Supplement of "HTAP3 Fires: Towards a multi-model, multi-pollutant study of fire impacts" by Whaley et al

Contents

S1. Regional discussions

Additional information about biomass burning in several global regions are included below to supplement that in the main paper.

Sub-Saharan Africa

Fire-induced BC concentration and direct climate forcing vary significantly spatially and temporarily, with the highest emissions globally occurring in sub-Saharan Africa (van der Werf et al., 2010).

Amazon Basin

Occurrences of wildfires in the Amazon Basin respond strongly to climate change and play an increasingly important role in changing the global climate.

Arctic

During extreme fire years like 2020 in the Arctic and boreal driven by both lightning and human-caused fires, BC emissions from wildfires as estimated by GFAS are several times larger than anthropogenic sources estimated from the GAINS model (McCarty et al., 2021). The BC levels and climate forcing sourced from wildfire biomass burning across the Northern boreal forest have increased in the past decades, particularly in recent several years (Liu et al., 2023).

The biogeochemistry in the Arctic Ocean has been shown to be influenced by Siberian fires emissions (Section 3.2.3), as well as a large fraction of the nitrogen was likely to be coming from Boreal peat burning; linking the impacts of a warming climate on fire activity to widescale ecosystem change across the Arctic region.

Australia

The 2019-2020 Australian wildfires were the most expensive to-date for that country with total costs of US$4.5 billion (Masters, 2021).

Equatorial Asia

An estimated 100,000 premature deaths across Equatorial Asia occurred due to the 2015 severe wildland fire season in Indonesia (Koplitz et al., 2016; Crippa et al. 2016).

Europe

In Greece, 800 families had lost their forest-based livelihoods in the wildfires on the island of Evia in 2021 (Psaropoulos, 2021). There have also been increased civilian fatalities since the late 1970s in per-urban or wildland-urban interface (WUI) areas of the Mediterranean (Molina-Terre ́net al. 2019).

In another study of 2009, 323 896 ha were burned in France, Portugal, Spain, Greece and Italy (European commission, 2010). While Mediterranean fires are small compared to fires in other areas of the world, they often cause significant damage to homes and businesses and threaten human beings and animals, because they occur so close to urban areas and are fueled by hot temperatures and high wind speeds.

India

Forests in India are of diverse types but much focus remains on fires in Himalayas or shifting cultivation led fires in north-east India. However, central India forest fires often go neglected. In the study conducted by Jain et al. (2021), from 2001 to 2020, about 70% of forest fires over central India domain occurred during 2 months March (1,857.5 counts/month) and April (922.8 counts/month). However, owing to warmer conditions in the Indian subcontinent from 2006 to 2020 (as compared to 2001–2005), a doubling and tripling of forest fire activity is noted in forest fire (FMAMJ) and non-fire (JASONDJ) seasons, respectively. The study further highlights the role of multiple simultaneous climate extremes for example, El Niño, heat waves, weak ISM, and droughts in causing anomalously high fire activity periods over central India. Statistical associations among monthly forest fire counts and various meteorological and environmental variables over a smaller but a high forest fire activity region are highlighted for FMAMJ. High forest fire counts decrease the soil moisture content, evapotranspiration, and normalized difference vegetation index (NDVI) and are associated with an increase in BC and CO emissions. High surface air temperatures prior to ISM significantly increase soil temperature and significantly reduce NDVI, creating a drier environment. Moreover, precipitation shows a significant positive correlation with soil moisture content, evapotranspiration and NDVI. During FMAMJ, chances of precipitation are very low. Thus, high near surface air low precipitation, low soil temperature and moisture, low evapotranspiration and low NDVI during FMAMJ create conducive conditions for high forest fire activity in central India domain.

Agricultural burning smoke has been shown to cause asthma, chronic obstructive pulmonary disease (COPD), bronchitis, reduced lung capacity, emphysema, cancer, and more (Ghosh et al., 2019). For example, people residing in Punjab, agricultural state of India, are exposed to recurrent fires, and have suffered from those respiratory diseases (Alexaki et al. 2019; Saxena et al. 2021). Among these sources, agricultural crop residue burning (ACRB) stands out as a significant contributor to ambient PM, alongside biowaste burning and forest fires (Mittal et al., 2009). Stubble burning has been linked to a 3.25% increase in mortality (1.56% per month) with a 10 μg/m3 rise in particulate matter, notably leading to a 1.82% surge in cardiopulmonary disease cases (Liu et al., 2018). A mere 10-point increase in stubble burning could elevate overall mortality by 1.71% and cardiopulmonary mortality by 1.91%. The burning of crop residues in northwest India has directly impacted Delhi's Air Quality Index (AQI), contributing to 149 million tons (Mt) of carbon dioxide (CO_2), 9.0 Mt of carbon monoxide (CO), 0.25 Mt of sulphur oxide (SOX), 1.28 Mt of particulate matter (PM), and 0.07 Mt of black carbon (BC) (He et al., 2020). Heart disease affected 84.5% of the population, eye irritation impacted 76.8%, nasal irritation affected 44.8%, and throat irritation impacted 45.5%. Instances of hacking-related issues increased by 41.6%, while wheezing problems rose by 18.0% (Yadav, 2019).

Lower Mekong Region

Upper Southeast Asia has a tropical-subtropical climate and experiences fires recurring during the dry season (November-April). Its first half is influenced by the northeast monsoon, which induces cool dry air with no or little precipitation favorable for fuels to dry and fires to spread. In the second half, the monsoon weakens and ceases, with March-April corresponding to the summer when relatively high temperature promotes fire ignitability. Almost all fires in the region are caused by or linked to human activities, such as gathering of non–timber forest products, hunting, deforestation, land clearing, slash–and–burn agriculture, and carelessness (Tanpipat et al. 2009). According to Phoo et al. (2024), three distinct fire–prone areas exist in Upper Southeast Asia, which are western Myanmar, northern Cambodia, and the tri-state zone (including eastern Myanmar, northern Thailand, and northern Laos combined). The region that aggregately encompasses the last two fire-prone areas is here referred to as the Lower Mekong Region. The peak fire timing of northern Cambodia is January-February but shifted later to March–April for the other fire-prone areas. The tri-state zone has diverse land covers with forests being dominant (followed by croplands and then urbanized areas) and is also topographically complex with mountains-valleys, highlands, and plains. Pollutants emitted from fires and other anthropogenic sources can thus easily accumulate under stagnant air with low mixing height. This fire-prone area has been recognized as having severe smoke haze occurrences, which cause public health concern, socio–economic impacts, reduced visibility for transport and tourism, and transboundary air pollution (Bran et al. 2022; Moran et al. 2019; Thao et al. 2022). Effort has been made through Trilateral Consultation on Transboundary Haze Pollution, among leaders of Laos, Myanmar and Thailand, with collaboration towards making CLEAR Sky Strategy Joint-Plan of Implementation to prevent, mitigate and manage open fires (Unapumnuk and Yensrong, 2024) , while scientific support is required, as emphasized in the ASEAN Haze Free Roadmap 2023-2030, starting from Thailand collaboration with NASA and International community in the field campaign conducted during March 2024 (https://espo.nasa.gov/asia-aq/content/ASIA-AQ_White_Paper).

United States

In California, along with the neighbouring states of Oregon and Washington (ODF, 2020), the last 5 years have seen a historic increase in wildfire activity. In 2017, the Tubbs Fire became the most catastrophic wildfire on state record, claiming 5,636 structures and 22 lives (CAL FIRE, 2020). The approximated economic impacts from lost infrastructure and homes, health costs and other damages in California, from overall economic and business disruptions was US$148.5 billion in 2018, or roughly 1.5% of the state's GDP (Wang et al. 2021).

S2. Health impacts from acute exposure to fire emissions

Some VOCs and PAHs released during wildfires causes skin and eye irritation, drowsiness, coughing and wheezing while other like benzene may be carcinogenic (Sahu and Saxena, 2015). There were studies conducted in firemen provide an accurate model for understanding health impact of wildfire emissions. Extensive research conducted during forest firefighting in the United States and Australia identified carbon monoxide and respiratory irritants as the main wildfire pollutants of concern to firefighters (Aisbett et al., 2012). Brotherhood et al. (1990) assessed the carboxyhemoglobin saturation (COHb%) levels from alveolar CO levels in 24 firefighters working with hand tools and in 12 accompanying scientific observers, before and after firefighting (duration 37 to 187 min) on 15 experimental bushfires. Carboxyhemoglobin levels increased on average by 0.7% per hour in the firefighters and by 0.3% per hour in the observers that indicate that firefighters are generally unlikely to experience hazardous levels of CO exposure. A risk assessment of firefighter exposure during wildfires was conducted in Australia (Reisen et al. 2011). This study monitored air toxins within the breathing zone of the firefighters and showed that 30% of firefighters were exposed to high levels of hazardous pollutants like CO, respirable particles and formaldehyde that increased the occupational exposure standard (OES) for 5% to 20% of time.

Similarly, farmers and those close to recurrent agricultural burning can also be acutely exposed to the smoke, with negative consequences. For example, due to prolonged pollutant presence from stubble burning and limited dispersion owing to atmospheric conditions, the smoke accumulates in the lower atmosphere, posing heightened risks to people's well-being (Govardhan et al., 2023). Prolonged exposure at high levels can result in permanent health issues, including the development of chronic lung diseases such as asthma, chronic obstructive pulmonary disease (COPD), bronchitis, reduced lung capacity, emphysema, cancer, and more (Ghosh et al., 2019). Many farmers exposed to stubble smoke report eye and lung irritation and significant healthcare expenses (Kumar et al., 2015).

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Finally, high blood pressure is a primary risk factor for non-communicable disease-related deaths across diverse economic settings (IHME, 2017). Medical and epidemiological investigations have connected air pollution from fires to elevated rates of hypertension and cardiovascular stress (Hadley et al., 2018). The adverse effects of exposure span from skin and eye irritation to severe neurological, cardiovascular, and respiratory ailments (Lelieveld et al., 2015). In specific cases, it can lead to fatal consequences, particularly among individuals with pre-existing respiratory conditions (Saggu et al., 2018).

S3. Fire Management Policies

S.3.1: Agricultural fire management

Amidst the escalating detrimental health effects of crop residue burning, the implementation of sustainable residue management practices is essential to safeguard both the environment and public health. Several studies have highlighted various environmentally sustainable crop residue management methods that not only offer economic advantages but also reduce healthcare expenses (Jiang et al., 2018). Alternative approaches proposed by researchers involve utilizing stubble for purposes such as raw material in liquor production, mushroom cultivation, or as fuel for boilers via gasification processes (Gummert et al., 2020). Moreover, employing crop residue in the construction industry for making diverse types of cement and blocks presents a feasible strategy (Bories et al., 2015). Despite extensive research confirming the positive impacts of Sustainable Crop Residue Management Practices (SCRMPs) and their feasibility at a local level, their adoption rate remains relatively low (Smith et al., 2007). This limited adoption might stem from inadequate awareness about the advantages of these strategies, particularly concerning their environmental and health implications (Domingo et al., 2014).

S.3.2: Prescribed burns
In the field of conservation of biodiversity, controlled burning is an effective method. Controlled burns, which replicate natural fire regimes, provide different habitat structures that sustain a wide range of plant and animal species (Pausas and Keeley, 2019). Fire-adapted flora survives, maintains ecological balance, and avoids species domination, all of which contribute to biodiversity enhancement (He et al., 2019). Prescribed burning increases ecosystem resilience by proactively lowering fuel loads, resulting in fire-adapted landscapes that recover faster from disturbances (Thacker et al., 2023; Volkova et al., 2021). This technique not only guards against catastrophic fires, but it also increases adaptive capacity, hence supporting long-term ecological stability (Ascoli et al., 2023; Pais et al., 2023).

The reaction of plants to targeted fires is noteworthy, triggering systems that promote regeneration (Sagra et al., 2019). Fire-adapted plant species thrive thanks to adaptations including serotinous cones and fire-resistant bark (He et al., 2019; Pausas and Keeley, 2019). Controlled fires also eliminate invasive species and stimulate the germination of certain seeds, modifying vegetation composition in accordance with ecological goals (Ditomaso et al., 2006; Lamont, 2022; Sagra et al., 2019).

Addressing air quality concerns is a critical component of sustainable land management. Although controlled fires emit emissions, planned execution reduces their negative effects (Bowman et al., 2018; Jaffe et al., 2020; Neidermeier et al., 2023). Timing, fuel moisture, and atmospheric conditions all play important roles in reducing air quality concerns, ensuring a balanced approach that corresponds with environmental goals while protecting public health (Rafaj et al., 2018). Prescribed burning has effects on carbon sequestration in ecosystems. Controlled burns promote the establishment of fire-adapted plants and avoid uncontrolled wildfires, resulting in a sustainable carbon footprint (Lipsett-Moore et al., 2018; Simões et al., 2023). Prescribed burning is most successful when it is integrated into comprehensive land management schemes (Neidermeier et al., 2023). Controlled burn solutions aim to balance ecological, social, and economic advantages with conservation aims (Pais et al., 2023; Simões et al., 2023).

S.3.3 Options for future changes to fire management
The ABC-iCAP project has produced fire emissions “storylines” for different fire management, natural resource and fire fighting policies, and socioeconomic drivers of fire activity for the countries that comprise the Arctic Council, with a focus on Arctic, boreal, and temperate ecosystems (Paunu and McCarty, 2023). The primary aim is that these future Arctic and boreal fire storylines will be integrated with SSP-aligned emission scenarios and SSP emission estimates and modeling efforts. Three storylines were developed for each of the eight Arctic states, representing low fire activity (dubbed the “We Got This” storyline), high fire activity (“Let It Burn” storyline), and middle-of-the-road fire activity (“The Fire Will Come” storyline). A natural extension of these Fire Management storylines is the product of a spatiotemporally explicit emissions dataset that can be used in future climate modeling efforts. Further, the process by which the storylines was developed, including country- and ecosystem-specific management and policy variables, could be replicated globally via local experts. The future fire management scenarios and needed emission datasets are

unfortunately not available in time for this project, but the specific need to include fire management, fire policies, and socioeconomic influences on global fire activity is a parallel effort required to produce more accurate modeling of global fire emissions.

S4. Inverse modelling of atmospheric transport

Observations of atmospheric concentrations can provide information on sources and sinks in the atmosphere. As mentioned previously, gases concentrations can have their surface fluxes either modified by atmospheric transport or by chemical reactions or physical process in the atmosphere. By combining a chemistry transport model (CTM) and observed atmospheric gas mole fractions, we can infer surface-atmosphere gas emissions with an atmospheric inversion (also called top-down approach, Bolin and Keeling, 1963). Inversions consist in finding a set of statistically optimal fluxes satisfying measurements and prior inventories (or bottom-up emission inventories) within their respective uncertainties. As an inverse problem, the upwind gas fluxes are estimated from the downwind observed gas mole fractions. The surface gas fluxes are adjusted so that forward-simulated gas mole fractions better match the gas measurements while considering the uncertainty statistics on the observations, transport, and prior surface fluxes. Hence, with inversions, the CTM are better constrain from observed concentration than with forward simulation alone.

Particularly, with dense satellite constellations and networks of surface observations, data assimilation and so inversion is commonly used to quantify emissions.
Inverse modeling has been largely used and applied to different scale problems, going from locale and regional emissions (Vautard et al., 1998, Byrne et al., 2022), to optimize global estimations (Houweling et al., 1999, Arellano et al., 2006, Peiro et al., 2022a, 2022b).

Inverse problem are ill-posed meaning that the solution is underdetermined by the observational constraints, which is why additional information are required, such as prior emissions and their uncertainties. This is performed using Bayesian techniques to produce a unique solution. If the amount of observation used in the inversion is high, then the posterior emissions will be more strongly impacted by the assimilated data. However, for regions with low density observations, the posterior fluxes will remain similar to the prior fluxes. This is why in recent inversions, satellite measurements are generally used in addition to ground based observations (Peiro et al., 2022a).

Although CTM performances have improved, there are still uncertainties due to complex interplay of source distributions, transport, and chemistry. Inverse modeling hence allows for a better quantification of the variables driving the physical atmospheric system. If prior error settings are posed appropriately, optimizing emissions and concentrations allows the data assimilation system to address issues on transport or observing errors (Schuh et al., 2019, 2022). As described in the model intercomparison projetcs (MIPs), the use of multiple inversions performing using different CTM and prior constraints, can help to partially account for systematic errors related to model transport and prior information (Crowell et al., 2019, Peiro et al., 2022a). Even though variability among transport models remains the largest source of uncertainty across global flux inversion systems, Schuh et al., (2019) suggest the importance of using model ensembles and independent observations for evaluation.

Table S1: Observations available for model evaluation.

Observation	**time period**	**region**	**species**	**link to dataset if publicly available**	**link to information about the dataset**	**Comments**
FIREX-AQ campaign	Summer 2019	Western North America		https://csl.noaa.gov/projects/firex-aq/; https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022JD037758	https://csl.noaa.gov/projects/firex-aq/	aircraft and surface measurements
HAPs lab, Passive air samplers	2010-2015	Athabasca Oil Sands Region	polycyclic aromatic compounds	https://donnees.ec.gc.ca/data/air/monitor/deposition-oil-sands-region/ecosystem-exposure-polycyclic-aromatic-compounds-passive-oil-sands-region/?lang=en	https://pubs.acs.org/doi/10.1021/acs.estlett.9b00010	the data is on the OSM portal, paper linked here, passive air sampling captured regional forest fires in Northern Alberta, Canada
TOAR tropospheric ozone database	Long-term, but depends on each site	global	ozone and precursors	https://toar-data.org/	https://toar-data.org/	surface, satellite, aircraft, ozonesondes
Canadian Aerosol Baseline Monitoring (CABM): Aerosol physical properties	2006-2020 (Alert); 2009-2020 (ETL, Egbert, Whistler)	Canada	1) Aerosol absorption, 2) Aerosol scattering, 3) particle number concentration size distribution	https://ebas.nilu.no/data-access	https://ebas.nilu.no/data-access	surface measurements for aerosol optical measurements

Canadian Aerosol Baseline Monitoring (CABM): Aerosol chemical properties	2006-2020 (Alert); 2009-2020 (ETL, Egbert)	Canada	Sulphate, Nitrate, Ca, K and some major inorganic ions.	https://ebas.nilu.no/data-access	https://ebas.nilu.no/data-access	surface measurements for aerosol chemical measurements
Canadian Aerosol Baseline Monitoring (CABM)__Carbonaceous aeosols (EC: Elemental carbon, OC: organic carbon, POC: pyrolysed OC as proxy of Brown carbon	2006-2016	Canada	1). Elemental carbon (EC), 2). Brown carbon (POC), 3). Organic carbon (OC); 4). carbon isotopes (13C)	https://ebas.nilu.no/data-access	https://ebas.nilu.no/data-access	All data are surface measurements. Only EC/OC datasets from Alert, Egbert & Toronto data were in the database. Other datasets are accessible from the PI. 2006-2016 for Alert, ETL, Egbert, Toronto. 2008-2016 for Whistler Mt., 2014-2016 for Mauna Loa Observatory
The Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN) field campaign	Summer 2018	Western U.S.	CO, CO2, CH4, N2O, H2O, NO, NO2, O3		https://www2.acom.ucar.edu/lab-annual-report/2018/1c-western-wildfire-experiment-cloud-chemistry-aerosol-absorption-and-nitrogen-we-can	
DOE Layered AtlanticSmoke Interactions with Clouds (LASIC) campaign	June 2016-October 2017	Ascension Island	SP2, ACSM, optical properties	ARM archive: https://www.arm.gov/research/campaigns/amf2016lasic	also on ARM archive: https://www.arm.gov/research/campaigns/amf2016lasic	surface measurements only
CLARIFY UK aircraft campaign	August-September 2017	Ascension Island (8S, 14.5W)	see Haywood et al. 2021 ACP overview paper	BADC		ORACLES, LASIC, CLARIFY publications collected into an ACP special issue
Organic aerosol observation campaign in East Asia	December 2009–November 2011	Rishiri (45.2N, 141.3E), Okinawa (26.9N, 128.2E), Japan	Carbonaceous (OC, EC), some organic tracers (e.g.,levoglucosan, mannitol, SOA tracers), inorganic ions.		https://doi.org/10.5194/acp-15-1959-2015, https://doi.org/10.1016/j.envpol.2019.01.003	surface measurements for aerosol chemical components

EMEP data	1990-2022	Europe	BC, CO, Hg, POPs	https://ebas.nilu.no/data-access	https://ebas.nilu.no/data-access	
AMAP data	1990-2022	Arctic	polycyclic aromatic compounds, POPs	https://ebas.nilu.no/data-access	https://pubs.acs.org/doi/10.1021/acs.est.8b05353	
Great Lakes Basin Monitoring and Surveillance Program (GLB)	1990-2022	Great Lakes	polycyclic aromatic compounds, POPs, metals	https://open.canada.ca/data/en/dataset/5d8548c5-e284-4e85-aed4-c22536de615a	https://pubs.acs.org/doi/10.1021/acs.est.0c07079	
Integrated Atmospheric Deposition Network (IADN)	1990-2022	Great Lakes	polycyclic aromatic compounds, POPs	https://iadnviz.iu.edu/#/about/		
Stockholm Convention Global Monitoring Plan Data Warehouse	Depending on reporting programs (up to 2020)	Global	POPs	https://www.pops-gmp.org/		Annual averages (all national programs contribute to this data warehouse, e.g. GAPS, GLB, EMEP, AMAP etc.)
National Air Pollution Surveillance (NAPS) Program	varies at sites	Canadian urban sites	PAHs, PCDD/Fs	https://data-donnees.az.ec.gc.ca/data/air/monitor/national-air-pollution-surveillance-naps-program/Data-Donnees/?lang=en		
Global Atmospheric Passive Sampling (GAPS)	2004-2020	Global (46 sites)	POPs	Data included in the Stockholm Convention GMP Data Warehouse		

Monitoring Network in the Alpine Region for Persistent and other Organic Pollutants (PureAlps, MONARPOP, POPAlp, EMPOP, VAOII)	2005-2020	European Alpine Region	POPs	Stockholm Convention Third Regional Global Monitoring Plan Report of Western Europe and Other Groups (WEOG) Annex 8.1		
MONET (EU)	2009-2020	Europe	POPs	Same as above		
Spanish Monitoring Program on POPs (SMP-POPs)	2008-2020	Spain	POPs	Same as above		
Swedish National Monitoring programme for Air	1996-2020	Sweden	POPs	Data included in the Stockholm Convention GMP Data Warehouse		3 long-term stations, Råö, Aspvreten/Norunda, Pallas, for the monitoring of POPs. These stations are also part of EMEP and Pallas is part of AMAP as well.
UK/Norway SPMD Transect	1994-2020	UK and Norway	POPs	Same as above		
Toxic Organic Micro Pollutants (TOMPs)	1991-2020	UK	PAHs, PCDD/F, PCBs, PBDEs	Same as above		
ICOS		Europe	CH_4, CO	https://www.icos-cp.eu/observati		

				ons/atmosphere/stations		
AGES+ campaign	Summer 2023	North America			https://csl.noaa.gov/projects/ages/	multiple aircraft measurements
MOYA campaign	2017 and 2019	Africa			https://acp.copernicus.org/articles/20/15443/2020/	
BORTAS campaign	2010-2011	North America and Europe	tropospheric oxidants		https://data.ceda.ac.uk/badc/bortas	ACP Special issue: Quantifying the impact of Boreal fires on tropospheric oxidants over the Atlantic using aircraft and satellites (BORTAS) (copernicus.org) Palmer et al. (2013)
WE-CAN campaign	2018					

Table S2. Summary of historical meteorological datasets/reanalyses.

reanalysis	organization	years	Temporal resolution	Vertical resolution	Horizontal resolution	reference
MERRA-2	NASA's Global Modelling and Assimilation Office and distributed by the Goddard Earth Sciences Data and Information Services Center	1980 to the present	hourly	42 pressure vertical levels	0.625° × 0.5° (latitude x longitude)	Gelaro et al., 2017
ERA5	ECMWF	1940 to the present	hourly	37 vertical pressure levels + optional 137 sigma levels	~31 km	Hersbach et al. 2020
NCEP/NCAR Reanalysis 1	NCEP, NCAR	1948 to the present	6-hourly, daily, monthly	17 pressure levels, and 28 sigma levels	2.5° x 2.5°	Kalnay et al., 1996
JRA-55	Japan Meteorological Agency	1958 to the present	3-hourly	60 vertical levels up to 0.1 hPa	TL319	Kobayashi et al., 2015

Table S3. Widely used quantitative Health Risk Assessment tools (Adapted from: Hassan Bhat et al., 2021)

S. No.	Tool	Developer	Reference
1.	Air Quality (Air Q+)	World Health Organization (WHO)	WHO, 2016; Goel et al., 2021
2	BenMAP-CE	United States Environmental Protection Agency (USEPA)	Sacks et al., 2018; 2020
3	The Simple Interactive Model for better Air quality (SIM-air)	Urban Emissions	Guttikunda and Jawahar, 2012; Guttikunda and Calori 2009
4	EcoSense	Institute of Energy Economics and Rational Energy Use (IER), University of Stuttgart	Wagner et al., 2013; Weichenthal et al., 2014
5	Greenhouse gas—Air pollution Interactions and Synergies (GAINS) model	International Institute for Applied Systems Analysis (IIASA)	Nguyen et al., 2008; Liu et al., 2013

6	CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool	The United States Environmental Protection Agency (EPA)	USEPA, 2021; Mailloux et al., 2022
7	Aphekom	French Institute of Public Health Surveillance	Henschel et al., 2013; Pascal et al., 2013
8	BaP*eq* and Incremental Lifetime Cancer Risk (ILCR)	The United States Environmental Protection Agency (EPA)	USEPA, 2005; Chen and Liao, 2006

Table S4. Comparative analysis between the different Air pollution Health Risk Assessment tools (Adapted from: Hassan Bhat et al., 2021)

Characteristic	**AIRQ2.2**	**BenMAP-CE**	**COBRA**	**ILCR**	**SIM-Air**	**GAINS**	**EcoSense**
Health Impacts							
Mortality (cases)	√	√	√	√	√	√	√
Disability-adjusted life years (DALY)	√	√	√			√	√
Morbidity (cases)	√	√	√	√	√		√
Economic Impacts	√	√	√		√		√
Pollutants:							
$PM_{2.5}$	√	√		√	√	√	√
PM_{10}	√	√			√	√	√
Ozone	√	√				√	√
NO_2	√	√	√			√	√
SO_2	√	√	√			√	√
CO	√	√				√	√
Other	Black smoke		VOC	VOCs, PAHs		CO_2, VOC, CH_4, N_2O	Hydrocarbons, dioxins and heavy metals
Spatial Resolution							
Regional	√	√	√	√	√	√	√
National	√	√	√	√		√	
City-level	√	√	√	√	√	√	
Household/Indoor	√		√	√		√	√

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