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• **News & Views** •

Severe Global Environmental Issues Caused by Canada's Record-Breaking Wildfires in 2023

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ABSTRACT

Due to the record-breaking wildfires that occurred in Canada in 2023, unprecedented quantities of air pollutants and greenhouse gases were released into the atmosphere. The wildfires had emitted more than 1.3 Pg CO_2 and 0.14 Pg CO_2 equivalent of other greenhouse gases (GHG) including CH_4 and N_2O as of 31 August. The wildfire-related GHG emissions constituted more than doubled Canada's planned cumulative anthropogenic emissions reductions in 10 years, which represents a significant challenge to climate mitigation efforts. The model simulations showed that the Canadian wildfires impacted not only the local air quality but also that of most areas in the northern hemisphere due to long-range transport, causing severe $PM_{2.5}$ pollution in the northeastern United States and increasing daily mean $PM_{2.5}$ concentration in northwestern China by up to 2 μg m^{-3}. The observed maximum daily mean $PM_{2.5}$ concentration in New York City reached 148.3 μg m^{-3}, which was their worst air quality in more than 50 years, nearly 10 times that of the air quality guideline (i.e., 15 μg m^{-3}) issued by the World Health Organization (WHO). Aside from the direct emissions from forest fires, the peat fires beneath the surface might smolder for several months or even longer and release substantial amounts of CO_2. The substantial amounts of greenhouse gases from forest and peat fires might contribute to the positive feedback to the climate, potentially accelerating global warming. To better understand the comprehensive environmental effects of wildfires and their interactions with the climate system, more detailed research based on advanced observations and Earth System Models is essential.

Key words: Canada, forest fire, greenhouse gases, $PM_{2.5}$, transboundary air pollution

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1. Introduction

Wildfires are essential disturbances in the Earth's system, which can affect the biosphere, atmosphere, hydrosphere, and cryosphere, and can cause substantial environmental damage, severe air pollution, human mortality, and economic losses (Bowman et al., 2020). Direct exposure to the flames of wildfires can cause human fatalities, e.g., more than 1 000 people died due to the Peshtigo Fire in October 1871, which was the deadliest fire in the recorded history of the United States of America (USA). However, the exposure to air pollution caused by wildfires can affect much larger populations and potentially cause much larger human mortality, since the smoke from such fires can be transported hundreds or even thousands of kilometers away (Xu et al., 2023). One estimation indicated that the annual average mortality due to exposure to wildfire-related $PM_{2.5}$ was 677 745 globally, with the highest mortality occurring in Africa and Asia (Roberts and Wooster, 2021).

Although wildfires began soon after the appearance of terrestrial plants and have been a natural feature of the Earth system for the last 420 million years (Bowman et al., 2009, 2020), their severity and frequency are thought to be increasing as a

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result of anthropogenic climate change (Xu et al., 2023). The enhanced wildfires can release more greenhouse gases (e.g., CO_2, CH_4, N_2O), which may result in positive fire-climate feedback. Forest fires are an important component of wildfires due to a higher CO_2 emission per unit area burned compared with grassland fires, and the burned area and CO_2 emission from forest fires were found to be increasing over the past two decades (Zheng et al., 2021a). In recent years, wildfires have rapidly expanded into boreal forests due to the most rapid warming occurring over the northern high-latitude regions, consequently, boreal fires contributed 23% to global fire CO_2 emissions in 2021, which was the highest fraction since 2000 (Zheng et al., 2023).

In 2023, serious wildfires occurred over the boreal forests in Canada and caused widespread concern. As of 31 August, 6049 fires were reported across Canada, resulting in a cumulative burned area that exceeded 156 000 km^2, shattering the record of 71 060 km^2 set in 1995, according to the Canadian Interagency Forest Fire Center (CIFFC, https://ciffc.ca). The burned area accounts for 1.7% of Canada's land area, surpassing the size of more than half of the countries in the world. The unprecedented wildfires have released significant amounts of air pollutants and greenhouse gases into the atmosphere, leading to severe air pollution and the potential exacerbation of global warming.

2. Severe air pollution due to the Canadian wildfires

Wildfires can release a variety of air pollutants, such as primary fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). Among these air pollutants, $PM_{2.5}$ causes the most severe air pollution and directly endangers human health. An epidemiological study based on a large international dataset found that the relative risks were 1.019 for all-cause mortality, 1.017 for cardiovascular mortality, and 1.019 for respiratory mortality, associated with each 10 μg m^{-3} increase in the 3-day moving average of wildfire-related $PM_{2.5}$ exposure (Chen et al., 2021). The $PM_{2.5}$ pollution due to the wildfires in Australia in 2019–2020 was responsible for an excess of 417 all-cause deaths, 1124 hospital admissions for cardiovascular diseases and 2027 for respiratory diseases, and 1305 emergency department visits with asthma over eastern Australia (Arriagada et al., 2020). A recent study based on respiratory hospitalizations in Southern California suggested that wildfire-specific $PM_{2.5}$ is up to 10 times more harmful to human health than $PM_{2.5}$ from other sources (Aguilera et al., 2021).

The emissions of air pollutants could be derived using satellite observations and land use-dependent emission factors, e.g., fire emissions estimated from the Global Fire Assimilation System (GFAS) (Di Giuseppe et al., 2018). Based on the GFAS emission data, it is evident that the Canadian wildfire season usually starts in May and ends in September (Fig. 1). As of 31 August, the cumulative $PM_{2.5}$ emission in the year 2023 had reached 10.07 Tg which is 6.6 times greater than the average value of the previous 20 years. The $PM_{2.5}$ emission from Canadian wildfires in 2023 was much larger than the annual anthropogenic primary $PM_{2.5}$ emission from China which was about 6 Tg (Zheng et al., 2021b). The maximum daily $PM_{2.5}$ emission reached 0.55 Tg on 13 August 2023.

According to the GFAS emission data, the area where wildfires occurred in Canada significantly changed from May to August 2023 and thus were capable of affecting the air quality in different areas (Fig. 2). In May 2023, wildfires mainly occurred in the southwestern region of Canada. In addition to the southwestern region of Canada, the southeastern region also suffered from widespread wildfires in June. Compared to May and June, the areas with wildfires in July and August had shifted significantly to the north because the weather became warmer in mid and late summer due to seasonal variations over north Canada.

Massive $PM_{2.5}$ emissions not only affect local air quality but also significantly impact downstream areas through long-range transport. Air quality models play an important role in analyzing the long-range transport of air pollutants. By using the Aerosol and Atmospheric Chemistry Model of the Institute of Atmospheric Physics (IAP-AACM) in the Chinese Academy of Sciences Earth System Model (CAS-ESM) (Wei et al., 2019), the impacts of the Canadian wildfires on global air quality were analyzed, and the preliminary results showed that the Canadian wildfires did indeed significantly impact air quality in the Northern Hemisphere (Fig. 3).

Six widespread air pollution episodes due to the Canadian wildfires were found from May to August: 15–22 May, 5–9 June, 24 June–1 July, 12–19 July, 7–15 August, and 17–22 August. In addition to Canada itself, the first episode also affected the air quality of the north-central parts of USA (Fig. 3a). The second episode caused severe pollution in the northeastern USA (Fig. 3b). On 7 June, the average of the observed daily mean $PM_{2.5}$ concentration in 11 monitoring sites of New York City reached 148.3 μg m^{-3}, with a range of 115.6–203.5 μg m^{-3} for each site, which was the worst air quality there in more than 50 years (https://www.cbsnews.com/newyork/news/mayor-adams-to-address-nycs-air-quality-alert-from-canadian-wildfires-residents-urged-to-avoid-outdoor-exertion). During the third episode, fire-induced $PM_{2.5}$ was transported over long distances to Europe (Fig. 3c). The fourth episode caused severe pollution in western Canada and the north-central USA (Fig. 3d). The fifth episode mainly affected northern Canada (Fig. 3e), while the sixth episode affected both the western and eastern coastal regions of the USA (Fig. 3f). Due to the northward movement of the wildfires, high concentrations of $PM_{2.5}$ were transported to the Arctic region in July and August.

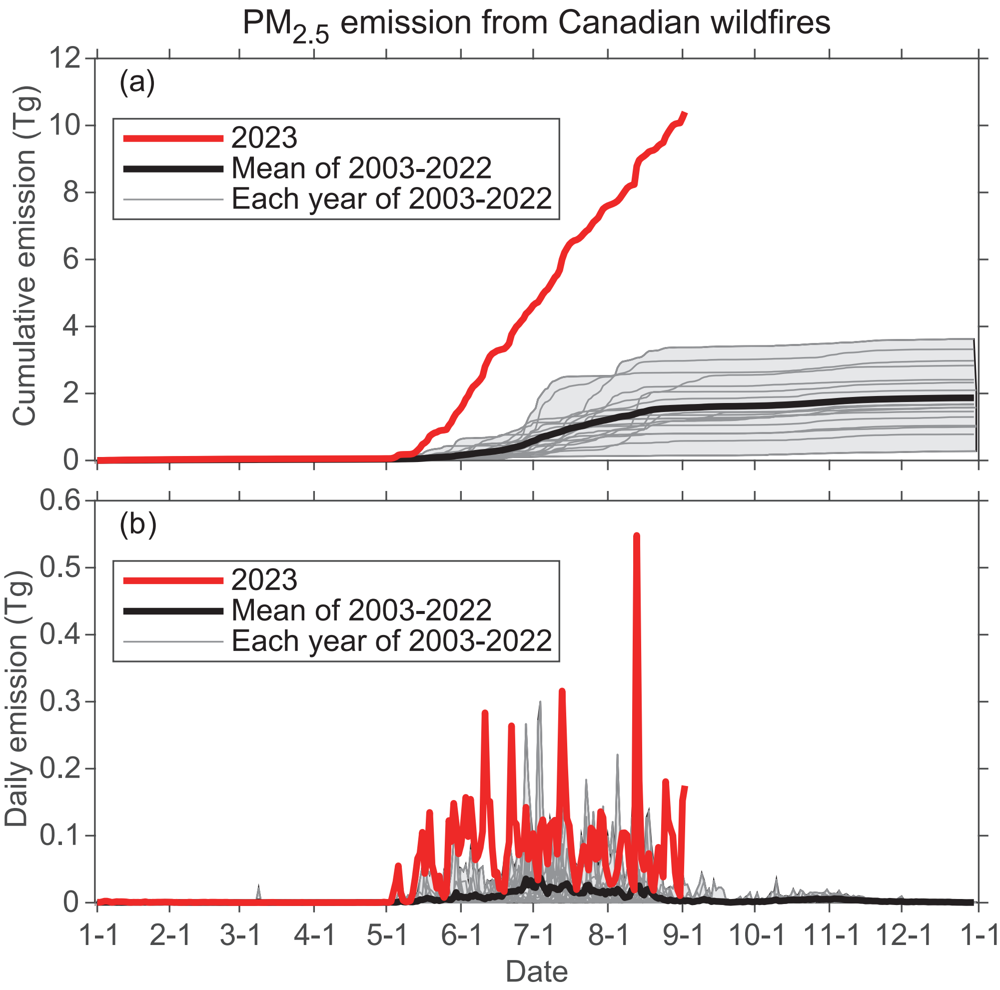

Fig. 1. Cumulative and daily $PM_{2.5}$ emissions from Canadian wildfires based on GFAS emission data.

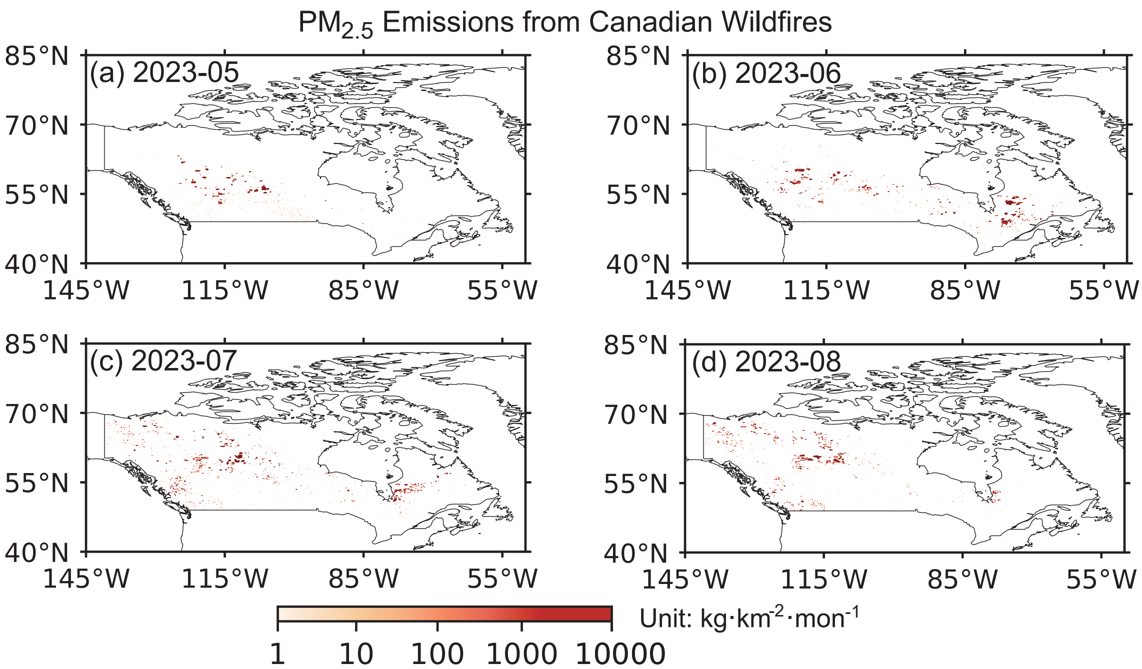

Fig. 2. Horizontal distribution of monthly $PM_{2.5}$ emissions from Canadian wildfires in 2023 based on GFAS emission data.

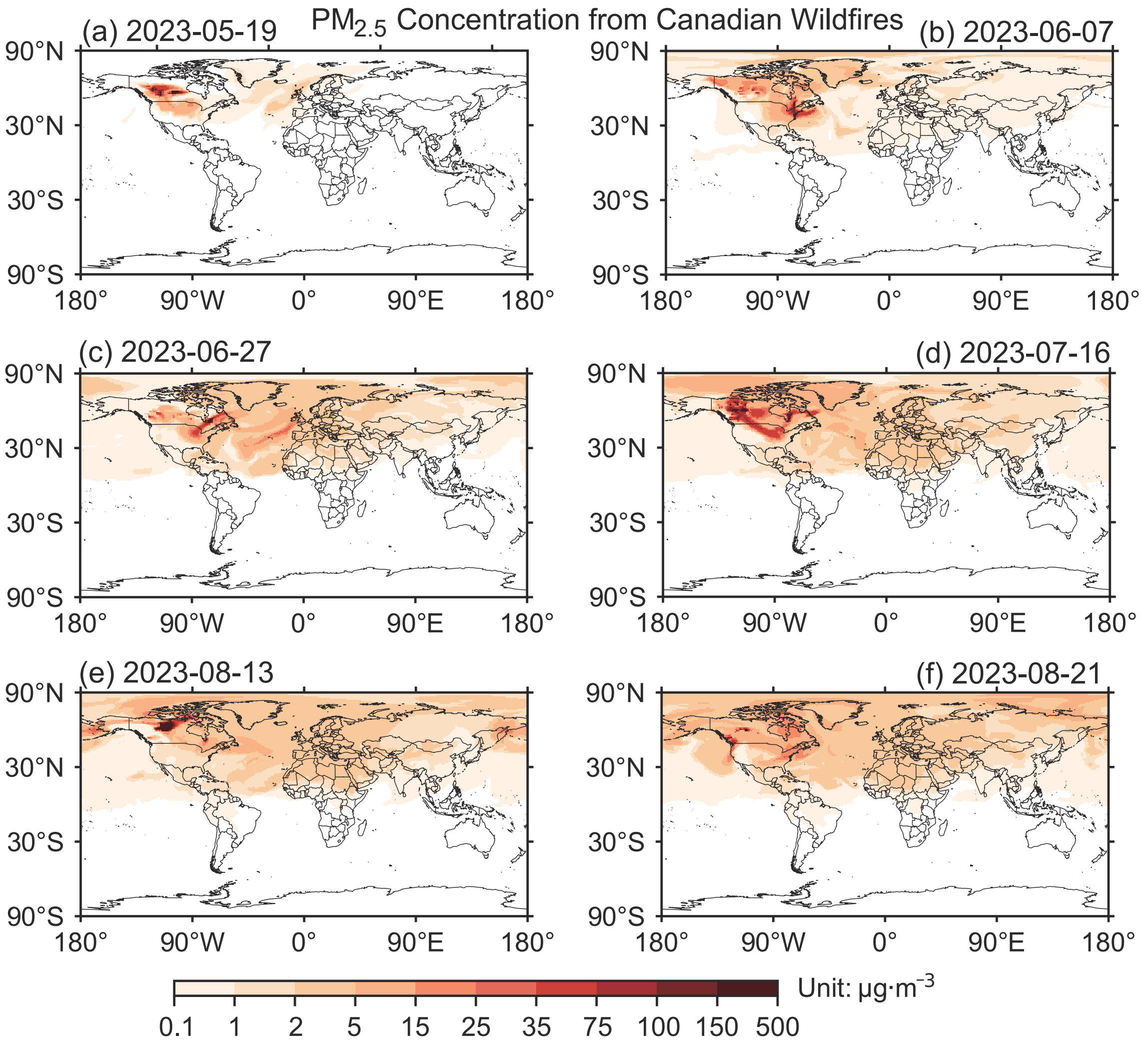

Fig. 3. Long-range transport of $PM_{2.5}$ from Canadian wildfires from May to August, 2023.

Figure 4a shows the distribution of the simulated maximum daily mean $PM_{2.5}$ due to the Canadian wildfires from 1 May to 31 August 2023, at each model gridpoint. The maximum $PM_{2.5}$ concentrations were larger than 1 μg m^{-3} over most areas of the northern hemisphere and were larger than 150 μg m^{-3} over both western and eastern Canada. Because the Canadian wildfire plume was transported across the Atlantic Ocean to Europe, Western and Central Asia, and eventually to East Asia under the prevailing westerly winds, the $PM_{2.5}$ concentrations in the northwest region of China increased by about 2 μg m^{-3}. The $PM_{2.5}$ pollution ($PM_{2.5}$ concentration higher than the WHO air quality guideline, i.e., 15 μg m^{-3}) mainly occurred over North America, with more than 40 pollution days over both western and eastern Canada, as well as more than 10 days over the northeastern USA (Fig. 4b).

3. Vast greenhouse gases released from the Canadian wildfires

According to a recent study (Liu et al., 2023), the Canadian wildfires in 2023 also emitted huge amounts of greenhouse gases, including more than 1.3 Pg CO_2 and 0.14 Pg CO_2 equivalent (e) of CH_4 and N_2O as of 31 August. The CO_2 emission from the Canadian wildfires in 2023 was higher than that from the Australian wildfires in 2019–20 which was 0.715 Pg (van der Velde et al., 2021). The transport of wildfire-related CO_2 was also simulated using the IAP-AACM model. From the distribution of the monthly averaged surface CO_2 concentration due to the Canadian wildfires (Fig. 5), it is evident that the wildfire-related CO_2 reached high concentrations of >30 ppm near the source areas. The anomalously high CO_2 concentrations were transported to most northern hemisphere areas within two months. The Canadian wildfires increased the CO_2 concentrations mainly over North America in May, and by June, high concentrations were also observed Europe and the northwest part of Asia. The wildfire-related CO_2 concentrations were more than 0.1 ppm over most northern hemisphere areas except Southeast Asia, India, and South China in July, and increased to more than 0.2 ppm in August. The high concentrations of greenhouse gases over the fire areas and their downwind regions might enhance high temperatures due to the

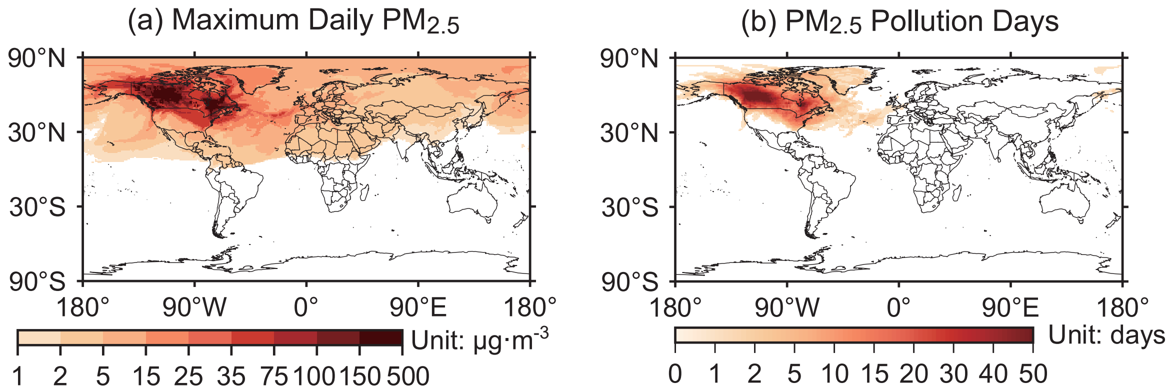

Fig. 4. Horizontal distribution of maximum daily mean $PM_{2.5}$ concentration and $PM_{2.5}$ pollution days due to Canadian wildfires from May to August 2023.

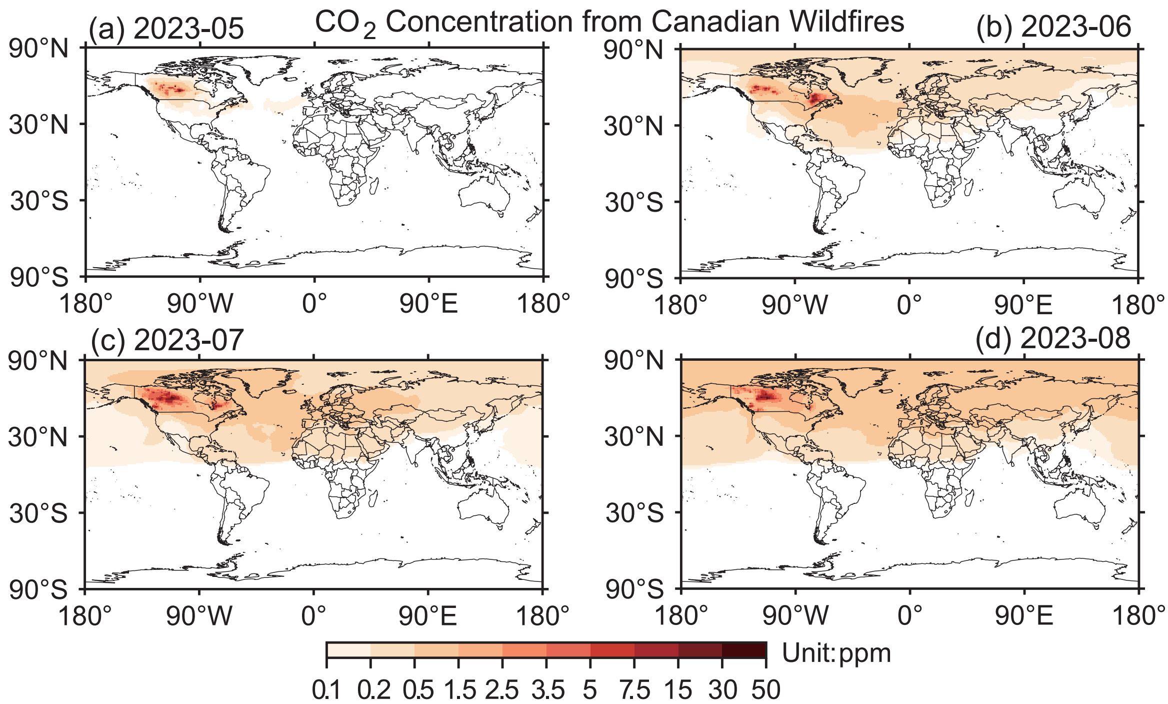

Fig. 5. Global distribution of monthly averaged surface CO_2 concentration due to the Canadian wildfires.

greenhouse effect and consequently may lower relative humidities as a result of the higher temperatures. Warmer and drier conditions would tend to increase the likelihood for fires to occur, which potentially demonstrates positive feedback between wildfires and greenhouse gases. This proposed mechanism is not well understood and is worthy of future study.

The greenhouse gas emissions due to the wildfires from May to August 2023 were enough to offset Canada's planned cumulative anthropogenic emissions reductions for more than 10 years (Fig. 6). According to Canada's 2030 Emissions Reduction Plan (https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/emissions-reduction-2030/plan.html), the annual anthropogenic GHG emissions are to be reduced from 0.669 Pg CO_2e in 2020 to 0.472 Pg CO_2e in 2030. The cumulative emissions reduction (CER) between 2020 and 2030 was 0.718 Pg CO_2e as calculated according to the following formula:

$$\mathrm{CER} = \sum_{y=2021}^{2030} -\left(\mathrm{Emis}_y - \mathrm{Emis}_{2020}\right) . \quad (1)$$

Therefore, the wildfire-related greenhouse gas emissions were more than twice Canada's planned cumulative anthropogenic emission reduction over 10 years, which poses a significant challenge to controlling global warming.

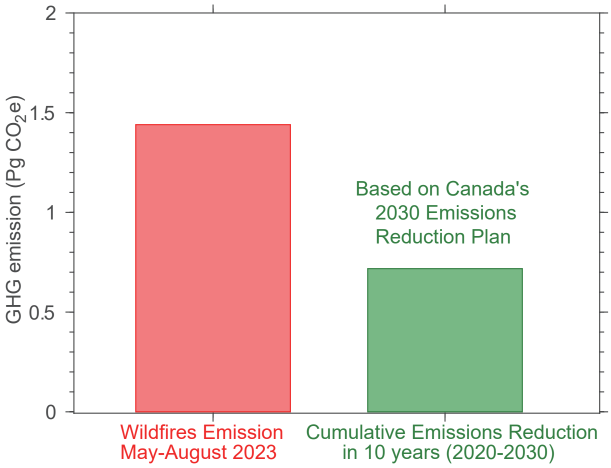

Fig. 6. Comparison of greenhouse gas emissions due to the wildfires from May to August 2023 (red) with the planned cumulative anthropogenic emission reduction between 2020 and 2030 (green).

4. Summary and discussion

As a result of Canada's record-breaking wildfires in 2023, record-high amounts of air pollutants and greenhouse gases were released into the atmosphere, which caused severe air pollution and have the potential to enhance global warming. The Canadian wildfires impacted not only the local air quality but also that of most northern hemisphere areas due to long-range aerosol transport, causing severe $PM_{2.5}$ pollution in the northeastern USA and increasing the daily mean $PM_{2.5}$ concentration in northwestern China by up to 2 μg m^{-3}. Wildfire aerosols not only directly harm human health, but also affect the climate through processes such as aerosol-radiation interactions, aerosol-cloud interactions, and reducing the albedo of snow/ice surfaces and enhancing ocean phytoplankton blooms upon deposition (Tang et al., 2021; Aubry-Wake et al., 2022). Due to the solar heating of the absorbing aerosol (e.g., black carbon), the wildfire smoke could be lifted into the stratosphere (Yu et al., 2019), which could destroy stratospheric O_3 (Bernath et al., 2022). Unlike the stratosphere, wildfires would enhance O_3 pollution near the surface due to the emissions of wildfire-related CO, NO_x, and VOCs (Xu et al., 2023).

The Canadian wildfires in 2023 also emitted huge amounts of greenhouse gases, including more than 1.3 Pg CO_2 and 0.14 Pg CO_2 equivalent of CH_4 and N_2O as of 31 August. The wildfire-related emissions were more than twice Canada's planned cumulative anthropogenic emissions reductions in 10 years. The wildfires could enhance global warming not only via biogeochemical processes, e.g., emissions of greenhouse gases, but also through direct biophysical processes, e.g., changing the albedo and energy budget at Earth's surface. Forest fires could increase surface temperature by 0.15°C in the next year over burned areas globally (Liu et al., 2019).

Canada stores more than 300 billion tons of carbon in its terrestrial ecosystem. The vast carbon storage is equivalent to several decades' worth of human-caused global greenhouse gas emissions. Notably, 94% of this carbon is stored in soil, with peatland alone accounting for 32% of the total soil carbon content. Peat fires, once ignited, exhibit remarkable persistence, smoldering and spreading beneath the surface for several months or even longer. Extinguishing these fires presents formidable challenges. The combustion of peat not only releases substantial amounts of carbon dioxide but also contributes to a perilous feedback loop, potentially accelerating global warming. Recognizing the pivotal role of peatlands in Canada's carbon cycle and their vulnerability to wildfires is of paramount importance. Prompt suppression measures are essential in breaking this dangerous feedback loop and propelling our endeavors toward a more sustainable future.

Wildfires have become one of the significant environmental challenges in the world today, with far-reaching impacts on the atmosphere, land, and water resources. These effects extend beyond the immediate outbreak areas and can have complex and interconnected relationships with the climate system. To better understand the comprehensive environmental effects of wildfires and their interactions with the climate system, it is essential to conduct more detailed research based on advanced observations and Earth System Models for our ability to address this global issue effectively. This will help us predict and respond to the impacts of wildfires in a more effective manner and provide more accurate data and scientific evidence for environmental conservation and climate change mitigation.

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