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SUPPLEMENT

Canada's Changing Climate Report

in Light of the Latest Global Science Assessment

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Authors

Elizabeth Bush (Environment and Climate Change Canada)

Barrie Bonsal (Environment and Climate Change Canada)

Chris Derksen (Environment and Climate Change Canada)

Greg Flato (Environment and Climate Change Canada)

John Fyfe (Environment and Climate Change Canada)

Nathan Gillett (Environment and Climate Change Canada)

Blair J.W. Greenan (Fisheries and Oceans Canada)

Thomas S. James (Natural Resources Canada)

Megan Kirchmeier-Young (Environment and Climate Change Canada)

Lawrence Mudryk (Environment and Climate Change Canada)

Xuebin Zhang (Environment and Climate Change Canada)

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Environment and Climate Change Canada

Public Inquiries Centre

12th Floor, Fontaine Building

200 Sacré-Coeur Boulevard

Gatineau QC K1A 0H3

Telephone: 819-938-3860

Toll Free: 1-800-668-6767 (in Canada only)

Email: ec.enviroinfo.ec@canada.ca

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Preface

The Intergovernmental Panel on Climate Change (IPCC) assessments of climate change science comprehensively review the state of knowledge produced by the global science community, and they are used to inform governments around the world about taking action to address the risks from climate change. By providing this foundational state-of-knowledge assessment of the climate system and how it responds to human influences, and of large-scale changes in climate, the IPCC assessments underpin Canada's climate change assessments. The 2019 Canada's Changing Climate Report (CCCR) assessed the state of knowledge on how and why Canada's climate has changed and what changes are projected for the future. International and national assessments are complementary, and both are needed to inform Canadian decision-makers.

The Working Group I Contribution to the IPCC Sixth Assessment Report (AR6 WGI) – Climate Change 2021: The Physical Science Basis– was released in August 2021. Many of the updated science findings, particularly for regions of North America, are broadly relevant to the CCCR key messages. The purpose of this document is to provide some perspectives on the implications of the AR6 WGI's findings regarding the conclusions of the CCCR.

Summary

The 2019 Canada's Changing Climate Report (CCCR) remains an authoritative source of information on past and future changes in Canada's climate. New science assessed in the Working Group I Contribution to the Intergovernmental Panel on Climate Change Sixth Assessment Report (AR6 WGI) provides additional information on regional changes in climate to support regional risk assessment. While the AR6 WGI did not assess changes in climate for Canada as a whole, many of the global and regional findings are consistent with, and in some cases strengthen the evidence for, the conclusions of the CCCR (*see* Table Summary.1).

The following conclusions from the AR6 WGI are particularly relevant to Canada's Changing Climate: amplification of warming for northern regions is a robust feature of both past and future warming, and further declines in snow cover, glaciers, sea ice and permafrost extent are projected with additional warming; changes in many types of extremes are already observed, their attribution to human influence has strengthened, and changes in many types of extremes are expected to increase in frequency and severity with every additional increment of global warming; continued global warming is projected to further intensify the global water cycle, including its variability and the severity of wet and dry events; the frequency and severity of extreme sea-level events will also increase where relative sea level is projected to rise. The CCCR's conclusions, in particular the ten headline statements that tell a concise story about Canada's changing climate based on the findings of that Report, are all closely aligned with and well supported by key findings in the Summary for Policymakers (SPM) of the AR6 WGI report (*see* Table Summary.1).

Table Summary.1: Assessment of consistency of Canada's Changing Climate Report (CCCR) Headline Statements with conclusions of the latest global science assessment of the Intergovernmental Panel on Climate Change (IPCC)

CCCR Headline Statements represent conclusions for which there is at least *high confidence*. IPCC Summary for Policymakers (SPM) conclusions are expressed as either statements of fact, or with calibrated qualifiers expressing assessed levels of confidence in and/or likelihood of an outcome[1]. The assessment of consistency in this Table was based on expert judgment of the authors of this document. Green circles with checkmarks indicate that IPCC conclusions are generally consistent with and support the CCCR findings although the spatial scales and time periods of analysis for observed and projected changes may differ. Open grey circles indicate that consistency could not be assessed because conclusions on the topic were out of scope for the WGI assessment. Statements in blue font are direct quotes from the CCCR and IPCC SPM, and the font style is consistent with that in the original source. Explanatory text is in grey font.

CCCR HEADLINE STATEMENTS[2]		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS[3]
Canada's climate has warmed and will warm further in the future, driven by human influence.	✔	**It is unequivocal that human influence has warmed the atmosphere, ocean and land.**
Global emissions of carbon dioxide from human activity will largely determine how much warming Canada and the world will experience in the future, and this warming is effectively irreversible.	✔	**From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions.**
Both past and future warming in Canada is, on average, about double the magnitude of global warming. Northern Canada has warmed and will continue to warm at more than double the global rate.	✔	It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming.
Oceans surrounding Canada have warmed, become more acidic, and less oxygenated, consistent with observed global ocean changes over the past century.	✔	It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and *medium confidence* that human influence contributed to this drop.
Ocean warming and loss of oxygen will intensify with further emissions of all greenhouse gases, whereas ocean acidification will increase in response to additional carbon dioxide emissions. These changes threaten the health of marine ecosystems.	✔	Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions.

CCCR HEADLINE STATEMENTS[2]		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS[3]
The effects of widespread warming are evident in many parts of Canada and are projected to intensify in the future.	✓	**Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.**
In Canada, these effects include more extreme heat, less extreme cold, longer growing seasons, shorter snow and ice cover seasons, earlier spring peak streamflow, thinning glaciers, thawing permafrost, and rising sea level.	✓	**Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.**
Because some further warming is unavoidable, these trends will continue.	✓	**Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, proportion of intense tropical cyclones as well as reductions in Arctic sea ice, snow cover and permafrost.** All regions are projected to experience further increases in hot climatic impact-drivers (CIDs) and decreases in cold CIDs (*high confidence*). Further decreases are projected in permafrost, snow, glaciers and ice sheets, lake and Arctic sea ice (*medium to high confidence*).
Precipitation is projected to increase for most of Canada, on average, although summer rainfall may decrease in some areas.	✓	Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics (*very likely*).
Precipitation has increased in many parts of Canada, and there has been a shift toward less snowfall and more rainfall. Annual and winter precipitation is projected to increase everywhere in Canada over the 21st century. However, reductions in summer rainfall are projected for parts of southern Canada under a high emission scenario toward the late century.	✓	The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). Globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). **The SPM did not include much additional detail on regional and seasonal changes in precipitation, but support from the underlying chapters, and expert judgement based on these, determined these assessments are consistent.**
The seasonal availability of freshwater is changing, with an increased risk of water supply shortages in summer.	✓	There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*).
Warmer winters and earlier snowmelt will combine to produce higher winter streamflows, while smaller snowpacks and loss of glacier ice during this century will combine to produce lower summer streamflows.	✓	There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.

CCCR HEADLINE STATEMENTS[2]		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS[3]
Warmer summers will increase evaporation of surface water and contribute to reduced summer water availability in the future despite more precipitation in some places.	✓	**The SPM did not include much additional detail on seasonal changes in freshwater availability, but support from the underlying chapters, and expert judgement based on these, determined these assessments are consistent.**
A warmer climate will intensify some weather extremes in the future.	✓	With every additional increment of global warming, changes in extremes continue to become larger.
Extreme hot temperatures will become more frequent and more intense. This will increase the severity of heatwaves, and contribute to increased drought and wildfire risks.	✓	For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*).
While inland flooding results from multiple factors, more intense rainfalls will increase urban flood risks. It is uncertain how warmer temperatures and smaller snowpacks will combine to affect the frequency and magnitude of snowmelt-related flooding.	✓	A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks.
Canadian areas of the Arctic and Atlantic Oceans have experienced longer and more widespread sea-ice-free conditions.	✓	In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*).
Canadian Arctic marine areas, including the Beaufort Sea and Baffin Bay, are projected to have extensive ice-free periods during summer by mid-century.	✓	Additional warming is projected to further amplify permafrost thawing, and loss of seasonal snow cover, of land ice and of Arctic sea ice (*high confidence*). The Arctic is likely to be practically sea ice free in September at least once before 2050 under the five illustrative scenarios considered in this report, with more frequent occurrences for higher warming levels.
The last area in the entire Arctic with summer sea ice is projected to be north of the Canadian Arctic Archipelago. This area will be an important refuge for ice-dependent species and an ongoing source of potentially hazardous ice, which will drift into Canadian waters.	○	**Conclusions on this topic were out of scope for the WGI assessment.**
Coastal flooding is expected to increase in many areas of Canada due to local sea level rise.	✓	**Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts (*high confidence*).**

CCCR HEADLINE STATEMENTS[2]		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS[3]
Changes in local sea-level are a combination of global sea level rise and local land subsidence or uplift. Local sea level is projected to rise, and increase flooding, along most of the Atlantic and Pacific coasts of Canada and the Beaufort coast in the Arctic where the land is subsiding or slowly uplifting.	✔	It is *very likely* to *virtually certain* that regional mean relative sea level rise will continue throughout the 21st century, except in a few regions with substantial geologic land uplift rates.
The loss of sea ice in Arctic and Atlantic Canada further increases the risk of damage to coastal infrastructure and ecosystem as a result of larger storm surges and waves.	○	**Conclusions on this topic were out of scope for the WGI assessment.**
The rate and magnitude of climate change under high versus low emission scenarios project two very different futures for Canada.	✔	**Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.**
Scenarios with large and rapid warming illustrate the profound effects on Canadian climate of continued growth in greenhouse gas emissions. Scenarios with limited warming will only occur if Canada and the rest of the world reduce carbon emissions to near zero early in the second half of the century and reduce emissions of other greenhouse gases substantially.	✔	Scenarios with low or very low GHG emissions (SSP1-1.9 and SSP1-2.6) [in which CO_2 emissions decline to net zero around or after 2050 (Box SPM.1)] would have rapid and sustained effects to limit human-caused climate change, compared with scenarios with high or very high GHG emissions (SSP3-7.0 or SSP5-8.5) [in which CO_2 emissions roughly double from current levels by 2100 and 2050, respectively (Box SPM.1)] but early responses of the climate system can be masked by natural variability.
Projections based on a range of emission scenarios are needed to inform impact assessment, climate risk management, and policy development.	✔	**See Box SPM.1 Scenarios, Climate Models and Projections**

1 Level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain: 99–100% probability; very likely: 90–100% probability; likely: 66–100% probability; about as likely as not: 33–66% probability; unlikely: 0–33% probability; very unlikely: 0–10% probability; and exceptionally unlikely: 0–1% probability.

2 Bush, E. and Lemmen, D.S. (Eds.) (2019). Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, 444 p.

3 IPCC [Intergovernmental Panel on Climate Change]. (2021): Summary for Policymakers, in Climate Change 2021: The Physical Science Basis. (Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change), (Eds.) V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou . Cambridge University Press. In Press.

1.0 Introduction

This section provides some background about Canada's Changing Climate Report (CCCR) and the Assessments of the Intergovernmental Panel on Climate Change (IPCC). The purpose of the Report is explained and a road map to the remaining sections is provided.

1.1 Background

Canada's Changing Climate Report (CCCR; Bush and Lemmen, 2019) was published in 2019 as the first in a series of reports comprising the current national assessment, *Canada in a Changing Climate: Advancing our Knowledge for Action*. The CCCR assessed how and why Canada's climate is changing, and what changes are projected for the future, based on publicly available peer-reviewed scientific literature. The completion of the CCCR marked the first time that physical changes in climate across Canada had been comprehensively assessed as part of a national assessment process. Other reports from the national assessment provide a wealth of information about the consequences of climate change for Canadians, and how communities and businesses are adapting, and about building resilience to future changes. All national assessment reports are being made available to the Canadian public on the website ChangingClimate.ca as they are completed.

Internationally, the Intergovernmental Panel on Climate Change (IPCC) is the body responsible for periodically assessing the scientific basis of climate change, as well as the knowledge base on climate change impacts, adaptation and mitigation, to inform international climate policy (*see* Chapter 1, Box 1.1 in Canada's Changing Climate Report). IPCC Assessment Reports are internationally recognized as the most comprehensive and authoritative global assessments of climate change. The IPCC is currently in its Sixth Assessment cycle. The Working Group I Contribution to the Sixth Assessment Report (AR6 WGI report)—Climate Change 2021: The Physical Science Basis—was released in August, 2021 (IPCC, 2021a). The contributions of IPCC Working Groups II and III—Climate Change 2022: Impacts, Adaptation and Vulnerability, and Climate Change 2022: Mitigation of Climate Change—will be released in 2022 along with a final Synthesis Report.

The IPCC WGI assessments of changes in the climate system at the global scale anchor the assessments of changes in Canada's climate. Regional changes occur within the larger context of ongoing changes to the Earth's system as a whole in response to changes in human and natural factors. This context is the reason why the CCCR began with a summary of key findings from the previous IPCC Assessment Report—the Fifth Assessment (AR5)—about observed changes in large-scale indicators of climate change and the extent to which these could be attributed to human influence. The projections of future climate developed specifically for Canada provided in the CCCR used the climate models and emission scenarios featured in the IPCC AR5. Therefore, the CCCR also included a chapter explaining the basis for making projections of future climate.

The IPCC AR6 WGI report provides updated information and conclusions about large-scale climate changes and their causes, and features a new generation of climate models and emission scenarios that are used to develop projections of future climate for the world as a whole, as well as for a set of defined regions. Relative to previous IPCC WGI reports, the AR6 WGI provides additional emphasis and information about past and future changes in regional climate to help support regional risk assessments. New science presented in the AR6 WGI provides relevant information that contributes to our understanding of Canada's changing climate.

1.2 Purpose of this report

The purpose of this document is to provide some perspectives about the implications of the AR6 WGI findings for the conclusions of the CCCR. Not all topics covered in the CCCR will be discussed. Instead, the focus will be on those topics for which relevant updates and/or significant advances in science have been made, as assessed in the IPCC AR6 WGI. The intent is to enhance understanding of the broader picture of global and regional changes in climate, within which changes in climate in Canada are occurring, and to offer an expert perspective on the ongoing validity of the CCCR's conclusions regarding changes in Canada's climate. No new literature was assessed as part of this effort.

1.3 Roadmap to the report

In conformity with the approach adopted in the CCCR, this document also begins by communicating key conclusions on historical changes in climate at the global scale and on their attribution because this global context fundamentally sets the stage for assessing regional changes in climate. This is followed by an introduction to the new generation of climate models and emission scenarios used as the basis for projecting future global and regional climate change in the AR6 WGI report. Evaluation of future climate projections for Canada with these new models and scenarios, relative to those featured in the CCCR, is beyond the scope of this report; however, an overall perspective is provided about the general consistency of results for large-scale patterns of change. Subsequently, highlights from the assessment of regional changes in climate are discussed in the context of major topics covered in the CCCR.

To maintain consistency with IPCC conclusions, calibrated terms to express confidence in the results and their likelihood are maintained as in the original IPCC AR6 WGI assessment . Since the guidance to IPCC authors of the Sixth Assessment on the use of uncertainty terms has not changed since the AR5, the explanation of these terms and their usage by the IPCC presented in section 1.4.1 of the CCCR is still relevant (Chapter 1 — Canada's Changing Climate Report). References to chapters of the full AR6 WGI report (IPCC, 2021a) and to its Summary for Policymakers (IPCC, 2021b), from which conclusions have been drawn, are provided in square brackets, and direct quotations are indicated as such using quotation marks. Some technical terms are used in this document to describe elements of the climate system and/or their changes. The CCCR glossary (Definitions — Canada's Changing Climate Report) is a useful reference for understanding these terms.

2.0 Global Changes

This section highlights some of the key findings from the Working Group I Contribution to the IPCC Sixth Assessment (AR6 WGI) about historical changes in climate at the global scale and their attribution. The basis of the updated assessment of possible future climates in the AR6 WGI report is also explained, as is the need for net-zero CO_2 emissions to stabilize the global temperature.

The AR6 WGI made use of updated observational evidence, attribution studies and newly available model results to assess past changes in climate, the role of human activities in driving those changes, and the range of future climates that would accompany different future emission pathways.

2.1 A warming climate system: Observed changes and their causes

In general, the AR6 WGI assessments of global or large-scale observed changes in climate and their attribution to human influence are strengthened compared to corresponding assessments in the AR5 WGI, which underpinned Canada's Changing Climate Report (*see* Chapter 2 — Canada's Changing Climate Report, and Table 1). This strengthened assessment in the AR6 WGI assessment draws on observations from seven more years (since the previous assessment was completed in 2013), during which the climate system has continued to warm considerably, and emissions of greenhouse gases (GHGs) from human activity (anthropogenic emissions) have continued to increase. The assessment also draws on new and improved observational datasets for many climate system variables, and on new climate model simulations of historical changes in climate, which have been analyzed in a growing body of scientific literature.

The increased confidence about the role of human influence in climate system warming in the AR6 WGI compared to the AR5 WGI is clearly evident when comparing key conclusions from the respective reports.

The AR6 WGI concluded that:

> "It is unequivocal that human influence has warmed the atmosphere, ocean and land." [SPM A.1]

This statement is based on a synthesis of the evidence on changes across all components of the Earth's system, and applies to changes relative to pre-industrial times. In comparison, relevant conclusions from the AR5 WGI were that "warming of the climate system is unequivocal" [SPM Section B, IPCC, 2013]—a statement about observed changes only, without any attribution to human influence—and that "it is *extremely likely* that human influences have been the dominant cause of the observed global warming since the mid-20th century" [SPM D.3, IPCC, 2013], where attribution to human influence focused on changes in global temperature over a shorter time period.

2.1.1 Global temperature

Observed global warming since pre-industrial times can be fully explained by human factors, with little contribution from natural factors. As one line of evidence for this, the best estimate of human-caused global warming from the pre-industrial era to the most recent decade, and the best estimate of observed warming are both about 1.1 °C.

Furthermore, the AR6 WGI advanced understanding about the contribution of individual factors to global warming. These analyses showed that global warming from human emissions of greenhouse gases would have caused more warming than has been observed since some of the greenhouse-gas-induced warming has been offset by cooling effects from emissions of anthropogenic aerosols.

> "The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8 °C to 1.3 °C, with a best estimate of 1.07 °C. It is *likely* that well-mixed GHGs contributed a warming of 1.0 °C to 2.0 °C, other human drivers (principally aerosols) contributed a cooling of 0.0 °C to 0.8 °C, natural drivers changed global surface temperature by -0. 1 °C to 0.1 °C, and internal variability changed it by -0. 2 °C to 0.2 °C." [SPM A.1.3]

2.1.2 Other climate variables

Observed changes in temperature also led to the *high confidence* conclusions that climate zones have shifted poleward in both hemispheres, and that the growing season has on average lengthened by up to two days per decade since the 1950s in the Northern Hemisphere extratropics. [SPM A.1.8].

The AR6 WGI assessed it is likely that human influence contributed to the pattern of observed precipitation changes since the mid-20th century. It assessed that there is *medium confidence* that global average precipitation over land has *likely* increased since 1950 and that mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s. [SPM A.1.4]

Confidence in the drivers of observed changes in the global oceans has also increased compared to assessments in the AR5 WGI:

> "It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and *medium confidence* that human influence contributed to this drop. Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. Human influence was *very likely* the main driver of the increase since at least 1971." [SPM A.1.6 and SPM A.1.7]

Changes in elements of the cryosphere—snow, ice and permafrost—are discussed in section 3.5, where changes in the Canadian cryosphere are put in context with global-scale changes. Regional changes in the oceans and sea level are discussed in more detail in section 3.7.

2.1.3 Changes in extremes

The AR6 WGI report included, for the first time, a chapter dedicated to changes in extremes, which put forward stronger assessments of observed changes in extremes globally and their attribution relative to the AR5:

> "It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver of these changes." [SPM A.3.1]

> "The frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis (*high confidence*), and human-induced climate change is likely the main driver." [SPM A.3.2]

Overall, based on the assessment of many types of extremes, the AR6 WGI report concluded:

> "It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial times, in particular for temperature extremes." [Chapter 11, Executive Summary]

2.2 Possible Future Climates

Chapter 3 of the CCCR described what climate models are and how they are used to make projections of climate change, and also addressed future global-scale changes in climate. Relevant updates from the AR6 WGI report are provided below on these topics.

2.2.1 Stabilizing global temperature

The dominant role of anthropogenic CO_2 in past and future climate change was reaffirmed in the AR6 WGI. The AR6 WGI reaffirmed with *high confidence* the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions over time and the global warming that they cause [SPM D.1.1]. This relationship implies that there is a limit on how much more CO_2 can be emitted to hold global temperature to a specific level (taking non-CO_2 emissions into account). This relationship also implies that reaching net-zero CO_2 emissions, globally, is a precondition for stabilizing global temperature. As the AR6 WGI concluded:

> "From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net-zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions." [SPM D.1]

The reference to "*at least* net-zero CO_2 emissions" in this conclusion acknowledges that stabilizing global temperature at some levels—low levels in particular—may require global net *negative* CO_2 emissions. That is, if the limit on carbon emissions for a given global temperature goal were exceeded, excess positive emissions would need to be compensated by negative emissions . This is evident in the new set of emission scenarios featured in the AR6 WGI report (see below).

2.2.2 New emission scenarios

As in previous IPCC Assessments, future model-based climate projections are based on a range of scenarios that include information on changes in greenhouse gases and other climate-relevant emissions, as well as land-use change. The figure below shows the CO_2 emissions pathways in the five illustrative scenarios considered by the IPCC AR6 WGI (*see* AR6 WGI Figure SPM.4, which also shows contributions from a selection of non-CO_2 GHGs and aerosol emissions).

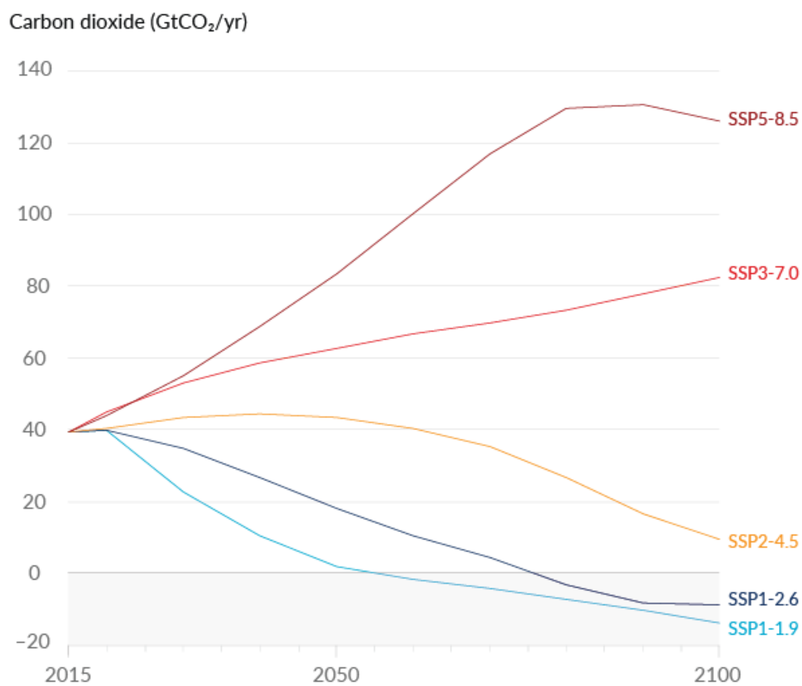

Figure 1: Future annual emissions of CO_2 across five illustrative scenarios. From Figure SPM.4, Panel (a), IPCC, 2021b.

All of the scenarios start in 2015, and range from high and very high GHG emissions (SSP3-7.0 and SSP5-8.5) where CO_2 emissions roughly double from current levels by 2100 and 2050, respectively, to very low and low GHG emissions where CO_2 emissions decline to net zero around or after 2050, followed by net negative CO_2 emissions (SSP1-1.9 and SSP1-2.6). These two lowest emission scenarios were selected to provide projections aligned with the Paris Agreement goals of limiting global warming to well below 2 °C (SSP1-2.6) and aiming for 1.5 °C (SSP1-1.9). The net negative global CO_2 emissions in these scenarios lead to small declines in global temperature after reaching peak temperature around or after 2050 (*see* Figure 2).

The naming scheme for these illustrative emission scenarios has two components. The "SSP" nomenclature refers to one of five Shared Socioeconomic Pathways, each of which is characterized by a set of socioeconomic assumptions consistent with a defined storyline about how societies and economies may develop during this century. The baseline conditions and consequent emissions from these storylines were then combined with different levels of climate change mitigation and air pollution controls. The numbers at the end of these scenarios (i.e., 1.9, 2.6, … 8.5) represent the approximate radiative forcing at year 2100 (in W/m2), with low numbers reflecting more stringent mitigation and hence a smaller warming influence. The scenario naming scheme allows for comparison with results based on earlier "Representative Concentration Pathways" (RCPs) that followed the same numbering scheme and were used in the IPCC AR5 and in the CCCR. The very low (1.9) scenario was not available for the AR5 or the CCCR, but was subsequently added for the AR6 to provide a scenario consistent with the most ambitious goal of the Paris Agreement. Additional information about the scenarios featured in the AR6 WGI is available in Cross-Chapter Box 1.4 in Chapter 1 of the AR6 WGI (Sixth Assessment Report (ipcc.ch)), and also on the Canadian Climate Data and Scenarios website.

2.2.3 New climate models

The sixth phase of the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP6) continued the coordinated efforts of climate modelling centres around the world to produce projections of future climate based on a common set of driving scenarios. Results from CMIP5 were assessed in the IPCC AR5 and used as the basis for projections of future climate in the CCCR.

The AR6 WGI found that the collection of models used in CMIP6 was improved in many ways over those used in CMIP5. However, the general characteristics of the new climate projections featured in the AR6 are very consistent with those in the AR5 and in the CCCR. The overall patterns of more warming over land than over the ocean, and more warming at high latitudes (particularly in the Arctic) are clearly evident and, given the strong relationships between mean warming and changes in other climate variables, the Canada-focused projection results in CCCR remain consistent with the new model results and updated scenarios. There are of course modest differences at smaller scales, but overall the results are very consistent, both qualitatively and quantitatively.

2.2.4 Assessed future climate outcomes

For the first time, the AR6 WGI provided assessed global temperature outcomes for a range of emission scenarios based on multiple lines of evidence rather than outcomes of model projections alone. This was done to reflect the emerging literature on observationally constrained climate model projections. Projections of most other climate quantities (e.g., precipitation, snow and sea-ice cover, etc.) were based solely on CMIP6 results, whereas the assessment of future sea-level rise was also based on multiple lines of evidence. Assessed global surface air temperature changes are shown below relative to the pre-industrial era (*see* Figure SPM.8, which also shows projections for Arctic sea ice cover, surface ocean acidity, and global sea-level rise).

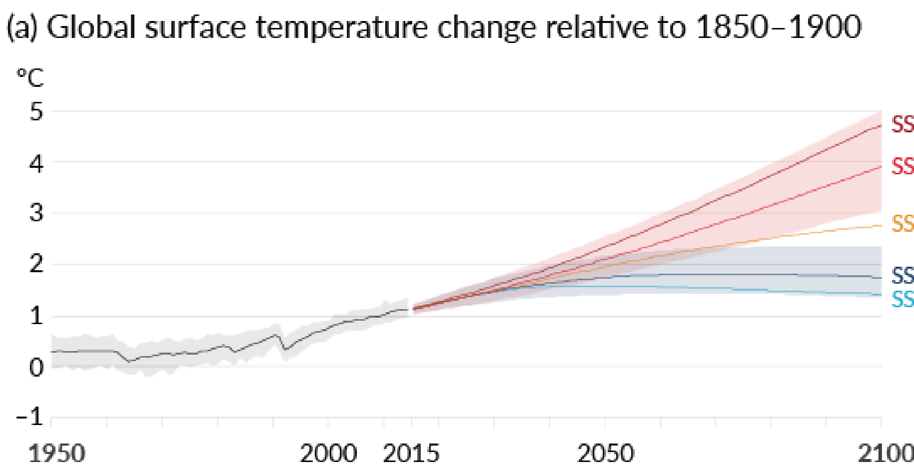

Figure 2: Global surface temperature change relative to 1850–1900. From Figure SPM.8, Panel (a), IPCC, 2021b.

Under the very-low-emission scenario, global warming is assessed to be 1.6 °C by mid-century (with a *very likely* range of 1.2 to 2.0 °C) and 1.4 °C by late century (with a *very likely* range of 1.0 to 1.8 °C) (*see* Table SPM.1). Other scenarios with higher emissions result in higher temperatures.

The IPCC AR6 WGI also presents future global and regional climate quantities at different levels of global warming. This is possible because of the close relationship between changes in global mean temperature and the corresponding changes in other variables. The aim was to provide a presentation that is easier to understand, more policy-relevant, and more closely tied to impacts of climate change, due to the fact that it eliminates much of the uncertainty related to scenarios and to modelled climate sensitivity.

3.0 Regional Changes and Implications for Canada

This section provides some highlights from the assessment of regional changes in climate in the AR6 WGI report and discusses these in the context of major topics covered in the CCCR.

3.1 Availability and interpretation of regional-scale information

An important advance in the AR6 is the increased emphasis on regional assessments of climate change and "climatic impact-drivers " to help support decision-makers at regional and national levels. The AR6 WGI report includes three chapters devoted to regional climate change, as well as an online Interactive Atlas providing users with the capability to download and plot observational and model results used in the AR6 for a standard set of variables associated with a set of defined regions (<https://interactive-atlas.ipcc.ch/>). Scenario-based future climates for different time periods are included in the Atlas, as well as regional projections for global warming of 1.5, 2, 3 and 4 °C.

The use of defined regions was intended to bring consistency across the AR6 to regional-scale assessments. The boundaries of the regions explicitly avoided aligning with political boundaries; therefore, Canada is covered by parts of five regions illustrated in Figure 3. The southern boundaries of the North-Eastern North America (NEN) and North-Western North America (NWN) regions are at 50 degrees north latitude. The AR6 WGI assessment was conducted at a regional scale, and findings should be interpreted as applying to a region as a whole. A regional assessment included review of the relevant literature and, for many variables, the calculation of averages across the region from observations and model simulations. Separate assessments would need to be conducted to extract information for sub-regions (e.g., to separate the Canadian portion of the Eastern North America region).

While many users will find that the climate information for North American regions in the IPCC WGI Atlas and for specific chapters is useful, the results cannot be directly compared to those in the CCCR due to different region definitions. Therefore, the CCCR remains an authoritative source of climate trends assessed for Canada as a whole. The CCCR also reported trends and projections for regions of Canada used in the national assessment process (which do follow political boundaries), with the caveat that uncertainties in regional-scale trends were not formally assessed and noting, in general, that the smaller the spatial scale of analysis, the lower the level of confidence in results, especially when assessing magnitudes of change (rather than direction) (*see* CCCR, Chapter 8, section 8.4).

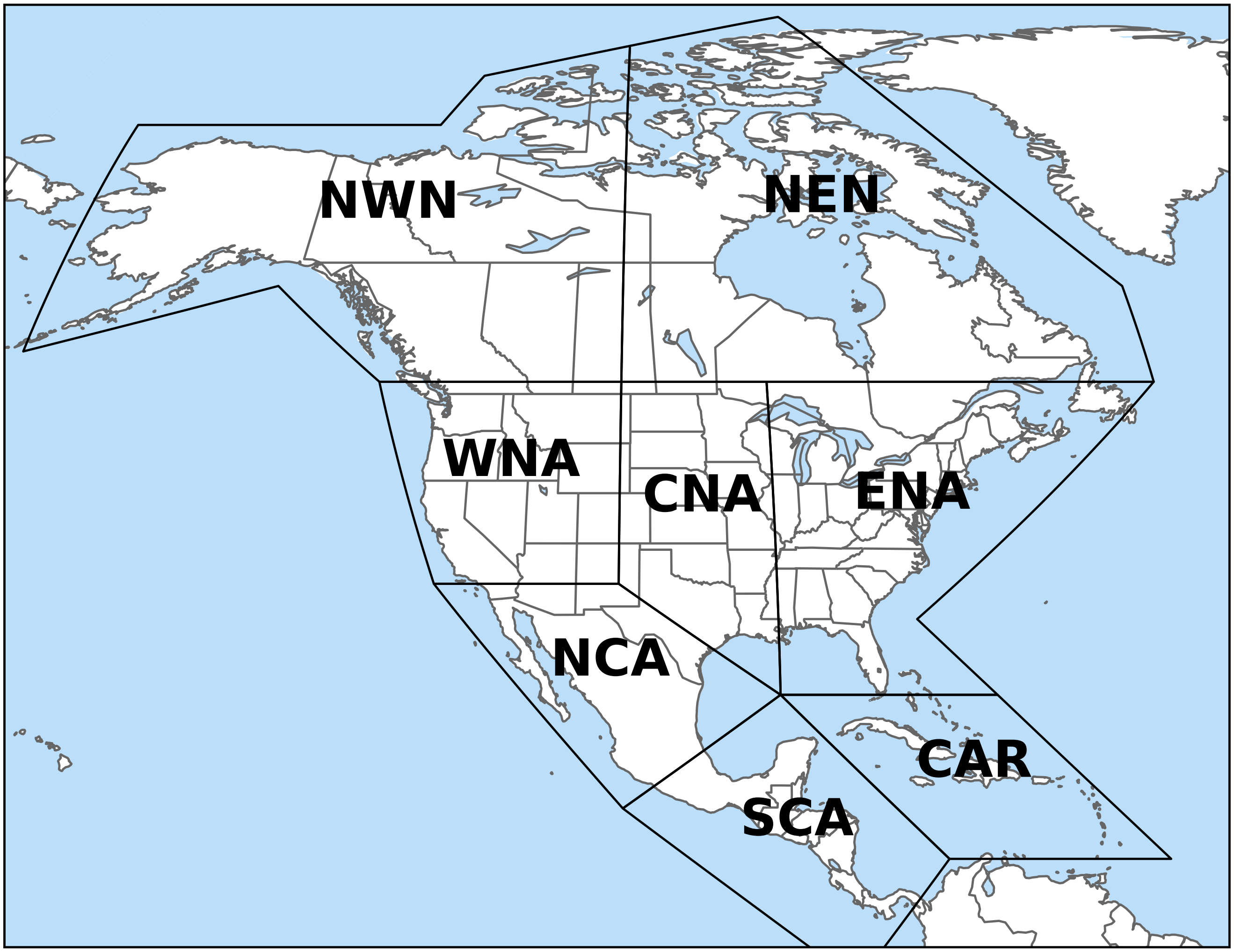

Figure 3: IPCC North America, Central America and the Caribbean regions for regional assessments of climate change in the AR6 WGI report. NWN: North-Western North America. NEN: North-Eastern North America. WNA: Western North America. CAN: Central North America. ENA: Eastern North America. NCA: Northern Central America. SCA: Southern Central America. CAR: Caribbean.

Canada-specific climate information, including data for provinces and territories, is also available through various portals and websites, including ClimateData.ca and the Canadian Climate Data and Scenarios website. These sites provide users with access to a range of climate datasets and products, for both historical and future changes in climate that are specific to Canada. Both sites provide high-resolution (downscaled) climate projections currently (November 2021), based on the CMIP5 suite of global climate models. Since ClimateData.ca is aimed at a broader audience, climate projections on that site are provided in easy-to-use formats and visualizations. Similar products specific to Canada based on CMIP6 projections, as well as some new products, will be released on these sites as they become available, including relative sea-level rise projections for Canadian coastlines that carefully account for vertical land motion of the Canadian land mass.

3.2 Common changes in climate across IPCC regions covering Canada

Changes in many variables in the regions over Canada are similar to changes throughout other global regions, especially those in the high latitudes of the Northern Hemisphere. Historical and future changes over Canada presented in the AR6 WGI are broadly consistent with those shown in the CCCR.

Sections 3.3–3.7 present information from the AR6 WGI report on regional changes in key climate variables that were assessed in the CCCR. Below, a few fundamental results common to all regions, including those covering Canada, are highlighted:

Human-driven global warming affects Canada and the globe, and all regions have already experienced changes in many aspects of their climate.

> "Human-induced climate change is already affecting many weather and climate extremes in every region across the globe" [SPM A.3]

Climate-model projections show that these observed changes will continue, with additional global warming for all regions of the world, including those regions covering Canada. With additional warming, new changes in other variables will also emerge on the regional scale. For most variables, larger changes are expected with larger increases in global mean temperature.

> "Many changes in the climate system become larger in direct relation to increasing global warming" [SPM B.2]

Every region has experienced and will continue to experience changes in multiple aspects of the climate system, including extremes of many climate variables. The changes discussed below for temperature and precipitation and related extremes, the cryosphere, the water cycle, and the oceans and sea level are all occurring simultaneously. When planning for the impacts of climate change, it will be important to consider that numerous changes are occurring in the same region at the same time, and that local vulnerabilities may overlap.

> "With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Changes in several climatic impact-drivers would be more widespread at 2 °C compared to 1.5 °C global warming, and even more widespread and/or pronounced for higher warming levels." [SPM C.2]

3.3 Changes in temperature and related extremes

Annual mean temperatures across the northern high latitudes, including in Canada, have increased more than the global mean. Seasonally, the largest increases in mean temperatures have been in winter. An increase in annual mean temperature has been observed in all AR6 regions in North America. In parts of the continent, including over Canada, this warming is attributed to human influence, consistent with the CCCR conclusion that human influence is the main driver of observed warming over Canada. Mean temperatures across Canada are projected to continue to increase, with larger changes associated with higher emission scenarios and thus greater increases in global mean temperature. Projected warming is largest over the northernmost regions of Canada and the Northern Hemisphere:

> "It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming." [SPM B.2.1]

In most of the IPCC regions covering Canada, there has been an observed increase in the intensity and frequency of hot extremes, and a decrease in the intensity and frequency of cold extremes. These changes are attributed to human influence on the climate. Weak or uncertain trends in the central and eastern US contributed to the assessment of a lack of observed trends in hot extremes for the regions of Central North America and Eastern North America, of which some of Canada is a small part. Further increases in the intensity and frequency of hot extremes and decreases in the intensity and frequency of cold extremes are projected in all North American regions and for the continent as a whole:

> "Increase in the intensity and frequency of hot extremes: *extremely likely* (compared with the recent past (1995–2014)), *virtually certain* (compared with pre-industrial times)". [AR6 WGI Table 11.19, for North America region at 2 °C of global warming]

Such changes in extremes are larger with higher levels of global warming. Additionally, recent record-breaking extreme events, such as the heatwave in western Canada in June 2021, occurred in a world where human influence on the climate has greatly increased the frequency and severity of hot extremes across the globe:

> "Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system." [SPM A.3.1]

Increasing temperatures influence many other components of the climate system, including through the increased capacity of the atmosphere to hold water, resulting in more heavy precipitation, and through increased evaporative demand that can cause more drought and reduced surface water availability. In addition, increasing temperatures will contribute to increases in fire weather, growing degree days, growing season length and cooling degree days, and a decrease in heating degree days. Considering that changes in mean and extreme temperatures in Canada will occur at the same time as changes in numerous other variables, it is important to prepare for climate impacts associated with changes in multiple climatic impact-drivers.

The AR6 WGI findings are very similar to those in the CCCR for changes in temperature and related extremes (*see* Chapter 4 — Canada's Changing Climate Report, and Table 1). The AR6 WGI assessment was based on additional evidence since the CCCR, including from new observational datasets and extended records (through 2020), and new model datasets. The AR6 WGI assessment used the same main metric for heat extremes as the CCCR. Although different region designations can complicate the comparison, the AR6 WGI assessment is fully consistent with the CCCR findings.

3.4 Changes in precipitation and related extremes

For most of the regions encompassing Canada (*see* Figure 3), the AR6 WGI concluded that mean precipitation did not show robust observed trends, with the exception of some increases in Central North America and Eastern North America. The CCCR concluded that there is *medium confidence* that annual mean precipitation has increased on average in Canada, with larger percentage increases in northern Canada (*see* Section 4.3 in Chapter 4 — Canada's Changing Climate Report). The challenges of sparse data and detecting small changes amongst large natural variability limit the identification of trends in precipitation on the scale of the AR6 regions. In particular, limited observing stations covering Canada's north, which is divided into two AR6 regions, inhibit an identification of robust trends compared to the national level assessment in the CCCR. In addition, the Atlas Chapter assessment for North America assessed trends for the period of 1960–2015, which does not include recent years of data.

Increases in mean annual precipitation and winter and spring precipitation are projected for several North American regions, most strongly in the northern and eastern portions of the continent and including most of Canada. Larger percentage increases are projected for the north, annually and during all seasons.

> "Mean precipitation is projected to increase in all polar, northern European and northern North American regions, most Asian regions and two regions of South America (*high confidence*)." [for 2 °C of global warming, SPM C.2.3]

During summer, increases are projected in Northeastern North America and Northwestern North America, but changes in other regions of the continent, including more southern areas of Canada, are uncertain. These annual and seasonal precipitation projections are all consistent with the CCCR.

The AR6 WGI concluded that at the continental scale, there has been a *likely* observed intensification of heavy precipitation over North America and that "Human influence *likely* contributed to the observed intensification of heavy precipitation" [for North America, Table 11.20]. Since the CCCR, a key advancement of the AR6 WGI assessment is increased evidence of human influence on the intensification of heavy precipitation at continental scales, including over North America. There is evidence of an observed increase in heavy precipitation in some AR6 regions, including Central North America and Eastern North America. As with mean precipitation, limited data in some areas and small changes amongst large variability inhibit the identification of trends at the regional scale for the other AR6 regions covering parts of Canada. This is consistent with the CCCR, which found no detectable trends in short-duration extreme precipitation for Canada as a whole. However, as was concluded in the CCCR for Canada, increases in heavy precipitation are projected for North America and all of its sub-regions, along with additional warming [AR6 WGI Chapter 11, Table 11.20]. For each region, increases in heavy precipitation are proportional to the global mean temperature increase, with larger changes accompanying greater increases in global warming. In addition, larger increases in frequency are projected for more rare events (e.g., a bigger change in the frequency of the 50-year event compared to the 10-year event).

The AR6 WGI findings for mean and extreme precipitation are broadly similar to those from the CCCR (*see* Chapter 4 — Canada's Changing Climate Report, and Table 1). The ability to distinguish changes in precipitation from the natural variability depends on the spatial scale considered, which can make it difficult to compare national results from the CCCR with AR6 WGI regional or continental results. An understanding of the physical climate system and the relationship between spatial scales increases confidence that results from the two reports are consistent.

3.5 Cryosphere changes

3.5.1 Observed changes to the cryosphere

Observed changes to the cryosphere identified from surface observations, satellite data, and paleoclimate records have been summarized and synthesized in many recent climate assessments [Arctic Monitoring and Assessment Programme (AMAP), 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA); Canada's Changing Climate Report (2019) (Chapter 5 — Canada's Changing Climate Report); IPCC Special Report on Oceans and Cryosphere in a Changing Climate (2019); NOAA Arctic Report Card (2020)]. The IPCC AR6 WGI provides a comprehensive overview of these changes at the global scale, further emphasizing a consistent and clear message: the cryosphere is losing extent (through reductions in sea ice, seasonal snow, and permafrost) and is also losing mass (through thinning of glaciers, ice sheets, and sea ice) [AR6 WGI 2 ES and Chapter 9 ES]. An important new aspect of the AR6 WGI assessment is the strengthened attribution of observed cryosphere changes to human influence. The AR6 WGI Summary for Policymakers (SPM) states that:

> "Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019." [SPM A.1.5]

> "Human influence *very likely* contributed to the decrease in Northern Hemisphere spring snow cover since 1950." [SPM A.1.5]

The AR6 WGI states that annual Arctic sea ice area between 2011 and 2020 was the lowest in the past 150 years (*high confidence*), while summer sea ice over the past decade was less than any time in the past 1,000 years (*medium confidence*) [SPM A.2.3]. These assessment statements are based on data for the whole Arctic, and do not specifically apply to the primarily landfast ice of the Canadian Arctic. Still, observed sea ice loss across Canadian marine regions since the late 1960s is consistent with the pan-Arctic assessment of sea ice loss in the AR6 WGI. As assessed in the CCCR, summer sea ice area has declined across the Canadian Arctic at a rate of 5% to 20% per decade (depending on the region), while winter sea ice area has decreased in eastern Canada by approximately 8% per decade since 1968.

The AR6 WGI highlights the perilous state of glacier mass balance change around the world:

> "The global nature of glacier retreat, with almost all of the world's glaciers retreating synchronously since the 1950s, is unprecedented in at least the last 2,000 years (*medium confidence*)." [SPM A.2.3]

Glaciers in western Canada are part of this global retreat, experiencing a four-fold increase in mass loss during 2009–2018 compared to 2000–2009 [AR6 WGI Chapter 9.5]. As highlighted in the CCCR, monitored glaciers in the Canadian Arctic have been losing mass since 2005 at a rate five times faster than the 1960–2004 period.

Over the past decade, permafrost temperatures have hit record warm levels across the Arctic, active layer thickness has increased, and complete permafrost thaw has started to occur across discontinuous and sporadic permafrost regions [AR6 WGI Chapter 2.3.2]. For northern countries like Canada, this is resulting in changes to the physical integrity of the landscape (particularly in areas rich with ground ice), as documented in the CCCR as well, affecting ground stability, erosion, slope movement, and water drainage, and in turn ecosystems and northern infrastructure.

3.5.2 Future changes in the cryosphere

The AR6 WGI emphasizes with *high confidence* that every increment of additional warming will drive further changes to the cryosphere because the magnitude of decreases in snow, sea ice and near surface permafrost extent are directly proportional to global surface temperature increases [SPM B.2.5]. These changes will be larger at 2 °C global warming than at 1.5 °C [SPM C.2.1; *high confidence*], but climate model projections indicate that snow and sea ice loss will stabilize in the future under low-GHG-emission scenarios as global surface temperature stabilizes. Moreover, since the very-low-GHG-emission scenario projects a slight decline in global temperature following peak temperature (reversal of global warming), this means that fast-response elements of the cryosphere, such as snow and sea ice, could recover to some extent with little temporal delay [AR6 WGI Chapter 9.3].

There are some important regional factors to sea ice projections that are specific to Canada. For example, while the AR6 WGI report highlights that the central Arctic Ocean is *likely* to be practically sea ice-free in September at least once before 2050 [SPM B.2.5], the last summer sea ice will remain in the Canadian Arctic Archipelago (CAA) and areas north and west of Greenland for a longer period of time (as assessed in the CCCR). Although new evidence suggests that vulnerability to extreme ice loss events is greater than previously thought, this “Last Ice Area” will retain a higher fraction of summer sea ice cover than the central Arctic Ocean, providing an important habitat refuge. As highlighted in the CCCR, this remaining ice will drift through waterways of the CAA, including the Northwest Passage, and will continue to influence ecosystems, northern livelihoods and safe shipping access across northern Canada.

The AR6 WGI confirms that changes in slow response components of the cryosphere (glaciers, ice sheets, deep permafrost) are effectively irreversible [SPM B.5.2]. This means that, regardless of the future carbon emissions pathway, there is *very high confidence* that glaciers in western Canada will continue to lose mass in the coming decades (which is consistent with other mid-latitude mountain regions across the Northern Hemisphere) before largely disappearing by the end of this century. As emphasized in the CCCR, this will place further pressure on seasonal snow as a freshwater resource, and alter seasonal runoff dynamics for Canadian rivers. In the Canadian Arctic, continued glacier mass loss is expected on century time scales, which will continue to contribute significantly to global sea-level rise. Permafrost thaw is also effectively irreversible at centennial time scales (*high confidence*), and will continue in the coming decades regardless of the carbon emissions pathway [SPM B.5.2]. CMIP6 models project (with *medium confidence*) that the annual mean frozen volume in the top 2 m of the soil could decrease by approximately 25% per degree of global mean surface air temperature increase [AR6 WGI Chapter 9]. As a result, additional greenhouse gases (carbon dioxide and methane) will be released into the atmosphere with the potential for substantial feedbacks on the global climate system, particularly in driving further increases in global temperature [AR6 WGI Chapter 5]. Future emissions of carbon dioxide and methane over permafrost regions remain highly uncertain, but they are considered in the WGI assessment of carbon emission budgets as consistent with limiting global warming to different levels.

3.5.3 Summary of cryosphere changes

In summary, the IPCC AR6 WGI assessment highlights that human influence on warming is responsible for the observed changes to the cryosphere in recent decades. These changes are synchronous around the world. Every increment of additional warming will drive further changes to the cryosphere. While these key findings are generally applicable to Canada, the AR6 WGI does not assess the regional differences in changes to the cryosphere across Canada. Furthermore, observed and projected changes to freshwater ice (lake and river ice), an important aspect of the cryosphere across Canada, were not assessed in the AR6 WG1. Hence, other assessments should be consulted, like the nationally focused CCCR, which provides the relevant national-scale assessment for Canadian policymakers and stakeholders. The key cryosphere messages from the CCCR remain relevant and are broadly consistent with the AR6 WGI (*see* Table 1). Across Canada, the following changes are observed: fall and spring snow cover, the duration of seasonal lake ice cover, and summer sea ice extent have decreased; glaciers have thinned; and permafrost has warmed. Canadians can expect these changes to continue, with significant impacts on the climate system, global sea-level rise, and our terrestrial, freshwater, and marine ecosystems.

3.6 Changes in the water cycle

Changes in the water cycle and the resultant timing and magnitude of freshwater availability are primarily governed by changes in precipitation and temperature both directly, and indirectly through changes to snow, ice, and permafrost. Changes in precipitation and temperature extremes directly affect water cycle extremes, including floods and droughts. The AR6 WGI included for the first time a dedicated chapter on water cycle changes, concluding with *high confidence* that global warming is projected to cause substantial changes in the water cycle at both global and regional scales unless large-scale reductions in GHG emissions occur, and that water cycle variability and extremes are projected to increase faster than average changes in most regions of the world under all emission scenarios. [AR6 WGI Chapter 8 ES].

3.6.1 Water cycle timing and magnitude

As discussed in section 3.3, an increase in mean temperature has been observed in all AR6 regions in North America, with the largest increases during winter. Mean temperatures across Canada are projected to continue to increase, with larger changes associated with higher emission scenarios. These temperature changes have already influenced, and will continue to influence, the timing and magnitude of water cycle changes. For example, with additional evidence from new observations and model (CMIP6) datasets and more literature assessing past and future changes, AR6 WGI concluded:

> Earlier onset of spring snowmelt and increased melting of glaciers have already contributed to seasonal changes in streamflow in high-latitude and low-elevation mountain catchments (*high confidence*). [AR6 WGI Chapter 8 ES].

Mountain glaciers and seasonal snow cover duration will continue to decrease across the globe. The AR6 WGI assessment of seasonal temperature and associated water cycle changes is fully consistent with the CCCR findings (*see* Chapter 6 — Canada's Changing Climate Report, and Table 1). This includes the CCCR assessment of continued earlier spring peak streamflow, with corresponding shifts from more snowmelt-dominated regimes toward rainfall-dominated regimes.

For most of the regions encompassing Canada, the AR6 WGI concluded that mean precipitation (which affects annual streamflow magnitude) did not show robust observed trends, but increases are projected annually and during winter and spring, with larger percentage changes in the North. During summer, increases are projected in Northeastern and Northwestern North America, but changes in other regions of the continent, including more southern areas of Canada, are uncertain (*see* section 3.4). The AR6 WGI findings for mean and seasonal precipitation and associated changes in streamflow magnitude are broadly similar to those from the CCCR. This includes CCCR's assessment of projected increases in annual streamflow across much of Canada due to higher annual precipitation, with greater relative increases in the North, and the potential for increased risk of water supply shortages in summer due to higher temperatures and uncertainty in future summer precipitation.

3.6.2 Water cycle extremes

Heavy or extreme precipitation is directly linked to both pluvial floods (i.e., those that are rainfall-related, including urban floods) and fluvial (river) floods (with numerous other causes). The AR6 WGI concluded that increases in heavy precipitation are projected for North America and all of its sub-regions, with additional warming [Table 11.20] (*see* section 3.4). The report also concluded that:

> The projected increase in the intensity of extreme precipitation translates to an increase in the frequency and magnitude of pluvial floods – surface water and flash floods – (*high confidence*), as pluvial flooding results from precipitation intensity exceeding the capacity of natural and artificial drainage systems. [AR6 WGI Chapter 11 ES].

The AR6 WGI also noted that regional changes in river floods are more uncertain than changes in pluvial floods because of complex hydrological processes and forcings, including land cover change and human water management [AR6 WGI Chapter 11 ES]. These AR6 findings are broadly similar to those of the CCCR, which concluded that projected increases in extreme precipitation are expected to increase the potential for future urban (pluvial) flooding. However, the frequency and magnitude of future snowmelt-related fluvial flooding remains uncertain due to the complexities involved (*see* Chapter 6 — Canada's Changing Climate Report, and Table 1).

Increasing temperatures and changes to seasonal precipitation patterns affect the amount of water vapour in the atmosphere, with implications for drought and surface water availability in Canada. The AR6 WGI assessed several types of drought including meteorological, hydrologic, and agricultural/ecological [AR6 WGI Chapter 8, Figure 8.6]. In the CCCR, this distinction between types of drought was for the most part not made; however, the section on soil moisture relates to agricultural drought while those associated with low streamflow and lakes/wetland levels relate to hydrologic drought. The section on drought indices was primarily analogous with meteorological drought. The AR6 WGI concluded that there are no significant trends in all types of drought in regions encompassing Canada. This is consistent with the CCCR, which found no changes in low streamflow events, surface water levels, soil moisture, and drought indices during the historical period of record.

The AR6 WGI concluded that in the future, Central and Western North America will be affected by more frequent and severe agricultural/ecological droughts (higher confidence for higher warming levels) and Western North America would also be affected by more frequent hydrological drought at higher warming levels (*medium confidence*). However, there is limited evidence and there are inconsistent trends (and thus *low confidence*) for future meteorological and hydrological droughts under all warming scenarios across other IPCC AR6 regions encompassing Canada, with the exception of Western North America where there is *medium confidence* of more frequent hydrological droughts under higher warming levels [AR6 WGI Chapter 11, Table 11.21]. This is largely similar to the CCCR, which concluded that southern regions of Canada are at higher risk for future drought including the following: a decline in future freshwater levels and reduced summer freshwater availability where increased evaporation may exceed increased precipitation; and increased future drought and soil moisture deficits across the southern Canadian Prairies and the Interior of British Columbia (*see* Chapter 6 — Canada's Changing Climate Report, and Table 1).

3.6.3 Groundwater

The AR6 WGI did not have enough information to provide any confident assessment of future groundwater projections, but noted that important climate-related changes in groundwater recharge are expected. This is consistent with the CCCR, which concluded that the complexity of groundwater systems and a lack of information make it difficult to assess past and future changes to groundwater. The CCCR also noted that projected changes to temperature and precipitation will influence future groundwater levels. However, the magnitude and even direction of change are not clear.

3.7 Changes in the ocean and sea level

Evidence of ocean climate change has strengthened with new research supporting the CCCR statements on ocean temperature and heat content, salinity and stratification (*see* Chapter 7 — Canada's Changing Climate Report, and Table 1). Noteworthy new findings on marine heatwaves, ocean acidification and deoxygenation, and sea-level change are summarized in this section. Confidence in the drivers of observed changes in the global oceans has also increased compared to assessments in the IPCC AR5.

3.7.1 Ocean warming and marine heatwaves

The AR6 WGI strengthened the conclusions of the AR5 regarding the human-induced warming of the global ocean:

> "It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver [SPM A.1.6]. Past GHG emissions have committed the global ocean to future warming (*high confidence*) [SPM B.5.1] and ocean warming will continue with additional emissions of GHGs."

Marine heatwaves were not assessed in the CCCR for oceans surrounding Canada; however, the understanding of heatwaves in the ocean environment has developed significantly since the CCCR. Marine heatwaves are defined as sustained periods of anomalously high near-surface water temperatures that can lead to severe and persistent impacts on marine ecosystems. Evidence has been documented of the widespread occurrence of marine heatwaves in all ocean basins and marginal seas, and the AR6 WGI states:

> "Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006." [SPM A.3.1]

There is *high confidence* that marine heatwaves will continue to increase in frequency with additional global warming [SPM B.2.3], with the Arctic Ocean expected to be among the regions with the largest changes. This could have significant implications for marine ecosystems in the Canadian Arctic.

3.7.2 Ocean acidification

The ocean is a carbon sink, taking up about 25% of the carbon emitted from human activities each year. This uptake of carbon emissions leads to ocean acidification, with the AR6 WGI stating that:

> "It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. [SPM A.1.6].

The coastal ocean, from the shore line to the edge of the continental shelf, is highly heterogeneous due to the complex interplay between physical, biogeochemical and anthropogenic factors. It is therefore expected that, for the coastal northeast Pacific and northwest Atlantic oceans, it will be several decades before the climate signal for acidification emerges at this regional scale [AR6 WGI Chapter 5.3.5]. There is *high confidence* that surface ocean acidification could be reversed if global net negative CO_2 emissions (from human activity) were achieved [SPM D.1.5]. Global net negative CO_2 emissions are a feature of both the low- and very-low-GHG-emission scenarios in the second half of this century (*see* section 2.2). There is *high confidence* that CO_2

emissions will leave a long-term legacy in ocean acidification, and are therefore irreversible at multi-human generational scales, even with aggressive atmospheric CO_2 removal [AR6 WGI Chapter 5.3.4.2].

3.7.3 Ocean deoxygenation

Changes in oxygen concentrations in the ocean are linked to climate change through increasing upper-ocean temperature (warmer waters hold less oxygen) as well as changes in stratification. The global loss of oxygen in the world's oceans has been further documented in recent literature, leading to the following assessment:

> "There has *very likely* been a net loss of oxygen over all ocean depths since the 1960s linked to global ocean deoxygenation at a range of 0.3–2.0%, and that the oxygen levels in the global upper 1,000m of the ocean had decreased by 0.5–3.3% during 1970–2010 (*medium confidence*)." [AR6 WGI Chapter 2.3.3.6]

Key new insights into ocean deoxygenation have resulted from recent regional-scale assessments. In the Northeast Pacific off Canada, the magnitude of oxygen loss substantially exceeds global averages. A decline in oxygen content of 11.7 ± 3.5% in the upper 4,000 m, including a decline of 20.4 ± 7.2% in the upper 1,550 m, is reported over the period of 1956–2018 in the Alaskan gyre [AR6 WGI Chapter 2.3.3.6]. A similar rate of oxygen loss (15% over 1960–2019 in the upper 3,000 m) was reported for the nearby Seamounts region (about 700 km closer to the coast of British Columbia). Vertical expansion of low-oxygen zones is also documented in this region at a rate of 3.1 ± 0.5 m yr-1 35 [AR6 WGI Chapter 2.3.3.6], and this further supports the observation that the volume of severely oxygen-depleted water has expanded in some locations of the global ocean.

3.7.4 Sea-level change

Global mean sea level is projected to rise, with significant contributions from expansion of warming ocean waters and from the meltwater of glaciers and ice sheets, while groundwater withdrawal and damming of lakes and rivers play a smaller role in global sea-level change. Because the land-ice and ocean responses to warming climates are slow, projected sea-level changes do not differ greatly among different scenarios until the latter part of the 21st century. The AR6 WGI provides best estimates and *likely* ranges for global sea-level projections with *medium confidence* that differ little from the AR5 sea-level projections described in the CCCR (*see* Chapter 7 — Canada's Changing Climate Report), except that these projections extend to 2150, while the AR5 provided projections to 2100. Under a low-emission scenario (SSP1-2.6), global sea level is projected to rise by 0.44 m [0.32–0.62 m] by 2100, and under a very-high-emission scenario (SSP5-8.5), sea level will rise by 0.77 m [0.63–1.01 m] by 2100, relative to 1995–2014 [SPM.B.5.3; Chapter 9 Table 9.9].

Projected relative sea-level change, which is the change that is experienced at a coastline and that affects infrastructure, ecosystems and human activities, will vary substantially over Canada owing to pronounced differences in vertical land motion and other effects, as described in Chapter 7 — Canada's Changing Climate Report. Where the land is rising quickly, such as in Hudson Bay and the eastern Canadian Arctic Archipelago, relative sea level is projected to continue to fall. In the Atlantic provinces, the Western Arctic, and British

Columbia, where the land is rising at slower rates, or sinking, relative sea level is projected to rise. Where relative sea-level is projected to rise, extreme high-water-level events generated by storm surges, waves and high tides will increase in frequency and severity.

A major change for the AR6, compared to the AR5, is that low-likelihood, high-impact sea-level projections are provided, extending to 2300. These incorporate the possibility of additional amounts of sea level rise, chiefly due to enhanced contributions from the Antarctic Ice Sheet. The CCCR discussed the potential for larger amounts of sea-level rise, but the discussion focused on the year 2100. The high-end projections in the AR6 WGI are based on a combination of model projections, as well as information from two additional publications canvassing expert opinion and modelling Antarctic ice sheet evolution. The high-end projections infer much larger amounts of sea-level change that may be relevant in cases of low tolerance to risk of sea-level rise. The AR6 WGI states:

> "Global mean sea-level rise above the *likely* range—approaching 2 m by 2100 and 5 m by 2150 under a very high GHG emission scenario (SSP5-8.5) (*low confidence*)—cannot be ruled out due to deep uncertainty in ice sheet processes." [SPM B.5.3]

Under these larger amounts of global sea-level rise, relative sea-level rise and the impacts of that rise would be larger. In Hudson Bay and the eastern Canadian Arctic Archipelago, the larger amounts of global sea-level rise would cause a change from projected relative sea-level fall to relative sea-level rise in the latter part of this century and beyond.

The AR6 WGI emphasized that some climate processes, such as sea-level rise, will continue well beyond the current century regardless of the climate pathway. By 2300, global sea level is projected to rise by about 0.5 to 3 m under a low-emission scenario (SSP1-2.6). Under a very-high-emission scenario (SSP5-8.5), global sea level is projected to rise by about 2 to 7 m by 2300, and sea-level rise approaching 15 m cannot be ruled out (*low confidence*) [SPM B.5.3].

> "In the longer term, sea level is committed to rise for centuries to millennia due to continuing deep-ocean warming and ice sheet melt, and will remain elevated for thousands of years (*high confidence*)." [SPM B5.4]

In summary, the key findings of the CCCR on the oceans are further strengthened by the new evidence from the AR6 WGI (Table 1). As concluded in the CCCR, the health of marine ecosystems in oceans surrounding Canada will be threatened by further ocean warming, acidification and loss of oxygen. Sea-level projections are similar to those reported in the CCCR, but the AR6 WGI brings increased emphasis to the possibility of larger amounts of sea-level rise this century and beyond, due to potential instabilities and feedbacks of the large ice sheets. The AR6 also reports, as did the AR5, that there is a long-term commitment to continued global sea-level rise beyond 2100. This indicates the importance of planning for larger amounts of sea-level rise in cases of low tolerance to risk of sea-level rise and for long planning horizons. These findings continue to support the conclusion of the CCCR that coastal flooding and associated risks of damage to coastal infrastructure and ecosystems are projected to be an increasing hazard in many coastal areas of Canada.

Table 1: Assessment of consistency of Canada's Changing Climate Report (CCCR) Headline Statements with conclusions of the latest global science assessment of the Intergovernmental Panel on Climate Change (IPCC)

CCCR Headline Statements represent conclusions for which there is at least *high confidence*. IPCC Summary for Policymakers (SPM) conclusions are expressed as either statements of fact, or with calibrated qualifiers expressing assessed levels of confidence in and/or likelihood of an outcome. The assessment of consistency in this Table was based on expert judgment of the authors of this document. Green circles with checkmarks indicate that IPCC conclusions are generally consistent with and support the CCCR findings although the spatial scales and time periods of analysis for observed and projected changes may differ. Open grey circles indicate that consistency could not be assessed because conclusions on the topic were out of scope for the WGI assessment. Statements in blue font are direct quotes from the CCCR and IPCC SPM, and the font style is consistent with that in the original source. Explanatory text is in grey font.

CCCR HEADLINE STATEMENTS		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS
Canada's climate has warmed and will warm further in the future, driven by human influence.	✓	**It is unequivocal that human influence has warmed the atmosphere, ocean and land.**
Global emissions of carbon dioxide from human activity will largely determine how much warming Canada and the world will experience in the future, and this warming is effectively irreversible.	✓	**From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions.**
Both past and future warming in Canada is, on average, about double the magnitude of global warming. Northern Canada has warmed and will continue to warm at more than double the global rate.	✓	It is *virtually certain* that the Arctic will continue to warm more than global surface temperature, with *high confidence* above two times the rate of global warming.
Oceans surrounding Canada have warmed, become more acidic, and less oxygenated, consistent with observed global ocean changes over the past century.	✓	It is *virtually certain* that the global upper ocean (0–700 m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. It is *virtually certain* that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. There is *high confidence* that oxygen levels have dropped in many upper ocean regions since the mid-20th century, and *medium confidence* that human influence contributed to this drop.
Ocean warming and loss of oxygen will intensify with further emissions of all greenhouse gases, whereas ocean acidification will increase in response to additional carbon dioxide emissions. These changes threaten the health of marine ecosystems.	✓	Past GHG emissions since 1750 have committed the global ocean to future warming (*high confidence*). Based on multiple lines of evidence, upper ocean stratification (*virtually certain*), ocean acidification (*virtually certain*) and ocean deoxygenation (*high confidence*) will continue to increase in the 21st century, at rates dependent on future emissions.

CCCR HEADLINE STATEMENTS		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS
The effects of widespread warming are evident in many parts of Canada and are projected to intensify in the future.	✓	**Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.**
In Canada, these effects include more extreme heat, less extreme cold, longer growing seasons, shorter snow and ice cover seasons, earlier spring peak streamflow, thinning glaciers, thawing permafrost, and rising sea level.	✓	**Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5.**
Because some further warming is unavoidable, these trends will continue.	✓	**Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, proportion of intense tropical cyclones as well as reductions in Arctic sea ice, snow cover and permafrost.** All regions are projected to experience further increases in hot climatic impact-drivers (CIDs) and decreases in cold CIDs (*high confidence*). Further decreases are projected in permafrost, snow, glaciers and ice sheets, lake and Arctic sea ice (*medium to high confidence*).
Precipitation is projected to increase for most of Canada, on average, although summer rainfall may decrease in some areas.	✓	Precipitation is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and limited areas in the tropics (*very likely*).
Precipitation has increased in many parts of Canada, and there has been a shift toward less snowfall and more rainfall. Annual and winter precipitation is projected to increase everywhere in Canada over the 21st century. However, reductions in summer rainfall are projected for parts of southern Canada under a high emission scenario toward the late century.	✓	The portion of the global land experiencing detectable increases or decreases in seasonal mean precipitation is projected to increase (*medium confidence*). Globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). **The SPM did not include much additional detail on regional and seasonal changes in precipitation, but support from the underlying chapters, and expert judgement based on these, determined these assessments are consistent.**
The seasonal availability of freshwater is changing, with an increased risk of water supply shortages in summer.	✓	There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (*high confidence*), with precipitation and surface water flows projected to become more variable over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*).
Warmer winters and earlier snowmelt will combine to produce higher winter streamflows, while smaller snowpacks and loss of glacier ice during this century will combine to produce lower summer streamflows.	✓	There is *high confidence* in an earlier onset of spring snowmelt, with higher peak flows at the expense of summer flows in snow-dominated regions globally.

CCCR HEADLINE STATEMENTS		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS
Warmer summers will increase evaporation of surface water and contribute to reduced summer water availability in the future despite more precipitation in some places.	✓	**The SPM did not include much additional detail on seasonal changes in freshwater availability, but support from the underlying chapters, and expert judgement based on these, determined these assessments are consistent.**
A warmer climate will intensify some weather extremes in the future.	✓	With every additional increment of global warming, changes in extremes continue to become larger.
Extreme hot temperatures will become more frequent and more intense. This will increase the severity of heatwaves, and contribute to increased drought and wildfire risks.	✓	For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*).
While inland flooding results from multiple factors, more intense rainfalls will increase urban flood risks. It is uncertain how warmer temperatures and smaller snowpacks will combine to affect the frequency and magnitude of snowmelt-related flooding.	✓	A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (*high confidence*), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks.
Canadian areas of the Arctic and Atlantic Oceans have experienced longer and more widespread sea-ice-free conditions.	✓	In 2011–2020, annual average Arctic sea ice area reached its lowest level since at least 1850 (*high confidence*). Late summer Arctic sea ice area was smaller than at any time in at least the past 1000 years (*medium confidence*).
Canadian Arctic marine areas, including the Beaufort Sea and Baffin Bay, are projected to have extensive ice-free periods during summer by mid-century.	✓	Additional warming is projected to further amplify permafrost thawing, and loss of seasonal snow cover, of land ice and of Arctic sea ice (*high confidence*). The Arctic is likely to be practically sea ice free in September at least once before 2050 under the five illustrative scenarios considered in this report, with more frequent occurrences for higher warming levels.
The last area in the entire Arctic with summer sea ice is projected to be north of the Canadian Arctic Archipelago. This area will be an important refuge for ice-dependent species and an ongoing source of potentially hazardous ice, which will drift into Canadian waters.	○	**Conclusions on this topic were out of scope for the WGI assessment.**
Coastal flooding is expected to increase in many areas of Canada due to local sea level rise.	✓	**Relative sea level rise contributes to increases in the frequency and severity of coastal flooding in low-lying areas and to coastal erosion along most sandy coasts (*high confidence*).**

CCCR HEADLINE STATEMENTS		RELEVANT STATEMENTS FROM THE IPCC AR6 WGI SUMMARY FOR POLICYMAKERS
Changes in local sea-level are a combination of global sea level rise and local land subsidence or uplift. Local sea level is projected to rise, and increase flooding, along most of the Atlantic and Pacific coasts of Canada and the Beaufort coast in the Arctic where the land is subsiding or slowly uplifting.	✔	It is *very likely* to *virtually certain* that regional mean relative sea level rise will continue throughout the 21st century, except in a few regions with substantial geologic land uplift rates.
The loss of sea ice in Arctic and Atlantic Canada further increases the risk of damage to coastal infrastructure and ecosystem as a result of larger storm surges and waves.	○	**Conclusions on this topic were out of scope for the WGI assessment.**
The rate and magnitude of climate change under high versus low emission scenarios project two very different futures for Canada.	✔	**Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades.**
Scenarios with large and rapid warming illustrate the profound effects on Canadian climate of continued growth in greenhouse gas emissions. Scenarios with limited warming will only occur if Canada and the rest of the world reduce carbon emissions to near zero early in the second half of the century and reduce emissions of other greenhouse gases substantially.	✔	Scenarios with low or very low GHG emissions (SSP1-1.9 and SSP1-2.6) [in which CO_2 emissions decline to net zero around or after 2050 (Box SPM.1)] would have rapid and sustained effects to limit human-caused climate change, compared with scenarios with high or very high GHG emissions (SSP3-7.0 or SSP5-8.5) [in which CO_2 emissions roughly double from current levels by 2100 and 2050, respectively (Box SPM.1)] but early responses of the climate system can be masked by natural variability.
Projections based on a range of emission scenarios are needed to inform impact assessment, climate risk management, and policy development.	✔	**See Box SPM.1 Scenarios, Climate Models and Projections**

1 Level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain: 99–100% probability; very likely: 90–100% probability; likely: 66–100% probability; about as likely as not: 33–66% probability; unlikely: 0–33% probability; very unlikely: 0–10% probability; and exceptionally unlikely: 0–1% probability.

2 Bush, E. and Lemmen, D.S. (Eds.) (2019).

3 IPCC [Intergovernmental Panel on Climate Change]. (2021b).

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