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The road to net-zero in Canada through regionalization and segmentation of GHG emissions and the role of water resources management

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ABSTRACT

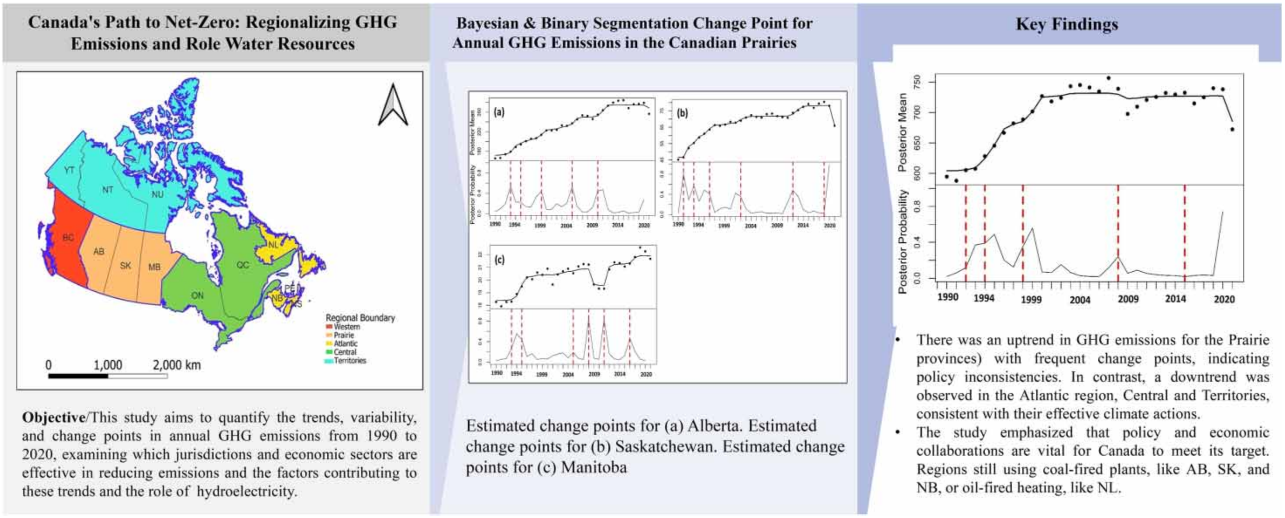
The primary goal of this study was to assess the temporal variations, trends, and aberrations in the greenhouse gas (GHG) series for Canada from a regional and economic sector perspective. A Bayesian Change Point method based on the Markov Chain Monte Carlo method and Binary Segmentation were used to detect aberrations, the number of changes, and locations. Trend analysis and change point results show that all the Prairie provinces have uptrends and frequent change points. On the other hand, Central, Atlantic, and the Territories show evidence of a downtrend. There is a consistent uptrend and frequent change points for the economic sectors in the oil and gas, agriculture, transportation, and building economic sectors. This upward trend could be due to a consistent increase in petroleum extraction, increased population, and increased number of on-road cars. The increase in the agriculture sector could be due to an increase in livestock products and the application of fertilizer and manure for farming purposes, especially in the Prairie jurisdictions. From the foregoing, Canada's abundant water resources potential will be crucial in mitigating GHG emission in the heat and electricity sector across various jurisdictions.

Key words: Bayesian Change Point analysis, Canada, climate change, greenhouse gas, IPCC, net-zero

HIGHLIGHTS

- Greenhouse gas (GHG) emissions in Canada show uptrends for the Prairie provinces, while there was a downtrend in Central and Atlantic Canada.
- Consistent uptrends in the GHG for oil and gas, agriculture, and transportation for the entire county.
- Renewable energy resources through hydroelectricity generation will play a significant role in reducing GHG emissions in all jurisdictions of Canada.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The impact of climate change due to increasing greenhouse gas (GHG) emissions is well-known. Since GHG emissions are not restricted to a political boundary, it is a global problem that impacts many regions of the world. For most of the year 2022, impacts such as extreme precipitation that caused flooding with associated fatalities were seen in many parts of the world. A good example is the catastrophic landslide in Uttarakhand state in India, caused by ice warming and a massive rock tumbling down the Himalayan valley leading to 200 fatalities (Shugar *et al.* 2021). Canada is not exempted from these impacts. There is evidence of climate change such as sea-level rise in coastal Atlantic areas (Boon 2012; Carson *et al.* 2016), heat stress and the frequency of droughts in central and Canadian prairies (Yusa *et al.* 2015). Important studies have been done on GHG emissions trends, mitigation, and adaptation strategies. Davis *et al.* (2018) used a bottom-up multi-regional accounting-based Long-range Energy Alternative Planning systems model to assess the disaggregated GHG emissions in Canada for 2014, 2030, and 2050. The authors concluded that Alberta's oil and gas and Ontario's transportation will be the two largest economic sources of GHG emissions by 2050. Studies such as Talaei *et al.* (2018) have also found that changes in energy-intensive processes such as oil sand mining can contribute significantly to reduced GHG emissions in the industrial sector. From the agroforestry and crop production standpoint, Kulshreshtha *et al.* (2011) also found that 'central Canada emits the largest GHG emissions per hectare basis.' Furthermore, Baah-Acheamfour *et al.* (2017) found '*increases in vegetation and soil organic Carbon (C) storage in areas with woody species compared to herbaceous crops*.' Both studies show that good Best Management Practices (BMP) can help reduce emissions such as methane (CH_4) and nitrous oxide (N_2O) and provide ecosystem services benefits such as terrestrial C storage and sequestration. It has been reported that jurisdictions (i.e., provinces) with 'greater populations, younger ages, and more income produce higher levels of greenhouse gas emissions' (Azad 2021). Further, alignment of investments (from research and development (R&D) to capital expenditures) and policies at the level of the jurisdiction has been suggested as one of the ways to enhance clean energy innovation and reduce emissions in Canada (Jordaan *et al.* 2017).

The federal government has implemented several strategies to combat and reduce GHG emissions. Indeed, Canada was at the forefront of the United Nations Conference on Environment and Development, Earth Summit held in Rio de Janeiro in 1992. Although Canada withdrew from the Kyoto protocol in December 2011 (Dolter & Victor 2016), the country is a strong contributor to the Paris Agreement (Government of Canada 2022a). As of 2018, Canada accounted for around 1.6% of global GHG emissions (Climate Watch 2023; ECCC 2022). Furthermore, as of 2019, Canada is the 10th GHG-emitting country (ECCC 2023). Nationally, Canada has implemented several climate action plans. The Pan-Canadian Framework on Clean Growth and Climate Change, also known as the Pan-Canadian Framework (hereafter: PCF), is an initiative developed in 2018 and adopted by all jurisdictions. Using more than 50 measures, the objective of this initiative is to reduce GHG emissions, build resilience and support the country's goal of clean economic growth (ECCC 2022). The Healthy Environment and a Heathy Economy (HEHE) was introduced in December 2020. HEHE's objective was to build on the strength of the PCF and reduce GHG emissions to 31% below 2005 levels. This is aimed to be achieved by 2030 (ECCC 2022). Substantial financial commitment has been made to achieve this goal. According to ECCC (2022), $15 billion has been budgeted for public and active transportation. In other words, this specific budget is targeted toward reducing emissions from transportation, which is one of the main contributors to GHG emissions in Canada. Further, an additional over $17 billion has also been budgeted for economic recovery and reducing emissions from heavy industry and buildings. The Canadian Net-Zero Emissions Accountability Act (CNZEAA) is a legislative framework that will strengthen and provide transparent and accountability protocols for achieving emissions reductions by 2030 and achieving net-zero emissions by 2050. All these initiatives show that the federal government is serious about reducing GHG emissions. Also, it also shows the government is committed to the international treaties on emission reductions. The Emission Reduction Plan (ERP) is another initiative established by the federal government as part of the relevant sectorial strategy to achieve the 2030 emissions target. From the international front, Canada ratified the United Nations Framework Convention on Climate Change (UNFCC) in December 1992 (ECCC 2022). The UNFCC's main goal was to address climate change impacts and stabilize the atmospheric GHG concentration (ECCC 2022). One main commitment to this treaty is for member states to submit a National Inventory Report (NIR) (UNFCCC 2014). Canada has been consistent in submitting this report to the UNFCC. In Canada's NIR report, GHG emissions according to jurisdictions (province and territories) and economic sectors are detailed in both tabular and graphical formats. This presentation shows how Canada is doing in reducing GHG emissions from various sectors of the economy and from individual regions. This report provides the necessary datasets required to carry out further analysis. This is necessary since no additional statistical modeling or analysis is included in the report. Therefore, the aim of this study is to apply standard and advanced statistical analysis and modeling in providing further insights into the temporal variations, trends and change points in the NIR datasets. One important resource that can contribute to GHG reduction in Canada is the abundant water resources. Globally, the electricity and heat sector has been reported as the largest contributor to the GHG emissions (Ritchie *et al.* 2020). As of 2019, electricity and heat has about 15.83 billion tonnes (CO_2 eq.). For Canada, with its huge landmass and significant renewable energy resources such as hydroelectricity dams, biomass, wind turbines and geothermal, there should be no reason why emissions from energy sector should not be reduced. Hydroelectricity is the most important renewable energy with approximately 59% of Canada's electrical energy sources (NRC 2017). As this energy source does not emit greenhouse gases, it is responsible for preventing the global emissions of approximately 2.1 billion tons of CO_2 annually, which is equivalent to the carbon emissions from 450 million cars (Utilities One 2023). In 2019 alone, hydroelectricity saved around 4 billion cubic meters of fossil fuels, which would have been used for power generation (Utilities One 2023). The Trottier Energy Future Project (TEFP) has identified hydropower as an important contributor to minimum cost emissions reduction pathways (Haffner & Burpee 2018). Additionally, hydropower in Canada would not only improve Canada's impressive mark of 80% of the countries' electricity coming from non-emitting sources, but surplus energy exports to the USA could increase as well. This is important as that country has much further to go in decarbonizing its electric system than Canada (Haffner & Burpee 2018). One final non-emission related benefit is that hydroelectric dams can act as a reservoir for water storage. This can mitigate the effects of droughts and floods by storing water during wet periods and releasing it during dry spells. This is a crucial factor in terms of water resource management for communities (Utilities One 2023).

Trend analysis is useful in providing the orientation and pattern in the annual GHG emissions based on jurisdictions and economic factors. The NIR change in a certain jurisdiction or economic sector does not state if there has been a sustained downtrend or uptrend. For the above-mentioned initiatives to be successful, there is a need for understanding the variabilities or trends of these emissions from both a jurisdiction and economic perspective. This will allow the effective targeting and usage of financial resources for the jurisdictions and sectors that show an increase in their GHG emissions trends. The trend analysis will show if past climatic actions, policies, or regulations have been effective in changing the orientation of historical emissions. The Mann–Kendall Trend Test (MKTT) is a non-parametric technique (Pohlert 2020) that can detect trends in a certain time-ordered series such as annual GHG emissions. The presence of a positive trend indicates there has been a sustained increase in GHG emissions or that past climate actions have not been effective in reducing them. Likewise, a negative trend means the climate change efforts must have been effective in reducing emissions. Change point analysis also helps determine the number of change points or aberrations and the location of change points in a time-ordered series. It gives an indication of when the change occurs. Change point analysis can be based on frequentist or Bayesian techniques (Erdman & Emerson 2007). The Bayesian Change Point (BBSCP) is based on the Barry & Hartigan (1993) method and '*offers a probability distribution, which is the probability of a change point at each location in a sequence*' (Erdman &

Emerson 2007). The Circular Binary Segmentation (CBS) (Olshen & Venkatraman 2004), a modification of binary segmentation introduced by Sen & Srivastava (1975), is another method that can be used in change point analysis. It is based on likelihood ratio statistics and has shown to be consistent with BBSCP since both procedures assume normality. The main advantage of Bayesian statistics over the frequentist approach is the benefit of quantifying uncertainty in Bayesian parameters (Banerjee *et al.* 2004). This study combines the strength of both techniques called Bayesian Binary Change point (BBBSCP).

The primary objective of this study is to quantify the temporal variability, trend, change points and location of change points in the annual GHG emissions from 1990 to 2020. In other words, pertinent questions such as what jurisdictions are doing well in their efforts to reduce GHG emissions, which economic sectors are doing well and what are the contributing factors to either uptrends or downtrends seen in jurisdictions and economic sectors will be examined. The novelty of this study involves evaluating the trend and change point of Canada's GHG emission from both jurisdictions and economic sector perspectives. This study provides insight into the trajectory of Canada's GHG emissions and specific years where there are aberrations or changes. The difference between the current and previous studies is that this study specifically applied change point analysis to all jurisdictions and economic sectors in Canada. This study also provides the connection and role of abundant water resources in Canada through hydroelectric potential in climate mitigation. In other words, water resources will be critical in meeting the drastic GHG reduction target. This study will also be important an information resources for informed decision-making in Canada's commitment to achieving net-zero emissions status by 2050.

2. METHODOLOGY

2.1. Canada's jurisdictions and economic sectors

Canada has a population above 38 million people (Statistics Canada 2022a), and it is the second largest country by landmass with an area of approximately 9,984,670 km^2. In terms of jurisdictions, Canada consists of 10 provinces and three territories (Figure 1). These provinces and their 2021 populations are Alberta (4.46 million, hereafter: A.B.), British Columbia (5.23 million, hereafter: B.C.), Manitoba (1.39 million, hereafter: M.B.), New Brunswick (795,851, hereafter: N.B.), Newfoundland (521,854, hereafter: N.L.), Nova Scotia (998,387, hereafter: N.S.), Ontario (14.9 million, O.N.), Prince Edward Island (166,435, hereafter: P.E.), Quebec (8.6 million, hereafter: Q.C.), and Saskatchewan (1.18 million, hereafter: S.K.). The

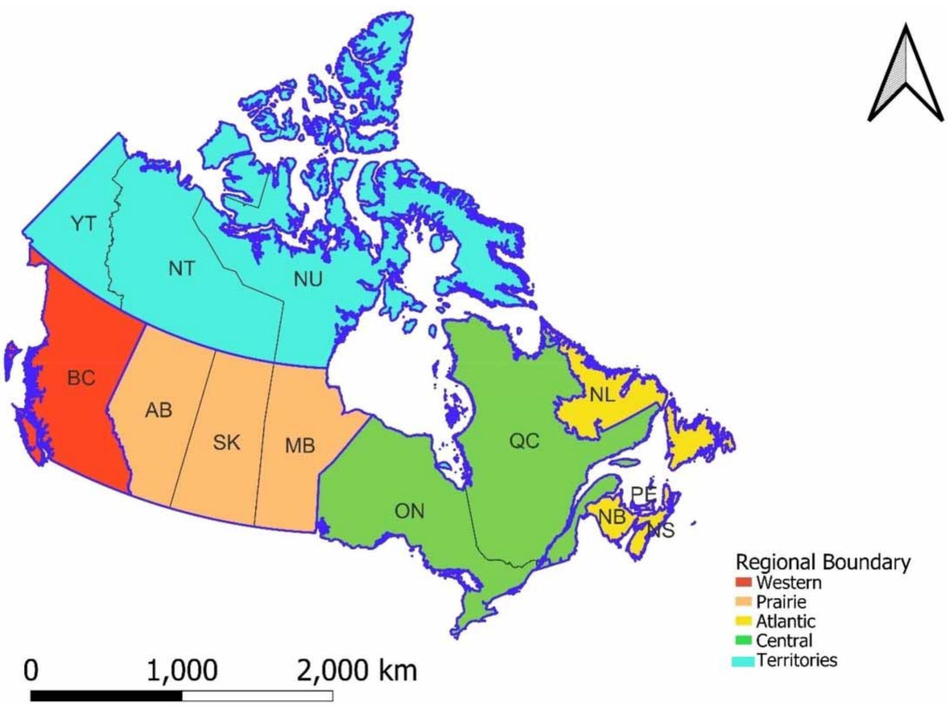


Figure 1 | Map of Canada showing the 10 provinces and three territories.

three territories are Nunavut (39,931, hereafter: N.U.), Yukon (43,373, hereafter: Y.T.) and Northwest Territories (45,607, hereafter: N.T.).

In terms of governance, Canada is a constitutional monarchy and a parliamentary democracy (Government of Canada 2022b). The parliament system is composed of the Crown (His Majesty, represented in Canada by the Governor General), Senate (upper house), and House of Commons. The House of Commons (or the Parliament) is responsible for making laws such as income tax laws, criminal legislation, and international and national regulations that affect industries or economic sectors. The Senate is also responsible for the ratification of laws made by the parliament. In other words, all the various national climate actions and policies are made by these arms of the government. The 10 provinces and three territories also make laws that fall within their jurisdiction. This is performed by each provincial arm of Parliament. It has been reported that stronger leadership and coordination are required to drive progress in climate change commitment (House of Commons 2022). In other words, there is need for bipartisan and depolarization policies toward GHG reduction, adoption and clean energy technologies across various jurisdiction and political parties.

From an economic perspective, Canada is a developed economy with a gross domestic product (GDP) and GDP per capita of approximately $1.99 trillion and $52,085, respectively (ECCC 2022). As a percentage of GDP, real estate (including renting and leasing), manufacturing, mining, quarrying, oil and gas extraction, finance and insurance, and construction have 13.01, 10.37, 8.21, 7.06 and 7.08%, respectively (Statistics Canada 2022b). These industries are located across the entire jurisdiction. Since several of these industries are sources of total GHG emissions, related policies and regulations are important issues to be considered in climate change studies.

2.2. Total GHG emissions in Canada

GHG emissions in Canada are heterogenous from both a jurisdiction and economic sector standpoint. The GHG emissions by type in Canada are composed of carbon dioxide (79%), methane (14%), nitrous oxide (5%), and other (2%) (Auditor General 2022). For the most part, emissions according to jurisdiction depend on the population, economic structure, and energy system of the region. In other words, provinces that have a resource extraction-based economy (e.g., oil in Alberta) tend to generate more GHG emissions than those with a service-based economy (e.g., Quebec). A.B. contributes the largest percentage (38%, see Supplementary material) of emissions followed by O.N. at 22%. Q.C., S.K., B.C., and M.B. have percentage contributions of 11.34, 9.80, 9.18, and 3.22%, respectively. The lowest contributions are from P.E., N.T., Y.T., and N.U. with 0.23, 0.19, 0.089, and 0.067, respectively. S.K. and A.B. have GHG emissions of 68 and 67 tonnes/per capita respectively (Boothe & Boudreault 2016). In addition, B.C., O.N., and Q.C. are in the 10–14 tonne/per capital range (Boothe & Boudreault 2016).

According to various economic sectors in 2020 (see Supplementary material), Oil and Gas (hereafter: O.G.), Transportation (hereafter: T.R.), Building (hereafter: B.D.), Heavy Industry (hereafter: H.I.), Agriculture (hereafter: A.G.), Electricity (hereafter: E.L.), Waste (hereafter: W.S.), Light Manufacturing (hereafter: L.M.), and Coal Production (hereafter: C.P.) have a percentage contribution of 26.59, 23.67, 13.05, 10.68, 10.21, 8.36, 4.07, 3.03 and 0.34%, respectively. As of 2017, renewable energy is only 18.9% of Canada's total energy source (NCR 2017). This shows that there are still opportunities in leveraging this abundant natural resource. Juridictions with low number of installed hydroelectric capacity can improve on their renewable energy use. From the water resources (hydroelectricity) standpoint and as of 2015, the total Current Installed Potential (CIP), Technical Potential (TP) and Untapped Capacity (UP) is 76,000 WM, 160,000 MW and 84,000 MW, respectively (Haffner & Burpee 2018).

Figure 2 displays both the current installed capacity and the hydroelectric potential for each province and territory in Canada (in MW). In its entirety, Canada has about 160,000 MW of TP. The bulk of that potential comes from provinces which are also leaders in current installed capacity: Q.C. and B.C. out front and in a second tier: M.B., O.N. and N.L. Each of the Northern territories has a sizable amount of hydroelectric potential but very little current installed capacity. A lack of an electrical grid system up north has many northern communities relying still on diesel-powered generators (Canadian Geographic 2023). N.S. has a decent amount of untapped hydroelectric potential, while N.B. has a small amount. P.E. has a miniscule amount of hydroelectric potential, 3 MW, which is not surprising as it is the smallest province, and currently the only province without a hydroelectric dam facility (Haffner & Burpee 2018). One other item to note is that, while A.B. and S.K. each have a decent portion of hydroelectric potential, these potential projects have attracted limited interested investors. Instead, these provinces are more focused on wind and solar projects as the prairie conditions have more potential for these projects than Canada's coastlines (Climenhaga 2023)

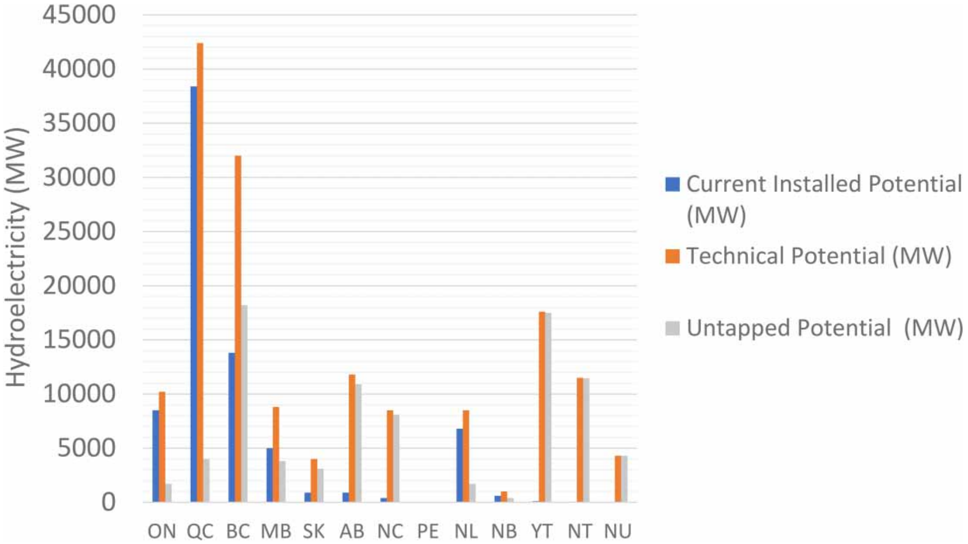


Figure 2 | Technical, current, and untapped hydroelectricity potential in Canada (*Source:* Haffner & Burpee 2018).

2.3. National inventory dataset

The dataset used in the study is obtained from Canada's National Greenhouse Gas Inventory prepared by ECCC (2022) available at: https://data.ec.gc.ca/data/substances/monitor/Canada-s-official-greenhouse-gas-inventory/B-Economic-Sector/?lang=en. The dataset is available for both Canadian jurisdictions and economic sectors from 1990–2020. The jurisdiction GHG emissions were further aggregated into regions based on the divisions shown in Figure 1 above. Other industrial sectors that constitute the main industrial sector are shown in the Supplementary material. Notably, emissions data for both N.U. and N.T. are combined from 1990 to 1999. This is because N.U. was part of N.T. until 1999. Since there is no way to separate the datasets from each territory for this period, they are presented as zeros to allow for the statistical analysis requiring no missing datasets.

2.4. Mann–Kendall Trend Test

The MKTT is a non-parametric statistical test that determines if a series (such as GHG emission data) has a trend or not. It is based on a null hypothesis establishing that there is no trend in the data. In other words, the MKTT is based on the null hypothesis that data from a particular population with independent realizations are identically distributed (Pohlert 2020). In other words, for a two-sided test, the alternative hypothesis states that data will follow a monotonic trend. Further, an alternative hypothesis could also establish the presence of a trend, which can be an uptrend (positive) or downtrend (negative). If the *p*-value of the MKTT is less than the chosen significance level (5% in this case) then there is statistically significant evidence, which indicates the presence of a trend. The uptrend (positive) and downtrend (negative) is determined by the value and sign of τ. More information about the MKTT can found in Pohlert (2020), Hipel & McLeod (1994) and Libiseller & Grimvall (2002).

2.5. Bayesian change point method

Bayesian Change Point (BCP) is a technique used to detect distributional changes or aberrations within a time-ordered series or in observations. The method can also estimate both the number of changes and locations of changes concurrently. BCP also returns both the posterior mean and posterior probability of a change point. BCP is based on Barry & Hartigan (1993), which has been implemented in R statistics as the 'BCP' R package (Erdman & Emerson 2007). The algorithm and implementation in R and how it is applied in this study has been summarized in Boluwade *et al.* (2018) and Boluwade (2020) as follows (using the author's notations):

(a) Create an unknown partition of the GHG annual series ψ into contiguous blocks. It is assumed that mean values within each block are uniform.

(b) There is an assumption of observation independence $N(\mu_i, \sigma^2)$ and the probability of a change point at position (i.e. year) i is ξ.

(c) The prior distribution of μ_{ij} (the mean of block at position i + 1 and ending at position j) is given by $N(\mu_0, \sigma_0^2/(j-i))$.
(d) According to Barry & Hartigan (1993), independent priors are selected for μ_0, ξ, σ^2, and $w = \sigma^2/\sigma^2 + \sigma_0^2$, where w is the ratio of signal error to error variance.
(e) The priors for all the parameters are defined as follows:

(i)
$$\prod(\mu_0) = 1, \; -\propto \leq \mu_0 \leq \propto,$$
$$\prod(\sigma^2) = 1/\sigma^2, \; 0 \leq \sigma^2 \leq \propto,$$
$$\prod(\psi) = 1/\psi_0, \; 0 \leq \psi \leq \psi_0,$$
$$\prod(w) = 1/w_0, \; 0 \leq w \leq w_0,$$

$$\prod(\xi) = \frac{1}{\xi_0}\left(\int_0^{\xi_0} \xi^{(b-1)}(1-\xi)^{n-b} d\xi\right) \tag{1}$$

(ii) ξ_0 and w_0 are preselected numbers in [0,1], and b is the number of blocks in the partition.

(f) Partition $\psi = (U_1, U_2, \ldots\ldots U_n)$, where n is the number of observations and $U_i = 1$ indicates a change point at position $i + 1$.
(g) $U_i = 0$
(h) In each step of the Markov Chain at position i, a value U_i is drawn from the conditional distribution of U_i and the current partition.
(i) The transition probability ξ for the conditional probability of a change point at position $i + 1$ is obtained from the simplified ratio presented in Barry & Hartigan (1993):

$$\frac{\xi_i}{1-\xi_i} = \frac{P(U_i = 1|Z, U_j, j \neq i)}{P(U_i = 0|Z, U_j, j \neq i)} = \frac{\int_0^{\gamma} \xi^b (1-\xi)^{(n-b-1)} dp}{\int_0^{\gamma} \xi^{(b-1)}(1-\xi)^{(n-b)} dp} \cdot \frac{\left[\int_0^{\lambda} \frac{w^{b/2}}{(W_1 + B_1 w)^{(n-1)/2}} dw\right]}{\left[\int_0^{\lambda} \frac{w^{(b-1)/2}}{(W_0 + B_0 w)^{(n-1)/2}} dw\right]} \tag{2}$$

where W_0, B_0, W_1 and B_1 are within and between block sums of squares obtained when $U_i = 0$ and $U_i = 1$, respectively, and Z is the dataset (in this case, annual GHG emissions from 1990 to 2020). The tuning parameters γ and λ should be within [0, 1]. This is to allow a situation in which there are not too many changes (i.e., γ is small) (Erdman & Emerson 2007; Boluwade *et al.* 2018). To further confirm the change point locations, CBS analysis in R Bioconductor (Gentleman *et al.* 2004) software was also used to support the BBSCP technique. CBS (Olshen & Venkatraman 2004) is a modification of the binary segmentation developed by Sen & Srivastava (1975) which is based on likelihood ratio statistics. Figure 3 shows the procedure used in this study. The methodology involves data extracted from the Canadian NIR repository. The trend, BBSCP, and CBS computation used the R statistical packages mentioned above. The combination of both techniques (BCP and CBC) is called Bayesian Binary Segmentation Change point (BBSCP), which is used in the current study.

3. RESULTS AND DISCUSSION

To investigate and evaluate the temporal variability and change points in the GHG emissions for Canada, the following results and associated discussions will be considered:

- Trend, temporal variations and change point analysis of Canadian GHG emissions based on jurisdiction
- Trend, temporal variations, and change point analysis of Canadian GHG emissions based on economic sector.

3.1. Descriptive statistics of GHG emissions in Canadian jurisdictions

Table 1 shows that A.B., B.C., M.B., N.B., N.L., N.T., N.S., and N.U. have annual average GHG emissions of 234.11, 60.54, 20.37, 17.37, 10.04, 1.06, 19.51, and 0.40 Mt CO_2eq, respectively. The jurisdictions O.N., P.E., Q.C., S.K., and Y.T. have

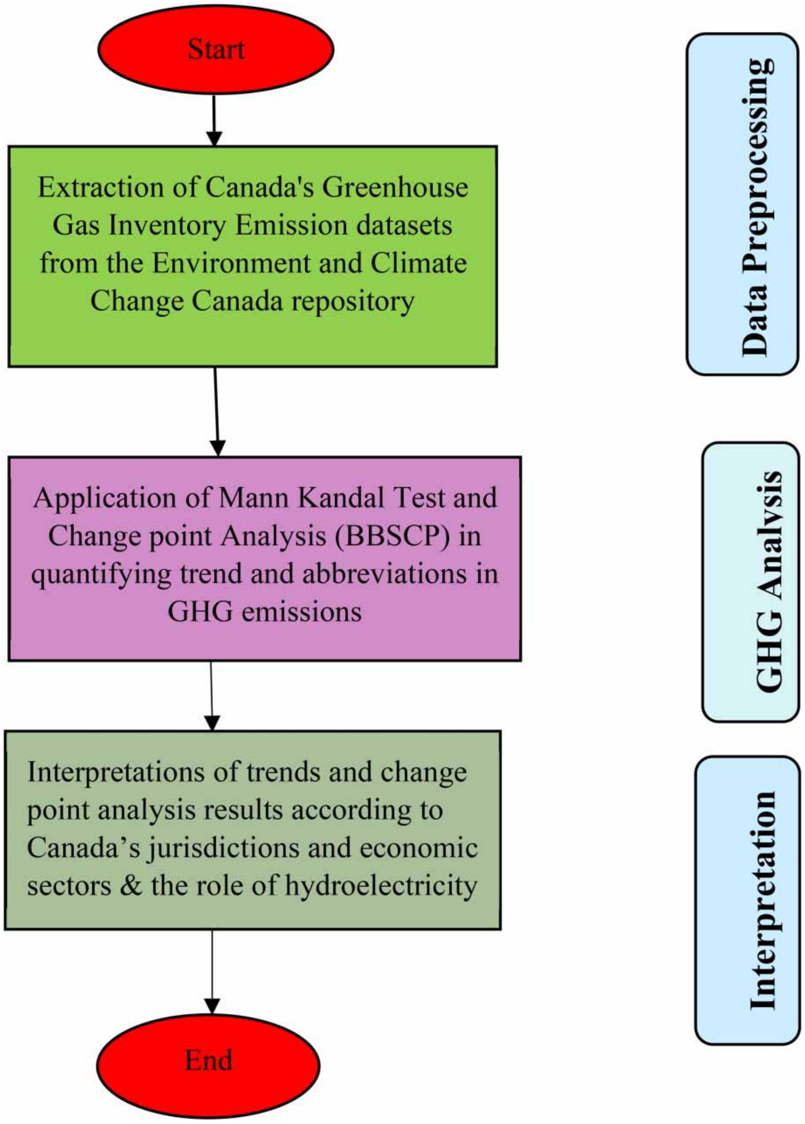


Figure 3 | Flow chart of Canada's greenhouse gas trend and change point analysis according to jurisdictions and economic sectors.

average emissions of 181.91, 1.79, 82.63, 68.29, and 0.57 Mt CO_2eq, respectively. This shows that A.B. and O.N. have the largest emissions in Canada. In terms of the coefficient of variation (CV), A.B. and O.N. have the largest CV at 1363.57 and 283.26%, respectively. The jurisdictions N.U., N.T., P.E. and N.L. have a CV of 0.27, 0.49, 0.02 and 1.13%, respectively. This shows the level of volatility and dispersion of the GHG emissions around the average for each province and territory. In other words, A.B. and O.N. have more variability in GHG generation compared to those with small CV values. The next sections of this study will explore more what drives this variability and these fluctuations in all the jurisdictions. A.B. and O.N. have the highest GHG emissions at 284.29 and 209 Mt CO_2eq, respectively. This is followed by Q.C. and S.K., which have GHG emissions of 89.84 and 80.44 Mt CO_2eq, respectively. The lowest values are recorded in the territories (N.U., N.T. and Y.L.).

To further explore the temporal variability of the GHG emissions according to jurisdictions, some years were selected. The temporal changes in GHG emissions for 1990, 2005, 2015 and 2020 were considered (see Supplementary material). There is a consistent increase for A.B. (except 2020), S.K. (except 2020), and M.B. A.B. has been expanding oil extraction for each of the years. The reduction in 2020 may be attributed to the impact of the COVID-19 pandemic, which put restrictions on movement leading to reductions in economic sectors such as T.R. This will be explored further in other sections of this study. In contrast,

Table 1 | Descriptive statistics of Canadian GHG emissions according to jurisdiction

Province	Mean (Mt CO_2 eq.)	Standard deviation (Mt CO_2 eq.)	Coefficient of variation (%)	Minimum (Mt CO_2 eq.	Maximum (Mt CO_2 eq.
A.B.	234.11	36.93	1,363.57	165.65	284.29
B.C.	60.54	4.34	18.83	49.65	65.84
M.B.	20.37	1.21	1.46	17.92	22.57
N.B.	17.37	2.83	7.99	12.44	22.54
N.L.	10.04	1.07	1.13	7.65	11.93
N.T.	1.06	0.70	0.49	0.00	1.92
N.S.	19.51	2.38	5.64	14.60	23.76
N.U.	0.40	0.27	0.07	0.00	0.76
O.N.	181.91	16.83	283.26	149.58	209.16
P.E.	1.79	0.13	0.02	1.56	2.01
Q.C.	82.63	3.24	10.49	76.24	89.84
S.K.	68.29	9.04	81.71	45.13	80.44
Y.T.	0.57	0.06	0.00	0.50	0.69

there are consistent reductions in O.N., Q.C., N.S., and N.B. These are provinces that have taken drastic steps in climate actions. For instance, in 2005, O.N. started closing all its coal-based electric generating plants, with the last closure in 2014 (ECCC 2022). Similarly, Q.C., O.N., N.S. and N.L. all closed petroleum refineries in their jurisdictions in the years 2010, 2005, 2013 and 2020, respectively. The jurisdictions P.E., N.U., and N.T. also show a decreasing trend for the years (see Supplementary material). It will be interesting to see how the significant actions taken by the jurisdictions impact the change point locations in the next sections.

3.2. Descriptive statistics of GHG emissions in Canadian economic sectors

Table 2 shows that O.G., E.L., T.R., HI, B.D., and A.G. have an annual GHG average of 164.21, 97.93, 151.97, 87.05, 81.75, and 62.82Mt CO_2eq, respectively. This shows that O.G. is the largest source of GHG emissions for Canada from the economic sector perspective. The table also shows that TR is the second largest contributor. The implications of these two largest contributors are that mitigation strategies should focus more on these two industries. Furthermore, the lowest annual average GHG emission is from C.P. and L.M. with values of 3.01 and 23.68 Mt CO_2 eq, respectively. The highest emissions are reported in O.G., E.L., T.R. and H.I. with values of 205.02, 129.24, 185.46 and 103.21Mt CO_2eq, respectively.

Table 2 | Descriptive statistics of Canadian GHG emissions according to economic sector

Economy	Mean (Mt CO_2 eq.)	Standard deviation (Mt CO_2 eq.)	Coefficient of variation (%)	Minimum (Mt CO_2 eq.)	Maximum (Mt CO_2 eq.)
Oil and gas	164.21	32.10	19.55	102.18	205.02
Electricity	97.93	21.05	21.50	56.18	129.24
Transport	151.97	21.92	14.42	114.32	185.46
Heavy industry	87.05	9.64	11.07	71.53	103.21
Buildings	81.75	5.72	6.99	70.58	92.95
Agriculture	62.82	4.00	6.36	51.73	68.65
Waste	26.84	1.26	4.71	24.42	28.85
Coal production	3.01	0.68	22.46	2.23	4.17
Light manufacturing, construction	23.68	2.30	9.71	20.11	28.24

Further analysis of the temporal variability for some chosen years (see Supplementary material). There is a consistent increase in O.G., T.R., B.D., AG and W.S. There is also a consistent increase in fuel consumption in O.G. (ECCC 2022). On the other hand, there are consistent reductions in H.I., E.L., and C.P. Electricity generation from C.P., which has been decreasing from year to year, is largely responsible for the reduction seen in C.P. For instance, according to ECCC (2022), jurisdictions such as N.S., N.B., and M.B. have significantly reduced their coal consumption. In addition, the reduction seen in E.L. is due to reductions in oil consumption for electricity in several jurisdictions such as N.B. and N.S.

Percentage change from 1990 to 2020, 2005 to 2019 and 2005 to 2020 were also considered (see Supplementary material). The consideration for percentage change from 2005 to 2019 was able to compare without the impacts of the COVID-19 pandemic on 2020 emissions. O.G. shows a consistent increase for all the periods considered. The reductions seen in E.L. are because of the reduction of electricity generation from C.P. and oil consumption for heating from the jurisdictions mentioned above. This significant gain in emissions from E.L. is offset by the increase in O.G. There were increases for all the periods for T.R. (except 2005/2020). The driving factor behind these increases could be an increase in population and the number of vehicles between the two periods. The slight reductions seen in 2005/2020 could be attributed to the impact of COVID-19 restrictions, when all the jurisdictions implemented various restrictions. These restrictions required people to stay indoors, and therefore emissions from T.R. were reduced. There is a percentage increase in B.D. and A.G. There are more buildings now due to the population increase, which explains this increase. Specifically, Canada's population in 1990, 2005, 2015 and 2020 was above 27, 32, 35 and 37 million, respectively (Statistics Canada 2022a). For AG, there are also consistent increase percentage changes for all the periods. This is due to increased agricultural intensity with the application of manure and fertilizer. An increase in animal husbandry can also contribute to an increase in methane. Vergé *et al.* (2008) also concluded that there has been an increase in GHG from the Canadian beef industry mainly driven by expansion of the industry. These are very common among farmers in the Canadian Prairies.

3.3. Trends, aberrations and change point analysis in Canadian GHG emissions according to jurisdiction

Table 3 shows the MKTT test results. A.B., MB, and S.K. all show statistically significant positive trends; therefore, the null hypothesis of no trend is rejected. These are the Prairie provinces, which have shown increasing temporal variability in the sections above. B.C., N.S., P.E., Q.C., and Y.K. show values greater than the significance level (0.05); therefore, the null hypothesis is accepted, meaning there is no trend. On the other hand, O.N. and N.B. also show a *p*-value greater than the significance level but with negative τ. This indicates the presence of a trend but with a downward orientation. The implication of this result is that both the federal government and jurisdictions can understand what has worked in reducing GHG emissions in regions with a significant downtrend. Also, it will help regions where there has been an increase in GHG values. For regions without any evidence of a trend, it shows there is a need for more to be done in bringing down the trend of emissions.

Table 3 | Mann–Kendall trend test for the Canadian jurisdictions

Canadian jurisdictions	Tau	*p*-value
Alberta	0.88	3.2×10^{-12}
British Columbia	0.29	0.0208
Manitoba	0.66	1.65×10^{-7}
New Brunswick	−0.33	0.008859
Newfoundland	0.45	0.000463
Northwest Territories	0.34	0.008832
Nova Scotia	−0.23	0.06641
Nunavut	0.45	0.000502
Ontario	−0.39	0.002218
Prince Edward Island	−0.14	0.292
Quebec	−0.23	0.07161
Saskatchewan	0.79	4.95×10^{-10}
Yukon	0.27	0.03223

In other words, mitigation and adaptation strategies need to be strengthened and made more effective to bring the desired and needed positive change (downtrend).

Figures 4 and 5 present the BBSCP analysis for all the jurisdictions (except the Territories which is in the Canadian Territories). Figure 3(a) and 3(b) show the BBSCP analysis for the Central region (O.N. and Q.C.) of Canada. The posterior mean for the two provinces shows a downtrend orientation. This is consistent with the MKTT presented above. The estimated change points for O.N. (Figure 4(a)) are located at 1995, 1998, 2005, 2008, and 2013. Also, the estimated change points for Q.C. (Figure 4(b)) are located at 2002 and 2007. The changes seen in O.N. from 2005 are consistent with O.N. permanently closing all C.P. starting from 2005 until 2014, which has already been discussed above. Also, Q.C. closed petroleum refineries in 2010. Although not a change point location, there is a drastic reduction in GHG emissions from Q.C. in 2010 (see the posterior mean in Figure 4(b)). The reduction seen in 2020 for both provinces can be attributed to the impacts of COVID-19 pandemic movement restrictions. In general, it seems the Central region is on the right track and continues to implement policies and regulations that will continue to reduce emissions and maintain the downtrend.

Figure 5 shows the BBSCP for the Atlantic region. Figure 5(a) shows that the estimated change points for N.S. are located at 1998, 2003, 2007, 2011, and 2013. The posterior mean also shows drastic reductions at 2013/2014. N.S. also permanently

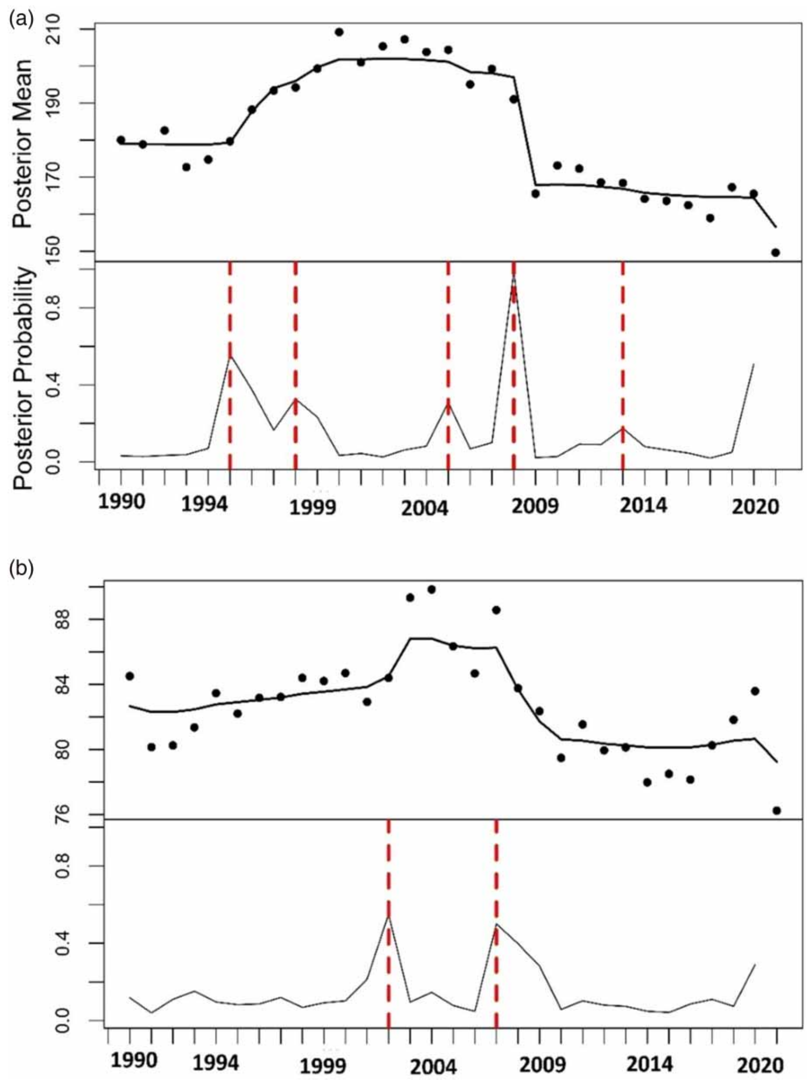


Figure 4 | Bayesian and binary segmentation change point for annual GHG emissions in Central Canada. Estimated change point locations are indicated by dashed vertical lines. Estimated change points for (a) Ontario are located at 1995, 1998, 2005, 2008, and 2013. Estimated change points for (b) Quebec are located at 2002 and 2007.

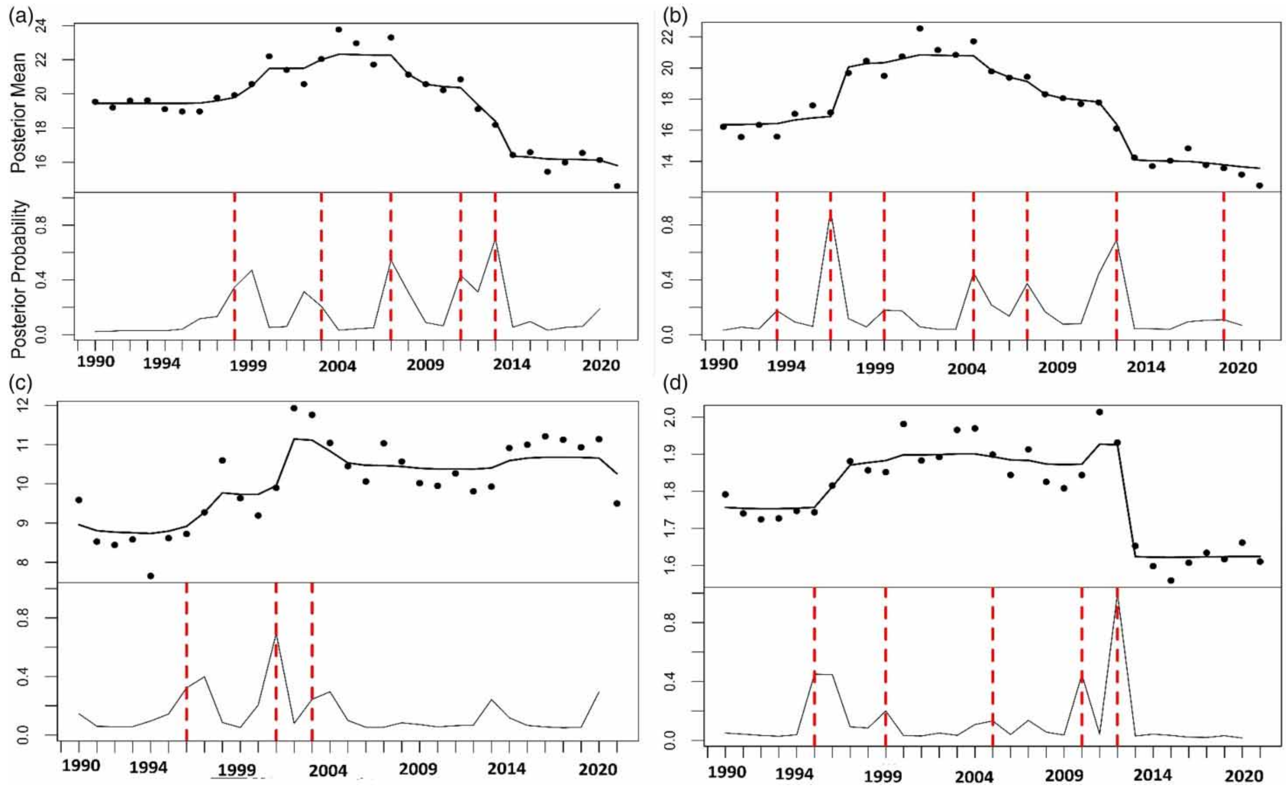


Figure 5 | Bayesian and binary segmentation change point for annual GHG emissions in Atlantic Canada. Estimated change point locations are indicated by dashed vertical lines. Estimated change points for (a) Nova Scotia are located at 1998, 2003, 2007, 2011, and 2013. Estimated change points for (b) New Brunswick are located at 1993, 1996, 1999, 2004, 2007, 2012, and 2018. Estimated change points for (c) Newfoundland are located at 1996, 2001, and 2003. Estimated change points for (d) Prince Edward Island are located at 1995, 1999, 2005, 2009, and 2012.

closed a petroleum refinery in 2013. This may be the reason for the drastic reductions seen in 2013. Figure 5(b) shows that the estimated change points for N.B. are located at 1993, 1996, 1999, 2004, 2007, 2012, and 2018. According to ECCC (2022), N.B. reduced coal and oil consumption. These drastic climatic actions are responsible for all the (positive) changes seen in Figure 5(b). Estimated change points for N.L. are located at 1996, 2001, and 2003. N.L. saw increases in 1996 and 2001. There is a reduction in 2005, which seems constant until 2020, which is when the pandemic began. The MKTT shows a positive trend for N.L. ECCC (2023) reported that there has been an increase in oil consumption for electricity in N.L. This may be attributed to the increase seen in the posterior mean. Figure 5(d) shows that estimated change points for P.E. are located at 1995, 1999, 2005, 2009, and 2012. P.E. also shows an increasing trend until a drastic reduction in 2013. In general, it seems this region is also on the right track for meeting the net-zero goal if the provinces can continue to implement drastic climate actions that will reduce the posterior mean (average GHG emissions) as shown in Figure 5. For N.U. (see supplementary materials), the estimated change points are located at 1998, 2000, 2002, 2004, 2010, and 2018. The estimated change points for N.T. are located at 1998, 2000, and 2002. Also, the estimated change points for Y.K. are located at 2004, 2013, 2012, and 2018. The posterior mean for both N.U. and N.T. seems constant; however, the MKTT shows that there is evidence of a positive trend. After the drastic reduction seen in Y.K. between 2013 and 2017, there is an increasing trend seen. This is consistent with the ECCC (2022) report on increasing emissions from the Y.K. jurisdiction.

Figure 6 shows the BBSCP analysis for the Prairie region. Figure 6(a) shows the estimated change points for A.B. are located at 1993, 1995, 1999, 2005, and 2010. Figure 6(b) also shows the estimated change points for S.K. are located at 1991, 1993, 1995, 2002, 2012, and 2018. Figure 6(c) also shows that the estimated change points for M.B. are located at 1993, 1995, 2005, 2008, 2011, and 2016. For the three provinces, there are consistent increases in their posterior mean. This is an indication of uptrend, which is consistent with the MKTT results explained in the section above, where all three provinces have positive τ with a p-value lower than the significance level. The increasing GHG emissions in A.B. are

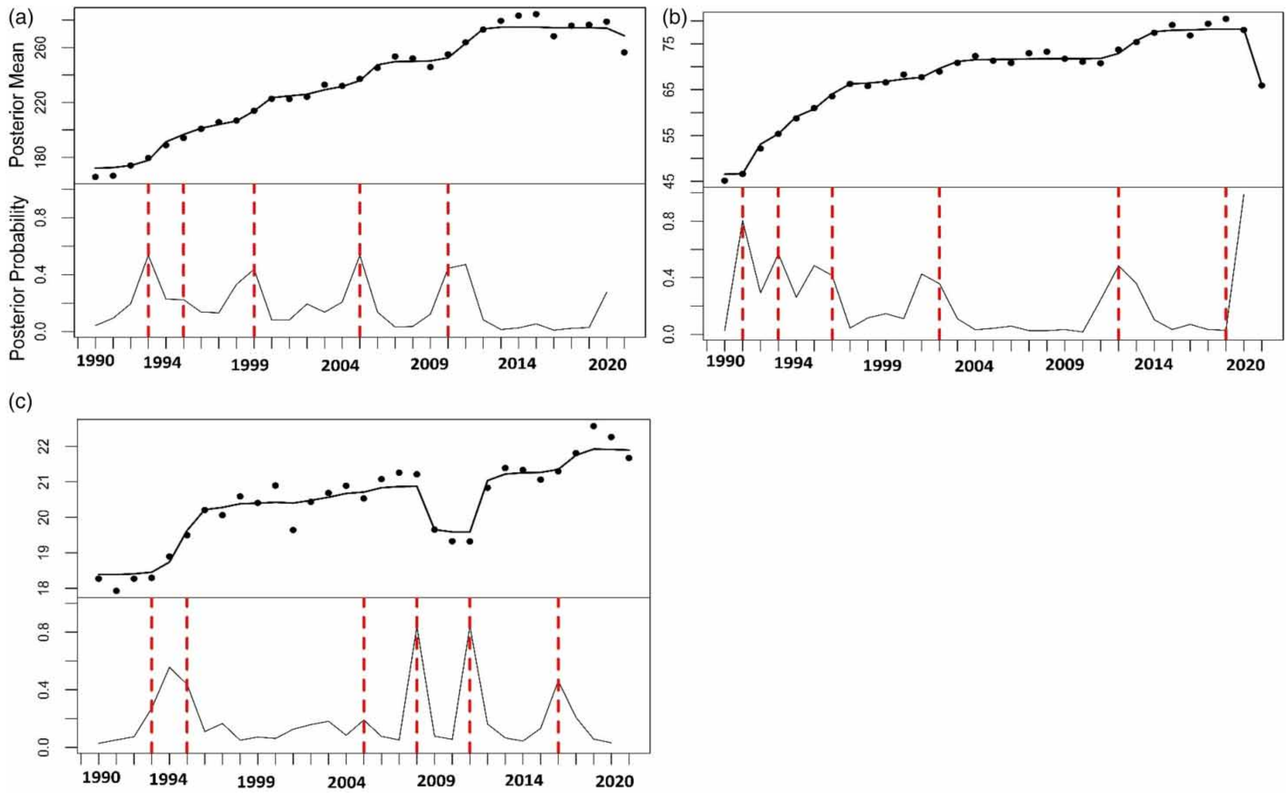


Figure 6 | Bayesian and binary segmentation change point for annual GHG emissions in the Canadian Prairies. Estimated change point locations are indicated by dashed vertical lines. Estimated change points for (a) Alberta are located at 1993, 1995, 1999, 2005, and 2010. Estimated change points for (b) Saskatchewan are located at 1991, 1993, 1995, 2002, 2012, and 2018. Estimated change points for (c) Manitoba are located at 1993, 1995, 2005, 2008, 2011, and 2016.

consistent with O.G. expansion over the course of the years under study. The slight decrease seen in 2020 has been attributed to the impact of the COVID-19 pandemic. In other words, there has not been a consistent decrease in any of the years for all three provinces. This region is dominated by agricultural practices such as animal husbandry and the cropping system. Increased manure and fertilizer use can trigger an increase in methane. Also, an increase in the number of animal herds can increase methane emissions. This result shows that this region needs to do more by doubling their efforts in mitigating GHG emissions. The results presented in this section for the Prairie region are consistent with the result presented by Mertins-Kirkwood (2017). His report presented the successes and shortcomings of Canadian climate policy at the central and jurisdiction levels. Mertins-Kirkwood (2017) concluded that A.B. is the '*source of more than a third of the country's emissions, and despite the introduction of a carbon tax the province is not on track to reduce overall emissions*'.

3.4. Trends, aberrations and change point analysis in Canadian GHG emissions according to economic sector

The MKTT result is shown in Table 4. O.G., T.R., B.D., and A.G. all have a p-value less than the significance level (0.05). In addition, they all have τ that is positive. This indicates the presence of an uptrend. This result is consistent with the result discussed in the earlier section. In other words, in general, there have been increased GHG emissions from these economic sectors from 1990 to 2020 (pandemic notwithstanding). The expansion in O.G. extraction, especially from the Prairie region, is a contributing factor. The increase in population and the number of people owning and driving cars contributes to the T.R. uptrend. An increase in population also leads to an increase in buildings, which leads to an increase in B.D. uptrend. Also, A.G. activities have also increased, especially in the Prairie region.

To quantify which of these sectors has the most impact on the total GHG emissions for the entire country, the estimated change points for all of Canada (Figure 7(a)) are located at 1992, 1994, 1998, 2008, and 2016. The estimated change points for O.G. (Figure 7(b)) are located at 1992, 1995, 1998, 2001, 2005, and 2011. Apart from the magnitude of the posterior mean, there are clear similarities between O.G. and the entire country. Also, the shape of the posterior probability looks similar,

Table 4 | Mann–Kendall Trend test for the Canadian economic sectors

Economic sector	τ	*p*-value
Oil and gas	0.88	3.20×10^{-12}
Electricity	−0.46	0.000276
Transportation	0.90	1.21×10^{-12}
Heavy industry	−0.76	2.19×10^{-9}
Building	0.60	1.95×10^{-6}
Agriculture	0.54	2.50×10^{-5}
Waste	0.23	0.07712
Coal production	−0.69	5.36×10^{-8}
Light manufacturing	−0.71	2.04×10^{-8}

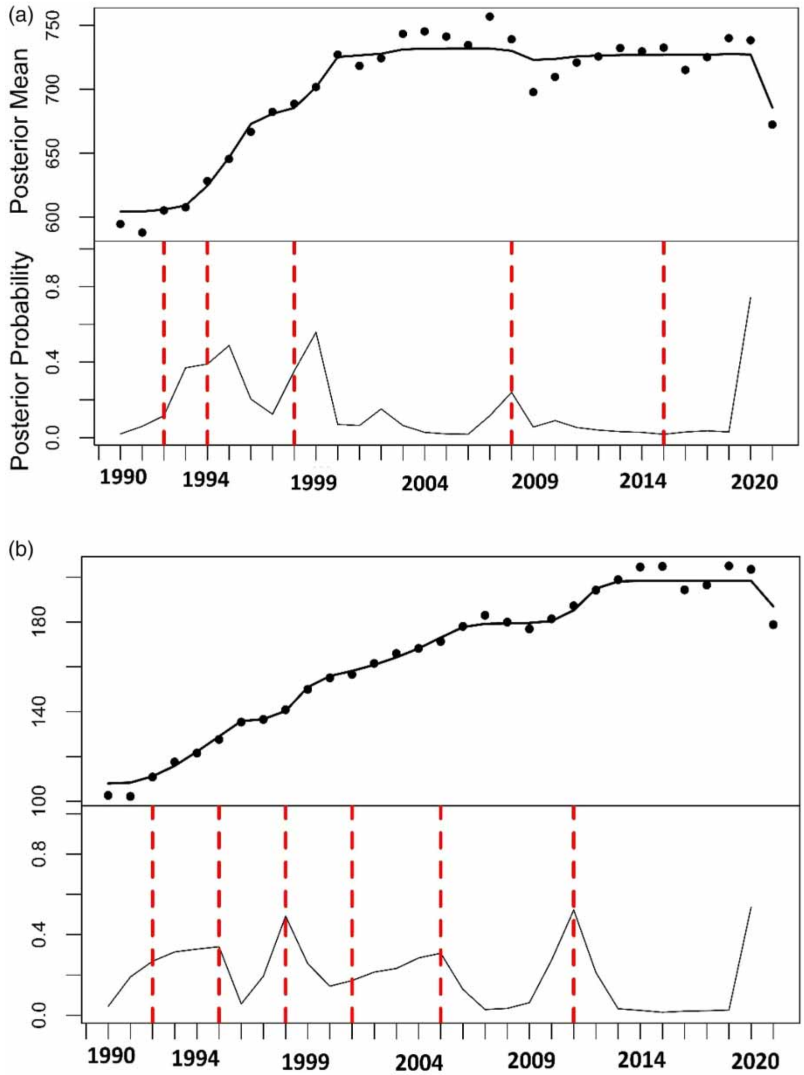


Figure 7 | Bayesian and binary segmentation change point for annual GHG emissions in (a) entire Canada and (b) oil and gas. Change point locations are indicated by dashed vertical lines. Estimated change points for (a) entire Canada are located at 1992, 1994, 1998, 2008, and 2016. Estimated change points for (b) oil and gas are located at 1992, 1995, 1998, 2001, 2005, and 2011.

meaning that all climatic actions and inactions are propagating to the national GHG emission average, year to year. In other words, OG is a significant contributor to the national GHG emissions. Furthermore, the shape and orientation of the posterior mean for the entire country is also like those of the Prairie region. The implication of this is that this region holds the highest responsibility in emissions reduction. For Canada to meet the net-zero goal, there should be double and drastic climatic actions from this region.

The estimated change points for E.L. (see Supplementary material) are located at 1996, 1999, 2003, 2008, 2011, and 2017. Likewise, the estimated change points for T.R. are located at 1997, 2003, and 2010. Furthermore, the estimated change points for H.I. (see Supplementary material) are located at 1993, 1997, 2000, 2004, 2008, 2010, and 2015. The reduction trend and orientation seen in E.L. is due to the drastic actions taken in reducing emissions from electricity from oil and coal. Specifically, jurisdictions such as N.B. and N.S. have taken drastic actions in reducing emissions from E.L. due to their stopping the use of oil for electricity generation. The increase in T.R. posterior mean and change point locations is consistent with the increase seen in the transportation sector discussed in the previous sections. For instance, Canada's population in 1990 and 2020 was approximately 27 and 37 million, respectively (Statistics Canada 2022a). The 10 million additional residents will increase the number of vehicles needed for transportation, which will translate to the increase seen in T.R. For H.I., there is a downtrend as evident in the posterior mean. According to ECCC (2023), there has been a reduction in heavy industries such as cement and pulp, paper, and print. The estimated change points for B.D. are located at 1992, 1999, and 2017. The posterior mean also shows an increasing uptrend. Emissions from B.D. can also be attributed to an increase in population. This increase in population will increase demand for the combustion of fossil fuels for space and water heating.

The estimated change points for A.G. are located at 1992, 1994, 2002, 2008, 2011, and 2017 (graph shown in Supplementary material). The estimated change points for W.S. are located at 1992, 1997, 1999, 2007, and 2009. Also, the estimated change points for C.P. are located at 1997, 2001, 2004, 2009, and 2013. The estimated change points for L.M. are located at 1992, 1994, 1997, 2005, and 2008. There have been reported increases in GHG emissions from agricultural practices (Vergé *et al.* 2008; ECCC 2022). This is the driving factor contributing to the increasing trend seen in the posterior mean (see Supplementary material). The MKTT for W.S. shows a lack of trend in the series, but the posterior mean orientation shows an increasing positive trend from 2016. It is likely that population increase may have a negative influence on waste generation; therefore, there is a need for continued waste management efforts with adaptations such as recycling and the banning of plastic-based packing in each of the jurisdictions. The reduced consumption of coal is seen in jurisdictions such as N.B., MB, and N.S. In O.N., there has been closure of coal-based electricity generation starting from 2005. The drastic reductions in the posterior mean in C.P. can be attributed to these significant climatic actions in the C.P. industry. Although there was a drastic increase in GHG emissions from W.S. between 1999 and 2008, this was offset by the drastic reductions seen at the block of 2009–2016.

Generally, the BBSCP and CBS analysis agree well with the MKTT results. Furthermore, BBSCP shows the number of change points and the locations where the change points occurred. Some of the change point locations can be explained by drastic actions taken in each sector of the economy. The total number of change points and frequency of change points can be attributed to frequent policies and regulations taken by each jurisdiction or the federal government. For those economic sectors with uptrend, this study shows that more climatic action is needed. From an economic standpoint, O.G. contributes substantially to the total GHG emissions. This shows that a transition from fossil fuels is non-negotiable if Canada wants to achieve net-zero.

3.5. How provinces with less hydroelectric potential acquire electricity from provinces with more hydro dams

What gives hydropower the ability to backup other renewables, and what makes hydropower a great electricity source to export is that it is relatively easy to start and stop hydroelectric plants (Bordeleau 2011). Dams can be closed when the electric grid has an abundance of energy or when prices are low. During this time, water will collect in the reservoir, building energy and potential revenue. If domestic demand increases or export prices on the spot increase, the floodgates will open, literally (Bordeleau 2011). For instance, in 2009, Hydro-Quebec's net exports to the US accounted for 10% of its total sales but 22% of its net profits (Bordeleau 2011). A setback for Canadian provinces with less hydroelectric potential acquiring electricity from hydro provinces is that, from a planning standpoint, Canada's provinces often treat their borders like fences (Haffner & Burpee 2018). This is tough, especially when each province in Canada is responsible for their own high voltage transmission line (how hydroelectric energy can travel between provinces) planning (IEA 2022). Interprovincial collaboration on improving high voltage transmission lines is a must to drive down Canada's emissions (IEA 2022). Fortunately, there have been major transmission and infrastructure upgrades being planned across Canada including major lines in B.C., A.B., S.K., M.B., and Q.C. (IEA 2022). Canada's Atlantic region has made important strides to enhance the transmissions of clean power across the region. The completion of the Muskrat Falls hydroelectric station (albeit with its fair share of issues during construction) in Labrador and transmission links from Labrador to Newfoundland and then Newfoundland to the Maritime provinces (Figure 3) will both reduce Labrador's emissions and supply hydroelectric power to the Maritime provinces with less hydroelectric potential (IEA 2022). If projects like this continue to occur, hydro's role may increase from primarily base load to offering multiple contributions to the North American Continental Grid, including ancillary services and large-scale storage (IEA 2022).

From the foregoing, collaborations from both policy and economic perspectives will be crucial in Canada for the country to meet its target. Jurisdictions where electricity and heating are still generated from coal coal-fired power plants: A.B., S.K., N.B., and N.B. or oil-fired heating systems: N.L. (which are significant sources of GHG emissions) can take advantage of the available UP (84,000 MW).

3.6. Implications for policy formulation and regulations in Canada

The implication of this study is that subtle or drastic changes in policies, such as establishing regulations as part of climate change efforts, have a profound impact. Some of the jurisdictions that have taken drastic climatic actions in reducing their emissions have seen downtrends in their GHG footprints. For the most part, this is evident in the Central, Atlantic and Territories jurisdictions. Other regions such as the Prairie region have a consistent increasing uptrend. This region is also the largest contributor to the national annual GHG emissions. This analysis should, therefore, help this region in their climate change mitigation strategies. Drastic climatic actions such as effective policies and regulations are needed for any meaningful reduction in GHG emissions. Therefore, there should be more collaboration and synchronous policies on emission reductions from the municipal to the national level (Mahamat 2019). From a global GHG emissions reduction standpoint, Canada's emission profile is consistent with that of other developed countries; however, for the country to be a major global player in climate change and GHG reductions, more work needs to be done to reach all the climate change goals. Canada's national climate plans such as the PCF, HEHE, CNZEAA and ERP need to be strengthened. Effective monitoring and evaluation need to be performed at every stage of these projects and not at the end. Furthermore, there should be more initiative and funding for innovations (Jordaan *et al.* 2017) in climate change mitigation. Energy transition from fossil fuels requires innovations that can only be produced through R&D. Also, there is a need for effective climate diplomacy, communication, and governance. The highest contributors to the national GHG emissions are regions with the largest O.G. extractions. These regions are also agricultural-intensive areas. Natural Climate Solutions (NCS) are approaches that can be applied in these areas for carbon conservation and storage (Fargione *et al.* 2018). NCS actions such as natural forest management, avoided forest conversion, cover crops, improved plantations, grazing optimization, and improved manure management can be applied to mitigate GHG emissions in the Canadian prairies. Furthermore, diplomacy is required in communicating the federal government's climate plans with these regions, especially at the national level.

Canada has done a great job in leveraging the potential water resources available, and they can do even better. Over 50% of all dams in Canada were constructed prior to 1970, making them over half a century old. In order to tap into the full potential of this existing infrastructure, complex and extensive repairs to large dams, reservoirs and powerhouses are needed. (Morgenroth & Bayliss 2023) Additionally, a look at installing new pumped-storage plants would be beneficial. These plants can store energy from non-dispatchable renewables and release renewable energy back into the system when it is needed during peak electricity demand. Even though there have been no new facilities of this kind for 70 years, there is no time like the present to consider action (Morgenroth & Bayliss 2023). As noted earlier, many areas in Northern Canada (namely the Territories) have an abundance of untapped hydro potential, but many of these remote communities rely on diesel generators for their power needs (Canadian Geographic 2023). Aside from improving hydroelectric infrastructure, ski and other winter activity areas in Canada with extensive snowfall could look at following Banff Sunshine Village Ski Resort's snow-farming model. This is not only using existing water resources more effectively, but also reducing the GHG emissions that would be released by the snowmakers. Essentially, setting up fences to catch drifts of snow which can then be dispersed by machinery areas where snow is needed as opposed to making snow (Lorelli 2023). Additionally, mandating greywater use infrastructure (i.e. diverting water from showers to flush toilets, saving 20% of household water use) should be something the government should investigate for water conservation (Zeidler 2023).

For future research opportunities, this study used aggregated datasets from all the jurisdictions and main economic sectors, it would be interesting for a further study to actually use datasets from local municipal or counties and from the sub-economic sectors shown in Table 1. This would allow the quantification and identification of specific sectors in each jurisdiction where there has been increased GHG emissions.

4. CONCLUSION

This study assessed the temporal variations, trends, and aberrations in the annual GHG emissions for Canada from both regional and economic sector perspectives using theMKTT and Bayesian and Binary Segmentation Change Point (BBSCP) analysis. The results show that some regions and economic sectors are doing well (downtrend), and some are not (uptrend). The locations of the change points for the annual GHG emissions agree with the time when certain regulations and policies were implemented in these regions and economic sectors. This study concludes with the following summaries:

(i) There was an uptrend for all the Prairie provinces (Alberta (A.B.), Saskatchewan (S.K.), Manitoba (M.B.)). From a change point perspective, A.B., S.K., and M.B. also have frequent change points. This implies that there are likely inconsistencies or contradictions in their policies and strategies for reducing GHG emissions. There was a downtrend for other regions such as the Atlantic region (New Brunswick (N.B.), Newfoundland (N.L.), Nova Scotia (N.S.), and Prince Edward Island (P.E.)), Central region (Ontario (O.N.) and Quebec (Q.C.)), and Territories (North Territories (N.T.), and Nunavut (N.U.)). The downtrend seen in O.N., N.S., Q.C., N.T., and N.B. are consistent with drastic climatic actions taken by these jurisdictions in reducing their GHG emissions.

(ii) For the economic sector, there is evidence of a consistent uptrend in Oil and Gas (O.G.), Agriculture (A.G.), and Transportation (T.R.). There has been a sustained increase in O.G. extractions and A.G. activities, especially in the Prairie region. Canada's population increase is an underlying driver for the increase in T.R. There was downtrend evidence in Coal Production and Electricity. Several of the jurisdictions closed C.P. and oil-based electricity generation methods. The BBSCP's posterior mean agrees with the trend orientation and the location of change points agrees when some of the drastic climatic actions were taken.

(iii) The study emphasized that policy and economic collaborations are vital for Canada to meet its target. Regions still using coal-fired plants, like A.B., S.K., and N.B., or oil-fired heating, like N.L., can tap into up to 84,000 MW of available hydroelectricity potential to reduce GHG emissions.

This study extends the research on understanding GHG emissions, trends, and change points in Canada from both jurisdiction and economic sectors perspectives. To the author's knowledge and after searching through peer-reviewed repositories, no previous research has been able to apply a BCP-based approach in quantifying and analyzing GHG emissions and trajectories in Canada. This study will further guide regional and economic sector informed decisions in the efforts to reduce GHG emissions and help Canada achieve net-zero by 2050.

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AUTHORS CONTRIBUTIONS

A.B. conceptualized the study, prepared the methodology, did formal analysis and investigated the study, wrote and prepared the original draft; A.B. and J.M. wrote, reviewed, and edited the article and contribution to the final manuscript.

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AVAILABILITY OF DATA AND MATERIALS

The datasets used in this study are from the Environment and Climate Change Canada (2022) National Inventory Report 1990–2020 which is publicly available.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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