Quantifying greenhouse gas emissions through atmospheric inversion systems

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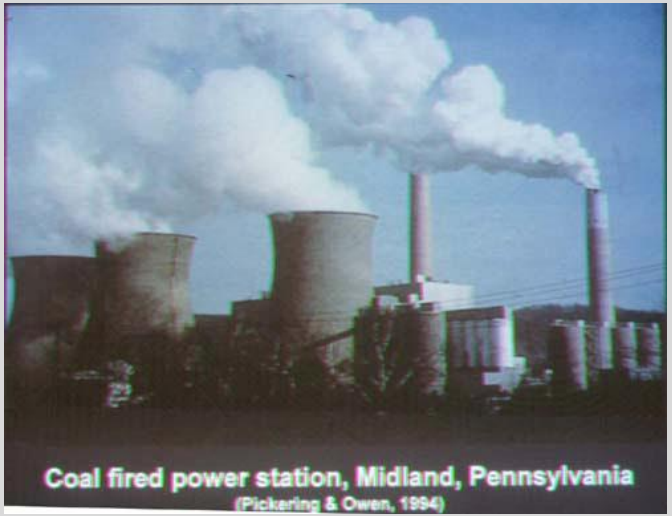
Overview

- Introduce use of atmospheric trace gas measurements to quantify sources/sinks

$$Atmospheric\ Concentration = f(Flux)$$



Article

Carbon emissions from the 2023 Canadian wildfires

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The 2023 Canadian forest fires have been extreme in scale and intensity with more than seven times the average annual area burned compared to the previous four decades[1]. Here, we quantify the carbon emissions from these fires from May to September 2023 on the basis of inverse modelling of satellite carbon monoxide observations. We find that the magnitude of the carbon emissions is 647 TgC (570–727 TgC), comparable to the annual fossil fuel emissions of large nations, with only India, China and the USA releasing more carbon per year[2]. We find that widespread hot–dry weather was a principal driver of fire spread, with 2023 being the warmest and driest year since at least 1980[3]. Although temperatures were extreme relative to the historical record, climate projections indicate that these temperatures are likely to be typical during the 2050s, even under a moderate climate mitigation scenario (shared socioeconomic pathway, SSP 2–4.5)[4]. Such conditions are likely to drive increased fire activity and suppress carbon uptake by Canadian forests, adding to concerns about the long-term durability of these forests as a carbon sink[5–8].

Canadian forests cover a vast area of nearly 362 million ha (ref. 9), amounting to 8.5% of the global forested area[10]. These forests are an important sink of carbon, absorbing fossil carbon dioxide (CO_2) from the atmosphere and slowing the pace of climate warming[11,12]. However, climate change is increasing forest fire activity, acting to suppress the carbon uptake capacity of these forests[13]. Although more frequent fires have been widespread, 2023 has seen forest fires on an extreme scale. With 15 million ha of Canadian forests burned (about 4% of forest area)[1], 2023 saw more than seven times (8 σ) the average burned area over the preceding 40 years (1983–2022 mean, 2.2 million ha; range, 0.2–7.1 million ha)[3]. The adverse societal impacts of these fires are clear: 232,000 evacuations and poor air quality affecting millions[14]. However, the carbon emissions from the fire events remain uncertain. In this study, we quantify these emissions through inverse modelling of satellite observations of carbon monoxide (CO). Then, we examine concurrent climate anomalies and projected changes in the prevalence of hot–dry weather under climate change. Finally, we discuss the implications of fires for the Canadian carbon budget.

Fire emissions

Fire carbon emissions can be tracked from space using bottom-up and top-down approaches. Bottom-up approaches use satellite observations to track fire activity, such as burned area[15] or fire radiative power[16]. Emissions of CO_2, CO and other trace gases are then estimated by combining the estimates of fire activity with quantities such as fuel loads and emission factors. Although these bottom-up estimates are continually improving, inventories can vary significantly in global and regional trace gas and aerosol emission estimates[15,17]. Top-down approaches provide a method for refining bottom-up trace gas emission estimates by optimally scaling emission estimates to be consistent with the observed concentrations of trace gases in fire plumes. A strength of this approach is that it integrates emissions from both flaming and smouldering combustion to capture net emissions.

In this study, we perform top-down estimates of CO emissions from the 2023 Canadian fires based on observational constraints from the TROPOspheric monitoring instrument (TROPOMI) space-based CO retrievals (Fig. 1a,b). These estimates are performed using three different bottom-up fire emission inventories: the global fire emissions database (GFED4.1s)[15], the global fire assimilation system v.1.2 (GFAS)[16] and the quick fire emissions dataset v.2.6r1 (QFED)[18]. For each inversion, the combined carbon emissions released as CO and CO_2 (CO_2 + CO) are then estimated using the CO_2/CO emission factors from the same bottom-up database. The CO_2/CO emission ratios can be highly variable, adding uncertainty to our analysis. We incorporate some of this uncertainty here as each bottom-up database has different mean emission ratios for Canadian forests (range, 7.7–10.8 gC of CO_2 per gC of CO_2). Details for these inversions are provided in the methods and a description of the inversion results and evaluation of the performance of the top-down estimates are provided in Supplementary Information sections 1 and 2). We find the top-down estimates are relatively insensitive to choices about inversion configuration but do show sensitivity to prescribed hydroxyl radical (OH) abundances[19], which determine the atmospheric lifetime of the CO emitted (Supplementary Information section 1 and Supplementary Fig. 1).

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Overview

- Introduce atmospheric inversions through case study of 2023 Canadian wildfires
- Highlight other applications including large-scale carbon monitoring and monitoring oil and gas methane leaks.

2023 Canadian fire impacts

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Ideas

World on Fire: 2023 is Canada's worst wildfire season on record — and it's not over yet

Fires have scorched more than 15 million hectares across Canada this year

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The Eagle Bluff Wildfire crosses the border from Washington state on July 30, 2023, prompting evacuation orders in Osoyoos, B.C. (Jesse Winter/Reuters)

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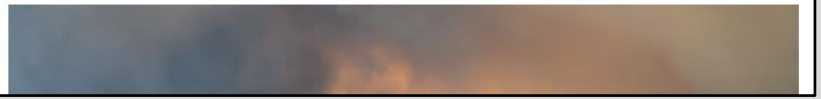
Canada wildfires

Wildfires turn Canada's vast forests from carbon sink into super-emitter

Leyland Cecco in Toronto

Fri 22 Sep 2023 08.15 EDT



Goals of this study

- Estimate amount of carbon emitted by 2023 Canadian forest fires.
- Examine the climate context (why was 2023 so unusual?)
- What are the Implications/lessons?

Tracking fire carbon emissions: bottom-up

- Fire carbon emissions are estimated from remote-sensing observations of burned area and fire radiative power

<u>Datasets</u>

- GFED4.1s
- GFAS
- QFED

Sentinel-2 based burned area

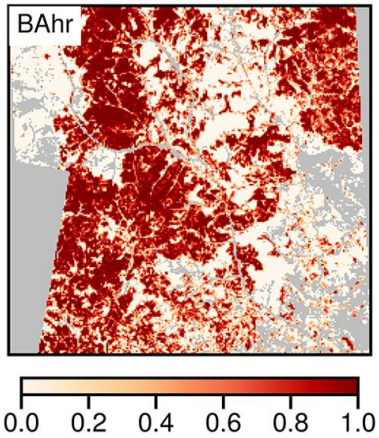
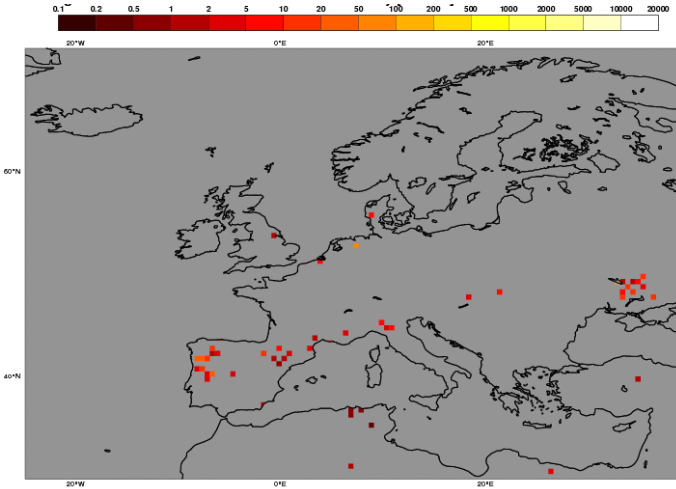


Fig: Chen et al., 2023, ESSD

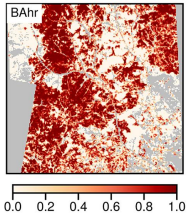
C emissions = burned area
× fuel consumption
× emission factor

GFAS Fire Radiative Power



C emissions = Fire radiative power
× dry matter combustion rate
× emission factor

Tracking fire carbon emissions: top-down

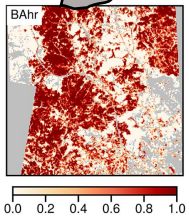


$\boldsymbol{x}_{prior}$: prior estimate of fluxes

Tracking fire carbon emissions: top-down

Simulate atmospheric transport

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{v} = F$$



$\boldsymbol{x}_{prior}$: prior estimate of fluxes

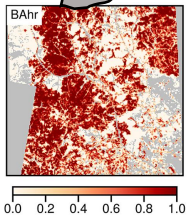
Tracking fire carbon emissions: top-down

$\boldsymbol{y}$: observation of the atmosphere

$\boldsymbol{y}_{prior} = \boldsymbol{H}\boldsymbol{x}_{prior}$: simulated obs with prior flux

Simulate atmospheric transport

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{v} = F$$



$\boldsymbol{x}_{prior}$: prior estimate of fluxes

Tracking fire carbon emissions: top-down

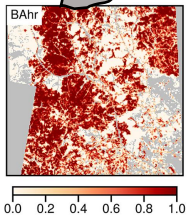
$\boldsymbol{y}$: observation of the atmosphere

$\boldsymbol{y}_{prior} = \boldsymbol{H}\boldsymbol{x}_{prior}$: simulated obs with prior flux

Simulate atmospheric transport

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{v} = F$$

$$J = \frac{1}{2}(\boldsymbol{y} - \boldsymbol{H}\boldsymbol{x})^T \boldsymbol{S}_{obs}^{-1}(\boldsymbol{y} - \boldsymbol{H}\boldsymbol{x}) + \frac{1}{2}(\boldsymbol{x} - \boldsymbol{x}_{prior})^T \boldsymbol{S}_{prior}^{-1}(\boldsymbol{x} - \boldsymbol{x}_{prior})$$



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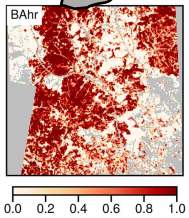
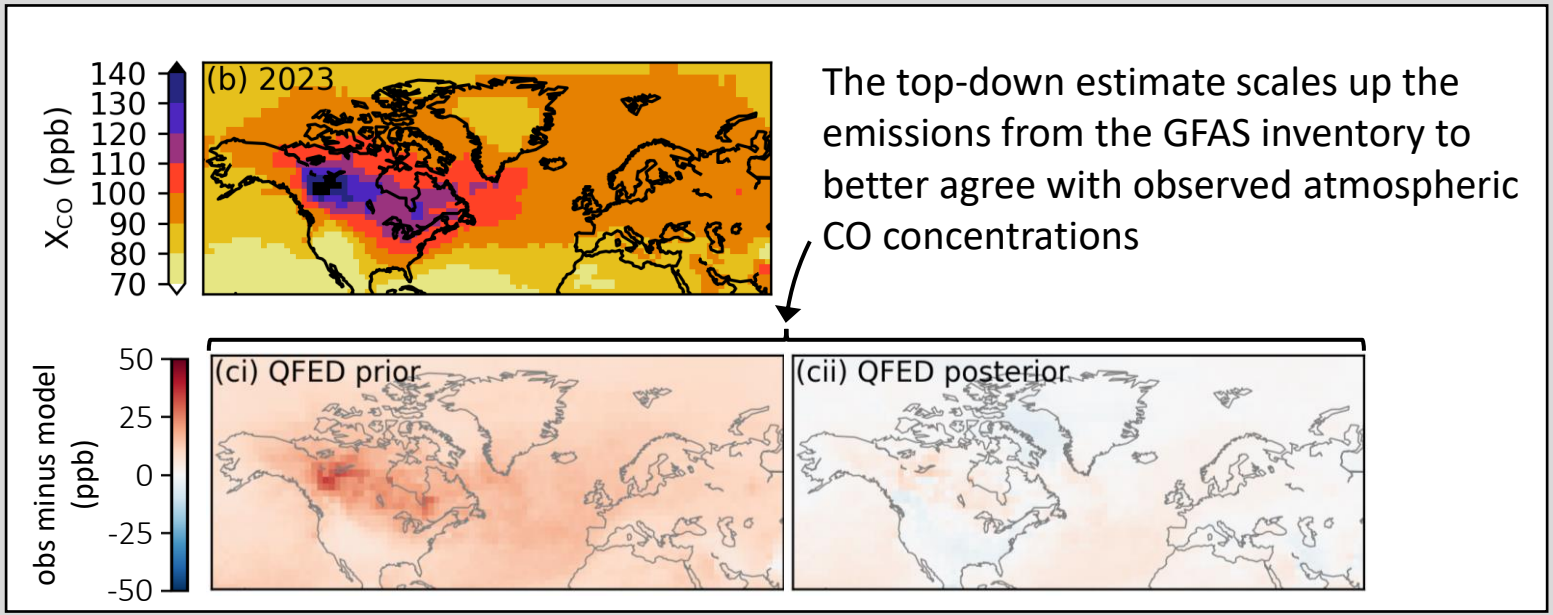


$\boldsymbol{x}_{prior}$: prior estimate of fluxes

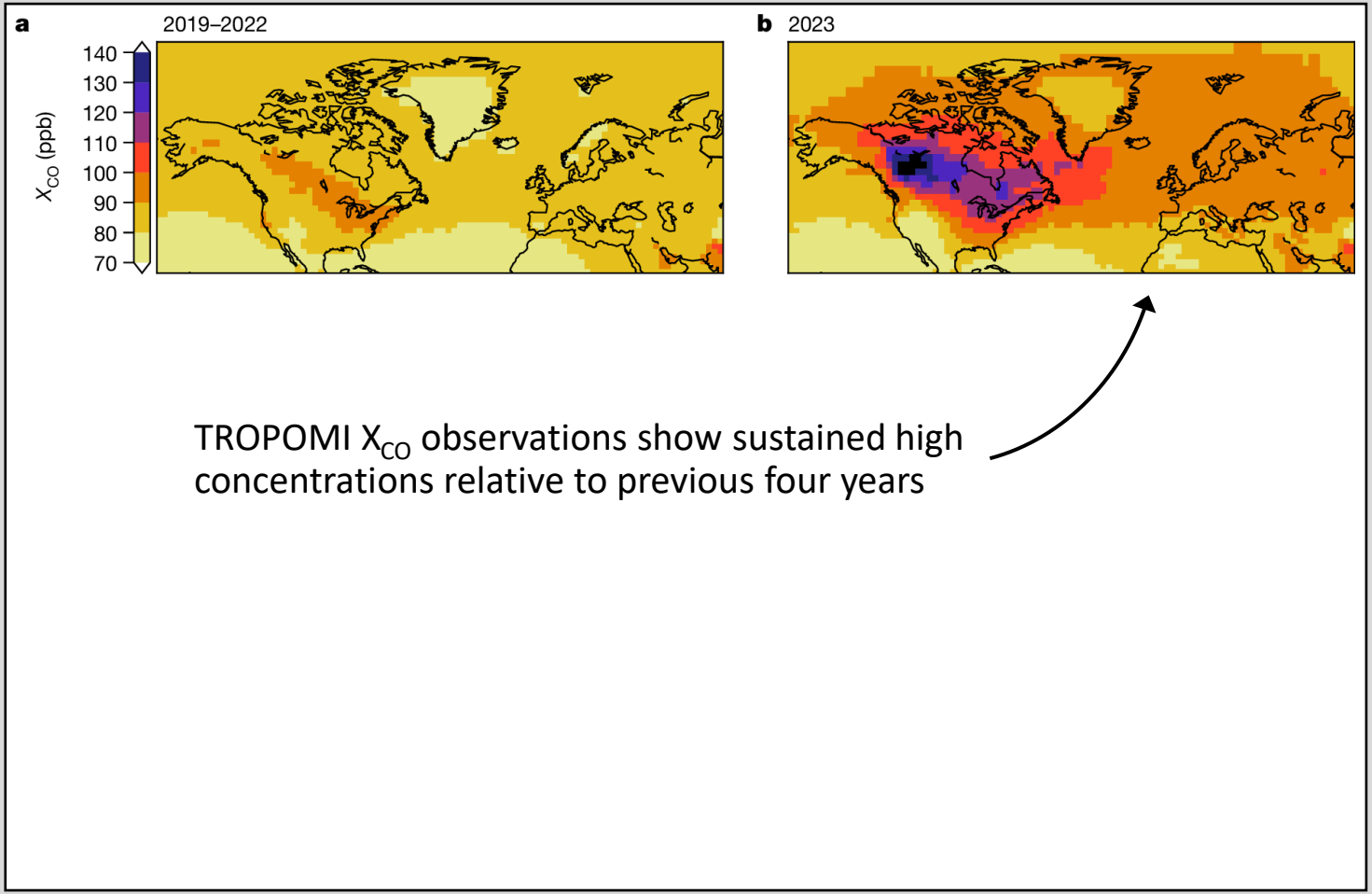
Minimize J --> maximum a posteriori solution

Tracking fire carbon emissions: Top-down

- Top-down approaches adjust bottom-up inventories to be consistent with observed trace-gas concentrations.
- We use TROPOMI X_{CO} observations with the CMS-Flux inversion system

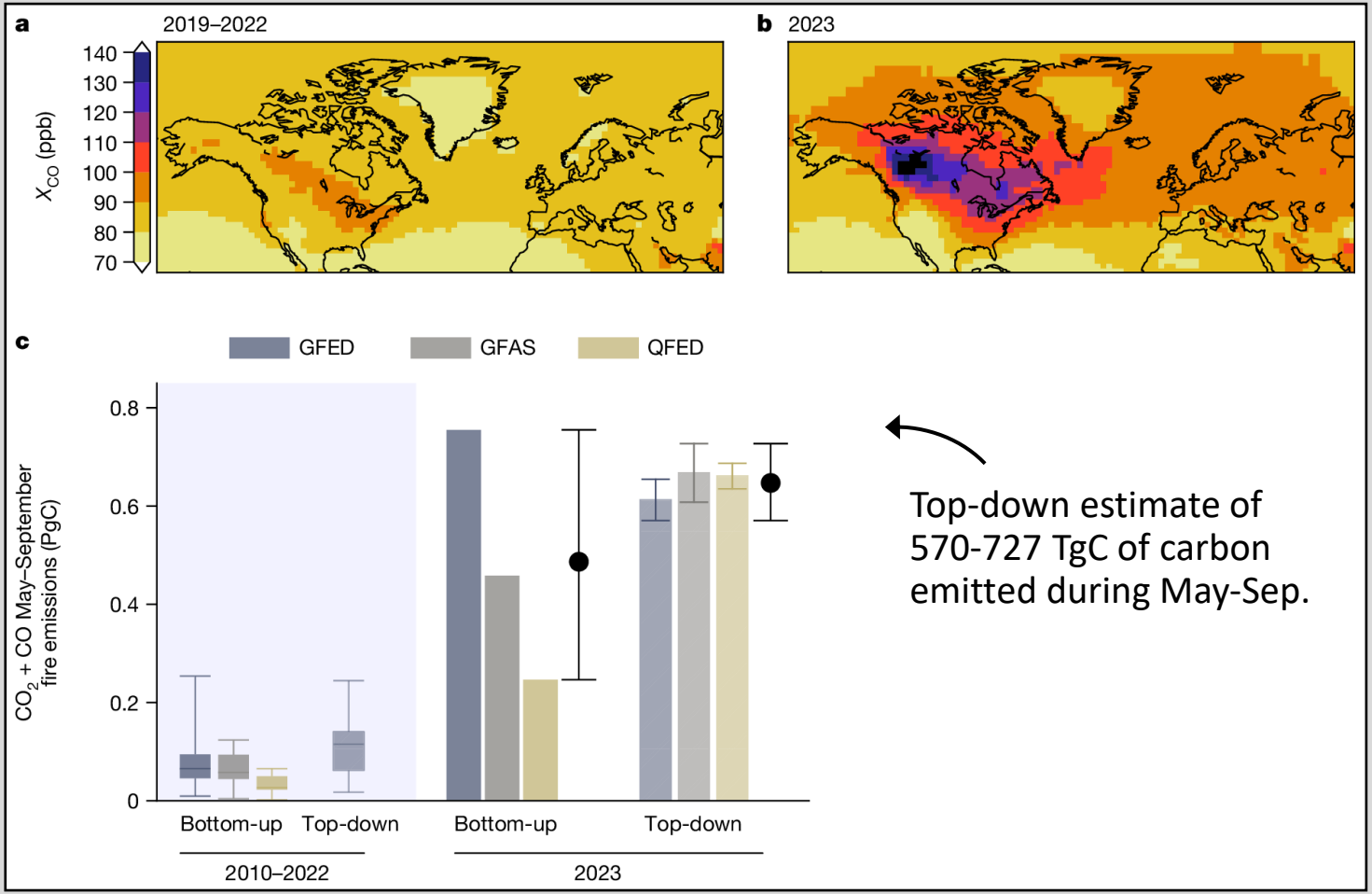


2023 Canadian forest fire emissions



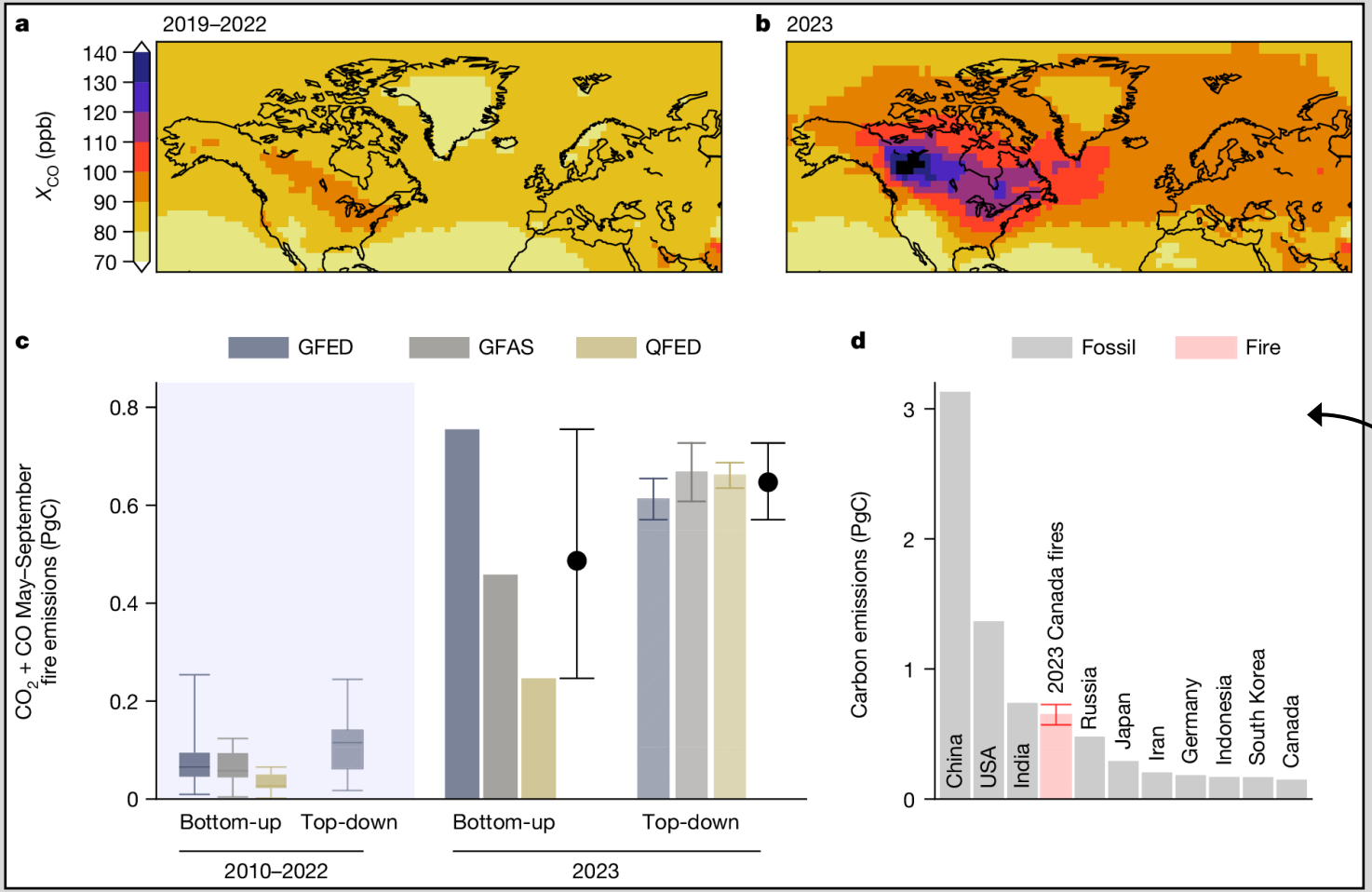
TROPOMI X_{CO} observations show sustained high concentrations relative to previous four years

2023 Canadian forest fire emissions

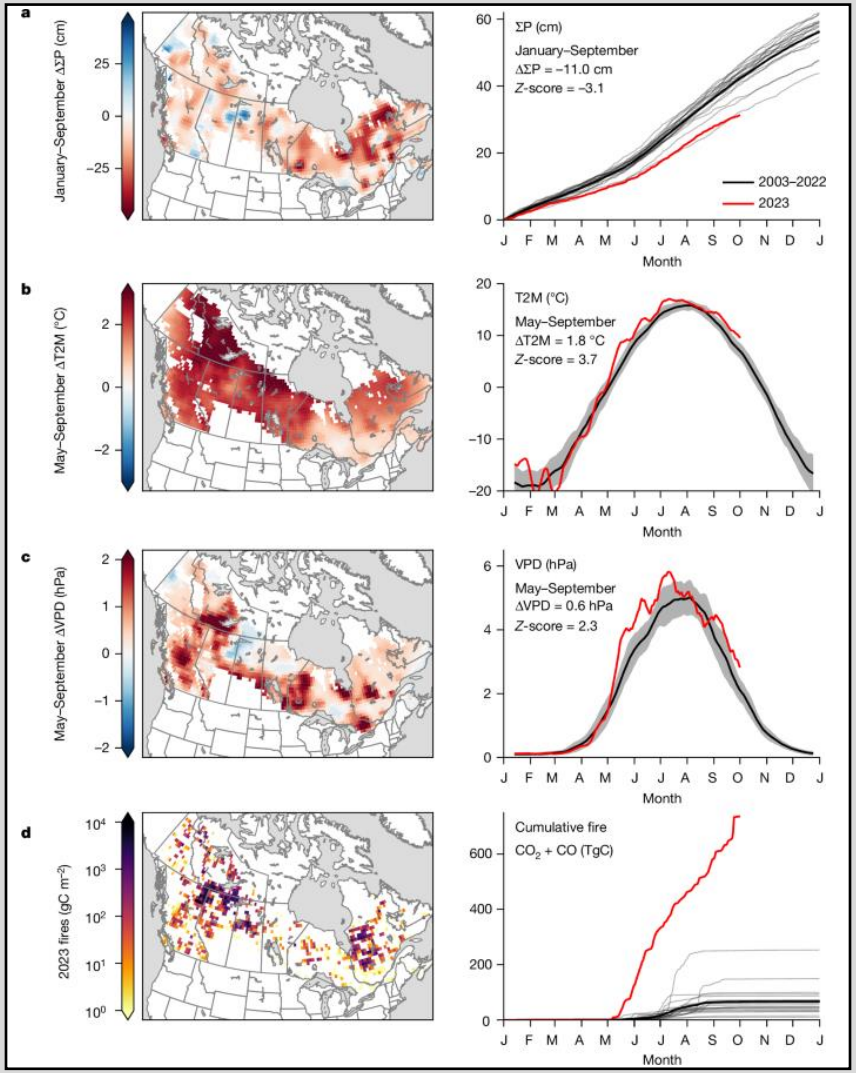


Top-down estimate of 570-727 TgC of carbon emitted during May-Sep.

2023 Canadian forest fire emissions

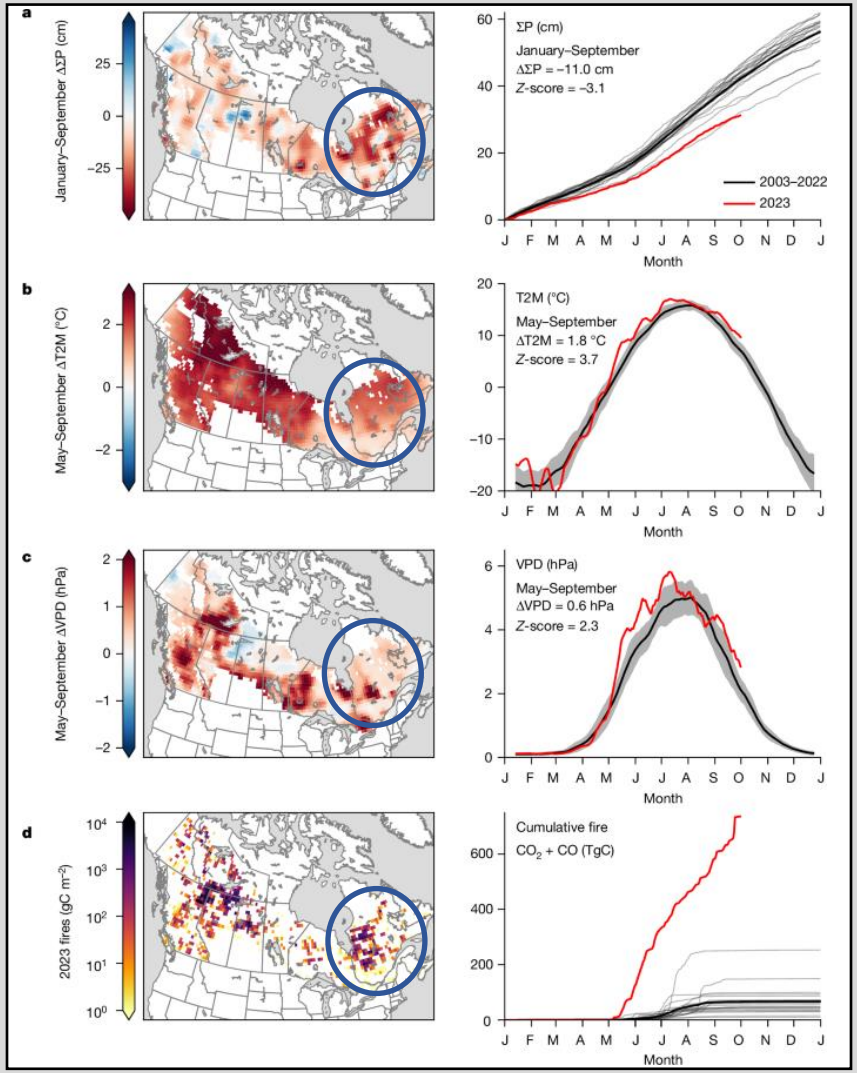


These fire emissions are larger than most countries annual fossil fuel emissions. Only China, U.S.A., and India have larger emissions.



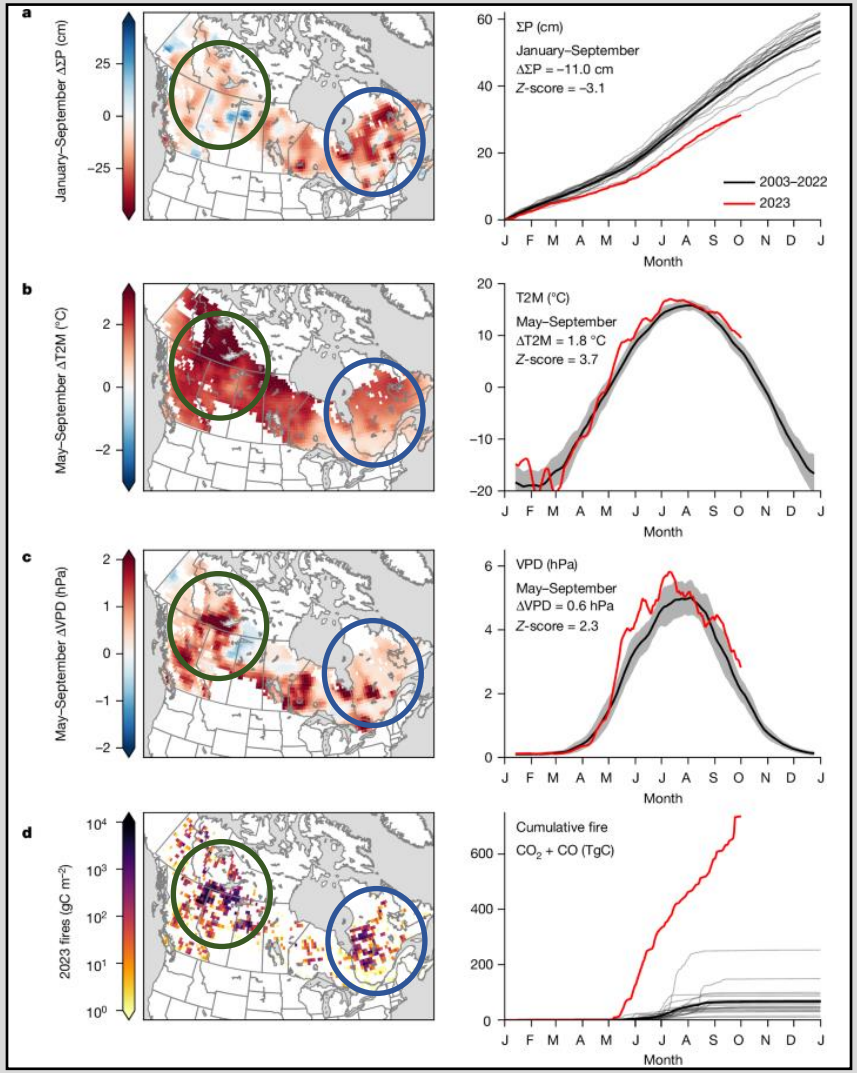
Climate context: 2023 was hot and dry

- 2023 was both the hottest and driest year for Canadian forests in MERRA-2 dataset (1980—2023)



Climate context: 2023 was hot and dry

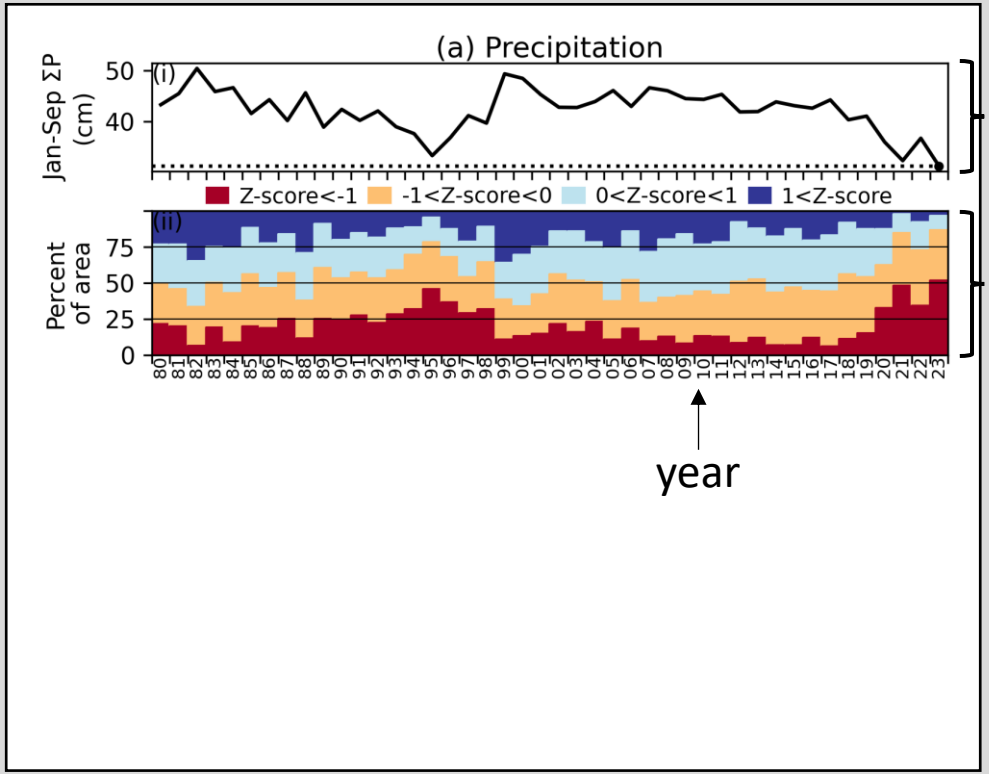
- 2023 was both the hottest and driest year for Canadian forests in MERRA-2 dataset (1980—2023)
- Northern Quebec was extremely dry



Climate context: 2023 was hot and dry

- 2023 was both the hottest and driest year for Canadian forests in MERRA-2 dataset (1980—2023)
- Northern Quebec was extremely dry
- Great Slave Lake area was extremely hot

Climate context: 2023 was hot and dry

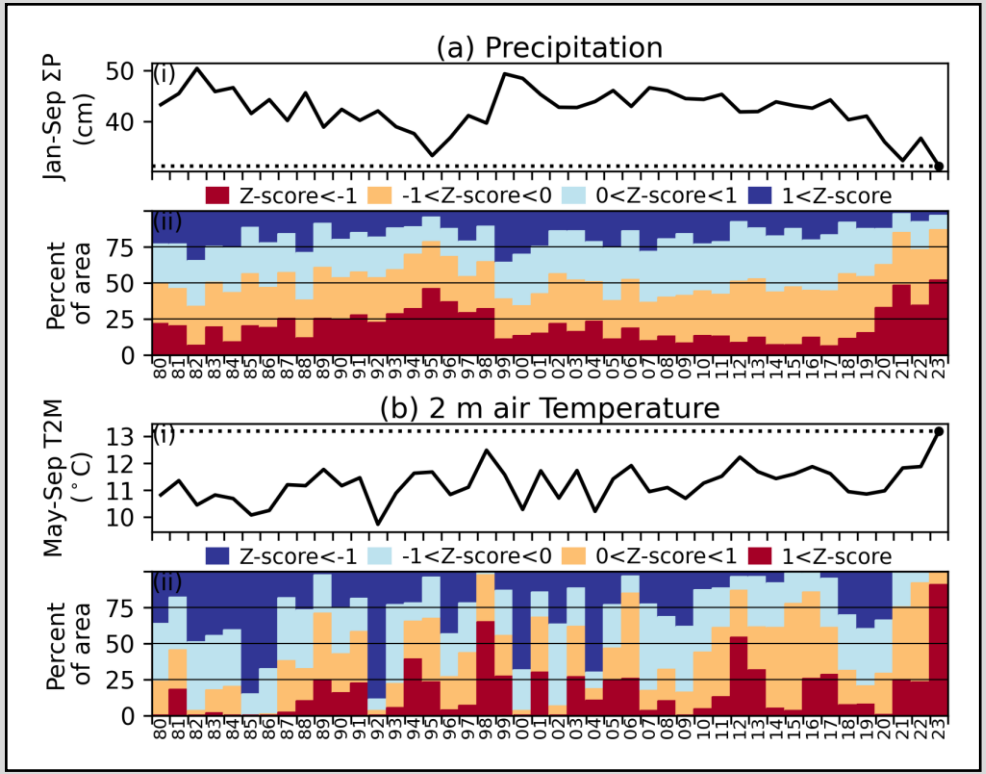


Forest integrated value

Fraction of forest within each threshold

Z-score<-1
-1<Z-score<0
0<Z-score<1
1<Z-score

Climate context: 2023 was hot and dry



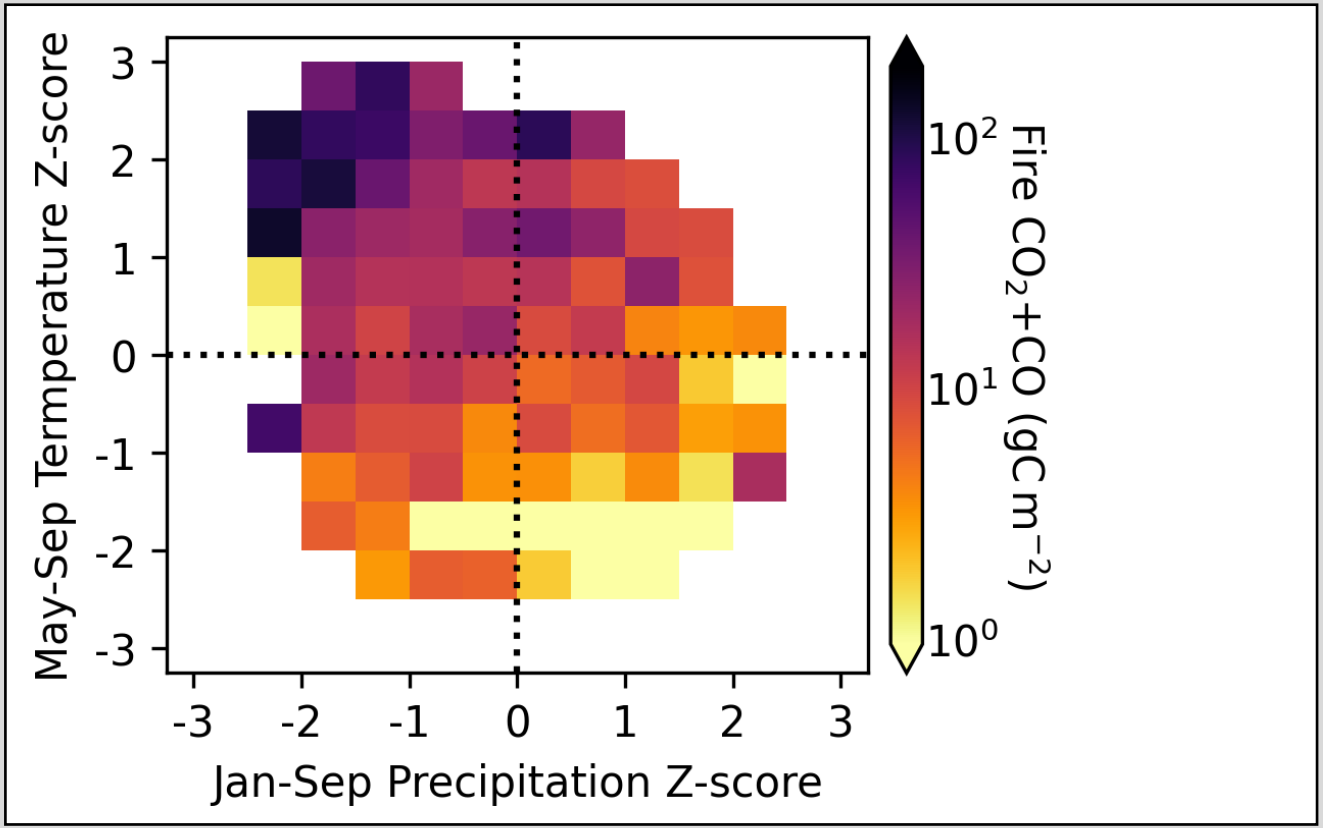
<u>Precipitation</u>

- 86% area below average
- 52% area was <1 standard deviation

<u>Temperature</u>

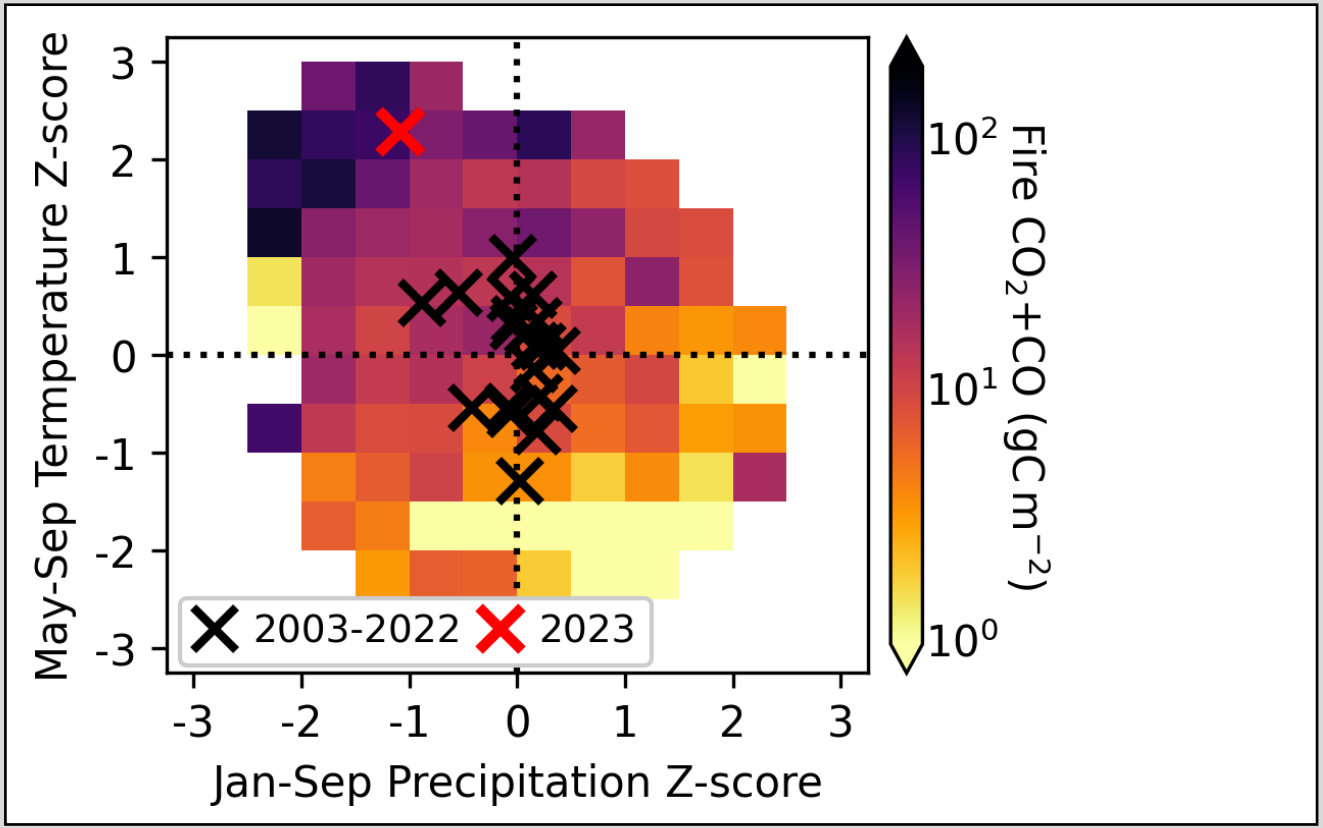
- 100% area above average
- 88% area was >1 standard deviation

Relationship between fire and climate



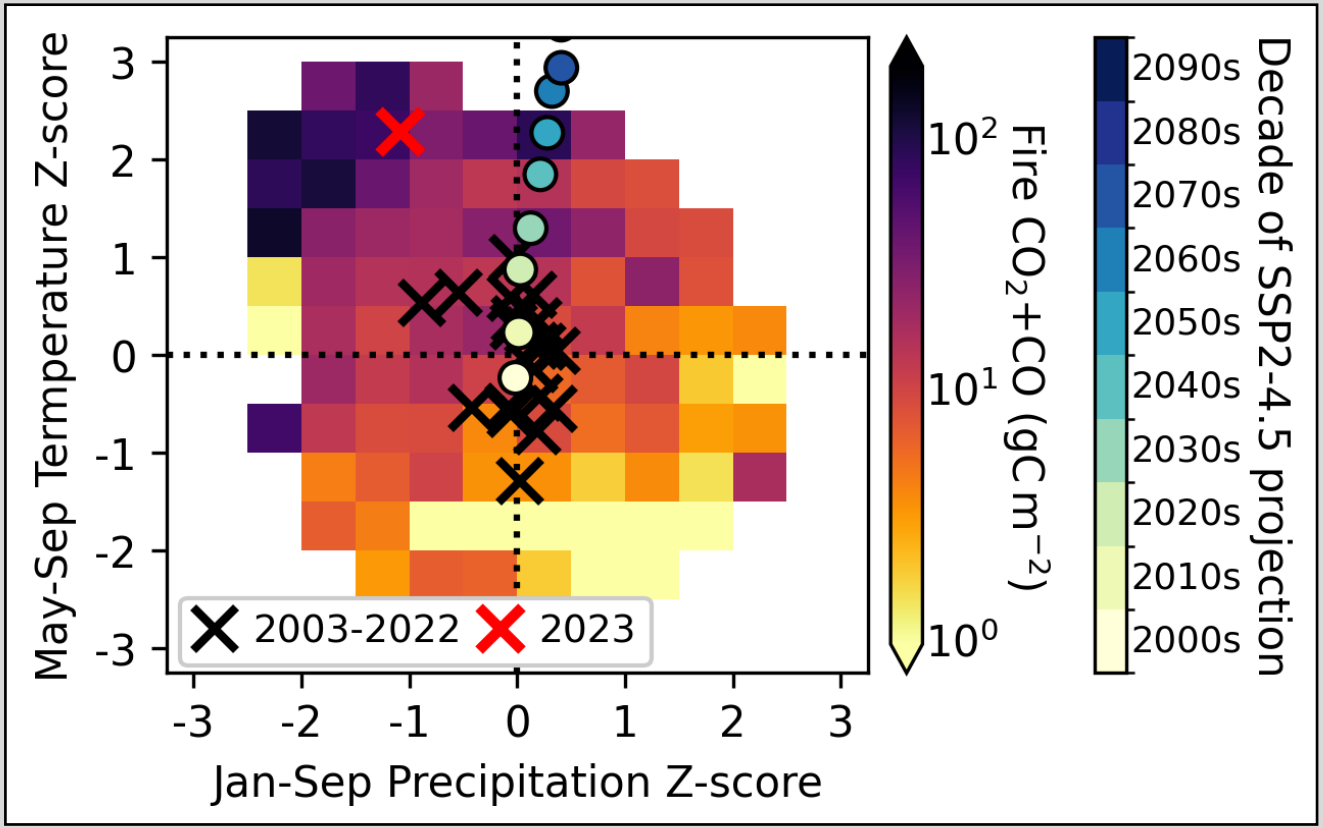
- **Fire emissions are largest under hot (Z-score>0) and dry (Z-score<0) conditions.**

Relationship between fire and climate



- Fire emissions are largest under hot (Z-score>0) and dry (Z-score<0) conditions.
- **2023 was much hotter and drier than the preceding 20 years.**

Relationship between fire and climate



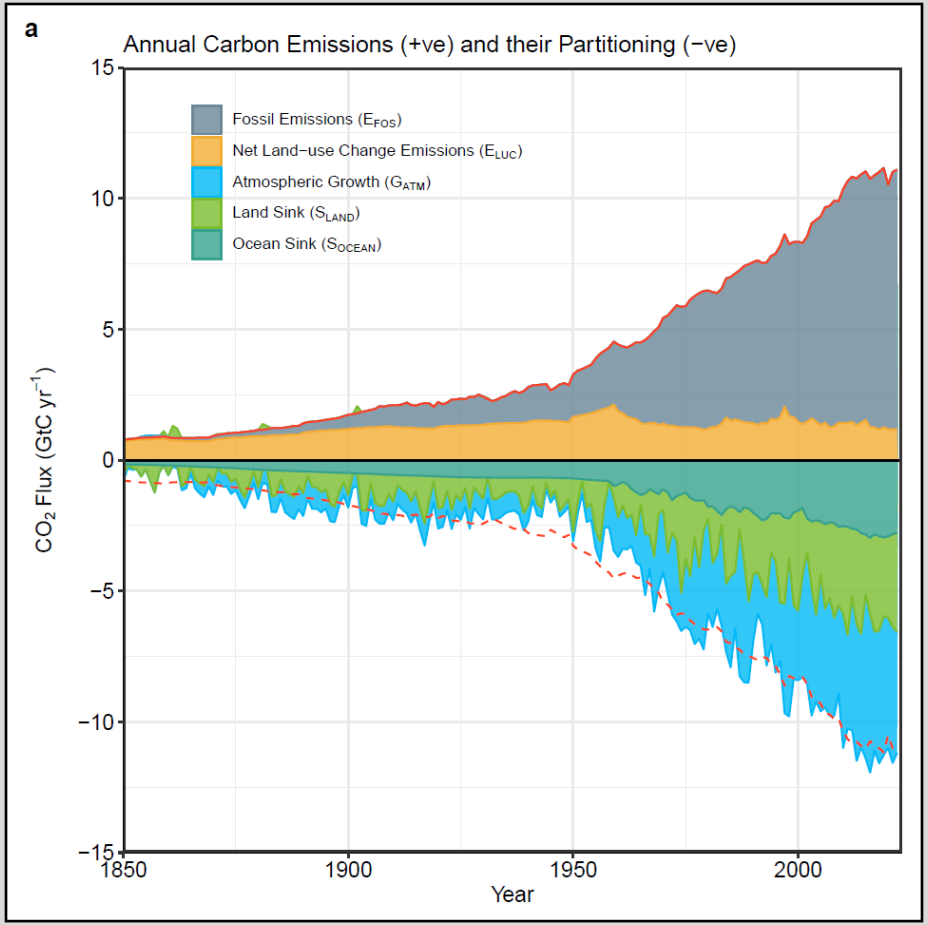
- Fire emissions are largest under hot (Z-score>0) and dry (Z-score<0) conditions.
- 2023 was much hotter and drier than the preceding 20 years.
- **CMIP6 models suggest that temperatures of 2023 will be the norm by 2050s under SSP2-4.5**

2023 Canadian Fires - Conclusions

- 2023 Canadian forest fire carbon emissions were 570-727 TgC.
  - Compared to Fossil Fuels, only China, USA, and India emit more annually
- These fires occurred during the hottest and driest year since at least 1980.
- The temperatures of 2023 will become the norm by 2050s.

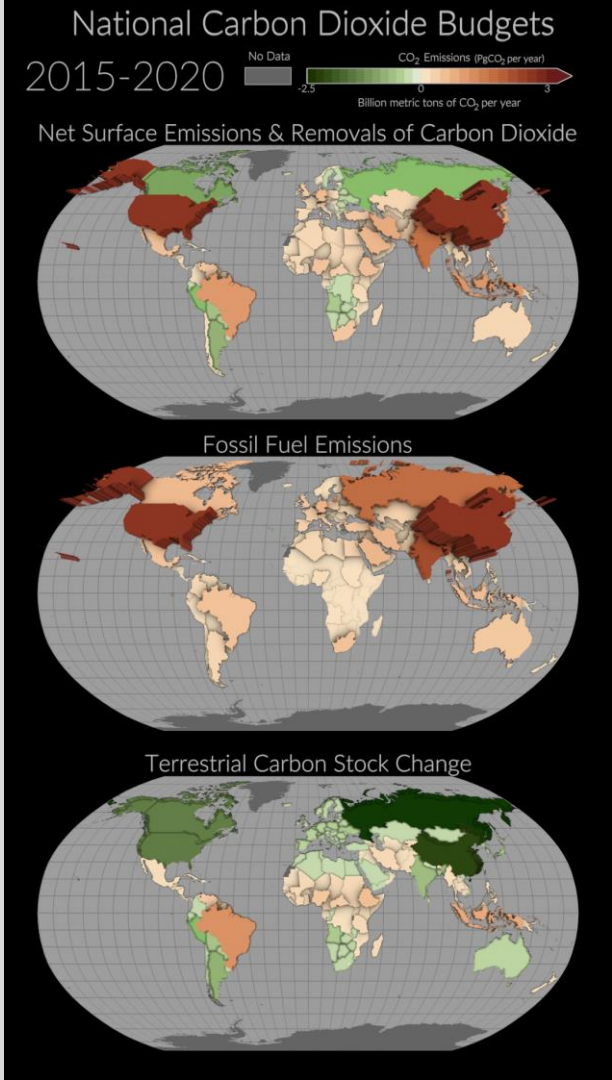
Atmospheric CO_2 inversions

- About half of economic CO_2 emissions remain in the atmosphere
- Carbon uptake and release by land ecosystems and oceans are important for growth of atmospheric CO_2 but poorly understood.
- Success of the Paris Agreement depends on knowledge of where CO_2 is being emitted and absorbed



Atmospheric CO_2 inversions

- Through ensemble of inversion systems, we produced a dataset of country carbon emissions informed by atmospheric CO2 data.
- Ensemble of inversion systems allowed better characterization of systematic errors.
- Find robust source/sink signals for large countries (USA, Russia, China) but challenging to isolate smaller countries (e.g., European countries).



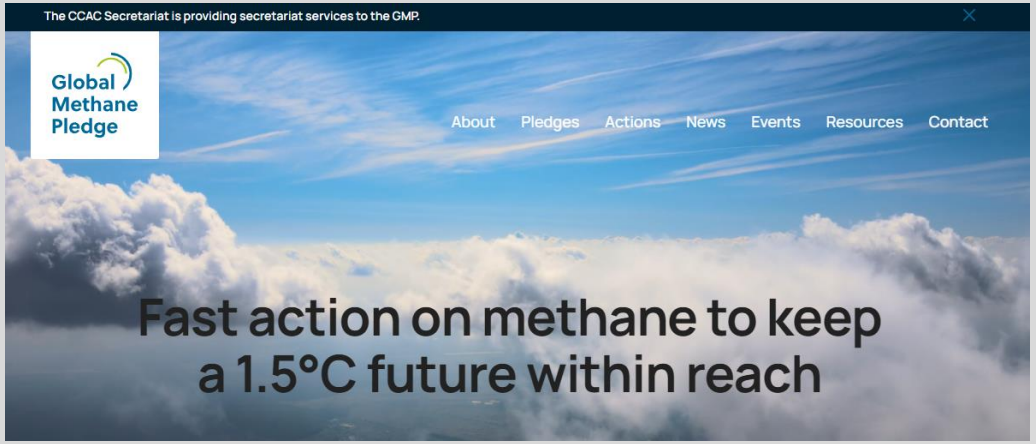
Atmospheric CO_2 inversions challenges

- Requirements in measurement and model accuracy are stringent!
  - Large-scale fluxes have a tiny imprint in atmospheric CO2
- Rapid atmospheric mixing means strong regularization is needed without extremely dense data.

Tracking methane emissions

- Global methane pledge aims to reduce global methane emissions at least 30 percent from 2020 levels by 2030.

- Need to identify and track emissions



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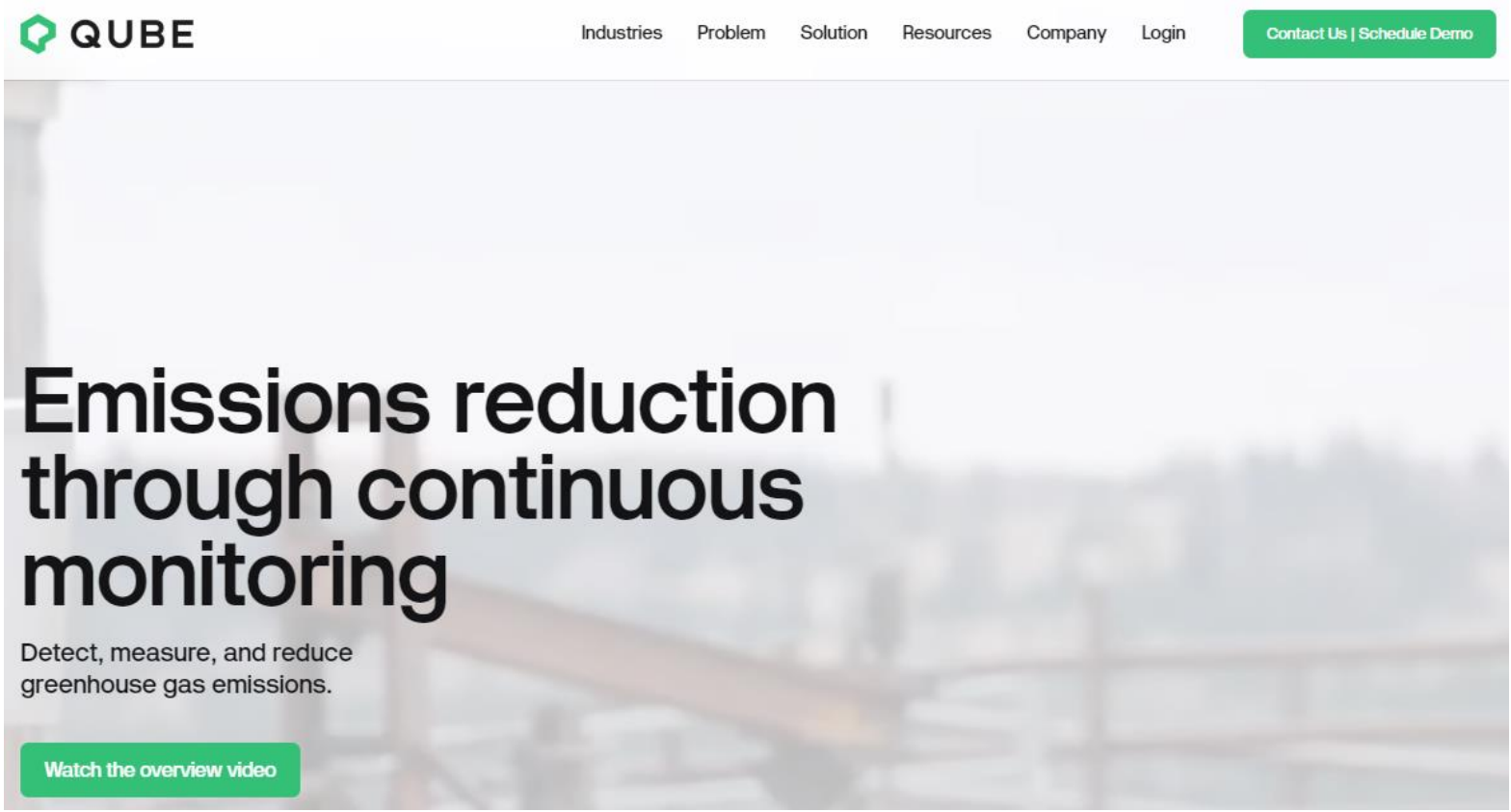

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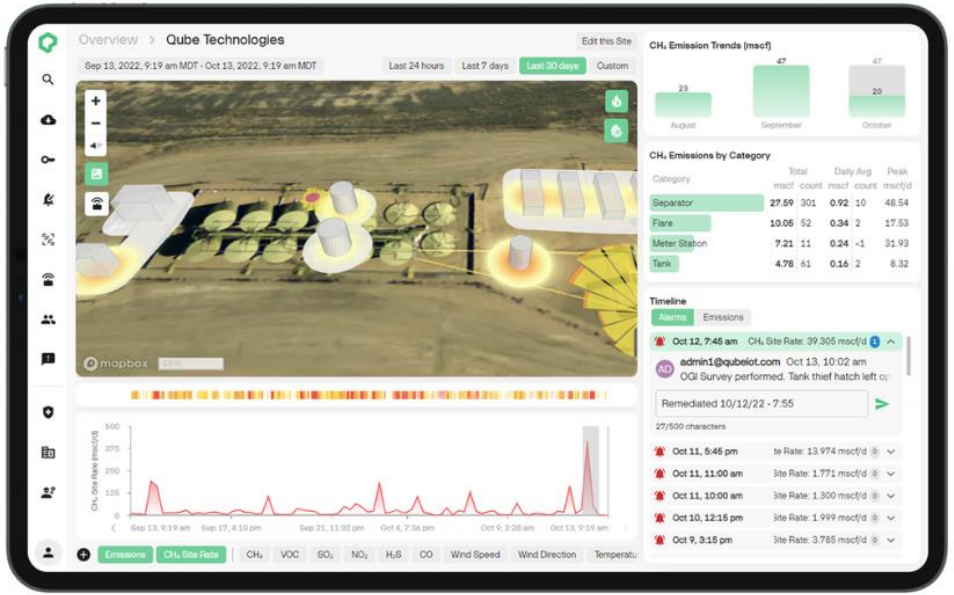
- Fast information enables action.



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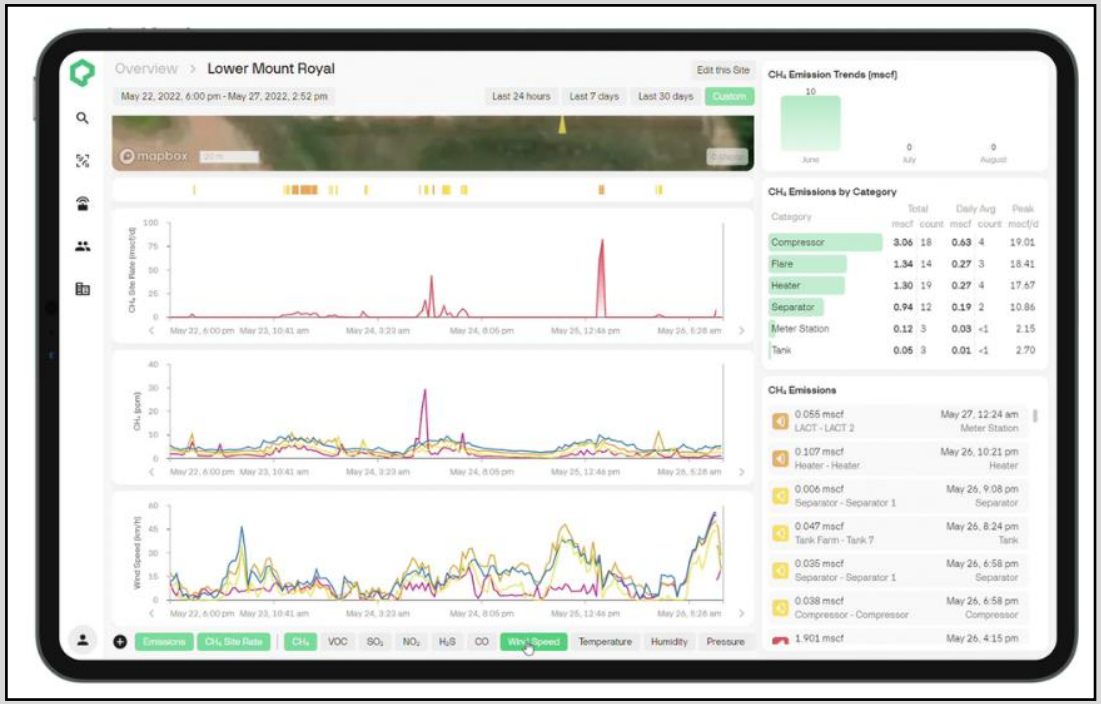
- Inversions at meter-scale have different challenges than kilometer at representing atmospheric transport.

- Localization is important for fixing leaks.



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