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Supplementary information

Long-range $PM_{2.5}$ pollution and health impacts from the 2023 Canadian wildfires

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Supplementary Information for

Long-range $PM_{2.5}$ pollution and health impacts from the 2023 Canadian wildfires

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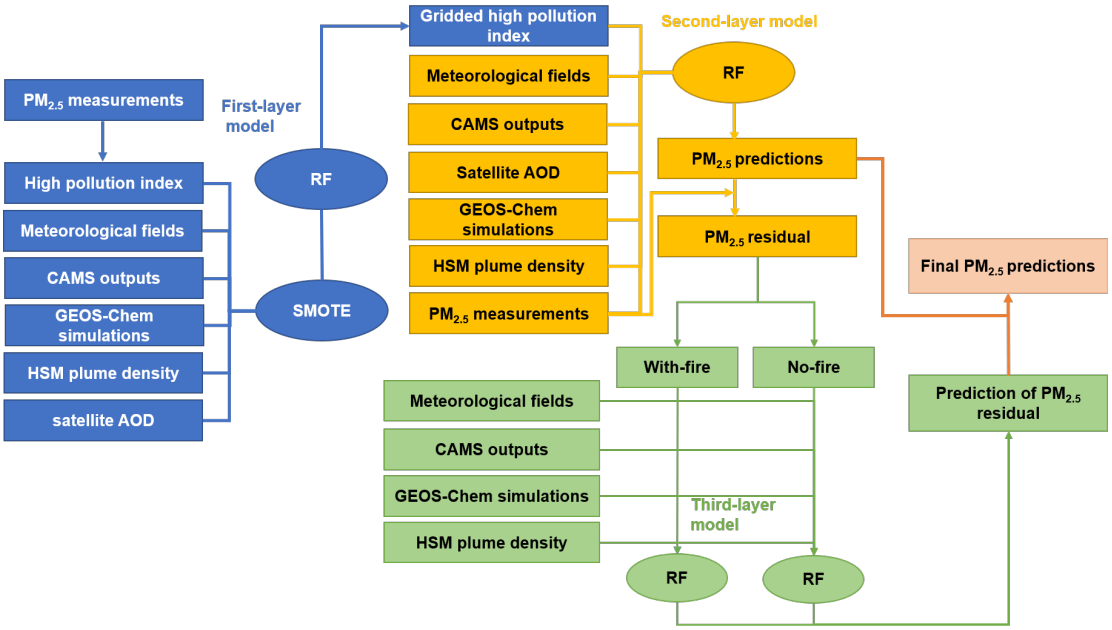
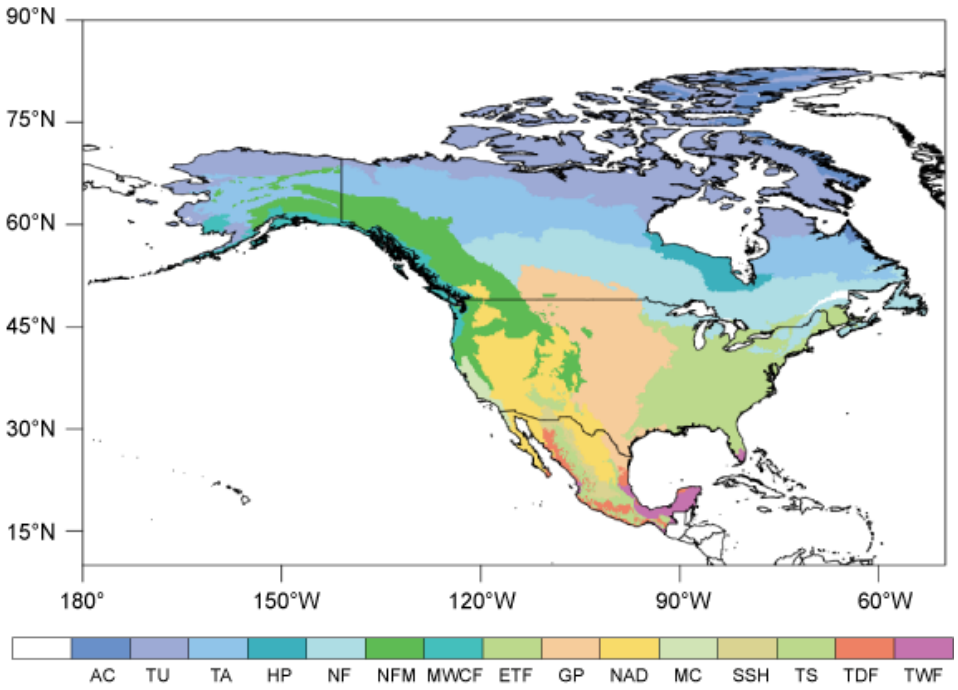
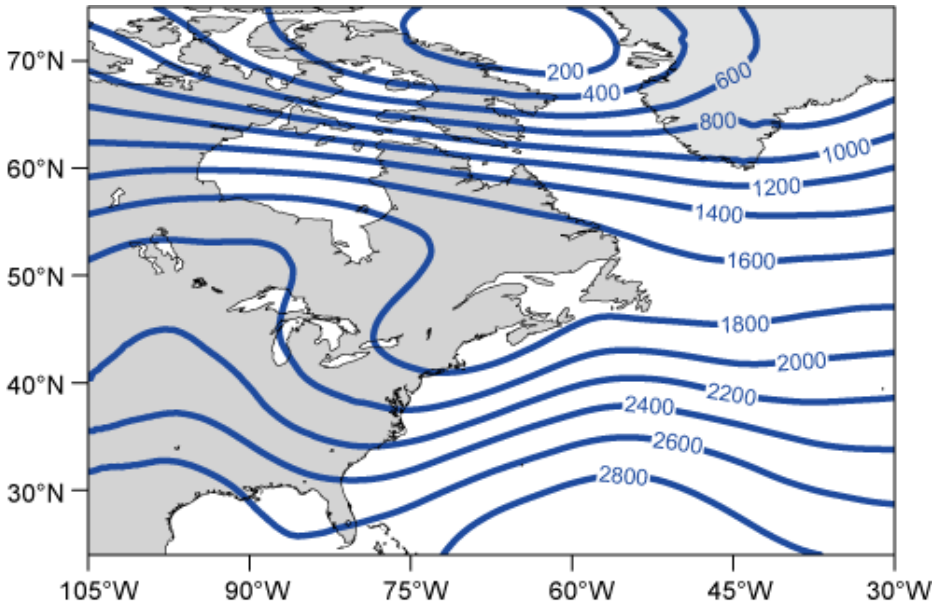
Supplementary Figures



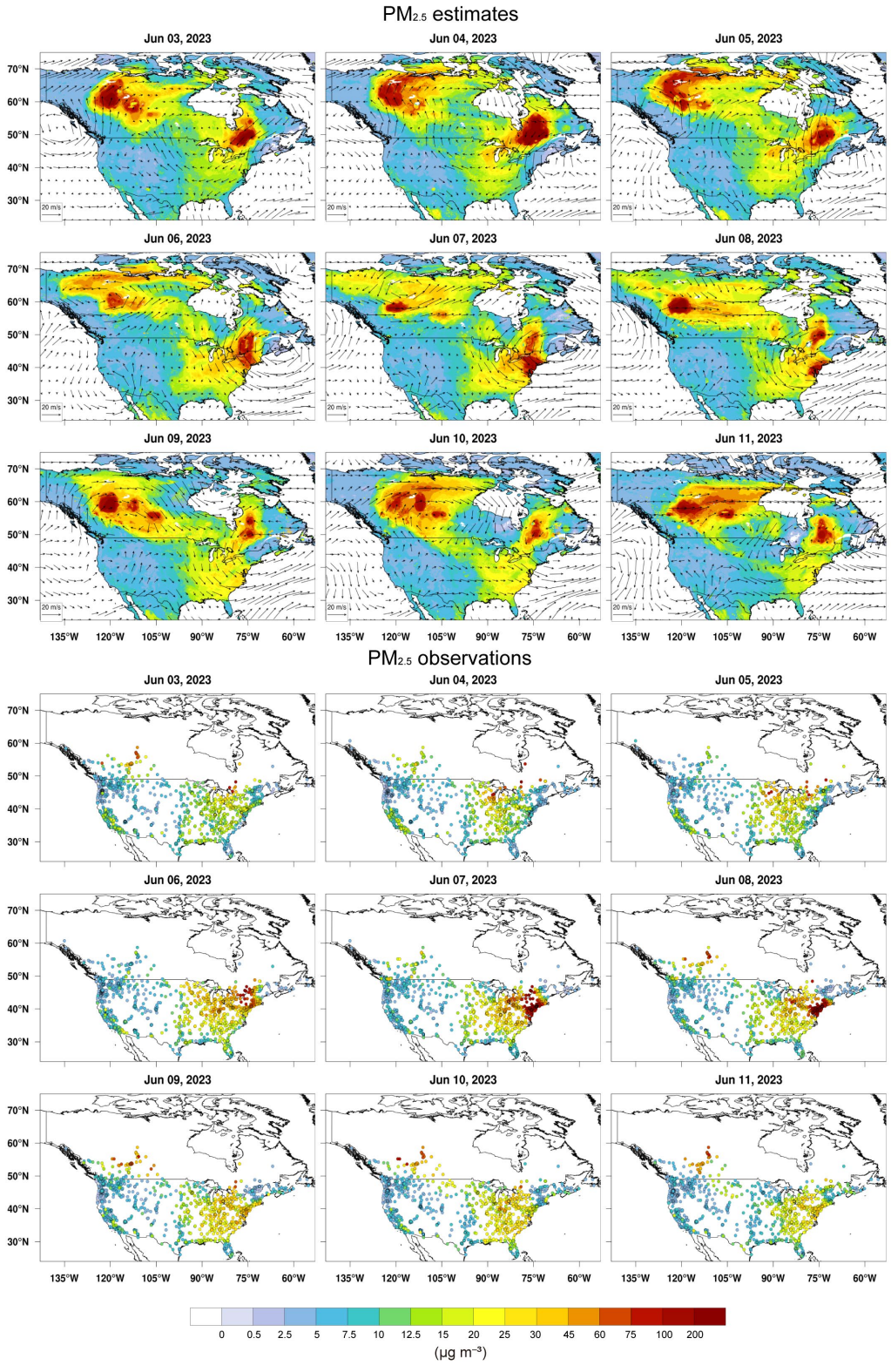
Supplementary Fig. 1 | $PM_{2.5}$ retrieval model structure.



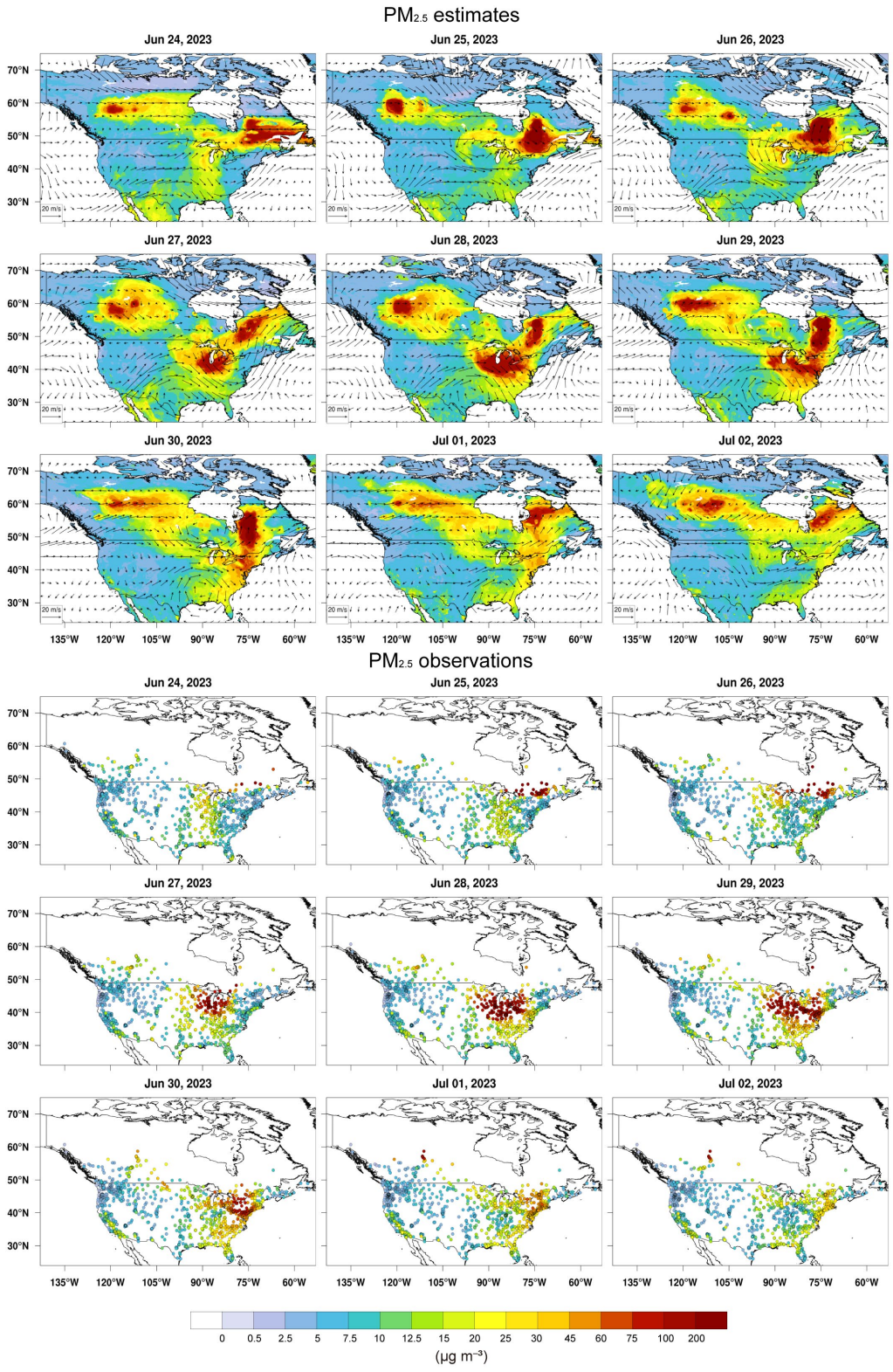
Supplementary Fig. 2 | The delineation of ecological regions (https://www.epa.gov/eco-research/ecoregions-north-america/). AC: Arctic Cordillera, TU: Tundra, TA: Taiga, HP: Hudson Plains, NF: Northern Forests, NFM: Northwestern Forested Mountains, MWCF: Marine West Coast Forests, ETF: Eastern Temperate Forests, GP: Great Plains, NAD: North American Deserts, MC: Mediterranean California, SSH: Southern Semi-Arid Highlands, TS: Temperate Sierras, TDF: Tropical Dry Forests, TWF: Tropical Wet Forests.



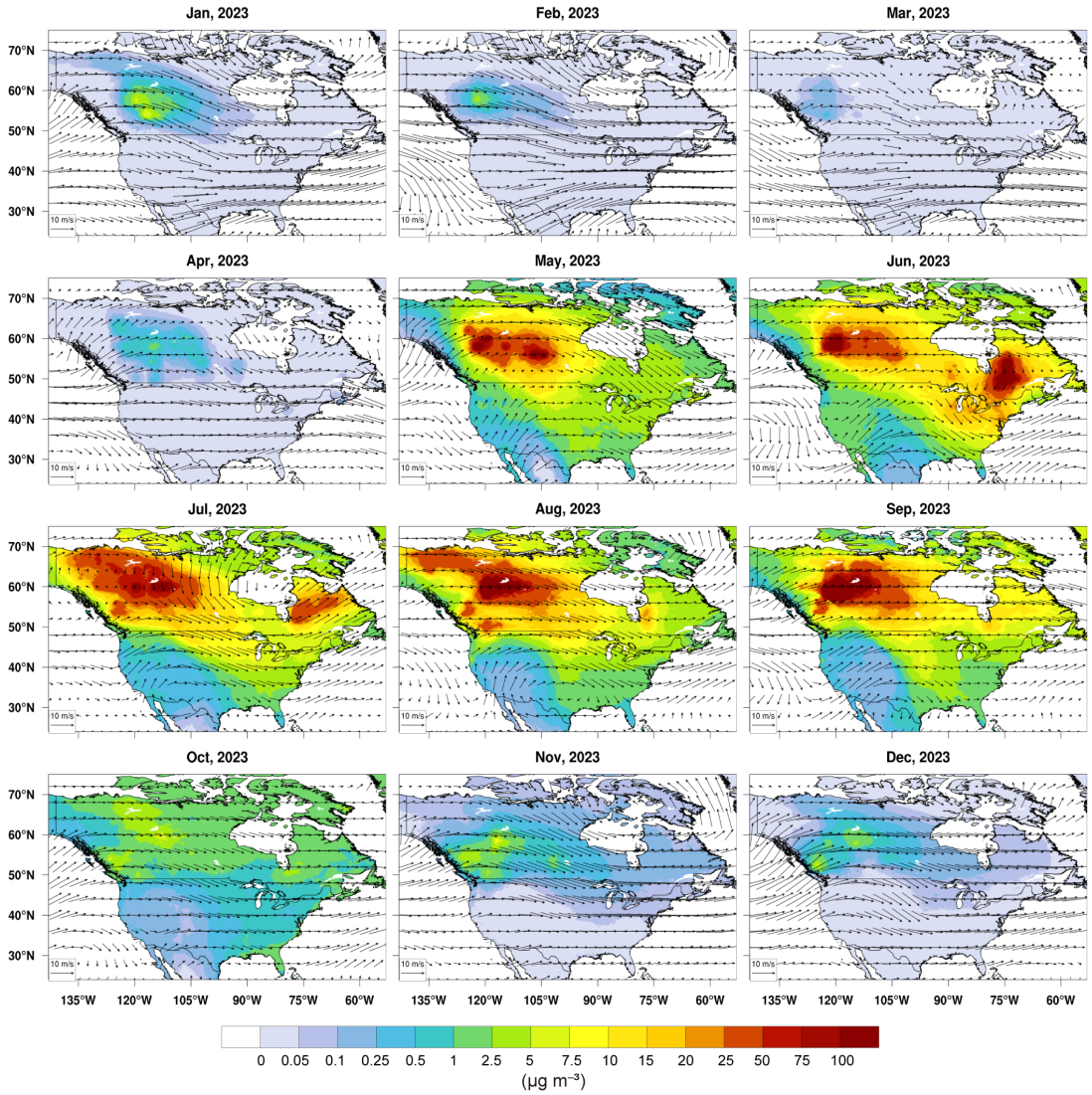
Supplementary Fig. 3 | The geopotential height contours on the 700 hPa surface in June 2023. Data are derived from the ERA5 reanalysis dataset (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5/).



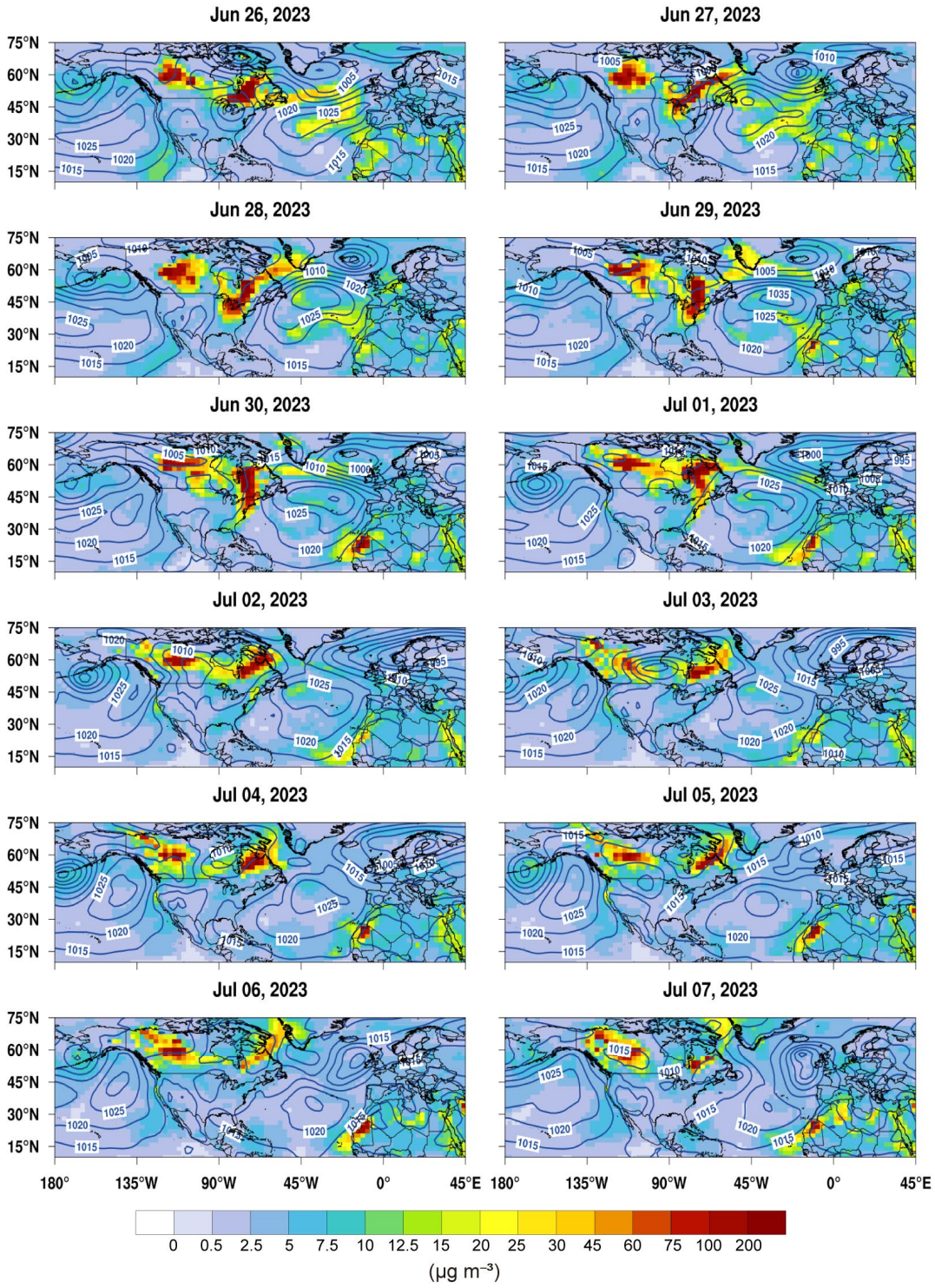
Supplementary Fig. 4 | The estimated $PM_{2.5}$ concentrations, station observations, and 700 hPa wind vectors over North America during June 3rd to 11th in 2023. The colored spatial distribution maps denote estimated $PM_{2.5}$ concentrations. The colored dots on the maps denote station observations. The arrows on the maps denote the 700hPa wind vectors. Station observations are derived from the U.S. EPA (https://www.epa.gov/), and wind data are derived from the GEOS-FP dataset (https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das/).



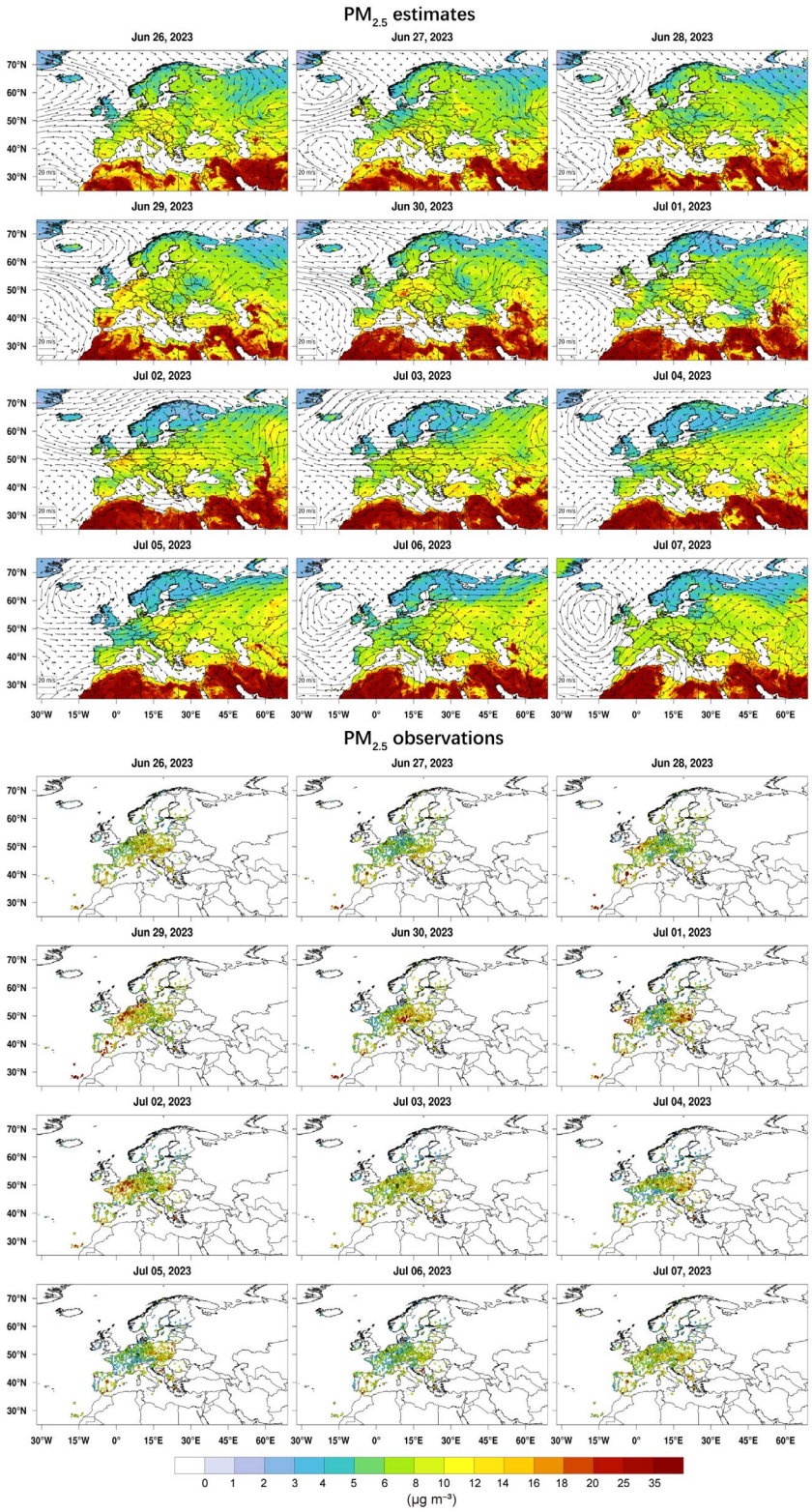
Supplementary Fig. 5 | The estimated $PM_{2.5}$ concentrations, station observations, and 700 hPa wind vectors over North America during June 24th to July 2nd in 2023. The colored spatial distribution maps denote estimated $PM_{2.5}$ concentrations. The colored dots on the maps denote station observations. The arrows on the maps denote the 700hPa wind vectors. Station observations are derived from the U.S. EPA (https://www.epa.gov/), and wind data are derived from the GEOS-FP dataset (https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das/).



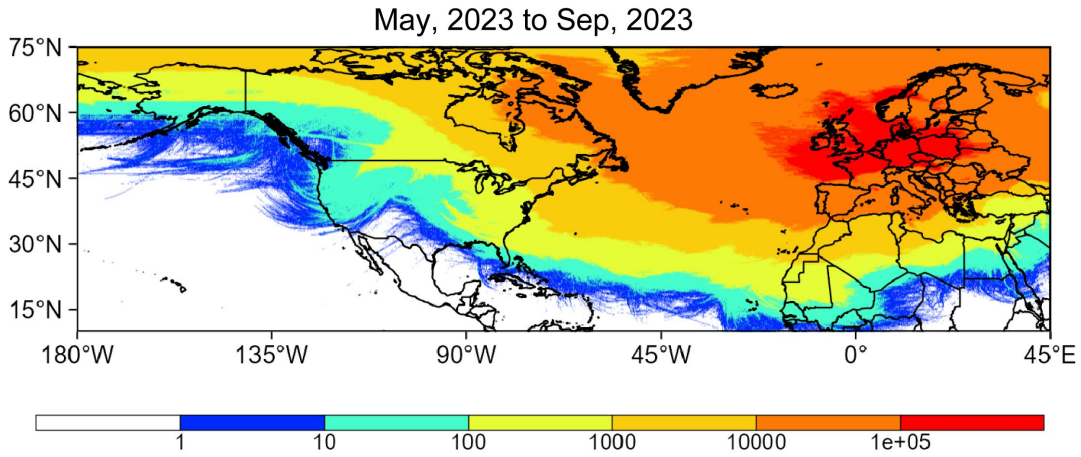
Supplementary Fig. 6 | The estimated monthly Canadian-fire-related $PM_{2.5}$ concentrations, and 700 hPa wind vectors over North America in 2023. The colored spatial distribution maps denote estimated monthly Canadian-fire-related $PM_{2.5}$ concentrations. The arrows on the maps denote the 700hPa wind vectors. Wind data are derived from the GEOS-FP dataset (https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das/).



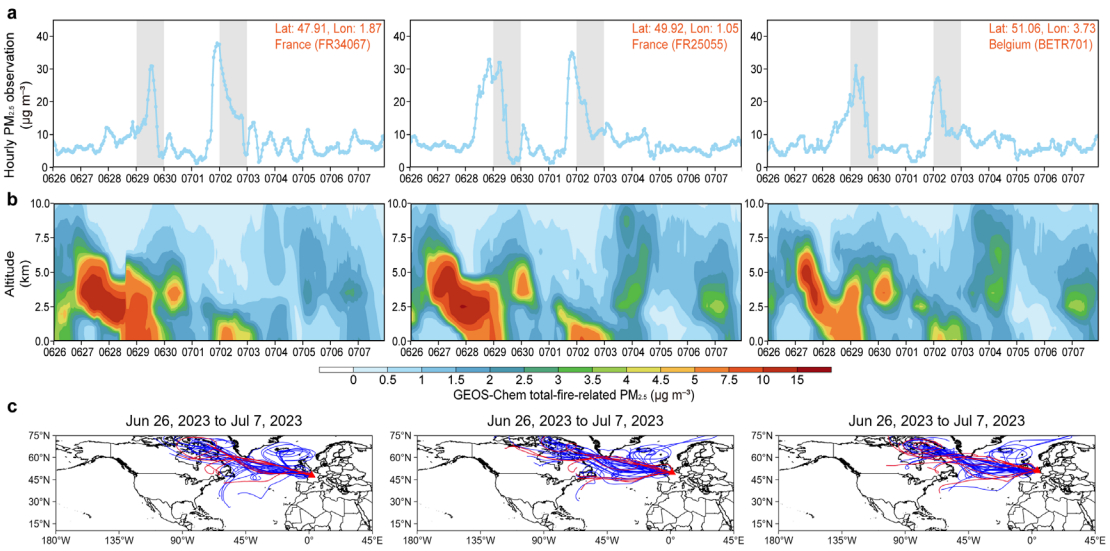
Supplementary Fig. 7 | The simulated $PM_{2.5}$ concentrations from the GEOS-Chem model, and sea level pressure during June 26th to July 7th in 2023. The colored spatial distribution maps denote simulated $PM_{2.5}$ concentrations from the GEOS-Chem model. The contours on the maps denote sea level pressure (hPa). Sea level pressure data are derived from the GEOS-FP dataset (https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das/).



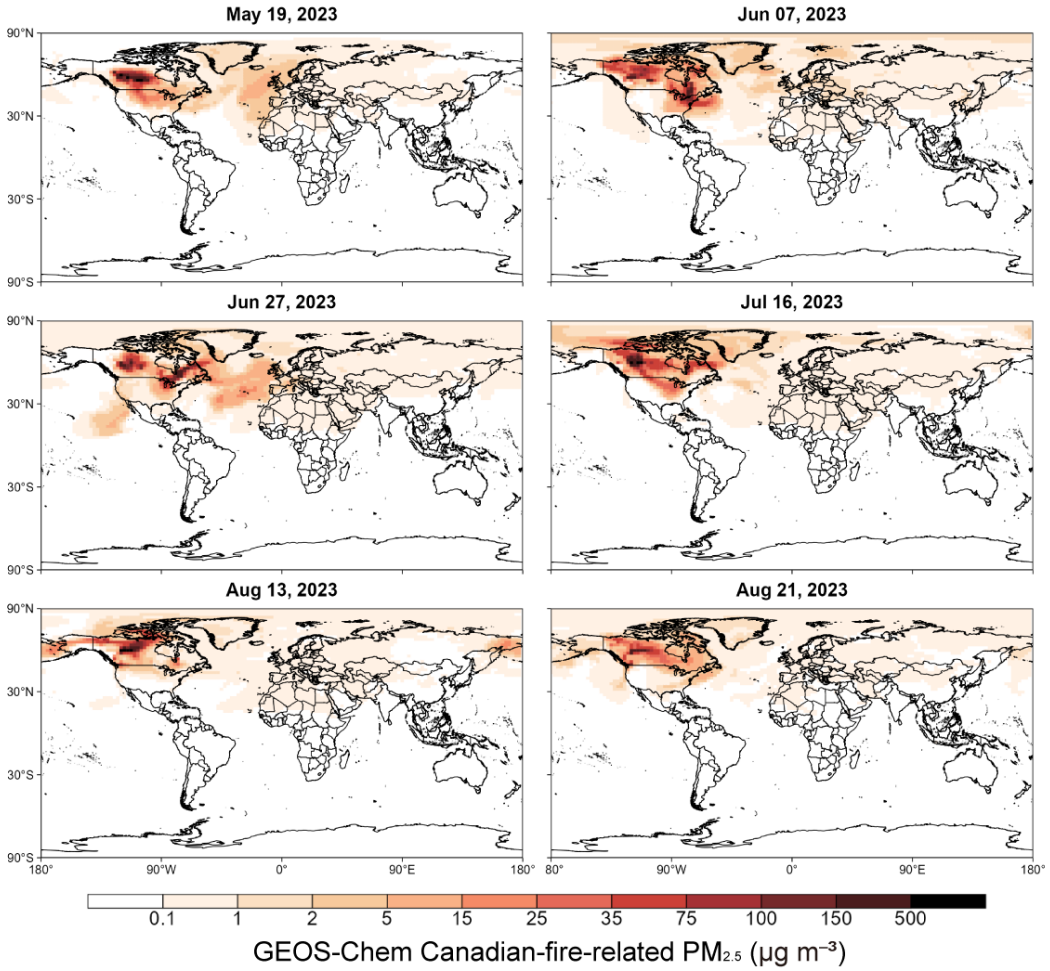
Supplementary Fig. 8 | The estimated $PM_{2.5}$ concentrations, station observations, and 700 hPa wind vectors over Europe during June 26th to July 7th in 2023. The colored spatial distribution maps denote estimated $PM_{2.5}$ concentrations. The colored dots on the maps denote station observations. The arrows on the maps denote the 700hPa wind vectors. Station observations are derived from the EEA (https://www.eea.europa.eu/), and wind data are derived from the GEOS-FP dataset (https://portal.nccs.nasa.gov/datashare/gmao/geos-fp/das/).



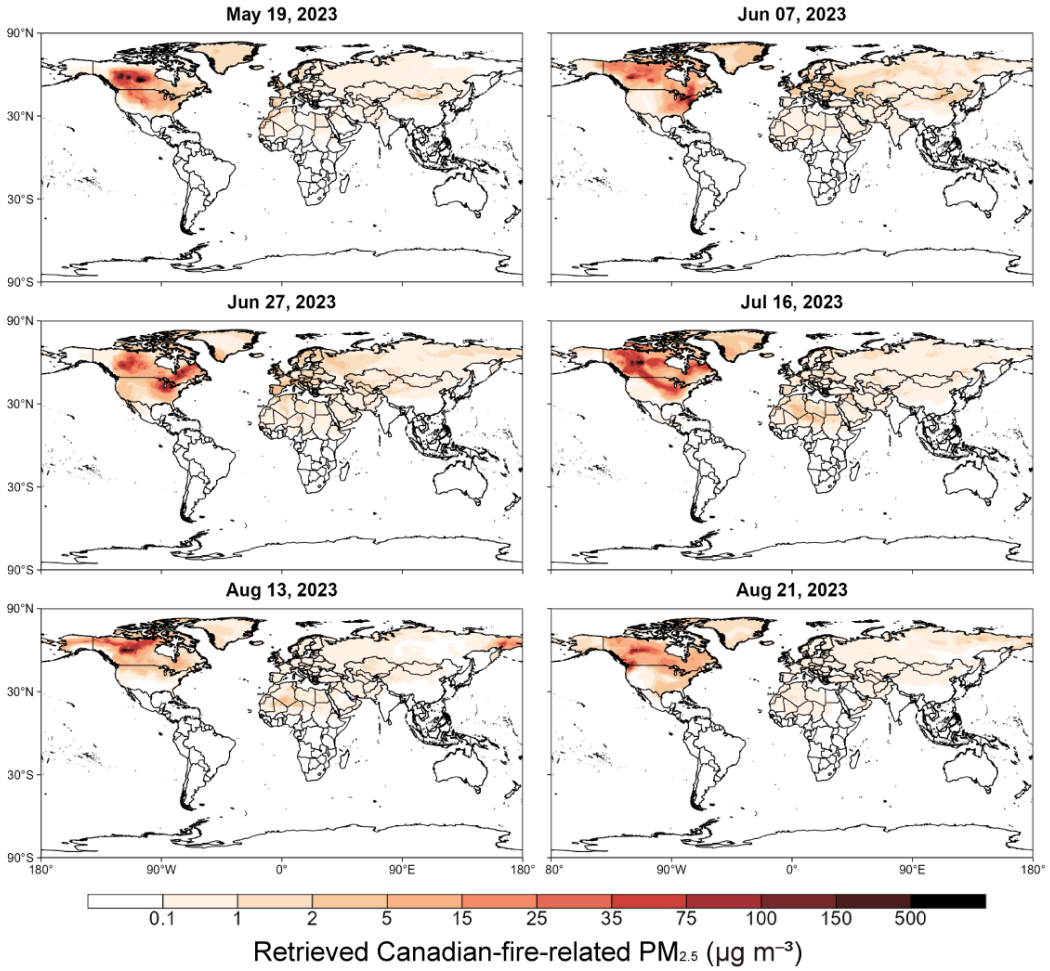
Supplementary Fig. 9 | The transport trajectory density of Europe from May to September in 2023. Colors on the map denote the total number of trajectories passing through the 0.1°×0.1° grid area. Trajectory densities are calculated using HYSPLIT (https://www.ready.noaa.gov/ready2-bin/getlinuxtrial.pl/).



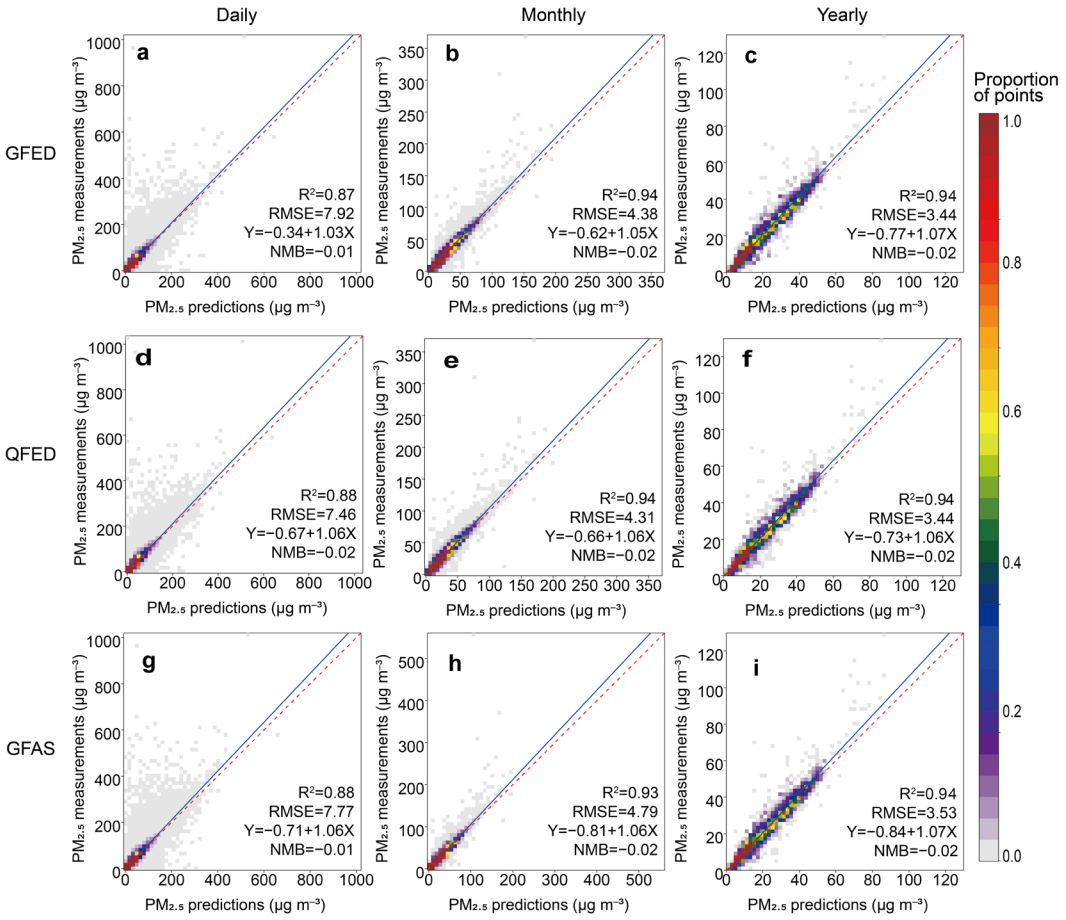
Supplementary Fig. 10 | $PM_{2.5}$ enhancement from Canadian wildfires on June 29th and July 2nd in 2023 over Northern France and Belgium. a, Hourly $PM_{2.5}$ station observations (https://www.eea.europa.eu/) at specific stations. b, Vertical timeseries of GEOS-Chem hourly total-fire-related $PM_{2.5}$ simulations at the locations of the stations. c, 7-day backward transport trajectories arrived to the stations (showed by red triangles) during June 26th to July 7th in 2023. Trajectories arrived on June 29th and July 2nd are marked in red.



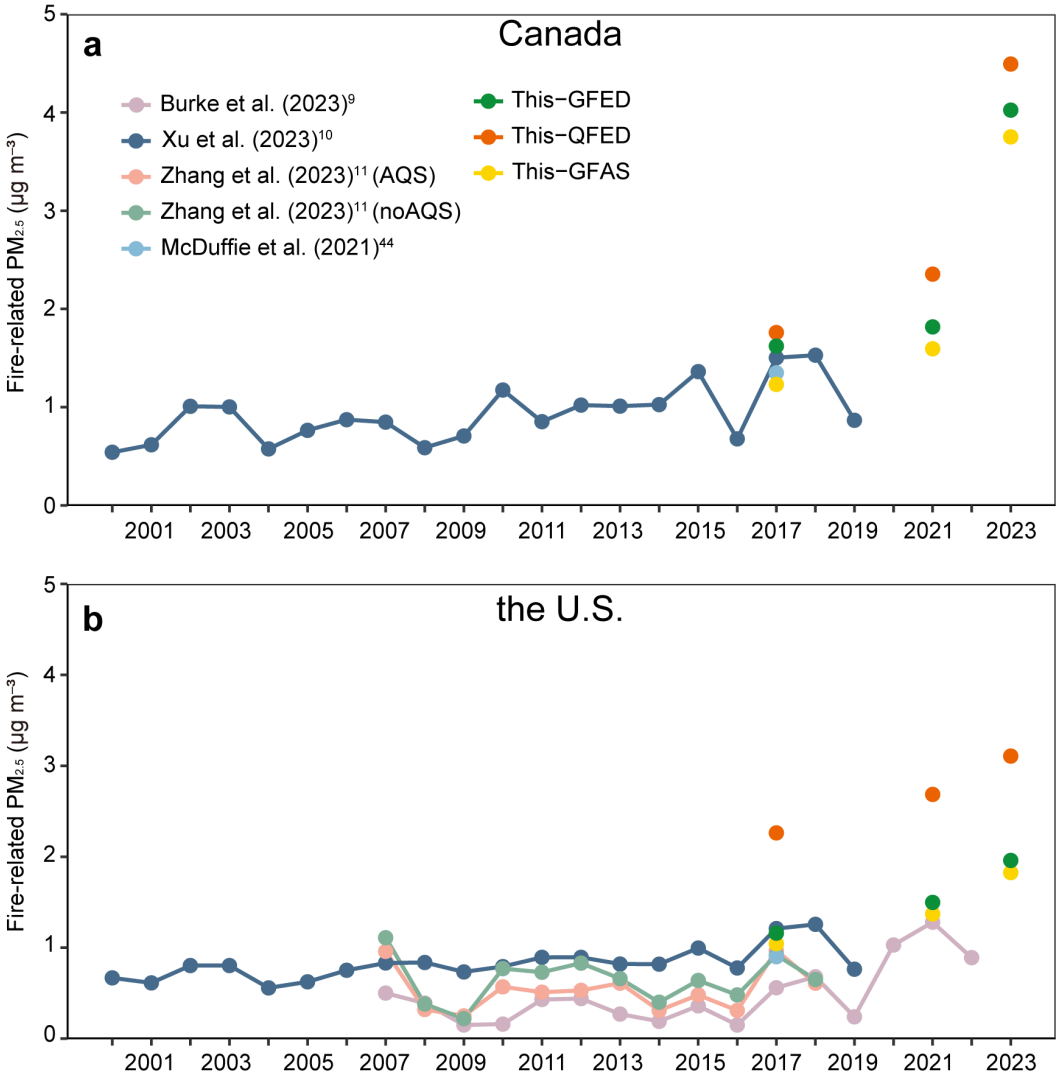
Supplementary Fig. 11 | GEOS-Chem simulated $PM_{2.5}$ concentrations from Canadian wildfires for selected long-range transport events during May to August, 2023.



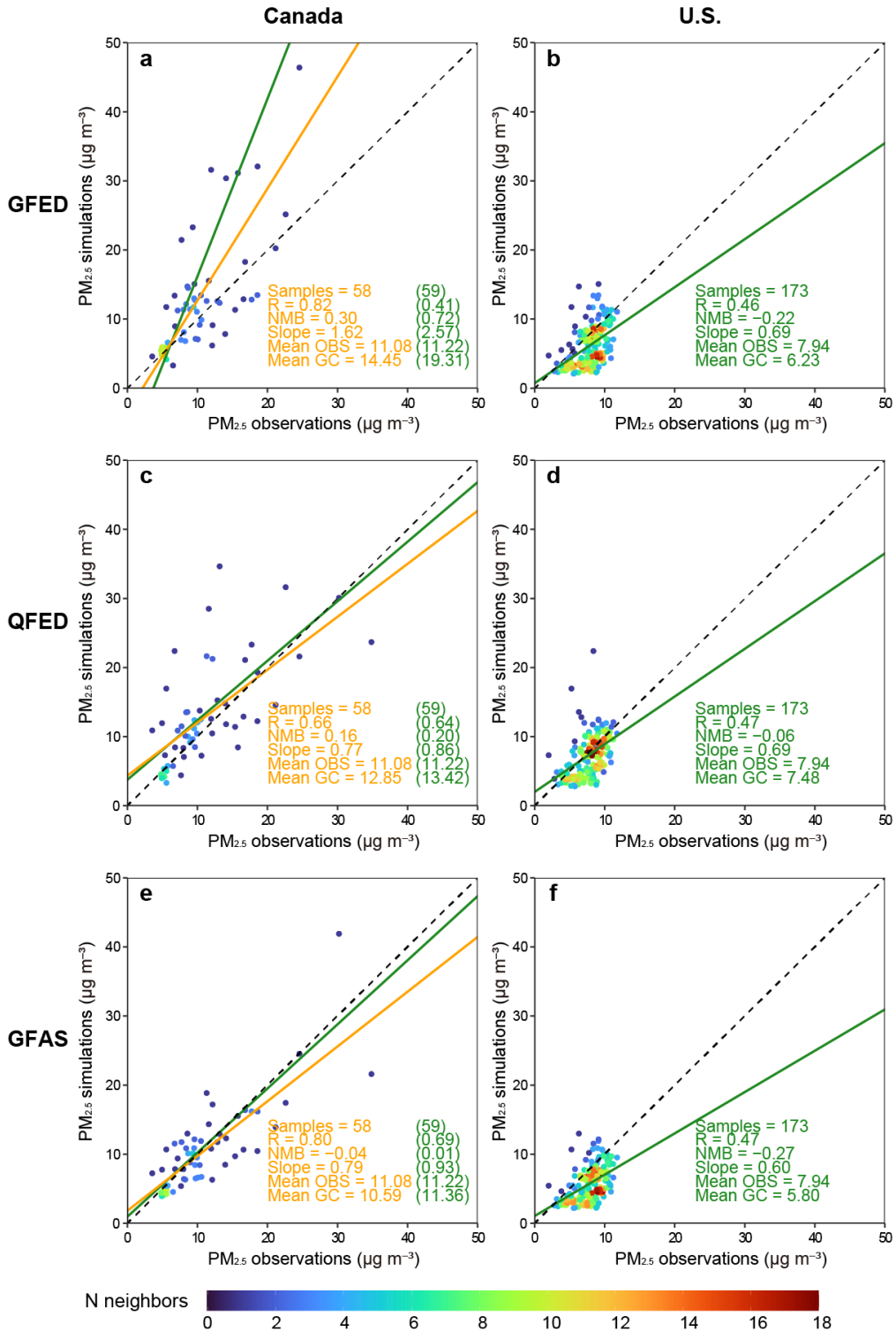
Supplementary Fig. 12 | Retrieved $PM_{2.5}$ concentrations from Canadian wildfires for selected long-range transport events during May to August, 2023.



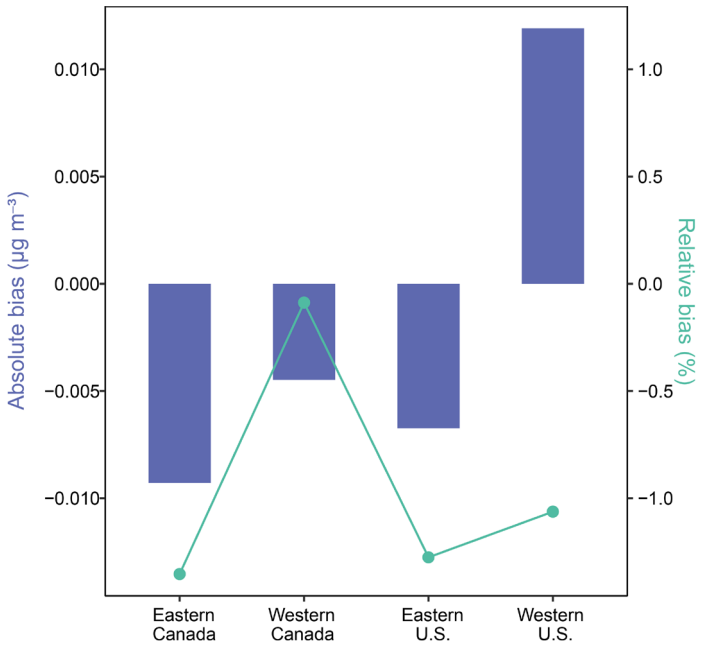
Supplementary Fig. 13 | Sample-based cross-validation performance for estimating all-source PM2.5 concentrations. a,b,c,d,e,f,g,h,i, Sample-based twenty-fold cross-validation results for estimating all-source $PM_{2.5}$ using GFED (**a–c**), QFED (**d–f**) and GFAS (**g–i**) as *a prior* fire emissions at daily (**a,d,g**), monthly (**b,e,h**), and yearly (**c,f,i**) scale in the year 2023, respectively.



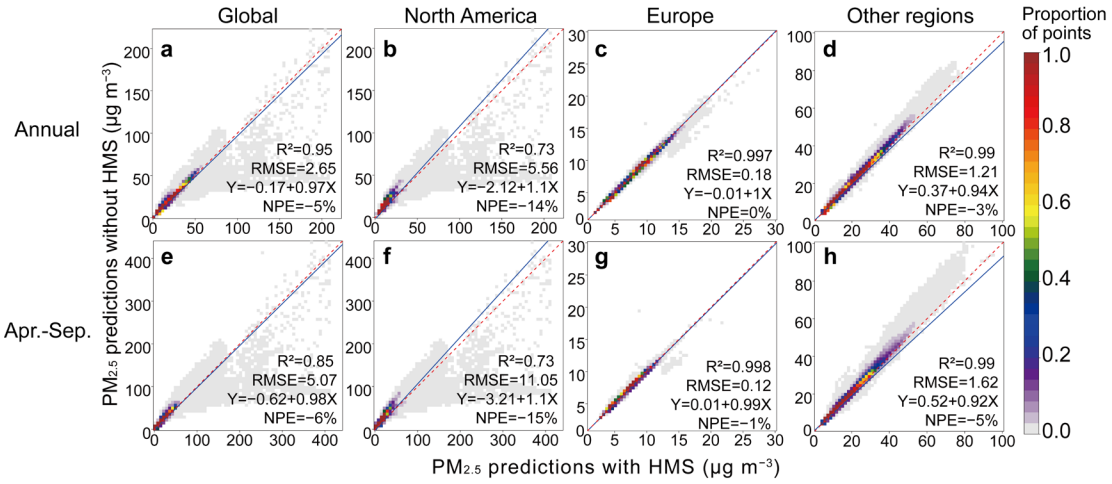
Supplementary Fig. 14 | Comparison of fire-related $PM_{2.5}$ concentrations among three fire emission inventories (GFED, QFED, and GFAS) and with previous studies in Canada and the U.S. a, Canada. **b,** the U.S.



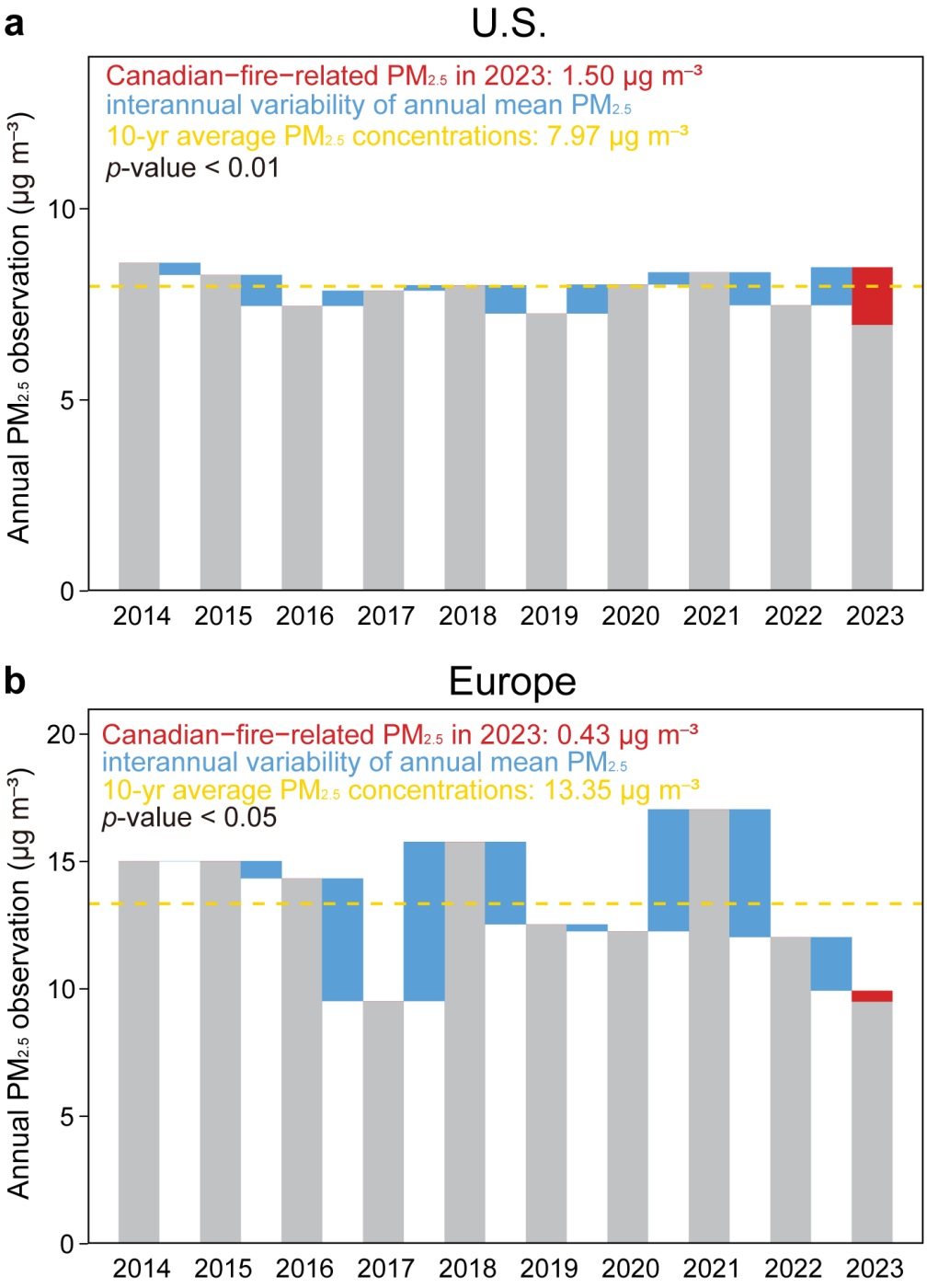
Supplementary Fig. 15 | Comparisons between the GEOS-Chem simulated annual-mean $PM_{2.5}$ concentrations driven by different fire emission inventories (GFED, QFED, and GFAS) and station observations of annual-mean $PM_{2.5}$ concentrations in Canada and the U.S. in 2023. **a,b,** GFED. **c,d,** QFED. **e,f,** GFAS. The texts in the figures describe the statistical results of original (green) and excluding one outlier with unreal high $PM_{2.5}$ simulation in Canada (orange). NMB denotes normalized mean bias. OBS denotes station observations. GC denotes GEOS-Chem simulations.



Supplementary Fig. 16 | The absolute and relative biases of $PM_{2.5}$ concentrations for turned-off regional wildfire emissions due to non-linear effect. Bars denote the absolute biases. Dotted lines denote the relative biases.



Supplementary Fig. 17 | Impact of excluding HMS smoke data on model-predicted wildfire-related $PM_{2.5}$ concentrations across global regions. a,b,c,d, Impact on annual mean $PM_{2.5}$ concentrations. **e,f,g,h,** Impact on mean concentrations during the wildfire season (April–September).



Supplementary Fig. 18 | Comparison of the 2023 Canadian-fire-related $PM_{2.5}$ concentrations in the U.S. and Europe to 2014–2023 $PM_{2.5}$ interannual variation in the two regions. a, the U.S. **b,** Europe. The annual mean $PM_{2.5}$ observations in the U.S. and Europe are averaged from the stations from EPA (https://www.epa.gov/) and EEA (https://www.eea.europa.eu/), respectively.

Supplementary Tables

Supplementary Table 1 | Summary of simulations to quantify $PM_{2.5}$ concentrations attributable to wildfires, anthropogenic and other sources using three fire emission inventories.

Case group	Anthropogenic emissions	Fire emissions	Other emissions	Year
base	CEDS	GFED	Described in *Method*	2023, 2021, 2017
	CEDS	QFED	Described in *Method*	2023, 2021, 2017
	CEDS	GFAS	Described in *Method*	2023, 2021, 2017
nofire	CEDS	Turned off	Described in *Method*	2023, 2021, 2017
noanthro	Turned off	GFED	Described in *Method*	2023, 2021, 2017
	Turned off	QFED	Described in *Method*	2023, 2021, 2017
	Turned off	GFAS	Described in *Method*	2023, 2021, 2017

Supplementary Table 2 | Summary of simulation scenarios to quantify the transboundary impact of regional fire-related $PM_{2.5}$ concentrations.

Case	Anthropogenic emissions	Fire emissions	Other emissions	Year
offCE	CEDS	GFED (close fire emissions in Eastern Canada)	Described in *Method*	2023, 2021, 2017
offCW	CEDS	GFED (close fire emissions in Western Canada)	Described in *Method*	2023, 2021, 2017
offUE	CEDS	GFED (close fire emissions in Eastern U.S.)	Described in *Method*	2023, 2021, 2017
offUW	CEDS	GFED (close fire emissions in Western U.S.)	Described in *Method*	2023, 2021, 2017
offNA	CEDS	GFED (close fire emissions in all four regions above)	Described in *Method*	2023, 2021, 2017

Supplementary Table 3 | Comparison of $PM_{2.5}$ estimates in Northeastern U.S. during the Canadian wildfire pollution events in June 2023. SD denotes standard deviation.

	Mean (SD) $PM_{2.5}$ concentration, unit: μg m^{-3}	
Dates	**Yu et al. (2024)[29]**	**This study**
6.1–6.5	12.03 (5.14)	10.25 (2.93)
6.6–6.8	78.84 (46.21)	46.12 (31.83)
6.9–6.27	12.13 (7.63)	11.07 (2.64)
6.28–6.30	38.92 (26.12)	36.59 (21.91)

Supplementary Table 4 | Evaluation of $PM_{2.5}$ prediction models using GFED, QFED, and GFAS emissions during fire events in 2023 over Canada and the U.S. RMSE denotes root mean square error). NMB denotes normalized mean bias.

	Region	$PM_{2.5}$ during fire events		
		R^2	RMSE (μg m^{-3})	NMB
GFED	Canada	0.59	16.50	–0.13
	U.S.	0.78	12.50	–0.13
QFED	Canada	0.70	14.39	–0.14
	U.S.	0.78	12.36	–0.12
GFAS	Canada	0.75	12.83	–0.09
	U.S.	0.80	11.70	–0.10

Supplementary Table 5 | Evaluation of $PM_{2.5}$ retrieval model using GFED, QFED, and GFAS emissions in 2023 by the sample-based cross-validation. RMSE denotes root mean square error. NMB denotes normalized mean bias. Numbers in the brackets indicate model evaluation statistics after removing data points outside 2σ of the Cook's distance of the linear regression.

	Region	Total $PM_{2.5}$ concentration				
		R^2	Fix-month R^2	Fix-month-and-station R^2	RMSE (μg m^{-3})	NMB
GFED	Global	0.87 (0.93)	0.86	0.80	7.92 (3.75)	–0.01 (0.01)
	North America	0.53 (0.81)	0.52	0.48	6.63 (2.75)	–0.01 (0.00)
	Canada	0.26 (0.76)	0.23	0.21	14.7 (4.8)	0.00 (0.00)
	U.S.	0.79 (0.80)	0.78	0.77	3.98 (2.75)	–0.01 (0.00)
	Europe	0.65 (0.77)	0.62	0.58	5.34 (3.57)	–0.01 (0.00)
	Asia	0.88 (0.92)	0.86	0.84	10.8 (5.91)	–0.01 (0.01)
QFED	Global	0.88 (0.93)	0.88	0.82	7.46 (3.60)	–0.02 (0.00)
	North America	0.76 (0.81)	0.76	0.75	4.58 (2.89)	–0.01 (0.00)
	Canada	0.79 (0.78)	0.80	0.79	5.49 (5.11)	–0.02 (–0.02)
	U.S.	0.79 (0.80)	0.78	0.78	3.97 (2.73)	–0.01 (0.00)
	Europe	0.65 (0.77)	0.62	0.58	5.34 (3.54)	–0.02 (0.00)
	Asia	0.88 (0.92)	0.86	0.84	10.9 (5.84)	–0.01 (0.01)
GFAS	Global	0.88 (0.93)	0.87	0.82	7.77 (3.61)	–0.01 (0.01)
	North America	0.72 (0.82)	0.72	0.70	6.12 (2.70)	–0.01 (0.01)
	Canada	0.69 (0.83)	0.67	0.65	11.8 (4.44)	–0.02 (0.01)
	U.S.	0.77 (0.80)	0.77	0.76	4.39 (2.68)	–0.01 (0.01)
	Europe	0.65 (0.77)	0.62	0.60	5.35 (3.57)	–0.01 (0.00)
	Asia	0.88 (0.92)	0.86	0.84	10.8 (5.92)	–0.01 (0.01)

Supplementary Table 6 | Spatial and temporal Pearson correlation coefficient *r* between $PM_{2.5}$ retrievals with different fire emissions.

Type	Emissions	Spatial Pearson correlation			Temporal Pearson correlation		
		Global	Canada	U.S.	Global	Canada	U.S.
All $PM_{2.5}$	GFED vs QFED	0.99	0.71	0.89	0.99	0.93	0.95
	GFED vs GFAS	0.99	0.78	0.91	0.99	0.93	0.95
	QFED vs GFAS	0.99	0.98	0.99	0.99	0.99	0.99
Fire $PM_{2.5}$	GFED vs QFED	0.88	0.75	0.86	0.74	0.95	0.94
	GFED vs GFAS	0.94	0.81	0.97	0.92	0.95	0.96
	QFED vs GFAS	0.95	0.97	0.91	0.82	0.99	0.97

Supplementary Table 7 | Estimates of global acute health impacts attributable to 2023 Canadian wildfires with different exposure-response functions. Numbers in parentheses represent the 95% confidence interval of estimates.

Sources of exposure	Wildfire (global)	Wildfire (global)	Wildfire (U.S.)	Wildfire (U.S.)	All sources
Global	5,400 (3,400, 7,400)	2,800 (1,600, 4,000)	1,300 (700, 1,900)	2,600	1,800 (1,100, 2,500)
North America	5,400 (3,400, 7,400)	2,800 (1,600, 4,000)	1,300 (700, 1,800)	2,600	1,800 (1,100, 2,400)
U.S.	4,100 (2,600, 5,600)	2,100 (1,200, 3,000)	1,000 (500, 1,400)	1,900	1,300 (800, 1,800)
Canada	1,300 (800, 1,800)	700 (400, 1,000)	300 (200, 400)	600	400 (300, 600)
References	**Chen et al. (2021)[15]**	**Xu et al. (2024)[46]**	**Doubleday et al. (2020)[48]**	**Connolly et al. (2024)[49]***	**Orellano et al. (2020)[50]**

* 95%CI of the estimates is missing due to the 95%CI of exposure-response functions are not provided in the reference.

Supplementary Table 8 | Estimates of global chronic health impacts attributable to 2023 Canadian wildfires with different exposure-response functions. Numbers in parentheses represent the 95% confidence interval of estimates.

Region	All-cause			Cause-specific
Global	82,100 (47,700, 116,500)	152,000	117,500 (60,400, 174,600)	31,000 (16,900, 45,200)
North America	41,900 (28,400, 55,400)	79,300	60,700 (33,100, 88,300)	13,900 (9,300, 18,500)
U.S.	33,000 (22,500, 43,500)	62,700	47,900 (25,900, 69,800)	10,900 (7,100, 14,700)
Canada	8,300 (5,800, 10,800)	15,500	11,900 (6,600, 17,200)	2,700 (1,800, 3,700)
References	**Chen & Hoek (2020)[40]**	**Connolly et al. (2024)[49]***	**Pope III et al. (2019)[47]**	**Murray et al. (2020)[45]**

* 95%CI of the estimates is missing due to the 95%CI of exposure-response functions are not provided in the reference.

Supplementary Table 9 | Reviews of the approaches for estimating chronic deaths from wildfire-related $PM_{2.5}$ exposure in the literature.

Fire related-$PM_{2.5}$ exposure		Exposure-response function		Spatial resolution	References
Region	**Time period**	**Cause**	**Relative Risk**		
Global	1997–2006	All-cause	1.064 (1.035, 1.094)	Grid	**Johnston et al. (2012)[12]**
Global	2010	Cause-specific (ALRI, IHD, CEV, COPD, LC)	GBD2010	Grid	**Lelieveld et al. (2015)[108]**
Global	2016–2019	All-cause	1.064 (1.035, 1.094)	Grid	**Roberts & Wooster (2021)[109]**
Global	2017	Cause-specific (IHD, Stroke, COPD, LC, DM)	GBD2019	Country	**McDuffie et al. (2021)[44]**
Global	2017	Cause-specific (Stroke, LC, IHD, COPD, LRI)	GEMM	Grid	**Gordon et al. (2023)[110]**
Global	2000–2019	All-cause	1.08 (1.06, 1.09)	Country	**Xu et al. (2024)[46]**
Amazon Basin	2012	All-cause	GEMM	Grid	**Butt et al. (2020)[111]**
Arctic Council	2001–2020	All-cause	GEMM	Grid	**Silver et al. (2024)[31]**
Brazil	2016–2019.7–9	Cause-specific (IHD, Stroke, COPD, LC, ALRI)	GBD2016	Grid	**Nawaz & Henze (2020)[112]**
Canada	2013–2015, 2017–2018.5–9	All-cause	1.10 (1.05, 1.15)	State	**Matz et al. (2020)[113]**
Equatorial Asia	2006, 2015.7–10	All-cause	1.06 (1.02, 1.11)	Grid	**Koplitz et al. (2016)[114]**
Equatorial Asia	2015.9–11	Cause-specific (LRI, COPD, LC, IHD, Stroke)	GBD2013	Grid	**Crippa et al. (2016)[115]**
Equatorial Asia	2004–2015	All-cause	GEMM	Grid	**Kiely et al. (2020)[116]**
Portugal	2015–2018	Cause-specific (IHD, Stroke, COPD, LC, ALRI)	GBD2019	Grid	**Barbosa et al. (2024)[117]**

Southeast Asia	2014	All-cause	GEMM	Grid	**Reddington et al. (2021)[118]**
U.S.	2008–2012	All-cause	1.06 (1.04, 1.06)	County	**Fann et al. (2018)[119]**
U.S.	2000–2100	All-cause	1.06 (1.04, 1.06)	Grid	**Ford et al. (2018)[120]**
U.S.	2006–2018	All-cause	GEMM	Grid	**O'Dell et al. (2021)[121]**
U.S. Washington State	2020.9.7–19	All-cause	1.056 (1.035, 1.078)	County	**Liu et al. (2021)[122]**
Western U.S.	2000–2100	All-cause	1.06 (1.04, 1.06)	Grid	**Neumann et al. (2021)[123]**