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Global greenhouse gas emissions and Canadian GDP

OFFICE OF THE PARLIAMENTARY BUDGET OFFICER
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The Parliamentary Budget Officer (PBO) supports Parliament by providing economic and financial analysis for the purposes of raising the quality of parliamentary debate and promoting greater budget transparency and accountability.

This report examines the long-term impact on the Canadian economy of changing weather patterns due to climate change.

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Summary

In previous analyses, PBO estimated the economic impact of the Government's policies to reduce Canada's greenhouse gas (GHG) emissions. This report extends those analyses to examine the long-term impact on the Canadian economy of changing weather patterns due to climate change, which is summarized by the change in real GDP.

Our analysis is intended to be a first step in reporting the economic impacts of climate change to parliamentarians. Given that our analysis draws from a literature still in the early stages of development, our results are best seen as reflecting some of the major factors linking climate change and the economy, with more refinement to come in future work.

To obtain the climate effects, we use a generalised relationship recently outlined by the Intergovernmental Panel on Climate Change (IPCC) linking cumulative global GHG emissions to global mean surface temperature change. This is combined with emissions projections under global policies from the International Energy Agency (IEA) to obtain Canadian mean surface temperature and precipitation projections.

Our interest is focused on the IEA's November 2021 Announced Pledges Scenario (APS), which incorporates all climate commitments made by governments around the world (even if the required policies are not yet fully specified) and assumes that "they will be met in full and on time". Under this APS scenario, the projected increase in global temperature would be limited to 1.8 degrees Celsius (relative to pre-industrial levels: the 1850-1900 average).

The IEA's Stated Policies Scenario (STEPS) is also of interest since it lines up with the framework we have used in the past, where only implemented policies are included. Such a scenario would result in global warming to rise significantly above 2 degrees Celsius.

For context, the Paris Agreement commits signatories to "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Further, scientists warn that there are major climate risks for breaching the 1.5 °C warming level.

When combined with the relationship from the IPCC results, global GHG emissions under our benchmark APS emissions scenario would result in an increase in average surface temperature for Canada of 1.3 degree Celsius in 2100 relative to 2021 levels (Table S-1).

Table S-1 Change in climate indices for Canada (relative to 2021)

	Announced Pledges Scenario (APS)	
	2050	**2100**
Mean surface air temperature (°C)	0.7	1.3
Total precipitation (%)	2.3	3.9
Growing seasons: warm season crops (days)	5	9

Sources: Office of the Parliamentary Budget Officer and Environment and Climate Change Canada from IEA (2021b) and Meinhausen et al. (2022).

Note: These changes are in addition to climate impacts up to 2021.

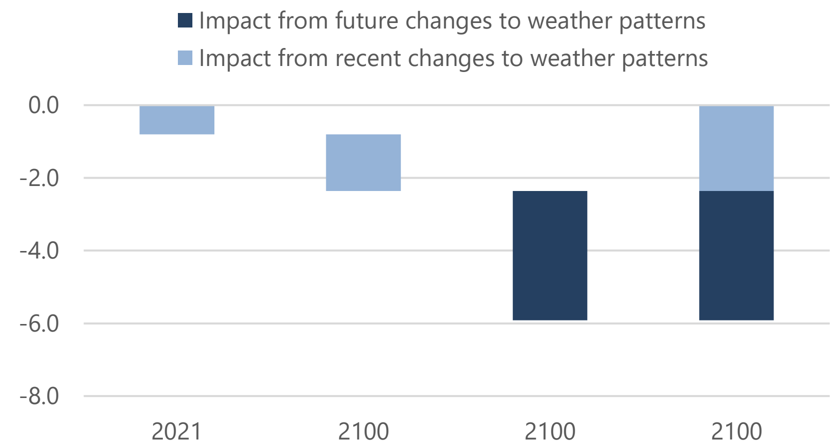
To assess the economic impact of APS-based global GHG emissions on Canada, we follow a framework similar to Herrnstadt and Dinan (2020) at the Congressional Budget Office (CBO) based on rising temperatures and precipitation. Our review of the literature and our econometric analysis suggests that changing weather patterns have a (net) negative impact on Canada's annual real GDP growth.

We use the relationships between GHG emissions and climate variables (temperature and precipitation), and between climate variables and real GDP growth, to estimate the impact of climate change on Canada's real GDP. This impact is estimated relative to a counterfactual scenario where climate variables remain at their average levels observed over 1961 to 1990.

- We estimate that the 0.9-degree Celsius average increase in Canada's surface temperature and 2.5 per cent average increase in precipitation (relative to the 1961-1990 reference levels) have lowered the level of Canadian real GDP in 2021 by 0.8 per cent (first bar, Figure S-2).
- Recent changes in weather patterns will continue to reduce real GDP in Canada over the long term, lowering it by 1.6 per cent in 2100 through lower annual labour productivity growth (second bar, Figure S-2).
- Future changes to weather patterns including a further 1.3-degree Celsius increase in Canada's temperature and 3.9 per cent increase in precipitation will reduce the level of real GDP in 2100 by an additional 3.6 per cent (third bar, Figure S-2). We estimate a total climate change impact on real GDP in 2100 of 5.8 per cent (fourth bar, Figure S-2).

Figure S-2 Estimated impact on Canada's real GDP in 2100 from climate change

Percentage difference, real GDP under APS emissions scenario relative to real GDP under counterfactual 1961-1990 climate scenario



Source: Office of the Parliamentary Budget Officer.

Note: The counterfactual 1961-1990 climate scenario assumes that average annual surface temperature and precipitation over 1981 to 2100 remain at their average levels observed over 1961 to 1990.

Our estimates are based on an assumed linear relationship between low levels of temperature change and the impact on real GDP, although global temperatures under the APS scenario are not projected to exceed 2 degrees Celsius above pre-industrial levels. Also not fully captured in our analysis are some complex issues such as adaptation, international economic spillovers, transition within industries and regions, as well as exceptional increases in extreme weather events and tipping points. Our estimation captures detectable impacts of changing temperatures and precipitation that have already occurred, so it accounts for what might be considered first-order effects under the APS emissions scenario.

Nonetheless, the APS emissions scenario provides a means to focus on climate policy, even if uncertainty in a broad range of areas (such as emissions, climate impacts and GDP impacts) makes this analysis highly conditional. If global policies remain closer to current settings—consistent with the IEA's STEPS scenario—the negative impact on Canada's GDP would be even larger.

- Based on a longer-term projection of the IEA's emissions scenarios, if global policies remain closer to current settings and global climate commitments are not met (per the STEPS scenario), we estimate that the level of real GDP in 2100 would be approximately three-quarters of a percentage point lower (Table S-2) compared to an APS emissions scenario in which all countries fully meet their climate commitments.

- However, our estimate likely understates the negative impact on GDP under the STEPS scenario given that it does not capture exceptional increases in severe climate events that scientists warn would occur as global temperatures rise significantly above key thresholds.
- The APS scenario in Table S-2 limits the projected increase in global temperature to 1.8 degrees Celsius above pre-industrial levels. The STEPS scenario results in global warming to rise significantly above 2 degrees Celsius.

Table S-2 Estimated impact of climate change on Canada's real GDP based on global GHG emissions scenarios

Percentage difference	2021	2050	2075	2100
Current policies plus announced pledges (APS)	-0.8	-2.4	-4.1	-5.8
Current policies only (STEPS)	-0.8	-2.5	-4.4	-6.6

Source: Office of the Parliamentary Budget Officer.

Note: Estimated from projections outlined in Appendix B (Figure B-2).

Our use of the APS as a benchmark is not intended to minimise uncertainty, rather it complements our earlier work that estimated the economic impacts of the Government's policies to reduce Canada's GHG emissions. A more in-depth discussion of uncertainty and risk around the APS scenario can be found in Meinhausen et al. (2022).

1. Introduction

In previous analyses, PBO estimated the economic impact of the Government's policies to reduce Canada's greenhouse gas (GHG) emissions, or of the distributional impacts of those policies.[1] This report extends those analyses to examine the long-term impact on the Canadian economy of changing weather patterns due to climate change, which is summarized by the change in real GDP. Other metrics such as the dollar impact on various sectors are partial analyses since they tend to omit inter-actions within the economy (for example, Martinich and Crimmins, 2019).

Economic costs would include, for example, the effects from warmer weather on various industries, human activity, potential impacts of exceptional increases in extreme weather events, tipping points, rising sea levels, as well as difficult-to-quantify aspects such as species and ecosystems loss.

For the quantifiable aspects, accounting for the cost of climate change is not straightforward. Extreme weather events and tipping points create inflection points that are uncertain but could have large consequences. Combined with variability and uncertainty in both economic and climate projections means that there is a wide range of potential outcomes, suggesting the use of risk assessments of future outcomes.

However, such risk assessments would make the exposition of some important interrelationships in the economics of climate change even more challenging. Since our objective in this report is to focus on those interrelationships, we use a particular scenario outlined by the International Energy Agency (IEA) in their 2021 World Energy Outlook (IEA, 2021a,b)—the Announced Pledges Scenario (APS).[2]

The economic (GDP) impact of a changing climate is a nascent but growing literature (for example, see Khan et al., 2019; Dell et al., 2012). The seasonal impacts of warmer winters and summers were quantified in Colacito et al. (2019). A more extensive analysis was done by the Congressional Budget Office (CBO) in the United States, which found that historically there is evidence for an impact on productivity growth under a warming climate. CBO also projected future impacts on the basis of a weighted average of IPCC model runs—with the weights reflecting their assessments of the plausibility of scenarios. More recent work reinforces the finding that weather can affect growth and not just the level of GDP (see Bastien-Olvera et al., 2022).

2. A benchmark GHG emissions scenario

In this report we focus on a particular GHG emissions scenario that is consistent with our previous analysis. It incorporates climate commitments made by governments around the world (even if the required policies are not yet fully specified) and assumes that "they will be met in full and on time". To do so, we use a combination of analyses done by both the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency.

Although we focus on one emissions scenario (APS), we do not endorse it as a "most likely" outcome. We use it as an anchor that is grounded in current climate policy commitments. In its work, the IPCC is careful not to favour a particular scenario—it allows users of its products to decide for themselves the relevance of each scenario—although its Summary for Policymakers does provide some risk assessment and describes some outcomes as more likely than others. That ambivalence leads to references of IPCC work that span the full range of emission outcomes, including the high-end emissions scenarios with considerable warming.

The IPCC also assigns levels of confidence in historical estimates of the drivers and impacts of climate change so as to convey to policymakers some of the uncertainty in the results. That said, in this report, we do not quantify uncertainty or otherwise provide a risk assessment.

2.1. IPCC and IEA scenarios

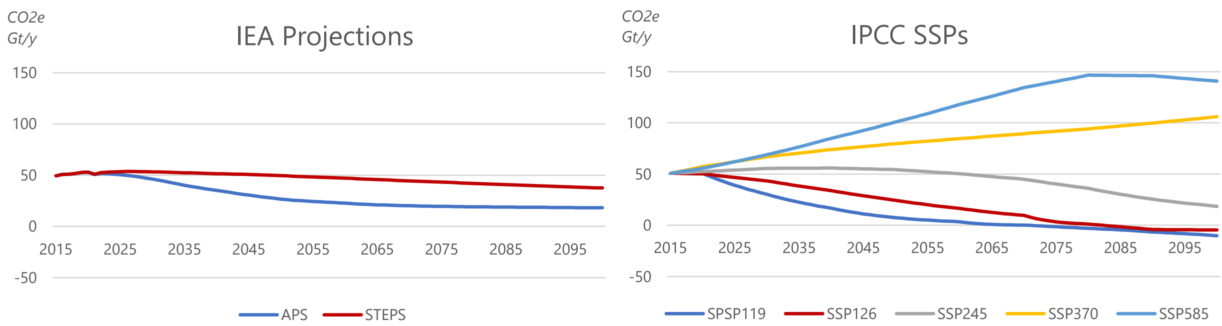
For its scenarios, the IPCC combines the behavioural drivers of emissions in the Shared Socio-economic Pathways (SSP) with quantified effects of emissions in the Representative Concentration Pathways (RCP).

The International Energy Agency, however, has a more hands-on approach to projecting emissions. It tracks and projects demand and supply for energy based on policies, technology, and economic trends, especially for fossil-fuel based energy.

In their 2021 World Energy Outlook, the IEA made a series of global emissions projections to 2050. One scenario that is particularly relevant to our analysis focuses on the climate commitments that have been made by governments over recent years: the Announced Pledges Scenario (APS). That scenario was updated and further explored in IEA (2021b) and Meinhausen et al. (2022), which extended the emissions projections to 2100 and serves as our benchmark global GHG emissions scenario.[3]

The IEA's scenarios are not in conflict with those of the IPCC, but instead they complement them by presenting emissions scenarios differentiated by government policy. Over the relatively short horizon to 2050, the difference between the ranges of the IPCC and IEA scenarios is quite sharp (Figure 2-1).

Figure 2-1 IEA emissions scenarios and IPCC representative emissions profile for individual SSPs.



Sources: IEA (2021b), Meinhausen et al. (2022), and IPCC (2021).

Note: SSP: Shared Socio-economic Pathway. Scenarios from the IPCC have considerable variation around each emissions projection. Those included here have been published as reference cases for each scenario—although this designation does not confer any greater weight for the likelihood of their occurrence.

The emphasis on policies and (historical) technology/economic trends creates an upper bound on emissions given the announced and implemented measures already undertaken (the STEPS scenario). This upper bound, however, is only as firm as governments' underlying commitments.

2.2. PBO benchmark GHG emissions projection

In the past, PBO has made use of the Environment and Climate Change Canada's (ECCC) scenarios for its analyses. For example, ECCC (2020) included a "with measures" (WM) scenario that was intended to project the impact of fully specified and implemented policies. Thus, it included the federal carbon levy (and provincial equivalents) but excluded the Clean Fuel Standard because that policy was not yet fully specified even though it had been announced.

Also included in ECCC's projections were the expected effects of those policies announced but not yet fully specified: the "with additional measures" (WAM) scenario.

PBO used the WAM scenario as its baseline to illustrate the difference between the Government's commitments—even those not yet fully specified—and the GHG emissions target it had set for itself.

For Canada, the APS scenario includes,

- Energy provisions in the 2020 Healthy Environment and a Healthy Economy Plan,

- Spending in the Hydrogen Strategy and Strategic Innovation Fund Net Zero Accelerator, and
- Immediate targets and plans established to meet net zero GHG emissions target by 2050.

These elements make APS a natural choice for a benchmark scenario that projects WAM-comparable global greenhouse emissions.

Missing from the IEA scenarios, however, are analyses of their climate impacts for Canada.[4] To help fill that gap, the Climate Research Division of ECCC assisted PBO by using a relationship reported in Canadell et al. (2021) to link emissions and temperature (and other climate variables). Those results were double-checked by using the MAGICC model to run the same simulation (Meinhausen et al., 2011). Additional detail concerning methodology is provided in Appendix B. To summarise, a large collection of simulations from international modelling teams were used to identify a relationship between emissions and temperature. That relationship was then used to estimate the climate consequences for Canada of the IEA global emissions scenarios.[5]

The results for Canada in the APS scenario give a 1.3-degree increase in mean surface temperature change between 2021 and 2100 (Table 2-1).

Table 2-1 Change in climate indices for Canada (relative to 2021)

	Announced Pledges Scenario (APS)	
	2050	**2100**
Mean surface air temperature (°C)	0.7	1.3
Total precipitation (%)	2.3	3.9
Days with max. temperature above 30°C	1	3
Heating degree days	-246	-441
Cooling degree days	16	30
Growing season length (days)		
Overwintering crops	5	9
Cool season crops	2	3
Warm season crops	5	9

Sources: Office of the Parliamentary Budget Officer and Environment and Climate Change Canada.

Note: Degree days are the number of degrees Celsius a given day's mean temperature is different from 18 °C. The asymmetry between increases in heating degree days and cooling is indicative of seasonal effect where winters warm more than summers.

In our benchmark emissions scenario, total precipitation in Canada is expected to increase by 3.9 per cent in 2100 compared to 2021. The annual number of days where daily maximum temperature is above 30 degrees Celsius is also expected to increase by 3 days. Consistent with the increased warming, heating degree days will decrease while cooling degree days increase. This means that more energy will be needed for air conditioning and less will be required for heating. Growing seasons in Canada will increase in most regions.

While these point estimates are useful for considering the consequences of GHG emissions under existing climate commitments, they require context. These changes do not account for exceptional increases in extreme weather events, such as precipitation, which may increase non-linearly even with low levels of global warming (Zhang et al., 2021; Seneviratne et al., 2021). For example, under the IPCC's Representative Concentration Pathway (RCP) 2.6, a 1-in-50-year precipitation event is projected to become a 1-in-25-year event. The annual(ised) cost of those exceptional events under the APS scenario may become large enough to be detected in Canada's GDP growth by 2100, or even 2050.

There is also the possibility of breaching tipping points in earth's regional geochemical cycles (Canadell et al., 2021; Kopp et al., 2016). While these are more likely at higher emissions levels,[6] they may also be significant enough at lower emissions levels to be detectable in Canada's GDP growth.

The results we report here with respect to the impact of GHG emissions on Canada's GDP are therefore informative as first-order impacts, but not comprehensive for the APS scenario.

3. Impact of climate change on Canada's real GDP

Under IEA scenarios, weather is not expected to be a major driver of long-term economic growth in Canada relative to demographics, business investment and technology. Nonetheless, changing temperature and precipitation patterns due to climate change can affect the Canadian economy through the following channels:[7]

- Agricultural output and productivity;
- Heat effects on labour productivity and human health;
- Sea level rise in coastal regions;
- Energy use and demand;
- Damage to property and the capital stock; and,
- Tourism and climate-sensitive activities (for example, ski resorts).

Canada's weather patterns continue to deviate from historical experience due to climate change.[8] Some climate effects like longer growing seasons[9] and warmer weather could increase Canada's GDP while more frequent days over 30 degrees Celsius, droughts, and severe storms will have a negative economic impact. Studies showing a positive impact on Canada's GDP rely on a large boost in tourism[10] while those with a negative impact focus on labour productivity (Kahn et al., 2019, Dell et al., 2012). More recently, the Canadian Climate Institute (2022)[11] estimated that climate change could reduce Canada's real GDP by between 5.2 and 12.4 per cent by 2095.

The sign and magnitude of the climate impact on GDP can vary depending on the size of the climate shock, methodology and dominant channel. Studies have used different approaches to model the physical impact of climate change on economic output including:

- Estimating damages at the sectoral level and aggregating to compute economy-wide impacts such as Roson and Santori (2016);
- Top-down econometric models that assess the relationship between historical changes to weather variables and GDP such as Colacito, Hoffman and Phan (2019) or Kahn et al. (2019); and,
- Integrated Assessment Models which link detailed climate modelling to the global economy within a computable general equilibrium framework. A well-known one is the RICE/DICE family of models (e.g., Nordhaus, 2017).

We follow a similar framework as Herrnstadt and Dinan (2020) at the Congressional Budget Office (CBO)[12] to estimate the economic impact of climate change. We review studies which relate a specific weather shock (usually temperature from an IPCC scenario) to its impact on real GDP growth over time.[13] We augment this review by conducting an econometric analysis of the historical relationship between climate variables and real GDP growth in Canadian provinces. The data, methodology and estimation results are described in Appendix A.

Our review of the literature and econometric analysis suggests that, on average, a 1-degree Celsius increase in the average surface temperature relative to the 1961 to 1990 reference level would reduce Canada's annual real GDP growth by between 0 and 0.1 percentage points.[14] This range reflects a negative impact from rising summer temperatures that is somewhat offset by a positive economic impact from warmer winters. The economic impact of global GHG emissions compounds over time as those emissions cumulate. The increased stock of global GHGs permanently increases Canada's temperature and precipitation, which lowers labour productivity and real GDP growth.

We estimate that higher average temperatures and precipitation over 1981 to 2021 have reduced Canada's real GDP in 2021 by 0.8 per cent, and that continued changes to weather patterns over the long term under the APS scenario will reduce real GDP further by 5.0 per cent for a total impact of -5.8 per cent by 2100 (Table 3-1).

In terms of annual growth, we estimate that real GDP growth in Canada will be approximately 0.08 percentage points lower over the long term (Table 3-1). These impacts are measured relative to a counterfactual emissions scenario where temperature and precipitation remain at their 1961-1990 average levels over the period 1981 to 2100.[15]

Table 3-1 Estimated impact of climate change on Canada based on PBO's benchmark emissions scenario

	2021	2050	2075	2100
Impact on annual real GDP growth (percentage points)	-0.02*	-0.06	-0.07	-0.08
Impact on the level of real GDP (%)	-0.8	-2.4	-4.1	-5.8
Temperature change from 1961-1990 reference level (degrees Celsius)	0.9*	2.8	3.1	3.4
Precipitation change from 1961-1990 reference level (%)	2.5*	8.4	9.3	10.1

Source: Office of the Parliamentary Budget Officer.

Note: These estimates are derived by applying recent literature and our own econometric analysis to our emissions scenario and long-term economic projection. See Appendix A for further discussion.

* Refers to the average over 1981 to 2021.

Table 3-2 provides a breakdown of the historical and future impacts of climate change on real GDP in Canada. It shows that the continuation of recent weather changes will account for 2.4 percentage points of the estimated GDP loss in 2100. This includes a lower level of GDP in 2021 as well as lower annual labour productivity over 2022 to 2100. The remaining 3.6 percentage points is from future increases to temperature and precipitation beyond 0.9-degrees Celsius and 2.5 per cent respectively.

Table 3-2 Components of impact on Canada's real GDP based on PBO's benchmark emissions scenario

Percentage difference	2021	2050	2075	2100
Continuation of recent weather changes	-0.8	-1.4	-1.9	-2.4
Future weather changes	0.0	-1.1	-2.2	-3.6
Total weather impact	**-0.8**	**-2.4**	**-4.1**	**-5.8**
Components of total weather impact				
Temperature	*-0.7*	*-2.1*	*-3.6*	*-5.2*
Precipitation	*-0.1*	*-0.3*	*-0.5*	*-0.8*

Source: Office of the Parliamentary Budget Officer.

Note: Numbers may not add up due to rounding.

Historical climate change impacts are already partially included in PBO's long-term economic projections since we (essentially) project future productivity growth based on its historical average. However, our projections of growth in labour productivity over the long term do not include the impact of future changes to weather patterns in our benchmark emissions scenario.[16] Our estimated impacts of future changes in weather patterns in

Table 3-2 can be applied to our current long-term projection to better reflect the impact of climate change on the Canadian economy over the long term.

These estimates are a first step in PBO's analysis of the economic impact of climate change. The following issues are not fully captured by our methodology and may be addressed in our future work:

- **Adaptation:** Top-down econometric studies can only partially assess how adaptation can change the relationship between climate and economic growth over time. For example, our analysis does not consider transition costs and opportunities of evolving to a low carbon economy;
- **Global impacts:** Most studies show that the economic impact of climate change will be more severe in other countries than in Canada. This will negatively impact Canada through trade, finance and confidence channels;
- **Extreme weather events:** Changes in temperature and precipitation patterns in our benchmark scenario do not capture exceptional increases in extreme weather events and tipping points. Our modelling approach assumes a linear relationship between temperature and economic growth; and,
- **Canada's Arctic:** The Arctic region will experience the largest increase in temperature and precipitation. Due to data limitations, we were not able to include the territories in our econometric analysis.

Climate change will affect Canada beyond its impact on real GDP. Many effects—such as the impact on health, well-being, nature and ecosystems—have been studied extensively by Environment and Climate Change Canada, Natural Resource Canada, among others.[17]

4. Impact of global policy actions

In previous analysis, we provided estimates of the economic impacts of the Government's policies to reduce Canada's GHG emissions by 2030.[18] All else equal, the GDP impact of the Government's policies over that horizon would likely be discernible in terms of modestly slower economic growth relative to recent experience.

On the other hand, the effects of global emissions reduction policies to avoid climate damage to the economy have a much longer horizon and will not be as discernible; their success must be inferred from a lack of damage, or the avoidance of climate catastrophe.

We estimate that climate impacts from future global emissions under our benchmark APS scenario would lead to a reduction in Canada's GDP of

3.8 per cent by 2100. But since that scenario has (cumulative) global GHG emissions continuing to rise after 2100, the negative impact on GDP would increase further after 2100.

The IEA also publishes a STEPS scenario which is limited to including policies that were implemented by 2021. In that case, even for 2050 the impact on Canada's GDP from changes in weather patterns would be only marginally different from the APS scenario; however, the gap between the two scenarios suggests that after 2050 there would be a divergence in emissions, and therefore a greater negative impact on GDP under the STEPS scenario.

Indeed, using a longer horizon for IEA's scenarios (see Appendix B, Figure B-2), under the STEPS scenario, relative to 2021 levels, average Canadian surface temperatures that would be 1 degree Celsius warmer, and annual precipitation would be 2.7 percentage points higher in 2100 compared to our APS scenario.

Based on the IEA emissions scenarios, if global policies remain closer to current settings and global climate commitments were not met (per the STEPS scenario), we estimate that the level of Canadian real GDP in 2100 would be approximately three-quarters of a percentage point lower compared to the APS scenario in which all countries fully meet their climate commitments. That is, real GDP in Canada would be 6.6 per cent below its level under a counterfactual emissions scenario where temperature and precipitation remain at their 1961-1990 average levels over the long-term projection horizon (Table 4-1). However, our estimate likely understates the negative impact on GDP under the STEPS scenario given that it does not capture exceptional increases in severe climate events that scientists warn would occur as global temperatures rise significantly above key thresholds.

Table 4-1 Estimated impact of climate change on Canada's real GDP based on alternative emission scenarios

Percentage difference	2021	2050	2075	2100
Extended Announced Pledges Scenario (APS)	-0.8	-2.4	-4.1	-5.8
Extended Stated Policies Scenario (STEPS)	-0.8	-2.5	-4.4	-6.6

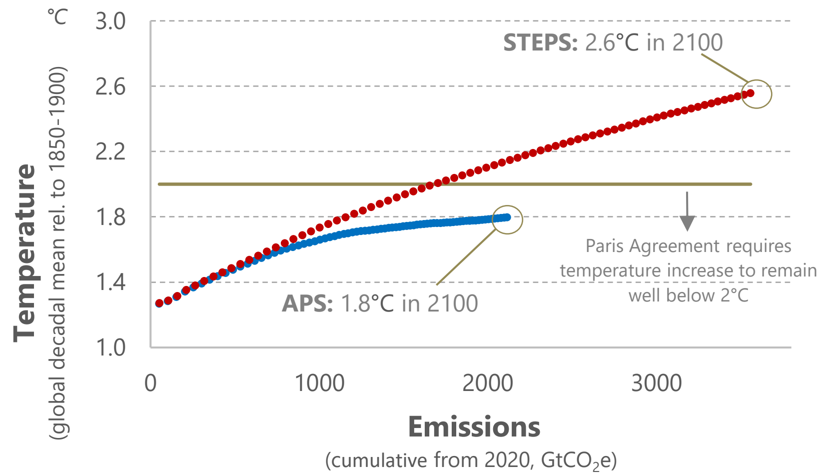
Source: Office of the Parliamentary Budget Officer.

Note: Estimated from projections outlined in Appendix B (Figure B-2).

Underlying the real GDP impact in 2100 in the APS scenario is a level of global warming that is 1.8 degrees Celsius above pre-industrial levels. In the STEPS scenario where only policies already implemented are undertaken, global warming is projected to rise significantly above 2 degrees Celsius (Figure 4-1).

For context, the Paris Agreement commits signatories to "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".[19] Further, scientists warn that there are major climate risks for breaching the 1.5 °C warming level (IPCC, 2022).

Figure 4-1 Global pledged policies (APS) versus implemented policies (STEPS)



Sources: Office of the Parliamentary Budget Officer from Meinhausen et al. (2022).

Note: The decadal mean global surface temperature for 2011-2020 was 1.1 degree Celsius above the mean over 1850 to 1900. For 2020-2029 it is projected to be just under 1.3 degree Celsius. In these scenarios, APS adds just under 0.6 degrees, and STEPS adds 1.3 degrees by 2100.

But even with pledges to get there, the means to achieve APS are not yet clear. Many of the needed technologies are still at the demonstration or prototype phase of development (IEA, 2021c).

For 2050, balancing the impact of global emissions on GDP in Canada with the GDP impact of the Government's climate policies would be mis-directed if a longer time horizon was not also considered. That is, it may take globally coordinated policies that lead to a GDP loss in excess of the contemporaneous climate-based GDP loss in 2050 in order to avoid even larger future climate-based losses (Table 4-1).

Indeed, the nearly identical climate-based GDP impacts in 2050 makes it clear that on a global basis, even the climate commitments in the APS scenario are not sufficient to avoid larger economic costs in 2050.

While the impact on Canadian GDP is from global GHG emissions, Canada's own emissions are not large enough to materially impact climate change. Consequently, Canada's primary means of limiting the economic costs of climate change are through participation in a globally coordinated emissions reduction regime.

Some discussion of the impact of policies on emissions on a global basis is outlined in Appendix B (Box B2-1).

Appendix A: Estimating the impact of climate change on Canada's real GDP

The variable linking real GDP growth and changes in weather patterns is generally expressed as a semi-elasticity—the percentage change in a region's real GDP resulting from a 1-degree Celsius increase in temperature compared to the historical average.[20]

A.1 Estimation database

We obtained historical climate data[21] by province over 1960 to 2021 from Environment and Climate Change Canada. Regional mean values are obtained by averaging monthly values for weather stations within the region.[22] We computed seasonal values of climate variables by averaging the monthly values in an economic quarter.[23] Our estimation uses annual data, so each year has corresponding climate variables for the winter (Q1), spring (Q2), summer (Q3) and fall (Q4) seasons.

We obtained provincial real GDP and population data by province from Statistics Canada.[24] We extended the provincial real GDP series from 1981 back to 1961 using an income per capita dataset constructed by Gutoskie and MacDonald (2019).[25]

A.2 Methodology

Our estimation methodology follows Colacito, Hoffman and Phan (2019) and Kahn et al., (2019). Both studies focus on the long-term, persistent impact of temperature and precipitation shocks on real GDP growth. Colacito, Hoffman and Phan (2019) estimate the long-term effect of seasonal temperature variations on U.S. real GDP growth using a panel regression on U.S. states. The authors' innovation to decompose annual temperature shocks into seasonal components is useful for Canada given that the economic impact of changing weather patterns is likely to vary by season.

Using a panel regression framework, we estimate the following equation (Figure A-1) where *RGDPPC* is a province's per capita real GDP, *TEMP* is the deviation of a province's seasonal average surface temperature in degrees Celsius from its 1961-1990 average and *PRECIP* is the percentage change in a province's annual precipitation from its 1961-1990 average. Weather variables are divided by season (S) and we include up to two lags depending on the specification:

Figure A-1

Estimated impact of seasonal weather shocks on provincial real per capita GDP growth

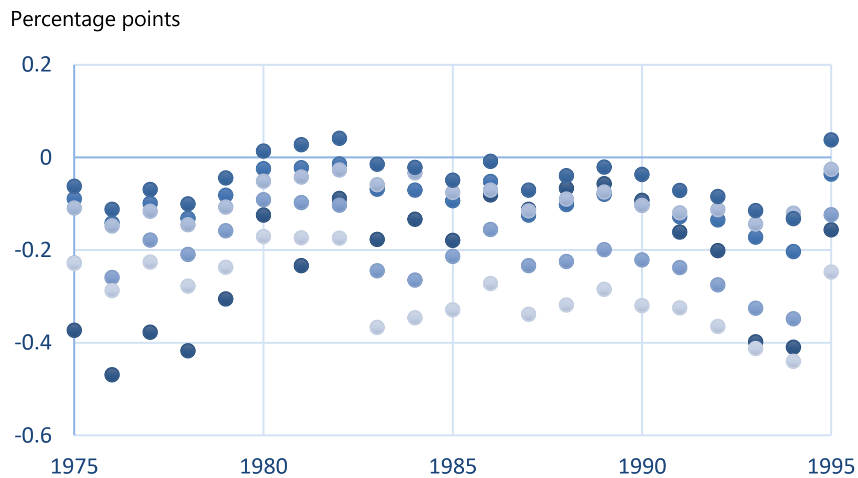
$$\Delta LN(RGDPPC_{p,t)} = \alpha_0 + \alpha_p + \gamma * \Delta LN(RGDPPC_{p,t-1}) + \sum_{s=S,t=T} \beta_{s,t} * TEMP_{s,p,t} + \sum_{s=S,t=T} \theta_{s,t} * PRECIP_{s,p,t} + \varepsilon_{p,t}$$

Overall, we find a negative relationship between higher temperatures and precipitation and economic growth in Canada. We find that hotter summers have negative impact while warmer winter temperatures have a positive effect. We did not find a significant impact from changes in spring and fall temperatures. The equation performs best over the early-1980s to 2019 sample where the lagged summer and contemporaneous winter coefficients are significant at the 1 per cent level.

Figure A-2 shows the net impact on Canada's real per capita GDP growth from a 1-degree Celsius temperature increase based on alternative specifications and sample periods of the equation in Figure A-1.[26] Compared to other studies, our econometric results suggest a somewhat larger negative impact on Canada's real GDP; though the coefficients are less stable, they remain statistically significant over time (Figure A-2).

Figure A-2

Aggregate weather impact on real GDP per capita growth using alternative specifications and sample periods



Source: Office of the Parliamentary Budget Officer.

Note: Each dot represents the net impact from all contemporaneous and one-period lagged temperature coefficients from alternative specifications of the equation in Figure A-1. The net impact is the percentage point change in real per capita GDP growth from an increase of 1 degree Celsius. The year refers to the starting period of the regression sample. All regression samples end in 2019.

While our estimation is based on growth in real GDP per capita, we assume that changes in weather patterns do not impact population growth. This way, we can translate the real GDP per capita growth semi-elasticity into a real

GDP growth semi-elasticity. Using real GDP growth as a dependent variable does not change the results of our econometric analysis.

Our review of the literature and econometric analysis suggests that, on average, a 1-degree Celsius increase in the mean surface temperature relative to the 1961-1990 reference levels would reduce annual real GDP per capita growth by between 0 and 0.1 percentage points. Based on our judgment, we use a semi-elasticity of -0.02 for real GDP growth in this report given that:

- Winter is projected to warm faster than summer in Canada which is estimated to have a relatively more positive impact. Our semi-elasticity assumption of -0.02 is consistent with our estimates when modelling the seasons separately;
- When we adjust for the relative size of provinces using weights proportional to GDP, the estimated coefficients are smaller;
- Our semi-elasticity is smaller than values reported at the global level reflecting the view that economic growth in Canada and other northern countries may be less effected economically by climate change than those in hotter climates; and,
- While our methodology considers the evolution of the relationship between changes in weather patterns and real GDP growth in Canada over time, it does not explicitly incorporate adaptation, which could bias our econometric estimate of the future impact of weather events.

We will continue to monitor developments related to climate change and the Canadian economy and update our analysis as required.

Based on our judgment, a 1 per cent increase in precipitation compared to the 1961-1990 reference period would reduce real GDP growth by 0.001 percentage points. Precipitation was found to have a small negative impact on real GDP growth but, unlike temperature, it was not statistically significant[27] in our estimation.

Appendix B: Policy-based projections of climate change

This Appendix outlines the methodology used to link IEA emissions scenarios to surface temperature changes and other climate variables such as precipitation.

Succinctly, a large number of model simulations from numerous participants in the World Climate Research Program's Coupled Model Intercomparison Project Phase 6 (CMIP6) are treated as observations to derive a relationship between GHG emissions and changes in mean surface temperature. This follows from work already identifying the consistency of that relationship (for example, Canadell et al., 2021; IPCC, 2021; Pielke et al., 2022, Figure 2 provides a visual representation of the relationship). A similar relationship is derived between changes in mean surface temperature and changes in precipitation for Canada (Zhang et al., 2019).

Those relationships then allow us to turn to IEA projections and assign changes in mean surface temperature, changes in precipitation, and other climate-related changes to their scenarios.

The models' simulation results are downscaled to provide regional detail for Canada. An adjustment is made to those regional results to, as closely as possible, replicate weather observation stations across Canada. This helps to ensure that projected regional climate change is built from actual historical climate data.

This analysis is conditional on the confidence one can have in the reliability of those models (as a whole) to be unbiased in their projections. The ongoing tests and reviews of those models provide a basis for that confidence (for example, Flato et al., 2013; Hausfather et al., 2019), though considerable uncertainty remains around the climate projections.

B.1 IPCC scenarios

For its analyses the IPCC combines two streams that effectively separate behavioural projections from GHG emissions. The Shared Socio-economic Pathways (SSP) produce scenarios that outline the potential evolution of economies and societies until 2100 (behavioural). In total 5 were created that begin from a low environmental impact with global sustainability (SSP1) and extend to a high environmental impact (SSP5) with a scenario where nothing is done toward reducing GHG emissions. In that latter case, fossil fuels are still the dominant energy source in a much larger world economy in 2100. Between SSP1 and SSP5 are varying degrees of inequality and regional rivalry (Table B-1).

For emissions, the IPCC also created a series of Representative Concentration Pathways (RCP) that focus on climate-system impacts. These were largely independent of the SSPs. The key metric in each RCP is the increase in radiative forcing, which measures the increased energy from the sun retained on the earth's surface in Watts per square metre (W/m^2). For reference, estimates put the increased human-induced radiative forcing between 1750 and 2020 at 3.2 W/m^2 (Butler and Montzka, 2022).

The average temperature change between 2011-2020 relative to 1850-1900 is estimated to be around 1.1 degrees Celsius. Greenhouse gases may have contributed by about 1.5 degrees warming, offset by the cooling effect of aerosols by about 0.4 degrees (Figure SPM.2, Panel (b), IPCC, 2021).

The IPCC's Fifth Assessment Report (AR5) was the first to use the RCPs, and included four of them (Table B-1). At the lower end was RCP2.6, where the change in radiative forcing peaks at 2.6 W/m^2 and then declines. Two intermediate scenarios were also chosen, RCP4.5 and RCP6.0, which both have changes in radiative forcing stabilizing after 2100. The final scenario is RCP8.5 at the high end of emissions, where radiative forcing continues to rise past 2100. Additional RCP scenarios were subsequently created to focus on lower-end emission outcomes. These latter scenarios were motivated by the public discussions, and in some cases policy announcements, toward achieving net zero emission around the middle of the century.

Table B-1 IPCC Shared Socio-economic Pathways and Representative Concentration Pathways

Increasing emissions

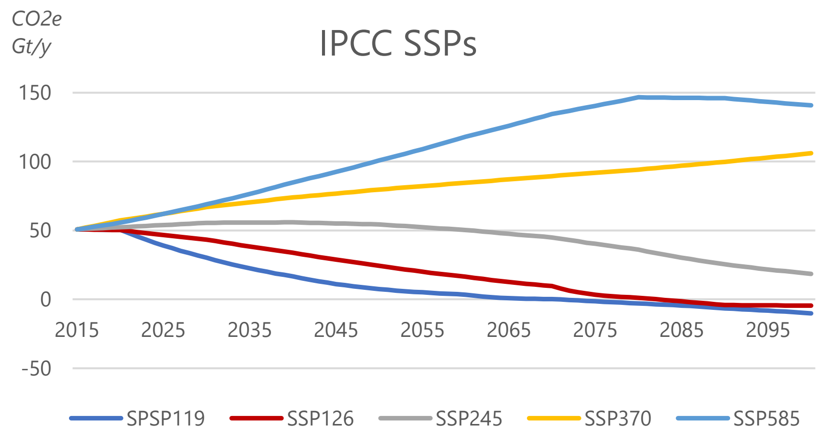
Socioeconomic Pathways	Representative Concentration Pathways
SSP1: Sustainability	2.6 W/m^2
SSP2: Inequality	4.5 W/m^2
SSP3: Middle of the road	6.0 w/m^2
SSP4: Rivalry	8.5 w/m^2
SSP5: Fossil fuels	

Source: IPCC.

Note: The tendency for emissions to increase when moving from SSP1 to SSP5 is not robust. Overlap can occur depending on how technology evolves between scenarios. Moreover, there is no tendency for GDP to grow more or less slowly when moving between the SSPs.

The combination of socioeconomic scenarios (SSP) and emissions scenarios (RCP) created a wide-ranging series of scenarios of socioeconomic drivers and their potential consequent climate consequences. With the addition of more scenarios at the lower end, emissions of GHGs range from very high, to ambitious reductions over the period to 2100 (Figure B-1).

Figure B-1 IPCC representative emissions profile for individual SSPs.



Sources: IPCC (2021), Box SPM.1

Note: SSP119 and SSP126 both have net negative emissions in their projections, implying that carbon is removed from the atmosphere.

For Canada these projections mean that at the high end (SSP585), the country-wide average temperature increases by 2100 could be more than 6 degrees Celsius (Zhang et al., 2019) relative to a 1986-2005 period. It would disproportionately raise winter temperatures—fewer days of extreme cold in the north.

B.2 IEA scenarios

In their 2021 World Energy Outlook, the International Energy Agency made a series of long-term emissions projections to 2050. Those scenarios are based on the technology trends as well as policy pronouncements that have been made over recent years by individual countries,

1) STEPS – stated policies
2) APS – announced policies
3) SDS – sustainable development
4) NZE – net-zero emissions by mid-century

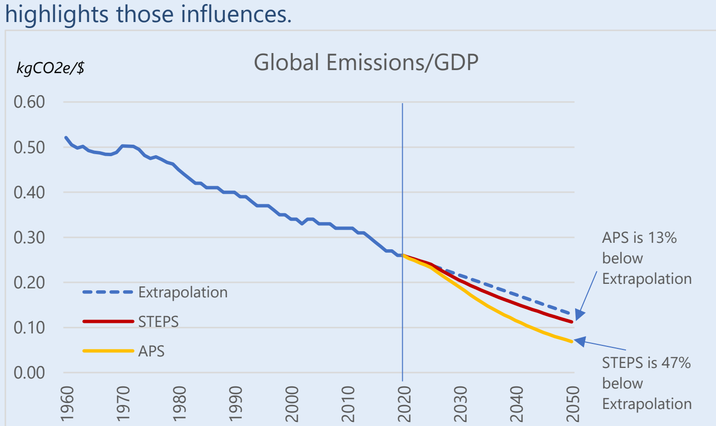
ASP and STEPS were updated and extended to 2100 in Meinhausen et al. (2022). These IEA scenarios are not in conflict with the SSPs. They represent potential outcomes based on informed views of policy. Indeed, the foundations of SSP were not based on policy drivers, but rather a vaguer evolution of the conditions creating emissions. In that sense, the IEA and SSP scenarios are complementary.

Some insight into the projected role of policy in reducing emissions can be gained by comparing historical trends and projections (Box B2-1).[28]

Box B2-1 Global emissions intensity of GDP

Policy, technology, and economic development are deeply intertwined in their influence on GHG emissions. Nonetheless, since policies to influence emissions have historically been rare in the global context, those emissions were essentially independent of policy. For economic development and technology, their influences would have, respectively: expanded the parts of the economy that did not use fossil fuels; and made those that used fossil fuels more efficient.

A historical downward trend in the global emissions intensity of GDP highlights those influences.



Sources: IEA (2022) extended back to 1960 using Bolt and van Zanden, (2020). Office of the Parliamentary Budget Officer

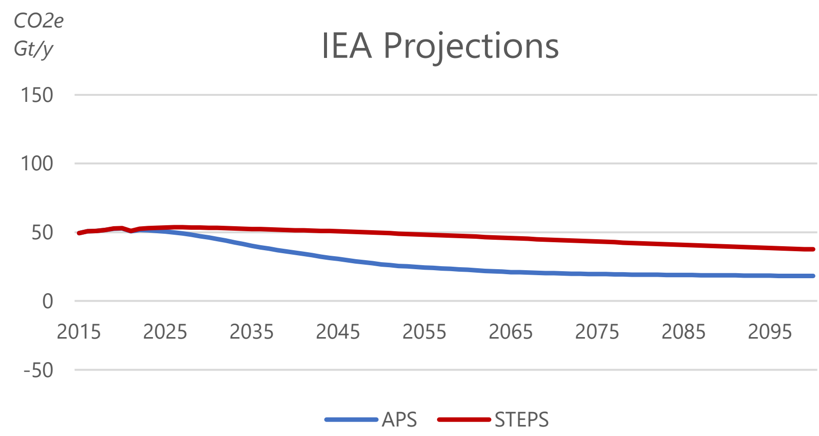
Note: For reference, emissions based on an SSP585 reference projection would imply that after 2020, the emissions-intensity of GDP would stop declining and reman largely unchanged until 2050. In $2015 PPP. GHG emissions include sources from energy and industry.

Interpreting past emissions (at least those after 1960) as generally free from the influence of policy, means that a linear extrapolation of the 1960-2020 emissions intensity trend to 2050 could also be considered broadly independent of policy (dashed line in the Box Figure). In that case, policies recently enacted (that is, those prior to 2020: the STEPS scenario) would lower global emission intensity of GDP by 13 per cent by 2050 relative to the non-policy factors alone. The pledges included in APS would lower emissions intensity by 47 per cent.

The linear extrapolation from 2020 to 2050 shown above would be difficult to continue past 2050 since its policy-free implication would include the availability of large-scale technologies that would be cheaper than readily available fossil fuels. Without policies that favoured them, such technologies would be unlikely.

The emphasis on policies, however, creates an upper bound to emissions given the announced measures and those already undertaken (Figure B-2; the vertical axis is identical to Figure B-1 for comparability).

Figure B-2 IEA greenhouse gas emissions projections



Sources: Office of the Parliamentary Budget Officer from IEA (2021b) and Meinhausen et al. (2022).

The STEPS scenario is slightly above SSP245; nonetheless, a modest decline of annual emissions is projected solely on the basis of policies and technologies implemented prior to 2020. Since SSP245 is centred on additional warming of some 2 degrees Celsius (or 3 degrees above pre-industrial temperatures), it still has strong implications for earth's climate.

The link between GHG emissions and changes in global mean surface temperature is summarised in Canadell et al., (2021). By looking at climate model analyses they were able to conclude that an additional global warming of 0.45 degree Celsius would occur with global emissions of 1000 gigatonnes of carbon dioxide equivalent ($GtCO_2$). This is illustrated clearly in IPCC (2021, Figure SPM.10). While that link is not precise (it could happen with emissions 70 per cent above or below 1000 $GtCO_2$), it is a mean estimate that is useful for our analysis.

Moreover, we used the MAGICC global climate model (Meinhausen et al., 2011) to confirm that relationship between global cumulative emissions and global temperature change for the APS scenario.

Results specifically for Canada and its regions were similarly calculated by ECCC for PBO's IEA-based scenarios (Figure B-2). The calculation was based on numerous simulations from 26 climate models participating in CMIP6. To obtain a wide sample of results from which to calculate the relationship between emissions and temperature (and other climate-related indices), simulations from SSP126, SSP245 and SSP585 were included.

Since those model simulations need to match Canada's regional temperature observations for a base period, they are statistically downscaled. That process is outlined in Cannon et al. (2015), and Werner and Cannon (2016).

That downscaling then makes it possible to estimate what a change in global emissions would mean for average surface temperatures in each of Canada's regions.

B.3 Scenario projections, regional and seasonal impacts

Table B-2 provides a summary of the changes in various climate indices across the IEA emissions scenarios.

Table B-2 Change in climate indices for Canada (relative to 2021)

	Announced Pledges Scenario (APS)		Stated Policies Scenario (STEPS)	
	2050	2100	2050	2100
Mean surface air temperature (°C)	0.7	1.3	1.0	2.3
Total precipitation (%)	2.3	3.9	2.9	6.5
Days with max. temperature above 30°C	1	3	2	5
Heating degree days	-246	-441	-326	-779
Cooling degree days	16	30	21	60
Growing season length (days)				
Overwintering crops	5	9	7	17
Cool season crops	2	3	3	6
Warm season crops	5	9	7	16

Sources: Office of the Parliamentary Budget Officer and Environment and Climate Change Canada.

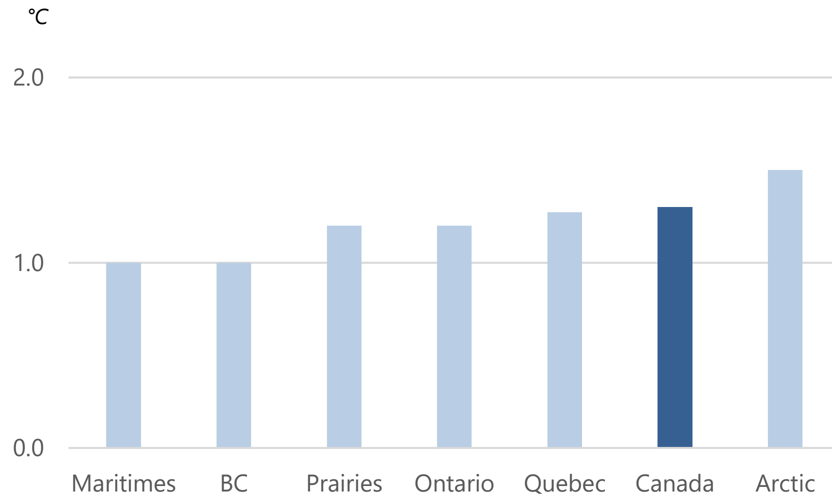
Note: Degree days are the number of degrees Celsius a given day's mean temperature is different from 18 °C. APS is treated in this report as the benchmark emissions scenario. These results are presented here as point estimates for illustrative purposes. The considerable uncertainty around them means that even these relatively low-emissions scenarios still carry risk of harsh outcomes.

For Canada, a country-wide result may not be as informative as it would be for other countries. The climate (temperature) in Canada is projected to change at double the rate of the rest of the world (Zhang et al., 2019), and even within Canada there is a distinction between its lower and higher latitude regions—with warming at higher latitudes greater than its more southerly regions.

This is a result observed in historical data. For the period from 1985 to 2015, a 5-year average surface temperature change is 1.7 degrees Celsius for Canada, but only 0.8 degrees Celsius for the world as a whole.[29]

Since the Arctic is approximately 40 per cent of Canada's land mass, the larger change in the north skews the national results. This is evident from the downscaled results of the global model simulations (Figure B-3).

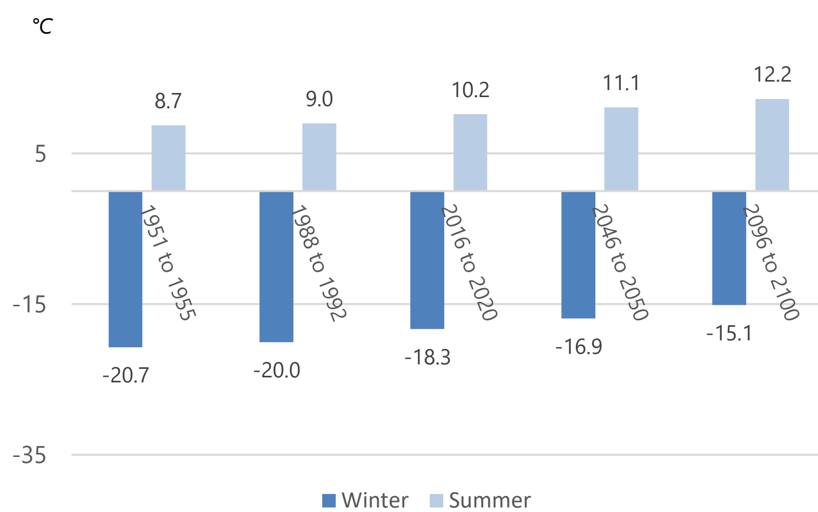
Figure B-3 Canadian regional average surface temperature change under the extended APS scenario (2100 relative to 2021)



Sources: Office of the Parliamentary Budget Officer and Environment and Climate Change Canada.

Related to the differences in regional impacts is the predominance of temperature change during winter months (Figure B-4). For Canada, given its cold winters, this is an important distinction—it is the primary source of the increased growing seasons for agriculture.

Figure B-4 Canada's seasonal average surface temperature under the extended APS scenario (1951 to 2100)



Source: Canadian Climate Data and Scenarios, www.climate-scenarios.canada.ca.

Note: Winter is defined as December to February, and summer as June to August.

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Notes

[1] See: https://www.pbo-dpb.ca/en/publications/RP-2122-009-S--beyond-paris-reducing-canada-ghg-emissions-2030--dela-paris-reduire-emissions-gaz-effet-serre-canada-ici-2030.

[2] See: https://iea.blob.core.windows.net/assets/932ea201-0972-4231-8d81-356300e9fc43/WEM_Documentation_WEO2021.pdf.

[3] In November 2021, the IEA updated its APS scenario (published in its October 2021 World Energy Outlook) to incorporate new climate commitments made by some countries in the run-up to the 26th Conference of Parties (COP26). The IEA projected that the updated APS scenario would limit global warming to 1.8 degrees Celsius in 2100. The IEA's estimate of global warming lines up with our estimate of 1.8 degrees Celsius, which is based on a generalized emissions-temperature relationship recently outlined by the IPCC.

In October 2022, the IEA released its 2022 World Energy Outlook, which under the most recent APS scenario, projected an increase in global warming of 1.7 degrees Celsius in 2100. According to the IEA, the 2022 APS scenario "gets close" to limiting global warming to well below 2 degrees Celsius. The IEA's 2022 World Energy Outlook (published on October 27) was released following the completion of our analysis. Future work will examine updated global emissions scenarios.

[4] Although they do provide some analysis using a small-scale model called MAGICC (a probabilistic reduced-complexity model with hemispheric resolution).

[5] Although the temperature changes used in this report's projections are calculated directly from model results from the Coupled Model Inter-comparison Project phase 6 exercise, the results for Canada should not be attributed to the IPCC's Sixth Assessment Report.

[6] For example, GHD (2022) projects a 5.5 per cent loss of GDP from weather events if temperatures increase by 2 degrees Celsius globally by 2050. That temperature change would be higher than the global change under the APS scenario reported here for 2050.

[7] Chapter 6 of Canada in a Changing Climate: National Issues Report provides a detailed overview of the economic costs of climate change. See: www.nrcan.gc.ca/sites/nrcan/files/pdf/National_Issues_Report_Final_EN.pdf.

[8] See: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/temperature-change.html.

[9] The impact of climate change on Canada's agricultural sector is particularly complex and could yield net positive or net negative effects over the long term. Agriculture and Agri-Food Canada provides an overview of the challenges and opportunities. See: https://agriculture.canada.ca/en/agriculture-and-environment/climate-change-and-air-quality/climate-scenarios-agriculture.

[10] That is, rising global temperatures will increase net tourism receipts in colder countries.

[11] See: https://climateinstitute.ca/reports/damage-control/.

[12] CBO compiles estimates of the relationship between weather variables and U.S. GDP from four recent top-down econometric studies and uses a random effects meta-analysis to synthesize literature results into a central estimate of the semi elasticity, which it then applies to its baseline emission scenario to derive a shock to U.S. GDP. CBO concludes that climate change from temperature, precipitation and hurricanes will reduce U.S. annual real GDP growth by 0.03 percentage points, on average, by 2050. Importantly, CBO controls for the extent to which past climate changes are already included in its economic projections via the extrapolation of historical trends in total factor productivity.

Like the CBO, we require a central estimate for adjusting long-term economic projections, which presents challenges given the range of future emissions scenarios and underlying modelling uncertainties.

[13] Our review focused on studies that provided empirical estimates of the impact of weather changes on Canada's real GDP growth. Stan, Watt and Sanchez-Azofeifa (2021) use a broad suite of climate variables—including temperature and precipitation—to quantify the impact of the climate on Canada's GDP. They estimate that the IPCC's high emission emission scenario (RCP 8.5) would increase Canada's real GDP growth by 0.03 percentage points annually from 2025 to 2090 relative to the average GDP growth rate of 2.6 per cent over the past two decades.

However, when only temperature changes are considered, the authors find that annual real GDP growth would fall by 0.04 percentage points. Kahn et al., (2019) estimate that Canada's annual real GDP growth could fall by between 0.02 and 0.12 percentage points by 2050 under a low and high emissions scenario respectively. Kalkuhl and Wenz (2020) estimate that real GDP in Canada's regions would be between 0 and 10 per cent lower by 2100 under the IPCC's high emission scenario (RCP 8.5).

For comparison, we also considered the U.S. findings in Colacito, Hoffman and Phan (2019) and Herrnstadt and Dinan (2020).

[14] Compared to other studies, our econometric results suggest a somewhat larger negative impact on Canada's real GDP, but the coefficients are less statistically significant over time.

[15] As climate variables deviate from their 1961-1990 reference levels under our emissions scenario, Canada's real GDP growth is affected proportionately. Our reference value for climate variables is the average over 1961 to 1990. This is consistent with ECCC analysis of weather changes over time. See: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/temperature-change.html.

[16] PBO's current long-term projection incorporates the impact on productivity growth of average changes to weather patterns over 1981 to 2021 – that is, a 0.9-degree Celsius increase in the average surface temperature and 2.5 per cent increase in precipitation. Weather changes beyond these thresholds are incremental to PBO's long-term projection.

See PBO's 2022 Fiscal Sustainability Report for our most recent long-term economic projection. Available at: https://www.pbo-dpb.ca/en/publications/RP-2223-012-S--fiscal-sustainability-report-2022--rapport-viabilite-financiere-2022.

[17] See featured reports available at: https://www.nrcan.gc.ca/climate-change-adapting-impacts-and-reducing-emissions/canada-changing-climate-advancing-our-knowledge-for-action/19918.

[18] In our June 2021 report we estimated that the GHG emissions reduction policies to which Canada has pledged would lead to a 1.4 per cent reduction in the level of real GDP by 2030. That impact was incremental to impacts from policies implemented by 2019 (for example, including the federal carbon levy rising to $50 per tonne in 2022 and remaining at that rate thereafter).

[19] The Paris Agreement is available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[20] See Table 3 in Kahn et al., (2019) and Table 1 in Colacito, Hoffman and Phan (2019).

[21] ECCC produced the following variables: mean surface temperature (levels and departures), maximum and minimum surface temperatures (departures), total precipitation (departures) as well as heating and cooling degree days (levels and departures).

[22] This approach gives stronger weight to areas with more stations and higher population density.

[23] For example, the winter surface temperature for a given region in a year is the average of January, February, and March values (Colacito, Hoffman and Phan 2019).

[24] See Statistics Canada Table 36-10-0222-01 for real GDP data and Table 17-10-0009-01 for population data.

[25] See: https://www150.statcan.gc.ca/n1/pub/11-626-x/11-626-x2019009-eng.htm.

[26] For example, we include probability weights on regressors based on provincial GDP share consistent with Colacito, Hoffman and Phan (2019). We also include additional lags, climate reference periods and include fall and spring temperatures. Some adjustments like weighting reduces the size and statistical significance of the coefficients. However, the results in Figure A-2 consistently show that combined seasonal temperature shocks have a small negative impact on real per capita GDP growth over a 1975-1995 rolling sample (via a one-step rolling regression). Precipitation was not statistically significant in any specifications.

[27] Kahn et al., (2019) also did not find statistically robust precipitation effects at the global level.

[28] Historical global GDP is calculated using PPP exchange rates. For the extrapolation, GDP growth to 2030 is calculated using its 10-year average growth rate. For growth to 2050, it is calculated using a 30-year average growth rate.

[29] Using data from the Canadian Climate Data and Scenarios, www.climate-scenarios.canada.ca.