirchmeier-Young, L. Vincent, H. Wan, X. Wang and e. al., “Changes in temperature and precipitation across Canada; Chapter 4,” in Canada’s changing climate report, E. Bush and D. Lemmen, Eds., Ottawa, Government of Canada, 2019, pp. 112-193.

[8] E. Bush and D. S. Lemmen, Eds., Canada’s Changing Climate Report, Ottawa, Ontario: Government of Canada, 2019, p. 444.

[9] IPCC, “Summary for policymakers,” in Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fith assessment report of the intergovernmenal panel on climate change, Cambridge, UK and New York USA, Cambridge University Press, 2014.

[10] D. Hartmann, A. Klein Tank, M. Rusticucci, L. Alexander, S. Brönnimann, Y. Charabi, F. Dentener, E. Dlugokencky, D. Easterling, A. Kaplan, B. Soden, P. Thorne, M. Wild and P. Zhai, “Observations: Atmosphere and surface,” in Climate change 2013: The physical science basis. Contribution of working group I to the first assessment report of the intergovernmental panel on climate change, T. F. Stocker, D. Quin, G. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and M. PM, Eds., Cambridge and New York, Cambridge University Press, 2013, pp. 159-254.

[11] O. Boucher, D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S. K. Satheesh, S. Sherwood, B. Stevens and X. Zhang, “Clouds and aerosols,” in Climate change 2013: The physical science basis. Contribution of working group I to the fith assessment report of the intergovernmental panel on climate change, T. F. Stocker, D. Qin, G. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Eds., Cambridge and New York, Cambridge University Press, 2013, pp. 571-658.

[12] M. Molina and F. Rowland, “Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone,” Nature, vol. 249, pp. 810-812, 1974.

[13] W. Steffen, P. J. Crutzen and J. R. McNeill, “The anthropocene: Are humans now overwhelming the great forces of nature?,” AMBIO, vol. 36, pp. 614-621, 2007.

[14] Cambridge University Press, 2013, pp. 465-570.

[15] D. L. Hartmann, A. M. G. Klein Tank, M. Rusticucci, L. V. Alexander, S. Bronnimann, Y. Charabi, F. J. Dentener, E. J. Dlugokencky, D. R. Easterling, A. Kaplan, B. J. Soden, P. W. Thorne, M. Wild and P. M. Zhai, "Observations: Atmosphere and Surface," in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fith Assessment Report of the Intergovernmental Panel on Climate Change, T. F. Stocker, D. Qin, G. -. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Eds., Cambridge; New York, Cambridge University Press, 2013, pp. 159-254.

[16] N. L. Bindoff, P. A. Stott, K. M. AchutaRao, M. R. Allen, N. Gillet, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I. I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, "Detection and attribution of climate change: From global to regional," in Climate change 2013: The physical science basis. Contribution of working group I to the firth assessment repor of the intergovernmental panel on climate change, T. F. Stocker, D. Qin, G. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Naguels, Y. Xia, V. Bex and P. M. Midgley, Eds., Cambridge and New York, Cambridge University Press, 2013, pp. 867-952.

[17] H. Ritchie and M. Roser, "CO2 and greenhouse gas emissions.," Our world in data , 2019. [Online]. Available: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

[18] World Resources Institute, "Climate Watch," Climate Watch, 2020. [Online]. Available: https://www.climatewatchdata.org/ghg-emissions.

[19] BP, "BP statistical review of world energy data," BP, 2020. [Online]. Available: www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

[20] FAO, "State of the world's forests," UN Food and Agriculture Organization , Rome, 2020.

[21] T. Searchinger, R. Waite, C. Hanson, J. Ranganathan and P. Dumas, World resources synthesis report. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050, E. Matthews, Ed., Washington, DC: , World Resources Institute, the World Bank Group, the United Nations Environment Programme, the, 2019.

[22] FAO, "State of the world's forests 2016. Forests and agriculture: Land-use challenges and opportunities," FAO, Rome, 2016.

[23] K. Butterbach-Bahl, E. Baggs, M. Dannenmann, R. Kiese and S. Zechmeister-Boltenstern, "Nitrous oxide emissions from soils: How well do we understand the processes and their controls?," Philosophical Transactions of the Royal Society B, vol. 368, p. 20130122, 2013.

[24] IPCC, "2019 Summary for policymakers," in Climate change and land: An IPCC special report on climte change, desertification, land degradation, sustainable land management, food security, and greehouse gas fluxes in terrestrial ecosystems, P. Shukla, J. Skea, E. Calvo Buenida, V. Masson-Delmonte and e. al., Eds., IPCC, 2019.

[25] L. A. Vincent, X. Zhang, R. D. Brown, Y. Feng, E. J. Mekis, H. Milewska, H. Wan and X. L. Wang, "Observed trends in Canada's climate and influence of low-frequency variability modes," Journal of Climate, vol. 28, no. 11, pp. 4545-4560, 2015.

[26] E. Bush and D. S. Lemmen, Eds., Canada's Changing Climate Report, Ottawa, Ontario: Government of Canada, 2019, p. 444.

[27] E. Milewska and W. Hogg, "Spatial representativeness of a long-term climate network in Canada," Atmosphere-Ocean, vol. 39, pp. 145-161, 2001.

[28] J. Screen and I. Simmonds, "Declining summer snowfall in the Arctic: Causes, impacts and feedbacks," Climate Dynamics, vol. 38, pp. 2243-2256, 2012.

[29] R. Brown, D. Schuler, O. Bulygina, C. Derksen, K. Luojus, L. Mudryk, L. Wang and D. Yang, "Arctic terrestrial snow: In Snow Water Ice and Permafrost in the Arctic (SWIPA) 2017 Assessment," Arctic Monitoring and Assessment Programme, Oslo, 2017.

[30] D. Barber, W. Meier, S. Gerland, C. Mundy, M. Holland, S. Kern, Z. Li, C. Michel, D. Perovich, T. Tamura, J. Berge, J. Bowman, J. Christiansen, J. Ehn, S. Ferguson, M. Granskog, T. Kikuchi, H. Kuosa, B. Light, N. Lundholm and e. al., "Arctic Sea Ice: in snow water ice and permafrost in the Arctic (SWIPA) Assessment," Arctic Monitoring and Assment Programme, Oslo, 2017.

[31] J. Walsh, F. Fetterer, J. Stewart and W. Chapman, "A database for depicting Arctic sea ice variations back to 1850," Geographical Review, vol. 107, p. 89, 2017.

[32] J. Maslanik, J. Stroeve, C. Fowler and W. Emery, "Distribution and trends in Arctic sea ice through spring 2011," Geophysical Research Letters, vol. 38, 2011.

[33] N. Tandon, P. Kushner, D. Docquier and J. Wettstein, "Reassessing sea ice drift and its relationship to long term Arctic sea ice loss in coupled climate models," Journal of Geophysical Research, 2018.

[34] W. Rouse, C. Oswald, J. Binyamin, C. Spence, W. Schertzer, P. Blanken, N. Bussieres and C. Duguay, "The role of northern lakes in a regional energy balance," Journal of Hydrometeorology, vol. 6, p. 291, 2005.

[35] K. Griffiths, M. N, M. Sugar, D. M and J. Smol, "Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds," PLoS ONE, vol. 12, 2017.

[36] X. Bai, J. Wang, J. Austin, D. Schwab, R. Assel, A. Clites, J. Bratton, M. Colton, J. Lenters, B. Lofgren, T. Wohlleben, S. Helfrich, H. Vanderploeg, I. Luo and G. Leshkevich, "A record-breaking low ice cover over the Great Lakes during winter 2011/2012: Combined effects of a strong positive NAO and La Nina," Climate Dynamics, vol. 44, pp. 1187-1213, 2015.

[37] L. Brown and C. Duguay, "The response and role of ice cover in lake-climate interactions," Progress in Physical Geography , vol. 34, 2010.

[38] J. Wang, X. Bai, H. Hu, A. Clites, M. Colton and B. Lofgren, "Temporal and spatial variability of Great Lakes ice cover, 1973-2010," Journal of Climate, vol. 25, pp. 1318-1329, 2012.

[39] V. Romanovsky, S. Smith and H. Christiansen, "Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: A synthesis," Permafrost and Periglacial Processes, vol. 21, p. 106, 2010.

[40] S. Smith, A. Lewkowicz, C. Duchesne and M. Ednie, "Variability and change in permafrost termal state in northern Canada; Paper 237 in GEOQuébec 2015," in Proceedings, 68th Canadian Geotechnical Conference and 7th Canadian Conference on Permafrost, Québec, 2015.

[41] D. Olefeldt, S. Goswami, G. Grosse, D. Hayes, G. Hugelius, P. Kuhry, A. McGuire, V. Romanovsky, A. Sannel, E. Schuur and M. Turetsky, "Circumpolar distribution and carbon storage of thermokarst landscapes," Nature Communications, vol. 7, pp. 1-11, 2016.

[42] P. Schuster, K. Schaefer, G. Aiken, R. Antweiler, J. Dewild, J. Gryziec, A. Gusmeroli, G. Hugelius, E. Jafarov, D. Karabbenhoft, L. Liu, N. Herman-Mercer, C. Mu, D. Roth, T. Schaefer, R. Striegl, K. Wickland and T. Zhang, "Permafrost stores a globally significant amount of mercury," Geophysical Research Letters, vol. 45, pp. 1463-1471, 2018.

[43] X. Wang, G. Huang, B. Baetz and S. Xhao, "Probabilisitic projections of regional climatic changes over the Great Lakes Basin," Climate Dynamics, vol. 49, no. 7-8, pp. 2237-2247, 2017.

[44] EBNFLO Environmental AquaResource Inc, "Guide for assessment of hydrologic effects of climate change in Ontario," Ontario Ministry of Natural Resources, Ministry of the Environment, Credit Valley Conservation, 2010.

[45] E. Hawkins and R. Sutton, "The potential to narrow uncertainty in regional climate predictions," Bulletin of the American Meterological Society, vol. 90, pp. 1095-1107, 2009.

[46] R. Wilby, S. Charles, E. Zorita, B. Timbal, P. Whetton and L. Mearns, "Guidelines for use of climate scenarios developed from statistical downscaling methods," Intergovernmental Panel on Climate Change (IPCC), 2004.

[47] L. Flint and A. Flint, "Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis," Ecological Processes, vol. 1, no. 2, 2012.

[48] C. Castro, R. Pielke and G. Leoncini, "Dynamical downscaling: Assesment of value retained and added using the Regional Atmospheric Modeling System (RAMS)," Journal of Geophysical Research, vol. 110, pp. 1-21, 2005.

[49] H. Auld, H. Switzman, N. Comer, S. Eng, S. Hazen and G. Milner, "Climate trends and future projections in the Region of Peel," Ontario Climate Consortium, Toronto, 2016.

[50] C. Tebaldi, L. Mearns, D. Nychka and R. Smith, "Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations," Geophysical Research Letters, vol. 31, no. 24, pp. 1-5, 2004.

[51] J. Sheffield, A. Barrett, B. Colle, D. Nelun Fernando, R. Fu, K. Geli, Q. Hu and e. al., "North American climate in CMIP5 experiements. Part I: Evaluation of historical simulations of continental and regional climatology," Journal of Climate, vol. 26, no. 23, pp. 9209-9245, 2013.

[52] UN, "Long-range world population projection (1950-2300). Based on the 2002 revision," United Nations, New York, 2003.

[53] T. Hanaoka, M. Kawase, Y. Kainuma, H. Matsuoka and O. Ishii, "Greenhouse gas emissions scenarios database and regional mitigation analysis," NIES, Tsukuba, 2006.

[54] L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose and M. Tavoni, "International climate policy architectures: overview of the EMF 22 international scenarios," Energy Economics, vol. 31, no. suppl 2, pp. S64-S81, 2010.

[55] O. Edenhofer, B. Knopf, T. Barker, L. Baumstark, E. Bellevarat, B. Chateu, P. Criqui and e. al., "The economics of low stabilization: Model comparison of mitigation strategies and costs," The Energy Journal, vol. 31, pp. 11-48, 2010.

[56] P. Smith, P. Gregory, D. van Vuuren, M. Obersteiner, P. Havlik, M. Rounsevell, W. J, E. Stehfest and J. Bellbary, "Competition for land," Philosophical Transcations of the Royal Society B: Biological Sciences, vol. 365, pp. 2941-2957, 2010.

[57] D. van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. Hurtt and e. al., "The representaive concentration pathways: An overview," Climatic Change, vol. 109, pp. 5-31, 2011.

[58] IPCC, "Climate Change 2014 Synthesis Report Summary for Policymakers," 2014.

[59] M. Collins, R. Knutti, J. Arblaster, J.-L. Dufrense, T. Fichefet, P. Friedlingsten and e. al., "Long-term climate change: Projections, commitments and irreversibility," in Climate change 2013: The physical science basis; Contibution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, T. Stocker, D. Qin, G. Plattner, M. Tignor, S. Allen, A. Boschung and e. al., Eds., Cambridge and New York, Cambridge University Press, 2013, pp. 1029-1136.

[60] G. Li, X. Zhang, A. J. Cannon, T. Murdock, S. Sobie, F. W. Zwiers, K. Anderson and B. Qian, "Indicies of Canada's future climate for general and agricultural adaptation applications," Climatic Change, vol. 148, pp. 249-263, 2018.

[61] V. V. Kharin, F. X. Zhang, N. P. Gillett, F. Zwiers and K. J. Anderson, "Risks from Climate Extremes Change Differently from 1.5°C to 2.0°C Depending on Rarity," Earth's Future, vol. 6, no. 5, pp. 704-715, 2018.

[62] D. Jeong and L. Sushama, "Rain-on-snow events over North America based on two Canadian regional climate models," Climate Dynamics, vol. 50, pp. 303-316, 2018.

[63] L. Mudryk, C. Derksen, S. Howell, F. Laliberté, C. Thackeray, R. Sospedra-Alfonso, V. Vionnet, P. Kushner and R. Brown, "Canadian snow and sea ice: Historical trends and projections," The Cryosphere, vol. 12, p. 1157, 2018.

[64] M. Stuecker, C. Bitz, K. Armour, C. Proistosescu, S. Kang, S.-P. Xie and et al., "Polar amplification dominated by local forcing and feedbacks," Nature Climate Change, vol. 8, pp. 1076-1081, 2018.

[65] R. Assel, "Maximum freezing degree-days as a winter verity index for the Great Lakes, 1897-1977," Monthly Weather Review, vol. 108, pp. 1440-1445, 1980.

[66] IPCC, "Summary for policy makers," in Climate change 2023: Synthesis report. A report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the sixth assessment report of the Intergovernmental Panel on Climate Change, C. W. Team, H. Lee and J. Romero, Eds., Geneva, IPCC, 2023, p. 36.

APPENDIX 1.1

Modeling Future Climate Change

To understand how climate drivers may impact our climate in the future, scientists use computer simulations of the climate system, referred to as climate models. These models make projections of future climate based on different plausible future scenarios of GHG emissions (causing warming) and aerosol forcing (causing cooling).

Global Climate Models (GCMs)

Climate projections are based on computer models that represent the global climate system that are then scaled down to develop local projections. [1, 2]

Since many of the processes and feedbacks that shape the climate system function at a global scale, climate projections need to be made using global models. GCMs are combined atmosphere-ocean-land-sea ice models that project future changes in climate over the entire earth surface under various GHG emissions scenarios. [3, 2] These models develop climate projections with a coarse geographic resolutions, usually ranging between 110 and 500 kilometres by 110 to 500 kilometres on continental scales (**Figure A1.1.1**). [4]

GCM Spatial Resolutions

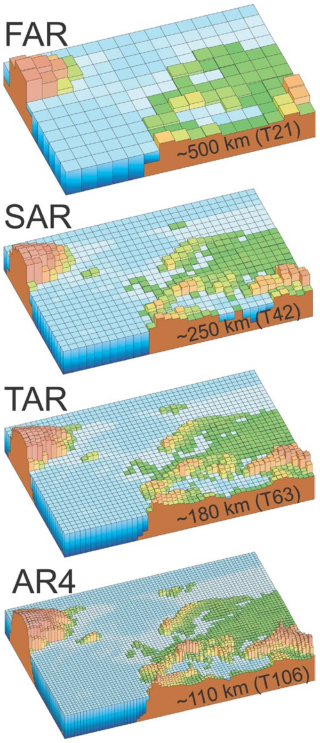
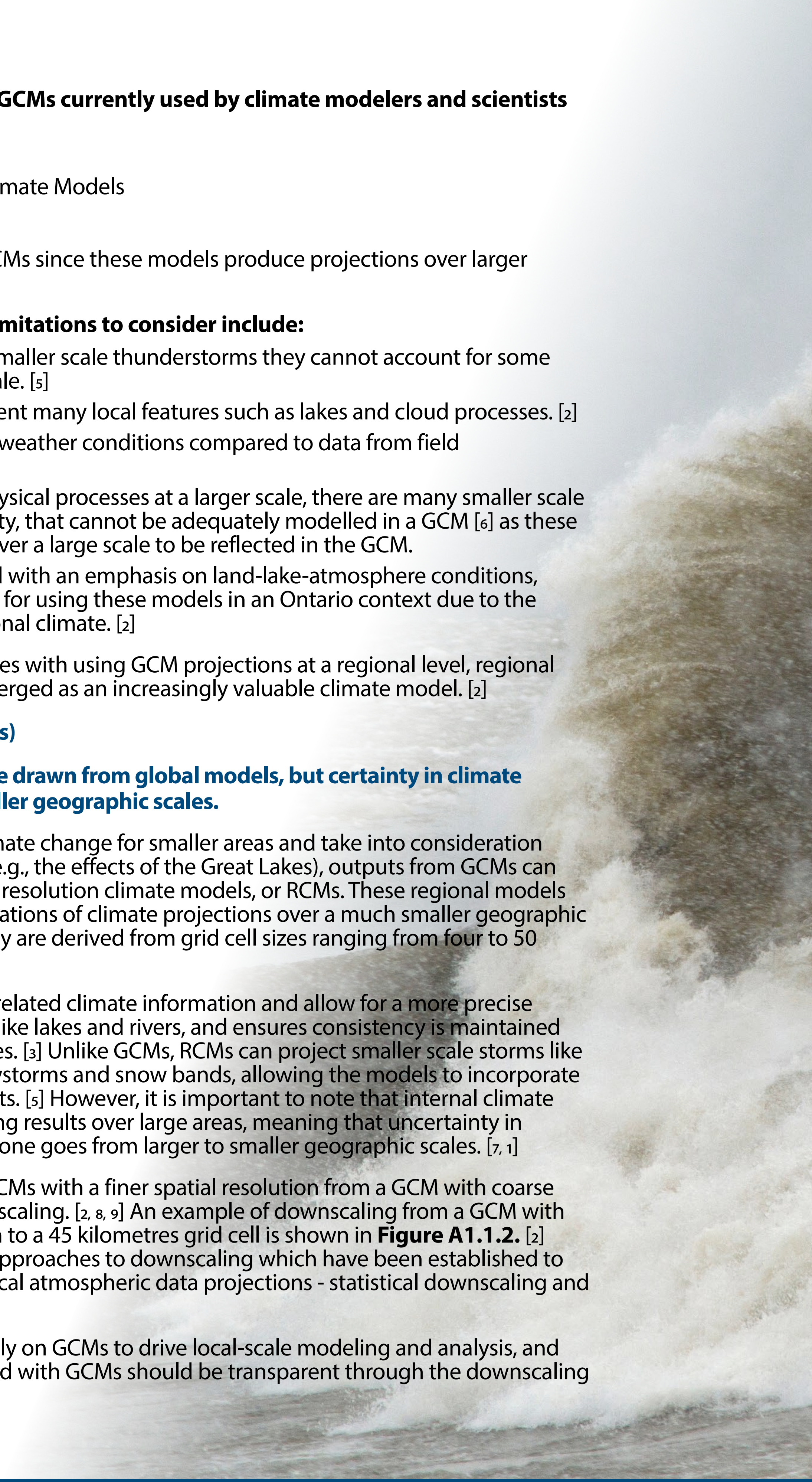


Figure A1.1.1 | Ranges of Global Climate Model (GCM) spatial resolutions ranging from approximately 110 km to 500 km spatial grids.

Figure Source: Adapted from IPCC, 2007. [6]



There are three main types of GCMs currently used by climate modelers and scientists [3]**:**

- Atmospheric General Models
- Atmospheric-Ocean Global Climate Models
- Earth System Models

There are many limitations in GCMs since these models produce projections over larger spatial scales.

Some of the most important limitations to consider include:

- Since GCMs cannot simulate smaller scale thunderstorms they cannot account for some extreme events at the local scale. [5]
- GCMs are known to misrepresent many local features such as lakes and cloud processes. [2]
- GCMs often dampen extreme weather conditions compared to data from field observations. [2]
- Since GCMs simulate many physical processes at a larger scale, there are many smaller scale processes, such as cloud activity, that cannot be adequately modelled in a GCM [6] as these processes must be averaged over a large scale to be reflected in the GCM.
- Most GMCs were not designed with an emphasis on land-lake-atmosphere conditions, which is a particular challenge for using these models in an Ontario context due to the Great Lakes' influence on regional climate. [2]

To address some of the challenges with using GCM projections at a regional level, regional climate models (RCMs) have emerged as an increasingly valuable climate model. [2]

Regional Climate Models (RCMs)

Regional climate models can be drawn from global models, but certainty in climate projections decrease with smaller geographic scales.

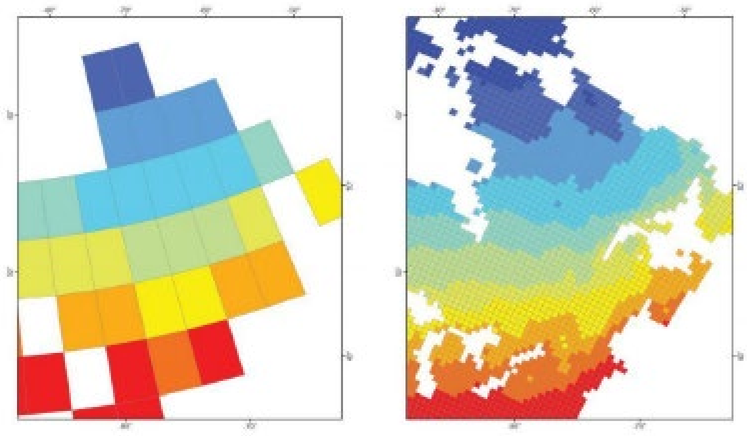
To understand the effects of climate change for smaller areas and take into consideration regionally-related information (e.g., the effects of the Great Lakes), outputs from GCMs can be downscaled to produce high resolution climate models, or RCMs. These regional models provide physically realistic simulations of climate projections over a much smaller geographic area; compared to the GCMs they are derived from grid cell sizes ranging from four to 50 kilometres. [3, 2]

RCMs produce more regionally-related climate information and allow for a more precise representation of land features, like lakes and rivers, and ensures consistency is maintained among different climate variables. [3] Unlike GCMs, RCMs can project smaller scale storms like thunderstorms, lake-effect snowstorms and snow bands, allowing the models to incorporate future storms and extreme events. [5] However, it is important to note that internal climate variability is reduced by averaging results over large areas, meaning that uncertainty in climate projections increases as one goes from larger to smaller geographic scales. [7, 1]

The method used to generate RCMs with a finer spatial resolution from a GCM with coarse spatial resolution is called downscaling. [2, 8, 9] An example of downscaling from a GCM with 200 kilometres spatial resolution to a 45 kilometres grid cell is shown in **Figure A1.1.2.** [2] There are two general types of approaches to downscaling which have been established to achieve detailed regional and local atmospheric data projections - statistical downscaling and dynamical downscaling. [2, 10]

Both downscaling techniques rely on GCMs to drive local-scale modeling and analysis, and ideally the uncertainty associated with GCMs should be transparent through the downscaling process. [8]

Downscaling



200 km x 200 km **45 km x 45 km**

Figure A1.1.2 | Downscaling from a GCM with 200 km spatial resolution to a 45 km grid cell.

Figure Source: Adapted from Delaney et al, 2020. [2]

Statistical Downscaling

This method of downscaling is based on a statistical model that compares large-scale climate variables form GCMs to smaller scale regional or local climate variables. [8]

This downscaling method relies on historical relationships between climate variables at different scales, also referred to as stationary assumption. [11] There are three types of statistically downscaled approaches that can be used, including:

1. Weather classification schemes
2. Regression models
3. Weather generators

As the impacts of climate change become more significant, using a stationary assumption, or in other words, relying on historical radiative forcing conditions, will result in greater uncertainty between the statistically downscaled data. [2] This is because important feedback cycles in the climate will not be accounted for in these projections.

This approach is not recommended as it is not physically verifiable [8] and it cannot account for future changes in climate, particularly extreme weather events and processes that are dependent on other climate forces. [2] Additionally, most statistical downscaling methods underestimate observed extremes. [2]

Dynamical Downscaling

This method of downscaling adds value to the downscaling estimates by incorporating additional physics of Earth's atmosphere (e.g., wind). [2]

This approach involves running a very high-resolution statistical model once over the area or region of interest driven by global climate model boundary conditions. Generally, you can either have 'many model runs at coarse resolution' or 'few model runs at high resolution'. [2, 3] The high-resolution models are called Regional Climate Models (RCM).

Traditional dynamical downscaling incorporates GCM data to provide the initial conditions for the model and then RCMs are integrated using the initial data and the boundary conditions form the GCM to develop the projections. Successful downscaling of RCMs requires incorporation of GCM radiative forcing into the RCM though development of a buffer zone, where the GCM and RCM both maintain their consistency which allows the RCM to produce its own smaller scale climate modeling. [2]

Depending on the purpose of the downscaling, RCMs can develop five types of downscaling, including [2]:

- Short-term weather predictions
- Seasonal predictions
- Regional weather simulations
- Seasonal predictions
- Climate prediction

Using an Ensemble Approach

Previous research has shown that no single model exists that can determine all possible future climates. [12] To get around this challenge, the joint, or multi-model approach, uses multiple models together to produce a full range of possible climate scenarios and represents those projections using statistical distributions. [2]

Previous research has demonstrated that the use of a single model to project climate trends increases the number of error within the climate modeling and can result in a misinterpretation of climate trends. [11] This is because each individual model represents specific climatological processes and has its own set of biases. [13] To get around the challenges identified with using a single model for projecting possible future climates, an joint, or multi-model approach, has been developed to use multiple models together to produce a full range of possible climate scenarios and represents those projections using statistics distributions. [2] Several joint approaches exist including CORDEX (Coordinated Regional Climate Downscaling Experiment) and NARCCAP (North American Regional Climate Change Assessment Program) among others.

Using a multi-model approach provides better predictions and compares more closely to historical observations than one single model. [11] With this approach, individual biases present in a single model tend to be reduced while the uncertainty associated with the overall process is maintained. [2] Representing the projections using statistical distributions allows the users to interpret trends probabilistically and address the uncertainties associated with the climate modelling process. [11]

Ensembles may consist of multiple GCMs, combined with a single or multiple RCMs, one GCM combined with multiple RCMs, or simply running one single model with a group of "runs" to multiple climate scenarios.

Climate Change Scenarios

A major uncertainty associated with modeling and projecting future climate is the future of human behaviour, technology, and the amount of carbon in the atmosphere.

In climate modeling, there are a series of plausible pathways or scenarios that represent the relationships among human behaviour, emissions, GHG concentrations, and temperature change. The most recently produced and commonly used scenarios are called Representative Concentration Pathways (RCPs). There are currently four RCPs endorsed by the IPCC listed in **Table A1.1.1** below that are commonly used as best practice in climate research. [14, 2]

Each RCP projection is based on a scenario from the scientific literature which includes a socioeconomic development pathway. These scenarios include assumptions and projections for the following key socioeconomic drivers:

- **Population growth** [15]
- **Economic activity:** primarily GDP [16]
- **Energy consumption:** includes things like primary energy consumption, oil consumption, carbon, and energy intensities [16, 17, 18]
- **Land use:** crop land, grassland, and vegetation [19]

Additionally, each RCP projection considers the impacts of different policies that may reduce GHG emissions. [20, 2] It is important to note that the socioeconomic scenarios underlying each RCP should not be considered unique. [20] The socioeconomic scenario for each RCP is based on is just one of many possible scenarios available in the scientific literature that could be consistent with the concentration pathway.

Table A1.1.1. **A summary of the four IPCC endorsed Representative Concentration Pathways (RCPs)**

Data source: *Adapted from Delaney et al. 2020 [2] and van Vuuren et al., 2011. [20]*

RCP	Definition	Scenario component		
		GHG emissions	Agricultural area	Air pollution
Worst-case scenario				
RCP 8.5	**Highest emission scenario**: Carbon dioxide (CO_2) emissions continue to rise throughout the rest of the century. [21]	High baseline	Medium for both cropland and pasture	Medium-high
Intermediate scenarios				
RCP 6.0	**Second highest emission scenario:** CO_2 emissions peak around 2080 and then start decreasing. [21]	Medium baseline; high mitigation	Medium for cropland by very low for pasture (total low)	Medium
RCP 4.5	**Second lowest emission scenario:** CO_2 emissions peak around 2040 and start decreasing by 2045 to reach half of the levels produced in 2050 by 2100. [21]	Very low baseline; Medium-low mitigation	Very low for both cropland and pasture	Medium
Best-case scenario				
RCP 2.6	**Lowest emission scenario:** Considered to be a very stringent pathway which would require all the main greenhouse gas emitting countries to participate in climate change mitigation. In this scenario, CO_2 emissions needed to begin decreasing in 2020 and reach zero by 2100. [21]	Very low	Medium for cropland and pasture	Medium-low

Each RCP plots a different emissions trajectory, or pathway, and cumulative GHG concentrations from a starting period until 2100 based on the socioeconomic scenarios described above. (**Figure A1.1.5**). [20, 2] When assessing the time periods for each projection (e.g., short-term vs. long-term), keep in mind the uncertainty of each projection decreases as we move farther through time. For example, there is less variation or uncertainty for short-term projections compared to long-term projections because we have more data available for estimating how things may look in the next 10 to 20 years.

It is also important to note the underlying scenarios developed for the RCPs were based on independent efforts from four individual climate modeling groups. This means that the RCPs do not necessarily form a complete set of elements other than the emissions and concentrations of the main GHGs and associated radiative forcing. [20] For example, the RCP 4.5 and 2.6 scenarios with lower radiative forcing are not developed from the RCP 6.0 and RCP 8.5 scenarios with higher radiative forcing levels. Differences between the RCPs, therefore, cannot be directly interpreted because of climate policy or specific socioeconomic developments, as they may be a result of differences between the models themselves. [20, 3]

Since RCPs are standardized, they allow different groups of scientists to estimate future climate projections in a consistent way. This allows for comparisons to be made. They provide a basis for assessing the risk of crossing pre-identified emissions thresholds in terms of both physical change in the environment and impacts on biological, ecological, and human systems. Ideally, climate change models that capture the best available science and considerations are used to assess potential risks and impacts. [2] Currently, the high emissions (RCP8.5) scenario is the most frequently used RCP by climate modelers and scientists. [2]

Trends in Ghgs

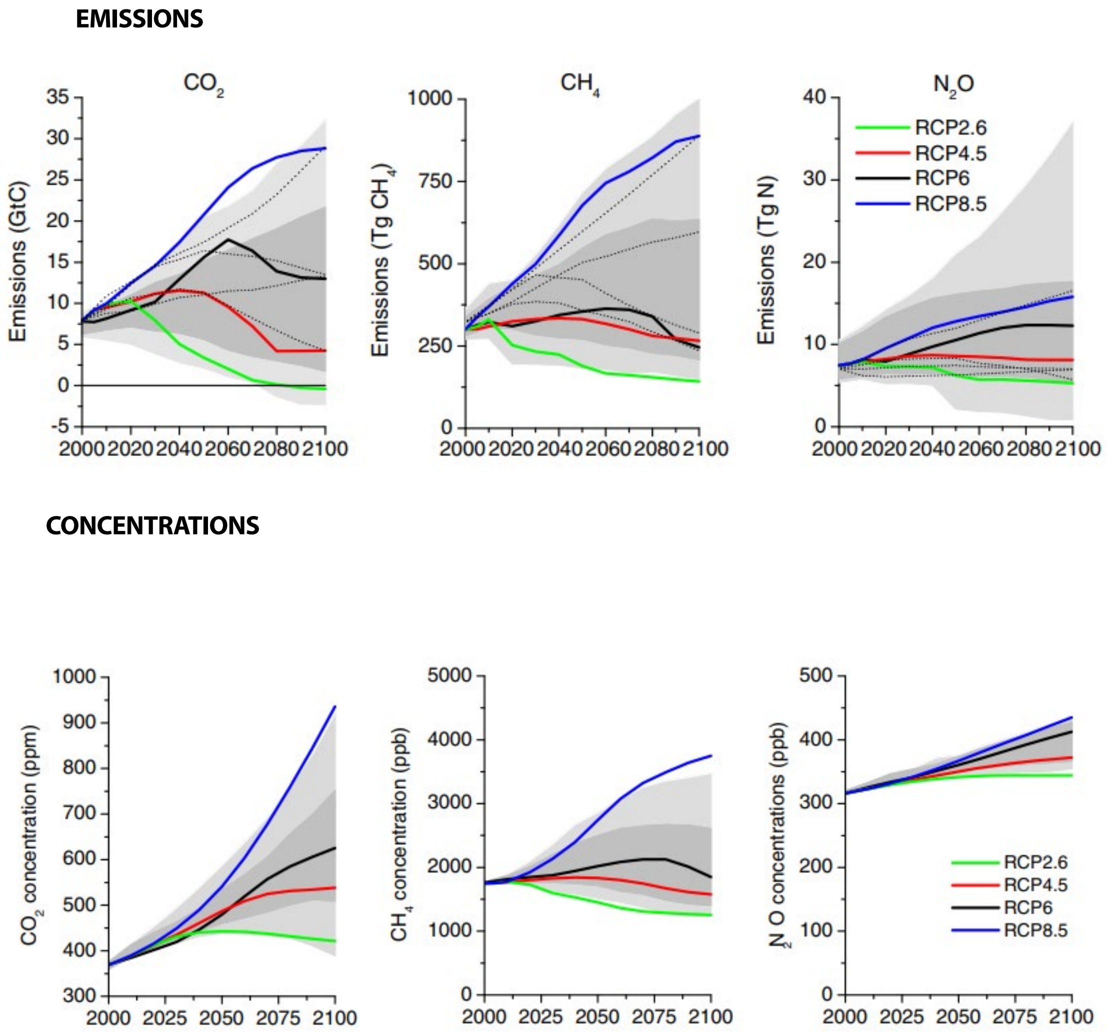


Figure A1.1.3 | Graphs demonstrating annual GHG emissions (top) and concentrations (bottom) for the four RCPs from 2000 to 2100 for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

The grey area on the graphs identifies the 98th (dark grey) and 90th (light grey) percentiles of the literature.

Figure Source: Adapted from Van Vuuren et al. 2011. [20]

Additional Resources

GUIDE TO CONDUCTING A CLIMATE CHANGE ANALYSIS AT THE LOCAL SCALE: LESSONS LEARNED FROM DURHAM REGION

Ontario Climate Consortium (OCC)

2020

This guide provides climate projections for the Region, and information to municipalities on how to undertake their own climate modeling studies.

THE REPRESENTATIVE CONCENTRATION PATHWAYS: AN OVERVIEW

van Vuuren et al. 2011 [20]

This paper provides a summary of the development process and main characteristics of the Representative Concentration Pathways (RCPs).

References

[1] E. Bush and D. S. Lemmen, Eds., Canada's Changing Climate Report, Ottawa, Ontario: Government of Canada, 2019, p. 444.

[2] F. Delaney, P. Ng, K. Dokoska, G. Milner, K. Potter and M. Notaro, "Guide to Conducting a Climate Change Analysis at the Local Scale: Lessons Learned from Durham Region," Ontario Climate Consortium, Toronto, 2020.

[3] I. Charron, "A Guidebook on Climate Scenarios: Using Climate Information to Guide Adaptation Research and Decisions," Ouranos, 2016.

[4] X. Wang, G. Huang, B. Baetz and S. Xhao, "Probabilisitic projections of regional climatic changes over the Great Lakes Basin," Climate Dynamics, vol. 49, no. 7-8, pp. 2237-2247, 2017.

[5] EBNFLO Environmental AquaResource Inc, "Guide for assessment of hydrologic effects of climate change in Ontario," Ontario Ministry of Natural Resources, Ministry of the Environment, Credit Valley Conservation, 2010.

[6] IPCC, Climate Change 2007: Synthesis Report, A. Allali, R. Bojariu, S. Diaz and e. al., Eds., IPCC, 2007, p. 73.

[7] E. Hawkins and R. Sutton, "The potential to narrow uncertainty in regional climate predictions," Bulletin of the American Meterological Society, vol. 90, pp. 1095-1107, 2009.

[8] R. Wilby, S. Charles, E. Zorita, B. Timbal, P. Whetton and L. Mearns, "Guidelines for use of climate scenarios developed from statistical downscaling methods," Intergovernmental Panel on Climate Change (IPCC), 2004.

[9] L. Flint and A. Flint, "Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis," Ecological Processes, vol. 1, no. 2, 2012.

[10] C. Castro, R. Pielke and G. Leoncini, "Dynamical downscaling: Assesment of value retained and added using the Regional Atmospheric Modeling System (RAMS)," Journal of Geophysical Research, vol. 110, pp. 1-21, 2005.

[11] H. Auld, H. Switzman, N. Comer, S. Eng, S. Hazen and G. Milner, "Climate trends and future projections in the Region of Peel," Ontario Climate Consortium, Toronto, 2016.

[12] C. Tebaldi, L. Mearns, D. Nychka and R. Smith, "Reginal probabilities of precipitation change: A Bayesian analysis of multimodel simulations," Geophysical Research Letters, vol. 31, no. 24, pp. 1-5, 2004.

[13] J. Sheffield, A. Barrett, B. Colle, D. Nelun Fernando, R. Fu, K. Geli, Q. Hu and e. al., "North American climate in CMIP5 experiements. Part I: Evaluation of historical simulations of continental and regional climatology," Journal of Climate, vol. 26, no. 23, pp. 9209-9245, 2013.

[14] IPCC, "Summary for policymakers," in Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fith assessment report of the intergovernmenal panel on climate change, Cambridge, UK and New York USA, Cambridge University Press, 2014.

[15] UN, "Long-range world population projection (1950-2300). Based on the 2002 revision," United Nations, New York, 2003.

[16] T. Hanaoka, M. Kawase, Y. Kainuma, H. Matsuoka and O. Ishii, "Greenhouse gas emissions scenarios database and regional mitigation analysis," NIES, Tsukuba, 2006.

[17] L. Clarke, J. Edmonds, V. Krey, R. Richels, S. Rose and M. Tavoni, "International climate policy architectures: overview of the EMF 22 international scenarios," Energy Economics, vol. 31, no. suppl 2, pp. S64-S81, 2010.

[18] O. Edenhofer, B. Knopf, T. Barker, L. Baumstark, E. Bellevarat, B. Chateu, P. Criqui and e. al., "The economics of low stabilization: Model comparison of mitigation strategies and costs," The Energy Journal, vol. 31, pp. 11-48, 2010.

[19] P. Smith, P. Gregory, D. van Vuuren, M. Obersteiner, P. Havlik, M. Rounsevell, W. J, E. Stehfest and J. Bellbary, "Competition for land," Philosophical Transcations of the Royal Society B: Biological Sciences, vol. 365, pp. 2941-2957, 2010.

[20] D. van Vuuren, J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. Hurtt and e. al., "The representaive concentration pathways: an overview," Climatic Change, vol. 109, pp. 5-31, 2011.

[21] IPCC, "Climate Change 2014 Synthesis Report Summary for Policymakers," 2014.