HTAP3 Fires: Towards a multi-model, multi-pollutant study of fire 1

impacts 2

- Cynthia H. Whaley¹, Tim Butler², Jose A. Adame³, Rupal Ambulkar^{4,5}, Steve R. Arnold⁶, Rebecca R. 3
- Buchholz⁷, Benjamin Gaubert⁷, Douglas S. Hamilton⁸, Min Huang⁹, Hayley Hung¹⁰, Johannes W. 4
- Kaiser¹¹, Jacek W. Kaminski¹², Christoph Knote¹³, Gerbrand Koren¹⁴, Jean-Luc Kouassi¹⁵, Meiyun Lin¹⁶, 5
- Tianjia Liu¹⁷, Jianmin Ma¹⁸, Kasemsan Manomaiphiboon¹⁹, Elisa Bergas Masso^{20,21}, Jessica L. McCarty²², Mariano Mertens²³, Mark Parrington²⁴, Helene Peiro²⁵, Pallavi Saxena²⁶, Saurabh Sonwani²⁷, 6
- 7
- Vanisa Surapipith²⁸, Damaris Y. T. Tan^{29,30}, Wenfu Tang⁷, Veerachai Tanpipat³¹, Kostas Tsigaridis^{32,33}, Christine Wiedinmyer³⁴, Oliver Wild³⁵, Yuanyu Xie³⁶, Paquita Zuidema³⁷ 8
- 9
- ¹Climate Research Division, Environment and Climate Change Canada, Victoria, BC, Canada 10
- ²Research Institute for Sustainability Helmholtz Centre Potsdam, Germany 11
- ³Atmospheric Sounding Station, El Arenosillo, National Institute for Aerospace Technology (INTA), Mazagón-Huelva. Spain 12
- ⁴Indian Institute of Tropical Meteorology (IITM), Pune, India 13
- 14 ⁵Department of Environmental Sciences, Savitribai Phule Pune University, Pune, India
- ⁶Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, UK. 15
- 16 ⁷Atmospheric Chemistry Observations & Modelling, National Science Foundation (NSF) National Center for Atmospheric 17 Research (NCAR), Boulder, Colorado, 80501, USA
- ⁸ Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC, USA 18
- ⁹Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA 19
- ¹⁰Air Quality Processes Research Section, Environment and Climate Change Canada, Toronto, ON, Canada. 20
- 21 ¹¹NILU, Department for Atmospheric and Climate Research, Kieller, Norway
- ¹²Institute of Environmental Protection National Research Institute, Warsaw, Poland 22
- 23 ¹³Model-based Environmental Exposure Science, Faculty of Medicine, University of Augsburg, Germany
- 24 ¹⁴Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands
- 25 ¹⁵UMRI Sciences Agronomiques et Procédés de Transformation, Institut National Polytechnique Félix Houphouët-Boigny
- (INP-HB), Yamoussoukro, Côte d'Ivoire 26
- ¹⁶NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA 27
- ¹⁷Department of Earth System Science, University of California, Irvine, Irvine, CA, USA. 28
- 29 ¹⁸College of Urban and Environmental Sciences, Peking University, China
- 30 ¹⁹The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, 31 Thailand
- 32 ²⁰Barcelona Supercomputing Center, Barcelona, Spain
- ²¹Universitat Politècnica de Catalunya, Barcelona, Spain 33
- ²²NASA Ames Research Center, Moffett Field, CA, USA 34
- ²³Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany 35
- ²⁴European Centre for Medium-Range Weather Forecasts, Bonn, Germany 36
- ²⁵SRON Netherlands Institute for Space Research, Leiden, The Netherlands 37
- ²⁶Department of Environmental Science, Hindu College, University of Delhi, Delhi, India 38
- 39 ²⁷Department of Environmental Studies, Zakir Husain Delhi College, University of Delhi, New Delhi, India
- 40 ²⁸Hub of Talents on Air Pollution and Climate (HTAPC), Thammasat University, Pathum Thani, Thailand
- ²⁹UK Centre for Ecology & Hydrology, Edinburgh, UK. 41
- ³⁰School of Chemistry, University of Edinburgh, Edinburgh, UK 42

- 43 ³¹WFSRU Kasetsart University, Thailand
- ³²Center for Climate Systems Research, Columbia University, New York, NY, USA
- 45 ³³NASA Goddard Institute for Space Studies, New York, NY, USA
- ⁴⁶ ³⁴Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder
- 47 ³⁵Lancaster Environment Centre, Lancaster University, Lancaster, UK
- 48 ³⁶Center for Policy Research on Energy and Environment, School of Public and International Affairs, Princeton University,
- 49 Princeton, NJ 08544, USA
- ³⁷Department of Atmospheric Sciences, Rosenstiel School, University of Miami, Miami, FL
- 51

52 *Correspondence to*: Cynthia H. Whaley (Cynthia.whaley@ec.gc.ca)

53 Abstract. Open biomass burning has major impacts globally and regionally on atmospheric composition. Fire emissions 54 include particulate matter, tropospheric ozone precursors, greenhouse gases, as well as persistent organic pollutants, mercury 55 and other metals. Fire frequency, intensity, duration, and location are changing as the climate warms, and modelling these fires 56 and their impacts is becoming more and more critical to inform climate adaptation and mitigation, as well as land management. 57 Indeed, the air pollution from fires can reverse the progress made by emission controls on industry and transportation. At the 58 same time, nearly all aspects of fire modelling – such as emissions, plume injection height, long-range transport, and plume 59 chemistry – are highly uncertain. This paper outlines a multi-model, multi-pollutant, multi-regional study to improve the 60 understanding of the uncertainties and variability in fire atmospheric science, models, and fires' impacts, in addition to 61 providing quantitative estimates of the air pollution and radiative impacts of biomass burning. Coordinated under the auspices 62 of the Task Force on Hemispheric Transport of Air Pollution, the international atmospheric modelling and fire science 63 communities are working towards the common goal of improving global fire modelling and using this multi-model experiment 64 to provide estimates of fire pollution for impact studies. This paper outlines the research needs, opportunities, and options for 65 the fire-focused multi-model experiments and provides guidance for these modelling experiments, outputs, and analyses that 66 are to be pursued over the next 3 to 5 years. The paper proposes a plan for delivering specific products at key points over this 67 period to meet important milestones relevant to science and policy audiences.

68 1 Introduction

69 Open biomass burning (BB), which includes wildland fires and agricultural burning (often called "fires" hereafter), has major 70 impacts on global and regional atmospheric chemistry, climate, air quality and the health of ecosystems, via emissions of air 71 pollutants and greenhouse gases, their long-range transport, and their deposition. Fire emissions include particulate matter; 72 tropospheric ozone precursors, such as nitrogen oxides (NO_x) , volatile organic compounds (VOCs) and carbon monoxide (CO): long-lived greenhouse gases such as methane, nitrous oxide, and carbon dioxide; persistent organic pollutants; mercury 73 74 and other metals. While contributions to poor air quality from industrial and transportation sources are decreasing in many 75 parts of the world due to emission controls, fires are a growing contributor to elevated air pollution episodes. Fire frequency, 76 intensity, duration, and location are changing as the climate warms (UN, 2022; Cunningham et al, 2024), and understanding and modelling these changes to fire regimes and their impacts is becoming more and more critical for climate adaptation and mitigation. At the same time, nearly all aspects of fire modelling – such as emissions, plume injection height, long-range transport, and plume chemistry – are highly uncertain. We propose a multi-model, multi-pollutant, multi-regional study to improve the understanding of the uncertainties and variability in fire atmospheric science and its impacts, in addition to providing quantitative estimates of the air pollution and radiative impacts of biomass burning.

82

83 The proposed study (herein referred to as HTAP3-Fires) is being planned under the auspices of the Task Force on Hemispheric 84 Transport of Air Pollution (TF HTAP, http://htap.org), an expert group organized under the Convention on Long-Range 85 Transboundary Air Pollution (UN, 1979), to improve understanding of the intercontinental flows of air pollutants, including 86 aerosols and their components, ozone and its precursors, mercury and other heavy metals, and persistent organic pollutants. 87 TF HTAP has an interest in understanding the relative contribution of fires as compared to other sources, to air pollution 88 impacts on health, ecosystems, and climate at the regional to global scale. TF HTAP is also well-positioned to bring together 89 the multi-disciplinary, international modelling and fire science communities to work towards the common goal of improving 90 global modelling of air pollutants released from fires. Although initiated under TF HTAP, this paper and the plan presented 91 herein is intended to reflect the interests of this broader community and to facilitate communication and coordination between 92 a variety of related ongoing activities and new activities that may be initiated as part of this community plan.

93

This paper outlines the research needs, opportunities, and options for improving understanding of the climate, air quality, and toxicological impacts of fires and identifies specific research activities and modelling products that could be pursued over the next 3-5 years. Specifically, Section 2 contains the motivational science policy questions; Section 3 contains background information and defines the scope of this study; Section 4 discusses the available options for the model design, providing consideration and justification for the specific plan. Finally, Section 5 provides that specific model design plan, which aims to deliver specific products at key points to meet important milestones relevant for science or policy audiences.

100 2. Motivation: Science Policy Questions

Several open online meetings were organized by TF HTAP in 2022 and 2023 to identify policy-relevant science questions that could be explored in a study of the transboundary air pollution impacts of fires. The questions identified through those meetings have been subsequently refined into the subsections below. The stated questions are not an exhaustive compilation, but the questions do provide important motivation and direction for the HTAP3-Fires multi-model experiments.

105 2.1 Transboundary transport of fire-emitted compounds

What are the impacts of fire emissions on air quality, human health, ecosystems, and climate at different scales, from near- to far-fields?

3

- What is the role of transboundary movements of fire plumes in impacting atmospheric composition in different regions? And how will the absolute and relative magnitudes of these contributions change over time?
- How does the location or seasonality of large fire events within regions affect the long-range transport potential? And
 how might these locations change over time with land use and climate change?
- How do plume dynamics and near-fire chemical transformations (e.g. sequestration of NO_x in peroxyacetyl nitrate
 (PAN), formation of secondary organic aerosols) affect the long-range transport potential and downwind impacts?
- Do different fire types (e.g. agricultural waste burning and wildland fires) have different extents of long-range
- 115 transport? What are their relative contributions to regional air pollution?

116 **2.2 Fire variability and uncertainty**

- What is the range of variability and uncertainty of the results from multiple models' simulations?
- How do model differences in physical and chemical processes manifest in the varied impacts of climate forcing and
 health that are due to fire emissions?
- Are there certain fire-related parameterizations that perform particularly well against observations, and why?
- What are key model parameters that require improved observational constraints to reduce uncertainty?
- What is the impact of different fire emissions inputs on atmospheric concentrations?
- How sensitive are model results to prescribed fire emissions versus prognostic (interactive fire modules that are coupled to climate) emissions?

125 2.3 Similarities and differences between different pollutants

- What is the contribution of fires to atmospheric concentrations of different air pollutants?
- How do the footprints of different pollutants differ and what are the principal drivers of those differences?
- How much do source-receptor relationships differ based on model type, which often have a different focus (e.g. air
 quality versus climate), but provide similar subsets of pollutants.
- How do fire emissions interact chemically with other anthropogenic emissions in the atmosphere?

131 **2.4** Questions identified by the research community, but that are beyond the scope of this study

- What are the implications of potential regional changes in prescribed burning, fire suppression policies, and other fire
 management strategies?
- What is the impact on transboundary smoke from local fire management policies?
- What impact does pyrocumulonimbus have on long-range transport of fire emissions? How often and where does
 pyrocumulonimbus occur and will they become more frequent with climate change?
- What emissions result when wildfires consume buildings and other infrastructure in the wildland-urban interface?
 What are the health impacts of built-environment burning?

How much do fires with small burned areas that are not detected by satellite observations influence the fire emissions amount and composition?

141 **3 Scope and background information**

142 The scope and further motivation for this undertaking are defined in this section, partially informing the multi-model 143 experiment design that will appear in Section 5, including the model output table (Section 5.4).

144 **3.1 Pollutants of interest**

Fires emit all the pollutants that the Convention on Long-Range Transboundary Air Pollution (CLRTAP) is concerned with. This study is an opportunity to address all pollutants with the common emission source of open burning. Below is additional information on these pollutants in the context of fires and this modelling study.

148 **3.1.1 Tropospheric ozone and its precursors**

149 Tropospheric ozone (O_3) is both an air pollutant detrimental to human health and vegetation, and a short-lived climate forcer 150 (SLCF) (Monks et al., 2015). O₃ is not emitted directly, but rather formed through photochemical processes involving nitrogen 151 oxides (NO_x = NO + NO₂), hydrocarbons, such as volatile organic compounds (VOCs), methane (CH₄), and carbon monoxide 152 (CO). This chemistry evolves in fire plumes: freshly emitted plumes, typically containing a lot of particulate matter, may 153 suppress O_3 formation due to low-light conditions, diminishing photolysis rates (Alvarado et al. 2015) or heterogeneous 154 chemistry on smoke particles (e.g., Konovalov et al. 2012), whereas aged fire plumes may produce O₃ more efficiently (e.g., 155 Real et al., 2007). Due to a large quantity of VOC emissions from biomass burning, O_3 formation in wildfire plumes is generally 156 NOx-limited. However, when VOC-rich smoke plumes are transported into NOx-rich urban pollution, O₃ formation may be 157 enhanced.

158 The overall impact of fires on O_3 concentrations remains highly uncertain. While NO_x is short-lived, it can be transported long 159 distances in the form of PAN (a reservoir for sequestering NO_x and HO_x radicals), leading to additional O_3 production in 160 downwind regions for moderate smoke plumes, and production increases with plume age (Jacob, 1999; Lin et al., 2010; Jaffe 161 and Wigder, 2012; Fiore et al. 2018). Recent field measurements show that emissions of NO_x and HONO in wildfire plumes 162 are rapidly converted into more oxidized forms such that O_3 production in wildfire plumes becomes rapidly NO_x -limited 163 (Juncosa Calahorrano et al., 2021; Xu et al., 2021). After a few daylight hours, 86% of the total reactive oxidized nitrogen 164 species (NO_y) is in the forms of PAN (37%), particulate nitrate (27%), and gas-phase nitrates (23%) (Juncosa Calaborrano et 165 al., 2021). When a VOC-rich smoke plume mixes into a NO_x -rich urban area, it can also create an environment for enhanced 166 O_3 production (Liu et al., 2016; Gao and Jaffe, 2020). The net impact of fires on regional and extra-regional O_3 therefore 167 depends on the emission of a range of precursor species and their chemical transformation in fresh and aged wildfire smoke 168 plumes. Previous HTAP assessments (HTAP1 and HTAP2) have shown that ground-level O₃ is significantly influenced by

- 169 long-range transport at the hemispheric scale and have demonstrated the utility of a large ensemble of models for quantifying
- 170 these effects and their uncertainty (Fiore et al., 2009). While fires contribute only a small amount to annual average ground-
- 171 level O_3 in the major northern hemisphere receptor regions, they can be important episodically, and may become more
- 172 important with global warming and reduction of traditional anthropogenic emissions.
- 173 The 1999 CLRTAP Gothenburg Protocol (GP, EMEP, 1999) as amended in 2012 regulates the emissions of O3 precursors in 174 member states. In a recent review, it was concluded that current air quality legislation in the United Nations Economic 175 Commission for Europe (UNECE) region is not sufficient to meet the long-term clean air objectives of CLRTAP. In support 176 of the CLRTAP response to the recent GP review, TF HTAP is currently organising a new set of multi-model experiments 177 (HTAP3) aimed at quantifying the contribution of long-range transport to ground-level O₃ in all world regions from remotely 178 emitted O₃ precursors, including from fire emissions (the "Ozone, Particles, and the deposition of Nitrogen and Sulfur", or 179 HTAP3-OPNS project). To avoid duplication of effort, the model runs contributing to both exercises will be harmonised as 180 much as possible (e.g., using common emission datasets and simulation years).

181 **3.1.2 Methane**

- 182 CH_4 is the second most important greenhouse gas after CO_2 and modulates the chemistry of many other air pollutants via its 183 impact on atmospheric concentrations of the hydroxy radical (OH). It is also involved in tropospheric O_3 photochemistry (Sec 184 3.1.1). In addition to CH₄ being directly emitted from biomass burning, NO_x, CO, and NMVOCs emitted by fires have the 185 potential to alter regional and global OH concentrations, thus influencing the atmospheric lifetime of CH₄ (e.g., Naus et al., 186 2022). Modelling studies suggest significant suppression of global OH concentration following enhanced CO emissions from 187 extensive wildfires in Southeast Asia during El Niño events (Duncan et al., 2003; Manning et al., 2005; Rowlinson et al., 188 2019). Butler et al. (2005), and Bousquet et al. (2006) both found that this change in global OH significantly contributed to 189 the observed increase in global CH₄ concentration during the 1997 El Niño fires. The influence of fires on global OH appears 190 to depend on the location of the fires. Leung et al. (2007) showed that the CO emissions from extensive boreal fires in 1998 191 did not significantly lower global OH, and thus did not significantly contribute to enhanced CH_4 growth. Rowlinson et al. 192 (2019) showed that the increase in CH₄ lifetime induced by El Niño-related fires in the tropics offsets an El Niño-driven 193 reduction in CH₄ lifetime caused by changes in humidity and in atmospheric transport.
- Extreme fires and fire seasons may lead to increased CH_4 emissions from wildland fires. For example, the 2020 extreme fire year in California accounted for approximately 14% of the state's total CH_4 budget, including all anthropogenic CH_4 sources (Frausto-Vicencio et al., 2023). Fires in Arctic tundra will also lead to more CH_4 emissions in the future, as recent observations in Alaska revealed that previously burned tundra (within 50 years) emit more CH_4 than the surrounding landscapes (Yoseph et al., 2023).

199 **3.1.3 Particulate Matter**

200 Particulate matter (PM) is emitted in great quantities from fires and is usually the main cause of air quality exceedances during 201 fire episodes. In addition, it has consequences for cloud interactions and radiative forcing. It is comprised of a range of species 202 including black carbon (BC, also known as elemental carbon or soot), primary organic carbon (OC, related to organic aerosol, 203 OA), sulfate (SO₄), nitrate (NO₃), ammonium (NH₄), and crustal material (CM, or dust). Particulate matter may be emitted 204 directly or can be formed as secondary aerosols through gas-to-particle conversion. Secondary organic aerosol (SOA) is 205 particularly important in the context of long-range transport (see Section 3.2.5). If smoke is transported through a cloudy 206 boundary layer, aqueous-phase processing can also facilitate the transformation of SO_2 gas into sulfate, with consequences for 207 cloud interactions (e.g., Dobracki et al, 2025). The chemical and radiative properties, as well as cloud interactions are all 208 dependent on the chemical composition, size, and vertical distributions of the particulate matter (e.g., Huang et al., 2012). BC 209 accounts for about 10% of smoke plume mass and is the largest contributor to aerosol radiative forcing (RF) (Veira et al., 210 2016). In contrast to other aerosol components, BC introduces a radiative warming into the Earth's climate system (Section 211 3.2.2). Compared to BC from fossil fuel combustion, BC from biomass burning consists of more, generally larger, particles 212 that are more thickly coated withmore absorption per unit mass (Schwarz et al., 2008).

213 3.1.4 Mercury

214 Mercury (Hg) is a potent neurotoxin that bioaccumulates in the environment, endangering human health, wildlife, and 215 ecosystems. Wildfires release mercury from plants and soils into the atmosphere, where it may be carried and deposited over 216 great distances, contaminating water bodies and terrestrial ecosystems (Obrist et al., 2018; Chen and Evers, 2023). The 217 Minamata Convention on Mercury (UN, 2013), a worldwide convention enacted in 2013, seeks to safeguard human health and 218 the environment against mercury's negative effects. It examines the complete life cycle of mercury, including extraction, 219 trading, use, and emissions, emphasizing the need of reducing mercury pollution internationally. A third set of multi-model 220 experiments being organized under HTAP3, known as the Multi-Compartmental Mercury Modelling and Analysis Project 221 (HTAP3-MCHgMAP), is aimed at attributing trends in environmental mercury concentrations to changes in primary mercury 222 emissions and releases or to changes in other drivers or processes (Dastoor et al, 2024). All three sets of HTAP3 experiments 223 (Fires, OPNS, and MCHgMAP) will aim to harmonise inputs and experimental designs as much as possible and avoid 224 duplication of effort.

225 **3.1.5 Persistent organic pollutants**

Persistent organic pollutants (POPs) are synthetic chemicals that are also bioaccumulative, toxic and subject to long-range transport. POPs that have been trapped through wet and dry deposition by trees and shrubs (Su and Wania 2005, Daly et al. 2007) can be re-released during a wildland fire. The high temperature and vertical winds of wildland fires can remobilize POPs from fuels such as leaves and needles and the forest soil, which otherwise act as a sink for POPs. Eckhardt et al. (2007) reported 230 record high concentrations of polychlorinated biphenyls (PCBs) at the Arctic station of Zeppelin (Svalbard) in a forest fire

231 plume after a transport time of 3-4 weeks. Many atmospheric models do not simulate POPs, however, several POPs models

exist, with some listed in Table A.2.

The UNEP Stockholm Convention on POPs provides the framework for global regulation and monitoring of POPs since 2004. However, many POPs, e.g. polychlorinated biphenyls, dichlorodiphenyltrichloroethane and its degradation products (DDTs), other organochlorine pesticides, polybrominated diphenyl ethers (PBDEs), and per- and polyfluoroalklyl substances (PFASs), were in use for decades before being regulated. While most legacy POPs in air are declining globally (Wong et al. 2021, Shunthirasingham et al. 2018, Kalina et al. 2019), increasing trends are observed for chemicals of emerging concern, e.g. PFASs (Wong et al. 2018, Saini et al. 2023).

239 Dioxins are one class of POPs that are formed during incomplete combustion processes. Dioxins are emitted from waste 240 incineration, industrial and residential combustion of fossil fuels, and biomass burning. Global gridded emission inventories 241 are now available for dioxins (EDGAR at http://edgar.irc.ec.europa.eu; and Song et al., 2022). Compared to the early 2000s. 242 global dioxin emission reduced by 26% in the late 2010s, attributable to emission mitigations in upper- and lower-middle 243 income countries. However, the declining trend of dioxin emissions over the past decades terminated from the early 2010s due 244 to increasing significance of wildfire induced emissions in the total emission. The highest levels of dioxin emissions (expressed 245 as polychlorinated dibenzodioxins/dibenzofurans (PCDD/Fs)) were identified in East and South Asia, Southeast Asia, and 246 part of Sub-Saharan Africa. In East and South Asia, growing dioxin emissions are attributed to industrialization, whereas 247 wildfire is a major contributor to high dioxin emissions in Southeast Asia and Sub-Saharan Africa.

248 **3.1.6 Polycyclic aromatic hydrocarbons**

249 Polycyclic aromatic hydrocarbons (PAHs) are organic pollutants primarily generated by incomplete combustion. PAHs are of 250 concern because their concentrations have remained stable despite global emission reductions. PAHs exist in both gas and 251 particulate phase in the atmosphere, allowing them to undergo long-range transport to remote locations (Muir and Galarneau, 252 2021; Zhou et al., 2012). PAHs are regulated under the UNECE Aarhus Protocol on POPs in the CLRTAP (Yu et al., 2019), 253 yet are still observed in pristine, remote areas, such as the Arctic and Antarctic regions. The long-range atmospheric transport 254 of PAHs has been extensively investigated and partly attributed to sources in global emission inventories (e.g., PEK-FUEL at 255 http://inventory.pku.edu.cn/ and EDGAR at http://edgar.jrc.ec.europa.eu). Further efforts to update global monthly PAH 256 emissions from wildland fire sources from 2001 to 2020 use carbon stock data up to 2020 based on satellite remote sensing 257 (Luo et al., 2020; Song et al. 2022). The new inventories improve modelling of wildfire-induced PAH levels and trends 258 particularly in the Arctic, Sub-Saharan Africa, Southeast Asia, and South America. In the Arctic, source-tagging methods have 259 identified local wildfire emissions as the largest sources of benzo[a]pyrene (BaP), a PAH with high carcinogenicity, accounting 260 for 65.7% of its concentration in the Arctic, followed by wildfire emissions of Northern Asia. Wildland fires account for 94.2% 261 and 50.8% of BaP levels in the Asian Arctic during boreal summer and autumn, respectively, and 74.2% and 14.5% in the 262 North American Arctic for the same seasons (Song et al., 2022). In the Arctic remote regions, the highly variable, non-changing long-term time trends of PAHs are inconsistent with the global PAH emission reduction and have significantly increased during summers with more frequent wildland fire events in Nordic countries (Yu et al., 2019). Retene (a PAH) was often used as tracer for wildland fire activities. However, volcanic eruption (Overmeiren et al., 2024) and volatilization from soil and ocean due to warming can also elevate PAHs' air concentrations in remote locations. Models together with observations can better link BB and long-range transport of fire-related substances to remote sites.

268 **3.1.7 Other metals and trace elements**

Biomass-burning aerosols also contain a large variety of metals and other trace elements (Perron et al. 2022). The source can be the vegetation consumed and/or surrounding soils entrained into plumes by strong pyroconvective updrafts (Wagner et al., 2018; Hamilton et al., 2022), or mixing of BB aerosol emissions into advecting dust plumes, as happens in sub-Saharan Africa (Quinn et al., 2022). Entrained soil dust is estimated to be the major (two-thirds) source component for the iron contained in smoke plumes (Hamilton et al., 2022), with other elements needing further investigation. Many of these elements are important components for biogeochemical cycles, human health impacts, and/or aerosol RF.

The mass of iron emitted by fires is particularly important to quantify because iron is a limiting nutrient in many open ocean regions, playing an important role in CO₂ sequestration, particularly in the southern oceans through increasing phytoplankton primary productivity (Tang et al., 2021; Hamilton et al., 2020).

Other nutrients (e.g., phosphorus) are also emitted from fires in sufficient quantities to warrant deeper understanding of their fluxes and related impact assessment on terrestrial and marine biogeochemical cycles. For example, African fires have been identified as an equal source to African dust in terms of the intercontinental transport of phosphorus to the Amazon Rainforest (Barkley et al. 2019). There is also growing evidence that increasing United States (US) fire activity is impacting downwind freshwater ecosystems through depositing phosphorous (Olsen et al., 2023).

283 One practical issue in determining the impact of changes in fire activity on metal aerosol emission and deposition fluxes is 284 quantifying the contribution of fire to the atmospheric loading of a given metal. There are many other sources of metals to the 285 atmosphere, including mineral and anthropogenic dust, fossil fuels and vehicular transport, metal smelting and mining, and 286 volcanoes to name a few (Mahowald et al., 2018; Hamilton et al., 2022). Once sources become well-mixed in the atmosphere 287 it becomes much more difficult to trace their individual source contributions. One potential avenue in "fingerprinting" the fire 288 source contribution is the use of metal isotopes. In general, different metal sources have different isotopic fractionations 289 (Fitzsimmons and Conway, 2023) and this difference in aerosol characteristic has been used successfully to differentiate iron 290 aerosol between dust and anthropogenic sources (Conway et al., 2019). However, there is currently no data on the iron isotopic

signature of fire, so that aspect is beyond the scope of this study.

3.2 Impacts from fires

293 **3.2.1 Human health**

294 Densely populated areas like Southeast Asia, North America, and the Mediterranean experience episodes of intense air 295 pollution from wildfires exceeding the ambient air quality standards that last multiple days or weeks on a regular basis (Liu et 296 al., 2015; Jaffe et al., 2020; Dupuy et al., 2020; and see Supplement, Sections S1 for further regional discussions and S2 for 297 acute exposure health impacts). An estimated 339,000 premature deaths per year (interquartile range: 260,000 - 600,000) can 298 be attributed to exposure to wildfire smoke worldwide (Johnston et al., 2012). Xu et al (2023) estimated each person in the 299 world having an average of 9.9 days of smoke exposure from 2010-2019, a 2.1% increase compared to the previous decade. 300 The impacts are projected to increase under future climate change (Xie et al., 2022). In many regions of the world, farmers 301 commonly burn crop residues to clear land for crop cultivation. However, these agricultural fires have health implications as 302 air pollution increases (Jones and Berrens, 2021). During peak fire periods, these agricultural fires can contribute more than 303 half of the particulate matter (PM) pollution, even in urban settings (Cusworth et al, 2018; Liu et al., 2018).

304 Health risk assessment models and air quality health indices are often based on surface level concentrations of PM_{2.5}, CO, O₃, 305 and NO_x. Emissions of PM_{2.5} from fires are of particular health concern, with no known safe PM_{2.5} concentration in air, as 306 noted by the World Health Organization (WHO 2006). Fine particles impact lung functions, encouraging respiratory and 307 cardiovascular mortality and morbidity including asthma and emphysema (Davidson et al., 2005; Lampe et al., 2008; Jain et 308 al., 2014; Reid et al., 2016; Cascio, 2018; Ghosh et al., 2019; Chen et al, 2021; Aguilera et al., 2021; Sonwani et al. 2022; Gao 309 et al., 2023; Bauer et al., 2024). There is also evidence that wildfire smoke affects mental health (Eisenman et al., 2022; To et 310 al., 2021), such as due to displacement and smoke exposure following wildfires which can lead to increased cases of anxiety 311 and post-traumatic stress disorder (e.g., Humphreys et al., 2022).

An additional consideration is how smoke influences the structure of the boundary layer and thus the concentration of pollutants that people are exposed to. Fire aerosols, by cooling the surface and reducing boundary layer turbulence (Section 3.2.2), can suppress mixing of air in the boundary layer, effectively increasing pollution exposure at the surface (Bernstein et al., 2021). This effect has been studied extensively in polluted urban environments, but its importance for fires, where the composition of aerosol may be substantially different, remains unclear.

Finally, the chemical composition of the PM influences its health impacts. For example, benzo(a)pyrene, the most toxic congener of 16 parent PAHs, has been linked to high lifetime cancer risk from inhalation. Knowledge of PM size distribution (e.g. Sparks and Wagner, 2021), and chemical composition is essential for understanding health impacts, thus, motivating our multi-pollutant approach to these model simulations.

321 **3.2.2 Climate and radiative forcing (RF)**

While wildland fires have long been considered a natural and relatively carbon-neutral component in the Earth system (CO₂ emitted during burning is reabsorbed as the forest regrows), land use change and anthropogenic climate change have caused

- the frequency and intensity of fires to rapidly change, potentially altering the global carbon budget. As radiative forcing is typically expressed as a change relative to the preindustrial era, and the magnitude of preindustrial fires is highly uncertain, there is a factor of 4 uncertainty in RFs from fires (Hamilton et al, 2018; Wan et al, 2021; Mahowald et al. 2023).
- 327 Fire emissions have diverse effects on the climate. In addition to the direct effects from released greenhouse gases and aerosols,
- 328 additional indirect effects arise from the formation of tropospheric O₃, reduction in lifetime of CH₄ by enhancing tropospheric
- 329 oxidation capacity, and changes in stratospheric water vapor caused by responses of the atmospheric chemistry. Co-emitted
- 330 SO_2 can also become converted to SO_4^{2-} , an effective cloud nucleator, thereby affecting cloud lifetime (Dobracki et al., 2025).
- 331 The aerosols have indirect (microphysical) and semi-direct (radiative) impacts on cloud fields and large-scale circulation
- 332 (Adebiyi and Zuidema, 2018; Diamond et al., 2020; Ding et al., 2022). Short-term radiative effects of smoke on surface wind,
- temperature, moisture, and precipitation can also substantially enhance fire emissions and weaken smoke dispersion (Grell et
 al, 2011; Huang et al., 2024). Snow and ice albedos also change dramatically when fire-emitted black and brown carbon are
- deposited. Additionally, indirect effects on biogeochemistry result from wildfire emissions (Sections 3.1.6 and 3.2.3).
- 336 The RF from fire plume components are summarized in Table 1. Though, most studies focus on specific components or regions
- for wildfire RF (e.g., Mao et al., 2012; Chang et al., 2021, Mubarak et al., 2023), Ward et al. (2012) conducted a comprehensive
 global analysis of wildfire emission's RF, encompassing all components.
- 339

Table 1: Summary of present-day RF from specific fire plume components. Please note, that the different studies use very different model simulations and approaches to estimate the RF (see original papers). This table only serves as a general overview about the order of magnitude of the effects found in previous studies.

Fire emission component	RF (W/m ²)	Comments
	0.03 to 0.05	Dahlman et al., 2011, Ward et al, 2012. Depends heavily on the emissions
Tropospheric O ₃		from other sources, emission location and plume height (e.g. Naik et al.,
		2007; Paugam et al., 2016).
Agrosol direct affect	-0.20 to 0.25	Rap et al., 2015; Tian et al, 2022. Depends on uncertainties in BC
Actosol direct effect		absorption, and height of the smoke plume.
Aerosol indirect effect	-1.11 to -0.09	Tian et al, 2022; Rap et al., 2015. Depends on background conditions.

343

The large range in aerosol indirect effect heavily depends on the background conditions. Aged smoke is an excellent source of cloud condensation nuclei (e.g., Kacarab et al, 2019), but increasing cloud condensation nuclei from other emission sources can reduce the RF from wildfire emissions (e.g. Ward et al., 2012; Hamilton et al., 2019), which is a general feature for natural emissions (Spracklen et al, 2013). A reduction of anthropogenic emissions in the future could increase the effects of natural emissions (see example for tropospheric ozone by Mertens et al., 2021). The estimate of the aerosol albedo effect also varies in sign, but the magnitude is in general rather small compared to the indirect aerosol effect (Tian et al., 2022). The height of the fire plume influences its RF, and recent studies suggest a large climate impact of fire emissions that rise into the stratosphere 351 (Stockeret al., 2021, Damany-Pearce et al., 2022). Moreover, new measurement data indicate a larger warming potential of the

aerosol emissions from grassland fires, in part because of low single-scattering albedos resulting from a high fraction of

refractive black-carbon (rBC) containing particles, and relatively low OA:rBC mass ratios (Dobracki et al., 2023). New data

on long-range transported aerosol might help to reduce these discrepancies between the models (Zhong et al., 2023).

355 **3.2.3 Ecosystems**

Fires impact land cover, runoff/infiltration, soil erosion, and water quality, via reducing water use by plants and increasing soil hydrophobicity. The impact depends on the surface (topography, vegetation type, soil type) and fire properties as well as the quantity and intensity of precipitation following the fires. For example, high forest fire counts in India can decrease the soil moisture content, evapotranspiration, and normalized difference vegetation index (Jain et al, 2021). Further regional discussions can be found in the Supplement, in Section S1. Note that human intervention/ management practices to reduce these fire impacts vary by region, but those activities may or may not be accounted for or represented well in atmospheric and Earth system models.

Fires can also positively or negatively impact aquatic and land ecosystems nearby and afar via deposition. Specifically, fires can impact downwind marine ecosystems if deposition is sufficient to alleviate nutrient limitation in the surrounding waters (Hamilton et al. 2022). For example, Siberian fires were recently linked to anomalously high phytoplankton growth in the Arctic Ocean through the additional atmospheric supply of nitrogen (Ardyna et al. 2022). Ozone produced from fire and other emissions can reduce the productivity of O₃ sensitive ecosystems, perturbing biogenic emissions.

The estimated deposition fluxes depend highly on the models' deposition schemes and vary by chemical species and surface types (e.g., Tan et al., 2018; Huang et al., 2022). Through radiative impacts which are only accounted for in some models, fires can perturb numerous variables relevant to the calculation of deposition velocity/coefficient and secondary pollutant formation (e.g., Huang et al. 2024, for a Canadian wildfire event in 2023 that enhanced O_3 and nitrogen deposition in the eastern US).

373 **3.2.4 Socioeconomics and fire management decisions**

In cases of forest fires that encroach on the wildland-urban interface, people are forced to evacuate or permanently relocate their homes. High fatalities of residents (e.g., Molina-Terre´n et al. 2019), firefighters, and fauna; severe air pollution ranging over a few to thousands of kilometers; and huge economic losses from property damages, national park closures, tourism and recreational activity curbs, highway blocks, air travel diversions, and forest-based livelihood losses (e.g., Psaropoulos, 2021) result from large scale, recurrent forest fires (Bowman et al. 2011).

Catastrophic wildfires around the world are increasingly more frequent and hazardous. For example, in the United States, fireloss events increased from an average of 1.5 events per decade from 1980-1999 to 7 per decade from 2000-2019, costing the nation a cumulative USD \$10 billion and USD \$75 billion, respectively (Smith et al. 2020). Few studies have reported on the

increasing socioeconomic impacts and diversity of people and communities being affected (Moritz et al. 2014; Bowman et al.

383 2017). Further studies denoting the dollar-cost of fire events include Masters (2021) for the 2019-2020 Australia fires and 384 Wang et al. (2021) for the 2018 California fires, Additional regional discussions can be found in the Supplement, Section S1. 385 The Wildland Urban Interface (WUI) is the area where human development meets or intermixes with wildlands (Stewart et 386 al., 2007; Platt, 2010). Increased human availability in the WUI leads to more human caused ignitions, while simultaneously 387 wildfires in this area pose a greater risk to structures and lives. Thus, WUI fires are harder to manage yet must be suppressed 388 (Choi-Schagrin, 2021). The demographics of the WUI are regionally-dependent (e.g., Wigtil et al., 2016; Davies et al., 2018; 389 Tang et al., 2024), and are changing with time, as housing costs (Greenberg, 2021), and immigration (Shaw et al. 2020) evolve 390 over time.

Moreover, some studies focused on environmental justice describe various impacts to, and the social vulnerability of, different communities. Wildfires preferentially impact US regions with lower populations of minorities and higher populations of elderly (Masri et al., 2021). Elderly populations are particularly vulnerable to the effects of fire (Masri et al. 2021; Liu et al. 2015; Murphy and Allard, 2015). Indigenous communities also have high vulnerability, because they are disproportionately located in areas of high fire risk (Davies et al. 2018).

Land management decisions have an important role in determining ecological and socio-economic pathways. Prescribed or controlled burning is an important tool within holistic land management plans for enhancing ecosystem resilience, biodiversity conservation, plant response, air quality, and carbon sequestration. Each of these benefits are expanded upon in the Supplement, Section S3, with the general conclusion that collaboration with local communities, incorporation of traditional ecological knowledge, and adaptive management techniques guarantee that land management decisions are consistent with sustainable practices. Further research beyond the scope of this study is needed to incorporate these kinds of land management decisions into fire emissions scenario inputs for atmospheric models.

403 **3.2.5 The role of atmospheric long-range transport**

404 Long-range transport of fire-related pollutants makes open biomass burning relevant for regions that are not typically impacted 405 by widespread, frequent or intense fires. For example, recent Canadian 2018 and 2023 fires were reported to cause high PM 406 and O_3 pollution episodes in the US (e.g., Xie et al., 2020; Lin et al., 2024; Huang et al., 2024), and these plumes can reach 407 Europe through long-range cross-Atlantic transport (Real et al., 2007; Alvarado et al., 2020; CAMS, 2023). In tropical regions, 408 prevailing easterlies and the African Easterly Jet South (Adeyemi and Zuidema, 2016) can readily transport biomass-burning 409 aerosol from Africa to South America (Holanda et al. 2020). The biomass-burning aerosol interactions with a large subtropical 410 low cloud deck vary microphysically and radiatively with the vertical colocation of aerosol and cloud (Kacarab et al., 2020; 411 Zhang and Zuidema, 2019; 2021). Smoke is also an annual occurrence in northern Thailand and upper Southeast Asia, 412 transported regularly to southern China and Taiwan. At even larger scales, global teleconnections such as the El Niño-Southern 413 Oscillation allow Indonesian peat fires to impact atmospheric loadings as far away as equatorial Africa (Doherty et al., 2006; 414 Lin et al., 2014). Smoke also impacts the southeast Asian monsoon through increasing the low cloud coverage (Ding et al., 415 2021).

416 Long-range transport depends on many factors including, but not limited to source proximity, plume height, synoptic weather 417 conditions, large-scale general circulation, atmospheric chemistry and deposition rates. Long-lived primary pollutants such as 418 CO may be transported on a hemispheric scale, while short-lived species such as PM and NO_x typically affect a much smaller 419 region. However, the formation of secondary pollutants within the plume introduces substantial uncertainty into the broader 420 atmospheric impacts of fires. In particular, the formation of longer-lived pollutants such as O₃, PAN and secondary fine 421 particles can substantially impact atmospheric composition over intercontinental distances, documented in both observational 422 and modelling studies (Real et al., 2007; Lin et al., 2024). The timing and magnitude of secondary pollutant formation in 423 transported plumes strongly influences the health and ecosystem impacts of distant downwind regions and introduces much 424 uncertainty in our assessment of these impacts. Sensitivity experiments with atmospheric chemistry transport models, 425 constrained with estimates of formaldehyde which can be detected from space (Zhong et al., 2023; Alvarado et al., 2020) are 426 important for understanding the long-range impact of fire-related primary and secondary pollutants on receptor regions.

427 As nations implement more stringent air quality targets, long-range transport will start to play an increasingly important role 428 in determining if these targets are met. The multi-model study proposed here will include regional emissions perturbation 429 experiments (Sections 4.5 and 5.3) to quantify the long-range impacts on local atmospheric composition.

430 **3.3 Leveraging recent and ongoing efforts**

431 Several distinct scientific communities are addressing fire research and applications in line with their specific objectives. Table 432 A.1 of the Appendix lists the recent and ongoing efforts in the community that are complementary, but not duplicating the 433 research outlined in this paper. For example, the IGAC BBURNED activity hosted a workshop in November 2023 to assess 434 current global biomass burning emissions datasets and recommend one as the baseline fire emissions dataset for this work 435 (Sections 5.2 and 5.3). The Arctic Monitoring and Assessment Programme (AMAP) SLCF expert group may utilise the model 436 output from this work for a future Arctic-focused biomass burning report. A further example is the Climate Model 437 Intercomparison Projects CMIP6 and CMIP7 activities: CMIP6 and FireMIP included simulations from dynamic vegetation 438 models with interactive fire modules. These provide future fire emissions for different climate scenarios as input for this work 439 (Section 4.2.3 and 5.2). AerChemMIP2, planned for CMIP7, will include fire-focused simulations for their aerosols and gas 440 chemistry climate impacts.

441 **4. Discussion of modelling options**

In this section, we establish the range of model types expected to participate, and then discuss different options for model inputs, such as emissions and driving meteorology. We also discuss what kinds of simulations could be carried out to answer the science policy questions of Section 2. Final guiding decisions on all of these topics are provided in Section 5.

445 **4.1 Model types and scope**

446 Models suitable for exploring the local, regional and global impacts of fires have a wide range of different geographic and 447 temporal scales and resolutions. Models of atmospheric processes have widely differing treatments of chemical complexity 448 and differ in their vertical and horizontal extent. Some models incorporate physical processes to simulate their own 449 meteorology, which may be nudged to match meteorological reanalyses, while others are driven with reanalysis data, either 450 directly or following downscaling with a meteorological model. More complex models may incorporate other Earth system 451 components including the land surface and vegetation (which may or may not be interactive), ocean exchange (and sometimes 452 biogeochemistry), and the cryosphere. In some models, fire ignition, spread and pollutant emission are explicitly represented, 453 governed by vegetative fuel loading and meteorology, while in others they are a specified input. This diversity in model types 454 and scope presents a technical challenge in comparing the simulated impacts of fires between models (e.g., Shinozuka et al., 455 2020; Doherty et al., 2022), but the different approaches and levels of complexity present a valuable opportunity to provide 456 fresh insight into our understanding of fire processes and how they are best represented for specific goals. The models 457 participating may fall into these categories:

- Earth System Models (ESM) or Coupled Chemistry-Climate Models (CCM)
- Regional or global Chemical Transport Models (CTM)
- multi-media POPs models
- Lagrangian Transport Models
- Reduced-form, surrogate models (e.g., emulators)
- Inverse models (see Section S4 for more information)

464 Of note, in hindcast or historical simulations, regional prognostic meteorological models can ingest (or downscale) reanalysis 465 data in two different ways, i.e., with or without nudging. The former deals only with initial and boundary conditions. The latter 466 dynamically nudges model output towards selected reanalysis fields, which helps preserve or maintain the underlying 467 meteorological conditions generally at meso- and synoptic scales. Modelers in the HTAP3-Fires can weigh which way is more 468 justifiable to their purposes. However, nudging in online coupled modelling may not be encouraged for some applications 469 since it potentially obscures or affects interactions between meteorology and chemistry. The modelling centres in Table A.2 470 have indicated interest in participating in this study. The characteristics of the models in Table A.2 are taken into consideration 471 for the experimental design.

472 **4.2** Available emissions inputs for historical and future simulations

473 Almost all atmospheric models will require some information about anthropogenic and natural emissions as inputs. In this 474 section, we discuss available data sets for both historical and future anthropogenic and natural emissions relevant for a global 475 multi-model study. Extricating truly natural from anthropogenic biomass burning is a tricky endeavour that is beyond the scope 476 of this study. For example, while agricultural and deforestation fires are considered uncontroversially as anthropogenic, would 477 accidental human ignition of a wildfire be considered natural or anthropogenic biomass burning? Similarly, would wildland 478 fires that are more frequent and intense due to anthropogenic climate change be considered natural or anthropogenic? For the 479 model design and interpretation of results, we simplify the total fire emissions into those with and without agricultural burning, 480 and classify traditional fossil-fuel emissions as anthropogenic. Agricultural burning appears in both kinds of emissions 481 datasets, so guidance is provided in Section 5.2 on which to use to not double-count those emissions.

482 **4.2.1 Historical and future anthropogenic emissions**

483 The HTAP v3 global anthropogenic emissions mosaic (Crippa et al., 2023) covers the time period 2000-2018 at 0.1 x 0.1 484 degree spatial resolution and monthly temporal resolution. This mosaic inventory is based on the EDGAR 6.1 global inventory 485 and incorporates detailed emissions (for 16 sectors) for SO₂, NO_x, CO, NMVOC, NH₃, PM₁₀, PM₂₅, BC, OC, and four POPs species from several national and regional inventories using the original spatial distributions wherever possible. Speciation 486 487 profiles are supplied for PM and NMVOC emissions. The REAS v3.2.1 regional inventory is used for Asia (South Asia, East 488 Asia, and South East Asia), the CAMS-REG v5.1 regional inventory is used for Europe, the CAPS S-KU national inventory 489 is used for South Korea, and emission data from the respective national authorities of Japan, Canada, and the United States of 490 America are used for the respective geographical zones. Wherever the respective regional or national inventories did not 491 include specific emission sectors, or wherever these sectors did not include the full set of species provided by EDGAR 6.1, 492 these emissions were gap-filled using EDGAR 6.1. Conversely, the minor sources that regional and national inventories had 493 that were *not* present in EDGAR 6.1 (eg., CO, NO_x, and SO₂ from the solvents sector), were included in the HTAPv3 mosaic. 494 HTAPv3 is thus a complete and model-ready dataset representing the best available emissions for global and regional model 495 simulations aimed at informing air quality policy. By January 2025, HTAP v3.1 global anthropogenic emissions are expected 496 to be released, which are as above, except covering the years 2000-2020, based on EDGAR v8, and including updated 497 emissions from the regional inventories.

498 Future scenarios of anthropogenic air pollutant and CH₄ emissions are available from the IIASA GAINS integrated assessment 499 model for the period 1990-2050. The scenarios are based on those originally produced in 2021 by IIASA to support the review 500 of the amended Gothenburg Protocol carried out under the Convention on Long-Range Transboundary Air Pollution, as well 501 as the AMAP SLCF assessment report (2021), and shown to be more realistic than those used in CMIP6 in Ikeda et al (2022). 502 The next version of these scenarios, called GAINS LRTAP are available as of January 2025 (Klimont et al, 2024) and will be 503 used to support HTAP3 activities aimed at modelling future air quality to inform the CLRTAP policy response to the 504 Gothenburg Protocol review. Three scenarios are provided: CLE (Current Legislation) is based on realistic implementation of 505 existing air quality plans; MTFR (Maximum Technically Feasible Reduction) is based on the same underlying activity data as 506 CLE, but with full implementation of all proven technical measures to abate CH₄ and air pollutant emissions regardless of cost 507 effectiveness; and LOW, which builds on MTFR, adding additional structural measures representing climate policies consistent 508 with Paris Agreement goals and dietary changes aimed at reducing emissions from the agriculture sector.

509 The HTAPv3.1 historical emissions and LRTAP future scenarios will be used in other concurrent HTAP3 projects 510 (MCHgMAP and OPNS). Use of these emissions datasets would provide consistency across the HTAP3 experiments and 511 would maximize policy relevance of the experiment results. While the historical emissions from HTAPv3.1 and the future 512 scenarios from LRTAP do overlap in time (2010-2020), they have not been harmonised with each other, so do not provide a 513 seamless timeseries of anthropogenic emissions from 2000 to 2050. Therefore, results from the historical simulations and 514 future simulations should be analysed separately. For example historical trends from the early 2000s to 2020 can be assessed, 515 and future trends from 2010 to 2050 can be assessed, each with a consistent source for anthropogenic emissions. In addition, 516 in Section 4.2.3, we will see that the future BB emissions are harmonized to the historical BB emissions, thus an absolute 517 change for BB emissions from early 2000 to 2050 is also possible. Note that the HTAPv3.1 emissions do not contain POPs, 518 PAHs, Hg, and other toxics. The anthropogenic emissions for those species are available from the EDGARv8.1 (Hg), PKU-519 GEMS (PAHs), and PKU-LZU (Song et al) for PCDD/Fs.

Each modelling centre will need to pre-process the selected emissions datasets to account for vertical profiles and diurnal variations of these emissions. As these processes may differ across models and it may not be possible to harmonize these characteristics, these processes will introduce a source of variability in emissions inputs across models. However, if models use their own default assumptions for vertical and temporal allocation, their methods and assumptions should be reported with their output and taken into consideration in the analysis of outputs.

525 **4.2.2** Historical biomass burning emissions

526 The latest available major global fire emissions datasets are: GFEDv4s (van der Werf et al., 2017), GFASv1.2 (Kaiser et al., 527 2012), FEERv1.0-G1.2 (Ichoku and Ellison, 2014), FINNv2.5 (Wiedinmyer et al., 2023), FLAMBE (Reid et al., 2009), 528 OFEDv2.5 (Darmenov and da Silva, 2013), GBBEXPv4, and IS4FIRES (Sofiev et al, 2009). Developers of each of these 529 attended and presented their methods at the Fire Emissions Workshop datasets (FEW2023 at 530 https://www2.acom.ucar.edu/bburned/fire-emission-workshop-virtual-2023; co-hosted by BBURNED and TF HTAP) in 531 November 2023. Intercomparison studies such as Griffin et al (2023), Pan et al (2020), Wiedinmyer et al (2023), and Liu et al 532 (2020) were also presented there, and the workshop attendees discussed options for which dataset to recommend for consistent 533 baseline fire emissions. An intercomparison tool called FIRECAM (https://globalfires.earthengine.app/view/firecam) was 534 useful for intercomparison. The different methodologies used to estimate fire emissions (e.g. Table 2) account for how and 535 why the emissions results are so different from one another (Figure 1). The intercomparison studies demonstrated that no one 536 fire emissions dataset performed best for all locations and all pollutants. The Parrington et al (submitted, 2024) report 537 summarizes all of these results.

538

Table 2: Summary of characteristics of major global fire emissions, adapted from Liu et al (2020). Dash indicates missing
 value. Note: FRP = fire radiative power, BA= burned area.

541

	Horizontal resolution	Temporal resolution	Near-real time availability	Input satellite fire product	Peatlands included	Cloud-gap adjustment	References
GFEDv4s	0.250	monthly	-	MODIS BA + active fire geolocations	✓ (tropical)	-	van der Werf et al. (2017)
GFASv1.2	0.10	daily	~	MODIS FRP	✓ (Siberian and tropical)	√	Kaiser et al. (2012)
FEERv1.0	0.10	monthly	✓	MODIS FRP	-	~	Ichoku and Ellison (2014)
FINNv2.5	1km	daily	~	Active fire geolocations from MODIS & VIIRS	-	-	Wiedinmyer et al. (2011, 2023)
FLAMBE	1-3km	hourly	✓	MODIS thermal anomalies	-		Reid et al. (2009)
QFEDv2.5	0.10	daily	✓	FRP	-	~	Darmenov and da Silva (2013)
GBBEXPv4	0.10	hourly	✓	VIIRS FRP	-		Parrington et al, (2024)
IS4FIRES	0.10	daily	√	MODIS FRP	-		Sofiev et al (2009)



Figure 1: Multi-species, multi-regional intercomparison of fire emissions datasets, from Wiedinmyer et al (2023), where
 regional acronyms and colours are defined in Figure 3c.

547

544

548 Fire emissions from peat

549 Satellite data assimilation studies have shown that emission inventory underestimations may often be due to lack of peat fires. 550 For example, Nechita-Banda et al. (2018) found that incorporating satellite measurements of CO increased CO emissions 551 (compared to GFAS and GFED) from peat fires in Indonesia during the 2015 El Niño event. The ability to account for 552 emissions from peat fires is a key issue in several regions. Recent work to improve peat fires for Indonesia was done in Kiely 553 et al. (2019). Out of several global fire emissions datasets, only GFASv1.2 and GFEDv4 have tropical peat fires, and only 554 GFASv1.2 contains high-latitude Siberian peatland fires. GFEDv5 emissions will have high-latitude peat fires, but as of this 555 writing, it has not yet been released, nor evaluated. Similarly, a newer version of GFAS (v1.4) is not published or documented 556 yet, though it could have improvements to long-term trends in fire emissions.

Regardless of their inclusion, peat fire emissions are highly uncertain (McCarty et al., 2021). There are different EFs for highlatitude and low-latitude peat fires, given the different vegetation that grows on top, and global maps of peatland are out of date (McCarty et al., 2021). It is also very difficult to detect smouldering (low intensity) peat fires from satellite measurements. That said, the consensus recommendation from FEW 2023 was to use GFASv1.2 based on its inclusion of high-latitude peat fires, ease of adjusting EFs, possibly somewhat better sensitivity to small fires in fire radiative power (FRP) than inburnt area, and availability of information on the diurnal cycle (more on timing of emissions below). Unlike other types of wildland fire

- 563 emissions, tropical and mid-latitude peat fires generally have a flat diurnal cycle, apparent in the FRP observations during
- 564 daytime and night-time. (e.g. Figure 10 in Kaiser et al. 2012). Diurnal information is directly available in the separately
- assimilated daytime and night-time FRP in GFASv1.4, but this database has not yet been used to adapt the emission factors.

566 Magnitude of Emissions

567 Substantial uncertainty arises from estimates of the magnitude and location of emissions. This can be explored through short 568 case study simulations investigating the use of alternative emission datasets, along with comparison of these with observations 569 and baseline model studies. Such sensitivity studies implicitly include differences in resolution and species fractionation (and 570 possibly injection height and timing), as well as fire magnitude and location but nevertheless can provide a useful estimate of 571 uncertainty to fire emissions across the models (Pan et al., 2015).

572 Timing of Emissions

573 Most long-term model studies, such as those performed for CMIP intercomparisons, apply monthly-mean fire emissions rather 574 than considering more temporally resolved emissions that capture the largely episodic nature of fires. The implications of this, 575 either for comparison with surface observations or for regional and global budgets, remain unclear. In addition, there are 576 substantial diurnal cycles in fire intensity, local meteorology and boundary layer dynamics that suggest that the impacts of 577 fires are likely sensitive to the timing of emissions through the day. Observational evidence indicates emerging overnight fires 578 due to increasing drought conditions that challenge the traditional diurnal cycle characterized by 'active day, quiet night' (Luo 579 et al., 2024). These uncertainties can be explored through short studies (one vear/several vears) that consider (1) monthly mean 580 fire emissions, based on the same set of emissions used at higher temporal resolution in the baseline run, and (2) emissions 581 provided without a diurnal variation in magnitude or injection height.

582 Fire emissions of other species: Hg, POPs, PAHs

Mercury fire emissions are not included by default in most global fire emissions datasets, like GFASv1.2. For the HTAP3 MCHgMAP project, Hg fire emissions are based on FINNv2.5 global fire emissions, using emission factors from Andreae et al (ACP, 2019), but replacing EFs for certain biomes with mean EFs from Friedli et al, (2003a;b) and McLagan et al, (2021). They also apply those EFs to GFED4 fire emissions for sensitivity simulations. Those biome-specific EFs could be applied to the chosen fire emissions datasets (GFAS4HTAP and Hamilton & Kasoar) for this project to generate consistent Hg fire emissions.

Similarly, EFs used for POPs and PAHs could be added and applied to the base fire (and anthropogenic) emissions for this study. For PAHs, there is a recently updated Peking University (PKU-FUEL) "global PAH emission inventory" spanning from 1961 to 2020 at http://inventory.pku.edu.cn/, which takes wildfire emission into account, and used measured PAH emission factors. That group also developed global OPFR, SCCP, and PCDD/Fs emissions, often using experimentally derived emission factors from the USEPA and UNEP as well as the literature (He et al, 2004; Jiang et al, 2017; Song et al, 2022;2023; Li et al., 2023).

595 Post-fire dust emissions

The removal of vegetation creates a more exposed soil surface from which dust can be emitted (Dukes et al., 2018; Jeanneau et al., 2019, Whicker et al., 2006). The emission of dust from a post-burn landscape will continue until the vegetation sufficiently recovers, spanning a period of days to potentially years. Approximately 1-in-2 large fires are estimated to be followed by increased dust emissions, with savanna ecosystems the most susceptible (Yu and Ginoux., 2022). Emission estimates are highly uncertain with the only global estimate to date of 100 Tg/year of additional soil dust emissions with an order of magnitude uncertainty (Hamilton et al., 2022). As there are no existing emissions datasets for this process, further research beyond the scope of this study would be needed to address this impact of fires.

603 Wildland urban interface fires

Wildland Urban Interface (WUI) fires account for ~4% of total fires globally. WUI fires can involve built-structure burning, and hence their emissions may be more harmful. They are also closer to humans and properties causing expensive damages. Studies have been conducted for specific WUI fires and regions (Holder et al., 2023) and a future version of FINN will include WUI fire emissions. However, currently there is no global BB emissions dataset that explicitly addresses WUI fire emissions and future research beyond the scope of this study would be needed to address this aspect of fire emissions.

609 Summary of recommended historical fire emissions dataset

The discussions at FEW 2023 suggested that several characteristics are important in selecting a fire emissions dataset for the multi-model experiments: 1) high temporal resolution, given the high variability of fires; 2) the inclusion of boreal peatland fires, particularly for those interested in boreal and Arctic locations; and 3) the inclusion of fire plume height for atmospheric modelling. For these reasons, GFASv1.2 became the recommended fire emissions dataset for the historical period (starting in 2003), but modified with updated fire type map, and emission factors (hereafter called GFAS4HTAP; Kaiser et al, in prep, 2024).

616 4.2.3 Future biomass burning emissions

617 Land models, such as those that participated in FireMIP (Li et al, 2019) can provide fire emission projections that are reflective, 618 not only of future land use changes, but also of the changing climate under different future climate scenarios. However, as of 619 this writing, the FireMIP future simulations have yet to be conducted.

620 Current CMIP6 SSP future fire datasets only account for human impacts on future fire activity, whereby fire activity is assumed 621 to decrease and includes no impact from the changing climate conditions on those future fire emissions (Figure 2, left bars). 622 An alternative set of future fire emission projections does however exist in six fire-climate-coupled models from CMIP6 (Xie 623 et al., 2022). The models have future fire results that take into account the changing climate under different SSP scenarios: "a 624 climate-consistent future fire emissions estimate" (Figure 2, right bars). Emissions for three SSP scenarios (SSP1-2.6, SSP3.70, 625 SSP5-.8.5) have been produced by Hamilton and Kasoar et al. (submitted), and other SSP scenarios using the same 626 methodology can be generated (i.e., SSP2-4.5 for this study from 2020 to 2050). In each emission projection "natural" fire 627 emissions are defined as boreal and temperate forest and all grassland fires and calculated as a product of the CMIP6 multi-628 model mean, accounting for similarities in land models. "Human" controlled agricultural and deforestation fires are then added 629 to natural fires. Agricultural fires are included using the GAINS anthropogenic emission estimates (Section 4.4.1 and Section 630 5.2 for this recommendation). Tropical forest fires are assumed to be primarily due to deforestation practices and were added 631 from the SSP dataset in place of CMIP6 model estimates in that forest biome. Peat fires are held at present day levels throughout 632 the century, also following SSP dataset protocols, very likely underestimating their contribution to future emission fluxes, but 633 this is because most interactive ESM fire modules did not contain these uncertain types of fires. Finally, each emission dataset 634 is bias corrected regionally to dry matter consumed in the present day (2015-2020 average). In Hamilton and Kasoar et al 635 (submitted), the present day bias correction used GFED4s emission data, but for this project, the dry matter consumed bias 636 correction is being redone with GFAS4HTAP so that the absolute changes in BB emissions for the historical and future time 637 period would be consistent. The bias correction was changed from emissions to dry matter to also allow the same GFAS4HTAP 638 fire emission factors to be applied.



Figure 2: Decadal average timeseries of future fire aerosol emissions from Hamilton et al (submitted). Right-hand bars are
 fire emissions from interactive ESMs and left-land bars are fire emissions from CMIP6, based on land use change only.

Note that in Tang et al (2023) and Romanello et al (2023), the Community Earth System Model 2 (CESM2) was used to project future burned area and total fire carbon emissions under different climate scenarios, however, it is only based on the one ESM, so it is not recommended for this project. As mentioned in Sections 2.4 and 3.2.4, applying fire management policies to future scenarios is beyond the scope of this study, however, further information on that topic is included in the Supplement, Section S.3.3.

648 **4.2.4 Other emissions**

Aside from the emissions mentioned above, models typically include biogenic and geological emissions from natural sources.
These can include isoprene and other VOC emissions from vegetation, NO_x emissions from soil microbes and lightning, sulfur
emissions from volcanos, etc. Most models rely on the same interactive biogenic emission database, namely MEGAN
(available at https://bai.ess.uci.edu/megan; Guenther et al., 2012) (Table A.2), or a derivative thereof.

653

639

654 **4.2.5 Methane emissions and concentrations**

655 While a few models are able to simulate CH4 from emissions, it is common in many participating models to prescribe CH4 656 concentrations instead. For emissions-driven models, BB emissions of CH4 are available (Sec 5.2) for the historic and future 657 time periods, and anthropogenic CH4 emissions are included in the IIASA GAINS emissions. However, CH4 is not included 658 in the historical HTAPv3.1 anthropogenic emissions. For concentration-driven CH4 models, the future surface concentrations 659 of CH4 will be created by MSC-W (Met Norway) based off of the IIASA GAINS emissions and a climate model, and provided 660 to participants. The historic CH4 concentrations are provided as annual average surface mixing ratio from the NOAA Global 661 Monitoring Laboratory (Thoning et al., 2022), which are based on measurements from the NOAA Global Monitoring 662 Laboratory, which operates a network of background monitoring stations in remote locations around the world.

663 **4.3 Available meteorological inputs**

The height reached by a smoke plume, its horizontal transport, vertical mixing, and subsequent impact on a region are greatly determined by the prevailing weather conditions. These effects occur across a wide range of scales, from turbulent mixing of pollutants in the boundary layer, to lifting into the free troposphere, and subsequent transport by the prevailing winds. Observation-based reanalysis datasets provide an important source of meteorological information needed to drive some of the models (included in Table A.2), but differences between these products, and between reanalyses and model-generated meteorology, provide an additional source of uncertainty (e.g., Adebiyi et al., 2024).

670 4.3.1 Historical meteorological datasets

Currently, several meteorological reanalysis data sets are available and could be utilized, such as MERRA2 (Modern-Era
 Retrospective Analysis for Research and Applications, version 2), ERA5, NCEP-NCAR (National Centers for Environmental
 Prediction - National Center for Atmospheric Research), or JRA-55 (Japanese 55-year Reanalysis), among others. They are
 summarized in Table S2 in the Supplement.

675 **4.3.2 Future meteorological input**

676 To assess the alterations in meteorological conditions across the 21st century and their potential implications on fires 677 (frequency, intensity, transport), the CMIP6 multi-model ensemble is the best available source for future meteorology that 678 would occur in the changing future climate. The IPCC (Intergovernmental Panel on Climate Change) defined the Shared 679 Socioeconomic Pathways (SSP) future scenarios which illustrate different potential pathways for societal development 680 throughout the 21st century and analyse their potential impacts on greenhouse gas emissions. The SSPs are classified into five 681 trajectories: SSP1 represents a sustainable world, SSP2 outlines a moderate pathway, SSP3 depicts a fragmented world with 682 considerable challenges, SSP4 illustrates a world emphasizing equality and sustainability, and SSP5 envisions a world driven 683 by rapid economic growth and dependence on fossil fuels. These five categories define different SSP emissions and 684 concentration pathways, providing unprecedented detail of input data for climate model simulations: SSP1 (1.9 and 2.6), SSP2685 4.5, SSP3-7.0, SSP4 (3.4 and 6.0), and SSP5 (3.4-OS and 8.5). The SSPX-Y scenarios refer to the estimated RF levels at the 686 end of the 21st century; for instance, the '1.9' in the SSP1-1.9 scenario signifies an estimated RF level of 1.9 W m⁻² in 2100. The SSP emissions and concentration pathways are used as input for freely running ESMs, which then simulate future 687 688 meteorological conditions for the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). Access to 689 the meteorological fields generated by the these ESMs under each of the specified SSP scenarios, is facilitated through 690 platforms such as those provided by CMIP6 (https://pcmdi.llnl.gov/CMIP6/), the IPCC Data Distribution Centre (DDC) 691 (https://www.ipcc-data.org/), and the Climate Data Store (CDS) by Copernicus (https://cds.climate.copernicus.eu/), among 692 others. It is generally believed at the present that SSP2-4.5 is the most likely future scenario (Gidden et al, 2019; Meinshausen 693 et al, 2020), and this one was chosen as the basis for the HTAP3 OPNS project.

694 **4.4 Observational data available for model evaluation**

The comparison of model results to observations is valuable for assessing how well models represent the real world and is critical for identifying gaps in our current understanding or weaknesses in how key processes are represented in models. Given the known uncertainties in fire and other model processes, observational comparisons provide a valuable opportunity to critically assess current parameterizations and identify which are most appropriate under particular conditions.

Comparisons with satellite-derived atmospheric composition will enable large-scale simulations to be evaluated consistently over the historical period under consideration. Observations of trace gases such as CO and aerosol properties can be used to evaluate long-range transport simulation (transport pathways, altitude, plume vertical extent and dilution). All surface monitoring measurements of the pollutants of Section 3.1 could be used for model evaluation, but we focus the rest of this section on highly-relevant fire-specific observational datasets and field campaigns. See also Table S1 in the Supplement for a non-exhaustive list of relevant observational datasets. Note that the simulation time periods are chosen based on the prevalence of fire-relevant observational data.

As shown in Section 3.1, no single tracer is emitted by wildfires only, and domestic wood burning has the same signature as wildfires. Enhanced Hg and POP concentrations are also often observed within biomass burning emissions, and come from the burned matter itself as well as being reemitted from soil. If those concentrations are enhanced simultaneously with those of other primary pollutants like CO, BC, and SOA, it is a strong indication that wildfire emissions are observed (e.g. Eckhardt et al., 2006).

For detecting wildfire plumes in observations, statistical methods use a combination of different trace species. For example, SO₄, BC, CO, NO₂ have been combined with a positive matrix factorization to identify biomass burning plumes (Karl et al., 2019). Yttri et al., (2023) used aerosol absorption coefficients recorded at different wavelengths by an aethalometer to distinguish BC emitted by fossil fuel or by biomass burning. Those observations are available for several stations in Europe.

715 Evaluation of modelled fluxes (e.g. deposition) are more challenging. These, as well as Nr impacts, may also be dynamically

716 modelled in some systems. Cross-disciplinary satellite and in-situ data (atmospheric, land surface, water quality, etc) can be

- vised to evaluate the modelled deposition results, helping identify weakness in individual models and reduce uncertainty in
- 718 impact assessments (e.g., Fu et al., 2022; Huang et al., 2024).
- 719

720 **4.5 Experiment design and sensitivity analyses**

This section outlines different model experiments to help answer the science policy questions of Section 2. These fall into several distinct sets, targeting different aspects of our understanding, and some include a range of sub-experiments to explore specific aspects in greater depth. Model groups may contribute to any number of experiments but are not required to complete them all. Where applicable, we indicate in Section 5.4 which experiments are higher priority for HTAP, and which experiments may be dependent upon completion of other experiments.

726 4.5.1 How well do models perform? Baseline and case study simulations

727 Models should conduct baseline simulations of recent historical conditions, with a common set of anthropogenic and fire 728 emissions, as both a basis of comparison for perturbation and sensitivity experiments and for general model intercomparisons 729 and evaluation with observations. The results can then be used to quantify the uncertainties and variability in atmospheric 730 modelling. As the type of models participating is highly variable, with a range of computational costs, both short and long time 731 periods are suggested for the baseline simulations. These time periods are selected based on the availability of reliable emission 732 assessments and periods with abundant observations. Very computationally expensive models (e.g. very high resolution, 733 inclusion of complex atmosphere chemistry) may only be able to simulate one year or less. Given how highly regional and 734 interannually variable fires are, we can identify short-term fire case studies for evaluation of those models and explore 735 particular fire events in detail. Fire event case studies can include the particularly large Australian fires of 2019-2020 (Filkov 736 et al. 2020; Johnston et al., 2021; Collins et al., 2021; van der Velde et al., 2021, Anema et al., 2024); the fires in the U.S that 737 coincided with the 2018 WE-CAN and 2019 FIREX-AO measurement campaigns (Juncosa Calahorrano 2021; Warneke et al., 738 2023); and the significant fire season in Indonesia in 2015 due to a strong El Niño (Chen et al, 2016; Nechita-Banda et al., 739 2018).

740 **4.5.2** What is the magnitude of pollution that comes from fires? Source-receptor/emissions perturbation experiments

To determine the magnitude of pollution from fires, species concentrations from baseline simulations can be compared to simulations with fire emissions removed. For additional detail, fire emissions from different geographical regions and from different types of burning can be perturbed for separate species, locations, and seasons to quantify source/receptor relationships and their uncertainties. However, the number of perturbation experiments can increase rapidly, so care is needed to prioritize and not define regions and sectors too finely.

746 Geographical Regions

747 Coarsely-defined regions help reduce the number of perturbation simulations. Figure 3 shows several options for the 748 geographical source regions that were considered for these experiments, including those used within the HTAP2 multi-model 749 experiments (Fig 3a). While those distinguished boreal fires in higher latitudes from the low-latitude fires associated with 750 agricultural, temperate and grasslands, further refinement is needed for HTAP3 Fires. Regions used for anthropogenic 751 emissions perturbation experiments in the HTAP3 OPNS project are shown in Fig 3b. We note that the southern hemisphere 752 Africa has been a focus of recent field campaigns (Zuidema et al., 2016) as the region emanates a third of the world's carbon 753 from biomass burning aerosol (van der Werf et al., 2010). South America also emits a significant fraction of the world's total 754 BB aerosols. Therefore, for global modelling completeness, the scientific modelling community would benefit from including 755 those southern hemispheric regions in HTAP3 Fires perturbation experiments as well. Figure 3c shows the GFED BB 756 emissions regions used in many analyses that balance political regions and fire-relevant biomes. However, there are 14 GFED 757 regions, which would be costly to run. Therefore, we merge the 14 GFED regions into 8 larger regions to make perturbation 758 experiments (exp 5 in Table 5) more feasible in Figure 3d. These merged regions are broadly consistent with the HTAP2 759 regions, but with improved coverage, and are loosely aligned with the regions used for anthropogenic emissions in HTAP3 760 OPNS. Regional models may have geographical domains that differ from these, and where possible, these should simulate a 761 subset of the regional perturbation experiments.



762

Figure 3: Regions for perturbation experiments: (a) BB source regions used in HTAP2 experiments. (b) regions used for anthropogenic emissions in HTAP3 O3PNS project, (c) GFED regions often used for fire emissions datasets, and (d) GFED regions (grey lines) and proposed merged regions (coloured areas). (a-c) are those used in other comparable studies, and (d) as the choice for this study.

767

768 Fire Sectors

Management decisions and policies are best informed by perturbing biomass burning sectors separately. The two main categories are agricultural burning and wildland fires. Agricultural biomass burning is the deliberate burning of agricultural waste products, such as crop waste products, stubble, and other organic matter left in fields after harvest, as a method of waste disposal or as a practice in land management. The burning of grasslands towards coaxing new growth is also included. Deliberate burning is frequently applied in agricultural areas, especially where traditional practises are still widely practised. The United National Economic Commission for Europe (UNECE) adopted a guidance document on how to define and build policies around reducing open agricultural burning (UNECE, 2022).

Perturbing emissions from these two sectors separately over the 9 regions (8 regions + all) implies that global models participating in perturbation experiments would have 18 simulations to run. Figure 4 shows the distribution of the dominant fire types, which was developed for the application of fire type-specific FRP-to-dry matter burnt conversion and smoke constituent emission factors. It is based on the original GFAS fire type classification and spatial maps of ESA CCI Land cover (ESA 2017) and PEATMAP (Xu et al. 2018). GFAS4HTAP will use a classification that is closer to the one of ESA CCI Land cover.





782

Figure 4: and cover map for the GFAS4HTAP BB emissions for CAMS: 0 is water and ice, 1 is savanna, 2 is savanna organic
soil, 3 is agriculture, 4 is agriculture organic soil, 5 is tropical forest, 6 is peat, 7 is extratropical forest, and 8 is extratropical
forest organic soil. (Fig. 8 of Kaiser & Holmedal, 2024).

786

787 **4.5.3** What is the impact of different fire processes? Process perturbation experiments

The following sensitivity studies perturbing key processes one at a time are meant to better understand and potentially reduce these key uncertainties.

790 Fire plume height

791 Most of the pollutants emitted from wildfires are released directly into the atmospheric boundary layer. However, depending 792 on the meteorological conditions and the strength of the fire, material can be lifted well into the free troposphere or in extreme 793 cases, the stratosphere. This can have a substantial influence on the downwind impacts of the fire, as horizontal transport is 794 typically faster in the free troposphere, the chemical processing of oxidants such as O_3 is typically more efficient, and the 795 removal of pollutants by deposition processes is less efficient than in the boundary layer. Previous model studies have 796 quantified the importance of injection height for key pollutants (e.g., Leung et al., 2007; Feng et al, 2023) but this has not been 797 explored in a rigorous manner across a range of models. On longer timescales, the presence of high levels of BC in plumes 798 can lead to local heating which causes further lofting of the plume (e.g., Ohneiser et al., 2023). The altitude of tropospheric 799 O3 also influences the magnitude of its warming potential. Therefore, fire plume height introduces substantial uncertainty into 800 assessment of impacts.

Some fire emission datasets (such as GFAS and GBBEPx) are based on FRP, whereas others, like GFED and FINN emissions, are based on burned area (BA). Both FRP and BA are (mainly) based on MODIS satellite observations. Daily information on wildfire injection heights, and/or FRP (Fire Radiative Power), in combination with meteorological parameters, can be used in the calculation of the vertical distribution of fire plumes. Daily fire emissions based on FRP and BA differ substantially on a daily basis. Some fire emissions datasets, such as GFAS provide injection height parameters based on satellite-observed FRP and available meteorological parameters (Remy et al., 2017).

807 Some models represent plume rise in their simulations while other models do not. Among the models that address plume rise, 808 some include online parameterization of fire plume rise. For example, the Freitas scheme (Freitas et al., 2007; 2010) calculates 809 plume rise by solving a set of 1-D differential equations vertically, while the Sofiev scheme considers the conservation of the 810 heat energy (Sofiev et al., 2012; 2013). The Canadian Forest Fire Emission Prediction System (CFFEPS) contains a 811 thermodynamically-based fire plume height parameterization based on fire energy and neutral buoyancy (Chen et al., 2019). 812 Other models use a simpler approach of a constant plume injection height climatology (e.g., Dentener et al, 2006; Val Martin 813 et al., 2010; 2012), which usually depends on region, season, and vegetation type, and does not consider FRP or fire size for 814 specific fires. It is important to understand the impacts of different plume rise treatments on the model results, exploring the 815 impacts of fuel type, moisture and heat flux assumptions across the plume rise schemes used. Fire plume heights derived from 816 CALIPSO, MISR, TROP-OMI (Griffin et al., 2020) global satellite data, and regional airborne instruments (Shinozuka et al., 817 2020; Doherty et al., 2022) could be used for quantitative model evaluation of fire plume height and vertical distribution. 818

818 Impacts of fire plume height were found to be different when looking at regional simulations versus at global climatological 819 scales, In Field et al (2024), using GFAS injection heights improved model performance at regional scales, whereas long-range 820 transport patterns, influenced by the winds in the driving meteorology, mattered more than individual fire events at

821 climatological time scales.

822 Fire plume chemistry

Biomass burning emits particles along with NO_x, nitrous acid (HONO), ammonia (NH₃), CO and CH₄, and hundreds of VOCs, including a large number of oxygenated VOCs (OVOCs) (Jaffe et al., 2020). Representing this chemical complexity is a key challenge for modelling fire impacts on air quality, especially for secondary pollutants such as O_3 (Section 3.1.1) and SOA.

826 State-of-the-art atmospheric chemistry models typically overpredict O_3 close to fires but have difficulty simulating the 827 influence of aged wildfire smoke plumes on downwind O₃ (e.g., Pfister et al., 2008; Singh et al., 2012; Zhang et al., 2014; 828 Fiore et al., 2014; Lin et al., 2017; Baker et al., 2016; Zhang et al, 2020; Jaffe et al., 2020). This may reflect: (1) inaccurate 829 fire emissions, especially underestimates of oxygenated VOC emissions from wildland fires (Arnold et al., 2015; Jin et al., 830 2023; Permar et al., 2023; Lin et al., 2024b); (2) lack of sufficient resolution or parameterization of smoke plume rise dynamics 831 (Paugam et al., 2016; Ye et al., 2023); (3) shortcomings in model representation of rapid photochemical processes in a 832 concentrated smoke plume (Singh et al., 2012). Several modelling studies have shown strong sensitivity of O₃ production to 833 differences in VOC chemistry, fire plume vertical transport, and NOy partitioning (Zhang et al., 2014; Arnold et al., 2015; Lin 834 et al., 2024b). Rapid conversion of NO_x to more oxidized forms typically reduces excessive ozone production simulated in 835 near-fire smoke plumes. A recent study by Lin et al. (2024b) shows that sequestration of wildfire NOx emissions in Canada as 836 PAN enhances ozone production during smoke transport and thereby increases the impacts of Canadian wildfires on ozone air 837 quality in US cities.

Additionally, large uncertainties in carbonaceous aerosol emissions from biomass burning (Pan et al., 2020; Carter et al., 2020; Xie et al., 2020) can also influence simulations through the impacts of aerosols on heterogeneous chemistry and photolysis rates. Further suggestions for model experiments to assess O_3 chemistry uncertainties appear in Section 5.3.1.

An additional challenge is the rate of SOA formation (Section 3.1.3). While SOA formation increases near-source, measurements taken after long-range free-trpopsheric transport suggest SOA loss (Sedlacek et al., 2022; Dobracki et al., 2023), hypothesized to occur through heterogeneous oxidation primarily. Estimates of the reaction rates with OH vary, and measurements focused on constraining these rates would improve model depictions. OA loss is not included in many models (e.g., Lou et al. 2022 only considers photolysis, although their modelling construction could be using photolysis as a proxy for heterogeneous oxidation OA loss as well) but could be encouraged in the model output for this project.

847 Dry and Wet deposition

Modelled dry and wet deposition fluxes are highly variable, uncertain, and a possibly significant cause for inter-model differences in pollutant concentrations. Models can test out different wet and dry deposition schemes, and/or turn deposition on and off to quantify its impact. Deposition is also important for evaluating ecosystem impacts. Wet and dry deposition fluxes should be diagnosed from all model simulations.

4.5.4 How will fires and their impacts change in the future? Future scenario experiments.

853 The frequency and severity of wildland fires are likely to increase within a warming climate, particularly in the northern 854 hemisphere (van Wees et al., 2021). Quantifying the influence of these changes, given different future emission scenarios, is 855 an important application of models (e.g., Xie et al., 2022). Future modelling experiments can be performed with chemical transport models that use provided future emissions and meteorology (see Section 5.2). Experimentation can also be performed 856 857 by ESMs with and without interactive fire modules. ESMs can typically simulate future climate/meteorological conditions in 858 a free running state out to 2100. Experiments for future fires with both interactive ESMs and other atmospheric models driven 859 offline will help determine the range of uncertainty on future fire projections and their impacts. While fire emissions are likely 860 to change under the effects of changes in human management practices and policies, those aspects that aren't already included 861 in the CMIP SSP scenarios (Xie et al., 2022) are beyond the scope of this study due to a lack of scenario emissions datasets.

862 5. Recommended Plan

863 5.1 Simulation periods

864 Given the combination of emissions dataset availability (Section 4.4) and existing observational datasets to compare against 865 (Section 4.4), we suggest the following time frames for simulation years (Table 3). The short historical option for the HTAP3 866 OPNS and Hg projects was selected to be 2015. However, 2015 had a strong El Niño and was an extreme fire year in Indonesia 867 as a result. Fires are so greatly variable on interannual scales that it would be unwise to base policy decisions on analysis of a 868 single year. We therefore encourage use of the medium historical option, which includes field campaigns of 2016-2018 that 869 were offshore from African fires (Redemann et al., 2021; Haywood et al., 2020; Zuidema et al., 2018), and 2019 which had a 870 field campaign in the US. The medium option stops by the end of 2019 to avoid incorporating the complexity in anthropogenic 871 emissions that arose with the COVID-19 pandemic in 2020. The medium future option includes 5 years on either side of the 872 2015 start and 2050 end dates of the GAINS future emissions to enable 10-year averages to be created around these start and 873 end dates, thus accounting for interannual variability, consistent with the HTAP3 OPNS project. The 2015 emissions may be 874 used for 2010-2014, and the 2050 emissions for 2051-2055. Finally, while the climate community routinely does simulations 875 out to 2100, given that the GAINS anthropogenic emissions end in 2050, and the AerChemMIP2/CMIP7 community (see 876 Table A.1 and Section 3.3) will focus on future simulations, including climate impacts from fires, we have elected not to 877 include a long future option within this study.

878

879 **Table 3:** Simulation time periods, with options for different types of models.

	Short option	Medium option	Long option
Historical	See Case studies (Sec 4.5.1 and Table 5)	2015-2019	2003-2020

	Future	2045	2010-2020 and 2040-2050	2010-2050
--	--------	------	-------------------------	-----------

880

881 5.2 Inputs: Emissions and Meteorology

Based on discussions in Section 4.2, the following emissions datasets are recommended, and summarized in Table 4 below.
For methane, the only options in Section 4.2.5 are recommended.

884 *Historical Fire emissions:*

885 The historical fire emissions datasets were carefully considered during and following a 4-day online workshop hosted by IGAC 886 BBURNED in November 2023. The methodology, advantages, and disadvantages of each major global fire emissions dataset 887 were discussed. It was agreed to recommend use of the fire emissions based on GFASv1.2 because (a) they provide daily 888 emissions (providing improved temporal variability over monthly emissions), (b) they include peatland fires, including in the 889 boreal region, the latter particularly important for the AMAP scientific community, and (c) they provide fire plume heights as 890 well as speciated emissions. The GFASv1.2 emissions have since been updated with the most recent emission factors and land 891 categories, and are called GFAS4HTAPv1.2.1. We furthermore note that peat fire emissions remain highly uncertain, and that 892 these fire emissions do not include special treatment of WUI fires. We also note that modellers may apply these emissions at

their preferred temporal resolution for baseline simulations.

894 Future fire emissions:

The future fire emissions dataset that is derived from a multi-model ensemble that includes the influence of the changing climate on fires is that from Hamilton and Kasoar (personal communication; Hamilton, Kasoar, et al, submitted). We recommend use of this future fire emissions dataset, but note that it does not include scenarios for future changes to fire management policy and practice, as these quantitative emissions adjustments are not available yet.

899 Historical anthropogenic emissions:

These are chosen to be consistent with the other concurrent HTAP3 projects. They are the HTAP v3.1 anthropogenic emissions, which were delivered in early 2025, for the years 2000 to 2020, inclusive. They include all relevant species except Hg, PAHs, and PCDD/Fs. The anthropogenic emissions for those species should be: EDGARv8.1 (Hg), PKU-GEMS (PAHs), and PKU-

903 LZU (PCDD/Fs), as discussed in Section 4.2.1.

904 Future anthropogenic emissions:

- 905 For consistency with other HTAP3 projects, the CLE (current legislation) future emissions from IIASA GAINS (LRTAP) will
- 906 be used in future simulations. Climate modellers may wish to simulate out to 2100, and while the SSP2-4.5 anthropogenic
- 907 emissions for 2015 to 2100 are available and are roughly equivalent to the GAINS CLE emissions scenario for CO₂ and energy,
- 908 they are not necessarily similar for other pollutant emissions. We therefore recommend for this project ending the future
- simulation in 2050 and participating in CMIP7/AerChemMIP2 for longer future simulations.
- 910 Biogenic and other natural emissions:

- 911 While it is useful to have consistent emissions across models, this can be difficult to achieve due to the dependence of natural
- 912 emissions on structural aspects of models including vegetation, soils and land use. Therefore, we suggest that each modelling
- 913 centre use their preferred emissions from biogenic and other natural sources. These should be documented and taken into
- 914 consideration in the analysis.
- 915
- 916 **Table 4:** Emissions inputs for model experiments. See Data Availability for more information.

Emission type	Recommendation	Notes			
Historical simulations (2003-2020)					
Fire	GFAS4HTAP for BB, including agricultural burning	Daily gridded global 0.1-degree resolution. Including its agricultural burning emissions.			
Anthropogenic	HTAPv3.1	Minus its agricultural burning.			
Future simulations (20	Future simulations (2010-2050)				
Fire	GFAS4HTAP for 2010- 2020 and Hamilton, Kasoar et al for 2020-2050)	SSP2-4.5-scenario-based climate- influenced future fire emissions, calibrated to GFAS4HTAP historical fire emissions. (Both <i>not</i> including agricultural burning).			
Anthropogenic	IIASA GAINS CLE	Including agricultural burning			
Biogenic and other natural emissions: Each modelling centre use their default					

917

918 Driving meteorology

As discussed in Section 4.3, there are several data reanalysis collections that could potentially be employed. Although the ERA5 collection offers greater spatial, temporal, and vertical resolution overall, any of the mentioned datasets would be suitable for use. It is recommended that modellers use ERA5 if possible, but otherwise use their preferred meteorology for historical simulations and ensure that they document this clearly. For future simulations, as discussed in Section 4.3.2, we suggest using inter annually varying, monthly mean sea surface temperatures and sea ice distributions from the SSP2-4.5 multimodel CMIP6 ensemble.

5.3 Model experiments

- 926 The following model experiments in Table 5 are proposed based on the discussions in Section 4.5, and further details for
- 927 selected experiments is described below.

Table 5: Model experiment (exp) types

Exp name	Description	Purpose	Priority
1. Baseline simulation	Historical time period(s) given in Table 3. Common set of emissions given in Table 4.	Model evaluation; baseline for subsequent sensitivity and perturbation exps	High
2. Case study(ies)	More detailed, specific fire events (Indonesia 2015; North America 2018,2019; and Australia 2019-2020) at higher spatial and temporal resolution	Model evaluation	High for regional models. Low for global models.
3. Fire emissions sensitivity	Same as exp 1, but driven by different sets of fire emissions (GFED, FINN, etc)	Model/emissions evaluation; to gauge differences between fire emission datasets across models	Low
4. Prescribed future fires	Future time period(s) given in Table 3. Future emissions given in Table 4.	To determine how wildland fires and their impacts will change in the future	High
5. Regional and sectoral emissions perturbations	Turn off all BB emissions for all species everywhere. Turn BB emissions off in each region of Figure 3d, and each of the 2 sectors: agricultural burning and wildland fires, over the historical time periods in Table 3.	To quantify regional source/receptor relationships and uncertainties	High for both fire sectors combined. Low for separate sectors.
6. Fire process perturbations	Parameter/process perturbations, for fire plume height, chemistry, emissions, and meteorology (see Section 5.3.1). Short-to-middle time periods of Table 3.	To determine importance of different processes and impacts of different model fire parameterizations	Medium
7. Interactive fire modules	Historical and future simulations (Table 3) with coupled land- atmosphere models.	To determine how wildland fires will change in the future with an interactive climate and	Medium

		compare to exp 4 results.	
8. Data assimilation	Inverse modelling to combine CTMs with observed atmospheric VMRs of CO (MOPITTv9), O3 (OMI), NO2 (OMI). See Table 6.	Infer surface-atmosphere emissions/fluxes.	Low

930

931 **5.3.1 Details for fire process perturbation experiments (exp6)**

- While a short time range for perturbation experiments can help keep model simulations manageable, they may not provide generalizable results, given the high interannual variability of fires. Therefore, the time ranges of Table 3 should be followed for perturbation experiments as well.
- *Injection height:* Repeat of exp1 with alternative fire plume height definitions. We suggest the following options, where
 modellers can opt into any number of these when possible:
- model's default fire plume height system, whatever it may be,
- the plume heights, specifically FRP-based "mean altitude of maximum injection" calculated by a plume rise model
 in baseline fire emissions dataset (GFAS4HTAP) (Section 4.5)
- climatological plume rise from AEROCOM (Dentener et al., 2006), assuming standard vertical profiles, and
- no plume rise: assuming all pollutants are released into the lower part of the planetary boundary layer.

942 *Chemistry:* To assess the impacts and uncertainties around fire plume chemistry, a few sensitivity runs are recommended:

- Partition total NO_y emissions from biomass burning into PAN (37%), HNO₃ (27%), and NO_x (36%), rather than emitting only NO in the baseline simulation (exp1), as recommended by Lin et al. (2024a, 2024b) based on recent aircraft measurements (WE-CAN 2018 and FIREX-2019).
- Doubling BB emissions of all NMVOCs, including formaldehyde and acetaldehyde producing acetyl peroxy radical
 (CH3CO3) for PAN formation;
- For models with suitable capability, exploration of the effects of different levels of complexity in VOC chemistry or
 differences in volatility or reactivity of VOC.
- Increasing BB emissions of OC and BC aerosols by 50% to explore their impacts on oxidative chemistry through
 heterogeneous chemistry or photolysis.
- 952 *Emissions temporal resolution:* Repeat of exp1 with hourly, daily, and monthly versions of the fire emissions to quantify the 953 importance of temporal resolution. Many previous major studies, such as CMIP6, have used monthly fire emissions and this 954 sensitivity study will allow these results to be placed in context.
- 955 *Meteorology*: Use repeating annual meteorology for 2018 with interannually changing emissions to determine how much of 956 interannual variability in impacts seen in exp 1 is due to meteorology, and not emissions.

957 **5.3.2 Details for future experiments (exp4)**

The SSP2-4.5 future climate scenario will be the driver for the future time period, which includes those future fire emissions from Hamilton & Kasoar (submitted), and the GAINS CLE anthropogenic emissions. For future agricultural burning emissions, which appear in both the BB and the anthropogenic emissions datasets, we recommend that the GAINS future agricultural burning emissions be used, and those removed from the BB emissions so as not to double-count them.

962

963 **5.3.3 Details for data assimilation experiments (exp8)**

Models that can do data assimilation of observations are recommended to assimilate measurements depending on the period of interest (see Table 6), in order to constrain CO, NO2 or O3 fire prior emissions used in the baseline experiments.

967 **Table 6:** Measurements to be assimilated depending on experiment and period of simulation.

	Gases	Long option (2003-2020)	Medium option (2015-2019)	2015 Indonesian fires	2019-2020 Australian fires
СО	Sensor, Satellite	MOPITT, TERRA		TROPOMI, Sentinel 5P	
	Version	Level 2 version 9			Level 2 v2.4.0
	Reference	Deeter et al., 2022			Apituley et al., 2022
NO2	Sensor, Satellite	OMI, AURA			TROPOMI, Sentinel 5P
	Version	Level 2 v3			Level 2 v2.4.0
	Reference	Lamsal et al., 2021			Eskes et al., 2022
03	Sensor, Satellite	OMI, AURA		TROPOMI, Sentinel 5P	
	Version	Level 2 v3		Level 2 v2.4.0	
	Reference	Veefkind et al., 2012b		Romahn et al., 2022	

968

969 Satellite observations to be considered are the Measurement of Pollution in the Troposphere (MOPITT, Deeter et al., 2003; 970 Edwards et al., 2006) CO measurements. Since MOPITTv9 has overpasses only every 16 days with a resolution of 25 km, we 971 recommend assimilating the Tropospheric Monitoring Instrument (TROPOMI, Veefkind et al., 2012a) Level 2 measurements, 972 launched in fall 2017, which has daily global coverage and fine resolution (5x7 km2 for CO at nadir) for the case study

973 simulation of Australia. For some CTMs at coarse spatial resolution (even at $1^{\circ}x1^{\circ}$ spatial resolution), and because of the fine 974 resolution of TROPOMI, large computational costs can rise. It is then possible to use TROPOMI super-observations (area-975 weighted average of the pixel at coarser resolution) following the approach of Miyazaki et al., (2012). For NO₂ and O₃ long 976 and medium term inversions, observations such as the Ozone Monitoring Instrument (OMI, Levelt et al., 2006) with data 977 available since 2005 can be used. Surface measurements can be considered to constrain background concentrations, 978 particularly for regional emission estimates (such as the nested zoom model TM5 and GEOS-Chem). The assimilation here 979 will help to determine how the GFAS4HTAPv1.2.1 emissions would be constrained. Assimilation algorithms (3Dvar, 4Dvar, 980 or Ensemble Kalman Filter) as well as prior and observations uncertainty, and OH fields do not have specific recommendations 981 and each user is free to choose these parameters.

982 **5.4 Model outputs**

To maximise accessibility of the results, the model output data request for this project is based on the AerChemMIP tables from CMIP6, as adopted by the HTAP OPNS project, with some additions for the extra species and impacts. The Table of model outputs is located online at <u>https://nextcloud.gfz-potsdam.de/s/sp8XmMY2rQizjA4</u>. We have added Hg, POPs, and PAHs, and place greater priority on hourly surface NO₂, PM_{2.5}, and O₃, as well as hourly O₃ deposition parameters needed for air quality, health, and ecosystem impacts analysis, in addition to monthly radiative flux output for climate impacts. When measurements and impacts are only related to surface concentrations (e.g., POPs), we have suggested only surface-level 2D model output be provided to save storage space.

990 Data workspace

The model output can be uploaded to METNO's AeroCom database and infrastructure as part of the HTAP3 component of the AeroCom database. Instructions for obtaining access to the aerocom-user server, formatting, uploading, downloading are found here: <u>https://aerocom.met.no/FAQ/data_access</u>. The AeroCom database infrastructure is available to host HTAP model data on a read-only permanent database, which can be accessed by authorised users with an account on the aerocom-user server. A scratch area on the AeroCom-user server can be used to upload data. Uploaded data can be transferred on demand by METNO to the read-only permanent database section for HTAP, under the directory HTAP-PHASE-III.

997

998 **5.5 Post processing and analysis**

This multi-pollutant, multi-model experiment will generate a large amount of data that will be analysed to answer the sciencepolicy questions of Section 2.

1001 5.5.1 Model evaluation: Comparison of experiments 1, 2, 3, and 6 to observations

By comparing the results of experiments 1, 2, 3, and 6 to the observations discussed in Section 4.4 (and listed in Table S1), specific model inputs and processes can be evaluated. Note that Table S1 is not an exhaustive list of measurements that may
1004 be used in model evaluation, and it also includes some measurements that may not overlap in time with the simulations. The 1005 aim of the evaluation would be to improve our understanding of fire processes, such as plume rise, plume chemistry and 1006 improve their parameterizations in models. We may also be able to determine which inputs (emissions, meteorology) and 1007 parameterizations are best, as well as identify gaps that require further research. One example would be to analyse the impacts 1008 of injection heights on PAN concentrations in the free troposphere and downwind O₃ formation as fire plumes subside into the 1009 boundary layer, by comparing the model simulations of PAN and related tracers to recent aircraft measurements. We suggest 1010 that, when possible, community tools like MELODIES (Model EvaLuation using Observations, DIagnostics and Experiments 1011 Software), and ESMValTool be used for inter-model comparisons and evaluation against observations. Regardless, the 1012 evaluation will require a large effort by the community.

1013 5.5.2 Assessing health impacts of fires

1014 The most cited and widely used approaches of risk analysis are: all cause of deaths; mortality and morbidity impacts; 1015 emergency hospitalization; reduced life expectancy; premature mortality; incremental life-time cancer risk; and health-related 1016 cost of air pollution (Goel et al., 2021; Sonwani et al., 2022; Nagpure et al., 2014; Gidhagen et al., 2009; Guttikunda et al., 1017 2014; Ghozikali et al., 2014; Farzaneh, 2019). Human health risk assessment is the mathematical estimation and modelling of 1018 several processes, including population estimates, population exposure to pollutants, and adverse health impacts assessment 1019 through specific concentration-response functions (WHO, 2021). Widely used quantitative health risk assessment tools of 1020 different agencies have been listed in Table S3. While Table S4 represents the comparison between the air pollution health 1021 risk assessment tools (methodologies, scopes, input parameters, and predicted health impacts). The surface-level model outputs 1022 of atmospheric composition at high spatial (O(10 km) for global, O(1 km) for regional models) and temporal (monthly down 1023 to daily) resolution will be invaluable for new health risk assessments, especially when fused with other modelling (e.g., land-1024 use regression) and observational (e.g., remote sensing) techniques (Johnson et al., 2020)

1025 5.5.3 Assessing climate impacts of fires

1026 Climate impacts can be assessed through the RF from fire-emitted pollutants by comparing the differences of the radiative 1027 fluxes of the simulations with and without fire emissions. (i.e. the Baseline simulation and the regional and sectoral emissions 1028 perturbations). To assess the component specific RFs more detailed simulations with source attribution techniques, such as 1029 those for O3 (Grewe et al., 2017; Butler et al., 2018), or for aerosols (Righi et al. (2021)) are helpful. Models capable of such 1030 possibilities therefore perform additional pollutant specific perturbations including source attribution techniques. Moreover, 1031 the model's composition fields can be applied in offline radiative transfer models or via the kernel method to calculate the 1032 component specific RF. These should be included in the regional perturbation experiments in order to have the required data 1033 to assess the RF impacts of biomass burning. For estimation of future fire RF, it is key to quantify the effects caused by the 1034 non-linearities on the O3 RF and for the aerosol-cloud interactions.

1035 5.5.4 Assessing future vs historical changes

While the future BB emissions are calibrated to the historical emissions, the future anthropogenic emissions are not calibrated to the historical anthropogenic emissions. Therefore, analysis of the full historical to future time period (2003-2050) should be done with care: The absolute, but not relative, changes to BB results can be assessed for 2003-2050, however, the future versus present changes (absolute and relative of 2040-2050 vs 2010-2020 for example) should be assessed from simulations using only the future anthropogenic emissions input for consistency (see Table 3).

1041 6 Conclusions

1042 In this paper we have described the need for a multi-model, multi-pollutant study focused on fires, and highlighted a range of 1043 important science-policy questions arising from discussions with the scientific and policy communities that this study is 1044 intended to answer. The study will address gaps in our current scientific understanding of fire processes and provide a more 1045 robust quantification of fire pollution and its impacts to inform decision-making. We have thoroughly discussed the scope of 1046 this study (Section 3), based on extended consultation with the science, impacts and policy communities, and have outlined a 1047 number of model design options that were considered (Section 4), with the ultimate choices justified. We then provide the 1048 recommended specifications for the modelling study (Section 5) to be carried out over the next ~3 years that will provide 1049 maximal benefit for the scientific community and for key policy-adjacent communities including HTAP and AMAP. HTAP3 1050 Fires is aimed at providing fresh understanding of the atmospheric and environmental impacts of fires and providing the 1051 foundation for sound policy decisions

1052 Acknowledgements

We thank the following people for contributing their ideas for this study: Sabine Eckhardt, Twan van Noije, Marianne Tronstad
Lund, Ilia Ilyin, Havala Pye, Siti Aminah Anshah, Keren Mezuman, Nikos Daskalakis, Solène Turquety, Matthew MacLeod,
Rosa Wu, and Terry Keating.

1056

1057 **Funding Sources**

PZ acknowledges support from DOE ASR DE-SC0021250 and NASA 80NSSC21K1344. The contributions from MM were funded by the German Federal Ministry of Education and Research (Funding Nr.: 01LN2207A, IMPAC²T). EBM would like to acknowledge: The European Research Council under the Horizon 2020 research and innovation programme through the ERC Consolidator Grant FRAGMENT (grant agreement no. 773051), the AXA Research Fund through the AXA Chair on Sand and Dust Storms at the Barcelona Supercomputing Center (BSC), and the BIOTA project PID2022-139362OB-I00 funded by MICIU/AEI/10.13039/501100011033 and by ERDF, EU. HP acknowledges funding through the 'Burning questions on carbon emission from fires' – project GO 2022-1 of the GO-program NWO.

1065 Data availability

- 1066 The regional land mask (Fig 3d) is available here: <u>https://zenodo.org/records/14908253</u> (Whaley et al, 2025).
- 1067 The HTAPv3.1 anthropogenic emissions files for the historical period are available here:
- 1068 https://edgar.jrc.ec.europa.eu/dataset_htap_v31 and https://doi.org/10.5281/zenodo.14499440 (Crippa et al, 2023)
- 1069 The IIASA GAINS anthropogenic emissions files for the future period are available here:
- 1070 https://zenodo.org/records/14748815 (Klimont et al, 2024)
- 1071 The GFAS4HTAPv1.2.1 biomass burning emissions for the historical period are available here:
- 1072 https://zenodo.org/records/13753452 (Kaiser et al, 2024).
- 1073 The Hamilton et al biomass burning emissions for the future period are freely available from the Coupled Model
- 1074 Intercomparison Project at https://aims2.llnl.gov/search (Hamilton et al, 2024, 2025) and the post-processed emissions will
- 1075 be provided to participants.
- 1076 The ERA5 reanalysis recommended for meteorology is available here:
- 1077 <u>https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form</u> (Hersbach et al, 2023)
- 1078 The observational datasets for the assimilation experiments are available here:
- 1079 MOPITTv9 CO: Level 2 data are available through the NASA EarthData portal https://urs.earthdata.nasa.gov/ (MOPITT
- 1080 <u>Team, 2022</u>)
- 1081 TROPOMI NO2, CO and O3: Level 2 datasets are made available operationally through the ESA Sentinel-5P data hub
- 1082 (<u>https://scihub.copernicus.eu/</u>).
- 1083 OMI NO2 v4: https://search.earthdata.nasa.gov/search?q=OMNO2G_003
- 1084 OMI O3 v3: https://search.earthdata.nasa.gov/search?q=OMTO3 003
- 1085

1086 Author Contributions

1087 CHW was coordinating lead on this paper, TB and JWK represented the TF HTAP steering committee, and *all* authors co-1088 wrote the paper.

1089 **References**

- 1090 Adebiyi, A. A., Akinsanola, A. A., Ajoku, A. F.: The misrepresentation of the African Easterly Jet in Models and its
- 1091 implications for aerosols, clouds and precipitation distributions. J. Climate., 36, p. 7785-7809. doi:10.1175/JCLI-D-23-
- 1092 0083.1, 2023.
- 1093 Adebiyi, A. and P. Zuidema, 2018: Low cloud sensitivity to biomass-burning aerosols and meteorology
- 1094 over the southeast Atlantic. J. Climate, **31**, p. 4329-4346, doi:<u>10.1175/JCLI-D-17-0406.1</u>

- 1095 Aguilera, R., Corringham, T., Gershunov, A., and Benmarhnia, T.: Wildfire smoke impacts respiratory health more than fine
- 1096 particles from other sources: observational evidence from Southern California, Nature Communications, 12, 1493,
- 1097 10.1038/s41467-021-21708-0, 2021.
- Aguilera, R., Corringham, T., Gershunov, A., Leibel, S., and Benmarhnia, T.: Fine Particles in Wildfire Smoke and Pediatric
 Respiratory Health in California, Pediatrics, 147, 10.1542/peds.2020-027128, 2021b.
- 1100 Aisbett, B., Wolkow, A., Sprajcer, M., Ferguson, S.A.: "Awake, smoky, and hot": providing an evidence-base for managing
- the risks associated with occupational stressors encountered by wildland firefighters. Appl. Ergon. 43, 916-925, 2012.
- 1102 Alexaki, N., van den Hof, M., Jol, K.: From Burning to Buying: Creating A CircularProduction Chain Out of Left-Over Crop
- 1103 Residue from Indian Farm Land. NetherlandsEnterprise Agency, Utrecht, pp. 1–30. Available online at.
- 1104 https://www.rvo.nl/sites/default/files/2019/12/MVO-Nederland-rapport-India.pdf., 2019.
- 1105 Alvarado, M. J., C. R. Lonsdale, R. J. Yokelson, S. K. Akagi, H. Coe, J. S. Craven, E. V. Fischer, G. R. McMeeking, J. H.
- 1106 Seinfeld, T. Soni, J. W. Taylor, D. R. Weise, and C. E. Wold: Investigating the links between ozone and organic aerosol
- 1107 chemistry in a biomass burning plume from a prescribed fire in California chaparral. Atmos. Chem. Phys. 15 (12):6667-
- 1108 6688. doi: 10.5194/acp-15-6667-2015, 2015.
- 1109 Alvarado, L. M. A.; Richter, A.; Vrekoussis, M.; Hilboll, A.; Hedegaard, A. B. K.; Schneising, O.; Burrows, J. P.
- 1110 Unexpected Long-Range Transport of Glyoxal and Formaldehyde Observed from the Copernicus Sentinel-5 Precursor
- Satellite during the 2018 Canadian Wildfires. Atmos Chem. Phys. 2020, 20 (4), 2057–2072, DOI: 10.5194/acp-20-20572020
- 1113 AMAP, AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human
- 1114 Health. Arctic Monitoring and Assessment Programme (AMAP), Tromso, Norway. x + 375pp, 2021.
- 1115 Anema, J. C. S., Boersma, K. F., Stammes, P., Koren, G., Woodgate, W., Köhler, P., Frankenberg, C., and Stol, J.:
- 1116 Monitoring the impact of forest changes on carbon uptake with solar-induced fluorescence measurements from GOME-2A
- and TROPOMI for an Australian and Chinese case study, Biogeosciences, 21, 2297–2311, <u>https://doi.org/10.5194/bg-21-</u>
 2297-2024, 2024.
- 1119 Amjad, S., Chojecki, D., Osornio-Vargas, A., and Ospina, M. B.: Wildfire exposure during pregnancy and the risk of adverse
- birth outcomes: A systematic review, Environment International, 156, 106644, https://doi.org/10.1016/j.envint.2021.106644,
 2021.
- 1122 Apituley, A., Pedergnana, M., Sneep, M., Veefkind, J. P., Loyola, D., Landgraf, J., and Borsdorff, T.: Sentinel 5 precursor
- 1123 TROPOMI Level 2 Product User Manual Carbon Monoxide, Tech.rep., ESA, https://sentinel.esa.int/documents/247904/
- 1124 2474726/Sentinel-5P-Level-2-Product-User-Manual-Carbon-Monoxide.pdf, 2022.

- 1125 Arellano AF, Kasibhatla PS, Giglio L, van der Werf GR, Randerson JT, Collatz GJ (2006) Time-dependent inversion
- estimates of global biomass-burning CO emissions using Measurement of Pollution in the Troposphere (MOPITT). J
- 1127 GeophysRes 111:D09303. doi:10.1029/2005JD006613.
- 1128 Ardyna, M., Hamilton, D. S., Harmel, T., Lacour, L., Bernstein, D. N., Laliberté, J., Horvat, C., Laxenaire, R., Mills, M. M.,
- 1129 van Dijken, G., Polyakov, I., Claustre, H., Mahowald, N., and Arrigo, K. R.: Wildfire aerosol deposition likely amplified a
- summertime Arctic phytoplankton bloom, Commun. Earth Environ., 3, 1–8, https://doi.org/10.1038/s43247-022-00511-9,
- 1131 2022.
- 1132 Arnold, S. R., Emmons, L. K., Monks, S. A., Law, K. S., Ridley, D. A., Turquety, S., Tilmes, S., Thomas, J. L., Bouarar, I.,
- 1133 Flemming, J., Huijnen, V., Mao, J., Duncan, B. N., Steenrod, S., Yoshida, Y., Langner, J., and Long, Y.: Biomass burning
- 1134 influence on high-latitude tropospheric ozone and reactive nitrogen in summer 2008: a multi-model analysis based on
- 1135 POLMIP simulations, Atmos. Chem. Phys., 15, 6047–6068, https://doi.org/10.5194/acp-15-6047-2015, 2015.
- 1136 Ascoli, D., Plana, E., Oggioni, S. D., Tomao, A., Colonico, M., Corona, P., Giannino, F., Moreno, M., Xanthopoulos, G.,
- 1137 Kaoukis, K., Athanasiou, M., Colaço, M. C., Rego, F., Sequeira, A. C., Acácio, V., Serra, M., and Barbati, A.: Fire-smart
- solutions for sustainable wildfire risk prevention: Bottom-up initiatives meet top-down policies under EU green deal, Int. J.
- 1139 Disaster Risk Reduct., 92, 103715, https://doi.org/10.1016/j.ijdrr.2023.103715, 2023.
- 1140 Baker, K. R., Woody, M. C., Tonnesen, G. S., Hutzell, W., Pye, H. O. T., Beaver, M. R., Pouliot, G., and Pierce, T.:
- 1141 Contribution of regional-scale fire events to ozone and PM2.5 air quality estimated by photochemical modelling approaches,
- 1142 Atmos. Environ.,140, 539–554, doi:10.1016/j.atmosenv.2016.06.032, 2016
- 1143 Barkley, A. E., Prospero, J. M., Mahowald, N., Hamilton, D. S., Popendorf, K. J., Oehlert, A. M., Pourmand, A., Gatineau,
- 1144 A., Panechou-Pulcherie, K., Blackwelder, P., and Gaston, C. J.: African biomass burning is a substantial source of
- 1145 phosphorus deposition to the Amazon, Tropical Atlantic Ocean, and Southern Ocean, Proc. Natl. Acad. Sci. U. S. A., 116,
- 1146 16216–16221, https://doi.org/10.1073/pnas.1906091116, 2019.
- 1147 Bernstein, D., Hamilton, D. S., Krasnoff, R., Mahowald, N. M., Connelly, D. S., Tilmes, S., and Hess, P. G. M.: Short-term
- 1148 impacts of 2017 western North American wildfires on meteorology, the atmosphere's energy budget, and premature
- 1149 mortality, Environ. Res. Lett., 16, 064065, https://doi.org/10.1088/1748-9326/ac02ee, 2021.
- 1150 Bories, C., L. Aouba, E. Vedrenne, G. Vilarem, Fired clay bricks using agricultural biomass wastes: study and
- 1151 characterization, Constr. Build. Mater., 91 (2015), pp. 158-163, https://doi.org/10.1016/j.conbuildmat.2015.05.006
- Bousquet, P., Ciais, P., Miller, J. B., Dlugokencky, E. J., Hauglustaine, D. A., Prigent, C., Van Der Werf, G. R., Peylin, P.,
- 1153 Brunke, E.-G., Carouge, C., Langenfelds, R. L., Lathière, J., Papa, F., Ramonet, M., Schmidt, M., Steele, L. P., Tyler, S. C.,
- and White, J.: Contribution of anthropogenic and natural sources to atmospheric methane variability, Nature, 443, 439–443,
- 1155 https://doi.org/10.1038/nature05132, 2006.
- 1156 Bowman, D. M., Balch, J., Artaxo, P., Bond, W. J., Cochrane, M. A., D'antonio, C. M., et al: The human dimension of fire
- regimes onEarth. Journal of Biogeography, 38(12), 2223–2236, 2011.

- Bowman, D., Daniels, L., Johnston, F., Williamson, G., Jolly, W., Magzamen, S., Rappold, A., Brauer, M., and Henderson,
- 1159 S.: Can Air Quality Management Drive Sustainable Fuels Management at the Temperate Wildland–Urban Interface?, Fire, 1,
- 1160 27, https://doi.org/10.3390/fire1020027, 2018.
- 1161 Brauer, M. et al.: Global burden and strength of evidence for 88 risk factors in 204 countries and 811 subnational locations,
- 1162 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021, The Lancet, Volume 403, Issue 10440, 2162
 1163 2203, 2024.
- 1164 Brotherhood, J.R., Budd, G.M., Jeffery, S.E., Hendrie, A.L., Beasley, F.A., Costin, B.P., Wu, Z.E.: Fire fighters' exposure to
- 1165 carbon monoxide during Australianbushfires. Am. Ind. Hyg. Assoc. J. 51, 234-240, 1990.
- 1166 Butler, T., Lupascu, A., Coates, J., and Zhu, S.: TOAST 1.0: Tropospheric Ozone Attribution of Sources with Tagging for
- 1167 CESM 1.2.2, Geosci. Model Dev., 11, 2825–2840, https://doi.org/10.5194/gmd-11-2825-2018, 2018.
- Butler, T. M., Rayner, P. J., Simmonds, I., and Lawrence, M. G.: Simultaneous mass balance inverse modelling of methane and carbon monoxide in the 1990s, J. Geophys. Res., 110, https://doi.org/10.1029/2005JD006071, 2005.
- 1170 Buysse, C. E., A. Kaulfus, U. Nair, and D. A. Jaffe: Relationships between particulate matter, ozone, and nitrogen oxides
- 1171 during urban smoke events in the western US. Environ. Sci. Technol. doi: 10.1021/acs.est.9b05241, 2019.
- 1172 Byrne, B., Baker, D. F., Basu, S., Bertolacci, M., Bowman, K. W., Carroll, D., Chatterjee, A., Chevallier, F., Ciais, P.,
- 1173 Cressie, N., Crisp, D., Crowell, S., Deng, F., Deng, Z., Deutscher, N. M., Dubey, M. K., Feng, S., García, O. E., Griffith, D.
- 1174 W. T., Herkommer, B., Hu, L., Jacobson, A. R., Janardanan, R., Jeong, S., Johnson, M. S., Jones, D. B. A., Kivi, R., Liu, J.,
- 1175 Liu, Z., Maksyutov, S., Miller, J. B., Miller, S. M., Morino, I., Notholt, J., Oda, T., O'Dell, C. W., Oh, Y.-S., Ohyama, H.,
- 1176 Patra, P. K., Peiro, H., Petri, C., Philip, S., Pollard, D. F., Poulter, B., Remaud, M., Schuh, A., Sha, M. K., Shiomi, K.,
- 1177 Strong, K., Sweeney, C., Té, Y., Tian, H., Velazco, V. A., Vrekoussis, M., Warneke, T., Worden, J. R., Wunch, D., Yao, Y.,
- 1178 Yun, J., Zammit-Mangion, A., and Zeng, N.: National CO2 budgets (2015–2020) inferred from atmospheric CO2
- 1179 observations in support of the global stocktake, Earth Syst. Sci. Data, 15, 963–1004, https://doi.org/10.5194/essd-15-963-
- 1180 2023, 2023.
- 1181 Juncosa Calahorrano, J. F., Lindaas, J., O'Dell, K., Palm, B. B., Peng, Q., Flocke, F., et al: Daytime oxidized reactive
- 1182 nitrogen partitioning in western U.S. wildfire smoke plumes. Journal of Geophysical Research: Atmospheres, 126,
- 1183 e2020JD033484. https://doi.org/10.1029/2020JD033484, 2021.
- 1184 California Department of Forestry and Fire Protection. Top 20 Most Destructive California Wildfires; CAL FIRE:
- 1185 Sacramento, CA,USA, 2020.
- 1186 CAMS: Europe experiences significant transport of smoke from Canada wildfires, https://atmosphere.copernicus.eu/europe-
- 1187 experiences-significant-transport-smoke-canada-wildfires, last access: 24 November 2023, 2023.
- 1188 Carter, T. S., Heald, C. L., Jimenez, J. L., Campuzano-Jost, P., Kondo, Y., Moteki, N., et al: How emissions uncertainty
- 1189 influences the distribution and radiative impacts of smoke from fires in North America. Atmospheric Chemistry and Physics
- 1190 20, 2073–2097. https://doi.org/10.5194/acp-20-2073-2020, 2020.

- 1191 Cascio, W. E.: Wildland fire smoke and human health, Science of The Total Environment, 624, 586-595,
- 1192 https://doi.org/10.1016/j.scitotenv.2017.12.086, 2018.
- 1193 Chang, D. Y., Yoon, J., Lelieveld, J., Park, S. K., Yum, S. S., Kim, J., & Jeong, S.: Direct radiative forcing of biomass
- burning aerosols from the extensive Australian wildfires in 2019–2020. In Environmental Research Letters (Vol. 16, Issue 4,
- 1195 p. 044041). IOP Publishing. https://doi.org/10.1088/1748-9326/abecfe, 2021.
- 1196 Chen C-C, Lin H-W, Yu J-Y, Lo M-H.: The 2015 Borneo fires: what have we learned from the 1997 and 2006 El Ninos?
- 1197 Environ. Res. Lett. 11, 104003, doi:10.1088/1748-9326/11/10/104003, 2016.
- 1198 Chen, C. Y. and Evers, D. C.: Global mercury impact synthesis: Processes in the Southern Hemisphere, Ambio, 52, 827–
- 1199 832, https://doi.org/10.1007/s13280-023-01842-3, 2023.
- 1200 Chen, H., Samet, J. M., Bromberg, P. A., and Tong, H.: Cardiovascular health impacts of wildfire smoke exposure, Particle 1201 and Fibre Toxicology, 18, 2, 10.1186/s12989-020-00394-8, 2021.
- 1202 Chen, J., Anderson, K., Pavlovic, R., Moran, M. D., Englefield, P., Thompson, D. K., Munoz-Alpizar, R., and Landry, H.:
- 1203 The FireWork v2.0 air quality forecast system with biomass burning emissions from the Canadian Forest Fire Emissions
- 1204 Prediction System v2.03, Geosci. Model Dev., 12, 3283–3310, https://doi.org/10.5194/gmd-12-3283-2019, 2019.
- 1205 Choi-Schagrin, W.: Wildfires are intensifying. Here's why, and what can be done. The New York Times. 2021 Sept 29 [Cited
 1206 2021 December 9], 2021.
- 1207 Chuwah, C., van Noije, T., van Vuuren, D. P., Hazeleger, W., Strunk, A., Deetman, S., Beltran, A.M., van Vliet, J.:
- 1208 Implications of alternative assumptions regarding future air pollution control in scenarios similar to the Representative
- 1209 Concentration Pathways. Atmospheric Environment, 79, 787-801. doi:10.1016/j.atmosenv.2013.07.008, 2013.
- 1210 Collins, L. et al.: The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity
- 1211 fire. Environ. Res. Lett. 16, 044029. https://doi.org/10.1088/1748-9326/abeb9e, 2021.
- 1212 Conway, T. M., Hamilton, D. S., Shelley, R. U., Aguilar-Islas, A. M., Landing, W. M., Mahowald, N. M., and John, S. G.:
- 1213 Tracing and constraining anthropogenic aerosol iron fluxes to the North Atlantic Ocean using iron isotopes, Nat. Commun.,
- 1214 10, https://doi.org/10.1038/s41467-019-10457-w, 2019.
- 1215 Crippa, M., Guizzardi, D., Butler, T., Keating, T., Wu, R., Kaminski, J., Kuenen, J., Kurokawa, J., Chatani, S., Morikawa,
- 1216 T., Pouliot, G., Racine, J., Moran, M. D., Klimont, Z., Manseau, P. M., Mashayekhi, R., Henderson, B. H., Smith, S. J.,
- 1217 Suchyta, H., Muntean, M., Solazzo, E., Banja, M., Schaaf, E., Pagani, F., Woo, J.-H., Kim, J., Monforti-Ferrario, F., Pisoni,
- 1218 E., Zhang, J., Niemi, D., Sassi, M., Ansari, T., and Foley, K.: The HTAP_v3 emission mosaic: merging regional and global
- 1219 monthly emissions (2000–2018) to support air quality modelling and policies, [dataset], Earth Syst. Sci. Data, 15, 2667–
- 1220 2694, https://doi.org/10.5194/essd-15-2667-2023, 2023.
- 1221 Crowell, S., Baker, D., Schuh, A., Basu, S., Jacobson, A. R., Chevallier, F., Liu, J., Deng, F., Feng, L., McKain, K.,
- 1222 Chatterjee, A., Miller, J. B., Stephens, B. B., Eldering, A., Crisp, D., Schimel, D., Nassar, R., O'Dell, C. W., Oda, T.,
- 1223 Sweeney, C., Palmer, P. I., and Jones, D. B. A.: The 2015–2016 carbon cycle as seen from OCO-2 and the global in situ
- 1224 network, Atmos. Chem. Phys., 19, 9797–9831, https://doi.org/10.5194/acp-19-9797-2019, 2019.

- 1225 Cunningham, C.X., Williamson, G.J., Bowman, D.M.J.S.: Increasing frequency and intensity of the most extreme wildfires
- 1226 on Earth. Nat Ecol Evol, <u>https://doi.org/10.1038/s41559-024-02452-2</u>, 2024.
- 1227 Cusworth, D.H., L.J. Mickley, M.P. Sulprizio, T. Liu, M.E. Marlier, R.S. DeFries, S.K. Guttikunda, and P. Gupta:
- 1228 Quantifying the influence of agricultural fires in northwest India on urban air pollution in Delhi, India. Environ. Res. Lett.,
- 1229 13(4), 044018, <u>https://doi.org/10.1088/1748-9326/aab303</u>, 2018.
- 1230 Dahlmann, K., Grewe, V., Ponater, M., & Matthes, S.: Quantifying the contributions of individual NOx sources to the trend
- 1231 in ozone radiative forcing. In Atmospheric Environment (Vol. 45, Issue 17, pp. 2860–2868). Elsevier BV.
- 1232 https://doi.org/10.1016/j.atmosenv.2011.02.071, 2011.
- 1233 Daly, G.L., Lei, Y.D., Teixeira, C., Muir, D. C. G., Castillo, L. E., Wania, F.: Accumulation of current-use pesticides in
- neotropical montane forests. Environmental Science and Technology, 41(4), 1118-1123, 2007.
- 1235 Damany-Pearce, L., Johnson, B., Wells, A. et al.: Australian wildfires cause the largest stratospheric warming since Pinatubo
- 1236 and extends the lifetime of the Antarctic ozone hole. Sci Rep 12, 12665, https://doi.org/10.1038/s41598-022-15794-3, 2022.
- 1237 Dastoor, A., Angot, H., Bieser, J., Brocza, F., Edwards, B., Feinberg, A., Feng, X., Geyman, B., Gournia, C., He, Y.,
- 1238 Hedgecock, I. M., Ilyin, I., Keating, T., Kirk, J., Lin, C.-J., Lehnherr, I., Mason, R., McLagan, D., Muntean, M., Rafaj, P.,
- 1239 Roy, E. M., Ryjkov, A., Selin, N. E., De Simone, F., Soerensen, A. L., Steenhuisen, F., Travnikov, O., Wang, S., Wang, X.,
- 1240 Wilson, S., Wu, R., Wu, Q., Zhang, Y., Zhou, J., Zhu, W., and Zolkos, S.: The Multi-Compartment Hg Modeling and
- 1241 Analysis Project (MCHgMAP): Mercury modeling to support international environmental policy, Geosci. Model Dev.
- 1242 Discuss. [preprint], https://doi.org/10.5194/gmd-2024-65, in review, 2024.
- Davidson, CI, Phalen RF, Solomon PA. : Airborne particulate matter and human health: a re-view. Aerosol Sci Technol,
 39:737-749., 2005.
- Davies IP, Haugo RD, Robertson JC, Levin PS.: The unequal vulnerability of communities of color towildfire. PloS ONE.,
 13, 11, e0205825, Nov 2, 2018.
- 1247 Deeter, M. N., Emmons, L. K., Francis, G. L., Edwards, D. P., Gille, J. C., Warner, J. X., Khattatov, B., Ziskin, D.,
- 1248 Lamarque, J.-F., Ho, S.-P., Yudin, V., Attie['], J.-L., Packman, D., Chen, J., Mao, D., and Drummond, J. R.: Operational
- 1249 carbon monoxide retrieval algorithm and selected results for the MOPITT instrument, J. Geophys. Res., 108, 4399,
- 1250 doi:10.1029/2002JD003186, 2003.
- 1251 Deeter, M., Francis, G., Gille, J., Mao, D., Martínez-Alonso, S., Worden, H., Ziskin, D., Drummond, J., Commane, R.,
- 1252 Diskin, G., and McKain, K.: The MOPITT Version 9 CO product: sampling enhancements and validation, Atmos. Meas.
- 1253 Tech., 15, 2325–2344, https://doi.org/10.5194/amt-15-2325-2022, 2022.
- 1254 Dentener, F., Kinne, S., Bond, T., Boucher, O., Cofala, J., Generoso, S., Ginoux, P., Gong, S., Hoelzemann, J. J., Ito, A.,
- 1255 Marelli, L., Penner, J. E., Putaud, J.-P., Textor, C., Schulz, M., van der Werf, G. R., and Wilson, J.: Emissions of primary
- 1256 aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom, Atmos. Chem. Phys., 6, 4321–
- 1257 4344, https://doi.org/10.5194/acp-6-4321-2006, 2006.

- 1258 Ding, K., X. Huang, A.J. Ding, M.H. Wang, H. Su, V.-M. Kerminen, T. Petäjä, Z. M. Tan, Z. L. Wang, D.R. Zhou, J. Sun,
- 1259 H. Liao, H.J. Wang, K. Carslaw, R. Wood, P. Zuidema, D. Rosenfeld, M. Kulmala, C.B. Fu, U. Pösch, Y. Cheng, M. O.
- Andreae: Aerosol-boundary-layer-monsoon interactions amplify semi-direct effect of biomass burning aerosols on low cloud
 formation in southeast Asia. Nature Comm., 12, p. 6416, doi:10.1038/s41467-021-26728-4, 2021.
- 1262 Ditomaso, J. M., Brooks, M. L., Allen, E. B., Minnich, R., Rice, P. M., and Kyser, G. B.: Control of Invasive Weeds with
- 1263 Prescribed Burning, Weed Technol., 20, 535–548, https://doi.org/10.1614/WT-05-086R1.1, 2006.
- 1264 Dobracki, A., P. Zuidema, S. Howell, P. Saide, S. Freitag, A. Aiken, S. Burton, A. Sedlacek, J. Redemann and R. Wood: An
- 1265 attribution of the low single-scattering albedo of biomass-burning aerosol over the southeast Atlantic. Atmos. Chem. Phys.,
- 1266 23, p. 4775-4799 doi:10.5194/acp-23-4775-2023, 2023
- 1267 Dobracki, A., P. Zuidema, E. Lewis, A. Sedlacek III, T. Tatro, M. Zawadowicz: Burning conditions and transportation
- 1268 pathways determine biomass-burning aerosol properties in the Ascension Island marine boundary layer. Atmos. Chem.
- 1269 Phys., 25, p2333-2363, doi:10.5194/acp-25-2333-2025, 2025.
- 1270 Doherty, S. J., P. Saide, P. Zuidema, Y. Shinozuka, G. Ferrada, H. Gordon, M. Mallet, K. Meyer, D. Painemal, S. G. Howell,
- 1271 S. Freitag, A. Dobracki, J. R. Podolske, S. P. Burton, R. A. Ferrare, C. Howes, P. Nabat, G. R. Carmichael, A. da Silva, K.
- 1272 Pistone, I. Chang, L. Gao, R. Wood, and J. Redemann: Modeled and observed properties related to the direct aerosol
- radiative effect of biomass burning aerosol over the Southeast Atlantic. *Atmos. Chem. Phys.*, **22**, p. 1-46, doi:<u>10.5194/acp-</u>
- 1274 <u>22-1-2022</u>, 2022.
- Domingo J., De Miguel E., Hurtado B., Métayer N., Bamière L., Pardon L., Bochu J., Pointereau P., Pellerin S.: Measures at
 farm level to reduce greenhouse gas emissions from EU agriculture. Notes. Policy Dep. B Struct. Cohes. Policies. 10:4922,
 2014.
- 1278 Duncan, B. N., I. Bey, M. Chin, L. J. Mickley, T. D. Fairlie, R. V. Martin, and H. Matsueda: Indonesian wildfires of 1997:
- 1279 Impact on tropospheric chemistry. J. Geophys. Res., 108, 4458, D15. https://doi.org/10.1029/2002JD003195, 2003.
- 1280 Dukes, D., Gonzales, H. B., Ravi, S., Grandstaff, D. E., Van Pelt, R. S., Li, J., Wang, G., and Sankey, J. B.: Quantifying
- 1281 Postfire Aeolian Sediment Transport Using Rare Earth Element Tracers, J. Geophys. Res. Biogeosciences, 123, 288–299,
- 1282 https://doi.org/10.1002/2017JG004284, 2018.
- 1283 Dupuy, Jl., Fargeon, H., Martin-StPaul, N. et al.: Climate change impact on future wildfire danger and activity in southern
- 1284 Europe: a review, Annals of Forest Science, 77, 35, https://doi.org/10.1007/s13595-020-00933-5, 2020.
- Eckhardt, S., Breivik, K., Manø, S., and Stohl, A.: Record high peaks in PCB concentrations in the Arctic atmosphere due to
 long-range transport of biomass burning emissions, Atmos. Chem. Phys., 7, 4527–4536, 2007.
- 1287 Edwards, D. P., Pe[']tron, G., Novelli, P. C., Emmons, L. K., Gille, J. C., and Drummond, J. R.: Southern Hemisphere carbon
- 1288 monoxide interannual variability observed by Terra/Measurement of Pollution in the Troposphere (MOPITT), J. Geophys.
- 1289 Res., 111, D16303, doi:10.1029/2006JD007079, 2006.
- 1290 Eisenman, D. P. and Galway, L. P.: The mental health and well-being effects of wildfire smoke: a scoping review, BMC
- 1291 Public Health, 22, 2274, 10.1186/s12889-022-14662-z, 2022.

- 1292 European Commission, 2010. Forest Fires in Europe 2010.
- 1293 EMEP Centre on Emission Inventories and Projections, 1999 Gothenburg Protocol under the LRTAP Convention,
- 1294 (https://unece.org/sites/default/files/2021-10/1999%20Multi.E.Amended.2005.pdf) 30 November, 1999.
- 1295 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E.: Overview of the Coupled
- 1296 Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development,
- 1297 9(5), 1937-1958. doi:10.5194/gmd-9-1937-2016, 2016.
- 1298 ESA. Land Cover CCI Product User Guide Version 2. Tech. Rep. (2017). Available at:
- 1299 maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf
- 1300 Eskes, H., van Geffen, J., Boersma, F., Eichmann, K.-U., Apituley, A., Pedergnana, M., Sneep, M., Veefkind, J. P., and
- 1301 Loyola, D.: Sentinel 5 precursor TROPOMI Level 2 Product User Manual Nitrogen Dioxide, Tech.rep., ESA,
- 1302 https://sentinel.esa.int/documents/247904/2474726/Sentinel-5P-Level-2-Product-User-Manual-Nitrogen-Dioxide.pdf, 2022.
- 1303 Farzaneh H.: Energy Systems Modelling. Springer International Publishing; Singapore, Climate Change Multiple Impact
- 1304 Assessment Models; pp. 107–129, 2019.
- 1305 Feng, X., L.J. Mickley, M.L. Bell, T. Liu, J.A. Fisher, and M. Val Martin: Improved estimates of smoke exposure during
- 1306 Australia fire seasons: Importance of quantifying plume injection heights. Atmos. Chem. Phys., 24, 2985-3007.
- 1307 <u>https://doi.org/10.5194/acp-24-2985-2024</u>, 2023.
- 1308 Field, R.D., M. Luo, S.E. Bauer, J.E. Hickman, G.S. Elsaesser, K. Mezuman, M. van Lier-Walqui, K. Tsigaridis, and J. Wu:
- 1309 Estimating the impact of a 2017 smoke plume on surface climate over northern Canada with a climate model, satellite
- 1310 retrievals, and weather forecasts. J. Geophys. Res. Atmos., accepted, 2024.
- 1311 Filkov, A. I., Ngo, T., Matthews, S., Telfer, S. & Penman, T. D.: Impact of Australia's catastrophic 2019/20 bushfire season
- 1312 on communities and environment: Retrospective analysis and current trends. J. Saf. Sci. Res. 1, 44–56, 2020.
- 1313 Fiore, A.M., Dentener F. J., Wild, O., et al., Multimodel estimates of intercontinental source-receptor relationships for ozone
- 1314 pollution, J. Geophys. Res., 114, D04301, doi:10.1029/2008JD010816, 2009.
- 1315 Fiore, AM, J.T. Oberman, M.Y. Lin, L. Zhang, O.E. Clifton, D.J. Jacob, V. Naik, L.W. Horowitz, J.P. Pinto: Estimating
- 1316 North American background ozone in U.S. surface air with two independent global models: Variability, uncertainties, and
- 1317 recommendations, Atmos. Environ., 96, 284-300, doi: 10.1016/j.atmosenv.2014.07.045, 2014.
- 1318 Fiore, A.M., E.V. Fischer, G.P. Milly, et al.: Peroxy acetyl nitrate (PAN) measurements at northern midlatitude mountain
- 1319 sites in April: a constraint on continental source-receptor relationships. Atmos. Chem. Phys., 18, no. 20, 15345-15361,
- 1320 doi:10.5194/acp-18-15345-2018, 2018.
- 1321 Fitzsimmons, J. N. and Conway, T. M.: Novel Insights into Marine Iron Biogeochemistry from Iron Isotopes, Ann. Rev.
- 1322 Mar. Sci., 15, 383–406, https://doi.org/10.1146/annurev-marine-032822-103431, 2023.

- 1323 Freitas, S. R., Longo, K. M., Chatfield, R., Latham, D., Silva Dias, M. A. F., Andreae, M. O., Prins, E., Santos, J. C.,
- 1324 Gielow, R., and Carvalho Jr., J. A.: Including the sub-grid scale plume rise of vegetation fires in low resolution atmospheric
- transport models, Atmospheric Chemistry and Physics, 7, 3385–3398, https://doi.org/10.5194/acp-7-3385-2007, 2007.
- 1326 Freitas, S. R., Longo, K. M., Trentmann, J., & Latham, D.: Sensitivity of 1-D smoke plume rise models to the inclusion of
- 1327 environmental wind drag. Atmospheric Chemistry and Physics, 10(2), 585-594, 2010.
- 1328 Fu et al: Improving Estimates of Sulfur, Nitrogen, and Ozone Total Deposition through Multi-Model and Measurement-
- 1329 Model Fusion Approaches, Environ. Sci. Technol., 56, 4, 2134–2142, 2022.
- 1330 Gao, Y., Huang, W., Yu, P., Xu, R., Yang, Z., Gasevic, D., Ye, T., Guo, Y., and Li, S.: Long-term impacts of non-
- 1331 occupational wildfire exposure on human health: A systematic review, Environmental Pollution, 320, 121041,
- 1332 https://doi.org/10.1016/j.envpol.2023.121041, 2023.
- 1333 Ghozikali M.G., Mosaferi M., Safari G.H., Jaafari J.: Effect of exposure to O3, NO2, and SO2 on chronic obstructive
- pulmonary disease hospitalizations in Tabriz, Iran. Environ. Sci. Pollut. Res., 22:2817–2823. doi: 10.1007/s11356-014-35125, 2014.
- 1336 Gidhagen L., Johansson H., Omstedt G.: SIMAIR—Evaluation tool for meeting the EU directive on air pollution limits.
- 1337 Atmos. Environ, 43:1029–1036, doi: 10.1016/j.atmosenv.2008.01.056, 2009.
- 1338 Ghetu, C. C., Rohlman, D., Smith, B. W., Scott, R. P., Adams, K. A., Hoffman, P. D., and Anderson, K. A.: Wildfire Impact
- on Indoor and Outdoor PAH Air Quality, Environmental Science & Technology, 56, 10042-10052, 10.1021/acs.est.2c00619,
 2022.
- 1341 Ghosh, P., S. Sharma, I. Khanna, A. Datta, R. Suresh, S. Kundu, A. Goel, D. Datt: Scoping study for South Asia air
- 1342 pollution, Energy Resour. Inst., p. 153, 2019.
- 1343 Ghozikali M.G., Mosaferi M., Safari G.H., Jaafari J.: Effect of exposure to O3, NO2, and SO2 on chronic obstructive
- pulmonary disease hospitalizations in Tabriz, Iran. Environ. Sci. Pollut. Res. 22, 2817–2823. doi: 10.1007/s11356-014-35125, 2014.
- 1346 Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D. P., van den Berg, M., Feng, L.,
- 1347 Klein, D., Calvin, K., Doelman, J. C., Frank, S., Fricko, O., Harmsen, M., Hasegawa, T., Havlik, P., Hilaire, J., Hoesly, R.,
- 1348 Horing, J., Popp, A., Stehfest, E., and Takahashi, K.: Global emissions pathways under different socioeconomic scenarios
- 1349 for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev., 12,
- 1350 1443–1475, https://doi.org/10.5194/gmd-12-1443-2019, 2019.
- 1351 Gidhagen L., Johansson H., Omstedt G.: SIMAIR—Evaluation tool for meeting the EU directive on air pollution limits.
- 1352 Atmos. Environ. 43, 1029–1036. doi: 10.1016/j.atmosenv.2008.01.056, 2009.
- 1353 Goel, A., Saxena, P., Sonwani, S., Rathi, S., Srivastava, A., Bharti, A. K., ... & Srivastava, A.: Health benefits due to
- reduction in respirable particulates during COVID-19 lockdown in India. Aerosol and Air Quality Research, 21, 5, 200460,
- 1355 2021.

- 1356 Govardhan, G., Rupal Ambulkar, Santosh Kulkarni, Ashok Vishnoi, Prafull Yadav, Begum Abida Choudhury, Manoj Khare,
- 1357 Sachin D. Ghude: Stubble-burning activities in north-western India in 2021: Contribution to air pollution in Delhi, Heliyon,
- 1358 9, 6, e16939, ISSN 2405-8440, https://doi.org/10.1016/j.heliyon.2023.e16939, 2023.
- 1359 Grant, E. and Runkle, J. D.: Long-term health effects of wildfire exposure: A scoping review, The Journal of Climate
- 1360 Change and Health, 6, 100110, https://doi.org/10.1016/j.joclim.2021.100110, 2022.
- 1361 Greenberg M. Seeking Shelter: How housing and urban exclusion shape exurban disaster. Sociologica, 15, 1, 67–89, 2021.
- 1362 Grell, G., Freitas, S. R., Stuefer, M., and Fast, J.: Inclusion of biomass burning in WRF-Chem: impact of wildfires on
- 1363 weather forecasts, Atmos. Chem. Phys., 11, 5289–5303, https://doi.org/10.5194/acp-11-5289-2011, 2011.
- 1364 Grewe, V., Tsati, E., Mertens, M., Frömming, C., and Jöckel, P.: Contribution of emissions to concentrations: the
- 1365 TAGGING 1.0 submodel based on the Modular Earth Submodel System (MESSy 2.52), Geosci. Model Dev., 10, 2615–
- 1366 2633, https://doi.org/10.5194/gmd-10-2615-2017, 2017.
- 1367 Griffin, D., Sioris, C., Chen, J., Dickson, N., Kovachik, A., de Graaf, M., Nanda, S., Veefkind, P., Dammers, E., McLinden,
- 1368 C. A., Makar, P., and Akingunola, A.: The 2018 fire season in North America as seen by TROPOMI: aerosol layer height
- intercomparisons and evaluation of model-derived plume heights, Atmos. Meas. Tech., 13, 1427–1445,
- 1370 https://doi.org/10.5194/amt-13-1427-2020, 2020.
- 1371 Griffin, D., Chen, J., Anderson, K., Makar, P., McLinden, C. A., Dammers, E., and Fogal, A.: Towards an improved
- 1372 understanding of wildfire CO emissions: a satellite remote-sensing perspective, EGUsphere [preprint],
- 1373 https://doi.org/10.5194/egusphere-2023-649, 2023.
- 1374 Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of
- 1375 Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling
- 1376 biogenic emissions, Geosci. Model Dev., 5, 1471–1492, https://doi.org/10.5194/gmd-5-1471-2012, 2012.
- 1377 Gummert, M., N.V. Hung, C. Pauline, B. Douthwaite: Sustainable Rice Straw Management, Springer International
- 1378 Publishing, https://doi.org/10.1007/978-3-030-32373-8, 2020.
- 1379 Guttikunda S.K., Kopakka R.V. Source emissions and health impacts of urban air pollution in Hyderabad, India. Air Qual.
- 1380 Atmos. Health. 2014;7:195–207. doi: 10.1007/s11869-013-0221-z, 2014.
- Guttikunda, S. K., & Jawahar, P.: Application of SIM-air modelling tools to assess air quality in Indian cities. Atmospheric
 Environment, 62, 551-561, 2012.
- Guttikunda, S., & Calori, G.: Simplified Atmospheric Transport Modelling System (ATMoS-4.0) for the SIM-air tool. SIMair Working Paper Series: 30-2009, 2009.
- 1385 Hadley, M., Vedanthan, R. & Fuster, V.: Air pollution and cardiovascular disease: a window of opportunity. Nat Rev Cardiol
- 1386 15, 193–194, https://doi.org/10.1038/nrcardio.2017.207, 2018.
- 1387 Hamilton, D. S., Kasoar, M., Bergas-Masso, E., Dalmonech, D., Hantson, S., Lasslop, G., Voulgarakis, A., Wells, C. D.:
- 1388 Global Warming Increases Fire Emissions but Resulting Aerosol Forcing is Uncertain, Nature, submitted 2024.
- 1389 Hamilton, D. S., Kasoar, M., et al, [dataset], Zenodo, 2025.

- 1390 Hamilton, D. S., Hantson, S., Scott, C. E., Kaplan, J. O., Pringle, K. J., Nieradzik, L. P., Rap, A., Folberth, G. A., Spracklen,
- 1391 D. V., and Carslaw, K. S.: Reassessment of pre-industrial fire emissions strongly affects anthropogenic aerosol forcing, Nat.
- 1392 Commun., 9, 3182, https://doi.org/10.1038/s41467-018-05592-9, 2018.
- 1393 Hamilton, D. S., Moore, J. K., Arneth, A., Bond, T. C., Carslaw, K. S., Hantson, S., Ito, A., Kaplan, J. O., Lindsay, K.,
- 1394 Nieradzik, L., Rathod, S. D., Scanza, R. A., and Mahowald, N. M.: Impact of Changes to the Atmospheric Soluble Iron
- 1395 Deposition Flux on Ocean Biogeochemical Cycles in the Anthropocene, Global Biogeochem. Cycles, 34, 1–22,
- 1396 https://doi.org/10.1029/2019GB006448, 2020.
- 1397 Hamilton, D. S., Perron, M. M. G., Bond, T. C., Bowie, A. R., Buchholz, R. R., Guieu, C., Ito, A., Maenhaut, W.,
- 1398 Myriokefalitakis, S., Olgun, N., Rathod, S. D., Schepanski, K., Tagliabue, A., Wagner, R., and Mahowald, N. M.: Earth,
- 1399 Wind, Fire, and Pollution: Aerosol Nutrient Sources and Impacts on Ocean Biogeochemistry, Ann. Rev. Mar. Sci., 14, 1–28,
- 1400 https://doi.org/10.1146/annurev-marine-031921-013612, 2022.
- 1401 Haywood, J. M., S. Abel, P. Barrett, N. Bellouin, A. Blyth, K. Bower, M. Brooks, K. Carslaw, H. Che, M. Cotterell, I.
- 1402 Crawford, Z. Cui, N. Davies, B. Dingley, P. Field, P. Formenti, H. Gordon, M. de Graaf, R. Herbert, B. Johnson, A. Jones, J.
- 1403 Langridge, F. Malavell, D. Partridge, F. Peers, J. Redemann, P. Stier, K. Szpek, J. Taylor, D. Watson-Parris, R. Wood, H.
- 1404 Wu, and P. Zuidema: Overview: The CLoud-Aerosol-Radiation Interaction and Forcing: Year-2017 (CLARIFY-2017)
- 1405 measurement campaign, Atmos. Chem. Phys., 21, p. 1049-1084, doi:10.5194/acp-21-1049-2021, 2021.
- 1406 He, Y., Zhao, B., Wang, S., Valorso, R., Chang, X., Yin, D., Feng, B., Camredon, M., Aumont, B., Deaerden, A., Jathar, S.
- 1407 H., Shrivastava, M., Jiang, Z., Cappa, C. D., Yee, L. D., Seinfeld, J. H., Hao, J., Donahue, N. M.: Formation of secondary
- 1408 organic aerosol from wildfire emissions enhanced by long-time aging, Nature Geoscience, 17, 124–129,
- 1409 doi:10.1038/s41561-023-01355-4, 2024.
- 1410 He, J., Z. Wang, L. Zhao, H. Ma, J. Huang, H. Li, X. Mao, T. Huang, H. Gao, J. Ma: Gridded emission inventory of
- organophosphorus flame retardants in China and inventory validation, Environmental Pollution, Volume 290, 118071,
 https://doi.org/10.1016/j.envpol.2021.118071, 2021.
- 1413 He, G., Liu, T., Zhou, M.: Straw burning, PM2.5, and death: Evidence from China. J. Dev. Econom., 145, 102468, 2020.
- 1414 He, T., Lamont, B. B., and Pausas, J. G.: Fire as a key driver of Earth's biodiversity, Biol. Rev., 94, 1983–2010,
- 1415 https://doi.org/10.1111/brv.12544, 2019.
- 1416 Heft-Neal, S., Driscoll, A., Yang, W., Shaw, G., and Burke, M.: Associations between wildfire smoke exposure during
- 1417 pregnancy and risk of preterm birth in California, Environmental Research, 203, 111872,
- 1418 https://doi.org/10.1016/j.envres.2021.111872, 2022.
- 1419 Henschel, S., Goodman, P., Atkinson, R., Zeka, A., Analitis, A., Katsouyanni, K., ... & Medina, S.: The assessment of the
- 1420 implementation of fuel related legislations and their impact on air quality and public health-the aphekom project. In ISEE
- 1421 Conference Abstracts 23 (Vol. 2011, No. 1), September 2011.

- 1422 Henschel, S., Goodman, P., Atkinson, R., Zeka, A., Analitis, A., Katsouyanni, K., ... & Medina, S.: (2011, September). The
- assessment of the implementation of fuel related legislations and their impact on air quality and public health-the aphekom
- 1424 project. In ISEE Conference Abstracts 23 (Vol. 2011, No. 1), 2011.
- 1425 Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum,
- 1426 I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N.: ERA5 hourly data on single levels from 1940 to present.
- 1427 [dataset], Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.adbb2d47 (Accessed on
- 1428 16-Jan-2025), 2023.
- Holder, A.L., Ahmed, A., Vukovich, J.M. and Rao, V.: Hazardous air pollutant emissions estimates from wildfires in the
 wildland urban interface. PNAS nexus, 2(6), p.pgad186, 2023.
- Houweling S, Kaminski T, Dentener F, Lelieveld J, HeimannM (1999) Inverse modelling of methane sources and sinks
 using the adjoint of a global transport model. J Geophys Res 104:26137–26160
- 1433 Huang, M., Carmichael, G. R., Kulkarni, S., Streets, D. G., Lu, Z., Zhang, Q., Pierce, R. B., Kondo, Y., Jimenez, J. L.,
- 1434 Cubison, M. J., Anderson, B., and Wisthaler, A.: Sectoral and geographical contributions to summertime continental United
- 1435 States (CONUS) black carbon spatial distributions, Atmos. Environ., 51, 165-174,
- 1436 https://doi.org/10.1016/j.atmosenv.2012.01.021, 2012.
- 1437 Huang, M., Crawford, J. H., Carmichael, G. R., Bowman, K. W., Kumar, S. V., and Sweeney, C.: Satellite soil moisture data
- assimilation impacts on modelling weather variables and ozone in the southeastern US Part 2: Sensitivity to dry-deposition
- 1439 parameterizations, Atmos. Chem. Phys., 22, 7461–7487, https://doi.org/10.5194/acp-22-7461-2022, 2022.
- 1440 Huang, M., Carmichael, G. R., Crawford, J. H., Bowman, K. W., De Smedt, I., Colliander, A., Cosh, M. H., Kumar, S. V.,
- 1441 Guenther, A. B., Janz, S. J., Stauffer, R. M., Thompson, A. M., Fedkin, N. M., Swap, R. J., Bolten, J. D., and Joseph, A. T.:
- 1442 Reactive nitrogen in and around the northeastern and Mid-Atlantic US: sources, sinks, and connections with ozone,
- 1443 EGUsphere [preprint], https://doi.org/10.5194/egusphere-2024-484, 2024.
- 1444 Huang, X., Ding, K., Liu, J., Wang, Z., Tang, R., Xue, L., ... & Ding, A. (2023). Smoke-weather interaction affects extreme
- 1445 wildfires in diverse coastal regions. Science, 379(6631), 457-461.
- 1446 Institute for Health Metrics and Evaluation: GBD compare IHME viz hub. global burden of disease, 2017.
- 1447 Jaffe, D. A., and N. L. Wigder: Ozone production from wildfires: A critical review. Atmos. Environ. 51:1-10. doi:
- 1448 10.1016/j.atmosenv.2011.11.063, 2012.
- 1449 Humphreys, A., Walker, E. G., Bratman, G. N. & Errett, N. A.: What can we do when the smoke rolls in? An exploratory
- 1450 qualitative analysis of the impacts of rural wildfire smoke on mental health and wellbeing, and opportunities for adaptation.
- 1451 BMC Public Health, 22:41. <u>https://doi.org/10.1186/s12889-021-12411-2</u>, 2022.
- 1452 Ikeda, K., Tanimoto, H., Kanaya, Y., Taketani, F.: Evaluation of anthropogenic emissions of black carbon from East Asia in
- 1453 six inventories: constraints from model simulations and surface observations on Fukue Island, Japan, Environ. Sci. Atmos.,
- 1454 2, 416-427, doi:10.1039/D1EA00051A, 2022.

- 1455 Jaffe, Daniel A., Susan M. O'Neill, Narasimhan K. Larkin, Amara L. Holder, David L. Peterson, Jessica E. Halofsky & Ana
- 1456 G. Rappold: Wildfire and prescribed burning impacts on air quality in the United States, Journal of the Air & Waste
- 1457 Management Association, 70:6, 583-615, DOI: 10.1080/10962247.2020.1749731, 2020.
- 1458 Jaffe, D. A., O'Neill, S. M., Larkin, N. K., Holder, A. L., Peterson, D. L., Halofsky, J. E., and Rappold, A. G.: Wildfire and
- 1459 prescribed burning impacts on air quality in the United States, J. Air Waste Manage. Assoc., 70, 583–615,
- 1460 https://doi.org/10.1080/10962247.2020.1749731, 2020.
- Jain N, Bhatia A, Pathak H.: Emission of air pollutants from crop residue burning in India. Aerosol Air Qual Res., 14, 422430, 2014.
- Jain, M., Saxena, P., Sharma, S. and Sonwani, S.: Investigation of forest fire activity changes over the central India domain
 using satellite observations during 2001–2020. GeoHealth, 5, 12, p.e2021GH000528, 2021.
- 1465 Jeanneau, A. C., Ostendorf, B., and Herrmann, T.: Relative spatial differences in sediment transport in fire-affected
- agricultural landscapes: A field study, Aeolian Res., 39, 13–22, https://doi.org/10.1016/j.aeolia.2019.04.002, 2019.
- 1467 Jiang L., Zhang J., Wang H.H., Zhang L., He K.: The impact of psychological factors on farmers' intentions to reuse
- agricultural biomass waste for carbon emission abatement. J. Clean. Prod., 189, 797–804. doi:
- 1469 10.1016/j.jclepro.2018.04.040, 2018.
- 1470 Jiang, W., T. Huang, X. Mao, L. Wang, Y. Zhao, C. Jia, Y. Wang, H. Gao, J. Ma: Gridded emission inventory of short-chain
- 1471 chlorinated paraffins and its validation in China, Environmental Pollution, Volume 220, Part A, Pages 132-141,
- 1472 <u>https://doi.org/10.1016/j.envpol.2016.09.031</u>, 2017.
- 1473 Jin, L., Permar, W., Selimovic, V., Ketcherside, D., Yokelson, R. J., Hornbrook, R. S., Apel, E. C., Ku, I.-T., Collett Jr., J.
- 1474 L., Sullivan, A. P., Jaffe, D. A., Pierce, J. R., Fried, A., Coggon, M. M., Gkatzelis, G. I., Warneke, C., Fischer, E. V., and
- 1475 Hu, L.: Constraining emissions of volatile organic compounds from western US wildfires with WE-CAN and FIREX-AQ
- 1476 airborne observations, Atmos. Chem. Phys., 23, 5969–5991, https://doi.org/10.5194/acp-23-5969-2023, 2023.
- 1477 Jöckel, P., Tost, H., Pozzer, A., Kunze, M., Kirner, O., Brenninkmeijer, C. A. M., Brinkop, S., Cai, D. S., Dyroff, C.,
- 1478 Eckstein, J., Frank, F., Garny, H., Gottschaldt, K.-D., Graf, P., Grewe, V., Kerkweg, A., Kern, B., Matthes, S., Mertens, M.,
- 1479 Meul, S., Neumaier, M., Nützel, M., Oberländer-Hayn, S., Ruhnke, R., Runde, T., Sander, R., Scharffe, D., & Zahn,
- 1480 A.: Earth System Chemistry integrated Modelling (ESCiMo) with the Modular Earth Submodel System (MESSy) version
- 1481 2.51, Geoscientific Model Development, 9, 1153–1200, <u>https://doi.org/10.5194/gmd-9-1153-2016</u>, 2016.
- 1482 Jöckel, P., Kerkweg, A., Pozzer, A., Sander, R., Tost, H., Riede, H., Baumgaertner, A., Gromov, S., & Kern,
- 1483 B.: Development cycle 2 of the Modular Earth Submodel System (MESSy2), Geoscientific Model Development, 3, 717–
- 1484 752, <u>https://doi.org/10.5194/gmd-3-717-2010</u>, 2010.
- 1485 Johnson, A.L., Abramson, M.J., Dennekamp, M. et al. Particulate matter modelling techniques for epidemiological studies of
- open biomass fire smoke exposure: a review. Air Qual Atmos Health 13, 35–75, https://doi.org/10.1007/s11869-019-00771-
- 1487 z, 2020.

- 1488 Johnston, F. H. et al.: Unprecedented health costs of smoke-related PM25 from the 2019–20 Australian megafires. Nat.
- 1489 Sustain. 4, 42–47. <u>https://doi.org/10.1038/s41893-020-00610-5</u>, 2021.
- 1490 Johnston, F. H., Henderson, S. B., Chen, Y., Randerson, J. T., Marlier, M., DeFries, R. S., Kinney, P., Bowman, D. M. J. S.,
- 1491 and Brauer, M.: Estimated Global Mortality Attributable to Smoke from Landscape Fires, Environmental Health
- 1492 Perspectives, 120, 695-701, doi:10.1289/ehp.1104422, 2012.
- 1493 Jones, B.A. and Berrens, R.P.: PRESCRIBED BURNS, SMOKE EXPOSURE, AND INFANT HEALTH. Contemp Econ
- 1494 Policy, 39: 292-309. https://doi.org/10.1111/coep.12509, 2021.
- 1495 Kacarab, M., K. L. Thornhill, A. Dobracki, S. Howell, J. O'Brien, S. Freitag, M. Poellot, R. Wood, P. Zuidema, J.
- 1496 Redemannand A. Nenes, 2020: Biomass Burning Aerosol as a Modulator of Droplet Number in the Southeast Atlantic
- 1497 Region. Atmos. Chem. Phys., 20,p. 3029-3040, doi:10.5194/acp-20-3029-2020.
- 1498 Kaiser, J. W., Heil, A., Andreae, M. O., Benedetti, A., Chubarova, N., Jones, L., Morcrette, J. J., Razinger, M., Schultz, M.
- 1499 G., Suttie, M., & van der Werf, G. R.: Biomass burning emissions estimated with a global fire assimilation system based on
- 1500 observed fire radiative power, Biogeosciences, https://doi.org/10.5194/bg-9-527-2012, 2012.
- 1501 Kaiser, J.W. & Holmendal, D.G.: ATOS-tested GFAS feature branch with enhanced treatment for geostationary observations
- and LC information based on ESA-CCI, CAMS Report CAMS2_64_D.4.2.2-2024a_GEO_and_LC, ECMWF,
- 1503 https://atmosphere.copernicus.eu/, 2024.
- 1504 Kaiser, J. W., & Holmedal, D. G. (2024). GFAS4HTAPv1.2.1 updated vegetation fire emissions 2003-2023 [Data set].
- 1505 Zenodo. https://doi.org/10.5281/zenodo.14051439, 2024.
- 1506 Kalina, J., White, K. B., Scheringer, M., Přibylová, P., Kukučka, P., Audy, O., Klánová, J. (2019) Comparability of long-
- 1507 term temporal trends of POPs from co-located active and passive air monitoring networks in Europe. Environ. Sci.:
- 1508 Processes Impacts, 21, 1132-1142.
- 1509 Kiely, L., Spracklen, et al: New estimate of particulate emissions from Indonesian peat fires in 2015, Atmos. Chem. Phys.,
- 1510 19, 11105-11121, https://doi.org/10.5194/acp-19-11105-2019, 2019.
- 1511 Klimont, Z., Heyes, C., Rafaj, P., Hoglund-Isaksson, L., Purohit, P., Kaltenegger, K., Gomez-Sanabria, A., Kim, Y.,
- 1512 Winiwarter, W., Warnecke, L., Schoepp, W., Lindl, F., Kiesewetter, G., Sander, R., Nguyen, B.: Global gridded
- 1513 anthropogenic emissions of air pollutants and methane for the period 1990-2050, [dataset], Zenodo,
- 1514 https://doi.org/10.5281/zenodo.14259955, 2024.
- 1515 Konovalov, I. B., M. Beekmann, B. D'Anna, and C. George: Significant light induced ozone loss on biomass burning
- 1516 aerosol: Evidence from chemistry-transport modelling based on new laboratory studies. Geophys. Res. Lett. 39. doi:
- 1517 10.1029/2012gl052432, 2012.
- 1518 Kumar, R., M.C. Barth, G.G. Pfister, V.S. Nair, S.D. Ghude, N. Ojha: What controls the seasonal cycle of black carbon
- aerosols in India?, J. Geophys. Res. Atmos., 120, pp. 7788-7812, http://dx.doi.org/10.1002/2015JD023298, 2015.
- 1520 Lampe, BJ, Park SK, Robin T, et al.: Association between 24-hour Urinary cadmium and Pulmonary Function among
- 1521 community-exposed men: the VA normative aging study. En-viron Health Perspect. 116:1226-1230, 2008.

- Lamont, B. B.: Historical links between climate and fire on species dispersion and trait evolution, Plant Ecol., 223, 711–732,
 https://doi.org/10.1007/s11258-022-01232-x, 2022.
- 1524 Lamsal, L. N., Krotkov, N. A., Vasilkov, A., Marchenko, S., Qin, W., Yang, E.-S., Fasnacht, Z., Joiner, J., Choi, S., Haffner,
- 1525 D., Swartz, W. H., Fisher, B., and Bucsela, E.: Ozone Monitoring Instrument (OMI) Aura nitrogen dioxide standard product
- version 4.0 with improved surface and cloud treatments, Atmos. Meas. Tech., 14, 455–479, https://doi.org/10.5194/amt-14455-2021, 2021.
- Lelieveld, J., J.S. Evans, M. Fnais, D. Giannadaki, A. Pozzer: The contribution of outdoor air pollution sources to premature mortality on a global scale, Nature, 525, pp. 367-371, http://dx.doi.org/10.1038/nature15371, 2015.
- 1530 Leung, F.-Y. T., J. A. Logan, R. Park, E. Hyer, E. Kasischke, D. Streets, and L. Yurganov: Impacts of enhanced biomass
- burning in the boreal forests in 1998 on tropospheric chemistry and the sensitivity of model results to the injection height of emissions, J. Geophys. Res., 112, D10313, doi:10.1029/2006JD008132, 2007.
- 1533 Levelt, P. F., Hilsenrath, E., Leppelmeier, G. W., van den Oord, G. H. J., Bhartia, P. K., Tamminen, J., de Haan, J. F., and
- 1534 Veefkind, J. P.: Science objectives of the Ozone Monitoring Instrument, Geosci. Remote Sens., 44, 1199–1208,
- 1535 doi:10.1109/TGRS.2006.872336, 2006.
- 1536 Li, F., Val Martin, M., Andreae, M. O., Arneth, A., Hantson, S., Kaiser, J. W., Lasslop, G., Yue, C., Bachelet, D., Forrest,
- 1537 M., Kluzek, E., Liu, X., Mangeon, S., Melton, J. R., Ward, D. S., Darmenov, A., Hickler, T., Ichoku, C., Magi, B. I., Sitch,
- 1538 S., van der Werf, G. R., Wiedinmyer, C., and Rabin, S. S.: Historical (1700–2012) global multi-model estimates of the fire
- emissions from the Fire Modelling Intercomparison Project (FireMIP), Atmos. Chem. Phys., 19, 12545–12567,
- 1540 https://doi.org/10.5194/acp-19-12545-2019, 2019.
- 1541 Li, H., Z. Wang, J. He, N. Zhang, X. Mao, J. Ma, H. Gao, Z. Yang, H. Ma: Deca-BDE emissions, validation, and
- 1542 environmental fate in China, Journal of Hazardous Materials, Volume 459, 132223,
- 1543 <u>https://doi.org/10.1016/j.jhazmat.2023.132223</u>, 2023.
- Lin, M., T. Holloway, G. R. Carmichael and A. M. Fiore: Quantifying pollution inflow and outflow over East Asia in spring with regional and global models. Atmos. Chem. Phys., 10, 4221-4239, 2010.
- 1546 Lin, M., L.W. Horowitz, S. J. Oltmans, A. M. Fiore, Songmiao Fan (2014): Tropospheric ozone trends at Manna Loa
- 1547 Observatory tied to decadal climate variability, Nature Geoscience, 7, 136-143, doi:10.1038/NGEO2066.
- 1548 Lin, M. et al.: US surface ozone trends and extremes over 1980-2014: Quantifying the roles of rising Asian emissions,
- domestic controls, wildfires, and climate. Atmos. Chem. Phys., 17, 4, doi:10.5194/acp-17-2943-2017, 2017.
- 1550 Lin, M., L. W. Horowitz, Lu Hu, and Wade Permar. Reactive nitrogen partitioning enhances contribution of Canadian
- 1551 wildfire plumes to US ozone air quality, Geophysical Research Letter, http://doi.org/10.1029/2024GL109369, 2024b.
- 1552 Lin, M., L. W. Horowitz, M. Zhao, L. Harris, P. Ginoux, J. P. Dunne, S. Malyshev, E. Shevliakova, H. Ahsan, S. Garner, F.
- 1553 Paulot, A. Pouyaei, S. J. Smith, Y. Xie, N. Zadeh, L. Zhou. The GFDL Variable-Resolution Global Chemistry-Climate
- 1554 Model for Research at the Nexus of US Climate and Air Quality Extremes. Journal of Advances in Modelling Earth
- 1555 Systems, in press, https://doi.org/10.1029/2023MS003984, 2024a.

- 1556 Lipsett-Moore, G. J., Wolff, N. H., and Game, E. T.: Emissions mitigation opportunities for savanna countries from early dry
- 1557 season fire management, Nat. Commun., 9, 2247, https://doi.org/10.1038/s41467-018-04687-7, 2018.
- 1558 Liu, X., et al.: Agricultural fires in the southeastern US during SEAC(4)RS: Emissions of trace gases and particles and
- evolution of ozone, reactive nitrogen, and organic aerosol, J. Geophys. Res.-Atmos., 121, 12, 7383-7414,
- 1560 doi:10.1002/2016jd025040, 2016.
- 1561 Liu, T., Miriam E. Marlier, Ruth S. DeFries, Daniel M. Westervelt, Karen R. Xia, Ar-lene M. Fiore, Loretta J. Mickley,
- 1562 Daniel H. Cusworth, George Milly: Seasonal impact of regional outdoor biomass burning on air pollution in three Indian
- 1563 cities: Delhi, Bengaluru, and Pune, Atmospheric Environment, 172, 83-92, ISSN 1352-2310,
- 1564 https://doi.org/10.1016/j.atmosenv.2017.10.024, 2018.
- Liu, F., Klimont, Z., Zhang, Q., Cofala, J., Zhao, L., Huo, H., ... & Heyes, C.: Integrating mitigation of air pollutants and
- greenhouse gases in Chinese cities: development of GAINS-City model for Beijing. Journal of Cleaner Production, 58, 25-33, 2013.
- 1568 Liu J. C., Pereira G, Uhl SA, Bravo MA, Bell M. L.: A systematic review of the physical health impacts from non-
- 1569 occupational exposure to wildfire smoke, Environ Res., 136, 120–32, 2015.
- 1570 Liu, T., L. J. Mickley, M. E. Marlier, R. S. DeFries, M. F. Khan, M. T. Latif, A. Karambelas: Diagnosing spatial biases and
- 1571 uncertainties in global fire emissions inventories: Indonesia as regional case study, Remote Sensing of Environment, Volume
- 1572 237, 111557, <u>https://doi.org/10.1016/j.rse.2019.111557</u>, 2020.
- 1573 Lou, S., Shrivastava, M., Easter, R. C., Yang, Y., Ma, P.-L., Wang, H., Cubison, M., Campuzano-Jost, P., Jimenez, J.L.,
- 1574 Zhang, Q., Rasch, P. J., Shilling, J. E., Zelenyuk, A., Dubey, M., Cameron-Smith, P., Martin, S. T., Schneider, J., and Schulz,
- 1575 C.: New SOA Treatments Within the Energy Exascale Earth System Model (E3SM): Strong Productionand Sinks Govern
- 1576 Atmospheric SOA Distributions and Radiative Forcing, J. Adv. Model. Earth Sy., 12, e2020MS002266,
- 1577 https://doi.org/10.1029/2020ms002266, 2020.
- Luo, K., Wang, X., de Jong, M., & Flannigan, M. (2024). Drought triggers and sustains overnight fires in North America.
 Nature, 627(8003), 321-327
- 1580 Luo, J., Han, Y., Zhao, Y., Huang, Y., Liu, X., Tao, S., Liu, J., Huang, T., Wang, L., Chen, K., and Ma, J.: Effect of northern
- boreal forest fires on PAH fluctuations across the arctic, Environmental Pollution, 261, 114186,
- 1582 https://doi.org/10.1016/j.envpol.2020.114186, 2020.
- 1583 MacLeod, M., von Waldow, H., Tay, P., Armitage, J.M., Wöhrnschimmel, H., Riley, W.J., McKone, T.E. and Hungerbuhler,
- 1584 K.: BETR Global–A geographically-explicit global-scale multimedia contaminant fate model. Environmental Pollution, 159,
- 1585 5, 1442-1445, 2011.
- 1586 Mahowald, N., Li, L., Albani, S., Hamilton, D., and Kok, J.: Opinion: The importance of historical and paleoclimate aerosol
- 1587 radiative effects, EGUsphere, 1–37, 2023.

- 1588 Mahowald, N. M., Hamilton, D. S., Mackey, K. R. M., Moore, J. K., Baker, A. R., Scanza, R. A., and Zhang, Y.: Aerosol
- trace metal leaching and impacts on marine microorganisms, Nat. Commun., 9, 2614, https://doi.org/10.1038/s41467-018-

1590 04970-7, 2018.

- 1591 Mallet, M., F. Solmon, P. Nabat, et al: Direct and semi-direct radiative forcing of biomass burning aerosols over the
- 1592 Southeast Atlantic (SEA) and its sensitivity to absorbing properties: a regional climate modeling study. Atmos. Chem. Phys.,
- 1593 20, p. 13191-13216, doi:10.5194/acp-20-13191-2020, 2020.
- 1594 Manning, M., Lowe, D., Moss, R. et al.: Short-term variations in the oxidizing power of the atmosphere. Nature 436, 1001–
- 1595 1004, https://doi.org/10.1038/nature03900, 2005.
- 1596 Mailloux, N. A., Abel, D. W., Holloway, T., & Patz, J. A.: Nationwide and regional PM2. 5-related air quality health
- benefits from the removal of energy-related emissions in the United States. GeoHealth, 6, 5, e2022GH000603, 2022.
- 1598 Masri S, Scaduto E, Jin Y, Wu J.: Disproportionate impacts of wildfires among elderly and low-incomecommunities in
- 1599 California from 2000–2020. Int J Environ Res Public Health., 18, 8, 3921, 2021.
- 1600 Masters J.: Reviewing the horrid global 2020 wildfire season. Yale Climate Connections. 2021.
- Mao, J., L. W. Horowitz, V. Naik, S. Fan, J. Liu, and A. M. Fiore: Sensitivity of tropospheric oxidants to biomass burning
 emissions: implications for radiative forcing, Geophys. Res. Lett., 40, 1241–1246, doi:10.1002/grl.50210, 2013.
- 1603 McCarty, J. L., Aalto, J., Paunu, V.-V., Arnold, S. R., Eckhardt, S., Klimont, Z., Fain, J. J., Evangeliou, N., Venäläinen, A.,
- 1604 Tchebakova, N. M., Parfenova, E. I., Kupiainen, K., Soja, A. J., Huang, L., and Wilson, S.: Reviews and syntheses: Arctic
- fire regimes and emissions in the 21st century, Biogeosciences, 18, 5053–5083, https://doi.org/10.5194/bg-18-5053-2021,
 2021.
- McClure and Jaffe: Investigation of high ozone events due to wildfire smoke in an urban area, Atmospheric Environment,
 194, 146–157, doi:10.1016/j.atmosenv.2018.09.021, 2018.
- 1609 Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A.,
- 1610 Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P.
- 1611 J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socio-
- 1612 economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500, Geosci. Model Dev., 13, 3571–3605,
- 1613 https://doi.org/10.5194/gmd-13-3571-2020, 2020.
- 1614 Menut L., B. Bessagnet, R.Briant, A.Cholakian, F.Couvidat, S.Mailler, R.Pennel, G.Siour, P.Tuccella, S.Turquety, and
- M.Valari: The CHIMERE v2020r1 online chemistry-transport model, Geoscientific Model Development, 14, 6781-6811,
 2021.
- 1617 Mertens, M., Jöckel, P., Matthes, S., Nützel, M., Grewe, V., & Sausen, R.: COVID-19 induced lower-tropospheric ozone
- 1618 changes. In Environmental Research Letters (Vol. 16, Issue 6, p. 064005). IOP Publishing. https://doi.org/10.1088/17481619 9326/abf191.2021.
- 1620 Mittal SK, Singh N, Agarwal R, Awasthi A, Gupta PK.: Ambient air quality during wheat and rice crop stubble burning
- 1621 episodes. Atmos Environ., 43, 238-244, 2009.

- 1622 Miyazaki, K., Eskes, H. J., and Sudo, K.: Global NOx emission estimates derived from an assimilation of OMI tropospheric
- 1623 NO2 columns, Atmos. Chem. Phys., 12, 2263–2288, doi:10.5194/acp-12-2263-2012, 2012.
- 1624 Molina-Terre´n, D.M., Xanthopoulos G, Diakakis M, Ribeiro L, Caballero D, Delogu GM, et al.: Analysis of forest fire
- 1625 fatalities in southern Europe: Spain, Portugal, Greece and Sardinia (Italy). Int J Wildland Fire, 28, 2, 85–98,
- 1626 <u>https://doi.org/10.1071/WF18004</u>, 2019.
- 1627 Monks, P., Archibald, A. T., Colette, A. et al.: Tropospheric ozone and its precursors from the urban to the global scale from
- air quality to short-lived climate forcer, Atmos. Phys. Chem., 15, doi:10.5194/acp-15-8889-2015, 2015.
- 1629 MOPITT Team: MOPITT Derived CO (Near and Thermal Infrared Radiances) V009, Atmospheric Science Data Center
- 1630 [data set], https://doi.org/10.5067/TERRA/MOPITT/MOP02J.009, 2022.
- 1631 Moubarak, M., Sistla, S., Potter, S., Natali, S. M., and Rogers, B. M.: Carbon emissions and radiative forcings from tundra
- 1632 wildfires in the Yukon–Kuskokwim River Delta, Alaska, Biogeosciences, 20, 1537–1557, https://doi.org/10.5194/bg-20-
- 1633 1537-2023, 2023.
- Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, et al.: Learning to coexist withwildfire. Nature,
 515, 7525, 58–66, 2014.
- 1636 Muir D.C.G. and Galarneau E.: Polycyclic aromatic compounds (PACs) in the Canadian environment: links to global
- 1637 change, Environ. Pollut. 273, doi: 10.1016/j.envpol.2021.116425, 2021.
- 1638 Murphy A.K., Allard S.W.: The changing geography of poverty. Focus. 32, 1, 19–23, 2015.
- Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, Hessburg PF, et al.: Learning to coexist with wildfire. Nature.
 515, 7525, 58–66, 2014.
- 1641 Nguyen, T. B., Schoepp, W., & Wagner, F.: GAINS-BI: business intelligent approach for greenhouse gas and air pollution
- 1642 interactions and synergies information system. In Proceedings Of The 10th International Conference On Information
- 1643 Integration And Web-Based Applications & Services (pp. 332-338), November 2008.
- 1644 Nagpure, A. S., Gurjar, B. R., & Martel, J. C.: Human health risks in national capital territory of Delhi due to air pollution.
- 1645 Atmospheric Pollution Research, 5(3), 371-380, 2014.
- 1646 Naik, V., D. L. Mauzerall, L. W. Horowitz, M. D. Schwarzkopf, V. Ramaswamy, and M. Oppenheimer: On the sensitivity of
- radiative forcing from biomass burning aerosols and ozone to emission location, Geophys. Res. Lett., 34, L03818,
- 1648 doi:10.1029/2006GL028149, 2007.
- 1649 Naus, S., Domingues, L. G., Krol, M., Luijkx, I. T., Gatti, L. V., Miller, J. B., Gloor, E., Basu, S., Correia, C., Koren, G.,
- 1650 Worden, H. M., Flemming, J., Pétron, G., and Peters, W.: Sixteen years of MOPITT satellite data strongly constrain Amazon
- 1651 CO fire emissions, Atmos. Chem. Phys., 22, 14735–14750, https://doi.org/10.5194/acp-22-14735-2022, 2022.
- 1652 Neidermeier, A. N., Zagaria, C., Pampanoni, V., West, T. A. P., and Verburg, P. H.: Mapping opportunities for the use of
- land management strategies to address fire risk in Europe, J. Environ. Manage., 346, 118941,
- 1654 https://doi.org/10.1016/j.jenvman.2023.118941, 2023.

- 1655 Ohneiser, K., Ansmann, A., Witthuhn, J., Deneke, H., Chudnovsky, A., Walter, G., and Senf, F.: Self-lofting of wildfire
- smoke in the troposphere and stratosphere: simulations and space lidar observations, Atmos. Chem. Phys., 23, 2901–2925,
- 1657 https://doi.org/10.5194/acp-23-2901-2023, 2023.
- 1658 Olson, N. E., Boaggio, K. L., Rice, R. B., Foley, K. M., and LeDuc, S. D.: Wildfires in the western United States are
- mobilizing PM2.5-associated nutrients and may be contributing to downwind cyanobacteria blooms, Environ. Sci. Process.
 Impacts, 25, 1049–1066, https://doi.org/10.1039/D3EM00042G, 2023.
- 1661 Oregon Department of Forestry (ODF): ODF Fire History 1911–2020; State Library of Oregon: Salem, OR, USA, 2020.
- 1662 Overmeiren, P. V., Demeestere, K, De Wispelaere, P., Gili, S., Mangold, A., De Causmaecker, K., Mattielli, N., Delcloo, A.,
- 1663 Van Langenhove, H., Walgraeve, C.: Four years of acive sampling and measurement of atmospheric polycyclic aromatic
- 1664 hydrocarbons and oxygenated polycyclic aromatic hydrocarbons in Dronning Maud Land, East Antarctica. Environ. Sci.
- 1665 Technol., in press. DOI: 10.1021/acs.est.3c06425, 2024.
- 1666 Pais, S., Aquilué, N., Honrado, J. P., Fernandes, P. M., and Regos, A.: Optimizing Wildfire Prevention through the
- Integration of Prescribed Burning into 'Fire-Smart' Land-Use Policies, Fire, 6, 457, https://doi.org/10.3390/fire6120457,
 2023.
- 1669 Pan, X., Ichoku, C., Chin, M., Bian, H., Darmenov, A., Colarco, P., et al.: Six global biomass burning emission datasets:
- 1670 intercomparison and application in one global aerosol model, Atmos. Chem. Phys., 20, 2, 969-994,
- 1671 https://doi.org/10.5194/acp-20-969-2020, 2020.
- 1672 Parrington, M., Whaley, C. H., French, N. H. F., Buchholz, R. R., Pan, X., Wiedinmyer, C., Hyer, E. J., Kondragunta, S.,
- 1673 Kaiser, J. W., van der Werf, G., R., Sofiev, M., Barsanti, K. C., da Silva, A. M., Darmenov, A. S., Tang, W., Griffin, D.,
- 1674 Desservettaz, M., Carter, T., Paton-Walsh, C., Liu, T., Uppstu, A., Palamarchuk, J.: Biomass burning emission estimation in
- 1675 the MODIS era: state-of-the-art and future directions, Elementa, submitted, 2024.
- 1676 Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., ... & Aphekom Group: Assessing the public
- health impacts of urban air pollution in 25 European cities: results of the Aphekom project. Science of the TotalEnvironment, 449, 390-400, 2013.
- 1679 Paugam, R., M. Wooster, S. Freitas, and M. V. Martin: A review of approaches to estimate wildfire plume injection height
- within large-scale atmospheric chemical transport models, Atmos. Chem. Phys., 16(2), 907-925, doi:10.5194/acp-16-9072016, 2016.
- 1682 Paunu, V.-V., J.L. McCarty, A. Lipsanen, I. Entsalo: Fire in the Arctic: Current Trends and Future Pathways. Arctic Black
- 1683 Carbon impacting on Climate and Air Pollution (ABC -iCAP) Project Technical Report 1. November 2023 vi+20pp, 2023.
- 1684 Pausas, J. G. and Keeley, J. E.: Wildfires as an ecosystem service, Front. Ecol. Environ., 17, 289–295,
- 1685 https://doi.org/10.1002/fee.2044, 2019.
- 1686 Peiro, H., Crowell, S., Schuh, A., Baker, D. F., O'Dell, C., Jacobson, A. R., Chevallier, F., Liu, J., Eldering, A., Crisp, D.,
- 1687 Deng, F., Weir, B., Basu, S., Johnson, M. S., Philip, S., and Baker, I.: Four years of global carbon cycle observed from the

- 1688 Orbiting Carbon Observatory 2 (OCO-2) version 9 and in situ data and comparison to OCO-2 version 7, Atmos. Chem.
- 1689 Phys., 22, 1097–1130, https://doi.org/10.5194/acp-22-1097-2022, 2022a
- 1690 Peiro, H., Crowell, S., and Moore III, B.: Optimizing 4 years of CO2 biospheric fluxes from OCO-2 and in situ data in TM5:
- 1691 fire emissions from GFED and inferred from MOPITT CO data, Atmos. Chem. Phys., 22, 15817–15849,
- 1692 https://doi.org/10.5194/acp-22-15817-2022, 2022b.
- 1693 Permar, W., Jin, L., Peng, Q., O'Dell, K., Lill, E., Selimovic, V., Yokelson, R. J., Hornbrook, R. S., Hills, A. J., Apel, E. C.,
- 1694 Ku, I.-T., Zhou, Y., Sive, B. C., Sullivan, A. P., Collett, J. L., Palm, B. B., Thornton, J. A., Flocke, F., Fischer, E. V., and
- 1695 Hu, L.: Atmospheric OH reactivity in the western United States determined from comprehensive gas-phase measurements
- 1696 during WE-CAN, Environ. Sci. Atmos., 3, 97–114, https://doi.org/10.1039/D2EA00063F, 2023.
- 1697 Perron, M. M. G., Meyerink, S., Corkill, M., Strzelec, M., Proemse, B. C., Gault-Ringold, M., Sanz Rodriguez, E., Chase, Z.,
- and Bowie, A. R.: Trace elements and nutrients in wildfire plumes to the southeast of Australia, Atmos. Res., 270, 106084,
- 1699 https://doi.org/10.1016/j.atmosres.2022.106084, 2022.
- 1700 Pfister, G. G., C. Wiedinmyer, and L. K. Emmons: Impacts of the fall 2007 California wildfires on surface ozone:
- 1701 Integrating local observations with global model simulations. Geophys. Res. Lett., 35, 19, L19814-L19814. doi:
- 1702 10.1029/2008GL034747, 2008.
- 1703 Platt, R.V.: The wildland–urban interface: evaluating the definition effect. Journal of Forestry, 108(1), pp.9-15, 2010.
- Psaropoulos J.: Greek wildfires devastated land. They also took away livelihoods. Al Jazeera. [cited 2021 December 9], Sept
 20, 2021.
- 1706 Quinn, P. K., T.S. Bates, D.J. Coffman, L.M. Upchurch, J.E. Johnson, A. Brewer, S. Baidar, I. L. McCoy, and P. Zuidema:
- 1707 Wintertime Observations of Tropical Northwest Atlantic Aerosol Properties 1 during ATOMIC: Varying Mixtures of Dust
- 1708 and Biomass Burning. J. Geophys. Res., 127, e2021JD036253, doi:10.1029/2021JD036253, 2022.
- 1709 Rabin, S. S., Melton, J. R., Lasslop, G., Bachelet, D., Forrest, M., Hantson, S., Kaplan, J. O., Li, F., Mangeon, S., Ward, D.
- 1710 S., Yue, C., Arora, V. K., Hickler, T., Kloster, S., Knorr, W., Nieradzik, L., Spessa, A., Folberth, G. A., Sheehan, T.,
- 1711 Voulgarakis, A., Kelley, D. I., Prentice, I. C., Sitch, S., Harrison, S., and Arneth, A.: The Fire Modelling Intercomparison
- 1712 Project (FireMIP), phase 1: experimental and analytical protocols with detailed model descriptions, Geosci. Model Dev., 10,
- 1713 1175–1197, https://doi.org/10.5194/gmd-10-1175-2017, 2017.
- 1714 Rafaj, P., Kiesewetter, G., Gül, T., Schöpp, W., Cofala, J., Klimont, Z., Purohit, P., Heyes, C., Amann, M., Borken-Kleefeld,
- 1715 J., and Cozzi, L.: Outlook for clean air in the context of sustainable development goals, Glob. Environ. Chang., 53, 1–11,
- 1716 https://doi.org/10.1016/j.gloenvcha.2018.08.008, 2018.
- 1717 Ramo, R., E. Roteta, I. Bistinas, D. van Wees, A. Bastarrika, E. Chuvieco, G. R. van der Werf, African burned area and fire
- 1718 carbon emissions are strongly impacted by small fires undetected by coarse resolution satellite data. Proc. Natl. Acad. Sci.
- 1719 U.S.A. 118, e2011160118 (2021).

- 1720 Rana, M., Mittal, S.K., Beig, G., Rana, P.: The impact of crop residue burning (CRB)on the diurnal and seasonal variability
- 1721 of the ozone and PM levels at a semi-urban site in the north-western Indo-Gangetic Plain, J.Earth Syst. Sci. 128 (6), 166,
- 1722 2019.
- 1723 Rap, A., C. E. Scott, D. V. Spracklen, N. Bellouin, P. M. Forster, K. S. Carslaw, A. Schmidt, and G. Mann: Natural aerosol
 1724 direct and indirect radiative effects. Geophys. Res. Lett., 40, 3297–3301. doi:10.1002/grl.50441. 2013.
- 1725 Real, E., et al.: Processes influencing ozone levels in Alaskan forest fire plumes during long-range transport over the North
- 1726 Atlantic, J. Geophys. Res., 112, D10S41, doi:10.1029/2006JD007576, 2007.
- 1727 Redemann, J., R. Wood, P. Zuidema, S. Doherty, B. Luna, S. LeBlanc, M. Diamond, Y. Shinozuka, L. Gao, I. Chang, R.
- 1728 Ueyama, L. Pfister, J.-M. Ryoo, A. Dobracki, A. DaSilva, K. Longo, M. Kacenelenbogen, C. Flynn, K. Pistone, N. Knox, S.
- 1729 Piketh, J. Haywood, P. Formenti, M. Mallet, P. Stier, A. Ackerman, S. Bauer, A. Fridlind, G. Carmichael, P. Saide, G.
- 1730 Ferrada, S. Howell, S. Freitag, B. Cairns, B. Holben, K. Knobelspiesse, S. Tanelli, T. L'Ecuyer, A. Dzambo, O. Sy, G.
- 1731 McFarquhar, M. Poellot, S. Gupta, J. Oâ€[™]Brien, T. Nenes, M. Kacarab, P. S. Wong, J. Small-Griswold, K. Thornhill, D.
- 1732 Noone, J. Podolske, S. Schmidt, P. Pilewskie, H. Chen, S. Cochrane, A. Sedlacek, T. Lang, E. Stith, M. Segal-Rozenhaimer,
- 1733 C. Hostetler, R. Ferrare, S. Burton, J. Hair, D. Diner, S. Platnick, Myers, K. Meyer, D. Spangenberg, H. Maring: An
- 1734 overview of the ORACLES (ObseRvations of Aerosols above CLouds and their intEractionS) project: aerosol-cloud-
- radiation interactions in the Southeast Atlantic basin. Atmos. Chem. Phys., 21, p. 1507-1563, doi:10.5194/acp-21-1507-2021
- 1736 Reid, C. E., Brauer, M., Johnston, F. H., Jerrett, M., Balmes, J. R., and Elliott, C. T.: Critical Review of Health Impacts of
- 1737 Wildfire Smoke Exposure, Environmental Health Perspectives, 124, 1334-1343, doi:10.1289/ehp.1409277, 2016.
- 1738 Reisen, F., Hansen, D., Meyer, C.P.: Exposure to bushfire smoke during prescribedburns and wildfires: firefighters' exposure
- 1739 risks and options. Environ.Int. 37, 314-321, 2011.
- 1740 Rémy, S., A. Veira, R. Paugam, M. Sofiev, J. W. Kaiser, F. Marenco, S. P. Burton, A. Benedetti, R. J. Engelen, R. Ferrare,
- and J. W. Hair: Two global data sets of daily fire emission injection heights since 2003, Atmos. Chem. Phys., 17, 2921-2942,
- 1742 https://doi.org/10.5194/acp-17-2921-2017, 2017.
- 1743 Righi, M., Hendricks, J., and Beer, C. G.: Exploring the uncertainties in the aviation soot-cirrus effect, Atmos. Chem. Phys.,
- 1744 21, 17267–17289, https://doi.org/10.5194/acp-21-17267-2021, 2021.
- 1745 Romahn, F., Pedegnana, M., Loyola, D., Apituley, A., Sneep, M., and Veefkind, J. P.: Sentinel 5 precursor TROPOMI Level
- 1746 2 Product User Manual O3 Total Column, Tech.rep., ESA, <u>https://sentiwiki.copernicus.eu/_attachments/1673595/S5P-L2-</u>
- 1747 DLR-PUM-400A%20-%20Sentinel-
- 1748 <u>5P%20Level%202%20Product%20User%20Manual%20Ozone%20Total%20Column%202022%20-%202.4.pdf</u>, 2022.
- 1749 Romanello, M., Napoli, C.D., Green, C., Kennard, H., Lampard, P., Scamman, D., Walawender, M., Ali, Z., Ameli, N.,
- 1750 Ayeb-Karlsson, S., Beggs, P.J., Belesova, K., Berrang Ford, L., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D.,
- 1751 Chambers, J., Cross, T.J., Van Daalen, K.R., Dalin, C., Dasandi, N., Dasgupta, S., Davies, M., Dominguez-Salas, P.,
- 1752 Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Freyberg, C., Gasparyan, O., Gordon-Strachan, G., Graham, H., Gunther,
- 1753 S.H., Hamilton, I., Hang, Y., Hänninen, R., Hartinger, S., He, K., Heidecke, J., Hess, J.J., Hsu, S.-C., Jamart, L., Jankin, S.,

- 1754 Jay, O., Kelman, I., Kiesewetter, G., Kinney, P., Kniveton, D., Kouznetsov, R., Larosa, F., Lee, J.K.W., Lemke, B., Liu, Y.,
- 1755 Liu, Z., Lott, M., Lotto Batista, M., Lowe, R., Odhiambo Sewe, M., Martinez-Urtaza, J., Maslin, M., McAllister, L.,
- 1756 McMichael, C., Mi, Z., Milner, J., Minor, K., Minx, J.C., Mohajeri, N., Momen, N.C., Moradi-Lakeh, M., Morrissey, K.,
- 1757 Munzert, S., Murray, K.A., Neville, T., Nilsson, M., Obradovich, N., O'Hare, M.B., Oliveira, C., Oreszczyn, T., Otto, M.,
- 1758 Owfi, F., Pearman, O., Pega, F., Pershing, A., Rabbaniha, M., Rickman, J., Robinson, E.J.Z., Rocklöv, J., Salas, R.N.,
- 1759 Semenza, J.C., Sherman, J.D., Shumake-Guillemot, J., Silbert, G., Sofiev, M., Springmann, M., Stowell, J.D., Tabatabaei,
- 1760 M., Taylor, J., Thompson, R., Tonne, C., Treskova, M., Trinanes, J.A., Wagner, F., Warnecke, L., Whitcombe, H., Winning,
- 1761 M., Wyns, A., Yglesias-González, M., Zhang, S., Zhang, Y., Zhu, Q., Gong, P., Montgomery, H., Costello, A.: The 2023
- report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing
 irreversible harms. The Lancet S0140673623018597. https://doi.org/10.1016/S0140-6736(23)01859-7, 2023.
- 1764 Rowlinson, M. J., Rap, A., Arnold, S. R., Pope, R. J., Chipperfield, M. P., McNorton, J., Forster, P., Gordon, H., Pringle, K.
- 1765 J., Feng, W., Kerridge, B. J., Latter, B. L., and Siddans, R.: Impact of El Niño–Southern Oscillation on the interannual
- variability of methane and tropospheric ozone, Atmos. Chem. Phys., 19, 8669–8686, https://doi.org/10.5194/acp-19-8669-
- 1767 2019, 2019.
- 1768 Saggu, G. S., S.K. Mittal, R. Agarwal, G. Beig: Epidemiological study on respiratory health of school children of rural sites
- 1769 of Malwa region (India) during post-harvest stubble burning events, M.A.P.A.N., 33, 3, 281-295,
- 1770 https://doi.org/10.1007/s12647-018-0259-3, 2018.
- 1771 Sagra, J., Moya, D., Plaza-Álvarez, P. A., Lucas-Borja, M. E., González-Romero, J., De las Heras, J., Alfaro-Sánchez, R.,
- 1772 and Ferrandis, P.: Prescribed fire effects on early recruitment of Mediterranean pine species depend on fire exposure and
- 1773 seed provenance, For. Ecol. Manage., 441, 253–261, https://doi.org/10.1016/j.foreco.2019.03.057, 2019.
- 1774 Sacks, J. D., Fann, N., Gumy, S., Kim, I., Ruggeri, G., & Mudu, P.: Quantifying the public health benefits of reducing air
- 1775 pollution: critically assessing the features and capabilities of WHO's AirQ+ and US EPA's Environmental Benefits Mapping
- and Analysis Program—Community Edition (BenMAP—CE). Atmosphere, 11(5), 516, 2020.
- 1777 Sacks, J. D., Lloyd, J. M., Zhu, Y., Anderton, J., Jang, C. J., Hubbell, B., & Fann, N.: The Environmental Benefits Mapping
- and Analysis Program–Community Edition (BenMAP–CE): A tool to estimate the health and economic benefits of reducing
 air pollution. Environmental Modelling & Software, 104, 118-129, 2018.
- 1780 Sahu, L.K. and Saxena, P.: High time and mass resolved PTR-TOF-MS measurements of VOCs at an urban site of India
- during winter: Role of anthropogenic, biomass burning, biogenic and photochemical sources. Atmospheric Research, 164,
- 1782 84-94, 2015.
- 1783 Saini, A., Chinnadurai, S., Schuster, J. K., Eng, A., Harner, T.: Per- and polyfluoroalkyl substances and volatile methyl
- 1784 siloxanes in global air: Spatial and temporal trends, Environmental Pollution, 323, 121291, 2023.
- 1785 Saxena, P., Sonwani, S., Srivastava, A., Jain, M., Srivastava, A., Bharti, A., Rangra, D., Mongia, N., Tejan, S. and Bhardwaj,
- 1786 S.: Impact of crop residue burning in Haryana on the air quality of Delhi, India. Heliyon, 7(5), 2021.

- 1787 Schuh, A. E., Jacobson, A. R., Basu, S., Weir, B., Baker, D., Bowman, K., Chevallier, F., Crowell, S., Davis, K. J., Deng, F.,
- 1788 Denning, S., Feng, L., Jones, D. B. A., Liu, J., and Palmer, P. I.: Quantifying the impact of atmospheric transport uncertainty
- 1789 on CO2 surface flux estimates, Global Biogeochem. Cycles, 33, 484–500, https://doi.org/10.1029/2018GB006086, 2019.
- 1790 Schuh, A. E., Byrne, B., Jacobson, A. R., Crowell, S. M. R., Deng, F., Baker, D. F., Johnson, M. S., Philip, S., and Weir, B.:
- 1791 On the role of atmospheric model transport uncertainty in estimating the Chinese land carbon sink, Nature, 603, E13–E14,
- 1792 https://doi.org/10.1038/s41586-021-04258-9, 2022.
- 1793 Sedlacek, A., Lewis, E., Onasch, T., Zuidema, P., Redemann, J., Jaffee, D., and Kleinman, L.: Using the black carbon
- 1794 particle mixing state to characterize the lifecyle of biomass burn aerosols, Environ. Sci. Technol., 56, 14315–14325,
- 1795 https://doi.org/10.1021/acs.est.2c03851, 2022.
- 1796 Shaw B.J., van Vliet J., Verburg P.H.: The peri-urbanization of Europe: A systematic review of a multifaceted process.
- 1797 Landsc Urban Plan. 2020 Apr 1; 196:103733.
- 1798 Shein, K.; Crouch, J.; Enloe, J.U.S. Billion-Dollar Weather & Climate Disasters 1980–2020; NOAA's National Centers for
- 1799 Environmental Information: Asheville, NC, USA, 2020.
- 1800 Shen, W., Meng, F., Qi, Y., & Shen, C.: Characteristics and sources of polycyclic aromatic hydrocarbons and heavy metals
- 1801 in atmospheric PM2. 5 in agricultural areas of Hangzhou Bay, China. Science of The Total Environment, 538, 662-671,
- 1802 2015.
- 1803 Shinozuka, Y., P. E. Saide, G. A. Ferrada, S. P. Burton, R. Ferrare, S. J. Doherty, K. Longo, M. Mallet, H. Gordon, D.
- 1804 Noone, Y. Feng, A. Dobracki, S. Freitag, S. G. Howell, S. LeBlanc, C. Flynn, M. Segal-Rosenhaimer, K. Pistone, J. R.
- 1805 Podolske, E. J. Stith, J. R. Bennett, G. R. Carmichael, A. da Silva, R. Govindaraju, R. Leung, Y. Zhang, J. Redemann, R.
- 1806 Wood and P. Zuidema: Modeling the smoky troposphere of the southeast Atlantic: a comparison to ORACLES airborne
- 1807 observations from September of 2016. Atmos. Chem. Phys., 20, p. 11,491-11,526, doi:10.5194/acp-20-11491-2020, 2020.
- 1808 Shunthirasingham, C., Alexandrou, N., Brice, K. A., Dryfhout-Clark, H., Su, K., Shin, C., Park, R., Pajda, A., Noronha, R.
- 1809 and Hung, H.: Temporal trends of halogenated flame retardants in the atmosphere of the Canadian Great Lakes Basin (2005–
- 1810 2014). Environ. Sci.: Processes Impacts, 20, 469-479, 2018.
- 1811 Simões, R. S., Ribeiro, P. F., and Santos, J. L.: Estimating the Trade-Offs between Wildfires and Carbon Stocks across
- 1812 Landscape Types to Inform Nature-Based Solutions in Mediterranean Regions, Fire, 6, 397,
- 1813 https://doi.org/10.3390/fire6100397, 2023.b
- 1814 Singh, H. B., C. Cai, A. Kaduwela, A. Weinheimer, and A. Wisthaler: Interactions of fire emissions and urban pollution over
- 1815 California: Ozone formations and air quality simulations, Atmos Environ., 56, 45-51, doi:10/1016/j.atmosenv.2012.03.046,
- 1816 2012.
- 1817 Smith P., Martino D., Cai Z., Gwary D., Janzen H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C.: Policy and
- 1818 technological constraints to implementation of greenhouse gas miti-gation options in agriculture. Agric. Ecosyst. Environ.,
- 1819 118:6–28. doi: 10.1016/j.agee.2006.06.006, 2007.

- 1820 Smith, A., Lott, N., Houston, T., Shein, K., Crouch, J., Enloe, J.U.S.: Billion-Dollar Weather & Climate Disasters 1980–
- 1821 2020; NOAA's National Centers for Environmental Information: Asheville, NC, USA, 2020.
- 1822 Sonwani, S., Saxena, P. and Khillare, P.S.: Profile of atmospheric particulate PAHs near busy roadway in tropical megacity,
- 1823 India. Inhalation Toxicology, 34, 1-2, pp.39-50, 2022.
- 1824 Sofiev, M., Ermakova, T., & Vankevich, R.: Evaluation of the smoke-injection height from wild-land fires using remote-
- 1825 sensing data. Atmospheric Chemistry and Physics, 12, 4, 1995-2006, 2012.
- 1826 Sofiev, M., Vankevich, R., Ermakova, T., & Hakkarainen, J.: Global mapping of maximum emission heights and resulting
- 1827 vertical profiles of wildfire emissions. Atmospheric Chemistry and Physics, 13(14), 7039-7052, 2013.
- 1828 Sofiev, M., Vankevich, R., Lotjonen, M., Prank, M., Petukhov, V., Ermakova, T., Koskinen, J., and Kukkonen, J.: An
- 1829 operational system for the assimilation of the satellite information on wild-land fires for the needs of air quality modelling
- 1830 and forecasting, Atmos. Chem. Phys., 9, 6833–6847, https://doi.org/10.5194/acp-9-6833-2009, 2009.
- 1831 Song, S., Chen, B., Huang, T., Ma, S., Liu, L., Luo, J., Shen, H., Wang, J., Guo, L., Wu, M., Mao, X., Zhao, Y., Gao, H., and
- 1832 Ma, J.: Assessing the contribution of global wildfire biomass burning to BaP contamination in the Arctic, Environmental
- 1833 Science and Ecotechnology, 14, 100232, https://doi.org/10.1016/j.ese.2022.100232, 2023.
- 1834 Song, S., Chen, K., Huang, T., Ma, J., Wang, J., Mao, X., ... Zhou, Z.: New emission inventory reveals termination of global
- dioxin declining trend. Journal of Hazardous Materials, 443, 130357. doi:10.1016/j.jhazmat.2022.130357, 2023.
- 1836 Sparks, T. L. and Wagner, J.: Composition of particulate matter during a wildfire smoke episode in an urban area, Aerosol
- 1837 Science and Technology, 55, 734-747, 10.1080/02786826.2021.1895429, 2021.
- Spracklen, D. V., and A. Rap: Natural aerosol–climate feedbacks suppressed by anthropogenic aerosol, Geophys. Res. Lett.,
 40, 5316–5319, doi:10.1002/2013GL057966, 2013.
- Stewart, S. I., V. C. Radeloff, R. B. Hammer, and T. J. Hawbaker: Defining the wildland–urban interface, Journal of Forestry
 105, no. 4, 201-207, 2007.
- 1842 Stocker, M., Ladstädter, F. & Steiner, A.K.: Observing the climate impact of large wildfires on stratospheric temperature, Sci
- 1843 Rep, 11, 22994, https://doi.org/10.1038/s41598-021-02335-7, 2021.
- 1844 Su, Y., Wania, F.: Does the forest filter effect prevent semivolatile organic compounds from reaching the Arctic?
- 1845 Environmental Science and Technology, 39(18), 7185-7193, 2005.
- 1846 Sutherland C, Celliers L, Scheffran J.: Vulnerability of informal settlements in the context of rapid urbanization and climate
- 1847 change, Environ Urban, 31, 1, 157–76, 2019.
- 1848 Tan, J., Fu, J. S., Dentener, F., Sun, J., Emmons, L., Tilmes, S., Sudo, K., Flemming, J., Jonson, J. E., Gravel, S., Bian, H.,
- 1849 Davila, Y., Henze, D. K., Lund, M. T., Kucsera, T., Takemura, T., and Keating, T.: Multi-model study of HTAP II on sulfur
- 1850 and nitrogen deposition, Atmos. Chem. Phys., 18, 6847–6866, https://doi.org/10.5194/acp-18-6847-2018, 2018.
- 1851 Tang, W., Llort, J., Weis, J., Basart, S., Li, Z., Sathyendranath, S., Jackson, T., Perron, M., Sanz Rodriguez, E., Proemse, B.,
- 1852 Bowie, A., Schallenberg, C., Strutton, P., and Matear, R.: Widespread phytoplankton blooms triggered by 2019-2020
- 1853 Australian wildfires, Nature, 597, https://doi.org/10.1038/s41586-021-03805-8, 2021.

- 1854 Tang, W., Emmons, L.K., Buchholz, R.R., Wiedinmyer, C., Schwantes, R.H., He, C., Kumar, R., Pfister, G.G., Worden,
- 1855 H.M., Hornbrook, R.S. and Apel, E.C.: Effects of fire diurnal variation and plume rise on US Air quality during FIREX-AQ
- 1856 and WE-CAN Based on the multi-scale infrastructure for chemistry and aerosols (MUSICAv0). Journal of Geophysical
- 1857 Research: Atmospheres, 127(16), p.e2022JD036650, 2022.
- 1858 Tang, W., Tilmes, S., Lawrence, D.M., Li, F., He, C., Emmons, L.K., Buchholz, R.R. and Xia, L.: Impact of solar
- 1859 geoengineering on wildfires in the 21st century in CESM2/WACCM6. Atmospheric Chemistry and Physics, 23(9), pp.5467-
- 1860 5486, 2023.
- 1861 Tang, W., He, C., Emmons, L. and Zhang, J.: Global expansion of wildland-urban interface (WUI) and WUI fires: insights
- 1862 from a multiyear worldwide unified database (WUWUI). Environmental Research Letters, 19(4), p.044028, 2024.
- 1863 Thacker, F. E. N., Ribau, M. C., Bartholomeus, H., and Stoof, C. R.: What is a fire resilient landscape? Towards an
- 1864 integrated definition, Ambio, 52, 1592–1602, https://doi.org/10.1007/s13280-023-01891-8, 2023.
- Thoning, K., Dlugokencky, E., Lan, X., and NOAA Global Monitoring Laboratory: Trends in globally-averaged CH4, N2O,
 and SF6, https://doi.org/10.15138/P8XG-AA10, 2022.
- 1867 Tian, C., Yue, X., Zhu, J., Liao, H., Yang, Y., Lei, Y., Zhou, X., Zhou, H., Ma, Y., and Cao, Y.: Fire–climate interactions
- through the aerosol radiative effect in a global chemistry–climate–vegetation model, Atmos. Chem. Phys., 22, 12353–12366,
 https://doi.org/10.5194/acp-22-12353-2022, 2022.
- 1870 Obrist, D., Kirk, J. L., Zhang, L., Sunderland, E. M., Jiskra, M., and Selin, N. E.: A review of global environmental mercury
- processes in response to human and natural perturbations: Changes of emissions, climate, and land use, Ambio, 47, 116–140,
 https://doi.org/10.1007/s13280-017-1004-9, 2018.
- To, P., Eboreime, E., and Agyapong, V. I. O.: The Impact of Wildfires on Mental Health: A Scoping Review, Behavioral
 Sciences, 11, 126, 2021.
- 1875 Turquety, S., Hadji-Lazaro, J., Clerbaux, C., Hauglustaine, D. A., Clough, S. A., Casse[´], V., Schlu[¨]ssel, P., and Me[´]gie, G.:
- 1876 Operational trace gas retrieval algorithm for the Infrared Atmospheric Sounding Interferometer, J. Geophys. Res., 109,
- 1877 D21301, doi:10.1029/2004JD004821, 2004.
- 1878 UN: Convention on Long-Range Transboundary Air Pollution, United Nations, Treaty Series, vol 1302, p217,
- 1879 (<u>https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-1&chapter=27&clang=_en</u>), Geneva,
 1880 1979.
- 1881 UN: Minamata Convention on Mercury, United Nations, Treaty Series, vol 3202,
- 1882 (https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-17&chapter=27&clang=_en), Kumamoto,
- 1883 2013.
- 1884 UN (United Nations) Environment Programme: Spreading like Wildfire The Rising Threat of Extraordinary Landscape
- 1885 Fires. A UNEP Rapid Response Assessment. Nairobi, 2022.

- 1886 Turquety, S., Menut, L., Siour, G., Mailler, S., Hadji-Lazaro, J., George, M., Clerbaux, C., Hurtmans, D., and Coheur, P.-F.:
- 1887 APIFLAME v2.0 biomass burning emissions model: impact of refined input parameters on atmospheric concentration in
- 1888 Portugal in summer 2016, Geosci. Model Dev., 13, 2981–3009, https://doi.org/10.5194/gmd-13-2981-2020, 2020.
- 1889 UNECE: Guidance document on reduction of emissions from agricultural residue burning, United Nations publication issued
- 1890 by the United Nations Economic Commission for Europe, eISBN: 978-92-1-002306-1, March 2023.
- 1891 UNEP: Global Mercury Assessment 2013: sources, emissions, releases and environmental transport, Geneva, Switzerland,
- 1892 44 pp., 2013.
- 1893 U.S. Environmental Protection Agency: Guidelines for carcinogen risk assessment. Federal Register, 17765–17817,
- 1894 https://www3.epa.gov/airtoxics/cancer_guidelines_final_3-25-05.pdf, 2005.
- 1895 US EPA: CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool.
- 1896 https://www.epa.gov/cobra, 2021.
- 1897 Val Martin, M., Logan, J. A., Kahn, R. A., Leung, F.-Y., Nelson, D. L., and Diner, D. J.: Smoke injection heights from fires
- 1898 in North America: analysis of 5 years of satellite observations, Atmospheric Chemistry and Physics, 10, 1491–1510,
- 1899 https://doi.org/10.5194/acp-10-1491-2010, 2010.
- 1900 Val Martin, M., Kahn, R. A., Logan, J. A., Paugam, R., Wooster, M., & Ichoku, C.: Space-based observational constraints
- 1901 for 1-D fire smoke plume-rise models. Journal of Geophysical Research: Atmospheres, 117, D22, 2012.
- 1902 Van Dingenen, R., Dentener, F., Crippa, M., Leitao, J., Marmer, E., Rao, S., ... & Valentini, L.: TM5-FASST: a global
- 1903 atmospheric source-receptor model for rapid impact analysis of emission changes on air quality and short-lived climate
- 1904 pollutants. Atmospheric Chemistry and Physics, 18, 21, 16173-16211, 2018.
- van der Velde, I.R., van der Werf, G.R., Houweling, S. et al. Vast CO2 release from Australian fires in 2019–2020 constrained
 by satellite. Nature 597, 366–369, <u>https://doi.org/10.1038/s41586-021-03712-y</u>, 2021.
- 1907 van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin,
- 1908 Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and
- 1909 peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, https://doi.org/10.5194/acp-10-11707-2010, 2010.
- van Wees, D., van der Werf, G.R., Randerson, J.T., Andela, N., Chen, Y. and Morton, D.C.: The role of fire in global forest
 loss dynamics. Glob Change Biol, 27: 2377-2391. https://doi.org/10.1111/gcb.15591, 2021.
- 1912 Vautard R, Beekmann M, Menut L, Lattuati M (1998) Applications of adjoint modelling in urban air pollution. In: Borrell
- 1913 PM, Borrell P (eds) Eurotrac 1998, Guest contribution to subproject Saturn. WIT, Southampton, pp 502–508Houweling et
- 1914 al., 1999
- 1915 Veefkind, J.P., Aben, I., McMullan, K., Förster, H., de Vries, J., Otter, G., Claas, J., Eskes, H.J., de Haan, J.F., Kleipool, Q.,
- 1916 van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, Ingmann, P., Voors, R., Kruizinga, B., Vink, R.,
- 1917 Visser, H., Levelt, P.F.: TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the
- 1918 atmospheric composition for climate, air quality and ozone layer applications, Remote Sensing of Environment, 120, 70-83,
- 1919 ISSN 0034-4257, https://doi.org/10.1016/j.rse.2011.09.027, 2012a.

- 1920 Veefkind, J.P.: OMI/Aura Ozone (O3) DOAS Total Column L3 1 day 0.25 degree x 0.25 degree V3, Greenbelt, MD, USA,
- 1921 Goddard Earth Sciences Data and Information Services Center (GES DISC), <u>https://doi.org/10.5067/Aura/OMI/DATA3005</u>,
- 1922 2012b
- 1923 Volkova, L., Roxburgh, S. H., and Weston, C. J.: Effects of prescribed fire frequency on wildfire emissions and carbon
- sequestration in a fire adapted ecosystem using a comprehensive carbon model, J. Environ. Manage., 290, 112673,
- 1925 https://doi.org/10.1016/j.jenvman.2021.112673, 2021.
- 1926 Wagner, F., Heyes, C., Klimont, Z., & Schöpp, W.: The GAINS optimization module: Identifying cost-effective measures
- 1927 for improving air quality and short-term climate forcing, 2013.
- 1928 Wagner, R., Jähn, M., and Schepanski, K.: Wildfires as a source of airborne mineral dust Revisiting a conceptual model
- using large-eddy simulation (LES), Atmos. Chem. Phys., 18, 11863–11884, https://doi.org/10.5194/acp-18-11863-2018,
- 1930 2018.
- 1931 Wan, J. S., Hamilton, D. S., and Mahowald, N. M.: Importance of Uncertainties in the Spatial Distribution of Preindustrial
- 1932 Wildfires for Estimating Aerosol Radiative Forcing, Geophys. Res. Lett., 48, https://doi.org/10.1029/2020gl089758, 2021.
- 1933 Wang D, Guan D, Zhu S, Mac Kinnon M, Geng G, Zhang Q, et al.: Economic footprint of California wildfires in 2018, Nat
- 1934 Sustain., 4, 3, 252–60, 2021.
- 1935 Ward, D. S., Kloster, S., Mahowald, N. M., Rogers, B. M., Randerson, J. T., and Hess, P. G.: The changing radiative forcing
- 1936 of fires: global model estimates for past, present and future, Atmos. Chem. Phys., 12, 10857–10886,
- 1937 https://doi.org/10.5194/acp-12-10857-2012, 2012.
- 1938 Warneke, C., Schwarz, J. P., Dibb, J., Kalashnikova, O., Frost, G., Al-Saad, J., et al.: Fire influence on regional to global
- environments and air quality (FIREX-AQ). Journal of Geophysical Research: Atmospheres, 128, e2022JD037758.
- 1940 <u>https://doi.org/10.1029/2022JD037758</u>, 2023.
- 1941 Watson, J. G., Cao, J., Chen, L.-W. A., Wang, Q., Tian, J., Wang, X., Gronstal, S., Ho, S. S. H., Watts, A. C., and Chow, J.
- 1942 C.: Gaseous, PM2.5 mass, and speciated emission factors from laboratory chamber peat combustion, Atmos. Chem. Phys.,
- 1943 19, 14173–14193, https://doi.org/10.5194/acp-19-14173-2019, 2019.
- 1944 Weichenthal, S., Villeneuve, P. J., Burnett, R. T., Van Donkelaar, A., Martin, R. V., Jones, R. R., ... & Hoppin, J. A.: Long-
- 1945 term exposure to fine particulate matter: association with nonaccidental and cardiovascular mortality in the agricultural
- 1946 health study cohort. Environmental health perspectives, 122, 6, 609-615, 2014.
- 1947 WHO: Air quality guidelines for particulate matter
- 1948 Whaley, C. (2025). Source region definitions for the HTAP3-Fires multi-model exercise [Data set]. Zenodo.
- 1949 <u>https://doi.org/10.5281/zenodo.14908253</u>
- 1950 Whicker, J. J., Pinder, J. E., and Breshears, D. D.: Increased Wind Erosion from Forest Wildfire: Implications for
- 1951 Contaminant-Related Risks, J. Environ. Qual., 35, 468–478, https://doi.org/10.2134/jeq2005.0112, 2006.
- 1952 Wiedinmyer, C., Kimura, Y., McDonald-Buller, E. C., Emmons, L. K., Buchholz, R. R., Tang, W., Seto, K., Joseph, M. B.,
- 1953 Barsanti, K. C., Carlton, A. G., and Yokelson, R.: The Fire Inventory from NCAR version 2.5: an updated global fire

- emissions model for climate and chemistry applications, Geosci. Model Dev., 16, 3873–3891, https://doi.org/10.5194/gmd16-3873-2023, 2023.
- Wild, O.: Modelling the global tropospheric ozone budget: exploring the variability in current models, Atmos. Chem. Phys.,
 7, 2643–2660, https://doi.org/10.5194/acp-7-2643-2007, 2007.
- 1958 Wong, F., Dryfhout-Clark, H., Hung, H., Aas, W., Bohlin-Nizzetto, P., Brevik, K., Nerentorp Mastromonaco, M., Brorström
- 1959 Lundén, E., Ólafsdóttir, K., Sigurðsson, Á, Vorkamp, K., Bossi, R., Skov, H., Hakola, H., Barresi, E., Sverko, E., Zapevalov,
- 1960 M., Samsonov, D., Wilson, S.: Time trends of persistent organic pollutants (POPs) and chemicals of emerging arctic concern
- 1961 (CEAC) in Arctic air from 25 years of monitoring. Science of the Total Environment, 775, 145109, 2021.
- 1962 Wong, F., Shoeib, M., Katsoyiannis, A., Eckhardt, S., Stohl, A., Bohlin-Nizzetto, P., Li, H., Fellin, P., Su, Y., Hung, H.:
- 1963 Assessing temporal trends and source regions of per- and polyfluoroalkyl substances (PFASs) in air under the Arctic
- 1964 Monitoring and Assessment Programme (AMAP). Atmospheric Environment, 172, 65–73, 2018.
- 1965 Xie, Y., M. Lin, and L.W. Horowitz: Summer PM2.5 Pollution Extremes Caused by Wildfires Over the Western United
- 1966 States During 2017–2018. Geophys. Res. Lett., 47, 16, DOI:10.1029/2020GL089429, 2020.
- 1967 Xie, Y., M. Lin, Bertrand Decharme, Christine Delire, Larry W. Horowitz, David M. Lawrence, Fang Li, Roland Séférian:
- Tripling of western US particulate pollution from wildfires in a warming climate. Proceedings of the National Academy of
 Sciences (PNAS), 119, e2111372119 (2022)2021.
- 1970 Xu, J., Morris, P. J., Liu, J., & Holden, J.: PEATMAP: Refining estimates of global peatland distribution based on a meta-1971 analysis. CATENA, 160, 134–140. https://doi.org/10.1016/J.CATENA.2017.09.010, 2018.
- 1972 Xu, R., Ye, T., Yue, X. et al.: Global population exposure to landscape fire air pollution from 2000 to 2019, Nature, 621,
- 1973 521–529, https://doi.org/10.1038/s41586-023-06398-6, 2023.
- 1974 Xu, L., J.D. Crounse, K.T. Vasquez, A. Hannah, P.O. Wennberg, I. Bourgeois, S.S. Brown, P. Campuzano-Jost, M.M.
- 1975 Coggon, J.H. Crawford, J.P. DiGangi, G.S. Diskin, A. Fried, E.M. Gargulinski, J.B. Gilman, G.I. Gkatzelis, H. Guo, J.W.
- 1976 Hair, S.R. Hall, H.A. Halliday, T.F. Haniscok, R.A. Hannunk, C.D. Holmes, L.G. Huey, J.L. Jimenez, A. Lamplugh, Y.R.
- 1977 Lee, J. Liao, J. Lindaas, J.A. Neuman, J.B. Nowak, J. Peischl, D.A. Peterson, F. Piel, D. Richter, P.S. Rickly, M.A.
- 1978 Robinson, A.W. Rollins, T.B. Ryerson, K. Sekimoto, V. Selimovic, T. Shingler, A.J. Soja, J.M. St. Clair, D.J. Tanner, K.
- 1979 Ullmann, P.R. Veres, J. Walega, C. Warneked, R.A. Washenfelder, P. Weibring, A. Wisthaler, G.M. Wolfe, C.C. Womack,
- and R.J. Yokelson: Ozone Chemistry in Western U.S. Wildfire Plumes, Science Advances, 2021.
- Yang, H., Huang, X., Westervelt, D. M., Horowitch, L., Peng, W.: Socio-demographic factors shaping the future global
 health burden from air pollution, Nature Sustainability, 6, 58-68, doi:10.1038/s41893-022-00976-8, 2023.
- 1983 Yoseph, E., E. Hoy, C. D. Elder, S. M. Ludwig, D. R. Thompson, C. E. Miller: Tundra fire increases the likelihood of
- 1984 methane hotspot formation in the Yukon-Kuskokwim Delta, Alaska, USA, Environ. Res. Lett., 18 104042,
- 1985 doi:10.1088/1748-9326/acf50b, 2023.

- 1986 Yu, Y., Katsoyiannis, A., Bohlin-Nizzetto, P., Brorström-Lundén, E., Ma, J., Zhao, Y., Wu, Z., Tych, W., Mindham,
- 1987 D., Sverko, E., Barresi, E., Dryfhout-Clark, H., Fellin, P., Hung, H.: Polycyclic aromatic hydrocarbons not declining
- 1988 in arctic air despite global emission reduction. Environ. Sci. Technol., 53, 2375–2382, 2019.
- 1989 Zhang, J. and P. Zuidema: The diurnal cycle of the smoky marine boundary layer observed during August in the remote
- 1990 southeast Atlantic. Atmos. Chem. Phys., 19, p. 14493-14516, doi:acp-19-14493-2019, 2019.
- 1991 Zhang, J. and P. Zuidema: Sunlight-absorbing aerosol amplifies the seasonal cycle in low cloud fraction over the southeast
- 1992 Atlantic. Atmos. Chem. Phys., 21, p. 11179-11199, doi:10.5194/acp-21-11179-2021, 2021.
- 1993 Zhang, L., Lin, M., Langford, A. O., Horowitz, L. W., Senff, C. J., Klovenski, E., Wang, Y., Alvarez II, R. J.,
- 1994 Petropavlovskikh, I., Cullis, P., Sterling, C. W., Peischl, J., Ryerson, T. B., Brown, S. S., Decker, Z. C. J., Kirgis, G., and
- 1995 Conley, S.: Characterizing sources of high surface ozone events in the southwestern US with intensive field measurements
- and two global models, Atmos. Chem. Phys., 20, 10379–10400, https://doi.org/10.5194/acp-20-10379-2020, 2020
- 1997 Zhang, L., Jacob, D. J., Yue, X., Downey, N. V., Wood, D. A., and Blewitt, D.: Sources contributing to background surface
- 1998 ozone in the US Intermountain West, Atmos. Chem. Phys., 14, 5295–5309, doi:10.5194/acp-14-5295-2014, 2014
- 1999 Zhou S., Lee A.K.Y., McWhinney R.D., Abbatt J.P.D.: Burial effects of organic coatings on the heterogeneous reactivity of
- 2000 particle-borne benzo[a]pyrene (BaP) toward ozone, J. Phys. Chem. A., 116, 7050–7056. doi: 10.1021/jp3030705, 2012.
- 2001 Zuidema, P., J. Redemann, J. Haywood, R. Wood, S. Piketh, M. Hipondoka, and P. Formenti, 2016: Smoke and clouds
- 2002 above the southeast Atlantic: Upcoming field campaigns probe absorbing aerosol's impact on climate.Bull. Am. Meteor.
- 2003 Soc., 97, pp. 1131-1135, doi: 10.1175/bams-d-15-00082.1
- 2004 Zuidema, P., A. Sedlacek, C. Flynn, S. Springston, R. Delgadillo, J. Zhang, A. Aiken and P. Muradyan, 2018: The
- Ascension Island boundary layer in the remote southeast Atlantic is often smoky. Geophys. Res. Lett., 45, pp. 4456-4465
- 2006 doi:10.1002/2017GL076926

2007 Appendix

Name	Objective	website	notes
Biomass Burning Uncertainty: Emissions, ReactioNs, and Dynamics (BBURNED)	To coordinate fire research community towards better understanding fire variability and uncertainty, particularly as it relates to atmospheric chemistry	https://www2.acom.uca r.edu/bburned	An International Global Atmospheric Chemistry (IGAC) activity
Arctic Monitoring and Assessment Programme (AMAP)	Inform the Arctic Council through science-based, policy relevant assessments regarding pollution and climate change issues	https://www.amap.no/a bout	Expert groups on SLCFs, POPs, Hg, Local v Long Range. SLCF EG may use these HTAP experiments for a future AMAP

2008 **Table A.1:** Complementary fire-related research activities.

			report.
Arctic Black Carbon impacting on Climate and Air Pollution (ABC-iCAP)	Creation of fire management scenarios for Arctic Coucil countries/states	https://abc- icap.amap.no/	
WMO Vegetation Fire Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS)	To enhance the ability of countries to deliver timely and quality vegetation fire and smoke pollution forecasts, observations, information and knowledge to users through an international partnership of research and operational communities	https://community.wm o.int/en/activity- areas/gaw/science/mod elling- applications/vfsp-was	
International Association of Wildland Fire (IAWF)	Organizes large-scale conferences around wildfire	https://www.iawfonline .org/	
integrated Land Ecosystem-Atmosphere processes Study (iLEAPS)	Recently conducted a meeting on fires in south Asia, focusing on the prescribed fires and its modelling and planning next workshop in March. Carry out the conversion on the prescribed fires and its impact on air quality, health and modelling including fire emission estimate.	https://ileaps.org/future -earth_and https://www.tropmet.re s.in/204-event_details	
Arctic Community Resilience to Boreal Environmental change: Assessing Risks from fire and disease (ACRoBEAR)	To predict and understand health risks from wildfire air pollution and natural-focal disease at high latitudes, under rapid Arctic climate change, and resilience and adaptability of communities across the region to these risks.	www.acrobear.net	Integrating health data and knowledge, community knowledge and stakeholder dialogue, with satellite and in-situ observations, and numerical modelling.
Air Pollution in the Arctic: Climate Environment and Societies (PACES)	Review existing knowledge and foster new research on the sources and fate of Arctic air pollution, and its impacts on climate, health, and ecosystems	https://igacproject.org/a ctivities/PACES	IGAC/IASC initiative. mproving knowledge of high latitude forcing from fire emissions. Key questions around ageing of fire plumes, mixing with anthropogenic pollution following export (e.g. POLARCAT cases). NO _y speciation, BC ageing, how these vary between models Need for improved observational constraint on these processes
AeroCom		https://aerocom.met.no, and more specifically e.g. https://aerocom.met.no/ node/110 and	

		https://aerocom.met.no/ node/115	
The Fire Model Intercomparisons Project (FireMIP)	Systematic examination of global fire models, which have been linked to different vegetation models. Relevant for ESM/coupled fire simulations.	https://gmd.copernicus. org/articles/10/1175/20 17/	ISIMIP3 [the Intersectoral Impacts MIP phase 3] which FireMIP is now merging with - ISIMIP3b [simulations currently in progress] will produce multi-model projected future fire emissions for different SSP scenarios)
Support for National Air Pollution Control Strategies (SNAPCS)	Part of this project involves investigating the impact of local and long-range transport of fire- related pollutants on the UK. There is particular interest in implications for health/air quality, and model development		Project involvement from the UKCEH, Imperial College London, EMRC and DEFRA
European Network on Extreme fiRe behaviOr (NERO)	bringing together wildfire researchers and practitioners to advance the current state of the science, thus making a crucial step in improving fire management, firefighter training and safety, and public safety planning Science-based wildfire management	https://www.cost.eu/act ions/CA22164/	European Cooperation in Science and technology (COST) Action
FLARE: Fire science Learning AcRoss the Earth system' (workshop)	The goal is to develop a roadmap for coordinated wildfire research for the next 5- 10 years.	https://futureearth.org/i nitiatives/funding- initiatives/esa- partnership/	Held 18-21 September 2023. Article: https://futureearth.org/2023/12/13/re flections-from-the-fire-science- learning-across-the-earth-system- flare-workshop/
AerChemMIP2 in CMIP7	Historical and future climate change simulations focused on aerosols and trace gas chemistry for CMIP7.		Will include a focus on wildland fires and biomass burning. Simulation design in 2024.

Table A.2 Model characteristics of potential participants.PI = principal investigator(s), BC/IC=boundary/initial conditions. Model types (see Section 4.1 for acronyms).

Organization	Ы	Model(s)	Туре	species	domain	Resolution (spatial and temporal)	BC/IC
University of Hertfordshire, Centre for Climate Change Research	Ranjeet S Sokhi	WRF/CMAQ, WRF-Chem	СТМ	PM _{2.5} (components), O ₃ , NO ₂	Europe, CORDEX	5-10km over Europe, hourly, daily, monthly (for future projections)	CAM-chem, ECMWF, GFS
Environment and Climate Change Canada Climate Research Division	Cynthia Whaley, Knut von Salzen, David Plummer, Vivek Arora	CanAM-PAM, CMAM, CanESM, CLASSIC (global & regional)	ESM and CCM	PM _{2.5} , O ₃ , NO _x , CH ₄	Global, Arctic, North America	T64, typically 3- hourly to monthly output	CanESM provides BC/IC for CanRCM
NSF National Center for Atmospheric Research Atmospheric Chemistry Observations and Modelling	Louisa Emmons, Rebecca Buchholz, Douglas Hamilton	MUSICAv0 (CESM/CAM- Chem)		O ₃ , NO _x , CO, VOCs, PM _{2.5} and speciated aerosols, metals	Global, U.S.	12-km over US (and other regions), 1-deg global	
NASA Goddard/University of Maryland	Min Huang	WRF-Chem (NASA version, LIS)	ESM	O ₃ , PM, CO, NO _x , VOCs	Eastern US	10 km or finer	CAMS, CAM- Chem/WACCM
NASA Goddard Institute for Space Studies	Keren Mezuman, Kostas Tsigaridis	NASA GISS ModelE	ESM	CO ₂ , CO, HCHO, CH ₄ , Acetone, Alkenes, Paraffin, SO ₂ , NO _x , NH ₃ , aerosols/PM _{2.5} (organic, black carbon)	global	Cubed-sphere 1x1 effective resolution. 30 minutes to monthly	
Cyprese Institute Climate and Atmosphere Research Centre	Theo Christoudias	EMAC, WRF- Chem	СТМ	PM (incl. Black carbon), CO, O ₃	Global, Middle East, North Africa	20km over Middle East (2 mins), 1- deg global (15 mins)	GFS/WACCM
University of Bremen, Institute of Environmental Physics	Nikos Daskalakis, Sarah-Lena Meyer, Mihalis Vrekousis	TM5-MP		PM _{2.5} , O ₃ , NO _x , NO ₂ , CO, CH ₄ , VOCs, OA, speciated Aerosols	global	1°x1°; 3-hourly to monthly	
UKCEH/Edinburgh University, Atmospheric Chemistry and	Damaris Tan, Stefan Reis, Mathew Heal, Massimo Vieno, Eiko Nemitz	EMEP4UK, EMEP MSC- W WRF	СТМ	PM _{2.5} and components	Global, Europe, UK	1km or 3km over UK, 27 km over Europe, 1 deg global resolution. Hourly output.	WRF with GFS/ERA5 reanalysis

			1			1	1
Effects/School of Chemistry							
UK Met Office, Hadley Centre	Steven Turnock, Gerd Folbert, Joao Teixeira	UKESM1+ INFERNO	ESM	PM _{2.5} , O ₃ , CH ₄	Global	Global grid at 1.25 x 1.75 resolution (~140km)	
Lancaster University, Lancaster Environment Centre	Oliver Wild	FRSGC/UCI CTM	СТМ	O ₃ , NO _x , CO, VOC, CH ₄ , gas-phase oxidants	global	Usually T42 (2.8x2.8 deg) but T106 (1.1x1.1 deg) feasible; output hourly/monthly	
Thailand Team (currently, King Mongkut's University of Technology Thonburi, Thammasart University)	Kasemsan Manomaiphiboon, Vanisa Surapipith	WRF-Chem	СТМ	PM _{2.5} (primary/secondary), O ₃	Upper Southeast Asia (with focus on Lower Mekong Region)	4-12 km; output hourly	
IITM Pune, India, AQEWS Urban Air Modelling	Rupal Ambulkar, Sachin D, Gaurav Govardhan	WRF-Chem	СТМ	PM _{2.5} , PM ₁₀ , CO	India	10km over India run with daily output	GFS
CICERO Center for International Climate Research, Oslo, Norway	Marianne Tronstad Lund	OlsoCTM3	СТМ	O ₃ , NO _x , CO, VOCs, PM _{2.5} and speciated aerosols	global	2.25x2.25 deg (possibly 1x1 deg depending on no. of simulations/scope), 60 vertical layers. Monthly output, with option of 3- hourly	
DLR Institute of Atmospheric Physics, Earth system modelling	Mariano Mertens	EMAC, MECO(n)		O_3 , NO_x , CO , $VOCs$, $PM_{2.5}$ and speciated aerosols	Global, Europe, West Africa		
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	Meiyun Lin	GFDL AM4VR		O_3 , PAN, NO _y , CO, VOCs, PM _{2.5} and speciated aerosols	Global, North America	~13 km over North America, 25-50 km over Europe, and 50-100 km over Asia. Monthly, daily	
MIT, Earth, Atmospheric and Planetary Sciences	Noelle Selin, Lexia Cicone, Eric Roy	GEOS-Chem	СТМ	PAHs, Hg	global	2x2.5, 47 vertical layers, monthly outputs	
Meteorological Research Institute, Japan Met Agency	Naga Oshima	MRI-ESM2, TL159	ESM	PM _{2.5} , speciated Aerosols, O ₃ , NO _x ,	global	AGCM: TL159 Aerosol: TL95 Ozone: T42	

(MRI-JMA), Dept of atmosphere, ocean, and Earth system modelling research				NO ₂ , CO, CH ₄ , VOCs			
Institut National Polytechnique Felix Houphouet-Boigny (INP-HB) Department of Forestry and Environment	Jean-Luc Kouassi			PM _{2.5} , O ₃ , NO ₂ , CO, CH ₄	Global, West Africa		
Space Research of the Netherlands, Earth Dept.	Helene Peiro, Ilse Aben, Ivar van der Velde	TM5-4DVar zoom	Inverse model	СО	Global, North America, Europe, Africa	Global 3x2, Regional 3x2 and 1x1; daily to monthly	
Norwegian Met Inst, Research Dept	Jan Eiof Jonson	EMEP		O ₃ , NO _x , CO, NMVOCs, PM	Global, Europe	daily to annual output	
NILU, Atmospheric Chemistry	Sabine Eckhardt, Nikolaos Evangeliou	FLEXPART	Lagrangian Transport Model	CO, BC	global	0.5 degrees, 3h resolution	
Finnish Meteorological Institute, Atmospheric Composition Research	Mikhail Sofiev, Rostislav Kouznetsov, Risto Hanninen, Andreas Uppstu, Evgeny Kadantsev	IS4FIRES- SILAM		O ₃ , NO _x , CO, VOCs, PM _{2.5} and speciated aerosols	Global to local	Several options, e.g., global 5-days forecast 10km for fire PM, 20km for full AQ tropo+strato, 10km Europe. Multi- annual reanalysis up to 50km global	Global nested, CAMS
Tsinghua University, School of Environment	Shuxiao Wang, Bin Zhao, Yicong He, Lyuyin Huang	CESM, WRF- Chem	ESM and CTM	PM _{2.5} , O ₃ , NO _x , NO ₂ , CO, CH ₄ , VOC, OA	Global, Southern China and SE Asia	0.9x1.25 hourly, daily, monthly. 27km overall domain with 9km nested domain; hourly	
University of Augsburg, Faculty of Medicine	Christophe Knote, Bin Zhou	WRF-Chem	СТМ	PM _{2.5} , OA	Europe	20km and 2km nest, hourly	GFS, CAM- Chem
Jožef Stefan Institute / MSC-E, Dept of Environmental Sciences	Oleg Travnikov	GLEMGLEOS	Multi-media POPs (?)	POPs, Hg, metals	Global, Europe	1x1 degrees, monthly or daily output	
--	--------------------------	-------------------	---	---	------------------------------------	--	------
Peking University, Lanzhou University	Jianmin Ma, Tao Huang	CanMETOP, CMAQ	Long-range atmospheric physical transport and CTM	POPs, heavy metals	Global, China, North America	from 10 km to 1°x1°. Hourly, daily, and yearly	
Sorbonne Université, LATMOS/IPSL	Solène Turquety	CHIMERE	СТМ	O ₃ , CO, VOCs, PAN, NH ₃ , aerosols	Northern Hemisphere, Europe	1°x1° hemispheric, 10km Europe	CAMS
Stockholm University	Matthew MacLeod	BETR Global	Multi-media POPs	POPs, PAHs	Global	3.75° x 3.75°, weekly or monthly output	

Table A.2 continued

Organization	meteorology	Anthro emissions	Fire emissions	Natural emissions	Simulation length	Fire plume height	References
University of Hertfordshire, Centre for Climate Change Research		CAMS regional	CAMS GFAS, NCAR FINN	MEGAN			
Environment and Climate Change Canada Climate Research Division	Free-running or nudged to ERA- Interim	CMIP6, ECLIPSEv6b	CMIP6/GFED4 or use online interactive fire module from CLASSIC		Season to multi- decade	Climatological distribution based on AEROCOM, or online with CFFEPS plume height scheme	
NSF National Center for Atmospheric Research Atmospheric Chemistry Observations and Modelling	Nudged to MERRA2 reanalysis	CAMS	FINN, QFED, or other	MEGAN online in CLM, prognostic sea spray and dust	Season to multi-year		https://wiki.ucar.edu/

NASA Goddard/University of Maryland	WRF, initial/boundary conditions from NARR	CAMS (multi- year), HTAPv3 for 2018	QFED, plume rise	Online biogenic and lightning	case studies and multi- year warm seasons		Huang et al. (2022; 2024)
NASA Goddard Institute for Space Studies		CMIP6	GFED4s, pyrE (interactive fire model)	MEGAN, wind driven sea salt and dust, lightning			
Cyprese Institute Climate and Atmosphere Research Centre		CAMS, EDGAR	FINN or GFED or other	MEGAN, lightning, dust/sea salt	2010- present		
University of Bremen, Institute of Environmental Physics		CMIP6	GFEDv3,GFEDv4,CMIP6	MEGAN-MACC	Multi-year		
UKCEH/Edinburgh University, Atmospheric Chemistry and Effects/School of Chemistry	WRF, with reanalysis from GFS/ERA5 depending on version/setup. Nudged every 6 hrs, 1 deg res.	NAEI for UK, CEIP for Europe, HTAP (2010) for global	NCAR FINN (v1.5 and transitioning to v2.5)	Online BVOCs, soil NO _x , volcano, seasalt, dust	Month to multi-year	Emissions evenly distributed over 8 lowest vertical layers (Simpson 2012)	Simpson et al. (2012); Vieno et al. (2016)
UK Met Office, Hadley Centre		Mainly CMIP6, but flexible	can run with prescribed emission datasets or use online interactive fire model INFERNO	various and depends on the configuration setup but mostly interactive for dust, BVOCs, sea salt, DMS	Typically years, multi-year, multi- decade		
Lancaster University, Lancaster Environment Centre	Driven by ECMWF-IFS cy38 met at TL159L60 3-hr resolution	flexible	flexible	MEGAN	Single- year/multi- year	Surface/PBL emissions only	Wild (2007)
Thailand Team, KMUTT		HTAP/CAMS, locally adjusted	FINN and others	MEGAN	Sub- seasons, selected events		
IITM Pune, India, AQEWS Urban Air Modelling		EDGAR- HTAP	FINNv1.5	MEGAN	Air quality forecast for 10 days		
CICERO Center for International		Flexible, but currently CEDS and	GFED4	MEGAN (online or offline)	Single- year/multi- year, likely		

Climate Research,		ECLIPSE most			time slice		
Oslo, Norway		used.			for selected		
					longer		
					timescales.		
DLR Institute of				Lightning NOx,			
Atmospheric	Free running or	flexible	flexible	air-sea exchange,			Jöckel et al. (2016;
Physics, Earth	nudged (ERA5)			dust, biogenic			2010)
system modelling				and soil-NOX			
NOAA Geophysical Fluid Dynamics Laboratory (GFDL)	Driven by observed SSTs or nudged to reanalysis winds	CEDS-v2021- 04-21	GFED4 (daily or monthly), but flexible	MEGAN BVOCs; Interactive dust coupled to vegetation cover; Lightning NO coupled to subgrid	Multi-year, multi- decade	Distributed vertically up to 6 km, based on an injection height climatology from MISR	Lin et al. (2024a,b)
				convection			
MIT, Earth,							
Atmospheric and		PKU	PKU	PKU			
Planetary Sciences							
Meteorological Research Institute, Japan Met Agency (MRI-JMA), Dept of atmosphere, ocean, and Earth system modelling research	Free-running or nudged to JRA55	CMIP6, ECLIPSEv6b	CMIP6/GFED, GFED				
Institut National Polytechnique Felix Houphouet-Boigny (INP-HB) Department of Forestry and Environment	ERA5	CMIP6	GFED4				
Space Research of the Netherlands, Earth Dept.	mainly ECMWF	CAMS	GFED4.1s, or GFED5, or GFAS			IS4FIRES	
Norwegian Met Inst, Research Dept	ECMWF	Variable, mainly EMEP	FINN, GFAS				
NILU, Atmospheric Chemistry	ECMWF, ERA5, CESM GCM, WRF,	ECLIPSEv6b	GFED, GFAS		Years	From GFAS emissions dataset	Pisso et al. (2019)

Finnish Meteorological Institute, Atmospheric Composition Research	nudged to MERRA2 reanalysis data	CAMS, CMIP, ECLISE, EDGAR	IS4FIRES	MEGAN or own model (Europe)	From 5 day forecasts up to multi- decades in climate mode	Sofiev et al. (2012)	
Tsinghua University, School of Environment	NCEP FNL reanalysis data	Huang et al. (2023) for full- volatility organic, CMIP6 for other pollutants. Chang et al. (2022) for full- volatility organic ABaCAS-EI for other pollutants	Full-volatility organic emissions based on the burning area of GFEDv4; Other pollutants from GFEDv4. FINN; full-volatility organic emissions based on the burning area of GFEDv4	dust/biogenic/sea salt: calculated online dust/biogenic/sea salt: calculated online	Multi-year (2015- 2020), 2018	Daily fire info from FRP and met data. Freitas plumerise scheme	
University of Augsburg, Faculty of Medicine	nudged to GFS during spinup above PBL	EDGARv5 + national German inventory	FINN	online	Season to multi-year		
Jožef Stefan Institute / MSC-E, Dept of Environmental Sciences	ECMWF, WRF	EMEP, EDGAR, PKU	FINN, MCHgMAP, PKU	MCHgMAP, PKU	Multi-year		
Peking University, Lanzhou University	ECMWF, NCEP FNL	PKU, LZU, EDGAR	PKU, LZU		Month to multi-year	Gaussian plume model to distribute to 3km height	Luo et al. (2020); Song et al. (2022)
Sorbonne Université, LATMOS/IPSL	ERA5, WRF	CAMS	CAMS GFAS, APIFLAME	MEGAN, dust, sea salt, lightning	Seasonal	Satellite observations, GFAS plume height	Menut et al. (2021); Turquety et al. (2020)
Stockholm University	Driven by ECHAM 5 model outputs	Flexible	Flexible	Flexible	Multi-year, multi- decade	Emission to boundary layer or free troposphere	MacLeod et al. (2011)