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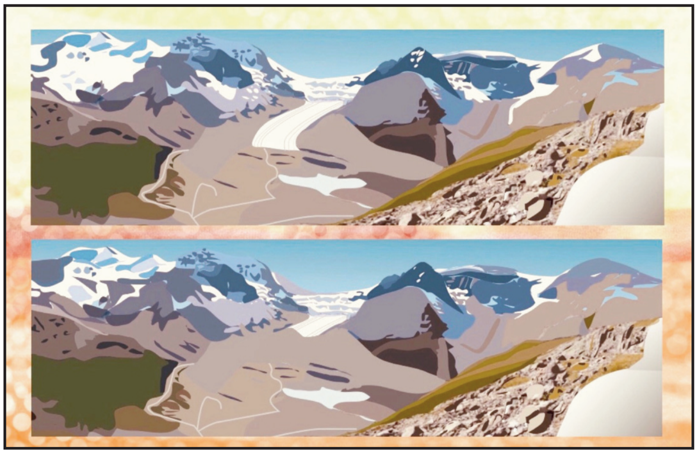

The Canadian Federation of Earth Sciences Scientific Statement on Climate Change – Its Impacts in Canada, and the Critical Role of Earth Scientists in Mitigation and Adaptation

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SUMMARY

The Canadian Federation of Earth Sciences (CFES) has issued this statement to summarize the science, effects, and implications of climate change. We highlight the role of Earth scientists in documenting and mitigating climate change, and in managing and adapting to its consequences in Canada. CFES is the coordinated voice of Canada's Earth Sciences community with 14 member organizations representing some 15,000 geoscientists. Our members are drawn from academia, industry, education, and government. The mission of CFES is to ensure decision makers and the public understand the contributions of Earth Science to Canadian society and the economy.

Climate change has become a national and global priority for all levels of government. The geological record shows us that the global climate has changed throughout Earth's history, but the current rates of change are almost unprecedented. Over the last 70 years, levels of common greenhouse gases (GHGs) in the atmosphere have steadily increased. Carbon dioxide (CO_2) concentration is now 418 parts per million — its highest of the last three million years. The chemical (isotopic) composition of carbon in the atmosphere indicates the increase in GHGs is due to burning fossil fuels. GHGs absorb energy emitted from Earth's surface and re-radiate it back, warming the lower levels of the atmosphere. Climatic adjustments that have recently occurred are, in practical terms, irreversible, but further change can be mitigated by lowering emissions of GHGs.

Climate change is amplified by three important Earth system processes and effects. First, as the climate warms evaporation increases, raising atmospheric concentrations of water vapour, itself a GHG — and adding to warming. Second, loss of ice cover from the polar ice sheets and glaciers exposes larger areas of land and open water — leading to greater absorption of heat from the sun. Third, thawing of near-surface permafrost releases additional GHGs (primarily CO_2 and methane) during decay of organic matter previously preserved frozen in the ground. Some impacts of climate change are incremental and steadily occurring, such as melting of glaciers and ice sheets, with consequent sea level rise. Others are intermittent, such as extreme weather events, like hurricanes — but are becoming more frequent. Summer water shortages are increasingly common in western Canada as mountain snowpacks melt earlier and summer river flows decline. In northern Canada, warming and thawing of near-surface permafrost has led to deterioration of infrastructure and increased costs for

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buildings that now require chilled foundations. Other consequences of unchecked climate change include increased coastal erosion, increases in the number and size of wildfires, and reduction in winter road access to isolated northern communities. Reductions in net GHG emissions are urgently required to mitigate the many effects of further climate change. Industrial and public works development projects must now assess the effects of climate change in their planning, design, and management. Cities, municipalities, and rural communities need to plan new residential development carefully to avoid enhanced risk of flooding, coastal erosion, or wildfire.

Earth Science knowledge and expertise is integral to exploration and development of new metals and Earth materials required for a carbon-neutral future, and in the capture and storage of CO_2 within the Earth. Earth Science is also central to society's adaptation to new climatic regimes and reduction of risks. This includes anticipation, assessment, and management of extreme events, development of new standards and guidelines for geotechnical and engineering practice, and revision to regulations that consider climate change. Geoscientists also have an important role in the education of students and the public on the reasons for necessary action. Canada is uniquely positioned with its strong global geoscientific leadership, its vast landmass, and its northern terrain to effectively leverage research activities around climate change. Geoscience tools and geoscientists' skills will be integral to Canada's preparation for climate change.

RÉSUMÉ

La Fédération canadienne des sciences de la Terre (FCST) a publié ce communiqué pour résumer la science, les effets et les implications des changements climatiques. Nous soulignons le rôle des scientifiques en science de la Terre dans la documentation et l'atténuation des changements climatiques, ainsi que dans la gestion de leurs conséquences et la création de mesures d'adaptation au Canada. La FCST est la voix coordonnée de la communauté canadienne des sciences de la Terre avec 14 organisations membres représentant environ 15 000 géoscientifiques. Nos membres sont issus du milieu universitaire, de l'industrie, de l'éducation et du gouvernement. La mission de la FCST est de s'assurer que les décideurs et le public comprennent les contributions des sciences de la Terre à la société canadienne et à l'économie.

Les changements climatiques sont devenus une priorité nationale et mondiale à tous les niveaux de gouvernement. Les archives géologiques nous montrent que le climat mondial a changé tout au long de l'histoire de la Terre, mais les taux de changement actuels sont presque sans précédent. Au cours des 70 dernières années, les niveaux de gaz à effet de serre (GES) communs dans l'atmosphère n'ont cessé d'augmenter. La concentration de dioxyde de carbone (CO_2) est maintenant de 418 parties par million - son plus haut niveau des trois derniers millions d'années. La composition chimique (isotopique) du carbone dans l'atmosphère indique que l'augmentation des GES est due à la combustion de combustibles fossiles. Les GES absorbent l'énergie émise par la surface de la Terre et la réfléchissent, réchauffant les niveaux inférieurs de l'atmosphère. Les modifications climatiques qui se sont produits récemment sont, concrètement, irréversibles, mais les changements additionnels peuvent être atténués en réduisant les émissions de GES.

Les changements climatiques sont amplifiés par trois processus et effets importants du système terrestre. Premièrement, à mesure que le climat se réchauffe, l'évaporation augmente, ce qui augmente les concentrations atmosphériques de vapeur d'eau, elle-même un GES, et contribue au réchauffement. Deuxièmement, la perte de la couverture de glace des calottes glaciaires polaires et des glaciers expose de plus grandes superficies de terre et d'eau libre, ce qui entraîne une plus grande absorption de la chaleur du soleil. Troisièmement, le dégel du pergélisol proche de la surface libère des GES supplémentaires (principalement du CO_2 et du méthane) lors de la décomposition de la matière organique jusqu'alors préservée gelée dans le sol. Certains impacts des changements climatiques sont progressifs et se produisent régulièrement, comme la fonte des glaciers et des calottes glaciaires, avec pour conséquence une élévation du niveau de la mer. D'autres sont intermittents, comme les événements météorologiques extrêmes, tels que les ouragans, mais deviennent de plus en plus fréquents. Les pénuries d'eau en été sont de plus en plus courantes dans l'ouest du Canada, car le manteau neigeux des montagnes fond plus tôt et le débit des rivières en été diminue. Dans le nord du Canada, le réchauffement et le dégel du pergélisol proche de la surface ont entraîné une détérioration des infrastructures et une augmentation des coûts des bâtiments qui nécessitent maintenant des fondations réfrigérées. Les autres conséquences des changements climatiques incontrôlés comprennent l'augmentation de l'érosion côtière, l'augmentation du nombre et de la taille des incendies de forêt et la réduction de l'accès aux routes d'hiver aux collectivités isolées du Nord. Des réductions des émissions nettes de GES sont nécessaires de toute urgence pour atténuer les nombreux effets de nouveaux changements climatiques. Les projets de développement industriel et de travaux publics doivent désormais évaluer les effets des changements climatiques dans leur planification, leur conception et leur gestion. Les villes, les municipalités et les communautés rurales doivent planifier soigneusement les nouveaux développements résidentiels pour éviter les risques accrus d'inondation, d'érosion côtière ou d'incendie de forêt.

Les connaissances et l'expertise en sciences de la Terre font partie intégrante de l'exploration et du développement de nouveaux métaux et matériaux terrestres requis pour un avenir neutre en carbone, ainsi que dans la capture et la séquestration du CO_2 dans la Terre. Les sciences de la Terre sont également au cœur de l'adaptation de la société aux nouveaux régimes climatiques et de la réduction des risques. Cela comprend l'anticipation, l'évaluation et la gestion des événements extrêmes, l'élaboration de nouvelles normes et directives pour les pratiques géotechniques et d'ingénierie, et la révision des réglementations qui tient compte des changements climatiques. Les géoscientifiques ont également un rôle important dans l'éducation des étudiants et du public sur le fondement des mesures

nécessaires. Le Canada occupe une position unique grâce à son solide leadership géoscientifique mondial, sa vaste étendue et son territoire nordique pour tirer efficacement parti des activités de recherche sur les changements climatiques. Les outils géoscientifiques et les compétences des géoscientifiques feront partie intégrante de la préparation du Canada aux changements climatiques.

Traduit par la Traductrice

INTRODUCTION

The evidence for climate change in Canada is compelling (Vincent et al. 2015, 2018). Northern Canada has experienced some of the most rapid climate warming on Earth. For example, mean annual air temperatures at Inuvik, NT, climbed from -9.7°C in 1961–70 to -6.1°C in 2011–20 (Burn and Kokelj 2009; Figs. 1, 2). The rates of change in southern Canada are lower, but just as definitive. At Ottawa, ON, for instance, the mean annual air temperatures for 1961–70 and 2011– 20 were 5.5 and 6.5°C, respectively (Fig. 2). The geological record shows us that global climate has changed throughout Earth's history, but the current and anticipated rates of change are almost unprecedented. The only known exception occurred after the meteorite impact 66 million years ago when most dinosaurs became extinct (Henehan et al. 2019; Lear et al. 2020).

The Canadian Federation of Earth Sciences has published this statement to summarize the scientific basis for some of the distinct challenges that Canada faces from climate change. We highlight the critical role of Earth scientists in documenting rates of change and variability in the climate, and in mitigating, managing, and adapting to the effects of climate change in Canada.

Simultaneously, Earth scientists will support a strong economy, including the exploration and development of natural resources needed to foster a carbon-neutral society. The scientific data, interpretations, and actions presented below are derived largely from the work of many geoscientists over decades of research.

UNDERSTANDING THE SCIENCE OF CLIMATE CHANGE

Climate change is caused by four fundamental factors: (1) changes in the energy Earth receives from the Sun; (2) changes at the surface of the Earth, including deforestation, that affect how solar energy is absorbed or redistributed; (3) changes in the composition of the atmosphere influenced by natural processes and human activity; and (4) changes in the circulation of the oceans (e.g. Broecker 2001; Veizer 2005; Stocker et al. 2013). Over the last 70 years, the greatest adjustment to these factors has been in the composition of the atmosphere, particularly the concentrations of several common gases that have been present for hundreds of millions of years. These include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). In addition, new fluorinated industrial gases (F-gases), such as the hydrofluorocarbons, have been introduced since 1950 (Lacis et al. 2010; Tans et al. 2020). All these gases absorb energy emitted from Earth's surface and re-radiate it, thereby further warming the lower levels of the atmosphere

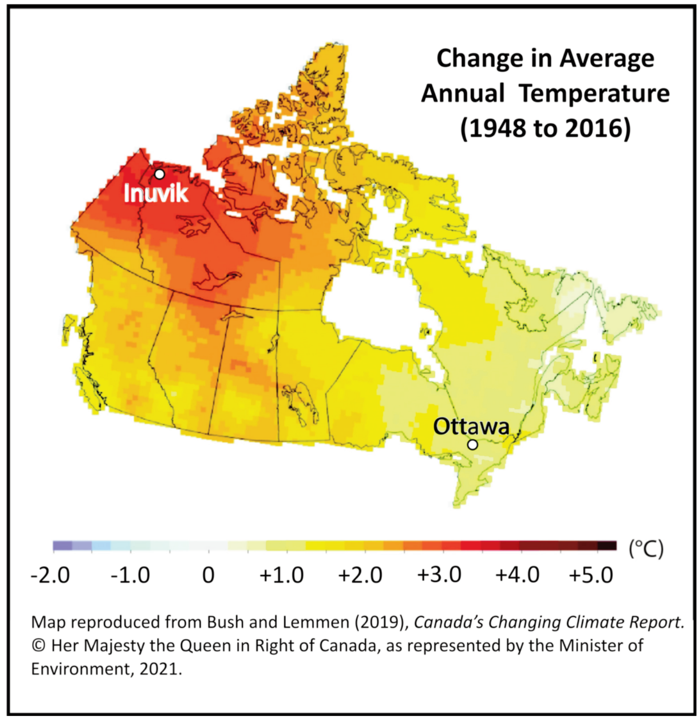

Figure 1. Observed changes in annual temperature between 1948 and 2016 across Canada. From figure 4.3 in Bush and Lemmen (2019).

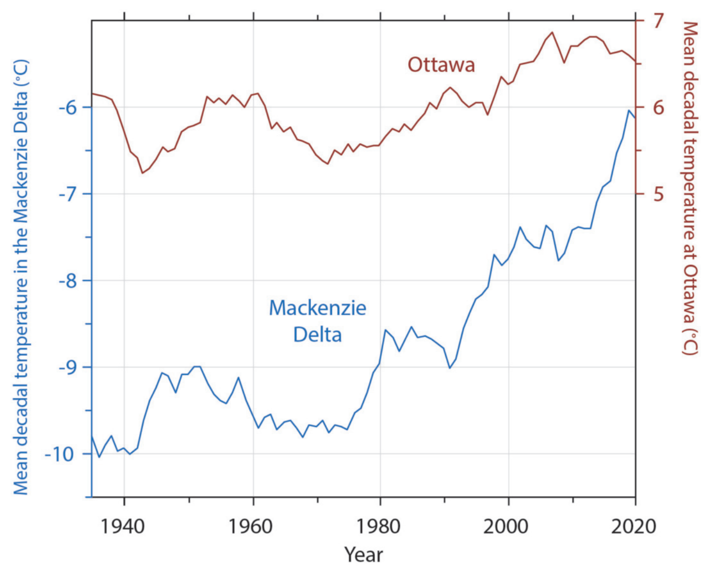

Figure 2. Change in mean decadal air temperature from 1926–35 to 2011–20 in the Mackenzie Delta area, Northwest Territories, and Ottawa, Ontario. For the Mackenzie Delta area, data are from Inuvik, Northwest Territories, (1958–2020) and nearby stations (1926–1957) (Burn and Kokelj 2009). Data are for the decade preceding the date on the horizontal axis.

(Fig. 3). The warming imitates heating in a greenhouse, hence the terms *greenhouse gases* (GHGs), and the *greenhouse effect*. As the concentration of GHGs increases, so does the greenhouse effect. Of all GHGs, CO_2 has had the most influence on climate recently (Fig. 4). The anthropogenic greenhouse effect reached an energy equivalent to 1.37% of Earth's absorbed solar radiation in 2019 (Tans et al. 2020).

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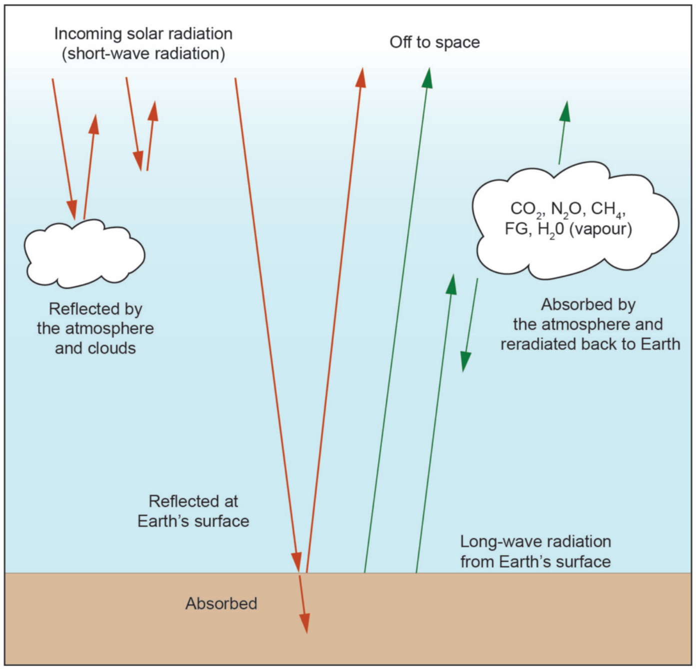

Figure 3. The distribution of solar (short-wave; red) and terrestrial (long-wave; green) radiation within the atmosphere and at Earth's surface.

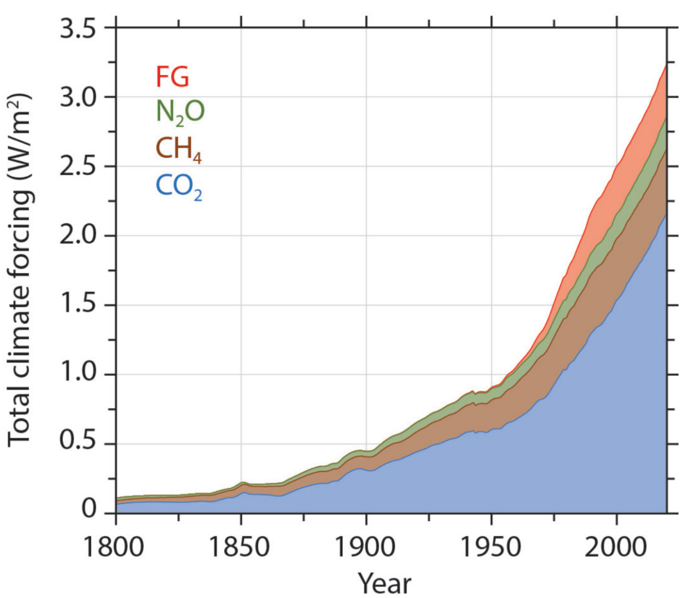

Figure 4. Climate forcing, i.e. the greenhouse effect, from CO_2, CH_4, N_2O, and fluorinated gases (FG), 1800–2019. In 2019, 66% of the anthropogenic climate forcing was from CO_2, 16% from CH_4, 6% from N_2O and 12% from the industrial gases. In comparison, 11-year average solar irradiance has declined by 0.5 W/m^2 since the late 1980s (NASA 2019). Data from Tans et al. (2020), used with permission.

We have known about the thermal impact of the atmospheric greenhouse effect for nearly 200 years. Life as we know it could not exist without the atmospheric greenhouse. The atmosphere's role in maintaining Earth's habitable surface temperatures was first proposed by Joseph Fourier in 1824. The radiative properties of CO_2 and their implications for climate were discovered independently by the American scientist Eunice Foote in 1856 and the Irish scientist John Tyndall in 1859. For more than 160 years we have known that CO_2 is one of the principal agents responsible for our climate. Now we simulate the climate using vast and detailed computer models, tested against decades of weather observations. These independent models each use slightly different sets of algorithms to represent physical interactions between the atmosphere, the oceans, landmasses, and the biosphere. They create consistent projections of the extent and direction of future climate change, which vary by region (e.g. Stocker et al. 2013).

The results primarily depend on the range of anticipated future atmospheric concentrations of greenhouse gases and characterization of energy exchanges between the atmosphere and the oceans. All models clearly point to a warming of the climate and shifting precipitation patterns as GHG emissions and other human activities further enhance the greenhouse effect (Stocker et al. 2013; Maslin 2014).

VALIDATION OF THE GREENHOUSE EFFECT BY THE GEOLOGICAL RECORD

The history of Earth's climate is best preserved in the sedimentary deposits laid down at the bottom of our lakes and oceans and in the annual layers of ice formed from compressed snow such as in the ice sheets of Greenland and Antarctica (e.g. Stuiver and Grootes 2000; Gajewski 2015). The annual growth rings of trees also document recent conditions (e.g. Porter et al. 2009). These sources give precise records of global climate change over the past thousand to even millions of years. For example, ocean sediments have preserved a record of successive glaciations determined by the chemical or isotopic composition of marine shells (Shackleton 1995; Wright 2000; Fig. 5), whereas the record in the ice sheets is determined by the isotopes of oxygen and hydrogen in the H_2O molecules of the ice (EPICA community members 2004). The glacial record from Antarctica provides a record of successive glaciations over the last 2.8 million years (Yan et al. 2019).

Layers of Antarctic ice provide a *continuous* record of climate change going back over 800,000 years (Fig. 6). Atmospheric gases were trapped as the snow fell and were subsequently compressed and sealed in the ice layers. The gas bubbles directly record the composition of the atmosphere when the ice formed. Analysis of these ancient atmospheric samples shows the CO_2 concentration varying cyclically, in step with the climate, over periods of 100,000 years, 41,000 years, and down to 500 and 100 years (Fig. 6). During climate fluctuations, CO_2 and methane concentrations correlate closely with temperature. This pattern continues during the present climate warming.

The geological record also reveals the profound effect of living organisms on atmospheric composition, greenhouse gases, and climate. Proliferation of the first trees and forests in the Devonian and Carboniferous periods, 419 to 299 million years ago, drew down atmospheric carbon, reducing the greenhouse effect and cooling the climate (e.g. Berner 2006). A southern polar ice cap developed toward the end of this time as CO_2 levels fell to about 320 parts per million by volume

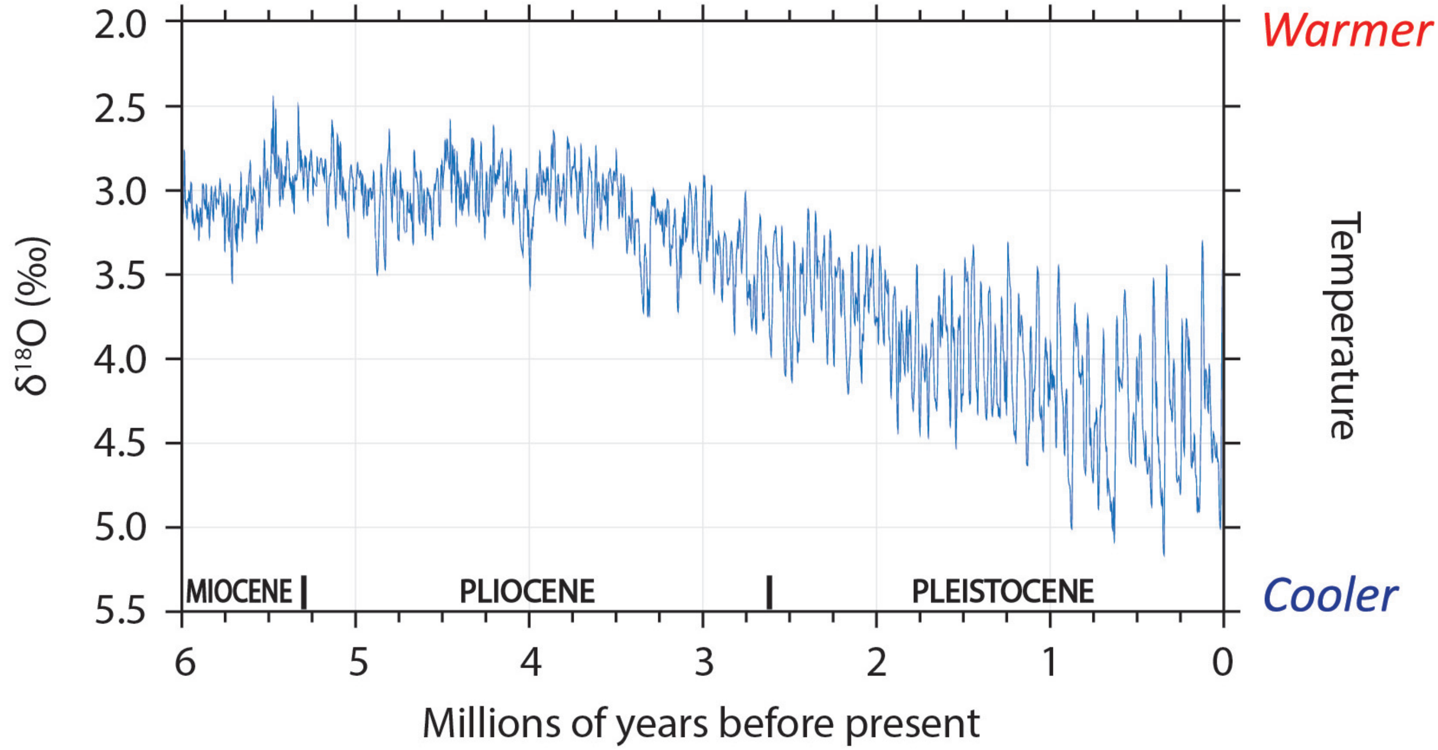

Figure 5. Climate record over 6 million years determined from the concentration of ^{18}O relative to ^{16}O ($\delta^{18}O$) in shells of ocean-bottom organisms recovered from depths up to 120 m beneath the ocean floor several hundred kilometres off the coasts of Ecuador and Peru (Shackleton 1995). The graph shows the beginning of the ice ages about 3 million years ago and the oscillation of climate between the glaciations, especially in the last million years. $\delta^{18}O$ in the ocean increases as the climate cools and water from the oceans is transferred to ice sheets.

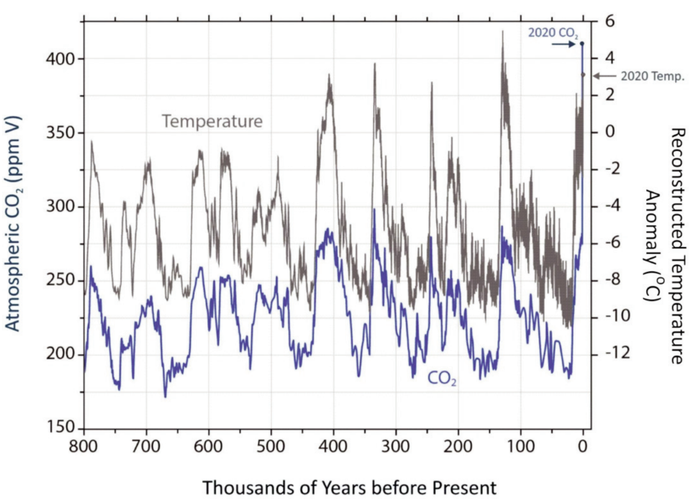

Figure 6. Co-variation of atmospheric CO_2 concentration and climate over the last 800,000 years, as determined from deep ice cores collected in Antarctica. CO_2 is in parts per million by volume measured from gases in bubbles in the ice and is presented in blue (Lüthi et al. 2008). Climatic fluctuations are inferred from the relative concentration of ^2H to ^1H in the ice and are shown in grey (Jouzel et al. 2007). Diagram after Pisaric and Smol (2021, figure 2.4).

(ppm), just higher than the atmospheric concentration of 280 ppm that preceded the Industrial Revolution (1760–1840).

ANTHROPOGENIC CO_2 EMISSIONS AND CLIMATE

Society's use of fossil fuels as its primary source of energy since the beginning of the Industrial Revolution has added CO_2 and other gases to the atmosphere. These fuels are used in all sectors of manufacturing, forestry, agriculture, construction, and transportation, and for domestic heating. Fossil fuel, or hydrocarbon resources were created by the entrapment of plants and micro-organisms over time, from at least 1.6 billion years ago right up to the present (Craig et al. 2013). Peat accumulation is one example of such storage taking place now (Robinson and Moore 1999). After burial, heat and pressure converted these vast quantities of carbon-rich organic matter to coal, oil, natural gas, and other reservoirs of stored carbon.

The return of the fossilized carbon to the atmosphere through the burning of fuel in the past 250 years accounts for about 80% of the increase in atmospheric CO_2 concentration. Deforestation, wildfires, cement manufacturing, and agriculture contribute the remainder (Fig. 7). About 75% of all CO_2 emissions from fossil fuel combustion have occurred since 1970 (Tans et al. 2020). Half of the CO_2 emissions remain in the atmosphere, whereas the oceans and plants on land each absorb about a quarter (Maslin 2014). The atmospheric CO_2 concentration is now 418 ppm (CO_2 Earth 2021), having risen steadily over the period of continuous measurement from about 315 ppm in 1958 (Fig. 8). The concentration at present is higher than it has been in the last 3 million years.

The current rate of anthropogenic emission, about 10 billion tonnes of carbon per year (EPA 2021), is the highest documented in the geological record (Gingerich 2019; Lear et al. 2020). It leads to an annual change in atmospheric CO_2 concentration of 2.4 ppm. The relative concentration of anthro-

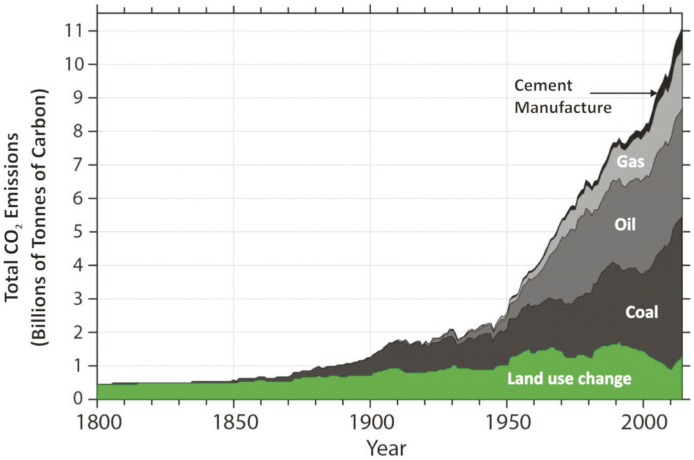

Figure 7. Anthropogenic carbon emitted as CO_2 in billions of tonnes per year from land use change, fossil fuel consumption, and cement manufacturing, 1800–2014. Data from Boden et al. (2017), Houghton (2008), and Houghton and Nassikas (2017). Diagram after Stocker et al. (2013, figure TS.4).

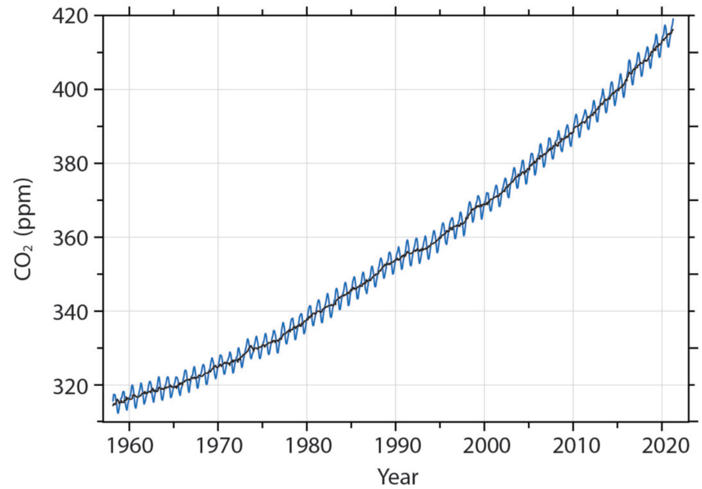

Figure 8. Increase in atmospheric concentration of CO_2 in parts per million by volume at Mauna Loa, Hawaii, 1958–2021. The annual fluctuation in concentration is due to absorption of CO_2 by plant growth in the Northern Hemisphere's growing season and release of CO_2 while burning fuels for heating in winter. Data from National Oceanic and Atmospheric Administration/Global Monitoring Laboratory May 1974 to present and C. David Keeling, Scripps Institution of Oceanography, from March 1958 to April 1974 (GML 2021), reproduced with permission.

pogenic carbon in the atmosphere can be determined by examining its chemical (isotopic) composition. The atmospheric concentration of the radioactive carbon isotope ^{14}C was diluted after the Industrial Revolution by burning fossil fuels which do not contain ^{14}C (Suess 1955). ^{14}C is manufactured in the atmosphere and is included in organic materials as they grow. It decays radioactively over about 60,000 years and is absent from organic materials that are millions of years old. Similarly, the isotopic concentration of ^{13}C has been diluted in the atmosphere by burning fossil fuels with their low concentrations of this isotope (Keeling et al. 2017).

Atmospheric CO_2 and methane concentrations have been much higher in the past, particularly 400 and 200 million years ago — a time when the Earth's overall climatic regime was very different. However, human activities today generate greenhouse gases at a rate far exceeding the capacity of vegetation or oceans to absorb them and hence the atmospheric concentration is increasing (Foster et al. 2017). Natural absorption of CO_2 occurs gradually. For the present atmospheric concentration, about 1000 years will be needed for the atmosphere and oceans to reach a new chemical equilibrium. After this equilibrium is reached, several more thousand years will be required for the oceans to absorb the excess CO_2 and return the atmosphere to pre-industrial concentrations (Archer et al. 2009). The climate change we have already experienced is, in practical terms, irreversible. Given our continued population growth and the time needed to move global society away from fossil fuels, atmospheric concentrations of greenhouse gases will most likely continue to increase over the next few decades and will drive ongoing climate change and its multiple effects (Stocker et al. 2013).

AMPLIFICATION OF GHG EFFECTS BY OTHER EARTH PROCESSES

Anthropogenic greenhouse gas emissions warm the climate, but the resulting adjustments in temperature, evaporation, and precipitation cause additional modifications at the Earth's surface that amplify or exacerbate climate change. An immediate amplifying effect is that evaporation and the potential amount of atmospheric water vapour, also a greenhouse gas, increases with temperature. Since water vapour cycles quickly through the atmosphere, its concentration is a response to temperature and its effect is not to drive climate change but to amplify it (Maslin 2014).

A second effect of global warming is the wasting of ice sheets in Greenland and Antarctica and of ice caps and glaciers in mountains worldwide (Hugonnet et al. 2021). This is apparent in the western mountains and Arctic islands of Canada, where glaciers are shrinking and ice shelves are collapsing (Marshall et al. 2011; Fig. 9). The loss of ice cover lowers surface reflectivity, so that more solar radiation is absorbed and the surface warms further. Reduction in the Arctic Ocean ice cover also reduces reflection of solar radiation from the polar regions and, in turn, contributes to the greater warming observed and expected in the North (Serreze et al. 2007). A similar reduction in reflectivity and enhanced warming occurs in the spring when seasonal snow cover melts earlier or is less extensive across Canada (Zhang et al. 2019).

A third effect follows the thawing of near-surface permafrost, with emissions of CO_2 and methane from the decay of soil organic matter formerly entombed in frozen ground (Schuur et al. 2015; Fig. 10). It is particularly relevant for Canada because, after Russia, we have the largest area of permafrost enriched in carbon, particularly in the Mackenzie River valley, NT, and the Hudson Bay Lowlands of Manitoba, Ontario, and Quebec (Fig. 11). Canada has about 400 billion tonnes of soil organic carbon in the uppermost 3 m of the ground in the permafrost regions (Hugelius et al. 2014). Worldwide, the quantity of carbon in the top 3 m of permafrost terrain, some 1000 billion tonnes (Tarnocai et al. 2009), is about 100 times greater than annual industrial emissions (EPA 2021), so the release of even a small fraction of the permafrost carbon will counteract

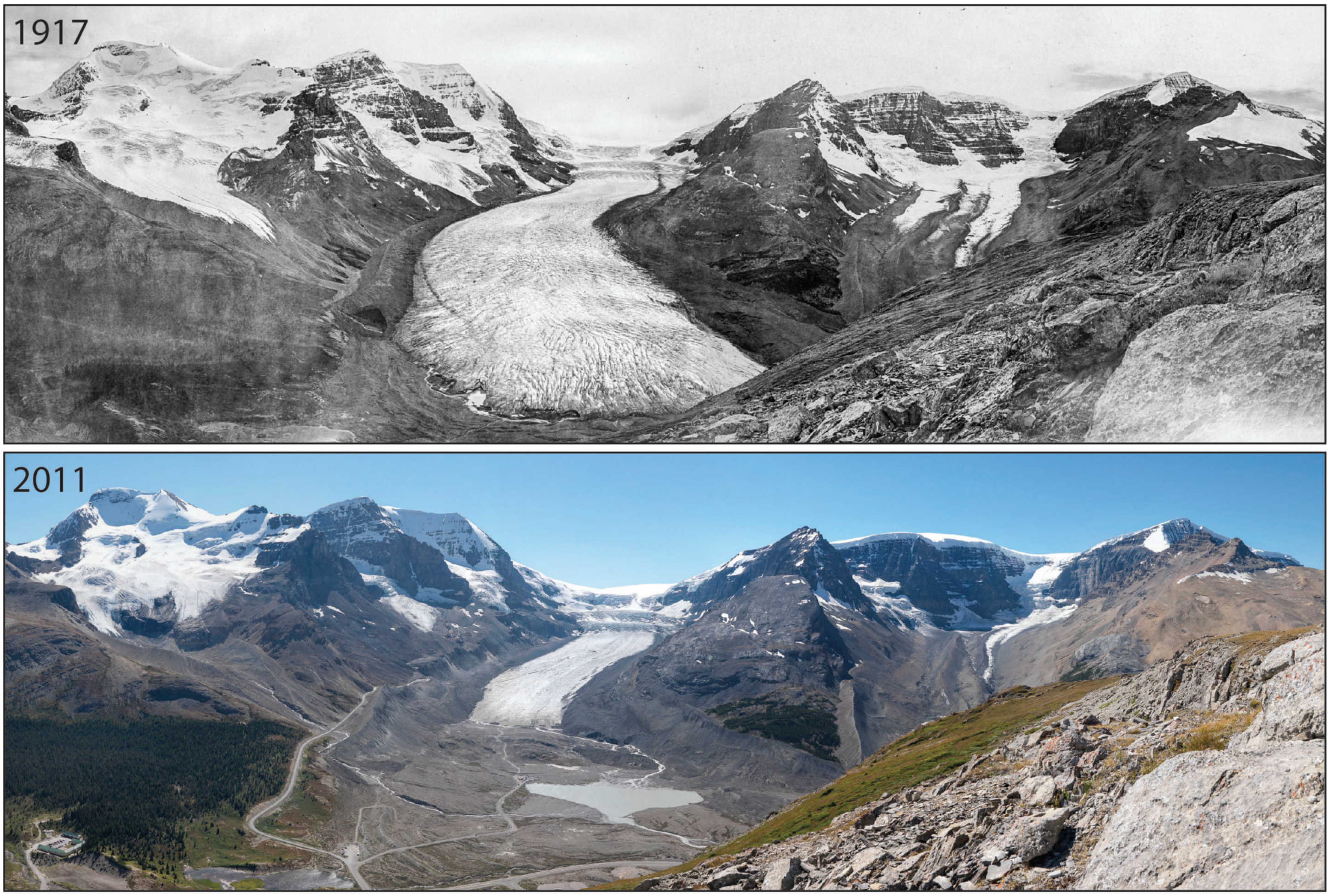

Figure 9. View of Athabasca Glacier from Wilcox Pass, Alberta, showing its reduction in size between 1917 and 2011. The distance from the road in the foreground to the head of the glacier is 6.25 km. 1917 photo reproduced courtesy of Library and Archives Canada / Bibliothèque et Archives Canada, photos e010675607 to e010675610. The 2011 photo courtesy of the Mountain Legacy Project, School of Environmental Studies, University of Victoria, Victoria, British Columbia (http://mountainlegacy.ca/).

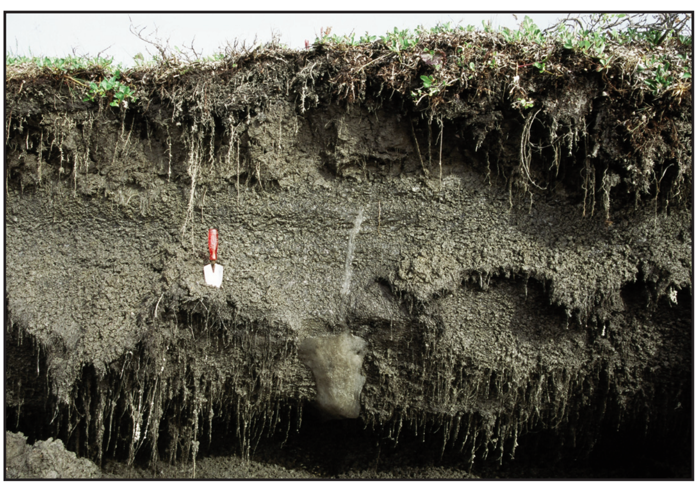

Figure 10. Organic matter (rootlets alongside ice) in near-surface permafrost at Herschel Island, Yukon. Decay of this formerly frozen matter emits CO_2 and methane to the atmosphere. The trowel is 22 cm long. Photo copyright © C.R. Burn.

governments' efforts to limit emissions (Natali et al. 2021). Methane emissions from permafrost sources are of particular concern because CH_4 has greater warming potential, about 30 times higher per tonne than CO_2 over 100 years (EPA 2020). Thawing of permafrost beneath lakes and in the continental shelves of the Arctic Ocean also leads to release of deeply stored geological methane (Walter Anthony et al. 2012; Kohnert et al. 2017).

Two further amplifying effects stem from the increase in area burned by wildfires as summers become drier in a warming climate (Wang et al. 2017). First, a reduction of forest cover reduces evapotranspiration and more of the available solar energy warms the soil and atmosphere. Second, tundra and peatland fires add to atmospheric concentrations of greenhouse gases. These fires have more net emissions than forest fires because burned forests commonly regrow and recapture their lost carbon over a few decades whereas peat takes hundreds to thousands of years to reaccumulate (Zoltai 1993).

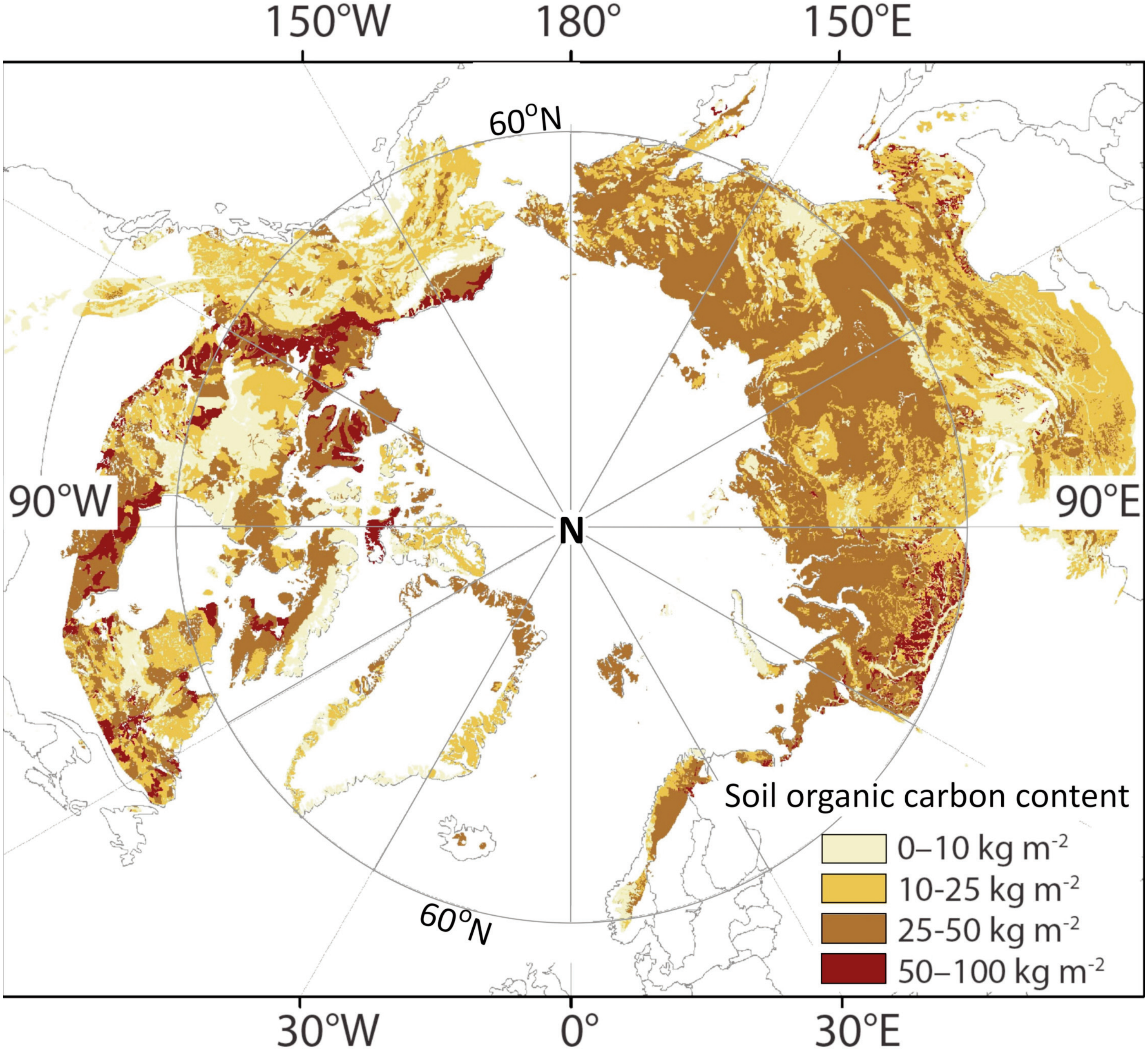

Figure 11. Soil organic carbon content in the uppermost 1 m of the ground throughout thecircumpolar permafrost region. Data from Hugelius et al. (2013); map after Bolin Centre for Climate Change (https://bolin.su.se/data/ncscd/), reproduced with permission.

Significant policy issues arise with such amplification for the responsibility of governments, under international climate protocols, to limit human-sourced emissions. Adjustments in 'natural' carbon sources, resulting from amplifying effects such as permafrost thawing or tundra fires, are not included in a country's emissions totals. Increases from these sources may outstrip actions currently being proposed by governments (Natali et al. 2021).

CONSEQUENCES OF CLIMATE CHANGE FOR CANADIAN SOCIETY

Some of the immediate consequences of climate change stem from the increasing frequency and intensity of unusual and, at times, extreme weather events (Vincent et al. 2018). These lead to flooding, especially in spring, as in Calgary (2013), Saskatchewan (2014 and 2016), eastern Ontario and Quebec (2017), and New Brunswick (2018 and 2019) (e.g. Pomeroy et

Figure 12. The 2013 flood at Heritage Drive, Calgary, Alberta. The flooding in 2013 caused $7.8 billion in insurance losses and direct costs in Alberta (CESD 2016). Photo copyright © The City of Calgary. All rights reserved. Reprinted with permission.

Figure 13. CN railway at Tantramar marshes on the New Brunswick–Nova Scotia border during high tide with storm surge of 60 cm, November 2015. Wave splash reached the rails. Photo by Mike Johnson, Cumberland Regional Emergency Management, reproduced with permission.

al. 2016; Fig. 12). In addition, the frequency of hurricanes and other major storms making landfall has increased, with 16 of these events battering Canada in the 45 years between 1950 and 1994, and, more recently, 25 hurricanes in the 25 years since 1995. Excessive precipitation and thawing permafrost also promote the conditions for landslides (Patton et al. 2019). Data published by both the federal Climate Disaster Database and the Insurance Bureau of Canada track increasing numbers of weather-related disasters over the last 50 years: the federal data show a doubling of events in 1970–2019, and the Insurance Bureau a tripling in 1983–2019 (Sawyer et al. 2020).

More frequent drought is anticipated with climate change. Many rivers of western Canada depend on runoff from glaciers in the mountains and are now facing reduced flow or drought in the summer as these ice fields melt away and snowmelt occurs earlier in the year (Dierauer et al. 2019). Acute summer drought in the interior of British Columbia is already a regular occurrence due to shifts in timing of spring melt of mountain snowpacks and high water use for irrigation. These factors lead to increased water shortages for municipal use and affect stream flows (Polar Geoscience Ltd. 2012). Reductions in the thickness of mountain snowpacks are leading to reduced replenishment of surface water reservoirs during spring melt, exacerbating water shortages (Schindler and Donahue 2006). Drought in the Prairies, like that in 1999–2004, is similarly expected to increase. However, in areas where recharge of aquifers mainly occurs in summer, more extreme rainstorms may benefit the water supply (Bonsal et al. 2019).

Sea level has risen and fallen over the last few million years, largely in response to glaciation. Current melting of ice sheets and glaciers and warming of the oceans is causing sea level to rise between 3 and 4 mm per year (Dangendorf et al. 2017), increasing the risk of flooding and destructive storm surges for communities near sea level. About 40% of the increase is due to expansion of the oceans as their temperature rises and most of the rest from melting of ice on land. The increase in sea level by the end of this century is projected to be between 0.5 and 1 m, with a further metre possible if melt of the Greenland ice sheet accelerates (Maslin 2014). In the long term, losses from the Greenland and West Antarctic ice sheets are expected to raise sea level significantly, because the level was 6–20 m higher the last time atmospheric greenhouse gas concentrations were similar to present values (Foster and Rohling 2013). Cities such as Charlottetown, PE, and Richmond, BC, will eventually become submerged if the ice caps respond fully to climate warming, but the time at which this may happen is not clear. Sea level also depends on long-term effects associated with movement of Earth's crust, especially continuing relaxation from the loss of the ice that formed during the last glaciation. The east coasts of Canada may experience over 1.5 m of sea level rise before 2100, but less is anticipated on the west coast (James et al. 2021). This century, the near-sea-level transportation corridor between New Brunswick and Nova Scotia, which includes the Trans-Canada Highway and the CN Railway, will become increasingly vulnerable and need protection by dykes or to be relocated (Fig. 13).

The effects of sea-level rise will be exacerbated by increased storm damage due to the loss of protective winter ice along shorelines of the Great Lakes, the coasts of eastern Canada, and in the Arctic (Lemmen et al. 2016). The longer open water season and greater area of open water increasing storm wave power has already led to more rapid coastal erosion, threatening Arctic settlements such as Hall Beach, NU, and Tuktoyaktuk, NT (Lim et al. 2020; Fig. 14). Erosion is prevalent along the coast of Prince Edward Island and the depositional shorelines of the Great Lakes (Genest and Joseph 1989; Keillor 2003).

The steady climate warming also has immediate consequences for the inhabitants, infrastructure, and environment of the North. The serviceability of winter roads to northern communities and mines and of infrastructure built upon permafrost will deteriorate. Chilled foundations are now needed for some new buildings with proposed service lives of 30–50 years (Hoeve and Zhang 2019), while roads and airport runways deteriorating through thaw settlement need new, similarly costly construction. Hundreds of waste disposal sites, or sumps, created by military (DEW Line) and resource exploration operations in 1950–2010 were designed to use the surrounding permafrost as a secure containment field but now

Figure 14. Waves breaking at Tuktoyaktuk, Northwest Territories, during a storm in August 2019. Coastal erosion at Tuktoyaktuk has forced relocation of houses such as these. Photo by Weronika Murray, courtesy of Natural Resources Canada.

Figure 15. Failed drilling waste disposal sump at Parsons Lake, Tuktoyaktuk Coastlands, Northwest Territories, June 2004. Photo copyright © C.R. Burn.

may fail (Kokelj et al. 2010; Fig. 15). Natural contaminants, such as mercury released by thawing permafrost, are already being detected in northern rivers but thawing of permafrost around sumps will lead to the release of other wastes (Thienpont et al. 2013; St. Pierre et al. 2018; Mu et al. 2019).

Ocean acidification, due to uptake of CO_2 and its combination with water to form carbonic acid, is a global consequence that will negatively affect marine biodiversity and production (Godbold and Calosi 2013). Climate change also has numerous biological effects; two such recorded examples are the proliferation of shrubs north of the treeline and adjustments in the ranges of various plant and animal species (Wilcox et al. 2019; Aronsson et al. 2021).

The problems that stem from large-magnitude precipitation events are commonly managed through emergency measures, but the gradual effects of climate change may require resources to be diverted from other government programs. There will be higher insurance costs for Canadians as forest fires and floods damage property. Insured losses in Canada from catastrophic weather events exceeded $20 billion in 2010–19, compared with $12.7 billion in the three previous decades (Sawyer et al. 2020). Many Canadians may appreciate the milder winters that climate change brings (Vincent et al. 2018) but not the higher coastal waters, lengthened forest fire seasons, and associated poor air quality in the elevated heat of summer.

CLIMATE CHALLENGES AND SOCIAL RESPONSIBILITY

Environment and Climate Change Canada has estimated that in 2016 Canada's anthropogenic emissions of greenhouse gases were about 1.5% of the global total (ECCC 2021a). We have 0.5% of the global population, and our per-capita emissions are amongst the highest in the world, currently at 19.5 tonnes of CO_2 equivalent per capita (ECCC 2021b). Our national annual emissions have been more than 700 million tonnes of CO_2 almost every year since 1999, even though they have declined on a per capita basis by about 10% since 2005. As of 2019, Canada had 10% of the world's proven oil reserves, the vast majority being in the Athabasca Oil Sands. About half of the world's total reserves that are open to private sector investment are contained in the Oil Sands (NRCan 2019). About 7% of our electricity was produced using coal in 2018, with the tonnage burned declining by 49% since 2008 to 26 million tonnes (NRCan 2021).

Emissions reduction is now recognized as imperative to limit climate change. Society is rapidly developing alternative energy sources and different technologies for a post-fossil-fuel economy. New technologies for power generation, heat storage, electric vehicles, and batteries all require new supplies of critical metals and materials, whose exploration and development must accelerate if we are to transform society away from dependence on carbon in the next 30 years. Earth scientists are involved directly in these initiatives as well as in helping to reduce emissions from operating mines and energy development projects. Direct reduction of atmospheric carbon may be achieved through capture and sequestration facilities that will need to proliferate at sites where the geology facilitates and ensures successful underground storage of CO_2. Government policy plays an essential role in supporting such activities, from research through to development.

There is widespread recognition that the climate is warming. Its anticipated effects are unprecedented in recent human history. The transition to a low-carbon economy must come quickly to mitigate the long-term consequences for future generations of Canadians. However, continued population growth, the amount of time required to transform the global economy, and long-term responses of the atmosphere-ocean-land system, including the time required for the oceans to adjust to atmospheric warming, all mean that climate change and its effects will continue for millennia partly because the rate of absorption of CO_2 by the oceans will decline as the temperature rises (Maslin 2014). Even if the causes could be remedied immediately, adaptation to these consequences will be necessary. Along with rapid reduction of emissions, society requires technical adaptations, better land-use planning, and new standards and regulations driven by sound understanding of the current and predicted environmental effects from climate change. These initiatives will take time to develop and need effective implementation.

CRITICAL ROLE OF THE EARTH SCIENCES

Canada is uniquely positioned with its strong global geoscientific leadership, its vast landmass, and its northern terrain to effectively leverage research activities around climate change. Practical measures, such as improved environmental assessment techniques that include and mitigate effects of climate change on all municipal and industrial development, are also needed. For example, climate change issues such as water availability, forest-fire potential, flooding, and use of cement should be rigorously assessed prior to new housing development and other construction within cities and smaller municipalities. Building codes, strict zoning, and other standards should protect Canadians from climate change effects especially in areas prone to forest fire, flooding, coastal erosion, and/or permafrost thaw (e.g. CSA 2019). Accurate prediction of extreme events by Earth scientists both statistically and in real time will be a key part of climate-change management. Education of students and the public in Earth Science aspects of climate change, as summarized in this statement, will explain the reasons why national action on climate change is necessary. Geoscientists, engineers, and their professional associations will be in the forefront of the activity to identify, mitigate, and adapt to the inevitable effects of climate change (CAPSG 2021).

The scientific knowledge of climate change and its impacts is physically robust. We cannot predict our climate precisely decades from now because we do not know how emissions will change, but we can trust the scientific knowledge regarding climate change because it has stood the test of historical examination of CO_2 and global conditions through the geological record. Our simulations of future climate are based on validated physical understanding of the atmosphere-ocean-land system (Stocker et al. 2013). Legislation, regulation, and policy development all need such knowledge and a long-term commitment to mitigate climate change and manage its effects, while creating opportunities for nation building through innovative and aligned research and development.

ABOUT THE CANADIAN FEDERATION OF EARTH SCIENCES (CFES)

CFES (www.cfes-fcst.ca) is the national organization for Canada's learned, technical, and educational societies in the Earth Sciences. With 14 member organizations, representing 15,000 geoscientists, the mission of CFES is to serve as the coordinated voice of Canada's Earth Science community, ensuring that decision makers and the public understand the contributions of Earth Science to Canadian society and the economy.

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